Detector requirements for future high-energy collider experiments

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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)

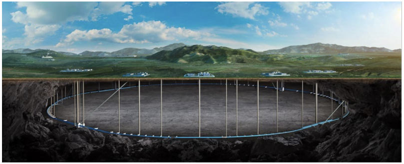
- Facilities under study
  - Hadron (pp) and lepton (e^+e^- / $\mu^+\mu^-$) colliders
  - Circular and linear
- Detector design mostly driven by facility-dependent
  - Physics objectives
  - Experimental conditions
- Proposed detector concepts
  - Design choices
  - Detector challenges

Overview:
High-energy collider proposals

High-energy e^+e^- collider proposals

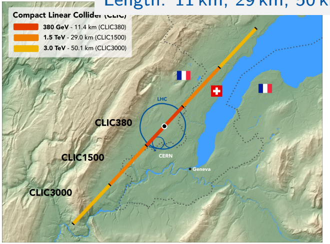
Circular Electron Positron Collider (CEPC)

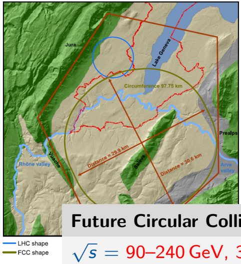
$\sqrt{s}$ = 90–240 GeV;
Circumference: 100 km



Compact Linear Collider (CLIC)

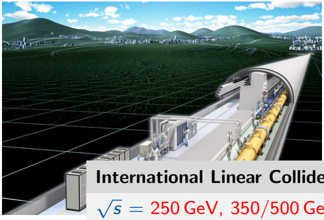
$\sqrt{s}$ = 350/380 GeV, 1.5 TeV, 3 TeV;
Length: 11 km, 29 km, 50 km





Future Circular Collider (FCC-ee)

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



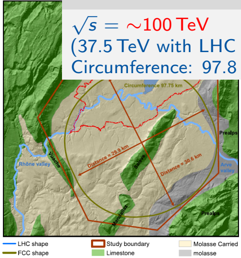
International Linear Collider (ILC)

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

High-energy hadron collider proposals

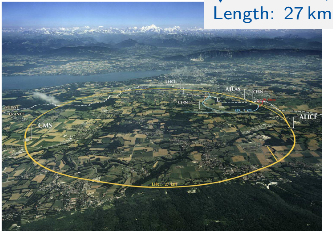
Future Circular Collider (FCC-hh)

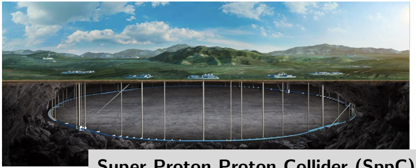
$\sqrt{s}$ = ∼100 TeV
(37.5 TeV with LHC type magnets);
Circumference: 97.8 km



High Energy-LHC

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



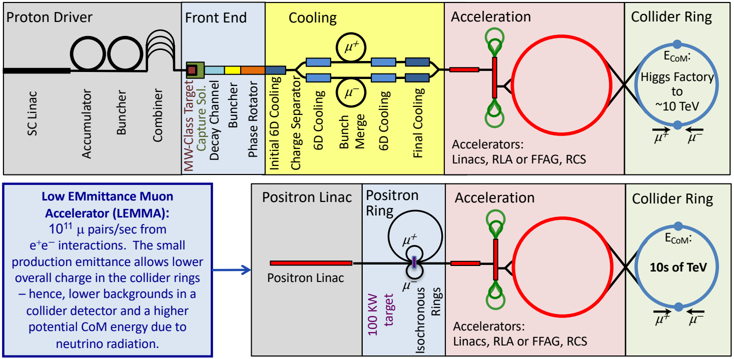


Super Proton Proton Collider (SppC)

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

High-energy muon collider proposals

- $m_{\mu^\pm} = 207 m_{e^\pm}$ → lower ΔE from synchrotron radiation: $\Delta E \sim E^4/(m^4 \cdot R)$
  → reach O(10 TeV) in circular collider of modest circumference
- Muons from primary proton or position beams
- Muon lifetime 2.2 μs at rest



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.

