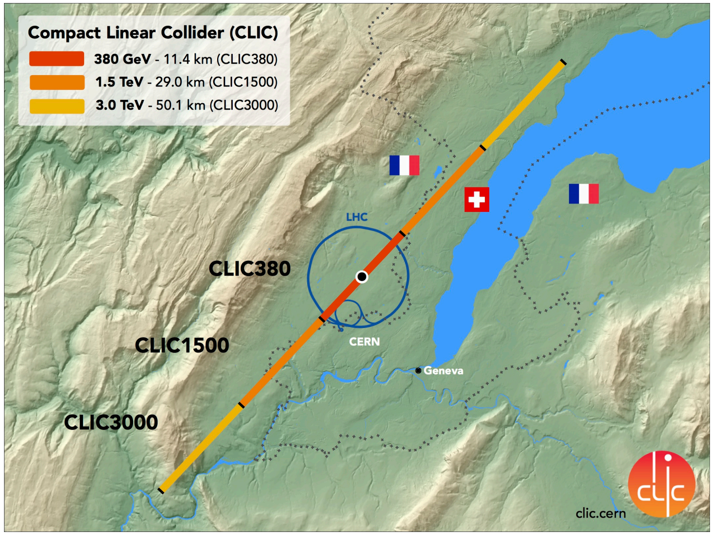
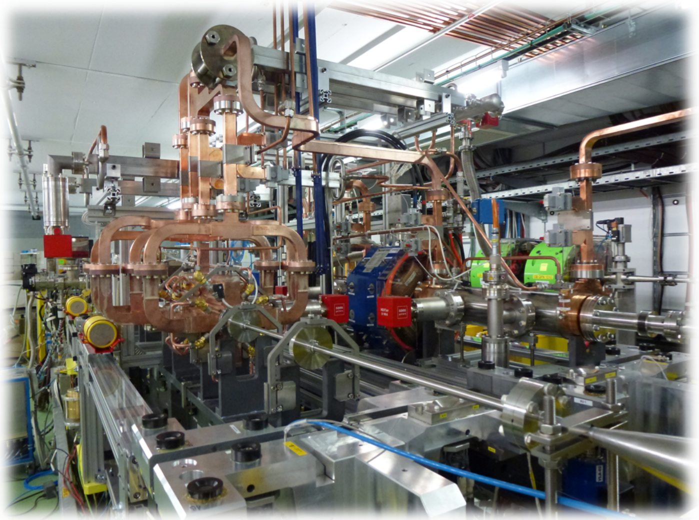
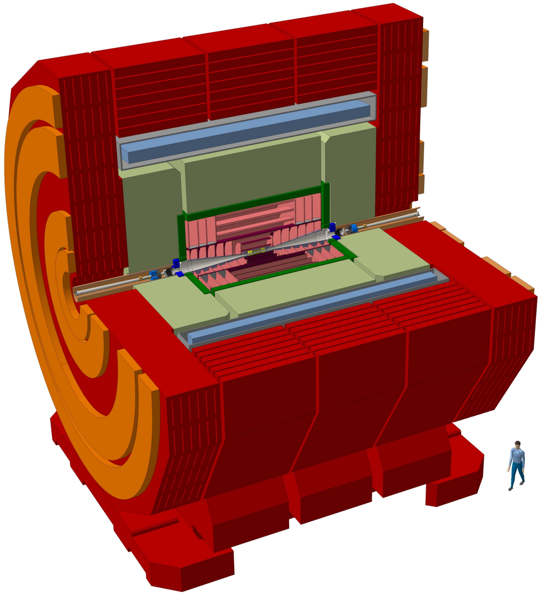
Future experiments (colliders): New Detectors



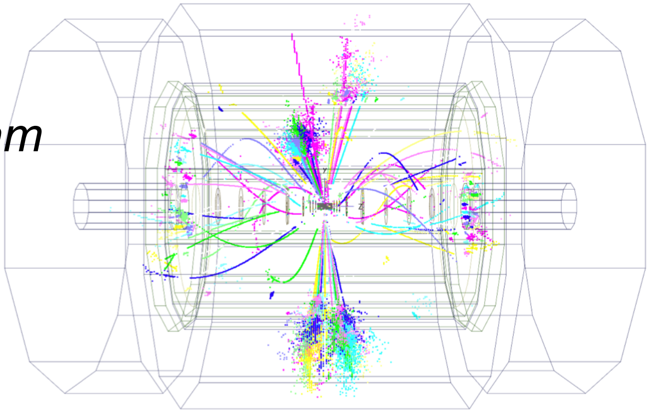


- **Physics**
- **Accelerators**
- **Detectors**
- **Design choices**
- **Challenges**
- **Future**



Nigel Watson

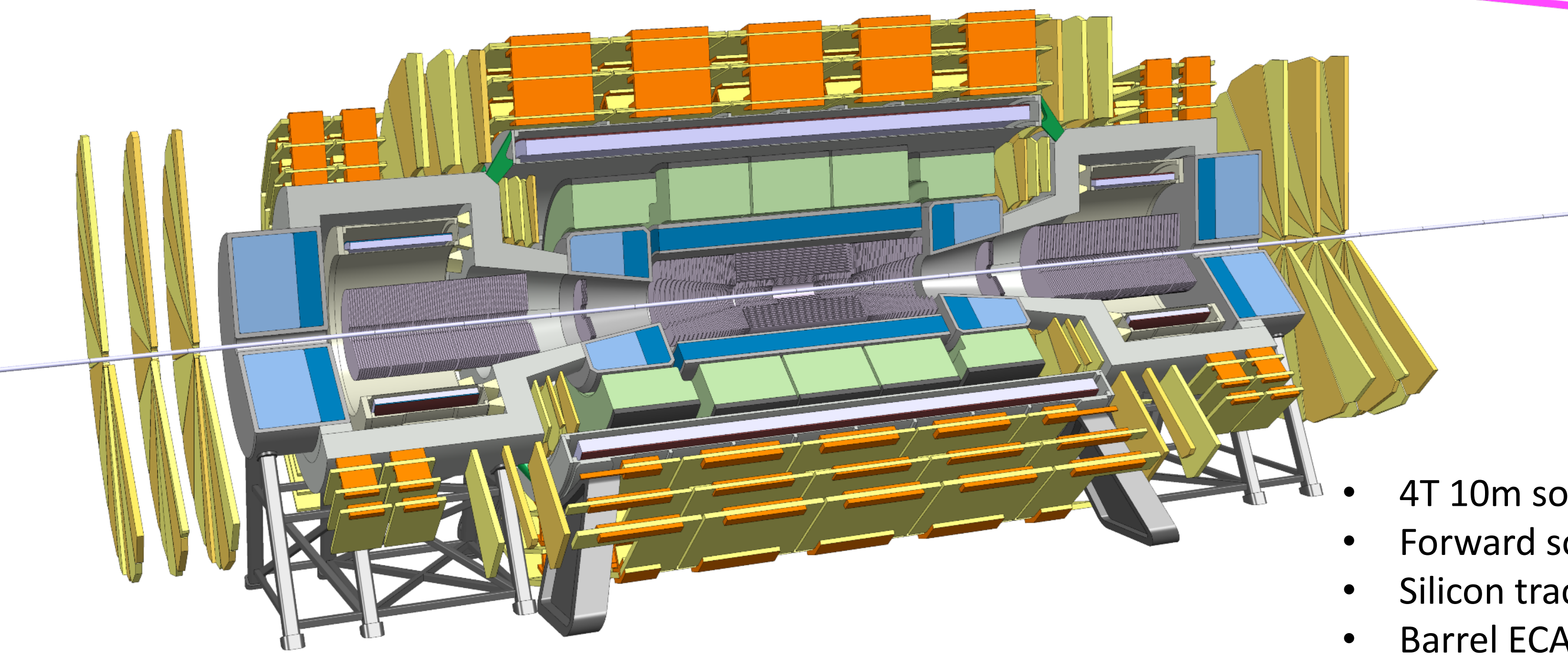
University of Birmingham



[With many thanks to colleagues as detailed for material]

FCC-hh reference detector for the CDR

Updated in 2018 since this version

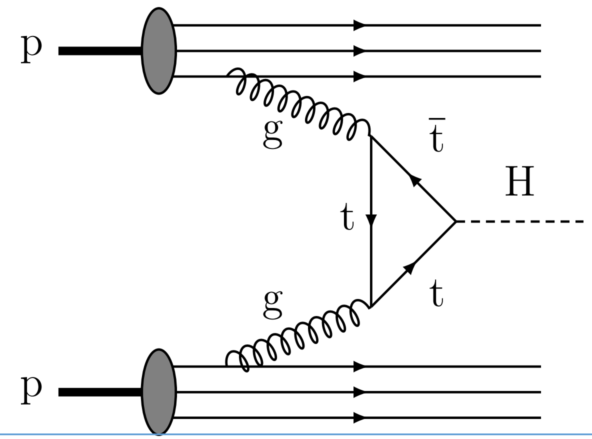


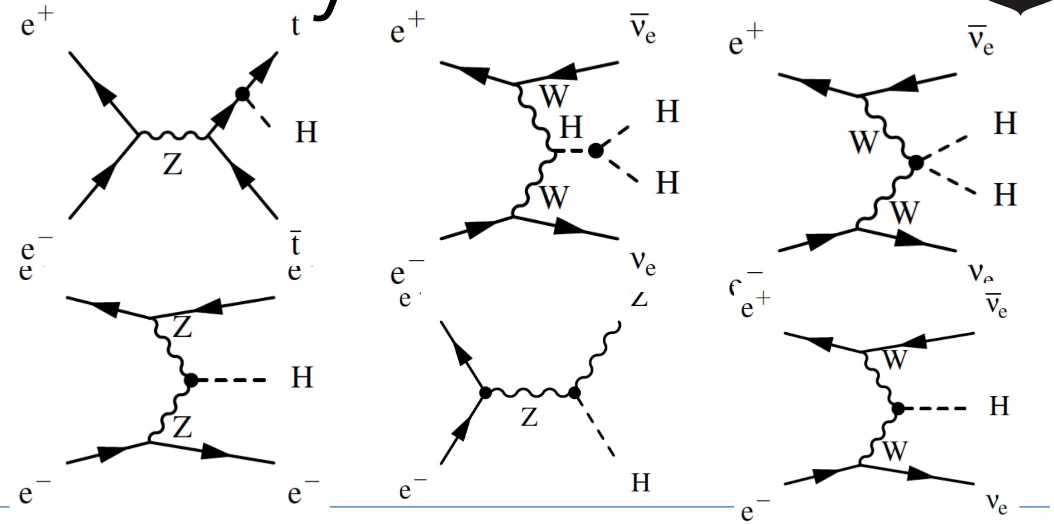
- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

This is a reference detector that 'can do the job' and that is used to define the challenges.
The question about the specific strategy for detectors at the two IPs is a different one.

W. Riegler, Acad.Training, Oct 2017

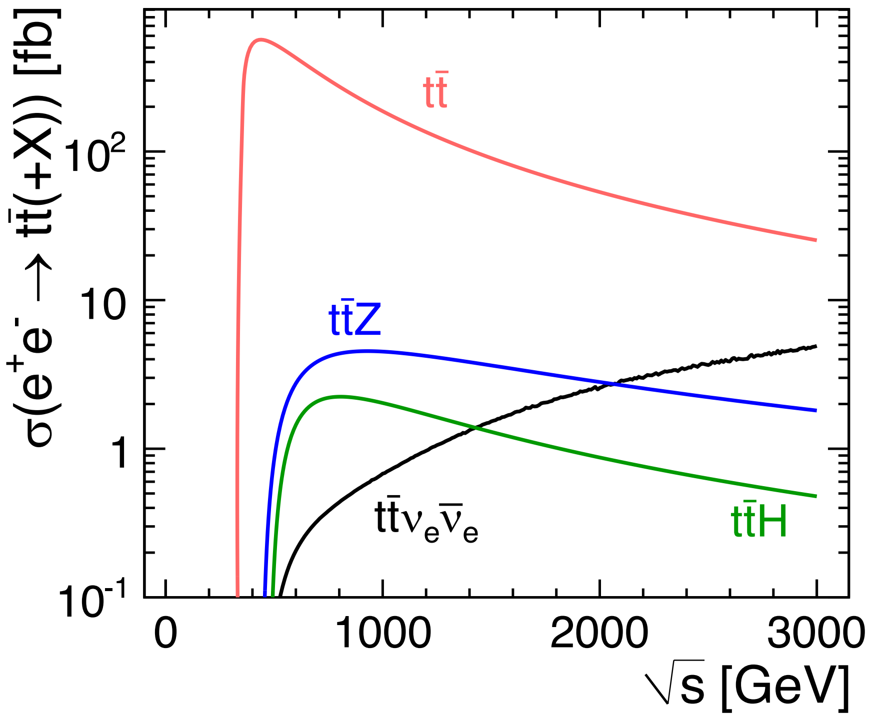
Motivation: why e^+e^-?





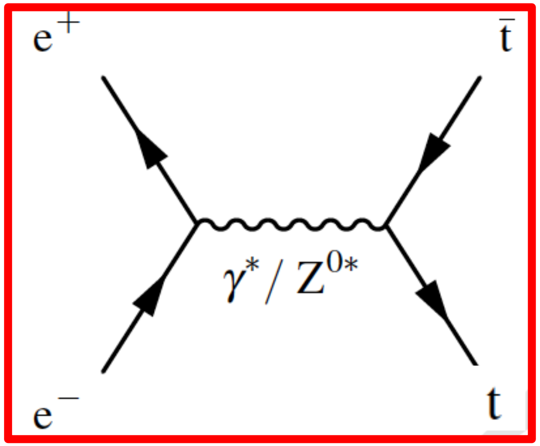
p-p collisions	**e^+e^- collisions**
Initial state for hard scatter? → Initial state/event unknown → Limits achievable precision → Proton are **complicated**...	Initial state → Initial state ~well defined → High-precision measurements → e^+/e^- are **point-like**
High rates of QCD backgrounds → Complex triggering schemes → High radiation levels	**Clean**er experimental environment → Simple trigger scheme/readout → Low radiation levels
High cross-sections for coloured states	Superior sensitivity for electroweak states
High-energy circular colliders feasible	>≈350 GeV needs a linear collider

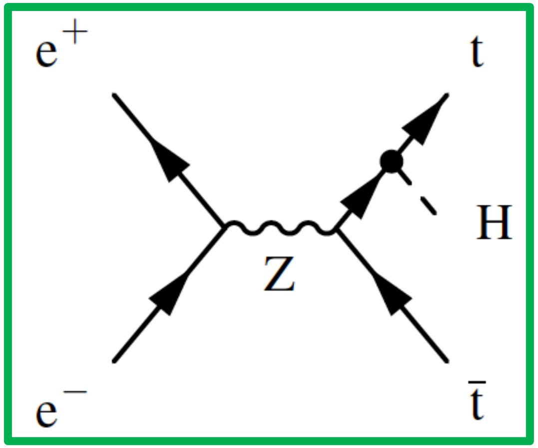
$t\bar{t}$ above threshold

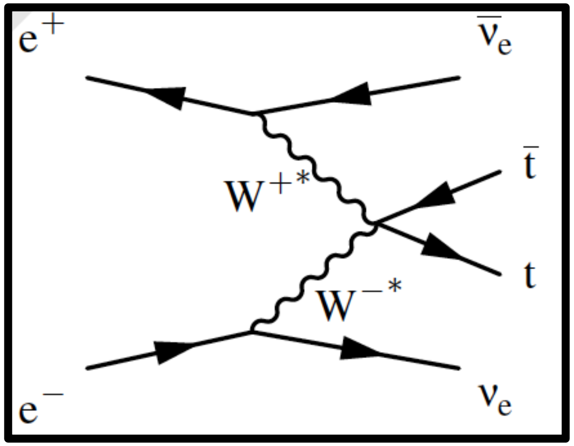


- $e^+e^- \rightarrow t\bar{t}$
  - Near max. but away from threshold
  - 500 fb^{-1} → 350k $t\bar{t}$, test rare decays

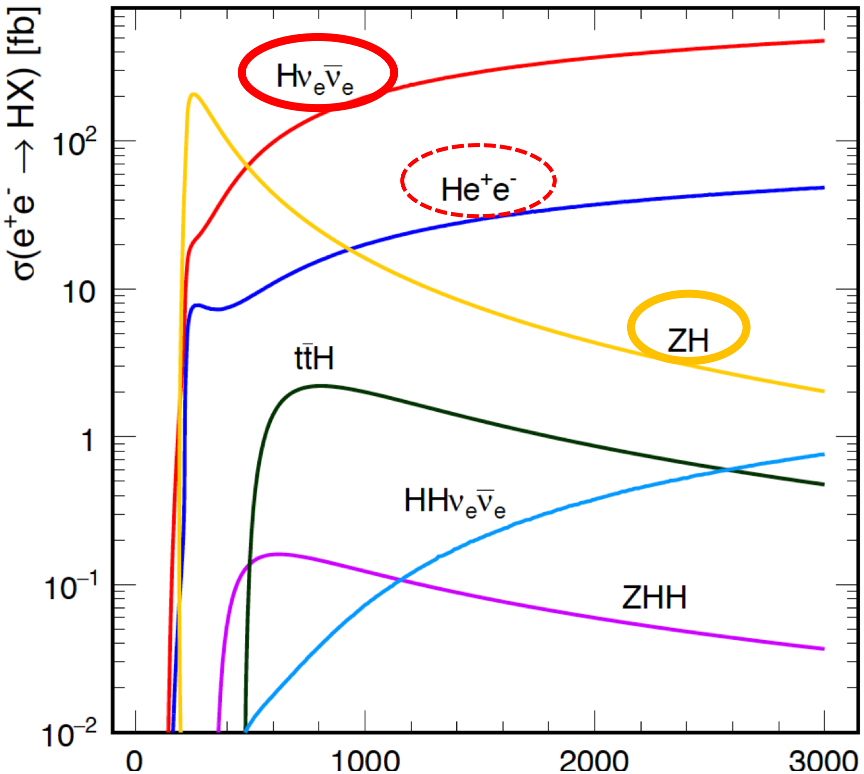
  Rich programme even in initial energy phase
- $e^+e^- \rightarrow t\bar{t}H$ peaks ~ 800 GeV
  - Only CLIC (ILC *just* in 500 GeV option)
- $e^+e^- \rightarrow t\bar{t}\nu\bar{\nu}$ VBF
  - The higher the $\sqrt{s}$ the better



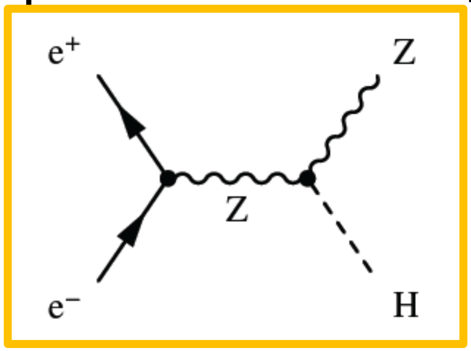




Higgs physics at CLIC



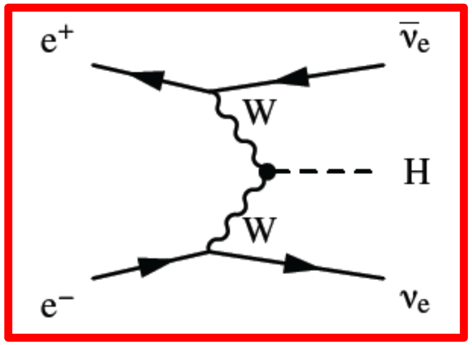
Dominant processes:



Higgsstrahlung

σ ~ 1/s

Higgs id. from Z recoil



WW(ZZ) - fusion

σ ~ log(s)

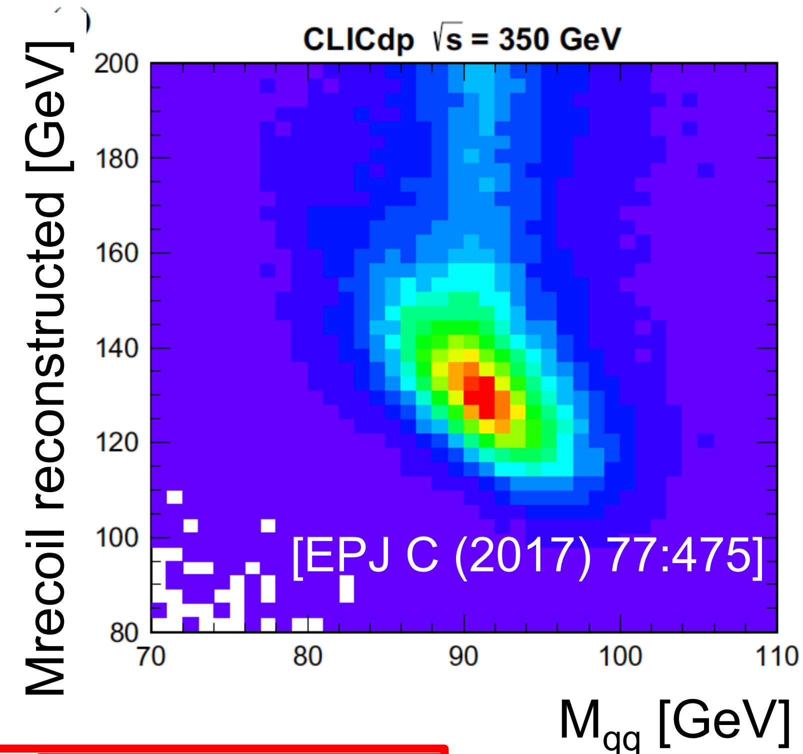
Large yield at high E

[EPJ C (2017) 77:475]	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 (baseline plan)

$e^+e^- \rightarrow ZH$ @ ~350 GeV

- Select via recoil mass of Z
  - model-independent measurement
    - ΔσHZ ~ gZHH
- $HZ \rightarrow Hq\bar{q}$ access to invisible Higgs decay
  - Estimated sensitivity, BR($H \rightarrow invisible$) < 1% @ 90% CL
  - Better precision at 350 GeV than 250/420 GeV
  - Trade-off between detector resolution and physics background



- Select via recoil mass of Z
  - model-independent measurement
    - ΔσHZ ~ gZHH

$Z \rightarrow \mu\mu$	BR~3.5%	very clean	$\Delta(\sigma_{HZ}) = \pm 3.8\%$
$Z \rightarrow ee$	BR~3.5%	very clean	
$Z \rightarrow qq$	BR~70%	almost model independent	$\Delta(\sigma_{HZ}) = \pm 1.8\%$

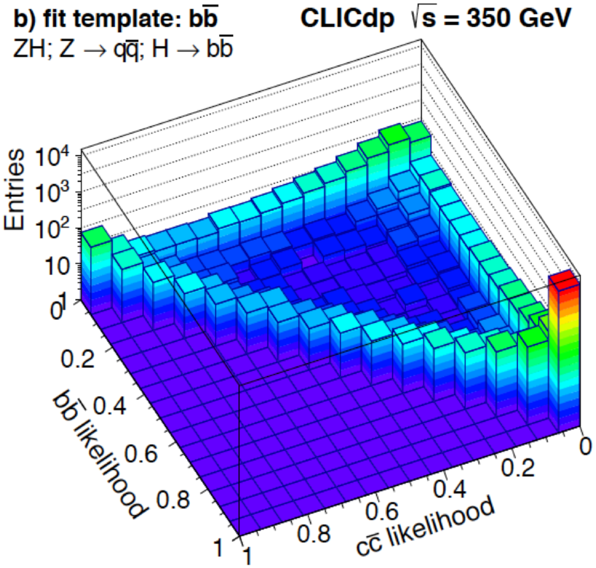
$\Delta(g_{HZZ}) = \pm 0.8\%$

- $HZ \rightarrow Hq\bar{q}$ access to invisible Higgs decay
  - Estimated sensitivity, BR($H \rightarrow invisible$) < 1% @ 90% CL
  - Better precision at 350 GeV than 250/420 GeV
  - Trade-off between detector resolution and physics background

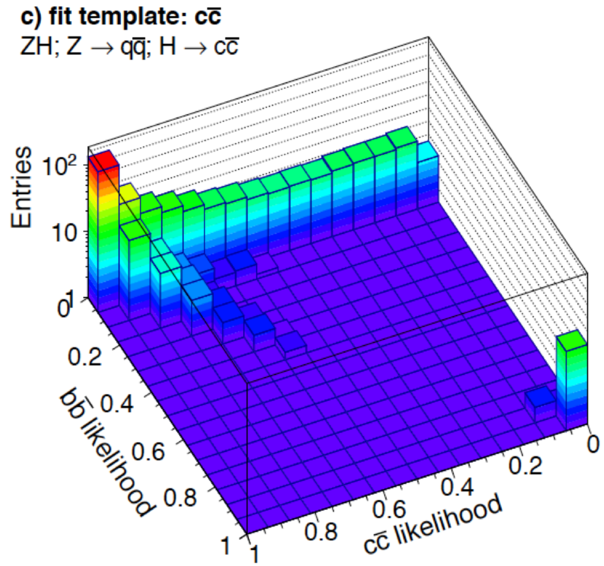
Simultaneous $H \to b\bar{b}, c\bar{c}, gg$ @ 350 GeV

Compare $b\bar{b}$ likelihood versus $c\bar{c}$ likelihood for different event classes

