Physics object performance of the FCC-hh calorimeter system

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Based on FCC CDRs Vol3 **Eur.Phys.J.ST 228 (2019)** and ongoing work

Outline

1. Expectations / Requirements
2. Object performances
3. Physics considerations

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Expectation from hadron future collider

Guaranteed deliverables

- Study Higgs and top-quark properties and exploration of EWSB phenomena with unmatchable precision and sensitivity

Exploration potential (New machines are build to make discoveries!)

- Mass reach enhanced by factor √s/14TeV (5-7 at 100TeV)
  - Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
- Benefit from both direct (large Q^2) and indirect precision probes

Could provide firm answers to questions like

- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is DM a thermal WIMPS?
- Was the cosmological EW phase transition 1st order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?

Environment and detector requirements

@100TeV FCC-hh

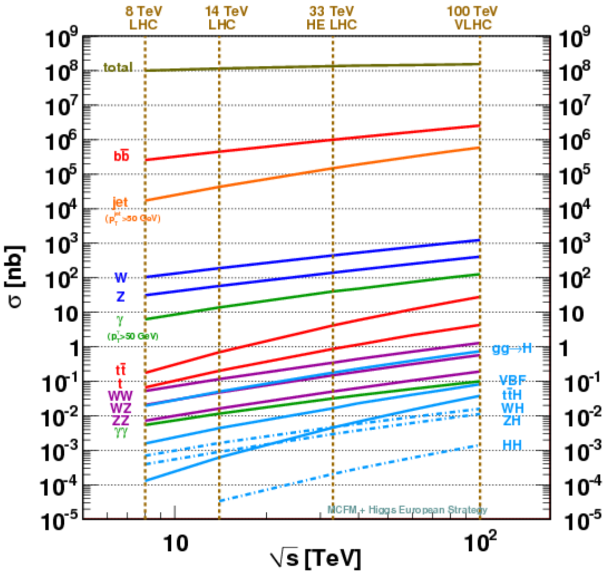
- The radiation level increase mostly driven by the jump in instantaneous luminosity
    - pp cross-section from 14 to 100TeV only grows by a factor 2
    - 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
    - Need radiation hard detectors

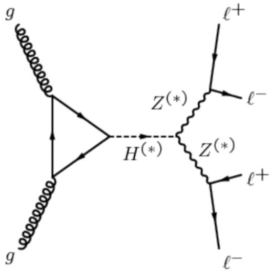
- More forward physics -> larger acceptance
    - Precision momentum spectroscopy and energy measurements up to |η|<4
    - Tracking and calorimetry up to |η|<6 (at 10cm of beam line at 18m of IP)

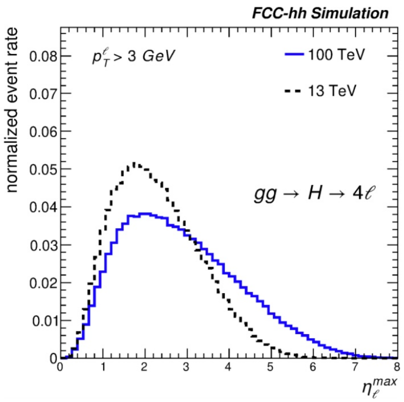
- More energetic particles
    - colored hadronic resonances up to 40TeV -> Full containment of jets up to 20TeV
    - Resonances decaying to boosted objects (top, bosons) -> need very high granularity to resolve such sub-structure

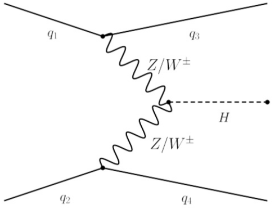
Physics req. for calorimeters (low p_T)

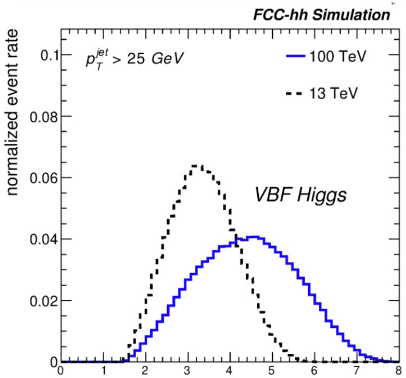
- Low p_T physics produced at threshold (EWK, Higgs, top) is more forward:
  - Need larger η coverage (up to |η|~6) compared to LHC
  - And radiation hard detectors (especially FWD)











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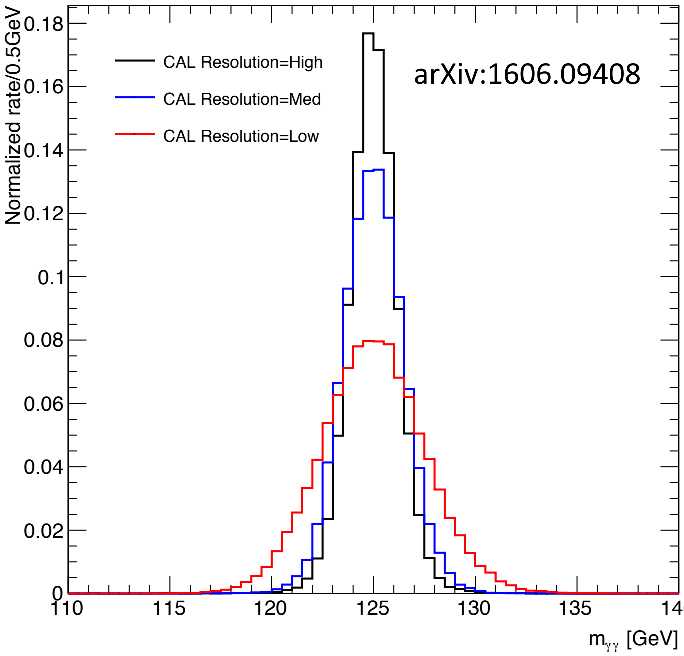
  - Need larger η coverage (up to |η|~6) compared to LHC
  - And radiation hard detectors (especially FWD)
- Need excellent energy and angular resolution at low energy for precision physics (ex: HH->bbγγ)
  - Small noise and stochastic terms
  - Robustness vs pile-up (noise)
  - π^0 rejection capabilities

$$m^2_{\gamma\gamma}=2E_1E_2(1-\cos\Delta\alpha)$$



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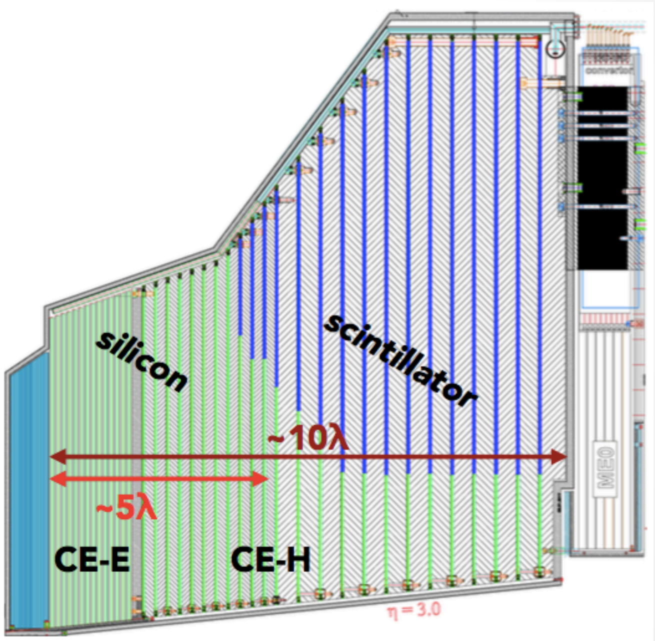
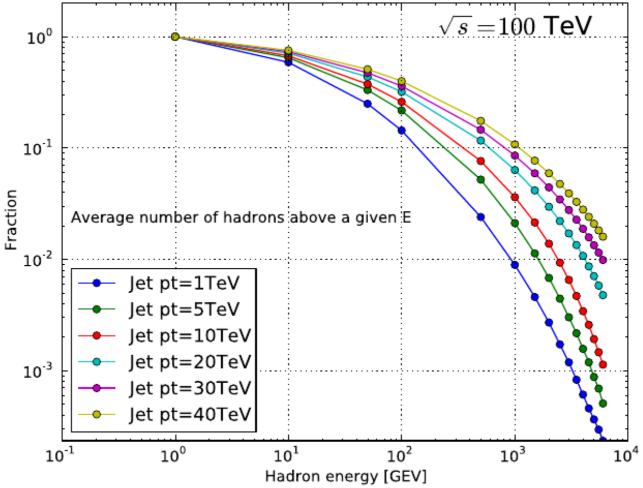
  - π^0 rejection capabilities
- Need excellent lateral and longitudinal granularity
  - Make Particle-Flow algorithm more effective
  - Pointing capabilities (needed to trigger on HH->bbγγ)
  - Helps with pile-up rejection

CMS HG-Cal



Physics req. for calorimeters (high p_T)

- The FCC-hh has sensitivity for (colored) hadronic resonances up to m ≈ 40 TeV, hence require:
  - Full containment for jets with p_T = 20 TeV → small constant term
  - Limit punch through, and helps muon ID
  - Assess requirements correctly drives detector size ⇒ magnet ⇒ cost



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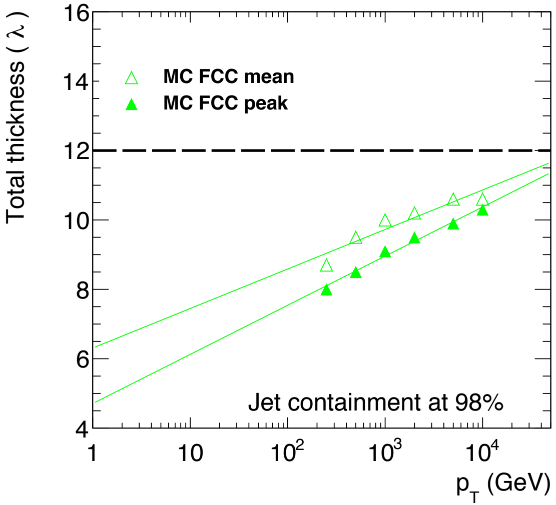

≥11 λ_I with E-Cal+H-Cal seems good enough

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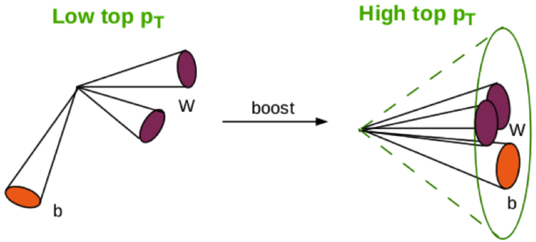

$\Delta R \cong 2m/p_T$

- The FCC-hh has sensitivity for boosted resonances (ex: Z’ → tt or RSG → WW) up to m ≈ 20 TeV
  - W jet with p_T = 10 TeV → ΔR = 0.02 (typical E-Cal cell size @ LHC)
  - Need very high granularity to resolve such substructure (tracking can achieve such separation)
    - target: 4x better granularity wrt ATLAS/CMS detectors
    - Has calorimetry the capability to resolve such objects?
    - Granularity translate to actual separation power?