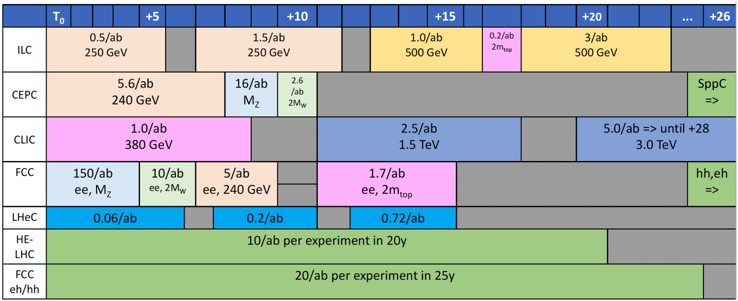
arXiv:1901.06150

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																							

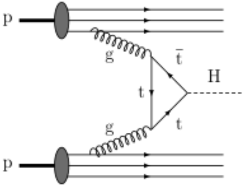
- Near future proposals (excluding ep colliders LHeC, EIC):
  - e^+e^- colliders (ILC, CEPC, CLIC, FCC-ee)
  - Low-energy FCC-hh (using LHC-type magnets in FCC tunnel: 37.5 TeV)
- Proposals for more distant future
  - Hadron colliders with high-field ($\sim$ 16 T) magnets (HE-LHC, FCC-hh, SppC)
    → 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**

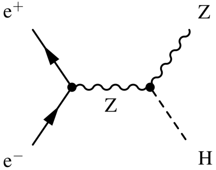
Hadron colliders (pp)



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^- / $\mu^+\mu^-$)

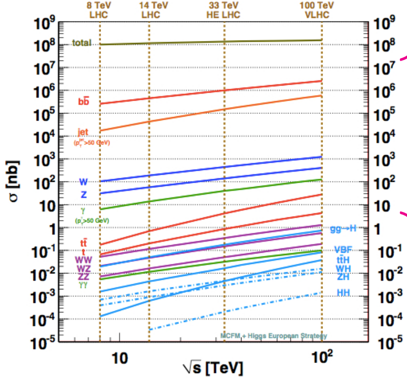


1) Leptons are point-like
   - Initial state well-defined
   - High-precision measurements

   → 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^-

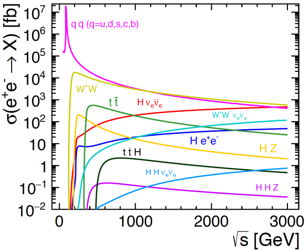
pp cross section



Factor > 10^8

arXiv:1310.5189

e^+ e^- processes

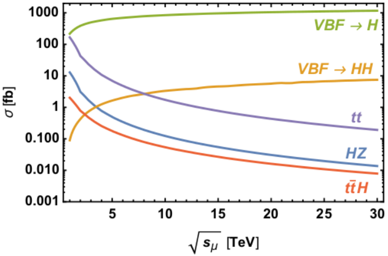


- In hadron collisions, interesting events need to be found in huge number of collisions
- Lepton collisions more clean

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

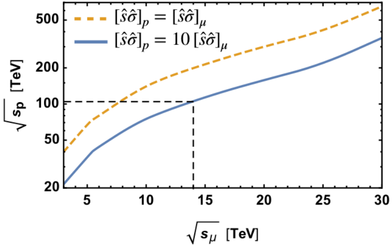
▸ arXiv:1901.06150 ▸ Andrea Wulzer, Barbara Mele

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



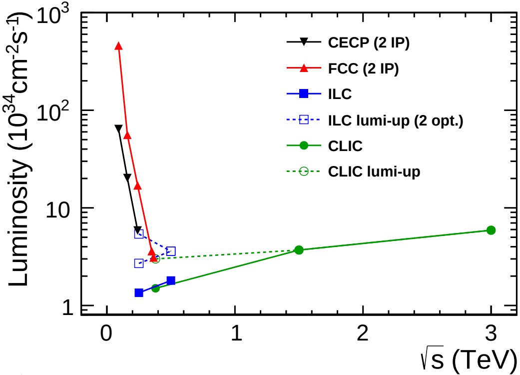
- Similar SM cross sections in e^+e^- and $\mu^+\mu^-$ (apart from QED-radiation and small Yukawa effects)
- Cross section for many Higgs production processes (t-channel) increases with $\sqrt{s}$
  → large Higgs samples
- Forward boost at high energies

