Detector requirements for future high-energy collider experiments

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With material from Lucie Linssen, Mogens Dam, Werner Riegler, Daniel Schulte, Konrad Elsener, Emilia Leogrande, Oleksandr Viazlo, Coralie Neubüser, Donatella Lucchesi, Barbara Mele, Jie Gao, Michael Benedikt, Michael Koratzinos, Manuela Boscolo, Andrea Wulzer

Content

Detector requirements for future high-energy pp, e^+e^- and $\mu^+\mu^-$ collider experiments

(ep, PbPb and pPb colliders not covered in this talk)

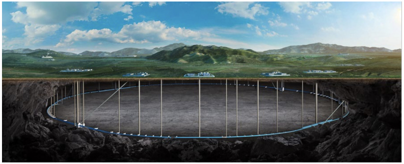
- Facilities under study
  - Hadron (pp) and lepton (e^+e^- / $\mu^+\mu^-$) colliders
  - Circular and linear
- Detector design mostly driven by facility-dependent
  - Physics objectives
  - Experimental conditions
- Proposed detector concepts
  - Design choices
  - Detector challenges

Overview:
High-energy collider proposals

High-energy e^+e^- collider proposals

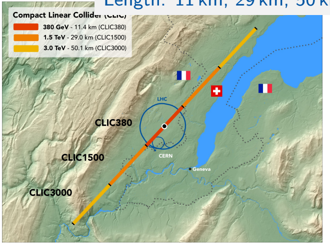
Circular Electron Positron Collider (CEPC)

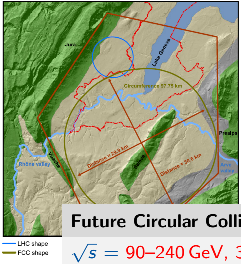
$\sqrt{s} =$ 90–240 GeV;
Circumference: 100 km



Compact Linear Collider (CLIC)

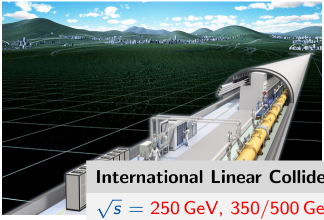
$\sqrt{s} =$ 350/380 GeV, 1.5 TeV, 3 TeV;
Length: 11 km, 29 km, 50 km





Future Circular Collider (FCC-ee)

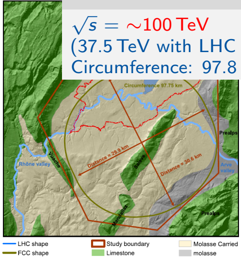
$\sqrt{s} =$ 90–240 GeV, 350–365 GeV;
Circumference: 97.8 km



International Linear Collider (ILC)

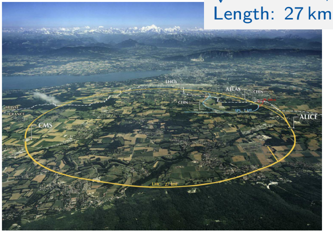
$\sqrt{s} =$ 250 GeV, 350/500 GeV (1 TeV);
Length: 20.5 km, 31 km (40 km)

High-energy hadron collider proposals



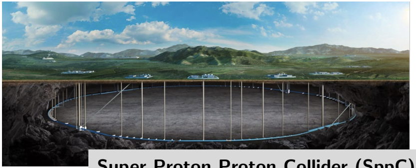
Future Circular Collider (FCC-hh)

$\sqrt{s}$ = ∼100 TeV
(37.5 TeV with LHC type magnets);
Circumference: 97.8 km



High Energy-LHC

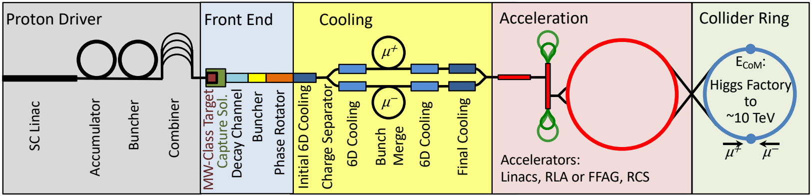
$\sqrt{s}$ = 27 TeV;
Length: 27 km



Super Proton Proton Collider (SppC)

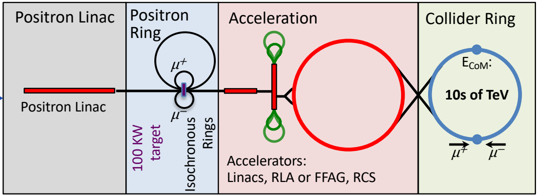
$\sqrt{s}$ = ∼75 TeV
(125–150 TeV "ultimate");
Circumference: 100 km

High-energy muon collider proposals



arXiv:1901.06150

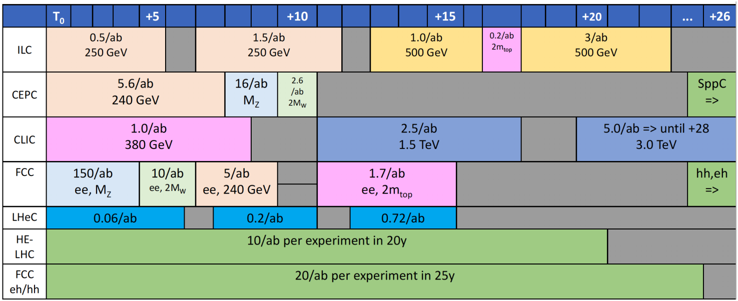
Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Muon colliders $\sqrt{s}$ = up to 10 TeV;
Circumference: few km
(+ larger pre-accelerator complex)
Example: MAP-MC: 126 GeV – 6 TeV

Future collider projects

Time lines



T_0 +5 +10 +15 +20 ... +26

ILC	0.5/ab 250 GeV	1.5/ab 250 GeV	1.0/ab 500 GeV	0.2/ab $2m_{top}$	3/ab 500 GeV	
CEPC	5.6/ab 240 GeV	16/ab M_Z	2.6 /ab $2M_W$	SppC =>		
CLIC	1.0/ab 380 GeV	2.5/ab 1.5 TeV	5.0/ab => until +28 3.0 TeV			
FCC	150/ab ee, M_Z	10/ab ee, $2M_W$	5/ab ee, 240 GeV	1.7/ab ee, $2m_{top}$	hh,eh =>	
LHeC	0.06/ab	0.2/ab	0.72/ab			
HE-LHC	10/ab per experiment in 20y					
FCC eh/hh	20/ab per experiment in 25y					

