Jet-flavour tagging at FCC-ee/hh experiments

FCC UK Meeting

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Overview

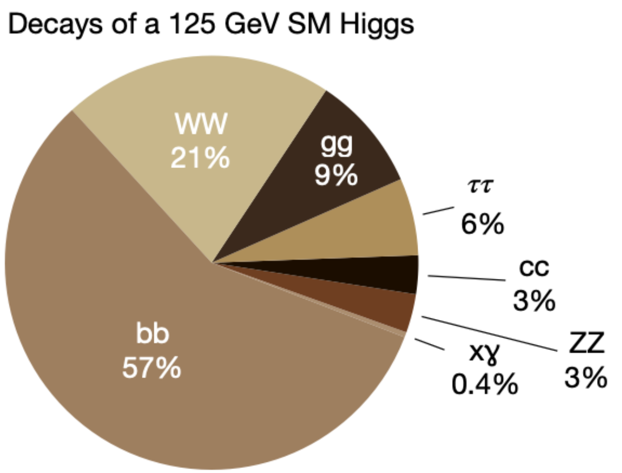
Very much a work in progress:

- Flavour tagging
  - Graph Neural Network (GNN) Algorithm
- FCC-ee (replicate ParticleNet results)
  - Data
  - Input variables
  - Results
- FCC-hh (first attempt at FCC-hh GNN tagger)
  - Data
  - Input variables
  - Results
- Summary

Flavour tagging (b-tagging)

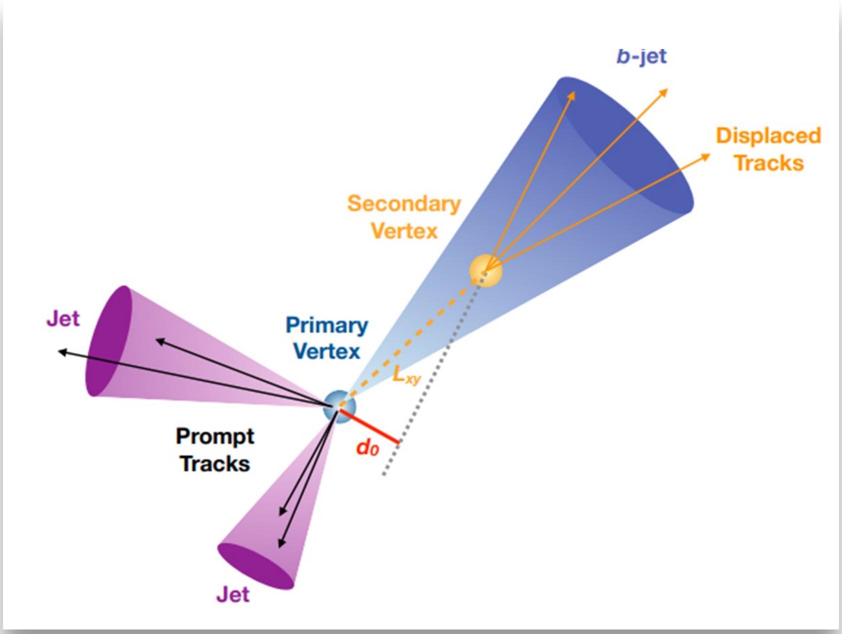
Why?

- Many signatures of interest contain b-jets
  - e.g Higgs boson decay
- Also useful for rejecting backgrounds
  - e.g. $t\bar{t}$ production can be troublesome ($t \rightarrow bW$)



How?

- b-hadrons have a relatively long lifetime (~1.5ps)
- Travel a measurable distance before decaying
- Presence of 1+ displaced vertex within the jet
- Tracks with large impact parameter values (d_0)

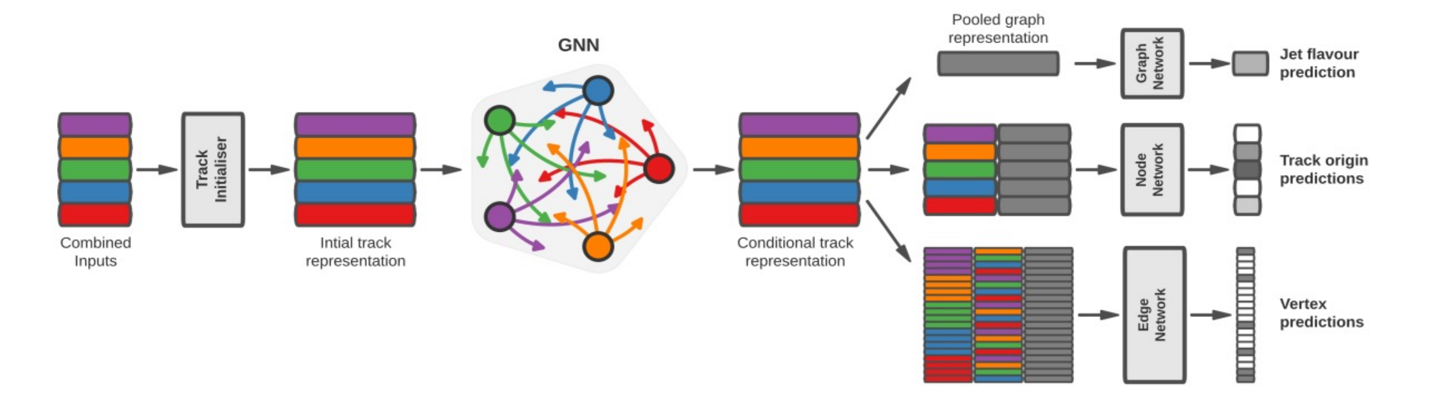


GN2

- Use Graph Neural Network (transformer architecture) to predict jet flavour
  - Using public ATLAS GN2 package [ATL-PHYS-PUB-2022-027]

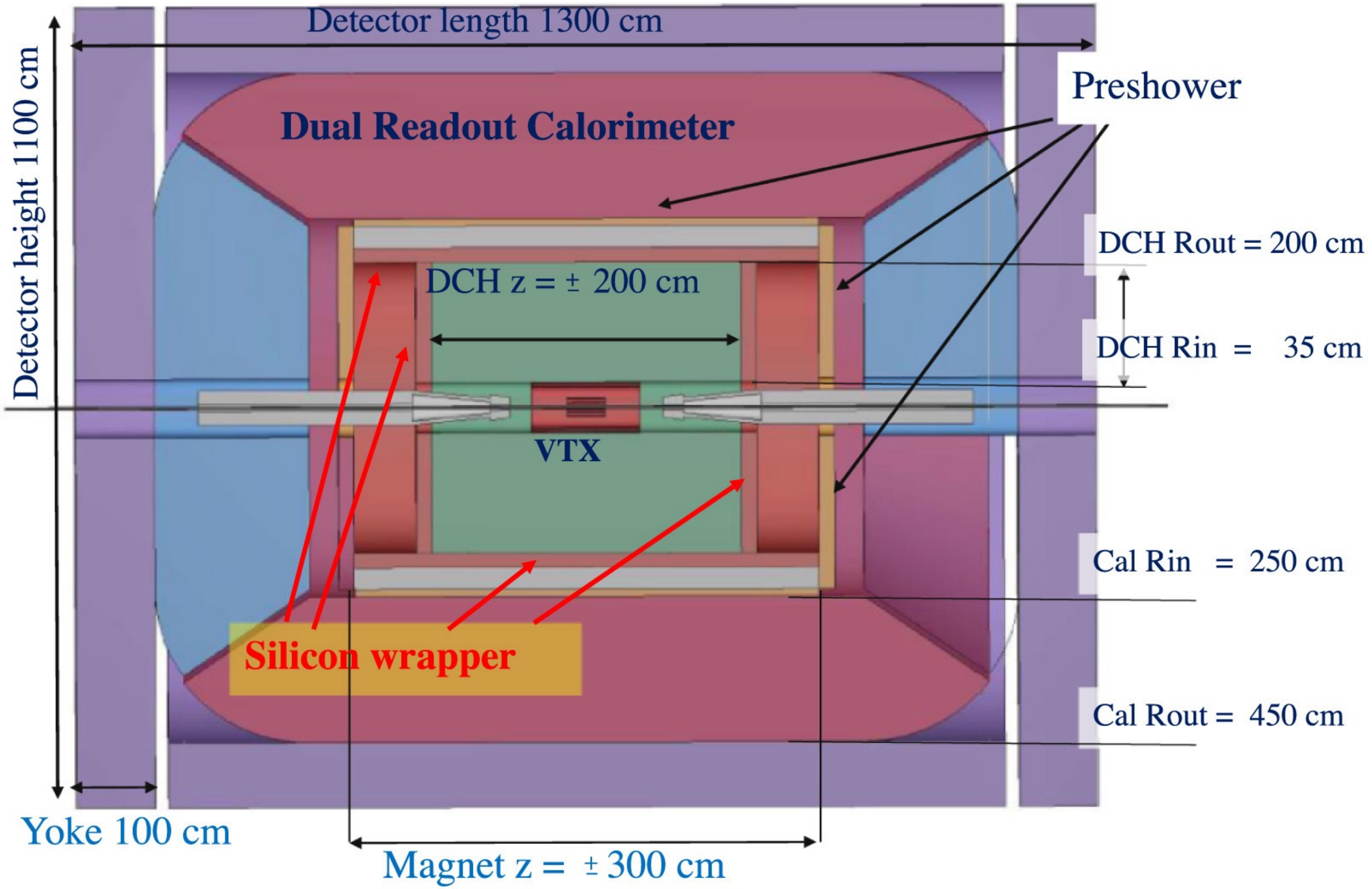
- Nodes (tracks) connected via edges (vertices)

- Predict: Jet flavour classification (primary objective),
  track truth origin and vertexing (auxiliary objectives)



Question:
Performance at future collider experiments?