Equivalent parton centre-of-mass energy



- In pp collisions, $\sqrt{s_{\text{parton-parton}}} \ll \sqrt{s_{\text{pp}}}$
- "Equivalent" reach at $\sqrt{s_{\mu^+\mu^-}} = 14$ TeV and $\sqrt{s_{\text{pp}}} = 100$ TeV
- Direct 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, Hνν, 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 $\mu^+ \mu^-$

▸ arXiv:1901.06150

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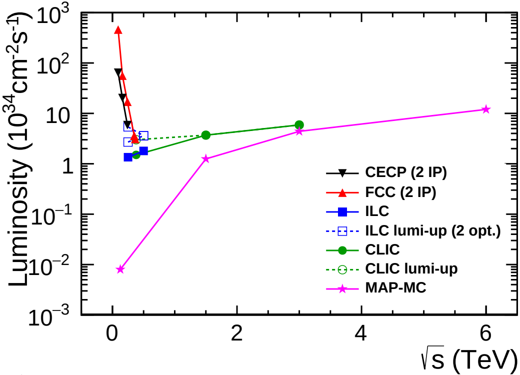

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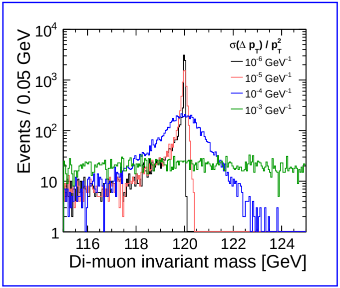
  - Beam polarisation → characterisation of new particles or processes in detail
- Circular and linear e^+e^- colliders
  - Comparable luminosities in overlap region (ZH, $t\bar{t}$)
- Muon collider: from $\mu^+\mu^- \to H$ resonance to several TeV

LC e^+e^- detector performance requirements

Reflect **needs for physics objectives** and what is **technological within reach**



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

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

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

   → $\sigma_E/E \sim 3.5\%$ (for high-energy jets, light quarks)
4. Angular coverage
   - Very forward electron and photon tagging
5. Requirements from beam structure and beam-induced background

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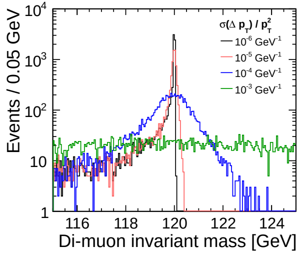

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   - Very forward electron and photon tagging
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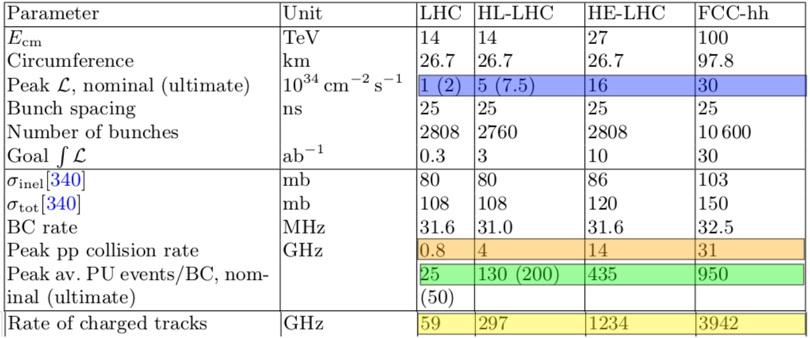
Differences between ILC, CLIC, FCC-ee, CEPC requirements rather small

Experimental conditions

Hadron colliders: Key parameters

▸ FCC-hh CDR ▸ Werner Riegler

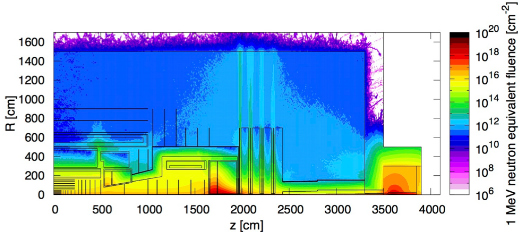


Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	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 **$30\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$**
    - pp collision rate of **31 GHz**
    - Charged track rate of **~4 THz**
  - Forward boost → forward coverage

