# Detector Requirements for Higgs Factories

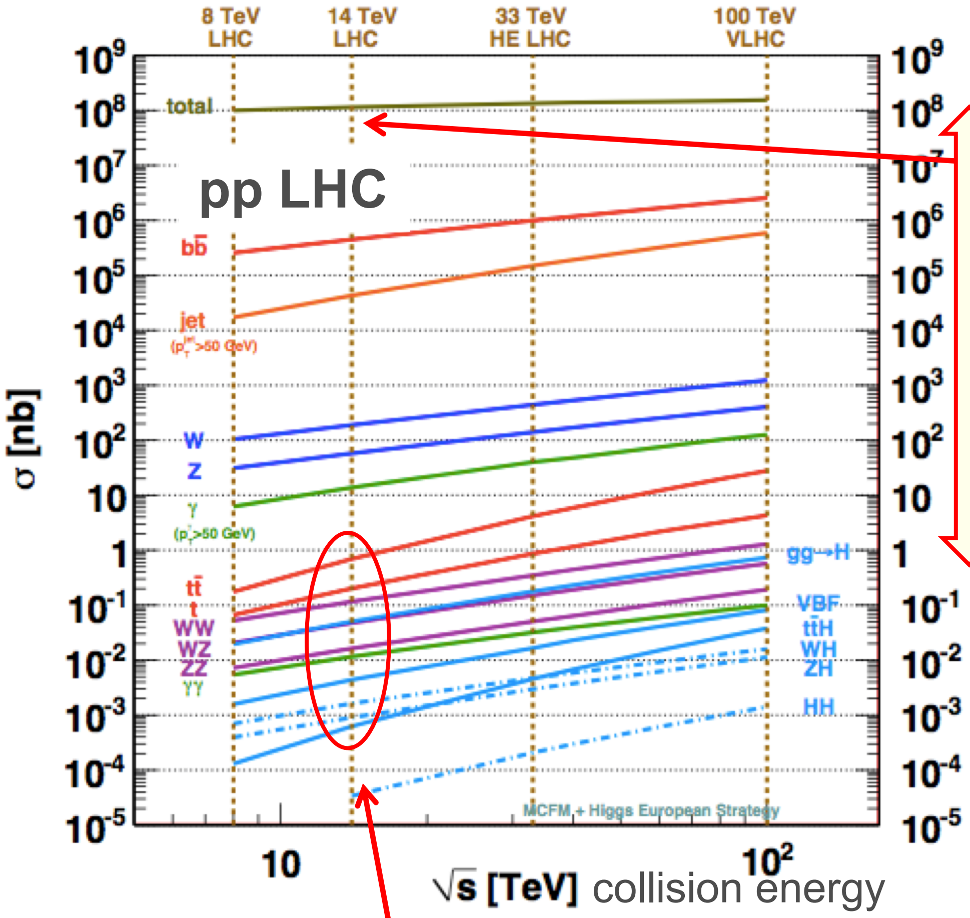
Mogens Dam, Niels Bohr Institute, Copenhagen

AIDA++ Open Meeting, CERN

September 4th 2019

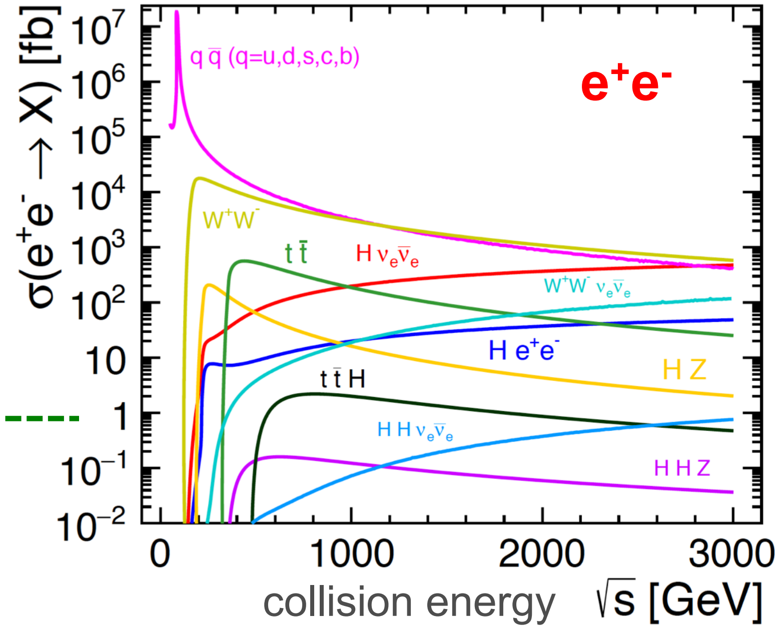
*With many thanks to the people from whom I have bottowed material. A special thanks to Lucie Linssen, for sharing her very nice slides from ESPPU, Granada*

# Prelude: pp collisions vs. $e^+e^-$ collisions




LHC total cross section
factor > 100 million !!

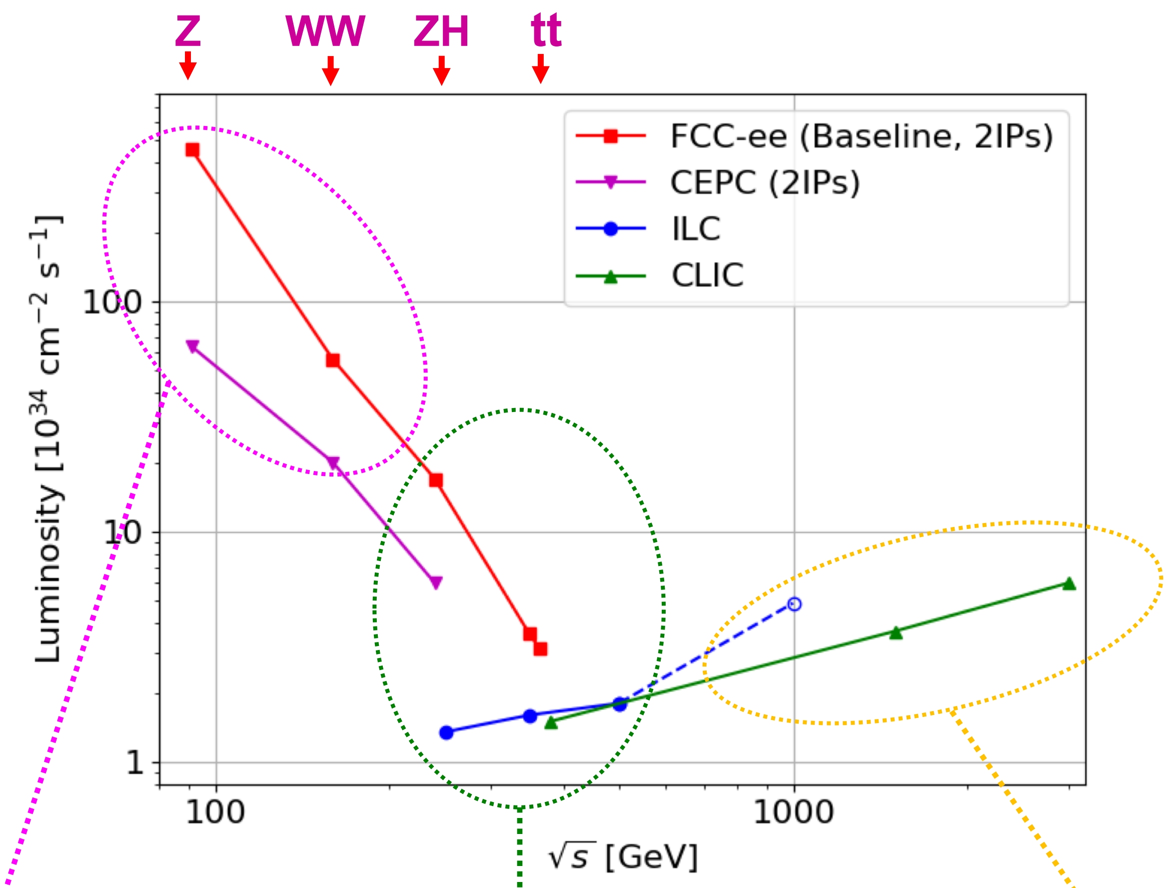
In $e^+e^-$ collisions the total cross section
~ equals the electroweak cross section.