FCC-ee IDEA detector



Setup and Data

Particle-Net [1902.08570] results already produced on FCC-ee [2202.03285]

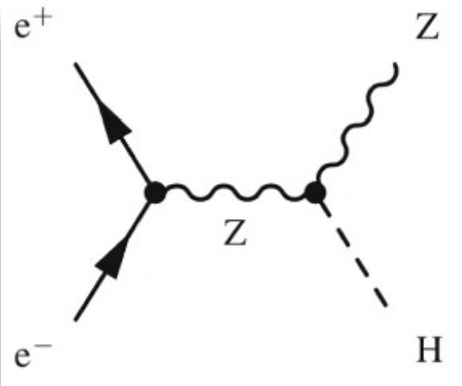
- Authors very helpfully provided their samples/code and input
- Use as benchmark to test setup, code generation and relative performance

Simulated using Delphes:

- Additional TrackCovariance Module to simulate track parameters

Event generation (Madgraph + Pythia)

- $ee \to ZH \to \nu\nu jj$ ($\sqrt{s} = 240$ GeV)
- Focus on identifying jets from Higgs decays (b, c, s, ud, gluon)
- 10 million jets labelled according to the Higgs decay process
    - Some issues, but kept to allow fair comparison



Input variables

Jet Variables	Description
p_T	Jet transverse momentum
η	Jet pseudorapidity
Track Variables	**Description**
$E_{\mathrm{const}}/E_{\mathrm{jet}}$	Energy of jet constituent divided by the jet energy
θ_{eta}	Polar angle of the jet constituent, relative to the jet momentum
ϕ_{rel}	Azimuthal angle of the jet constituent, relative to the jet momentum
d_{xy}	Transverse impact parameter of the track
d_z	Longitudinal impact parameter of the track
$\mathrm{SIP}_{2\mathrm{D}}$	Signed 2D impact parameter of the track
$\mathrm{SIP}_{2\mathrm{D}}/\sigma_{2\mathrm{D}}$	Signed 2D impact parameter significance of the track
$\mathrm{SIP}_{3\mathrm{D}}$	Signed 3D impact parameter of the track
$\mathrm{SIP}_{3\mathrm{D}}/\sigma_{3\mathrm{D}}$	Signed 3D impact parameter significance of the track
$d_{3\mathrm{D}}$	Jet track distance at their point of closest approach
$d_{3\mathrm{D}}/\sigma_{d3\mathrm{D}}$	Jet track distance significance at their point of closest approach
C_{ij}	Covariance matrix of track parameters
q	Electric charge of the particle
$m_{\mathrm{t.o.f}}$	Mass of particle calculated from time-of-flight
$\mathrm{d}N/\mathrm{d}x$	Number of primary ionisation clusters along track
isMuon	If the particle is identified as muon
isElectron	If the particle is identified as electron
isPhoton	If the particle is identified as photon
isChargedHadron	If the particle is identified as a charged hadron
isNeutralHadron	If the particle is identified as a neutral hadron

Jet kinematics

Relative kinematics

Track parameters

Particle Identification

Performance

GN2 trained on identical dataset used for ParticleNetIDEA model

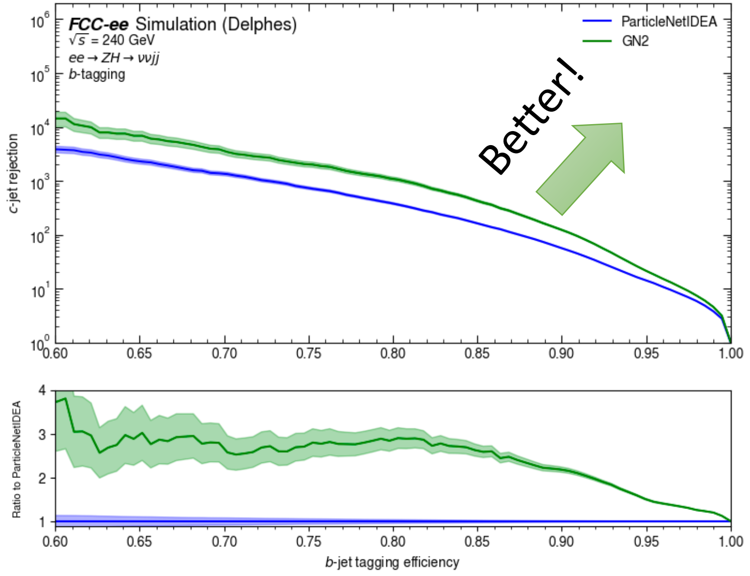
Discriminant Function constructed to study the discriminant between pairs of flavour

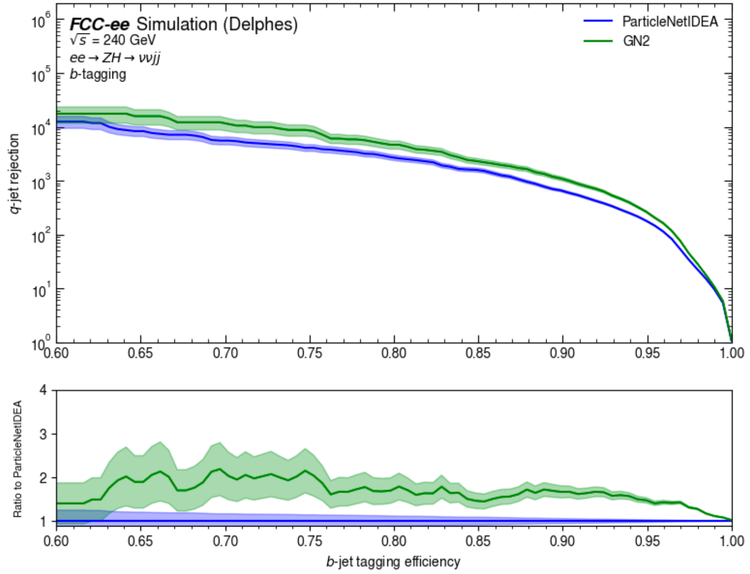
$$D_{ij} = \frac{p_i}{p_i + p_j}$$

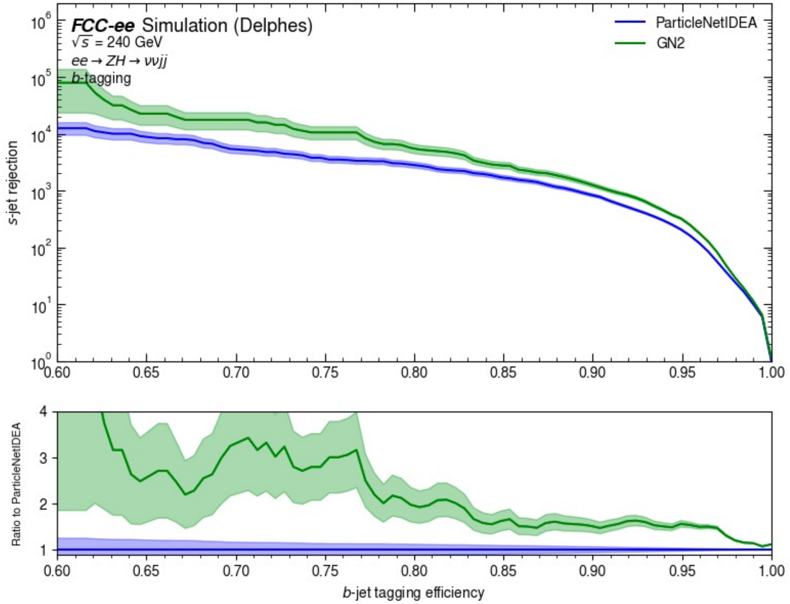
i = signal flavour
j = background flavour