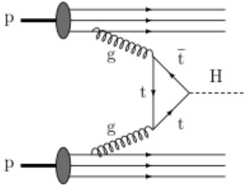
- Near future proposals (excluding ep colliders LHeC, EIC):
  - e^+e^- colliders (ILC, CEPC, CLIC, FCC-ee)
  - Low-energy FCC-hh (using LHC-type magnets in FCC tunnel: 37.5 TeV)
- Proposals for more distant future
  - Hadron colliders with high-field ($\sim$ 16 T) magnets (HE-LHC, FCC-hh, SppC)
    → Require further magnet development
  - Muon colliders
    → Require further studies towards design reports
  - Linear e^+e^- colliders with dielectric or plasma-wake-field acceleration
    → Require further studies towards design reports

Physics programmes
→ Detector requirements

High-energy hadron & lepton colliders

→ Aspects relevant for detector design

Hadron colliders (pp)



1) Hadrons are compound objects
- Initial state unknown
- Limits achievable precision

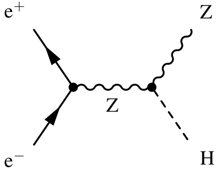
→ More relaxed accuracy requirements on detectors

2) High rates of QCD backgrounds
- Complex triggers
- High levels of radiation

3) Strong forward boost

4) O(10 ps) timing requirement (minimum bias)

Lepton colliders (e^+e^- / $\mu^+\mu^-$)



1) Leptons are point-like
- Initial state well-defined
- High-precision measurements

→ Very high accuracy requirements on detectors

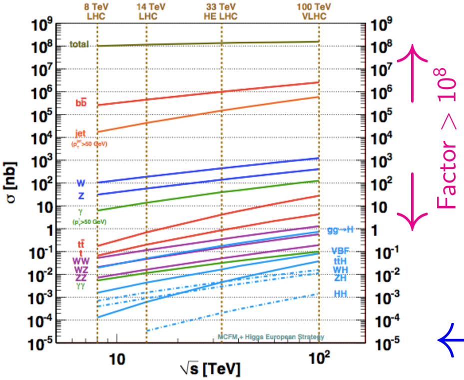
2) Clean experimental environment
- Less/no need for triggers
- Lower radiation levels

3) Less forward boost (increase with s)

4) No or O(1 ns) timing requirement (beam background)

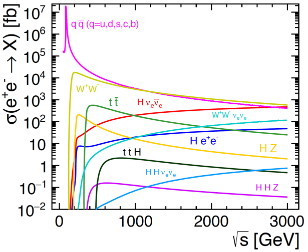
SM cross sections: pp versus e^+e^-

pp cross section



arXiv:1310.5189

$e^+\ e^-$ processes



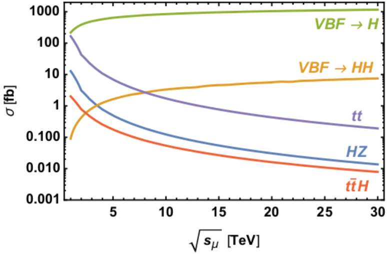
- In hadron collisions, interesting events need to be found in huge number of collisions
- Lepton collisions more clean

$\mu^+\mu^-$: BSM searches and SM cross sections

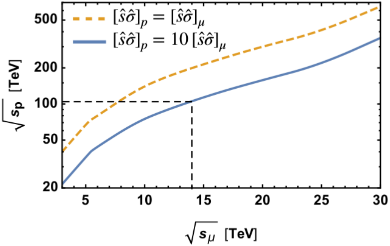
- $\mu^\pm$ less prone to synchrotron radiation: $\Delta E \sim E^4/(m^4 \cdot R)$ ($m_\mu = 207 m_e$) → potential to reach O(10 TeV) in circular collider of modest circumference

arXiv:1901.06150 ▸ Andrea Wulzer, Barbara Mele

Selected SM $\mu^+\mu^-$ cross sections



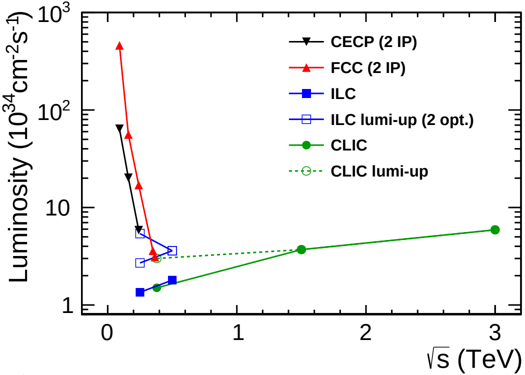
Equivalent parton centre-of-mass energy



- Similar SM cross sections in e^+e^- and $\mu^+\mu^-$ (apart from QED-radiation and small Yukawa effects)
- Cross section for many Higgs production processes increases with $\sqrt{s}$ → large Higgs samples

- In pp collisions, $\sqrt{s_{\text{parton-parton}}} \ll \sqrt{s_{pp}}$
- "Equivalent" reach at $\sqrt{s_{\mu^+\mu^-}} = 14$ TeV and $\sqrt{s_{pp}} = 100$ TeV
- Searches in $\mu^+\mu^- \to ff$ up to $m_f \leq \sqrt{s_{\mu^+\mu^-}}/2$

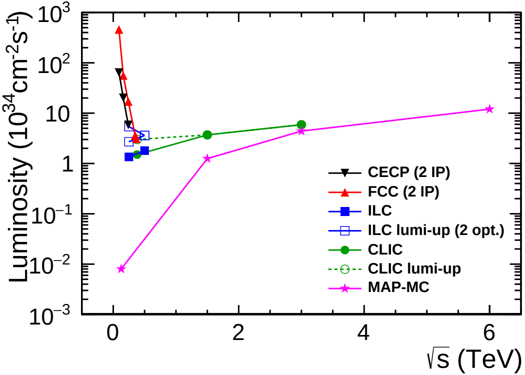
Luminosities and energy reach: e^+e^-



▲ Corresponds to Physics Briefing Book

- Circular e^+e^- colliders
  - Extremely high luminosities at low energies (Z, WW, ZH)
- Linear e^+e^- colliders
  - High centre of mass energies ($t\bar{t}$, ZH, H$\nu\nu$, double Higgs, direct searches)
  - Beam polarisation → characterisation of new particles or processes in detail
- Circular and linear e^+e^- colliders
  - Comparable luminosities in overlap region (ZH, $t\bar{t}$)