$e^+e^-$ events are "clean"

At LHC, much of the interesting physics needs to be found among a huge number of collisions

# High-energy $e^+e^-$ accelerator landscape



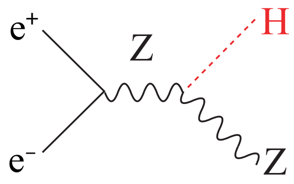

Circular colliders:
Extremely high luminosities at lower energies:
Z and WW factories

Overlap region, 240-380 GeV:
"Higgs Factories"

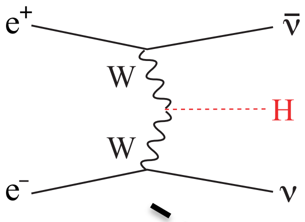
Linear colliders:
High centre-of-mass energies

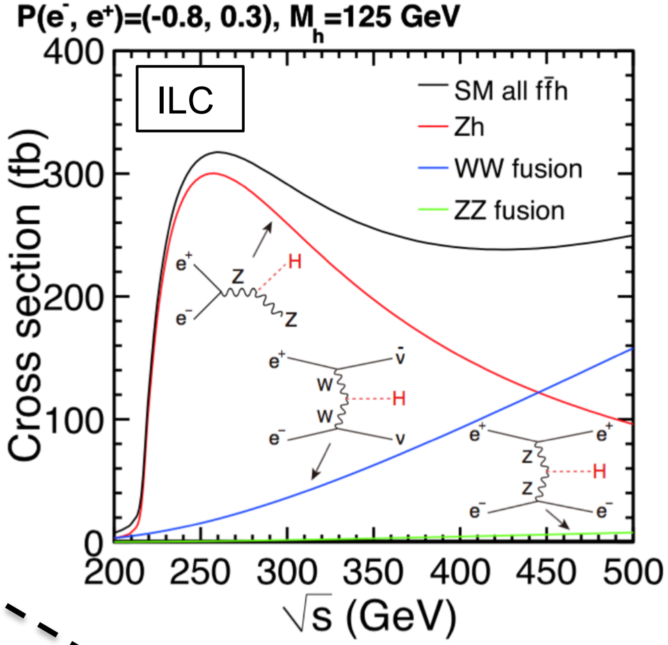
# Reminder: Higgs Production and Decay

Higgs-strahlung

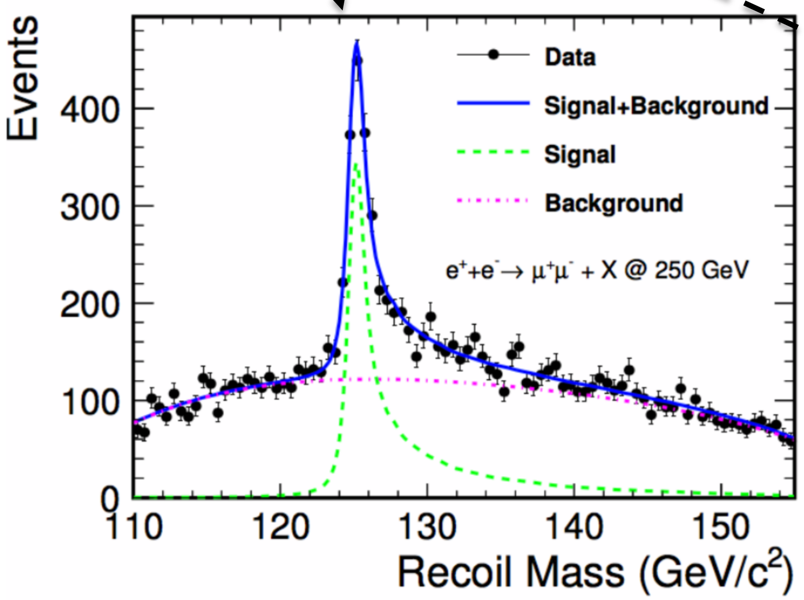


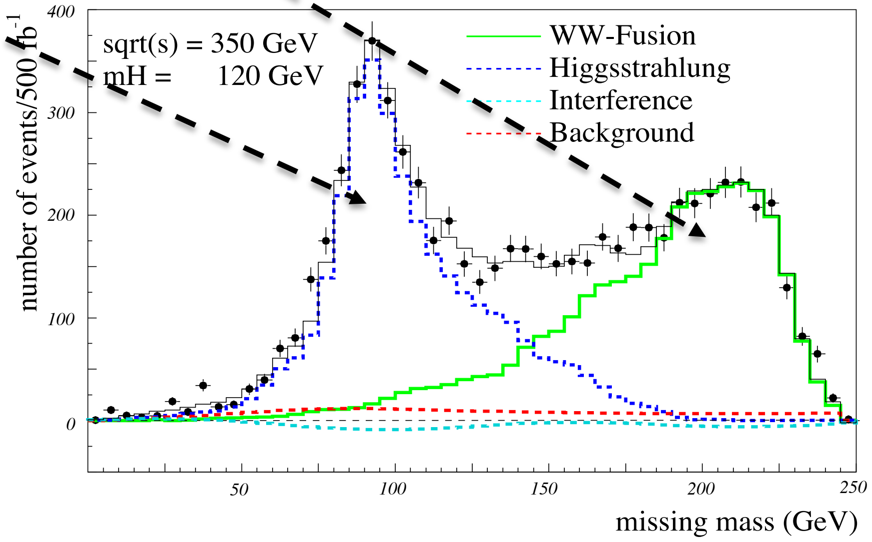

Boson fusion



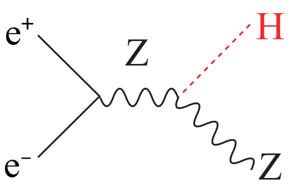

| $M_H$ = 126 GeV | SM Br |
|---|---|
| bb | 56.1% |
| WW* | 23.1% |
| gg | 8.48% |
| ττ | 6.16% |
| ZZ* | 2.89% |
| cc | 2.83% |
| γγ | 0.228% |
| Zγ | 0.162% |
| μμ | 0.0214% |



