Overview of the CLD detector proposal

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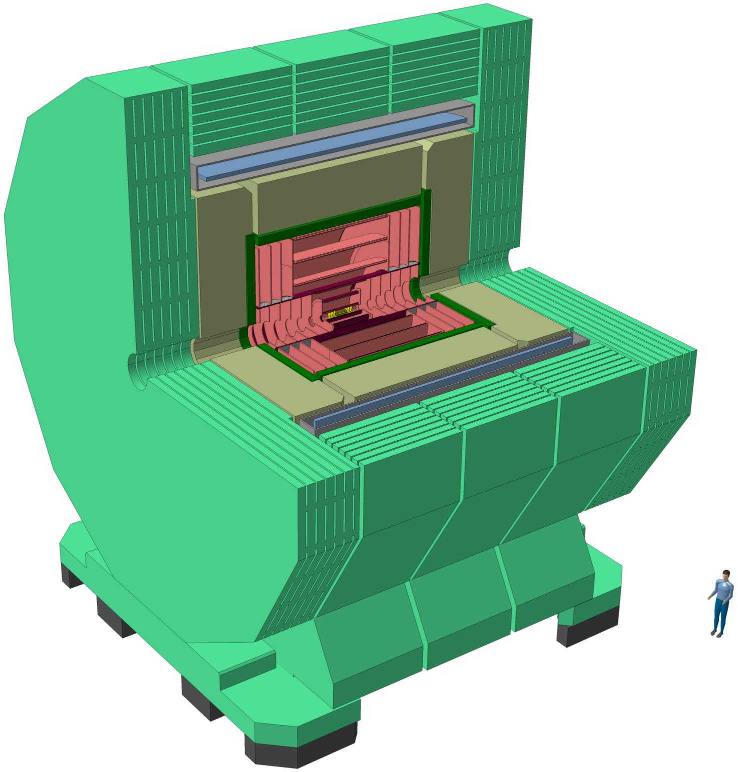
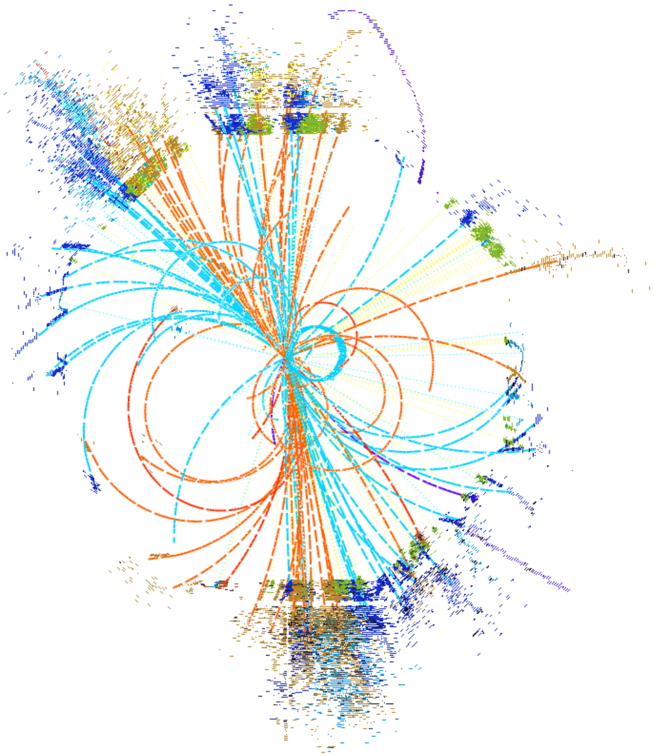
on behalf of the FCC collaboration





3rd FCC physics and experiments workshop
CERN, 13/01/2020

Outline

The CLD detector design:
- Overall dimensions and parameters
- Tracking system
- Calorimetry
- ECAL optimistion
- Beam-induced backgrounds

Physics performance:
- Track reconstruction
- Jet energy resolution
- Flavour tagging

arXiv:1911.12230

arXiv:1911.12230v3 [physics.ins-det] 12 Dec 2019

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CLD - A Detector Concept for the FCC-ee

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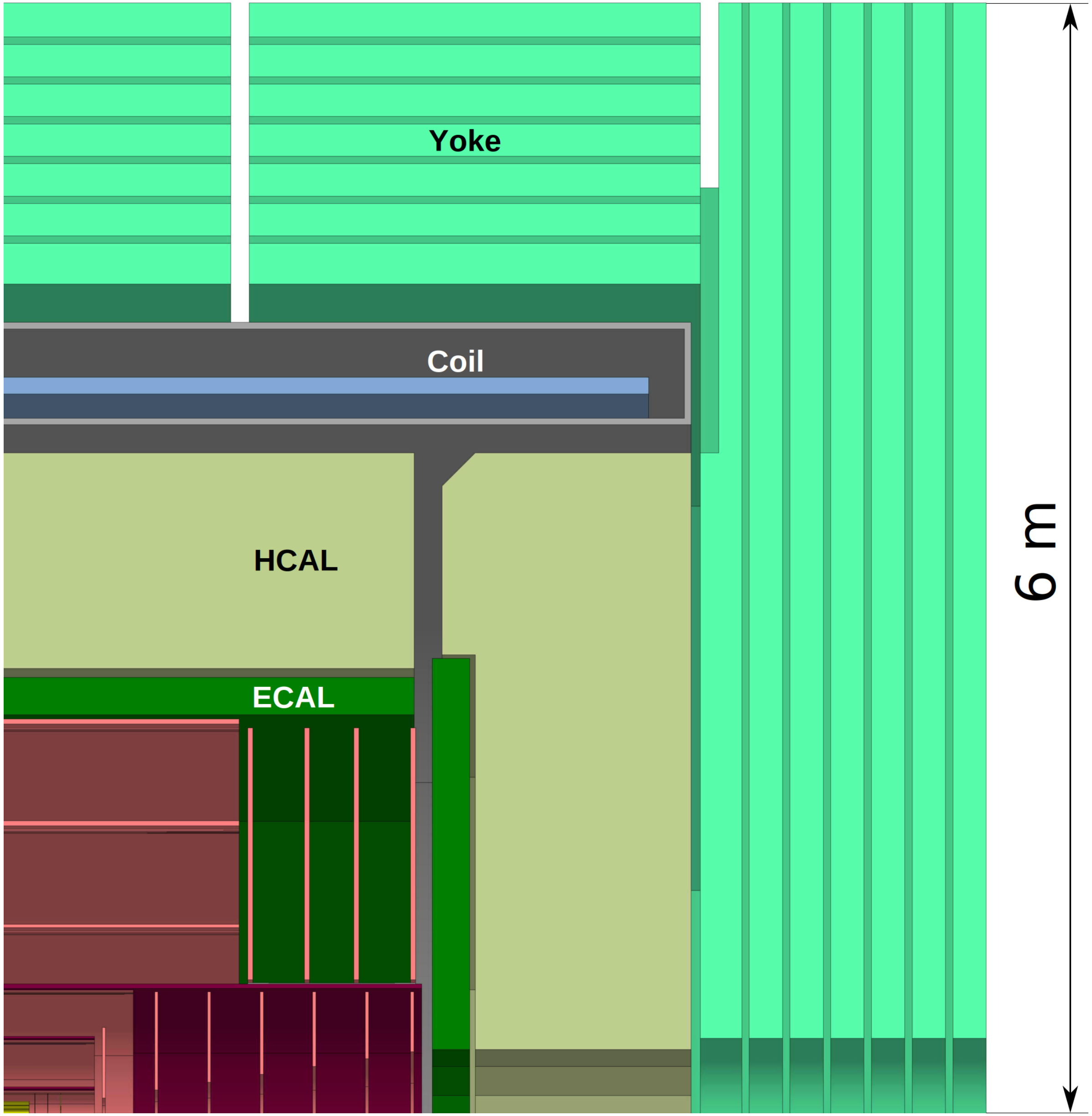
Abstract

This note gives a conceptual description and illustration of the CLD detector, based on the work for a detector at CLIC. CLD is one of the detectors envisaged at a future 100 km e^+e^- circular collider (FCC-ee). The note also contains a brief description of the simulation and reconstruction tools used in the linear collider community, which have been adapted for physics and performance studies of CLD. The detector performance is described in terms of single particles, particles in jets, jet energy and angular resolution, and flavour tagging. The impact of beam-related backgrounds (incoherent e^+e^- pairs and synchrotron radiation photons) on the performance is also discussed.

Overall dimensions are parameters

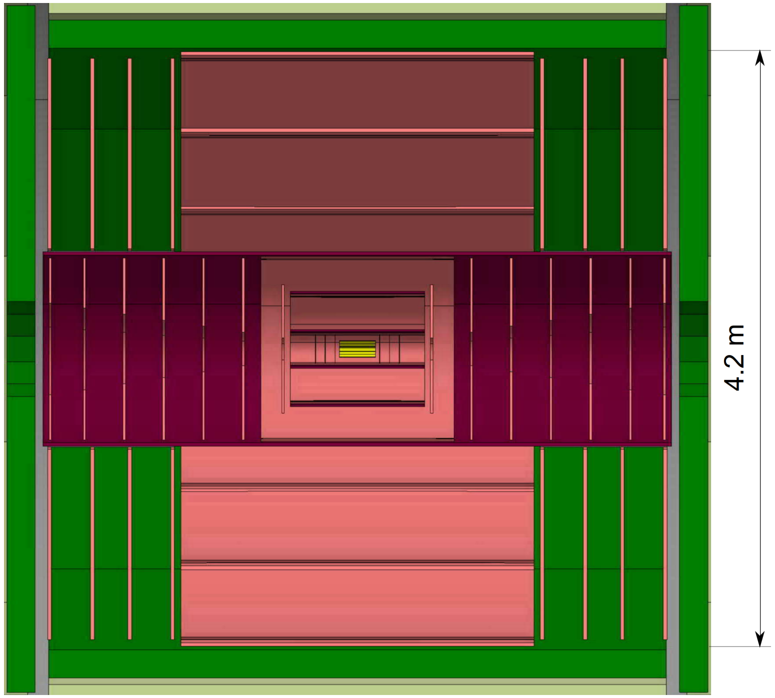


Optimised for particle flow calorimetry, inspired by CLICdet design:

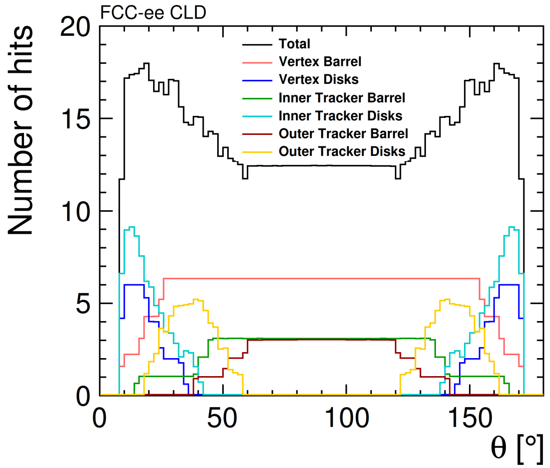
- 2 T magnetic field (limited by luminosity goal)
- Low-mass silicon vertex and tracking detectors
- High granularity calorimeters (ECAL and HCAL) inside solenoid
- Full detector simulation (including support structures, cables and services)

