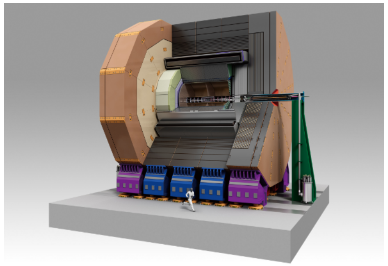
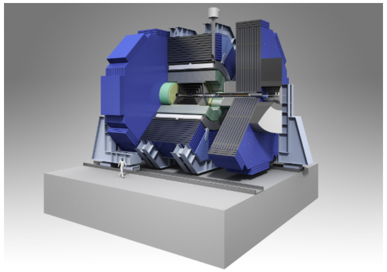
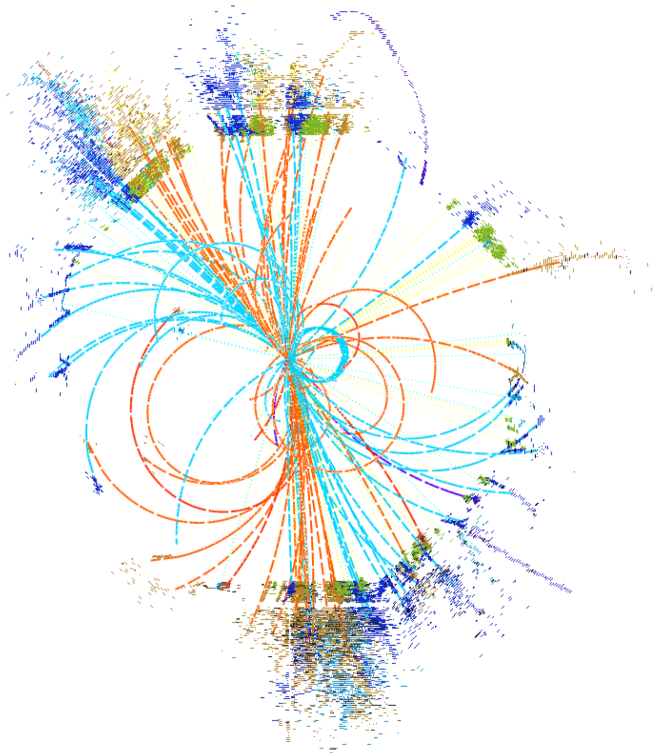
Physics performance

Philipp Roloff (CERN)

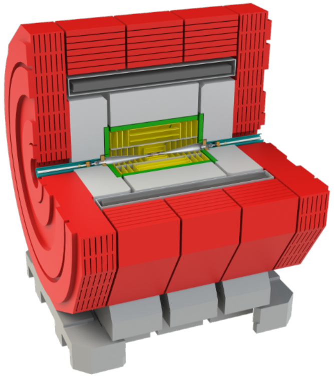
18/06/2021
ECFA PED-Higgs kick-off meeting

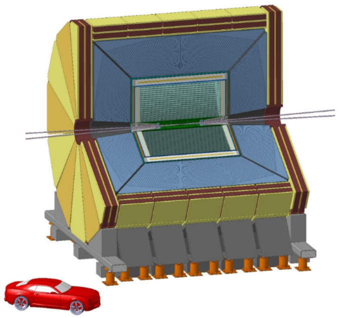


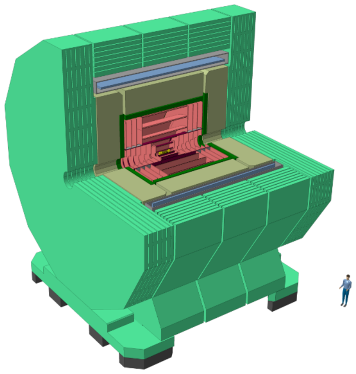




Outline:
- Tracking
- Particle flow analysis
- Jet clustering
- Kinematic fits
- Flavour tagging
- Particle ID

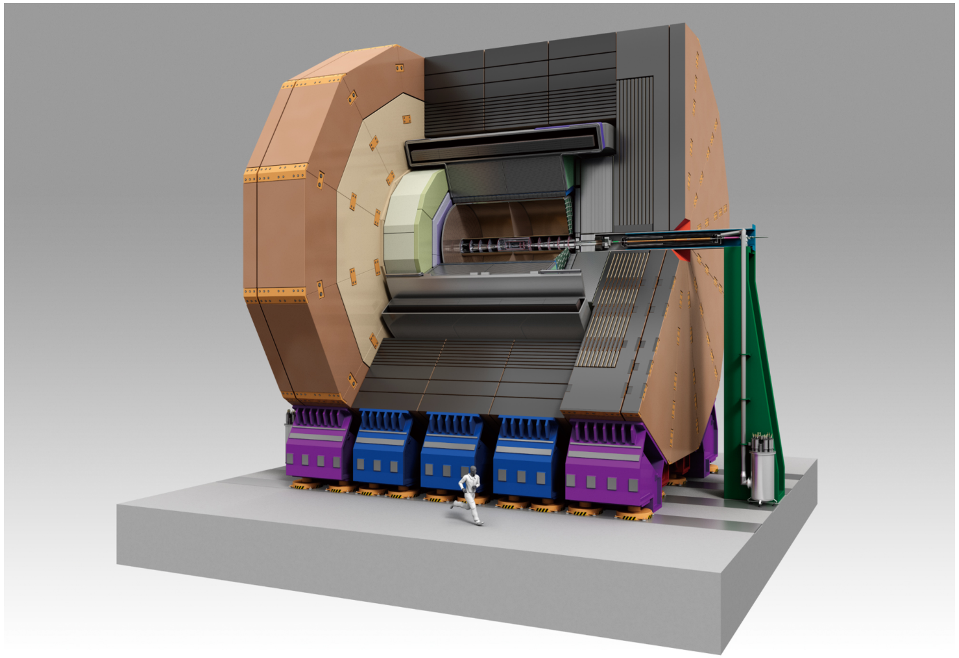


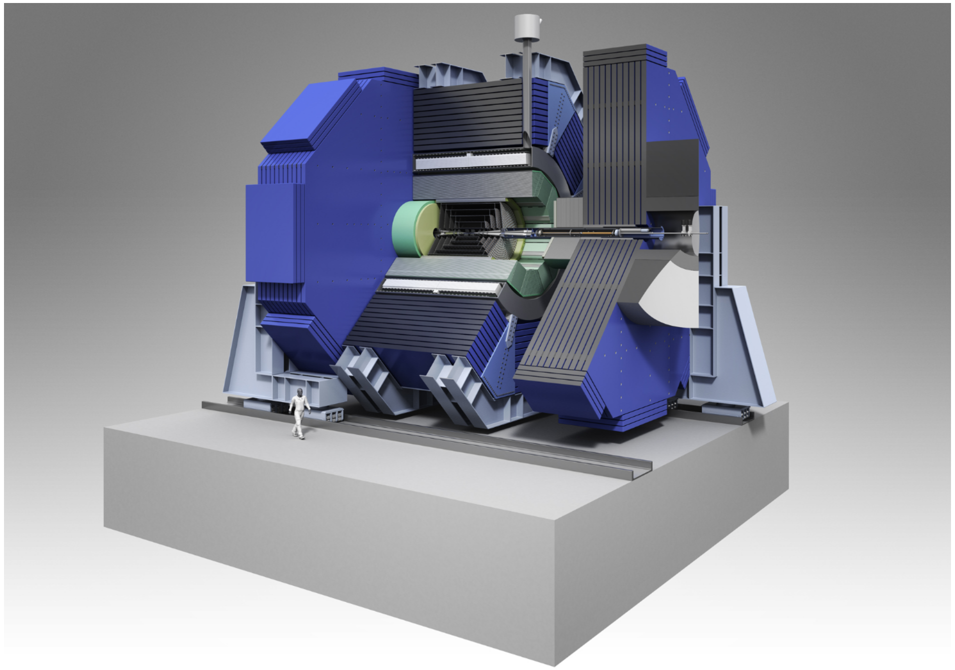




Reminder: ILC detector concepts

Designed for Particle Flow Calorimetry:
• High granularity calorimeters (ECAL and HCAL) inside solenoid
• Low mass trackers → reduce interactions / conversions

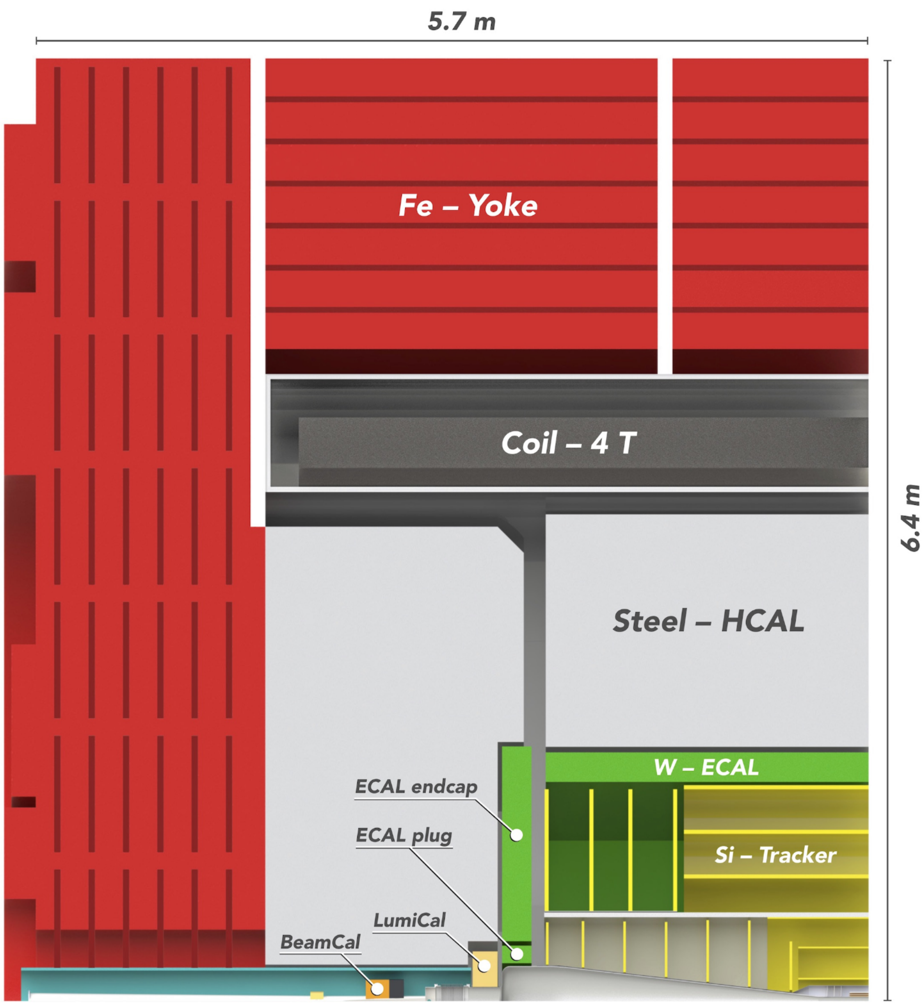




ILD (International Large Detector):
• TPC+silicon envelope, radius: 1.8 m
• B-field: 3.5 T
(small option: 1.46 m / 4 T recently studied)

SiD (Silicon Detector):
• Silicon tracking, radius: 1.2 m
• B-field: 5 T

Reminder: CLIC detector concept

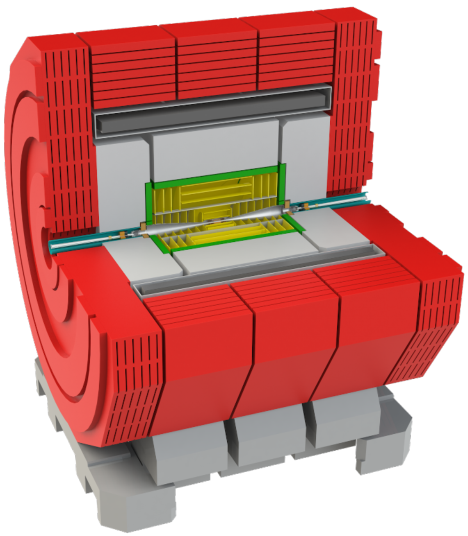


CLICdet basic characteristics:

- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (1.5 m radius)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ)

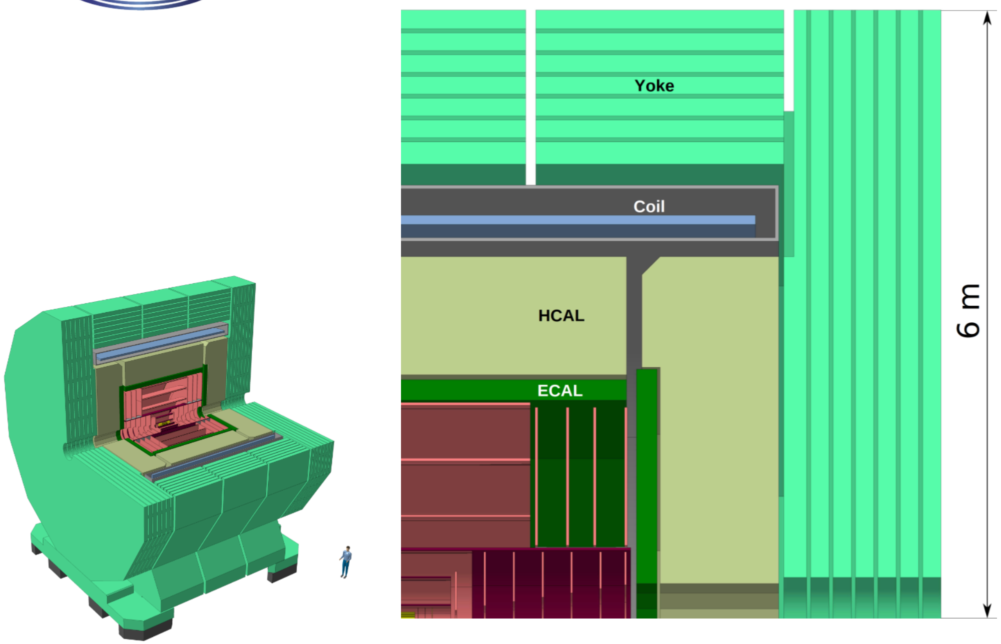
Precise timing:

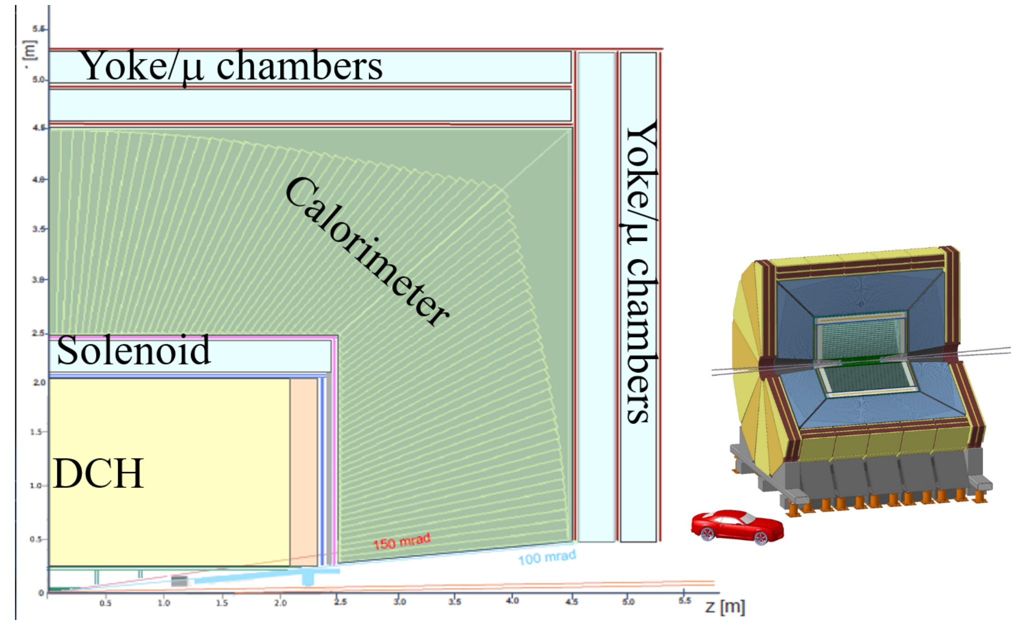
- ≈ 10 ns hit time-stamping in tracking
- 1 ns accuracy for calorimeter hits



CLICdp-Note-2017-001
arXiv:1812.07337

Reminder: FCC-ee detector designs





CLD concept (inspired by CLICdet):
- Smaller magnetic field (limited by luminosity goal): 2 T
- Larger tracker radius (2.15 m) to keep similar momentum resolution
- Lower $\sqrt{s}$ → HCAL less deep

IDEA detector concept:
- B-field: 2 T
- Vertex detector: 5 MAPS layers
- Drift chamber with PID, radius: 2 m, 112 layers → low material budget
- Double read-out calorimetry
- Instrumented return yoke

arXiv:1911.12230

Introduction: physics performance

- A set of common tools for particle flow analysis, jet clustering, kinematic fits, and flavour tagging has been developed for linear collider detector studies in full simulation → see talk by Daniel Jeans on simulations

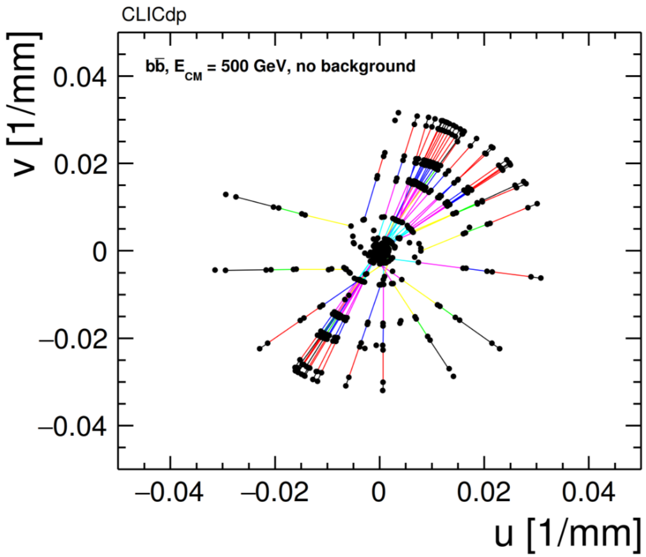
- These were used for the performance evaluation and optimisation of the ILD, SiD, CLICdet, CLD detectors → results are considered conservative as further improvement possible in many cases

- The physics potential of FCC-ee for Higgs and top physics was established (directly or indirectly) with linear collider full simulations

- Physics performance of IDEA studied using stand-alone simulations of various detector components, integration of full detector ongoing → see talk by Daniel Jeans on simulations

- In the future even more exchange of software tools through Key4hep → see talk by Gerado Ganis (the existing e^+e^- algorithms are being adapted or ported)

Tracking in full simulation: silicon

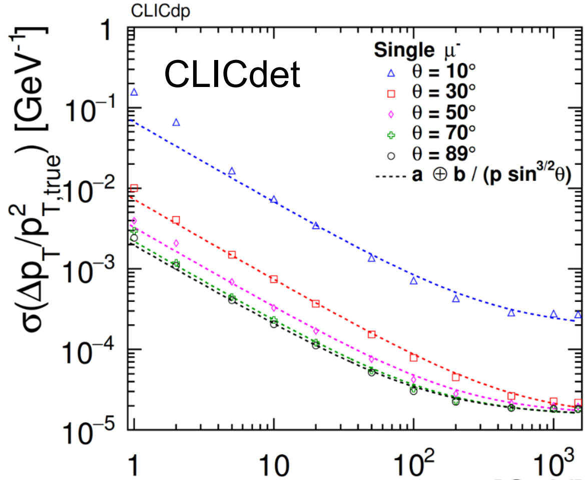


Example: “Conformal tracking”
→ Cellular automaton in conformal space for track finding used in CLICdet and CLD studies

$$u = x / (x^2 + y^2)$$
$$v = y / (x^2 + y^2)$$

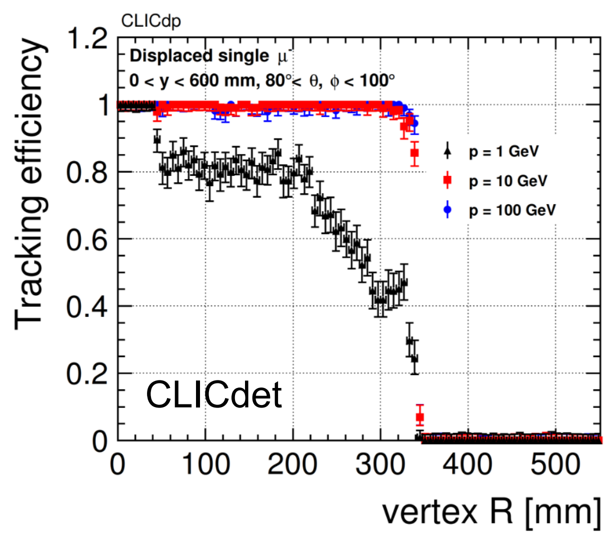
Nucl. Inst. Meth. A 956, 163304 (2020)

Momentum resolution

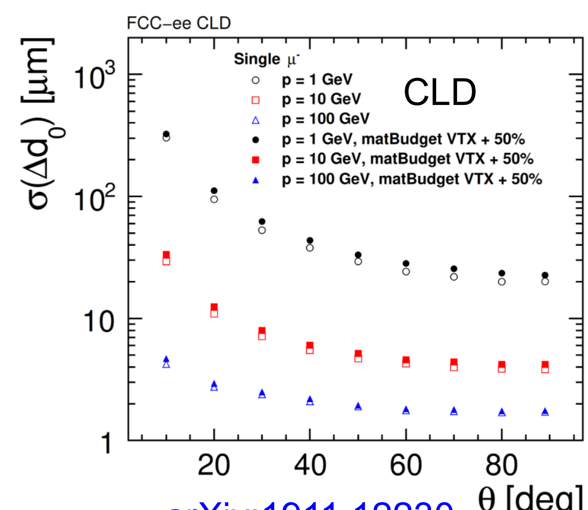


arXiv:1812.07337

Displaced tracks

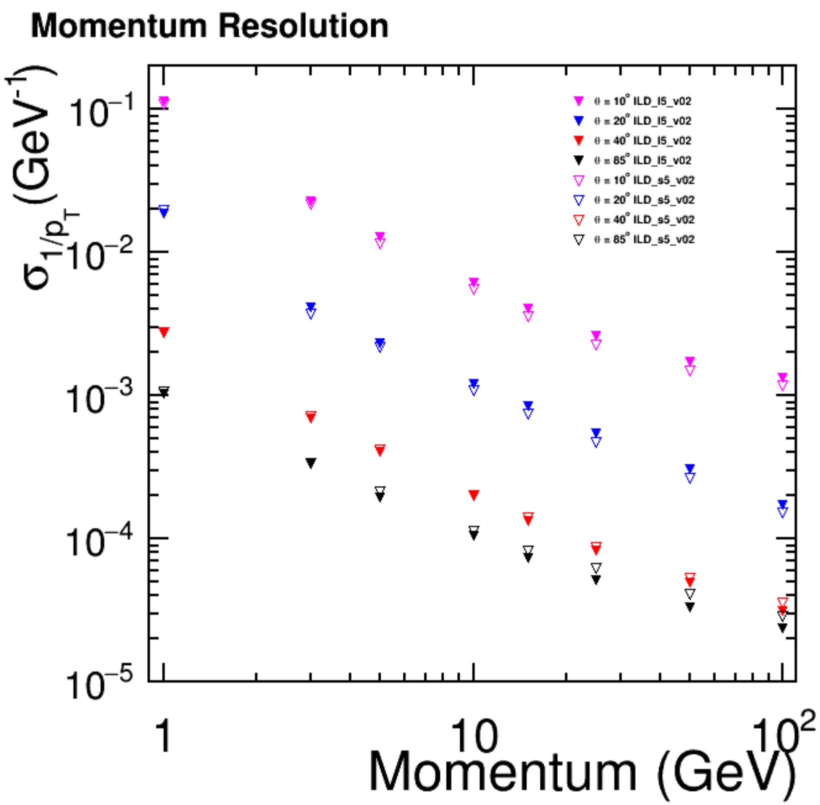


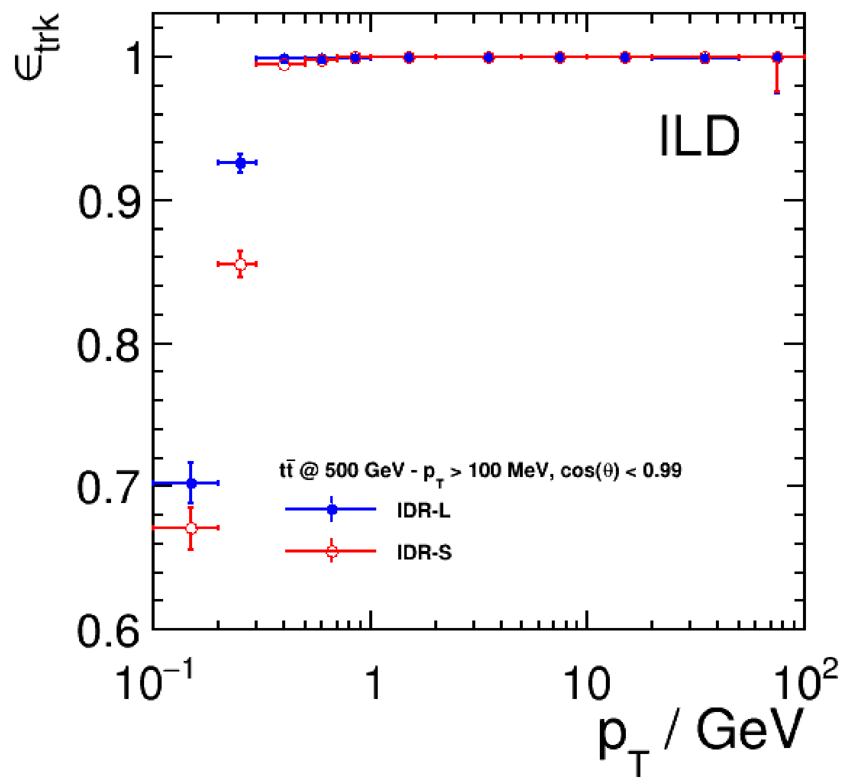
Detector optimisation



arXiv:1911.12230

Tracking in full simulation: ILD



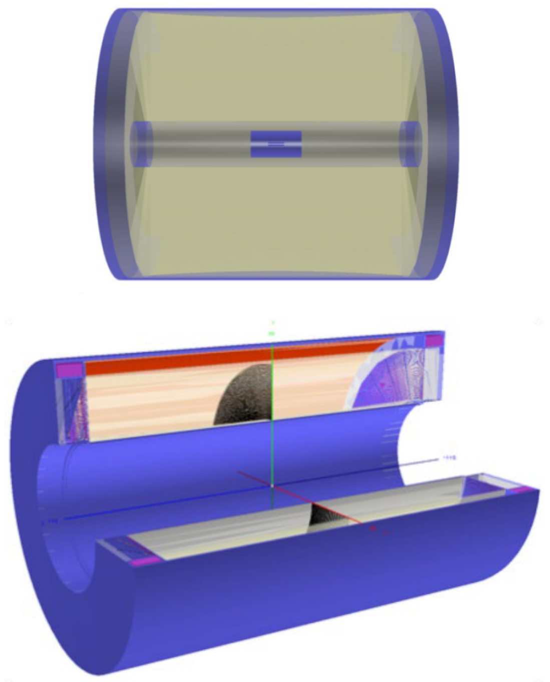


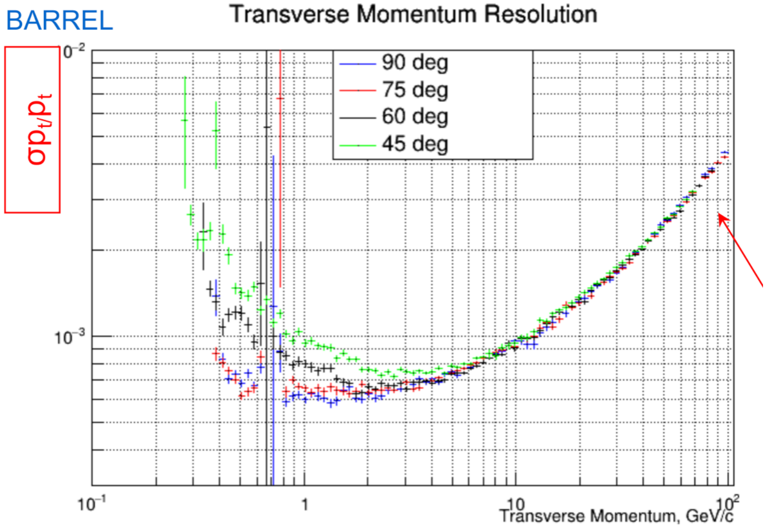
- **Momentum resolution:** larger detector slightly better in the barrel, worse in the forward (due to the magnetic field)
- **Efficiency in $t\bar{t}$ events:** larger detector better at low momentum (also due to the magnetic field)