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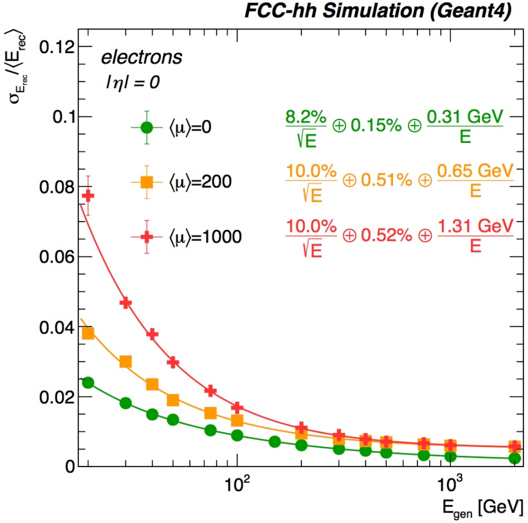
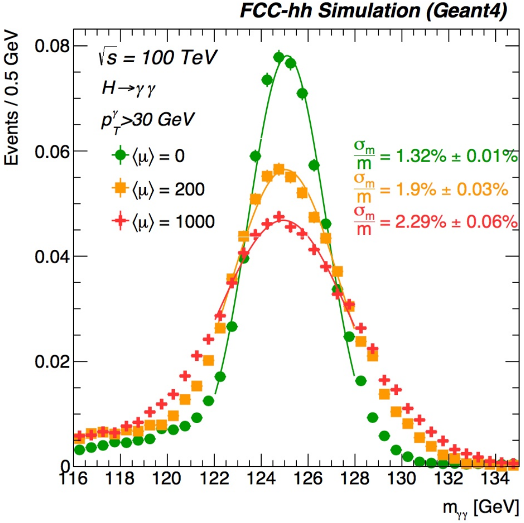
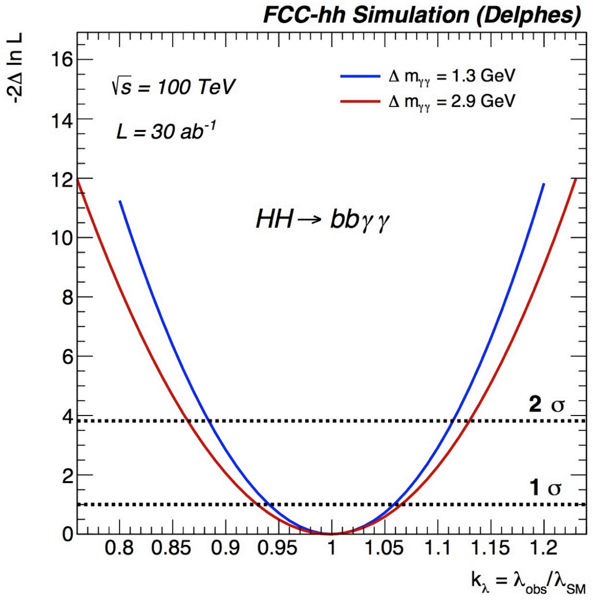
Single photon and Higgs



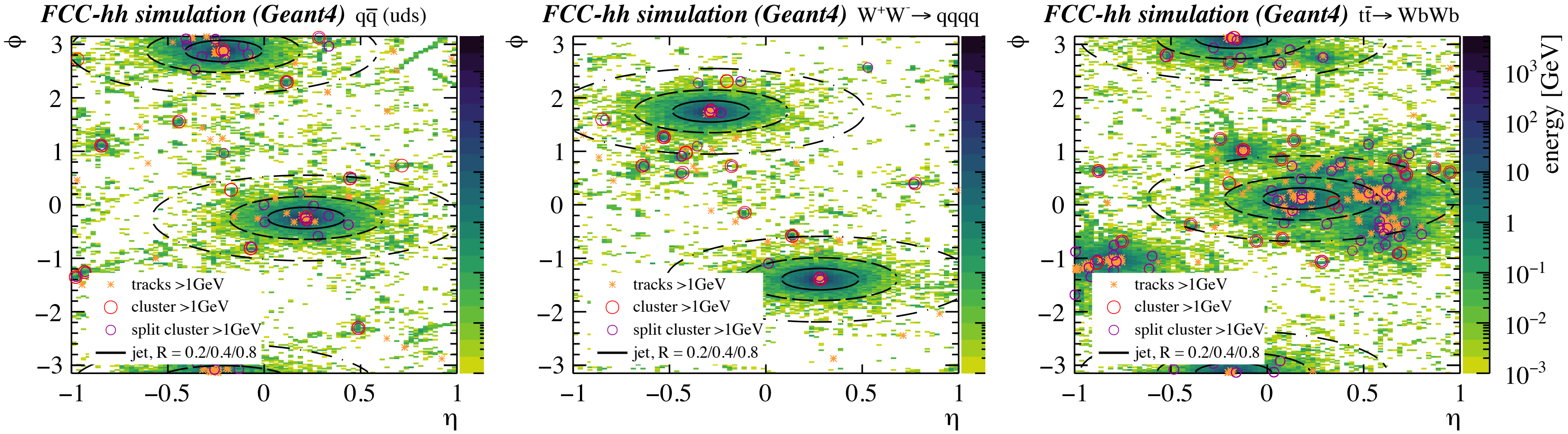




- Large impact of in time PU on the noise term
  - Out of the box with no sophisticated technics for removal!! (optimized the sliding window reco)
  - Severely degrades $m_{\gamma\gamma}$ resolution
  - Improving clustering, not sliding windows may help
  - Impacts Higgs self-coupling precision by $\delta\kappa_\lambda \approx 1\%$
  - Some thought needed (tracking, timing information can help?)

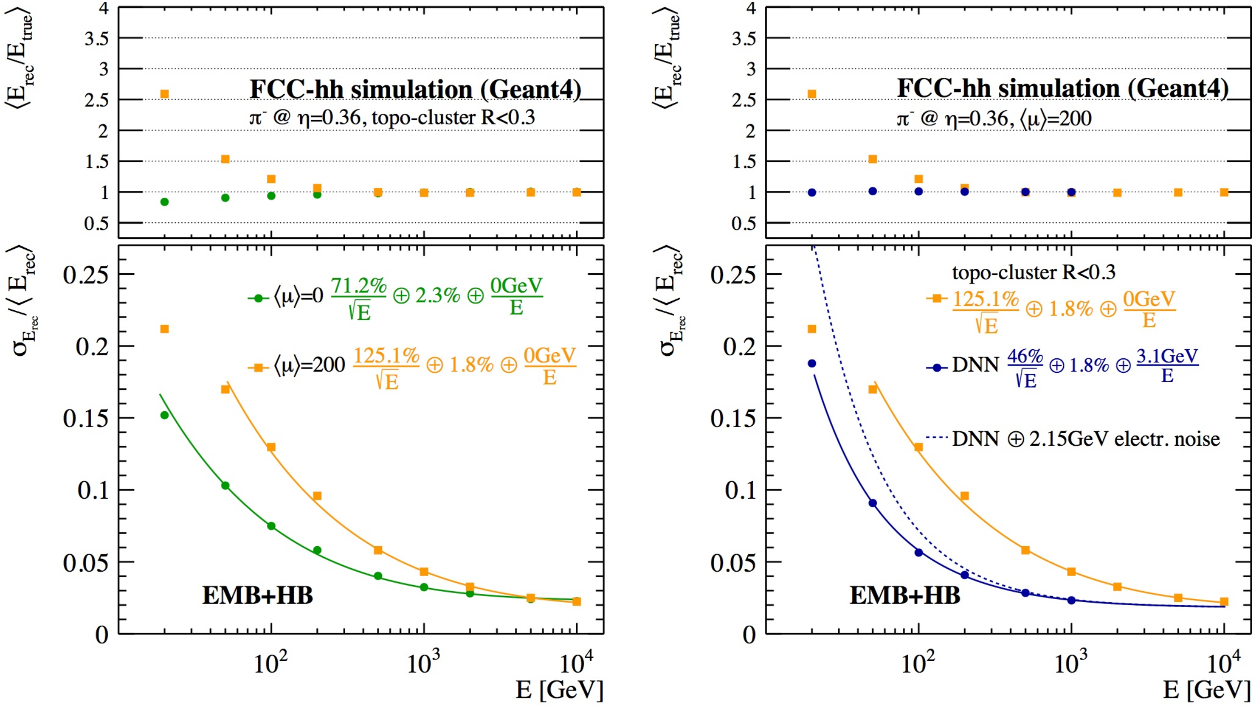
Reconstruction

- Reconstruction algorithms uses:
    - Calorimeter cells, topological cluster
    - Includes electronics/pile-up noise
    - Deep Neural Network energy reconstruction



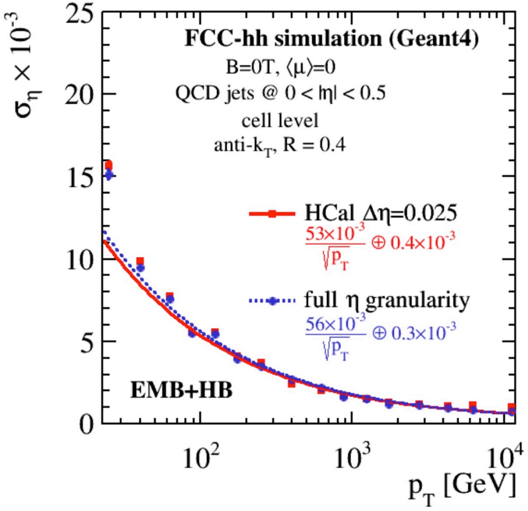
Single pion performance

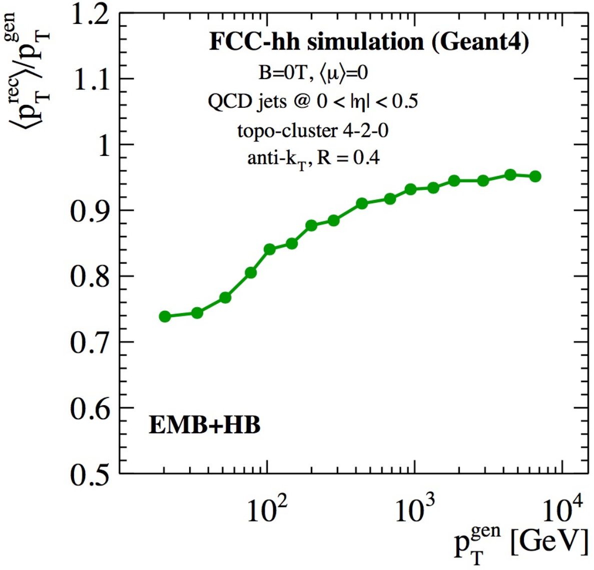
- No sophisticated PU removal for topo-clusters, thus large impact on performance
- DNN outperforms by a lot!