Layout of the tracking system

Vertex detector:
- Silicon pixels (25 x 25 μm^2), 3 µm single point resolution
- 3 double layers in barred (R = 17, 27, 57 mm)
- 3 double layers in endcap disks (Z = 160, 230, 300 mm)
- Material budget: 0.6% (0.7%) X_0 per double layer in barrel (endcaps)



Main tracker:
- Silicon pixels and microstips: 7 µm x 90 µm single point resolution, except 5 µm x 5 µm in 1st inner tracker disk
- <u>Inner tracker:</u> 3 barrel layers, 7 endcap disks
- <u>Outer tracker:</u> 3 barrel layers, 4 endcap disks
- Material budget: 1.1 - 1.5% X_0 per layer

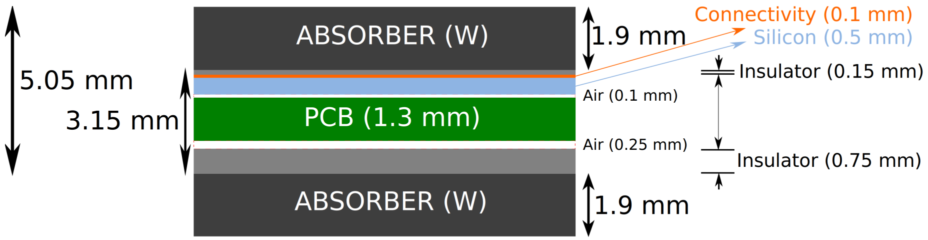


NB: Estimates of material budget inspired by ALICE ITS upgrade

Calorimeters

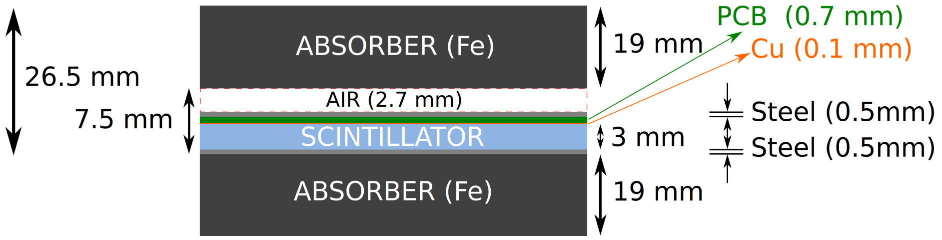
ECAL:

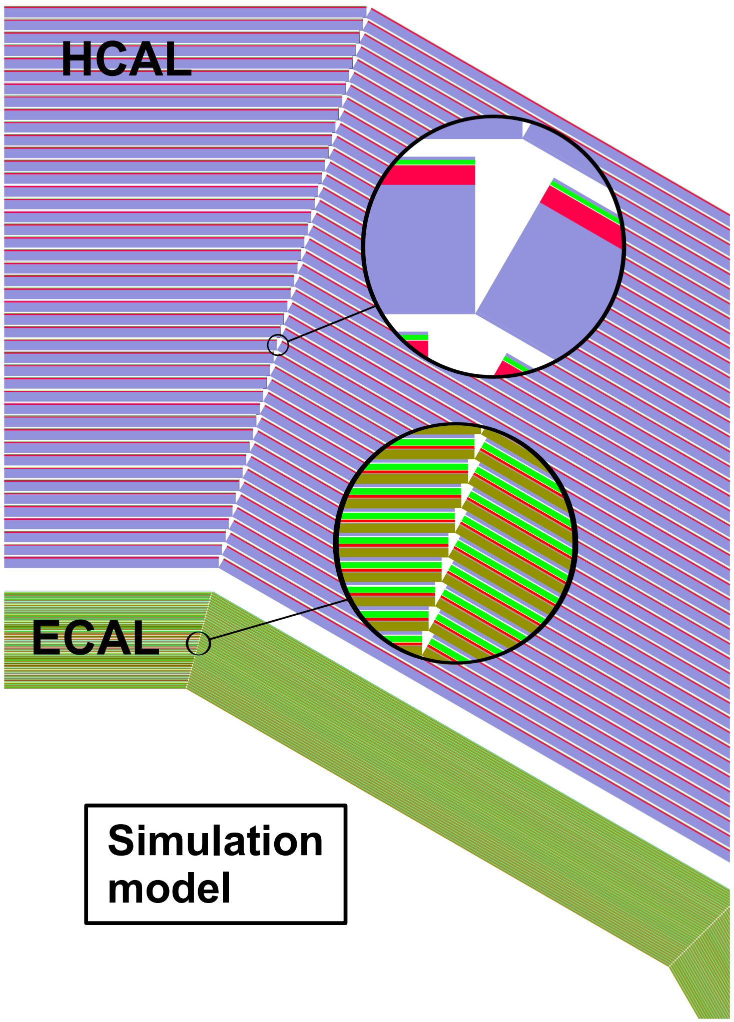
- Si-W sampling calorimeter
- Cell size: 5 x 5 mm^2
- 40 layers (1.9 mm W plates)
- 22 X_0, 1 λ_I, 20 cm thickness



HCAL:

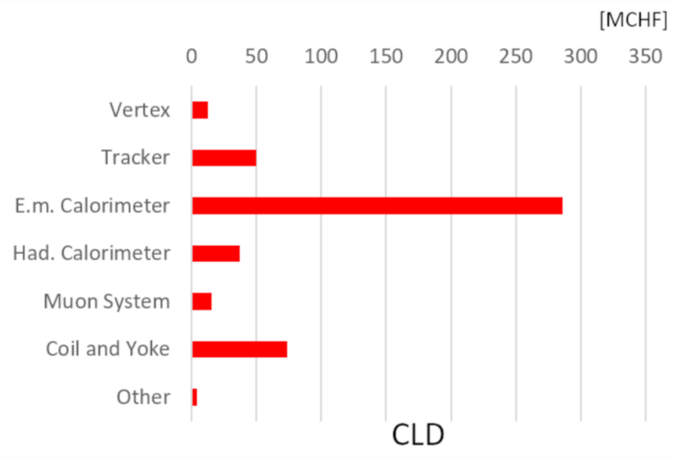
- Scintillator-steel sampling calorimeter
- Cell size: 30 x 30 mm^2
- 44 layers (19 mm steel plates)
- 5.5 λ_I, 117 cm thickness

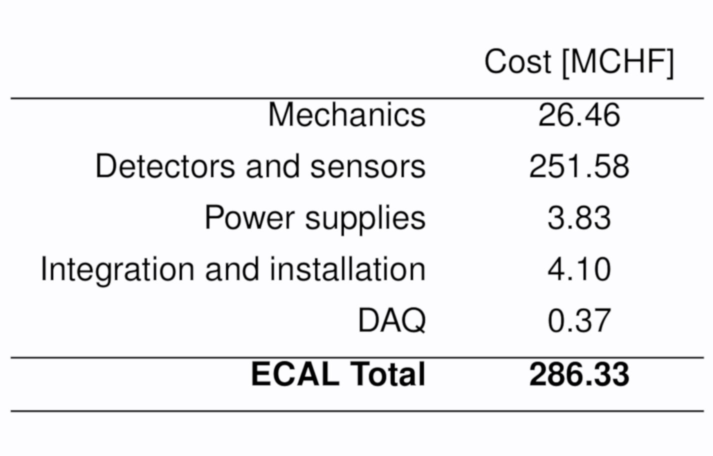




ECAL optimisation

ECAL is the main cost driver of the detector
→ reduction of number of layers significantly reduces overall price of the detector



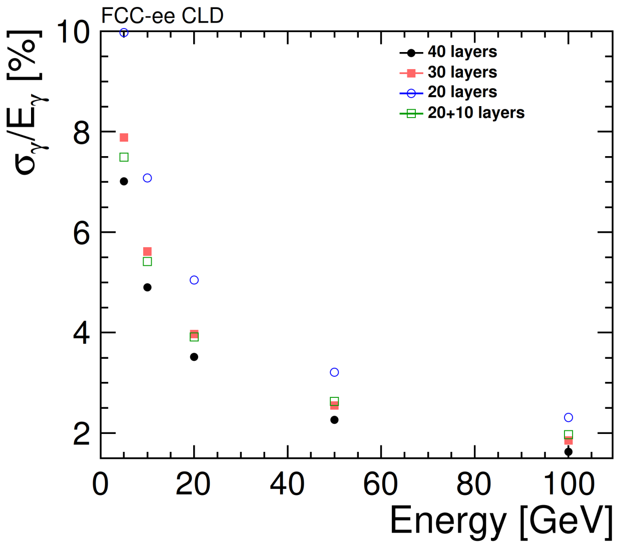


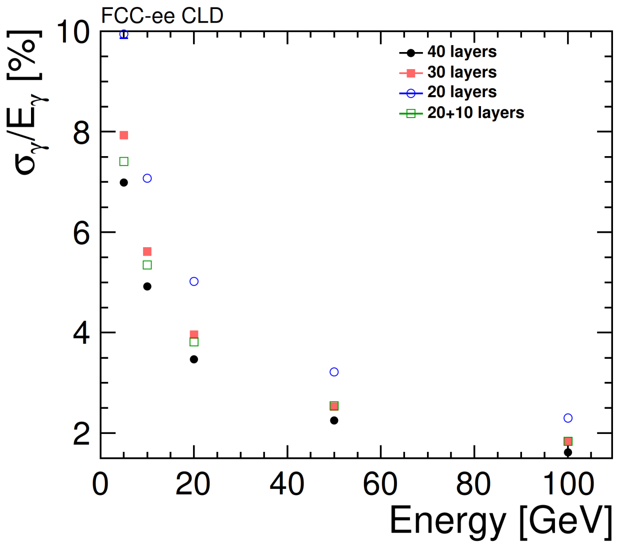
	Cost [MCHF]
Mechanics	26.46
Detectors and sensors	251.58
Power supplies	3.83
Integration and installation	4.10
DAQ	0.37
ECAL Total	**286.33**

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

ECAL options with different W layer thickness and 22 X_0 overall

Photon and jet energy resolutions





→ 40 layers best, 20 layers worst

→ 20+10 and 30 layer options similar (except at low energies)

→ 20+10 seems to be a good option for a new CLD baseline configuration

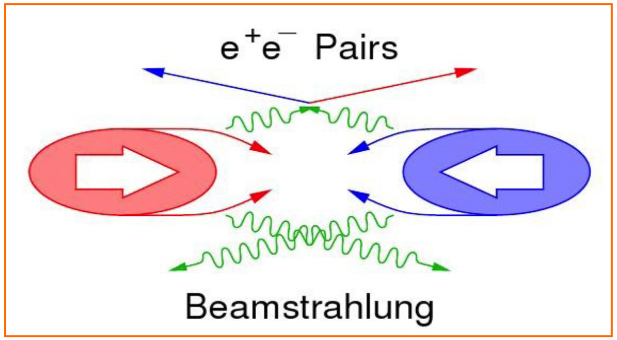
Layer structure	JER [%] $\sqrt{s} = 365$ GeV	JER [%] $\sqrt{s} = 91.2$ GeV
40 uniform	3.62 ± 0.05	4.52 ± 0.06
30 uniform	3.72 ± 0.05	4.45 ± 0.06
20 uniform	3.78 ± 0.05	4.82 ± 0.07
20 thin + 10 thick	3.67 ± 0.05	4.56 ± 0.06