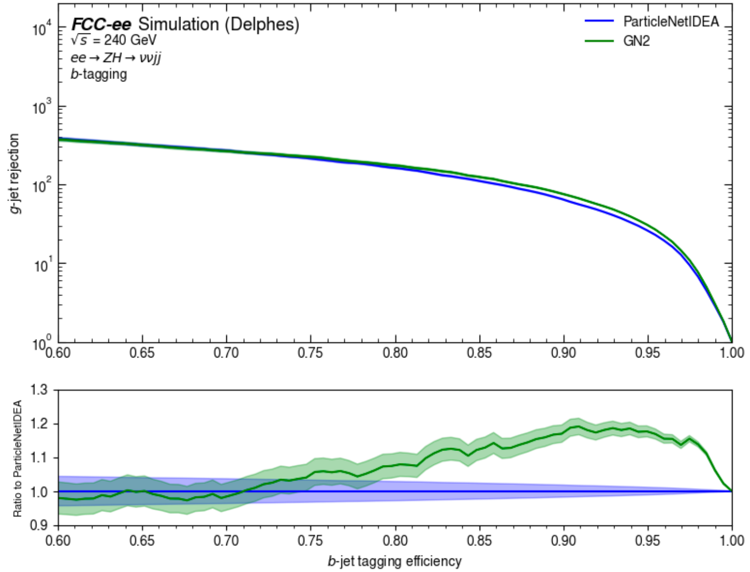
Results:

- Reproduced ParticleNetIDEA results
- Validated sample generation/evaluation
- Demonstrated superior GN2 performance

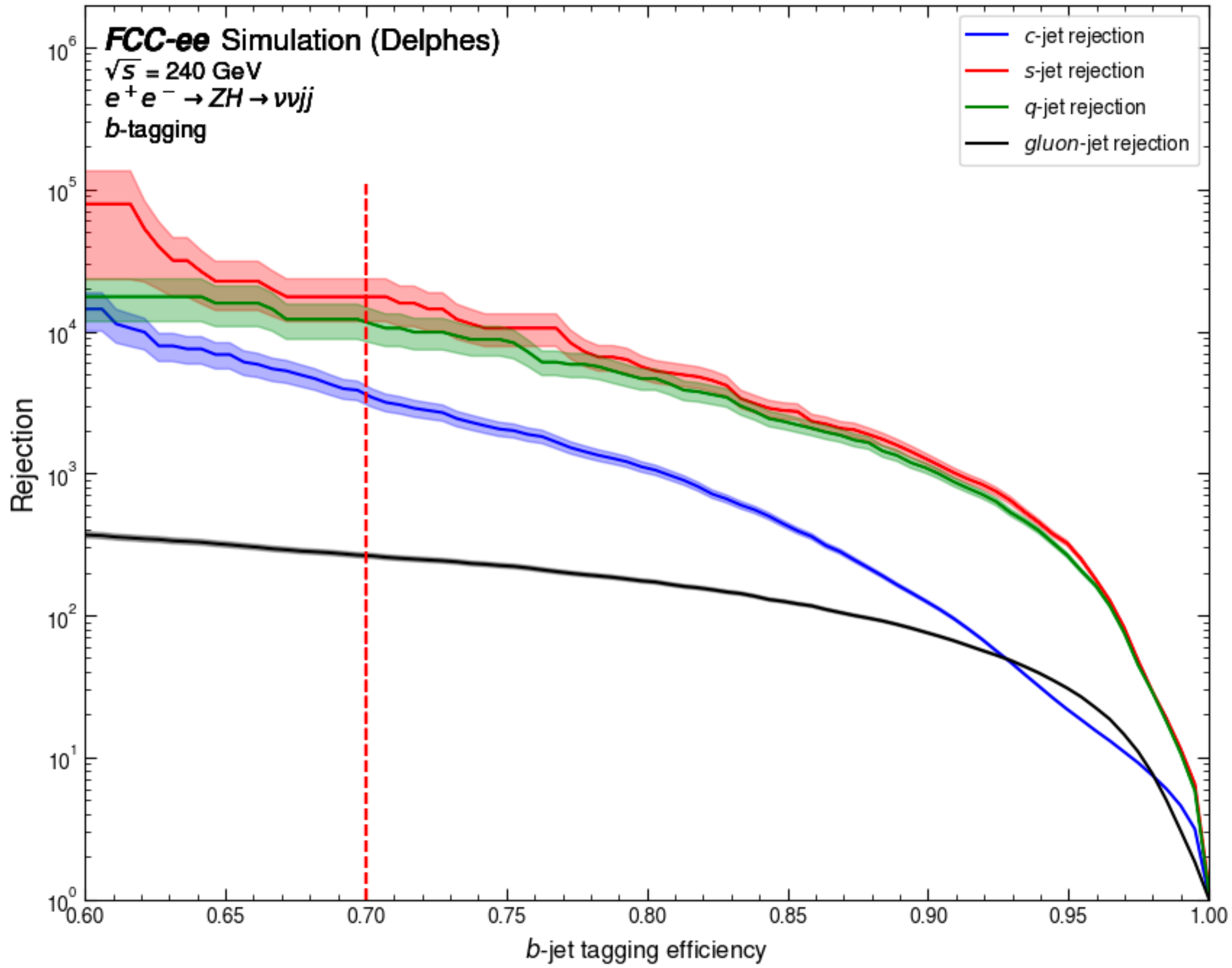








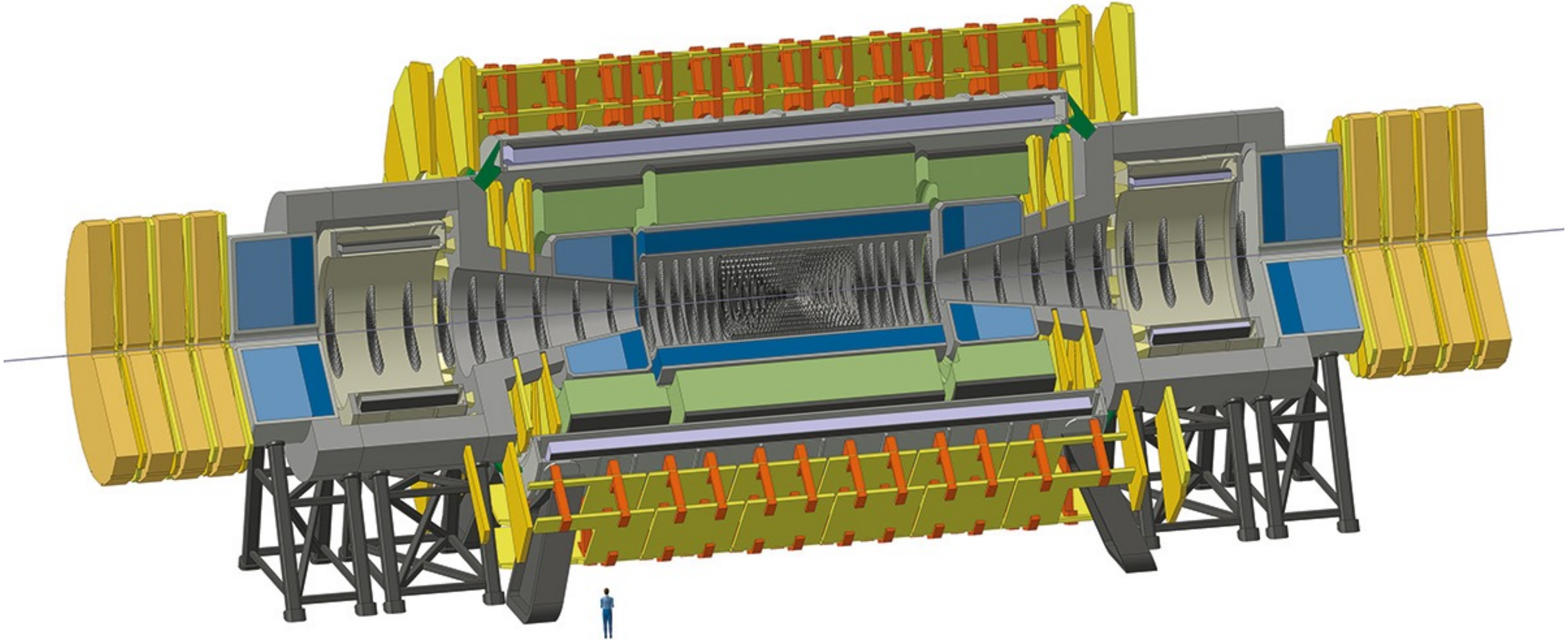
GN2 @ FCC-ee



At 70% b-jet efficiency:

c-jet rejection	~3000
s-jet rejection	~10^5
q-jet rejection	~10^5
gluon-jet rejection	~200

