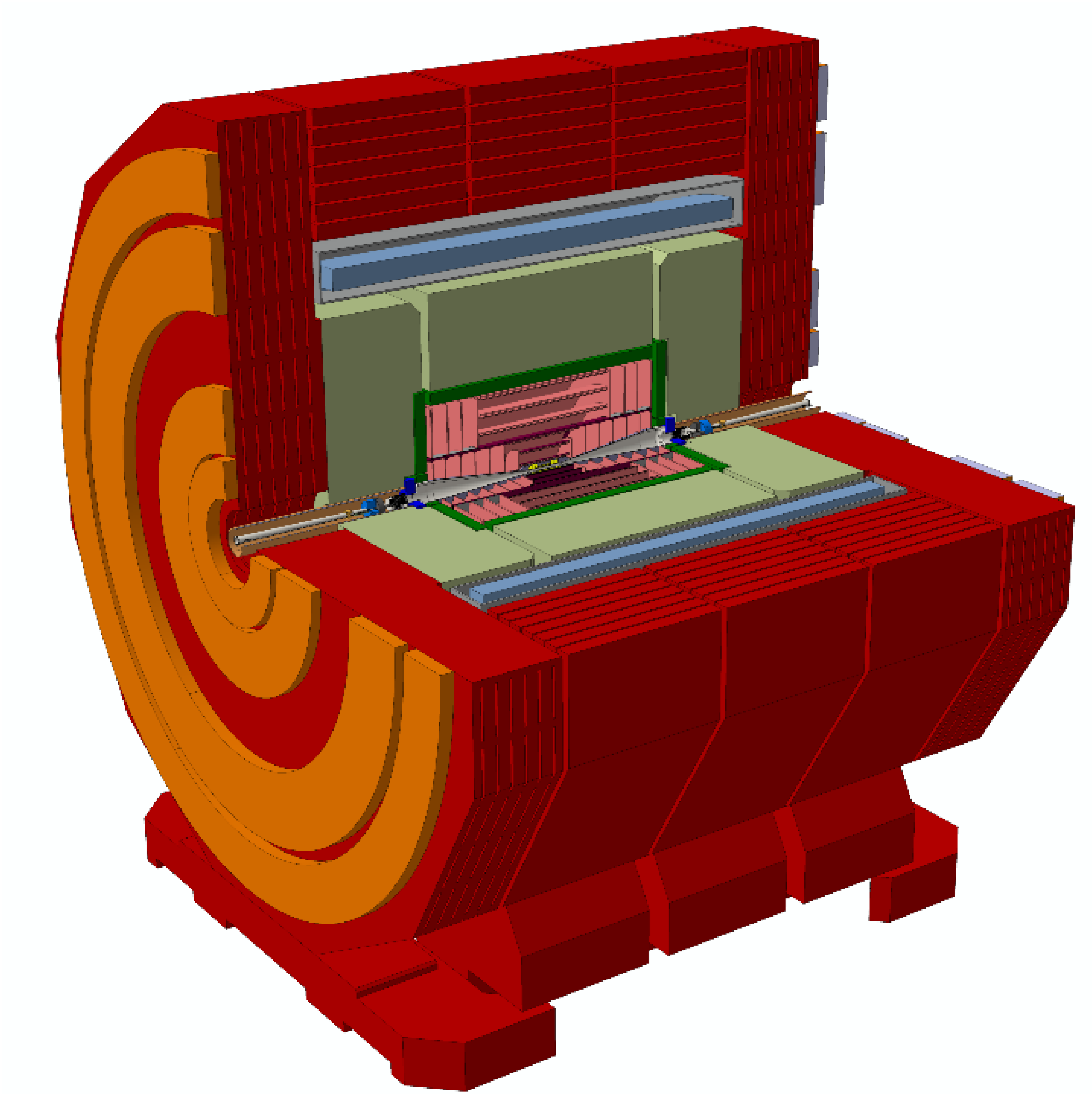
CLIC project: accelerator, detector and physics

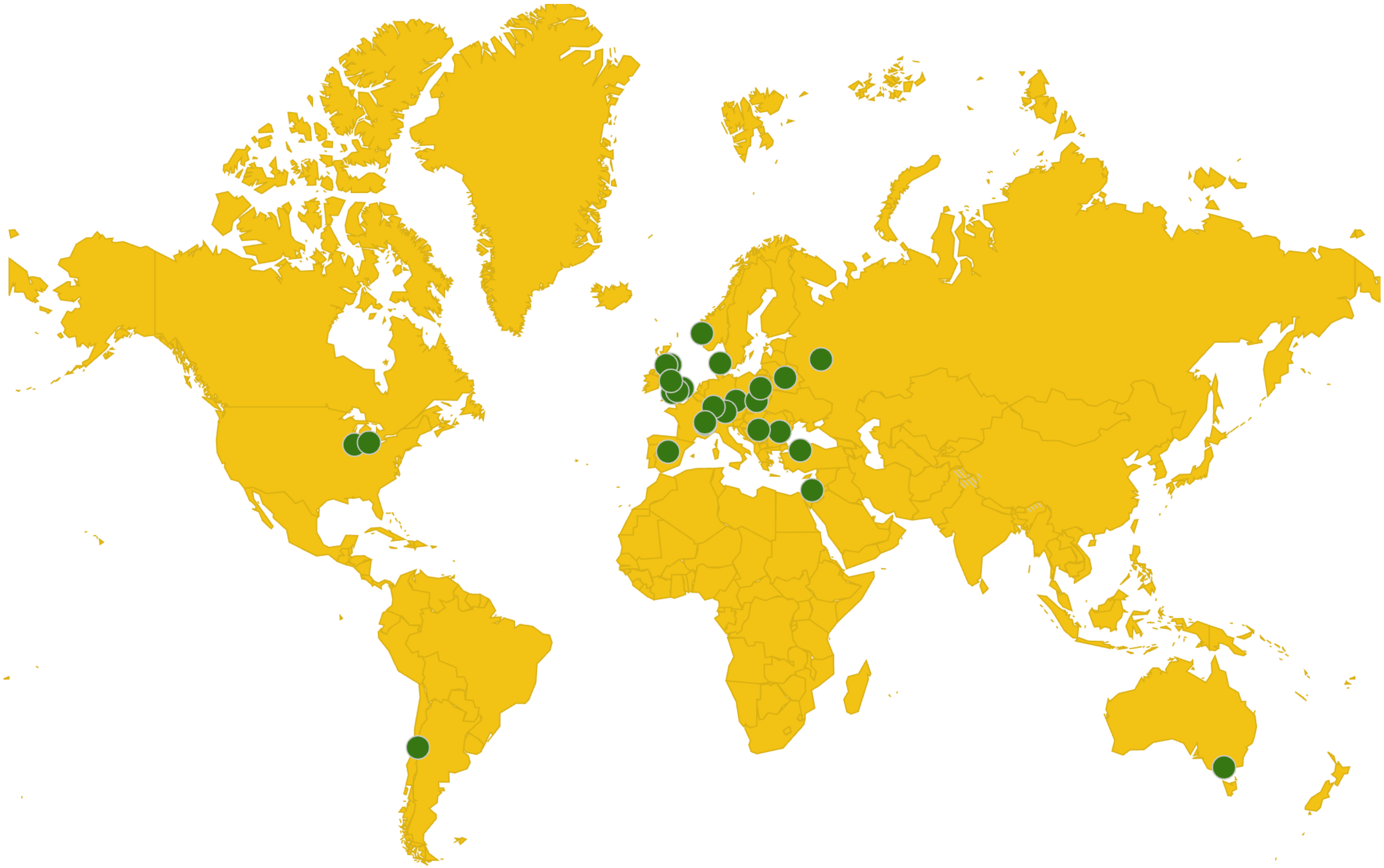


HEP Seminar
Warsaw
March 24, 2017

CLIC Collaborations

31 Countries – over 70 Institutes

CLIC detector & physics collaboration



- CLICdp collaboration addresses detector and physics issues for CLIC
- CERN acts as host laboratory
- Currently 29 institutes from 18 countries, ~180 members http://clicdp.web.cern.ch/
- Close connection to ILC detector concepts, CALICE, FCAL, AIDA-2020

CLICdp at this workshop

Workshop 2017:
- ~220 registrants (226 in 2016)
- ~80 physics/detector registrants (~67 at last CLICdp 2-day meeting)
- ~50 physics/detector presentations (all plenary)

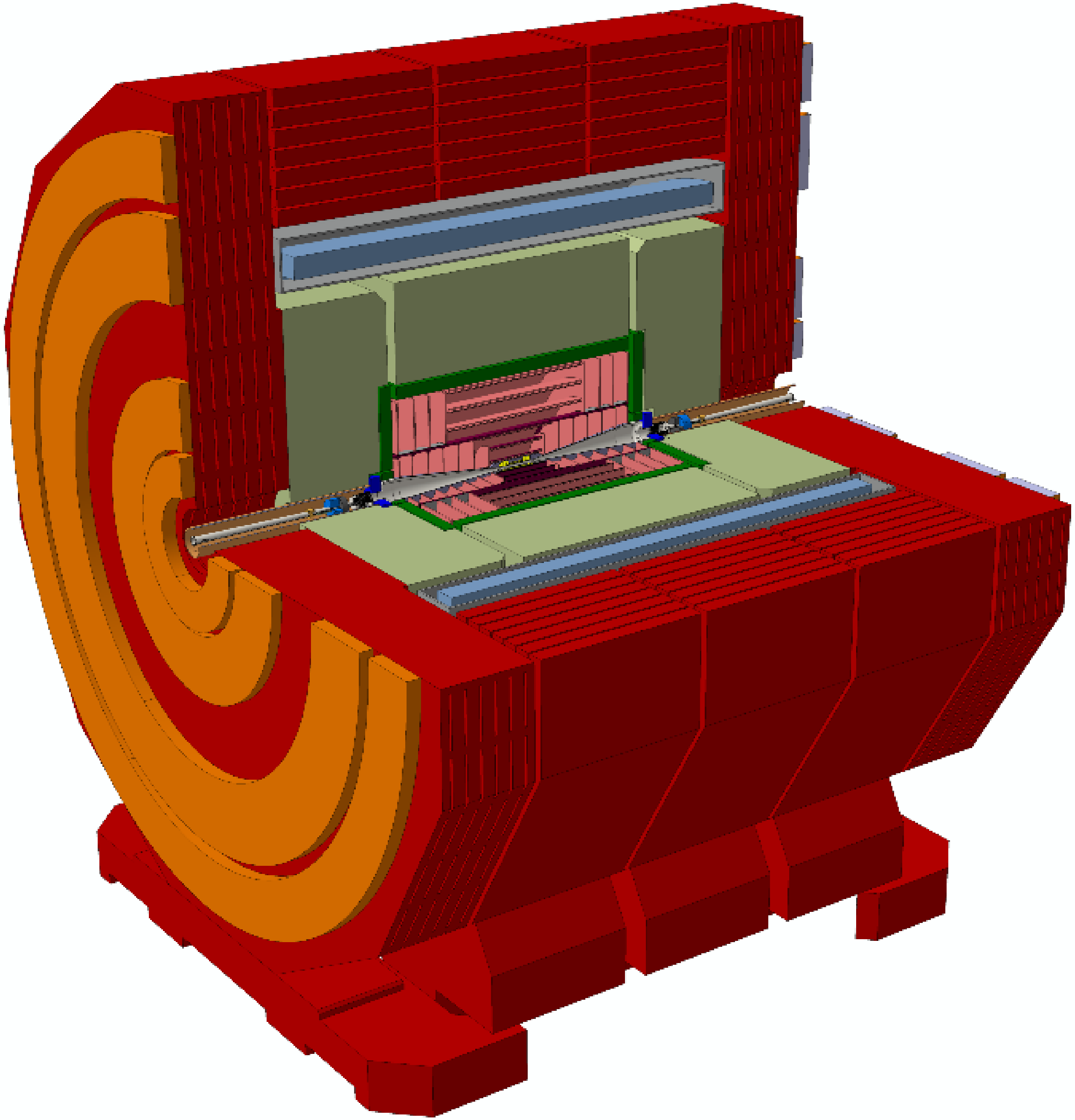
Topical sessions and conveners:
- Physics and Analysis (Igor Boyko, Wolfgang Kilian, Victoria Martin, James Wells)
- Detector Validation / Detector Calibration and Alignment (Jean-Jacques Blaising, Philipp Roloff, Matthias Weber)
- Software (Frank Gaede, Aidan Robson, Andre Sailer)
- Vertex and Tracker R&D (Daniel Hynds, Andreas Nurnberg, Joost Vossebeld)
- FCAL / ECAL / HCAL R&D (Marek Idzik, Eva Sicking)

Workshop dinner => Wednesday evening in CERN restaurant R1, included in workshop fee

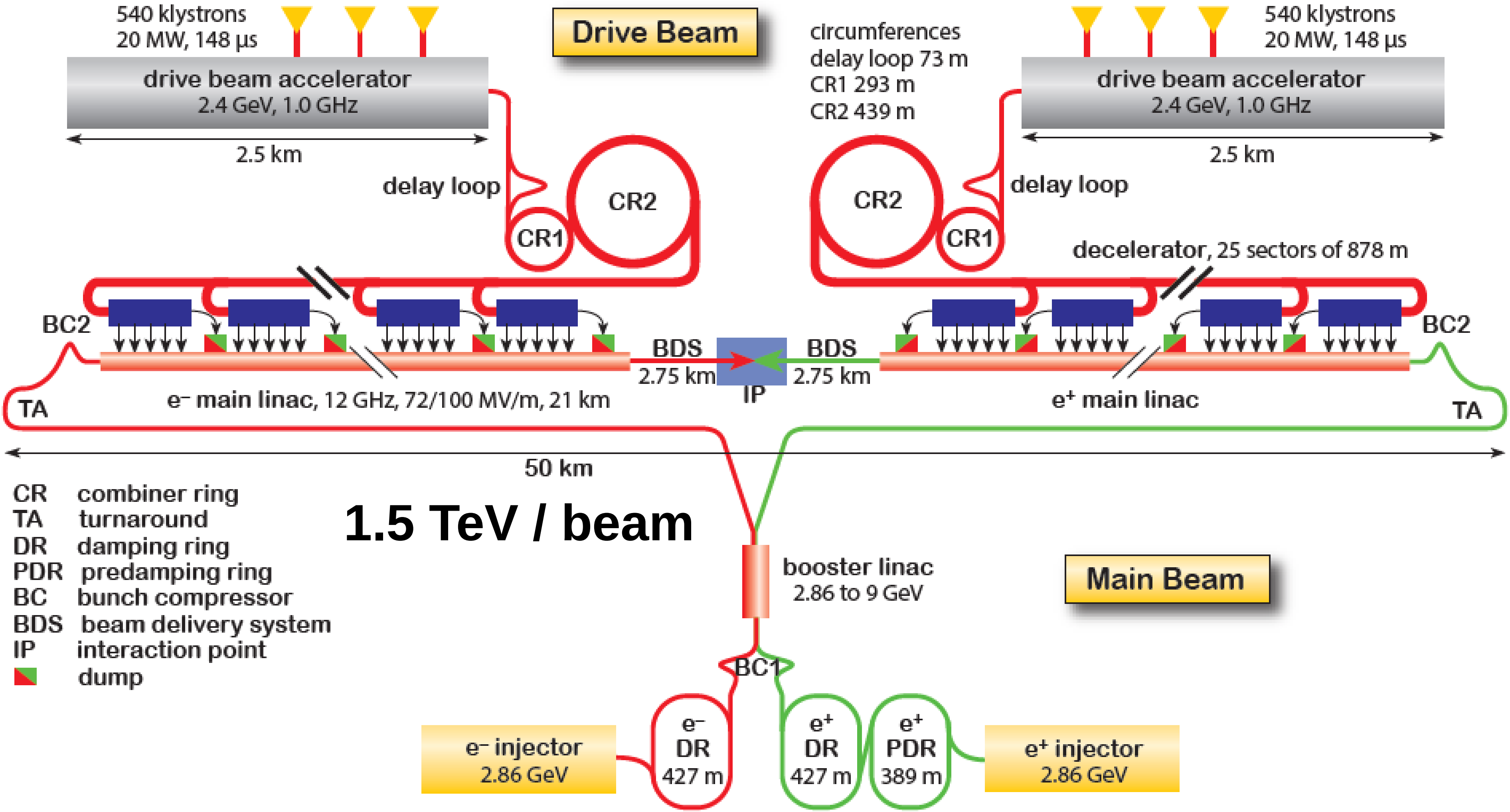
CLICdp dinner => Thursday evening in St Genis => 47 participants ≈ maximum

Unfortunately, no snowshoe outing on Friday, due to weather conditions

CLIC accelerator



CLIC layout (3 TeV)



540 klystrons
20 MW, 148 μs

Drive Beam

circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

540 klystrons
20 MW, 148 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

CR2

CR1

CR2

CR1

delay loop

decelerator, 25 sectors of 878 m

BC2

BDS
2.75 km

IP

BDS
2.75 km

BC2

TA

e⁻ main linac, 12 GHz, 72/100 MV/m, 21 km

e⁺ main linac

TA

50 km

1.5 TeV / beam

booster linac
2.86 to 9 GeV

Main Beam

BC1

e⁻ injector
2.86 GeV

e⁻
DR
427 m

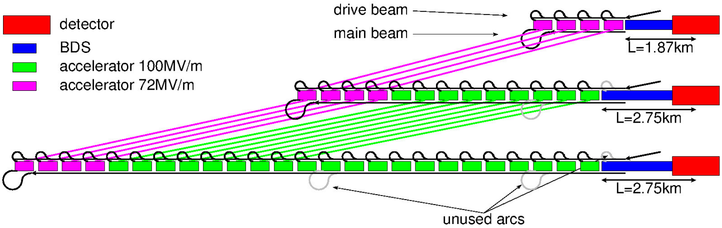
e⁺
DR
427 m

e⁺
PDR
389 m

e⁺ injector
2.86 GeV

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

Potential staging concept



- For the structures optimised for 380 GeV, staging scenario towards higher energy stages is available

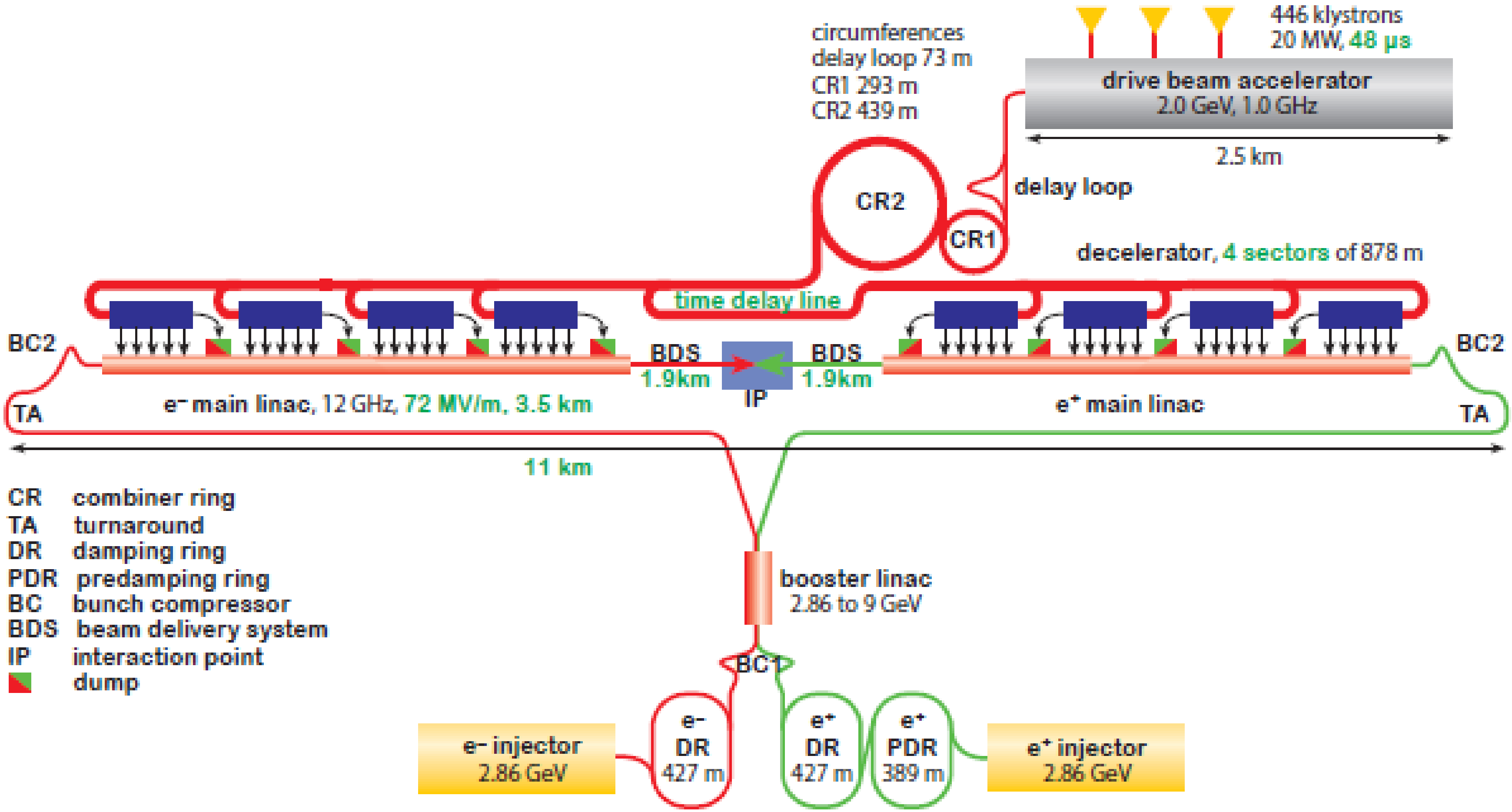
Conclusion on CLIC first energy stage

Find compromise for comprehensive physics programme of initial stage

- Higgs recoil mass measurement
  $\rightarrow$ 250 GeV$< \sqrt{s} <$ 420 GeV
- Higgs production via Higgsstrahlung and WW-fusion
  $\rightarrow$ 250 GeV$< \sqrt{s} <$ 450 GeV
- Top pair production
  $\rightarrow$ $\sqrt{s} >$ 350 GeV, maximum at $\sqrt{s} \approx$ 420 GeV
- Top as probe for BSM
  $\rightarrow$ $\sqrt{s} >$ 360 GeV
- Top not too close to threshold (theory uncertainties, boost)
  $\rightarrow$ $\sqrt{s} >>$ 350 GeV

$$\rightarrow \sqrt{s} = 380\,\text{GeV}$$

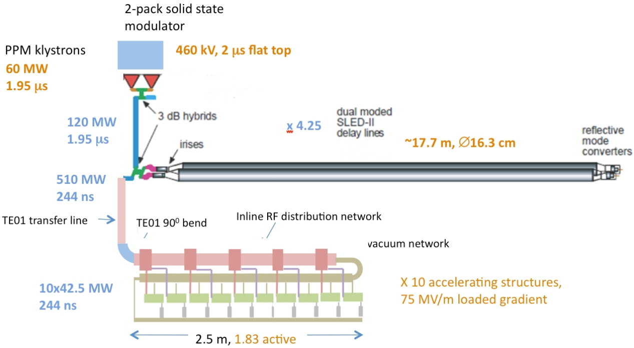
New CLIC layout 380 GeV



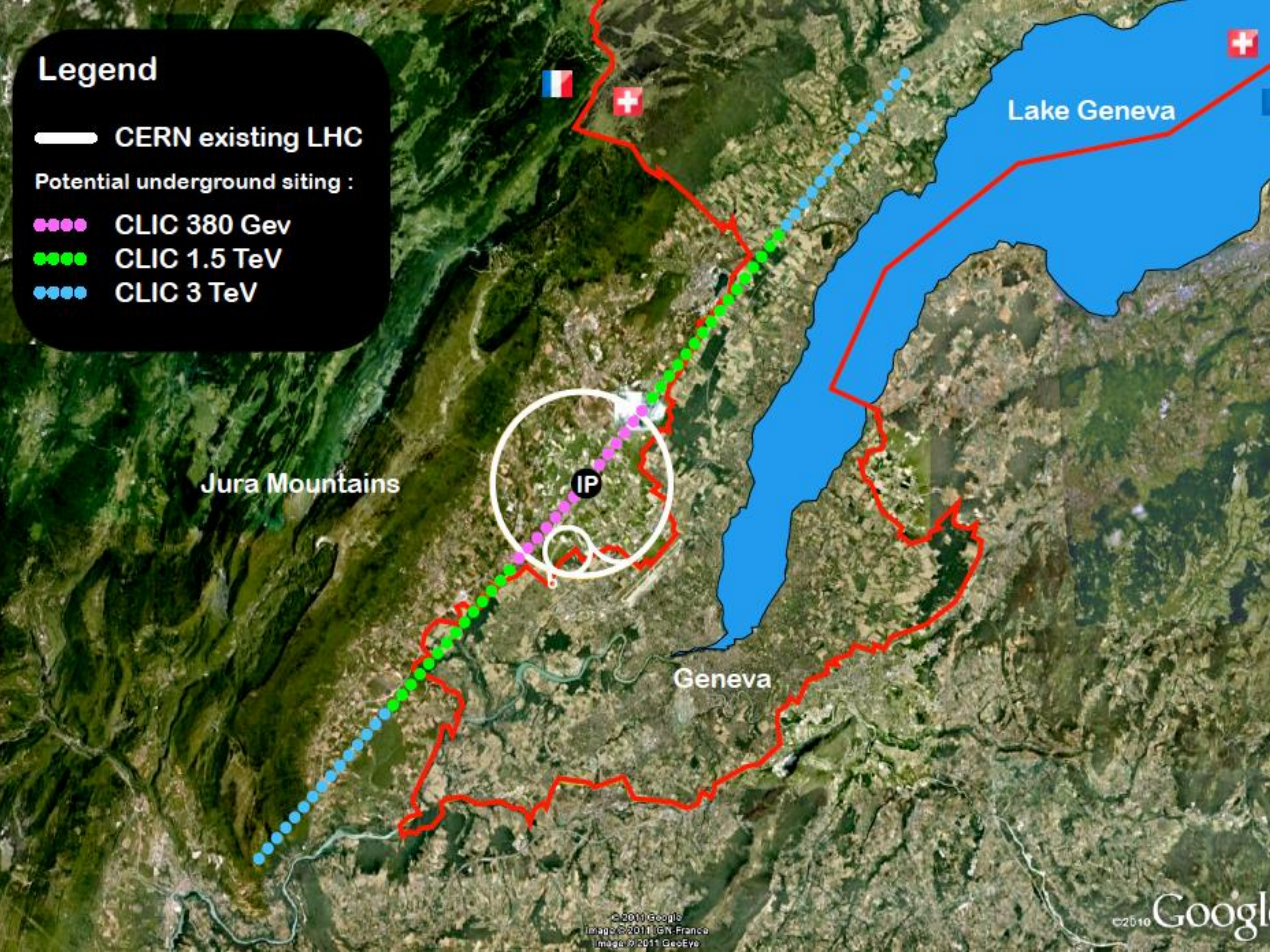
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Alternative klystron-based scenario

- At 3 TeV, drive-beam acceleration is more efficient and cost effective than klystrons
- At 380 GeV, X-band klystrons however interesting alternative



- Klystron-based CLIC concept for 380 GeV designed including
  - X-band klystrons
  - Pulse compressor
  - RF distribution system
  - Accelerating structures


Legend
CERN existing LHC
Potential underground siting :
CLIC 380 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
©2011 Google
Image ©2011 IGN-France
Image ©2011 GeoEye
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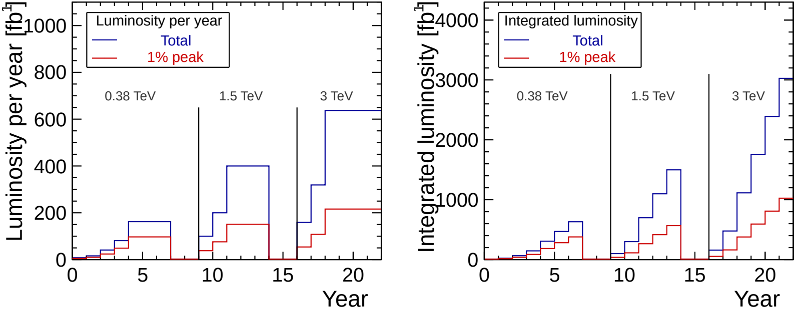
Updated luminosity development



- CLIC programme of 22 years:
  7 years (380 GeV), 5 years (1.5 TeV), 6 years (3 TeV)
  interleaved by 2-years upgrade periods
- Luminosity ramp up of 4 years / 2 years
  (5%, 10%,) 25%, 50%, 100%