→ Jet energy resolution almost identical for the 4 ECAL options

Beam-induced backgrounds (1)

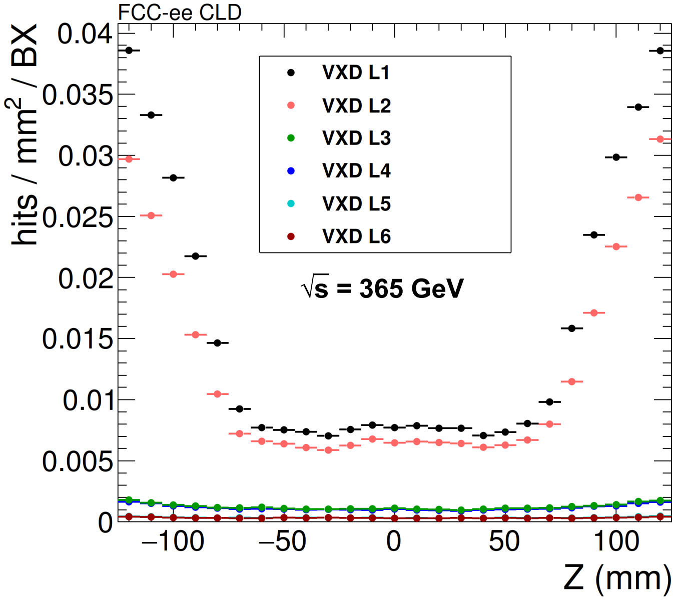
Contributions studied in detail:

- Incoherent e^+e^- pair production (dominant)
- γγ → hadrons (small)
- Hits from synchrotron radiation (small)

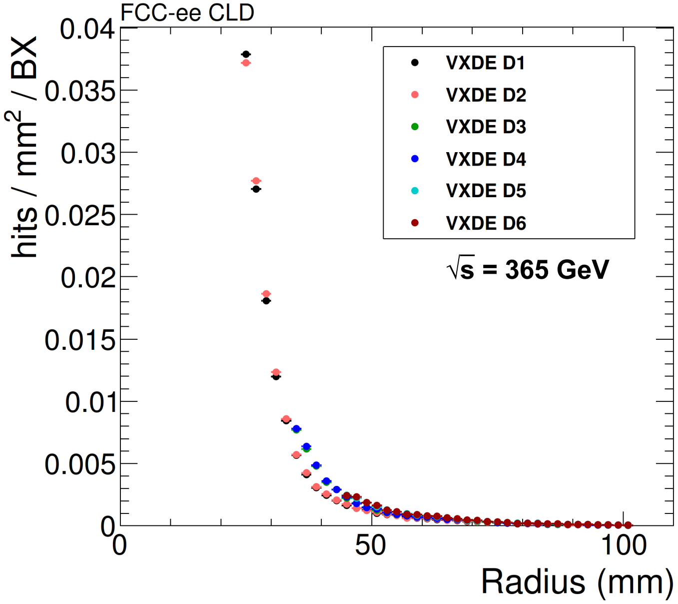


→ see talk by Emmanuel Perez

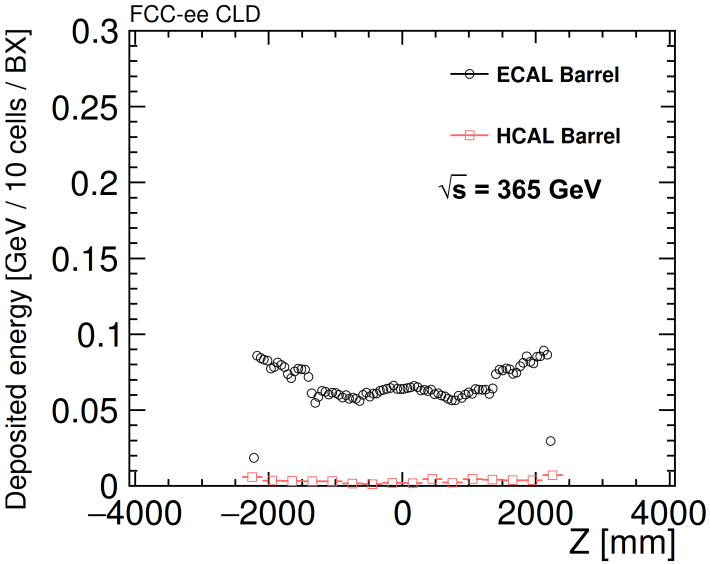
Vertex barrel

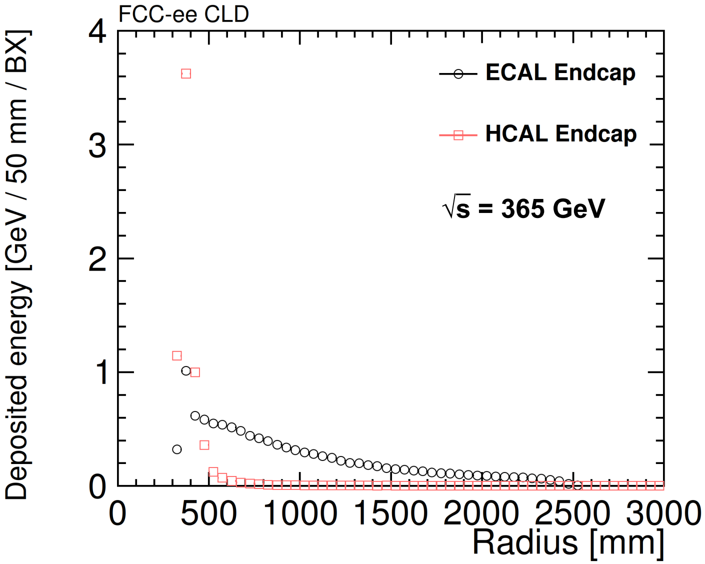


Vertex endcaps



Beam-induced backgrounds (2)





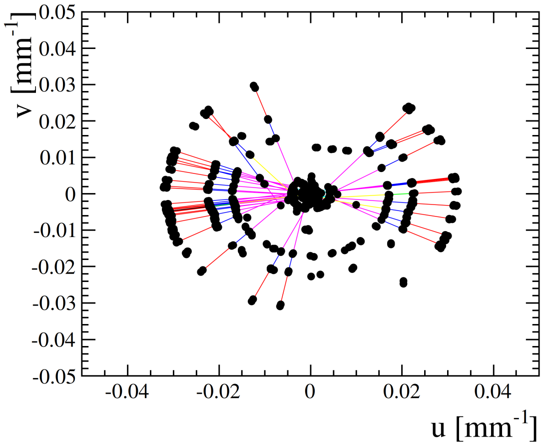
Maximal energy deposit per bunch crossing:
- 0.1 GeV / 10 cells in ECAL
- 4 GeV / 50 mm in HCAL

Physics performance studies

Detector geometry: DD4hep
Event reconstruction framework: Marlin

Key event reconstruction steps:

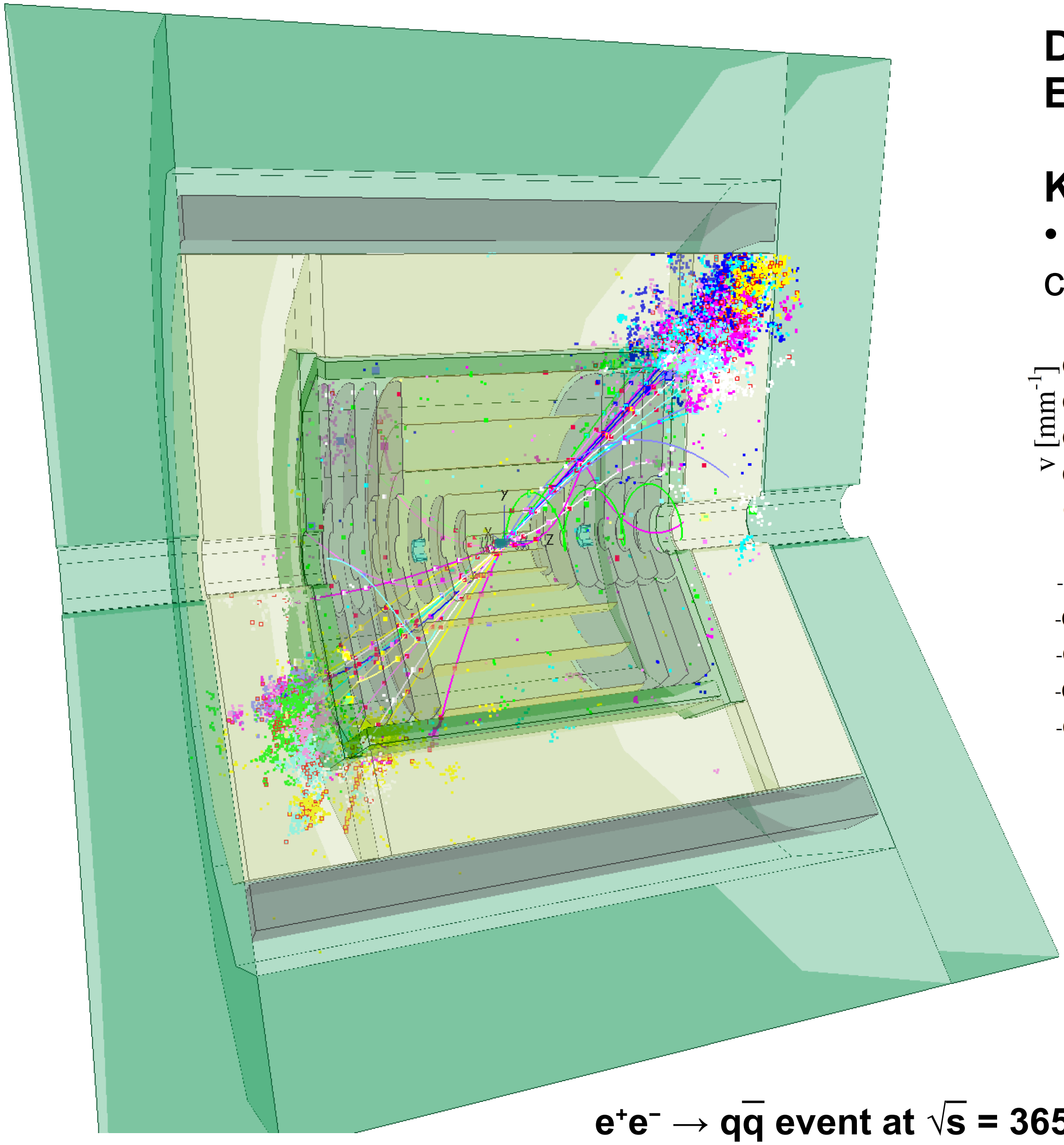
- “Conformal tracking”: cellular automaton in conformal space for track finding