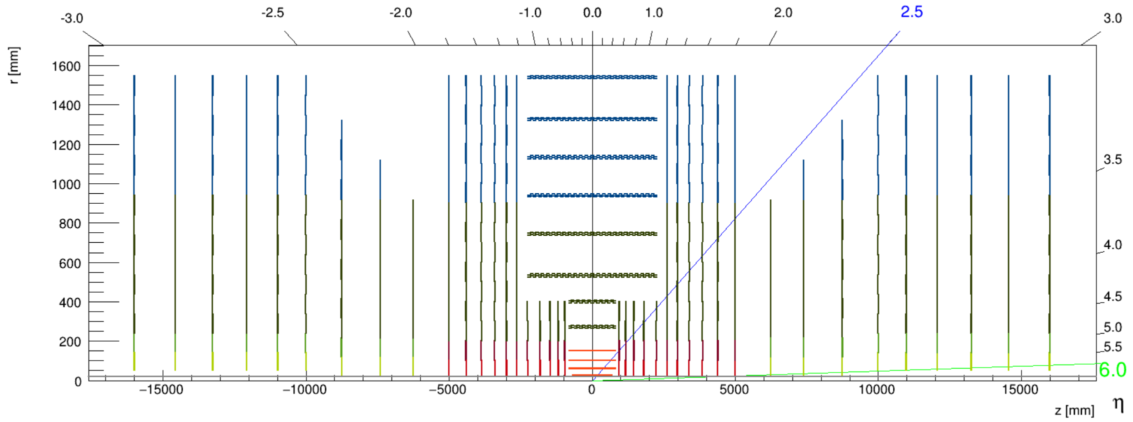
FCC-hh

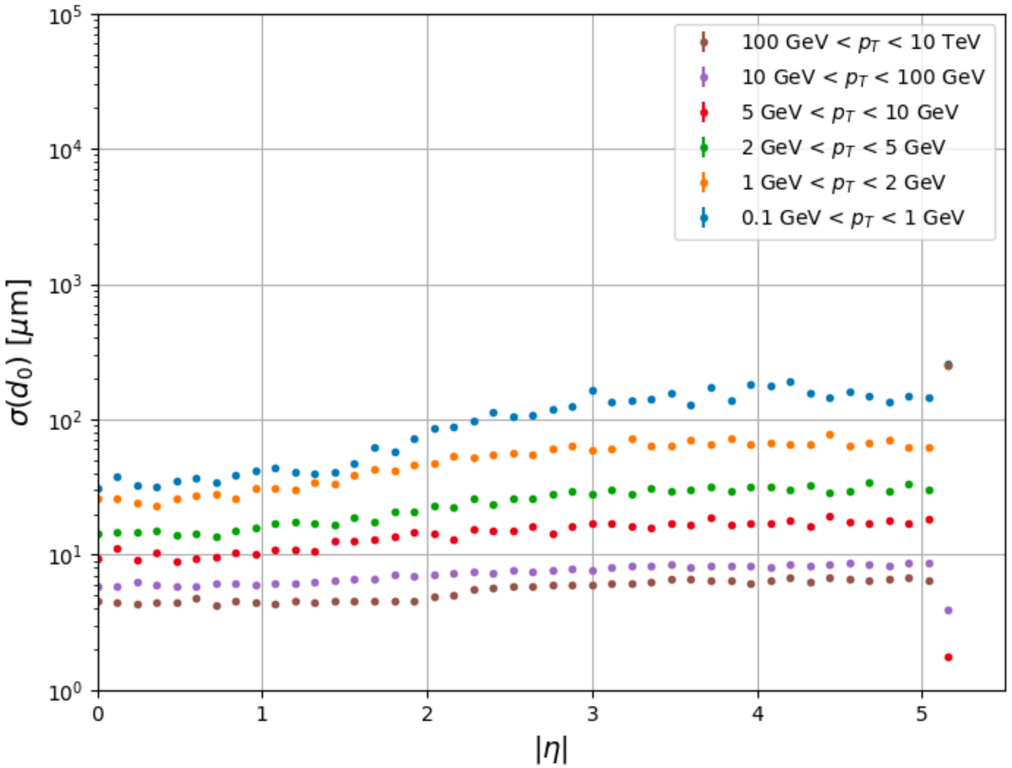


Goal: Study flavour-tagging performance for FCC-hh configuration

Simulating data

- Modified baseline FCC-hh Delphes cards based on conceptual design report (CDR) [CERN-2022-002]
- Using TrackCovariance module to simulate full track covariance matrix:
  - Implemented description of tracking detector (geometry, radiation length, resolution)
  - Validated resolutions agree with predictions from CDR
  - Will propagate back into official repository





Agrees with values in CDR!

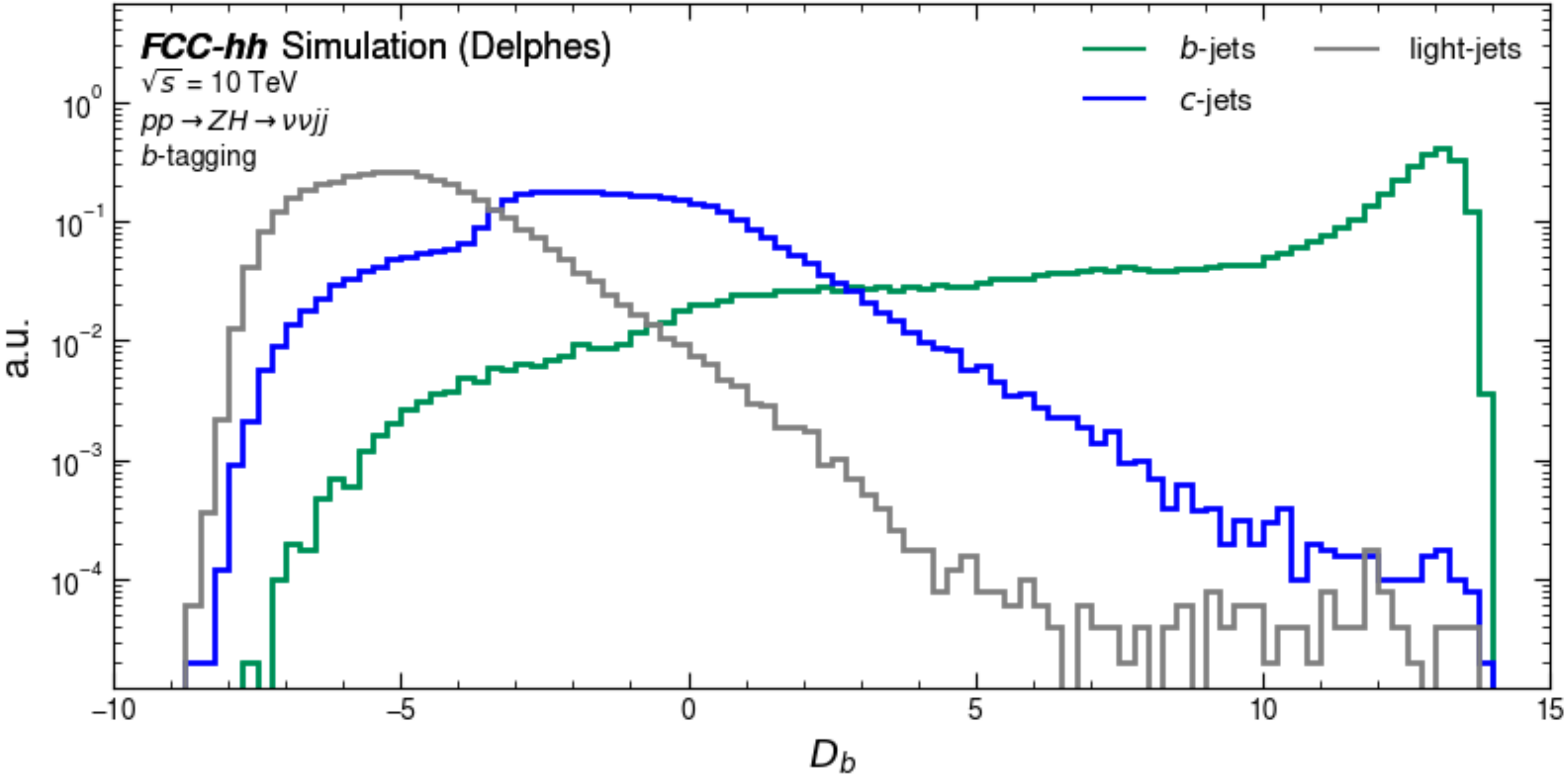
Simulating data

- $pp \to ZH \to \nu\nu jj$ ($\sqrt{s} = 100$ TeV)
- Start without pileup (6 million jets)
- Higgs decays into pair of different flavour jets
- Labelling of jet flavour is done based on truth hadron content
  - Similar to ATLAS/CMS approach

