FCChh Tracker Performance Studies

Estel Perez (CERN) on behalf of the FCChh detector working group

FCC Week, Berlin May 2017
Introduction and Outline

• Goal: show performance studies leading to changes in the FCChh tracker detector design*

1. Tools and validation
2. Pattern recognition studies
   – dependence on detector layout, material and granularity
3. Reconstruction of boosted objects
   – dependence on granularity
4. Flavor tagging performance
   – dependence on granularity, material, jet energy

*see Zbynek Drasal’s talk
• Different software tools were required for the various performance studies:

<table>
<thead>
<tr>
<th>Software previously used by</th>
<th>tkLayout* (CMS)</th>
<th>LicToy (ILC, CLIC)</th>
<th>CLIC SW (CLIC)</th>
<th>SiD SW (SiD, CLIC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>Fast</td>
<td>Fast</td>
<td>Full</td>
<td>Full</td>
</tr>
<tr>
<td>used for studying geometry</td>
<td>pattern</td>
<td>pattern</td>
<td>boosted</td>
<td>flavor tagging</td>
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<tr>
<td></td>
<td>recognition</td>
<td>recognition</td>
<td>objects</td>
<td></td>
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<td></td>
<td>v3.00</td>
<td>v3.00</td>
<td>v3.01</td>
<td>v3.02</td>
</tr>
</tbody>
</table>

• Validated the different tools against each other

*see Valentin Volkl’s talk
Very good agreement in the pT resolution at all pTs

Small differences due to tkLayout allowing several hits per layer

Nhits and Resolution reflects the layout structure, the two tools give consistent results
Pattern recognition studies

Technique to study in fast simulation how the detector parameters affect the pattern recognition:

1. seed direction

2. establish which hits belong to the same track:

3. The covariance matrix of the track at a given stage and the distance to the next layer define the area of the error ellipse

Not considered in the current studies

Area of error ellipse $(z_0, R\phi$ resolution)
We studied various layout variations. One example:
- **beampipe radius** variation and its effect on the impact parameter resolution
Dependence of the impact parameter resolution on the beampipe radius

By increasing the beampipe radius, the very forward particles will cross the beampipe more perpendicularly and will be less affected by multiple scattering.

Moving out the innermost barrel layer by 1 cm would degrade the impact parameter resolution by 45% for very forward tracks of pT=10 GeV. → keep radius as small as possible.
We studied also variation on the material budget and its effect on the d0 resolution at various track pT.
Dependence of the d0 resolution on the layers material budget

Reduce/increase all layers material by: 50%, 75%, 100%, 150%, 200%

Reducing the material budget by 50% would improve the d0 resolution by 20% (25%) for a forward track of $\eta=3.1$ and $p_T=10\,\text{GeV}$ ($1\,\text{GeV}$)
The success of the pattern recognition will depend on the amount of background particles in the error ellipse at each stage. Studied its dependence on the sensors granularity.
Background in the error ellipse vs granularity

**# bkg particles in error ellipse = Ellipse Area * Pile up * Fluence**

\[
\text{Ellipse Area} = \frac{1}{4} \pi \sigma_{R\phi} \sigma_z \tan \theta
\]

Assume # Pile up interactions per bunch crossing =1100

Granularity: Assume squared pixels and single point resolution = pitch/\sqrt{12}

Most critical stage: **extrapolation to the outer tracker**. Outside-in: depends on the granularity of the forward disks

In order to have less than **0.01 background particles** per bunch crossing in the error ellipse area, would need \(\sigma=10\times10\mu\text{m}\) single point resolution in the forward disks. **Not possible** to do pattern recognition for tracks below \(pT=1\ \text{GeV}\) with this layout.

At \(\eta=5.7\), \(pT=1\ \text{GeV}\) \(\rightarrow p=150\ \text{GeV}\)
Background in the error ellipse vs layout

One can reduce the error ellipse area by adding an **intermediate disk** and thus reducing the extrapolation distance.

By adding one **intermediate disk**, we can use $\sigma=25\times25$ μm single point resolution for the **forward disks** and reconstruct tracks down to $p_T=0.5$ GeV.

η=5.7 track

- Line at # particles in the error ellipse area per BC = 0.01
- Assume #PU/BC = 1100

$\Rightarrow$ factor of 5 less ellipse area

$\Rightarrow$ extra material is counter-productive for low $p_T$ tracks
Reconstruct the tracks from the decay of a boosted particle.

**Benchmark:** high-energy taus decaying to 3 prongs

Notice 2 effects are convoluted:
- small opening angle between the prongs
- very displaced decay vertex

Study the **efficiency of resolving tracks from tau decay**

vs tau flight distance

vs tau energy

vs detector granularity
Efficiency definition

- Tracks from taus decaying too far into the detector will be impossible to reconstruct: assume we need to resolve the hits in at least 4 layers.