Luminosities and energy reach: $e^+e^-$and $\mu^+ \mu^-$



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  - Beam polarisation → characterisation of new particles or processes in detail
- Circular and linear e^+e^- colliders
  - Comparable luminosities in overlap region (ZH, $t\bar{t}$)
- Muon collider: reach multi-TeV energies

LC e^+e^- detector performance requirements

- Momentum resolution
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons

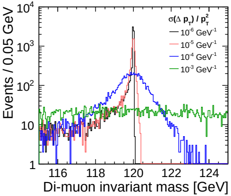
  → $\sigma_{p_\mathrm{T}}/p_\mathrm{T}^2 \sim 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios

  → $\sigma_{r\varphi} \sim a \oplus b/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\mu\mathrm{m}$
  - $a = 5\,\mu\mathrm{m}$, $b = 10 - 15\,\mu\mathrm{m}$
- Jet energy resolution
  - Separation of W/Z/H di-jets, Z and W width, HZ with $Z \rightarrow q\bar{q}$, background reduction

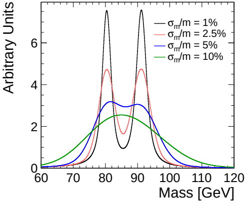
  → $\sigma_E/E \sim 3.5\%$

  (for high-energy jets, light quarks)
- Angular coverage
  - Very forward electron and photon tagging

Example: H→ μμ @ 3 TeV



Example: W/Z separation



+ Requirements from beam structure and beam-induced background

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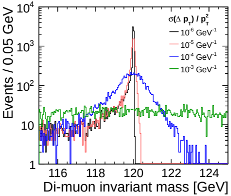

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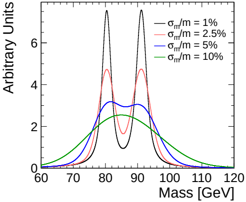
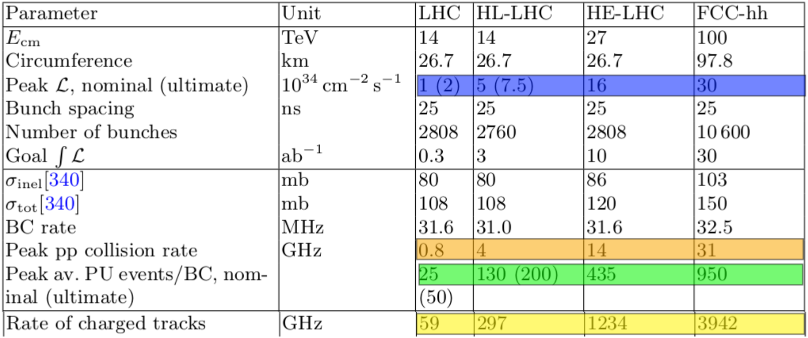


Differences between ILC, CLIC, FCC-ee, CEPC requirements rather small

Experimental conditions

Hadron colliders: Key parameters

▸ FCC-hh CDR ▸ Werner Riegler

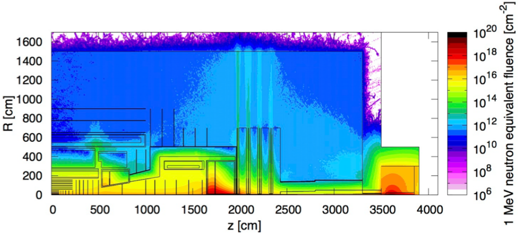


Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}[340]	mb	80	80	86	103
σ_{tot}[340]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Rate of charged tracks	GHz	59	297	1234	3942

- Example: pp collisions at 100 TeV (FCC-hh)
  - **Pileup: ∼1000 events/bunch crossing** → spatial resolution, timing
    - Average distance between vertices: 125 µm (7 times smaller than at HL-LHC)
  - High radiation levels → radiation hardness
    - High luminosity of **$30\text{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$**
    - pp collision rate of **31 GHz**
    - Charged track rate of **∼4 THz**
  - Forward boost → forward coverage

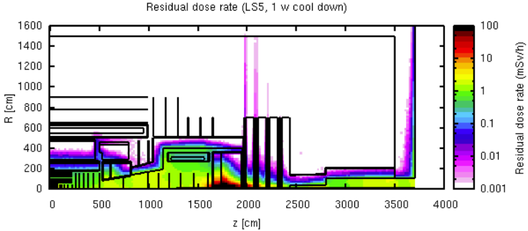
Hadron colliders: Radiation levels

Assuming $L = 30 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $30\,\mathrm{ab}^{-1}$



Neutron equivalent fluence

- $\sim 10^{18} n_{\mathrm{eq}}/\mathrm{cm}^2$ close to beam pipe,
- $10^{15} - 10^{16} n_{\mathrm{eq}}/\mathrm{cm}^2$ at $r > 40\,\mathrm{cm}$ ($\sim$ HL-LHC)
- Extreme fluence in forward calorimeters
  → Radiation levels 100 times larger than what present silicon sensors can sustain



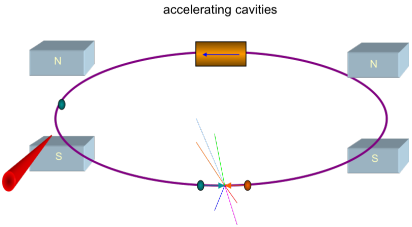
Residual dose rate

- Dose from activation towards the end of FCC operation
- Here: 1 week of cool-down, similar picture after 1 year
  → Impact on access conditions to experiment after several years of operation

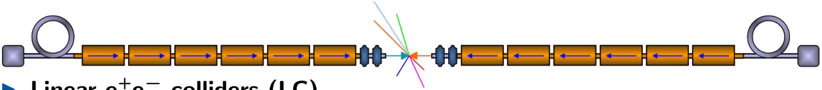
▸ Werner Riegler

▸ FCC-hh CDR

Circular vs. linear e^+e^- colliders: Overview



- **Circular e^+e^- colliders (CC)**
  1. Several interaction regions
  2. Continuous operation
  3. Synchrotron radiation
  4. Beam strahlung



- **Linear e^+e^- colliders (LC)**
  1. One interaction region in linear colliders, alternatives: push-pull scheme or 2 beam-delivery systems (shared lumi.)
  2. Operation in bunch trains
  3. Very little synchrotron radiation in a linac
  4. Have to achieve luminosity in single pass
     → Small beam size and high beam power
     → Beamstrahlung, energy spread