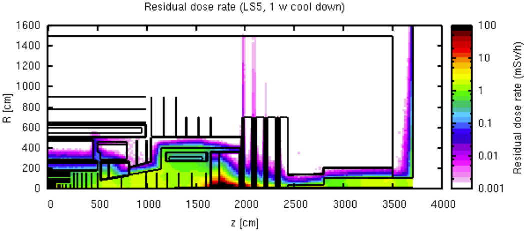
Hadron colliders: Radiation levels

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



Neutron equivalent fluence

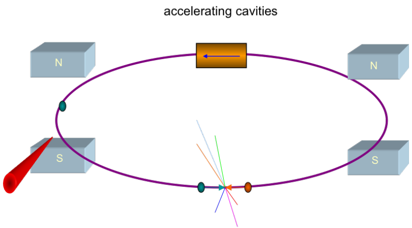
- $\sim 10^{18} n_{\text{eq}}/\text{cm}^2$ close to beam pipe
- $10^{15} - 10^{16} n_{\text{eq}}/\text{cm}^2$ at $r > 40\,\text{cm}$ ($\sim$ HL-LHC)
- Extreme fluence in forward calorimeters
  → Radiation levels 100 times larger than what present silicon sensors can sustain



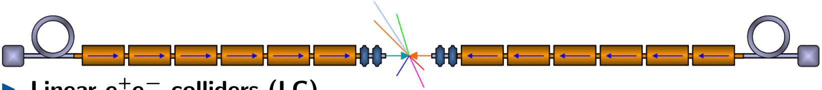
Residual dose rate

- 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

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



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



- **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	$10^{34}/\mathrm{cm}^2\mathrm{s}$	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
Sync.rad. pow.	MW	≤ 50	≤ 50	≤ 50	≤ 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)

▸ Michael Benedikt, Jie Gao

▸ Lucie Linssen

- 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

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

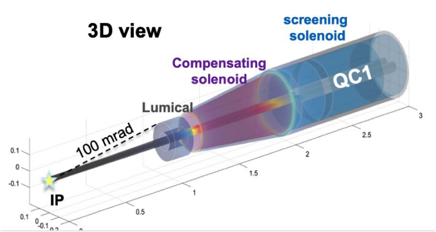
→ Lumical at only **1 m** from interaction point

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

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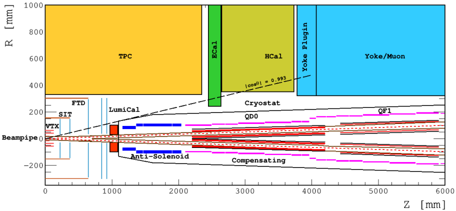
CEPC forward detector region

(expanded radial direction)



▲ Jie Gao ▲ Michael Koratzinos

- Limit on magnetic field of main solenoid varies with $\sqrt{s}$
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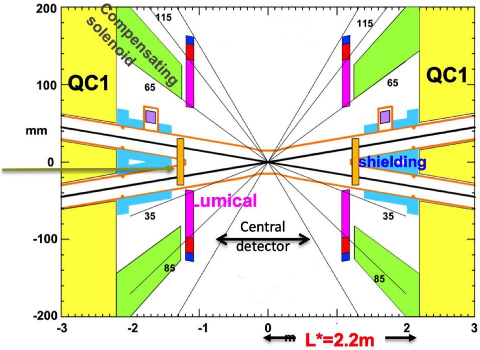
Circular e^+e^- colliders: Shielding and cooling

