Ideas for CLD optimisation

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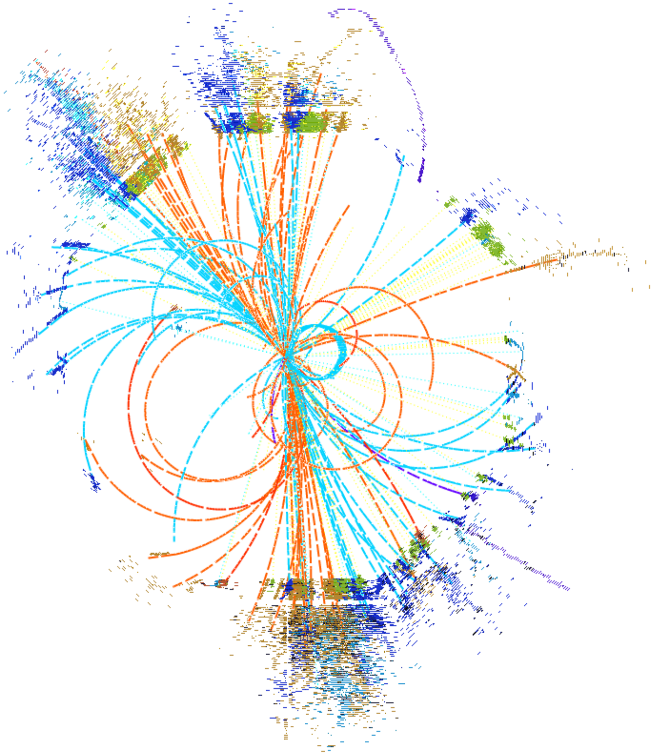
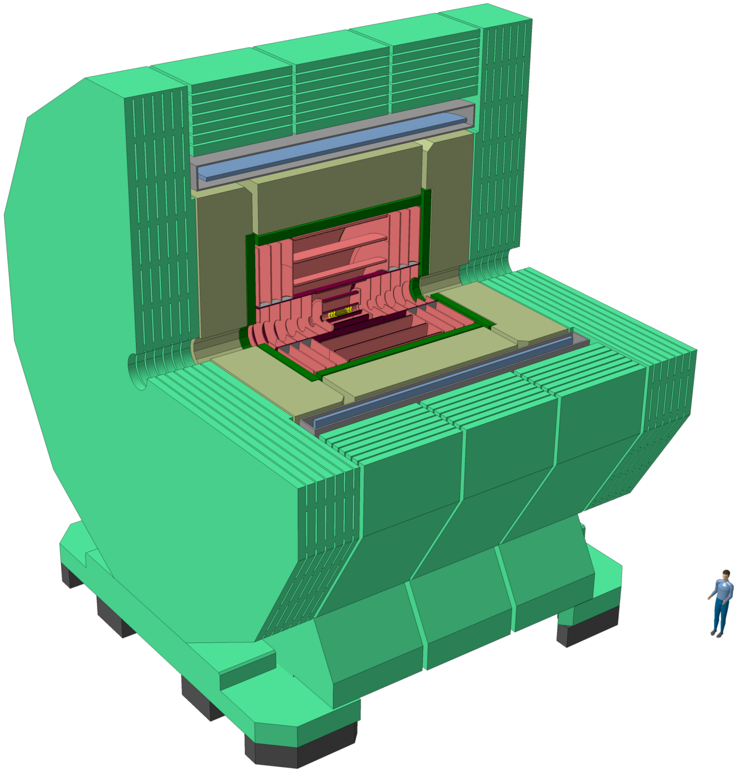
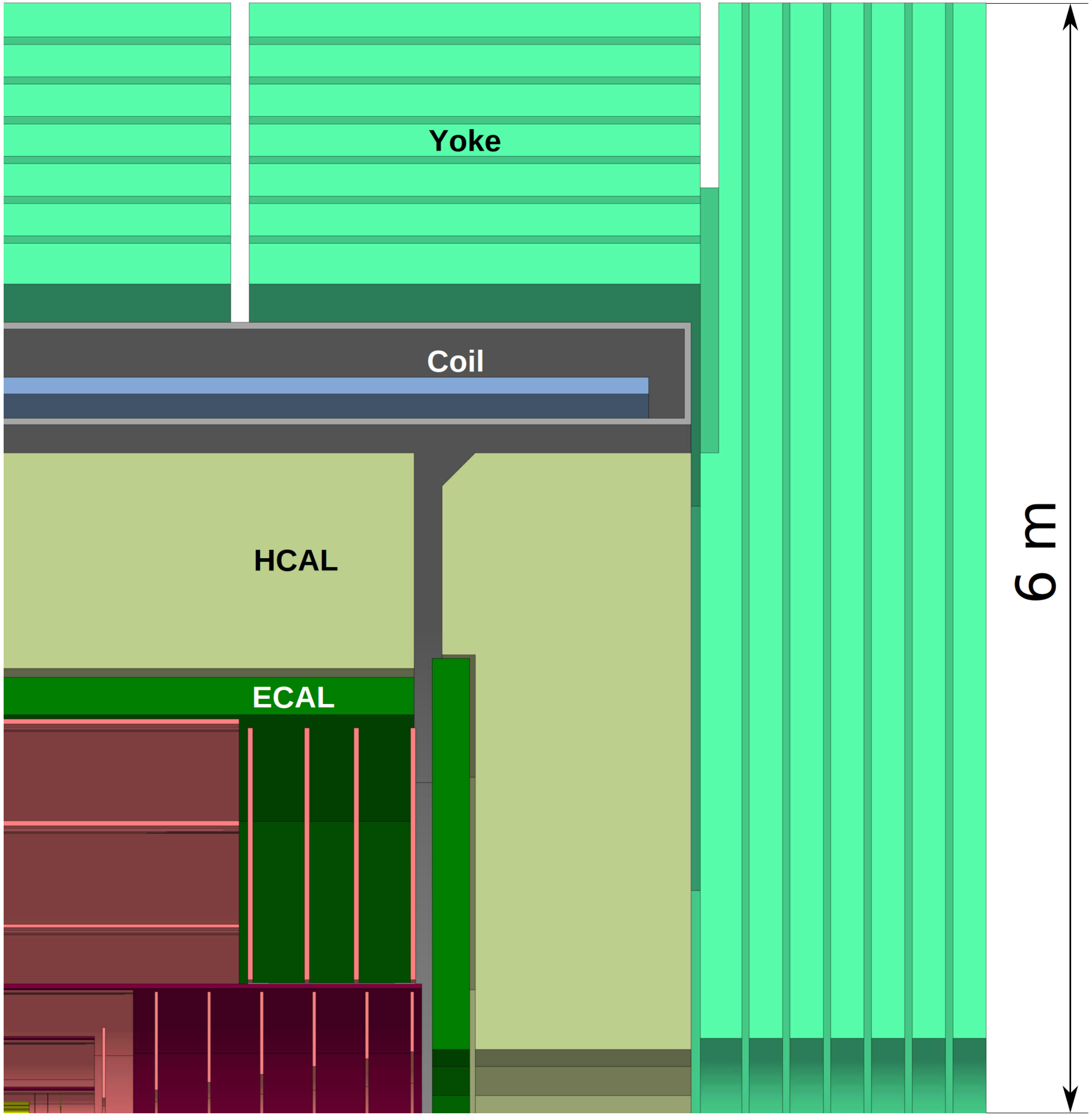
(CERN)





FCC Detector
Concepts Meeting
CERN, 04/04/2022

Reminder: overall dimensions



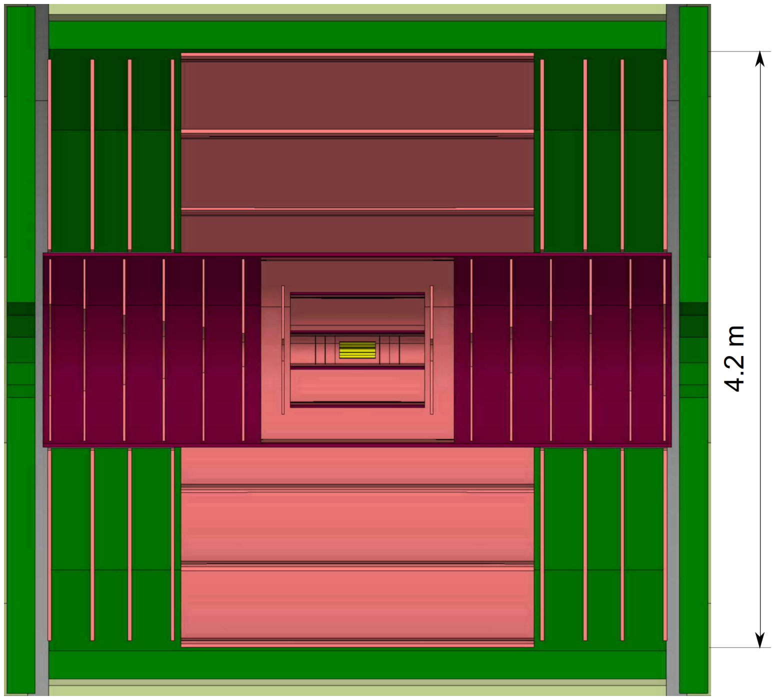
Optimised for particle flow calorimetry, inspired by CLICdet design:

- 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)

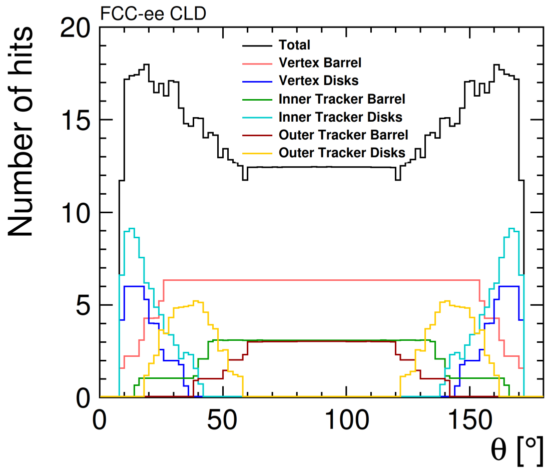
arXiv:1911.12230

Reminder: 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)
(smaller innermost layer under investigation)
- 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)



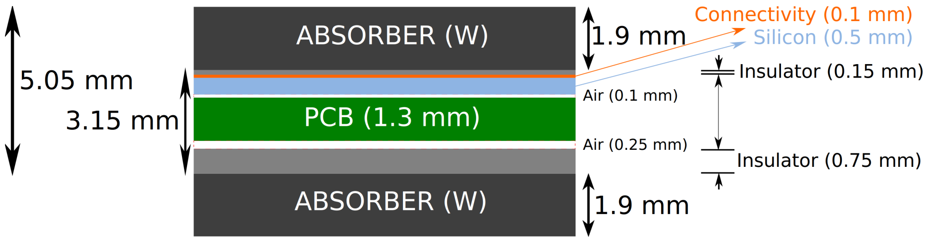
Main tracker:
- Silicon pixels and microstips: 7 μm x 90 μm single point resolution, except 5 μm x 5 μm in 1st inner tracker disk
- Inner tracker: 3 barrel layers, 7 endcap disks
- Outer tracker: 3 barrel layers, 4 endcap disks
- Material budget: 1.1 - 1.5% X_0 per layer



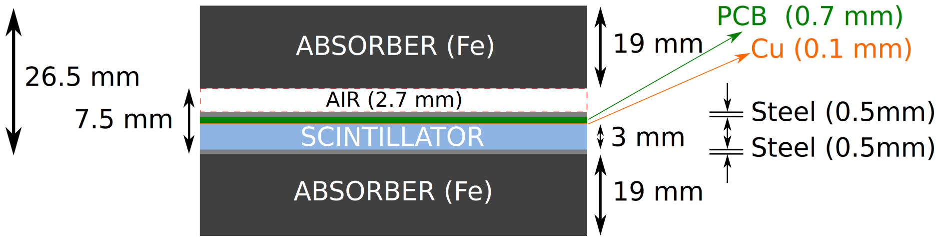
NB: Estimates of material budget inspired by ALICE ITS upgrade

