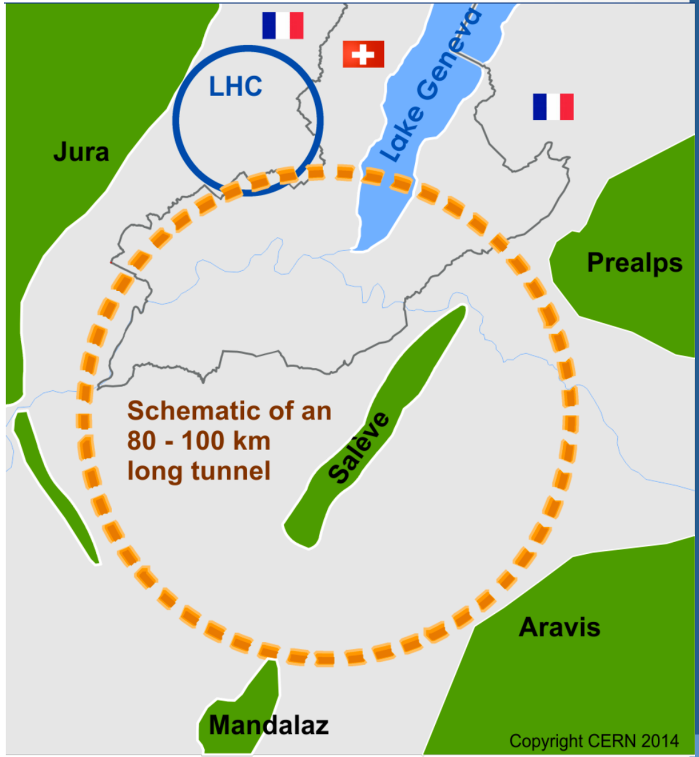
Design and performance studies of the calorimeter system for a FCC-hh experiment

Clement Helsens, CERN-EP
on behalf of the FCC-hh calorimeters group
14th PISA meeting, May 29th 2018

FCC-hh

FCC-hh scope

- FCC-hh Target:
  - $\sqrt{s}$ =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 ($\Delta\lambda/\lambda \approx 4\%$)
  - Higgs rare decays
  - EWK, Top physics in new extreme dynamical regimes



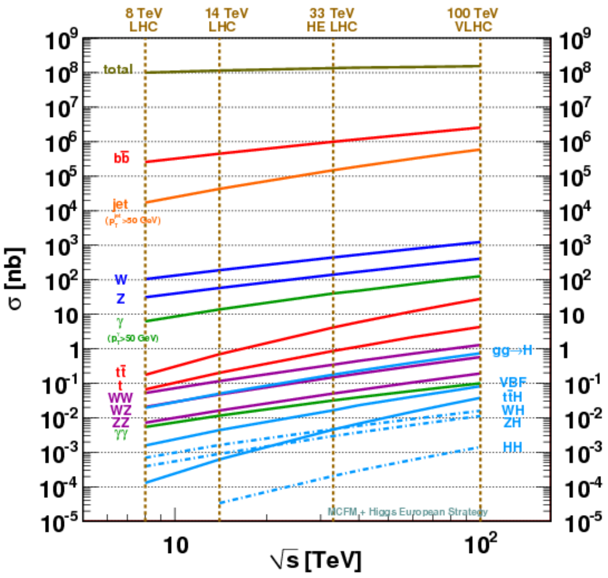
Key parameters

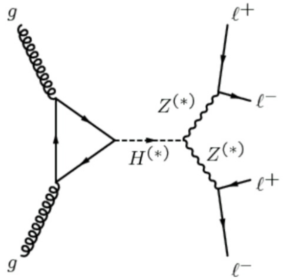
parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L}$	10^{34}cm^{-2}s^{-1}	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mb	85	85	91	108
σ_{tot}	mb	111	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)	GHz cm^{-2}	0.2	0.8	4.6	8 (12)
1MeV-neq fluence at 2.5 cm est.(FLUKA)	10^{16} 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

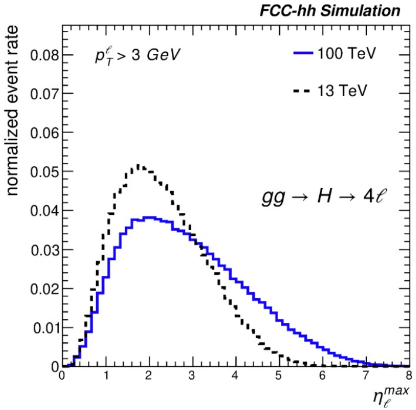
- Luminosity:
  - Baseline: 5 10^{34} cm^{-2} s^{-1}
  - Ultimate: 30 10^{34} cm^{-2} s^{-1}
- O(30 ab^{-1}) ~25 years of operations
- Radiation levels:
  - pp cross-section from 14 TeV → 100 TeV only grows by factor 2
  - radiation level increase mostly driven by increase in inst. luminosity
- 10 times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

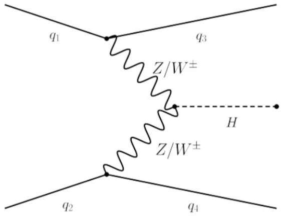
Physics req. for calorimeters (low p_T)

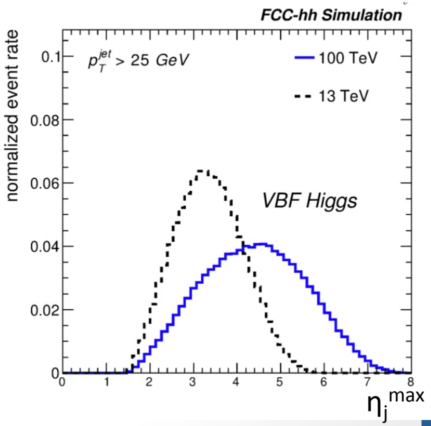
- Low p_T physics produced at threshold (EWK, Higgs, top) is more forward:
  - Need larger η coverage (up to |η|~6) compared to LHC
  - And radiation hard detectors (especially FWD)











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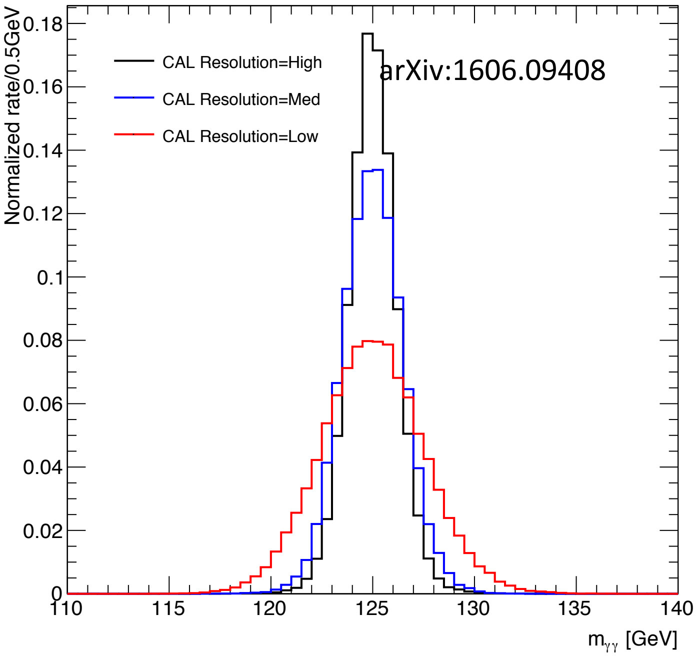
- Need excellent energy and angular resolution at low energy for precision physics (ex: HH->bbγγ)
  - Small noise and stochastic terms
  - Robustness vs pile-up (noise)
  - π^0 rejection capabilities