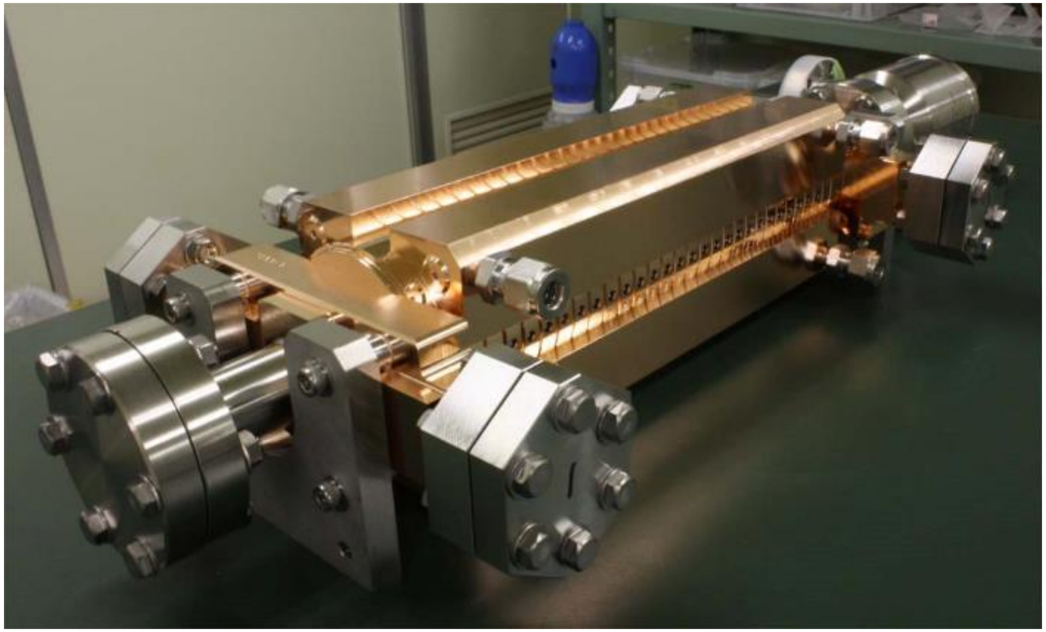
Updated CLIC parameter table: Stage 1–3

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	$\Delta\, t$	ns	0.5	0.5	0.5
Pulse length	τ_{pulse}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathcal{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Charge per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

CLIC accelerating structure

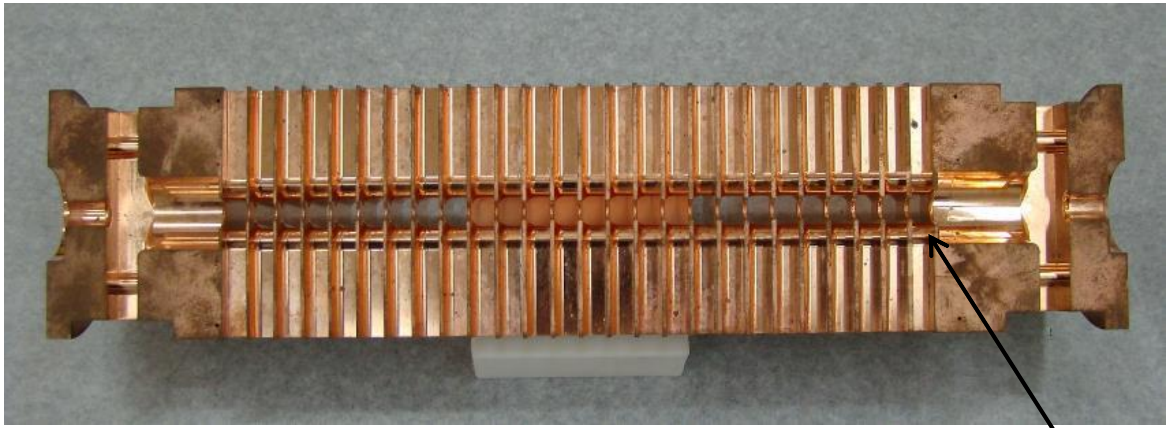
Outside

11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz



HOM damping waveguide

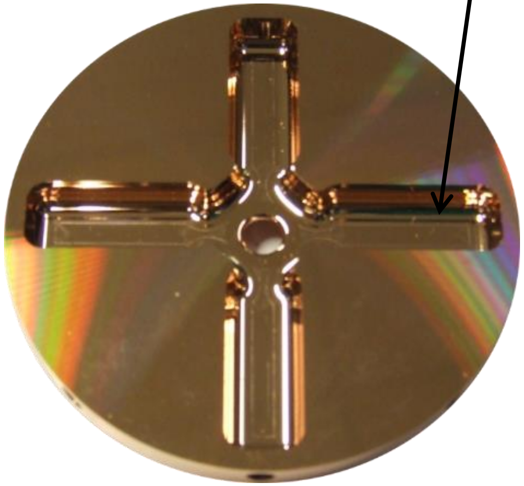
Inside



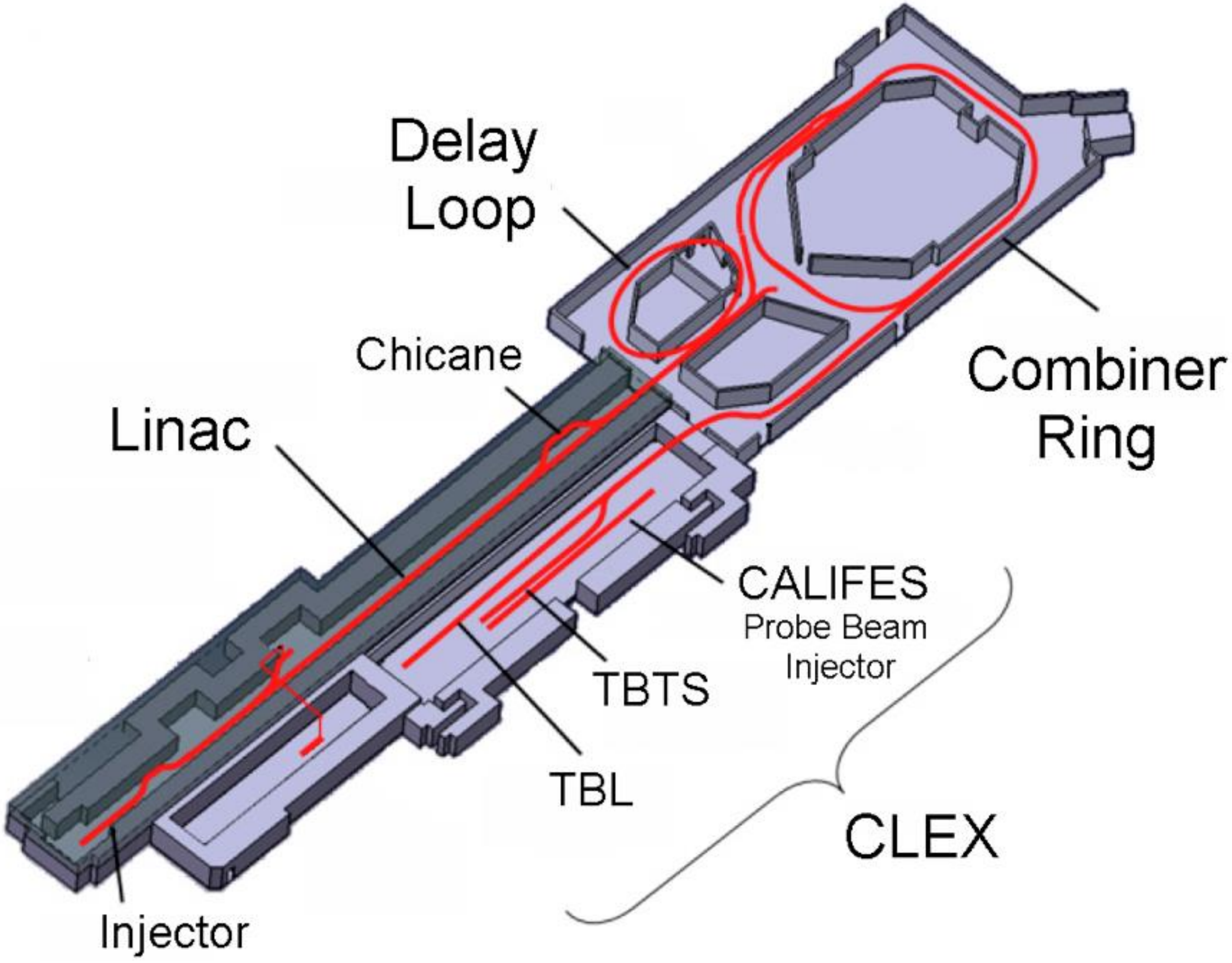
25 cm

6 mm diameter beam aperture

Micron–precision disk



CTF3


Delay Loop
Chicane
Linac
Combiner Ring
CALIFES
Probe Beam Injector
TBTS
TBL
CLEX
Injector

X-band CLIC prototypes

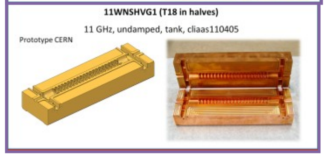
T18 (TD18)


11WNSDVG1 T (T18)
11 GHz, undamped, tank, cliaas11007, cut
Ø80 mm
2 pcs. CERN


11WNSDVG1KS (T18 KS)
Ø45 mm
11 GHz, undamped, CLICVG1-01-00
4 pcs. KEK-SLAC
1 pc. CERN


11WDSDVG1 Cu (TD18)
11 GHz, undamped, tank, cliaas110086
Ø80 mm
2 pcs. KEK-SLAC
1 pc. CERN


11WDSQVG1 (TD18 QUAD)
11 GHz, damped, cliaas110048
3 pcs. KEK-SLAC
2 pcs. CERN


11WNSHVG1 (T18 in halves)
11 GHz, undamped, tank, cliaas110405
Prototype CERN

T24

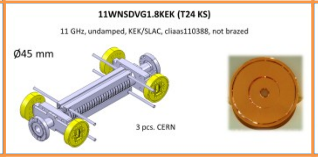

11WNSDVG1.8S (T24)
11 GHz, undamped, sealed, cliaas110139, not brazed
Ø80 mm
2 pcs. CERN


11WNSDVG1.8T (T24)
11 GHz, undamped, tank, cliaas110128
Ø80 mm
2 pcs. KEK-SLAC

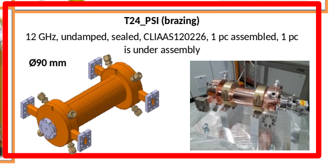

12WNSDVG1.8T (T24)
12 GHz, undamped, tank, cliaas120003
Ø80 mm
1 pc. CERN


11WNSDVG1.8VBS (T24 45 mm)
11 GHz, undamped, sealed, cliaas110277, not brazed
Ø45 mm
2 pcs. CERN


12WNSDVG1.8S (T24)
12 GHz, undamped, sealed, cliaas120014
Ø80 mm
1 pc. CERN

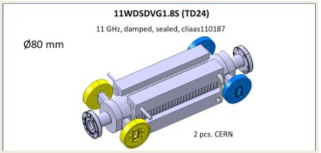

11WNSDVG1.8KEK (T24 KS)
11 GHz, undamped, KEK/SLAC, cliaas110388, not brazed
Ø45 mm
3 pcs. CERN


12WNSDVG1.8KEK (T24 KS)
12 GHz, undamped, cliaas120061
Ø45 mm
2 pcs. CERN


T24_PSI (brazing)
12 GHz, undamped, sealed, CLIAAS120226, 1 pc assembled, 1 pc is under assembly
Ø90 mm

TD24


11WDSDVG1.8T (TD24)
11 GHz, damped, tank, cliaas110167
Ø80 mm
2 pcs. CERN


11WDSDVG1.8S (TD24)
11 GHz, damped, sealed, cliaas110187
Ø80 mm
2 pcs. CERN


12WDSDVG1.8T (TD24)
Ø80 mm
12 GHz, damped, tank, cliaas120025
2 pcs. CERN

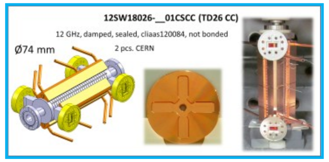

12WDSDVG1.8T WFM (TD24 WFM)
12 GHz, damped, tank, cliatcas0027
Ø80 mm
4 pcs. CERN


11WDSDVG1.8KEK (TD24 KS)
11 GHz, damped, KEK/SLAC, cliaas110349, not bonded
Ø74 mm
2 pcs. KEK-SLAC


12WDSDVG1.8KEK (TD24 KS)
Ø74 mm
12 GHz, damped, cliaas120075
2 pcs. CERN


12WDSDVG1.8R05 (TD24 R05 KS)
Ø74 mm
12 GHz, damped, sealed, cliaas120079
3 pcs. CERN

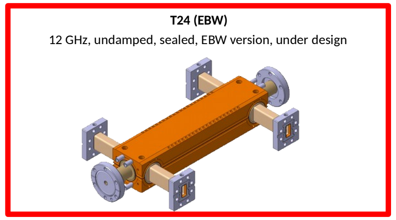
TD26 R05 CC


12SW18026-__01CSCC (TD26 CC)
12 GHz, damped, sealed, cliaas120084, not bonded
Ø74 mm
2 pcs. CERN

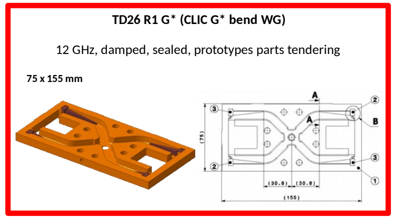
TD26 R1 CC


12SWV18026-01CSR1CC (TD26 R1 CC)
12 GHz, damped, sealed, CLIAAS120245, 4 pcs under machining
Ø83 mm

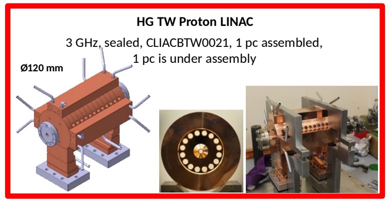
T24 (halves)

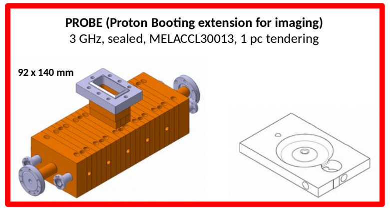

T24 (EBW)
12 GHz, undamped, sealed, EBW version, under design

*TD26 R1 G**

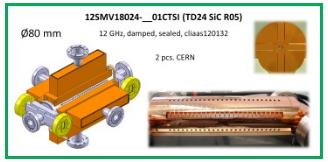

TD26 R1 G* (CLIC G* bend WG)
12 GHz, damped, sealed, prototypes parts tendering
75 x 155 mm

Medical structures 3 GHz

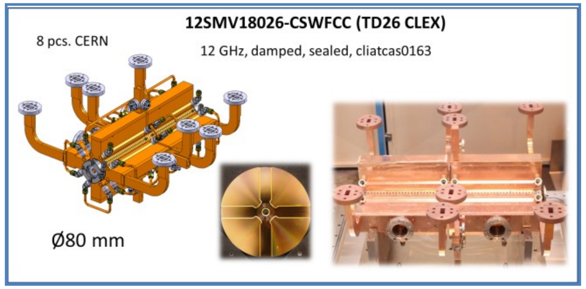

HG TW Proton LINAC
3 GHz, sealed, CLIACBTW0021, 1 pc assembled, 1 pc is under assembly
Ø120 mm


PROBE (Proton Booting extension for imaging)
3 GHz, sealed, MELACCL30013, 1 pc tendering
92 x 140 mm

TD24 SiC

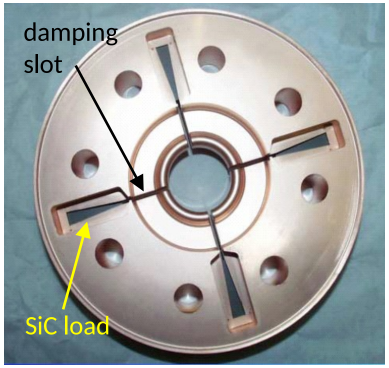

12SMV18024-__01CTSI (TD24 SiC R05)
Ø80 mm
12 GHz, damped, sealed, cliaas120132
2 pcs. CERN

TD26 CLEX

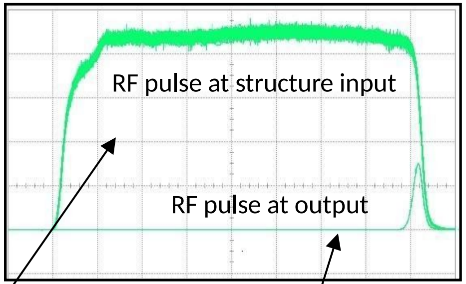

12SMV18026-CSWFCC (TD26 CLEX)
8 pcs. CERN
12 GHz, damped, sealed, cliatcas0163
Ø80 mm

Recently installed 2-beam acceleration module in CTF3
(according to latest CLIC design)

Drive Beam Generation

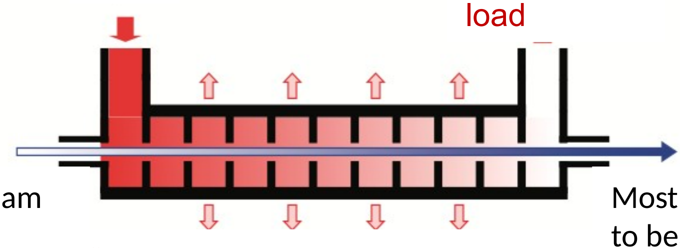


Full beam loading acceleration



95.3% RF to beam efficiency
Stable high current acceleration

Factor 8 current & frequency multiplication



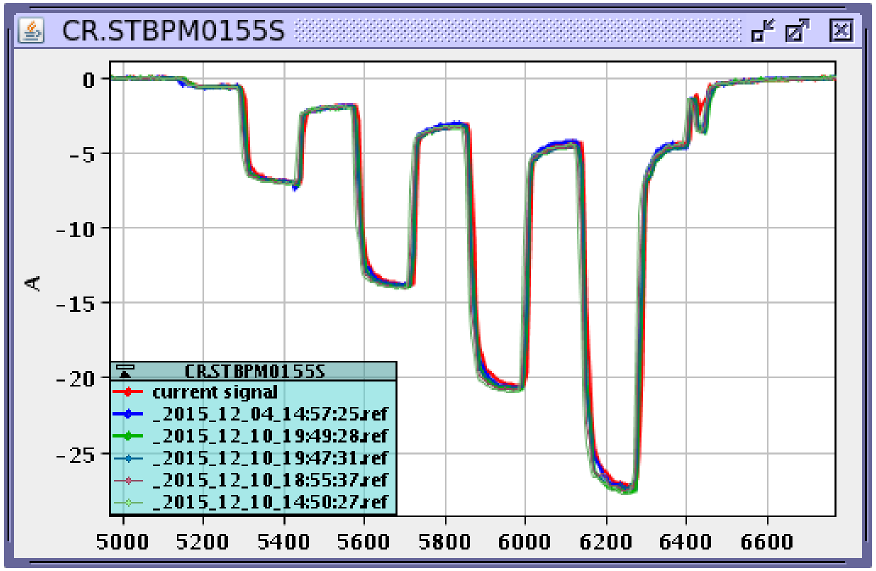
RF in

No RF to load

High beam current

Most RF power to beam

“short” structure – low Ohmic losses

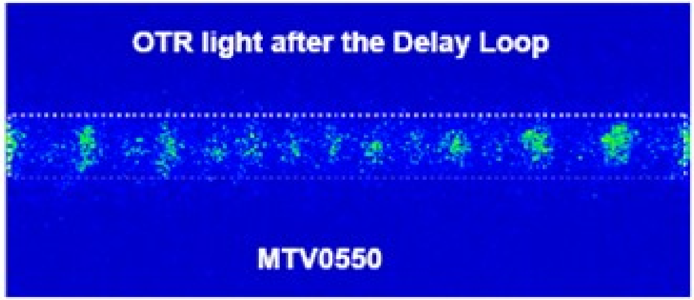


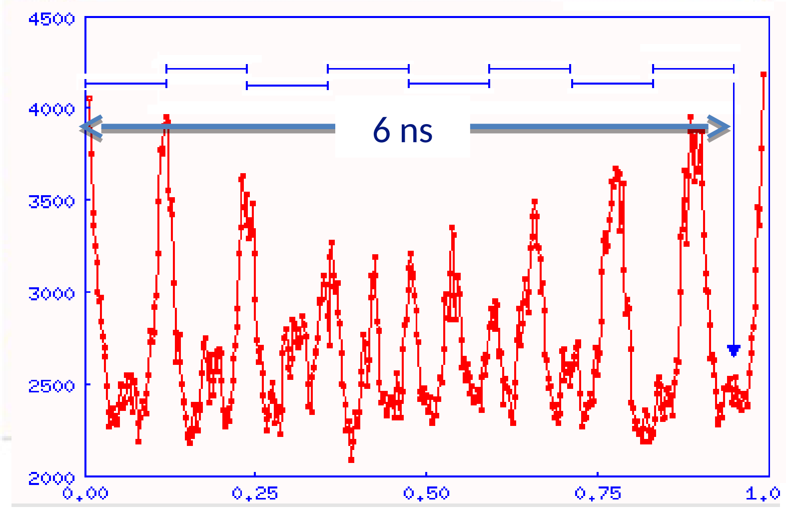
Factor 8 combination

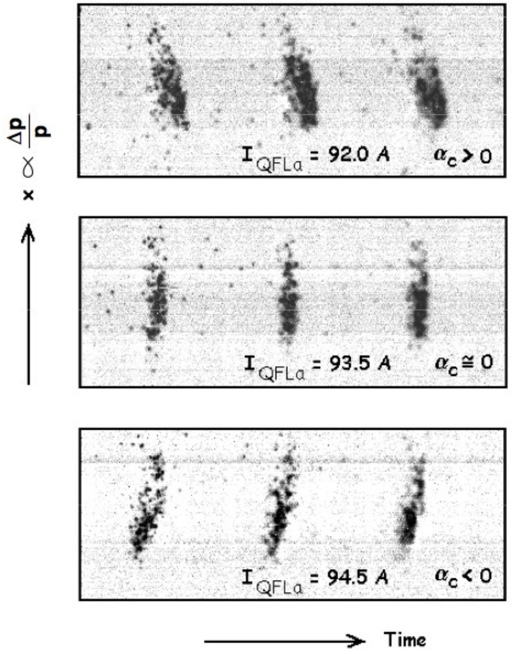
Drive Beam Generation

Beam recombination

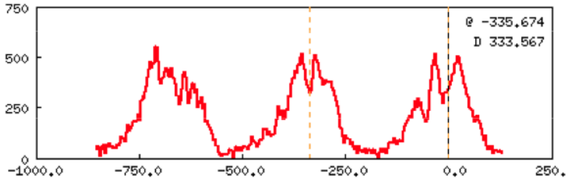
- Fast bunch phase switch in SHB system
- Operation of isochronous rings and beam lines



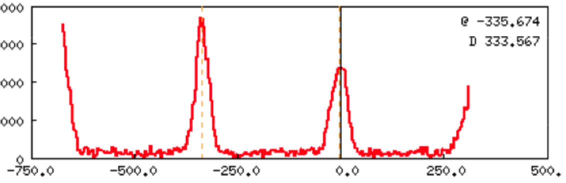




non-isochronous – 2nd turn

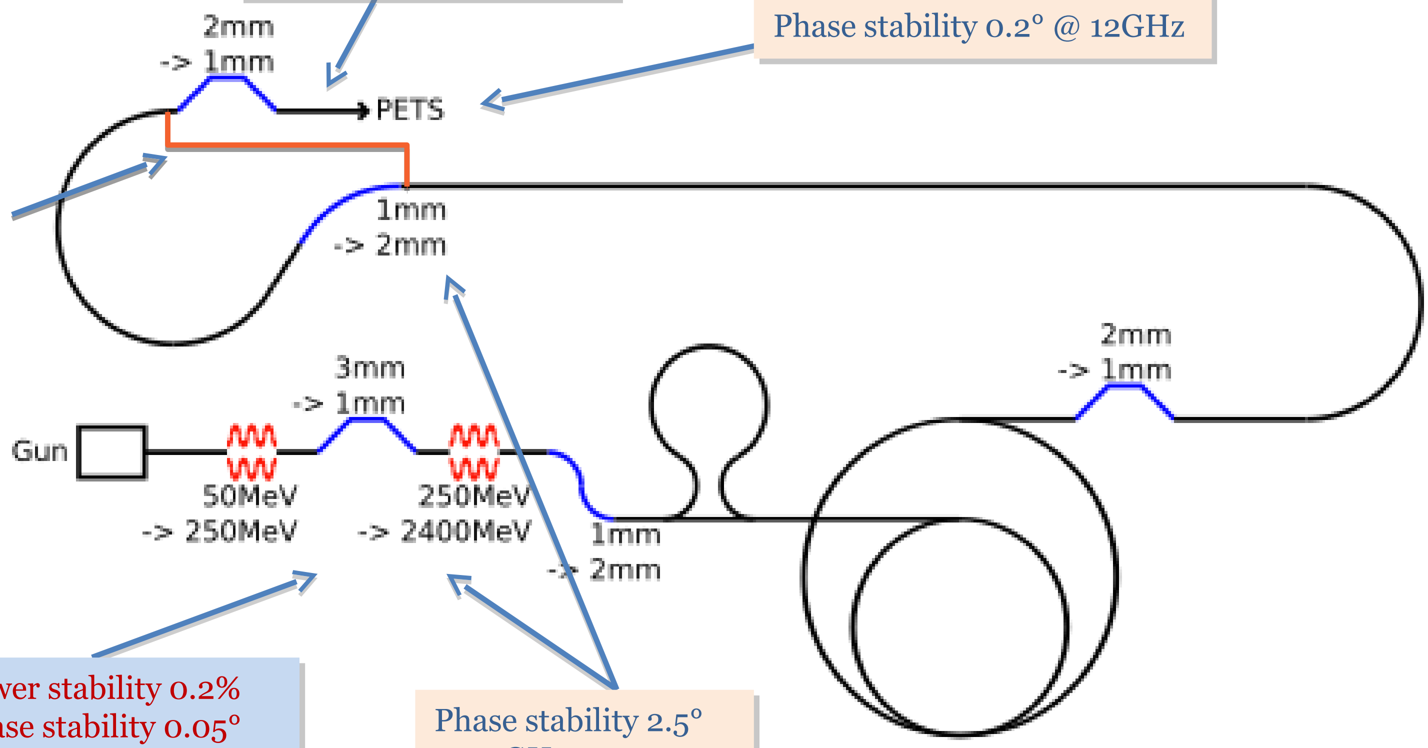


isochronous – 60th turn



Drive Beam Stability

Some CLIC Drive Beam requirements



Tests in CTF3

Emittance $\varepsilon_{x,y} \leq 150\mu m$
Transverse jitter $\leq 0.3\sigma$

Verified in CTF3

Current stability 0.75 ⊠ 10^{-3}
Phase stability 0.2° @ 12GHz

Feed-forward tests in CTF3

RF power stability 0.2%
RF phase stability 0.05°
Current stability 0.1%

Verified in CTF3

Phase stability 2.5° @ 12GHz
0.2° @ 1GHz

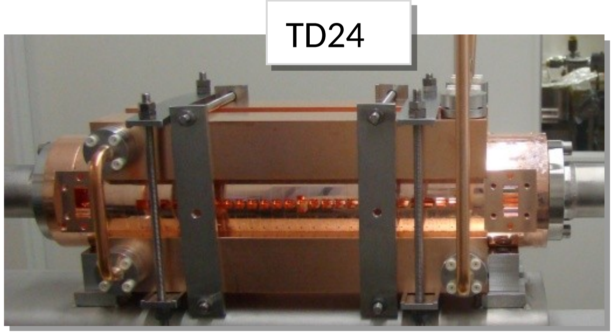
Verified in CTF3

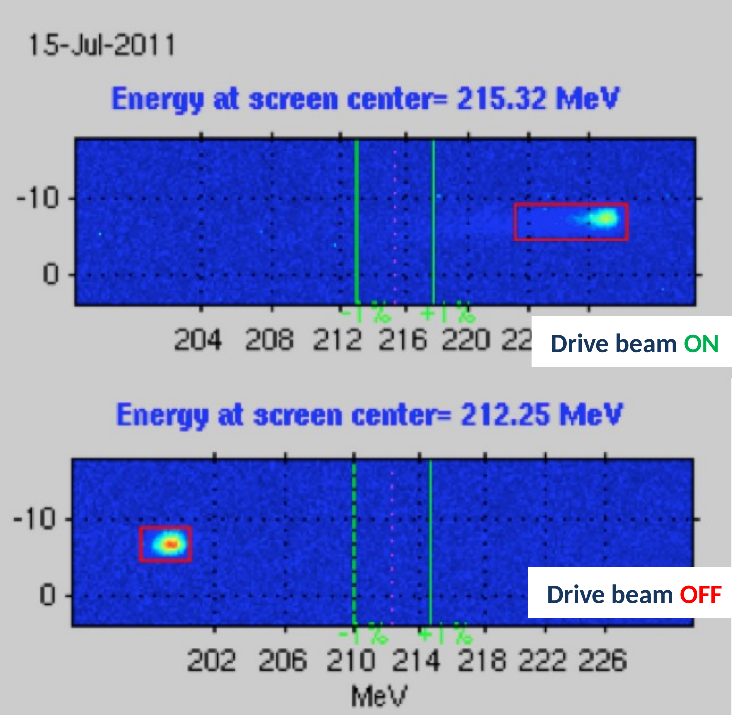
Two-Beam Acceleration

Two-Beam Acceleration demonstration in TBTS

Up to 145 MV/m measured gradient

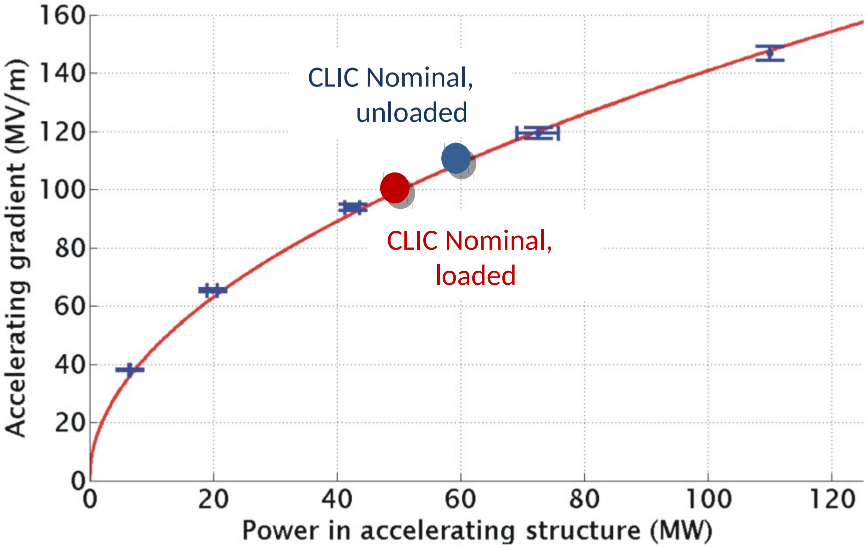
Good agreement with expectations (power vs. gradient)





Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of **145 MV/m**

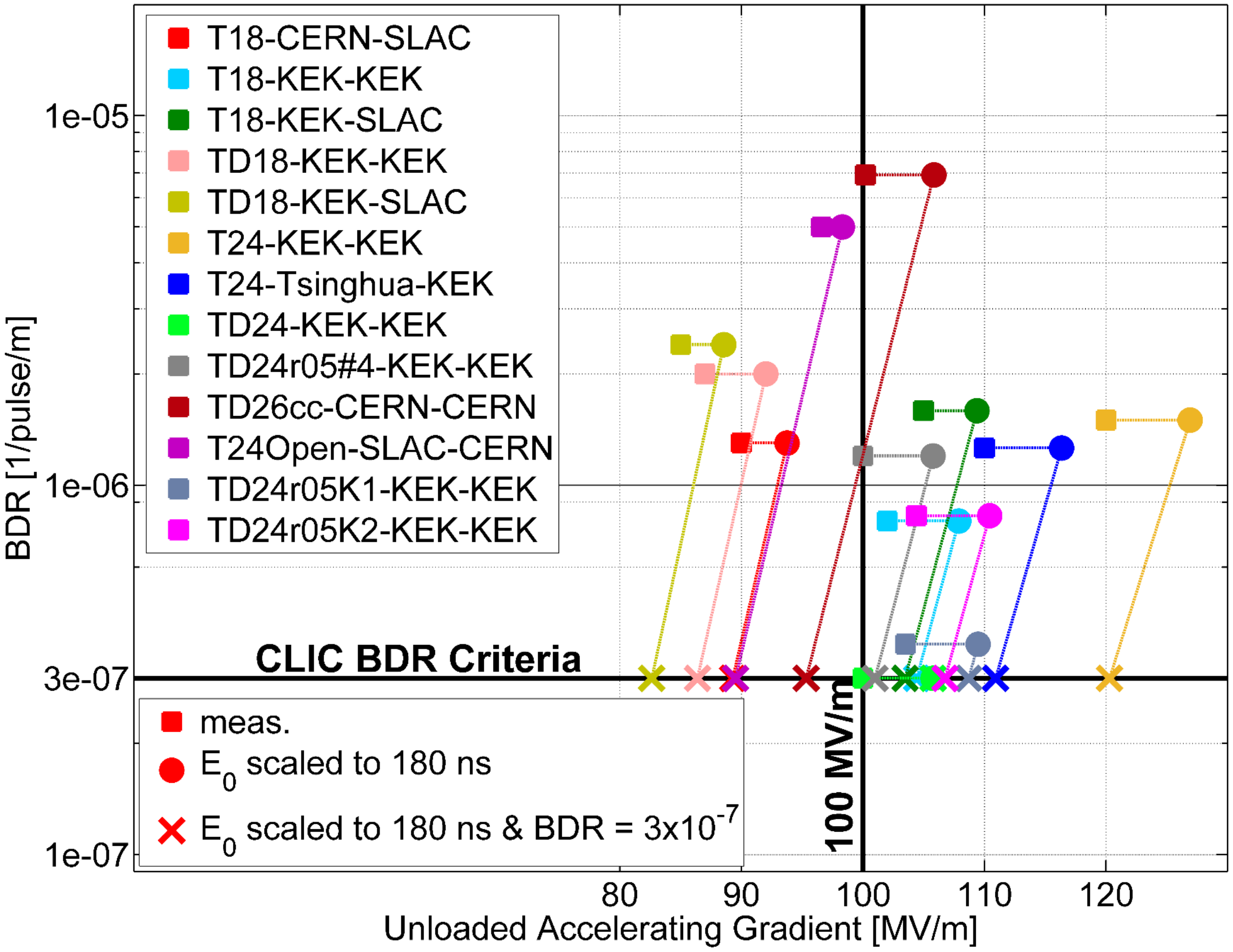


Structures performance requirements

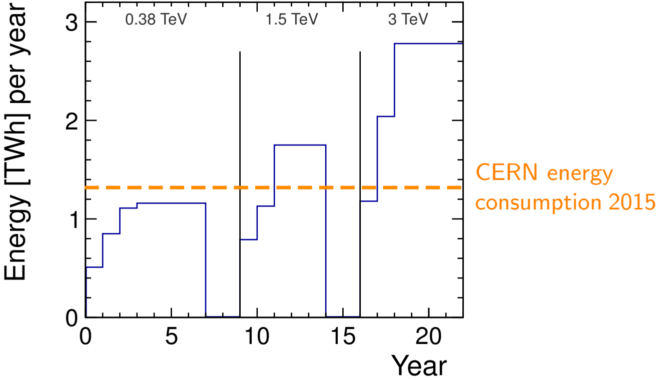
- Full performance expected for CLIC
  - ***120MV/m @ 3·10^{-7} BDR***
- BDR of 3 •10^{-7} will take 77 days of steady running at 50 Hz or 9 days at 400 Hz (100 BD)
- Based on empirical laws we can scale BDR with gradient and pulse length

$$BDR \propto E^{30}\tau^{5}$$

Phys. Rev. Spec. Top. Accel. Beams 12 (2009) 102001



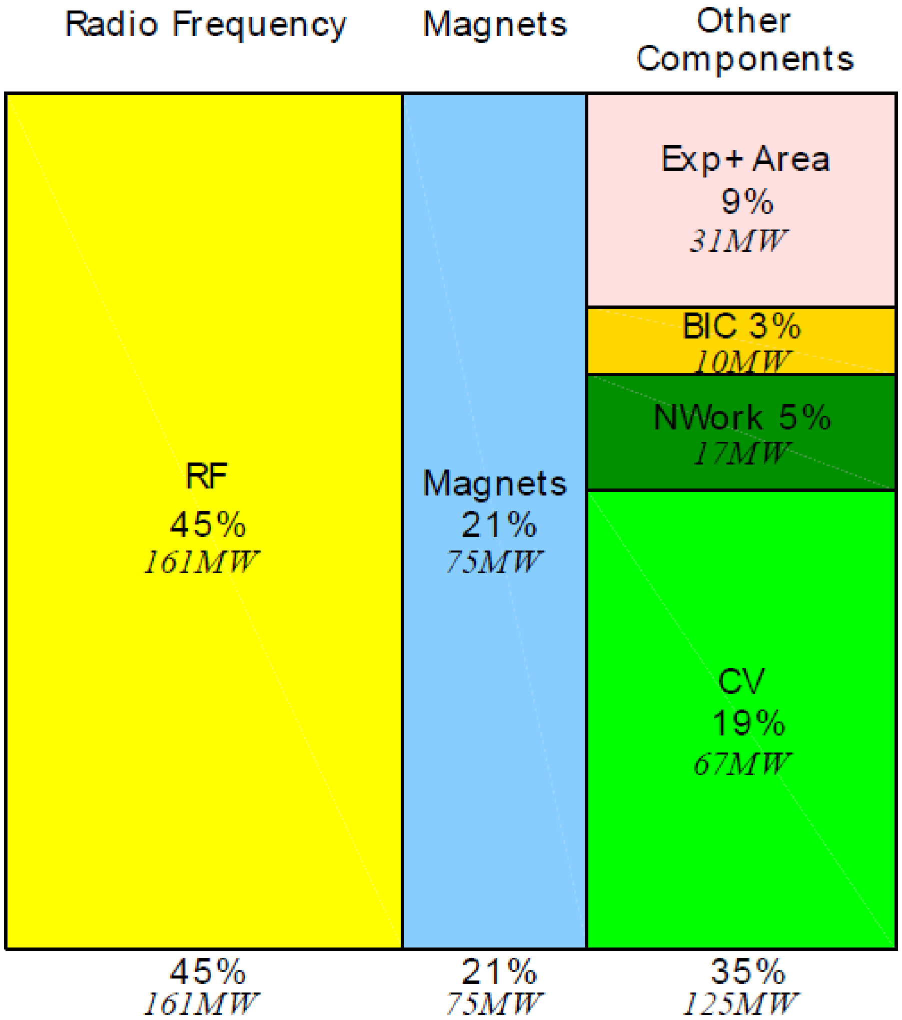
Yearly energy consumption



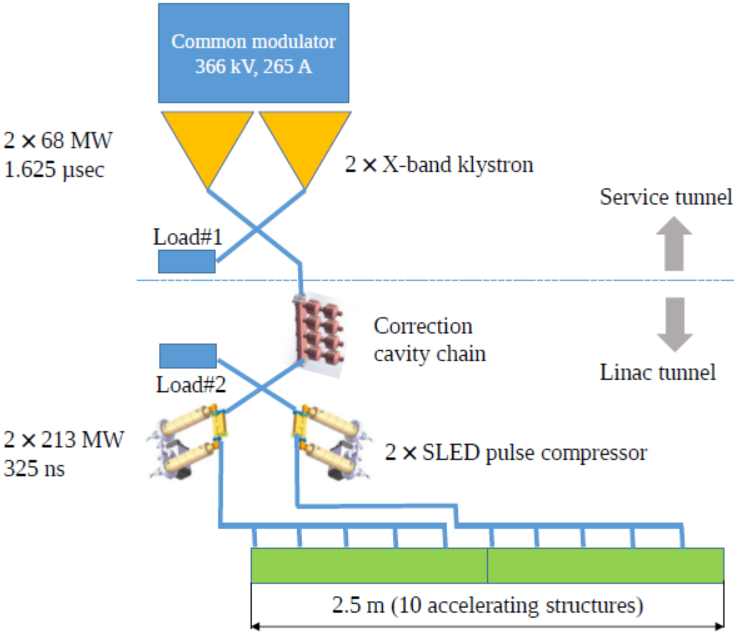
- Including reduced operation in the first years at each energy
- At 380GeV, a single positron target is used for the first three years (-10 MW with respect to nominal)

(Note → 380 GeV numbers scaled from CDR design at 500 GeV
→ To be repeated with detailed tech. description of 380 GeV CLIC)

AC power (1.5 TeV)



Klystron version (380 GeV)



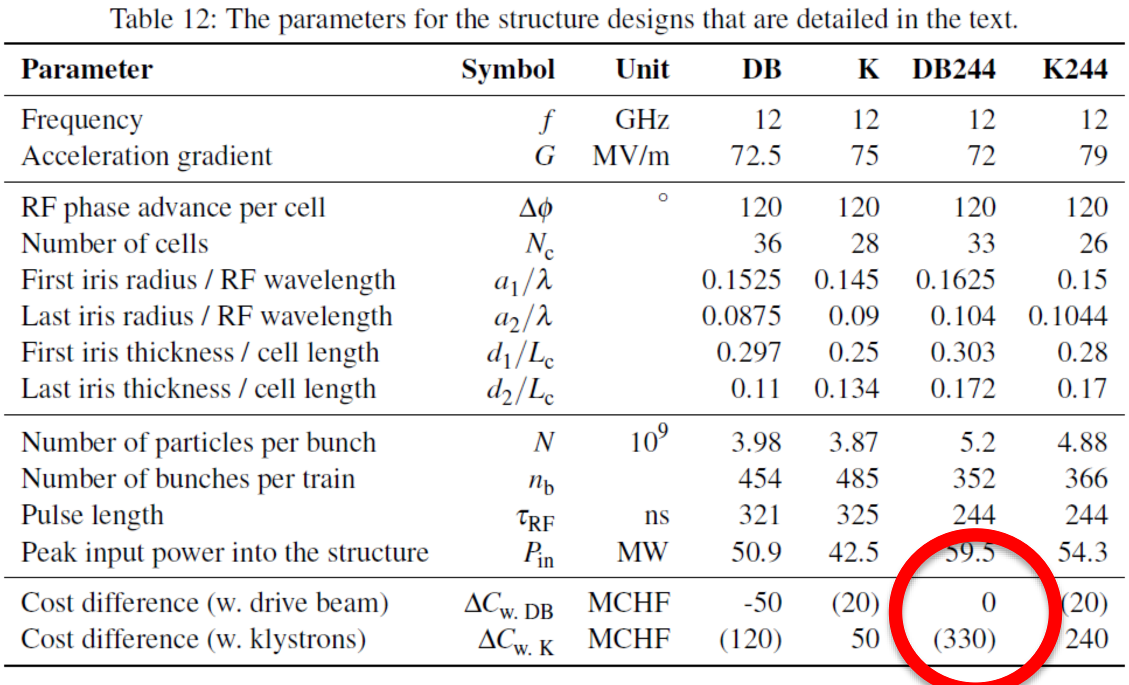


Table 12: The parameters for the structure designs that are detailed in the text.

Parameter	Symbol	Unit	DB	K	DB244	K244
Frequency	f	GHz	12	12	12	12
Acceleration gradient	G	MV/m	72.5	75	72	79
RF phase advance per cell	$\Delta\phi$	°	120	120	120	120
Number of cells	N_c		36	28	33	26
First iris radius / RF wavelength	a_1/λ		0.1525	0.145	0.1625	0.15
Last iris radius / RF wavelength	a_2/λ		0.0875	0.09	0.104	0.1044
First iris thickness / cell length	d_1/L_c		0.297	0.25	0.303	0.28
Last iris thickness / cell length	d_2/L_c		0.11	0.134	0.172	0.17
Number of particles per bunch	N	10^9	3.98	3.87	5.2	4.88
Number of bunches per train	n_b		454	485	352	366
Pulse length	τ_{RF}	ns	321	325	244	244
Peak input power into the structure	P_{in}	MW	50.9	42.5	59.5	54.3
Cost difference (w. drive beam)	$\Delta C_{w.\ DB}$	MCHF	-50	(20)	0	(20)
Cost difference (w. klystrons)	$\Delta C_{w.\ K}$	MCHF	(120)	50	(330)	240

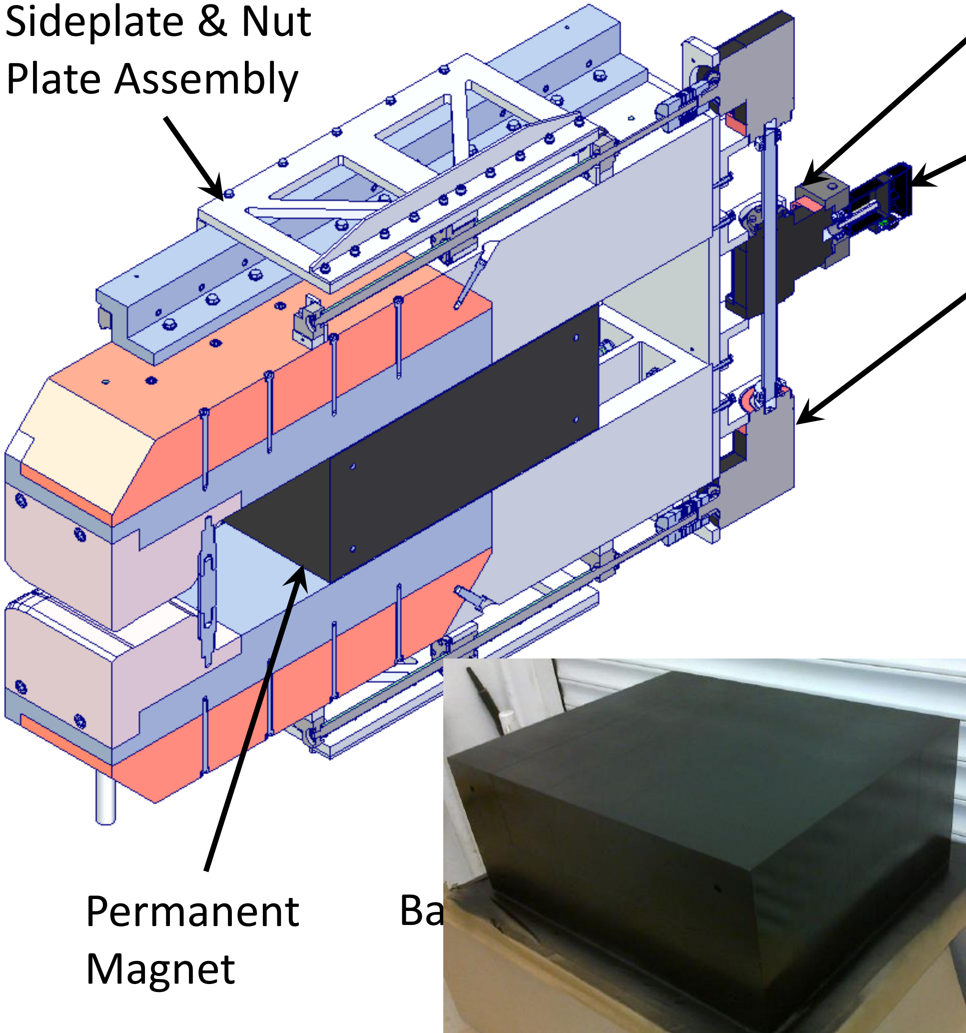
Costings relative to drive-beam version may be lower ~ 5%

Adjustable-field PM prototypes

High Energy Quad

Low Energy Quad

Dipole design

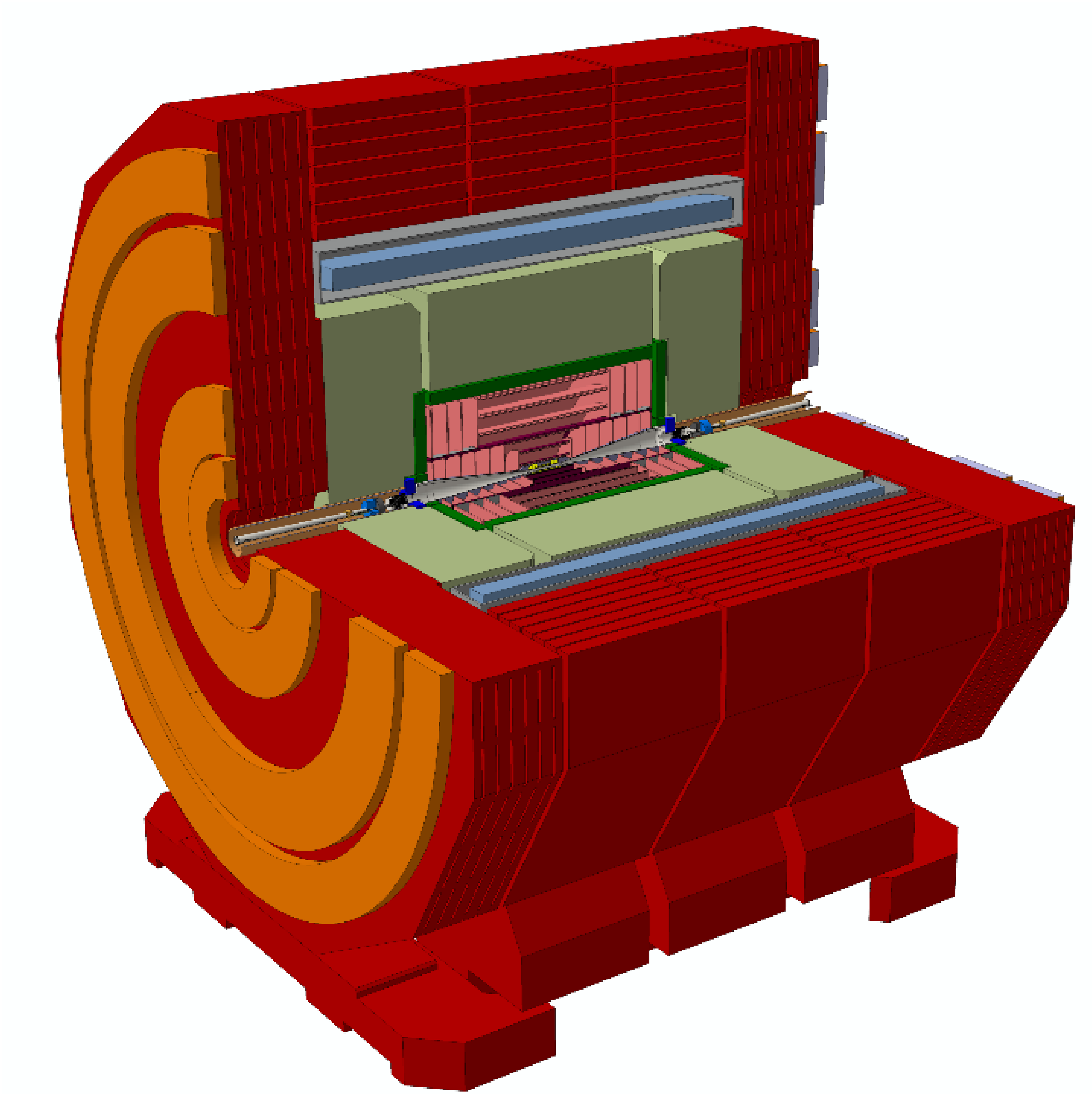


Sideplate & Nut Plate Assembly

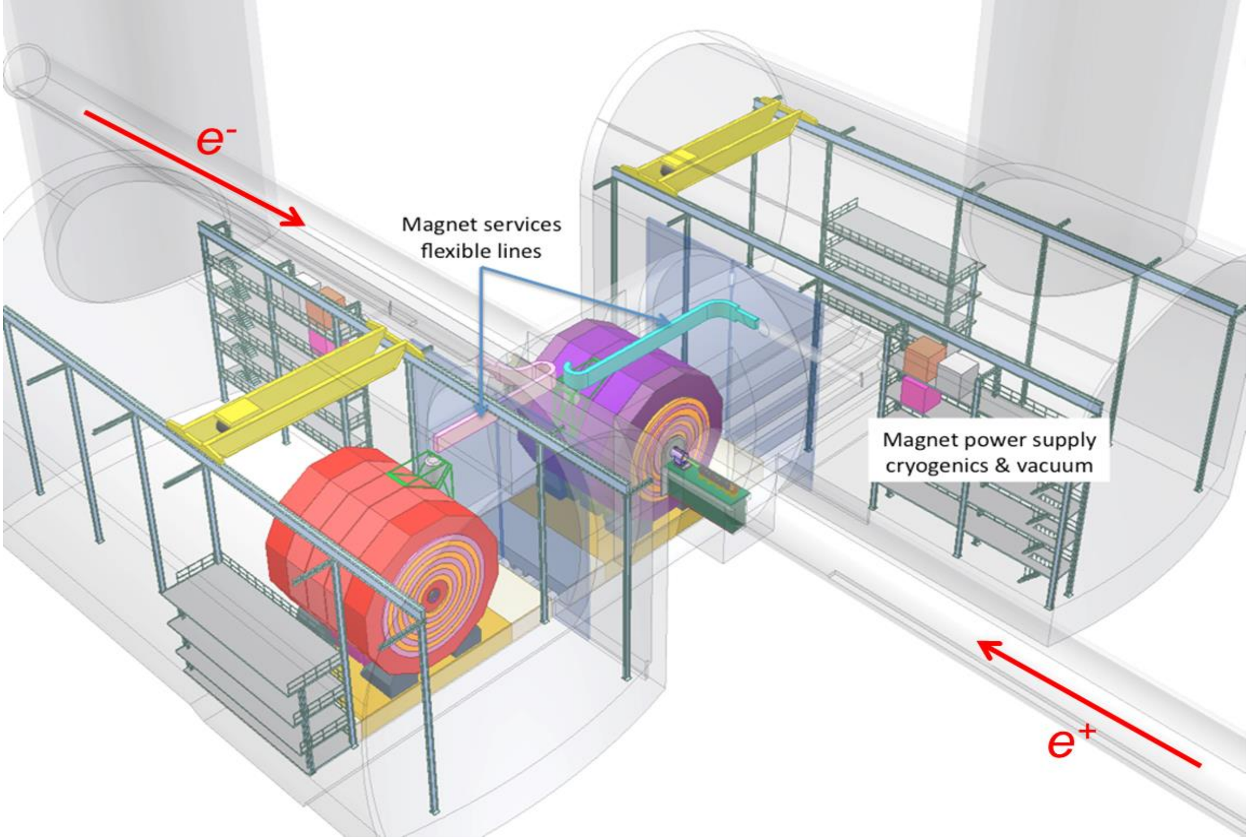
Permanent Magnet

Ba

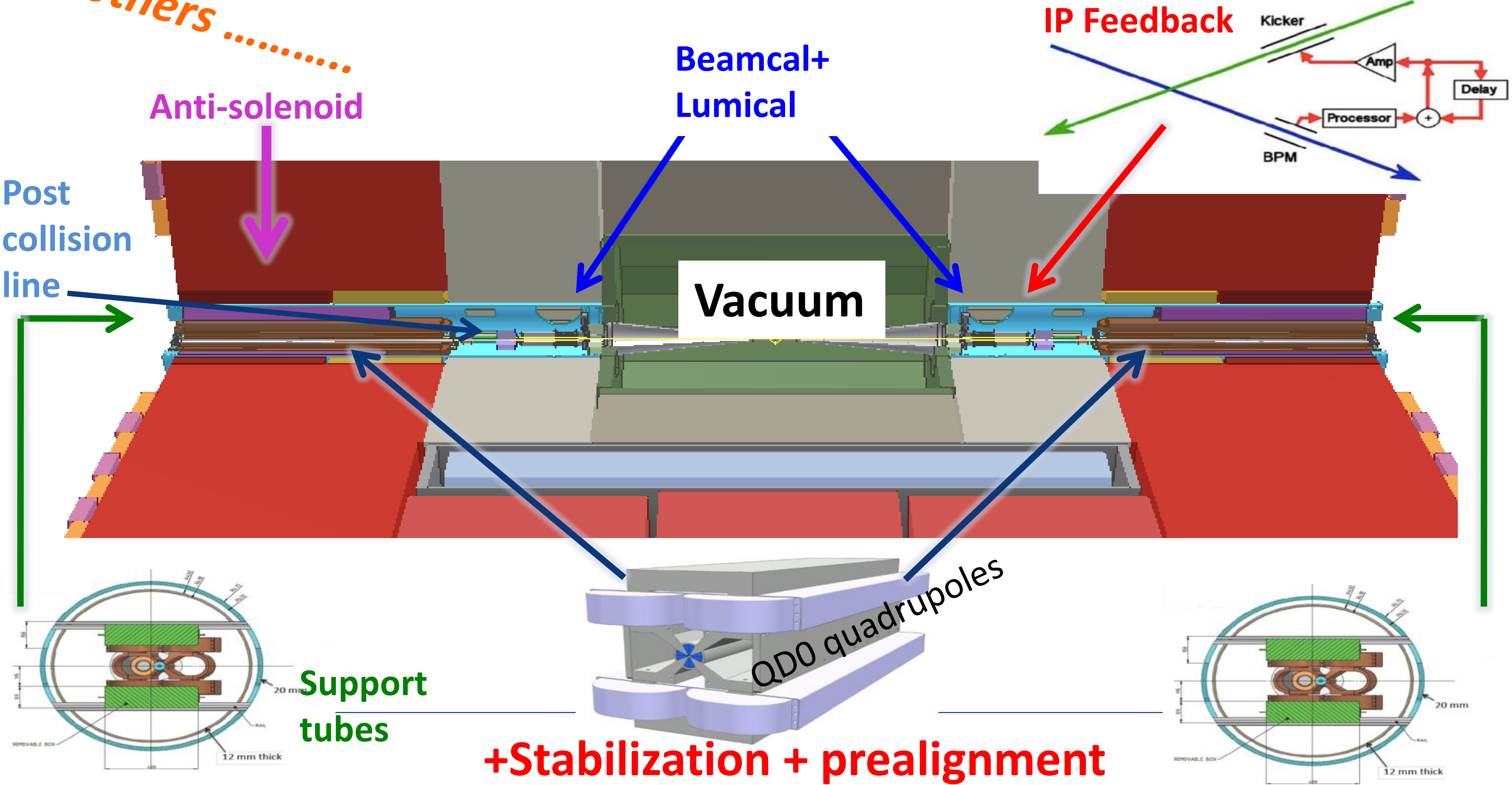
CLIC detector



The CDR concept (2012)



MACHINE DETECTOR INTERFACE



Plus others ....