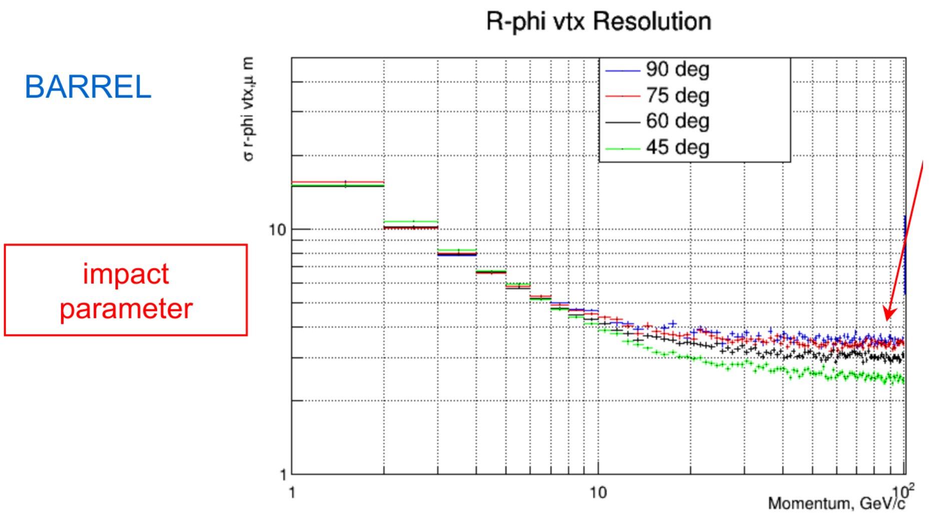
arXiv:2003.01116

Tracking for the IDEA drift chamber

Stand-alone Geant4 simulation:
- Detailed description of drift chamber
- Vertex detector and Si-wrapper simulated as simple layers







Drift chamber + vertex detector, single muons, no beam-induced background

N. De Filippis et al., FCC software meeting, 11/12/2020

Tracking: future usage of ACTS

Potential to exploit functionality provided in the framework of ACTS also for Higgs factory studies (e.g. to increase speed)

- ACTS aims to provide a toolkit for assembling a track reconstruction
- Current modules available:
  - Event Data Model (including time parameterisation)
  - Geometry
  - Propagation through all fields (Runge-Kutta-Nystroem integration)
  - Kalman Filter (KF) for track fitting
  - Combinatorial Kalman Filter (CKF) for track finding
  - Seeding
  - Primary vertex reconstruction
- In development:
  - Gaussian Sum Filter (GSF, electron reconstruction)
  - Global Chi2 Fitter (GX2F)
  - Secondary vertex reconstruction
  - Support for TPC through global KF formulation and GX2F
- R&D lines:
  - Parallelization (GPUs, …)
  - Machine Learning (Graph networks for track finding & vertexing, hashing, …)

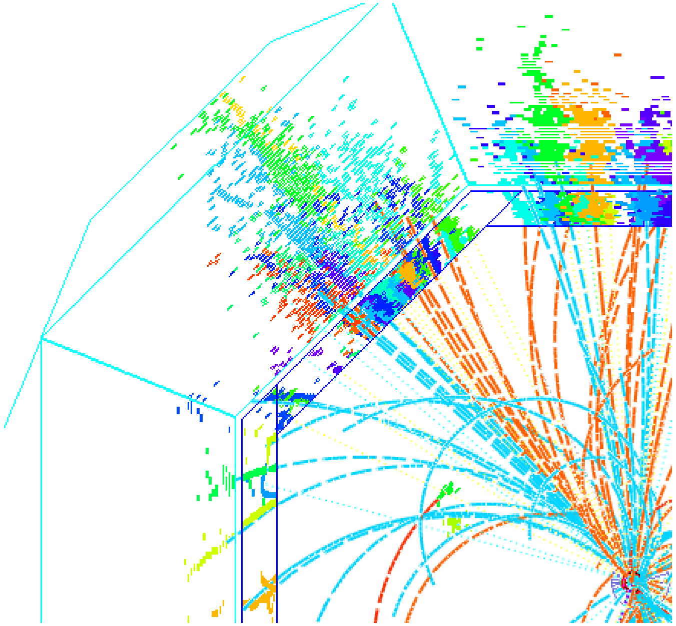
Andreas Salzburger

Particle flow calorimetry

Typical jet composition:
• 60% charged particles
• 30% photons
• 10% neutral hadrons

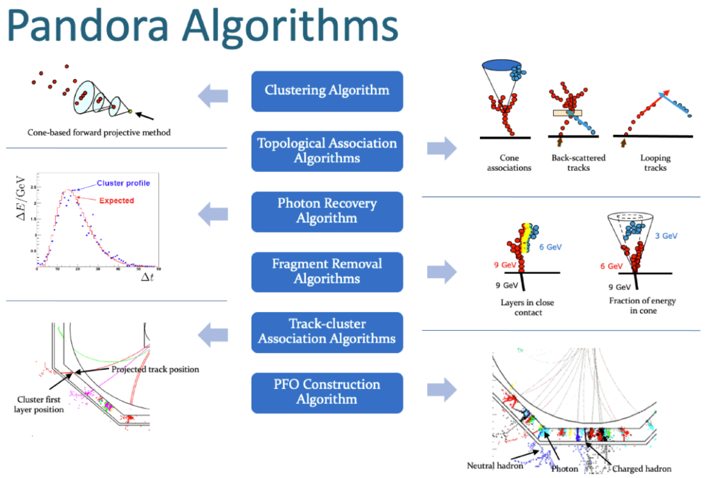
Always use the best available measurement:
• charged particles → tracking detectors:
• photons → ECAL:
• neutrals → HCAL:

Hardware and software!



• PandoraPFA is the de facto standard used for the ILD / SiD / CLICdet / CLD studies
→ Performance results on the following slides
→ Has been crucial for detector optimisation

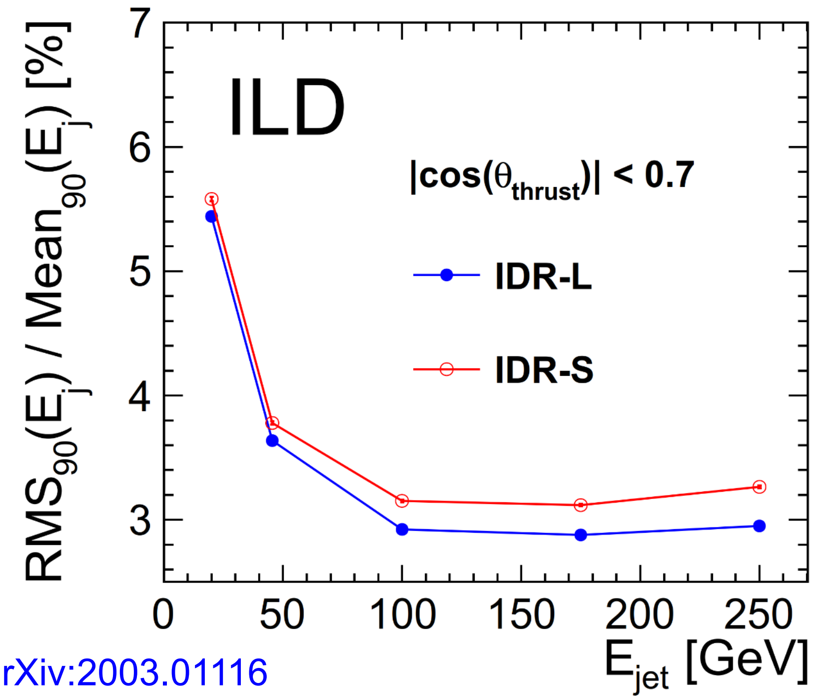
NIM **A 611**, 25 (2009)
NIM **A 700**, 153 (2013)
EPJ **C 75**, 439 (2015)



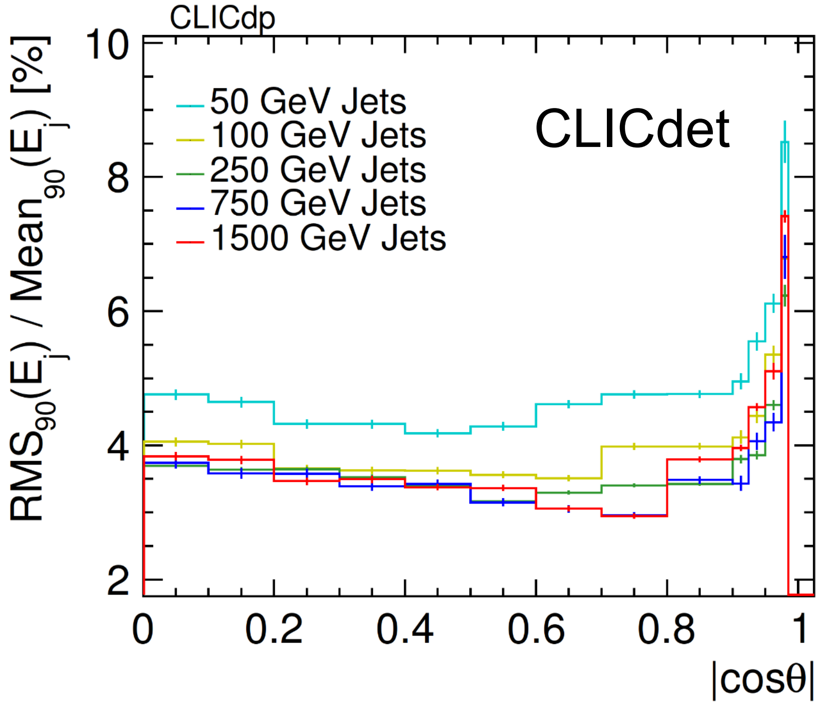
• Alternatives: Arbor (CEPC), April (ILD SDHCal)
→ Provide possibility to cross check

arXiv:1403.4784

PandoraPFA: basic performance



arXiv:2003.01116

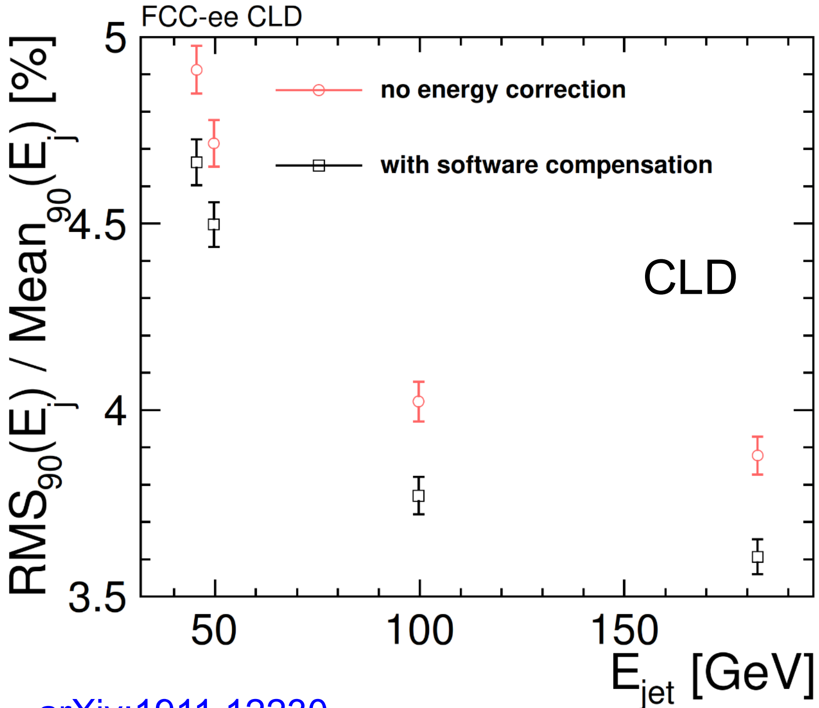


arXiv:1812.07337

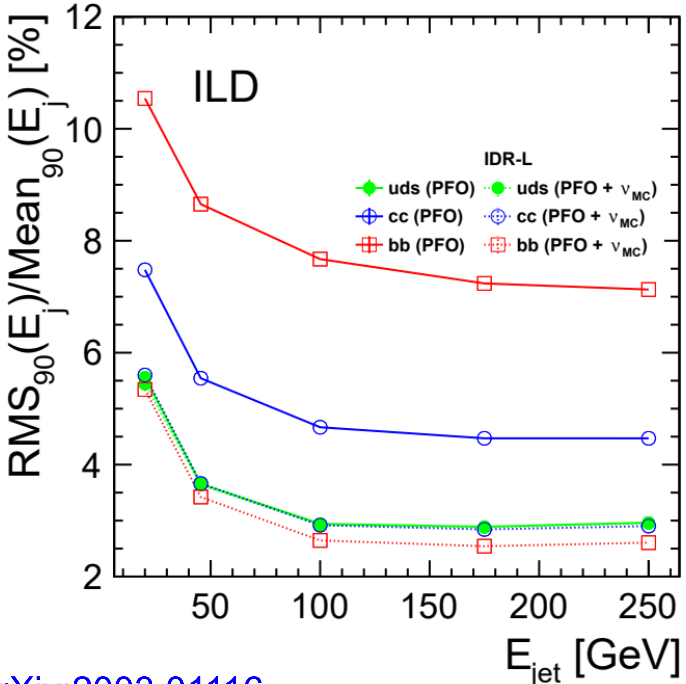
Jet energy resolution in di-jet events:

- Jet energy resolution requirement achieved (except in the very forward direction)
- Some differences in performance between the different detector parameters visible

PandoraPFA: a few more details



arXiv:1911.12230



arXiv:2003.01116

EPJ **C 77**, 698 (2017)

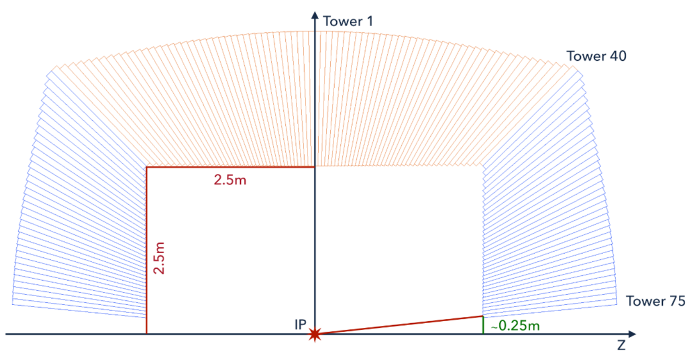
- Sizeable improvement from software compensation: use local energy density to discriminate electromagnetic and purely hadronic sub-showers within hadron showers

- Heavy-quark jets are much more difficult due to semi-leptonic decays
→ Much room for improvement (e.g. estimate neutrino momentum from leptons & secondary vertices, mass constrained fits of B-/D-decay chains, ...)