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



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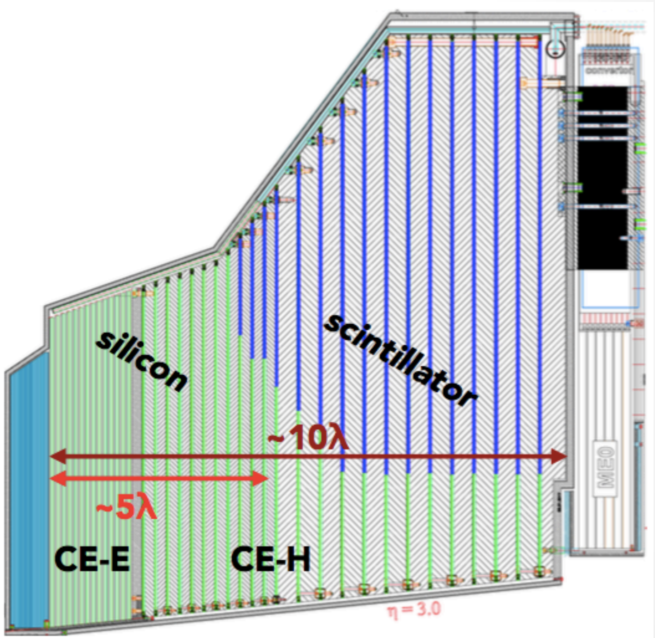
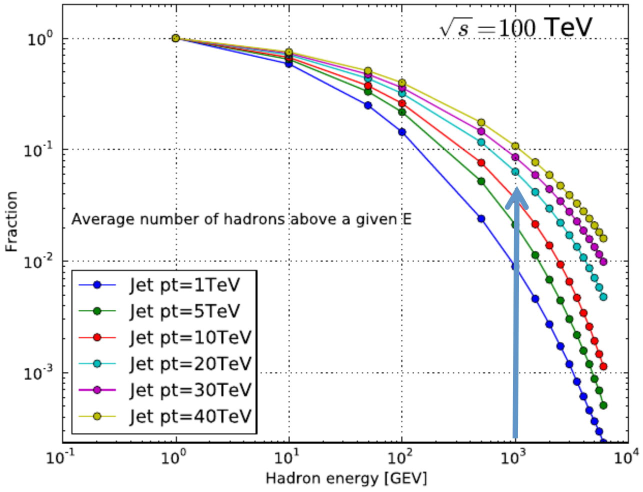
  - π^0 rejection capabilities
- Need excellent lateral and longitudinal granularity
  - Make Particle-Flow algorithm more effective
  - Pointing capabilities (needed to trigger on HH->bbγγ)
  - Helps with pile-up rejection

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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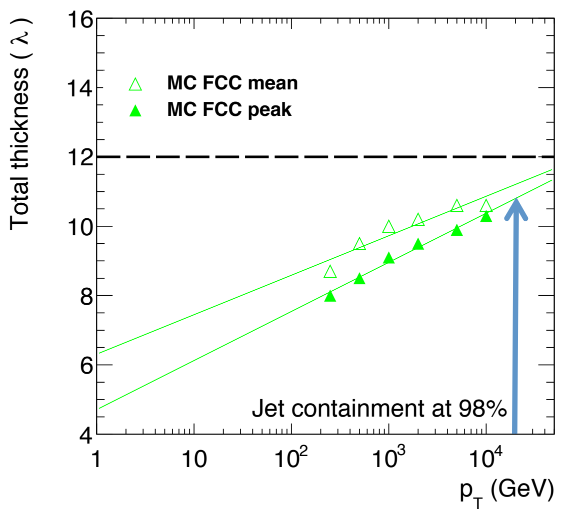

≥11 λ_I with E-Cal+H-Cal seems good enough

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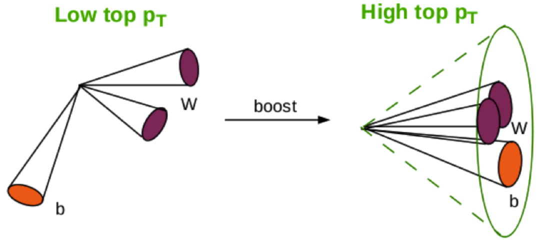


$\Delta R \cong 2m/p_T$

- 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)
  - 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?

FCC-hh detector

H-Cal barrel, extended barrel
$\Delta\eta = 0.025$, $\Delta\phi = 0.025$, ~10/8 layers
Goal $\sigma E/E = 50\text{-}60\%/\sqrt{E} \oplus 3\%$

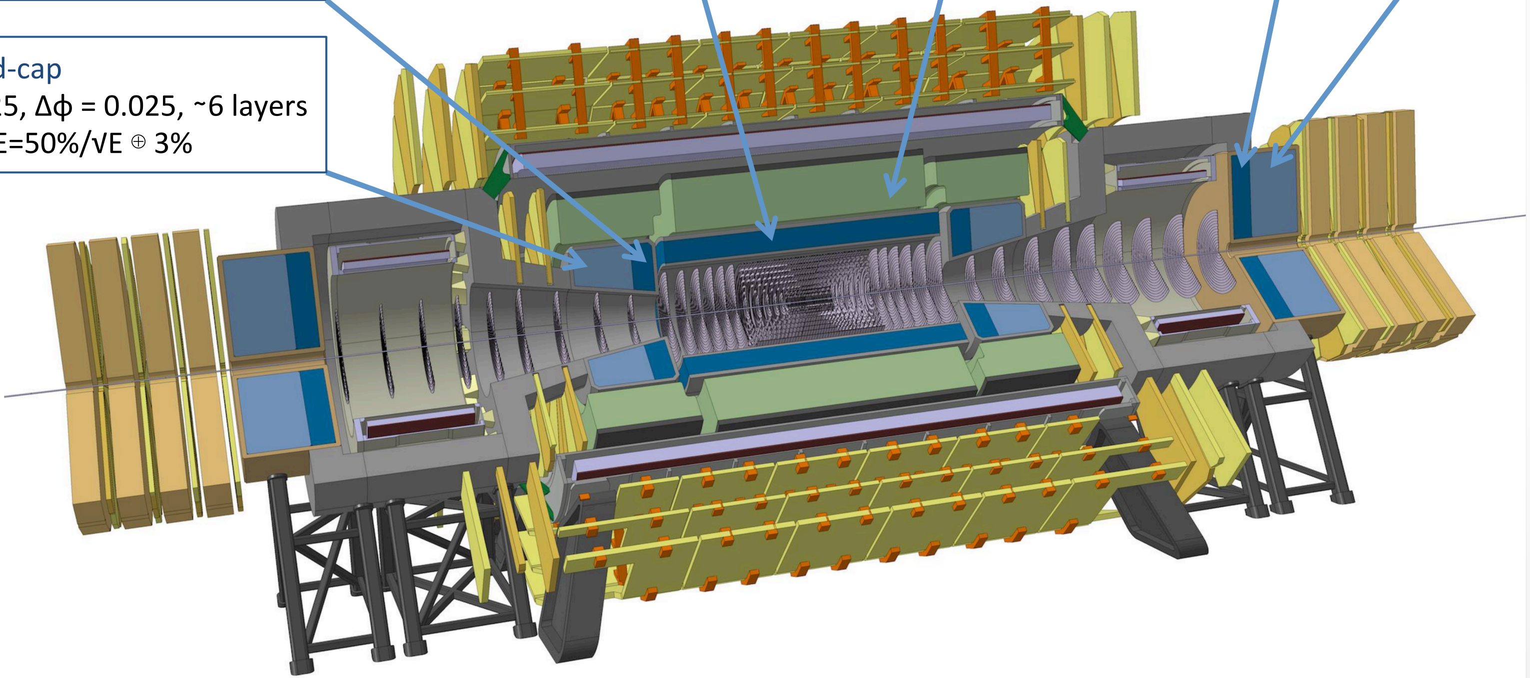
H-Cal forward
$\Delta\eta = 0.05$, $\Delta\phi = 0.05$, ~6 layers
Goal $\sigma E/E = 100\%/\sqrt{E} \oplus 10\%$