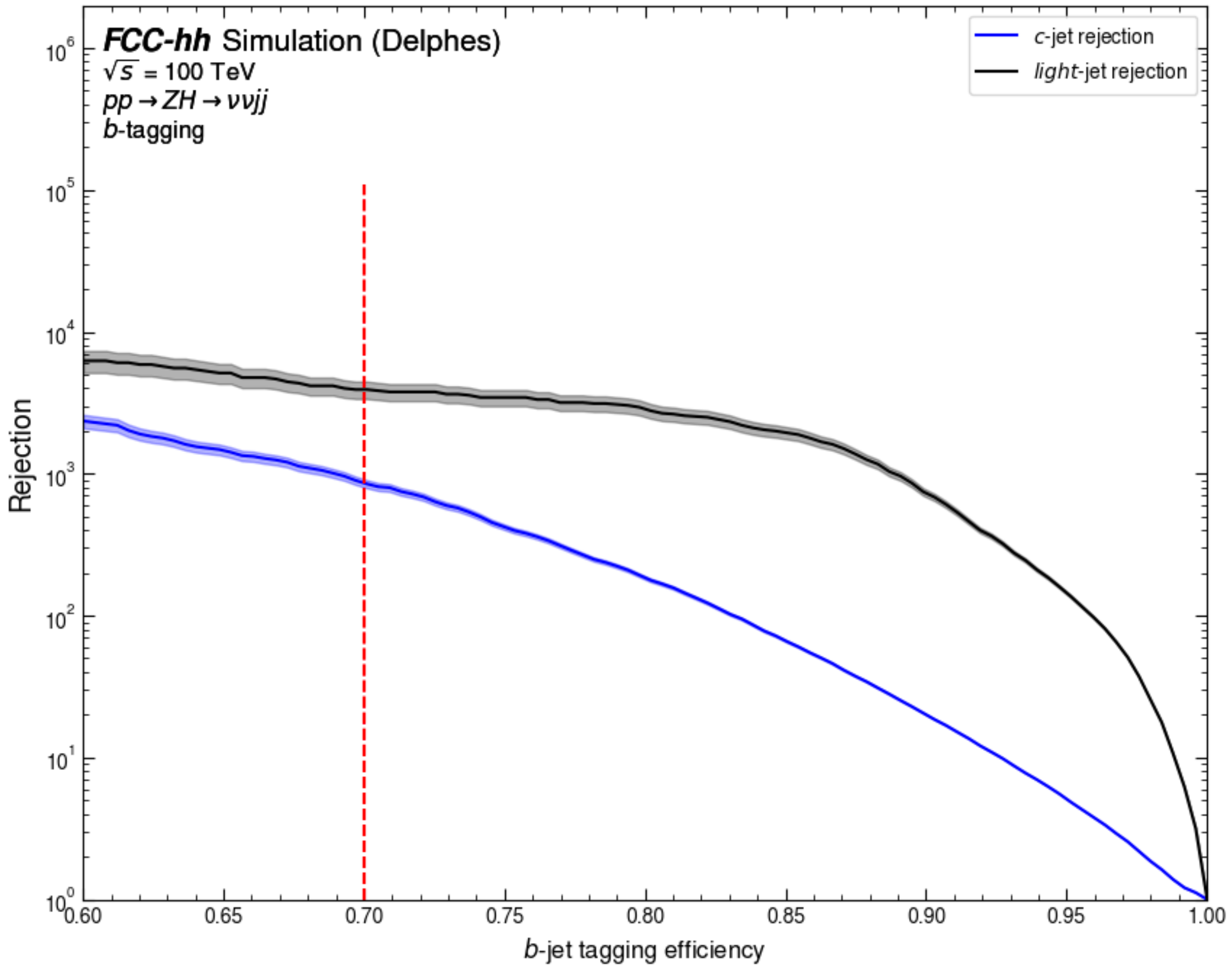
Jet Flavour	Presence of b-Hadron	Presence of c-Hadron
b-jet	✓	-
c-jet	✗	✓
light-jet	✗	✗

ATLAS-style discriminant

$$D_b = \ln\left(\frac{p_b}{f_c \cdot p_c + (1-f_c)\cdot p_l}\right)$$



GN2 @ FCC-hh



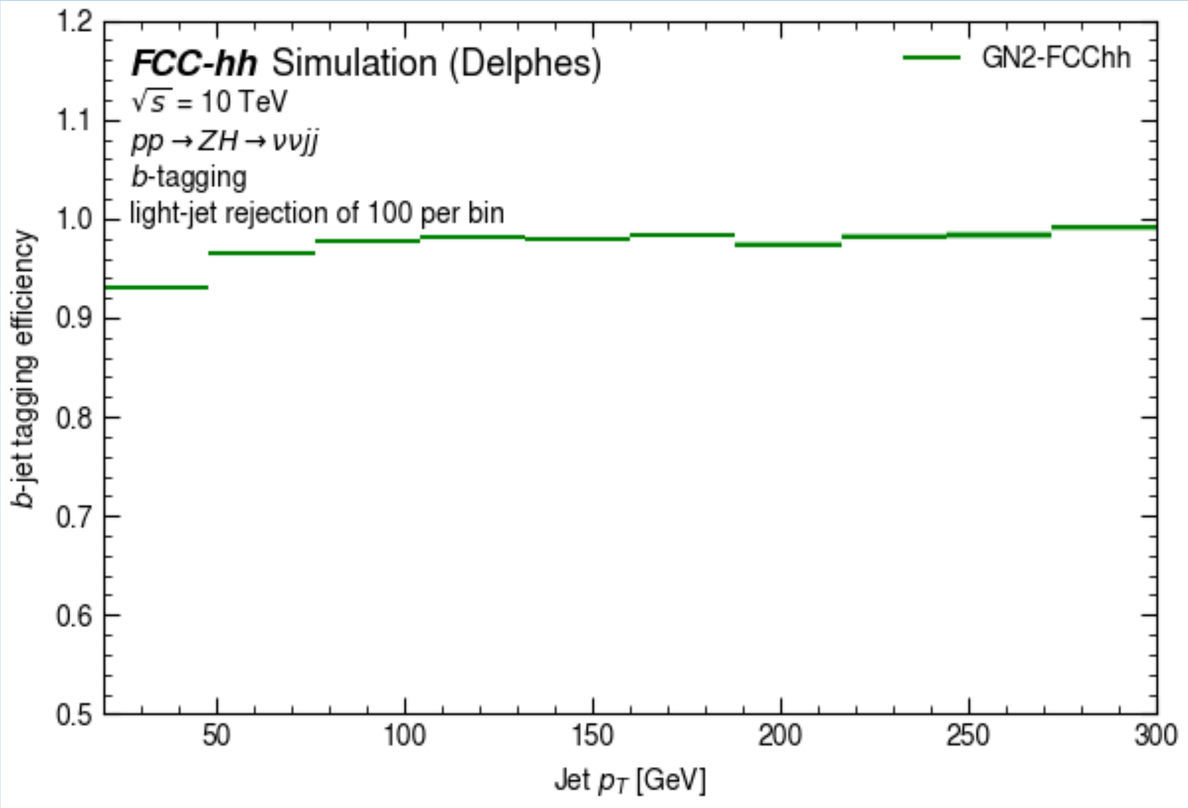
At 70% b-jet efficiency:

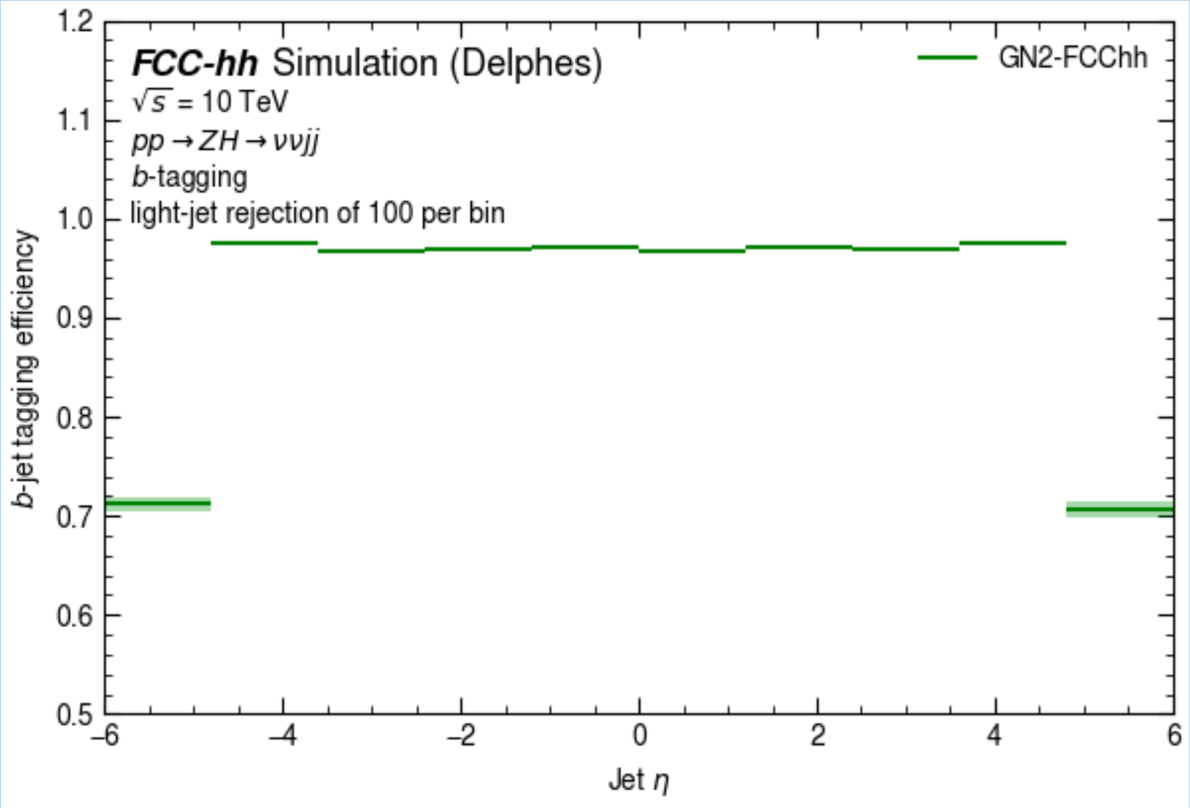
c-jet rejection	~10^3
$light$-jet rejection	~4000