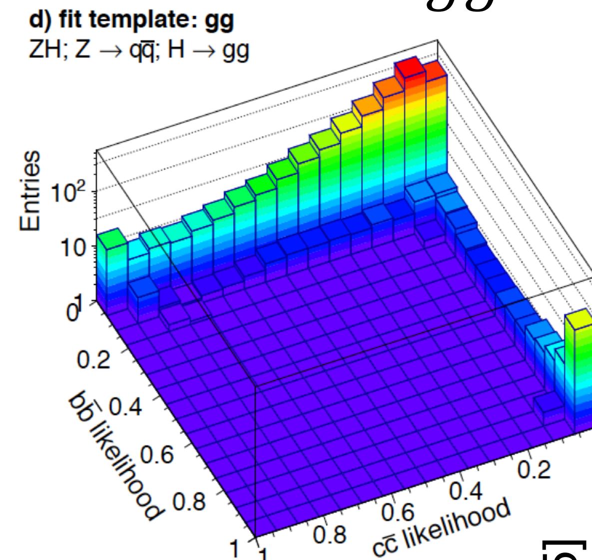
$H \to b\bar{b}$

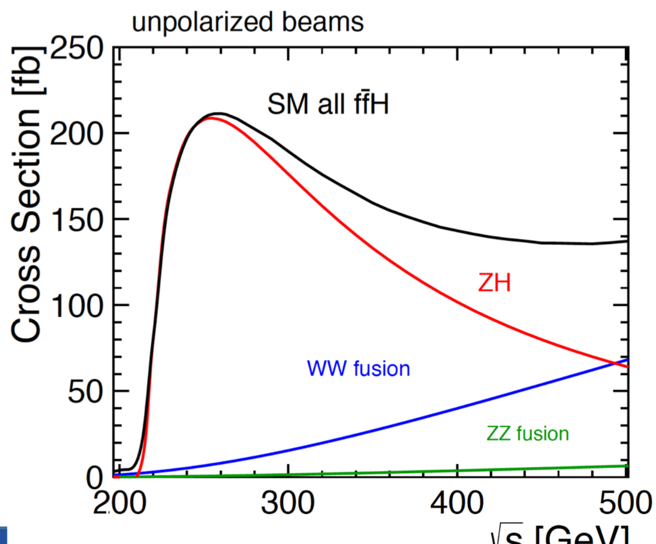


$H \to c\bar{c}$



$H \to gg$





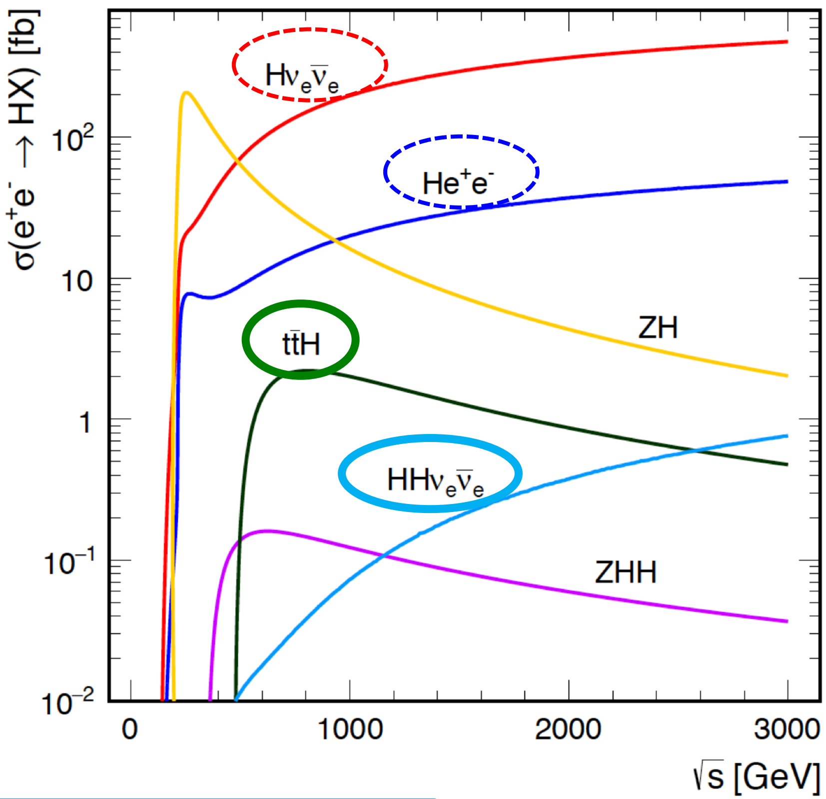
2 production and 3 decay modes

$\Delta(\sigma\times BR)_{SM}/(\sigma\times BR)_{SM}$ at 350 GeV, 500 fb^{-1}

Decay	Statistical uncertainty	
	Higgsstrahlung	WW-fusion
$H \to b\bar{b}$	0.84 %	1.9 %
$H \to c\bar{c}$	10.3 %	14.3 %
$H \to gg$	4.5 %	5.7 %

[EPJ C (2017) 77:475]

Higgs physics above 1 TeV

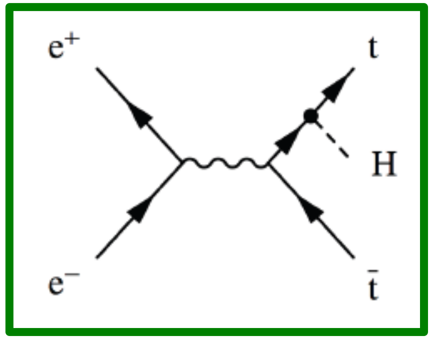


Vector boson fusion:

$e^+e^- \rightarrow H\nu\nu$, $e^+e^- \rightarrow He^+e^-$

High σ + increased luminosity

Access to rare Higgs decays



$t\bar{t}H$ production:

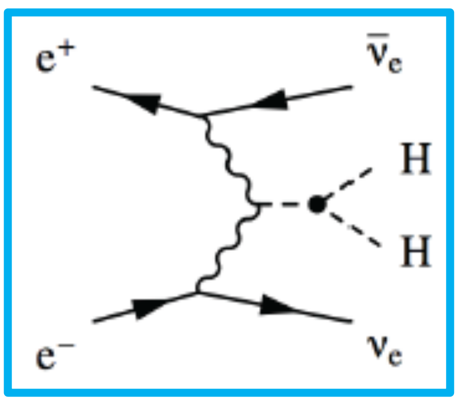
- Extraction of Yukawa coupling y_t
- Best at $\sqrt{s}$ above 700 GeV

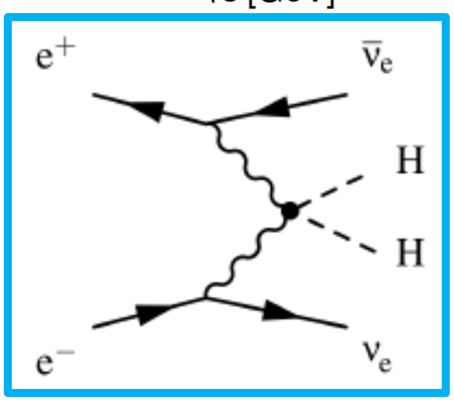
Studied at 1.4 TeV, 1.5 ab^{-1}

- Fully hadronic (8 jets)
- Semi-leptonic (6 jets + lepton + ν)

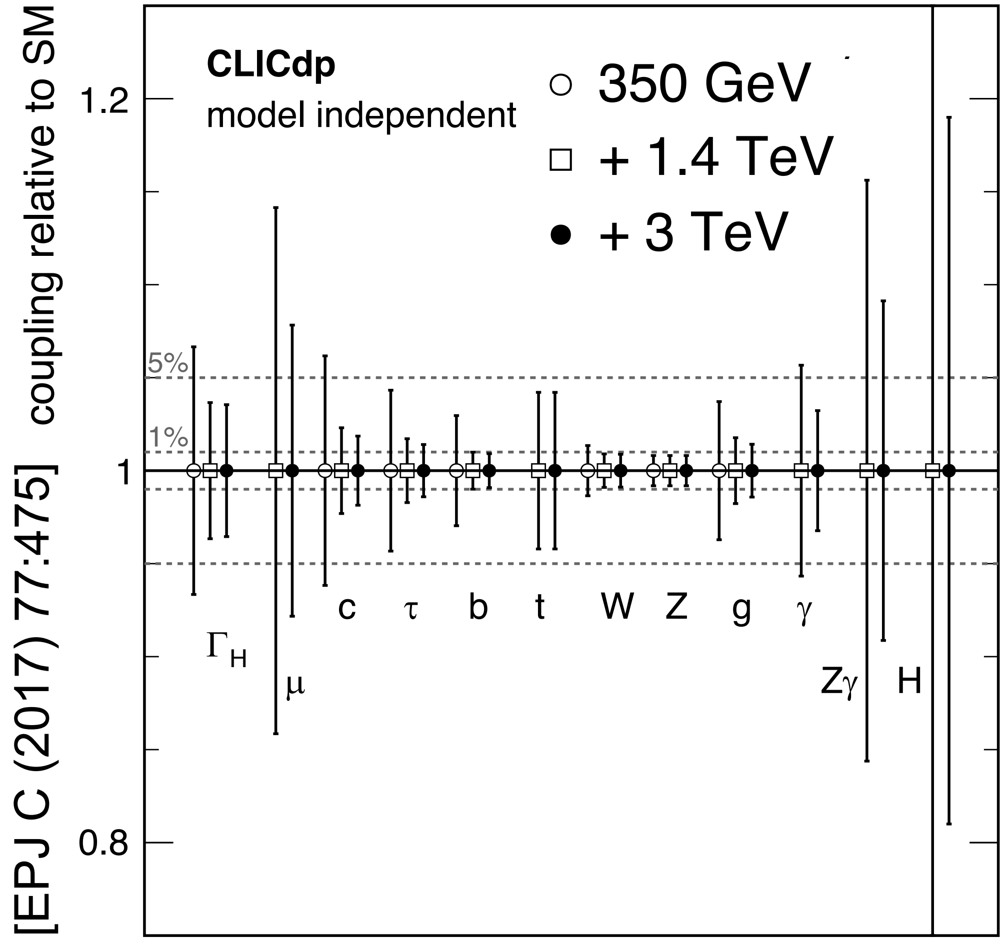
Statistical accuracy:

- **$\Delta(g_{Htt})$ = ±4.4%** at 1.4 TeV





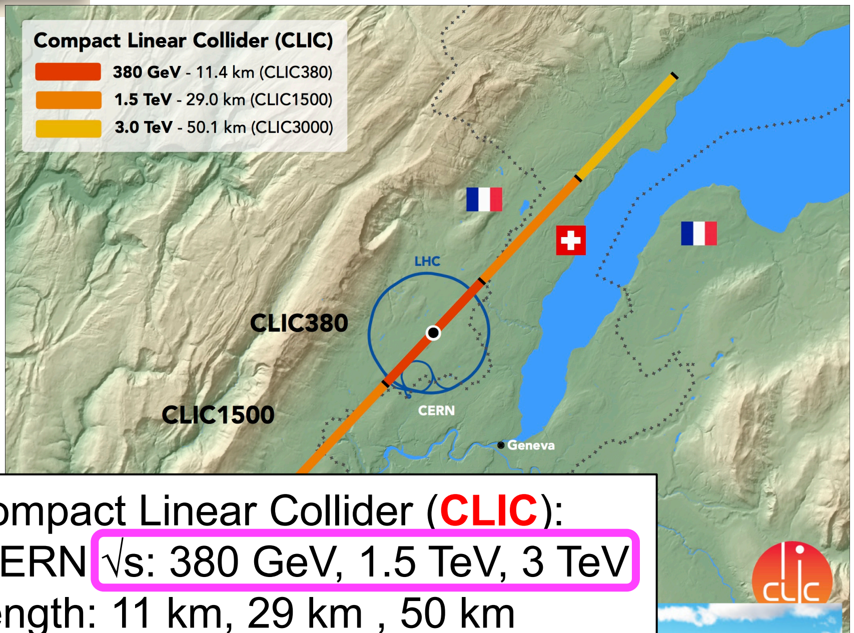
Higgs coupling precision



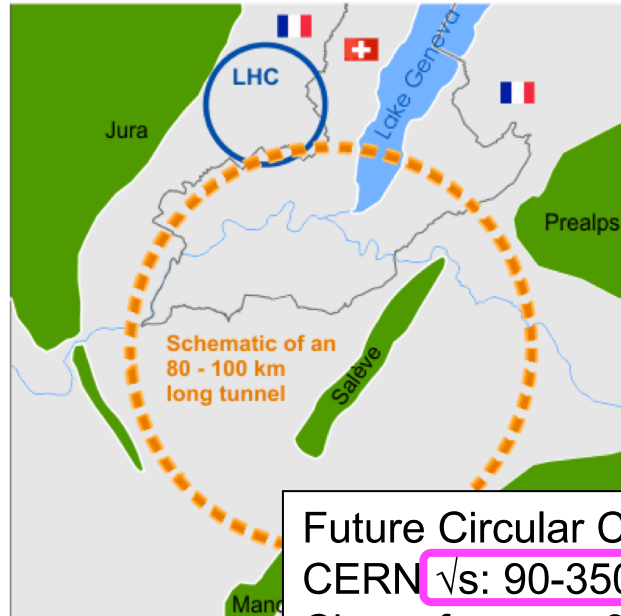
- Full CLIC programme, 5 years each stage
  - Assumes 80% e- pol., >1 TeV
- Recoil mass approach
  - Model independent analysis
  - ~1% level for most couplings
  - H width free, allows extra non-SM decays,
  - H width to +-3.6%
- Full simulation study, details
  - Eur. Phys. J. C 77, 475 (2017)

CLIC has unique sensitivity and energy reach

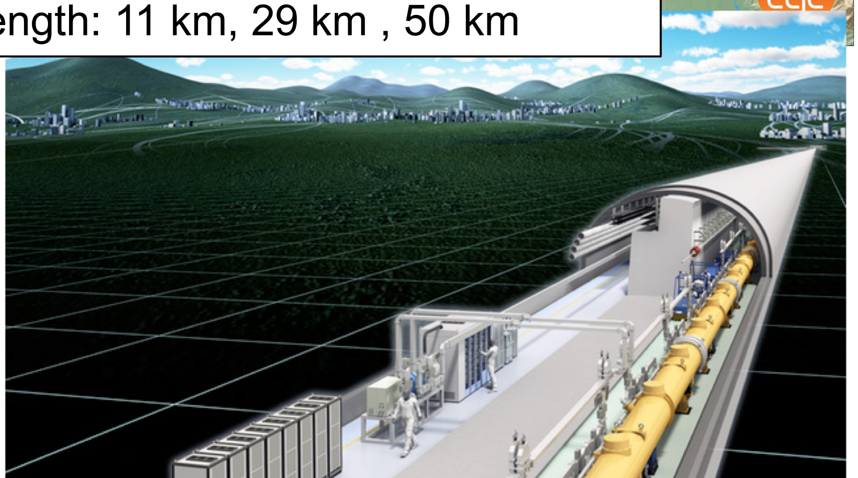
e+e− a la carte



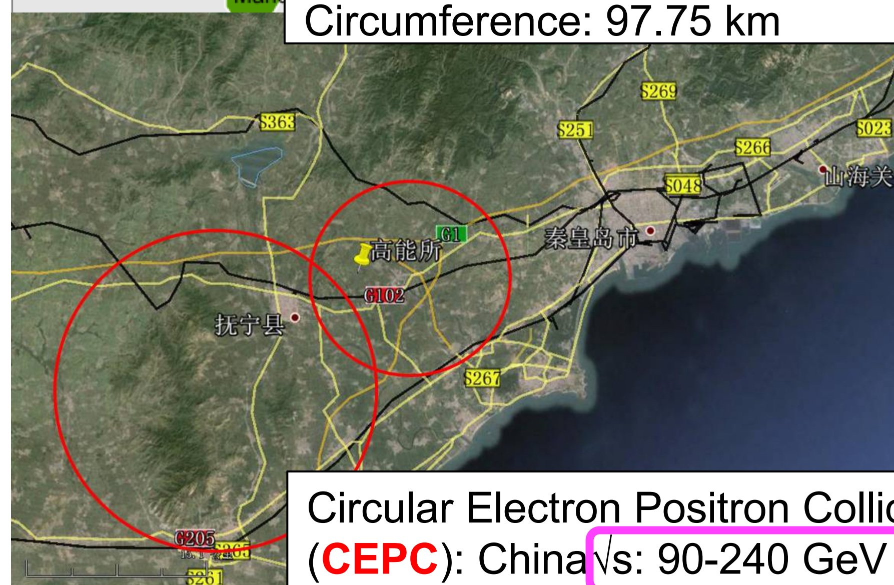
Compact Linear Collider (**CLIC**):
CERN √s: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**):
CERN √s: 90-350 GeV
Circumference: 97.75 km



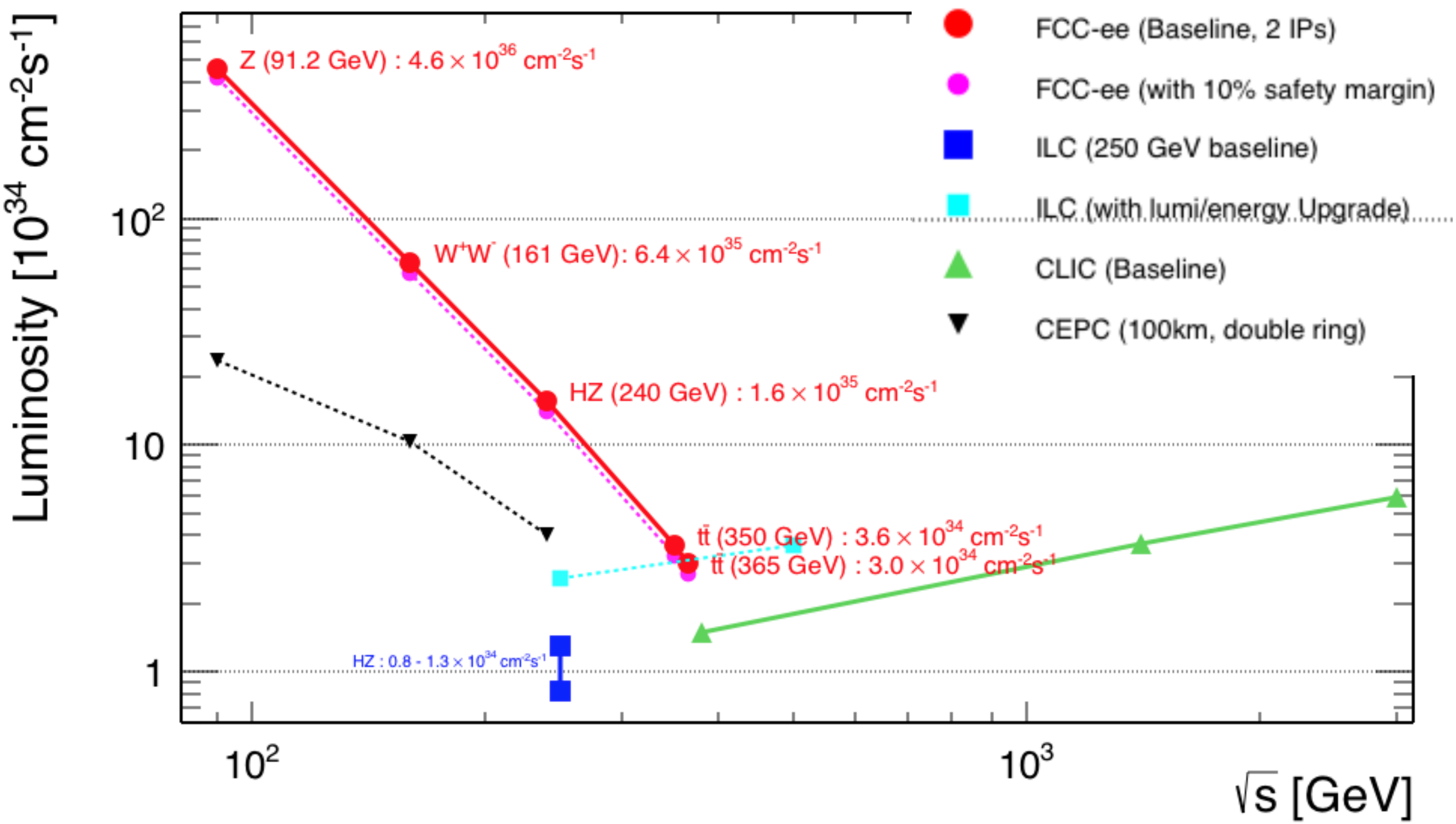
International Linear Collider (**ILC**):
Japan (Kitakami) √s: 250 (-500) GeV (+1 TeV)
Length: 17, 31 km (50 km)

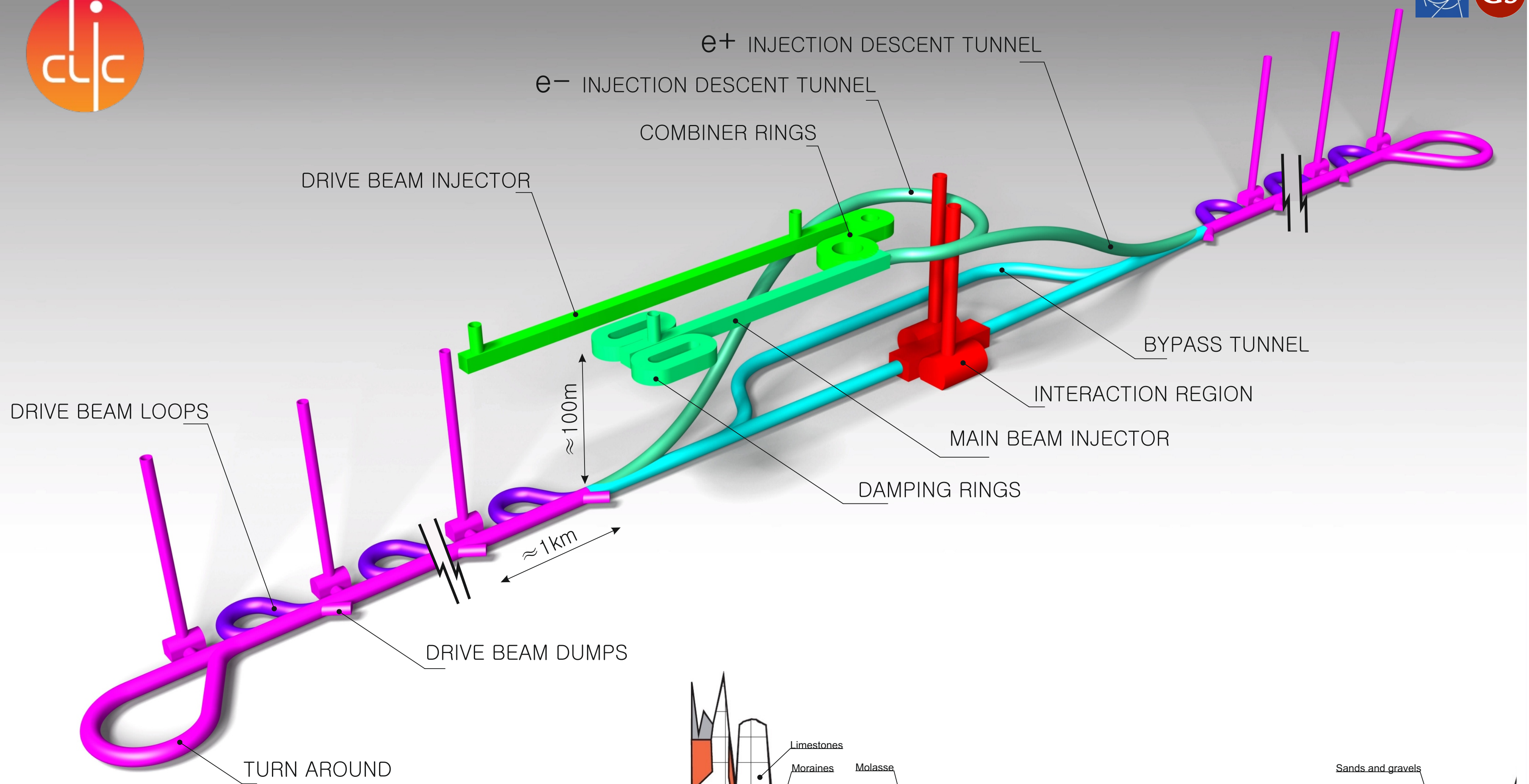


Circular Electron Positron Collider (**CEPC**): China √s: 90-240 GeV
Length: 100 km

How to get there? Introduction

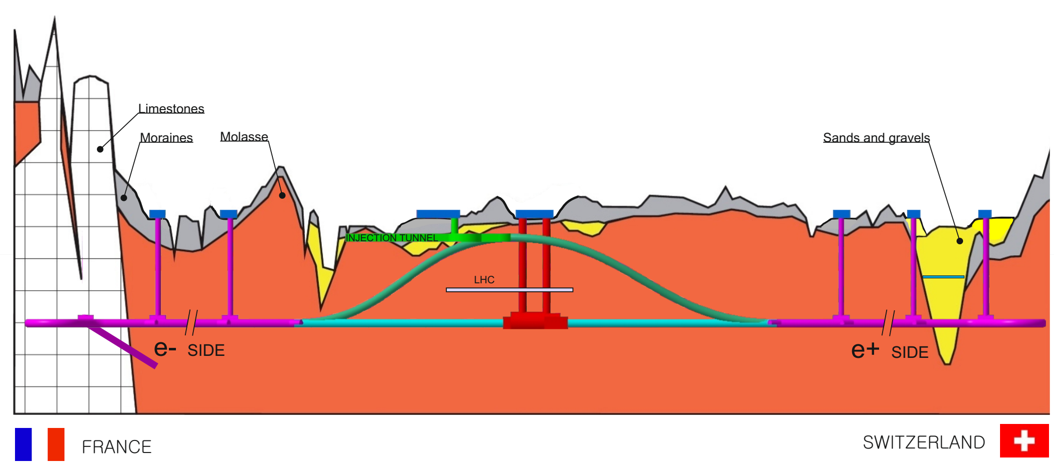
- Concentrating on detectors for e^+e^- machines after Freya's overview
- All e^+e^- machines are created equal? Note log-log scale





CLIC SCHEMATIC

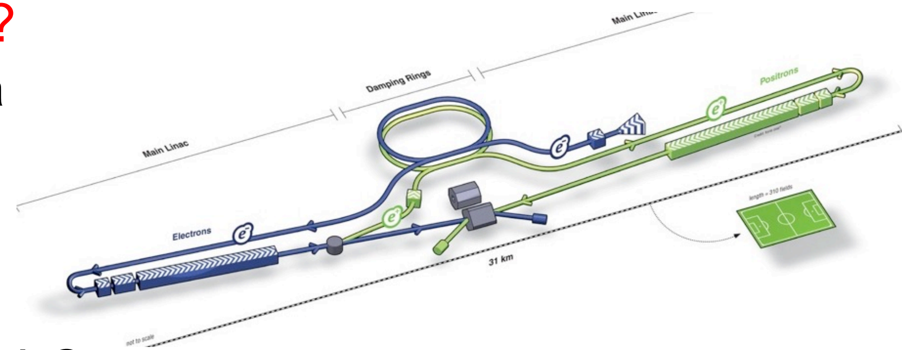
(not to scale)



[Steffan Dobbert CAS 2018]

Design choices

1. e⁺e⁻ decision: circular vs. linear ?
   - Imagine money not a major criteria
   - Consider timescales and √s
   - Upgrade path?