- **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

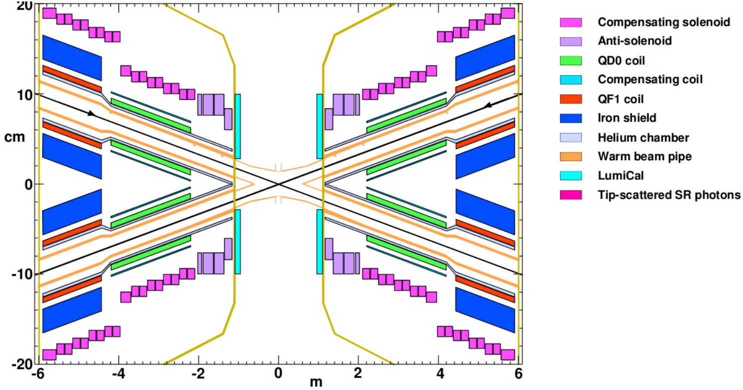
▸ Manuela Boscolo ▸ CEPC CDR

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

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

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

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



▸ Manuela Boscolo ▸ CEPC CDR

- Beam pipe
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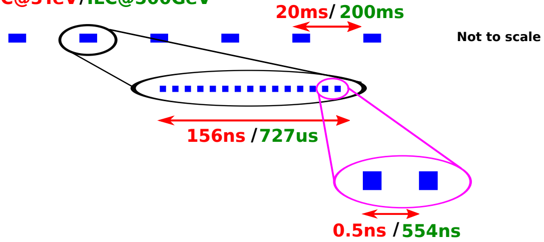
  - Be in central region, then Cu

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

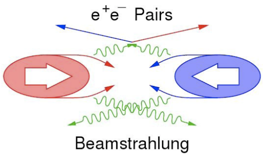


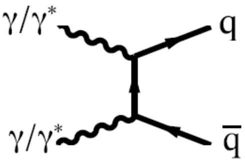
Linear e^+e^- colliders: Beam parameters (2)

Property	Unit	ILC			CLIC		
$\sqrt{s}$	GeV	250	250(Upg.)	500	380(Upg.)	1500	3000
Site length	km	20.5	20.5/31	31	11.4	29.0	50.1
Luminosity	10^{34} /cm^{2}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 $\sigma_{xy,\ \mathrm{IP}}$	nm/nm	516/7.7	516/7.7	474/5.9	149/2.9	∼60/1.5	∼40/1
Beam $\sigma_{z,\ \mathrm{IP}}$	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



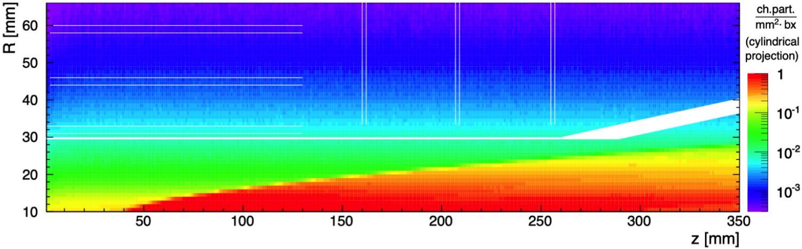


$\gamma\gamma \rightarrow$ hadrons

Linear e^+e^- colliders: Beamstrahlung

Impact on layout, granularity, shielding

Density of direct hits from incoherent e^+e^- pairs @ 3 TeV CLIC:
Cylindrical projection of beam pipe and vertex detector layers



▲ CLIC Detector and Physics 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)

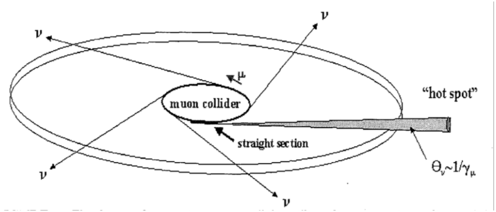
Parameter	**Units**	**Higgs**		**Multi-TeV**	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13’500	37’500	200’000	820’000
Circumference	km	0.3	2.5	4.5	6
No. of IP’s		1	2	2	2
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, $\varepsilon_{\mathrm{TN}}$	μm-rad	200	25	25	25
Norm. Long. Emittance, $\varepsilon_{\mathrm{LN}}$	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 × $10^{34}/\mathrm{cm}^2\mathrm{s}$)
- 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

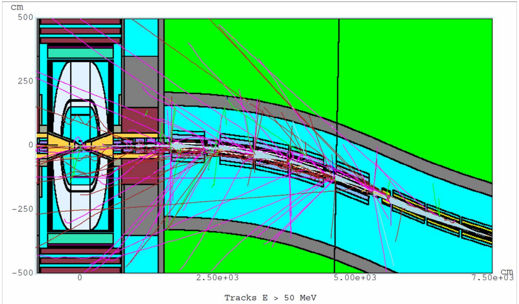
- In-flight muon decay
  - Neutrino continue in beam direction
  - Straight sections: neutrinos emerge in spot-like area