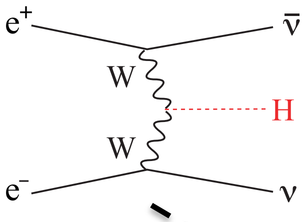



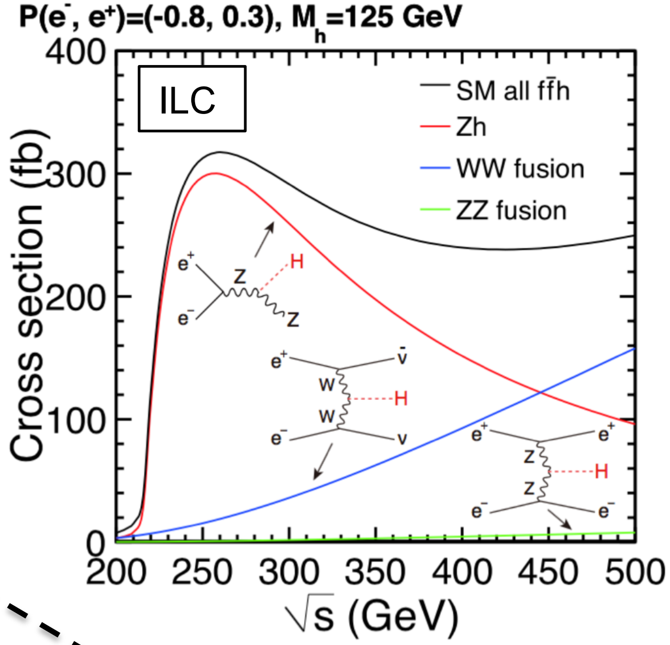
# Reminder: Higgs Production and Decay

**Higgs-strahlung**




**Boson fusion**

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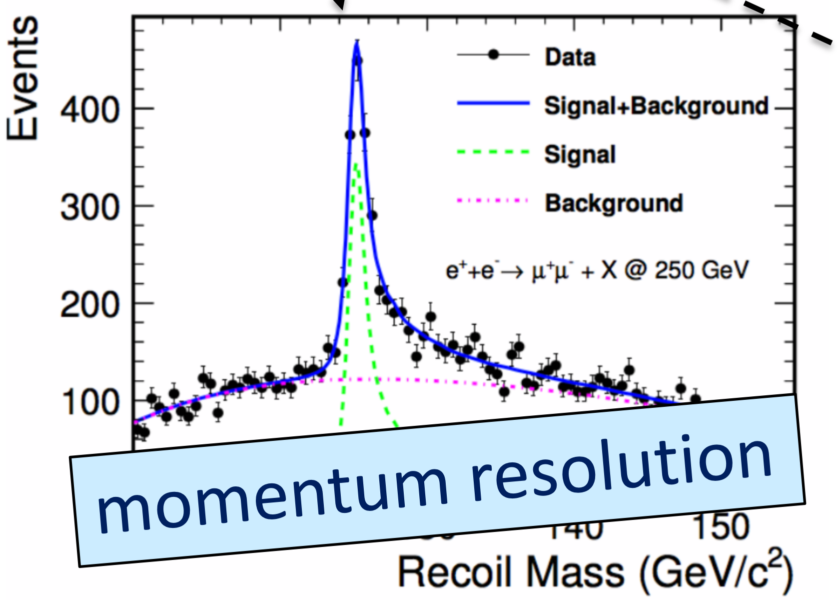
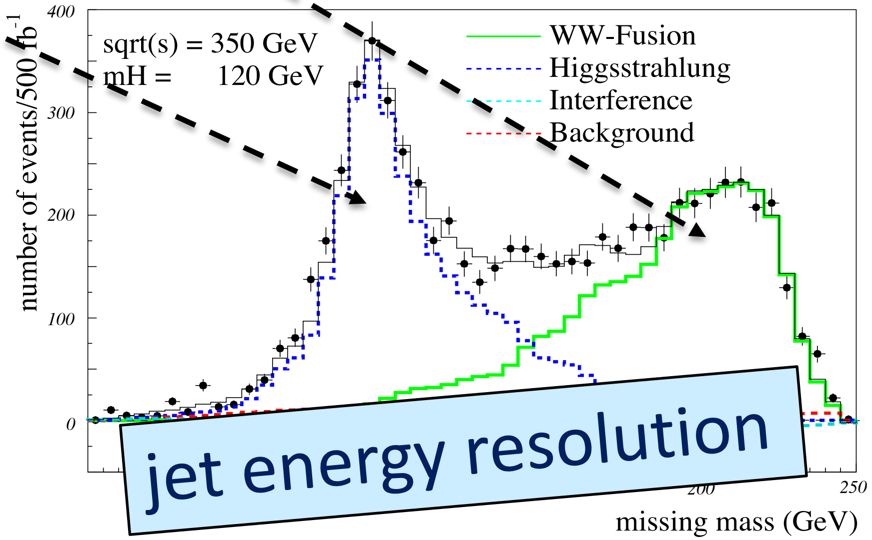
flavour tagging




momentum resolution




jet energy resolution

# $e^+e^-$ collider beam parameters

## Linear

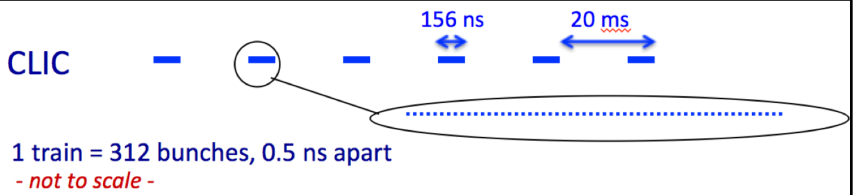
| Parameter | ILC 250 GeV | ILC 500 GeV | CLIC 380 GeV | CLIC 1.5 TeV | CLIC 3 TeV |
|---|---|---|---|---|---|
| **Luminosity L ($10^{34}cm^{-2}sec^{-1}$)** | **1.35** | **1.8** | **1.5** | **3.7** | **5.9** |
| L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$) | 1.0 | 1.0 | 0.9 | 1.4 | 2.0 |
| Repetition frequency (Hz) | 5 | 5 | 50 | 50 | 50 |
| Bunch separation (ns) | 554 | 554 | 0.5 | 0.5 | 0.5 |
| Number of bunches per train | 1312 | 1312 | 352 | 312 | 312 |
| Beam size at IP $\sigma_x/\sigma_y$ (nm) | 515/7.7 | 474/5.9 | 150/2.9 | ~60/1.5 | ~40/1 |
| Beam size at IP $\sigma_z$ (μm) | 300 | 300 | 70 | 44 | 44 |

ILC: Crossing angle 14 mrad, $e^-$ polarization ±80%, $e^+$ polarization ±30%
CLIC: Crossing angle 20 mrad, $e^-$ polarization ±80%

Very small beams + high energy => beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
**Triggerless readout**
**Power pulsing**




## Circular

| | FCC-ee Z | FCC-ee Higgs | FCC-ee ttbar | CEPC Z (2T) | CEPC Higgs |
|---|---|---|---|---|---|
| √S [GeV] | **91.2** | **240** | **365** | **91.2** | **240** |
| Luminosity / IP ($10^{34}cm^{-2}s^{-1}$) | **230** | **8.5** | **1.7** | **32** | **1.5** |
| no. of bunches / beam | 16640 | 393 | 48 | 12000 | 242 |
| Bunch separation (ns) | **20** | 994 | 3000 | **25** | 680 |
| Beam size at IP $\sigma_x/\sigma_y$ (μm/nm) | 6.4/28 | 14/36 | 38/68 | 6.0/40 | 20.9/60 |
| Bunch length (SR/BS) (mm)<br>Beam size at IP $\sigma_z$ (mm) | 3.5/12.1 | 3.3/5.3 | 2.0/2.5 | 8.5 | 4.4 |

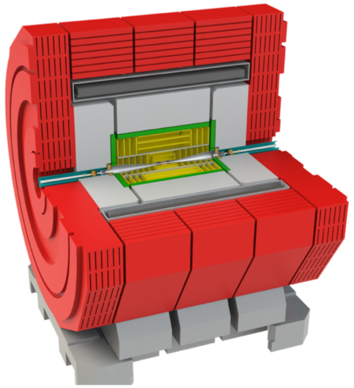
Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV)

**At Z-peak, very high luminosities** and **very high $e^+e^-$ cross section (40 nb)**
⇒ **Statistical accuracies at $10^{-4}$ -$10^{-5}$ level** ⇒ **drives detector performance requirements**
⇒ **Small systematic errors required** to match
⇒ This also drives requirement on **data rates** (physics rates 100 kHz)
⇒ Triggerless readout likely still possible

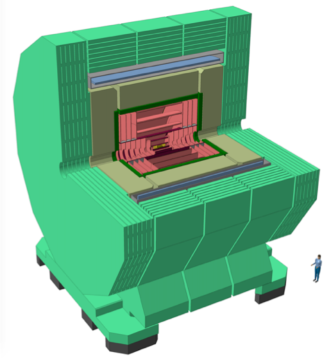
**Beam-induced background,** from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Mitigated through MDI design and detector design

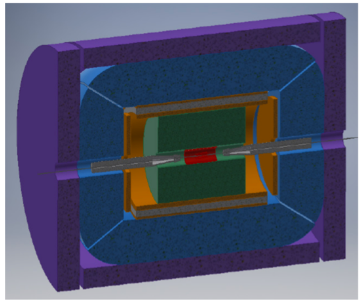
Modified from Lucie Linssen, ESPPU, 2019