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

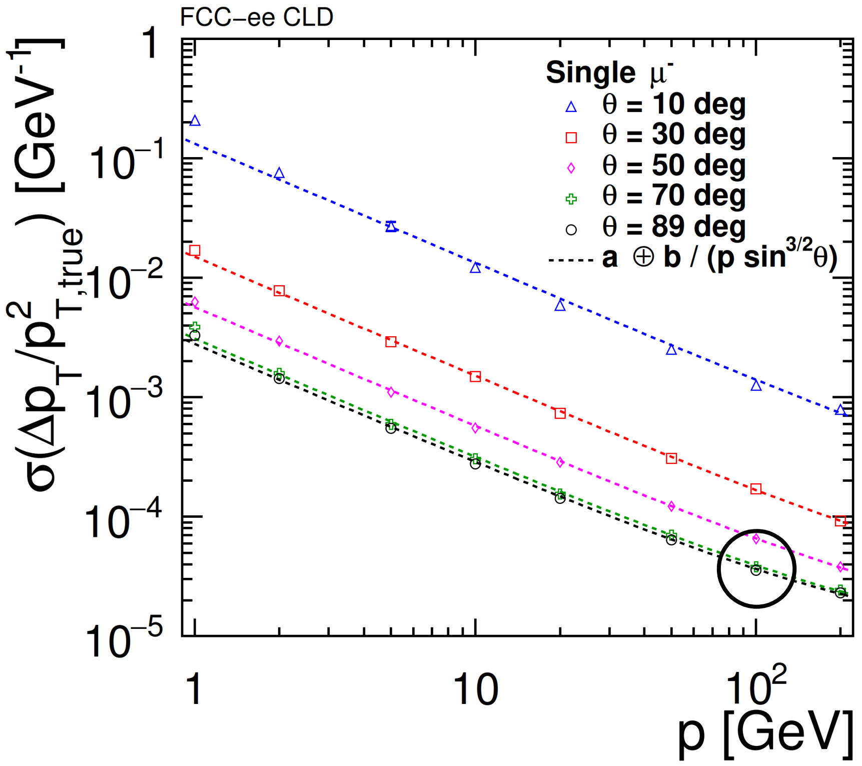
Nucl. Inst. Meth. A 956, 163304 (2020)

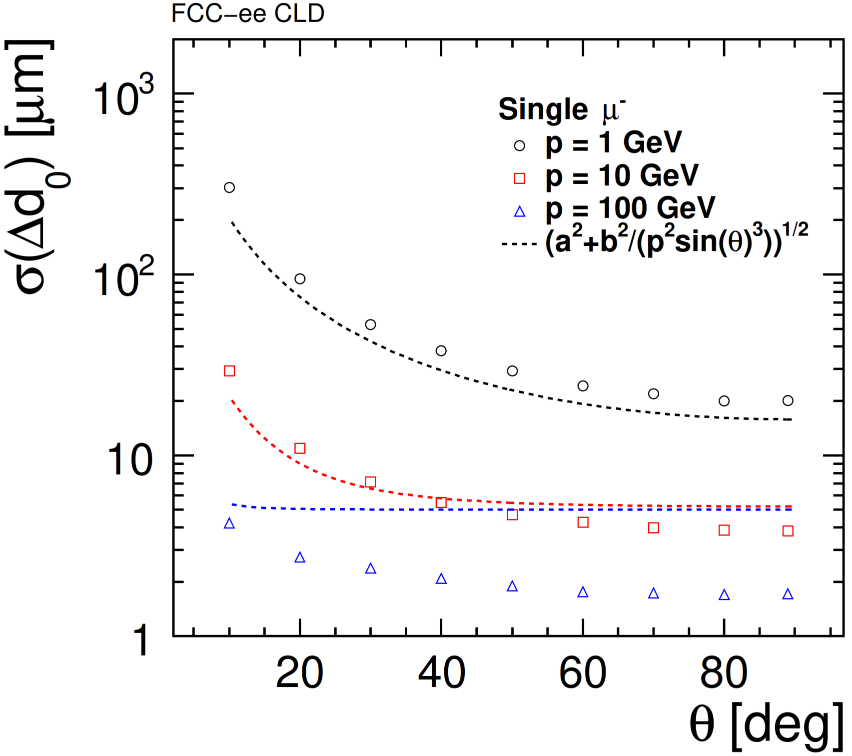
- Calorimeter clustering and particle flow analysis: PandoraPFA
- Flavour tagging: LCFIPlus



$e^+e^- \rightarrow q\bar{q}$ event at $\sqrt{s}$ = 365 GeV
(full detector simulation)

Single muons: tracking resolution





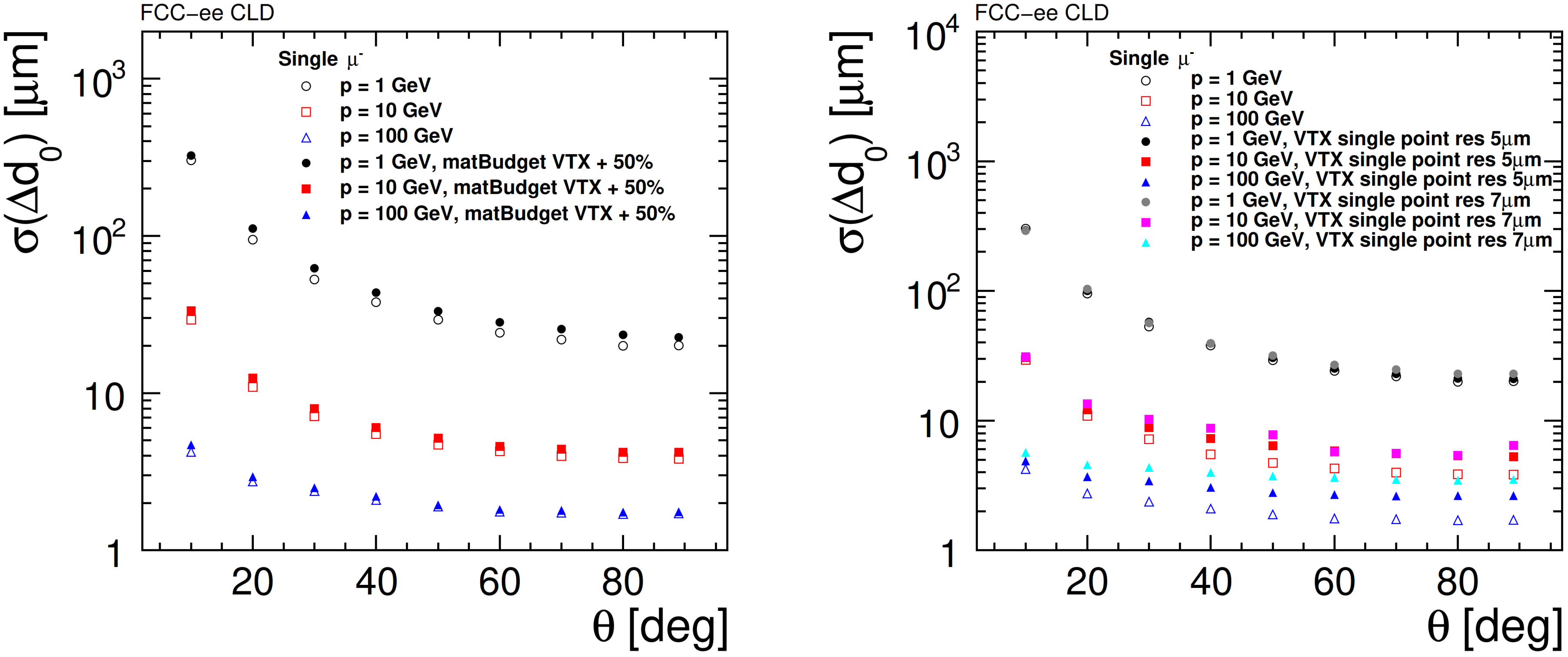
→ Transverse momentum resolution for 100 GeV muons in the barrel: 3.5×10^{-5} GeV^{-2}

Target impact parameter resolutions: a = 5 μm, b = 15 μm (dashed lines)

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2/(p^2 \sin^3(\theta))}$$

Material and single point resolution

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

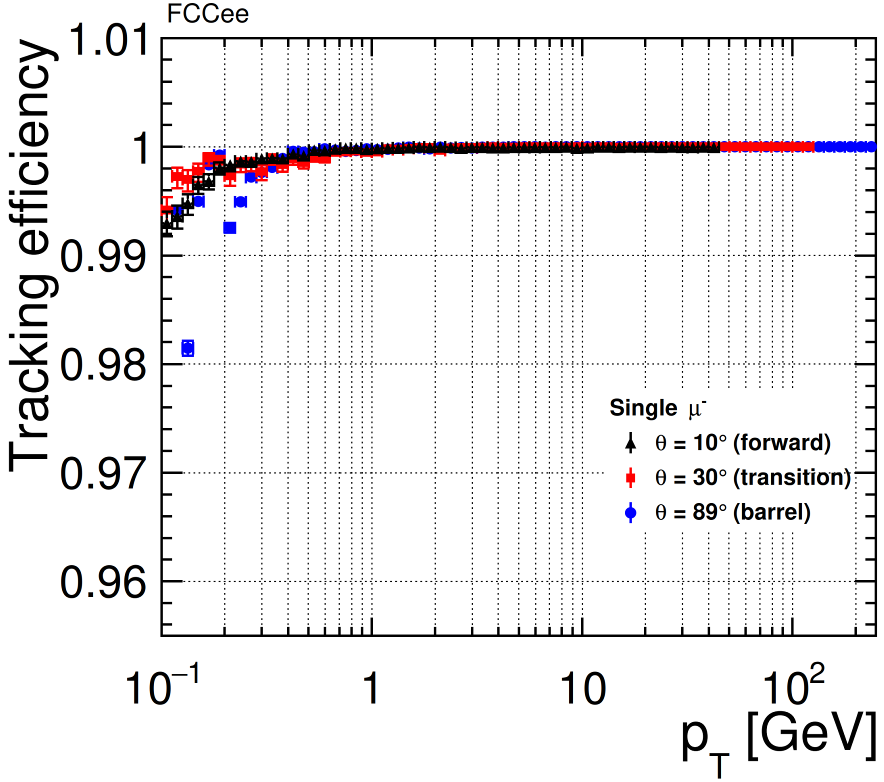


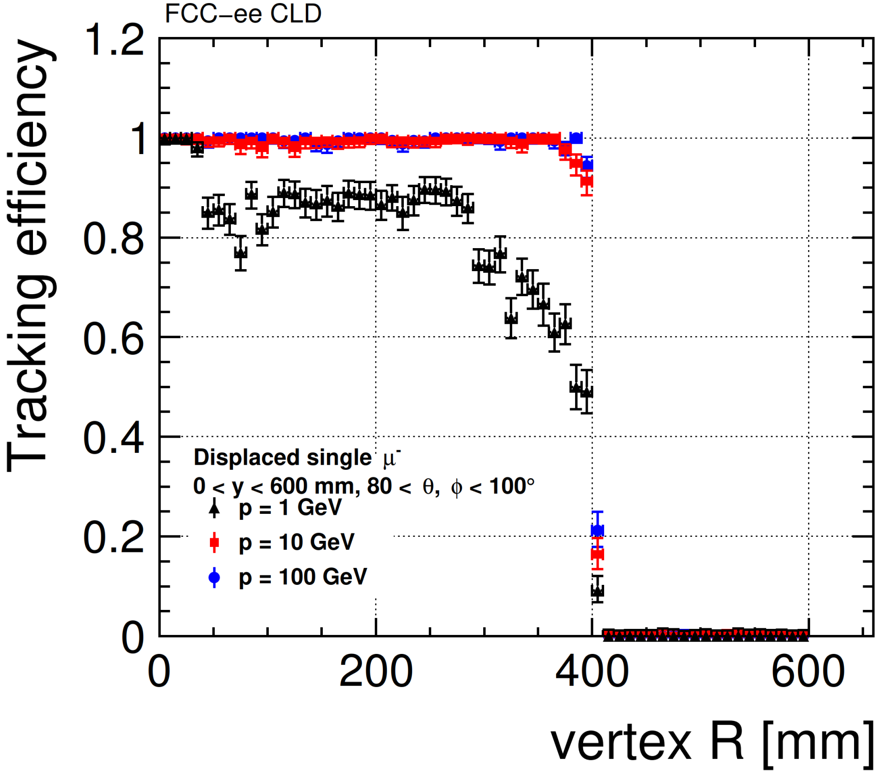
→ Small effect of increased material budget