E-Cal forward
$\Delta\eta = 0.05$, $\Delta\phi = 0.05$, ~6 layers
Goal $\sigma E/E = 30\%/\sqrt{E} \oplus 1\%$

E-Cal barrel
$\Delta\eta = 0.01$, $\Delta\phi = 0.009$, ~6 layers
Goal $\sigma E/E = 10\%/\sqrt{E} \oplus 0.7\%$

E-Cal end-cap
$\Delta\eta = 0.01$, $\Delta\phi = 0.01$, ~6 layers
Goal $\sigma E/E = 10\%/\sqrt{E} \oplus 0.7\%$

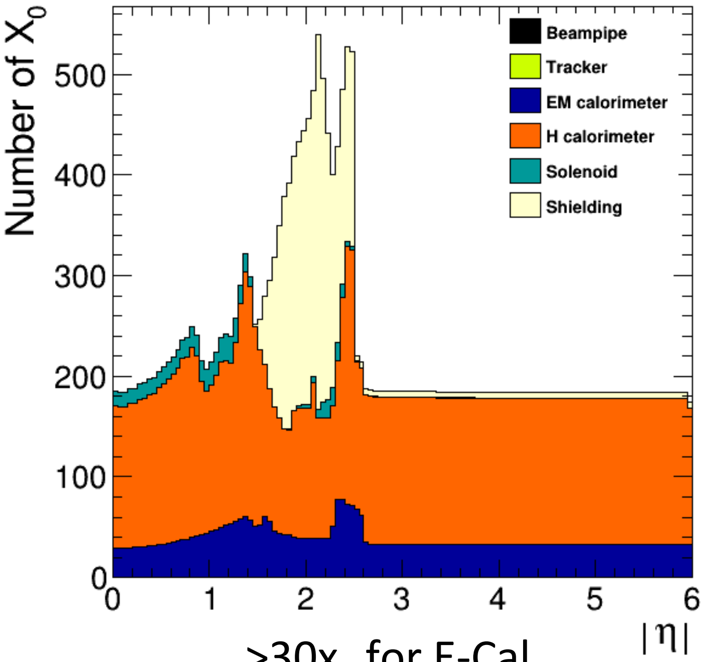
H-Cal end-cap
$\Delta\eta = 0.025$, $\Delta\phi = 0.025$, ~6 layers
Goal $\sigma E/E = 50\%/\sqrt{E} \oplus 3\%$



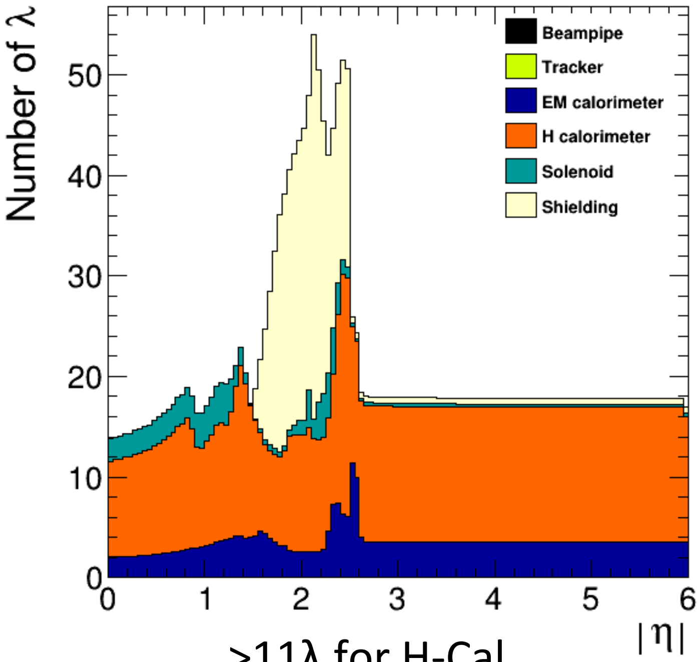
Calorimeter choices

- E-Cal: Liquid Argon used for barrel, end-cap and forward
- H-Cal: scintillator in the barrel, liquid argon in end-cap and forward

Radiation hardness



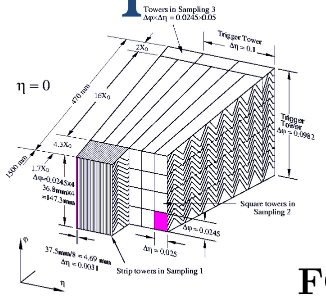
>$30x_0$ for E-Cal



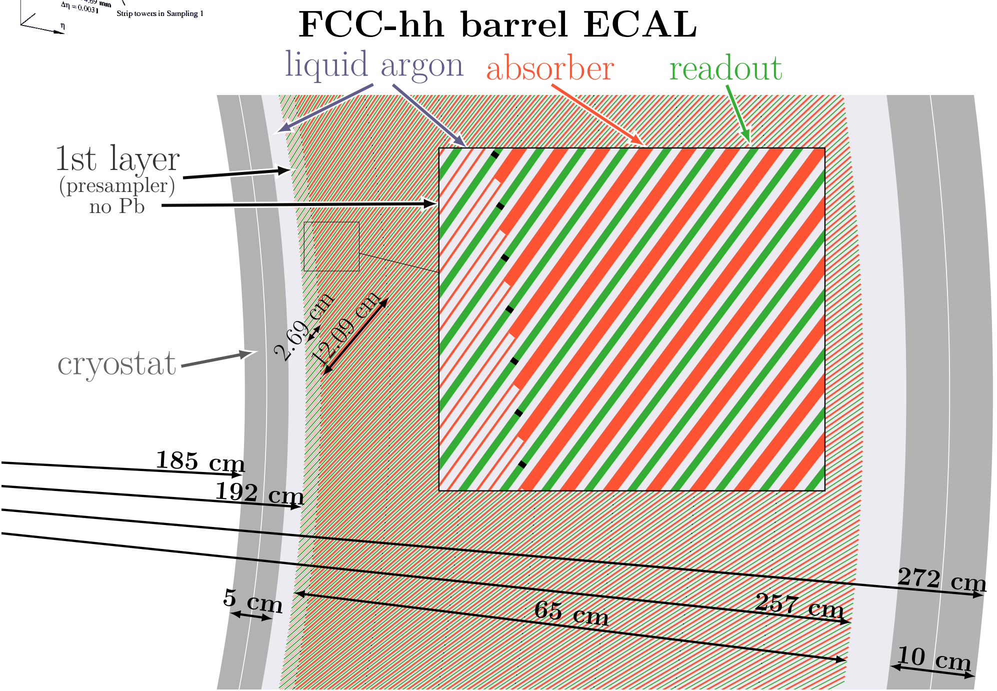
>11λ for H-Cal

Liquid Argon Calorimeters

Liquid argon calorimeter (barrel)