# High-energy $e^+e^-$ Collider Detectors

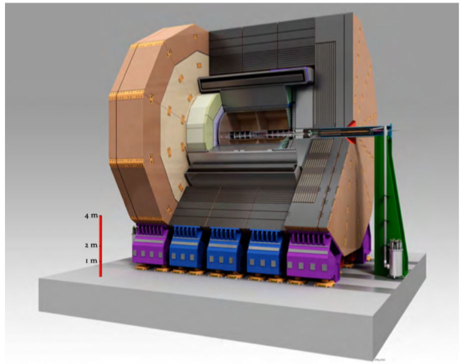


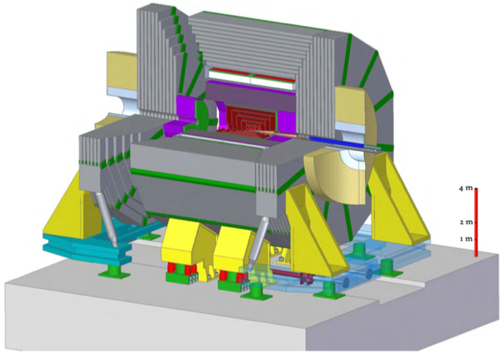
CLIC => CLICdet,
$\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV





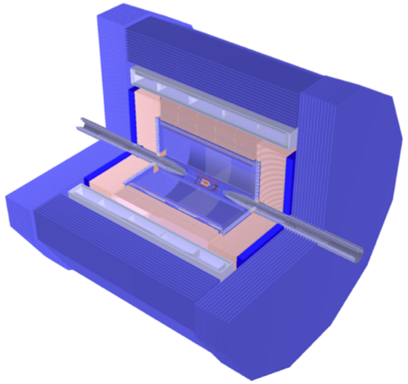
FCC-ee => CLD and IDEA
$\sqrt{s}$: 90 - 365 GeV

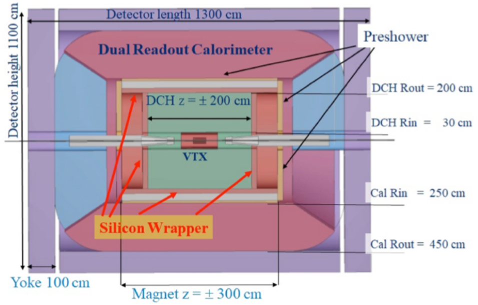




ILC => ILD and SiD:
$\sqrt{s}$: 250 – 500 GeV (1 TeV)

Strong solenoidal fields: 3.5 – 4 Tesla






CEPC => baseline and low-B
$\sqrt{s}$: 90-240 GeV

Lower solenoidal fields: ~2 Tesla
beam has to survive crossing of field at ~15 mrad angle

# Detector performance requirements

*"Canonical requirements"*: Rather similar between ILC, CLIC, FCC-ee, CEPC

★ **momentum resolution:**

e.g, HZ recoil, $g_{H\mu\mu}$

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

★ **jet energy resolution:**

e.g. W/Z/H di-jet mass, separation;
HZ with Z → qq, background reduction

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

★ **impact parameter resolution:**

e.g. c/b-tagging, Higgs branching ratios

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

★ **angular coverage, hermeticity, forward electron tagging**

- Reflect what is needed to fulfil the physics objectives
- But probably also reflects, to some extend, what is technologically feasible
    - example: nobody would probably claim that a better impact parameter resolution was a waste

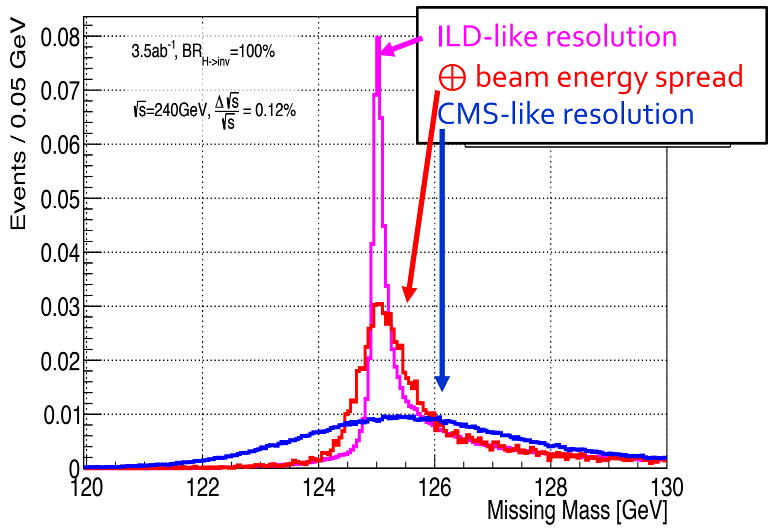
# Momentum resolution (i)

Generally, the requirement is expressed as

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

⇒ Mass reconstruction from lepton pairs in Higgs production

Reconstructed mass of lepton pair in HZ with Z $\rightarrow \ell^+\ell^-$



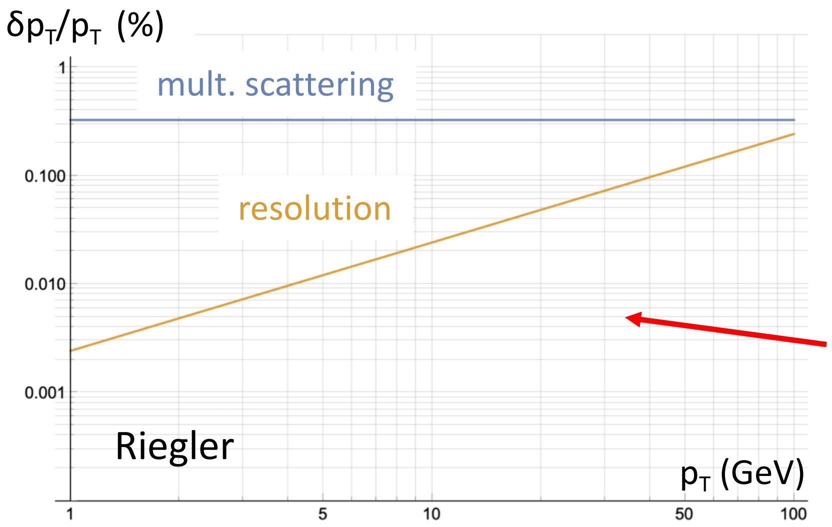

Eur.Phys.J. C77 (2017) no.2, 116

For the case of FCC-ee, this matches well the beam energy spread of $\delta E/E \simeq$ 1-2 × $10^{-3}$

In reality, there is of course a resolution term (*a*) and a multiple scattering term (*b*)

$$\boxed{\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = a \oplus \frac{b}{p\sin\theta}}$$

For "standard" ultra-light detectors (e.g. full Si), multiple scattering dominates up to $p_T$ of 100-200 GeV




Here illustrated for the CLD detector at 90º : Total material budget = 11% of $X_0$

From analytic expressions for track parameter resolutions.

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

$$\left.\frac{\Delta p_T}{p_T}\right|_{m.s.} \approx \frac{0.0136\ \mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

$$\left.\frac{\Delta p_T}{p_T}\right|_{res.} \approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

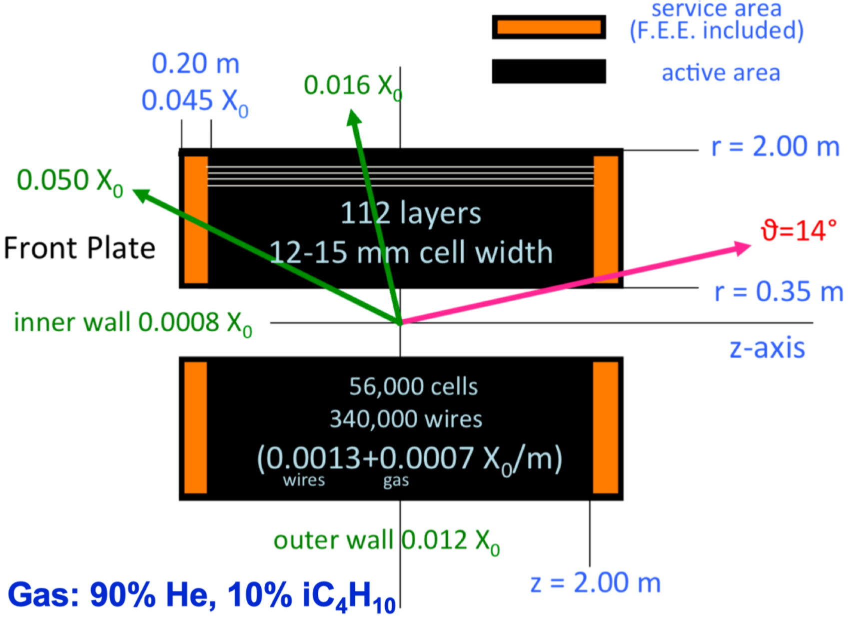
# Momentum Resolution (ii)