Towards PFA with the IDEA detector

Stand-alone Geant4 simulations of two variants:

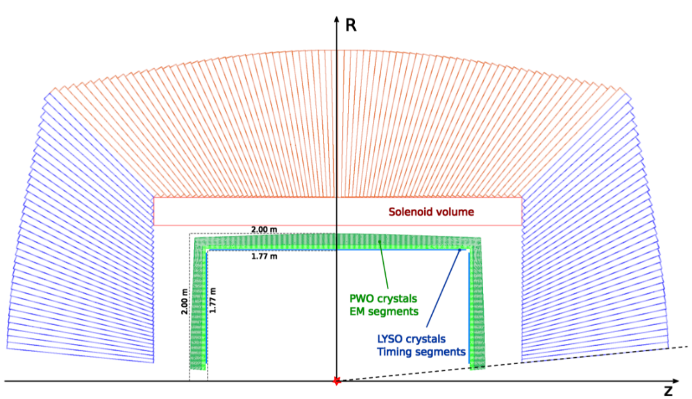
1.) Dual readout: Cherenkov and scintillation signals



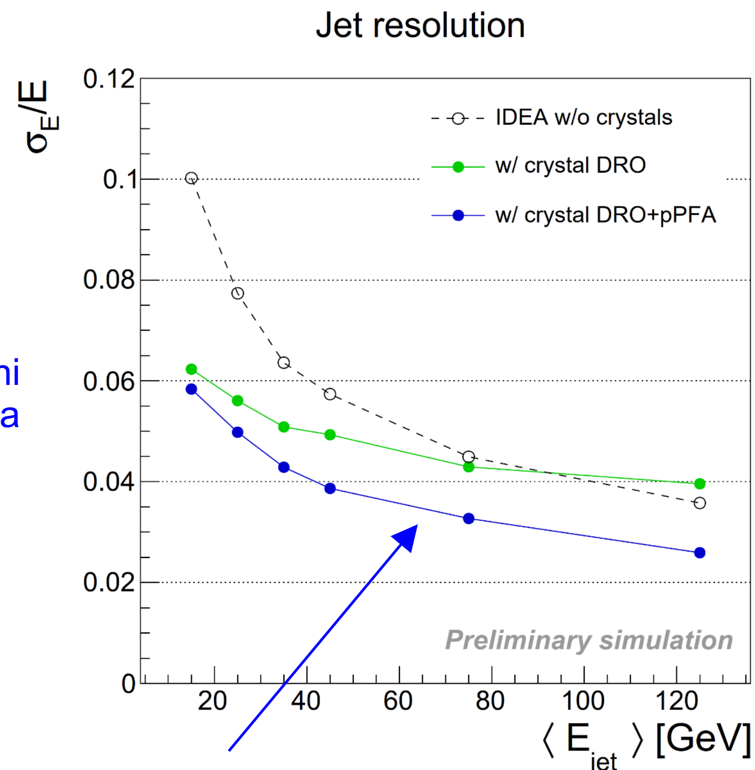
2.) Dual readout + crystal ECAL:

• Electromagnetic resolution from PbWO crystals inside solenoid ≈ 3% / √E

→ Important for $\pi^0 \rightarrow \gamma\gamma$ reconstruction



M. Lucchini
T. Shemma
Ch. Tully



First PFA estimate
(using MC information for tracking and photon ID)

NB: τ-lepton identification and π^0/γ separation studied using machine learning for the IDEA dual readout calorimeter

L. Pezzotti, IDEA collaboration meeting 2021

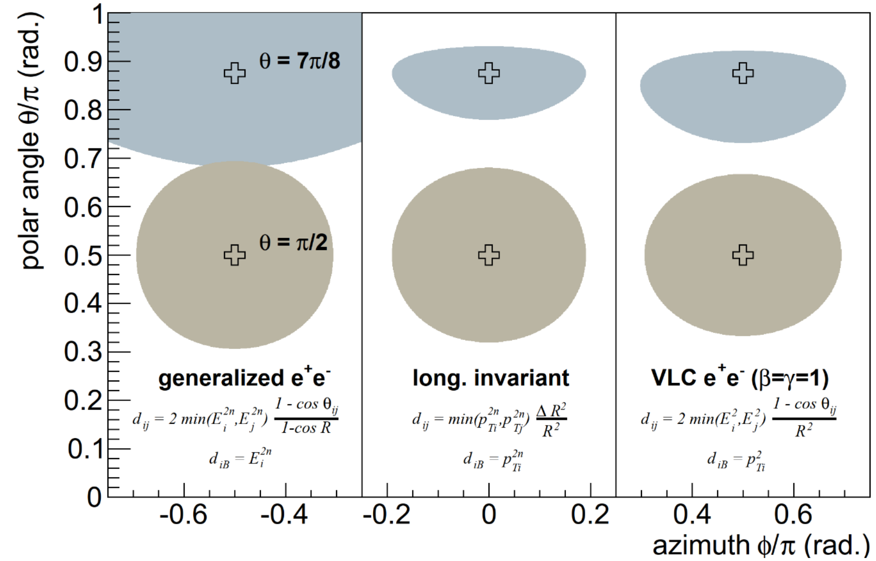
Jet clustering algorithms

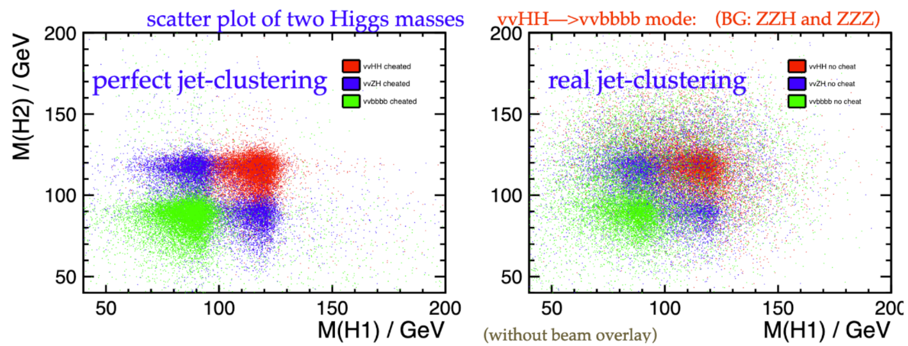
Additional challenges compared to LEP / SLC:

- **Beam-induced backgrounds:**
In the forward direction, modest compared to LHC environment
→ Retain exclusive clustering with k_t algorithm (best invariant mass resolution for hadronic resonances)
→ Use appropriate beam distance for robustness against background where needed

- **Complex multi-jet final states and harder gluon emissions at higher energies:**
e.g. Higgs self-coupling, $e^+e^- \to t\bar{t}$, $e^+e^- \to t\bar{t}H$, …
→ Impact of confusion in the jet clustering non-negligible
→ Interesting application for machine learning

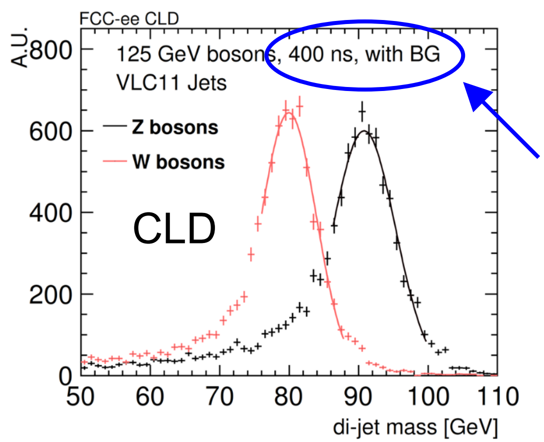
EPJ **C 78**, 144 (2018)





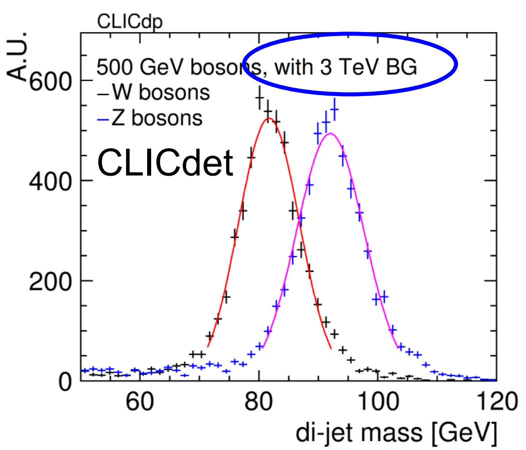
Separation of hadronic W/Z decays

Full simulation



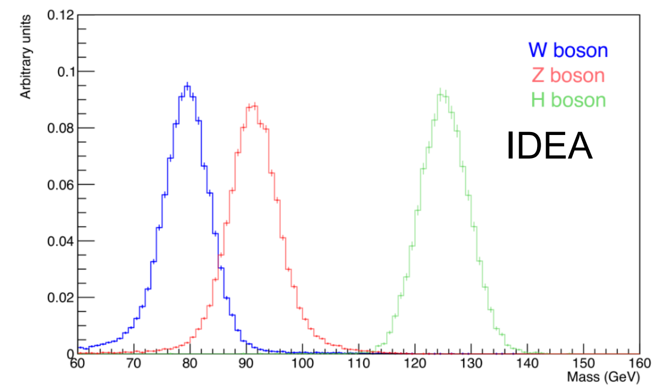
Beam-induced back-ground for 365 GeV FCC-ee

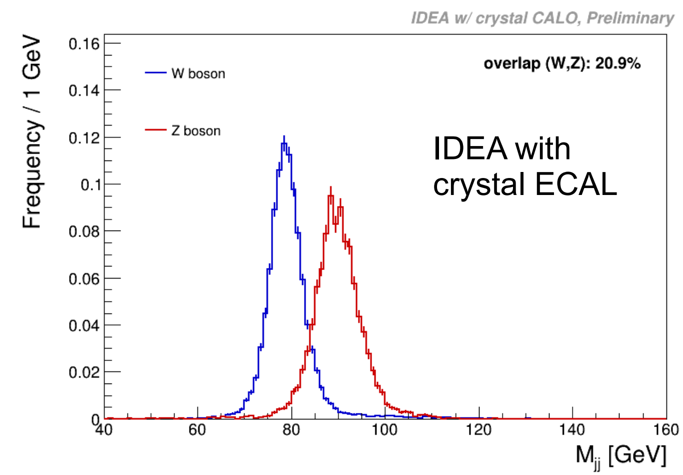
arXiv:1911.12230
arXiv:1812.07337



→ Separation of hadronic W and Z decays on 2 - 2.5σ level over a very large energy range
→ Particle flow reconstruction and jet clustering robust against experimental conditions

Stand-alone calorimeter simulation





• E(W/Z) = 120 GeV, no semileptonic decays
→ Very promising, to be studied in full simulation

Kinematic fitting

- Well established technique for s-channel processes, MarlinKinFit used for several linear collider physics studies: $e^+e^- \to W^+W^-, t\bar{t}, ZHH, \ldots$

- Important to include energy loss from ISR and Beamstrahlung above threshold

    NIM **A 624**, 184 (2010)

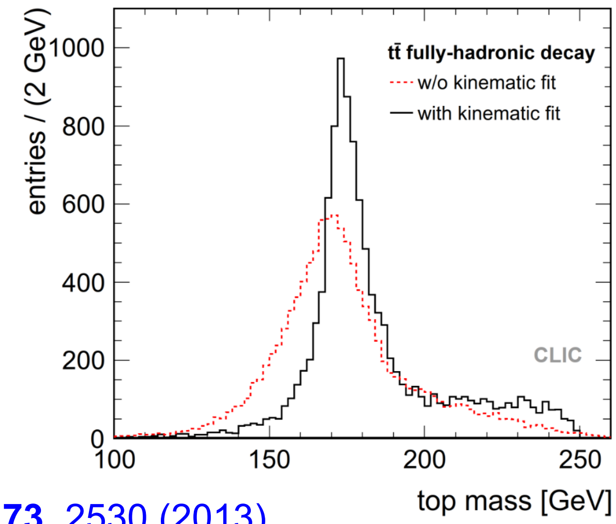
- Recent / ongoing developments:
  - Correction for semileptonic decays in c-/b-jets → important for Higgs physics
  - Jet error estimation from individual particle flow objects

    DESY-THESIS-2016-027
    DESY-THESIS-2017-045
    Y. Radkhorrami, LCWS 2021

- Kinematic fitting for W mass and width extraction studied also for FCC-ee

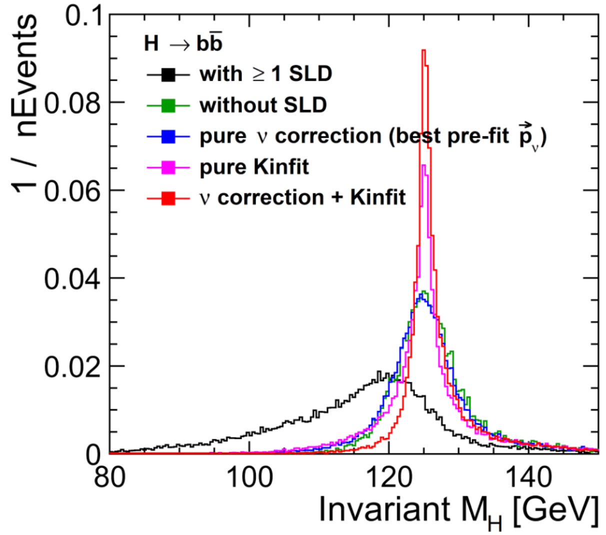
    CERN-THESIS-2019-291

Example: $e^+e^- \to t\bar{t} \to qqqqbb$ at 500 GeV



EPJ **C 73**, 2530 (2013)

Example: $e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$ at 250 GeV

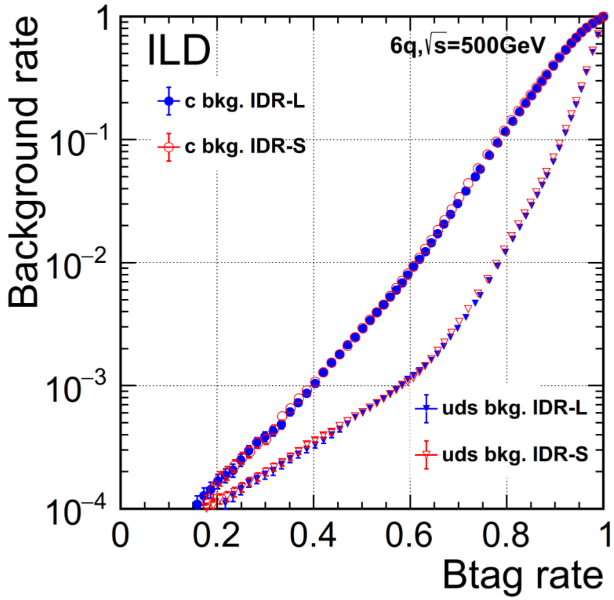


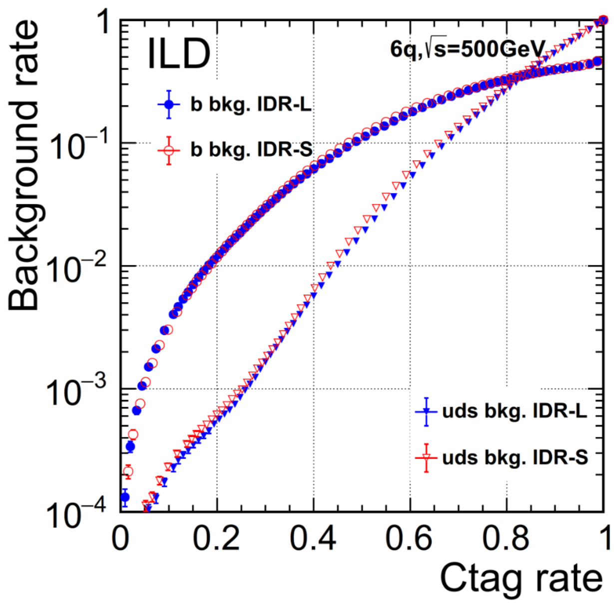
Flavour tagging

• Common tool: LCFIPlus (originally developed for the linear collider studies)
→ Includes vertex finding, jet clustering and flavour tagging (using BDTs from TMVA)