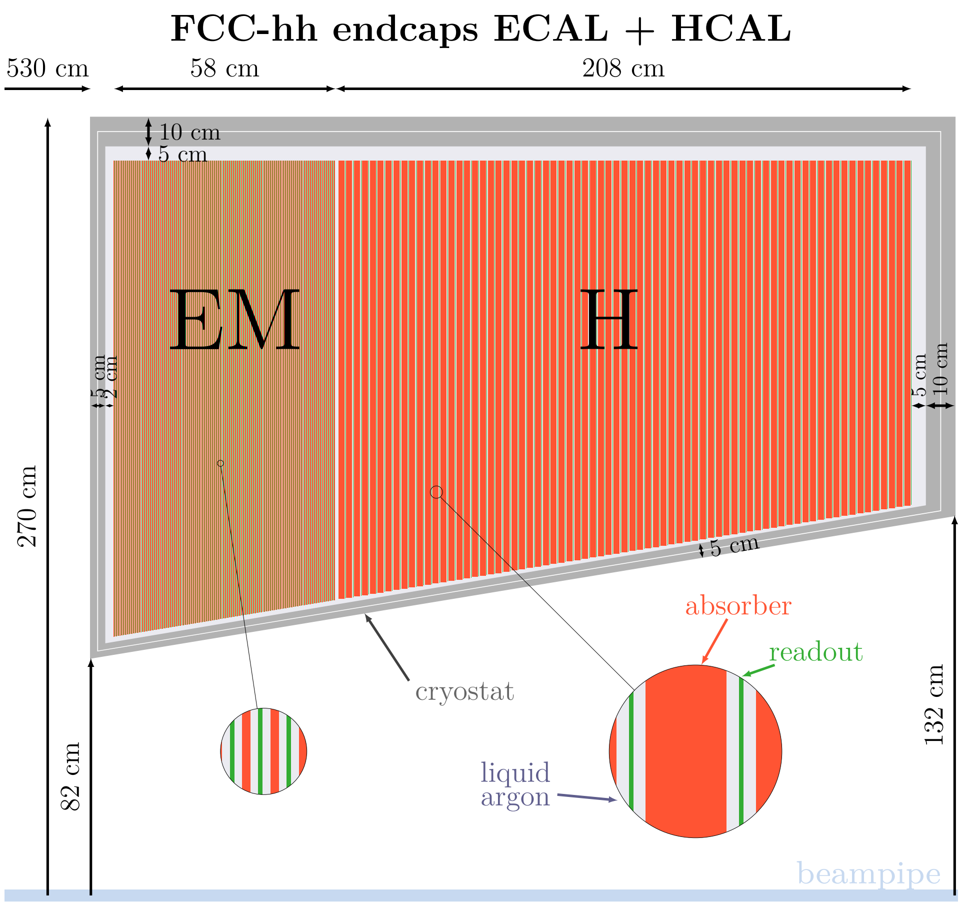


- Much more granular than ATLAS calorimeter (×10)
- High long. and lat. segmentation possible with straight multilayer electrodes
  - + Easier construction (inaccuracies enlarge the constant term)
  - − Sampling fraction changes with calorimeter depth



- Characteristics
  - 2 mm absorbers inclined by 50° angle
  - LAr gap increases with radius:
    - 1.15 mm–3.09 mm
  - 8 longitudinal layers
    - first one without lead as a pre-sampler
  - $\Delta\eta = 0.01$ (0.0025 in 2nd layer)
  - $\Delta\phi = 0.009$

Liquid argon calorimeter (end-caps)

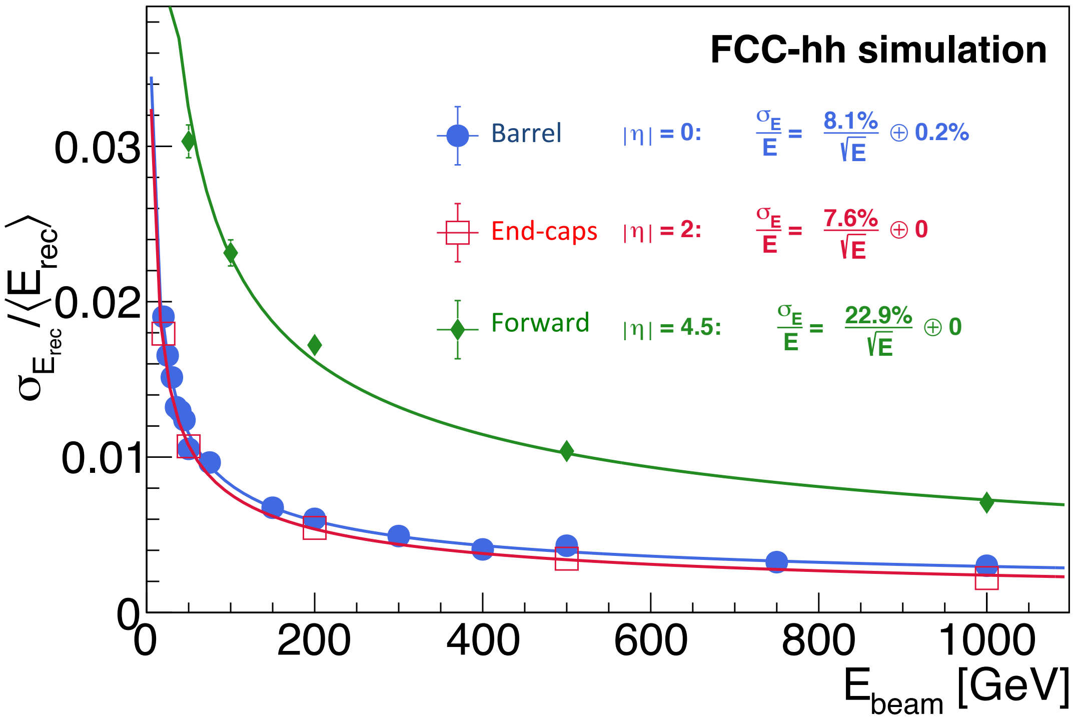


- Both E-Cal and H-Cal within same cryostat
- E-Cal:
  - 1.5 mm lead discs
  - 0.5 mm LAr gap
- H-Cal:
  - 2 cm copper discs
  - 2 mm LAr gap
- First layer serves as a pre-sampler
- Forward-Cal simulated with same layout
  - 0.1 mm LAr gap
  - 1 cm copper discs in E-Cal
  - 4 cm copper discs in H-Cal

Single electron performance

- Simulation of single electrons
- No noise in detector
- Reconstruction
  - sliding window algorithm
  - $\Delta\eta \times \Delta\phi = 0.07 \times 0.17$
- Very good performances over the acceptance range