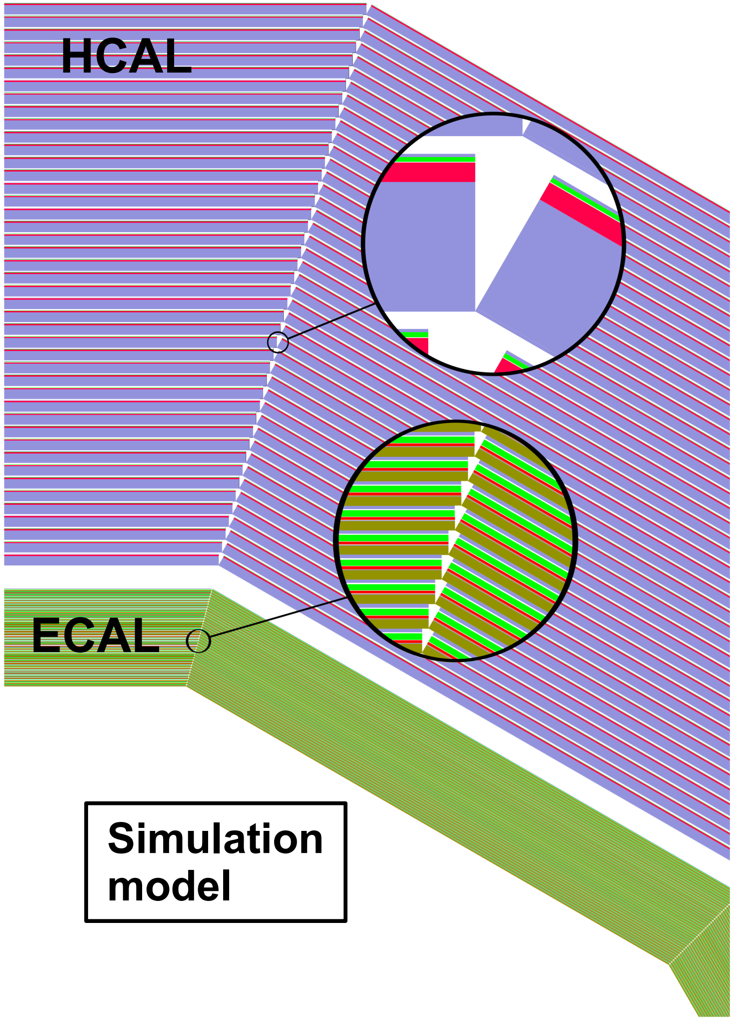
Reminder: calorimeters

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



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

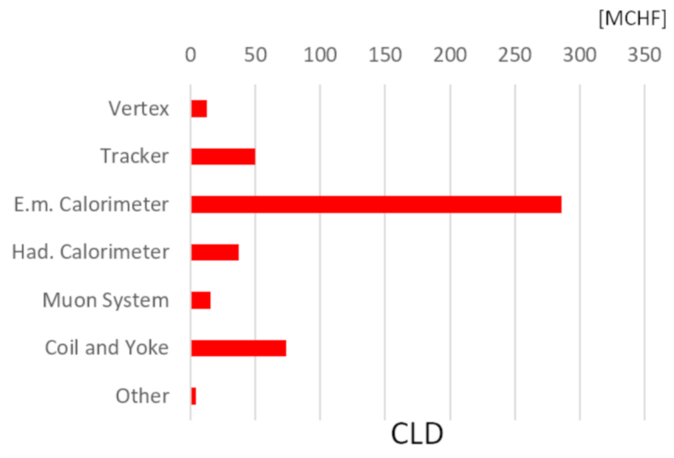


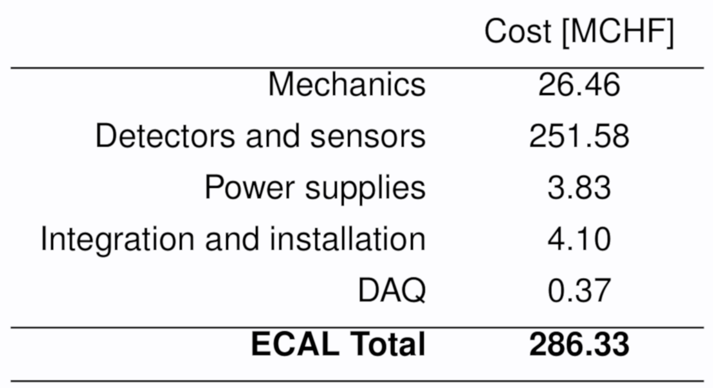


Simulation model

Example: ECAL optimisation (1)

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





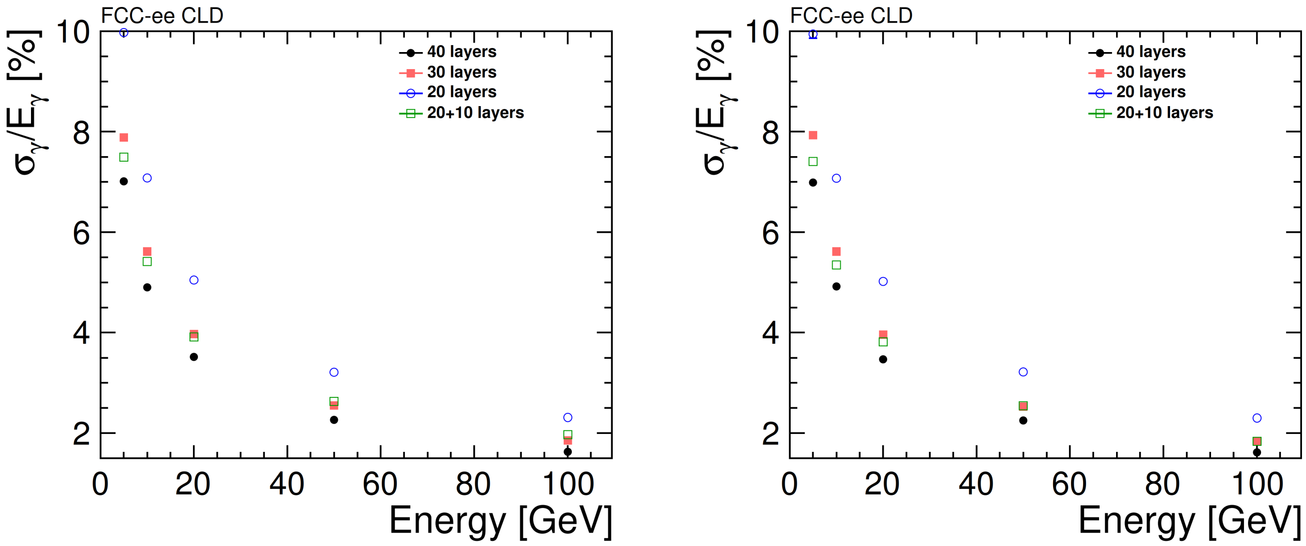
	Cost [MCHF]
Mechanics	26.46
Detectors and sensors	251.58
Power supplies	3.83
Integration and installation	4.10
DAQ	0.37
ECAL Total	**286.33**

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

arXiv:1911.12230

Example: ECAL optimisation (2)



→ 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

arXiv:1911.12230

Possible topics (1)

Vertex detector and flavour tagging:

- Study implications of cooling needs at FCC-ee due to absence of power pulsing

→ so far only rough estimate of additional material

- Optimisation of the vertex detector for the Z pole (backgrounds, lower jet energies)
- Improved treatment of material in the vertex detector region (in particular cooled beam pipe)
- Investigate potential of PID in the flavour tagging (together with physics performance)

Tracking:

- Study implications of cooling needs at FCC-ee due to absence of power pulsing

→ so far only rough estimate of additional material

- Further optimisation of the tracker configuration

→ e.g. overall size and tradeoff between more material from additional layers and better acceptance for long-lived particles

- Explore compatibility of alternative options (e.g. gaseous tracking?) with the presence of beam-induced background

Possible topics (2)

Calorimetry:
- Study implications of cooling needs at FCC-ee due to absence of power pulsing
→ additional space needed / impact on sampling fractions
- Impact of full beam-induced background in the forward direction at the Z pole
- Explore if alternative technology options are compatible with PFA calorimetry
and can provide better resolution for single EM particles
→ currently limited by Si-W ECAL

Luminosity detectors:
- Further background studies
- Inclusion of the MDI region and in particular the luminosity detectors in the CLD simulation

Possible topics (3)

Precise timing capabilities:
- Potential of timing information with O(few ns) precision to reject particles from beam-induced background (including backscattered fragments)
- Impact of very precise timing information with O(few 10 ps) precision for PID

→ comparison of different approaches (ECAL and/or dedicated timing layer, maybe complemented by time information from tracking layers)

Further PID issues:
- Investigate if dE/dx from (thin) tracking layers can be useful
- Add RICH detector?

Readout considerations:
- Further studies of detector integration times
- More detailed look at data rates and the possible need for a trigger

Calibration:
- Impact of calibration issues and the resulting systematic uncertainties with an emphasis on issues at the Z pole for which full simulation is needed (together with physics perf.)

→ e.g. uncertainties of various potential luminosity measurements, calibration of the b-tagging and c-tagging efficiencies and fake rates

Software: simulation

CLD software based on Key4hep: available on CVMFS
(/cvmfs/sw-nightlies.hsf.org/key4hep/setup.sh)

More options for DDSim

- `ddsim` python executable is part of the DD4hep release [3]
- Get steering file `ddsim --dumpSteeringFile > mySteer.py`
  - Steering file includes documentation for parameters and examples
  - The python file contains a `DD4hepSimulation` object at global scope
  - Configure simulation directly from command-line
  - Input: Particle Gun, stdhep, HepMC, slcio, GuineaPig Pairs; EDM4hep forthcoming

```python
from DDSim.DD4hepSimulation import DD4hepSimulation
from SystemOfUnits import mm, GeV, MeV, keV
SIM = DD4hepSimulation()
SIM.compactFile = ”CLIC_o3_v06.xml”
SIM.runType = ”batch”
SIM.numberOfEvents = 2
SIM.inputFile = ”electrons.HEPEvt”
SIM.part.minimalKineticEnergy = 1*MeV
SIM.filter.filters [’edep3kev’] =
dict (name=”EnergyDepositMinimumCut/3keV” ,
      parameter={”Cut” : 3.0*keV} )
```

```
$ ddsim
--action.calo                   --filter.tracker          --part.keepAllParticles
--action.mapActions             -G                        --part.minimalKineticEnergy
--action.tracker                --gun.direction           --part.printEndTracking
--compactFile                   --gun.energy              --part.printStartTracking
--crossingAngleBoost            --gun.isotrop             --part.saveProcesses
--dump                          --gun.multiplicity        --physics.decays
--dumpParameter                 --gun.particle            --physics.list
--dumpSteeringFile              --gun.position            --physicsList
--enableDetailedShowerMode      -h                        --physics.rangecut
--enableGun                     --help                    --printLevel
--field.delta_chord             -I                        --random.file
--field.delta_intersection      --inputFiles              --random.luxury
--field.delta_one_step          -M                        --random.replace_gRandom
--field.eps_max                 --macroFile               --random.seed
--field.eps_min                 -N                        --random.type
--field.equation                --numberOfEvents          --runType
--field.largest_step            -O                        -S
--field.min_chord_step          --outputFile              --skipNEvents
--field.stepper                 --output.inputStage       --steeringFile
--filter.calo                   --output.kernel           -v
--filter.filters                --output.part             --vertexOffset
--filter.mapDetFilter           --output.random           --vertexSigma
```