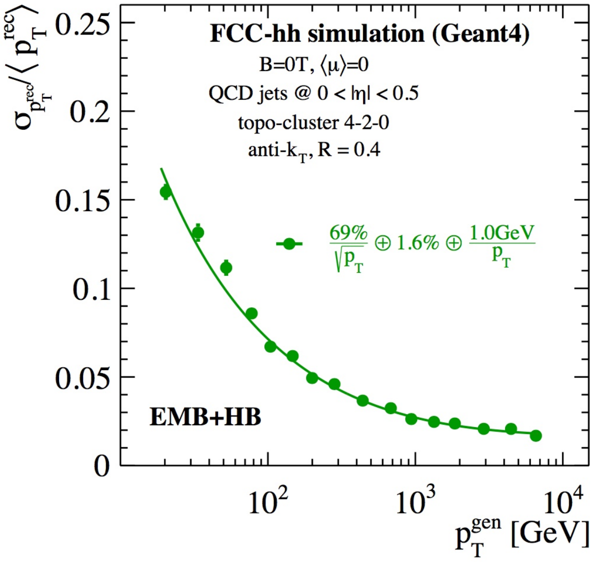


Jet performance

- No B-field as the acceptance will be significantly reduced w/o particle flow
- Those results shows best achievable with simple calibration

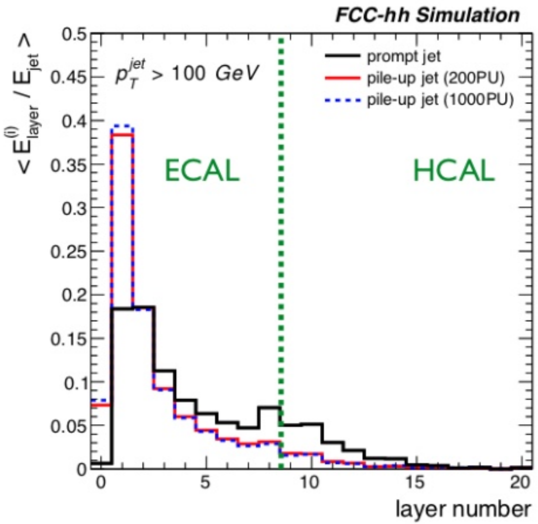


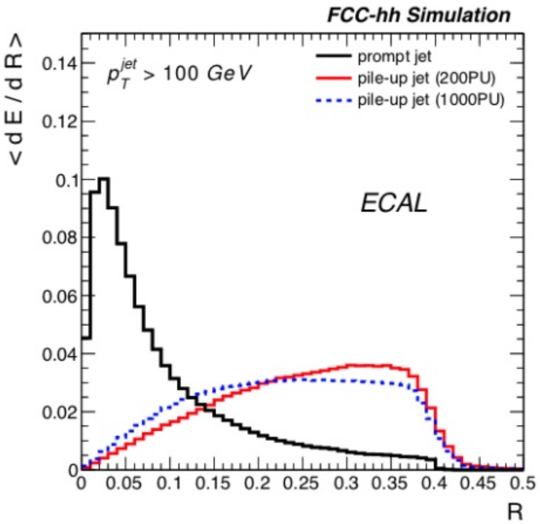


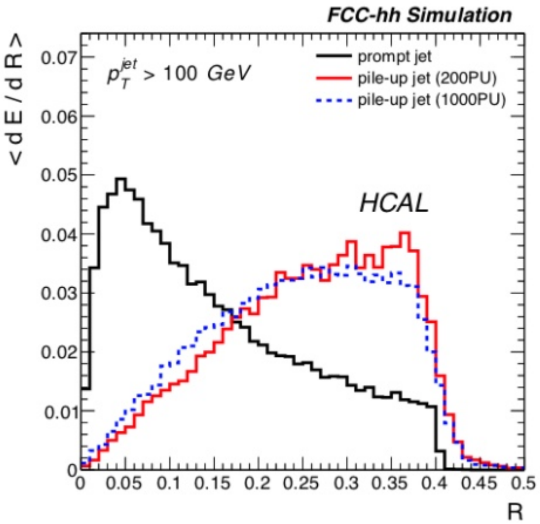


Jet pile-up identification

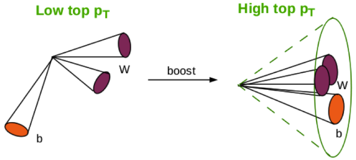
- With 200-1000PU
  - Will get large amount of fake-jets from PU combinatorics
  - Need both longitudinal/lateral segmentation for PU identification
  - Simplistic observables show possible handles, but are pessimistic…
  - In reality tracking and particle flow will help a lot

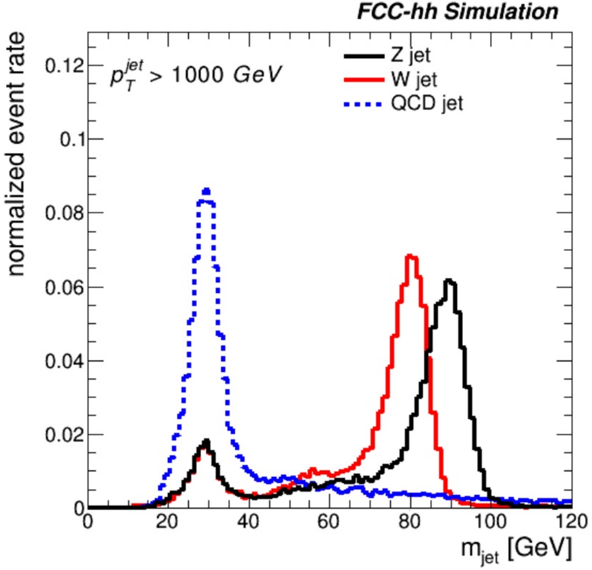




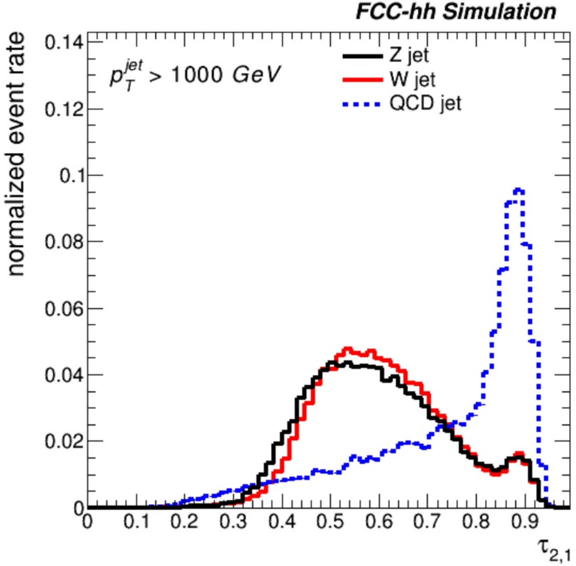


Jet sub-structure





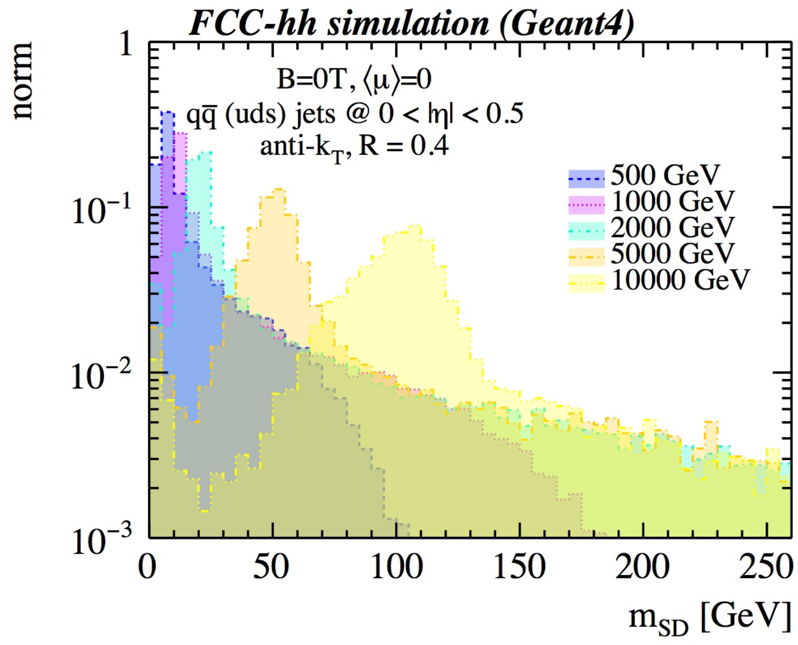
W/Z->qq

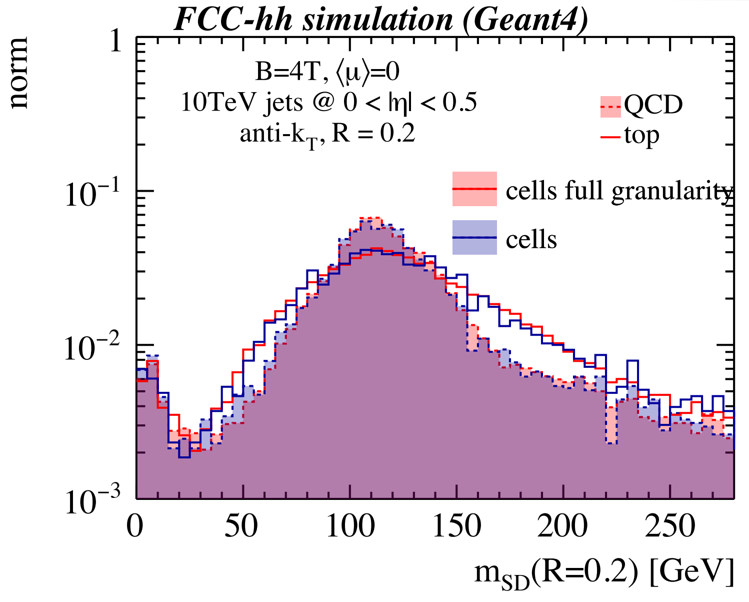


- Calorimeter standalone, and without B field
  - Performance good up to 1 TeV
- Far from having explored all possibilities:
  - Particle-Flow tracks and B field (decrease local occupancy) will improve
  - Machine Learning techniques will help a lot (train on 3D shower image)