Energy resolution, $|\eta|$= 0, 2, 4.5

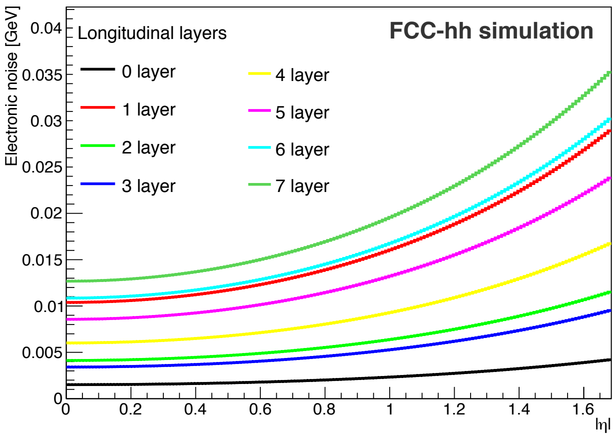


Noise (in cluster ΔηxΔΦ=0.07x0.17)

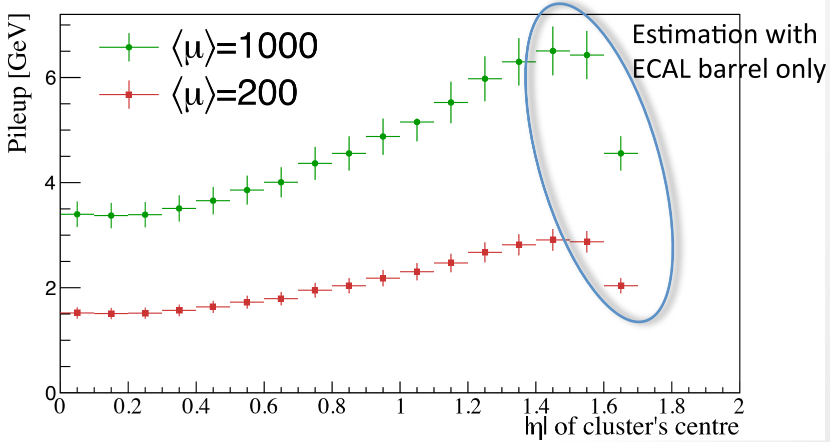
- Electronic noise
  - estimated for PCB readout (additional capacitance)
  - Noise in cluster ~ 300 MeV

- Pile-up noise
  - From Min-Bias simulation
  - In-time pile-up suppression
    - rejecting energy deposits from pile-up vertices tagged by the inner tracker (to be studied)
  - Out-of-time pile-up as correction factor (~ 1.5)
    - Not included
    - HL-LHC suppress it to a large extent

Electronic Noise for one cell Δη×Δϕ=0.01×0.009

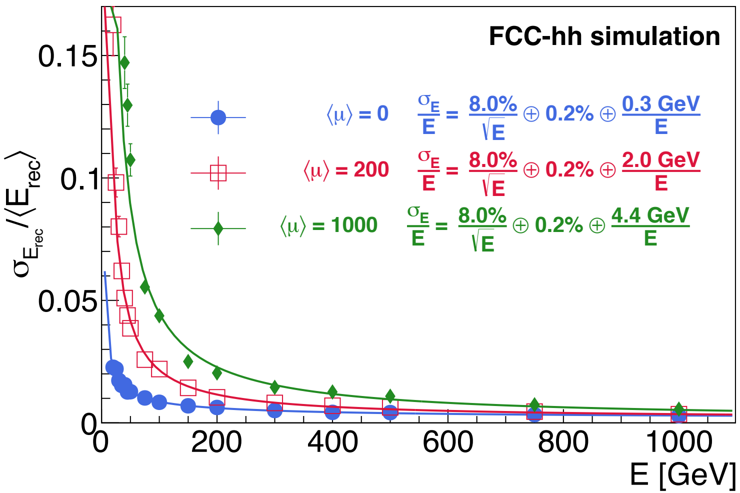


Pileup noise in cluster Δη×Δφ = 0.07×0.17

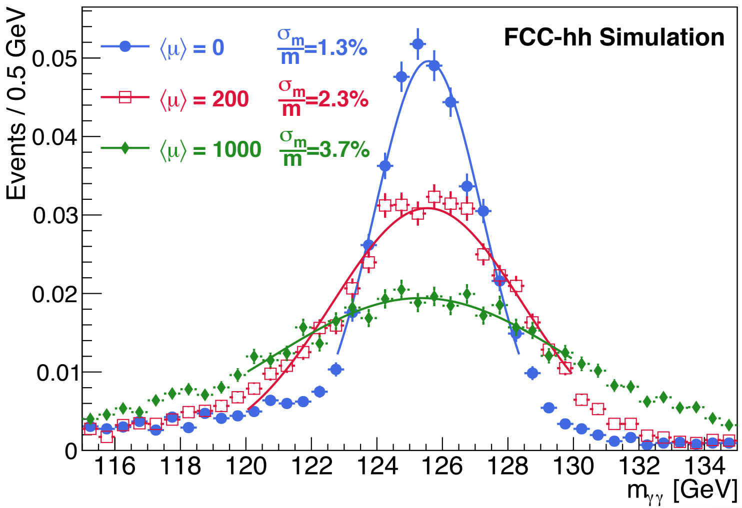


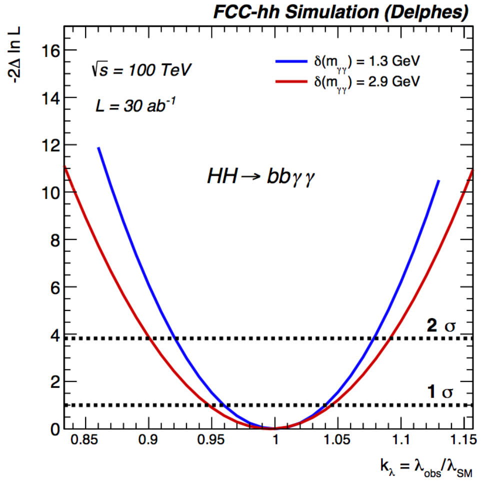
Photon resolution

Energy resolution, η=0



Invariant mass for two photon events (E_γ>40GeV)