FCC Physics WS, Feb. 11, 2022 A. Sailer: Status of CLD Software 13/18

→ see talk by A. Sailer at FCC Physics Workshop 2022

Software: reconstruction

CLD software based on Key4hep: available on CVMFS
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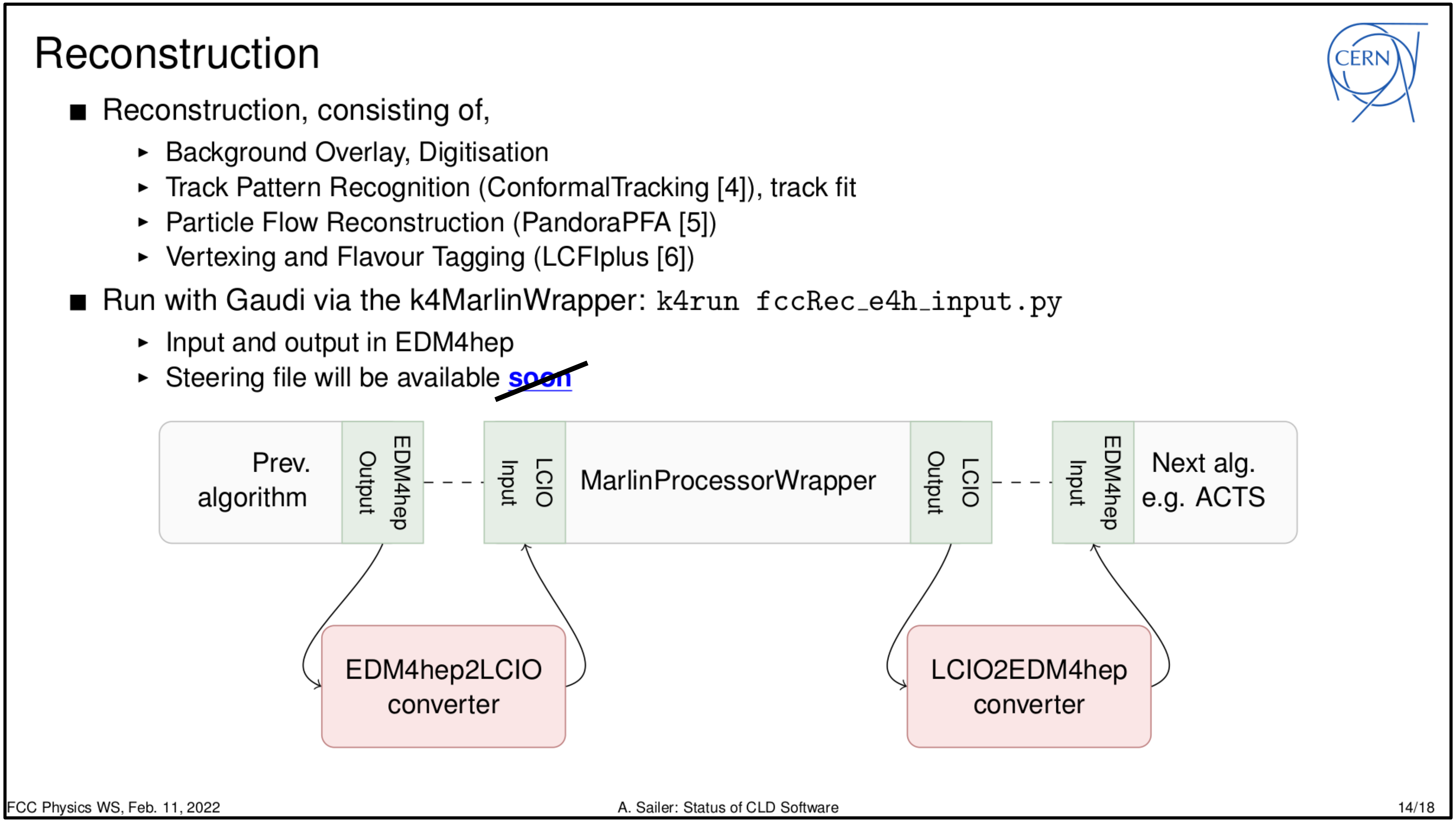

Reconstruction

- Reconstruction, consisting of,
  - Background Overlay, Digitisation
  - Track Pattern Recognition (ConformalTracking [4]), track fit
  - Particle Flow Reconstruction (PandoraPFA [5])
  - Vertexing and Flavour Tagging (LCFIplus [6])
- Run with Gaudi via the k4MarlinWrapper: `k4run fccRec_e4h_input.py`
  - Input and output in EDM4hep
  - Steering file will be available ~~soon~~

Prev. algorithm

EDM4hep Output

LCIO Input

MarlinProcessorWrapper

LCIO Output

EDM4hep Input

Next alg. e.g. ACTS

EDM4hep2LCIO converter

LCIO2EDM4hep converter

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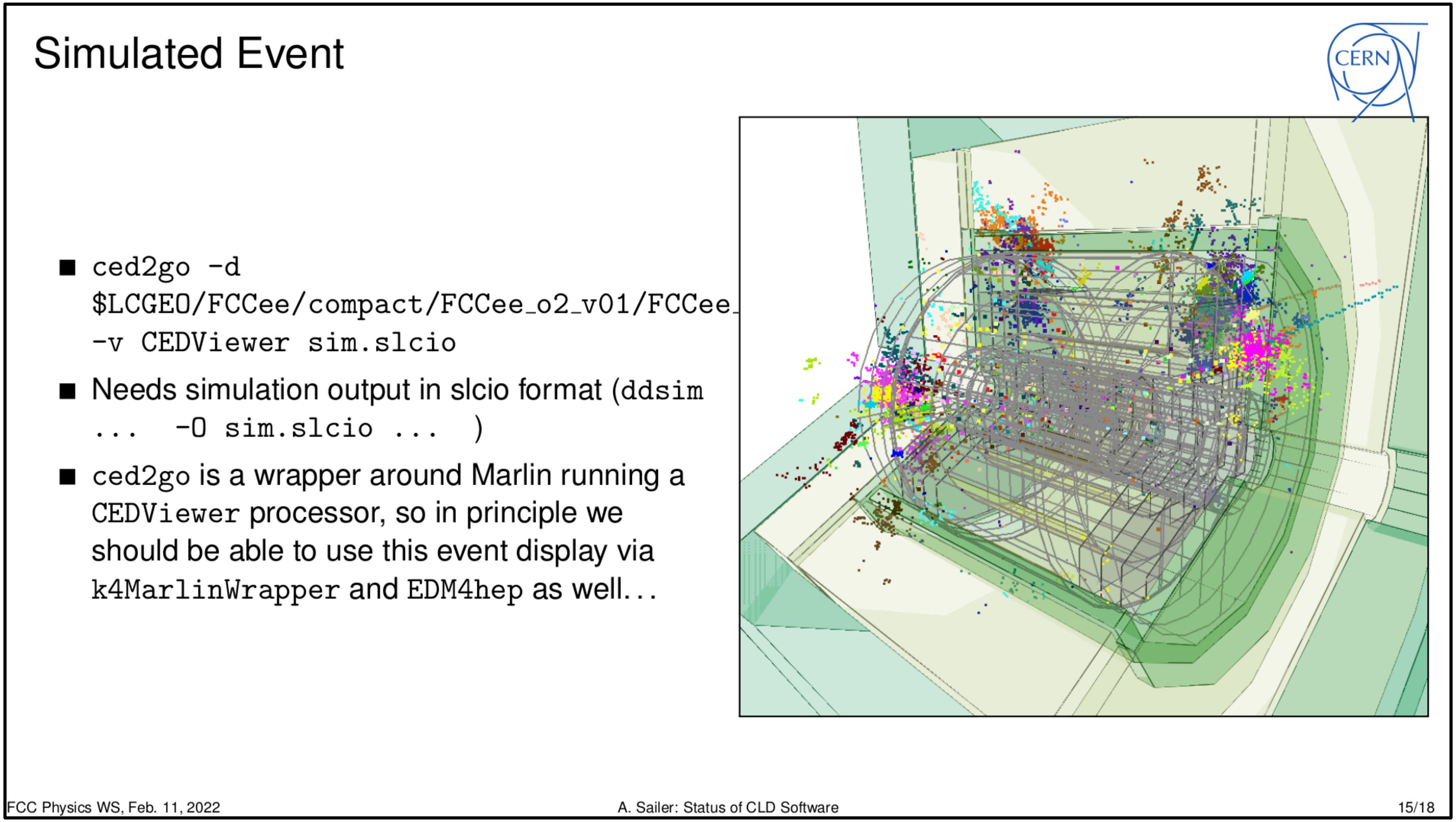
→ see talk by A. Sailer at FCC Physics Workshop 2022

Software: event display

CLD software based on Key4hep: available on CVMFS
(/cvmfs/sw-nightlies.hsf.org/key4hep/setup.sh)



Simulated Event

- `ced2go -d $LCGEO/FCCee/compact/FCCee_o2_v01/FCCee_ -v CEDViewer sim.slcio`
- Needs simulation output in slcio format (`ddsim ... -O sim.slcio ... `)
- `ced2go` is a wrapper around Marlin running a `CEDViewer` processor, so in principle we should be able to use this event display via `k4MarlinWrapper` and `EDM4hep` as well. . .

FCC Physics WS, Feb. 11, 2022 A. Sailer: Status of CLD Software 15/18

→ see talk by A. Sailer at FCC Physics Workshop 2022

Summary and conclusions

- The CLD detector was developed with an emphasis on energies at and above 250 GeV

- Further optimisation shall also include the lower FCC-ee energy stages

- Software for simulation and reconstruction based on Key4hep

- Many interesting possibilities for refinement of individual sub-detectors, exploration of new opportunties, global optimisation for higher-level observables, ...

Many thanks for André Sailer and Dominik Dannheim for input and discussions!

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:

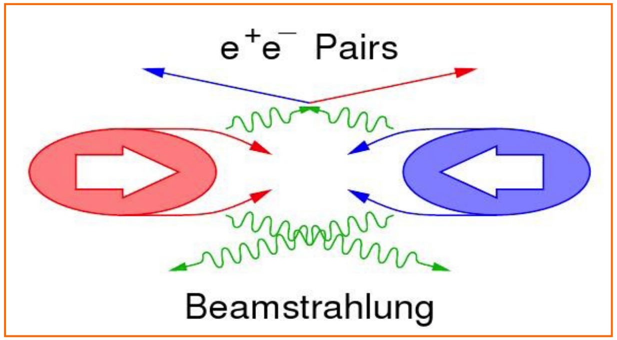
- Outer radius of silicon tracker:
  1.5 m → 2.15 m
  (reduced magnetic field)

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

Beam-induced backgrounds (1)

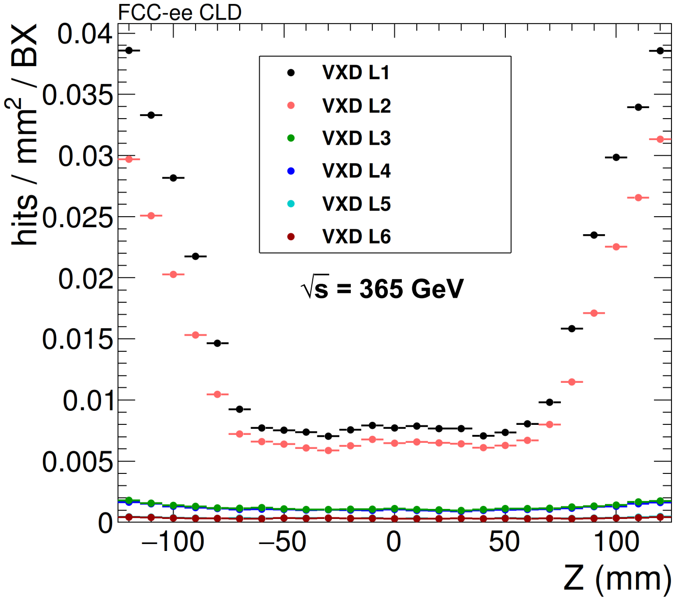
Contributions studied in detail:

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

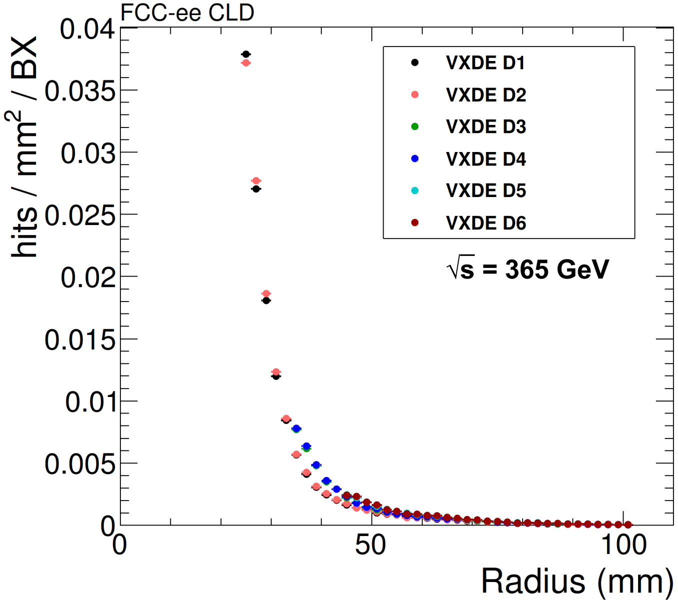


→ see talk by Emmanuel Perez

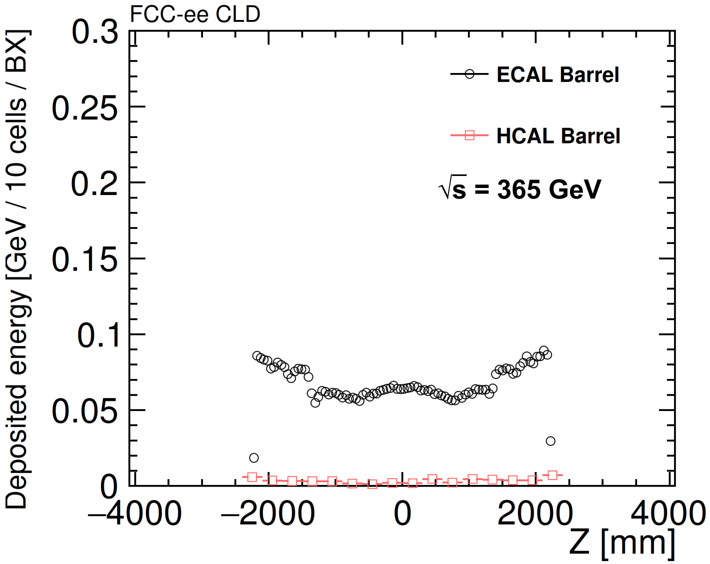
Vertex barrel

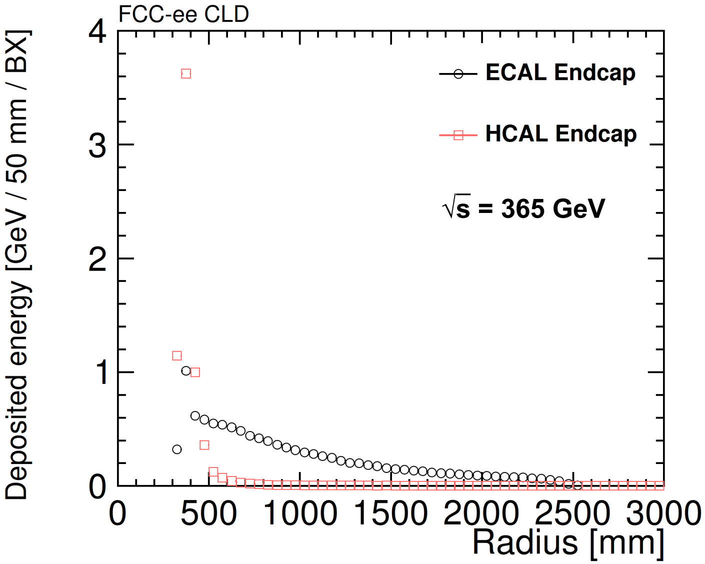


Vertex endcaps



Beam-induced backgrounds (2)

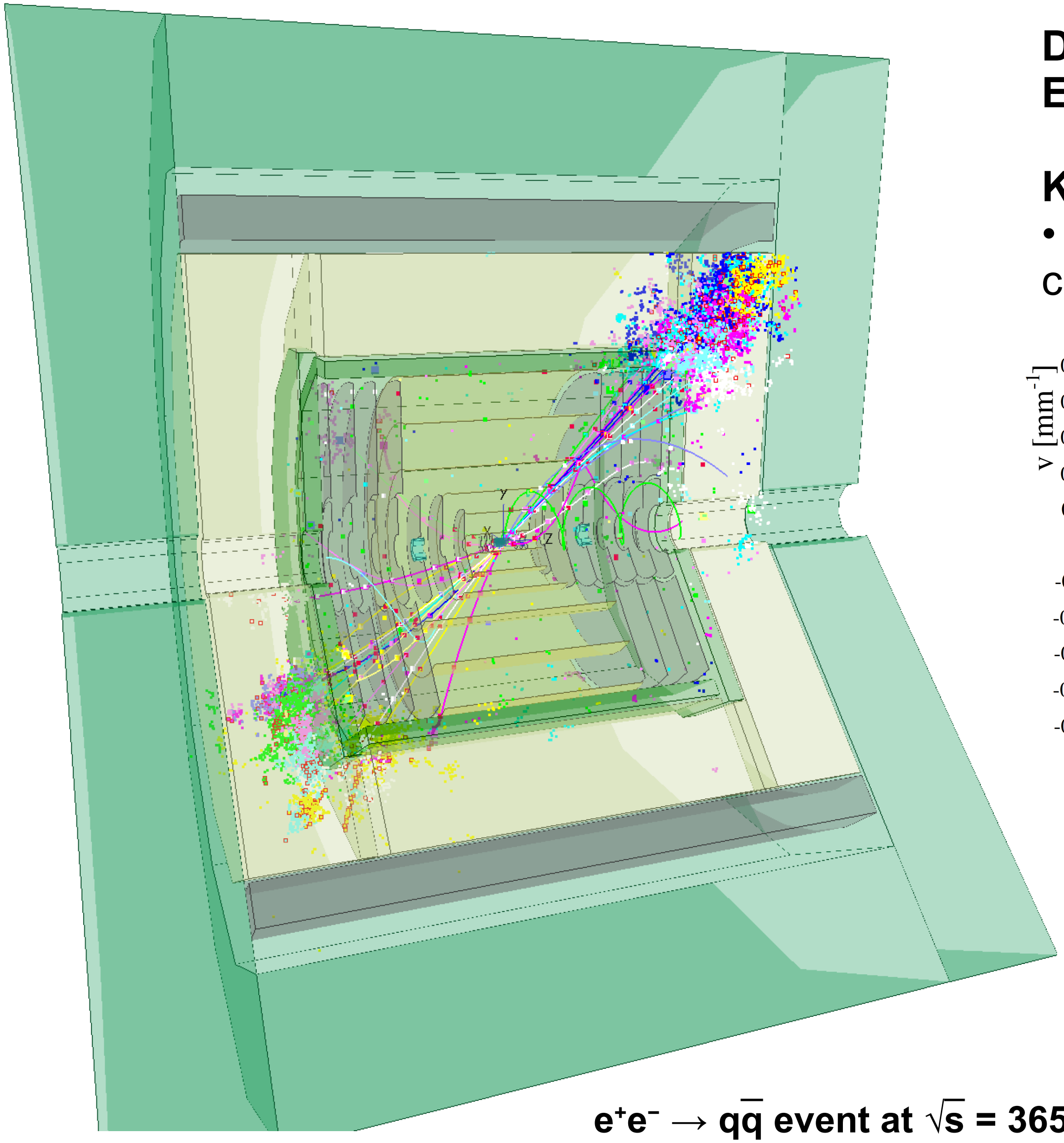




Maximal energy deposit per bunch crossing:

- 0.1 GeV / 10 cells in ECAL
- 4 GeV / 50 mm in HCAL

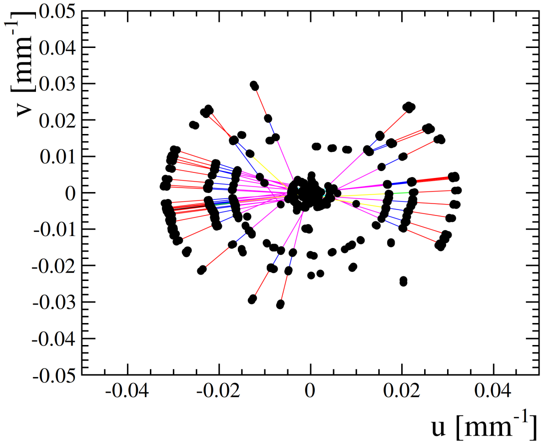
Physics performance studies



Detector geometry: DD4hep
Event reconstruction framework: Marlin

Key event reconstruction steps:

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



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

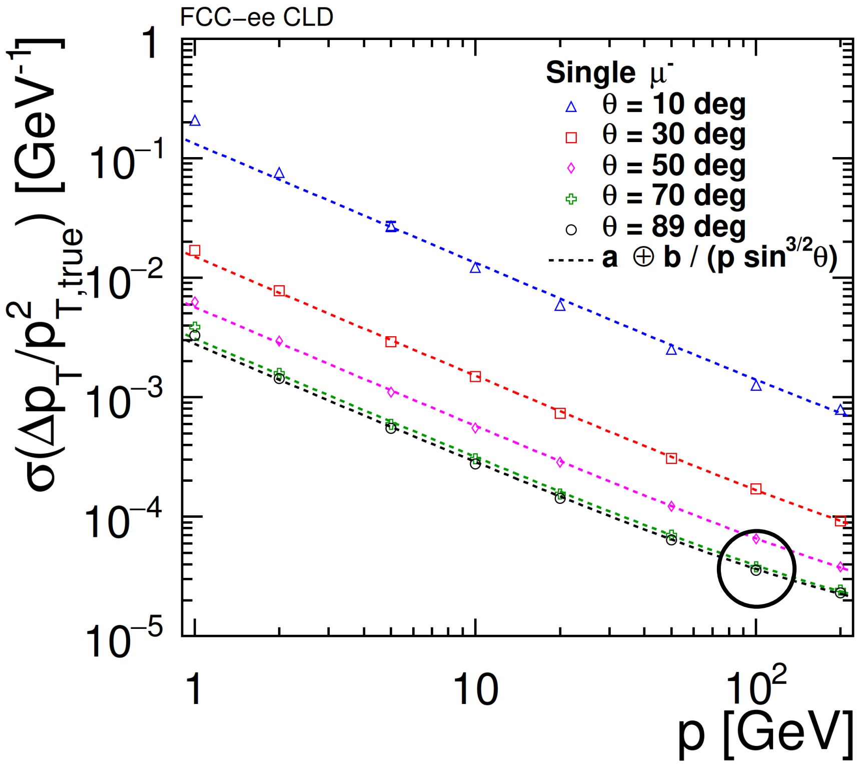
Nucl. Inst. Meth. A 956, 163304 (2020)