→ The single point resolution has a large impact on the impact parameter resolution at high p_T

Single muons: efficiency

Tracking efficiency = fraction of reconstructable MC particles that are reconstructed:
- Stable at generator level
- p_T > 100 MeV, |cosθ| < 0.99, at least 4 unique hits





→ Tracking fully efficient at 10°

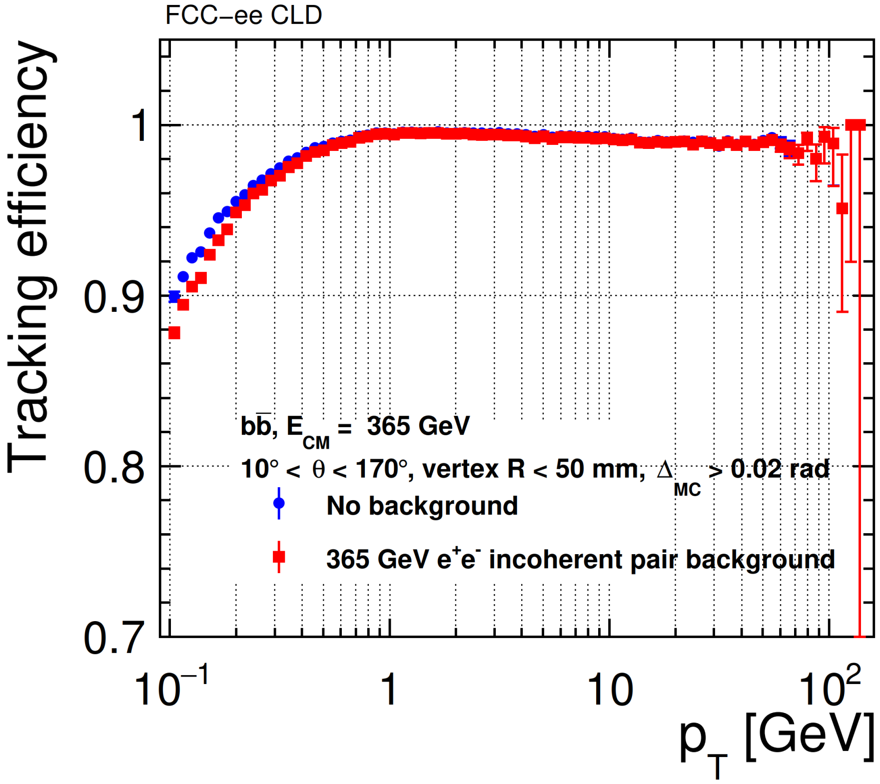
→ Tracking efficient up to 40 cm radius (due to minimum number of hits required)

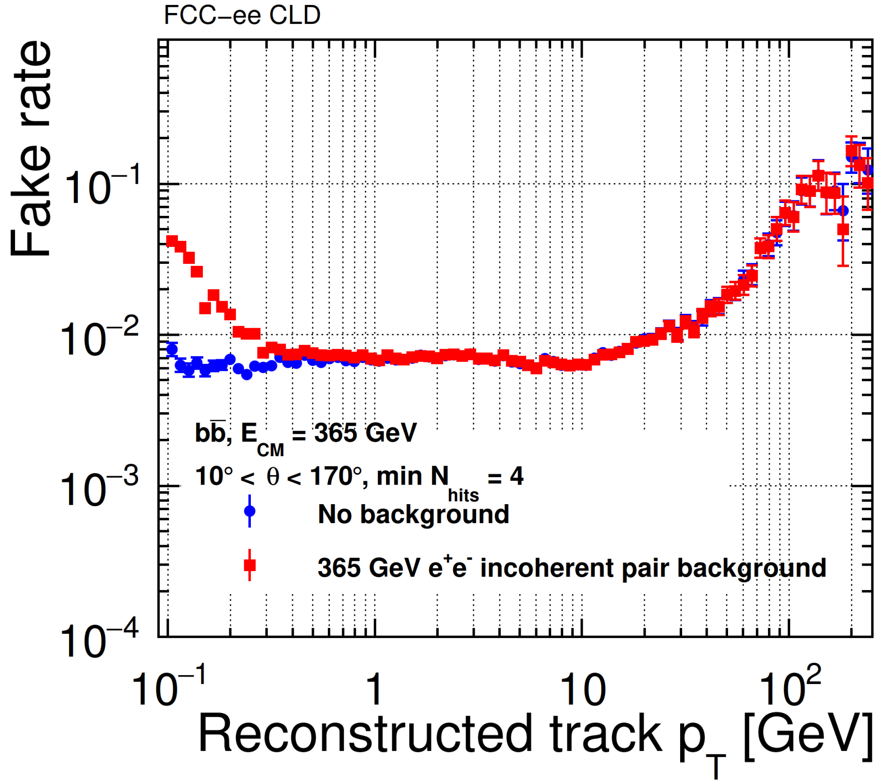
→ Drop by 15% efficiency at p = 1 GeV for R > 38 mm from particles loosing too much energy to reach the minimum number of hits

Tracking in complex events

Test case: $e^+e^- \rightarrow b\bar{b}$ events at $\sqrt{s}$ = 365 GeV

Fake rate = fraction of reconstructed tracks with purity < 75%
Purity = #hits caused by MC particle / #hits in reconstructed track





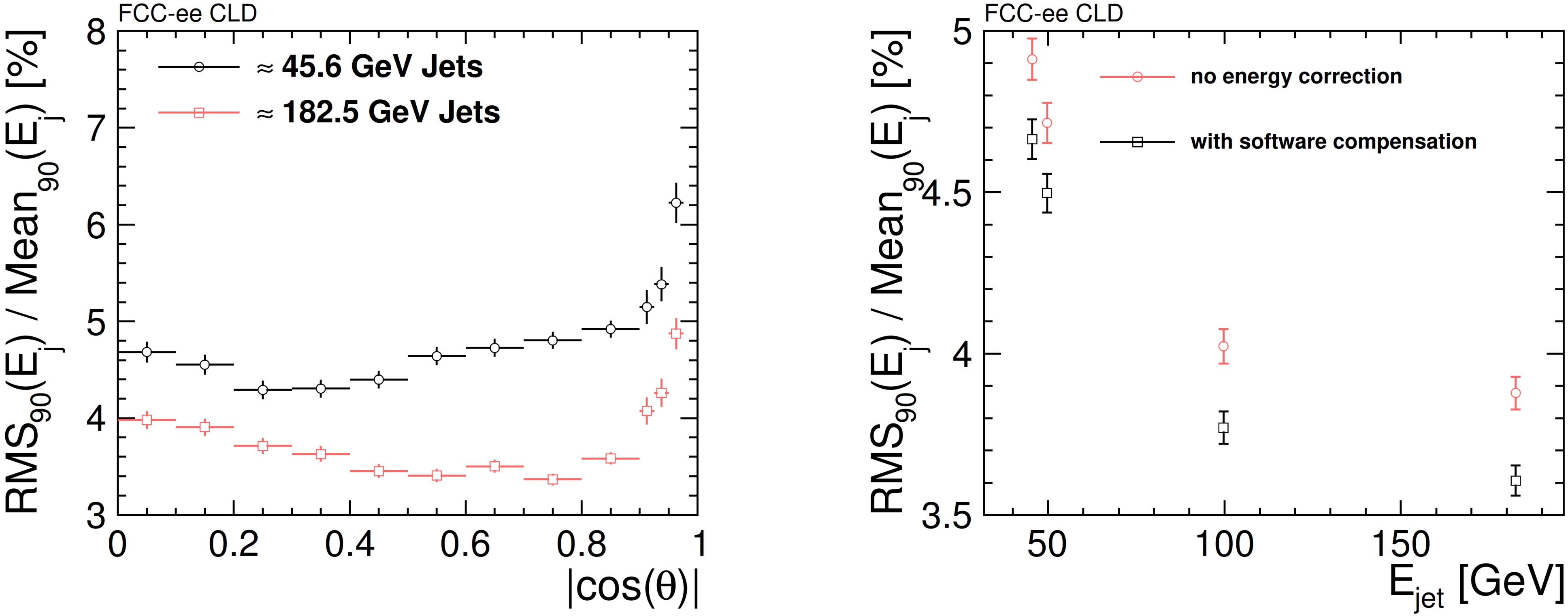
→ High efficiency over large p_T range with O(1%) level fake rate
→ Impact of beam-induced backgrounds is small

NB: 10 μs detector integration time assumed, no timing cuts applied

Jet energy resolution

Test case: $e^+e^- \rightarrow q\bar{q}$ (q = u,d,s) events at $\sqrt{s}$ = 91.2 and 365 GeV

Jet energy resolution = energy sum of all reconstructed particles
RMS_{90} = smallest range of reconstructed energy containing 90% of events