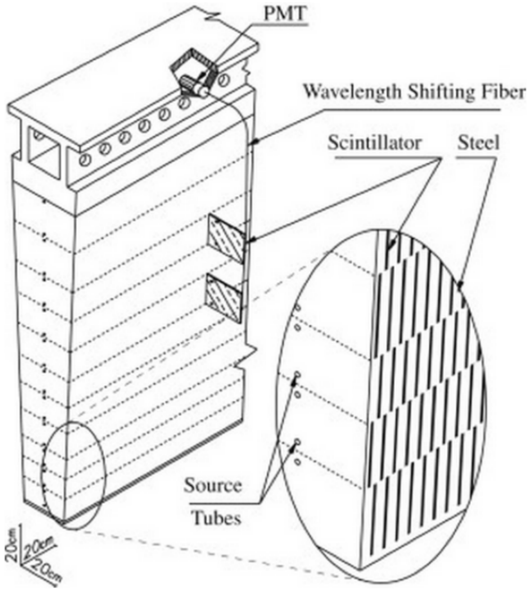


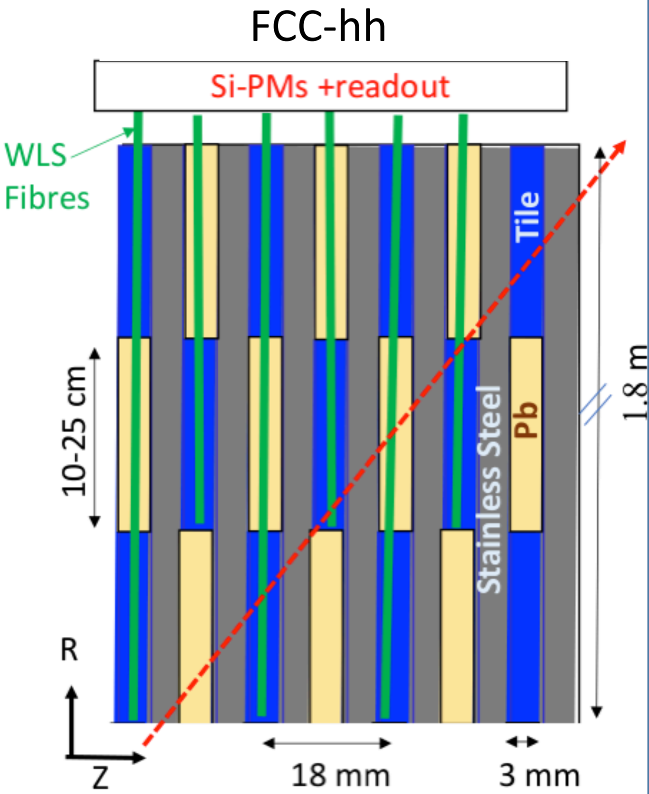
- Large impact of in time PU on the noise term
  - Out of the box with no sophisticated technics for removal!!
  - Severely degrades $m_{\gamma\gamma}$ resolution
  - Improving clustering, not sliding windows may help
  - Impacts Higgs self-coupling precision by $\delta\kappa_\lambda \approx 1\%$
  -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

Tile Calorimeters

Tile calorimeter

- Granularity
  - Much more granular than ATLAS (×10)
  - $\Delta\eta = 0.025$, $\Delta\phi = 0.025$
  - 10 longitudinal layers

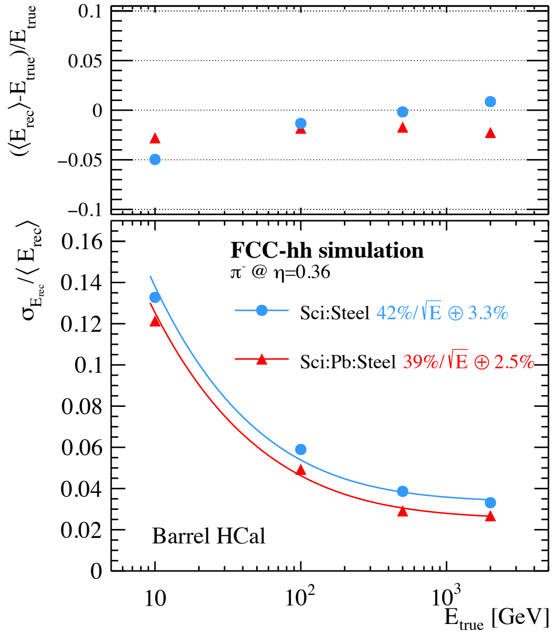


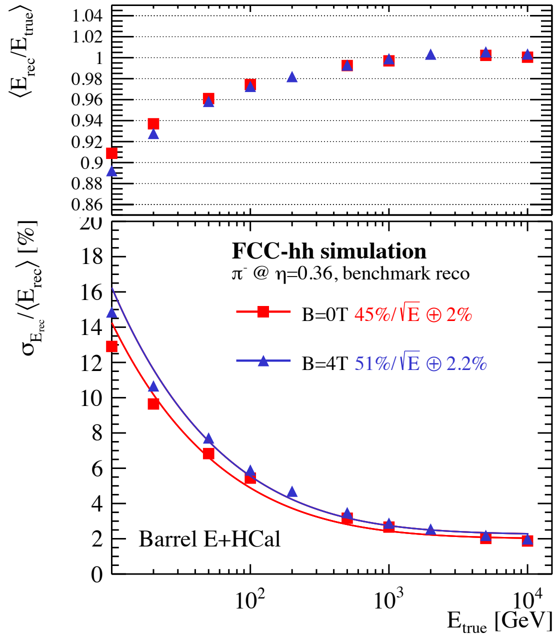


- High longitudinal and lateral segmentation possible with SiPMs
- Mechanical structure feasible, assembly study done
- First test of scintillator tiles started

H-Cal barrel optimisation

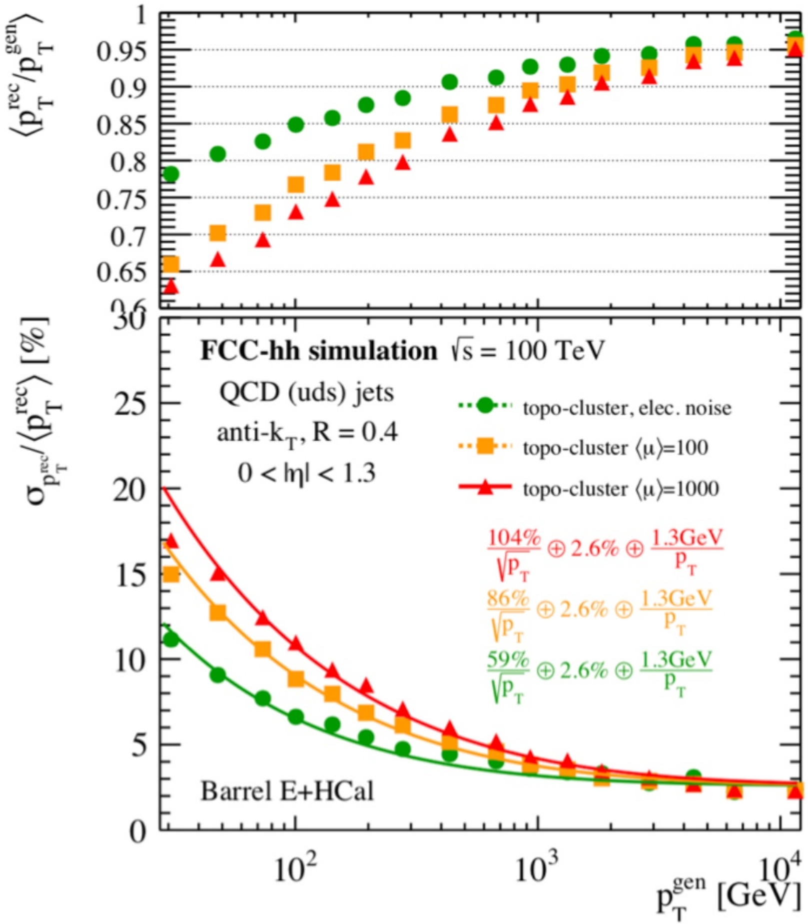
- Steel absorbers partially substituted with lead
  - Decreasing non-compensation by suppression of EM response
  - Reduction of depth by 0.4 λ (at η = 0)
- Simulation of single pions
  - No noise in detector
  - Achieved goal resolution for combined E-Cal H-Cal