**Acceptance**: Fraction of central taus decaying before the 4th-to-last barrel layer.

- $\etau=10$ TeV : 0.86
- $\etau=5$ TeV : 0.98
- $\etau=2$ TeV : 0.9999
- $\etau=1$ TeV : 1

Assume: single-hit clusters
Resolved hits = distance between two particles > 2*pixel pitch (in either the Rφ(u) or Z(v) direction)

Efficiency = # resolved hit pairs / closest pair of pion hits in the 4th-to-last layer.
Efficiency vs single point resolution:

Efficiency vs tau decay vertex position:
- 10 TeV “prompt” taus (decaying inside the beampipe) have ~60% efficiency only due to the small opening angle between their decay products
  - Could be improved by using higher detector granularity
- Efficiency drops in R due to tau displaced decay

No significant inefficiency for taus of $E < 1$ TeV

Efficiency vs single point resolution:
- Strong dependence on single point resolution, specially for high energy taus
- In the current design, efficiency driven by R$\phi$. Not much gain by improving Z resolution unless comparable to R$\phi$. 
Efficiency vs single point resolution

- Benchmark: B-hadrons
- Acceptance: Fraction of central B hadrons decaying before the 4th-to-last barrel layer

Acceptance:
- \( E_{b-quark} = 10 \text{ TeV} : 0.88 \)
- \( E_{b-quark} = 5 \text{ TeV} : 0.97 \)
- \( E_{b-quark} = 2 \text{ TeV} : 0.999 \)
- \( E_{b-quark} = 1 \text{ TeV} : 1 \)

Vertical line shows the default 10x100 [μm] single point resolution

Improving the single point resolution in \( R\phi \) by a factor of 2 would improve the efficiency from 55% → 70% for 10 TeV b-jets

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Flavor tagging requires full reconstruction of the events.

Studied variations in:
- Granularity
- Material Budget
- Jet pT

Samples: Central dijets
Madgraph5
Restricted quark pT
No pile-up
No Multiple Interactions
Detector Model:

- based on CLIC_SiD
- with **FCC vertex** and **squeezed FCC tracker** detector
- Implemented barrel only

**dijet (bb)**

\[ p_T(b) = 50 \text{GeV} \]

**using geometry version with 3 close-by vertex layers**
FCC Flavor tagging performance

central dijets, $\mathbf{pT(\text{quark})=50\text{GeV}}$

For 55% B-tagging efficiency, the background efficiency is about 1% for C-jets and 0.1% for light flavor jets

For 50% C-tagging efficiency, the background efficiency is of the order of 10%.

Reasonable performance compared to that achieved in CLIC and LHC *

(* = see backup)
Flavor tagging – variations

Variations:
- **Granularity:** Use 20x20μm pitch (instead of 25x50μm pitch) in the 3 innermost layers
- **Material Budget:** using half of the material budget in all layers
- Granularity and Material Budget combined

Both variations give a 30-60% improvement in the background rejection. Combining both, gives only a moderate improvement on top of that.
FCC Flavor tagging performance

central dijets, \( pT(\text{quark}) = 500 \text{ GeV} \)

Somewhat worse B-tagging performance for higher pT jets

For 40% B-tagging efficiency, the background efficiency is about 1% for C-jets and 0.1% for light flavor jets

C-tagging performance similar to 50 GeV jets

Plan to study performance at even higher pTs
Conclusions & Outlook

- Performance evaluation and optimisation **tools** (using fast and full simulation) are in place and **validated**
- **Studies serve as an input for the vertex and tracker optimization**
  - Need **interconnecting disks** between outer endcap and forward tracker, to facilitate pattern recognition
  - Boosted particle decay reconstruction strongly depends on the sensor granularity, **need high granularity also in the outer layers**.
  - Achieved **reasonable flavor tagging performance** for jets up to pT=500 GeV, showing significant dependence on granularity and material budget

Next steps:
- Perform further flavor tagging studies at **higher jet pT**, including evaluation of the performance for a **detector layout** with more barrel layers closer to the interaction point.
Flavor Tagging
**50GeV – Comparison with CLIC**

central dijets, \( p_T(\text{quark})=50\text{GeV} \)

ee\(\rightarrow\)jj, No ISR, narrower pT spectrum, x50 more stats
better single point resolution, very low material budget

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Figure 53: b-tag efficiency for jets in dijet events at \( \sqrt{s} = 91 \text{ GeV} \) with different polar angles using the \textit{double_spirals} geometry.