Jet sub-structure

- At higher p_T starts to be more challenging as light jets looks similar to top for m_{SD}





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Q*->jj

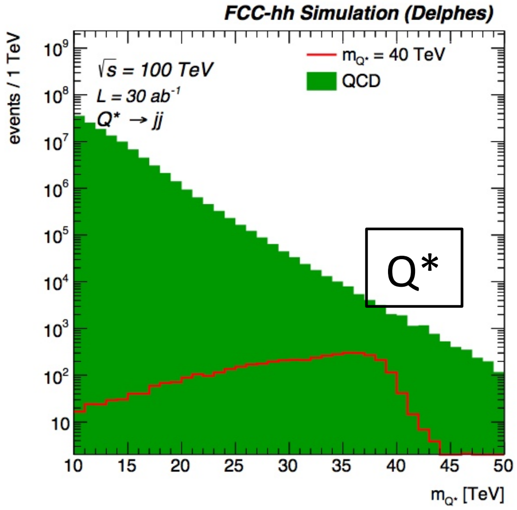
Q*/Z'->jj

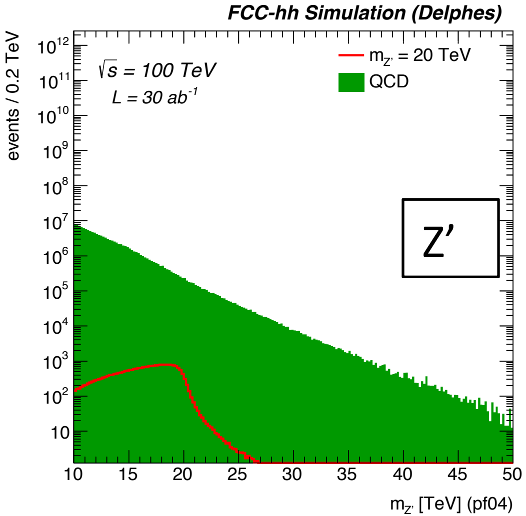
- Q* model
  - Strongly coupled
  - Wide, large cross section

- Z' model
  - Same benchmark as Z' -> leptons
  - Narrow, small cross section

- Analysis selection
  - $p_T(j_1)$ and $p_T(j_2)$>3TeV
  - $Y^*=|y_{j1}-y_{j2}|/2 < 1.5$

- Uncertainties
  - 50% uncertainty on the Di-jet normalization



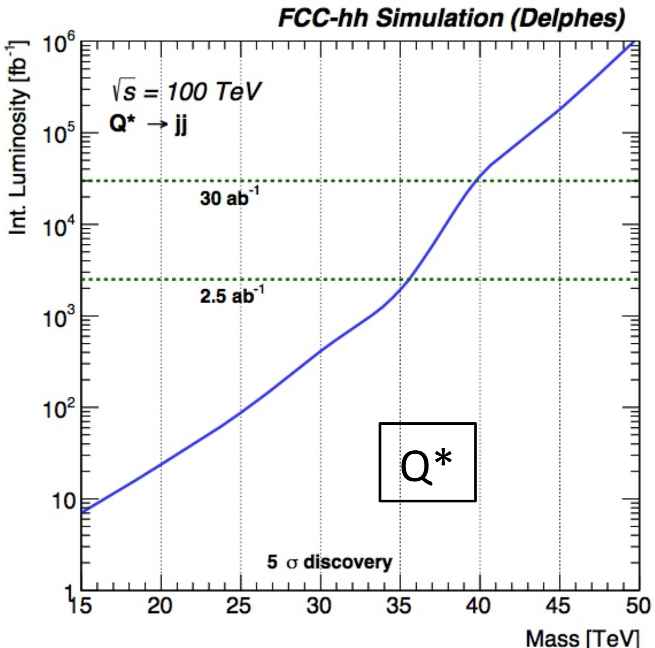


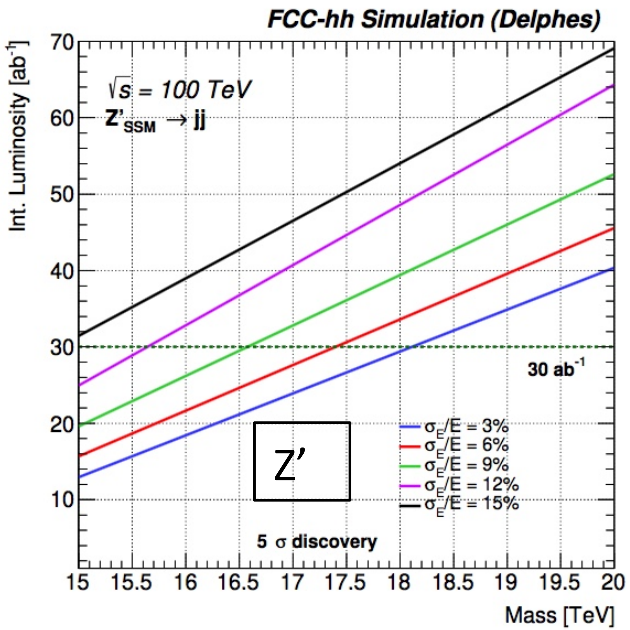
5σ discovery for Q* (wide):

- 15TeV after 1 day (1fb^{-1})
- 36TeV after 10 years @ baseline
- 40TeV after full operation 25 years

5σ discovery for Z’ (narrow):

- <15TeV after 10 years @ baseline
- 19TeV after full operation 25 years
- Increasing the calorimeter constant term has a large impact on the discovery potential



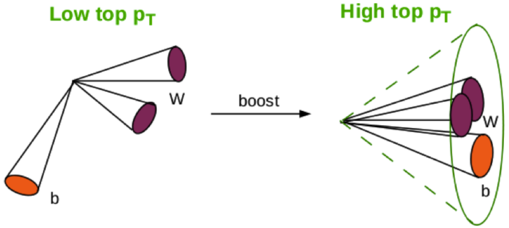


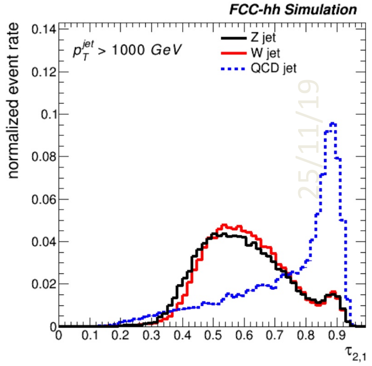
Z’->tt

G_{RS}->WW

W->jj

Boosted top/W



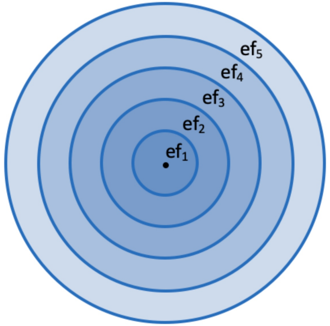


$\Delta R \cong 2m/p_T$

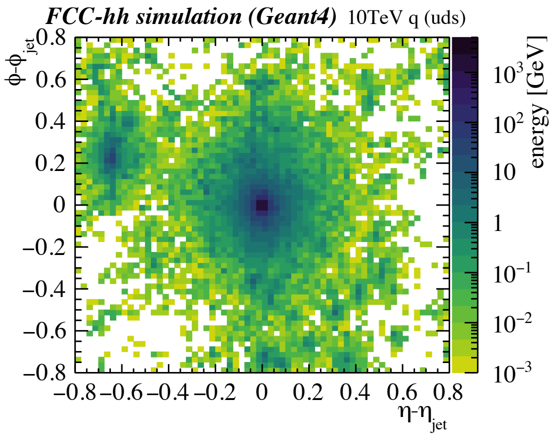
Top-quark/W-boson

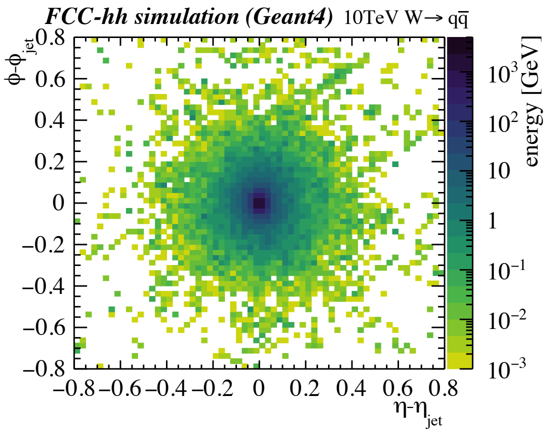
LHC: $p_T \sim 1$TeV $\rightarrow \Delta R = 0.5/0.15$

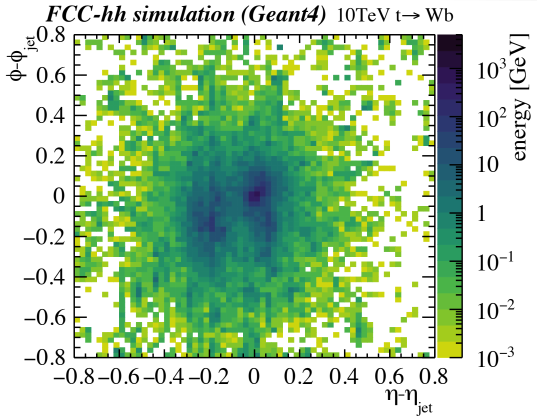
FCC: $p_T \sim 10$ TeV $\rightarrow \Delta R = 0.05/0.015$



$$\frac{n-1}{5}R \le \Delta R(k,\text{jet}) < \frac{n}{5}R, \quad \text{Flow}_{n,5} = \sum_k \frac{|p_T^k|}{|p_T^{\text{jet}}|}$$