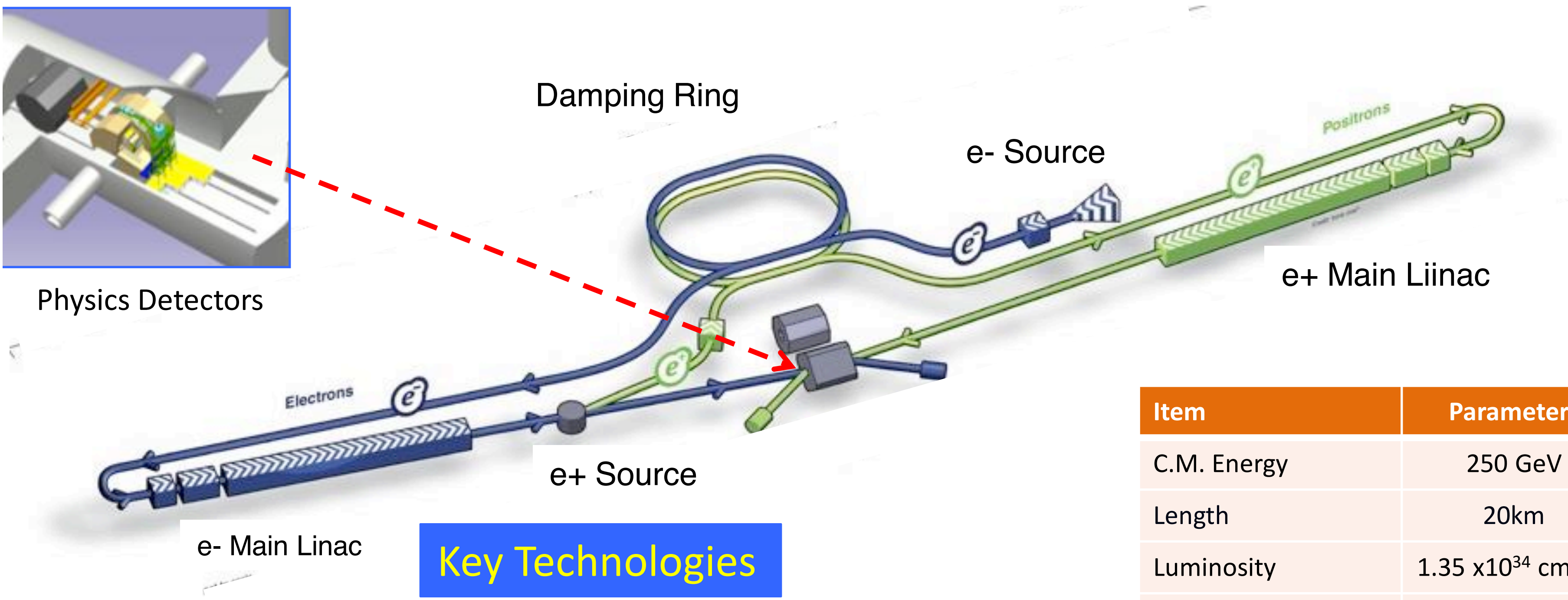


2. Physics goals >400 GeV ? ➔ **a** LC
   1. Beam crossing angle – single shot/bunch
   2. ➔ ++beam dumps

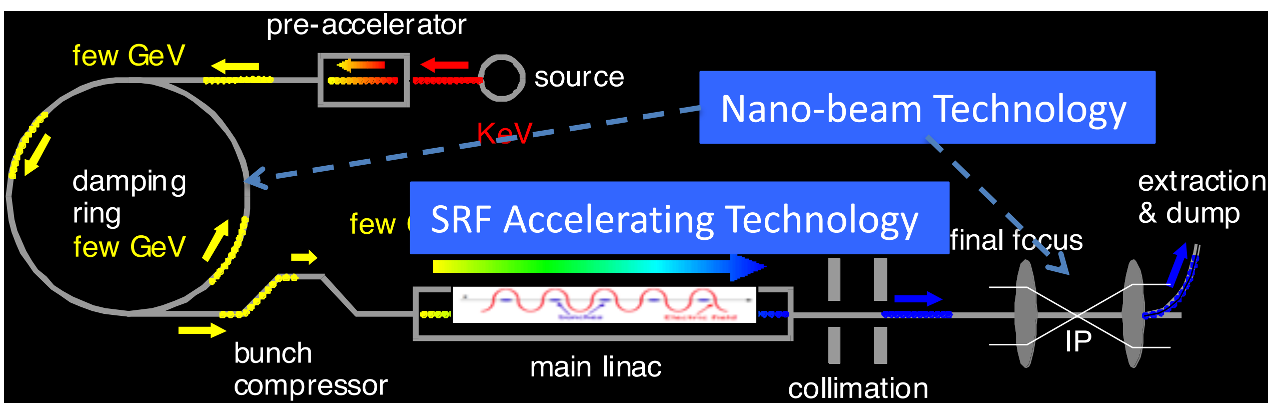
3. Increase luminosity
   1. ➔ small bunch σ_x, σ_y (transverse)
   2. ➔ "crab" scheme

4. Beamstrsahlung mitigation ➔ flat beams
   1. Q: σ_z, why so small?

ILC250 Acc. Design Overview



Key Technologies



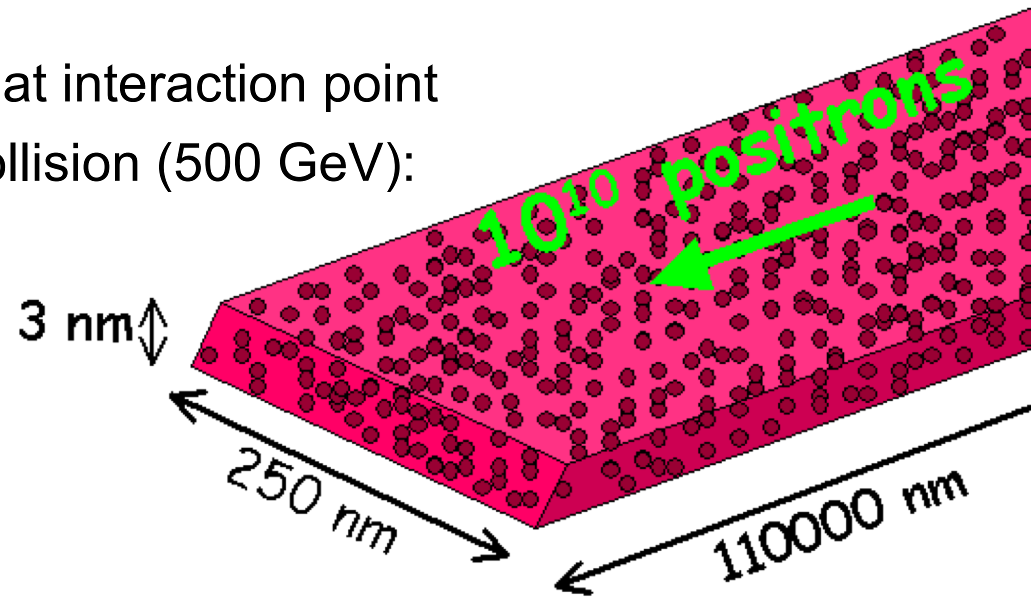
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	**7.7** nm@250GeV
SRF Cavity G. Q_0	**31.5** MV/m (**35** MV/m) Q_0 = 1x10 ^{10}

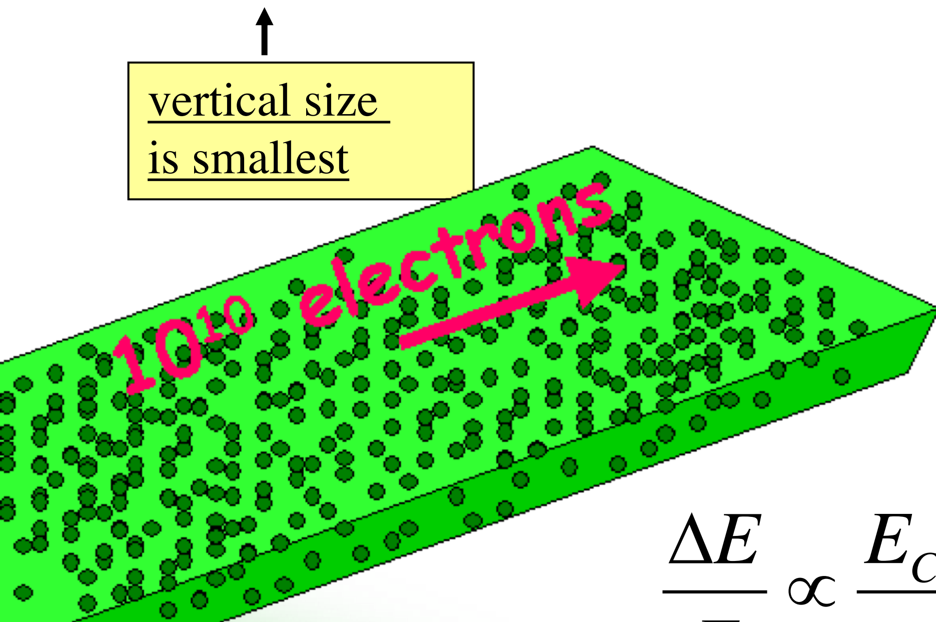
[Shin MICHIZONO, ICHEP'18]

Luminosity in future e^+e^- machine

[c/o Andrei Seryi]

- High luminosity achieved by
  - Many incident particles
  - Small transverse cross-section at interaction point
- e.g., LC beam sizes just before collision (500 GeV):
  250 * 3 * 110000 nm
  (x y z)



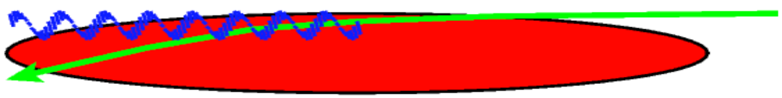


$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D$$

$$\frac{\Delta E}{E} \propto \frac{E_{CM}}{\sigma_z} \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

Beam-beam Effect

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

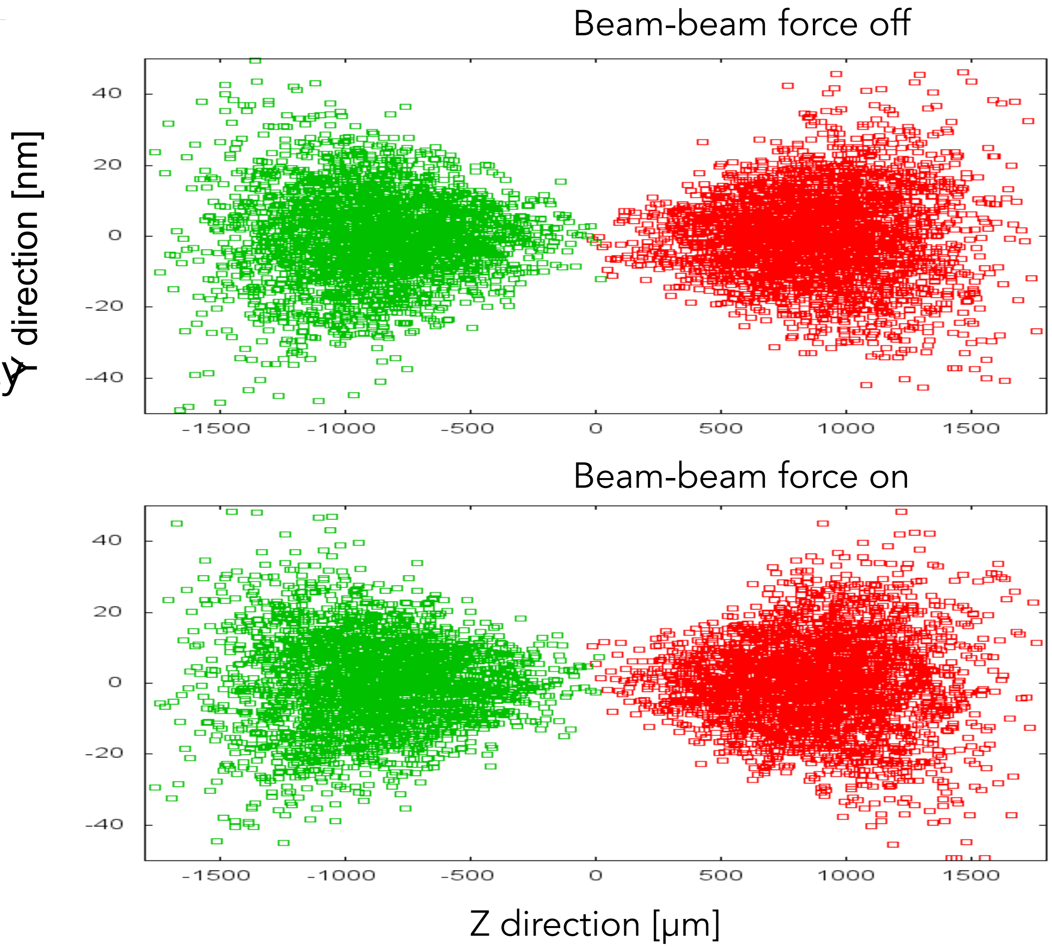


Dense beams to reach high luminosity

Beam focus each other

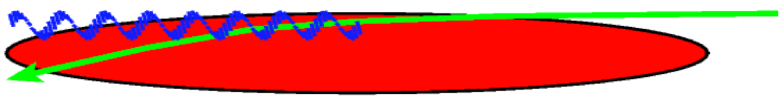
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$



Beam-beam Effect

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



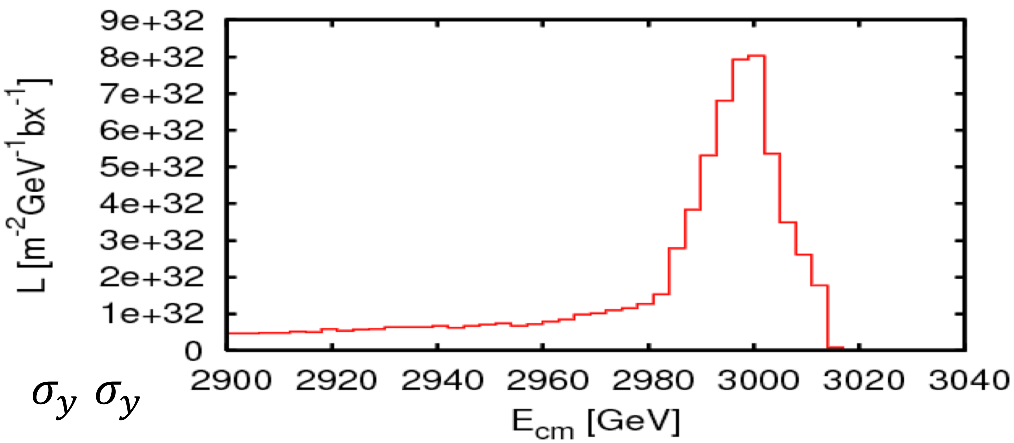
Emit beamstrahlung
Develop luminosity spectrum

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

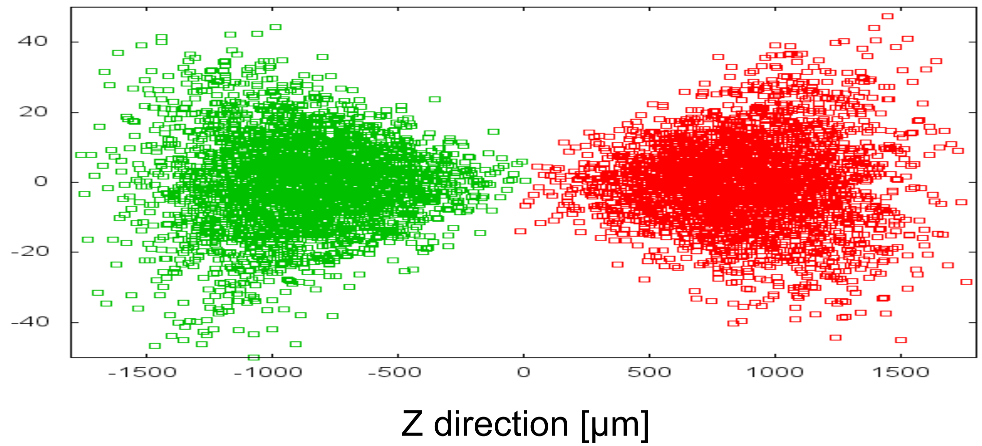
Aim for O(1) at 380 GeV

$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$



σ_y σ_y



Beam parameters

	ILC (500)	
Electrons/bunch	0.75	10**10
Bunches/train	2820	
Train repetition rate	5	Hz
Bunch separation	308	ns
Train length	868	us
Horizontal IP beam size	655	nm
Vertical IP beam size	6	nm
Longitudinal IP beam size	300	um
Luminosity	2	10**34

[Phil Burrows, Birmingham 2018]

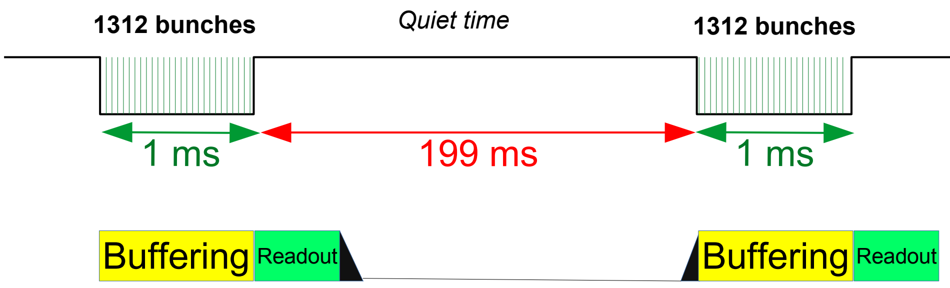
Design choices

ILC Bunch Train Structure

Bunches, Bunch trains & Power Pulsing

ILC Timing

- Bunch Structure at the ILC is very different compared to a synchrotron
  - Bunch spacing of 554 ns
  - 1 Train has 1312 bunches in ~ 1 ms
  - Then 199 ms quiet time until the next train
- Huge Impact on the Detector design
  - Occupancy dominated by beam background & noise
  - Triggerless Readout
  - Buffering on front-end &Readout after the last bunch
  - Powering off the front-ends during the quiet time
  - Power saving of a Factor 100 → No Active cooling



DESY. | ILC |103rd Plenary ECFA |Marcel Stanitzki

- Bunch timing very important difference ILC vs. CLIC
- Readout and power consumption (**heat!**)

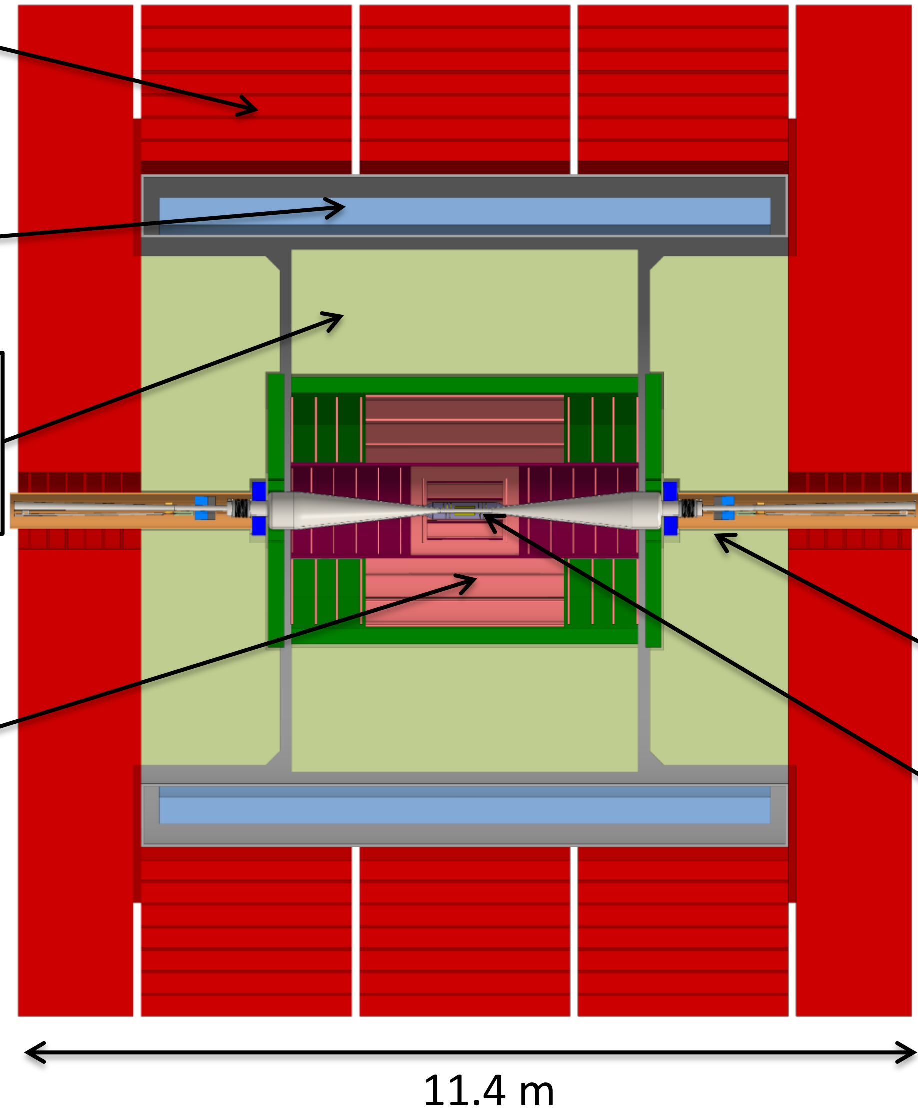
Anatomy of an e^+e^- detector: CLIC model

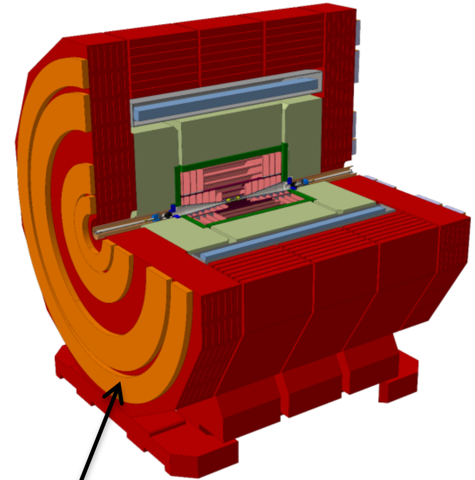
return yoke (Fe) with muon-ID detectors

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

low-mass vertex detector, ~25 μm pixels

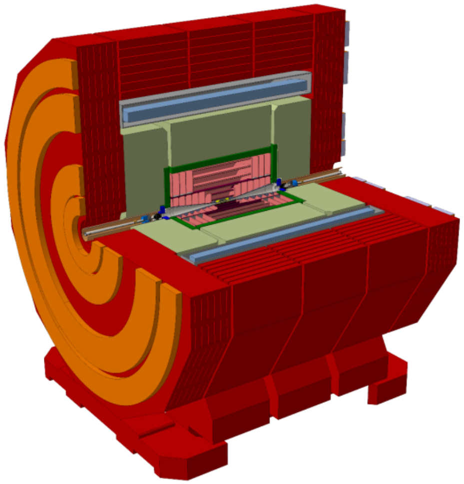
Final beam focusing is outside the detector

CLICdp-Note-2017-001

[Lucie Linssen, CAS 2018]