- **Impact on LC/CC detector designs**
  - Shielding
  - Granularity
  - Timing
  - Cooling

Circular e^+e^- colliders: Beam parameters

Property	Unit	FCC-ee (97.8 km)				CEPC (100 km)		
		Z	WW	ZH	tt	Z (2T)	WW	ZH
$\sqrt{s}$	GeV	91.2	160	240	365	91	160	240
Lumi./IP	10^{34} /cm^{2}s	230	28	8.5	1.55	32.1	10.1	2.93
Bunches/beam		16 640	2 000	393	48	12 000	1 524	242
Bunch sep.	ns	20	163	994	3396	25	210	680
Synch.rad. power	MW	$\leq$ 50	$\leq$ 50	$\leq$ 50	$\leq$ 50	16.5	30	30
Beam $\sigma_{xy,\ \mathrm{IP}}$	µm/nm	6.4/28	13/41	14/36	38/68	6/40	13.9/49	20.9/68

Beam energy can be measured to very high accuracy (∼50 keV)

- At Z peak, high luminosity combined with high e^+e^- cross section
  - Achieve very low statistical uncertainties ($\sim 10^{-4} - 10^{-5}$)
    → Drives detector performance req. to match systematic uncertainties
  - High number of bunches and small distance between bunches
    → Beam crossing angle: 30 mrad (FCC-ee)/33 mrad(CEPC)
  - Very high data rates (physics rates 100 kHz)
    → Requirements on readout
    → Triggerless readout can still be possible
- Backgrounds
  - Synchroton radiation, beamstrahlung, backgrounds from beam losses, etc.
    → Adapt detector and machine-detector interface

▸ Michael Benedikt, Jie Gao
▸ Lucie Linssen

Circ. e^+e^- colliders: Machine-detector interface

- High luminosities: last focusing quadrupole QC1 very close to IP
  - $L^* \approx 2.2\,\mathrm{m}$ @ FCC-ee and CEPC → QC1 inside detector volume
- Protect QC1 from main magnetic field of detector
  - Screening solenoid around QC1
- Compensating solenoid: prevent beam emittance blow-up in detector B field due to non-zero crossing angle

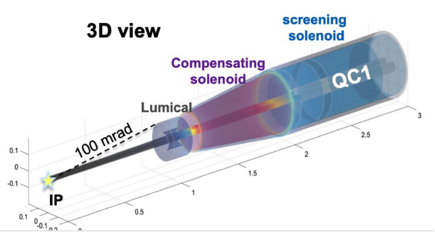
→ Lumical at only **1 m** from interaction point

→ Limits detector acceptance window

→ Limits magnetic field of main solenoid: **B=2 T at FCC-ee**

→ Relatively large tracker radius to achieve good momentum resolution

FCC-ee forward detector region
(expanded xy-direction)



▸ Michael Koratzinos ▸ Jie Gao

- Limit on magnetic field of main solenoid varies with $\sqrt{s}$
- Larger B would require thicker main magnet coil → impact on detector

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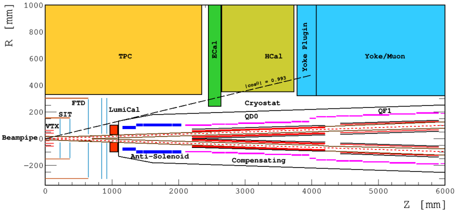
CEPC forward detector region
(expanded xy-direction)



▸ Michael Koratzinos ▸ Jie Gao

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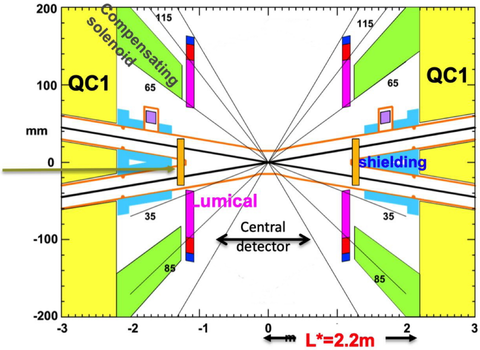
Circular e^+e^- colliders: Shielding and cooling

- **W shielding** inside of detector region to prevent synchrotron radiation/secondary radiation to enter the sub-detectors

FCC-ee detector: 2D-top view with expanded y-coordinate



Central detector region
Compensating solenoid
Lumical
QC1
HOM absorber
Pumps
Shielding

▸ Manuela Boscolo ▸ CEPC CDR

- Beam pipe
  - Heating, liquid cooled → increased material budget at the IP
  - Be in central region, then Cu

Circular e^+e^- colliders: Shielding and cooling

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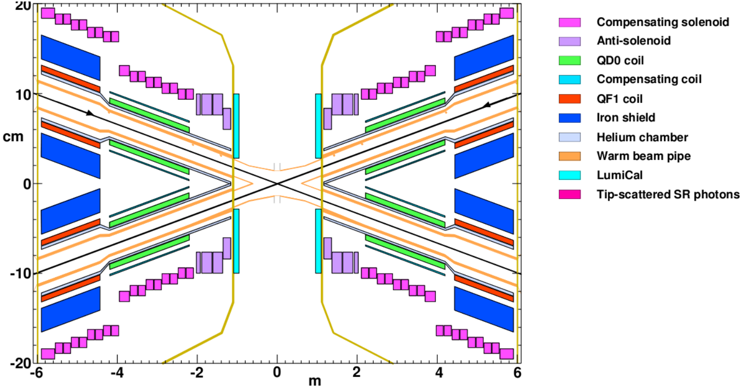
CEPC detector: 2D-top view with expanded y-coordinate



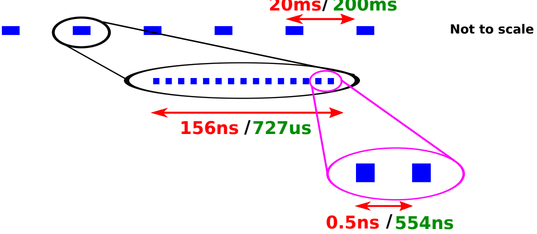
- Beam pipe
  - Heating, liquid cooled → increased material budget at the IP
  - Be in central region, then Cu

Linear e^+e^- colliders: Beam parameters (1)