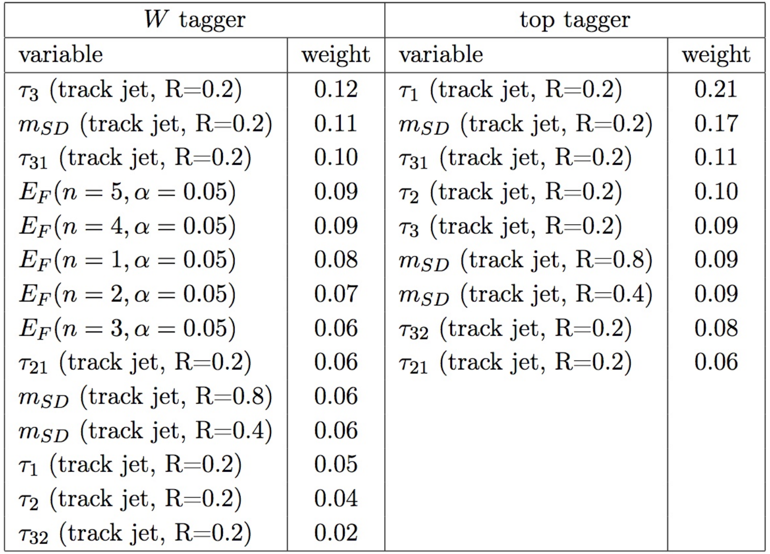




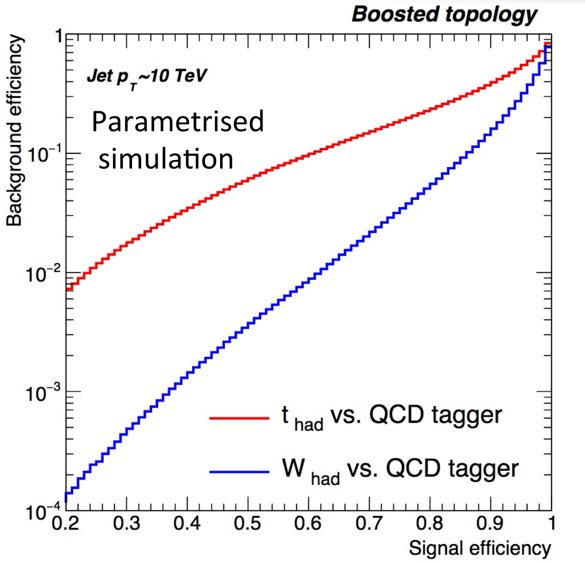


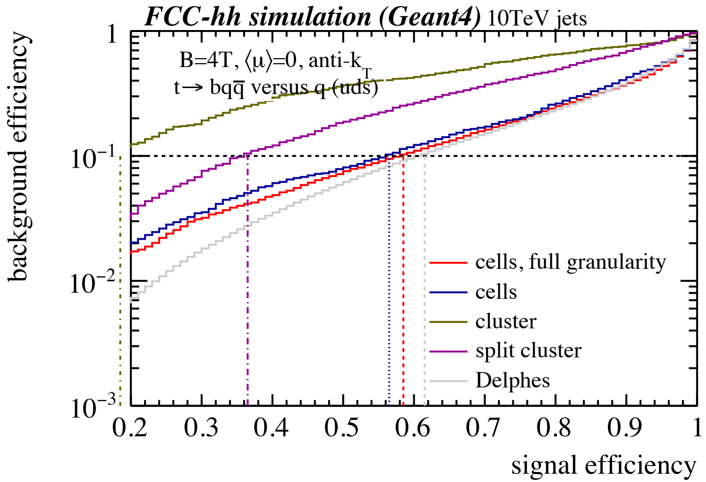
Multivariate discriminant

- MVA discriminant to disentangle overwhelming QCD jets from boosted W/tops
- Need to further validate this in full simulation, but work in ongoing, but it seems that the top tagging performance can be reproduced in full simulation with calorimeter granularity only



W tagger		top tagger	
variable	weight	variable	weight
τ_3 (track jet, R=0.2)	0.12	τ_1 (track jet, R=0.2)	0.21
m_{SD} (track jet, R=0.2)	0.11	m_{SD} (track jet, R=0.2)	0.17
τ_{31} (track jet, R=0.2)	0.10	τ_{31} (track jet, R=0.2)	0.11
$E_F(n=5, \alpha=0.05)$	0.09	τ_2 (track jet, R=0.2)	0.10
$E_F(n=4, \alpha=0.05)$	0.09	τ_3 (track jet, R=0.2)	0.09
$E_F(n=1, \alpha=0.05)$	0.08	m_{SD} (track jet, R=0.8)	0.09
$E_F(n=2, \alpha=0.05)$	0.07	m_{SD} (track jet, R=0.4)	0.09
$E_F(n=3, \alpha=0.05)$	0.06	τ_{32} (track jet, R=0.2)	0.08
τ_{21} (track jet, R=0.2)	0.06	τ_{21} (track jet, R=0.2)	0.06
m_{SD} (track jet, R=0.8)	0.06		
m_{SD} (track jet, R=0.4)	0.06		
τ_1 (track jet, R=0.2)	0.05		
τ_2 (track jet, R=0.2)	0.04		
τ_{32} (track jet, R=0.2)	0.02		





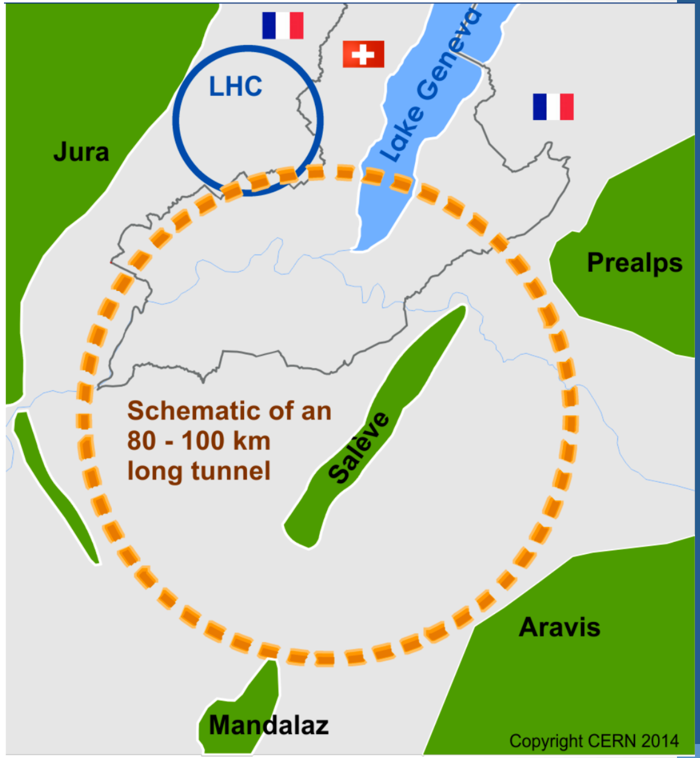
Summary

- Reference detector for FCC-hh experiments with high granularity
  - Demonstrated that it can be operated in such difficult conditions
- In no pile-up environment achieved the goal resolution:
  - Electrons/photons: $8\%/\sqrt{E} \oplus 0.2\%$
  - Pions: $50\%/\sqrt{E} \oplus 2.2\%$ (40% with DL)
  - Jets (without magnetic field): $70\%/\sqrt{E} \oplus 2.6\%$
- Pile-Up: a challenge for FCC-hh environment
  - Valid for any studied detector option
  - Optimization of reconstruction procedures necessary
  - Need help from tracking and timing
  - 1000 PU hostile environment also for calorimetry (energy resolution), but DNN is outstanding
- Longitudinal/lateral segmentation is suitable for
  - PU jet Identification Particle-Flow algorithms
  - Angular and energy resolution

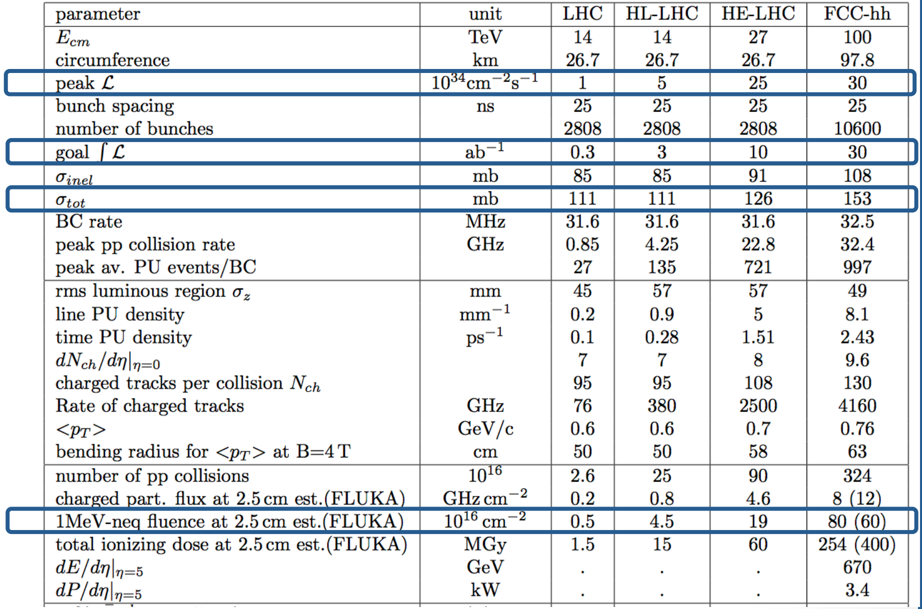
Backup

FCC-hh Scope

- FCC-hh Target:
  - √s =100TeV
  - 100 km long
  - Needs 16T magnets
- Direct search for New Physics:
  - Direct prod. of heavy resonances up to m ≈ 40 TeV
  - Stops up to m ≈ 10TeV
- Precision SM physics (complementary to e^+e^-):
  - Higgs self-coupling (Δλ/λ ≈ 4%)
  - Higgs rare decays
  - EWK, Top physics in new extreme dynamical regimes