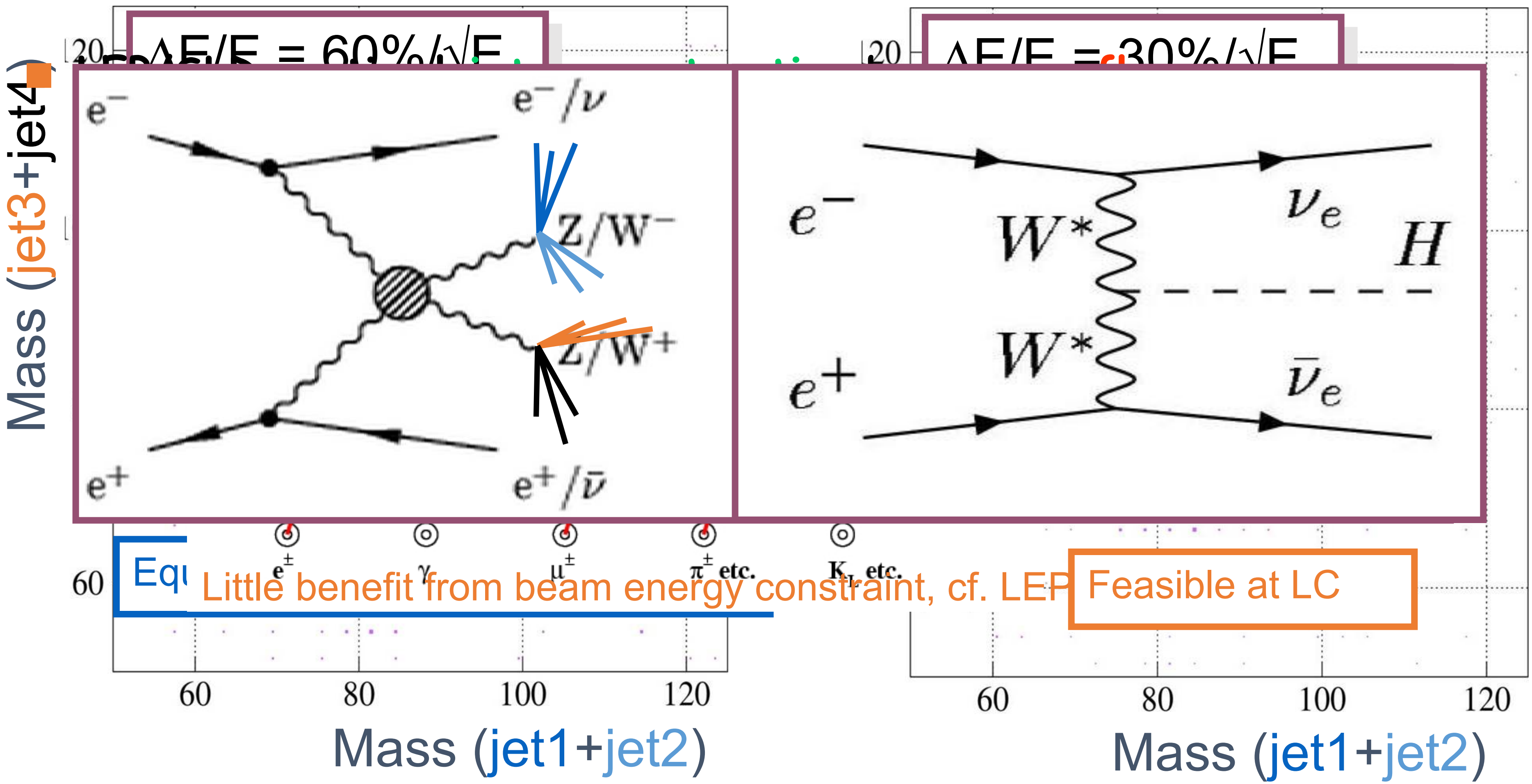
Overall design constraints

- “We think in generalities but we live in detail”
- Detector design optimised to accelerator choice
- Power pulsing (beam structure dependent)
- Particle flow algorithm (event reconstruction)
  - Vertex detector close to beamline (~10—30mm)
    - Limiting factor?
- Solenoid outside calorimeters
- Calorimeters thin (cost reduction)
- Trade off bulky calorimeters (cheap) for larger coil (expensive)
- ILC plans (…) two detectors – “push pull”
  - Competition; honesty/verification
  - Lumi shared? Halved
  - Q: Cost of two IPs – discuss swap time, concurrent running NO



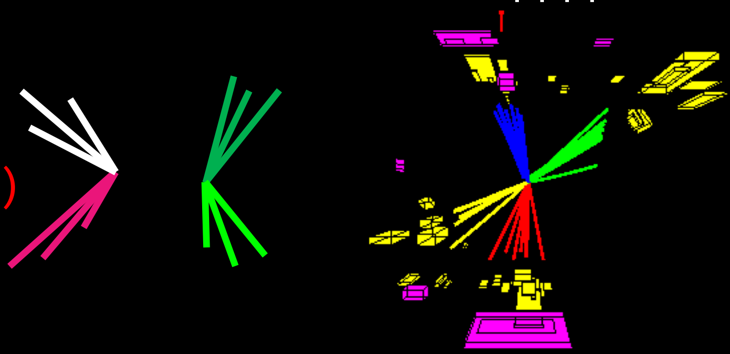
High Performance Calorimetry

- Essential to reconstruct jet-jet invariant masses in hadronic final states, e.g. separation of $\nu\nu W^+W^-$, $\nu\nu Z^0Z^0$, tth, Zhh



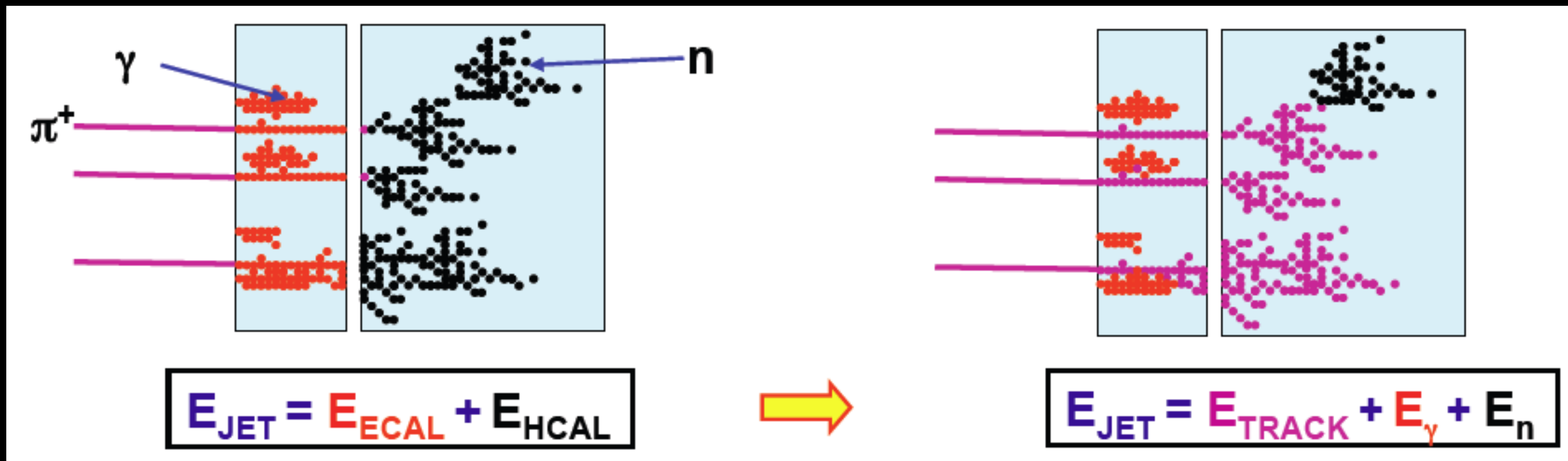
Jet energy reconstruction

LEP WW→qqqq data



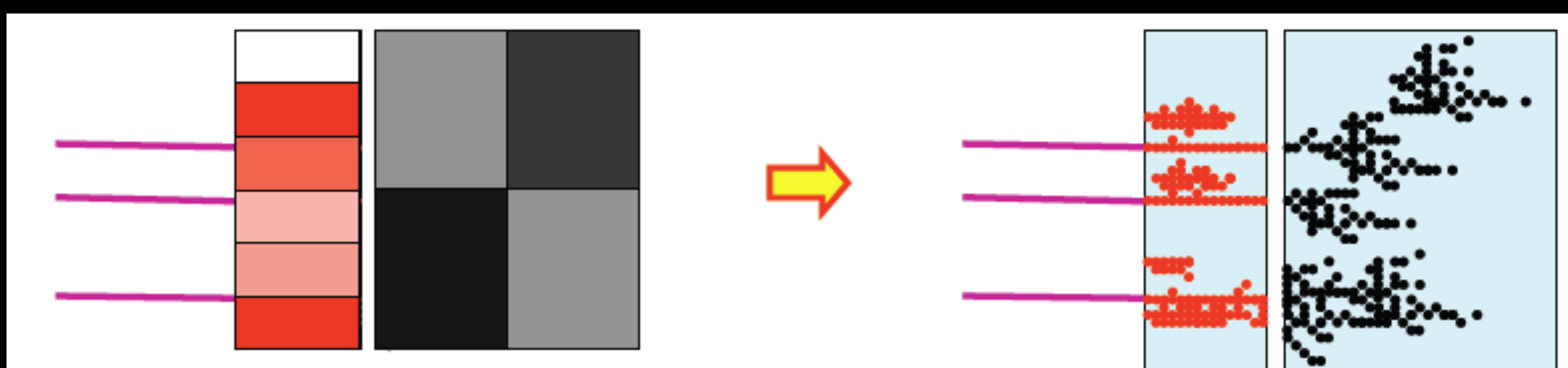
- Particle composition
  - ~60% charged hadrons (mostly pions)
  - ~30% photons (mostly from pions)
  - ~10% neutral hadrons (mostly K_L, n)
- Performance of tracking detector
  - Momentum resolution degrades with increasing momentum
- Performance of calorimetry
  - Energy resolution improves with increasing energy
- (Hadron collider) "Traditional" approach
  - Measure jet energies using calorimeters only
  - Means ~70% of total energy of jet measured by HCAL
    - resolution (50-100)%/sqrt(E)
  - Neglects that 60% of hadronic energy often better from tracker
- Try again for LC
  - Remember will be more boosted at ILC than at LEP

PFA Calorimetry

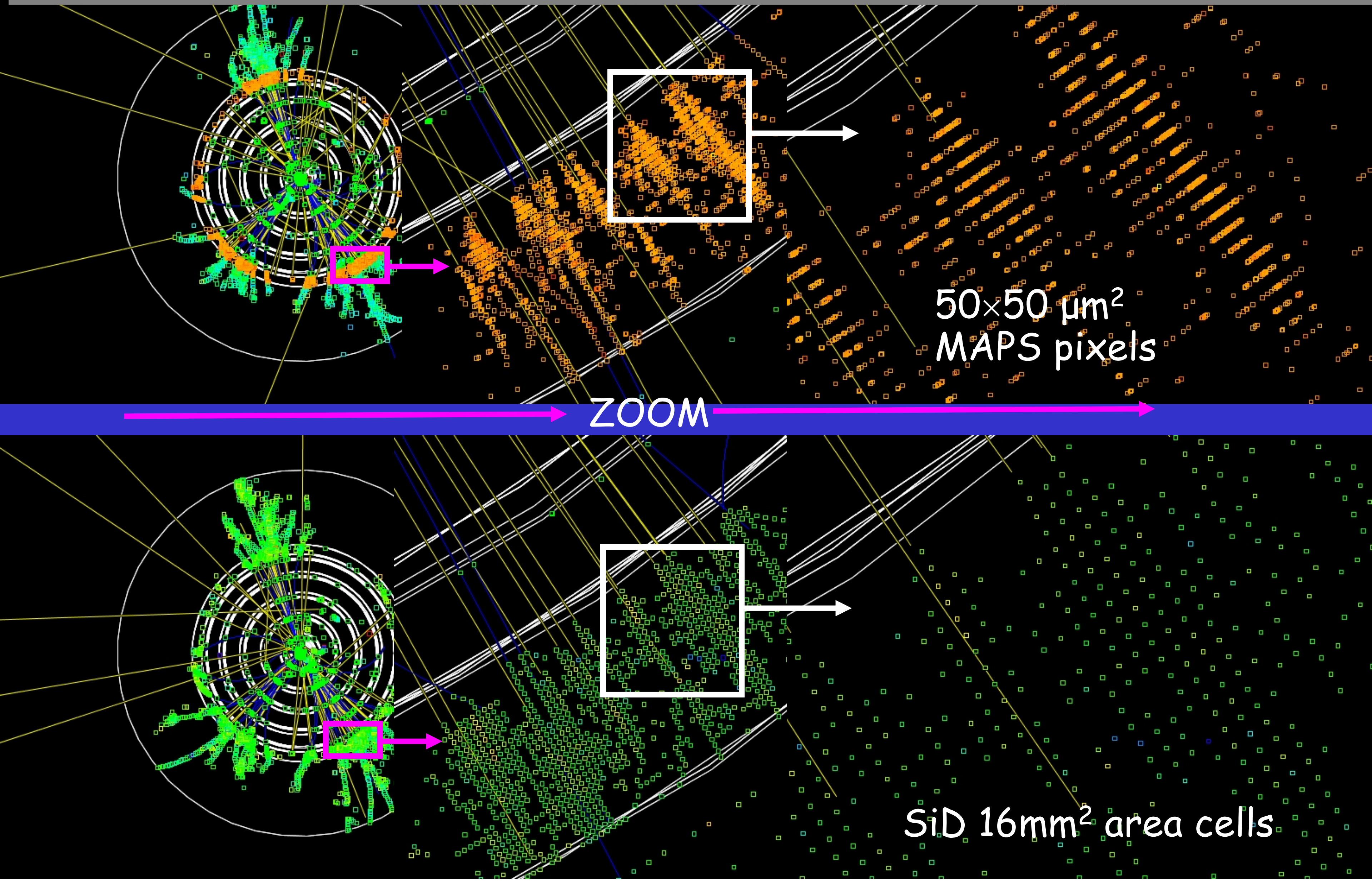


Detector must allow association of tracks with deposits in calorimeters

➔ $$



Ultimate Tracking Calorimeter: CMOS



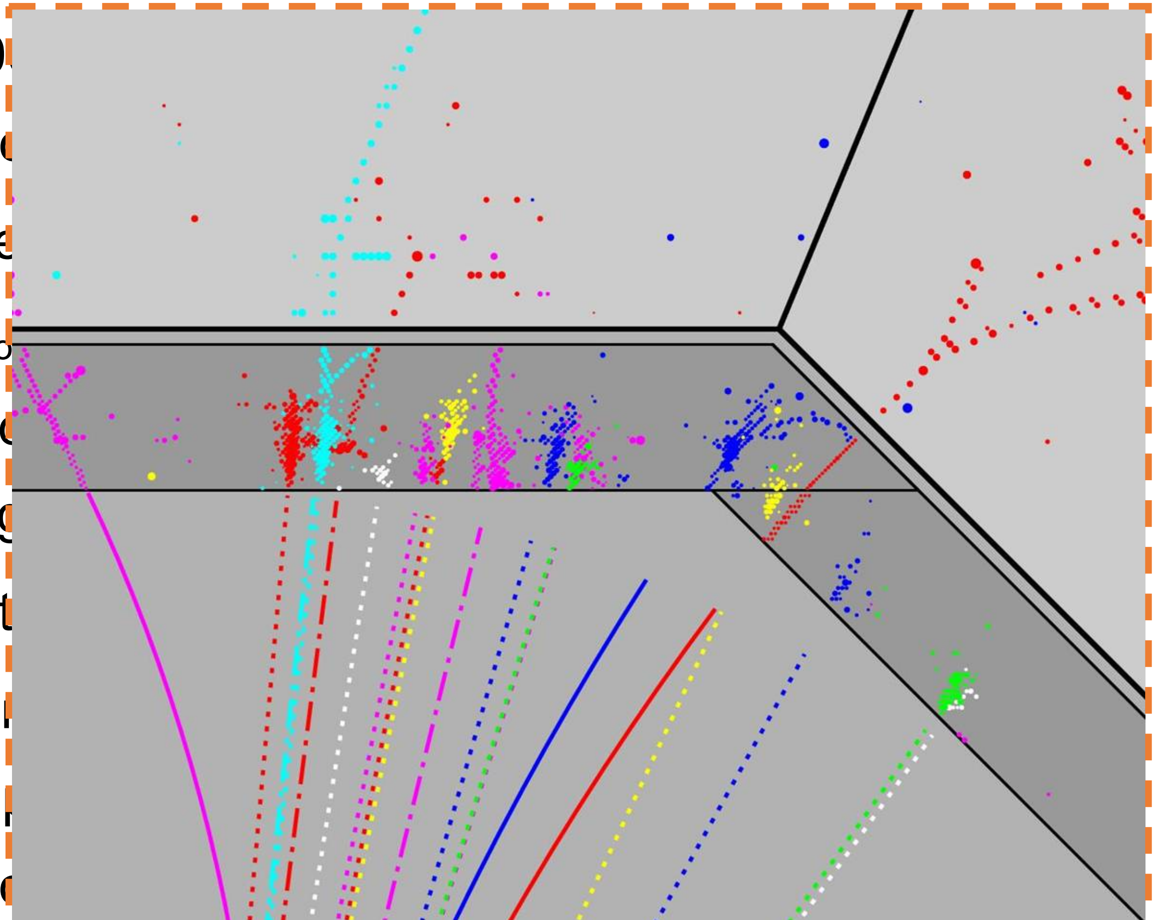
ECAL Design Principles

- Measure 100% EM energy
  - shower containment in ECAL, ΣX_0 large
- Resolve energy deposited by individual particles
  - small $R_{moliere}$ and X_0 – compact and narrow showers
- Separation of hadronic/EM showers
  - λ_{int}/X_0 large, $\therefore$ EM showers early, hadronic showers late
- Minimal material in front of calorimeters
- Strong magnetic field
  - lateral separation of neutral/charged particles
  - keeps a lot of background inside beampipe
- Active medium: Silicon (or scintillator)
  - Pixel readout, minimal interlayer gaps, stability

} ECAL, HCAL inside coil (cost!)

ECAL Design Principles

- Measure 10
  - shower c
- Resolve ene
  - small R_{mo}
- Separation
  - λ_{int}/X_0 lar
- Minimal mat
- Strong mag
  - lateral se
  - keeps a l



ECAL, HCAL inside coil (cost!)

- Active medium: Silicon (or scintillator)
  - Pixel readout, minimal interlayer gaps, stability

SiD and ILD

Detector concepts for the ILC

Common Aspects

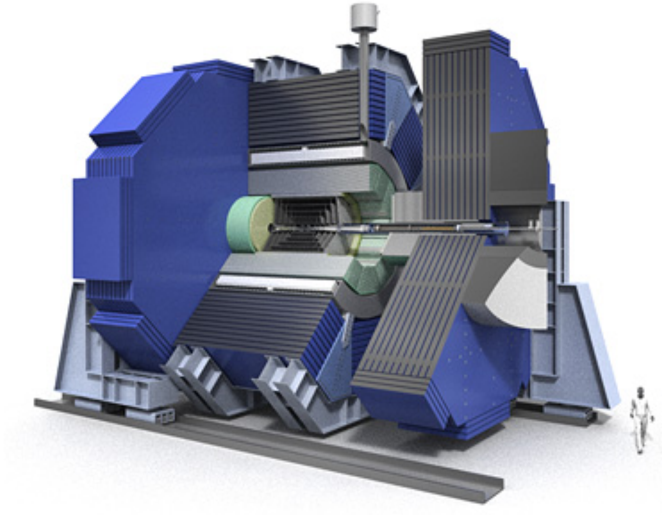
- Designed for Particle Flow
- Highly granular calorimetry
- Designed for easy Push-Pull operation

SiD

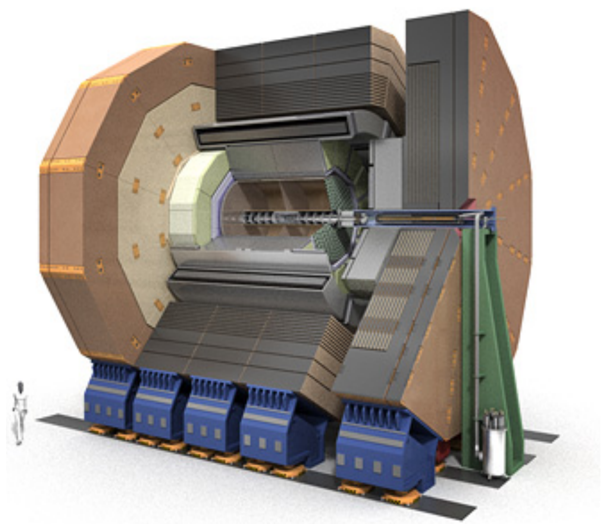
- Compact high-field design
- All-Silicon tracking
- B Field 5 T, r_{ECAL}=1.25 m

ILD

- Large medium-field design
- TPC as main tracking device
- B Field 3.5 T, r_{ECAL}=1.7 m



SiD



ILD

DESY. | ILC |103rd Plenary ECFA |Marcel Stanitzki

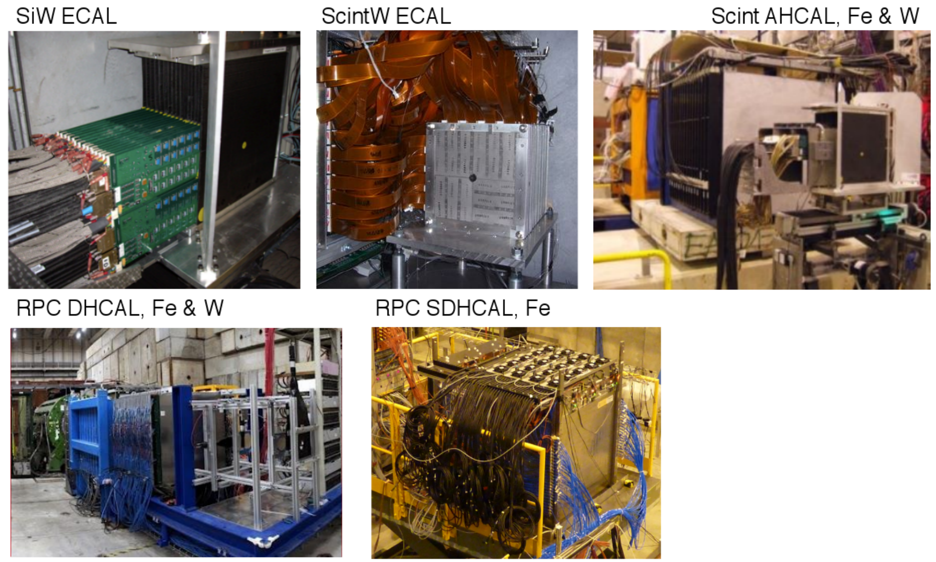
- Two distinct but many common features
- Discuss: ”push/pull”

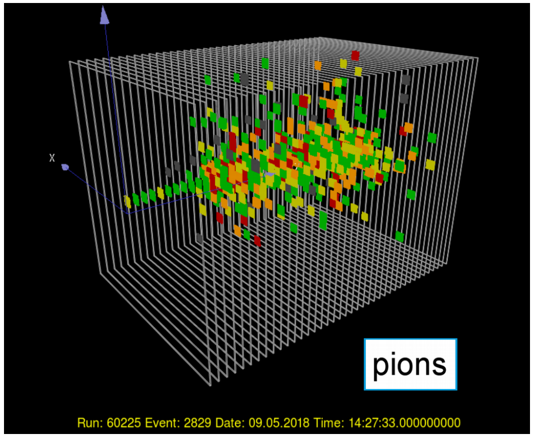
R&D Highlight: CALICE

Establishing Highly Granular Calorimetry

CALICE Collaboration

- R& D for highly granular calorimeters started in 2001
- CALICE collaboration started in 2005
- CALICE today:
  - 55 institutes in 19 countries (4 continents)
  - 350 members
- Various technologies approaching technological readiness
  - SiW, Scintillator+SiPM, GEM, RPC
- Game-changing impact on detector designs:
  - ILC, CLIC, CEPC, CMS, DUNE





DESY. | ILC |103rd Plenary ECFA |Marcel Stanitzki Page 27

- R&D either within a “detector concept” or “horizontal” – agnostic of overall detector.
- Why? Not clear how many detectors will be built…

Physics-goals driven

Detector Requirements

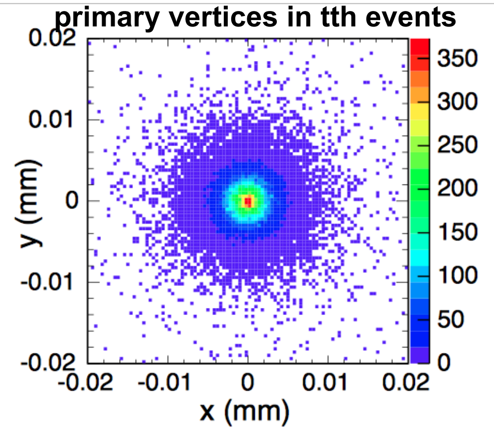
ILC requires precision detectors

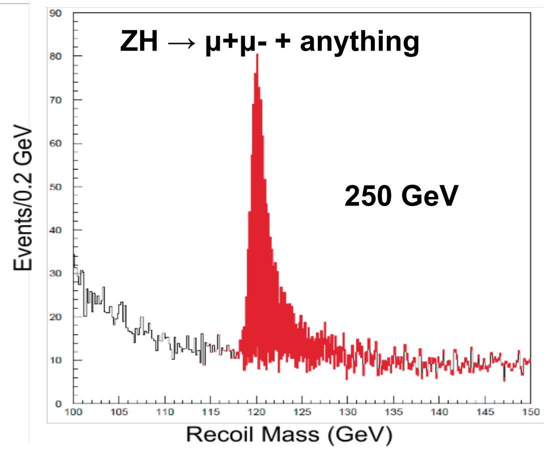
ILC detector design cornerstones

- Particle Flow
- Power Pulsing

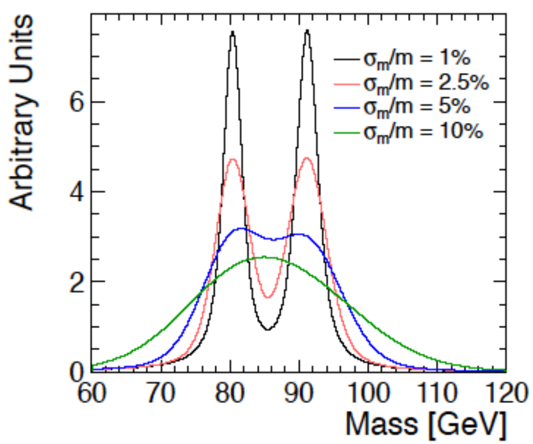
Performance Requirements

- Time stamping
  - Single Bunch resolution
- Vertex detector
  - < 4 μm precision
  - $\sigma_{r\phi} \approx 5 \ \mu m \oplus 10 \ \mu m / p \sin^{\left(\frac{3}{2}\right)}(\theta)$
- Tracker
  - $\sigma(1/p) \sim 2.5 \times 10^{-5}$
- Calorimeter
  - $\frac{\sigma_{E_{Jet}}}{E_{Jet}} = 3-4\%, E_{Jet} > 100 \ GeV$