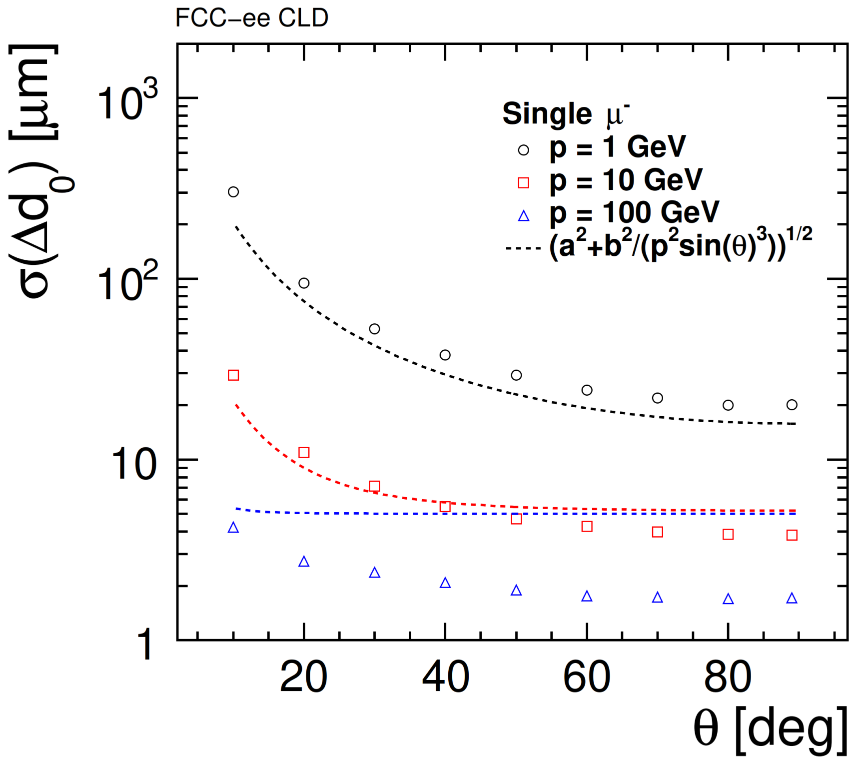
- Calorimeter clustering and particle flow analysis: PandoraPFA

- 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}

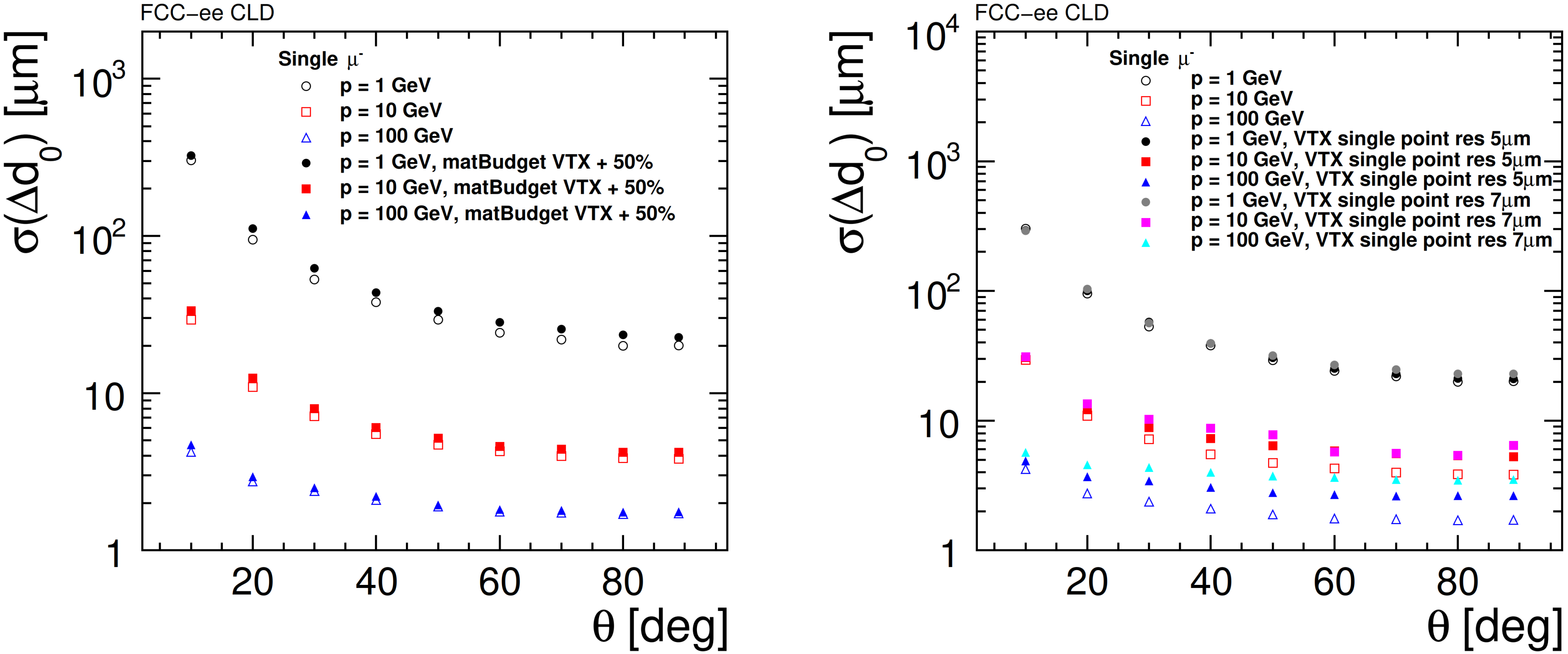
Target impact parameter resolutions: a = 5 μm, b = 15 μm (dashed lines)

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

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)

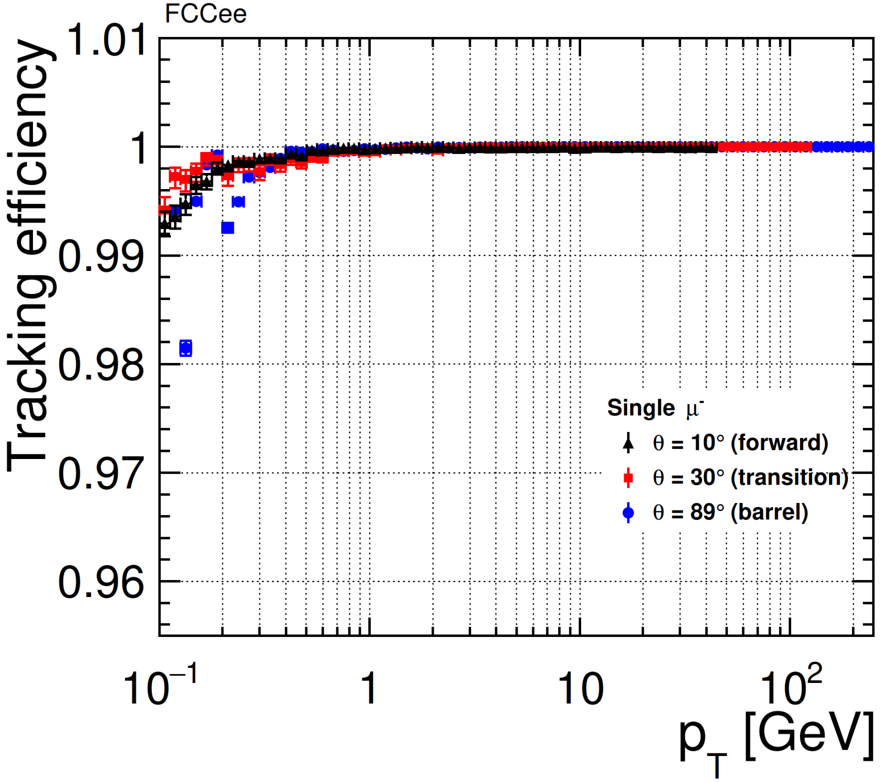


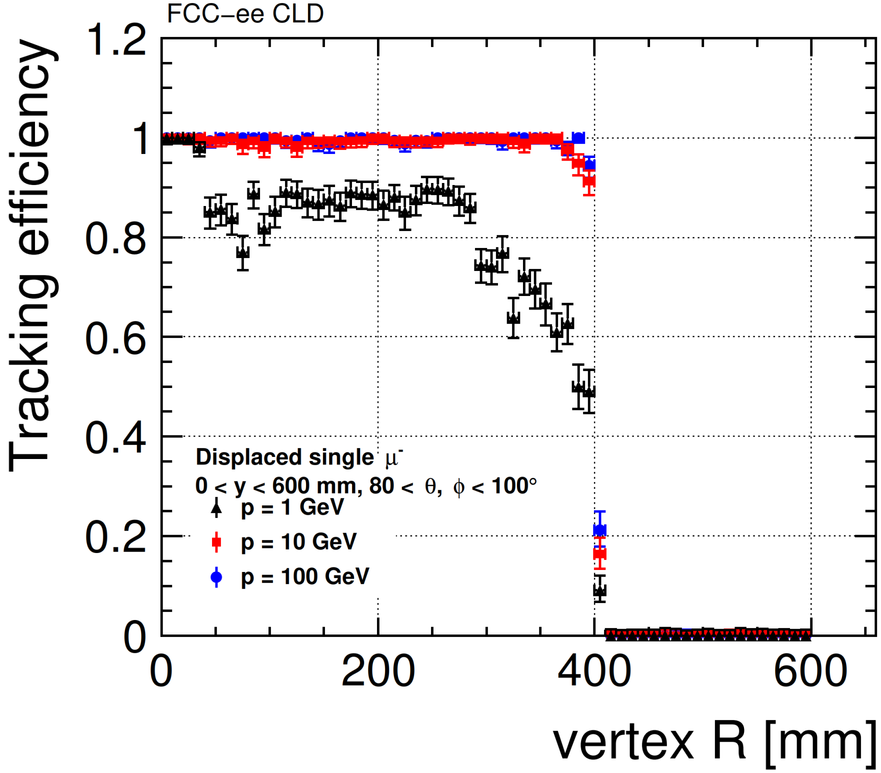
→ Small effect of increased material budget