GN2 @ FCC-hh

Measuring performance relative to most important kinematic variables

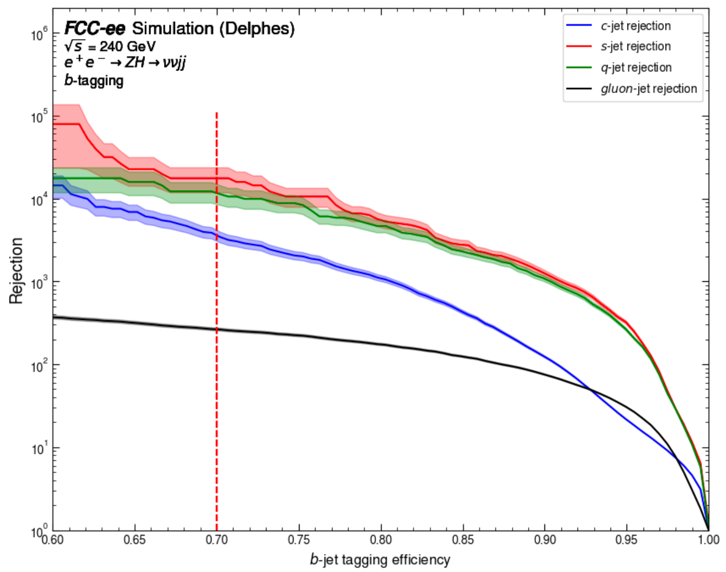
Fixed light-jet rejection at 100



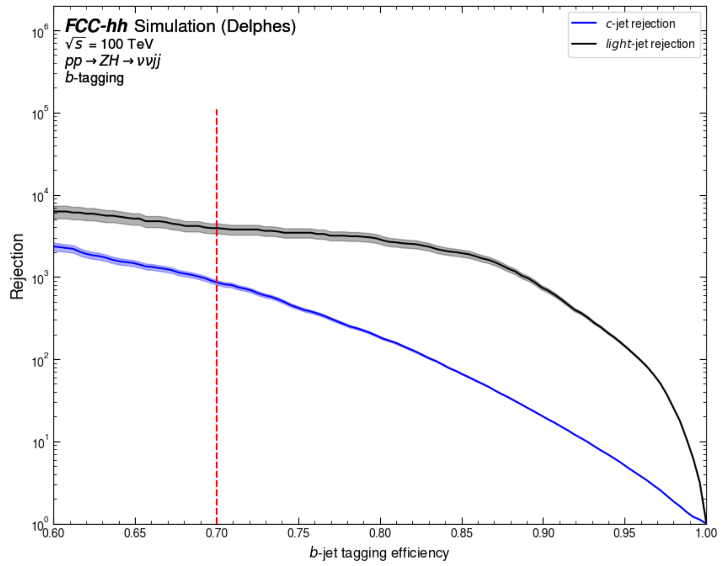


Summary

Workflow established to study flavour tagging performance at FCC experiments



GN2 FCC-ee



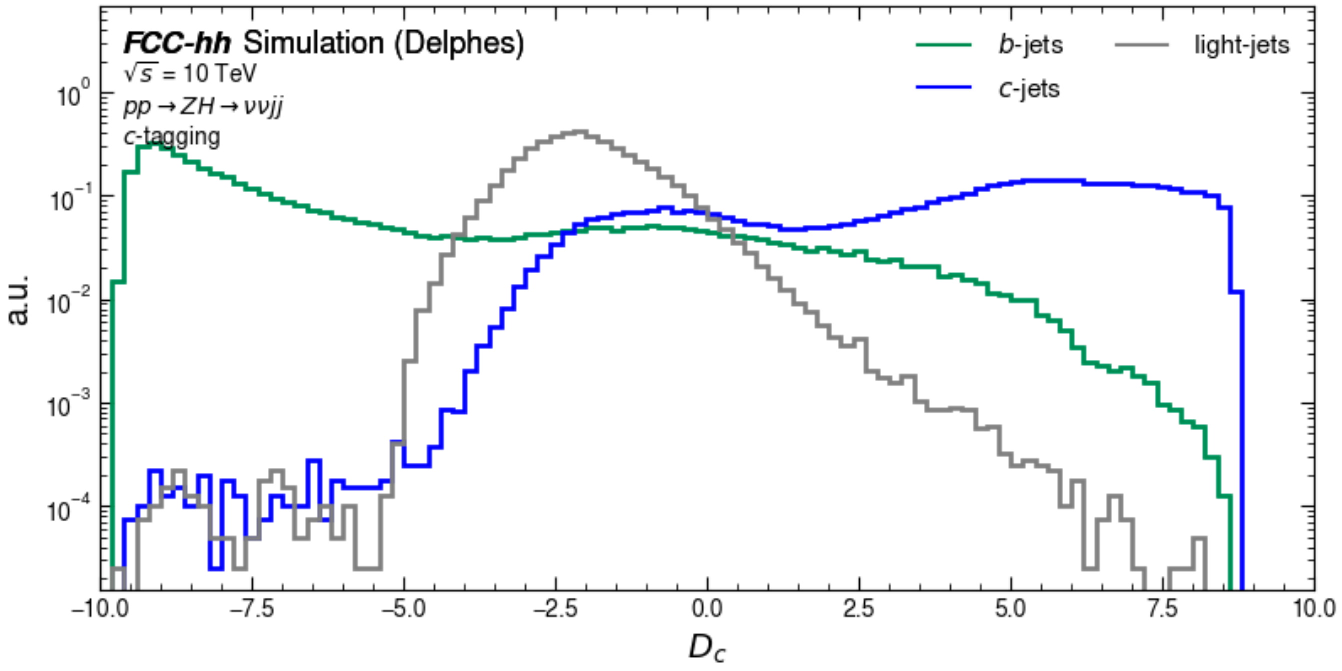
GN2 FCC-hh

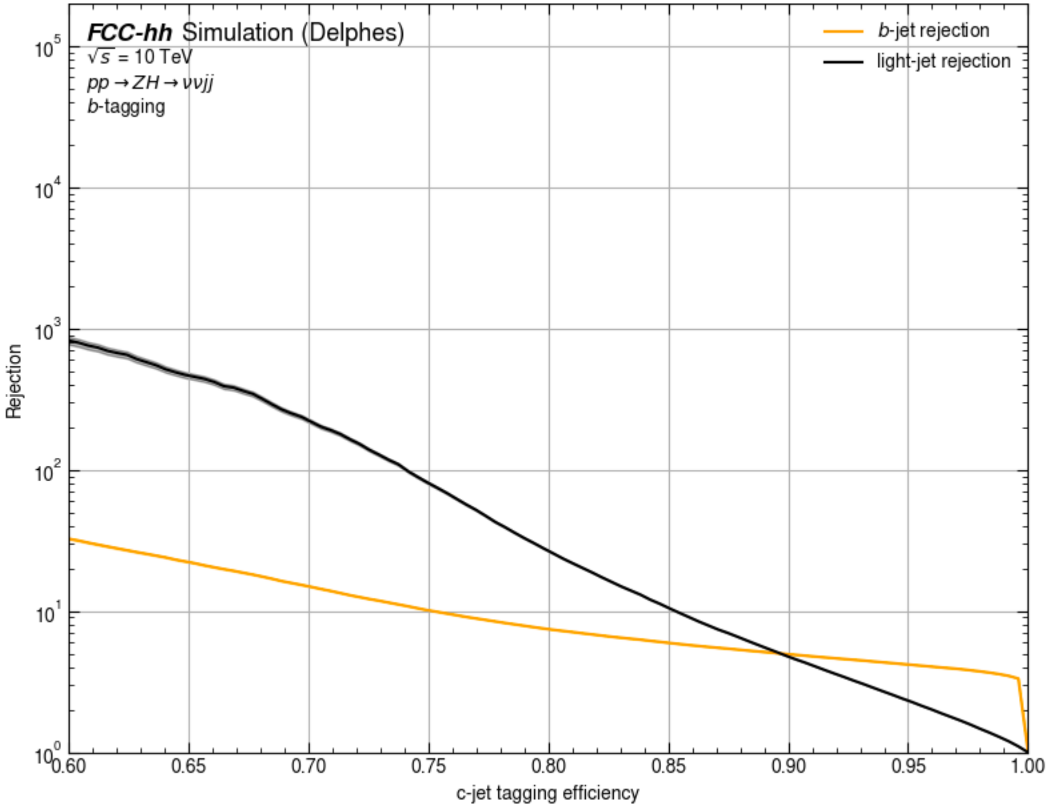
Next steps

- Further validation
- Generate higher p_T jets to study performance up to the TeV range (BSM Z')
- Include expected pile up of FCC-hh ($\mu = 1000$) [Very time consuming at first attempt]
- Test impact of different detector design
- Parameterise performance for di-Higgs and boosted Higgs analysis at FCC-hh

Backup

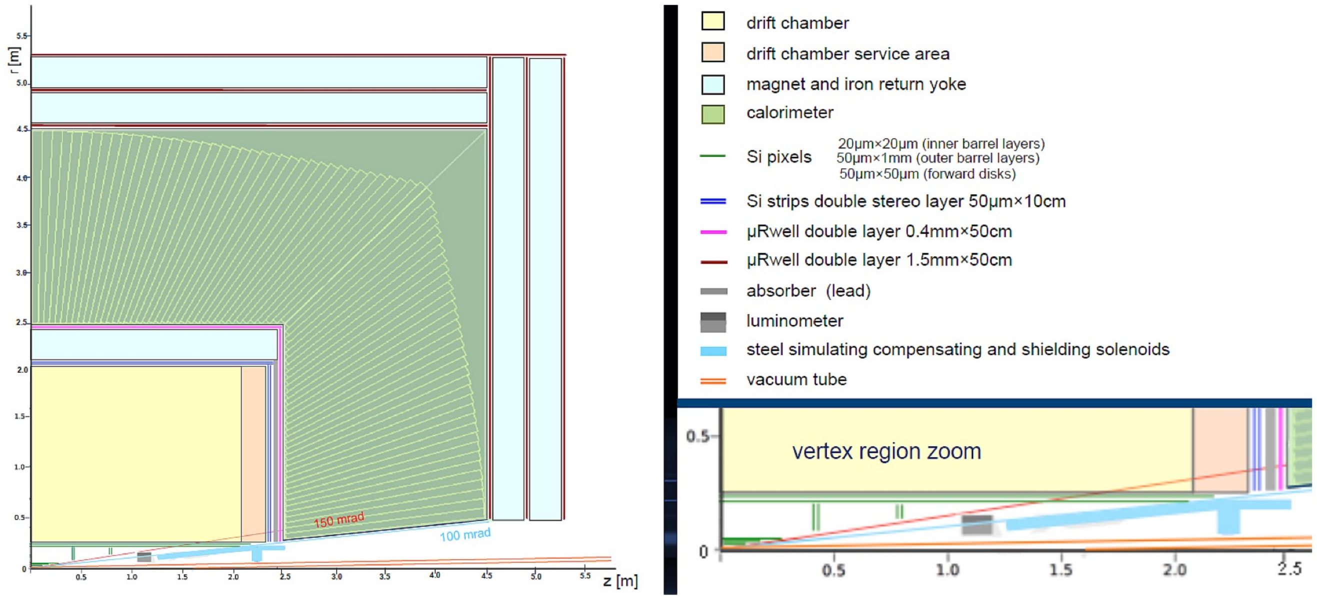
GN2 @ FCC-hh (c-tagging)





IDEA vs FCC-hh 1st layer

IDEA detector silicon pixel pitch size:
- 20um x 20um
- Resolution of 3um x 3um



FCChh detector silicon pixel pitch size:
- 25um x 50um
- Resolution of 7um x 14 um

Flat layout:

Pixels (inner)	Macro-pixels (middle)	Striplets/Macro-pixels (outer)
$25 \times 50\,\mu m^2$ (1–4th BRL) $25 \times 50\,\mu m^2$ (1st EC ring) $33.3 \times 100\,\mu m^2$ (2nd EC ring) $33.3 \times 400\,\mu m^2$ (3–4th EC ring)	$33.3 \times 400\,\mu m^2$	$33.3\,\mu m \times 50\,mm$ (BRL) $33.3\,\mu m \times 10\,mm$ (EC)

IDEA vs FCC-hh 1st layer

Inner layer of IDEA assumed to be closer to collision point

TABLE I. – *The main parameters of the IDEA concept detector.*

Parameters	
vertex technology	silicon
vertex inner/outer radius (cm)	1.7/34
tracker technology	drift chamber and silicon wrapper
tracker half length (m)	2.0
tracker outer radius (m)	2.0
solenoid field (T)	2.0
solenoid bore radius/half length (m)	2.1/3.0
preshower absorber	lead
preshower R_{min}/R_{max} (m)	2.4/2.5
DR calorimeter absorber	copper
DR calorimeter R_{min}/R_{max} (m)	2.5/4.5
overall height/length (m)	11/13

IDEA detector

Layer no :	1	2	3	4	5	6	Total
Average radius [mm] :	25.00	60.00	100.00	150.00	270.00	400.00	
Radius-min [mm] :	23.28	58.28	98.28	148.28	261.07	391.07	
Radius-max [mm] :	27.47	63.03	102.52	152.26	280.11	409.73	
Z-min [mm] :	-685.0	-820.0	-820.0	-820.0	-820.0	-820.0	
Z-max [mm] :	685.0	820.0	820.0	820.0	820.0	820.0	
Number of rods :	14	16	26	38	34	50	
Number of modules per rod :	20	40	40	40	17	17	
Number of modules :	280	640	1040	1520	578	850	**4908**
Disk no :	**1**	**2**	**3**	**4**	**5**	**Total (+Z & -Z)**	
Radius-min [mm] :	25.0	25.0	25.0	25.0	25.0		
Radius-max [mm] :	404.0	404.0	404.0	404.0	404.0		
Average Z pos. [mm] :	950.0	1178.5	1462.0	1813.7	2250.0		
Z-min [mm] :	941.1	1169.6	1453.1	1804.8	2241.1		
Z-max [mm] :	958.9	1187.5	1471.0	1822.6	2258.9		
Number of rings :	4	4	4	4	4		
Number of modules per disk :	108	108	108	108	108	**1080**	
Ring no :	**1**	**2**	**3**	**4**			
R-min [mm] :	25.0	101.3	198.9	302.6			
R-max [mm] :	104.7	204.6	303.4	404.0			
Number of modules per ring :	12	20	32	44			