W-Z separation



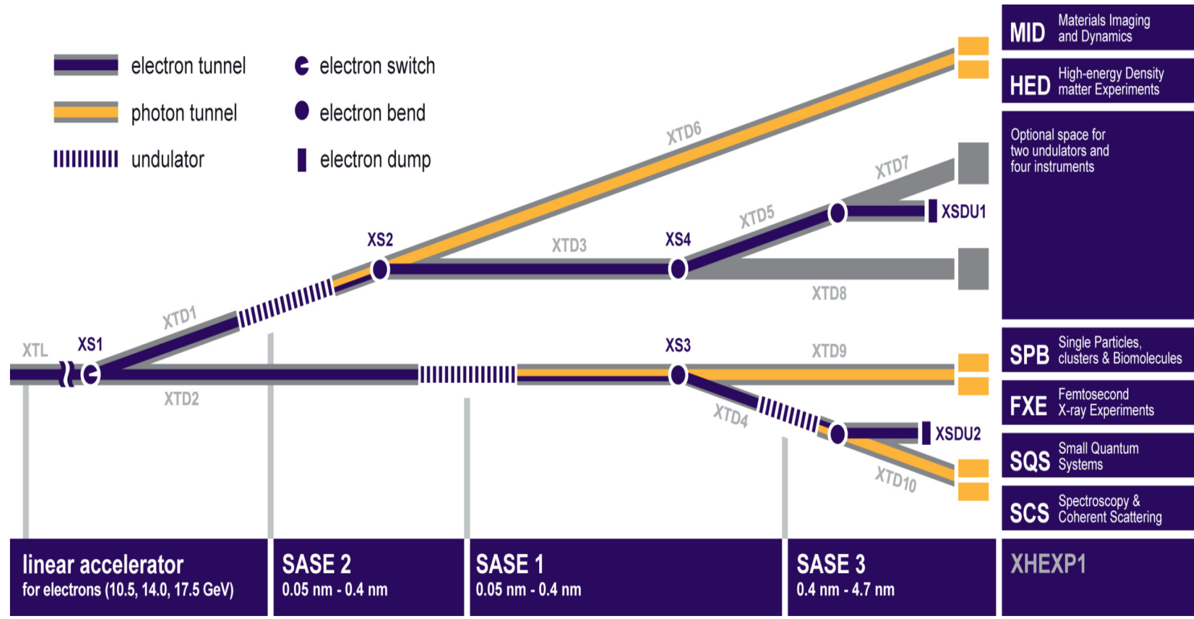
Industrialised process

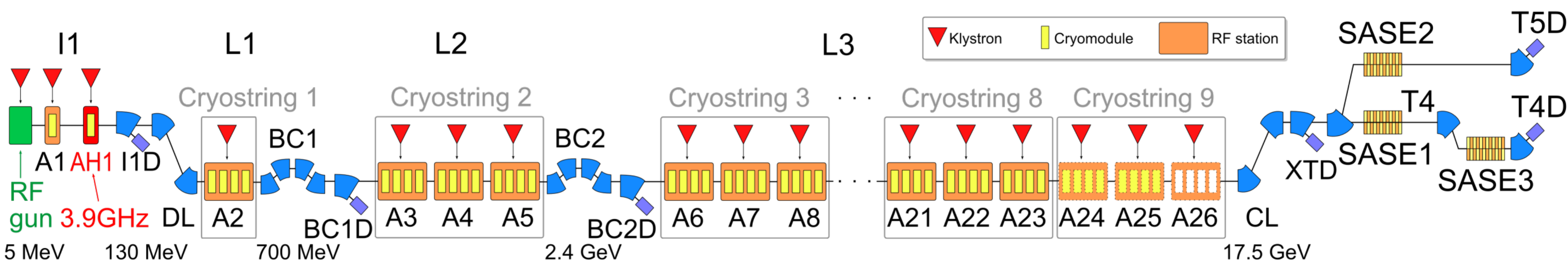
The European XFEL

10% of the ILC Main Linac

Soft and hard X-ray light experiment

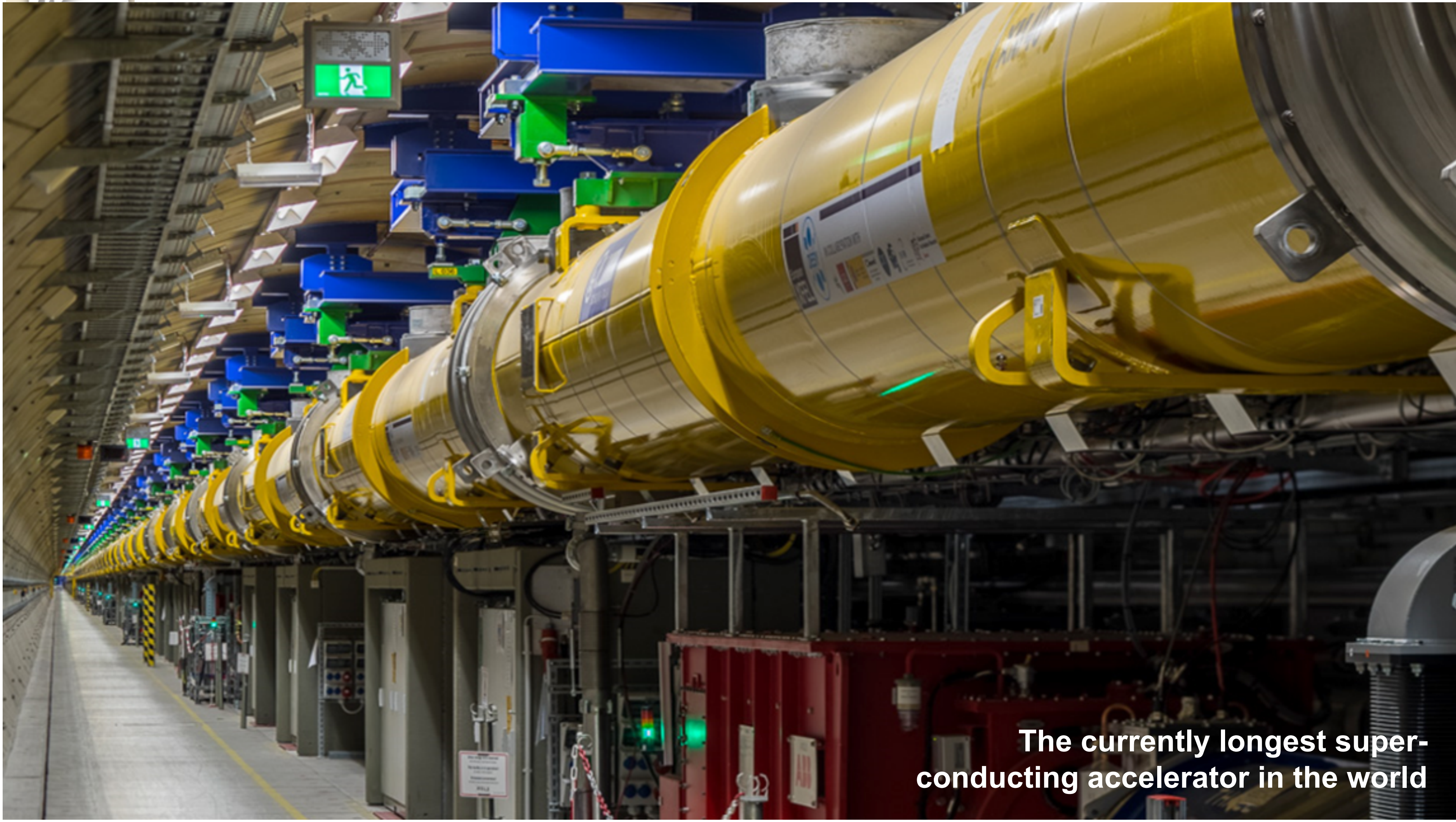
- ~800 TESLA-type cavities
- Resonance frequency 1.3 GHz
- 32 cavities per XTL RF station
- Design energy 17.5 GeV
- Pulsed operation 10 Hz
- Routine user operation at several stations





DESY. | ILC |103rd Plenary ECFA |Marcel Stanitzki **Page 12**

XFEL@DESY:~10% of ILC SC RF



Design drivers

- Vertex detector
  - Low power operation to reduce/avoid need for active cooling.
    - Big reduction in passive material
  - Minimal material in detector volume
    - How much?
  - Goal for impact parameter resolution in an ILC experiment is ≈ 3 μm
  - Reduction of backgrounds that drives the R&D for linear collider vertex detectors.
  - Proximity to beams links design to beam structure
  - Many discovery channels have t- or b- fermions, so this a criticial area

Vertex detector example

- Challenge (Chronopix)
  - Transition from small prototypes (few mm^2) to ILC size ($\approx 10\ cm^2$) may have problems
  - Lorentz forces on the power supply buses, especially when power pulsing.
  - Power pulsing ~mandatory for required power dissipation.
    - May generate varying Lorentz forces, act on power supply lines, cause vibrations unacceptable for spatial resolutions

Trackers

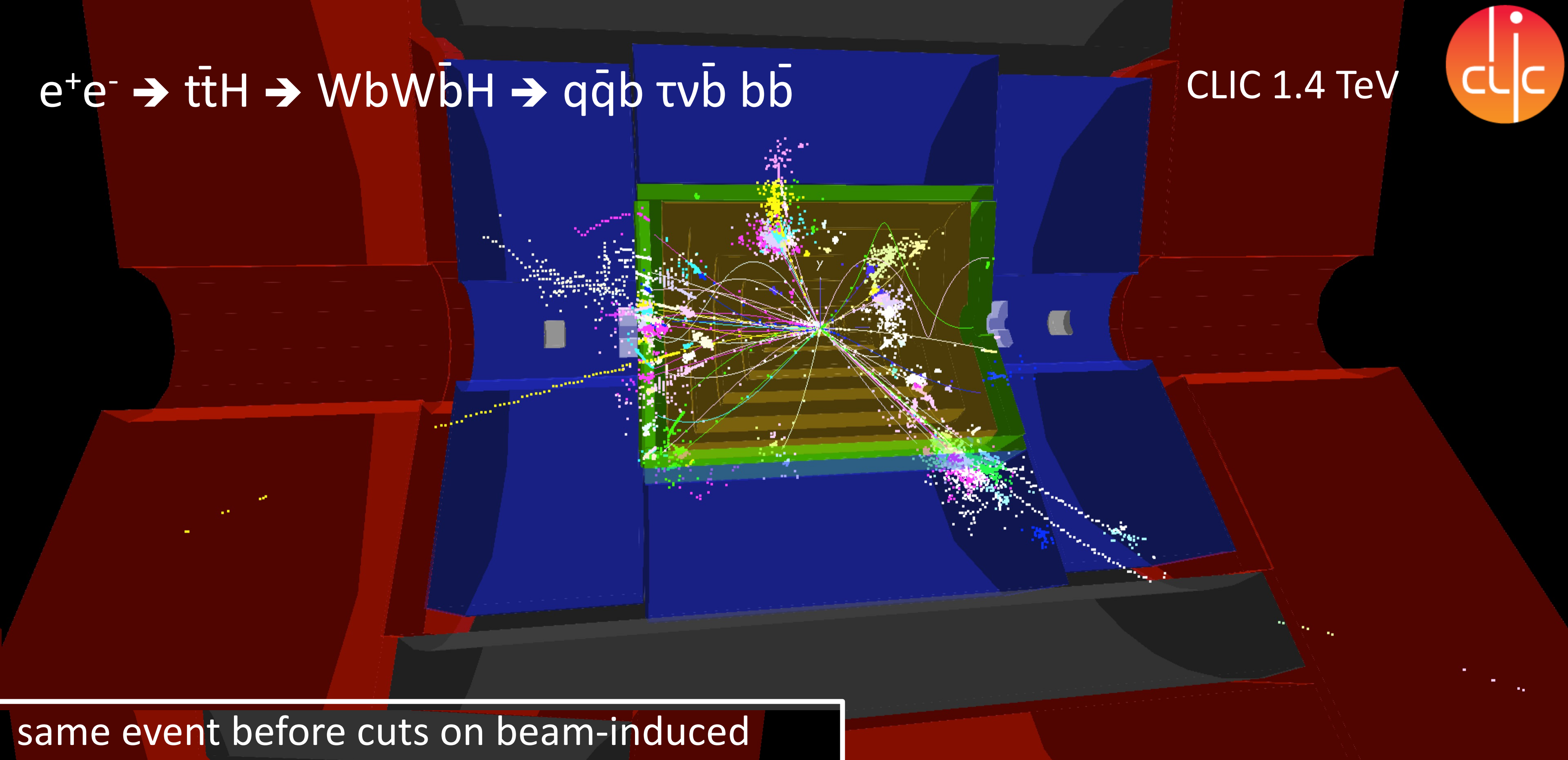
- Silicon
  - Occupancy may look overwhelming but good timing resolution and pt cuts can mitigate

Gaseous
  - Extremely successful in past, low mass, good pattern reco

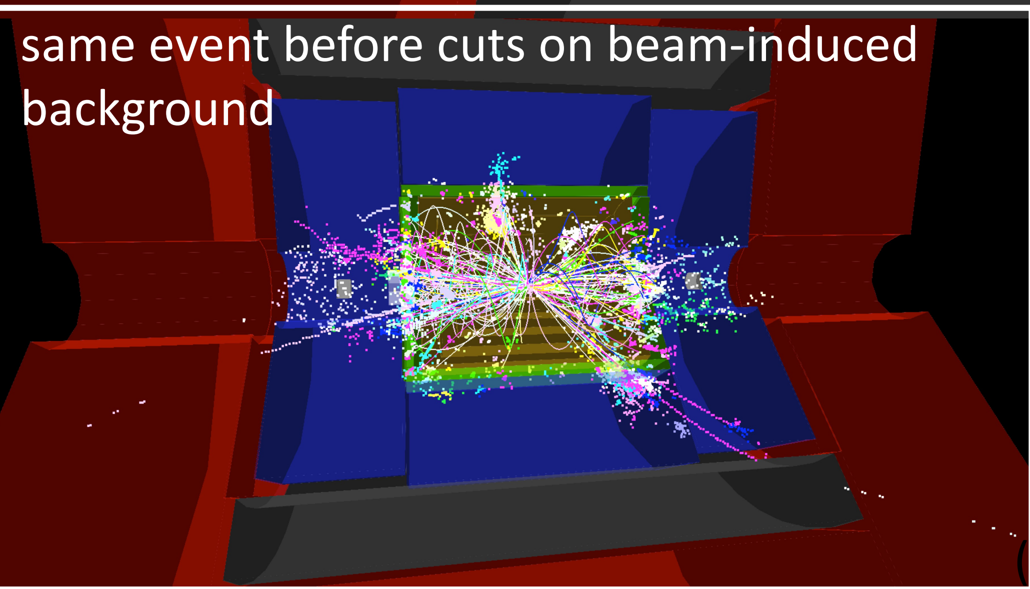
- Main challenges for a TPC from high B field
  - Need excellent field map
  - Potential problem with space charge buildup from ion back flow can cause problem with inhomogeneous E or B fields in the drift region

$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$

CLIC 1.4 TeV



same event before cuts on beam-induced background



Highly granular calorimetry + precise hit timing

↓

V. effective background suppression for fully reconstructed particles

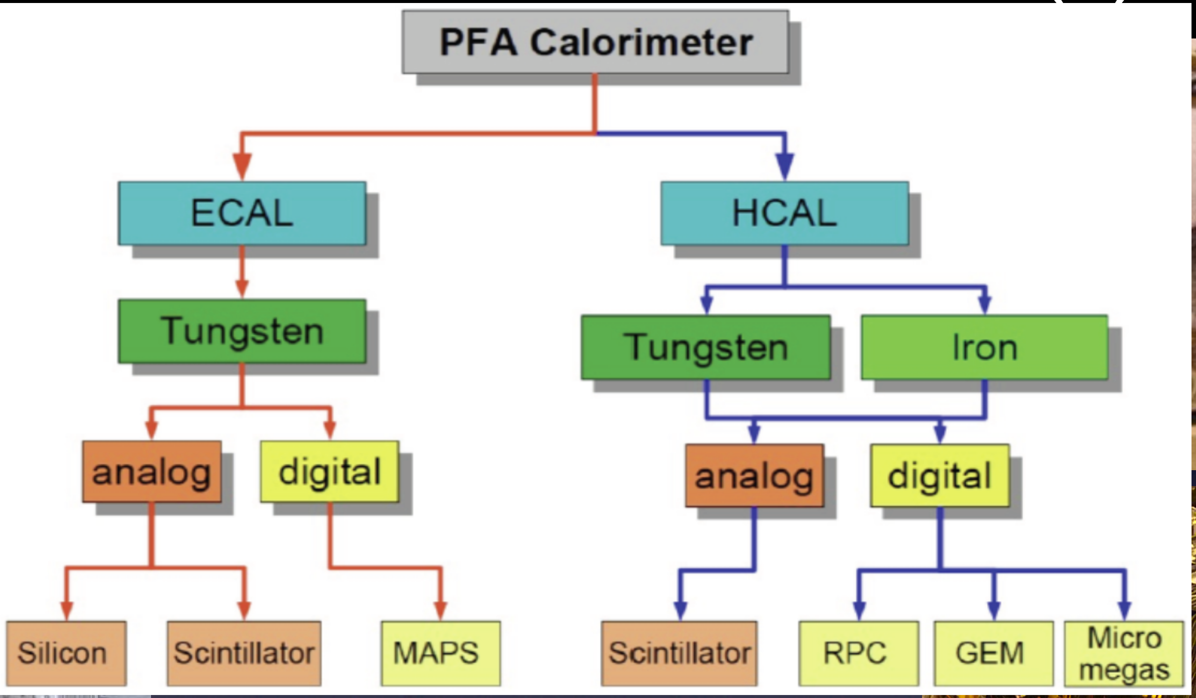
↓

General trend for **e^+e^-** and **pp** options

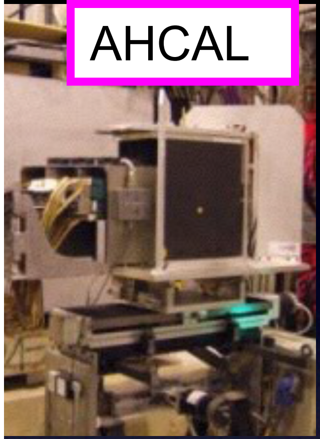
(e.g. CMS endcap calorimetry for HL-LHC)

CALICE-like solution(s)

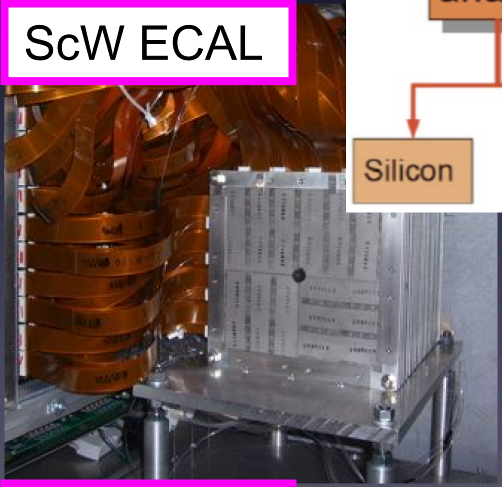
SiW ECAL



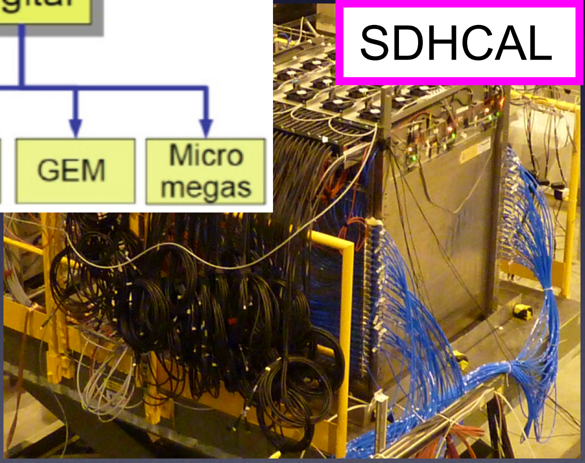
AHCAL



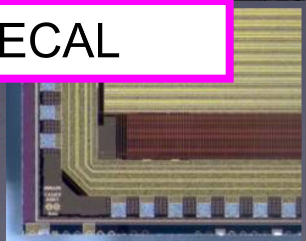
ScW ECAL

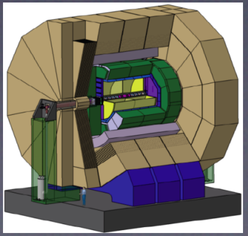


SDHCAL

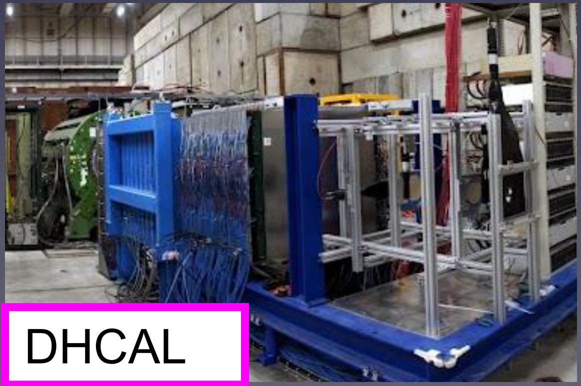


DECAL





DHCAL



CALICE Collaboration

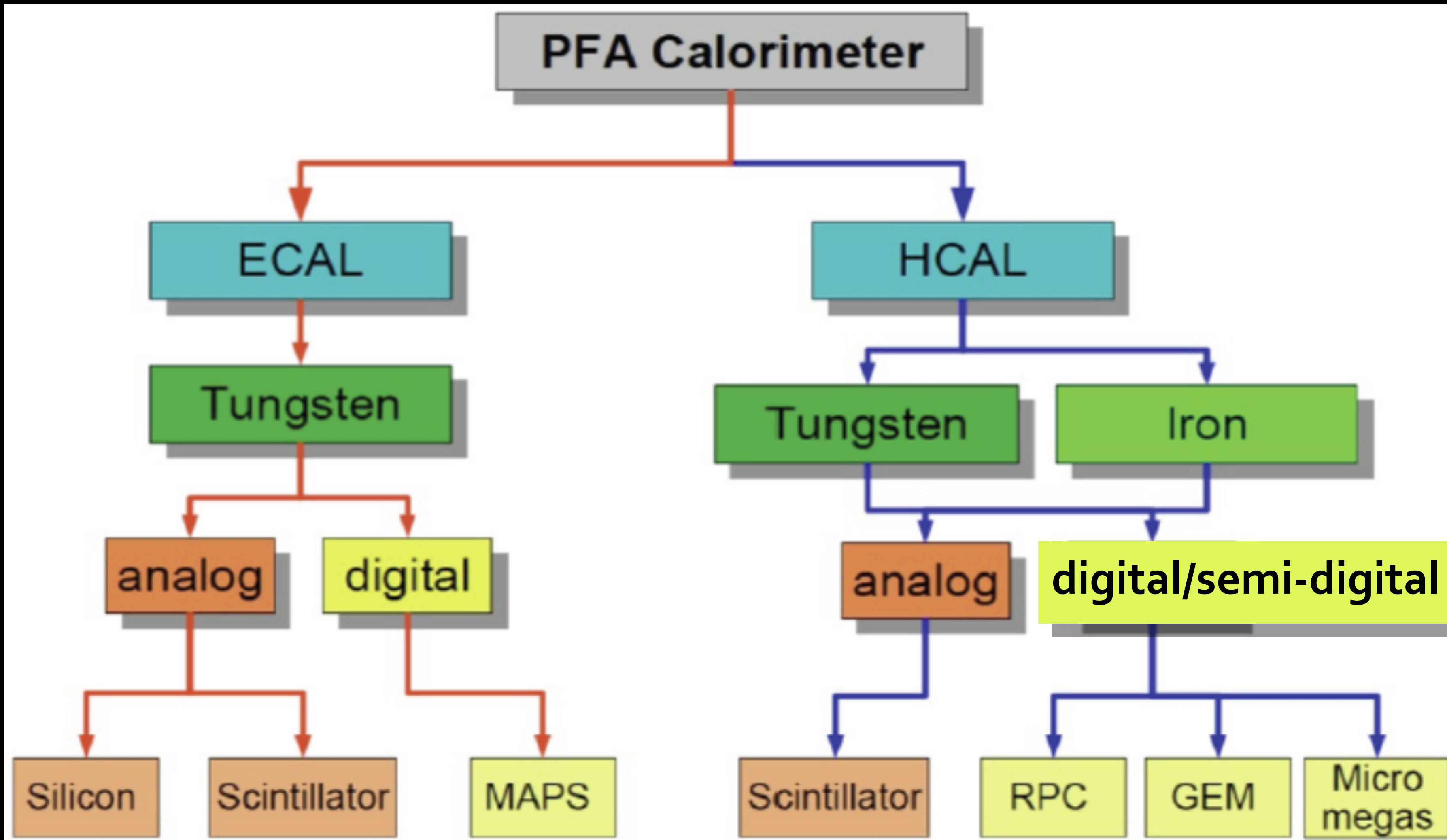
The CALICE Collaboration

Collaborating since 2001

336 physicists/engineers from 57 institutes and 17 countries coming from the 4 regions (Africa, America, Asia and Europe)