• High granularity and compact geometry of vertex detectors well suited for charm tagging (e.g. for $H \to c\bar{c}$)

Example: b- and c-tagging performance for $e^+e^- \to qqqqqq$ events in the ILD detector at $\sqrt{s}$ = 500 GeV



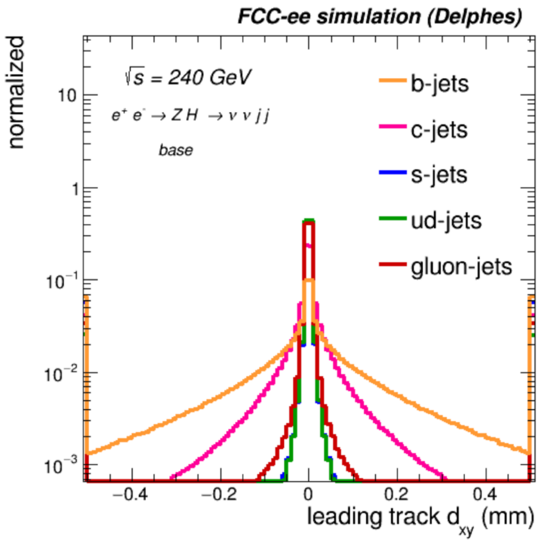


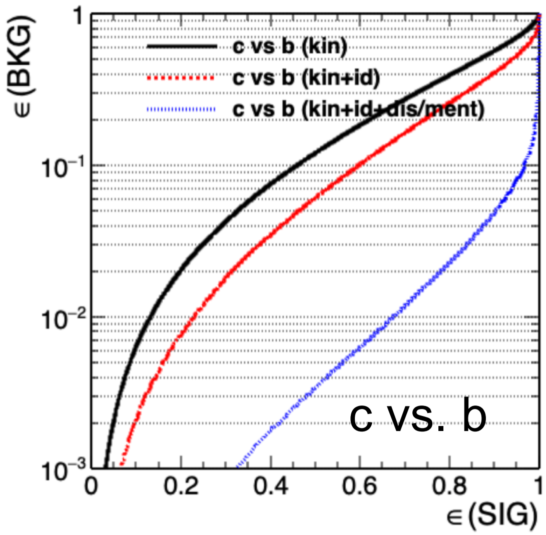
arXiv:2003.01116
Nucl. Inst. Meth. A 808, 109 (2016)

Flavour tagging: recent developments

- Possible improvements to LCFIPlus: faster vertex finding, refined treatment of material, …
- Exploration of additional possibilities: strange-quark tagging, …
- Several ongoing studies introducing advanced machine learning techniques to flavour tagging

→ Profiting from work for LHC in this area, example:





Advanced flavour tagging:

- Algorithm based on ParticleNet
- First focus on Higgs physics: $H \rightarrow c\bar{c}$, $H \rightarrow gg$, ...
- Fast simulation of the IDEA and CLD detectors (multiple scattering, but no secondary interactions)

→ First results very promising

L. Gouskos, 4th FCC Physics and Experiments Workshop

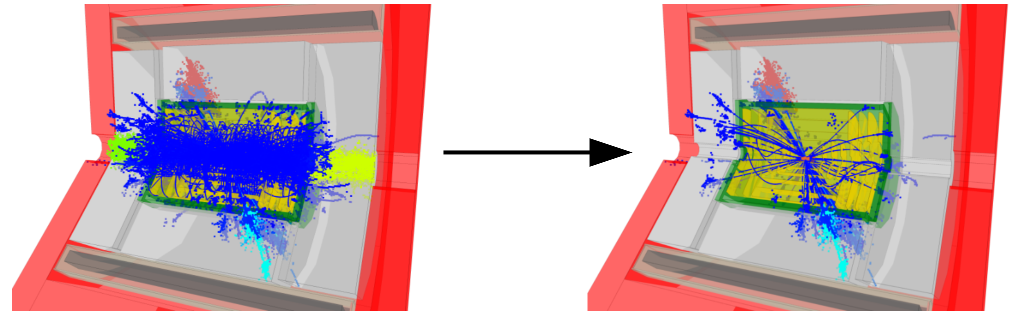
Usage of timing information

Timing with O(1) ns resolution:

• Assumed for CLIC to suppress pile-up from beam-induced background (by p_T-dependent timing cuts in individual reconstructed particles)

• Could potentially be exploited for other collider options, e.g. to suppress backscattered fragments

→ Benefit needs to be studied



$e^+e^- \rightarrow t\bar{t}$ at 3 TeV with background from $\gamma\gamma \rightarrow$ hadrons overlaid

Timing with ≈10 ps resolution:

• Recent interest triggered by recent developments for HL-LHC and other facilities

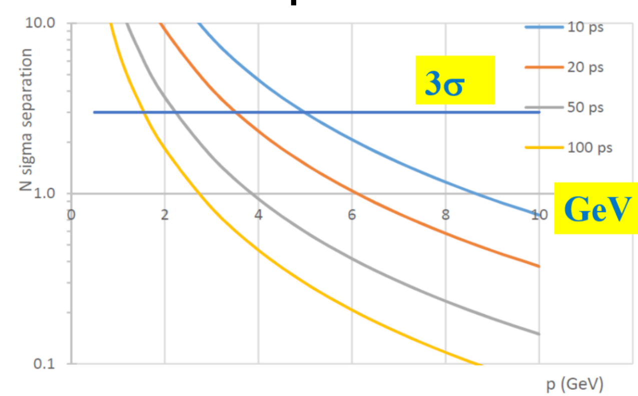
• Particle identification using time-of-flight: e.g. 3-sigma K/π separation up to 5 GeV for 10 ps measurement at R ≈ 2 m

• Identification of heavy long-lived particles, emerging jets, …

• Full 5D particle flow to reduce confusion (e.g. from “late” neutrons, improved photon position resolution)

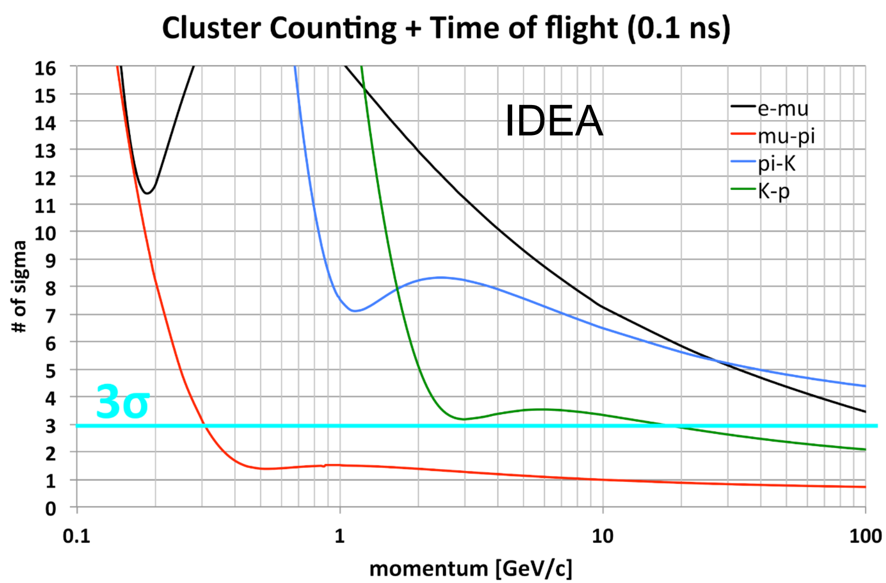
→ Need detailed simulation for all of these use cases

K/π separation

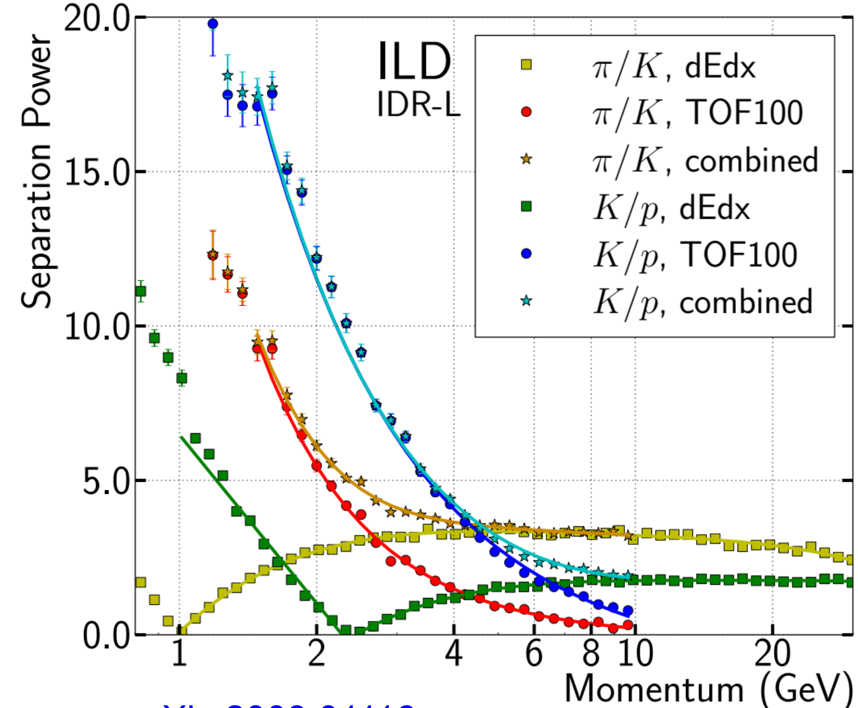


Particle ID

- dE/dx, dN/dx benefit from large gaseous tracking
- Timing can provide π/K(K/p)-separation around 1(2) GeV where dE/dx or dN/dx is not sensitive
- No study yet of dE/dx for silicon layers
- Could use PID in track / vertex re-fitting to improve momentum estimate



F. Grancagnolo, IAS HEP 2021 (analytic estimate)



arXiv:2003.01116

- Crucial for flavour physics at the Z-pole
- At higher energies helpful for b- and c-jet charge identification (via charged Kaons) for A_{FB} in $e^+e^- \to t\bar{t}/b\bar{b}/c\bar{c}$ events
- Aids the flavour tagging

Summary and conclusions

• Sophisticated reconstruction and high-level analysis tools are needed to demonstrate the physics potential of detector concepts for future Higgs factories

• The same software tools are crucial to optimise the detectors and provide input to the hardware studies

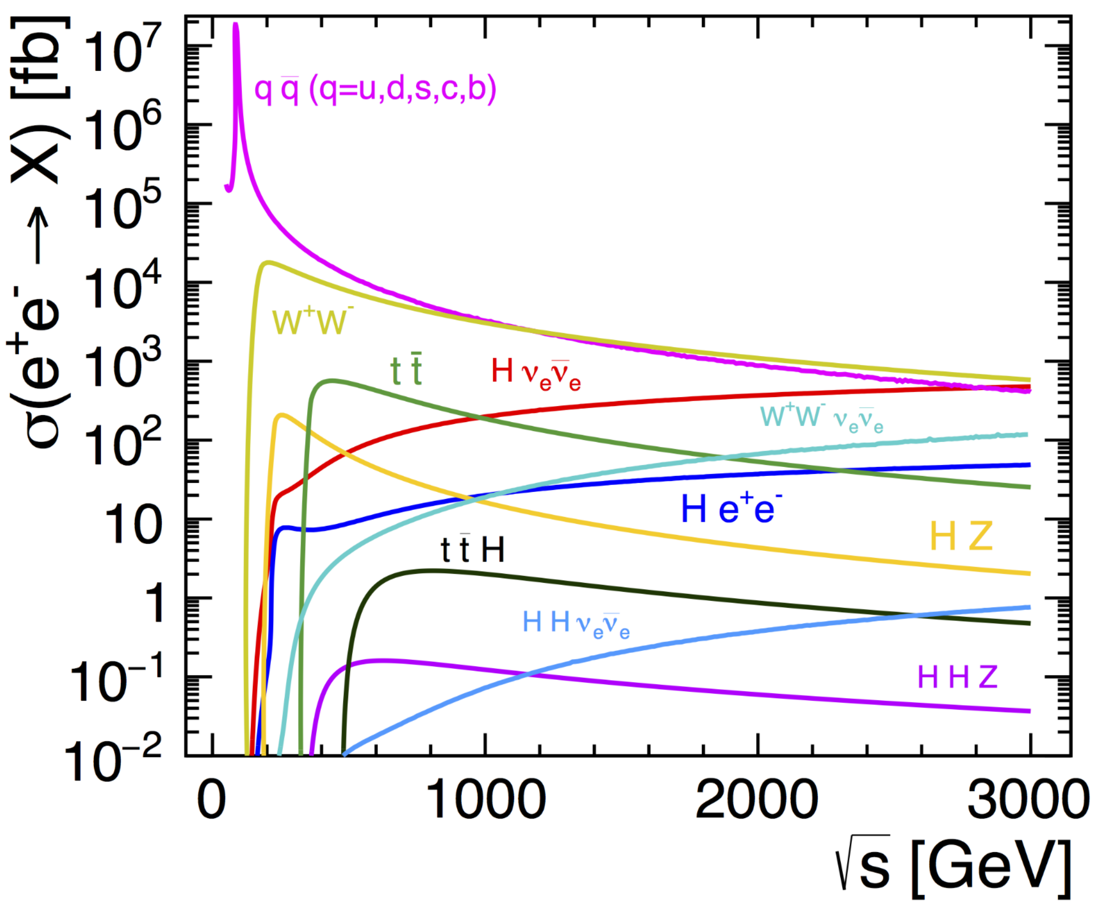
• The sharing of common tools among different collider options has already been essential
→ this will be intensified further through Key4hep

• New ideas, input and contributions from LHC physicists, machine learning experts, theorists are always welcome!

Thank you!