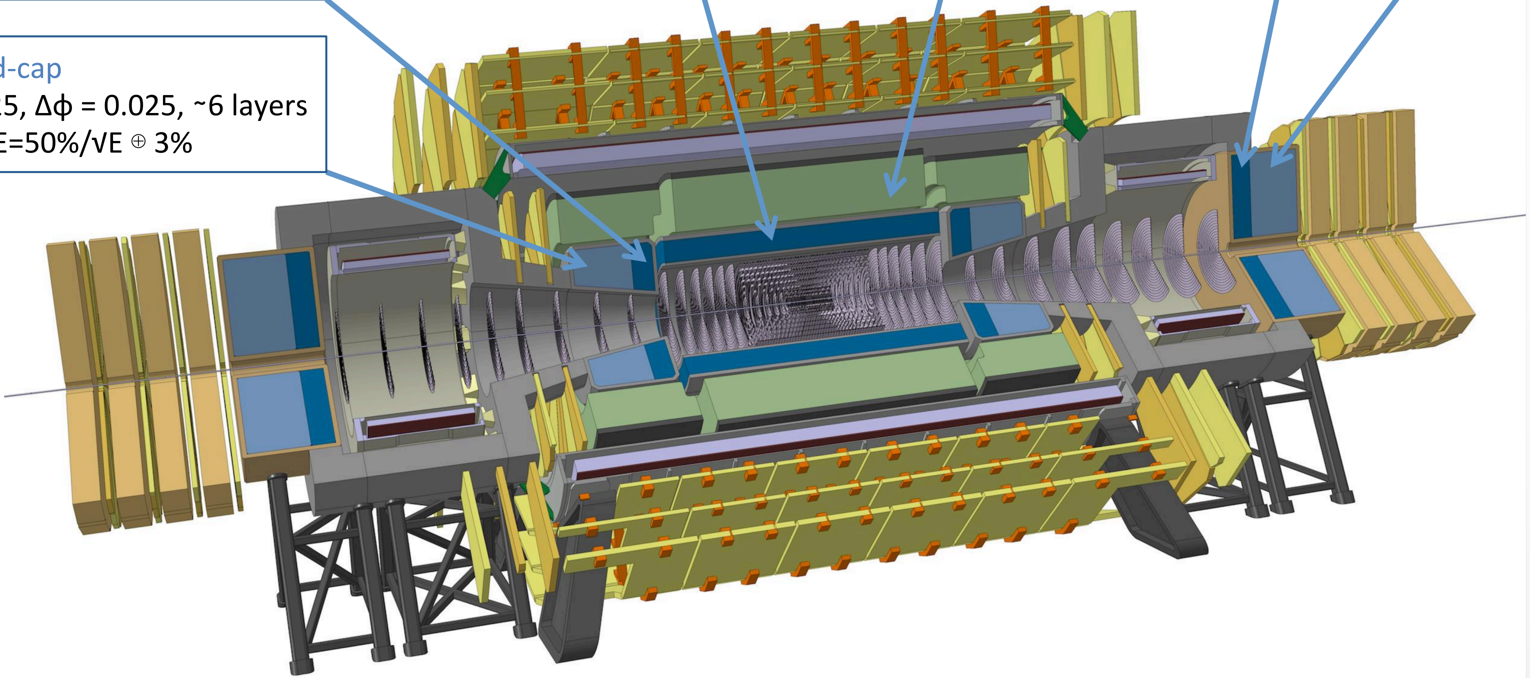
Key parameters



parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mb	85	85	91	108
σ_{tot}	mb	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
bending radius for $<p_T>$ at B=4 T	cm	50	50	58	63
number of pp collisions	10^{16}	2.6	25	90	324
charged part. flux at 2.5 cm est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.2	0.8	4.6	8 (12)
1MeV-neq fluence at 2.5 cm est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.5	4.5	19	80 (60)
total ionizing dose at 2.5 cm est.(FLUKA)	MGy	1.5	15	60	254 (400)
$dE/d\eta\|_{\eta=5}$	GeV	.	.	.	670
$dP/d\eta\|_{\eta=5}$	kW	.	.	.	3.4

- Luminosity:
  - Baseline: 5 10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  - Ultimate: 30 10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  - O(30 ab^{-1}) ~25 years of operations
- Radiation levels:
  - pp cross-section from 14 TeV → 100 TeV only grows by factor 2
  - radiation level increase mostly driven by increase in inst. luminosity
- 10 times more fluence compared to HL-LHC (x100 wrt to LHC)
  - For calorimetry
    - 1 MeV-neq fluence ≈ 4 $10^{15(14)}\mathrm{cm}^{-2}$ in the Barrel for E-Cal (H-Cal)
    - 1 MeV-neq fluence ≈ 2 10^{16} cm^{-2} in the End-Caps

FCC-hh detector



H-Cal barrel, extended barrel
Δη = 0.025, Δϕ = 0.025, ~10/8 layers
Goal σE/E=50-60%/√E ⊕ 3%

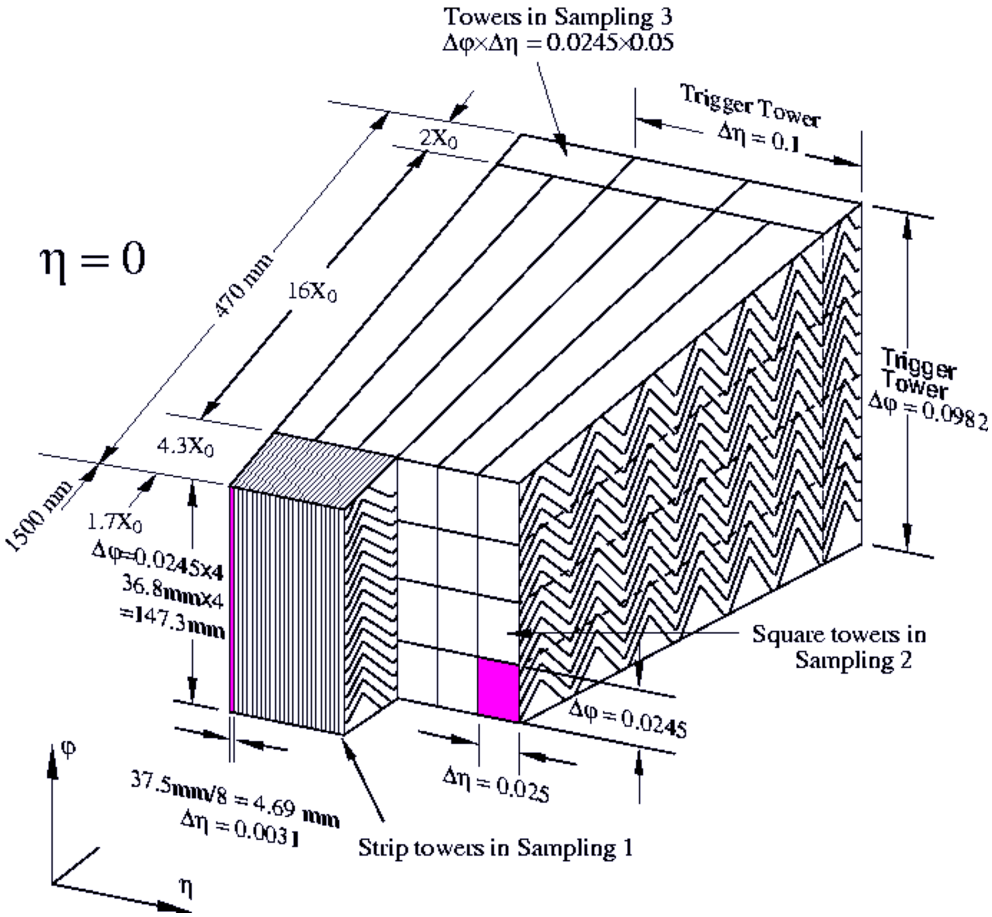
H-Cal forward
Δη = 0.05, Δϕ = 0.05, ~6 layers
Goal σE/E=100%/√E ⊕ 10%

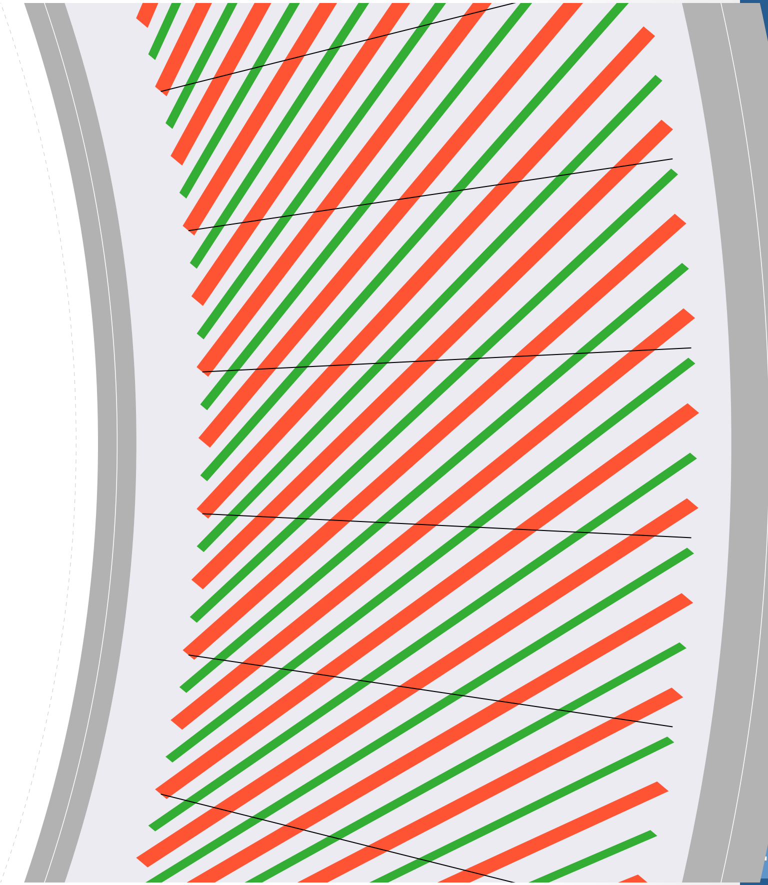
E-Cal forward
Δη = 0.05, Δϕ = 0.05, ~6 layers
Goal σE/E=30%/√E ⊕ 1%