Anti-solenoid

Post collision line

Beamcal+ Lumical

IP Feedback

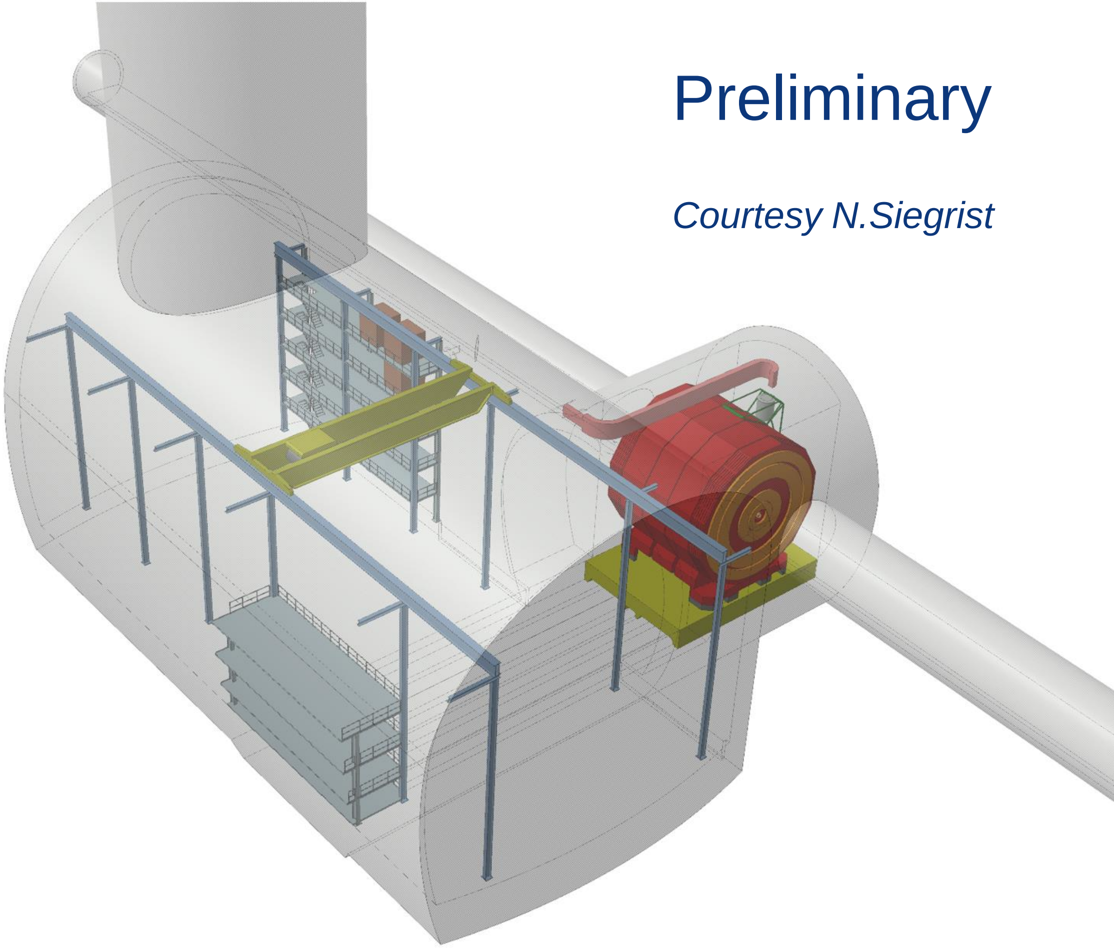
Vacuum

QD0 quadrupoles

Support tubes

+Stabilization + prealignment

New cavern layout

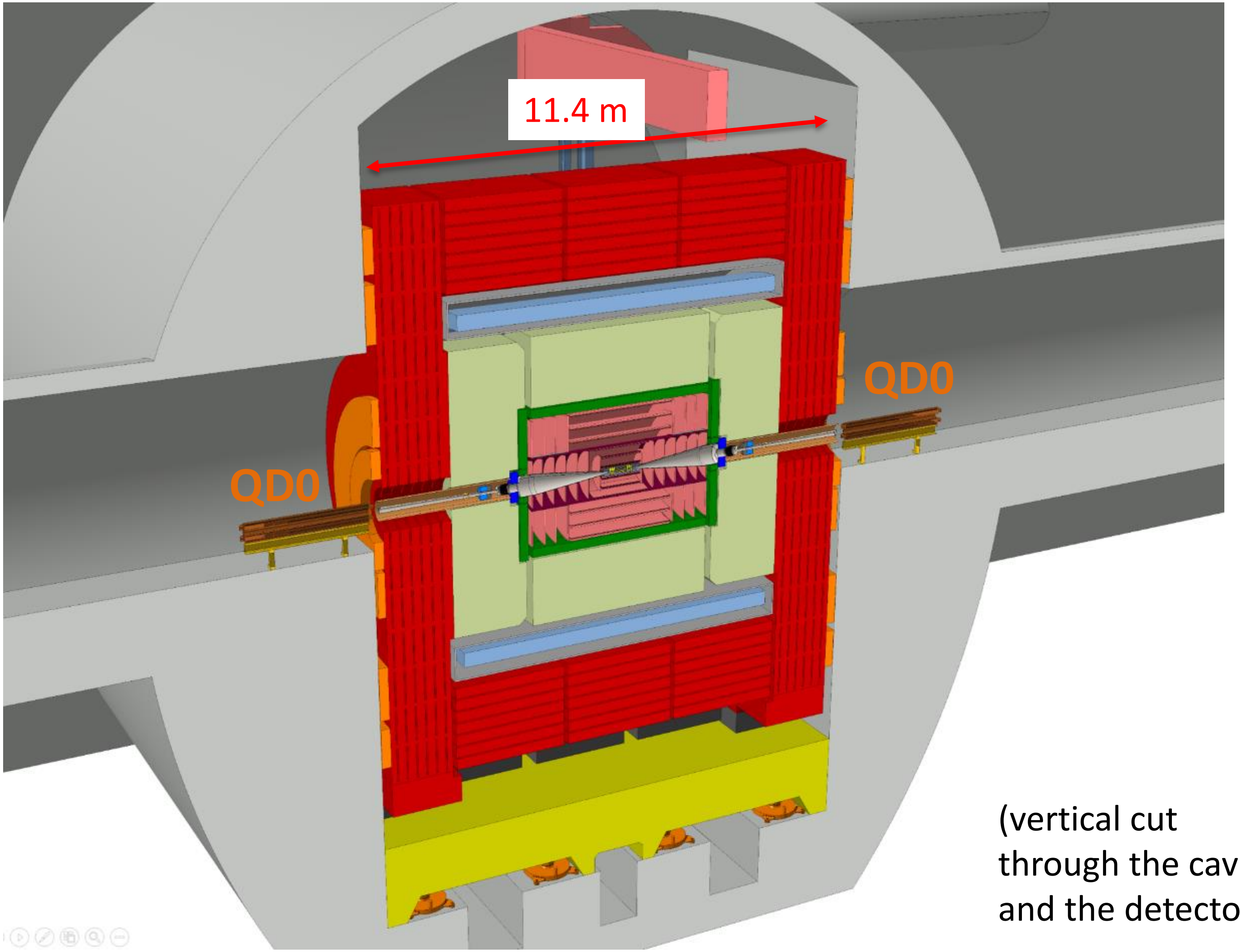


Preliminary

Courtesy N.Siegrist

- Proposal by EP/LCD
- Detector opening not on IP
- Mechanical and civil engineering stability to be verified

Working Hypothesis: QD0 outside of detector



(vertical cut
through the cavern
and the detector on IP)

Detector requirements

→Jet-energy resolution

e.g. W/Z/H di-jet mass separation, ZH with Z➔ qq

- $$\frac{\sigma_E}{E} \sim 3.5 - 5\ \%$$ (for high-E jets, light quarks)

→momentum resolution:

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

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

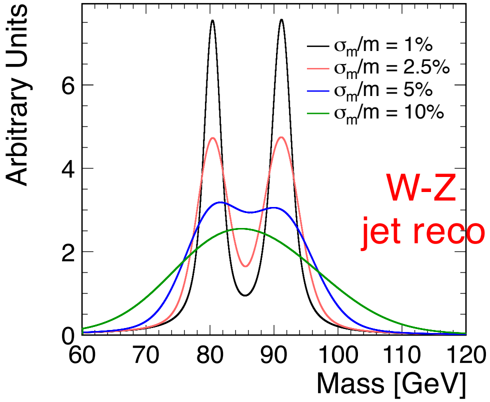
→impact parameter resolution:

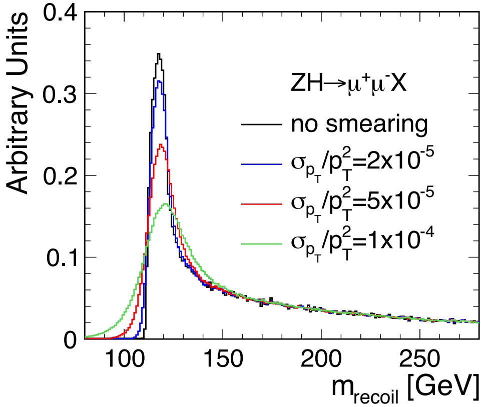
e.g. c/b-tagging, Higgs BR

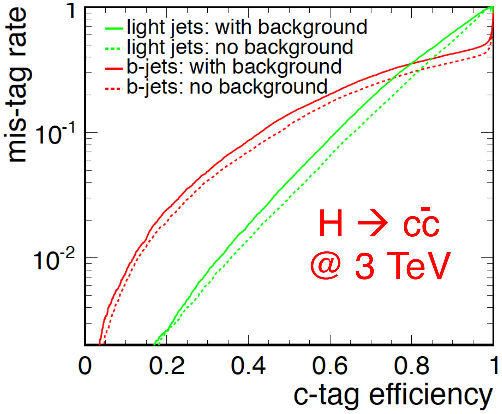
- $$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}] \sin^{\frac{3}{2}} \theta)\ \mu\mathrm{m}$$

→angular coverage, very forward electron tagging

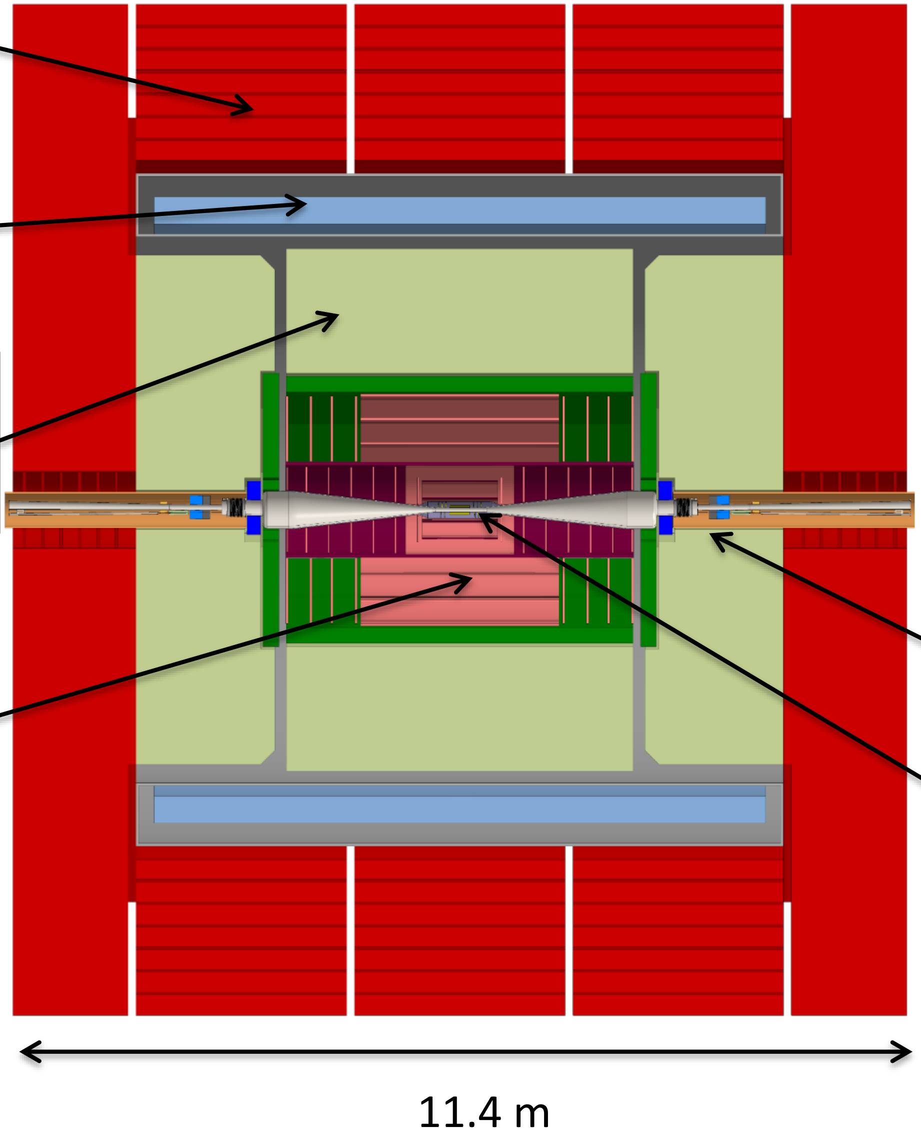
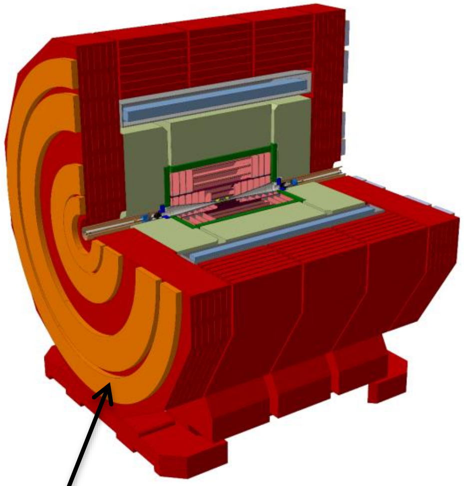
+ requirements from CLIC experimental conditions







New CLIC detector model

return yoke (Fe) with muon-ID detectors

superconducting solenoid, 4 Tesla

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i, Si-W ECAL, Sc-FE HCAL

silicon tracker, (large pixels / short strips)

end-coils for field shaping

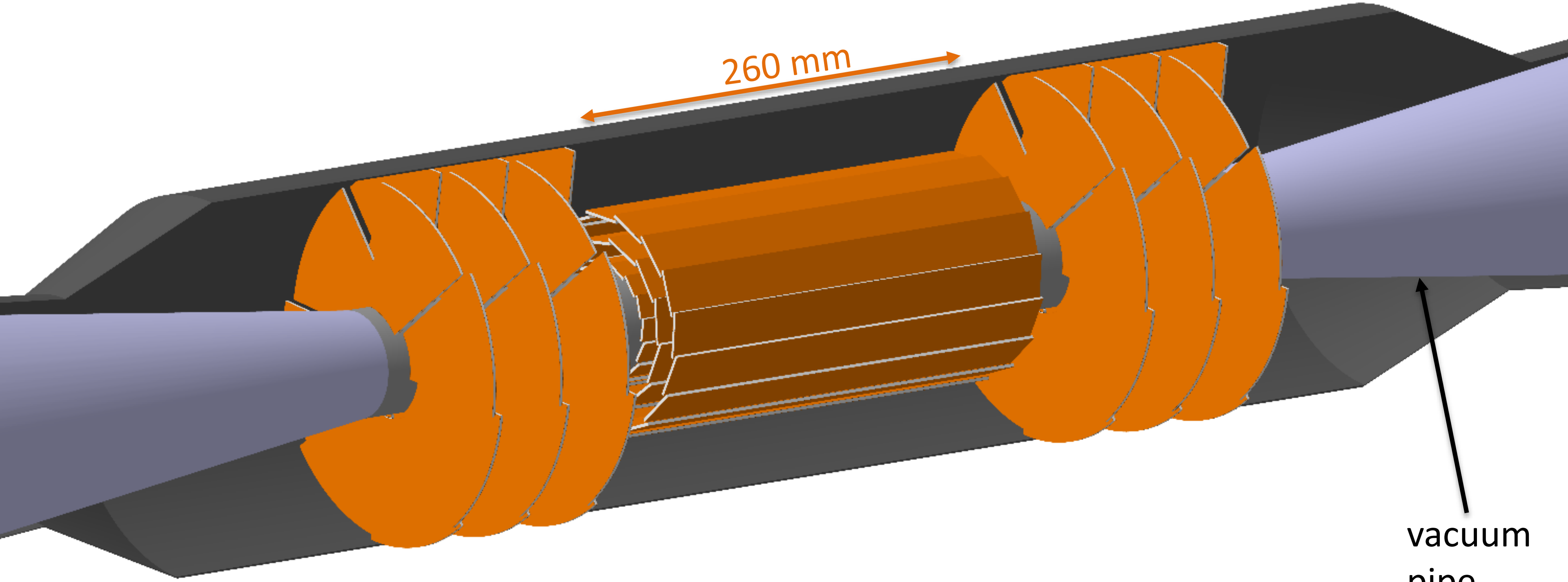
forward region with compact forward calorimeters

ultra low-mass vertex detector, ~25 µm pixels

Note: final beam focusing is outside the detector

11.4 m

a “better sketch” of the vertex detector

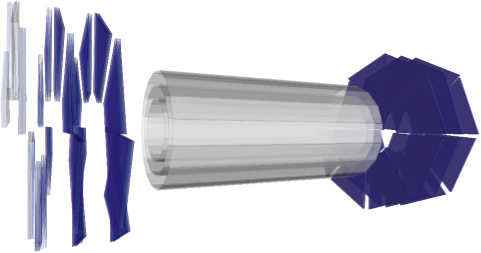


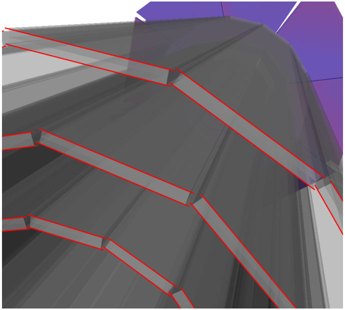
carbon fibre shell
to guide the air for
cooling of the VTX

vacuum
pipe

Vertex Detector

- Using flavour tagging, occupancy and resolution to optimise
  - Material Budget (most important)
  - Layer positions
  - Spiral geometry
  - Single vs. double layer
  - Coverage $\theta > 7^\circ$





Parameters

Double layers ($0.2\% X_0$ detection layer)

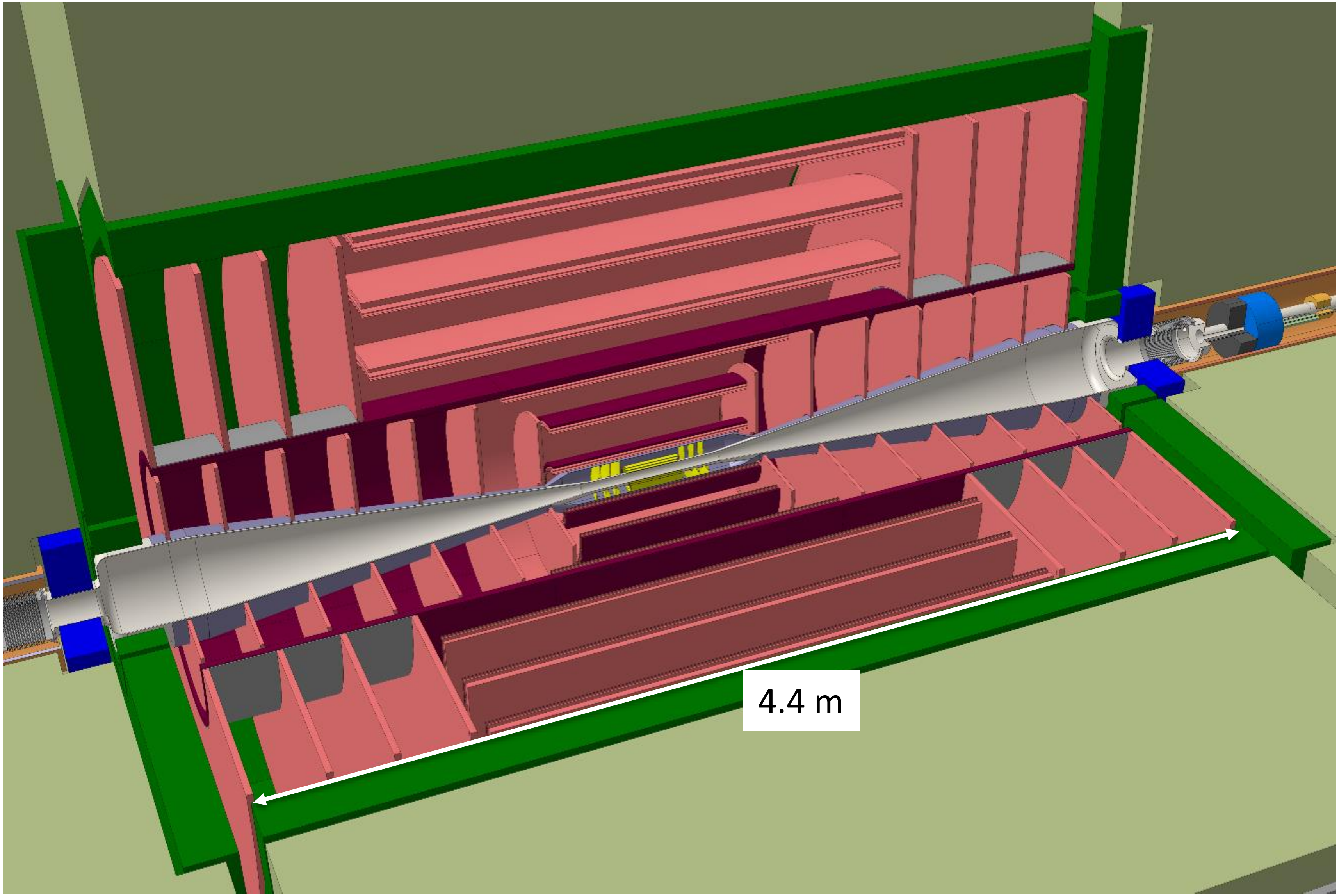
$R_{\text{in}} = 31$ mm

Spiral geometry in endcaps (airflow)

~ 1 m^2 area

$\sim$ 2G pixels (25 μm pixel)

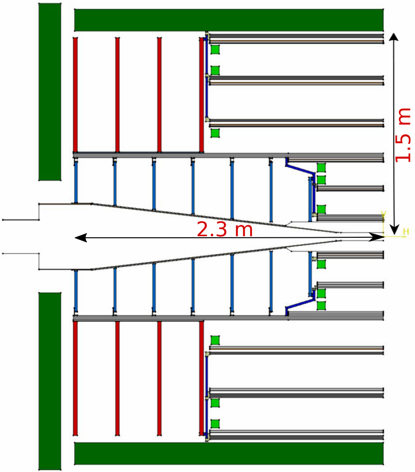
zoom into the ECAL/tracker/vertex region

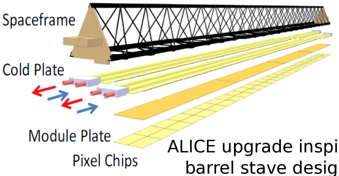


7 March 2017

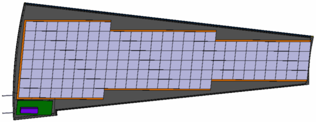
Silicon Tracker – Layout

- New engineering design
- Inner and Outer Tracker
  - Support tube for extraction with beampipe assembly
- 3 short + 3 long barrel layers
- 7 inner + 4 outer endcaps
- At least 8 hits for $\theta > 8^\circ$
- Tiled with 30x30 mm or 15x15mm chips





ALICE upgrade inspired barrel stave design



Emerging silicon technologies

- In the last (~5) years many novel detectors have been designed taking advantage of recent commercially available CMOS processes
  - Plethora of new devices, many with only subtle differences, processes typically differ by Foundry and technology size…

- CLIC has been heavily involved in several of these areas, which are also of interest for high luminosity LHC upgrades, as well as more broadly to HEP and medical imaging

LEP era

=>

LHC era

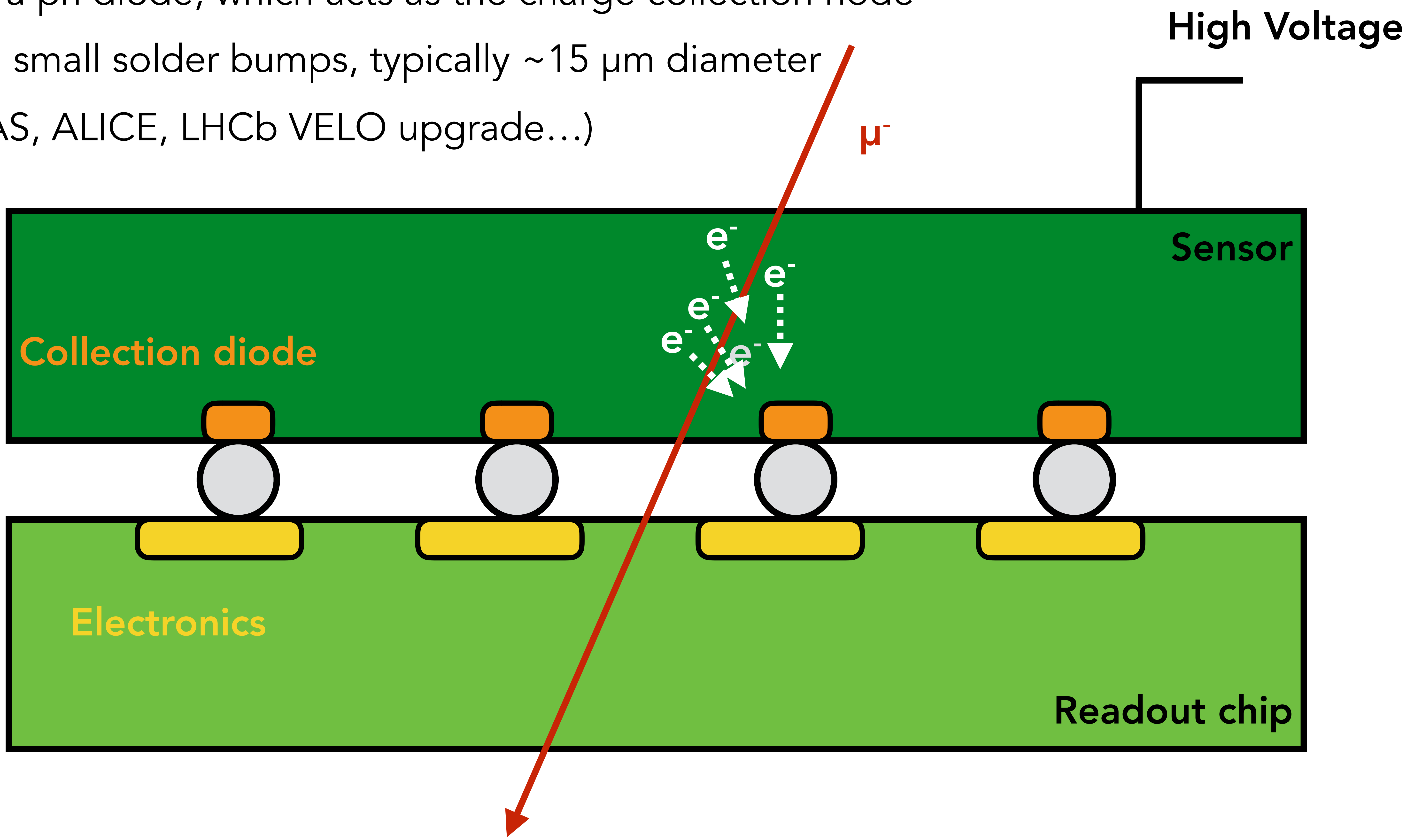
=>

HL-LHC-and-beyond era

Emerging silicon technologies

- **Conventional hybrid pixel detector**
  - Sensor (high resistivity) typically consists of a pn diode, which acts as the charge collection node
  - Readout chip (low resistivity) connected via small solder bumps, typically ~15 μm diameter
  - Widely used in particle physics (CMS, ATLAS, ALICE, LHCb VELO upgrade…)
  - Small cell sizes $\mathcal{O}$(50 - 250 μm)
  - Extensive functionality on-pixel

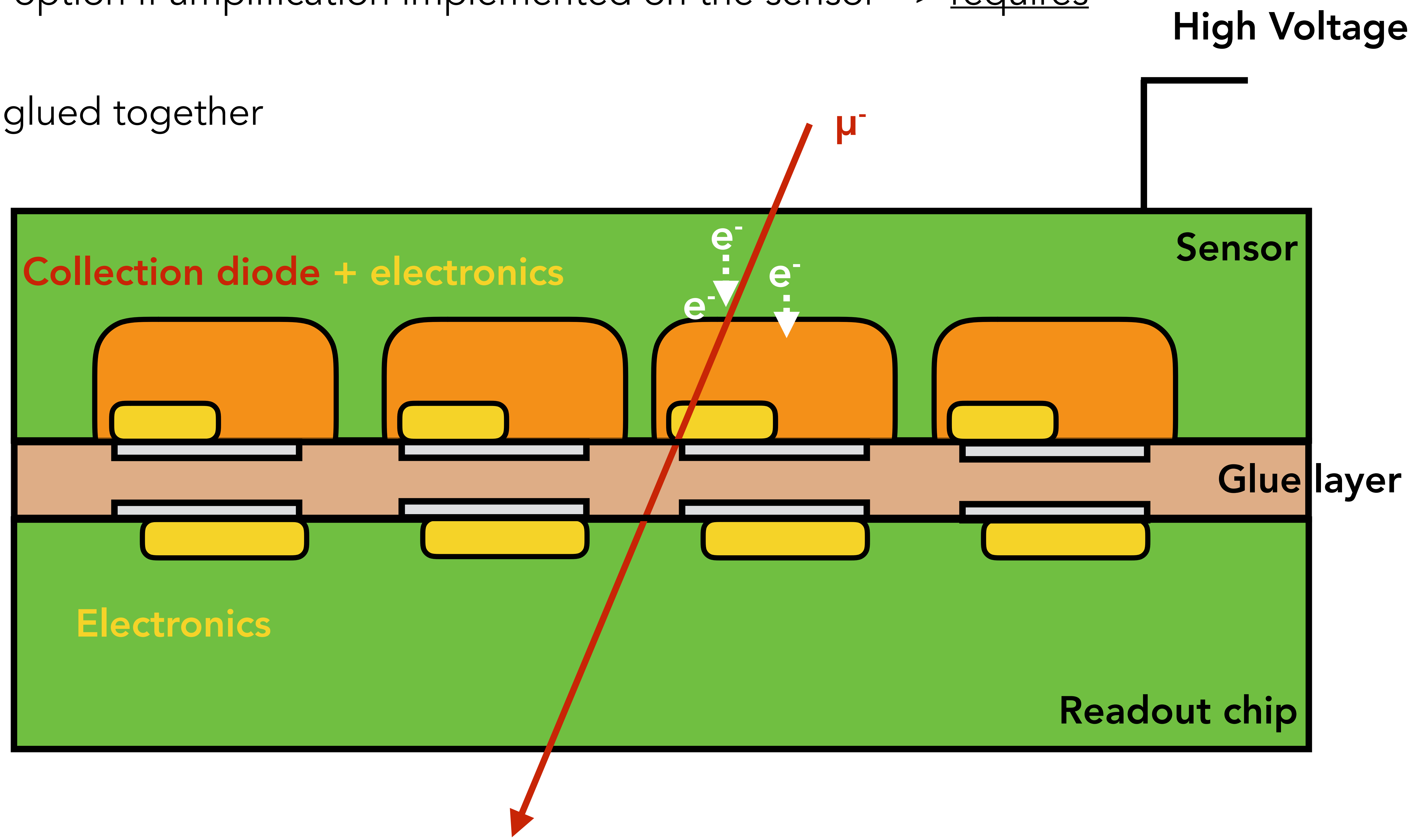
- But…
  - Bump bonding still costly
  - Limit on device thickness for stability
  - Currently limiting on pixel pitch