- 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



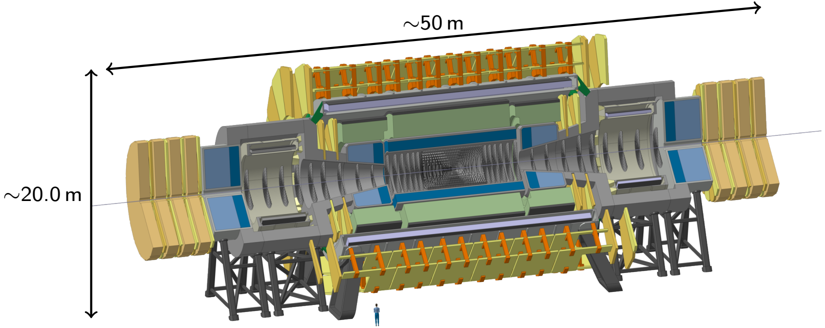
- Muons decay also near detector region
  e.g. @ 750 GeV, $2 \times 10^{12}\mu$ per bunch: 4×10^{5} decays/m/bunch
- $e^{\pm}$ inside accelerator magnets → Synchroton radiation (γ)
- El.-mag. showers from $e^{\pm}$ and γ interact with the machine components

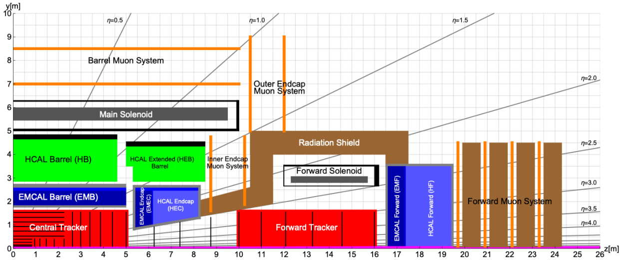
→ Photons, neutrons, electrons, charged hadrons and secondary muons reaching detector region

- Collimation, shielding and timing requirements for detector design

Detectors

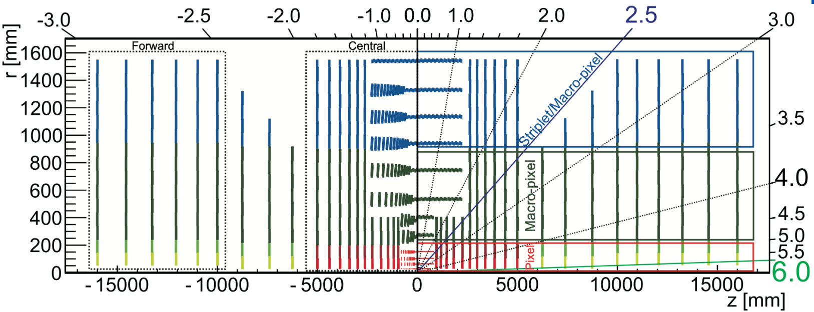
FCC-hh reference detector (100 TeV)





- 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

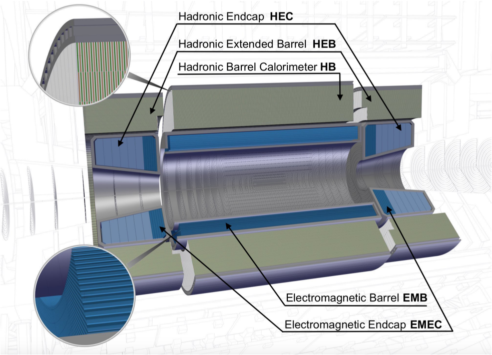
Tracking in FCC-hh detector



- 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 ($\sim 25 \times 50\,\mu\mathrm{m}^2$ in inner layers)
- Two-track separation in boosted objects
  - Small cell sizes + hit resolution $< 5\,\mu\mathrm{m}$ + O(5 ps) time resolution

- High-E → significant fraction of displaced vertices outside acceptance
- Radiation levels 100× higher than present silicon technologies can sustain
- Precise tracker alignment over very large distance (30 m length)

Calorimetry in FCC-hh detector



▸ arXiv:1912.09962

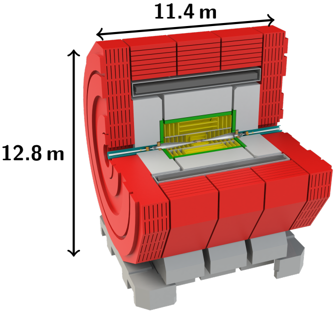
- Sampling calorimeters for FCC-hh: Liquid Argon (LAr) and Scintillator
- LAr only known technology for extreme radiation regions, requires development towards high granularity →particle flow analyis
- Silicon alternative for lower radiation regions