- All papers available from https://twiki.cern.ch/twiki/bin/view/CALICE/
- (or google "calice" – top hit)
- Cost-effective approach of testing both h/w and s/w in common framework
- "Friendly competition" to ensure best technology chosen objectively

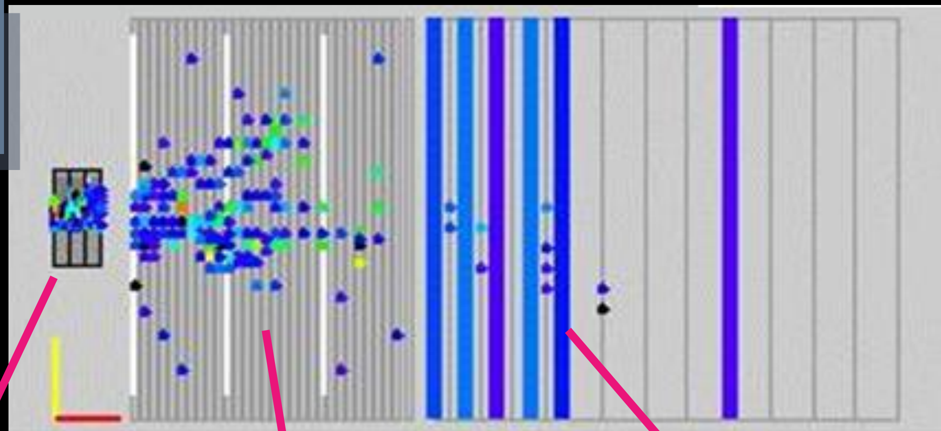
One-stop Calorimeter R&D

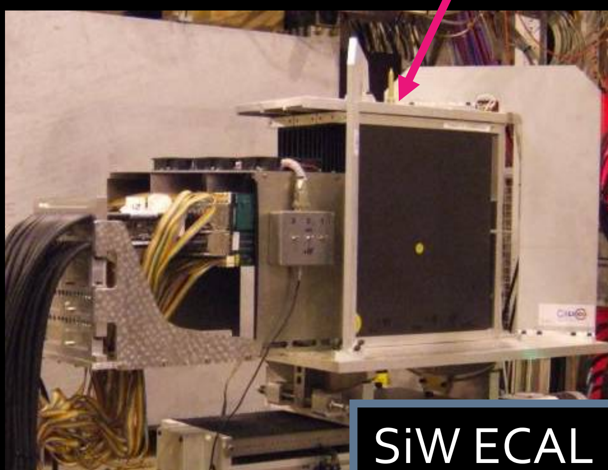


1^{st} test beam prototypes (c. 2006)

10 GeV pion shower
@ CERN test beam

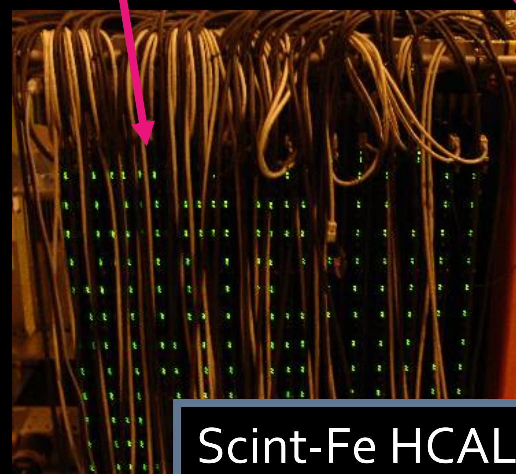
beam





SiW ECAL

1x1cm² lateral segmentation
1 X_0 longitudinal segment.
~1λ total material, ~24 X_0



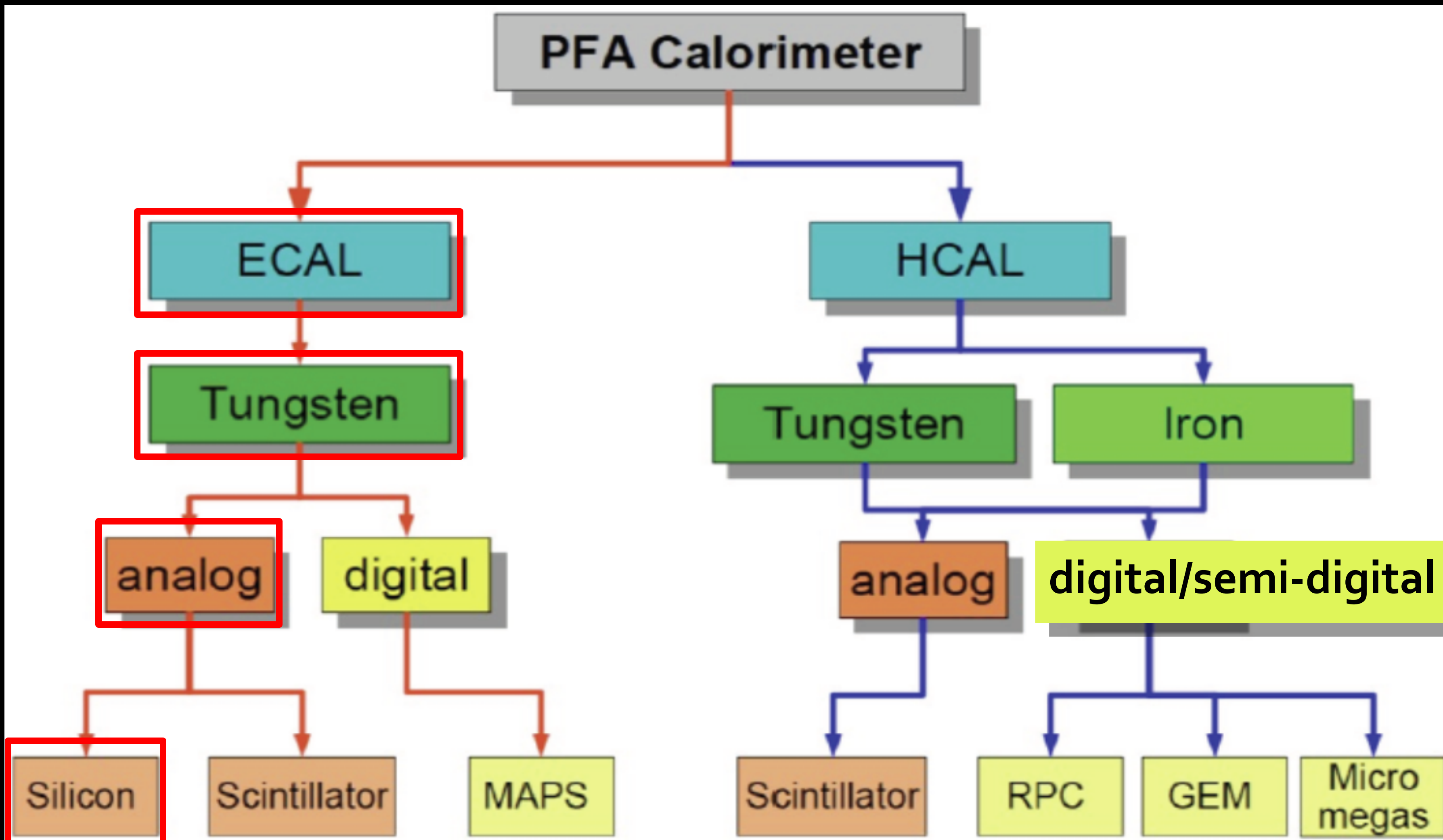
Scint-Fe HCAL

3x3cm² tiles lateral segmentation
~4.5 λ in 38 layers

Scint-Fe tail catcher/ muon tracker

5x100cm² strips
~5 λ in 16 layer

One-stop Calorimeter R&D



Si-W Electromagnetic Calorimeter (Si-W ECAL)

Absorber: **Tungsten** sheets wrapped in carbon fiber

Detector: **Silicon PIN diodes 1x1cm²** (Comparable to R_M:0.9 cm)

Si allows high granularity & compactness

Length: 30 layers~ $24X_0$ ~ $1\lambda_I$

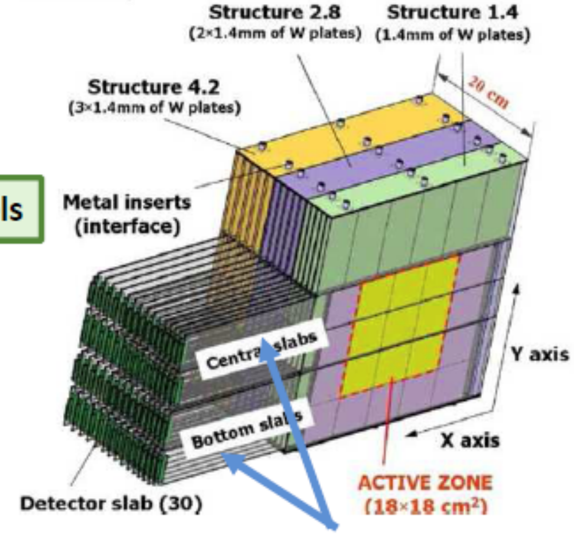
3 "stacks", 10 modules each

Different absorber thickness

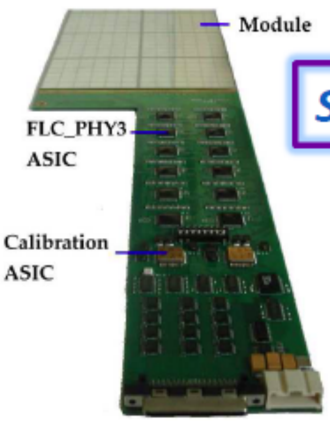
- 1.4 mm (0.4 X_0)
- 2.8 mm (0.8 X_0)
- 4.2 mm (1.2 X_0)

Lateral size: 18x18cm²

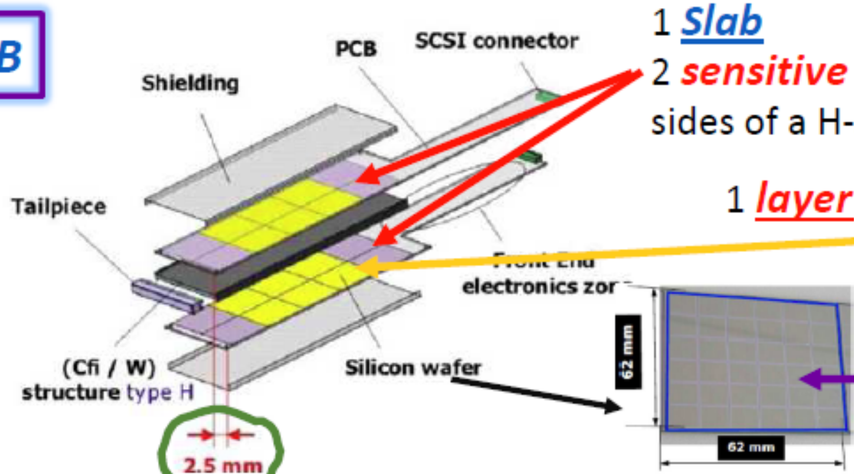
9720 channels



1 sensor plane= 2 detector *slabs*



SLAB



1 *Slab*

2 ***sensitive layers*** mounted on the two sides of a H-shaped W supporting structure

1 *layer* = 6 (3) ***Si wafers*** (525µm thick)

1 *wafer*= 6x6 ***pads*** 1x1cm²

Offset to reduce dead areas (+ 1.3 mm offset between successive slabs)

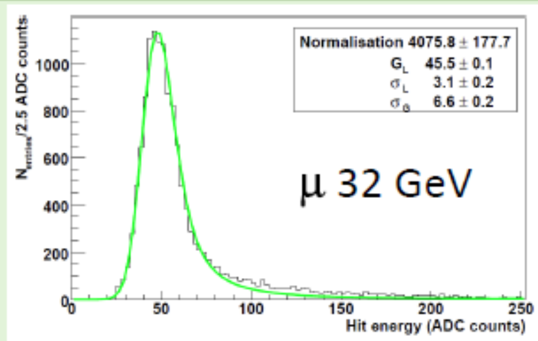
Si-W ECAL Calibration

FNAL e$^+$ test beam

1.- Pedestal subtraction

2.- ADC-MIP calibration

Response of *single channels to μ*
Landau convoluted with a Gaussian
MIP signal=
most probable value of the Landau



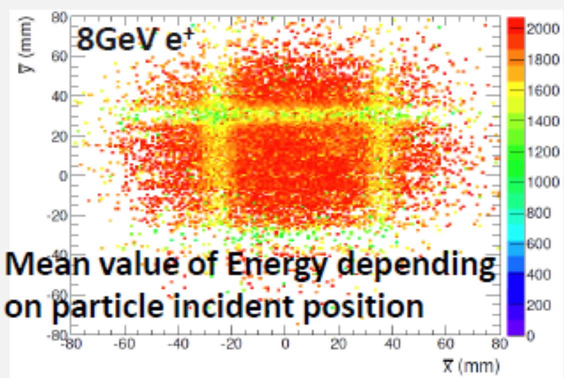
3.- Energy Reconstruction

$$E_{raw} = \sum_{i=0}^{9} E_i + 2\sum_{i=10}^{19} E_i + 3\sum_{i=20}^{29} E_i$$

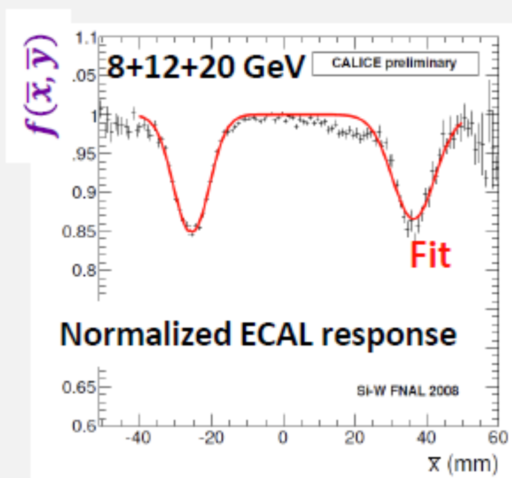
Stacks *weighted* according their thickness
E_i = Total energy plane *i*

4.- Gap correction

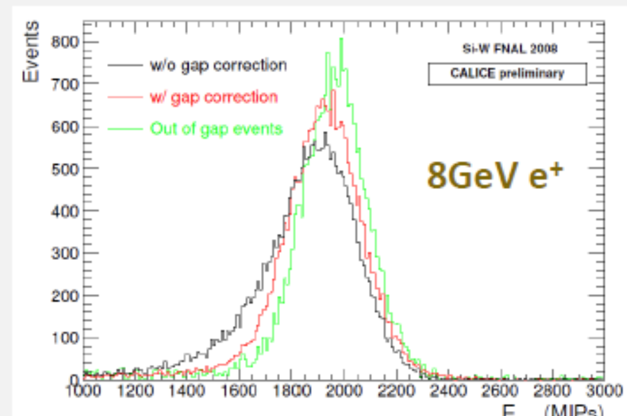
1+1 mm inactive area between wafers (guard ring)
➔ non-uniform energy response



Mean value of Energy depending on particle incident position



Energy can be corrected by $1/f(\bar{x},\bar{y})$

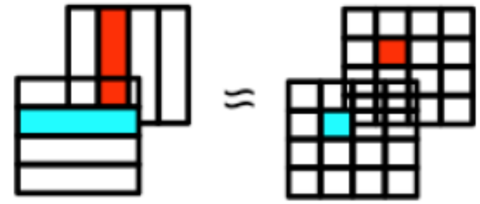


More Gaussian after gap correction

Scintillator – W Electromagnetic calorimeter (Sc-W ECAL)

Absorber: Tungsten (88%W 12%Co 0.5%C) 3.5mm thick

Detector: Plastic scintillator



Odd layers orthogonal to even layers

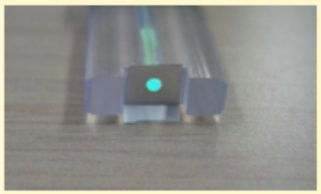
→ $1x1cm^2$ effective granularity

Less readout channels

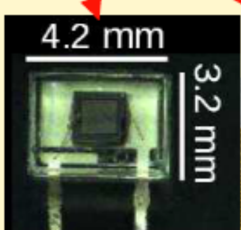
but shower reconstruction more complicated

Strip $4.5x1\ cm^2$ 3mm thick

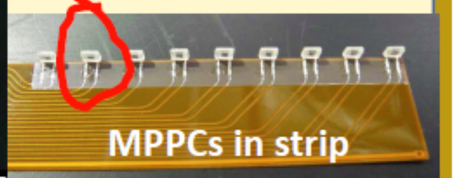
WLS (WaveLength Shifting) fiber



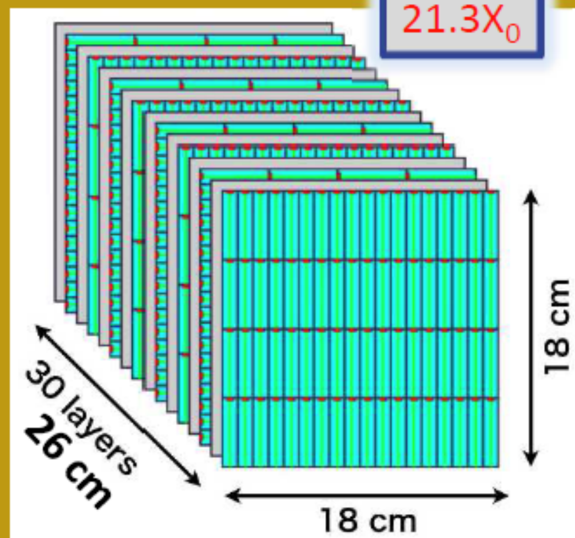
MPPC (MultiPixel Photon Counter)



1600 pixels

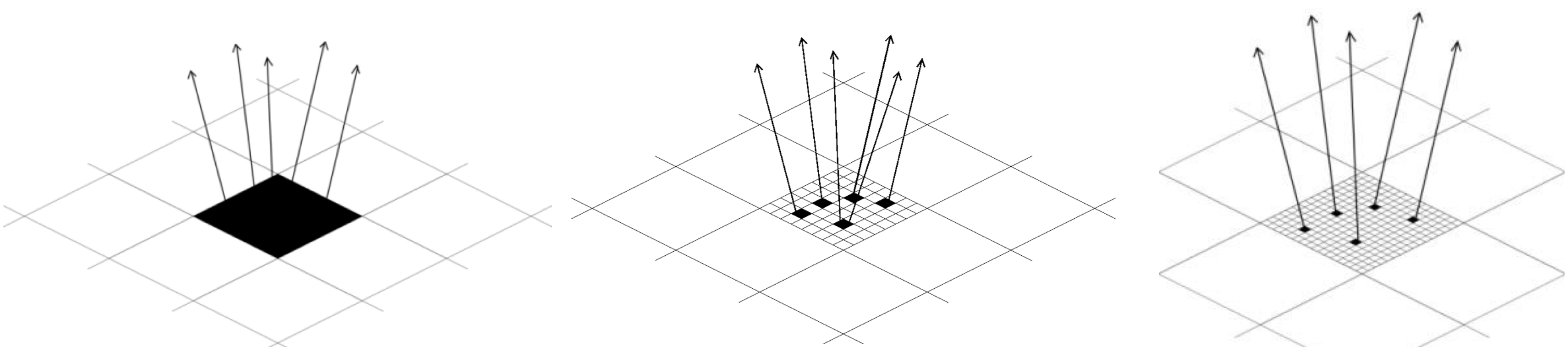


$21.3X_0$



DECAL Concept – cost reduction for ECAL??

- Concept, swap ~0.5x0.5 cm^2 Si pads with small pixels ("Small" := at most one particle/pixel,1-bit ADC/pixel - digital)
- How small to avoid saturation/non-linearity?
  - EM shower core density at 500GeV is ~100/mm^2
  - Pixels must be<$100\times100\mu m^2$
    - Used baseline $50\times50\mu m^2$
  - Gives ~10^{12} pixels for ECAL – "Tera-pixel APS"
  - Mandatory to integrate electronics on sensor