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https://cds.cern.ch/record/1606436?ln=en
Comparison to CMS run 2

Similar performance as CMS run 2.
FCC factor of ~1.5 better at LF-rejection (FCC result does not include pile-up).

https://twiki.cern.ch/twiki/bin/view/CMSPublic/BTV13TeVDPDeepCSV

central dijets,
$p_T(\text{quark})=50\text{GeV}$
Comparison to HL-LHC

central dijets,  
$pT(\text{quark})=50\text{GeV}$

Similar performance as ATLAS HL-LHC
FCC factor of 1.5 worse at LF-rejection (for HL-LHC pile up of $\mu=140$)

FCC Flavor tagging performance

central dijets, $p_T(\text{quark})=50\text{GeV}$

FCC B-tagging

<table>
<thead>
<tr>
<th>B eff. = 80%</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF bkg eff.</td>
<td>$2.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>C bkg eff.</td>
<td>$2.4 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

FCC C-tagging

<table>
<thead>
<tr>
<th>C eff. = 70%</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>B bkg eff.</td>
<td>$3.2 \times 10^{-1}$</td>
</tr>
<tr>
<td>LF bkg eff.</td>
<td>$2.8 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

Reasonable performance
Tagging efficiency relatively flat in jet $p_T$ above 40 GeV

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Flavor tagging – variations

- Granularity
- Material Budget
- Granularity+Mat.Budget

Using 20x20\,\mu m pitch (instead of 25x50\,\mu m pitch) in the 3 innermost layers, or using half of the material budget in all layers*, improves the light flavor rejection by 60-40%.

The two modifications combined do not add up in terms of improvement in LF rejection, but they do for C background rejection

performance for central dijets of $p_T(\text{quark})=50\,\text{GeV}$
Fast Simulation
Pattern recognition studies
Variation (II) vertex layers radius

Small differences in the resolution (single particle). Will become relevant when we take into account occupancy in terms of pT resolution at high pT.

*kept at least 3cm between layers: R1=21mm R2=50mm in all cases

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Equidistant option is the best in terms of pT resolution at high pT.

Half the Radius and logarithmic R options perform similarly in d0 resolution.

Half R is the best at z0 resolution for high pT tracks.
**d0 resolution dependence on the beampipe material**

Baseline: beampipe $X/X_0=0.00286$.
Reduce/increase the beampipe material by: 50%, 75%, . . ., 150%, 200%

![Graphs showing d0 resolution dependence on the beampipe material at different pT values](image)

- **pT= 1 GeV**
- **pT= 10 GeV**
- **pT= 100 GeV**
- **pT= 1000 GeV**

Significant dependence for low pT forward tracks.
# of background particles in the error ellipse?

1. Area of the error ellipse projected at the last endcap disk:
   \[ \text{EllipseArea} = \frac{1}{4} \pi \sigma_{R\phi} \sigma_z \tan \theta \]

2. Multiply by fluence at the last endcap disk

\[ \# \text{ bkg particles in error ellipse} = \text{Fluence} \times \text{Pile up} \times \text{EllipseArea} \]

Study, for **forward tracks**: (going through all fwd layers)
- Area as a function of the single-point resolution of the forward layers
- Area as a function of the gap distance (endcap – forward)

\[ A = \frac{1}{4} \pi \sigma_{R\phi} \sigma_R \]
\[ \sigma_R = \sigma_z \tan \theta \]

\[ \theta = 5.49 \text{ deg}; \eta = 3 \]
\[ \theta = 0.39 \text{ deg}; \eta = 5.7 \]

Note: In this study the upper and lower part of the disks have the same material budget and resolution
Boosted object studies
While 99% of central 100 GeV taus decay within the beampipe, only 4% of 10 TeV central taus do.
Efficiency definition (I)

- Resolve all prongs $\rightarrow$ reconstruct all tracks $\rightarrow$ have enough hits per track
- Assume: we need at least $3+1$ (backup) non-shared hits per track
- Assume: outside-in tracking
- $\rightarrow$ the hits from different prongs must be resolved in the 4$^{th}$-to-last layer of the tracker

«Acceptance»:
Fraction of **central** taus decaying before the 4$^{th}$-to-last barrel layer

- $\text{Et}_\tau=10$ TeV : 0.857
- $\text{Et}_\tau=5$ TeV : 0.978
- $\text{Et}_\tau=2$ TeV : 0.9999
- $\text{Et}_\tau=1$ TeV : 1

Fraction of **forward** taus decaying before the 4$^{th}$-to-last barrel layer

- $\text{Et}_\tau=10$ TeV : 0.9992

This problem is less important in the endcaps since we have a larger lever arm
Similarly, study the long-lived hadrons in a B-jet
Select B-hadrons as well as their C-hadron daughters
For different b-jet energies, use bb dijet events in the barrel

Flight distance distribution deviates from straight line because hadrons are not mono-energetic
Consider only the hits produced by the daughters of the long-lived B and C-hadrons
  – Require generator status==1
• Assume: we need to separate the closest pair of daughters
• Consider the closest pair of hits in the 4th-to-last layer
Efficiency vs decay vertex position