Backup slides

Important processes in e^+e^- collisions



- **2-fermion production,** e.g. $q\bar{q}$
- **W-boson pair production (WW)**
- **Higgsstrahlung (HZ):** best at 240 - 380 GeV → "Higgs factory"
- **$t\bar{t}$ threshold:** 350 GeV
- **$t\bar{t}$ continuum:** ≥ 365 GeV
- **Double Higgsstrahlung (HHZ):** cross section maximum ≈ 600 GeV
- **Single and double Higgs in WW fusion ($H\nu_e\bar{\nu}_e$ and $HH\nu_e\bar{\nu}_e$):** cross section rises with energy

→ Wide range of physics opportunities, best explored in several energy stages

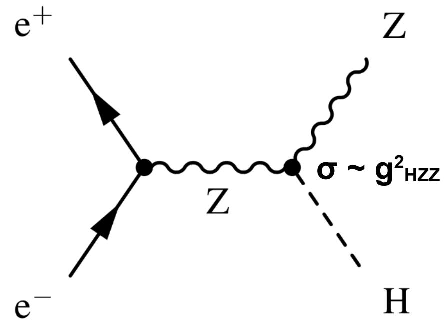
+ Direct searches for new particles:
highest possible energy

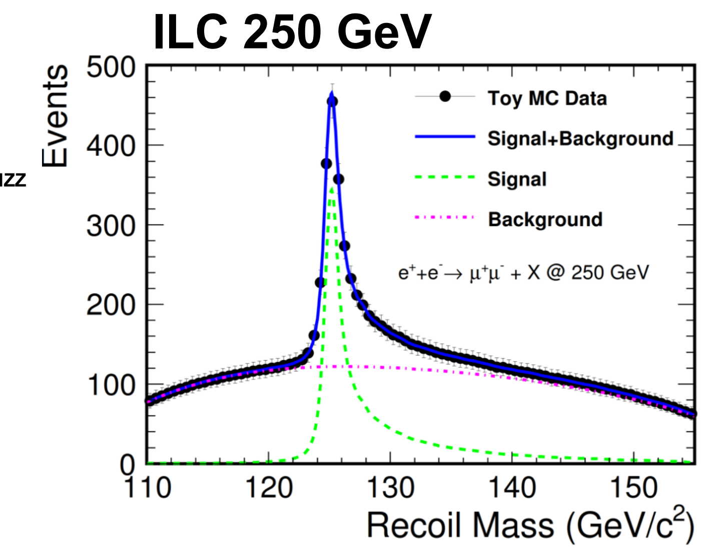
Higgs factory: $e^+e^- \rightarrow ZH$

Higgsstrahlung at e^+e^- colliders:
HZ events can be identified from the Z recoil mas
→ Model-independent measurement of the σ_{ZH} and the Higgs mass

$$m^2_{recoil} = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

Known at lepton collider

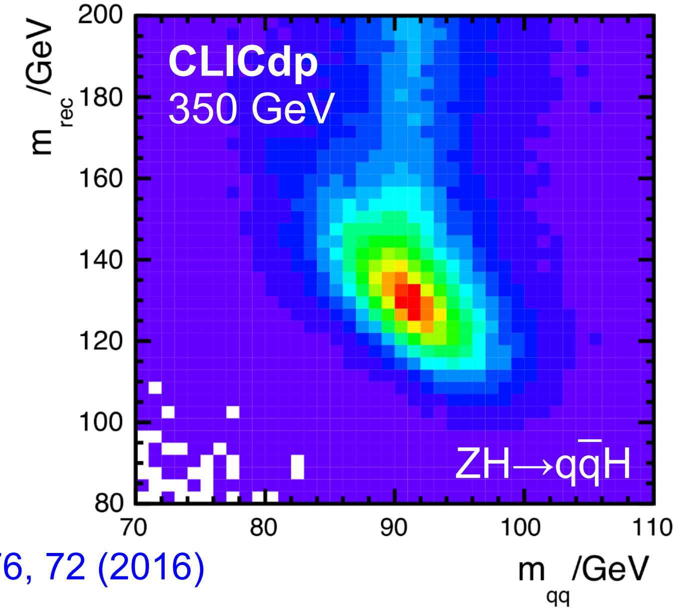




Phys. Rev. D 94, 113002 (2016)

$Z \rightarrow e^+e^-$ or $\mu^+\mu^-$:
- Best precision at 240-250 GeV (ILC / FCC-ee / CEPC)
- Cross section at maximum, impact of beam energy spectrum & ISR smallest
- Relevant detector parameter: tracking momentum resolution

$Z \rightarrow q\bar{q}$:
- Best precision at 350-380 GeV (ILC / FCC-ee / CLIC)
- Main backgrounds: WW / single-W / ZZ production
- Relevant detector parameter: jet energy resolution

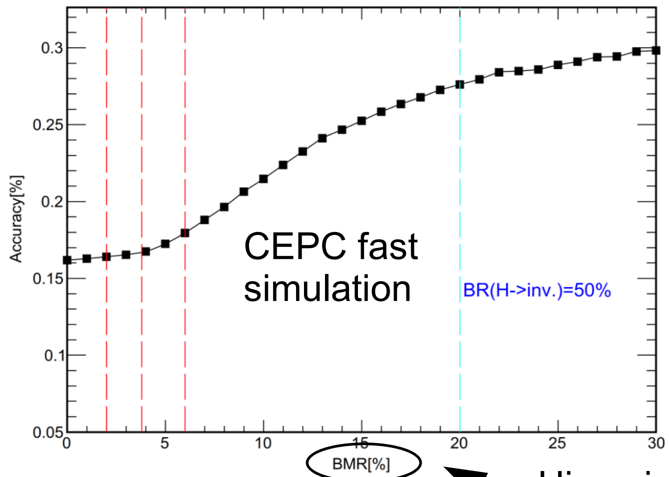


Eur. Phys. J. C 76, 72 (2016)

Higgs factory: other measurements

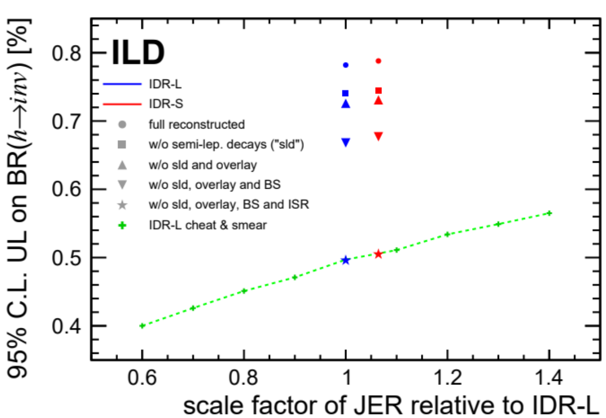
Exploration of all possible Higgs decay modes (including non-SM decays)

Example: H → inv. using ZH; Z→$q\bar{q}$



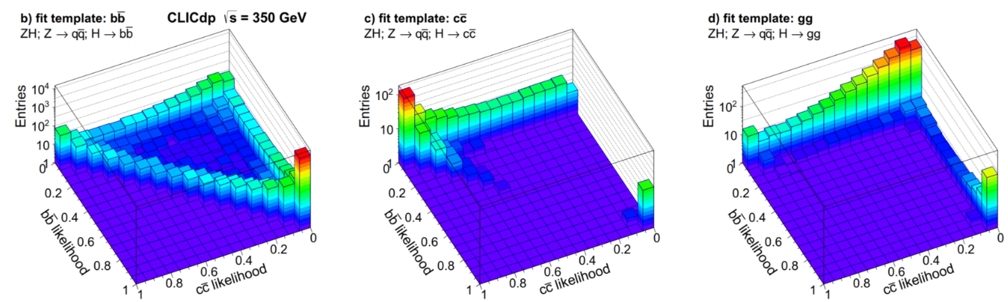
Higgs invariant mass resolution

arXiv:2001.05912



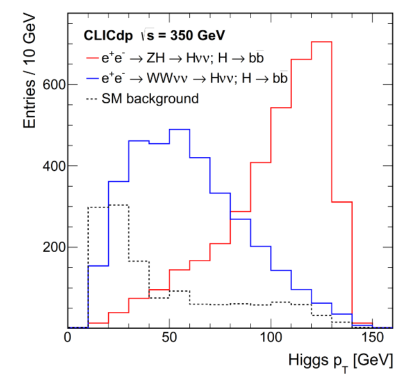
arXiv:2003.01116

Example: H → $b\bar{b}$/$c\bar{c}$/gg at $\sqrt{s}$ = 350 GeV CLIC



H→$b\bar{b}$ H→$c\bar{c}$ H→gg

→ Good charm tagging capability needed (small decay length)



Eur. Phys. J. C 77, 475 (2017)

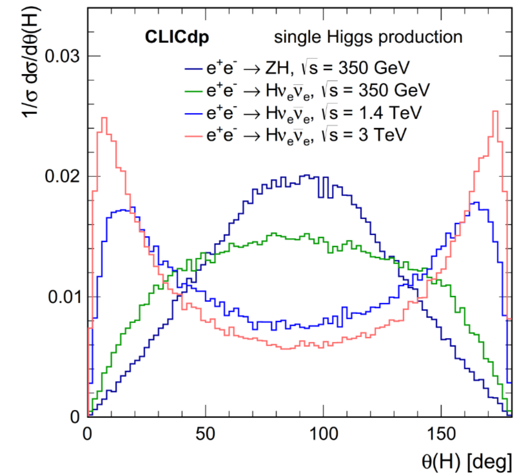
What about very high energies?

1. The forward detector region is increasingly important
Cross sections for VBF processes (e.g. single or double Higgs production) rise with energy

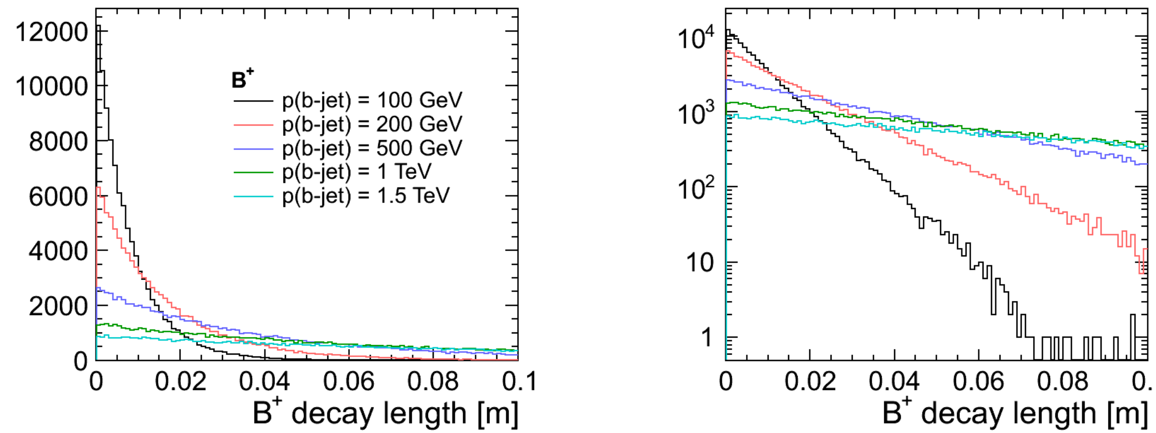
2. Boosted object reconstruction is crucial
The indirect sensitivity of 2→2 scattering processes rises very strongly with energy despite falling cross sections:

- $e^+e^- \rightarrow W^+W^-$ and ZH: tagging of boosted W/Z/H bosons arXiv:1911.02523
- $e^+e^- \rightarrow t\bar{t}$: boosted top tagging JHEP 11, 003 (2019)
- $e^+e^- \rightarrow b\bar{b}$: large secondary vertex decay lengths, very collimated decay b- and c-hadron decay products

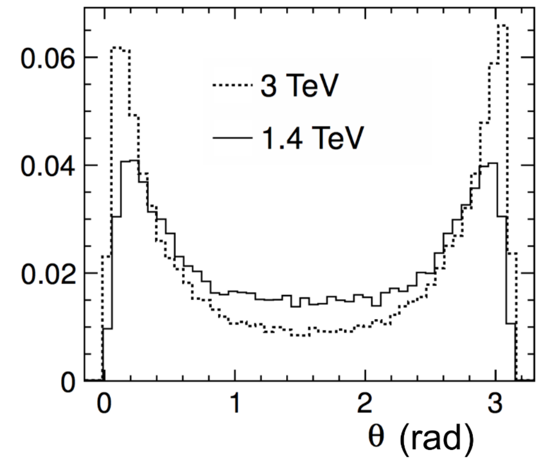
Higgs polar angle in $e^+e^- \rightarrow H\nu\bar{\nu}$ events



B^+ meson decay length for different b-jet energies



Higgs polar angle in $e^+e^- \rightarrow HH\nu\bar{\nu}$ events



Physics motivations detector requirements (1)

- **Momentum resolution**
(e.g. Higgs recoil mass, $H \to \mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2-5\times10^{-5}\,GeV^{-1}$$

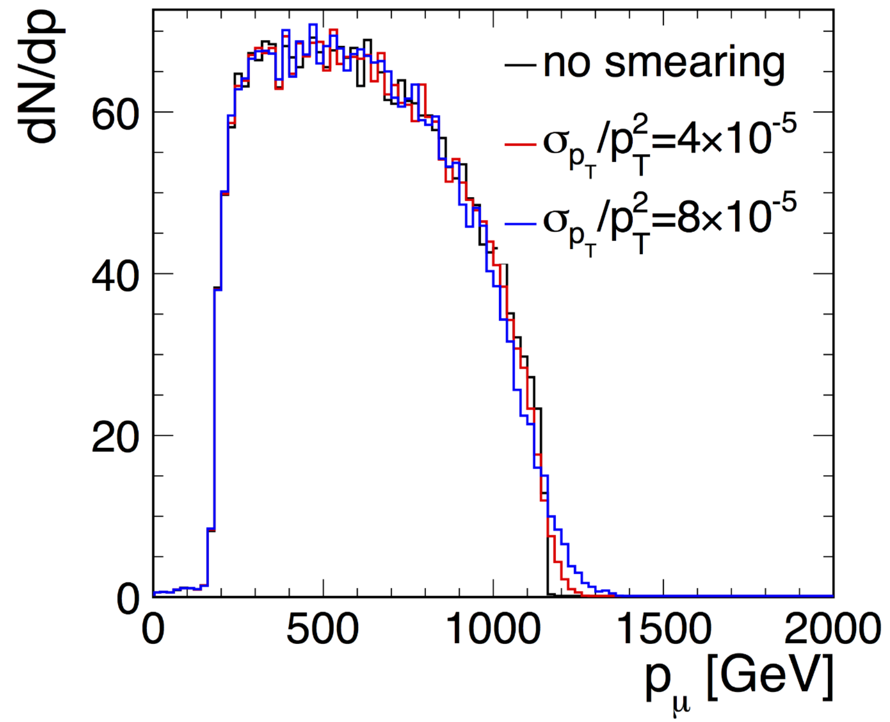
- **Jet energy resolution**
(W/Z/H separation, e.g. σ_{ZH}, H→inv.)