Emerging silicon technologies - CCPD

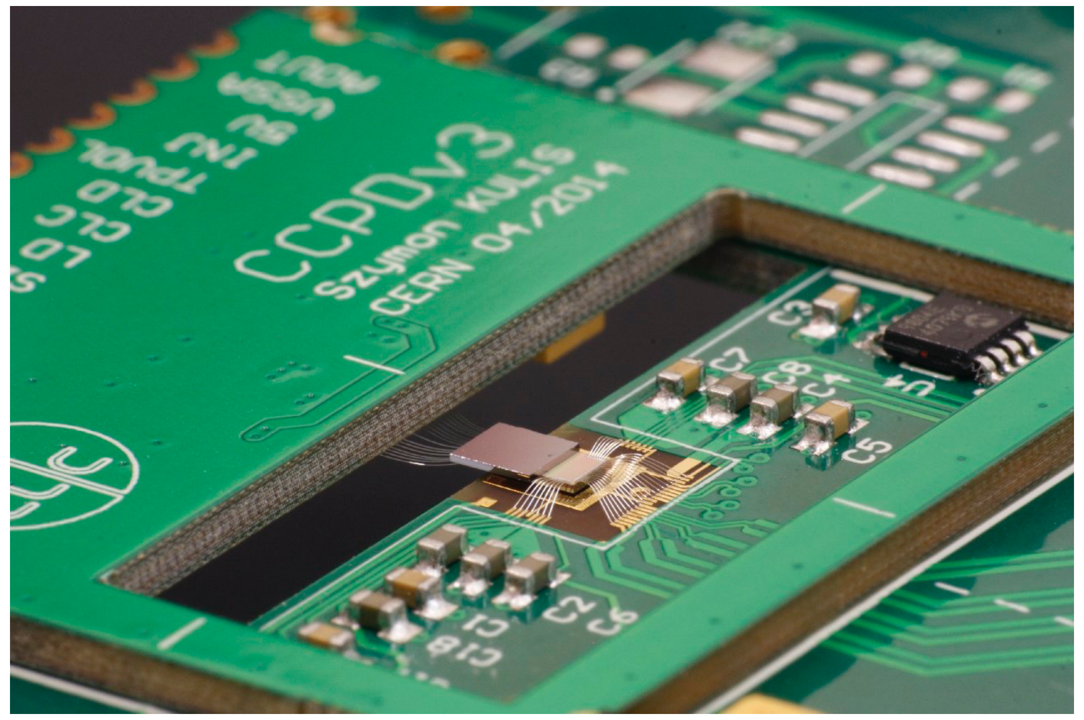
- **Another solution available: capacitive coupling of the sensor to the readout**
  - Given small pixel capacitance only a viable option if amplification implemented on the sensor => requires integrated technology (HR- or HV-CMOS)
  - Avoids bump-bonding, devices are simply glued together

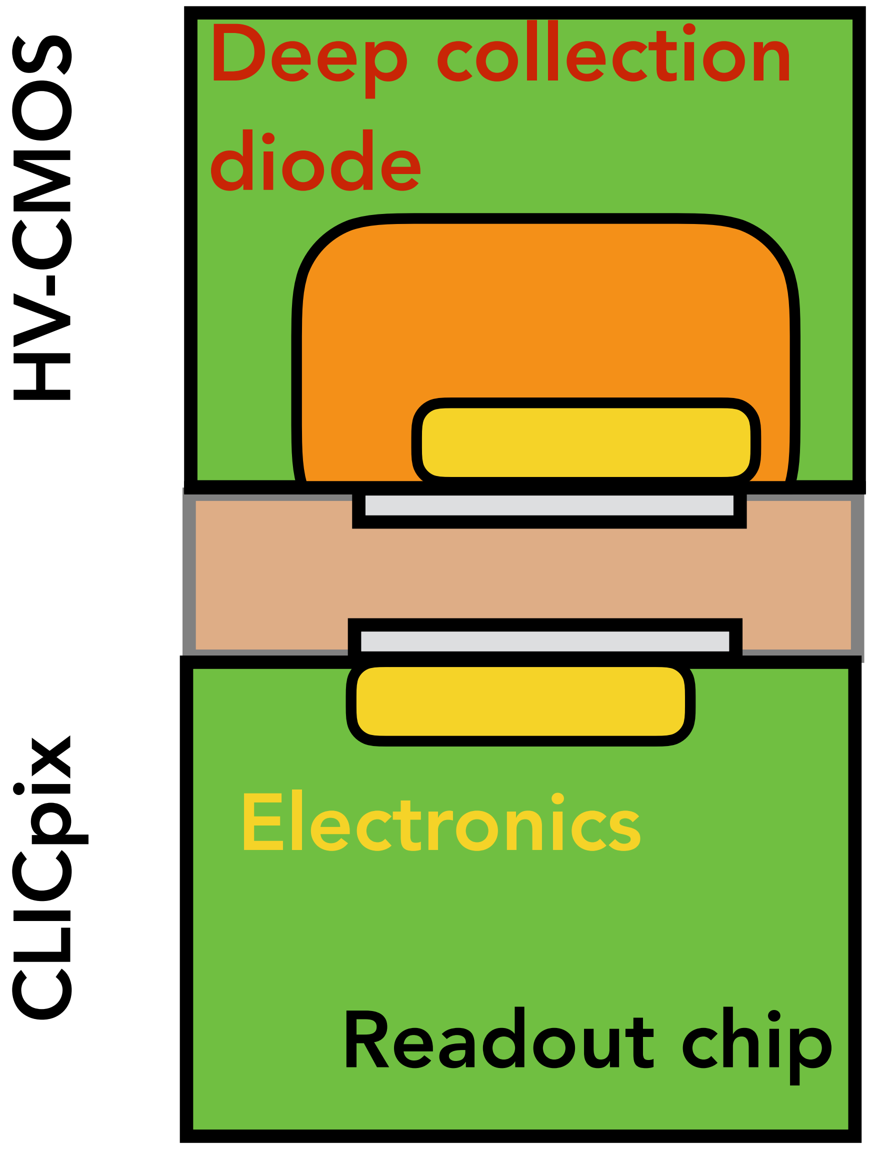
- **Capacitively Coupled Pixel Detectors**



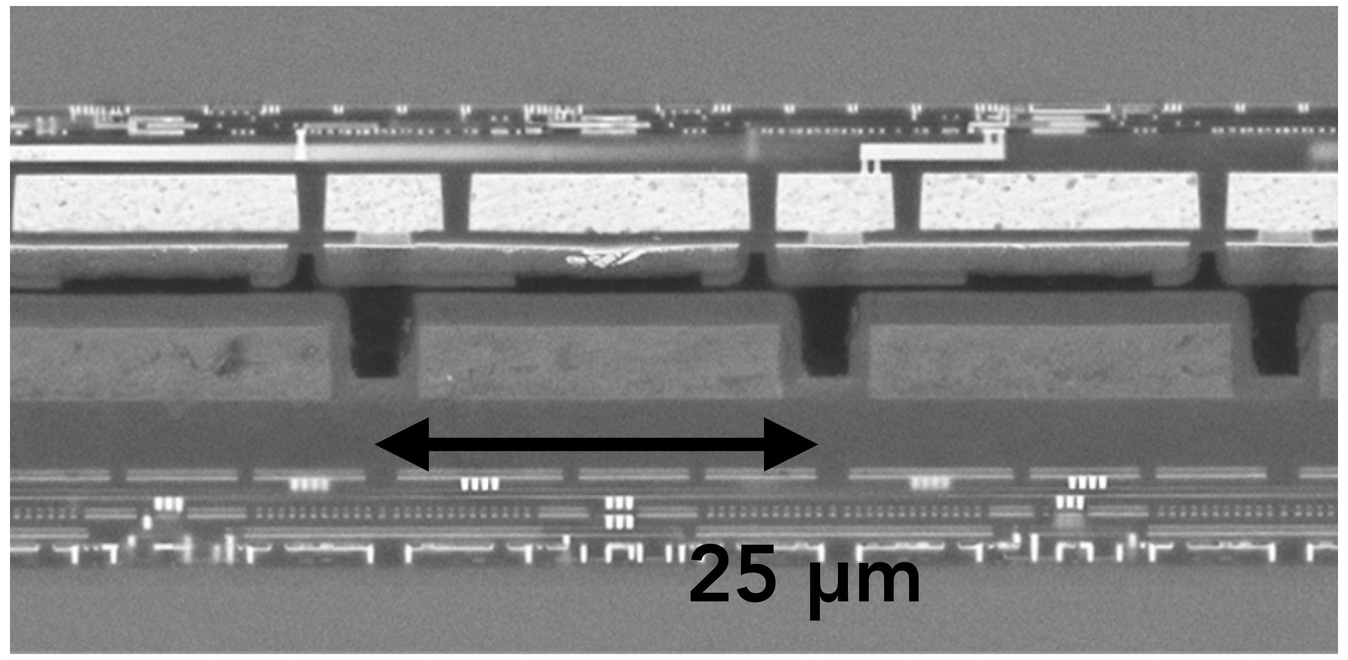
HV-CMOS sensors

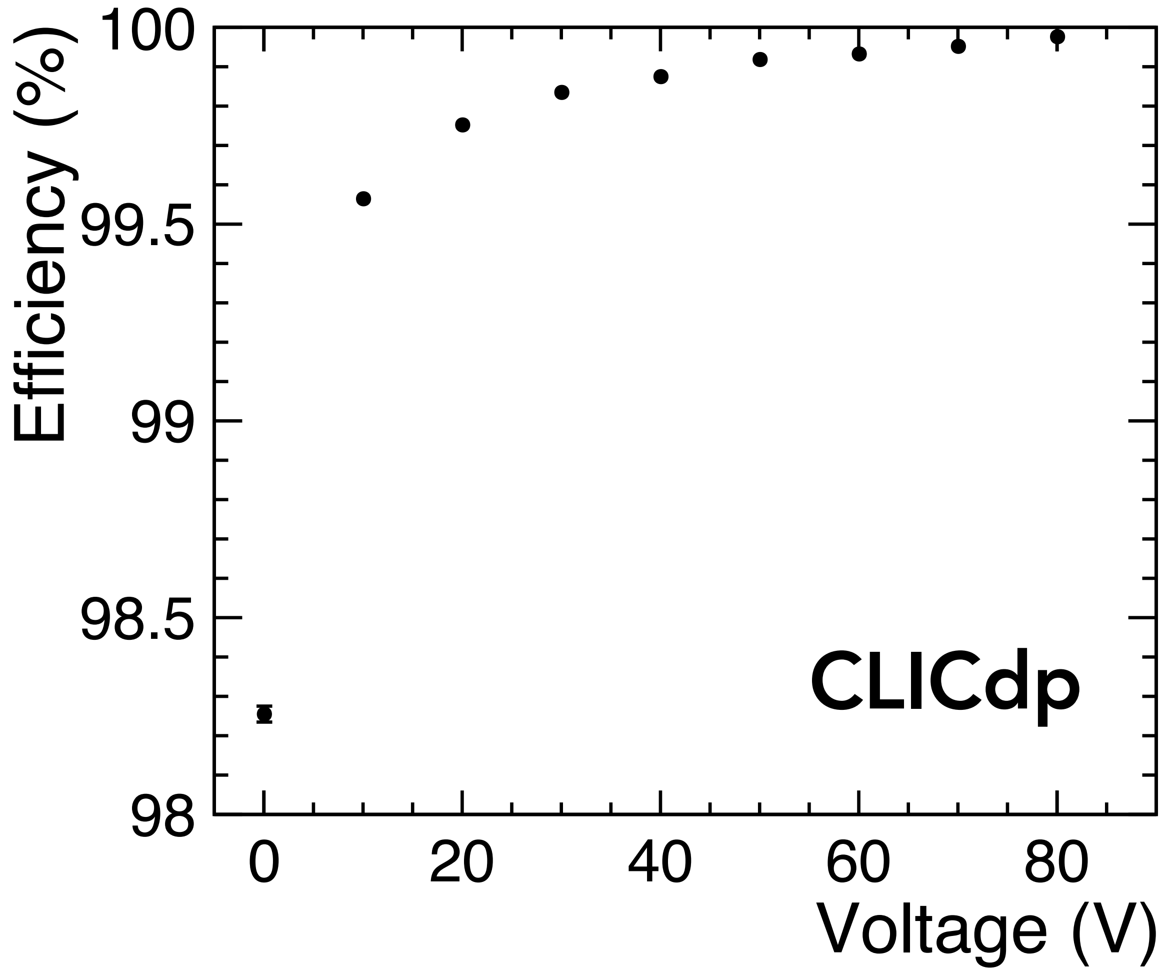
- In-depth studies of HV-CMOS devices have been carried out for CLIC, with knock-on contributions to high-luminosity LHC (ATLAS upgrade)
  - Proof-of-concept results on capacitively coupled pixel detectors showed high detection efficiency and reliable operation
  - Detailed fabrication studies carried out, for extrapolation to detector-scale production





- Common chip development with ATLAS
  - CCPD family, one of the first HV-CMOS chips developed for HEP
  - New ASIC produced in collaboration with the Medipix group - C3PD

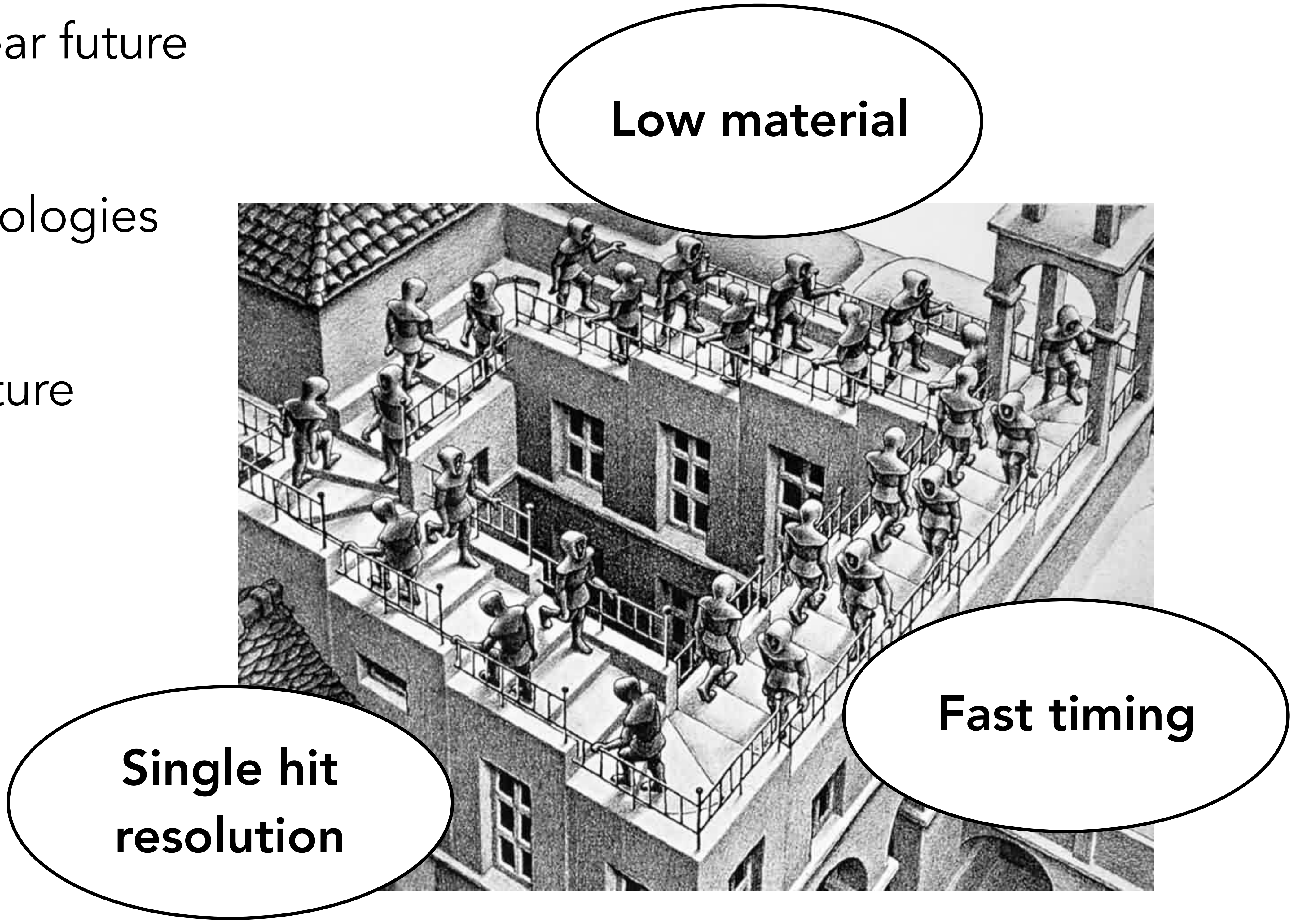




Future work

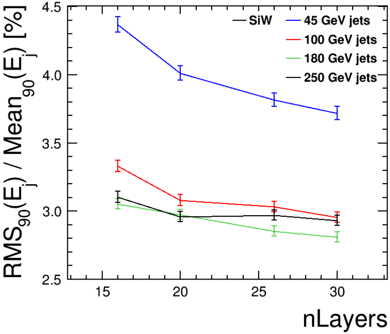
- Where are we now in terms of silicon?
  - Each of the requirements are achievable individually, trick is to reach all at once!
  - CLICpix with either HV-CMOS or planar silicon sensor getting close to vertex requirements
  - Dedicated monolithic chip for the tracker to be produced in the near future

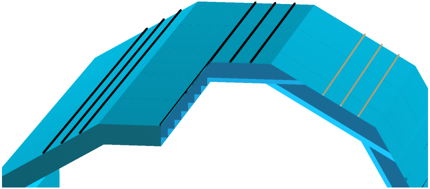
- CLIC silicon R&D touches on many areas, helping to push new technologies
  - Overlap with HL-LHC detector upgrades
  - Keep a close eye on developments in CMOS processing for the future



Electromagnetic Calorimeter

- Same performance 25 to 30 layers
    - PFA dominated by confusion
- Retaining $23X_0$
- Si and scintillation produce roughly same JER
- Cell size: JER degradation from 3% to 3.5% if going from 5x5 mm^2 to 15x15 mm^2 cells





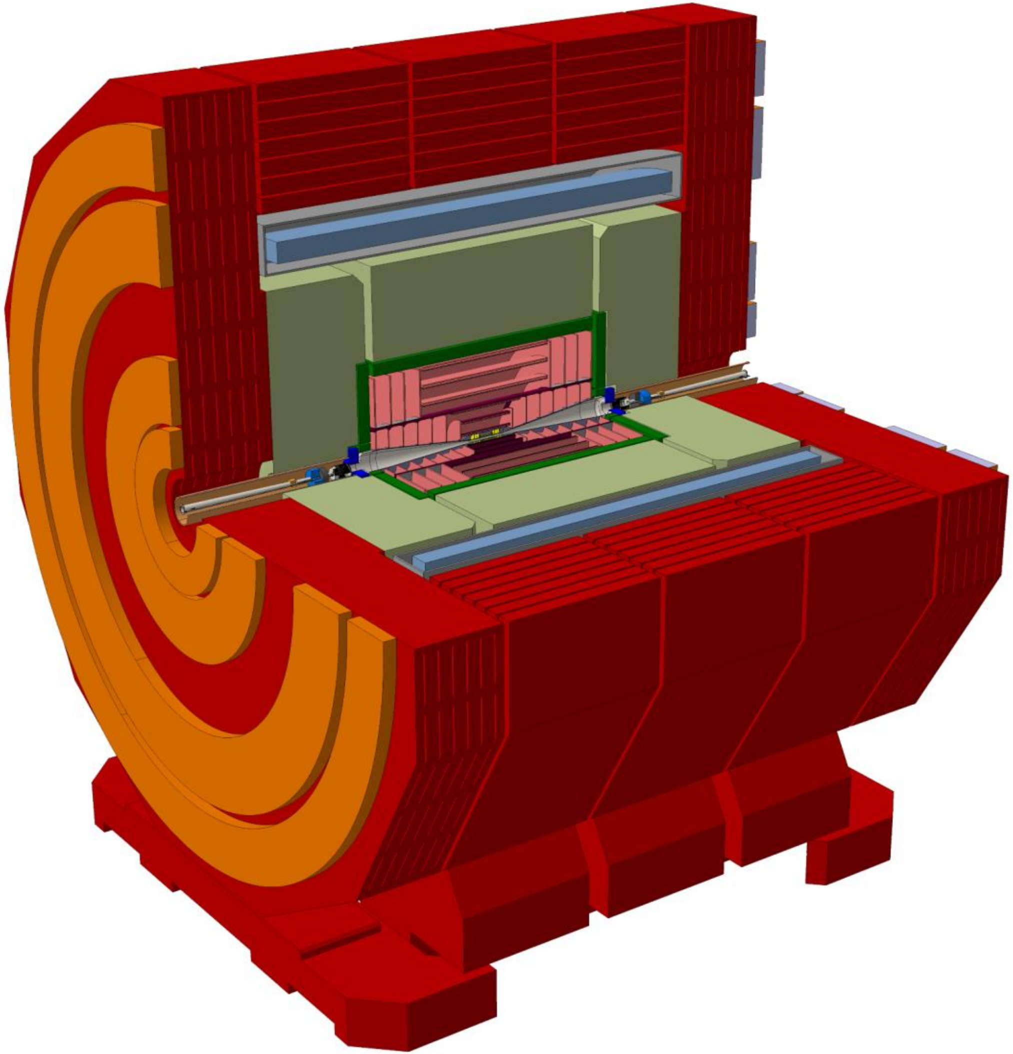
Parameters

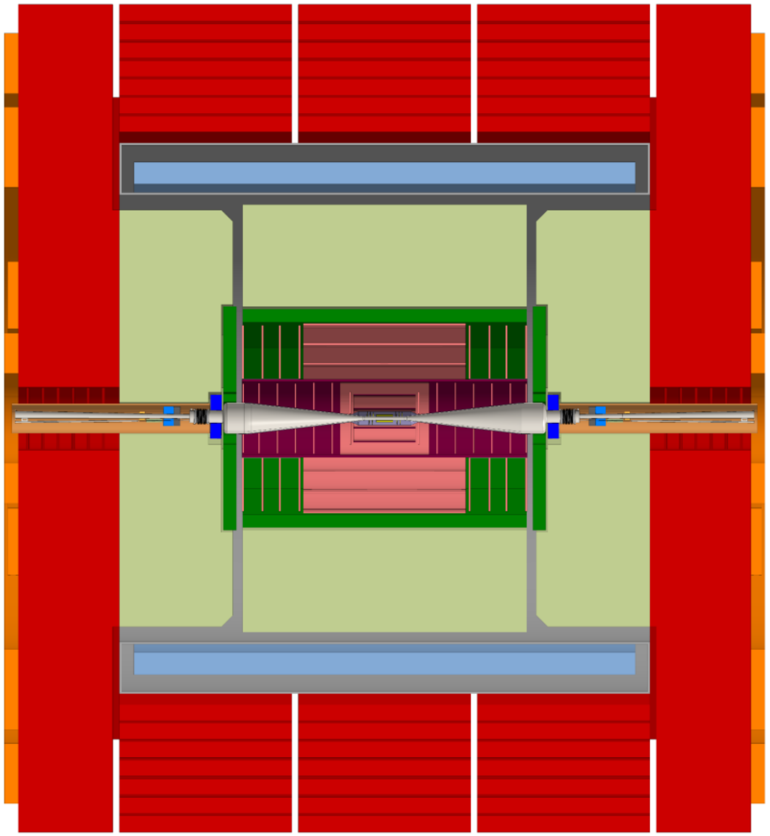
Tungsten absorber
Silicon active material
25 layers (17 × 2.4+8 × 4.8 mm)
Uniform cells 5.1 × 5.1 mm

Evolution of Detector Designs

- For the CLIC CDR (2012): Two general-purpose CLIC detector concepts
  - Based on initial ILC concepts (ILD and SiD) but optimised and adapted to CLIC conditions

Concept	CLIC_ILD	CLIC_SiD	CLICdet_2015	CMS
Tracker	TPC/Silicon	Silicon	Silicon	Silicon
B Field [T]	4	5	4	3.8
Solenoid R [m]	3.4	2.7	3.4	3
Solenoid L [m]	8.3	6.5	8.3	13
VTX R [mm]	31	27	31	40
ECal R [m]	1.8	1.3	1.5	1.3
ECal ΔR [mm]	172	135	159	500
HCal Absorber B / E	W/Fe	W/Fe	Fe	Cu+Zn
HCal λ_I B / E	7.5	7.5	7.55	5.8/10
Overall Height [m]	14	14	12.8	14.6
Overall Length [m]	12.8	12.8	11.4	21.6





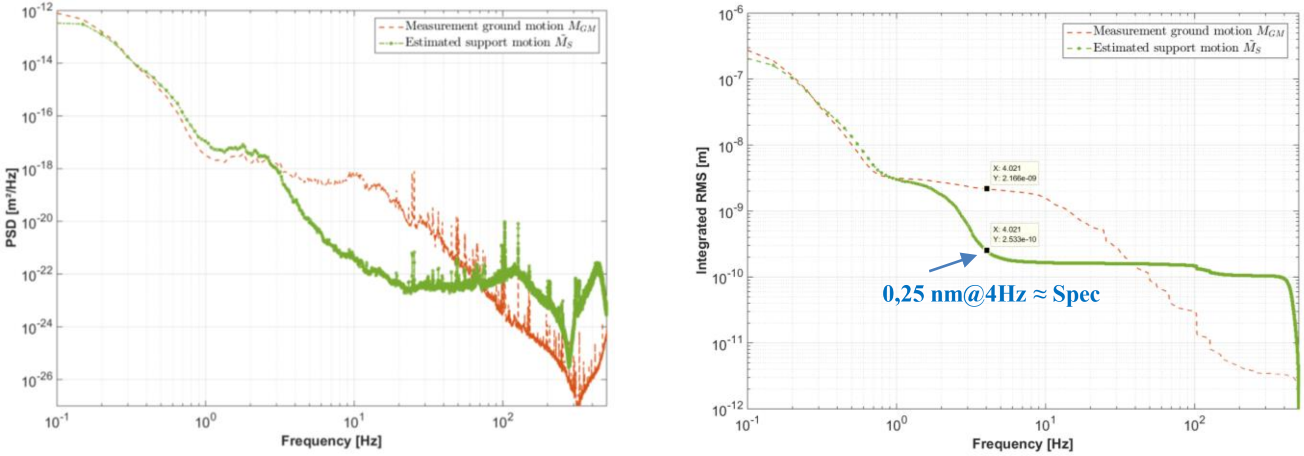
2016 : CLIC Demonstration of feasability at reduced scale

- CLIC specification (displacement of the QD0 final focus) : 0,20 nm RMS@4Hz
- Previous results with LAPP active foot + 4 commercial sensors : 0,60 nm RMS@4Hz
- Developpement of the vibration sensors at LAPP dedicated to control

➢ **Results of control (autumn 2016) with LAPP active foot + 1 LAPP vibrations sensor : 0,25 nm RMS@4Hz**

- *Only 1 sensor in feedback -> control less complex and more efficient*
- *Published in December 2016, in collaboration with SYMME (approbation in progress)*

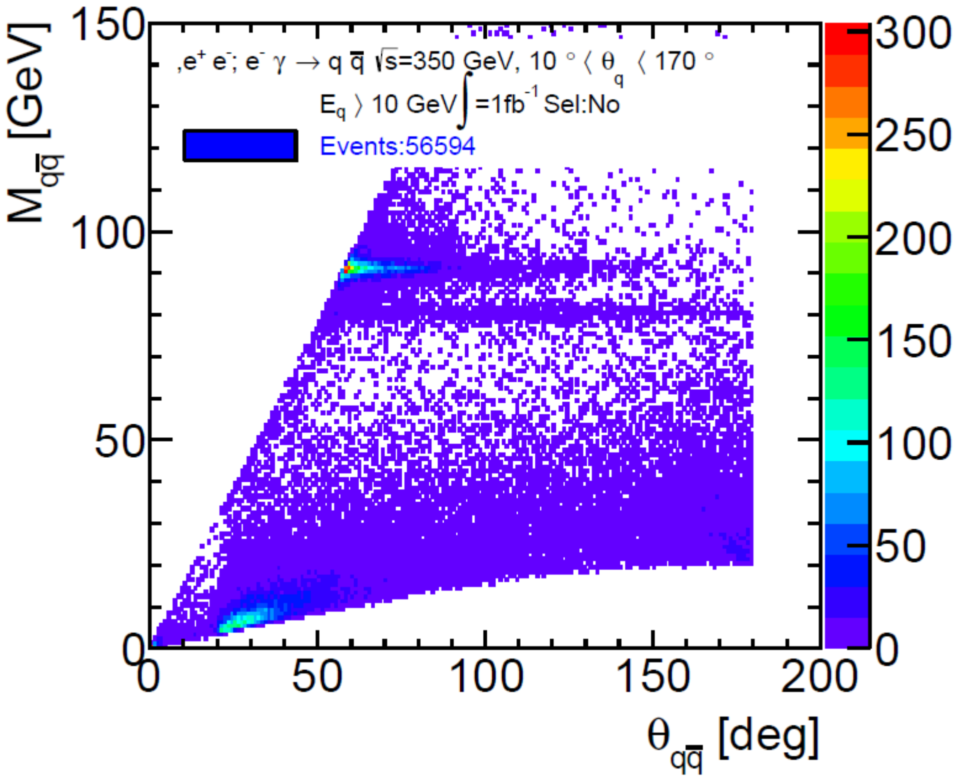
- LAPP active foot + LAPP sensors (one on ground used to monitor ground motion and 1 on top used in feedback) -