For various B-jet energies

For 10 TeV B-jets, with B or C-hadrons decaying before the beampipe: 
~80% efficiency only due to the small opening angle between decay products

• No significant inefficiency for B-jets of Pt < 1 TeV
# B jets acceptance

- **B hadrons**

<table>
<thead>
<tr>
<th>pT(b-quark) [GeV]</th>
<th>Fraction of B-hadrons decaying before R=20mm</th>
<th>Fraction of B-hadrons decaying before R=925mm (4\textsuperscript{th}-to-last layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.996848</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.959081</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.829957</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.583421</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.398114</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>0.275022</td>
<td>0.999217</td>
</tr>
<tr>
<td>5000</td>
<td>0.192235</td>
<td>0.965865</td>
</tr>
<tr>
<td>10000</td>
<td>0.161509</td>
<td>0.875244</td>
</tr>
</tbody>
</table>
# B jets acceptance

## C hadrons

<table>
<thead>
<tr>
<th>pT(b-quark) [GeV]</th>
<th>Fraction of C-hadrons decaying before R=20mm</th>
<th>Fraction of C-hadrons decaying before R=925mm (4\textsuperscript{th}-to-last layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.991606</td>
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<tr>
<td>100</td>
<td>0.92315</td>
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<tr>
<td>200</td>
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<tr>
<td>500</td>
<td>0.407441</td>
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<tr>
<td>1000</td>
<td>0.233609</td>
<td>1</td>
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<td>2000</td>
<td>0.147122</td>
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<td>5000</td>
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<td>0.934408</td>
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<tr>
<td>10000</td>
<td>0.102258</td>
<td>0.793054</td>
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</table>
Flavor tagging using full simulation
Software chain: Summary

- **Generation**: MG5 central dijets, restricted quark pT.
- **Detector Model**: CLIC_SiD with FCC vertex and squeezed FCC tracker (Option3_v02). Barrel only. Tracker outer layer R reduced from 1541mm (FCC) to 1206mm (CLIC)
- **Simulation**: FCC material budget (services included in the module)
- **Digitization**: FCC pixel sizes. Smear simulated hit position by a Gaussian of σ=pitch/√12.
- **Tracking**: Nhits>=6, chi2<10, d0<10 [mm] *(under study)*
- **Particle flow**: Pandora
- **Vertexing**: LCFIPlus. Use only PFOs in 2 kT jets R=0.5.
- **Flavour Tagging**: LCFIPlus. (BDT using same variables as CLIC)
Event Generation

• Event generation in MadGraph5:
  – pp->bb / cc / ll (udsg) at √s=100TeV
  – restricted quark pT: Ex: 47.5 < pT(b) < 52.5 GeV
  – Central eta: |η(b)|<0.05
  – DR(bb)>0.4

• Samples:
  – Quark pT in GeV: 50, 100, 200, 500, 1000, 2000, 5000, 10000
  – 20k events per sample
  – 1M events for 50 & 500 GeV samples

• Hadronization in Pythia6:
  – No Pile up
  – Multiple Interaction: OFF
  – FSR: ON
  – ISR: ON
• Tracking parameters used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MinPT</td>
<td>0.2 GeV</td>
</tr>
<tr>
<td>MinHits</td>
<td>6</td>
</tr>
<tr>
<td>MaxD0</td>
<td>10.0 mm</td>
</tr>
<tr>
<td>MaxZ0</td>
<td>10.0 mm</td>
</tr>
<tr>
<td>MaxChisq</td>
<td>10.0</td>
</tr>
</tbody>
</table>

• Tracking strategies trained with **displaced** single muon tracks (to account for missing inner hits)

Under review & optimization

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**Preliminary** track resolution comparison

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Full Sim*</th>
<th>Fast Sim**</th>
</tr>
</thead>
<tbody>
<tr>
<td>δpT/pT</td>
<td>0.75%</td>
<td>0.48%</td>
</tr>
<tr>
<td>δd0[μm]</td>
<td>6.1</td>
<td>5.02</td>
</tr>
<tr>
<td>δz0[μm]</td>
<td>13.1</td>
<td>10.59</td>
</tr>
</tbody>
</table>

*Full Sim
E=100GeV prompt muon |η|<0.175 (θ=80-100 degrees)

**Fast Sim
pT=100GeV prompt muon 0.001<|η|<1.5

(remember: we have **squeezed the tracker**, and fast sim averages over a larger eta range)

**good enough approximation for our purposes**

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Flavor Tagging

- Jets are classified in 4 categories according to the number of secondary vertices
- BDTs are trained using variables related to:
  - track d0/z0/momentum
  - vertex mass/momentum/angle/decay length

In the light flavor sample, vertices due mainly to interaction with the material

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