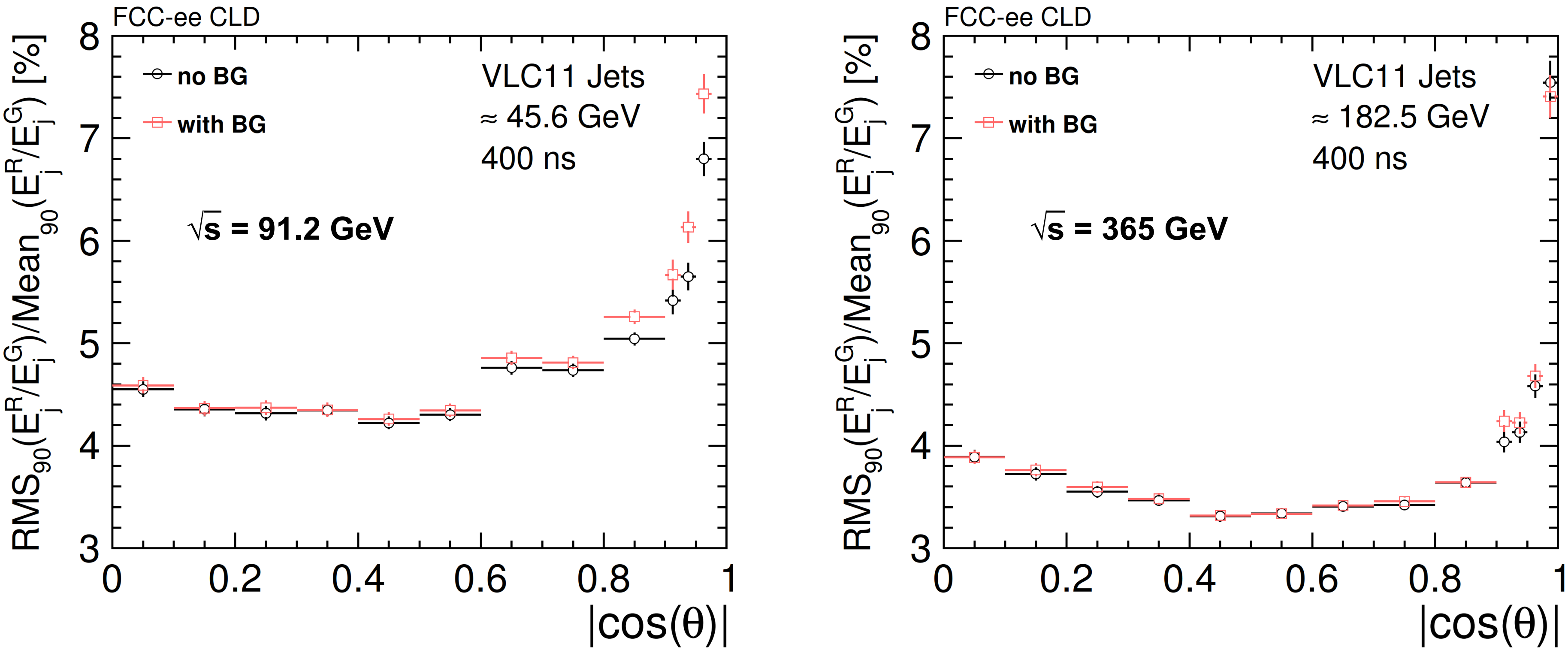
→ 3 - 4% jet energy resolution at 45.6 GeV, 4 - 5% at 182.5 GeV
→ Up to 10% improvement from software compensation

EPJ C 77, 698 (2016)

Impact of beam-induced background

- Jets reconstructed using VLC algorithm (R = 1.1) in exclusive mode with 2 jets
- 400 ns time integration window assumed at both energies

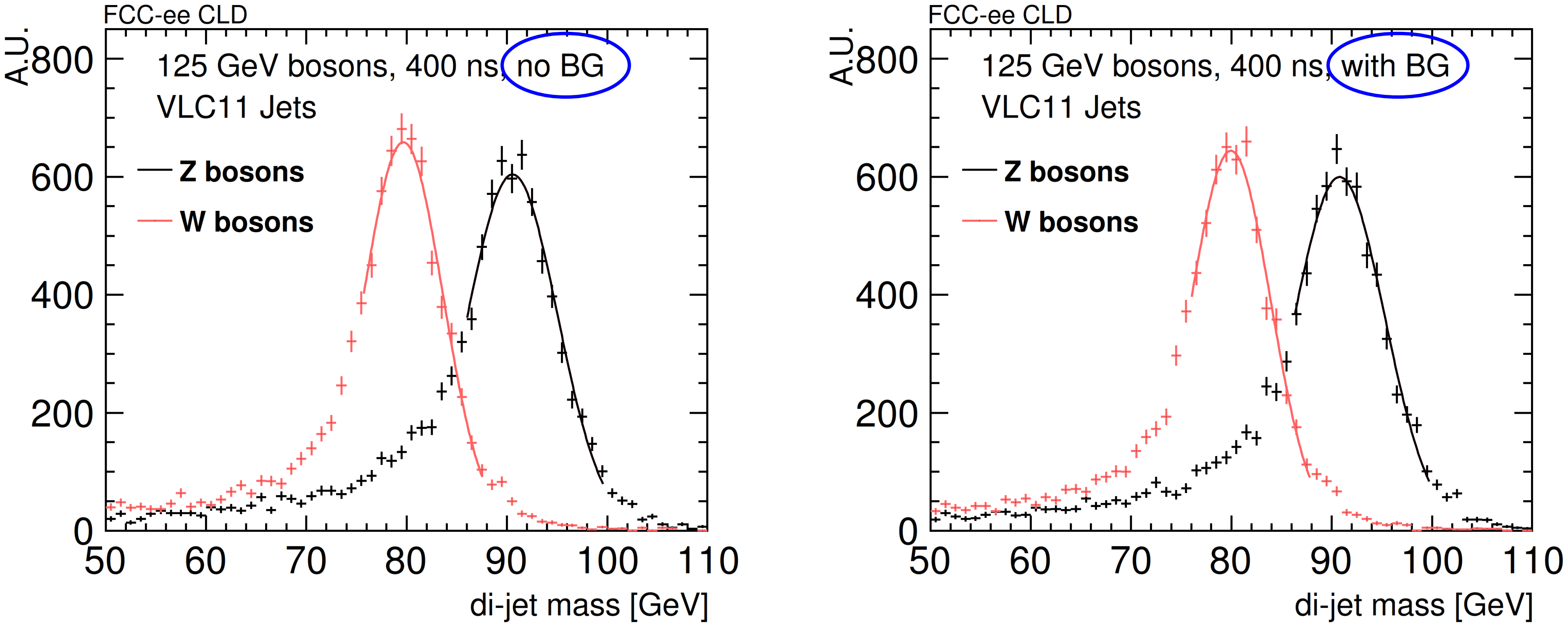
Eur. Phys. J. C78, 144 (2018)



→ Generally, the impact of beam-induced background is very small
→ Largest impact in the forward direction at 91.2 GeV
→ No timing cuts applied

W/Z separation (1)

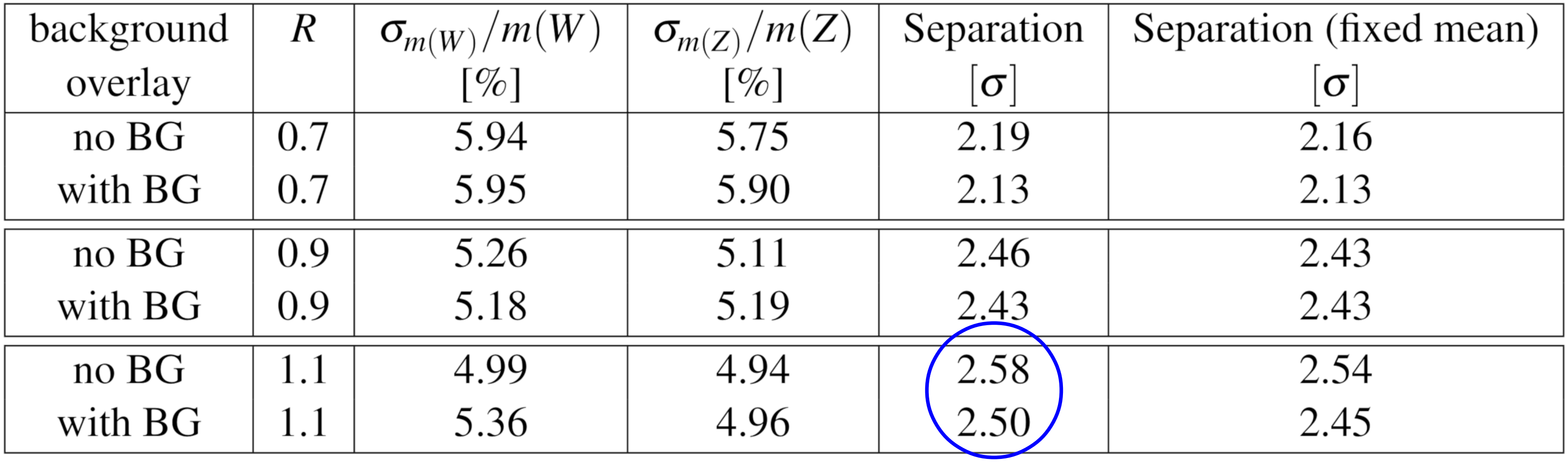
Test case: separation of hadronic W and Z boson decays in WW → $qq\mu\nu_\mu$ and ZZ → $qq\nu\nu$ events with $m_{WW/ZZ}$ = 250 GeV (charged leptons excluded from jet reconstruction)



W/Z separation (2)

Mass separation = $(m_Z - m_W) / \sigma_{av}$ with $\sigma_{av} = (\sigma_Z + \sigma_W) / 2$

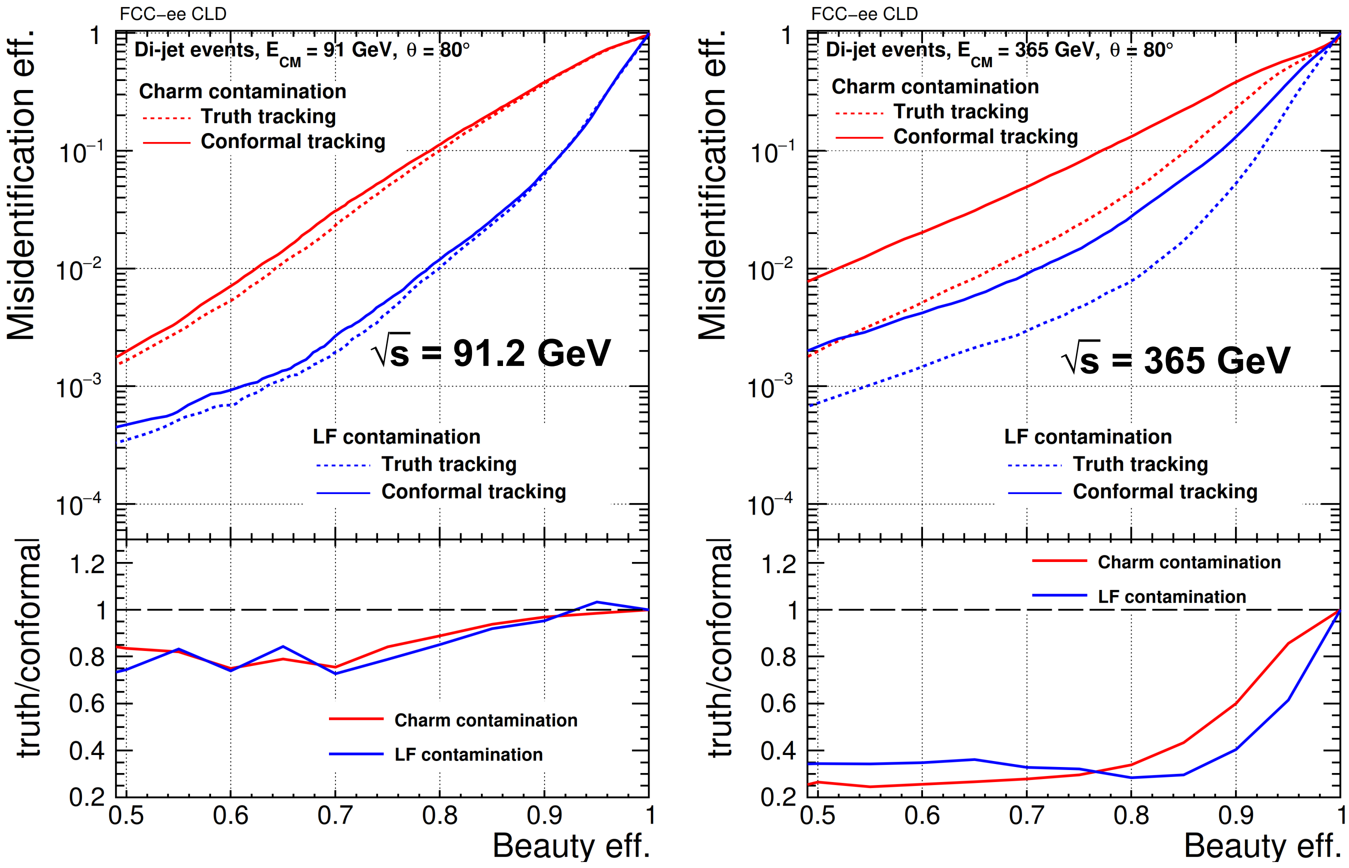
Two methods compared:
- W and Z masses from mean of Gaussian fit
- Mass distribution scaled so that mean of fit is equal to the PDG values of the W and Z masses