$$\frac{\sigma(E)}{E} \sim 3-5\%\ for\ E \geq 50\,GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2/(p^2 \sin^3\theta)},\ a \approx 5\,\mu m,\ b \approx 10-15\,\mu m$$

- **Lepton identification, very forward electron tagging**



$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

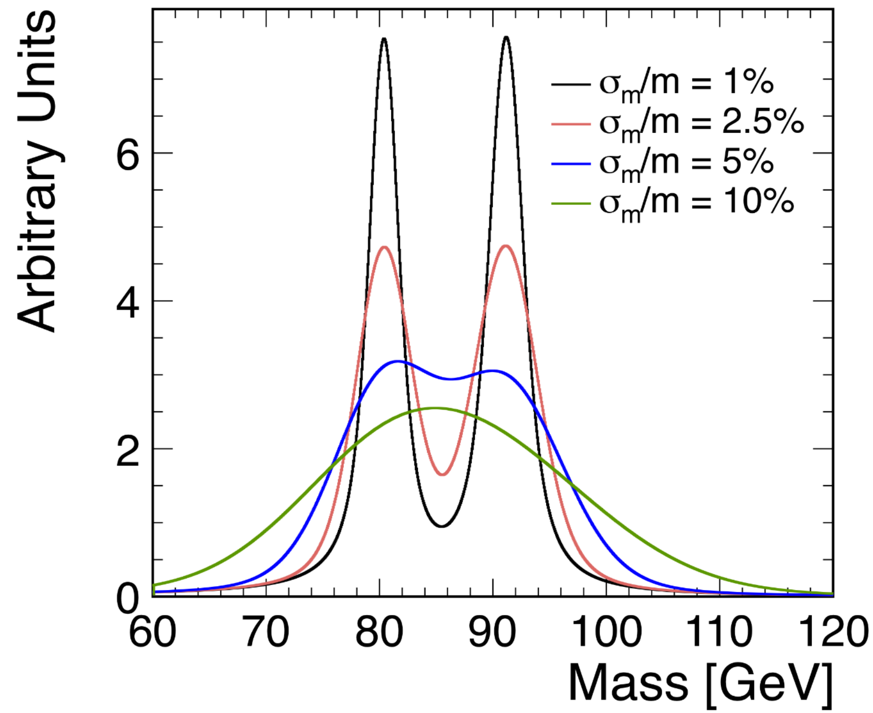
Physics motivations detector requirements (2)

- **Momentum resolution**
(e.g. Higgs recoil mass, $H \rightarrow \mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2-5\times 10^{-5}\,GeV^{-1}$$

- **Jet energy resolution**
(W/Z/H separation, e.g. σ_{ZH}, H→inv.)

$$\frac{\sigma(E)}{E} \sim 3-5\% \;\; for\; E \geq 50\,GeV$$



- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

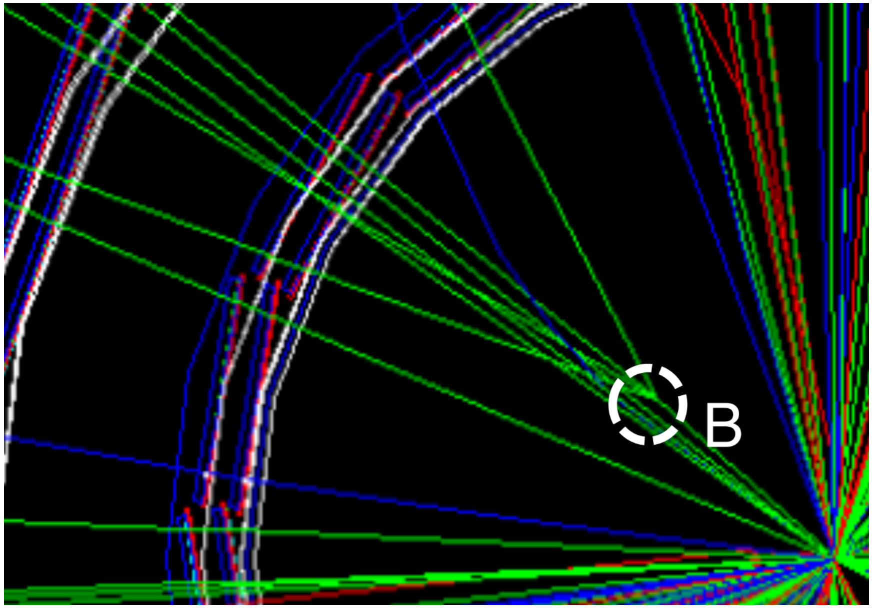
$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3\theta)}\,,\; a \approx 5\,\mu m\,,\; b \approx 10-15\,\mu m$$

- **Lepton identification, very forward electron tagging**

Physics motivations detector requirements (3)

- **Momentum resolution**
(e.g. Higgs recoil mass, H → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2-5\times10^{-5}\,GeV^{-1}$$



- **Jet energy resolution**
(W/Z/H separation, e.g. σ_{ZH}, H→inv.)

$$\frac{\sigma(E)}{E} \sim 3-5\%\ for\ E \geq 50\,GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

For the considered vertex detector designs

$$\sigma(d_0)=\sqrt{a^2+b^2\cdot GeV^2/(p^2\sin^3\theta)},\ a\approx5\,\mu m,\ b\approx10-15\,\mu m \rightarrow \sigma_{SP}\approx3\,\mu m$$

- **Lepton identification, very forward electron tagging**

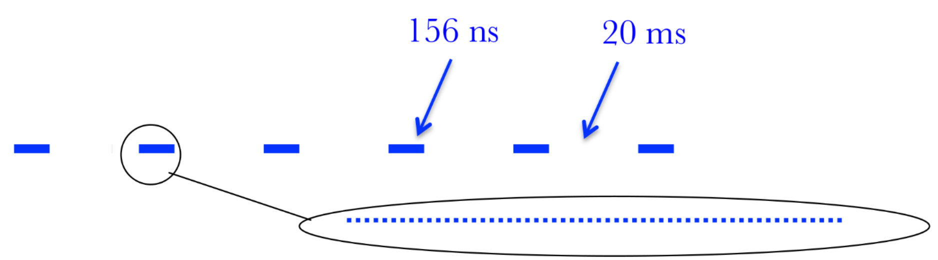
Linear collider beam parameters

Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity $\mathscr{L}$ ($10^{34}cm^{-2}sec^{-1}$)	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
$\mathscr{L}$ 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 σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44

Timing requirements for CLIC detector

Very small beams + high energy
→ Beamstrahlung
→ Beam-induced backgrounds

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



CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Circular collider 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 σ_x/σ_y (μm)				6.0/0.04	20.9/0.06
Bunch length (SR / BS) (mm) Beam size at IP σ_z (mm)	3.5 / 12.1	3.3 / 5.3	2.0 / 2.5	8.5	4.4

Example: 3 BX / 10 μs at 365 GeV FCC-ee
• Impact of beam-induced background to be mitigated through MDI and detector design (e^+e^- pairs dominant, γγ → hadrons and synchrotron radiation small in the detectors)
• Tracking detectors need to achieve good resolution without power pulsing

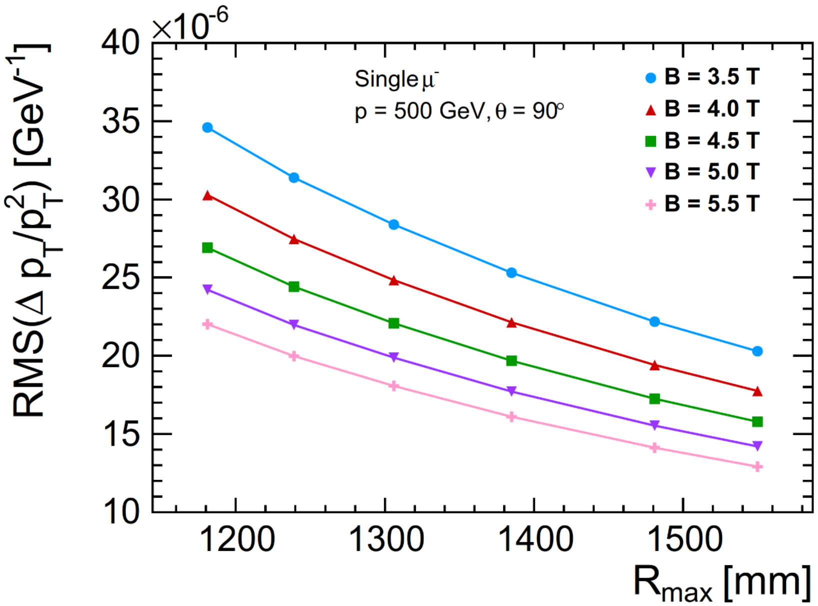
For reference: key detector parameters

	ILD (IDR_L/IDR_S)	**SiD**	**CLICdet**	**CLD**	**IDEA**	**CEPC baseline**
Vertex technology	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
Vertex inner radius	1.6 cm	1.4 cm	3.1 cm	1.75 cm	1.7 cm	1.6 cm
Tracker technololy	TPC + Silicon	Silicon	Silicon	Silicon	Drift chamber + Si	TPC + Silicon
Tracker outer radius	1.77 m / 1.43 m	1.22 m	1.5 m	2.1 m	2.0 m	1.8 m
Calorimeter	PFA	PFA	PFA	PFA	Dual readout	PFA
(ECAL) inner radius	1.8 m / 1.46 m	1.27 m	1.5 m	2.15 m	2.5 m	1.8 m
ECAL technology	Silicon	Silicon	Silicon	Silicon	-	Silicon
ECAL absorber	W	W	W	W	-	W
ECAL thickness	24 X_0 (30 layers)	26 X_0 (30 layers)	22 X_0 (40 layers)	22 X_0 (40 layers)	-	24 X_0 (30 layers)
HCAL technology	Scintillator	Scintillator	Scintillator	Scintillator	-	RPC
HCAL absorber	Fe	Fe	Fe	Fe	-	Fe
HCAL thickness	5.9 λ_I (48 layers)	4.5 λ_I	7.5 λ_I (60 layers)	5.5 λ_I (44 layers)	8 λ_I (2 m)	4.9 λ_I (40 layers)
(HCAL) outer radius	3.34 m / 3.0 m	2.5 m	3.25 m	3.57 m	≤4.5 m	3.3 m
Solenoid field	3.5 T / 4 T	5 T	4 T	2 T	2 T	3 T
Solenoid length	7.9 m	6.1 m	8.3 m	7.4 m	6.0 m	8.0 m
Sol. inner radius	3.42 m / 3.08 m	2.6 m	3.5 m	3.7 m	2.1 m	3.4 m

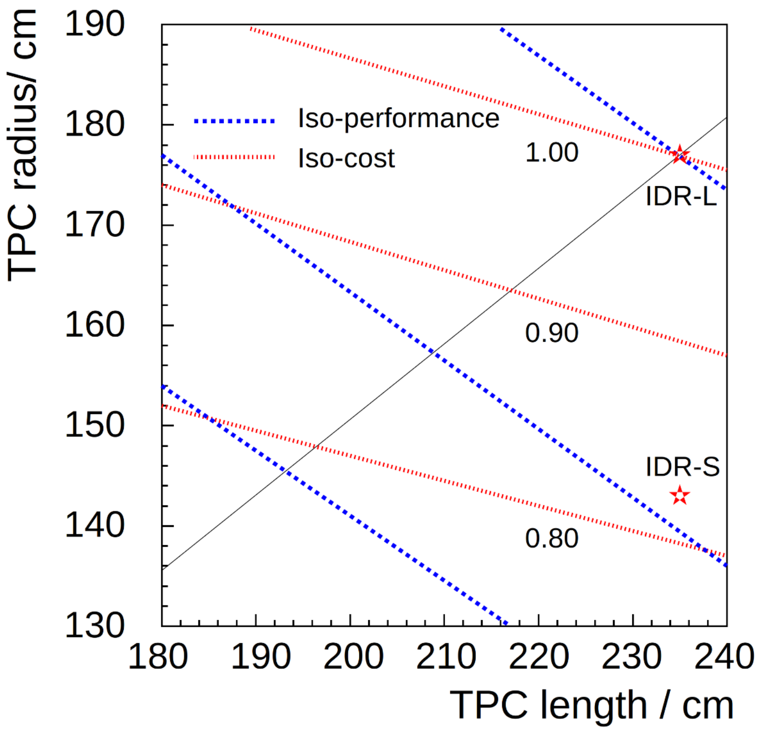
Majority of concepts based on PFA calorimetry → comparison of different choices can provide additional insight, e.g. IDR_S (TPC) vs. CLICdet (full silicon tracking), but similar magnetic field and tracker radius

Tracker size

Example: CLICdet



Example: ILD



- CLICdet: B = 4T, R_{max} = 1.5 m
- Choice of B-field and tracker radius also influenced by: PFA performance studies, occupancy in the vertex detector, technical considerations

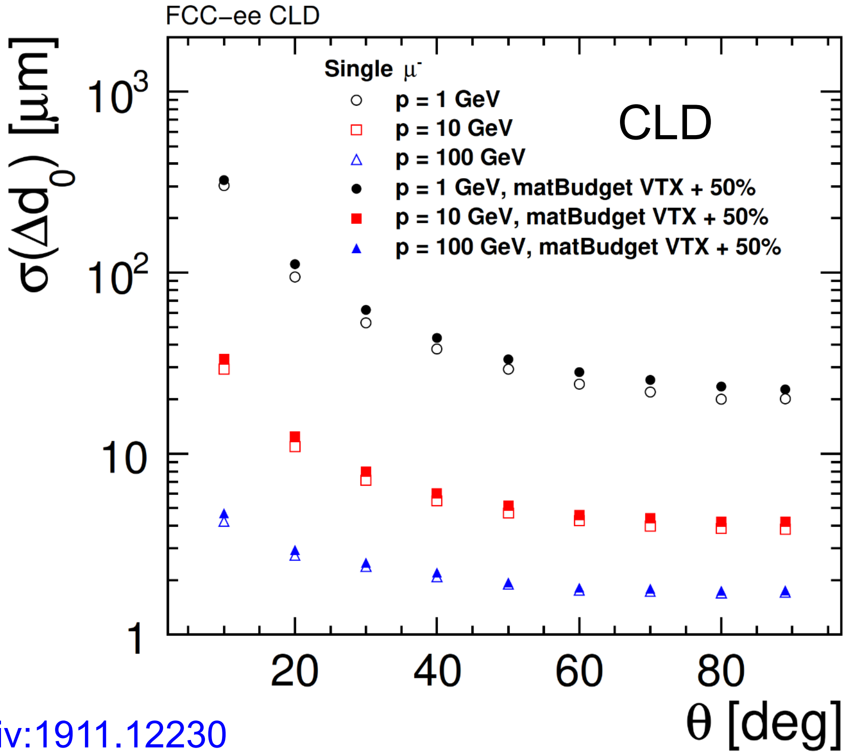
- Physics performance combines several tracking related quantities
- Magnetic field increased from 3.5 T (IDR-L) to 4 T (IDR-S) to compensate smaller TPC radius