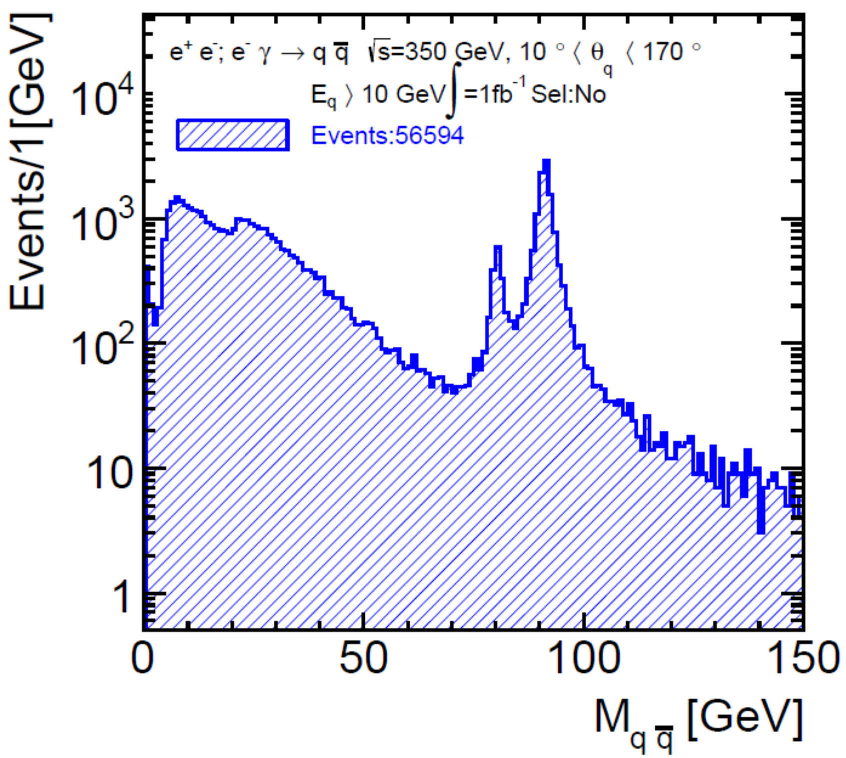


*- Displacement **without control** / **with control** at LAPP -*

Already an application in CMS, but need also passive insulation in CMS detector environment

Di-jet Mass Resolution at $\sqrt{s}$=350 GeV ; $\int L=1\,\mathrm{fb}^{-1}$



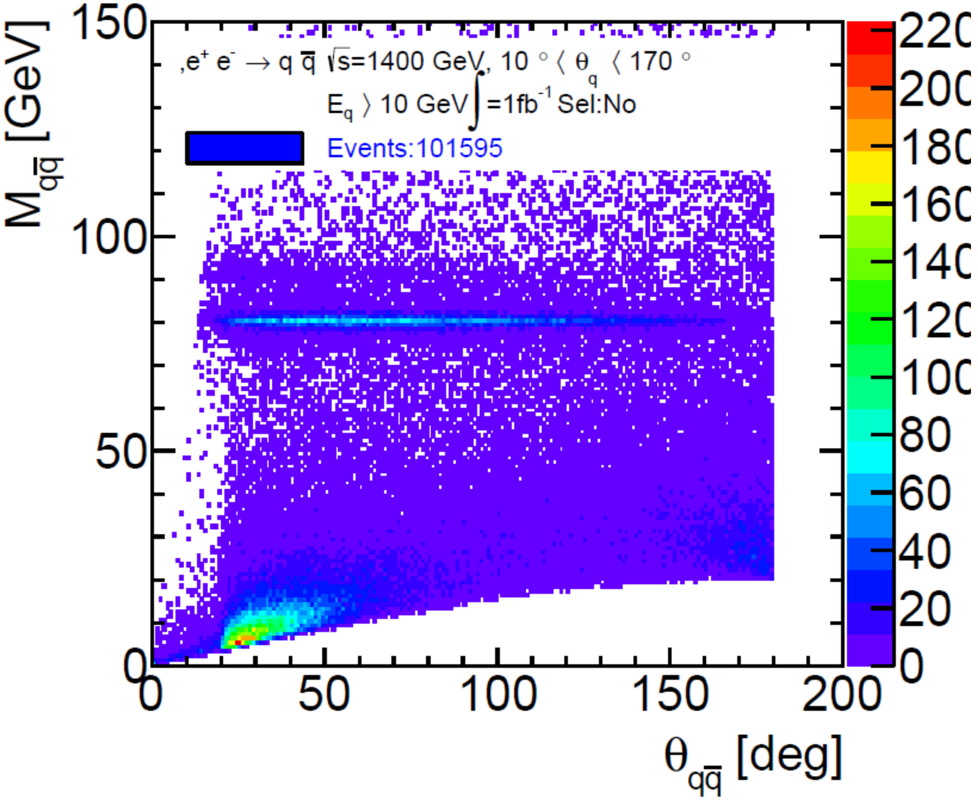


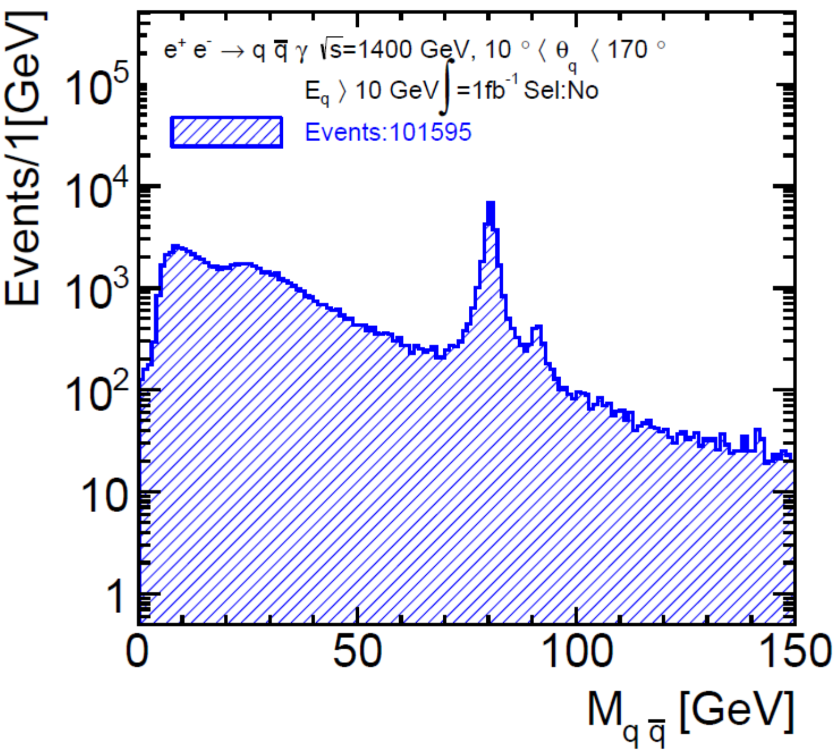
Left : Mqq̄ vs θqq̄; for e^+e^- and $e^-\gamma$ -> q q̄ x processes slide 8.

Z events ~ 60 °; W events θ ranges from 50 to 170°

Right: dN/dMqq̄; Largest contribution from Z→qq̄

Di-jet Mass Resolution at √s=1400 GeV ; ∫L=1fb⁻¹

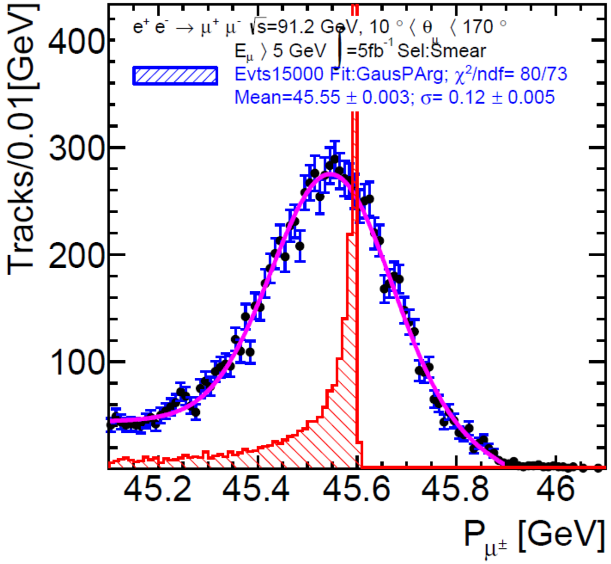


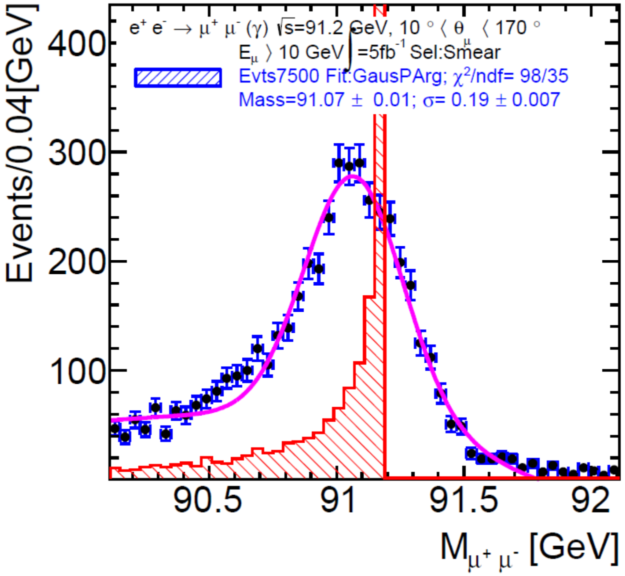


Left : Mqq̄ vs θqq̄; W events θ ranges from 20 to 170°

Right: dN/dMqq̄; Large contribution from W→qq̄; Z → qq̄ small.

Momentum Resolution and Scale at $\sqrt{s}=91$ GeV ; $\int L^{0}=5pb^{-1}$





$e^{+} e^{-} \rightarrow \mu^{+}\mu^{-}$ (γ)

- dN/dP(μ);

With smearing (blue), without (red scaled)

Tail towards low P from events with Isr γ

<Pμ>=45.55 ± 0.003 GeV; σ=0.12 GeV

$\sigma(P\mu)/P\mu=2.7\ 10^{-3}$.

Direct and accurate measurement of momentum resolution and scale.

- dN/dM($\mu^{+}\mu^{-}$);

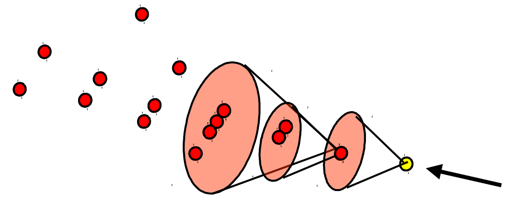
With smearing (blue), without (red, scaled)

<$M\mu^{+}\mu^{-}$>=91.07 ± 0.01 GeV

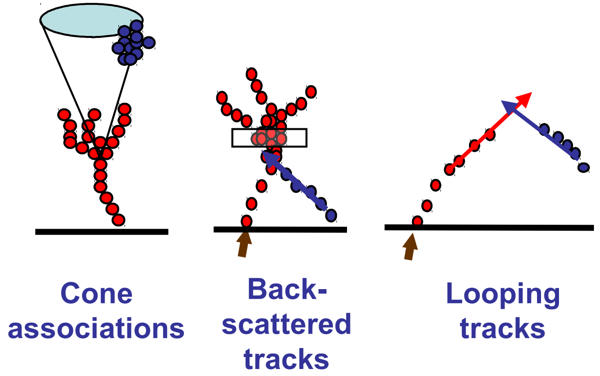
σ=0.2±0.007; no Z width in production

Particle Flow Algorithm

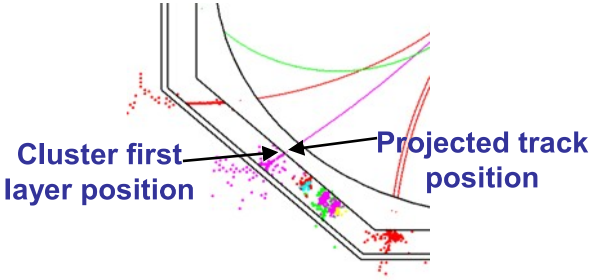
ConeClustering Algorithm



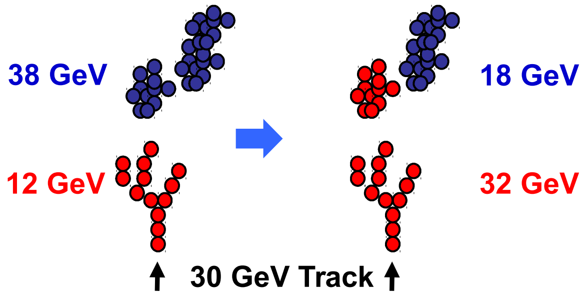
Topological Association Algorithms



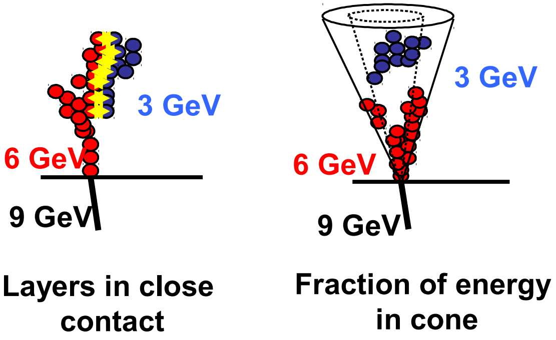
Track-Cluster Association Algorithms



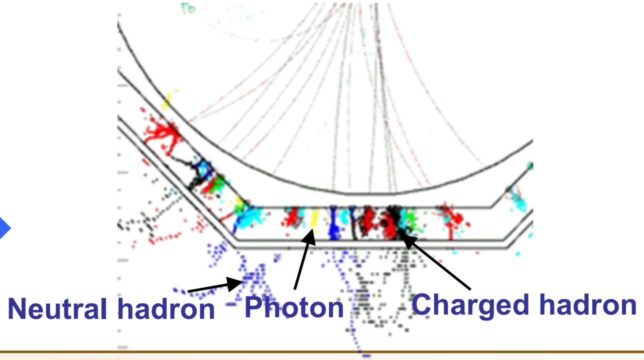
Reclustering Algorithms



Fragment Removal Algorithms



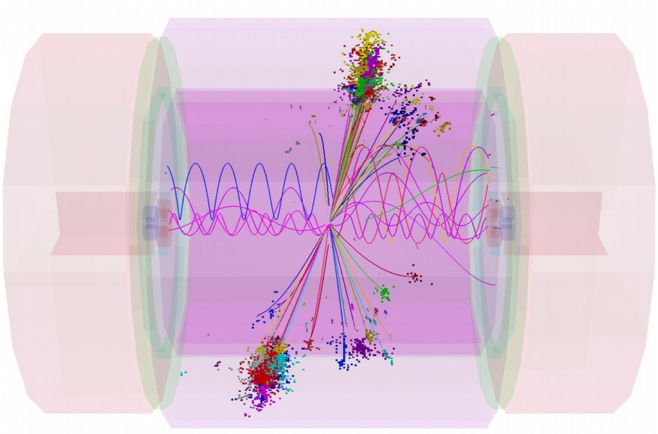
PFO Construction Algorithms



Perfomance

★ **Aim:** for high granularity PFlow Calorimetry

⇒ **Jet energy resolution:** $\boxed{\sigma_E/E < 3.5\%}$



★ **Benchmark** performance using jet energy resolution in Z decays to light quarks

M. Thomson, NIM 611 (2009) 24-40

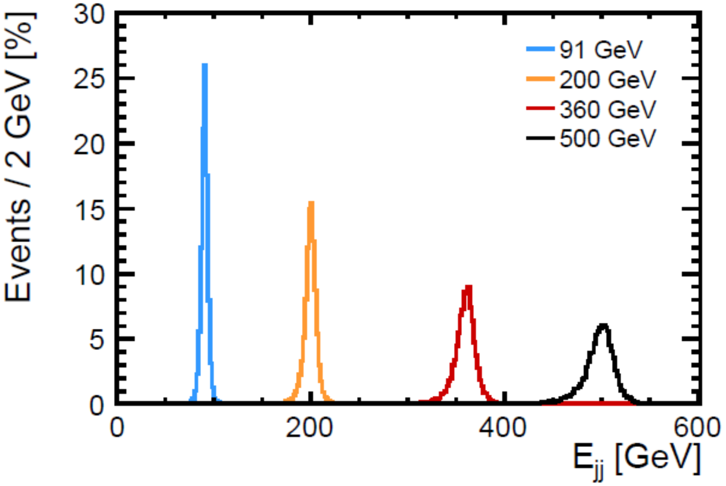
★ **Performance (**PandoraPFA + ILD)

- uds jets (full GEANT 4 simulations)

rms$_{90}$

E_{JET}	σ_E/E_j
45 GeV	3.7 %
100 GeV	2.8 %
180 GeV	2.9 %
250 GeV	2.9 %

→ **GOAL MET !**

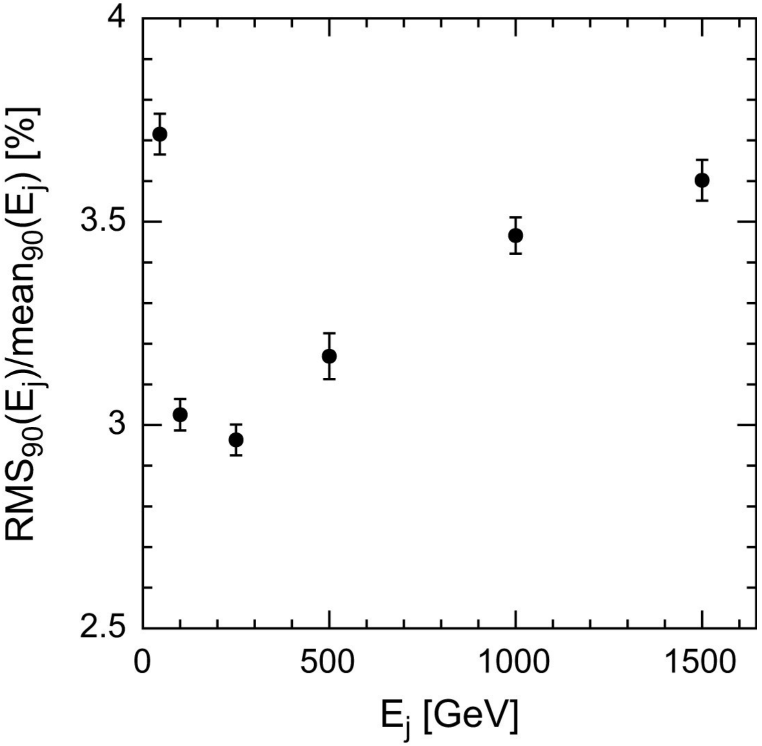


★ **Factor 2-3 better than traditional calorimetry !**

PFlow @ the High-Energy Frontier

- ★ **CLIC: very challenging environment due to pile up…**
  - But high-granularity calorimetry allows individual particles to be reconstructed – **many "hits" stress test the software…**
  - Pile-up from $\gamma\gamma \rightarrow$ hadrons can be effectively rejected using spatial and timing information

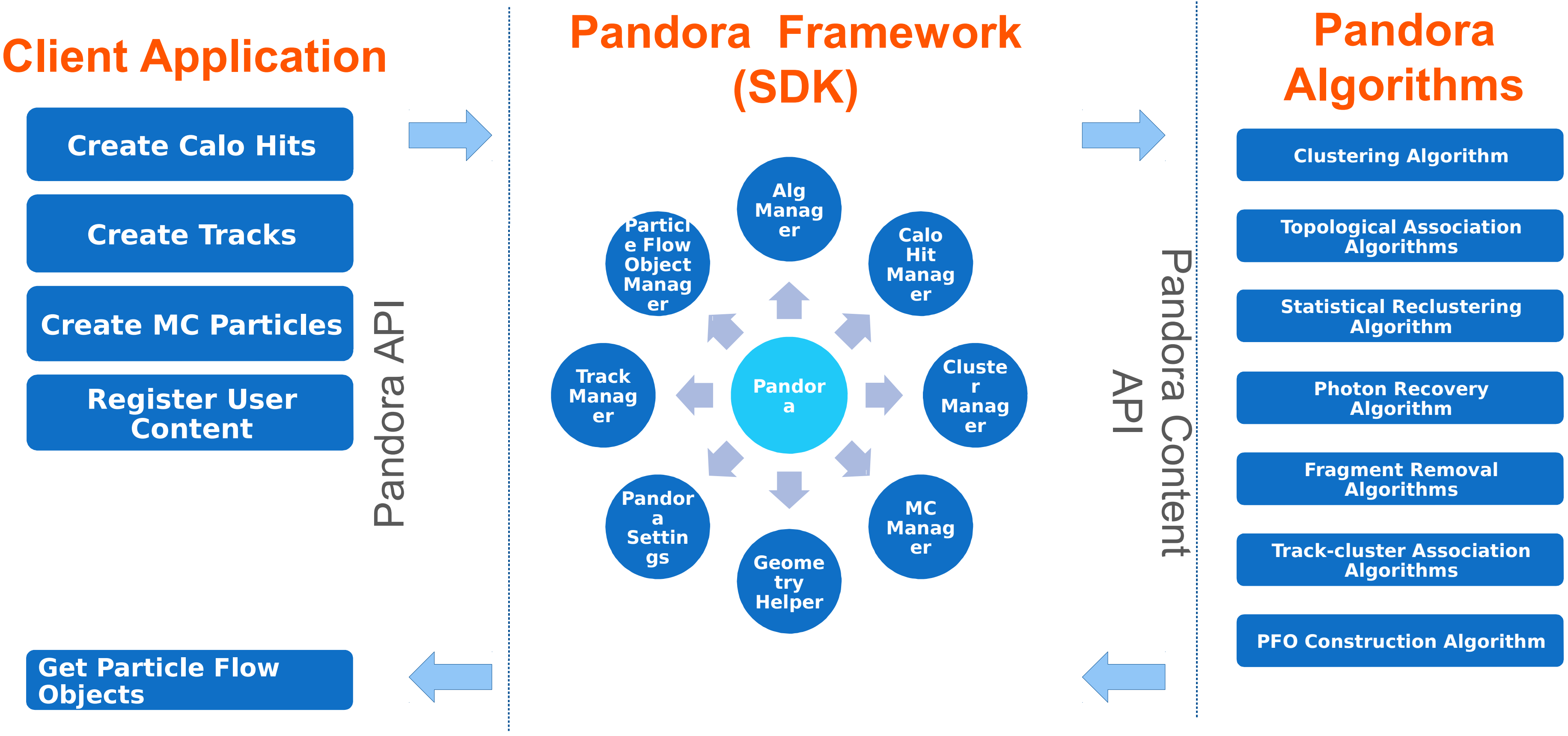
J. Marshall, A. Münnich, M. Thomson, NIM 700 (2013) 153 - 162



Particle Flow Calorimetry works at CLIC energies (in simulation)

Pandora Framework

- The current Pandora framework – detector independent



Client Application

- Create Calo Hits
- Create Tracks
- Create MC Particles
- Register User Content
- Get Particle Flow Objects

Pandora API

Pandora Framework (SDK)

- Pandora
- Alg Manager
- Calo Hit Manager
- Cluster Manager
- MC Manager
- Geometry Helper
- Pandora Settings
- Track Manager
- Particle Flow Object Manager

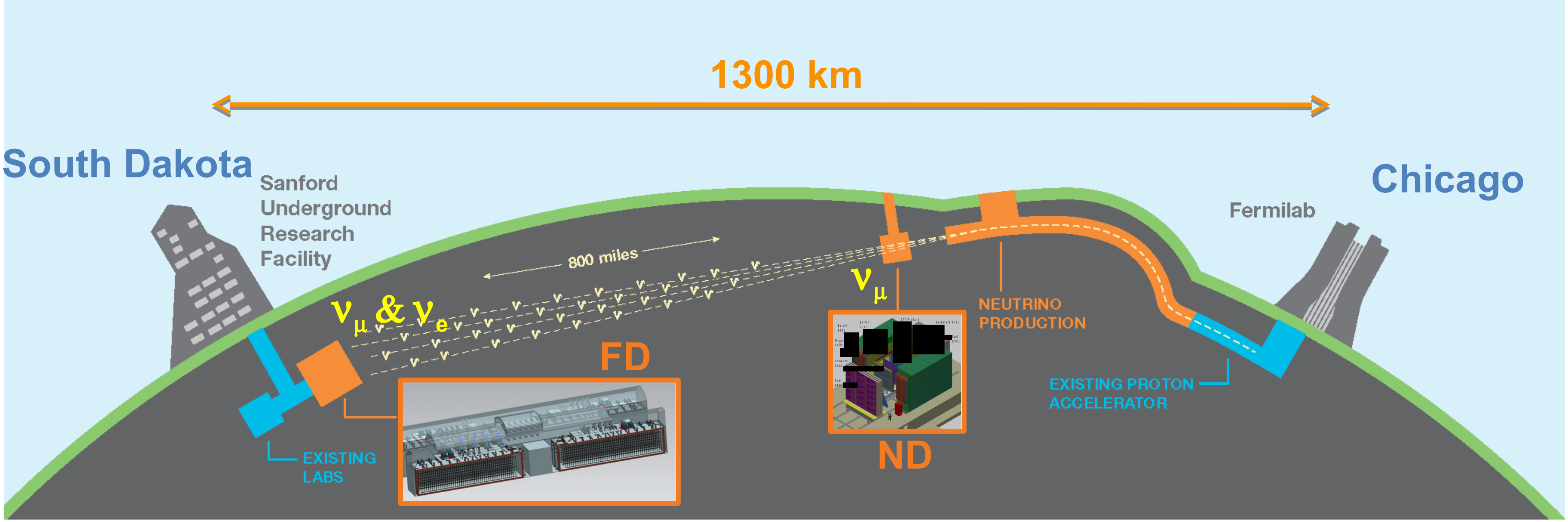
Pandora Content API

Pandora Algorithms

- Clustering Algorithm
- Topological Association Algorithms
- Statistical Reclustering Algorithm
- Photon Recovery Algorithm
- Fragment Removal Algorithms
- Track-cluster Association Algorithms
- PFO Construction Algorithm

- Highly optimised (CPU/memory footprint) framework
- User code “Algorithms” separated from Framework code

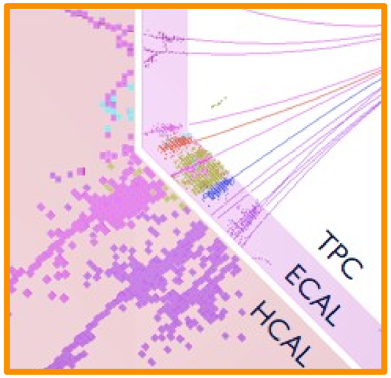
DUNE



[redacted]

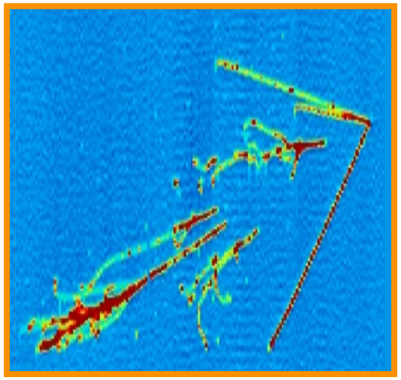
- **DUNE: Deep Underground Neutrino Experiment**
  - 1.2 MW neutrino beam fired 1300 km from Fermilab to SURF (S. Dakota)
  - Four vast (17,000 ton) Liquid Argon TPC detectors (1 mile underground)
  - Imaging calorimetry for neutrino interactions !
  - Ambitious physics goals:
    - CP violation for neutrinos, proton decay, supernova neutrinos, …

LC vs LAr-TPC



Many similarities

Many differences



LC PFlow reconstruction

- High-granularity calorimeter
- Track-like and shower-like structures in calorimeter
- Many “hits” (calorimeter cells)
- 3D readout
- External tracks guide clustering
- Challenging reconstruction

Proof-of-Principle from PandoraPFA

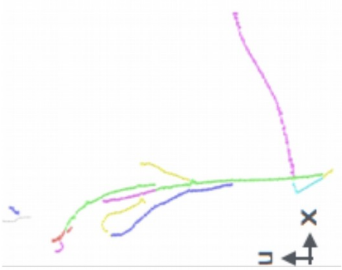
LAr-TPC ν reconstruction

- High-granularity calorimeter
- Track-like and shower-like structures in calorimeter
- Many “hits” (wire vs. time)
- 2D readout x 3 views
- Need to reconstruct ν vertex
- Very challenging reconstruction