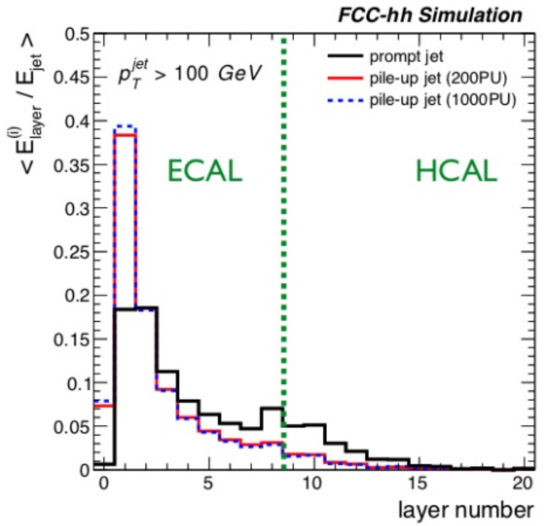
Jet performance

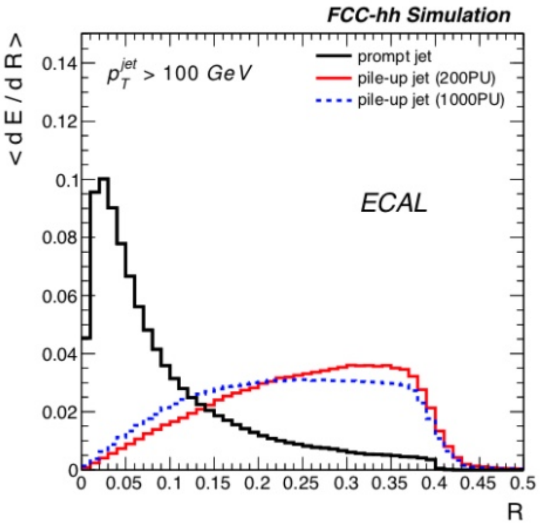
- Excellent resolution up to p_T =10 TeV
- Large impact of PU at low p_T (as exp.)
  - Crucial for low mass di-jet resonances
  - Again, such as HH→bbɣɣ
- Further motivation for Particle-flow
  - Charged PU contribution can be “easily” subtracted (Charged Hadron Subtraction)

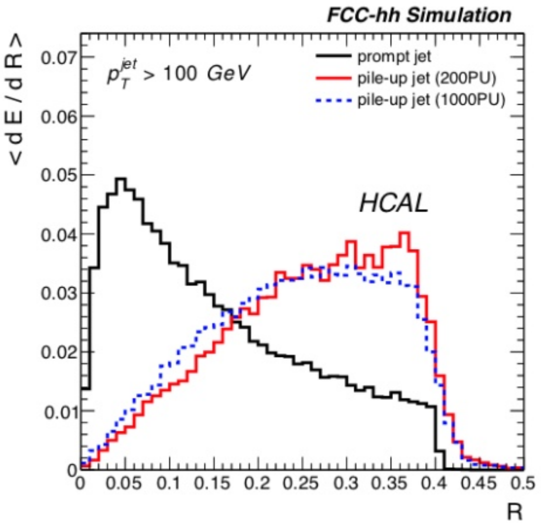


Jet pile-up identification

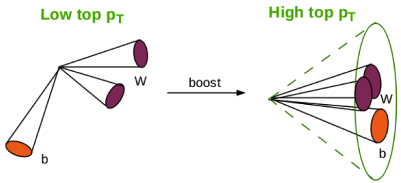
- With 200-1000PU
  - Will get large amount of fake-jets from PU combinatorics
  - Need both longitudinal/lateral segmentation for PU identification
  - Simplistic observables show possible handles, pessimistic…
  - In reality tracking will help a lot

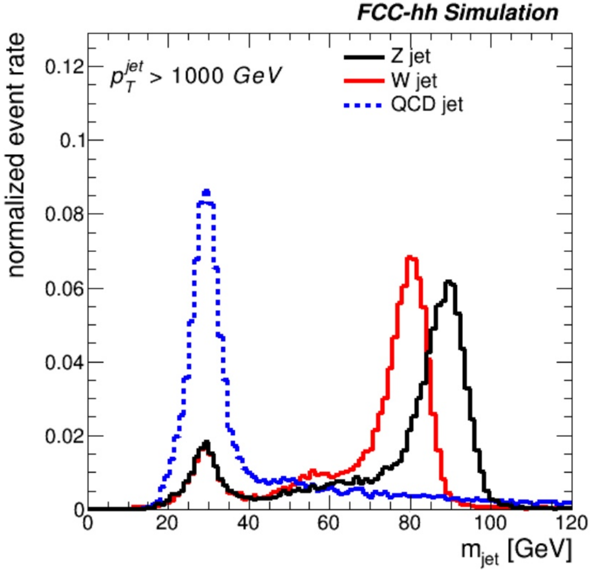




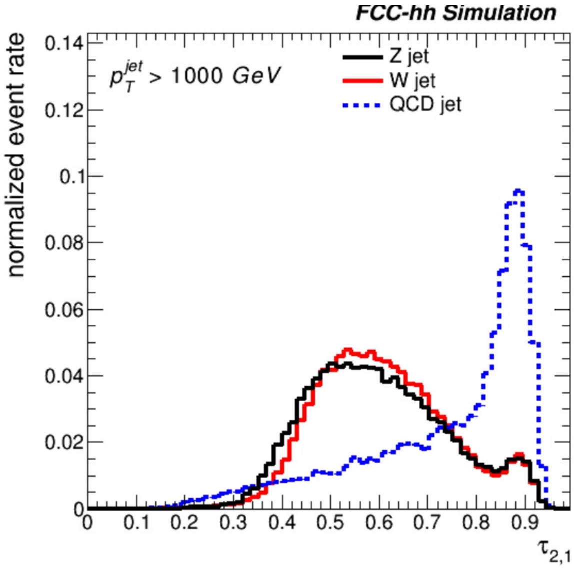


Jet sub-structure





W/Z->qq



- With 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)

Conclusion

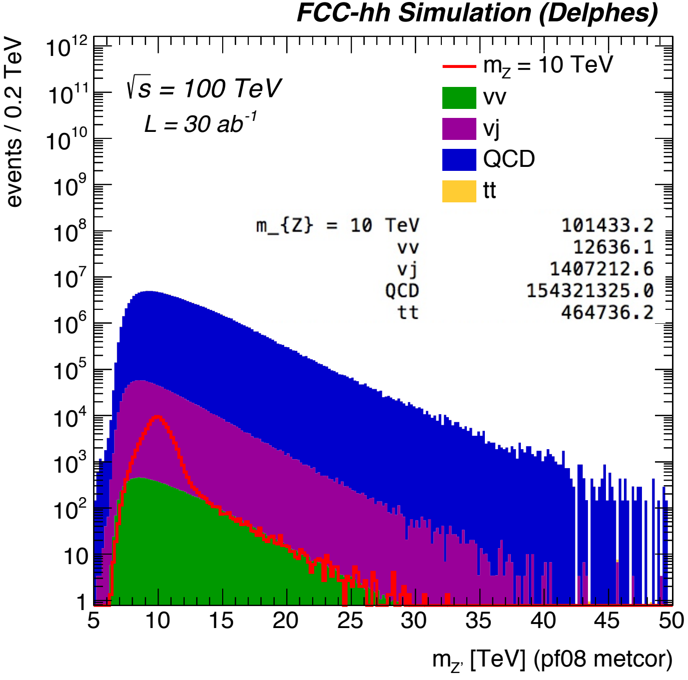
- Reference detector for FCC-hh experiments with high granularity
  - LAr-based for E-Cal and H-Cal in $1.4 < |\eta| < 6$ (radiation hard detector)
  - Scintillator-based H-Cal for $|\eta| < 1.4$
- In no pile-up environment achieved the goal resolution:
  - Electrons/photons: $8\%/\sqrt{E} \oplus 0.2\%$
  - Pions: $50\%/\sqrt{E} \oplus 2.2\%$
  - Jets (without magnetic field): $60\%/\sqrt{E} \oplus 2.6\%$
- Pile-Up: a challenge for FCC-hh environment
  - Valid for any studied detector option
  - Optimisation of reconstruction procedures necessary
  - Need help from tracking and timing
  - 1000 PU hostile environment also for calorimetry (energy resolution)
- Longitudinal/lateral segmentation is suitable for
  - PU jet Identification Particle-Flow algorithms
  - Angular and energy resolution