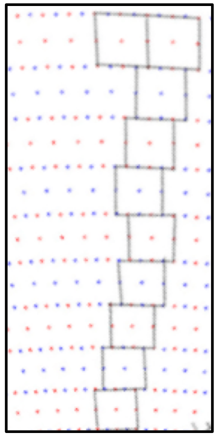
For energies ≲ Higgs factories, very few momentum measurements are not mult. scat. limited:

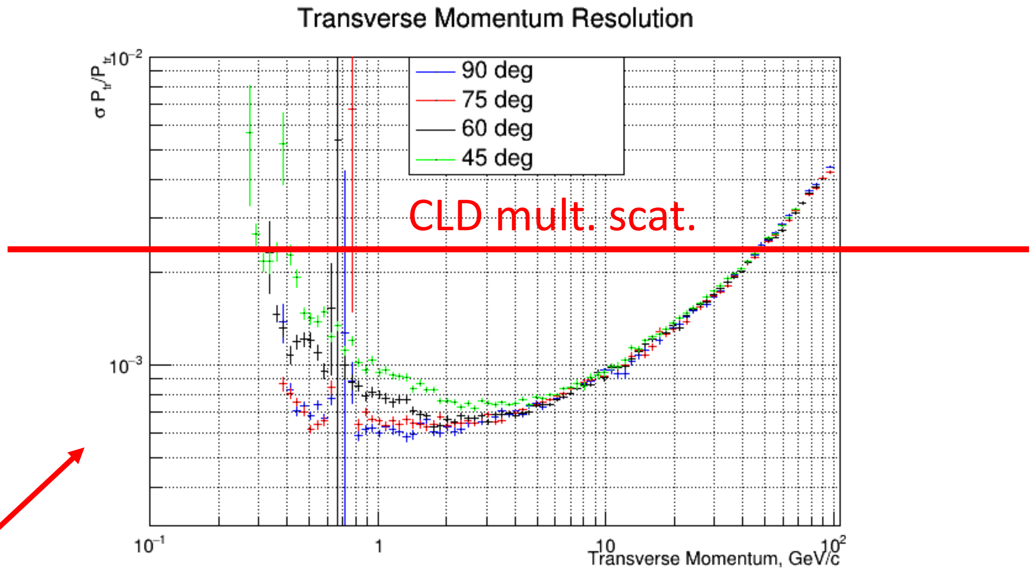
- Possible to reduce mult. scat. contribution?

## IDEA Drift Chamber

- GAS: 90% He – 10% $iC_4H_{10}$
- Radius 0.35 – 2.00 m
- Total thickness: 1.6 $X_0$ at 90°
  - Tungsten wires is dominant contribution to material
- Full tracker system includes Si VTX and Si wrapper






Further thinning of Si sensors is not very promising due to the √-behaviour

$$\left.\frac{\Delta p_T}{p_T}\right|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Other important benefit from reduced material:

- Minimize secondary interactions in material

# Calorimetry - Energy resolution

## Jet energy

$\boxed{\delta E/E \simeq 30\% / \sqrt{E}\ [\text{GeV}]}$

**⇒ Mass reconstruction from jet pairs**

Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- HZ → 4 jets, $t\bar{t}$ events, etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons

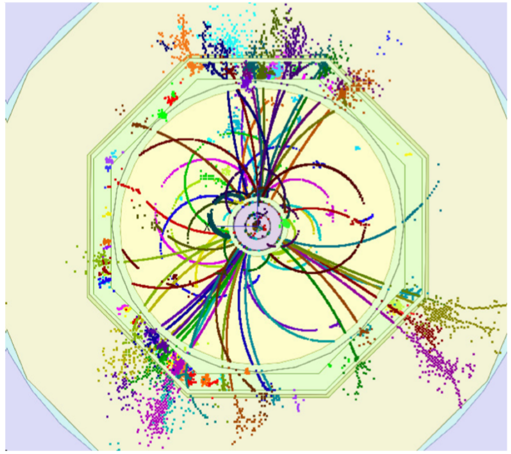
## e/γ energy

$\boxed{\delta E/E \lesssim 15\% / \sqrt{E}\ [\text{GeV}]}$ $\boxed{\text{or better!}}$

**⇒ Invariant masses**

- $H \rightarrow \gamma\gamma$
- $\pi^0$ identification and measurement for $\tau$ polarisation, etc.
- But also for searches of the kind $\tau \rightarrow \mu\gamma$

To reach jet energy resolutions of ~3%, detectors employ **highly granular calorimeters** and **Particle Flow Analysis techniques.**



Finely segmented calorimetry (transverse and longitudinal) is also important for the precise identification of photons and $\pi^0$s in dense topologies. Example: τ physics

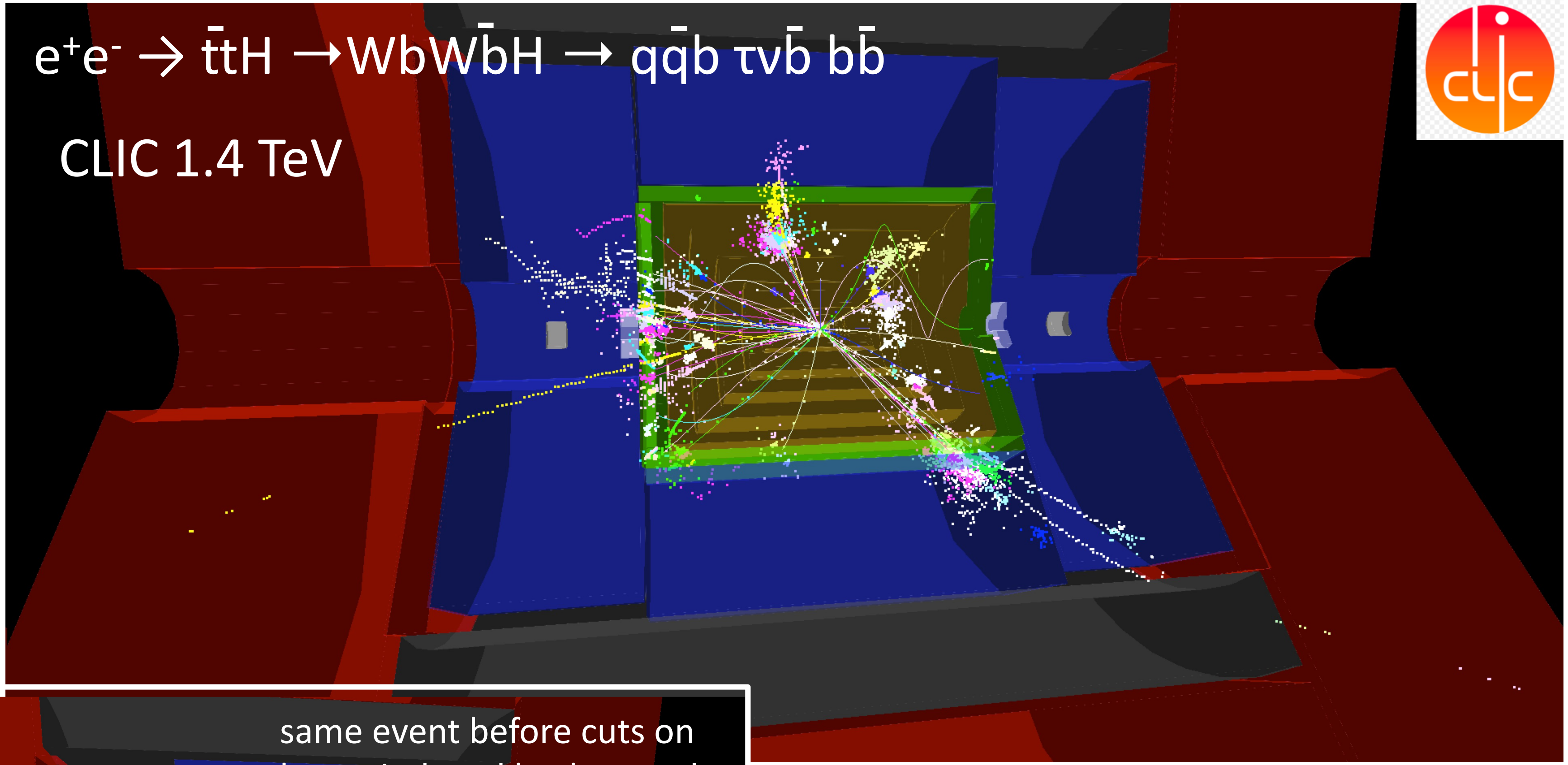
Technologies:

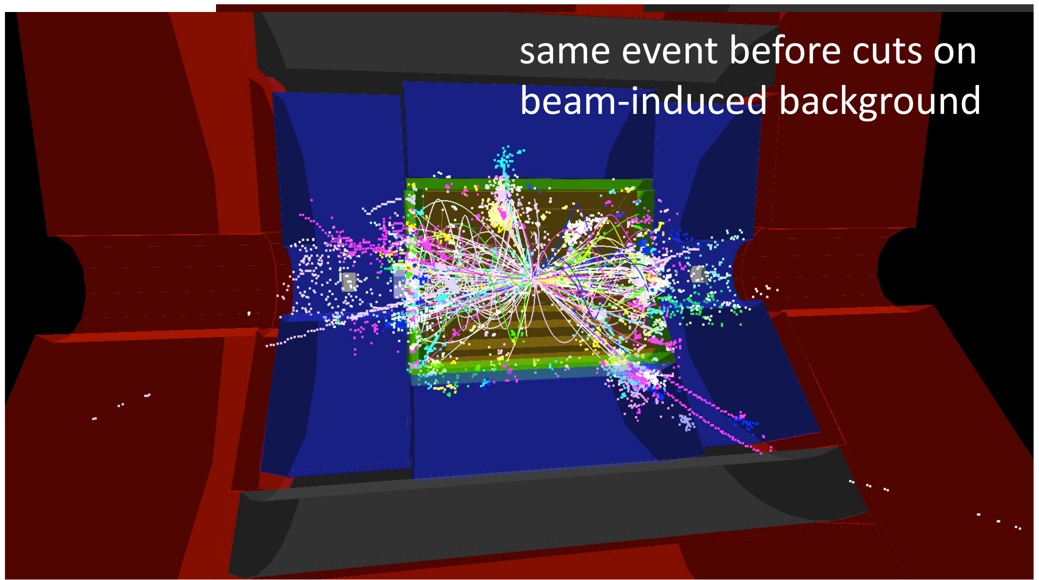
a) **CALICE** like (SiD, ILD, CLICdet, CLD, CEPC baseline)
   - ECAL: W/Si or W/scint+SiPM
   - HCAL: steel/scint+SiPM or steel/glass RPC

b) Parallel fiber **dual readout** calorimeter (IDEA)
   - Fine transverse, but no (weak) longitudinal segmentation
   - Proposals to also consider DR tile calorimetry

c) New development: **Liquid Argon** ECAL + Tile HCAL (ATLAS like)
   - Very fine segmentation, $\delta E_{EM}/E_{EM} \lesssim$ 8-9%

# Importance of precise calorimeter timing




Highly granular calorimetry + hit timing O(1ns)

$\Downarrow$

Very effective in suppressing backgrounds
for fully reconstructed particles

With less precision, timing also important for Z factories
where physics events may be separated by only 20 ns

# Impact parameter

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\mathrm{m}; \quad b \simeq 15\,\mu\mathrm{m\,GeV}$$

**⇒ Heavy flavour tagging, b/c**

- Precise Z and H branching fraction measurements
- $\mathcal{O}$(1%) measurement of BF for H → bb, cc, gg

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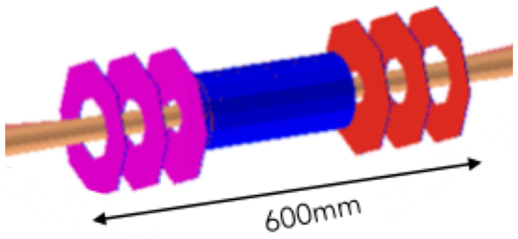
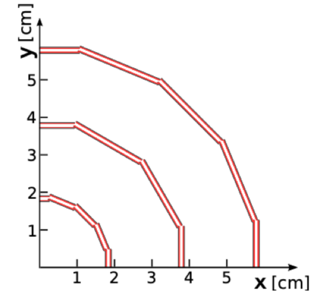
**⇒ Lifetime measurements, b- and c-hadrons, $\tau$-lepton**

Very compact and light vertex detectors



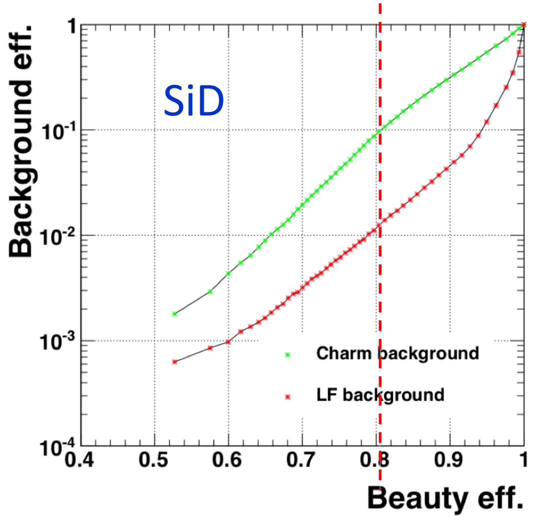




CLD

| | SiD | ILD | CLIC | CEPC | FCC-ee |
|---|---|---|---|---|---|
| *r* beam pipe | 12 mm | 12 mm | 29 mm | 14 mm | 15 mm |
| 1st VTX layer | 14 mm | 16 mm | 31 mm | 16 mm | 17 mm |

Demonstrated performance:
- At 80% b-efficiency, very low light-quark background, 10% background from c-quarks

Strong development:
- Lighter, more precise, closer
- CEPC, FCC-ee investigating 10 mm beam pipe



# Very high statistics Z factories - TeraZ

Running conditions:
- Extremely large statistics / statistical precision
  - …need small systematics ($10^{-5}$) to match
- Physics event rates up to 100 kHz
- Bunch spacing down to 20 ns
  - Continous beams, no power pulsing
- No pileup, no underlying event, …
  - …however, still pile-up at the $10^{-3}$ level

| FCC-ee parameters | | Z | $W^+W^-$ | ZH | ttbar |
|---|---|---|---|---|---|
| $\sqrt{s}$ | GeV | 91.2 | 160 | 240 | 350-365 |
| Luminosity / IP | $10^{34}$ cm$^{-2}$ s$^{-1}$ | **230** | 28 | 8.5 | 1.7 |
| Bunch spacing | ns | 19.6 | 163 | 994 | 3000 |
| "Physics" cross section | pb | 40,000 | 10 | 0.2 | 0.5 |
| Total cross section (Z) | pb | 40,000 | 30 | 10 | 8 |
| Event rate | Hz | **92,000** | 8,400 | 1 | 0.1 |
| "Pile up" parameter [$\mu$] | **$10^{-6}$** | 1,800 | 1 | 1 | 1 |