→ 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



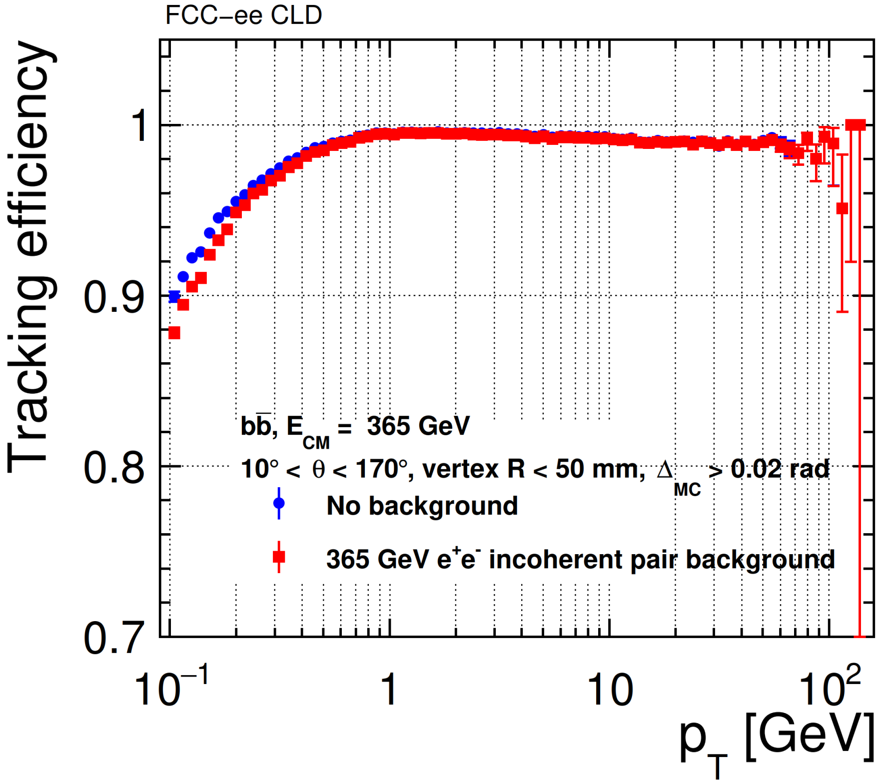


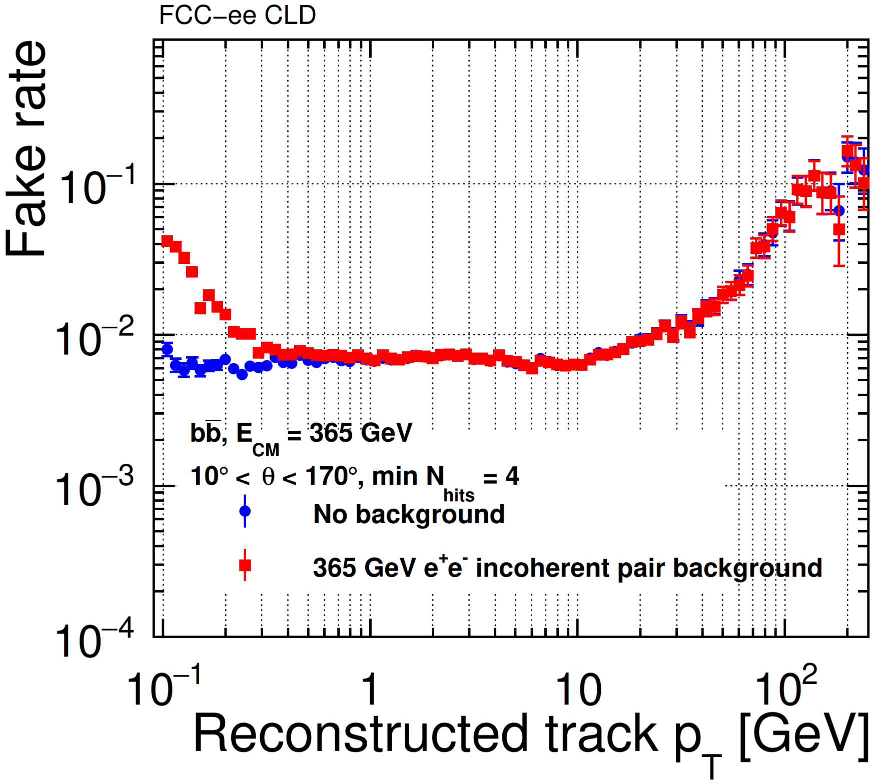
→ Tracking fully efficient at 10°
→ Tracking efficient up to 40 cm radius (due to minimum number of hits required)
→ Drop by 15% efficiency at p = 1 GeV for R > 38 mm from particles loosing too much energy to reach the minimum number of hits

Tracking in complex events

Test case: $e^+e^- \to b\bar{b}$ 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

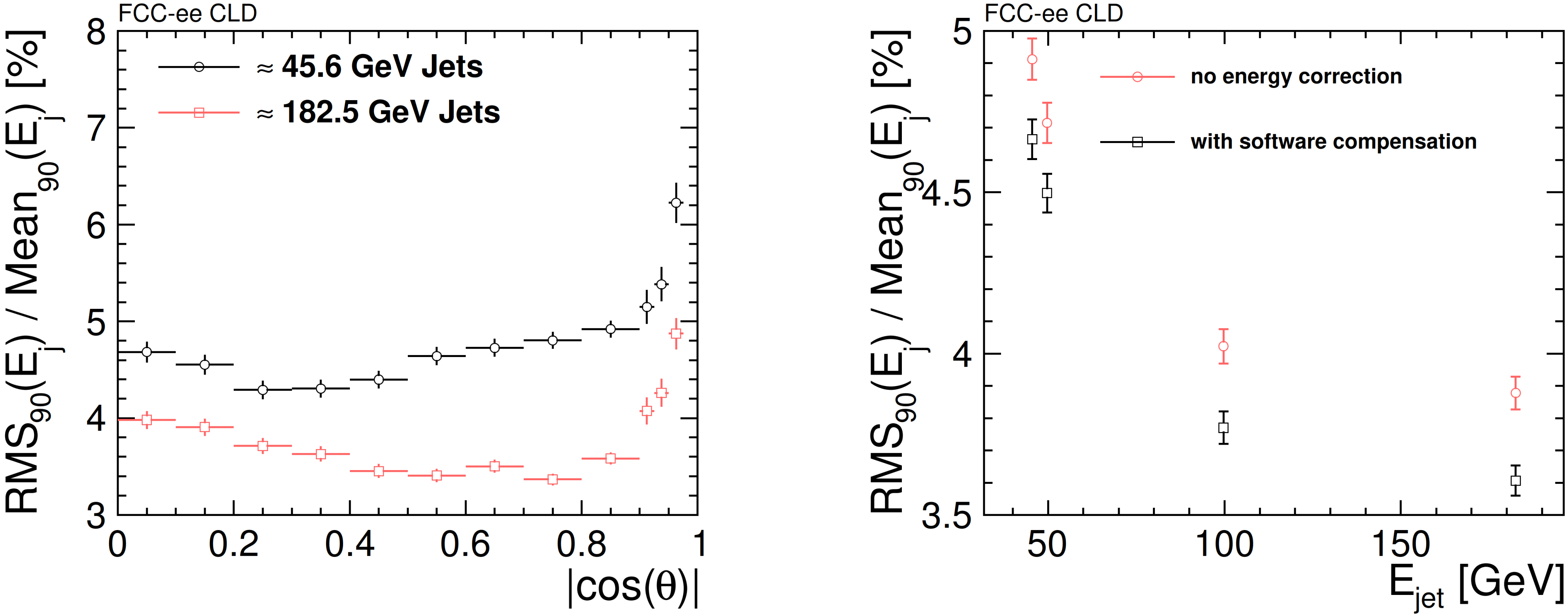
→ Impact of beam-induced backgrounds is small

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



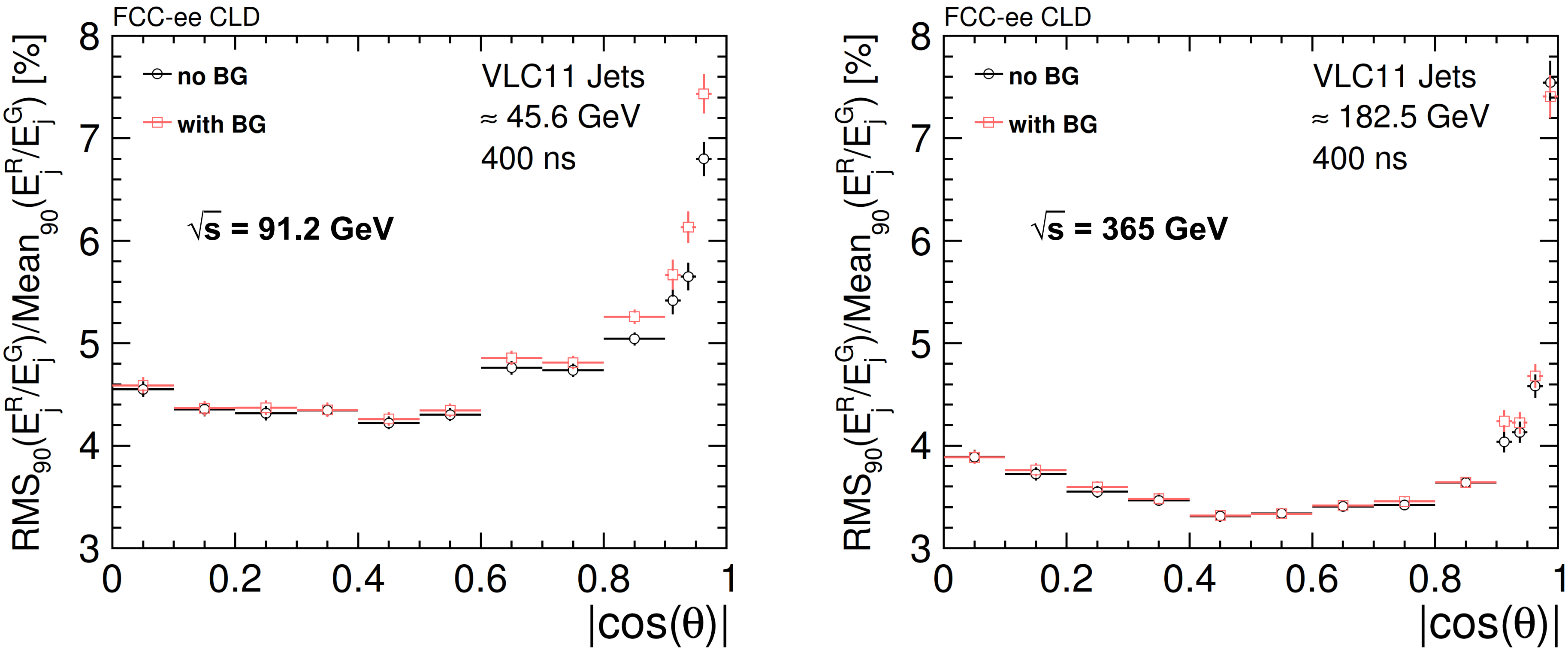
→ 3 - 4% jet energy resolution at 45.6 GeV, 4 - 5% at 182.5 GeV
→ Up to 10% improvement from software compensation

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

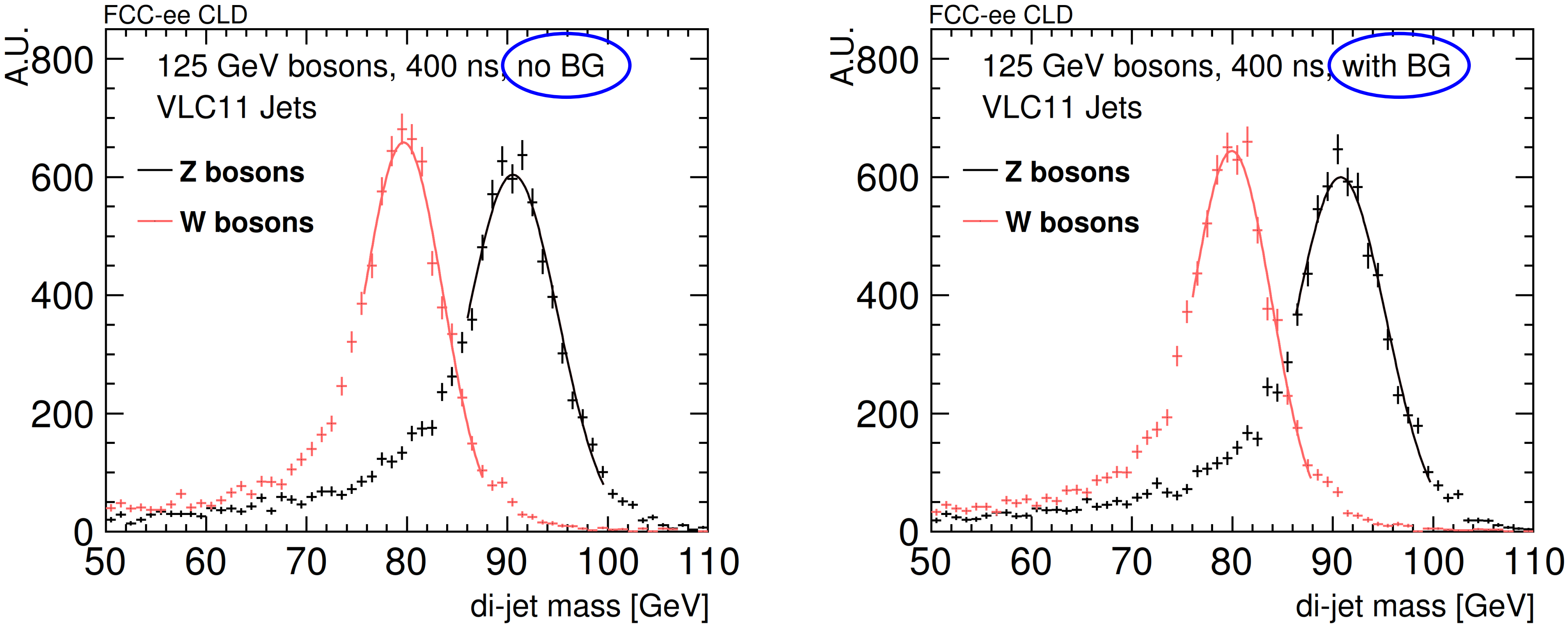
Eur. Phys. J. C78, 144 (2018)



→ 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)