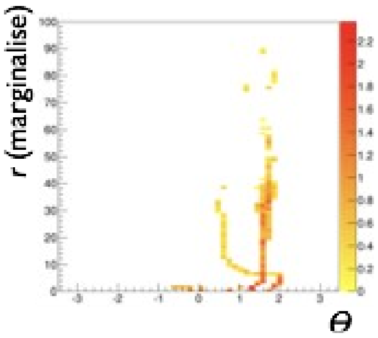
Fully-automated reconstruction being developed in Pandora

Algorithms

2D Track Clustering

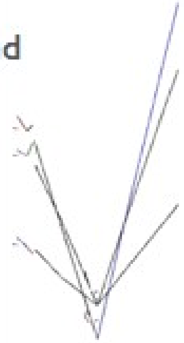


3D Vertex Reconstruction



3D Track Reconstruction

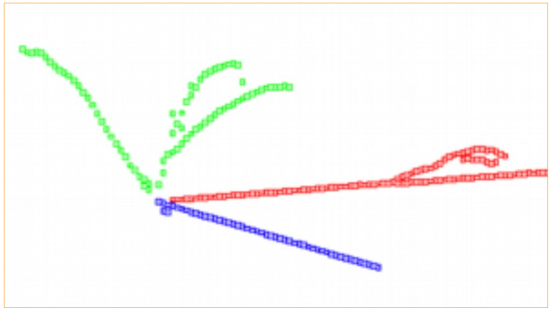
Overlay U,V and W Clusters



2D Shower Branch Growing

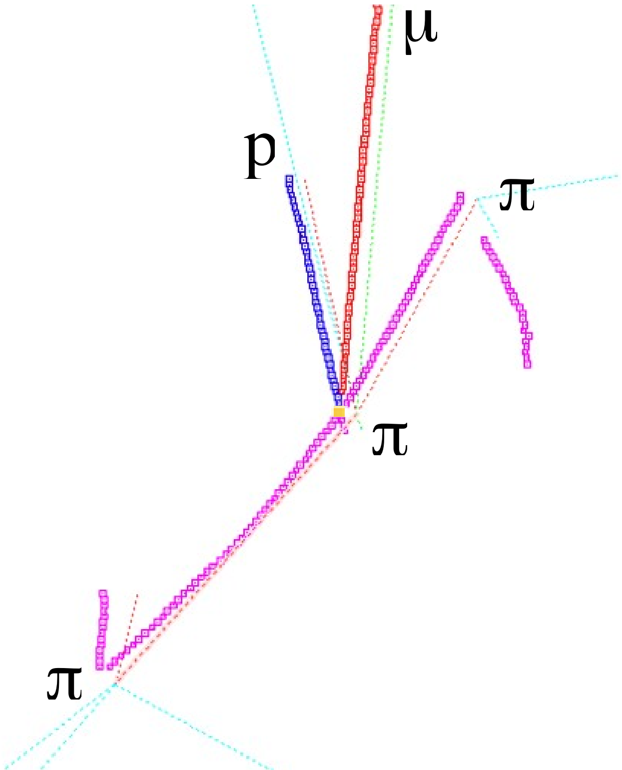
3D Shower Reconstruction

Neutrino PFO Hierarchy



Pandora @ MicroBooNE

- Development has been driven by MicroBooNE
  - Running experiment with neutrino beam data
  - Surface operation – reconstruction complicated by cosmic-ray background
  - Still work-in-progress, but performance metrics are encouraging…
  - Aim to reconstruct full particle hierarchy, starting from neutrino vertex



Performance

Compare to MC truth at the individual particle level:

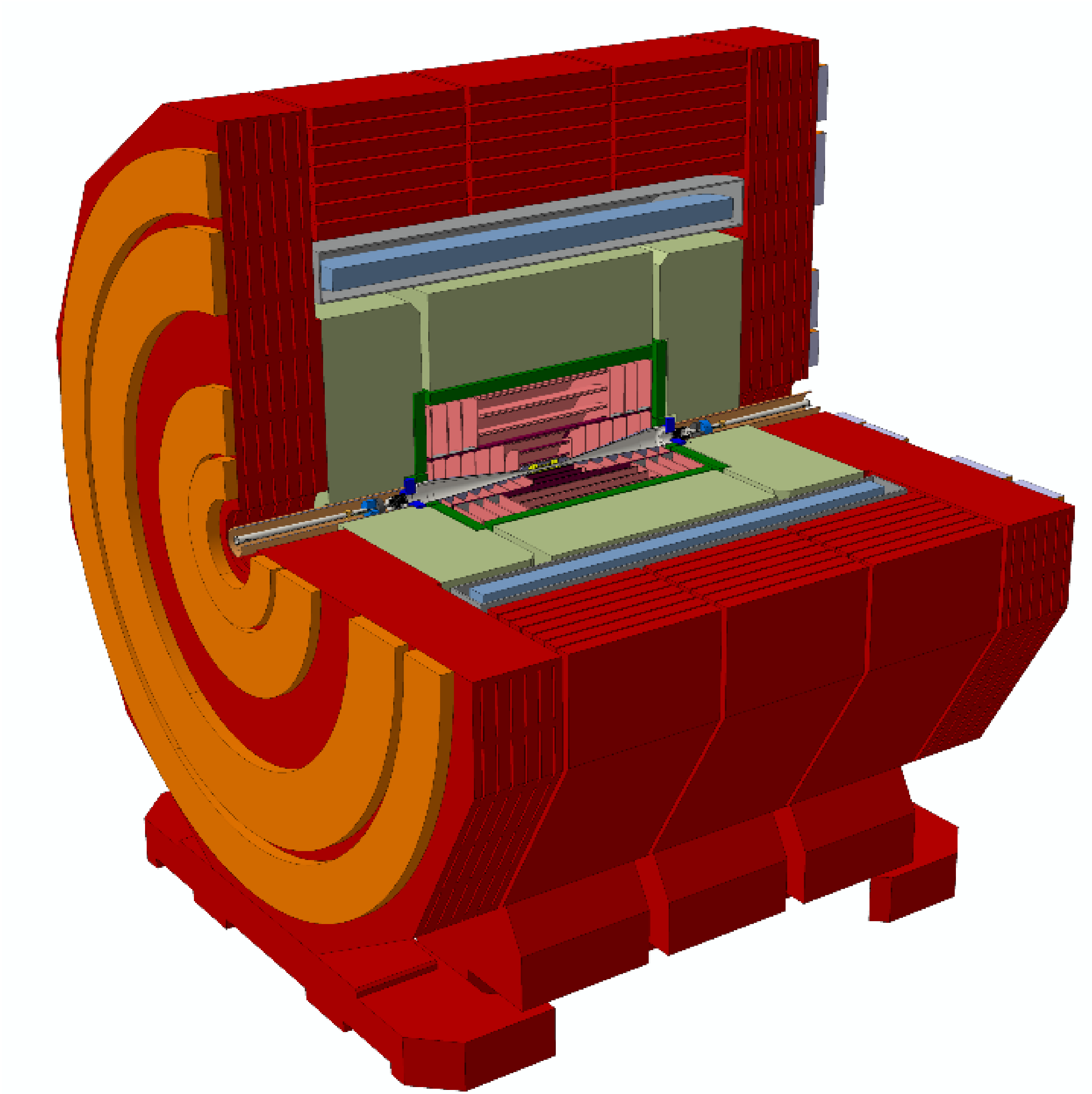
Achieve "Perfect Reconstruction" for:

~ 90 % of QE (μ + p) events

~ 70 % of RES ($\mu + \pi$ + p)

~ 50 % of RES ($\mu + \pi + \pi^0$ + p)

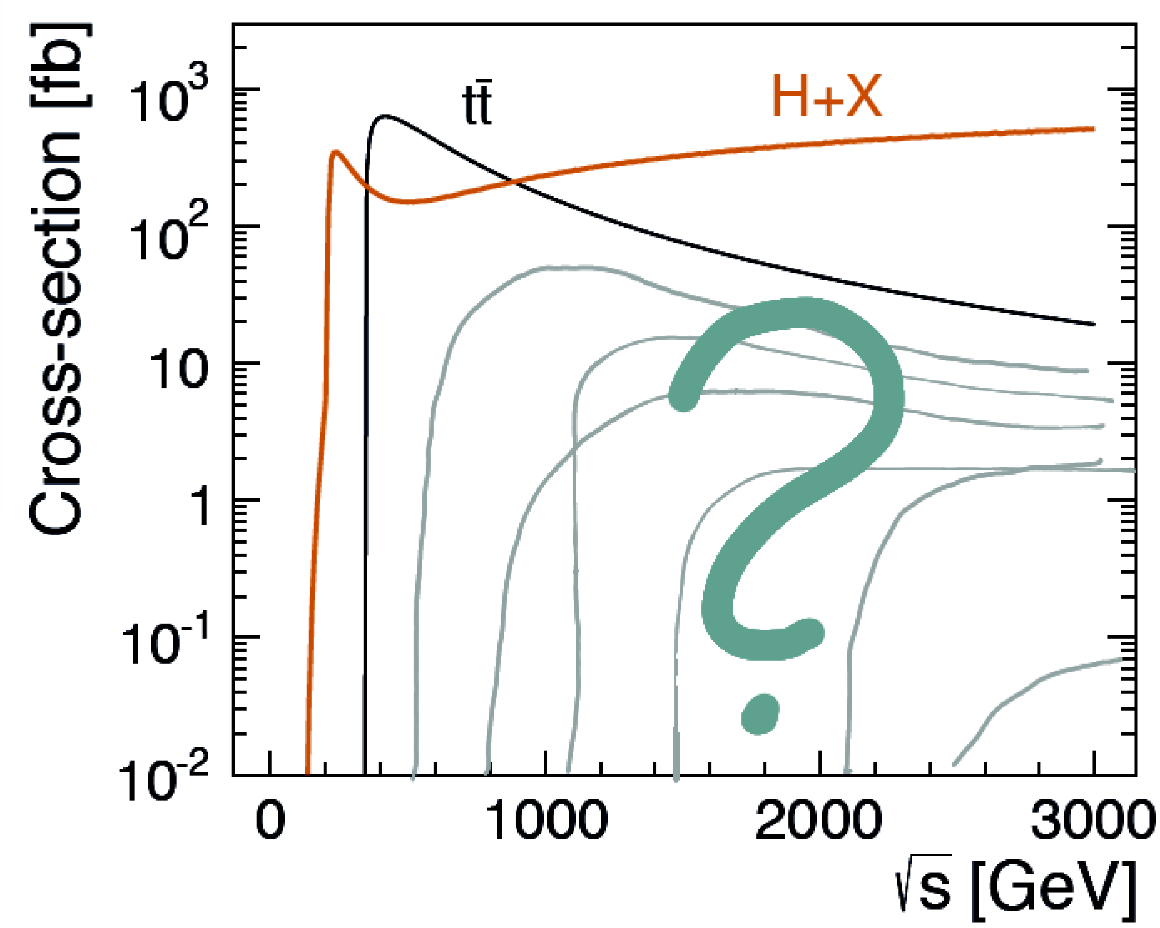
CLIC physics



CLIC physics context

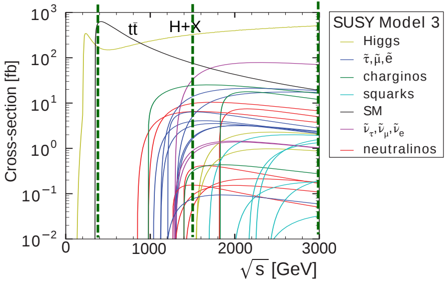
Energy-frontier capability for electron-positron collisions,

for precision exploration of potential new physics that may emerge from LHC



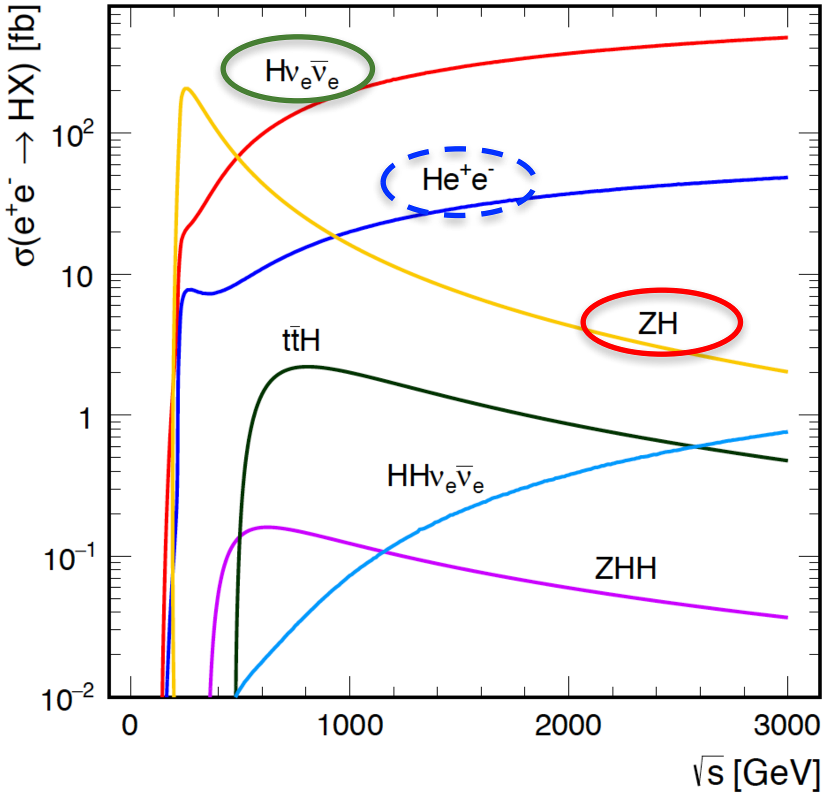
Proposed CLIC staging baseline

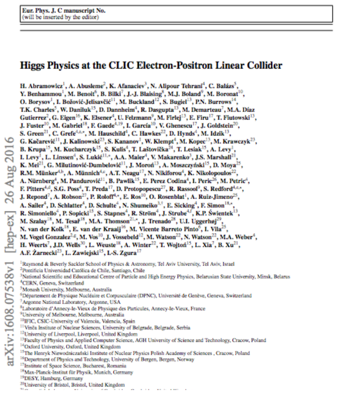
- CLIC energy stages defined by physics
- Proposed scenario
  1) $\sqrt{s} = 380\,\text{GeV}$
     - SM Higgs physics including total width measurement
     - Top precision measurements
     - New physics
  2) $\sqrt{s} = 1.5\,\text{TeV}$
     - New physics
     - $t\bar{t}H$, Higgs self coupling
     - Rare Higgs decays
  3) $\sqrt{s} = 3\,\text{TeV}$
     - New physics
     - Higgs self coupling
     - Rare Higgs decays



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

Higgs measurements




Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Higgs Physics at the CLIC Electron-Positron Linear Collider

- Comprehensive paper on Higgs physics at CLIC: *arXiv:1608.07538*, submitted to EPJC

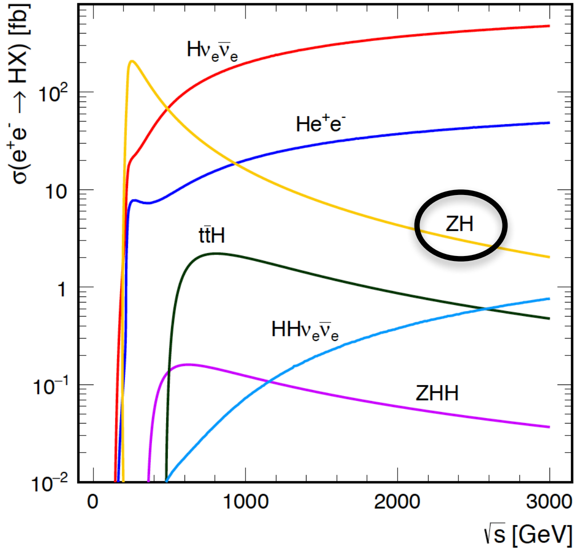
- Production cross sections for different processes cover wide energy range
  → Higgs measurements profit from all stages
- Large event samples for main production mechanisms expected

- Geant4-based full detector simulation studies with background and pile-up overlay for 350 GeV, 1.4 TeV and 3 TeV
- High selection efficiencies in most cases

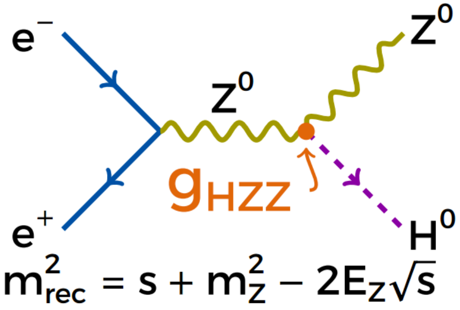
	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

For unpolarised beams. Hvv increases ×1.8 for -80% e- polarisation (CLIC baseline)

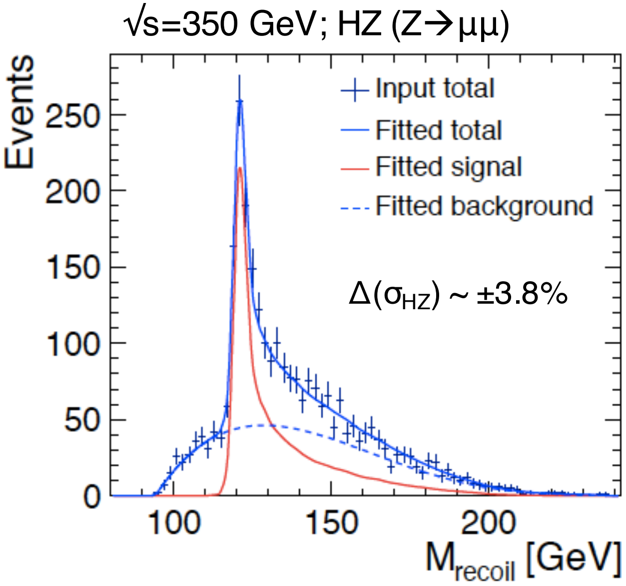
Higgsstrahlung $e^+e^- \to ZH$ @ ~350 GeV

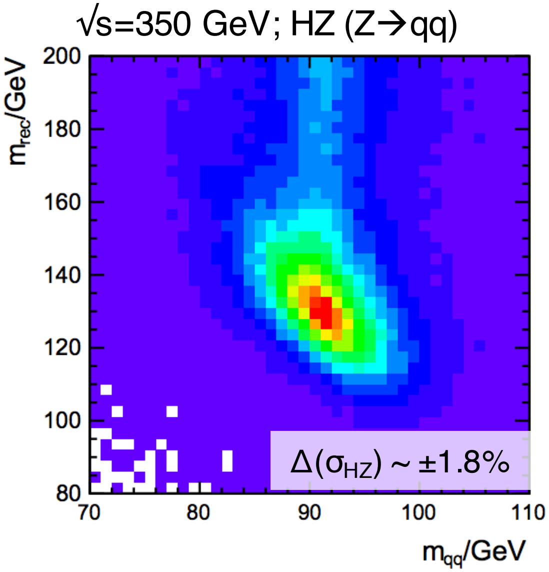


- Benchmark studies for $e^+e^- \to ZH$ @ 350 GeV, 500 fb^{-1}
- Select ZH through recoil mass against Z
  → model-independent measurement: $\Delta\sigma_{HZ} \sim g_{HZZ}^2$
- Combined uncertainty on $\Delta(g_{HZZ}) \sim \pm 0.8\%$
- ZH → Hqq gives access to invisible Higgs decays: BR(H→inv) < 1% @ 90% CL



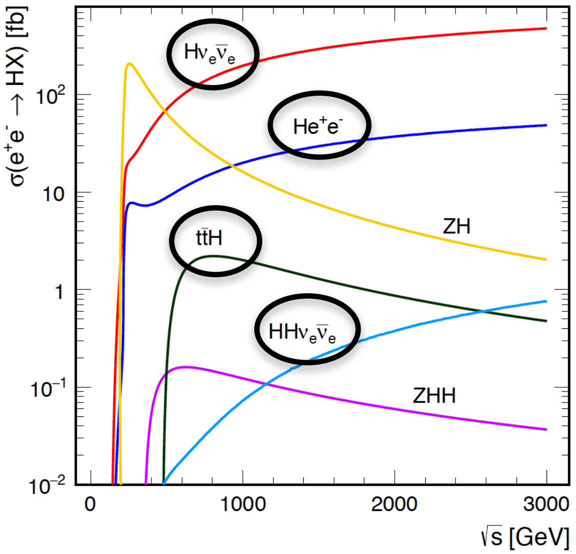
$$m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$


√s=350 GeV; HZ (Z→μμ)


√s=350 GeV; HZ (Z→qq)

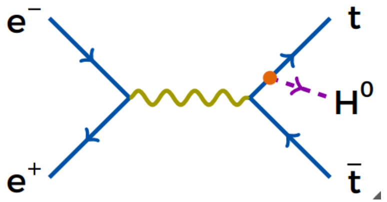
- ZH→Zqq studies for 250, 350, 420 GeV
- Trade-off between jet-energy resolution and signal/background
- Best performance at ~350 GeV
  → drives choice of 380 GeV for first energy stage (together with top physics)

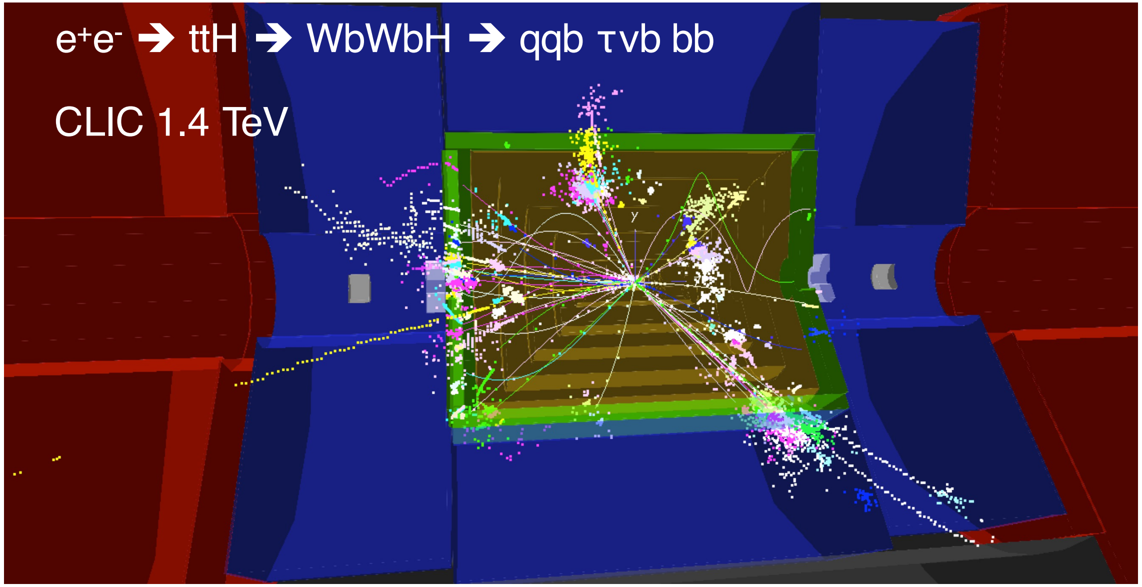
Higgs measurements at higher energies



ttH production: $e^+e^- \to ttH$

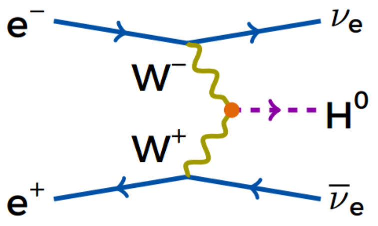
- Sensitive to top-Yukawa coupling
- 2400 events @ 1.4 TeV, $1.5ab^{-1}$ (1400 @ 3 TeV, $2ab^{-1}$)





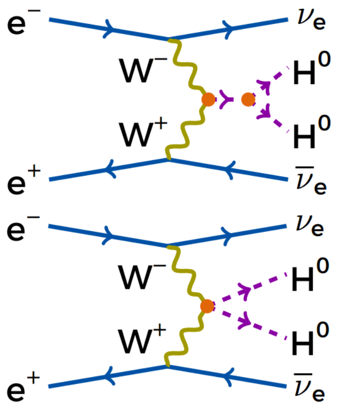
WW fusion: $e^+e^- \to H\nu\nu/He^+e^-$

- σ~log(s), dominant >450 GeV
- Access to H→cc and rare decays like H→μμ

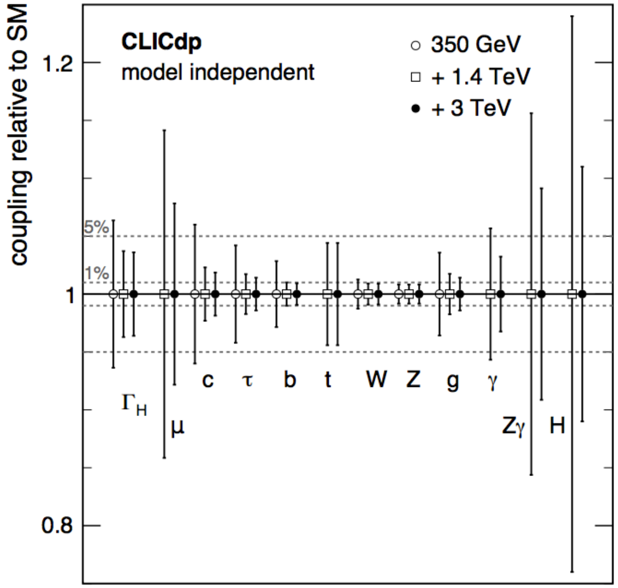


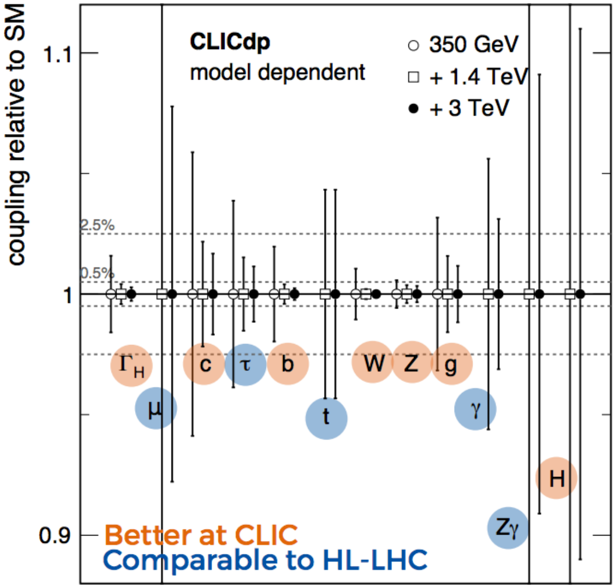
Double-Higgs production: $e^+e^- \to HH\nu\nu$

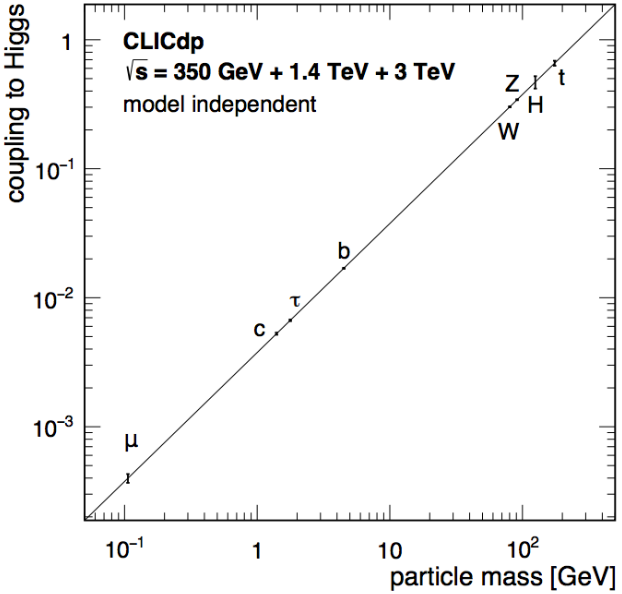
- Sensitive to trilinear self coupling parameter λ and to quartic coupling g_{HHWW}
- Small cross section: 225 events @ 1.4TeV, 1.5ab-1 (1200 @ 3TeV, 2ab-1) → needs high energy and luminosity