Property $\sqrt{s}$	Unit GeV	ILC 250	 250(Upg.)	 500	CLIC 380(upg.)	 1500	 3000
Train rep. rate	Hz	5	5/10	5	50/100	50	50
BX / train		1312	2625	1312/2625	356	312	312
Bunch sep.	ns	554	272	544/272	0.5	0.5	0.5
Duty cycle	‰	3.6	7.2	3.6/7.2	0.0089/ 0.0178	0.0078	0.0078

- Linear colliders operate in bunch trains
  → Low duty cycle
  → Possibility of power pulsing of detectors and triggerless readout

Beam structure: CLIC@3TeV/ILC@500GeV

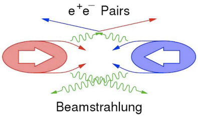


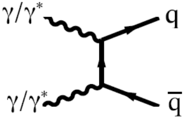
Linear e^+e^- colliders: Beam parameters (2)

Property $\sqrt{s}$ Site length	Unit GeV km	ILC 250 20.5	 250(Upg.) 20.5/31	 500 31	CLIC 380(Upg.) 11.4	 1500 29.0	 3000 50.1
Luminosity	$10^{34}/\text{cm}^2\text{s}$	1.35	2.7/5.4	1.8/3.6	1.5/3	3.7	5.9
Bunch sep.	ns	554	272	544/272	0.5	0.5	0.5
Beam $\sigma_{xy,\,\text{IP}}$	nm/nm	516/7.7	516/7.7	474/5.9	149/2.9	~60/1.5	~40/1
Beam $\sigma_{z,\,\text{IP}}$	µm	300	300	300	70	44	44

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

- Bunch separation → Impact on detector design (timing, granularity)
- Very small beams and high beam energy → beamstrahlung



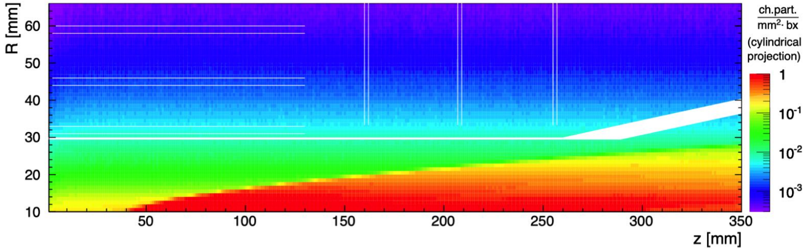


$\gamma\gamma \rightarrow$ hadrons

Linear e^+e^- colliders: Beamstrahlung

Impact on layout, granularity, shielding

$N_{\text{Charged particles}}/\text{mm}^2$/bunch crossing @ 3 TeV CLIC:
Zoom into vertex detector region

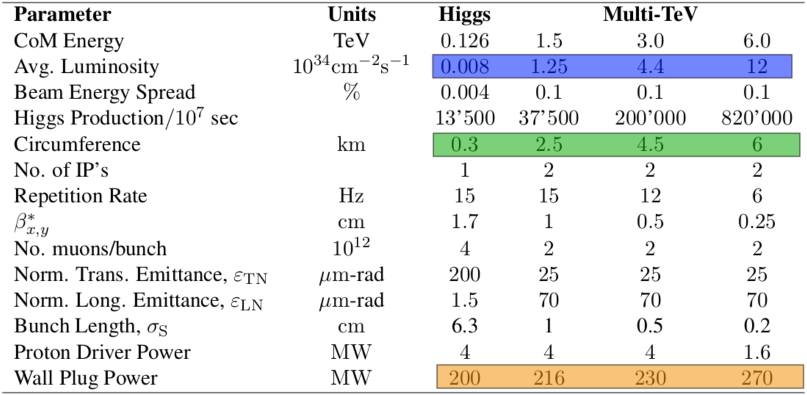


▲ CLIC CDR

- Adapt detector layout, granularity, shielding, timing requirements
  - Radius of beam pipe and first vertex detector layer: ∼ 3 cm @ 3 TeV
  - Thicker beam-pipe in forward direction: shielding for back scattered particles
  - Timing requirements: 5 ns for CLIC vertex and tracking detectors
- Timing also useful for ILC, FCC, CEPC:
  e.g. distinguish direct energy deposits from back scattering ones

Muon collider: Key parameters

Proton driven muon collider (MAP collaboration)



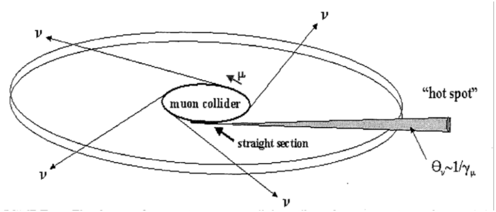
Parameter	Units	Higgs	Multi-TeV		
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1	0.5	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	μm-rad	200	25	25	25
Norm. Long. Emittance, ε_{LN}	μm-rad	1.5	70	70	70
Bunch Length, σ_{S}	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

▸ arXiv:1901.06150

- Luminosity at 3 TeV similar to CLIC (4.4 versus 5.9 × $10^{34}/\text{cm}^2\text{s}$)
- Luminosity per wall plug power increases for muon colliders
  → reach O(10 TeV)
- Luminosity increases with energy quadratically (beam size reduction)
- Each $\sqrt{s}$ foreseen in individual collider of few kilometres

Muon colliders: Neutrino background

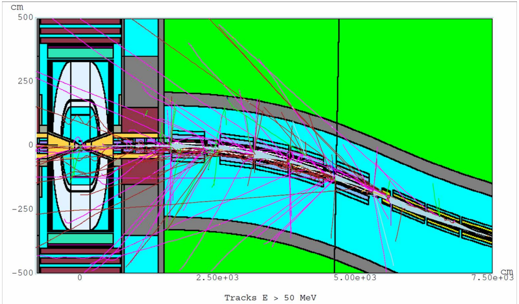
- In-flight muon decay
  - Neutrino continue in beam direction
  - Straight sections: neutrinos emerge in spot-like area



- Secondary hadronic interactions from initial neutrinos pose radiation hazard where the neutrino beam reaches earth surface
  → Dose in continuation of straight sections particularly high
- Radiation limit to population below 0.1 mSv/y
- Dose scales with energy following $\sim E^3$