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

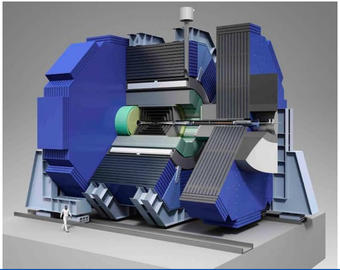
Linear e^+e^- collider detectors (up to 3 TeV)

CLIC: CLICdet

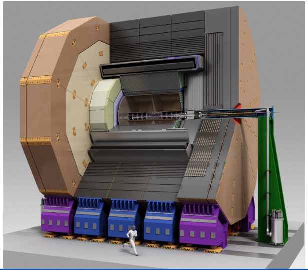


- 3.5–5 T solenoids
- CLICdet and SiD: all silicon tracker; ILD: Time Projection Chamber
- Vertex and tracking detector with very low material budget and unprecedented spatial resolution
- Highly granular calorimeters
- Forward calorimeters
- Muon system in return yoke
- Power pulsing possible due to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

ILC: SiD

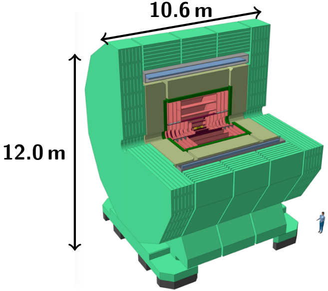


ILC: ILD

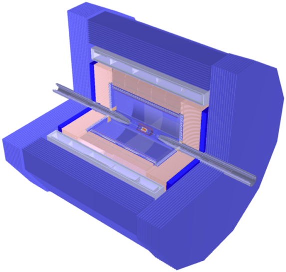


Circular e^+e^- collider detectors (up to 365 GeV)

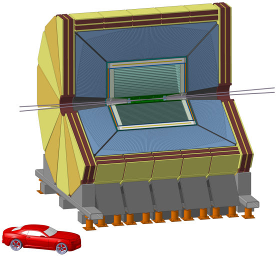
FCC-ee: CLD



CEPC: Baseline



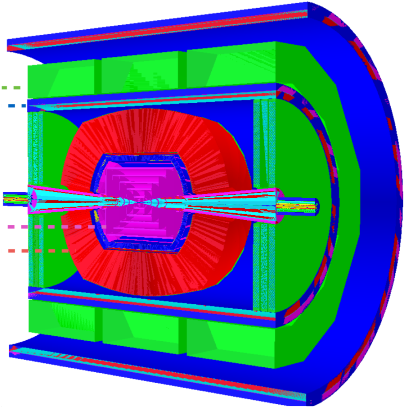
FCC-ee and CEPC: IDEA



- 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

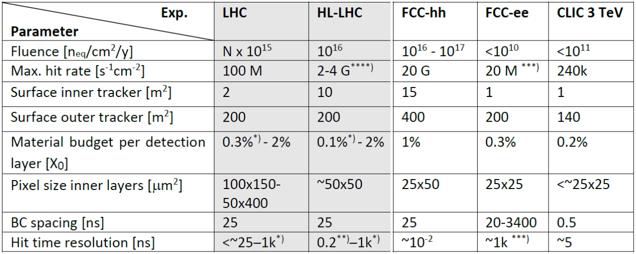


- Detector used for first background and performance studies
  - Magnetic coil 3.57 T
  - Silicon based vertex and tracking detectors
  - Dual readout calorimeter
  - Muon system
- Mitigate beam-induced backgrounds
  - Tungsten-polyethylene nozzles for background mitigation inside the detector
  - O(ps)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

Comparison: Silicon tracking detectors

Silicon vertex and tracking detector parameters

▸ CERN EP R&D 2018 ▸ Lucie Linssen



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)

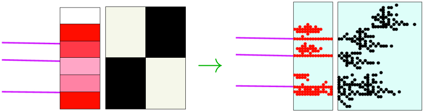
Remarks

- 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

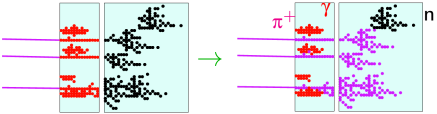
- Average jet composition
  - 60% charged particles
30% photons
10% neutral hadrons
- Always use the best information
  - 60% → tracker ☺
30% → ECAL ☺
10% → HCAL ☹
- **Particle Flow Analysis:** Hardware + Software