Higgs measurements - summary

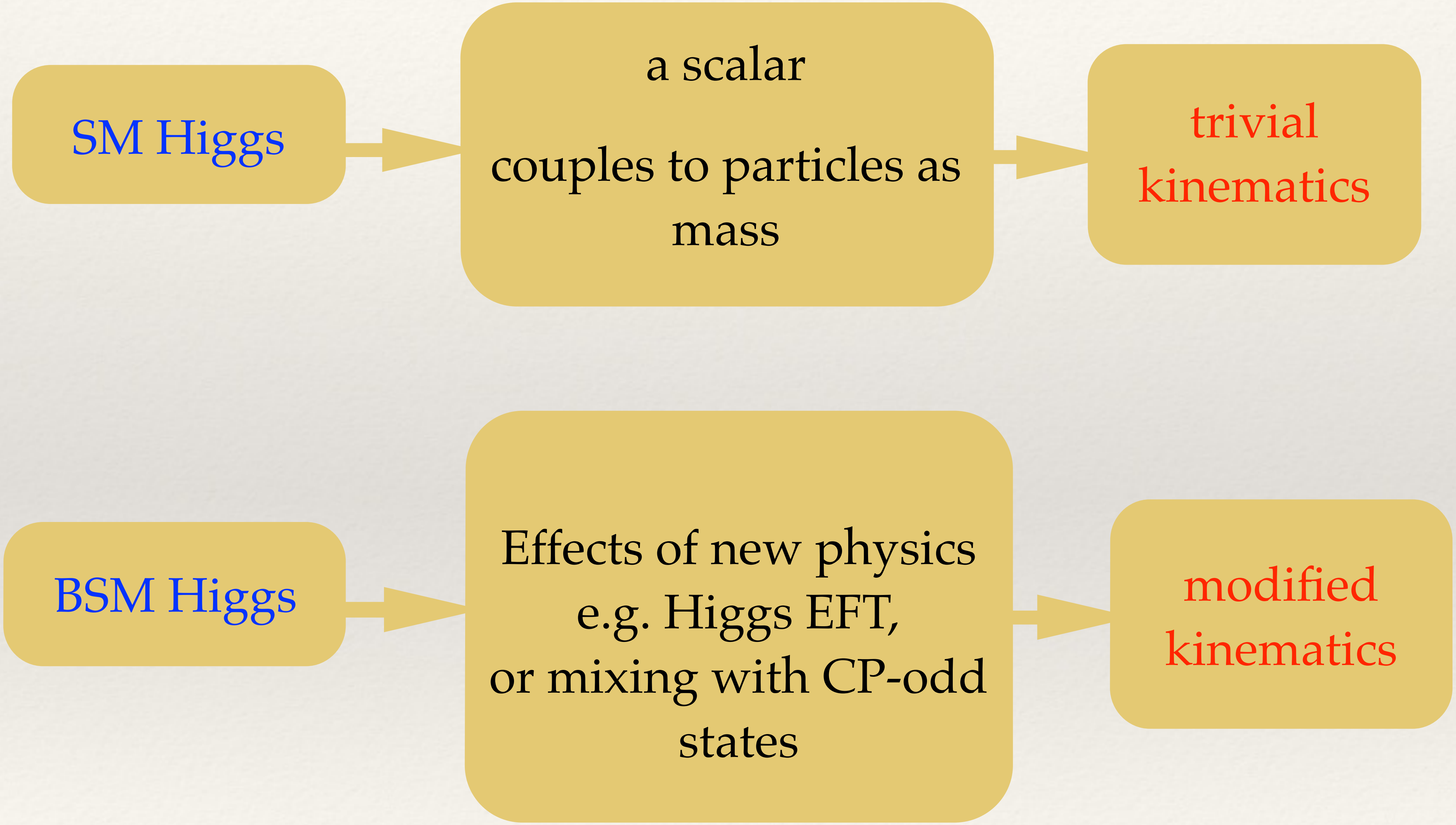






- Model independent extraction only at lepton colliders, due to model independent measurement of g_{HZZ}
- Significant improvements from higher energy stages
- Many couplings measured with ~1% precision
- Higgs width extracted with 5-3.5% precision
- Model dependent fits can achieve precision below 1%

Higgs as a window to new physics



SM Higgs

a scalar

couples to particles as mass

trivial kinematics

BSM Higgs

Effects of new physics
e.g. Higgs EFT,
or mixing with CP-odd states

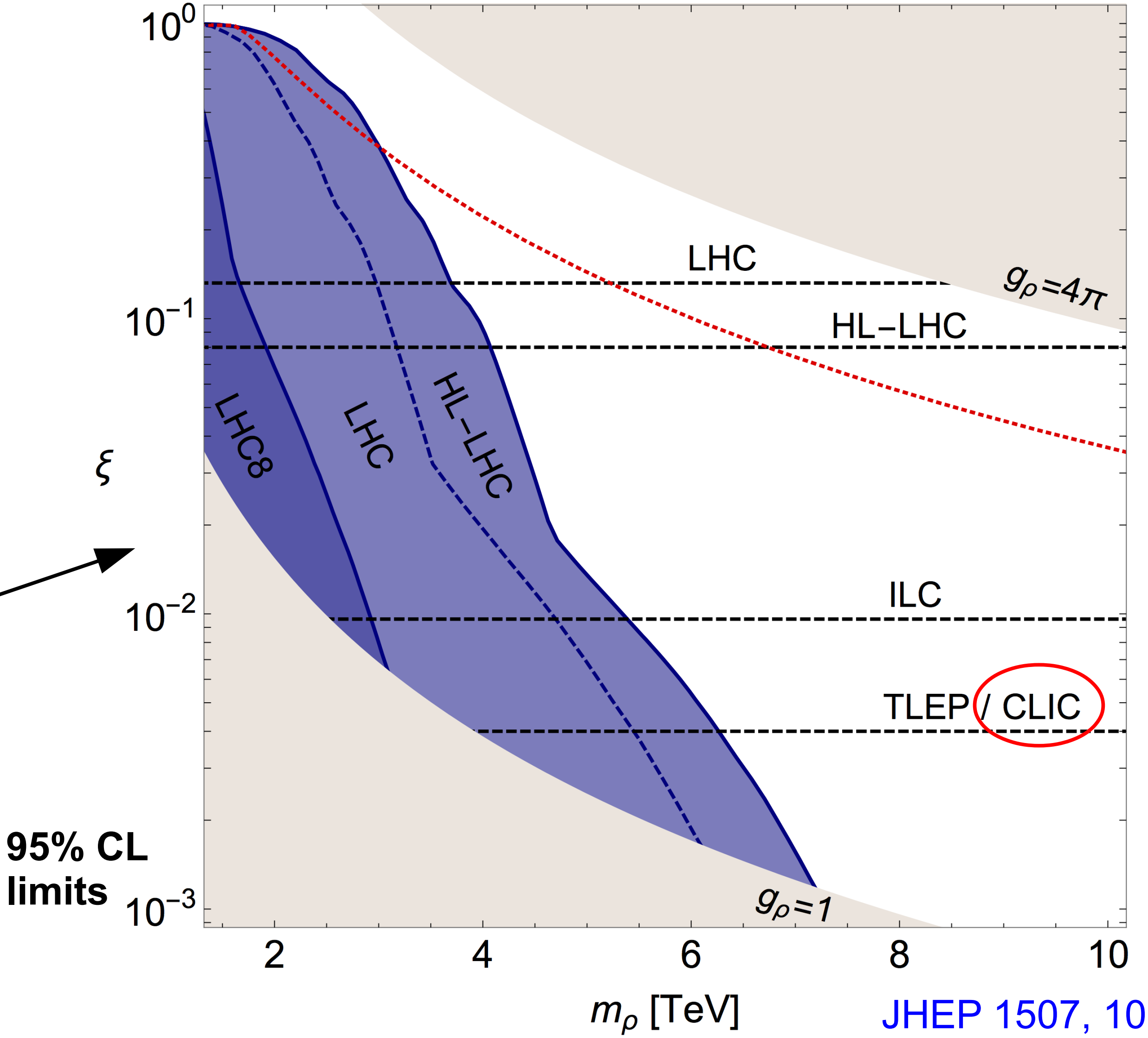
modified kinematics

Composite Higgs bosons

- Higgs as composite bound state of fermions

- m_ρ: mass of the vector resonance of the composite theory

- $\xi = (v / f)^2$ measures the strengths of the Higgs interactions



JHEP 1507, 100

CLIC provides an indirect probe of a Higgs composite scale of 70 TeV

BSM

New physics at CLIC:

- Direct searches via pair production up to ~√s/2
- Searches for deviations from SM expectation
- Precision measurements of new particles discovered at HL-LHC

Results from full-simulation studies for CLIC:

- ~1% precision on masses and cross sections
- Measurement of spin and quantum numbers

Ongoing full-simulation BSM studies:

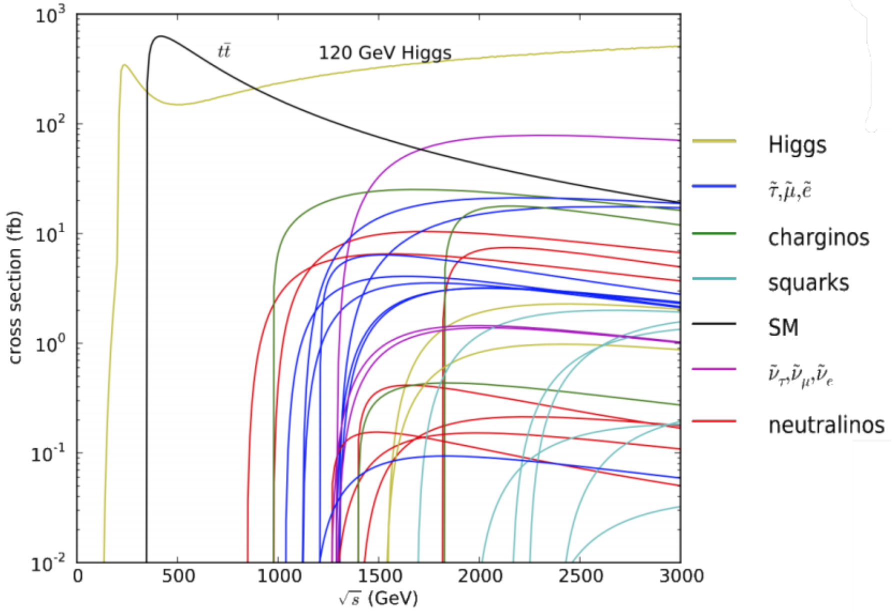
- Anomalous gauge couplings
- Hidden valley search
- FCNC: t→cH, t→cɣ
- ...

New phenomenological approaches:

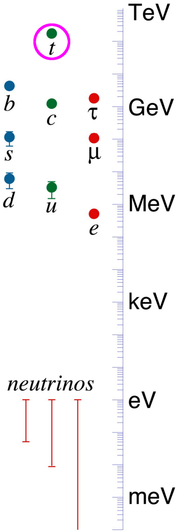
- Effective theories of universal theories
- Clockwork mechanism

More on top and BSM in following talk by P. Roloff and in analysis session contributions

Example SUSY model from CDR for 1.4 TeV



Motivation



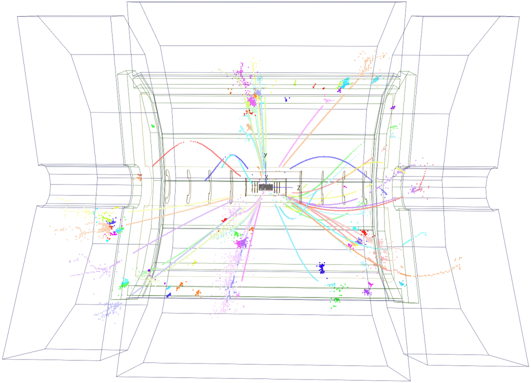
Credit: Hitoshi Murayama

Top quark

- the heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t \sim 1$
  $\Rightarrow$ key to understanding of EWSB
- decays before hadronizing:
  the only "naked" quark
  $\Rightarrow$ test ground for QCD
- large loop contributions to many precision measurements
- sensitive to many BSM scenarios
  $\Rightarrow$ a window to "new physics"

Top event reconstruction

Final state



$e^+e^- \longrightarrow t\bar{t} \longrightarrow 6\,j$ at $\sqrt{s} = 380$ GeV

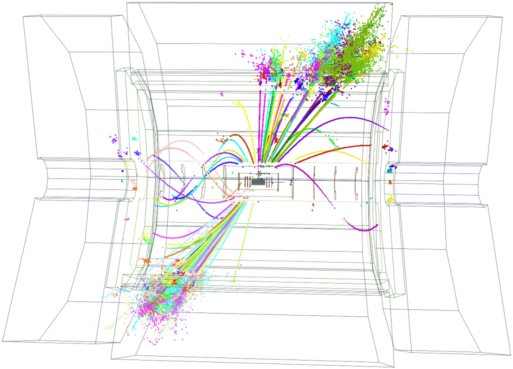
At low energy stage, top decay products (jets) well separated.

Direct reconstruction of the decay kinematics possible.

Crucial for efficient background suppression

Top event reconstruction

Final state



$e^+e^- \longrightarrow t\bar{t} \longrightarrow 6\,j$ at $\sqrt{s} = 3$ TeV

At higher energy stages, top quarks produced with large boost.

Decay products cluster in two "fat" jets.

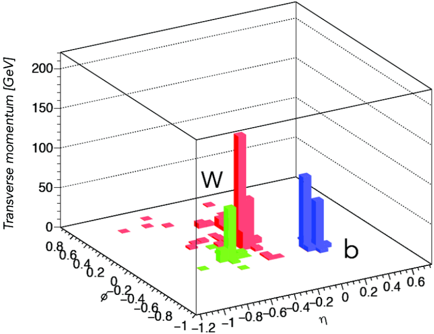
⇒ dedicated tools needed to discriminate between top and background events

Top tagging

Using jet substructure

to distinguish boosted top jets from light-quark and gluon jets using

Method proposed in Kaplan et al. Phys. Rev. Lett. 101, 142001



Structure of a single top jet

Cluster event into two jets, top candidates

Try to recluster candidate jet into three subjets to reconstruct decay kinematics

Impose kinematic constraints

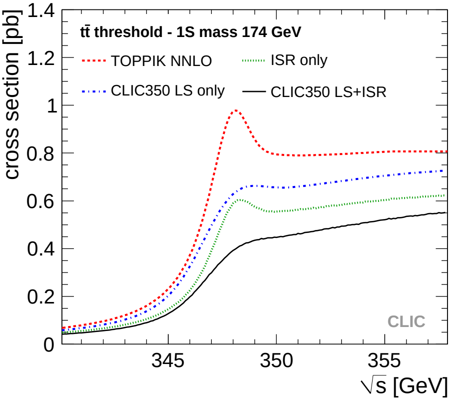
Look also at relative angles, jet multiplicity...

Threshold scan

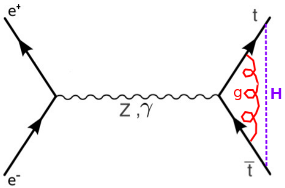
Top pair production cross section around threshold:

resonance-like structure corresponding to narrow $t\bar{t}$ bound state.

Very sensitive to top properties and model parameters:



- top quark mass m_t
- top quark width Γ_t
- strong coupling α_s
- top Yukawa coupling y_t

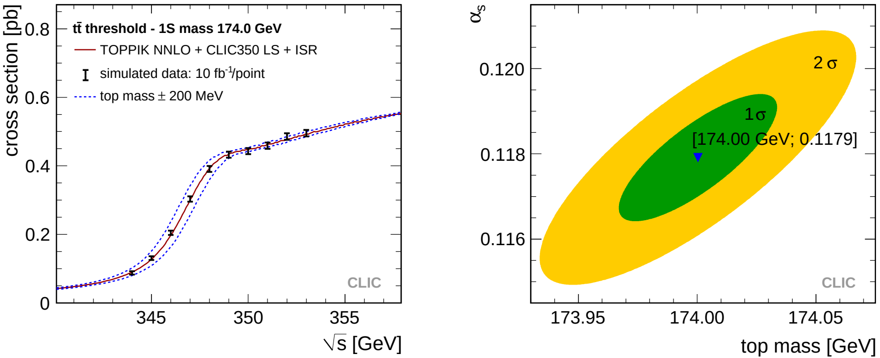


Significant cross section smearing due to luminosity spectra and ISR

Top mass determination

Already 100 fb^{-1} at the threshold sufficient for top mass measurement

Energy scan: 10 cross section measurements, 10 fb^{-1} each (to be optimised)



K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

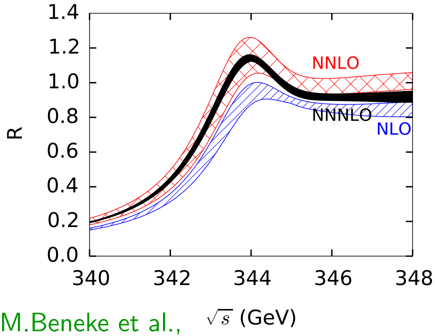
Expected statistical uncertainty on top mass: 15–20 MeV

on top width: ∼40 MeV

Top mass determination

Threshold scan

Main advantage: mass well defined from theoretical point of view
Enormous progress in precision of theoretical calculations



M.Beneke et al.,
Phys. Rev. Lett. 115, 192001 (2015)

Estimates for top mass
systematic uncertainties:

- theoretical predictions (NNNLO):
  $\sim$40 MeV
- parametric α_s uncertainty:
  $\sim$30 MeV (for today's WA)
- other uncertainties
  (backgrounds, spectra, etc.):
  on 10–20 MeV level

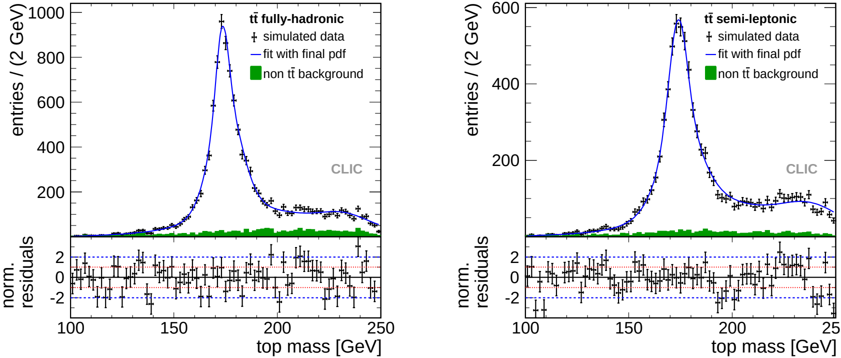
⇒ total uncertainty on the top mass of $\sim$50 MeV feasible
dominated by systematics

Top mass determination

Direct reconstruction

Possible for all energies above the threshold (continuum)

High statistical precision: 80 MeV estimated for 100 fb^{-1} at 500 GeV



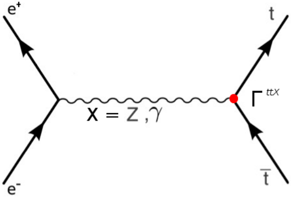
K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

Suffers from significant theoretical uncertainties when converting to particular mass scheme (as in LHC).

Electroweak couplings

Pair production: direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics"



Form factor approach:

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

Electroweak couplings

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Couplings can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle in top decays

Form factor approach:

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Electroweak couplings

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- total cross-section
- forward-backward asymmetry
- helicity angle in top decays

Alternative, more universal approach: effective field theory (EFT)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

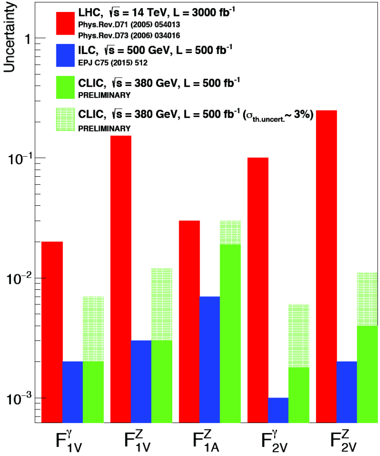
⇒ allows to connect different physics processes (sharing same operator)
⇒ allows to combine/compare different experiments
⇒ includes additional terms (i.e. four-fermion contact interactions)

Under development. Focus on 2-fermion and 4-fermion dim-6 operators.

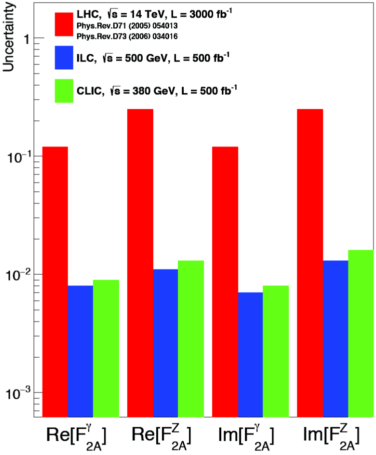
Electroweak couplings

Expected coupling precision at LHC, ILC (500 GeV) and CLIC (380 GeV)
initial stage

CP conserving couplings



CP violating couplings

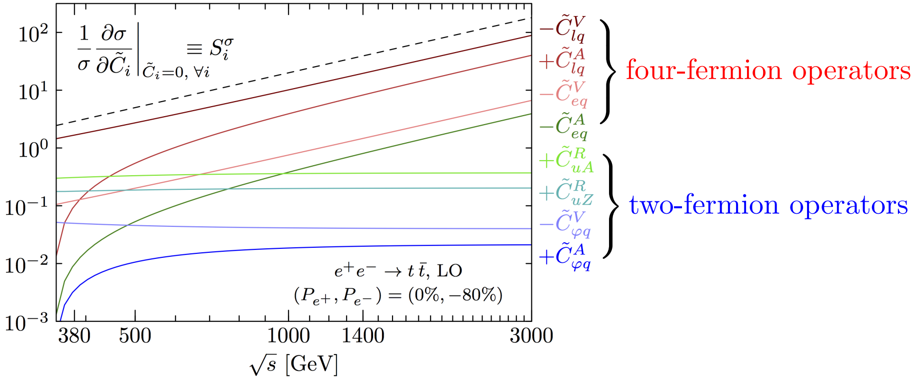


IFIC-LAL Collaboration, M.Perello @ ECFA LC'2016

Electroweak couplings

EFT prospects M.Perello, this workshop

Sensitivity of $\sigma(e^+e^- \to t\bar{t})$ to dimension-6 operators



Multi-TeV operation gives high sensitivity to four-fermion operators

High sensitivity to two-fermion operators at the initial stage

Yukawa coupling

Threshold scan ILC: A.Ishikawa @ TopLC'2015

Pair production at threshold: 9% Higgs exchange contribution

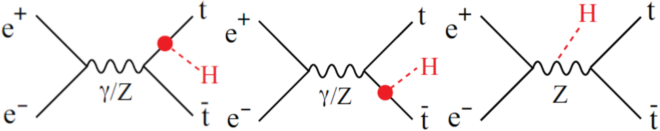
⇒ y_t can be extracted with statistical uncertainty ∼6% (100 fb^{-1})

assuming α_s can be constrained from other measurements

large theoretical uncertainties (∼20%) need to be reduced

Direct measurement for energies above 500 GeV

y_t can be extracted from the measured $e^+e^- \rightarrow t\bar{t}H$ cross section



Difficult measurement: very low statistics and large backgrounds.

Statistical uncertainty of 4.4% expected for 1.5 ab^{-1} at 1.4 TeV

CLICdp-Note-2015-001

New: analysis looking at CP violation in the *ttH* vertex at 1.4 TeV

Rare decays

FCNC top decays

Strongly suppressed in the Standard Model (GIM mechanism + CKM):

$BR(t \to c\,\gamma) \sim 5 \cdot\ 10^{-14}$, $BR(t \to c\,Z) \sim 1 \cdot 10^{-14}$, $BR(t \to c\,H) \sim 3 \cdot 10^{-15}$

Significant enhancement possible in many "new physics" scenarios

Two channels under study for CLIC at 380 GeV

$\boldsymbol{t \to c\ h}$

- enhancement up to 10^{-5}–10^{-2}
- test of Higgs boson couplings
- well constrained kinematics
- seems most difficult for LHC

  Run II: $BR < 0.46\%$

  HL-LHC: $BR < 2 \cdot 10^{-4}$

$\boldsymbol{t \to c\ \gamma}$

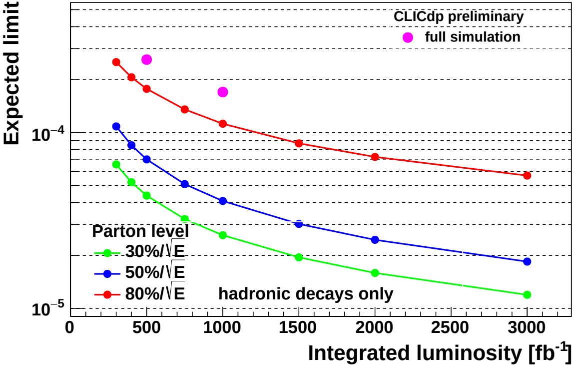
- enhancement up to 10^{-7}–10^{-5}
- clear signature
- less constrained kinematics
- expected limits from HL-LHC

  $BR < 2.5 \cdot 10^{-5}$

Rare decays

Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$ at $\sqrt{s} = 380$ GeV

Comparison with parton level results, different jet energy resolutions



AFŻ @ LCWS'16

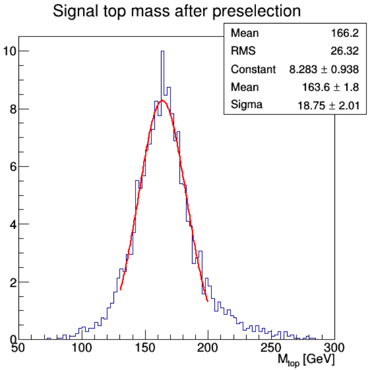
Kinematic fit performance still to be optimised

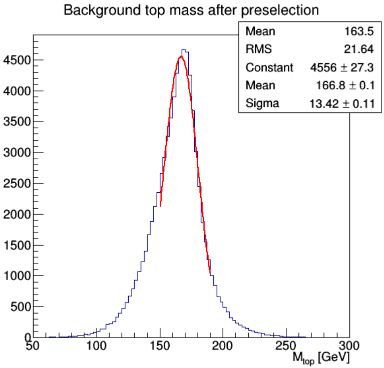
Background reduction primarily based on flavour tagging!

Mass reconstruction

Kinematic fit

The main reason for weak limit is poor performance of the kinematic fit.





Mass resolution much worse than expected.

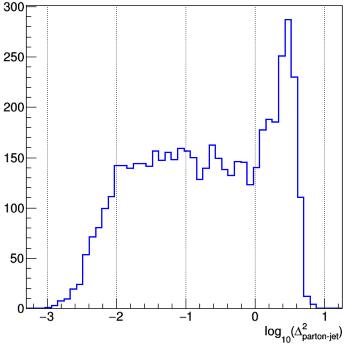
Signal reconstruction much worse than for background events...

Mass reconstruction

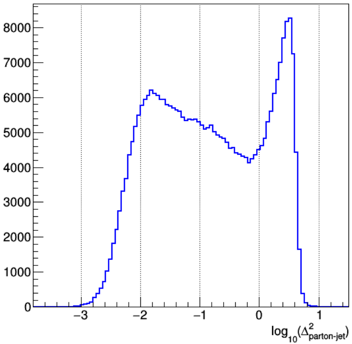
Jet matching

Distance between parton level and detector level jets

Signal events



Background ($t\bar{t}$) events



For significant fraction of events reconstructed detector-level jets have nothing to do with the generated fermion configuration!

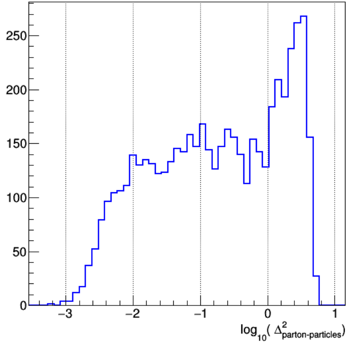
Mass reconstruction

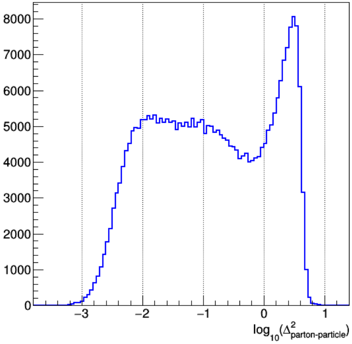
Jet matching

Distance between parton level and particle level jets (no detector involved)

Signal events

Background ($t\bar{t}$) events



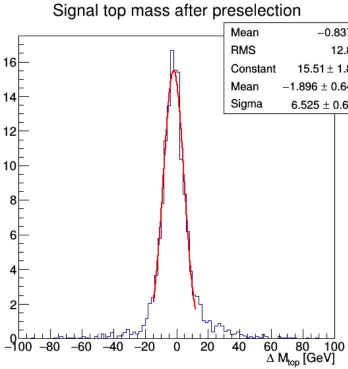


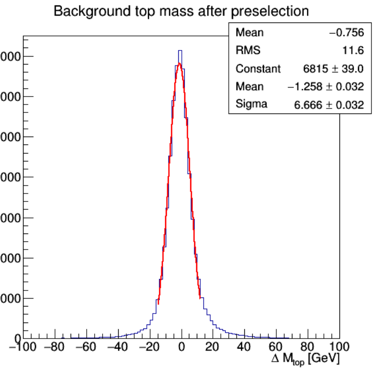
In most cases, information about the partonic final state is already lost on particle level!

Mass reconstruction

Mass resolution

Difference between top candidate mass reconstructed on particle level and detector level (for events with good matching)





⇒ very good detector performance confirmed

problem is most likely due to particle migrations between jets...

Status and plans for CLIC top quark studies

Summary of activities

	Threshold	380 GeV	1.4 TeV	3 TeV
Top reconstruction	✓	✓	➠	➠
Top mass	✓	✓		
EW couplings		✓	➠	➠
Yukawa coupling + CP	✗		✓➠	
FCNC decays		➠		
Single top/V_{tb}			➠	✗
Top squark production				➠?

✓ - available, ➠ - under study, ✗ - missing

The goal is to prepare the complete top paper draft before the end of 2017

Outlook → European Strategy

Aim to:

- Present CLIC as a credible post-LHC option for CERN
- Provide optimized, staged approach starting at 380 GeV, with costs and power not excessive compared with LHC, and leading to 3 TeV
- Upgrades in 2-3 stages over 20-30 year horizon
- Maintain flexibility and align with LHC physics outcomes

CLICdp documents
in preparation for next European Strategy

CLICdp reports serving as ingredients for a CLIC summary report:

- Updated Baseline for a Staged Compact Linear Collider (380 GeV, 1.5 TeV, 3 TeV) ✓
    - arXiv:1608.07537, CERN-2016-004
- Higgs Physics at the CLIC Electron-Positron Linear Collider ✓
    - arXiv:1608.07538
- The new optimised CLIC detector model CLICdet ✓✓
    - CLICdp note CLICdp-Note-2017-001 (detector/SW validation in progress)
- An overview of CLIC top physics
    - CLIC top physics publication => complete draft before the end of 2017
- Extended BSM studies (hopefully also motivated by LHC discoveries)
    - CLIC BSM overview publication in 2018
- CLIC R&D report => with main CLIC technology demonstrators
    - Summary publication(s) in 2018
- Plan for the period ~2019-2025 in case CLIC would be supported by next strategy

CLIC roadmap

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

Thank you!