E-Cal barrel
Δη = 0.01, Δϕ = 0.009, ~6 layers
Goal σE/E=10%/√E ⊕ 0.7%

E-Cal end-cap
Δη = 0.01, Δϕ = 0.01, ~6 layers
Goal σE/E=10%/√E ⊕ 0.7%

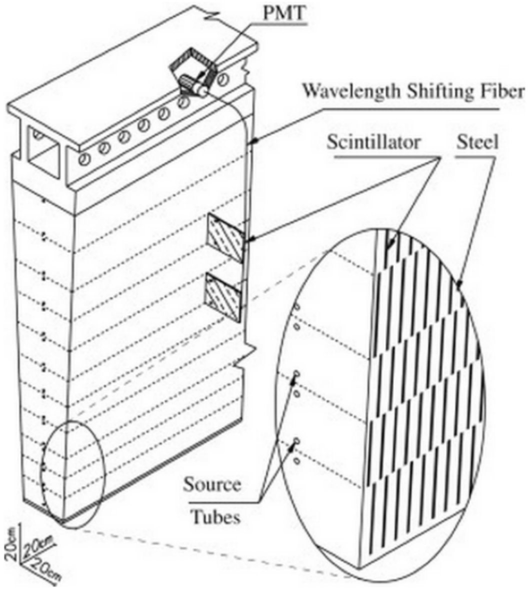
H-Cal end-cap
Δη = 0.025, Δϕ = 0.025, ~6 layers
Goal σE/E=50%/√E ⊕ 3%

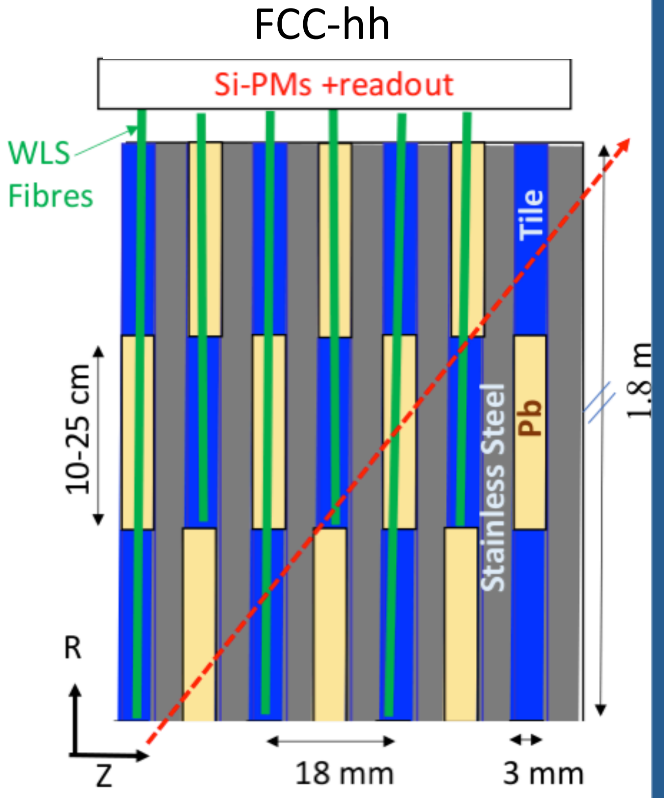

η = 0
Towers in Sampling 3
Δφ×Δη = 0.0245×0.05
Trigger Tower
Δη = 0.1
2X₀
16X₀
470 mm
4.3X₀
1500 mm
1.7X₀
Δφ=0.0245x4
36.8mmx4
=147.3mm
Trigger Tower
Δφ = 0.0982
Square towers in Sampling 2
Δφ = 0.0245
Δη = 0.025
37.5mm/8 = 4.69 mm
Δη = 0.0031
Strip towers in Sampling 1
φ
η



Tile calorimeter

- Granularity
  - Much more granular than ATLAS (×10)
  - Δη = 0.025, Δϕ = 0.025
  - 10 longitudinal layers



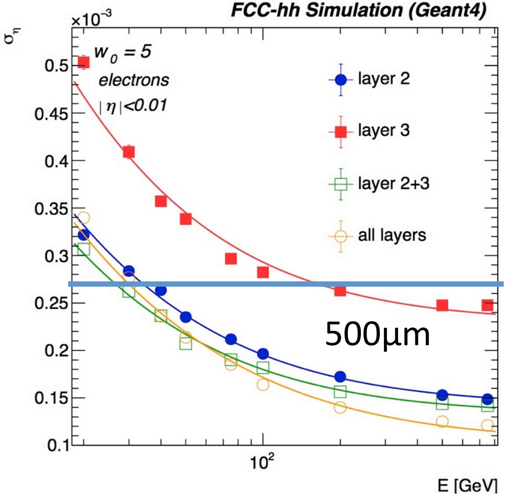


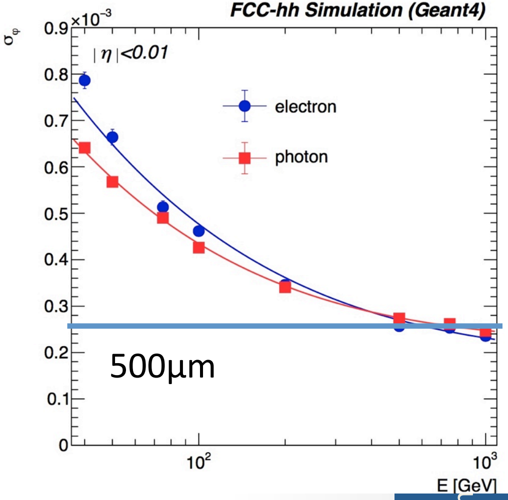
- High longitudinal and lateral segmentation possible with SiPMs
- Mechanical structure feasible, assembly study done
- First test of scintillator tiles started

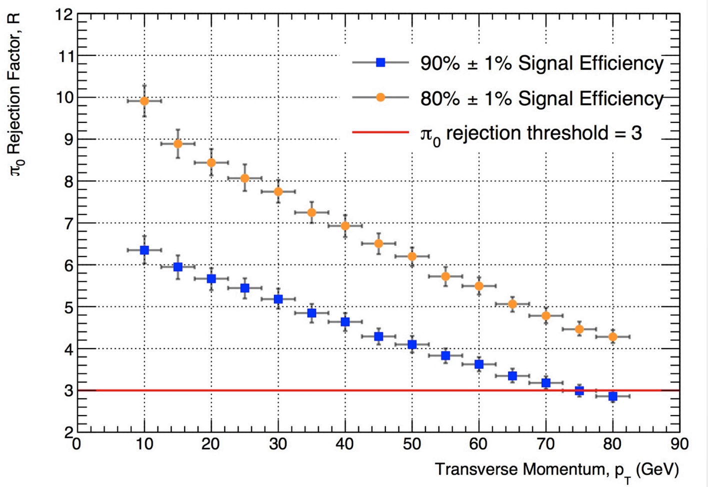
E-Cal performance

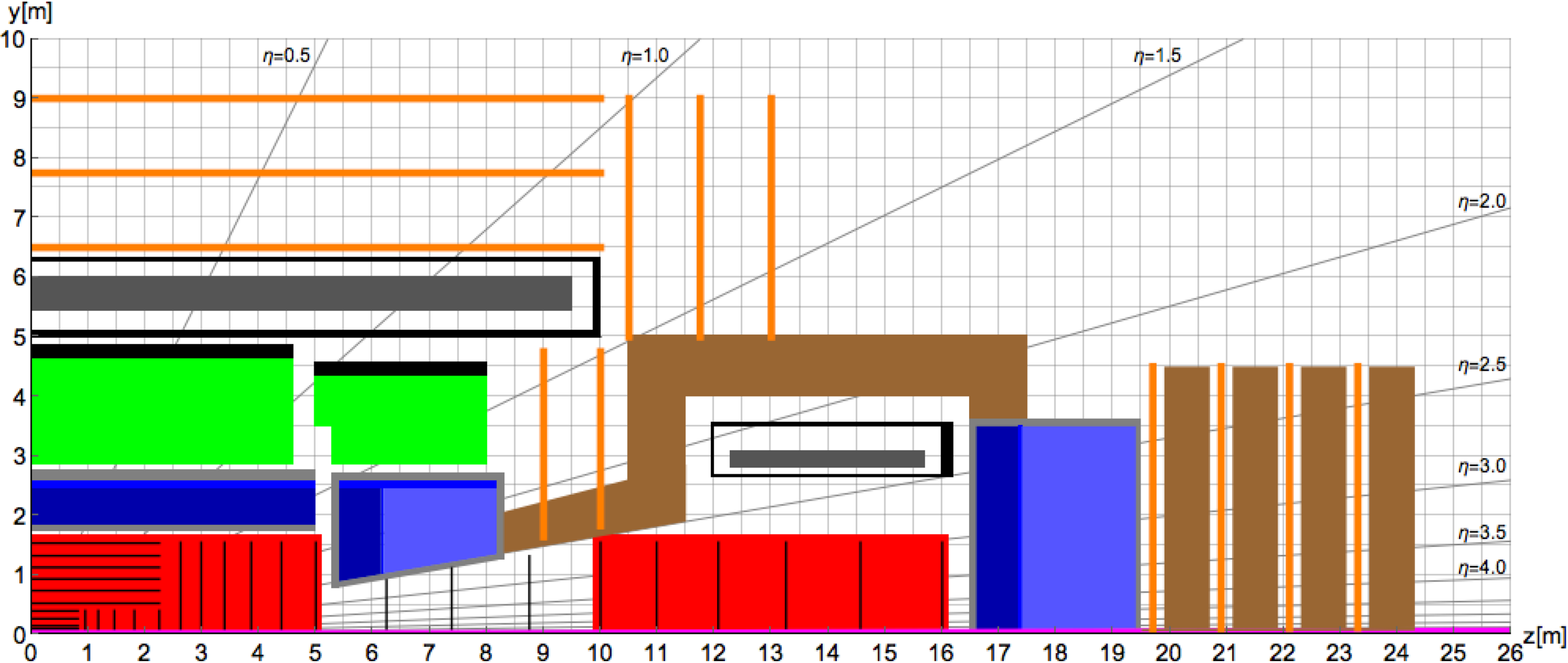
- Position resolution
  - essential to combine tracks and calorimeter clusters in high PU

- Segmentation
  - Fine ϕ in the 1st layer ($\Delta\eta \times \Delta\phi \approx 0.0025 \times 0.02$)
  - Fine η in other layers ($\Delta\eta = 0.01$) crucial for π^0 rejection ($H \to \gamma\gamma$)
  - Excellent results obtained with MVA and up to 15 variables
  - Deep Neural Network based analysis show similar results