Muon colliders: detector background

Beam induced background @ 1.5 TeV: Simulation



▲ Donatella Lucchesi ▲ arXiv:1807.00074

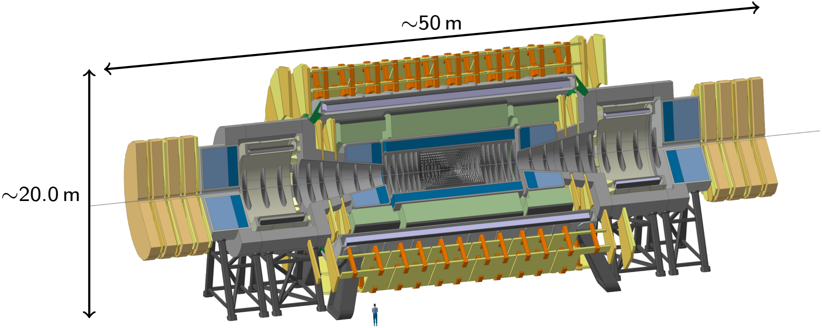
- Muons decay also near detector region
  e.g. @ 750 GeV, $2 \times 10^{12} \mu$ per bunch: 4×10^{5} decays/m/bunch
- $e^{\pm}$ inside accelerator magnets → Synchroton radiation (γ)
- El.-mag. showers from $e^{\pm}$ and γ interact with the machine components

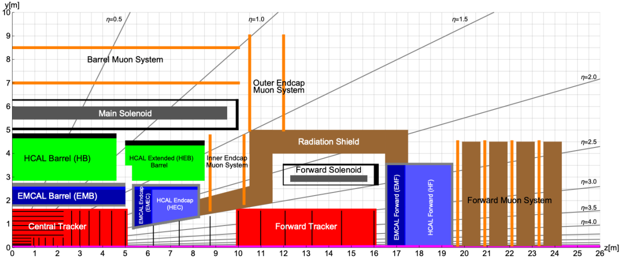
→ Photons, neutrons, electrons, charged hadrons and secondary muons reaching detector region

- Collimation, shielding and timing requirements for detector design

Detectors

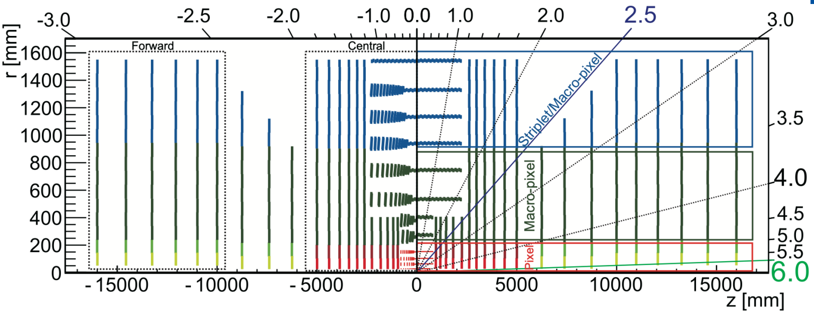
FCC-hh reference detector (100 TeV)





- Silicon tracker
- Barrel ECAL LAr
- Endcap and forward HCAL/ECAL LAr
- Barrel HCAL Fe/Sci
- Central solenoid (4 T, > 10 m diameter), two forward solenoids, unshielded
- Muon system

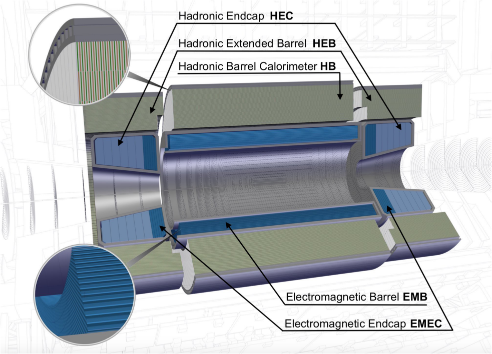
Tracking in FCC-hh detector



- Two tracker options studied: “Tilted” and “flat”, each O(400 m^2)
  - Tilted layout reduces material budget → improves reconstruction efficiency
- High occupancies
  - Small cells sizes ($\sim 25 \times 50\,\mu m^2$ in inner layers)
- Two-track separation in boosted objects
  - Small cell sizes + hit resolution $< 5\,\mu m$ + O(5 ps) time resolution

- High-E → significant fraction of displaced vertices outside acceptance
- Radiation levels 100× higher than present silicon technologies can sustain

Calorimetry in FCC-hh detector



arXiv:1912.09962

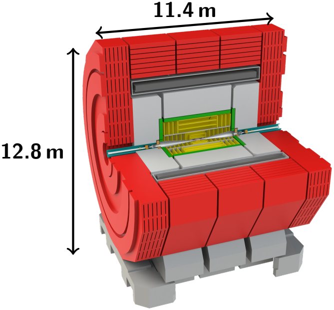
- Sampling calorimeters for FCC-hh: Liquid Argon (LAr) and Scintillator
- LAr only known technology for extreme radiation regions, requires development towards high granularity →particle flow analyis
- Silicon alternative for lower radiation regions

Requirements at 100 TeV

- Depth: $\geq 30\,X_0$, $\geq 11\,\lambda_I$
- High longitudinal and lateral segmentation
- Coverage up to $|\eta| = 6$
- Excellent resolution and linearity from GeV to multi-TeV (e.g. 1% mass resolution for $H \to \gamma\gamma/4e$)
- Timing O(30 ps) → pile-up reduction by factor 6
- Dynamic range: per-cell deposits from MIPs to heavy resonances up to 50 TeV

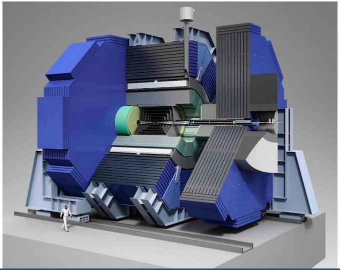
Linear e^+e^- collider detectors (up to 3 TeV)

CLIC: CLICdet

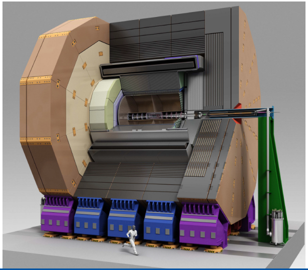


- 3.5–5 T solenoids
- CLICdet and SiD: all silicon tracker; ILD: Time Projection Chamber
- Vertex and tracking detector with very low material budget and unprecedented spatial resolution
- Highly granular calorimeters
- Forward calorimeters
- Muon system in return yoke
- Power pulsing possible due to low duty circle