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



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

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



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

Particle flow calorimeters

- Separate overlapping showers to reduce confusion

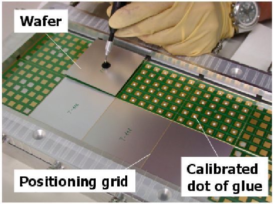
$$\sigma_{\text{jet}} = \sqrt{\sigma^2_{\text{track}} + \sigma^2_{\text{el.-m.}} + \sigma^2_{\text{had.}} + \sigma^2_{\text{confusion}}}$$

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

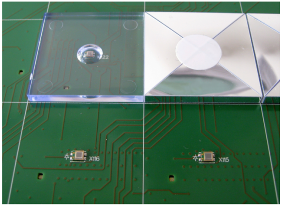
Example: Calorimeter in ILD
→ 10^8channels, $2500\,\text{m}^2$ Silicon
→ 10^7channels, $7000\,\text{m}^2$ Scintil.

- 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

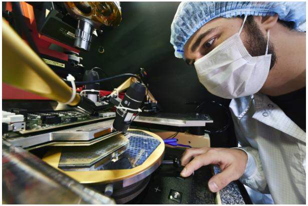
CALICE silicon PIN diodes
$1 \times 1\,\text{cm}^2$ in 6×6 matrices



CALICE/CMS HGCal scint. tiles
+ SiPMs $3 \times 3\,\text{cm}^2$



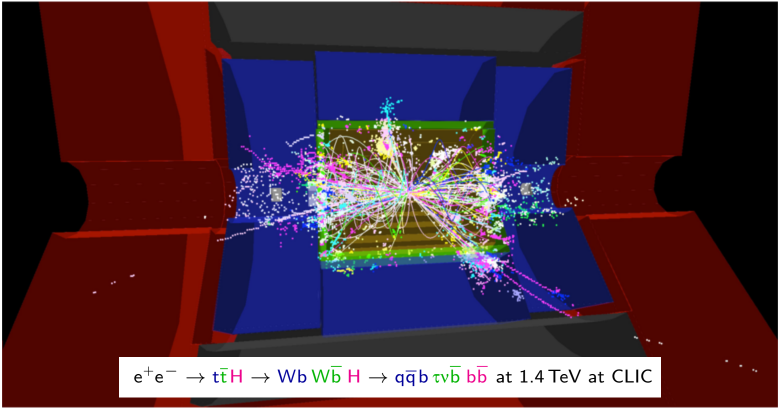
CMS HGCal silicon pad diodes
$0.5 - 1\,\text{cm}^2$, on 8-inch wafer



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



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

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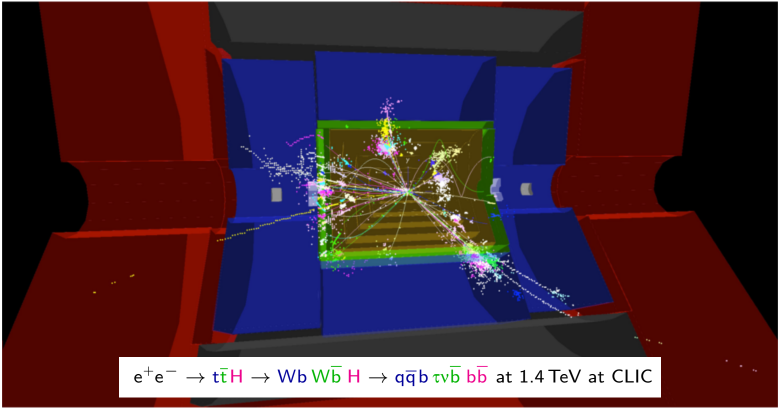

$e^+e^- \rightarrow t\bar{t}H \rightarrow Wb\,W\bar{b}\,H \rightarrow q\bar{q}b\,\tau\nu\bar{b}\,b\bar{b}$ at 1.4 TeV at CLIC

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 (∼ 3 µm, ∼ 7 µm,), 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

▸ Lucie Linssen

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