background overlay	R	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	Separation [σ]	Separation (fixed mean) [σ]
no BG	0.7	5.94	5.75	2.19	2.16
with BG	0.7	5.95	5.90	2.13	2.13
no BG	0.9	5.26	5.11	2.46	2.43
with BG	0.9	5.18	5.19	2.43	2.43
no BG	1.1	4.99	4.94	2.58	2.54
with BG	1.1	5.36	4.96	2.50	2.45

→ Effect of beam-induced background small
→ Separation on the level of 2.5 standard deviations possible

B-tagging performance



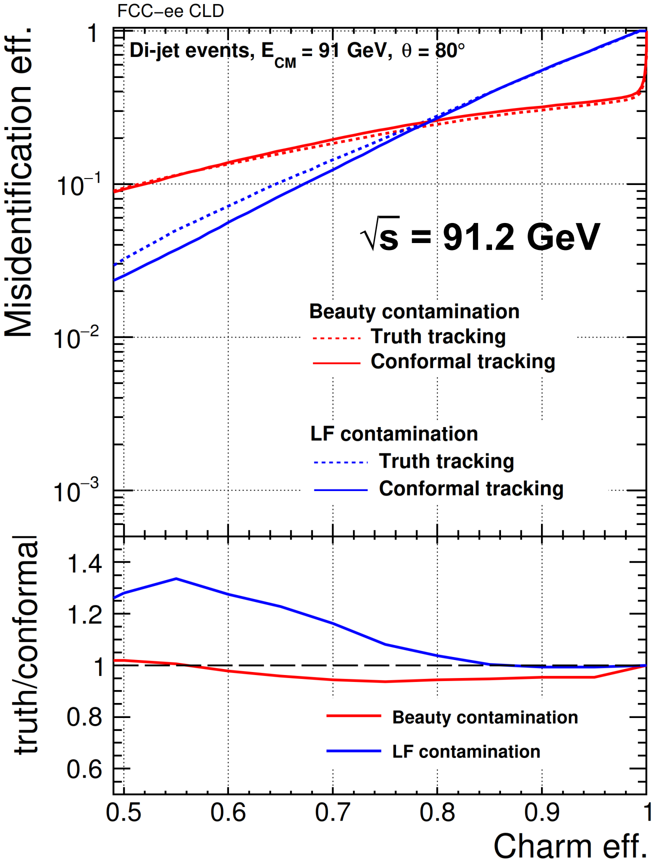
Sizeable difference between “truth” and conformal tracking at 365 GeV understood: large fraction of B-hadrons decay after the first vertex layer (improvement in progress)

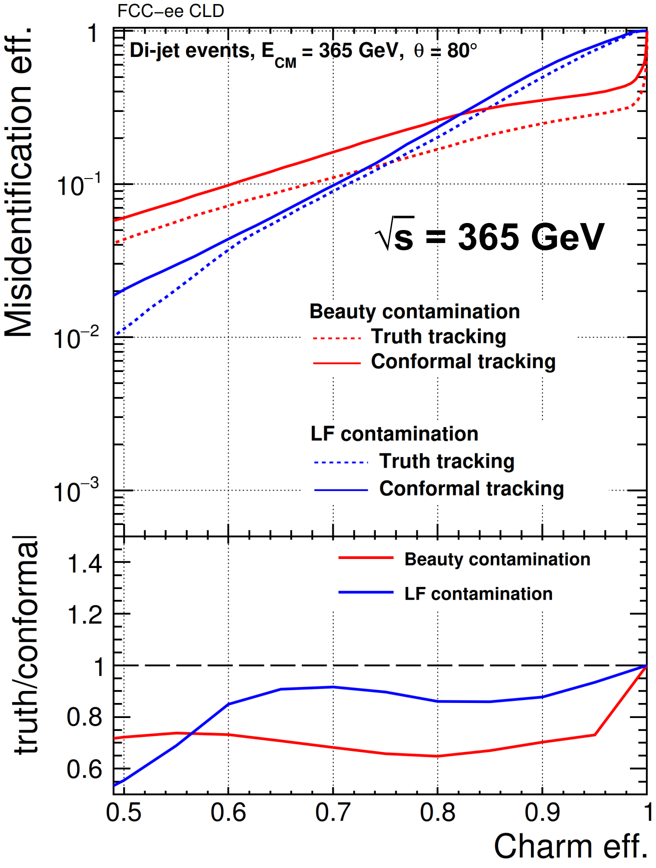
Test case: $e^+e^- \rightarrow q\bar{q}$ events with θ(q) = 80°

For 60% b-tagging efficiency:

- 0.1% (0.9%) fake rate from u/d/s (charm) at 91.2 GeV
- 0.4% (2%) fake rate from u/d/s (charm) at 365 GeV

C-tagging performance





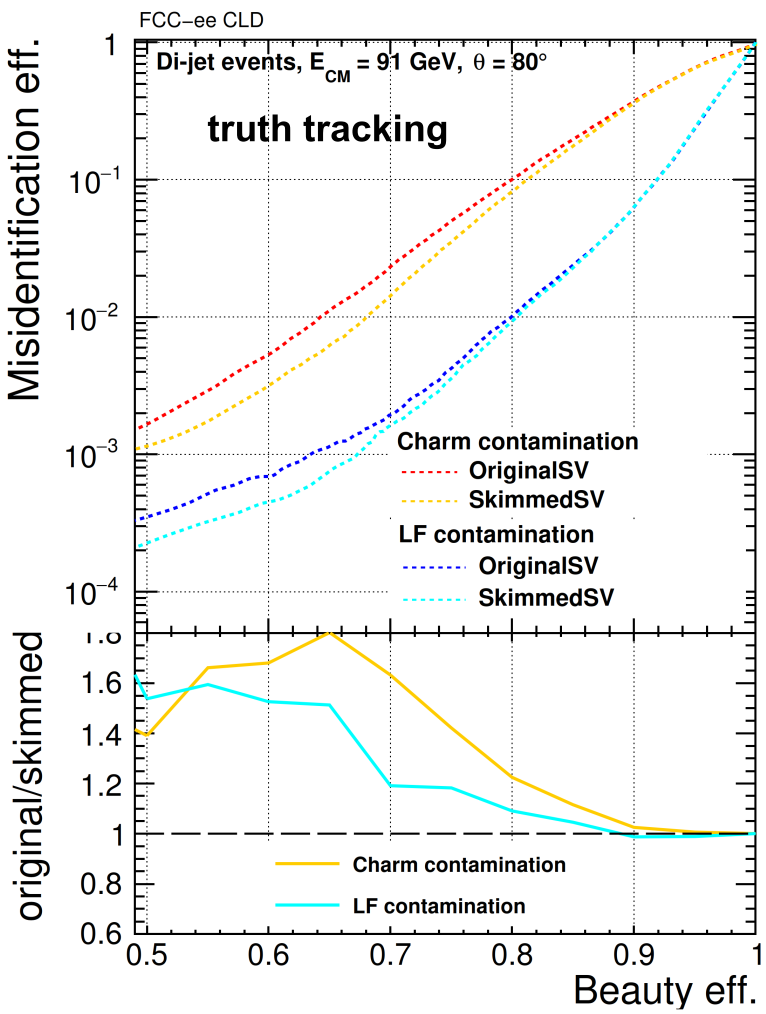
- Fraction of C-hadrons decaying after the first vertex layer smaller

- Higher energies benefit from larger boost

Test case: $e^+e^- \rightarrow q\bar{q}$ events with θ(q) = 80°

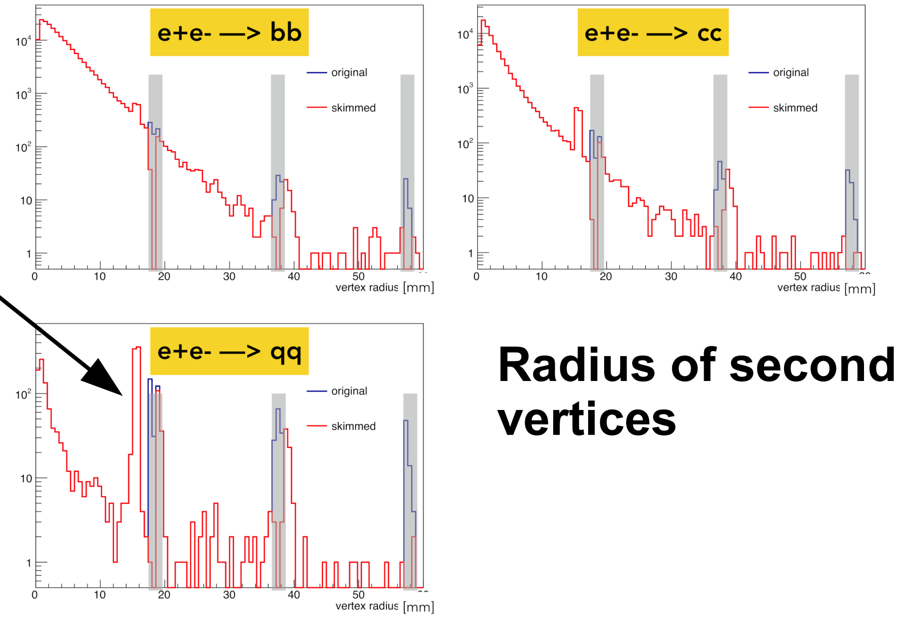
For 60% c-tagging efficiency:
- 5% (1.2%) fake rate from u/d/s (beauty) at 91.2 GeV
- 4% (10%) fake rate from u/d/s (beauty) at 365 GeV

Treatment of secondary interactions in the detector material



- Secondary vertices with a position compatible with the vertex detector layers are removed → Sizeable reduction of the fake rates at 91.2 GeV

- Large contribution from beam pipe not yet excluded → Further improvement possible