ILC: SiD

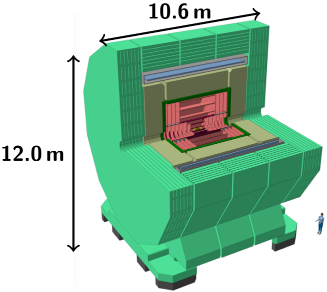


ILC: ILD

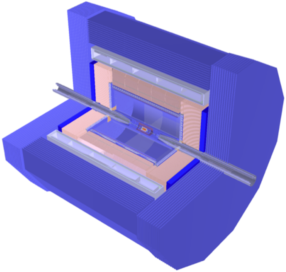


Circular e^+e^- collider detectors (up to 365 GeV)

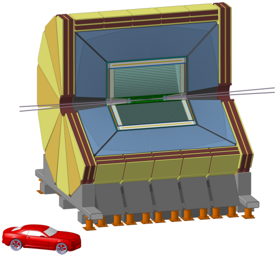
FCC-ee: CLD



CEPC: Baseline



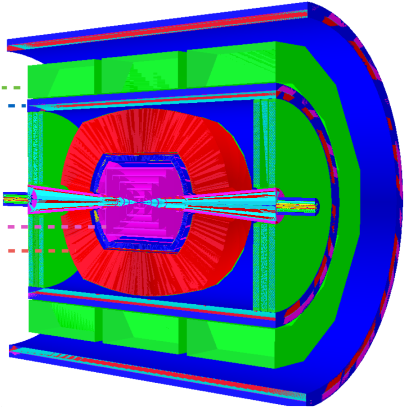
FCC-ee and CEPC: IDEA



- 2 T FCC-ee, 2–3 T CEPC
- Large tracker radius in case of lower magnetic field
- CLD: All silicon tracker,
  Baseline: TPC, IDEA: Drift chamber
- Highly granular calorimeter or dual readout calorimeter
- Forward calorimeters

Muon collider detectors

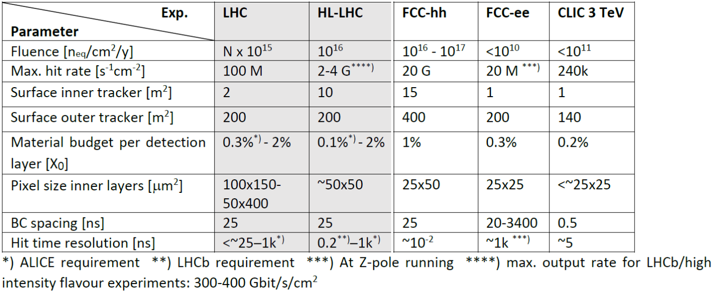
MAP (Muon Accelerator Programme) detector



- Detector used for first background and performance studies
  - Magnetic coil 3.57 T
  - Silicon based vertex and tracking detectors
  - Dual readout calorimeter
  - Muon system
- Mitigate beam-induced backgrounds
  - Tungsten-polyethylene nozzles for background mitigation inside the detector
  - O(ps) time resolution for background suppression

Comparison: Silicon tracking detectors

Silicon vertex and tracking detector parameters



Exp. Parameter	LHC	HL-LHC	FCC-hh	FCC-ee	CLIC 3 TeV
Fluence [$n_{eq}/cm^2/y$]	N x 10^{15}	10^{16}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [$s^{-1}cm^{-2}$]	100 M	2-4 G$^{****)}$	20 G	20 M $^{***)}$	240k
Surface inner tracker [m^2]	2	10	15	1	1
Surface outer tracker [m^2]	200	200	400	200	140
Material budget per detection layer [X_0]	0.3%$^{*)}$ - 2%	0.1%$^{*)}$ - 2%	1%	0.3%	0.2%
Pixel size inner layers [μm^2]	100x150-50x400	~50x50	25x50	25x25	<~25x25
BC spacing [ns]	25	25	25	20-3400	0.5
Hit time resolution [ns]	<~25–1k$^{*)}$	0.2$^{**)}$–1k$^{*)}$	~10^{-2}	~1k $^{***)}$	~5

*) ALICE requirement **) LHCb requirement ***) At Z-pole running ****) max. output rate for LHCb/high intensity flavour experiments: 300-400 Gbit/s/cm^2

Hadron colliders

- Very high radiation levels: $\leq 10^{18} n_{eq}/\mathrm{cm}^2$
- Very high hit rates
- Very precise timing: $\leq$O(5 ps)

Lepton colliders

- Very small single point resolution ($\leq$ 3 µm)
- Very low material budget ($\leq 0.2\% X_0$/layer)

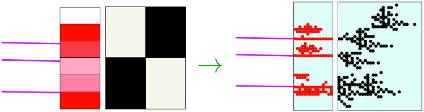
Remarks

- Note that ps-level timing was not part of initial HL-LHC detector requirements
- Became available through pioneering R&D on LGAD / MCP / precise timing with silicon
- Now well motivated for vertex separation / pattern reconstruction

Particle flow calorimetry

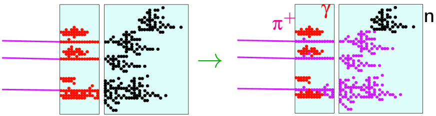
- Average jet composition
  - 60% charged particles
    30% photons
    10% neutral hadrons
- Always use the best information
  - 60% → tracker ☺
    30% → ECAL ☺
    10% → HCAL ☹
- **Particle Flow Analysis:**
  Hardware + Software

- Hardware: Resolve energy deposits from different particles
  → High granularity calorimeters



$E_{jet} = E_{ECAL} + E_{HCAL}$

- Software: Identify energy deposits from each individual particle
  → Sophisticated reconstruction software



$E_{jet} = E_{track} + E_{\gamma} + E_{n}$

Particle flow calorimeters

- Separate overlapping showers to reduce confusion

$$\sigma_{\text{jet}} = \sqrt{\sigma^2_{\text{track}} + \sigma^2_{\text{el.-m.}} + \sigma^2_{\text{had.}} + \sigma^2_{\text{confusion}}}$$

- JER of 3%–4% when using
  - → ECAL cell size: $\sim 5 \times 5\,\text{mm}^2$
  - → HCAL cell size: $\sim 30 \times 30\,\text{mm}^2$

Example: Calorimeter in ILD

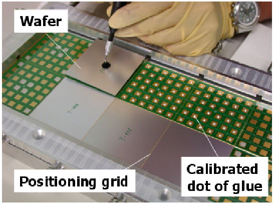
→ 10^8channels, $2500\,\text{m}^2$ Silicon

→ 10^7channels, $7000\,\text{m}^2$ Scintil.