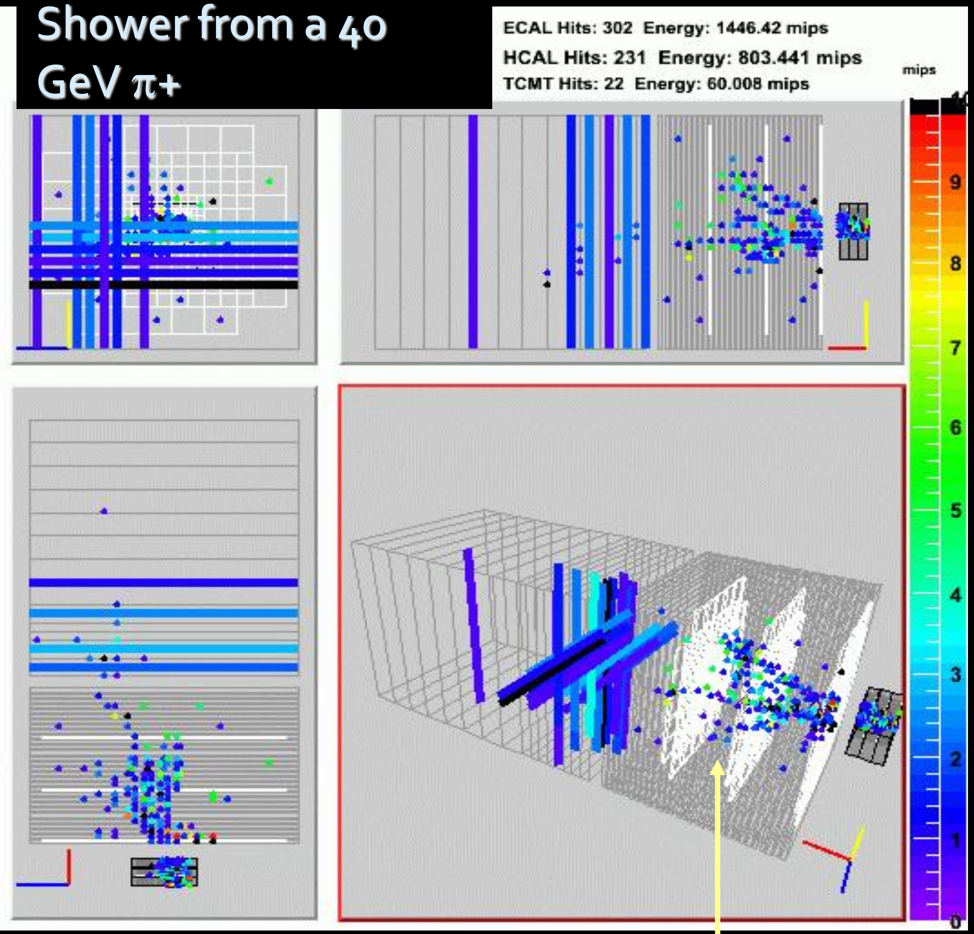


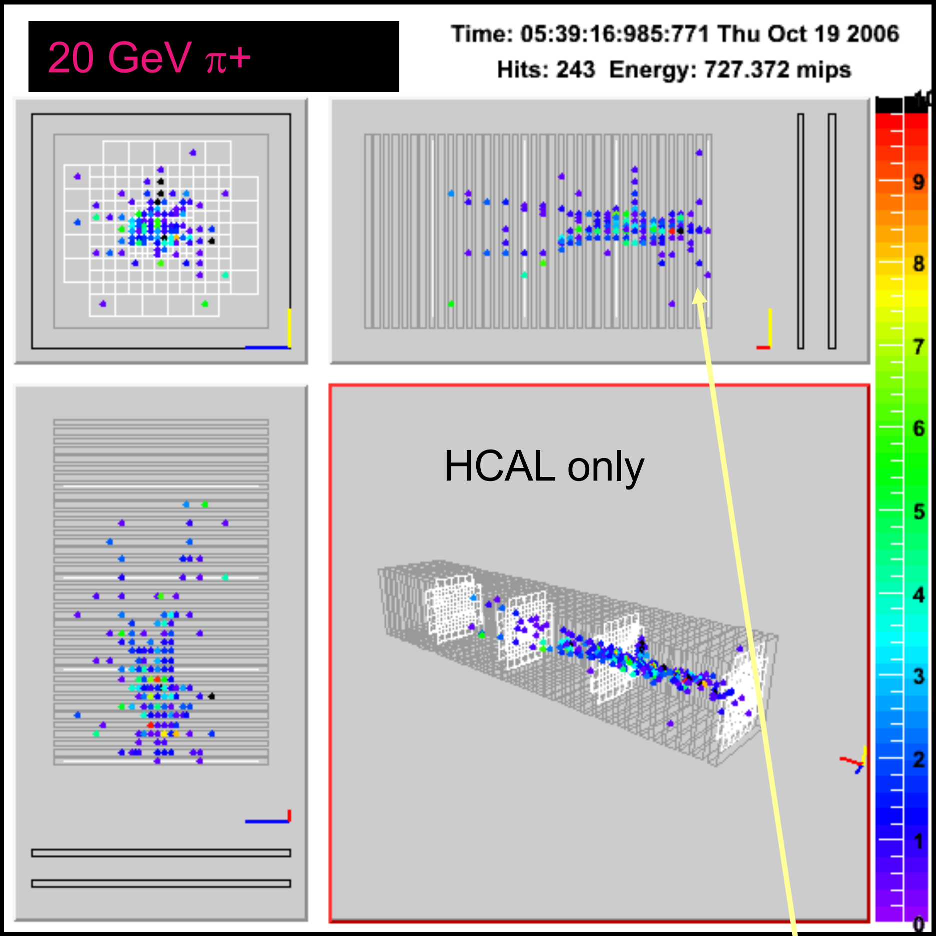
AECAL

DECAL $N_{pixels}<N_{particles}$

DECAL $N_{pixels}=N_{particles}$

Event display

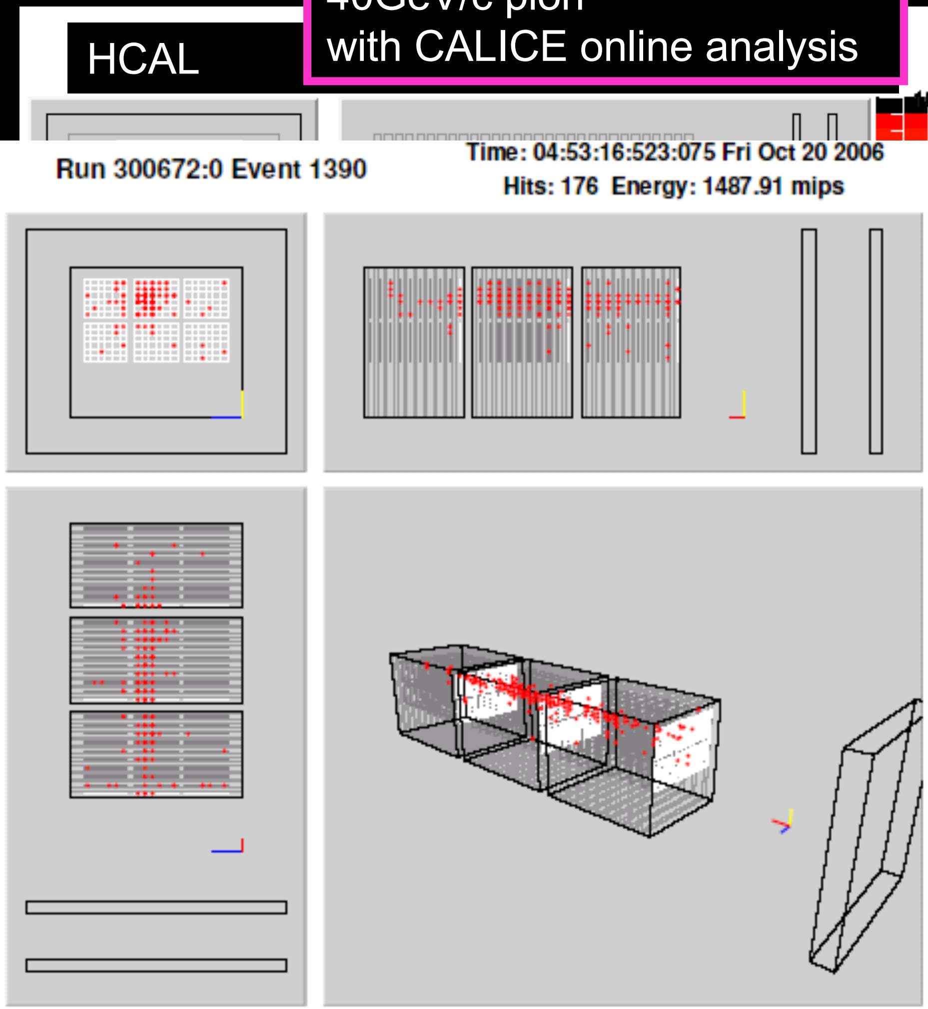




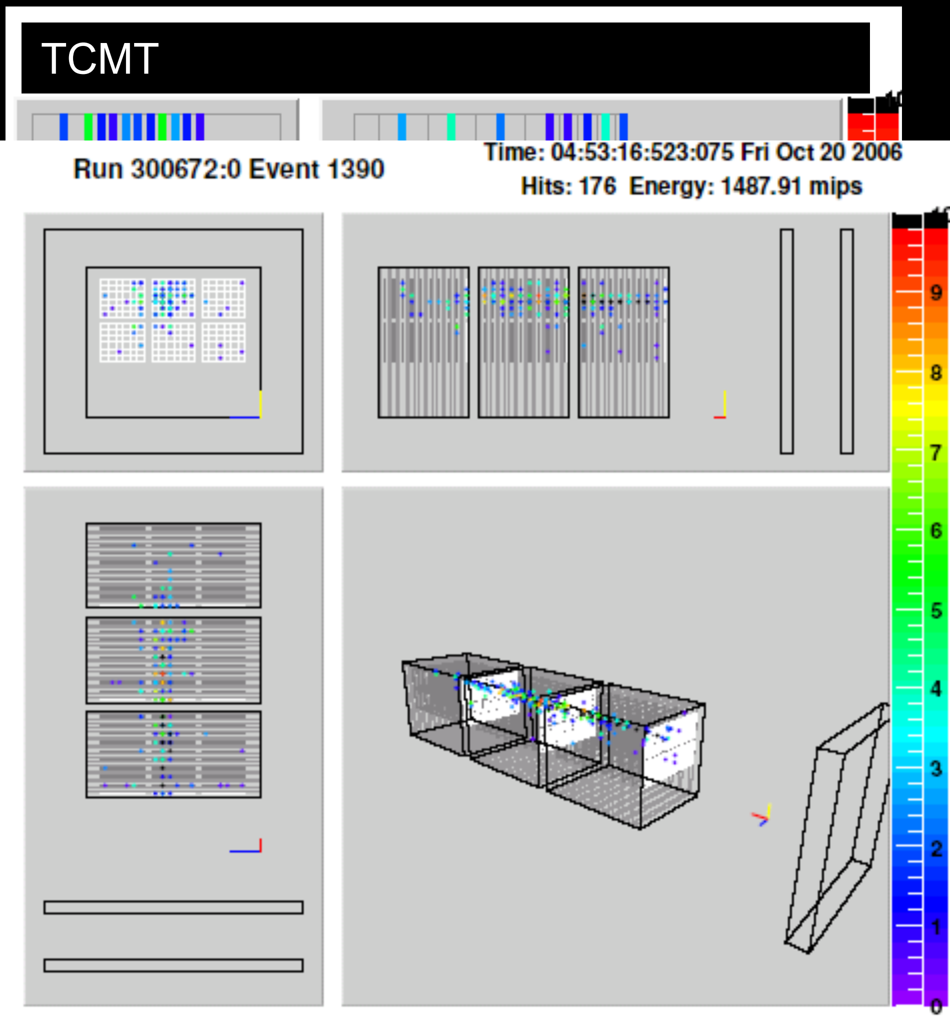
Clear structure visible in hadronic shower

Back-scattered particle

Event display



(digital display)



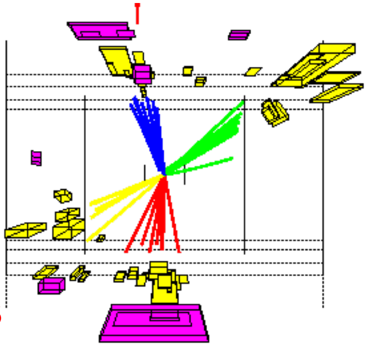
(analogue display)

Calorimeters: HCAL

- Energy scale for hadronic interactions is >> EM, ~pion mass so granularity of detector can be lower
- Distance from beam crossing point larger, so energy deposits from jets better separated
- Many different technologies considered!
- Key features are segmentation ~few cm
- Some ‘digital’ options, lower segmentation, ~1cm
- Absorber structure:
  - Earthquake stability calculations and tests – “always mind your surroundings”
  - Thermal tests with full-scale instrumented and powered structures
- Ample opportunities for new groups to join these fields, depending on the special competences they wish to contribute.

Summary

- e^+e^- machine at few 10^2 GeV will measure Higgs and top properties
  - Precision >> HL-LHC and less model dependent



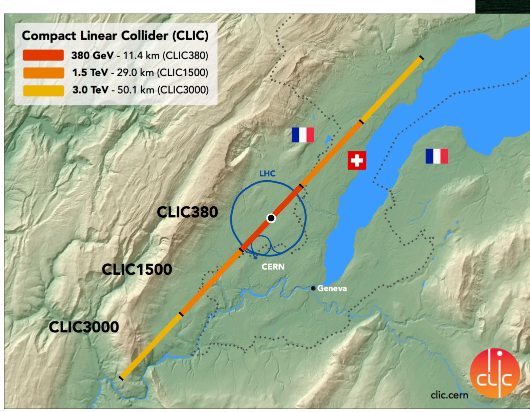
- First CLIC stage at 350/380 GeV allows
  - Higgs production: Higgsstrahlung and WW fusion
  - Top quark: threshold and continuum regions, and rare decays
- Higher-energy e^+e^- collider has more BSM discovery potential
  - Direct detection to kinematic limit
  - Indirect discovery via precise EW measurement to ~few x10 TeV
  - Sensitivity often rises steeply with the centre-of-mass energy

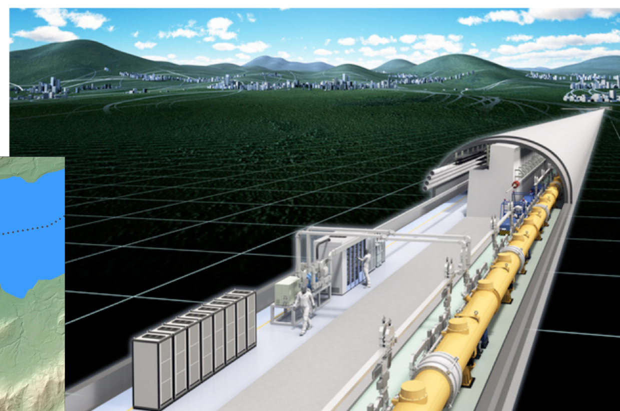
CLIC is unique, only proposed multi-TeV e^+e^- machine

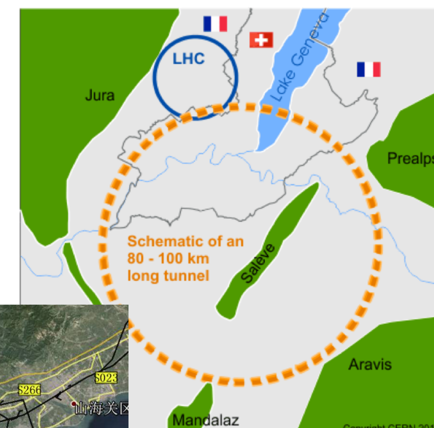
Outlook

- LC detector R&D, unprecedented collaborative R&D last ~15years
- Most could *work* already, many in cost-mitigation phase
- Detector development takes time, effort, attention to details
- Getting involved (here, elsewhere) reduces LHC “tunnel vision”

- Q: Would you choose CLIC, ILC, FCC-ee or CEPC?
- A: Yes, please!



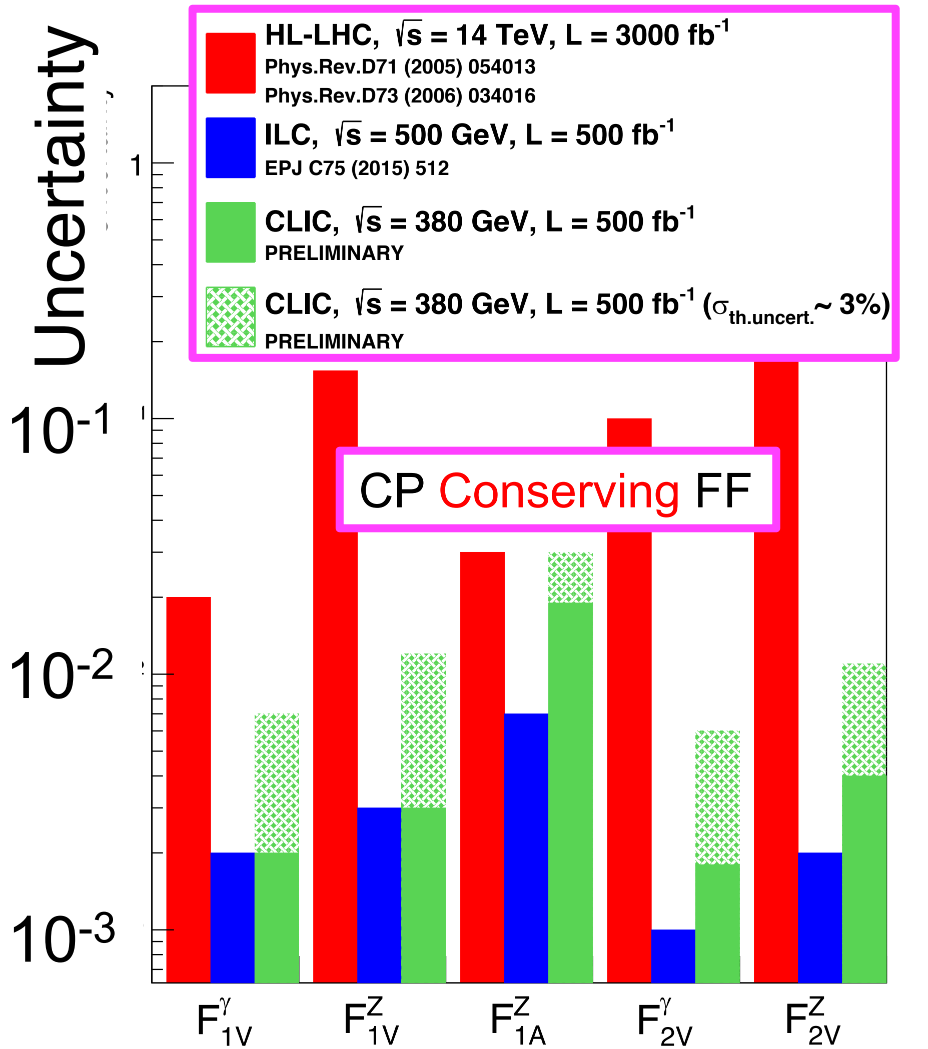




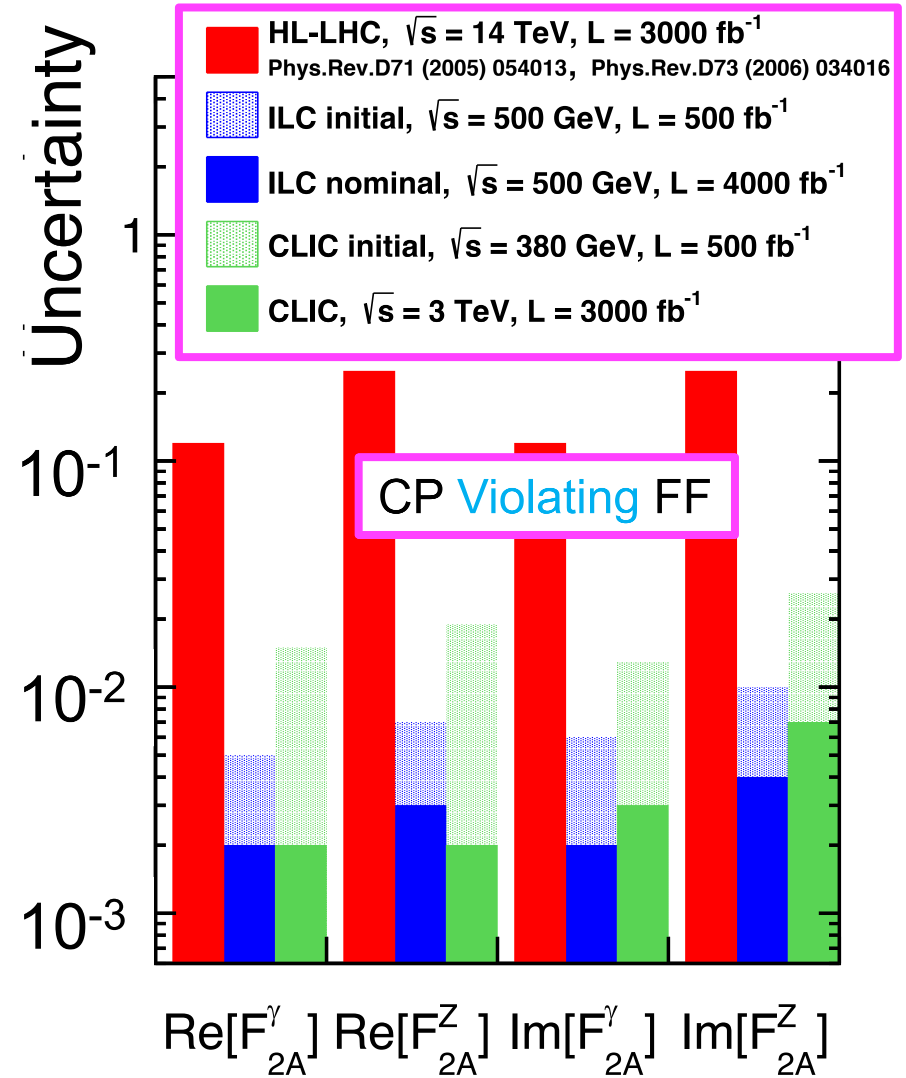
Backup material

Top Form Factors

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



[CERN YR 2016-004, arxiv:1710.06737]

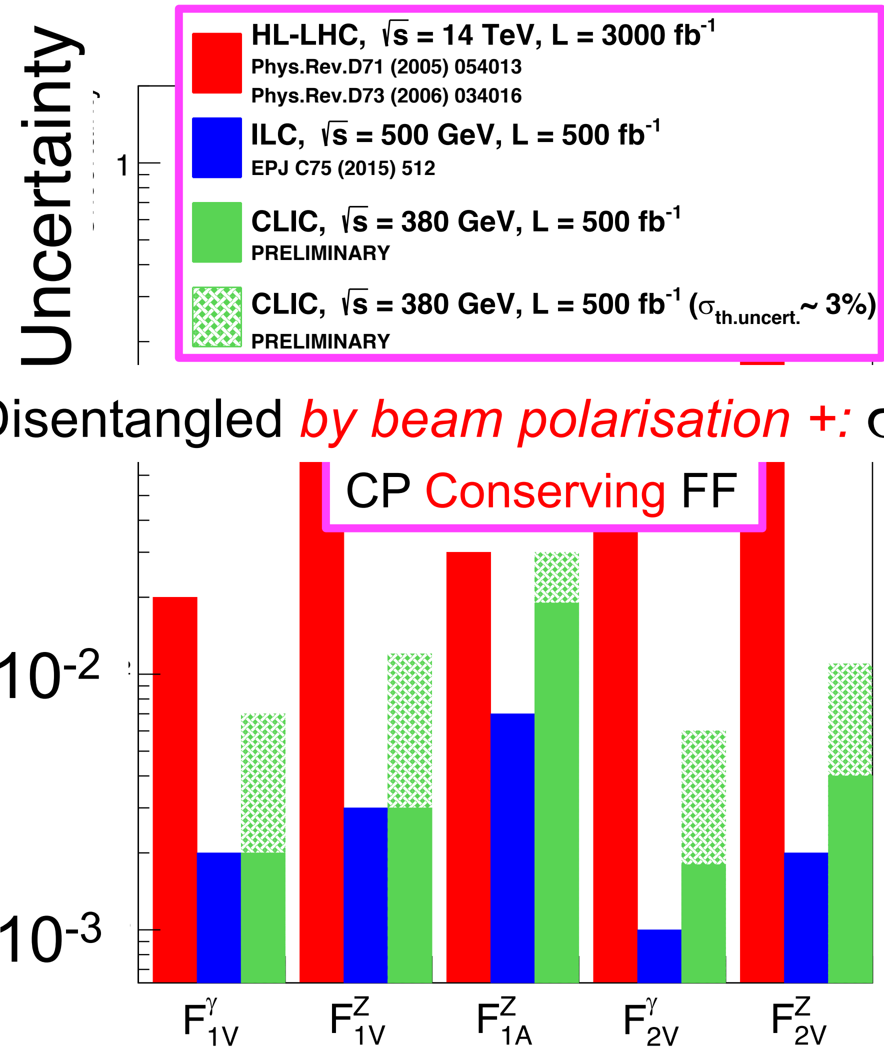


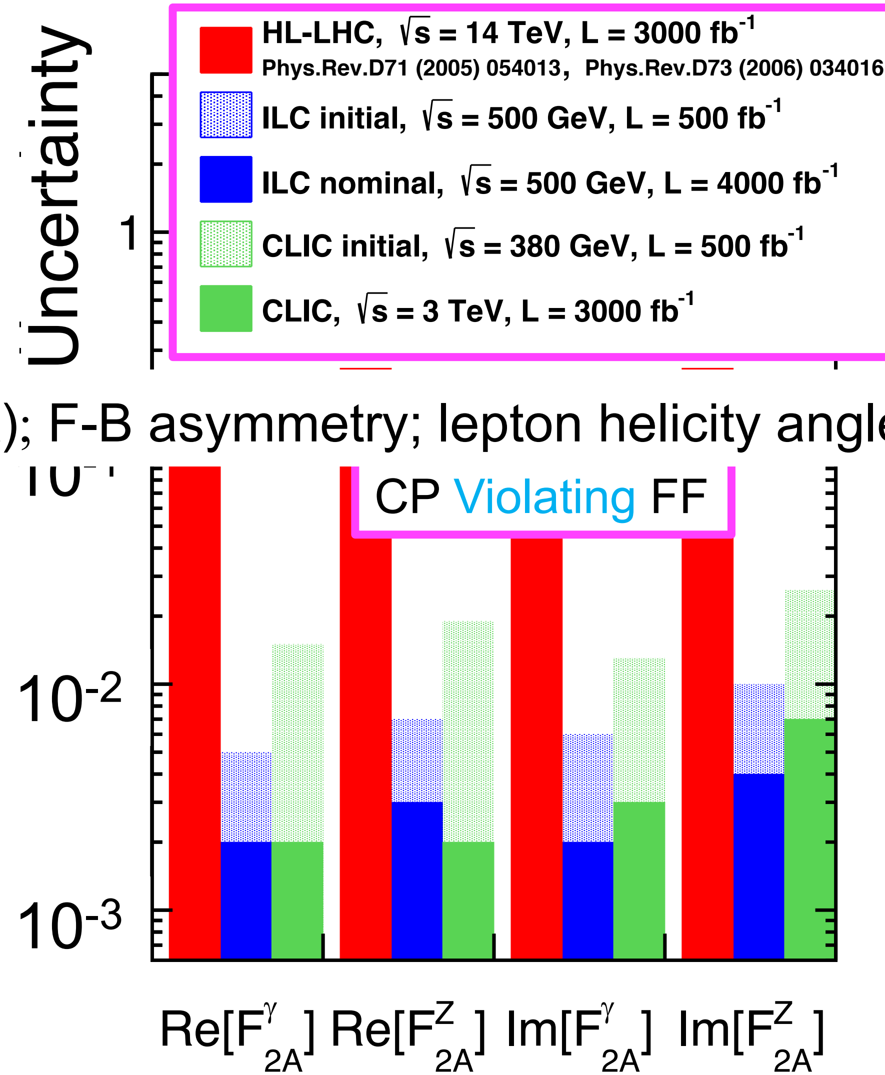
[Eur. Phys. J. C (2018) 78:155]

Top Form Factors

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

Disentangled *by beam polarisation +:* σ(tt); F-B asymmetry; lepton helicity angle





Sensitivity to contact interactions rises with energy – good for CLIC

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

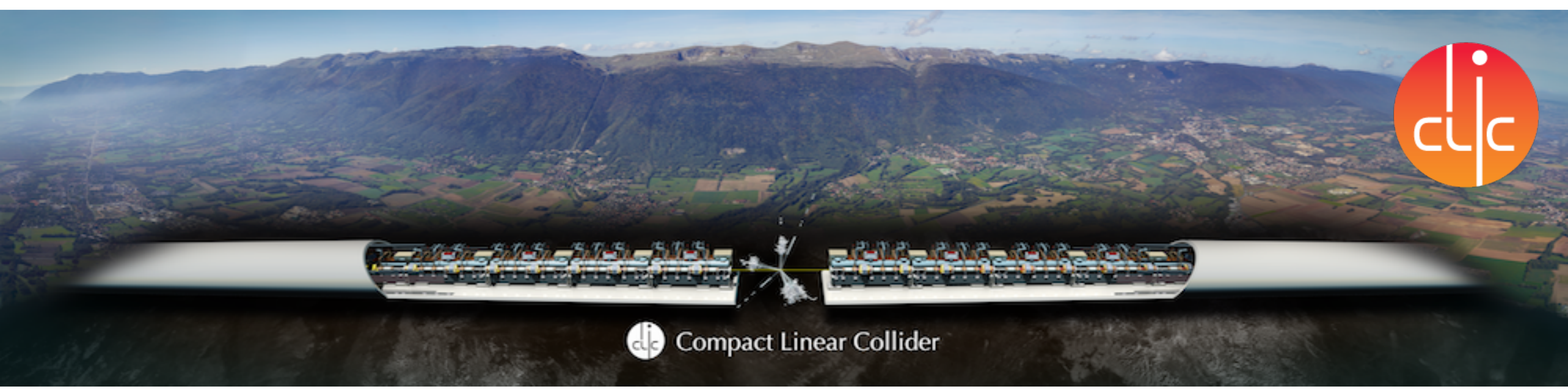
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