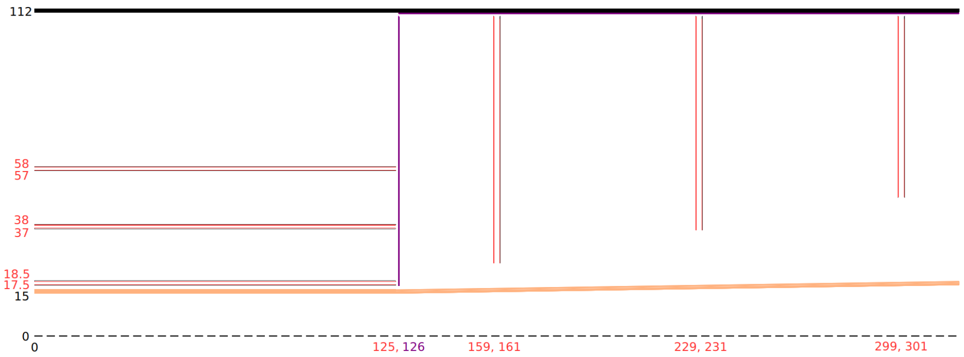
Beam pipe

Radius of secondary vertices

Flavour tagging with smaller beam pipe

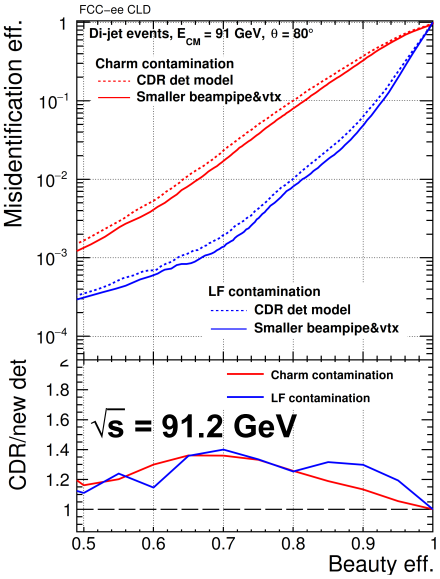
- Alternative FCC-ee interaction region with smaller beam pipe radius
- Innermost barrel layer moved from 17.5 mm to 12.5 mm, outer radius unchanged
- Vertex disks unchanged

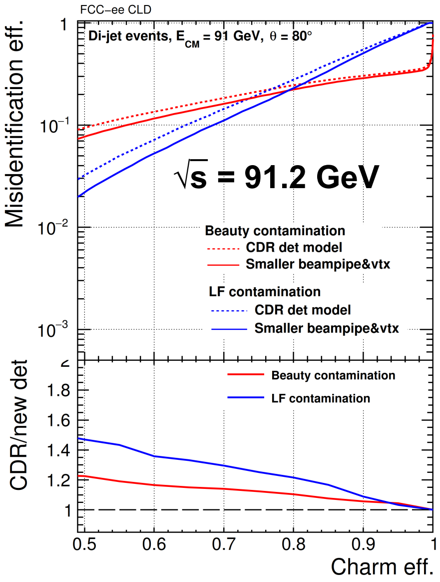
Vertex barrel layer	Radius for the default model [mm]	Radius for the new model [mm]
Layer 1	17.5	12.5
Layer 2	18.5	13.5
Layer 3	37	35
Layer 4	38	36
Layer 5	57	57
Layer 6	58	58

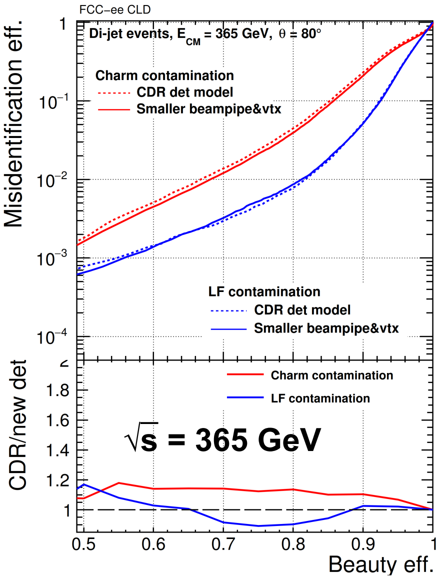


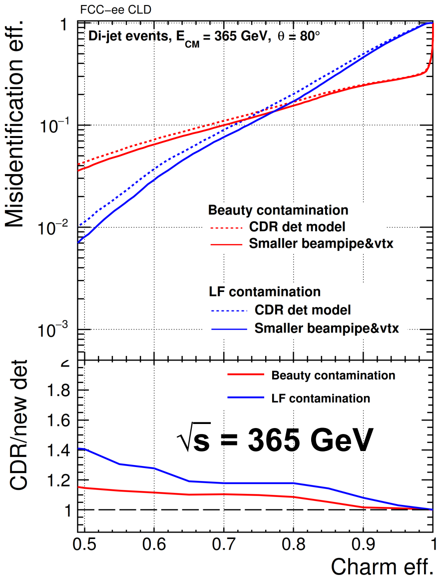
default model

Smaller beam pipe: barrel







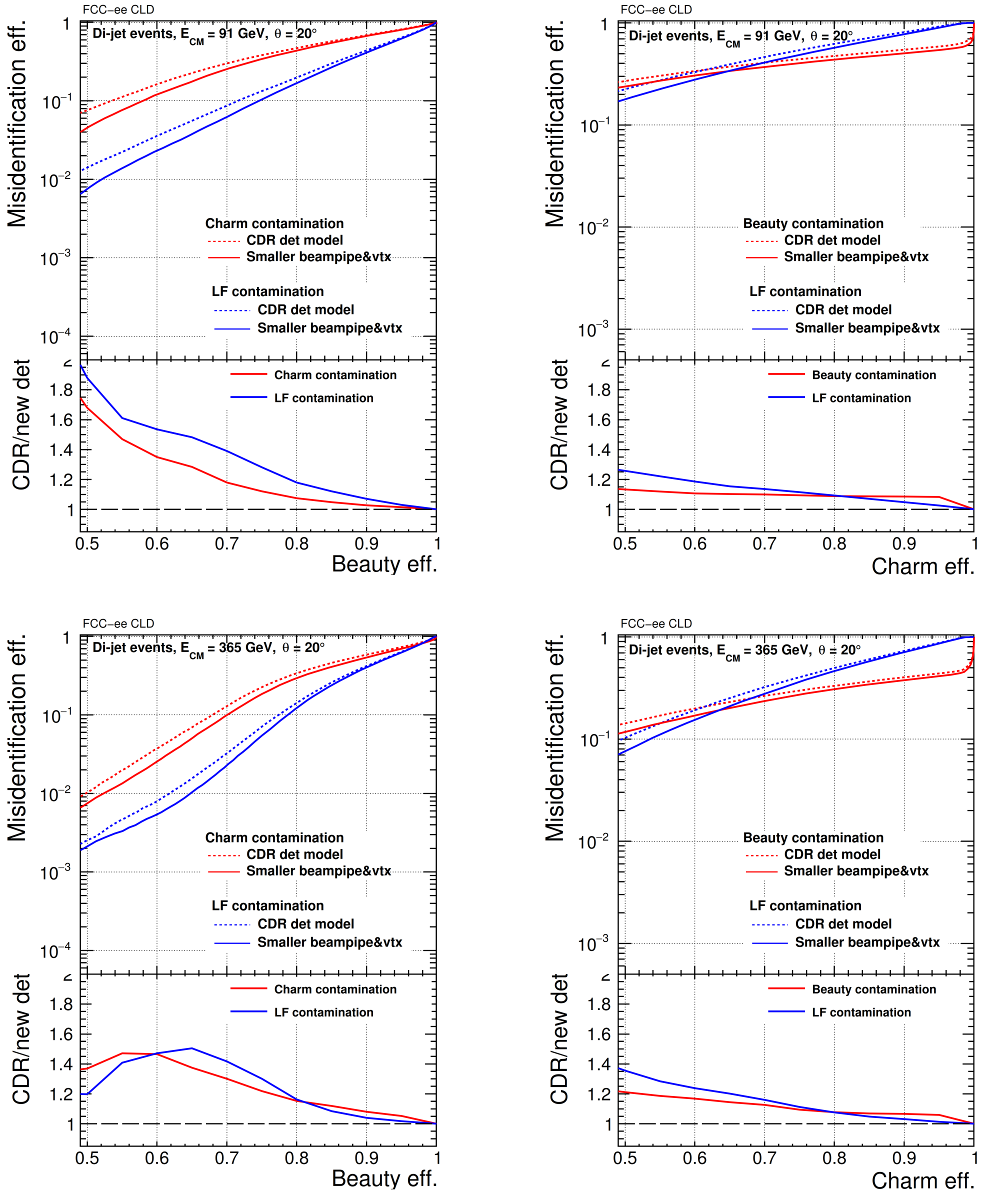


- $e^+e^- \to q\bar{q}$ events with θ(q) = 80°

- “Truth” tracking

→ Sizeable improvement
for charm at both energies and
beauty at 91.2 GeV

Smaller beam pipe: forward



- $e^+e^- \rightarrow q\bar{q}$ events with θ(q) = 20°

- “Truth” tracking

→ Larger impact compared to the barrel region

Summary and conclusions

- The CLD detector concept is based on the mature design of the CLIC detector model (CLICdet)

- Full simulation studies show promising performances for key aspects: track reconstruction, jet energy measurement, flavour tagging

- Recent developments include: ECAL optimisation, flavour tagging studies (impact of smaller beam pipe, rejection secondary interactions in the detector material)

Backup slides

Comparison to CLICdet

Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17.5
Vertex outer radius [mm]	60	58
Tracker technology	Silicon	Silicon
Tracker half length [m]	2.2	2.2
Tracker inner radius [m]	0.127	0.127
Tracker outer radius [m]	1.5	2.1
Inner tracker support cylinder radius [m]	0.575	0.675
ECAL absorber	W	W
ECAL X_0	22	22
ECAL barrel r_{min} [m]	1.5	2.15
ECAL barrel Δr [mm]	202	202
ECAL endcap z_{min} [m]	2.31	2.31
ECAL endcap Δz [mm]	202	202
HCAL absorber	Fe	Fe
HCAL λ_{I}	7.5	5.5
HCAL barrel r_{min} [m]	1.74	2.40
HCAL barrel Δr [mm]	1590	1166
HCAL endcap z_{min} [m]	2.54	2.54
HCAL endcap z_{max} [m]	4.13	3.71
HCAL endcap r_{min} [mm]	250	340
HCAL endcap r_{max} [m]	3.25	3.57
HCAL ring z_{min} [m]	2.36	2.35
HCAL ring z_{max} [m]	2.54	2.54
HCAL ring r_{min} [m]	1.73	2.48
HCAL ring r_{max} [m]	3.25	3.57
Solenoid field [T]	4	2
Solenoid bore radius [m]	3.5	3.7
Solenoid length [m]	8.3	7.4
Overall height [m]	12.9	12.0
Overall length [m]	11.4	10.6

Mayor modifications:

- Outer radius of silicon tracker:
1.5 m → 2.15 m
(reduced magnetic field)

- Depth of HCAL:
7.5 λ_I → 5.5 λ_I
(lower centre-of-mass energy)