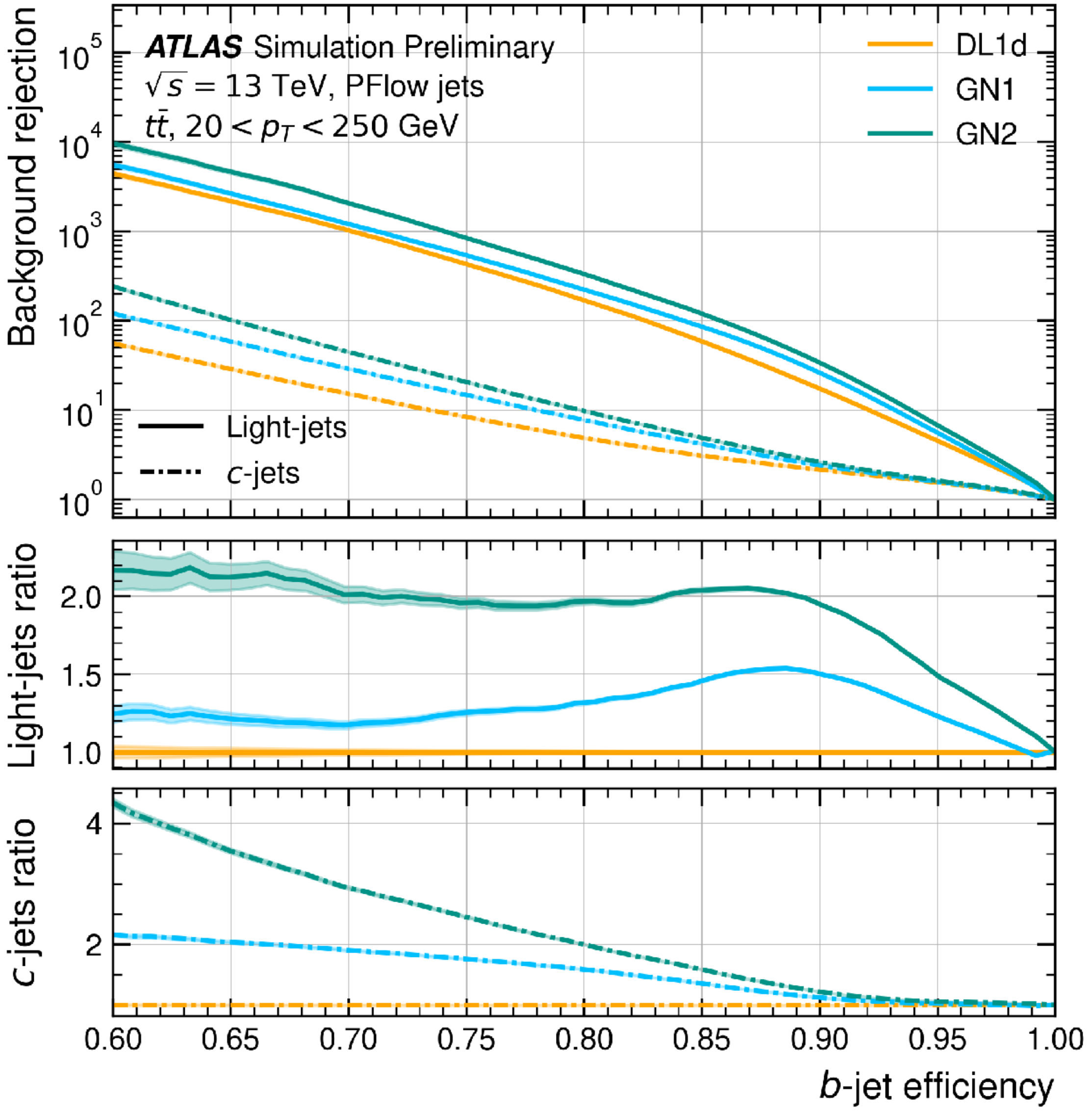
FCC detector

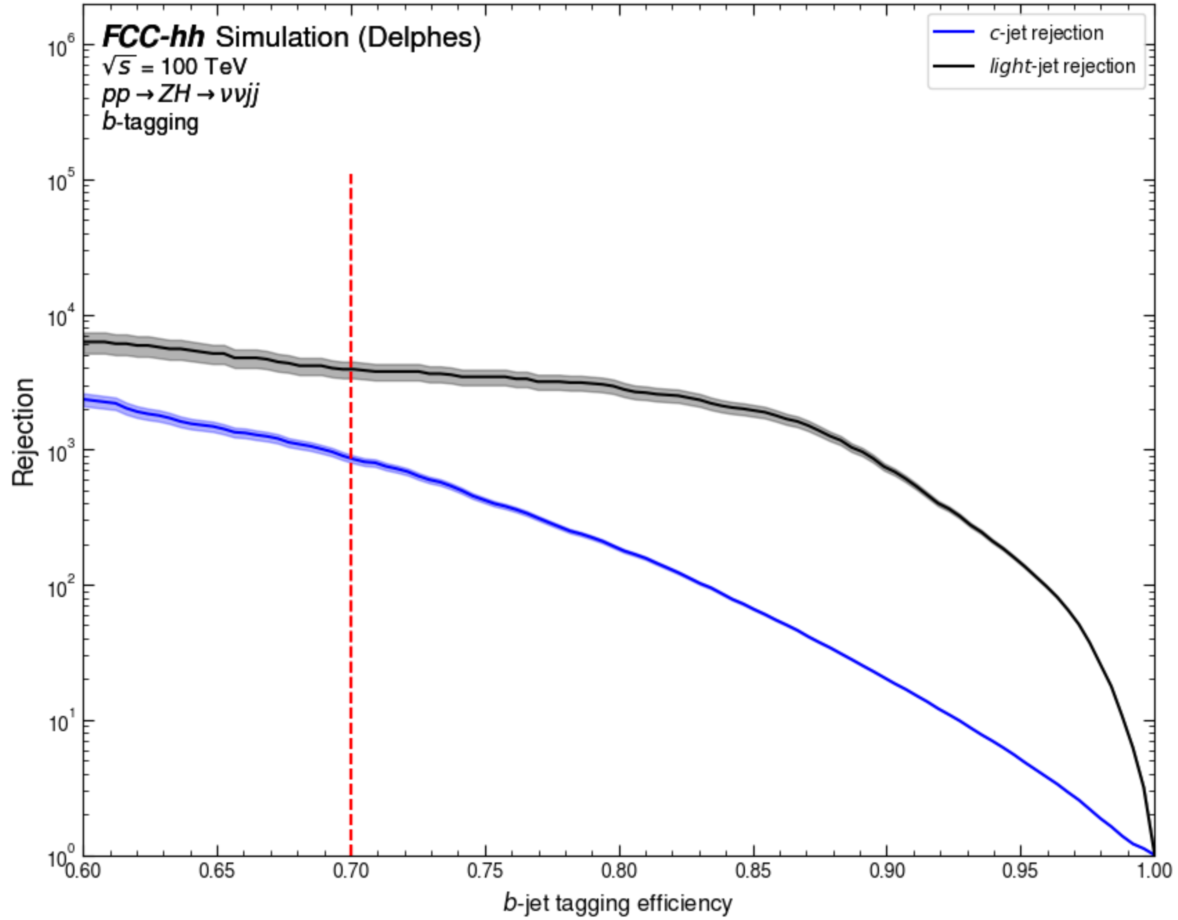
GN2 architecture

Type	Name	GN1	GN2
Hyperparameter	Trainable parameters	0.8M	1.5M
Hyperparameter	Learning rate	$1e{-}3$	OneCycle LRS (max LR $4e{-}5$)
Hyperparameter	GNN Layers	3	6
Hyperparameter	Attention Heads	2	8
Hyperparameter	Embed. dim	128	192
Architectural	Attention type	GATv2	ScaledDotProduct
Architectural	Dense update	No	Yes (dim 256)
Architectural	Separate value projection	No	Yes
Architectural	LayerNorm + Dropout	No	Yes
Inputs	Num. training jets	30M	192M

[FTAG-2023-01]

GN2 @ ATLAS vs FCC-hh





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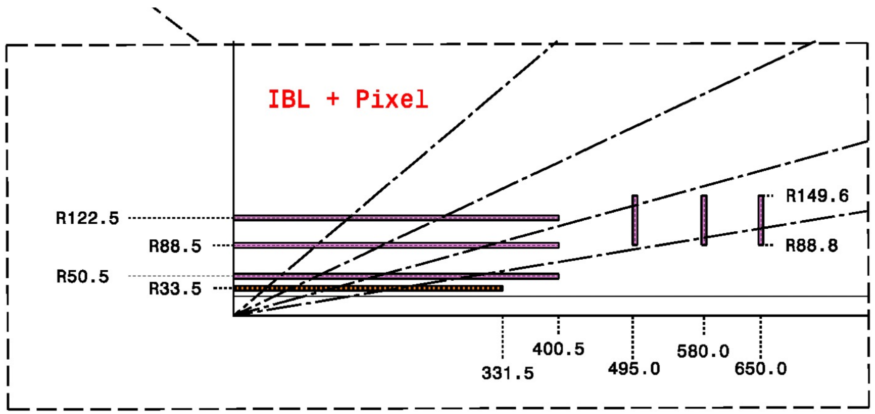

Detector envelopes (mm)

IBL	31<R<40
Pixel	42.5<R<242
SCT barrel	255<R<549
SCT end-cap	251<R<610
TRT barrel	554<R<1082
TRT end-cap	617<R<1106

Resolution values of 10.0±0.1 µm

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