- Hardware R&D for highly granular calorimeters: CALICE collaboration
- Concept by now under consideraton for ILC, CLIC, FCC-ee, CEPC, FCC-hh, CMS HGCal, DUNE ND

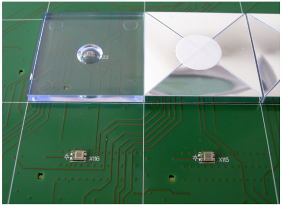
CALICE silicon PIN diodes

$1 \times 1\,\text{cm}^2$ in 6×6 matrices



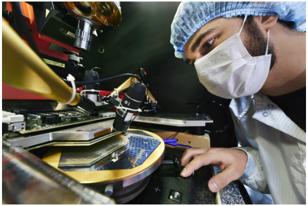
CALICE/CMS HGCal scint. tiles

+ SiPMs $3 \times 3\,\text{cm}^2$



CMS HGCal silicon pad diodes

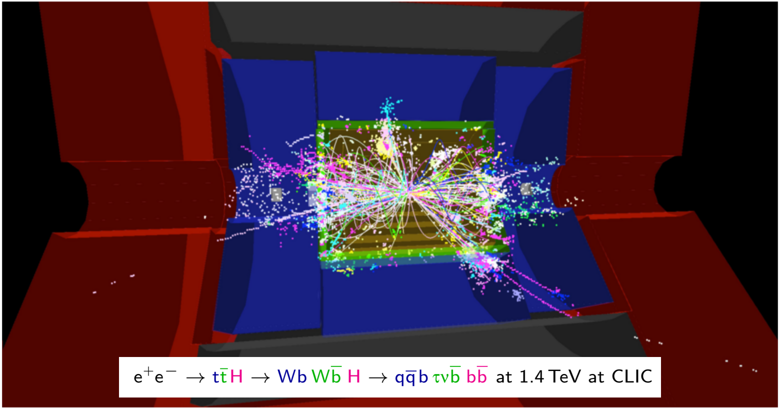
$0.5 - 1\,\text{cm}^2$, on 8-inch wafer



Background suppression

- Highly granular calorimeter + hit timing O(1 ns)
- Use combined p_T and timing cuts on fully reconstructed particles to reduce out-of-time background
  - Cuts optimised for detector regions
  - Cluster timing by combining hit timing information
    → tighter cuts possible on cluster timing

Before p_T and timing cuts



$e^+e^- \rightarrow t\bar{t}H \rightarrow Wb\,W\bar{b}\,H \rightarrow q\bar{q}b\,\tau\nu\bar{b}\,b\bar{b}$ at 1.4 TeV at CLIC

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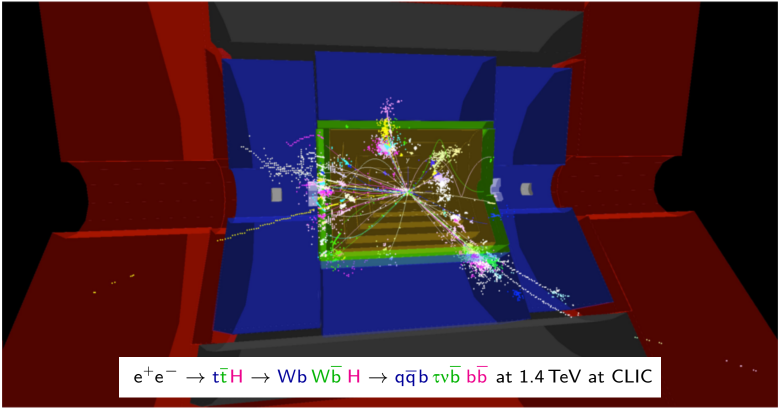
After p_T and timing cuts



$e^+e^- \rightarrow t\bar{t}H \rightarrow Wb\,W\bar{b}\,H \rightarrow q\bar{q}b\,\tau\nu\bar{b}\,b\bar{b}$ at 1.4 TeV at CLIC

Summary

Summary: pp collider detector challenges

Radiation levels

- Tracker: radiation for $< 40\,\mathrm{cm}$ radius of the tracker is 100 times larger than what present silicon sensors can sustain
- Calorimeter:
  Liquid Argon is only viable known technology, requires development towards high granularity; silicon or scintillator technologies could be used in regions with lower radiation levels

Activation

- Impact on access conditions after several years of operation → maximise automated access
- Engineering challenge

Pile-up and boost

- Requires much increased granularity in most regions of the detector
- High precision timing required ($\sim 5\,\mathrm{ps}$ per track) and computing power for reconstruction, both significantly above HL-LHC
- Very accurate tracker hit position resolution ($< 5\,\mu\mathrm{m}$), for 2-track separation in boosted objects
- Forward coverage

Data rate

- High collision rate and high granularity
  → Data rate of 1-2 Pbyte/s, mostly dominated by the tracker
  → Studies to be done whether this is possible and which level of triggering is required

Magnet systems

- Very large solenoid bore diameter of 10 m (6 m in CMS)
- Unshielded coil in baseline design → Stray field in cavern

▲ Lucie Linssen

Summary: e^+e^- collider detector challenges

Vertex detector and silicon tracker

- High spatial resolution ($\sim 3\,\mu m$, $\sim 7\,\mu m$,), very low mass, O(5 ns) hit timing (3 TeV CLIC)
- Linear Colliders: Engineering challenge to combine low mass with air cooling
- Circular Colliders: Maintain low mass for position resolution without power pulsing

Particle Flow Calorimetry

- Much experience gained through CALICE; CMS HGCal will be a benchmark
- Very large area of silicon for ECAL → cost driver

Power pulsing

- Much experience gained with laboratory set-ups, and in CALICE prototypes
- Power pulsing not yet tested at system level for vertex and tracking detectors
- Power pulsing can become an obstacle for e.g. cosmic ray calibration

Systematics on energy scale, luminosity measurement, calibration

- Keep systematics below level of statistical errors
- Most challenging at Z-peak, but also for top quark mass and per-mille level Higgs couplings

Summary: $\mu^+ \mu^-$ collider detector challenges

Muon decays

- Neutrino radiation hazard on earth surface
- Muon-decay induced backgrounds in detector → shielding, timing capabilities: O(ps)

SM event topologies

- Significant forward boost of Higgs events for O(10 TeV) collisions
  → New reconstruction challenges


CERN