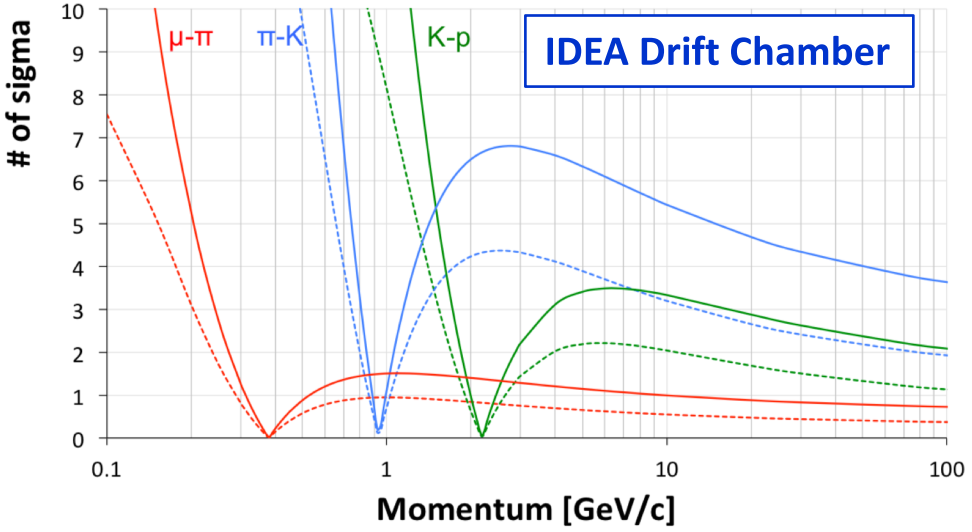
Detector optimization to be done for extremely rich physics capabilities especially at the Z pole with up to $5 \times 10^{-5}$ Z decays: $10^{12}$ bb, cc, $2 \times 10^{11}$ $\tau\tau$, etc…
- Search for rare processes: Excellent acceptance definition, hermeticity, sensitivity to displaced vertices
- Luminosity measurement at $10^{-4}$ (abs), $10^{-5}$ (rel)
- Acceptance definition at $\leq 10^{-5}$
- Excellent b/c/gluon separation
- **PID**: TOF, dE/dx, Cherenkov?

The Z physics programme is still under development, in particular for rare processes and for heavy flavours:
- Detailed detector requirements still to be finalised, especially for PID.

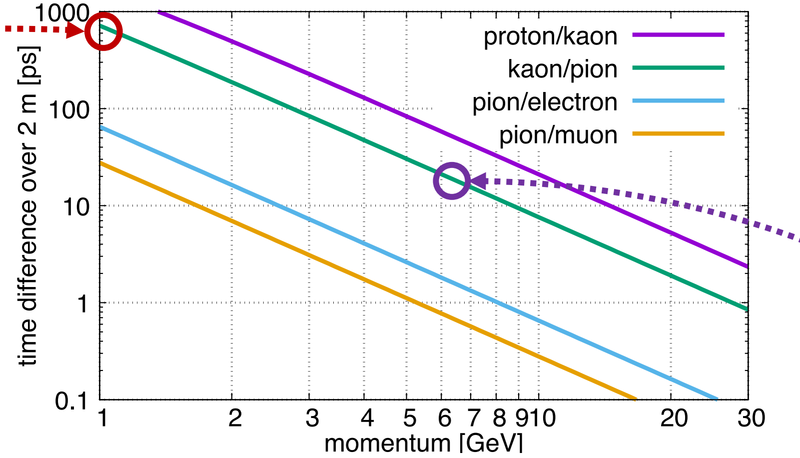
# PID possibilities

- The IDEA Drift Chamber provides very powerful PID. Improved considerably by the use of *cluster counting*
  - Standard truncated mean dE/dx : **σ ≃ 4.2%**
  - Cluster counting : **σ ≃ 2.5%**

dE/dx




- >3σ π/K separation all the way up to 100 GeV
  - Except for cross-over window at ~1 GeV.



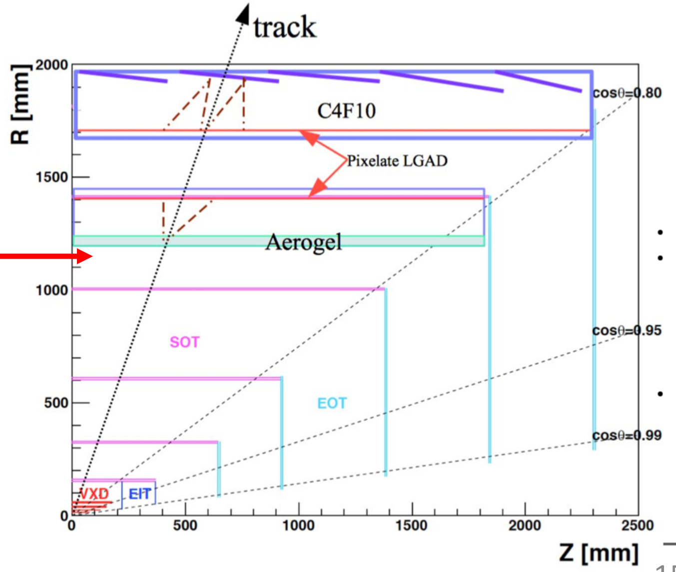

TOF

- Narrow cross-over window at ~1 GeV, can be alleviated by an unchallenging TOF measurement at r=2m of δT ≲ 0.5 ns
- TOF *alone* could give π/K separation up to a ~5 GeV if measurement precision would be δT ~ 20 ps (LGAD, TORCH)

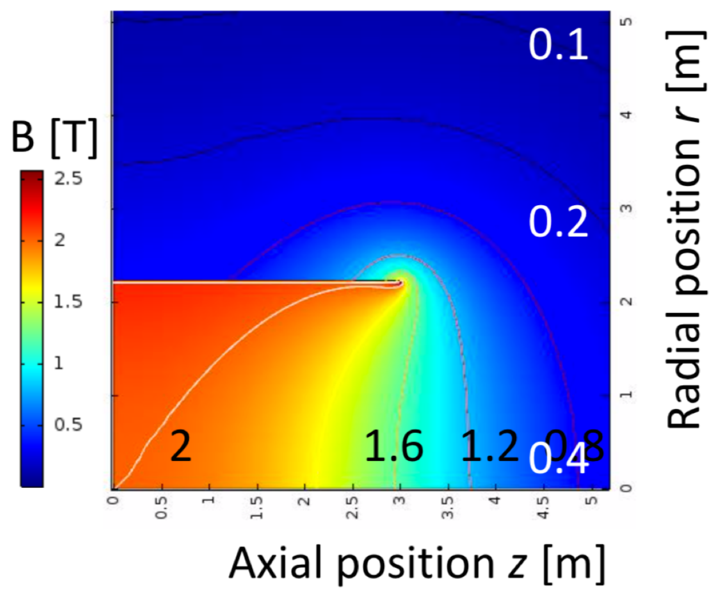
Cherenkov

Study of RICH counter for CEPC Full Silicon Detector

Also TORCH (LHCb) and TOP (BelleII): Essentially precise TOF devices: ~20 ps.