CLICdp-Note-2017-001

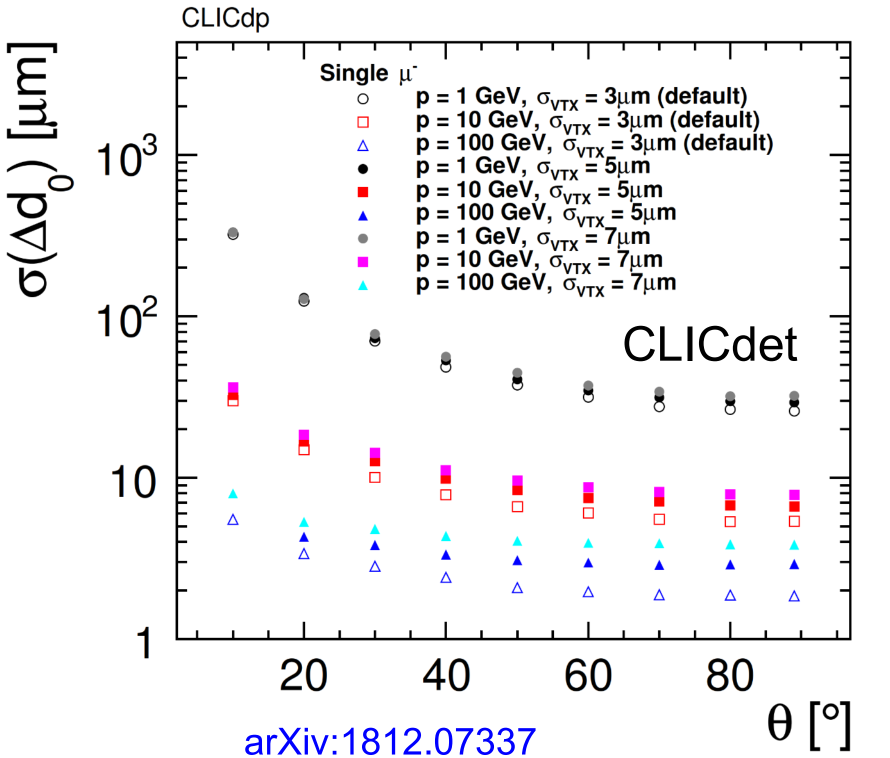
arXiv:2003.01116

Tracking: detector optimisation example

Modifications to the CLICdet and CLD vertex detectors:
- Impact parameter resolution with increased material (+50%)
- Worse single point resolution (3 μm → 5/7 μm)



arXiv:1911.12230



arXiv:1812.07337

→ Small effect of increased material budget (needs refinement of flavour tagging algorithm due to increased number of secondary interactions)
→ The single point resolution has a large impact on the impact parameter resolution at high p_T

Similar conclusions for CEPC baseline detector CEPC CDR, Volume 2

PFA: photon energy resolution

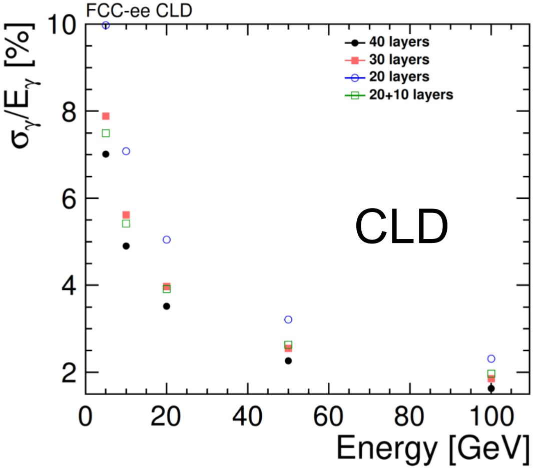
- Fine-grained sampling calorimeters with silicon or scintillator technology
- Tungsten absorber to minimise Molière radius and separate showers
- Increased number of layers gives better photon energy resolution (at additional cost)
- No impact on jet energy resolution

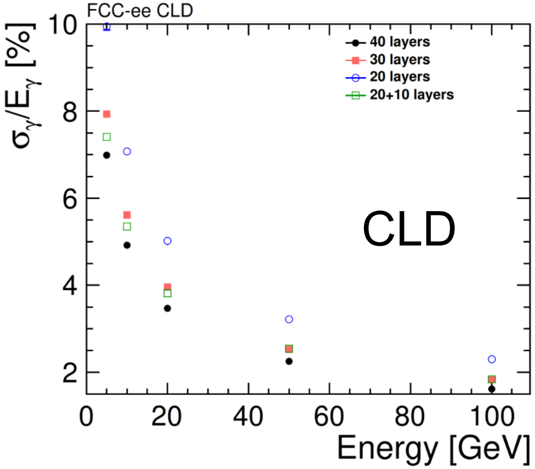
Example: ECAL options with different W layer thickness and 22 X_0 overall in CLD

Layer structure	Thickness tungsten alloy [mm]	Total thickness per layer [mm]
40 uniform	1.9	5.05
30 uniform	2.62	5.77
20 uniform	3.15	7.19
20 thin + 10 thick	1.9 + 3.8	5.05 + 6.95

Layer structure	JER [%] $\sqrt{s} = 365$ GeV	JER [%] $\sqrt{s} = 91.2$ GeV
40 uniform	3.62 ± 0.05	4.52 ± 0.06
30 uniform	3.72 ± 0.05	4.45 ± 0.06
20 uniform	3.78 ± 0.05	4.82 ± 0.07
20 thin + 10 thick	3.67 ± 0.05	4.56 ± 0.06

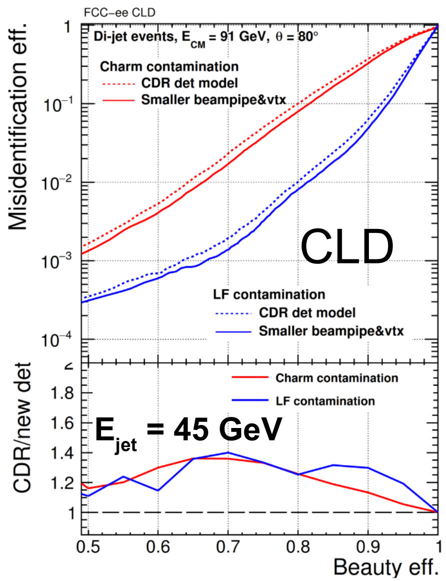
→ Jet energy resolution almost identical for the 4 ECAL options

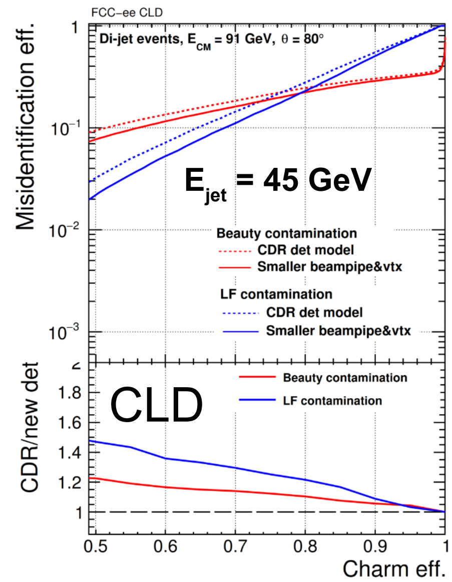


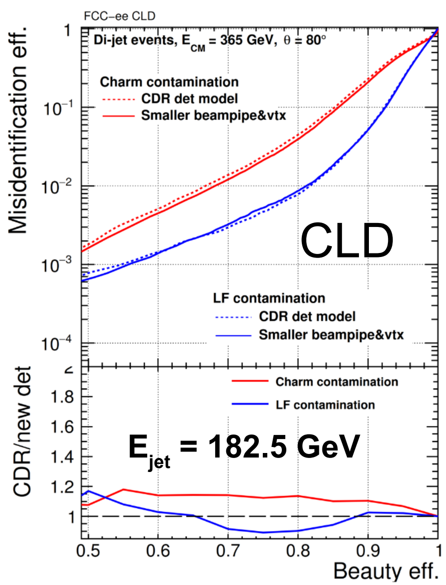


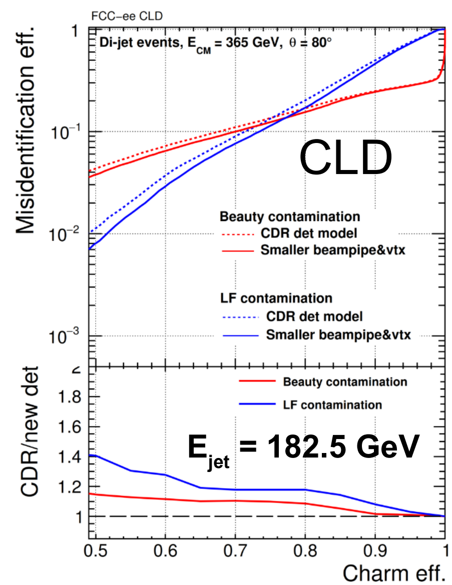
arXiv:1911.12230

Example: smaller beam pipe in CLD



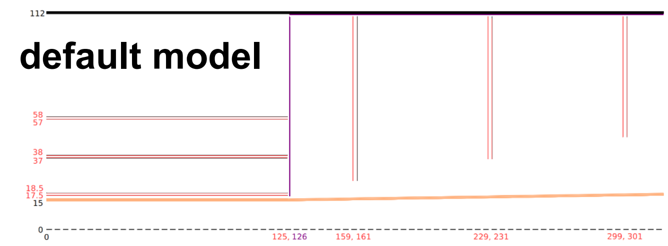






- Alternative FCC-ee interaction region with smaller beam pipe radius
- Innermost barrel layer moved from 17.5 mm to 12.5 mm, outer radius unchanged
- Vertex disks unchanged

Vertex barrel layer	Radius for the default model [mm]	Radius for the new model [mm]
Layer 1	17.5	12.5
Layer 2	18.5	13.5
Layer 3	37	35
Layer 4	38	36
Layer 5	57	57
Layer 6	58	58



- $e^+e^- \to q\bar{q}$ events with θ(q) = 80°
- "Truth" tracking

→ Visible improvement for charm at both energies and beauty at E_{jet} = 45 GeV (most decays before layer 1)

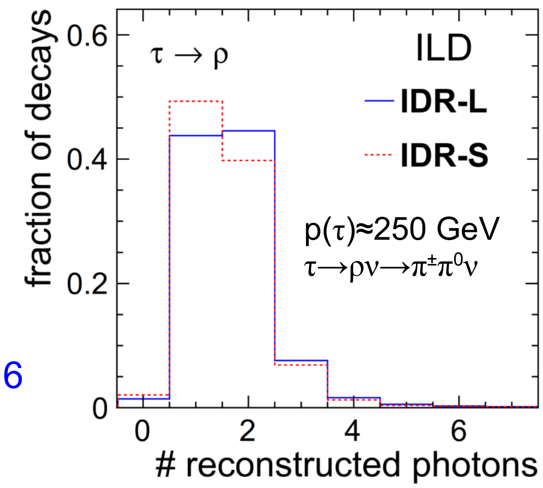
arXiv:1911.12230

Hadronic τ-lepton decays

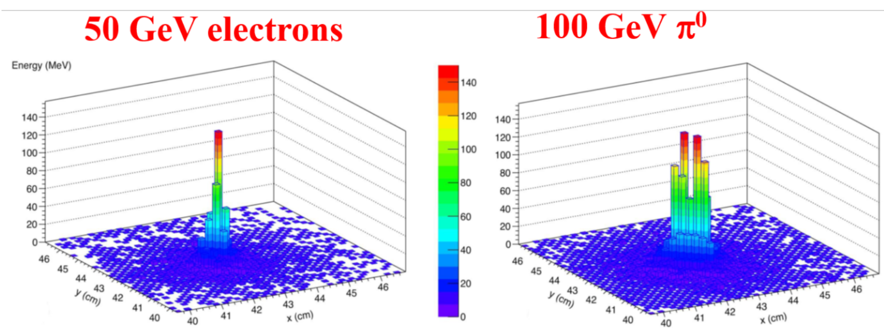
Decay modes with π^0 particularly challenging, e.g. for τ-polarisation measurement

Relevant detector parameters:

- Calorimeter inner radius
- (ECAL) transverse granularity

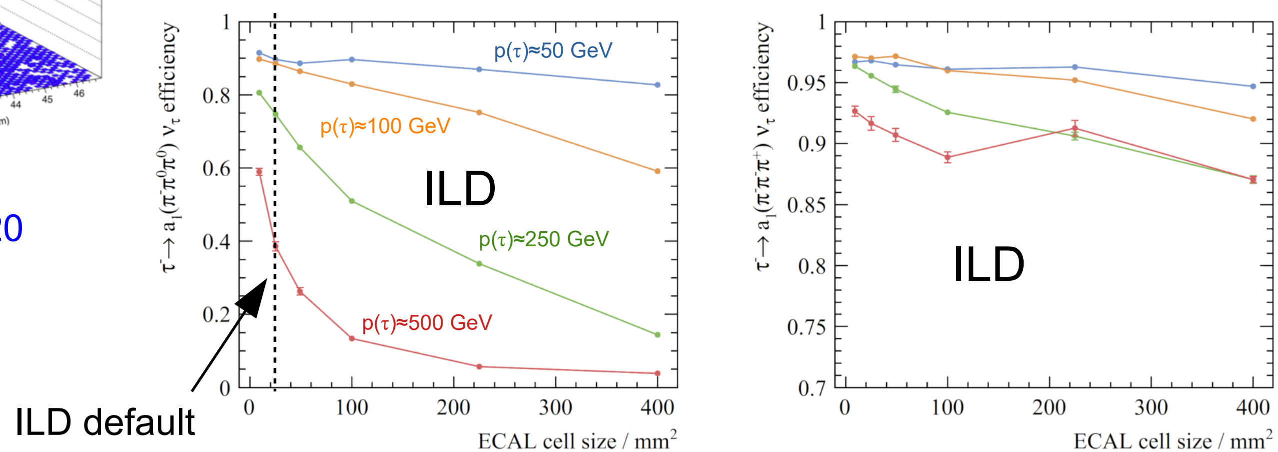


arXiv:2003.01116



F. Bedeschi, FCC phys. & exp. workshop 2020

→ Defines calorimeter granularity for IDEA detector



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