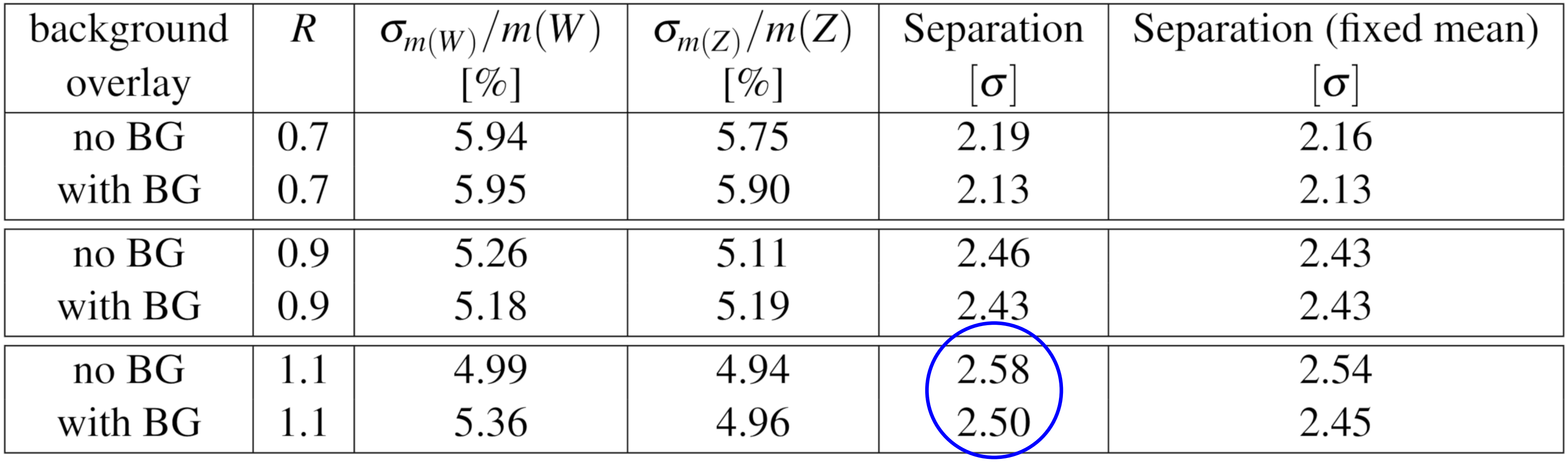


W/Z separation (2)

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

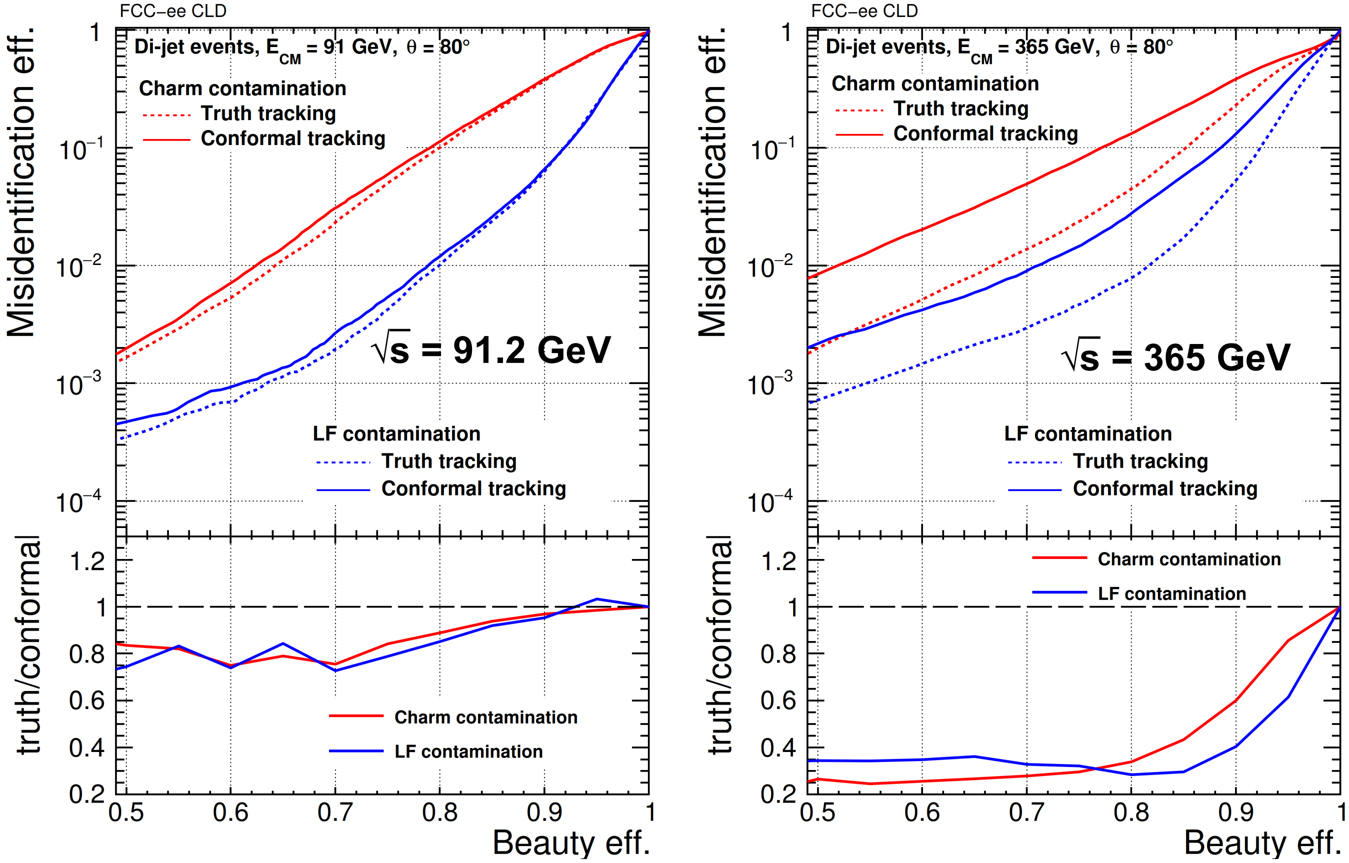


background overlay	R	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	Separation [σ]	Separation (fixed mean) [σ]
no BG	0.7	5.94	5.75	2.19	2.16
with BG	0.7	5.95	5.90	2.13	2.13
no BG	0.9	5.26	5.11	2.46	2.43
with BG	0.9	5.18	5.19	2.43	2.43
no BG	1.1	4.99	4.94	2.58	2.54
with BG	1.1	5.36	4.96	2.50	2.45

→ Effect of beam-induced background small

→ Separation on the level of 2.5 standard deviations possible

B-tagging performance



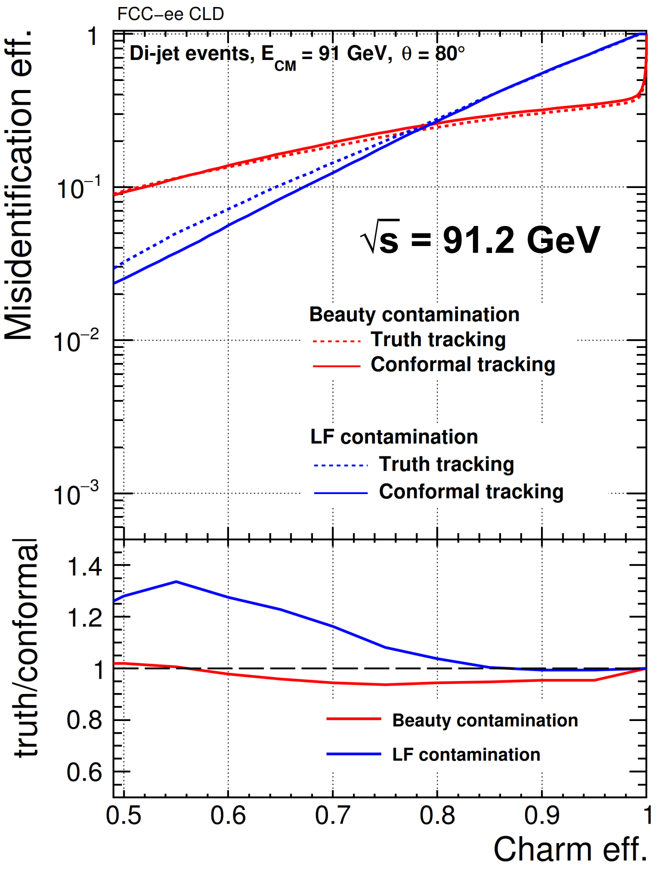
Sizeable difference between “truth” and conformal tracking at 365 GeV understood: large fraction of B-hadrons decay after the first vertex layer (improvement in progress)

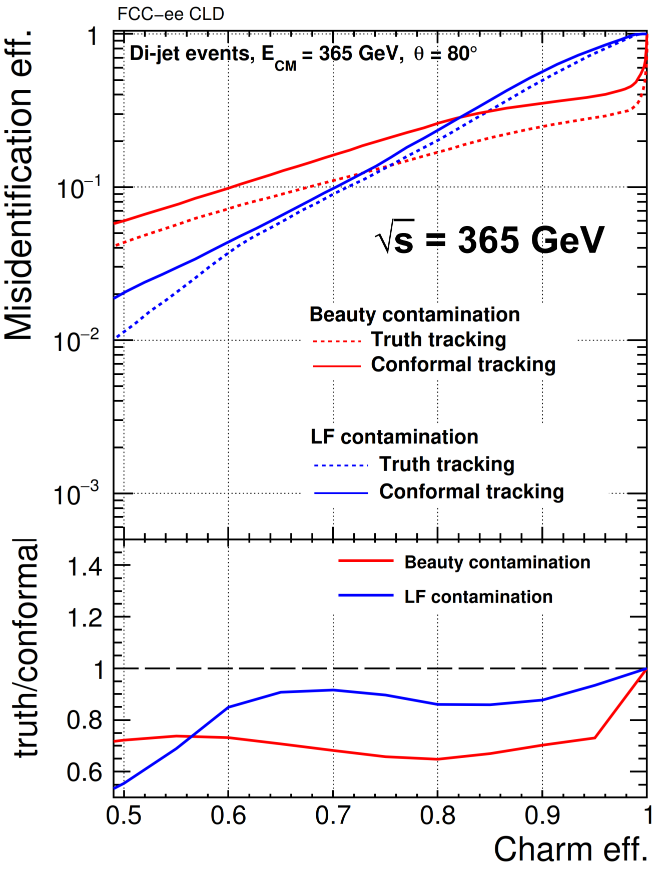
Test case: $e^+e^- \rightarrow q\bar{q}$ events with θ(q) = 80°

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

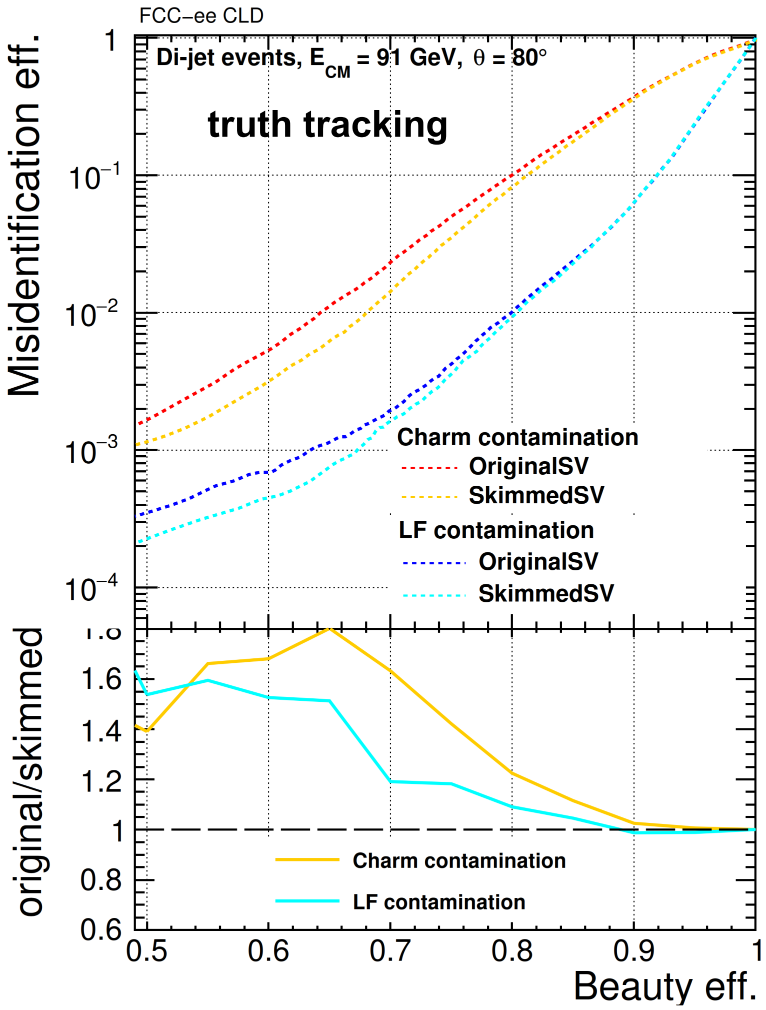
- Higher energies benefit from larger boost