# 2 T "light and thin" Solenoid inside Calorimeter



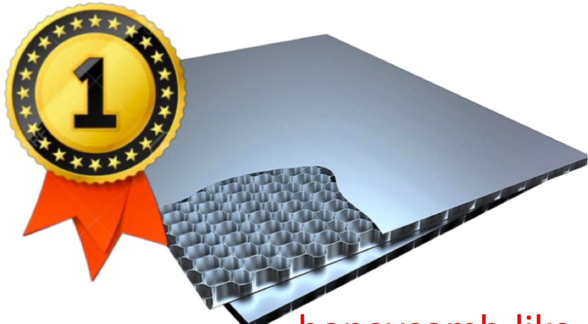

| Property | Value |
|---|---|
| **Magnetic field in center [T]** | **2** |
| Free bore diameter [m] | 4 |
| **Stored energy [MJ]** | **170** |
| Cold mass [t] | 8 |
| Cold mass inner radius [m] | 2.2 |
| Cold mass thickness [m] | 0.03 |
| Cold mass length [m] | 6 |

H. Ten Kate et al.

- **Objectives**
  - **Light**: certainly less than 1 $X_0$
  - **Thin**: As thin as possible for optimal tracker-to-calorimeter matching
- Self-supporting single layer coil
  - High yield strength conductor fully bonded
  - Thin Al support cylinder
- Coil composition
  - Aluminum (77 vol.%)
  - NbTi (5 vol.%) / copper (5 vol.%)
  - Glass-resin-dielectric films (13 vol.%)
- Radiation thickness (preliminary studies)
  - Cold mass: $X_0 \approx 0.46$
  - Cryostat (25 mm Al): $X_0 \approx 0.28$
  - Total $X_0 \approx 0.75$ achievable
  - Total radial envelope less than 30 cm
- Prospects for even lighter and thinner outer shell


reinforced


corrugated




honeycomb-like

# Summary

- Detectors for Higgs Factories at ILC, CLIC, FCC-ee, CEPC share to a large extend the same performance goals
  - Light, precise trackers for excellent momentum resolution (Full Si, Si + TPC, Si + drift chamber)
  - Fine grained calorimetry with good jet and EM energy resolution (CALICE like, dual readout, Lar + Tile)
  - Ultra light and precise vertex detectors extremely close to beam line for superiour flavour tagging (Hybrid → MAPS)
  - Hermiticity and Stability
- Different beam parameters impose additional requirements
  - Extremely low beam crossing time at CLIC: Precise time stamping of all detector elements
    - Timing also important for 20 ns beam-crossing time at circular Z factories
  - Cooling:
    - At linear colliders, bunch trains: Power pulsing minimises heat dissipation
    - At circular colliders, continous beams: Challenge to cool detectors without additional material
  - Machine backgrounds:
    - At linear colliders: high beamstrahlung backgrounds
    - At circular colliders: lower beamstrahlung backgrounds, but also synchrotron radiation
  - Transport of crossing beam (~15 mrad) through detector solenoidal field
    - Effectively reduces the maximum field strength from 4 to 2 T (ultrathin solenoid inside calorimetry possibly interesting)
- TeraZ programmes at circular colliders impose additional detector requirements
  - Extremely high precision to match $\mathcal{O}(10^{-5})$ statistical uncertainties
  - Very high, $\mathcal{O}$(100 kHz), physics event rates (triggerless readout? readout frequency?,…)
  - Very high statistics heavy flavour programme: Need for (some kind of) PID (precise requirements to be defined)

# Extras

# Linear: ILC / CLIC beam parameters

| Parameter | ILC 250 GeV | ILC 500 GeV | CLIC 380 GeV | CLIC 1.5 TeV | CLIC 3 TeV |
|---|---|---|---|---|---|
| **Luminosity L ($10^{34}cm^{-2}sec^{-1}$)** | **1.35** | **1.8** | **1.5** | **3.7** | **5.9** |
| L above 99% of √s ($10^{34}cm^{-2}sec^{-1}$) | 1.0 | 1.0 | 0.9 | 1.4 | 2.0 |
| Repetition frequency (Hz) | 5 | 5 | 50 | 50 | 50 |
| Bunch separation (ns) | 554 | 554 | 0.5 | 0.5 | 0.5 |
| Number of bunches per train | 1312 | 1312 | 352 | 312 | 312 |
| Beam size at IP $\sigma_x/\sigma_y$ (nm) | 515 / 7.7 | 474 / 5.9 | 150 / 2.9 | ~60/1.5 | ~40/1 |
| Beam size at IP $\sigma_z$ (μm) | 300 | 300 | 70 | 44 | 44 |

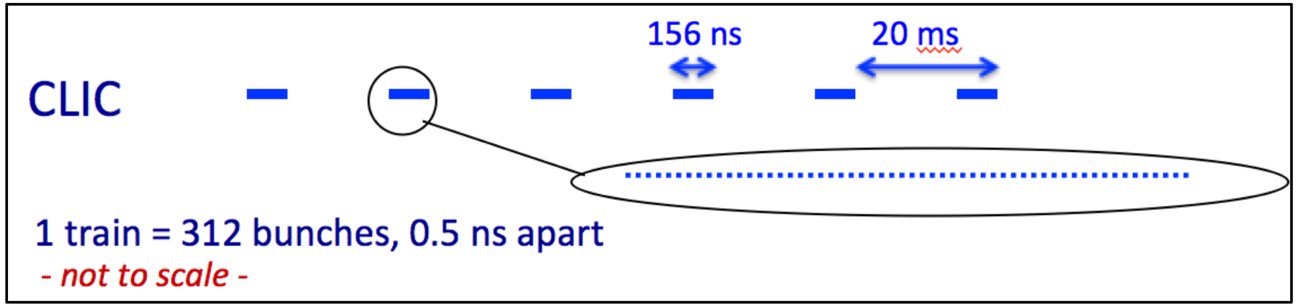
Drives timing requirements CLIC detector

Very small beams + high energy => beamstrahlung

ILC: Crossing angle 14 mrad, electron polarization ±80%, positron polarization ±30%
CLIC: Crossing angle 20 mrad, electron polarization ±80%

Very low duty cycle at ILC/CLIC allows for:
- Triggerless readout
- Power pulsing

**Beams arrive in "bunch trains"**




ILC strategy CLIC 2018 Summary

# Circular: FCC-ee / CECP beam parameters

| | FCC-ee | | | CEPC | |
|---|---|---|---|---|---|
| | **Z** | **Higgs** | **ttbar** | **Z (2T)** | **Higgs** |
| $\sqrt{s}$ [GeV] | **91.2** | **240** | **365** | **91.2** | **240** |
| Luminosity per IP ($10^{34}cm^{-2}sec^{-1}$) | **230** | **8.5** | **1.7** | **32** | **1.5** |
| no. of bunches / beam | 16640 | 393 | 48 | 12000 | 242 |
| Bunch crossing separation (ns) | **20** | 994 | 3000 | **25** | 680 |
| Beam size at IP $\sigma_x/\sigma_y$ (μm/nm) | 6.4 / 28 | 14 / 36 | 38 / 68 | 6.0 / 40 | 20.9 / 60 |
| Bunch length (SR / BS) (mm)<br>Beam size at IP $\sigma_z$ (mm) | 3.5 / 12.1 | 3.3 / 5.3 | 2.0 / 2.5 | 8.5 | 4.4 |

Beam transverse polarisation => beam energy can be measured to very high accuracy (~50 keV)

**At Z-peak very high luminosities** and **very high $e^+e^-$ cross section (40 nb)**

- ⇒ **Statistical accuracies at $10^{-4}$ -$10^{-5}$ level** ⇒ **drives detector performance requirements**
- ⇒ **Small systematic errors required** to match
- ⇒ This also drives requirement on **data rates** (physics rates 100 kHz)
- ⇒ Triggerless readout likely still possible

**Beam-induced background,** from beamstrahlung + synchrotron radiation

- Most significant at 365 GeV
- Mitigated through MDI design and detector design

FCC-ee slides, CDR CEPC CDR

# $e^+e^-$ colliders experimental conditions

**Linear Colliders**

- **Beam-induced background**:
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - **High occupancies** in the detector => **small readout cells** needed
  - **O(1-5 ns) timing** required at CLIC
- **Low duty cycle**
  - **Power pulsing** of electronics possible
  - **Triggerless readout**
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)

**Circular Colliders**

- **Beam-induced background**
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons) + Synchrotron radiation
- **Circulating beams**
  - Maximum detector solenoid field of ~2 T (3 T) => requires **larger tracker radius**
  - Complex **magnet shielding** schemes near the beam
  - Beam focusing quadrupole closer to IP (~2.2m)

    } **Stronger engineering and layout constraints**
  - No power pulsing
- **High luminosity and many bunches at Z pole**
  - Drives detector performance, moderate timing requirements, high data rates
  - Larger challenge to **keep systematics very low**
- **Beam crossing angle** 30 mrad (FCC-ee), 33 mrad (CEPC)