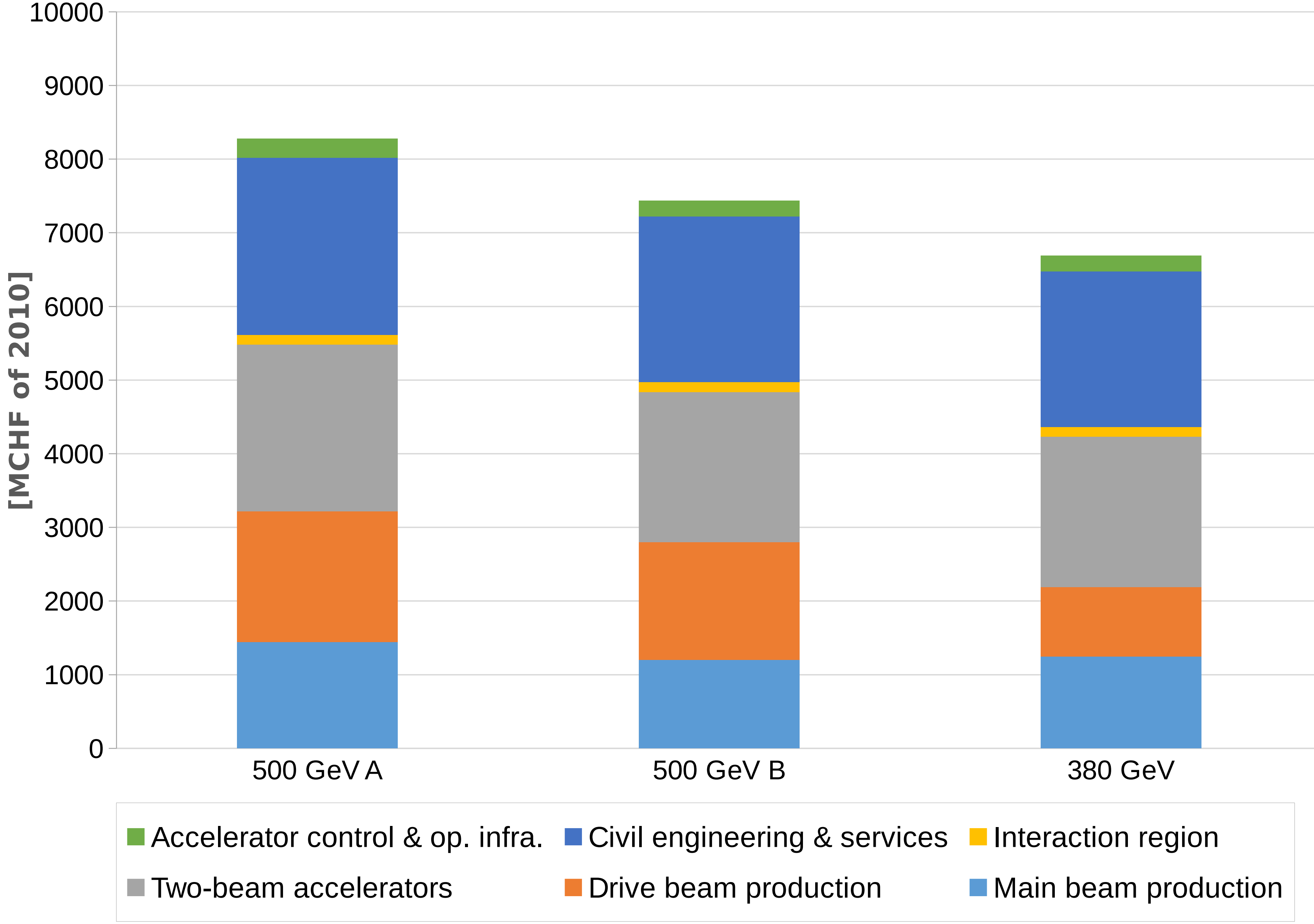
Ready for construction; start of excavations

2035 First Beams

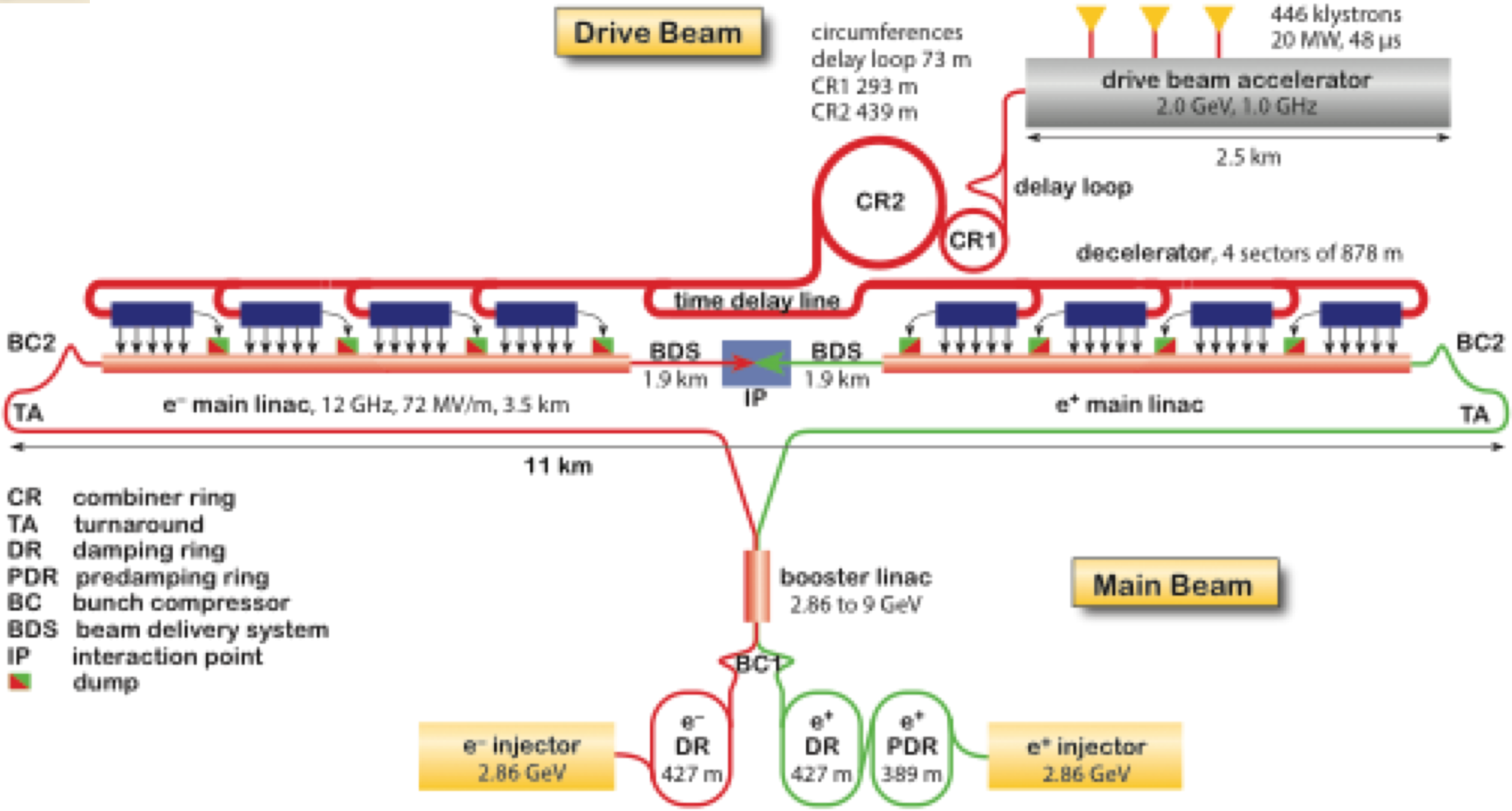
Getting ready for data taking by the time the LHC programme reaches completion



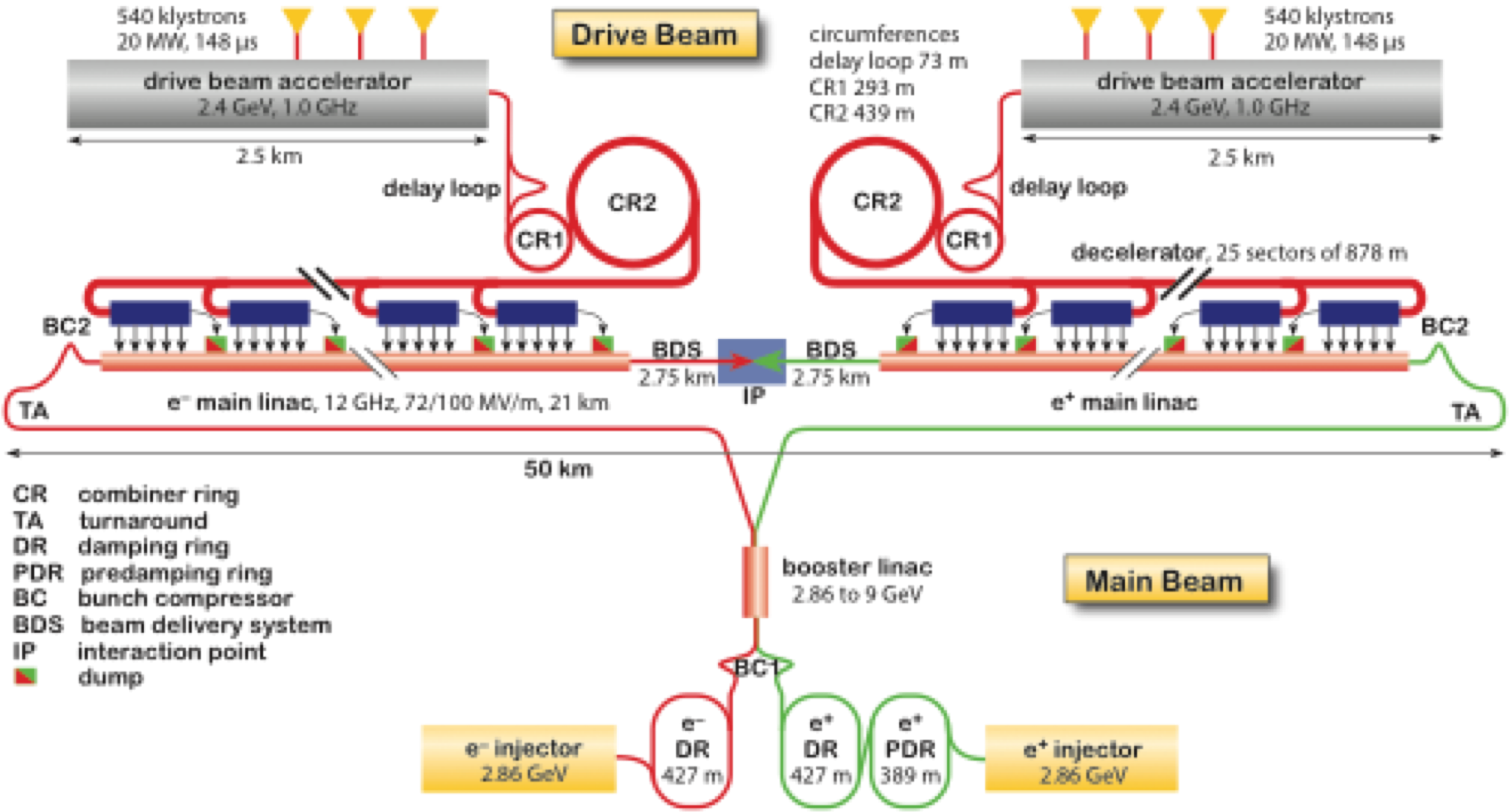
Costings

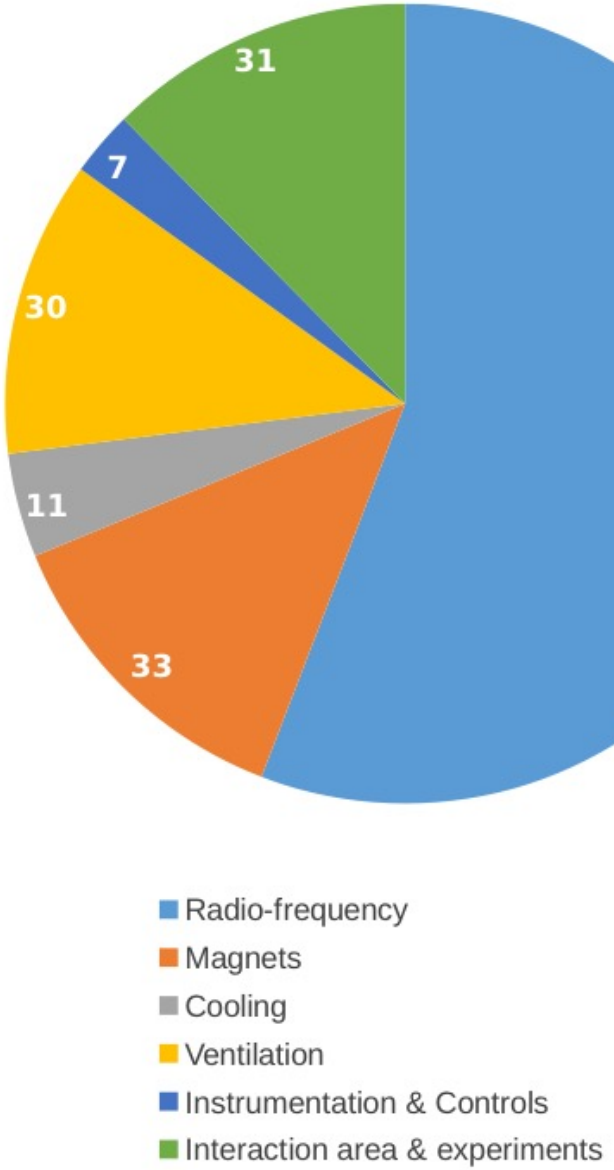

10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
[MCHF of 2010]
500 GeV A
500 GeV B
380 GeV
Accelerator control & op. infra.
Civil engineering & services
Interaction region
Two-beam accelerators
Drive beam production
Main beam production

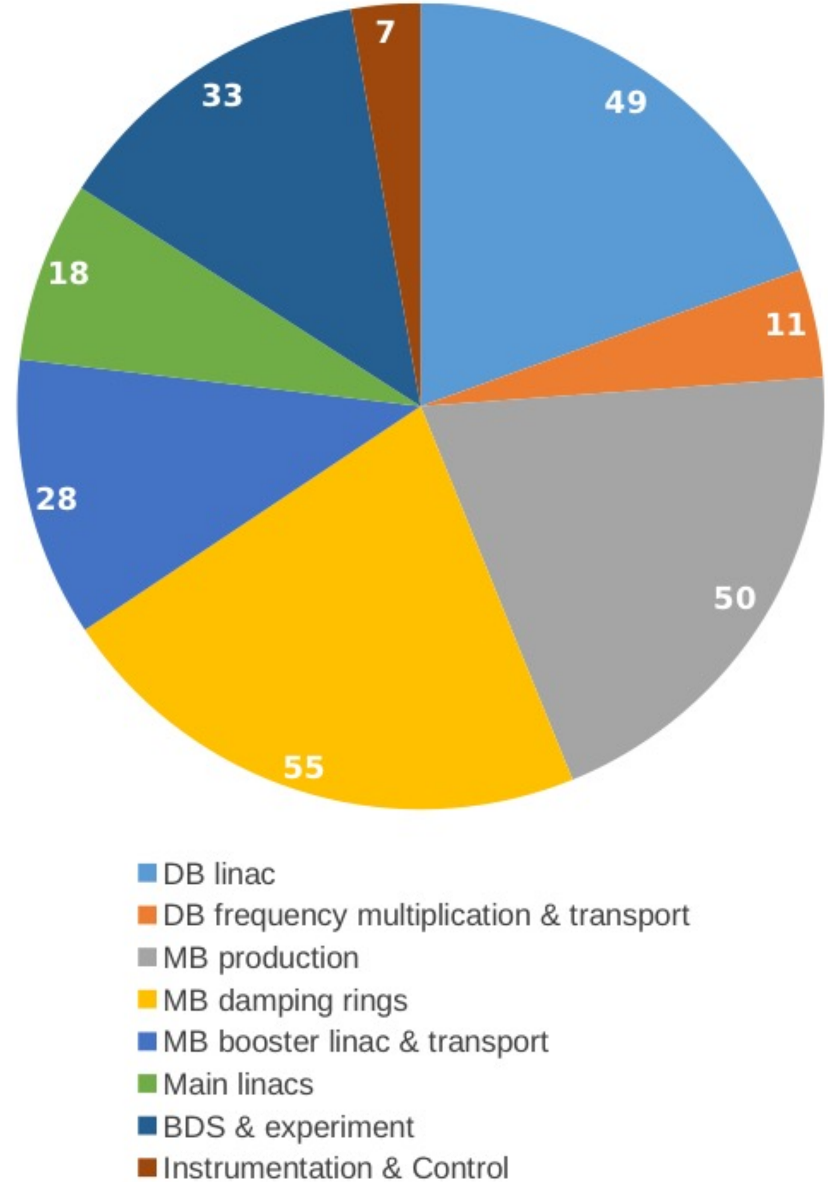
Initial energy



Higher energy

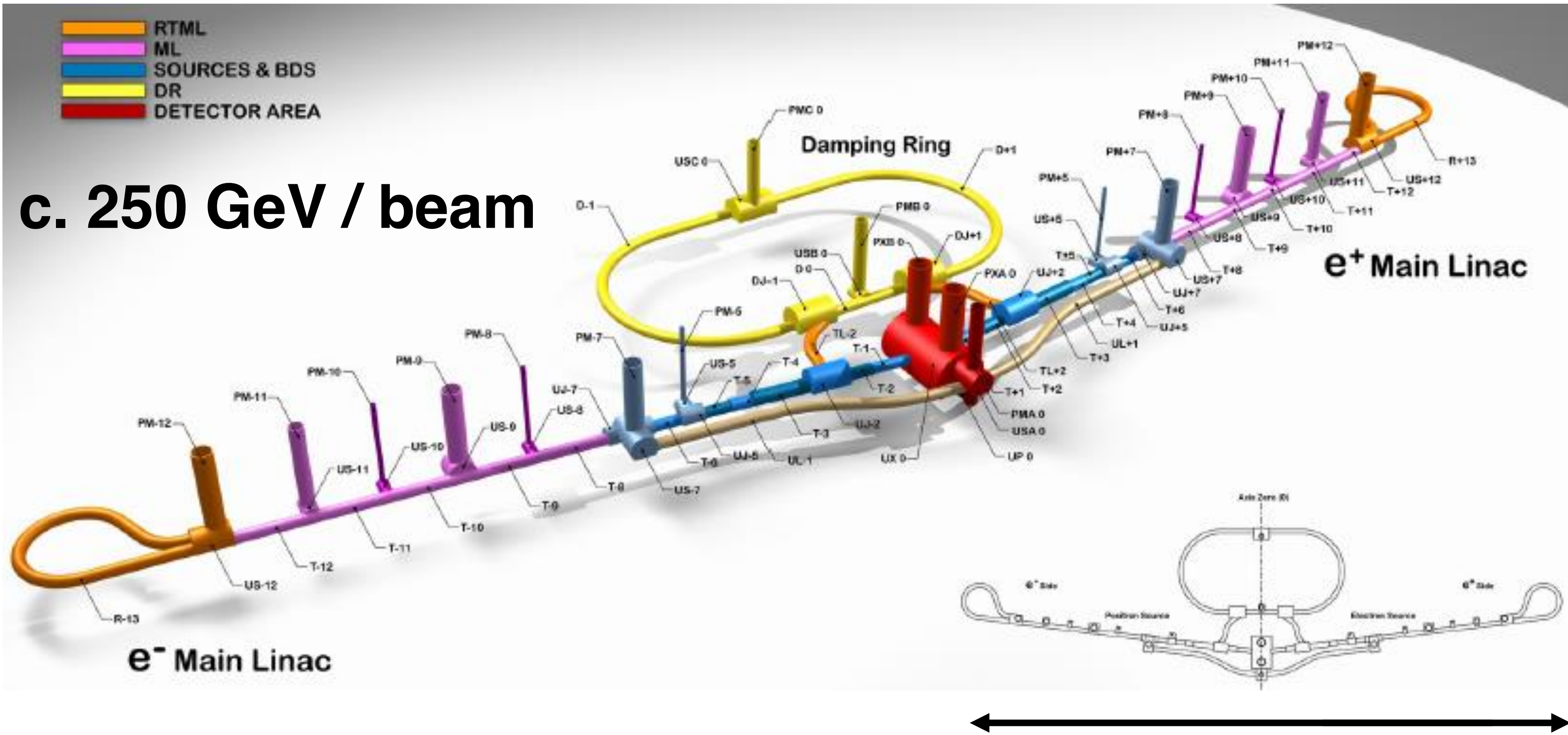



141
33
11
30
7
31
Radio-frequency
Magnets
Cooling
Ventilation
Instrumentation & Controls
Interaction area & experiments


49
11
50
55
28
18
33
7
DB linac
DB frequency multiplication & transport
MB production
MB damping rings
MB booster linac & transport
Main linacs
BDS & experiment
Instrumentation & Control

International Linear Collider (ILC)

c. 250 GeV / beam



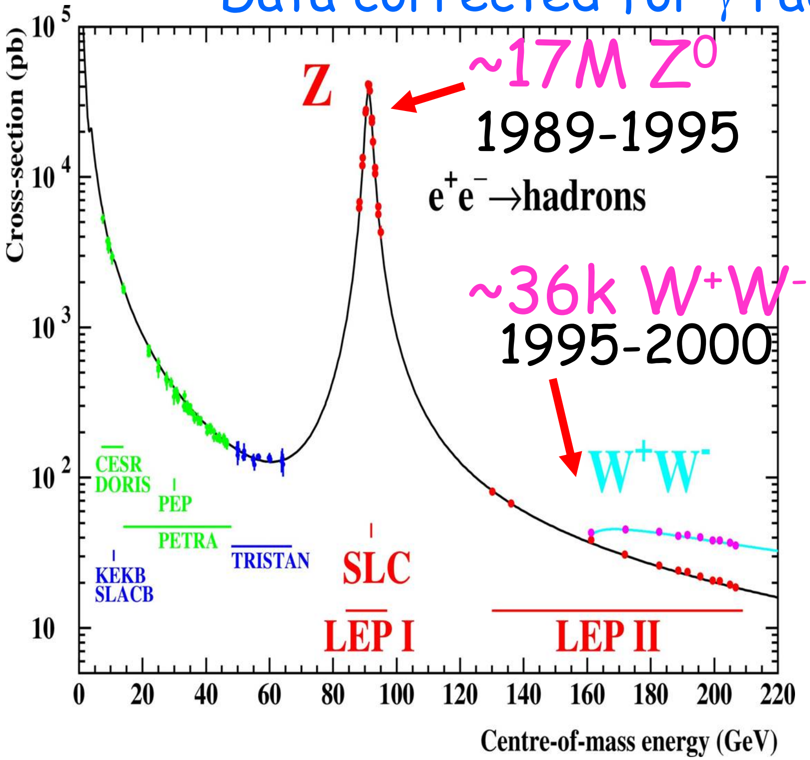
[Phil Burrows, Birmingham 2018]

Example e^+e^- (LEP)

Physics cross-sections

Data corrected for γ radiation

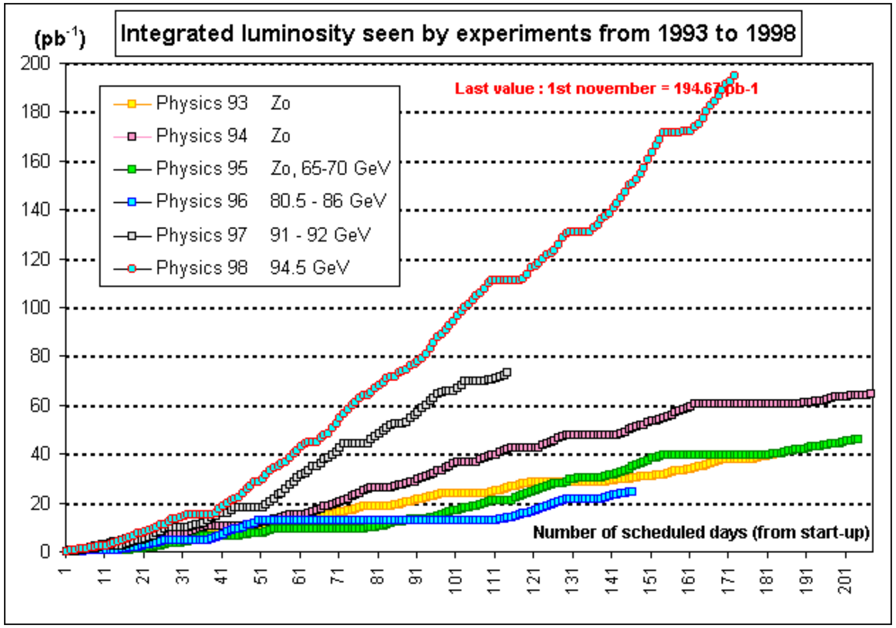
Cross-section (pb)



Centre-of-mass energy (GeV)

Integrated collider lumi.

Integrated lumi. (1/pb)



Days since start up