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

For 60% c-tagging efficiency:

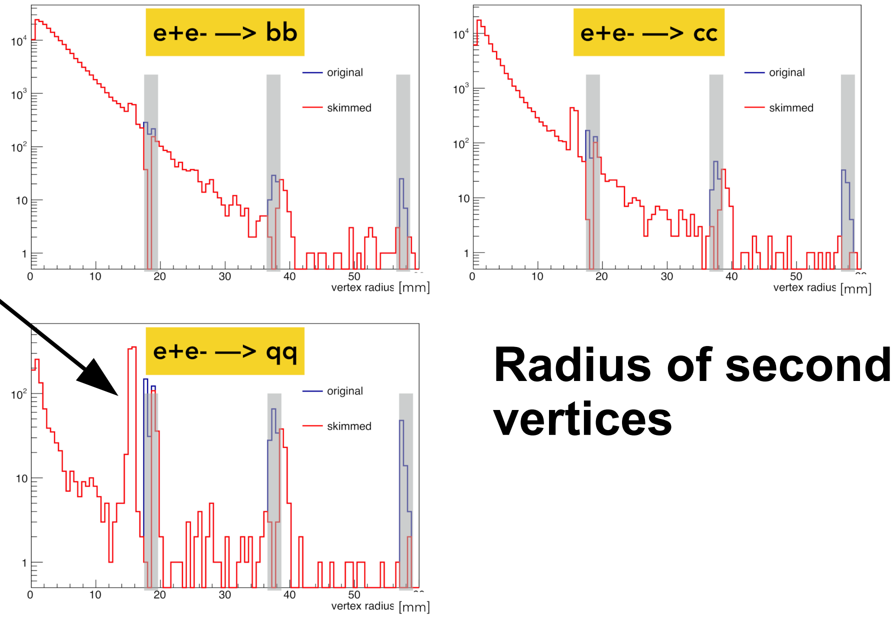
- 5% (1.2%) fake rate from u/d/s (beauty) at 91.2 GeV
- 4% (10%) fake rate from u/d/s (beauty) at 365 GeV

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



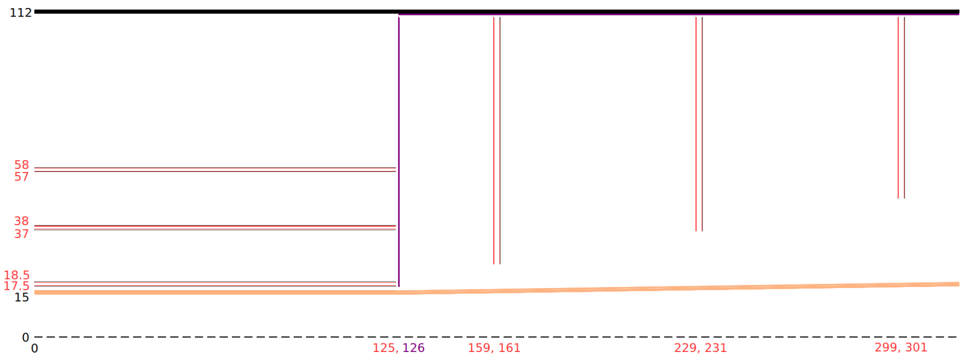
Beam pipe

Radius of secondary vertices

Flavour tagging with smaller beam pipe

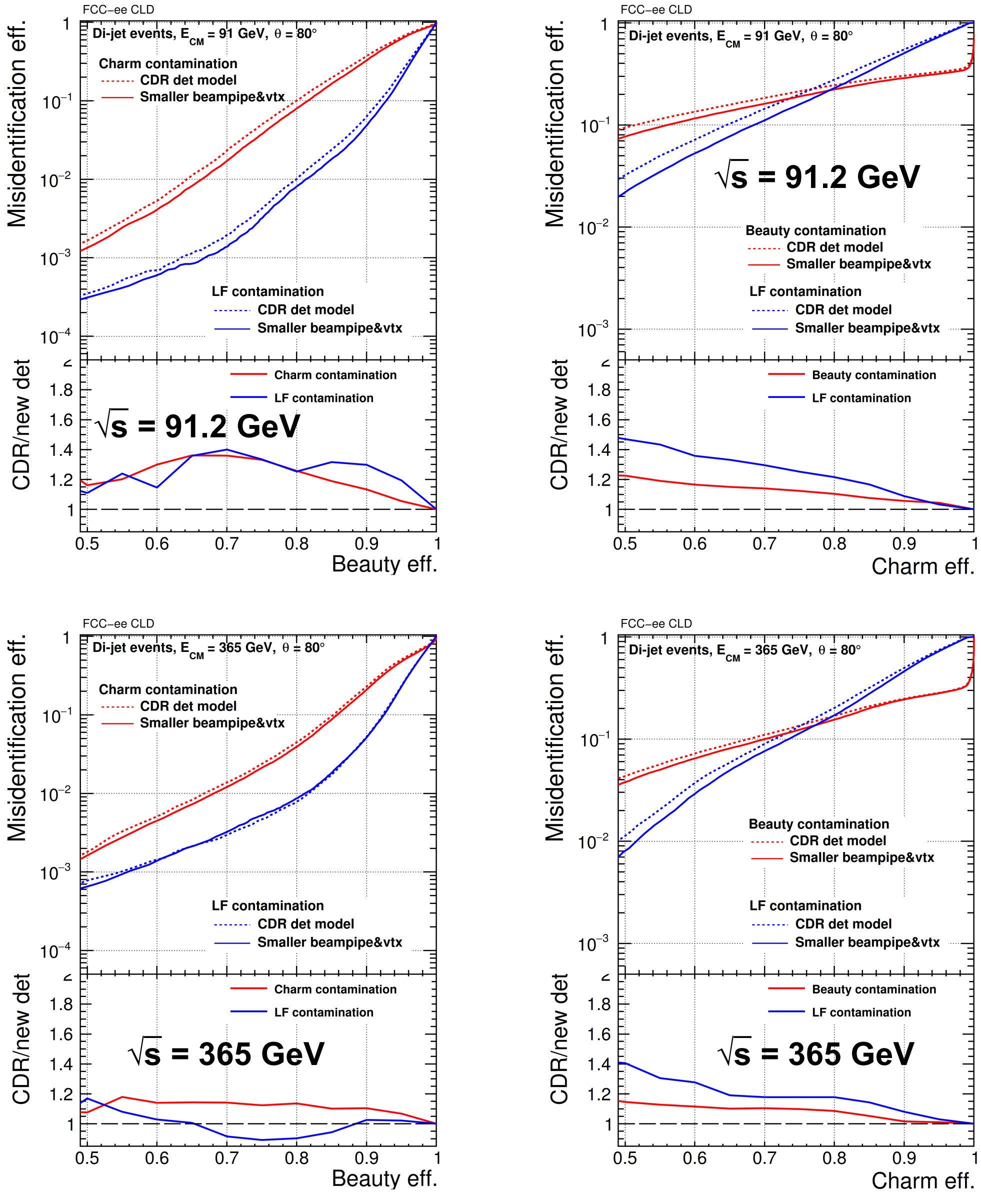
- Alternative FCC-ee interaction region with smaller beam pipe radius
- Innermost barrel layer moved from 17.5 mm to 12.5 mm, outer radius unchanged
- Vertex disks unchanged

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

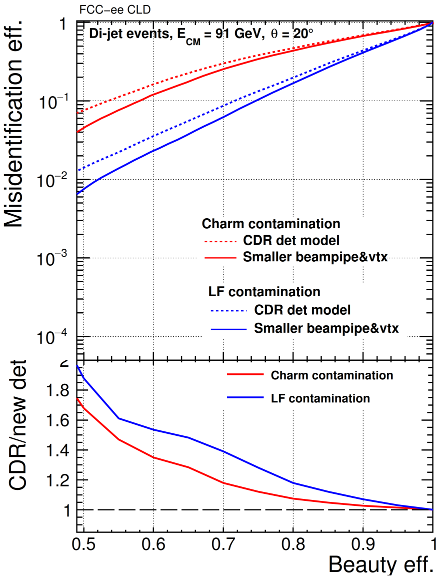
Smaller beam pipe: barrel

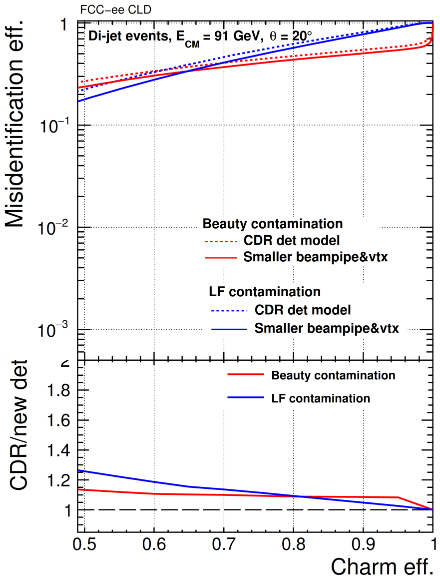


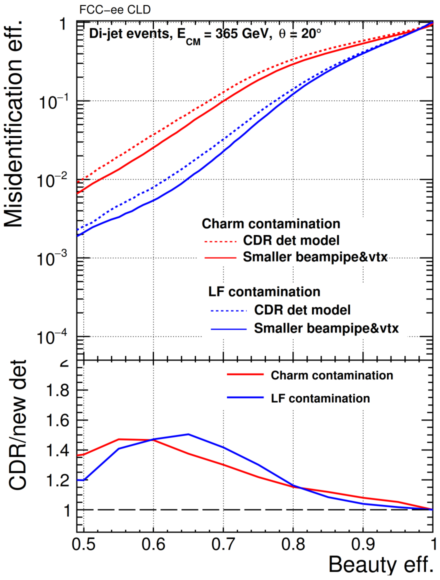
- $e^+e^- \rightarrow q\bar{q}$ events with θ(q) = 80°
- "Truth" tracking

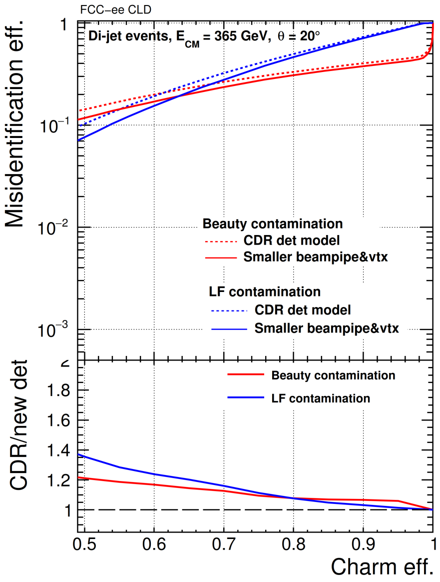
→ Sizeable improvement for charm at both energies and beauty at 91.2 GeV

Smaller beam pipe: forward









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

→ Larger impact compared to the barrel region