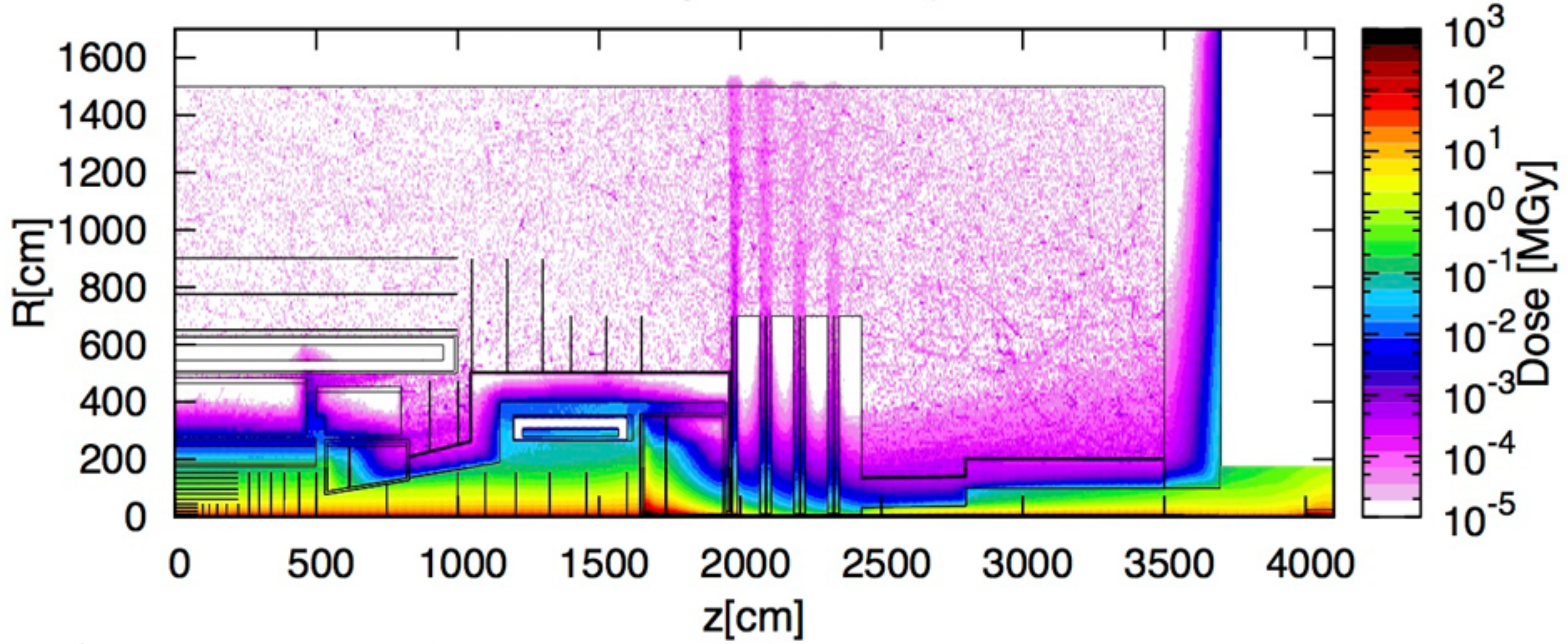







y[m]
10
9
8
7
6
5
4
3
2
1
0
η=0.5
η=1.0
η=1.5
η=2.0
η=2.5
η=3.0
η=3.5
η=4.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
z[m]

Radiations



	fluence $10^{14}\mathrm{cm}^{-2}$	**dose** MGy
ECal barrel	50	0.1
ECal endcap	300	1
ECal forward	5×10^{3}	5×10^{3}

	fluence $10^{14}\mathrm{cm}^{-2}$	**dose** MGy
HCal barrel	3	0.008
HCal endcap	200	1
HCap forward	5×10^{3}	5×10^{3}

Discovery tt degrading b-tag efficiency

High efficiencies ($\varepsilon_b > 60\%$) for corresponding low mis-identification probability ($\varepsilon_{u,d,s} < 1\%$) from light jets have to be achieved up to $p_T = 5$ TeV.

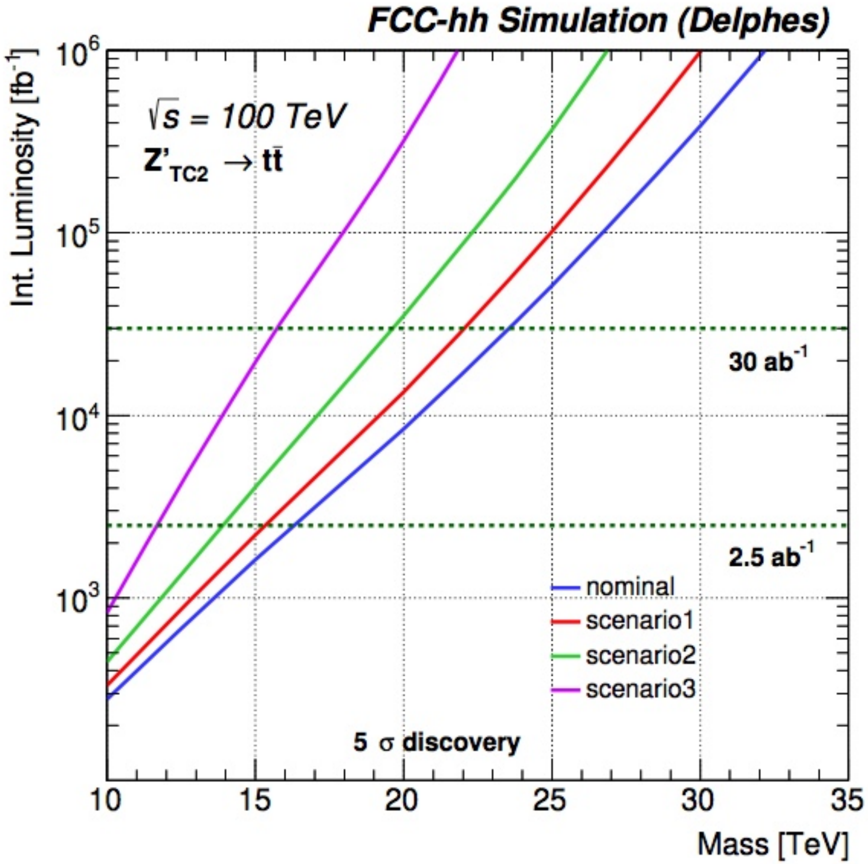
For example, searches for heavy resonances decaying to hadronic tt pairs heavily rely on efficient b-tagging performance at such energies.

The discovery reach for a specific Z′ model assuming several scenarios for b-jet identification at very large p_T are considered

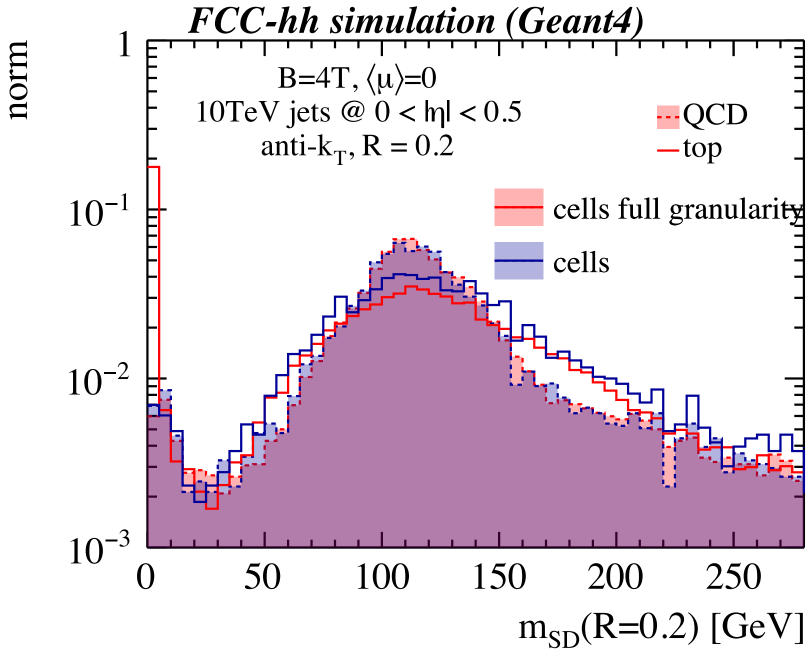
-> Nominal efficiency $(1-p_T/15)*85\%$

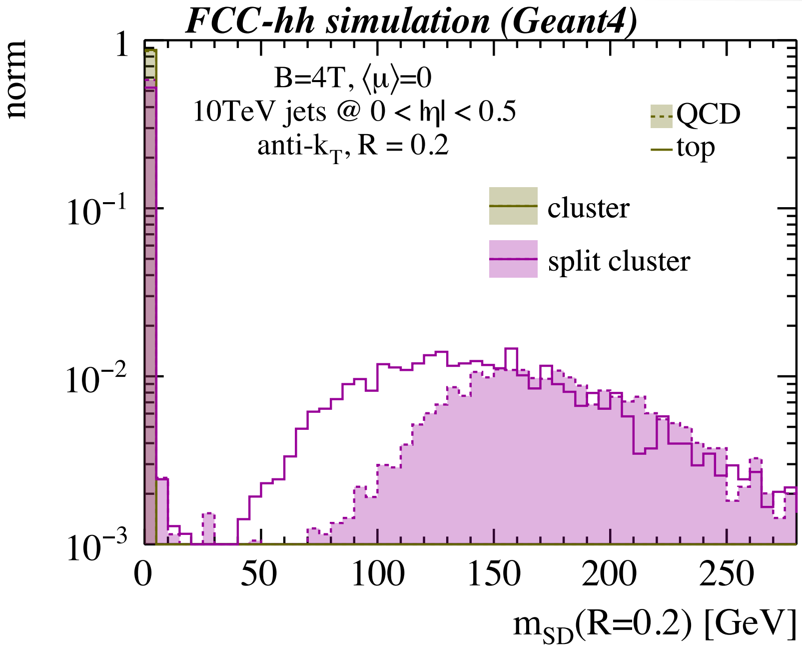
-> scenarios 1,2, 3 correspond to reduction of the slope by a factor 25%, 33% and 50%.

As expected the discovery reach strongly depends on the b-tagging performances.



Jet sub-structure





Jet sub-structure

- More plots from Coralie