Bonus slides

Z’->tt

Z'->ttbar

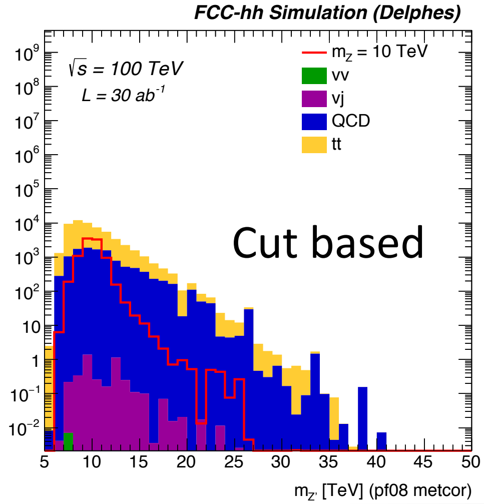
Pre-selection



Need more di-jet 36k out of 50M

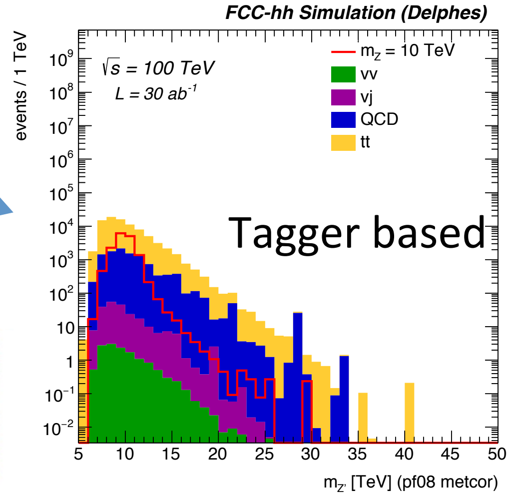
m_{Z} = 10 TeV	9272.5
vv	0.0
vj	4.1
QCD	11128.0
tt	44949.8

2tags
Jet1/2 $0.7>\tau_{21}>0.3$
Jet1/(2) $\tau_{32}<0.7(0.75)$
Jet1/2 SD m >100GeV

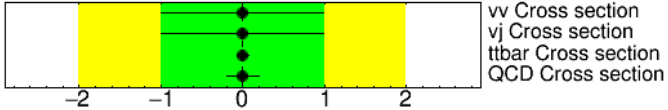


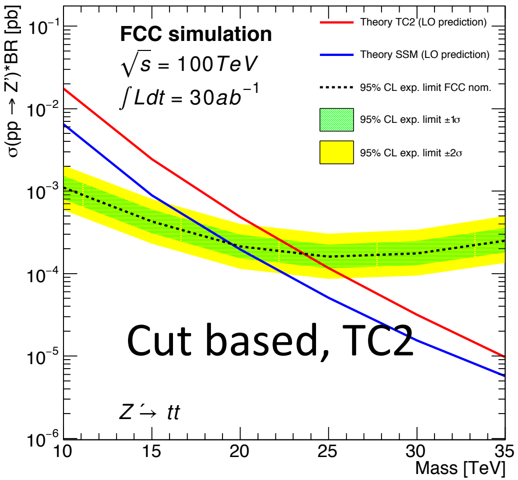
2tags
Jet1/2 tagger>0.15
Jet1/2 SD m >40GeV

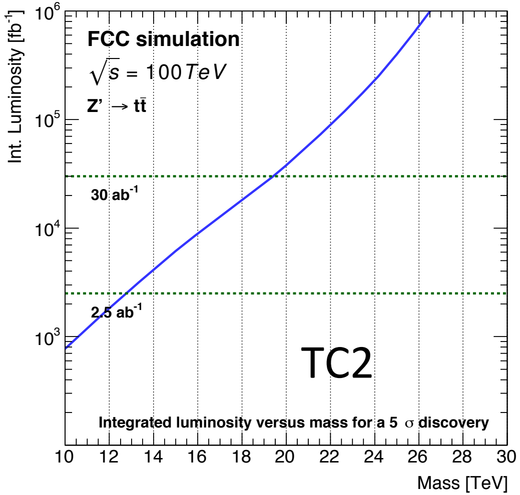
m_{Z} = 10 TeV	15600.0
vv	13.7
vj	210.1
QCD	10563.8
tt	73700.4



Z'->ttbar

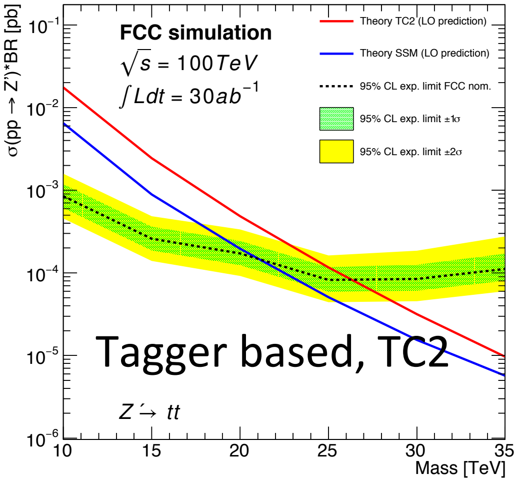


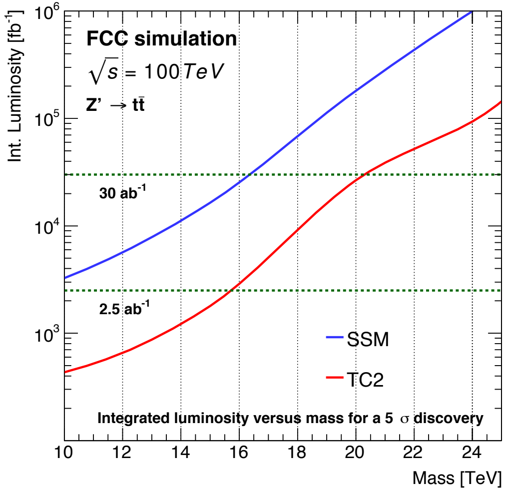




5σ discovery for TC2:

- 16TeV after 10 years @ baseline
- 20TeV after full operation 25 years





5σ discovery for SSM:

- <10TeV after 10 years @ baseline
- 16TeV after full operation 25 years

SSM is obviously a benchmark for leptonic decays

RSG->WW
W->jj

Di-boson res

- Randall-Sundrum Graviton
  - Signal with pythia8
  - Cross sections from Pythia8, no k-factor
  - Important benchmark model for detector performance on sub-structure

- Analysis pre-selection (Fully hadronic)
  - Jet1/2 p_T>3TeV, jet1/2 |η| <3
  - J1,2 τ_{21}, τ_{32}>0
  - |η jet1 − η jet2|<2.4

$$\mathrm{Flow}_{n,5} = \sum_k \frac{|p_T^k|}{|p_T^{\mathrm{jet}}|}$$

$$\frac{n-1}{5}R \leq \Delta R(k,\mathrm{jet}) < \frac{n}{5}R,$$

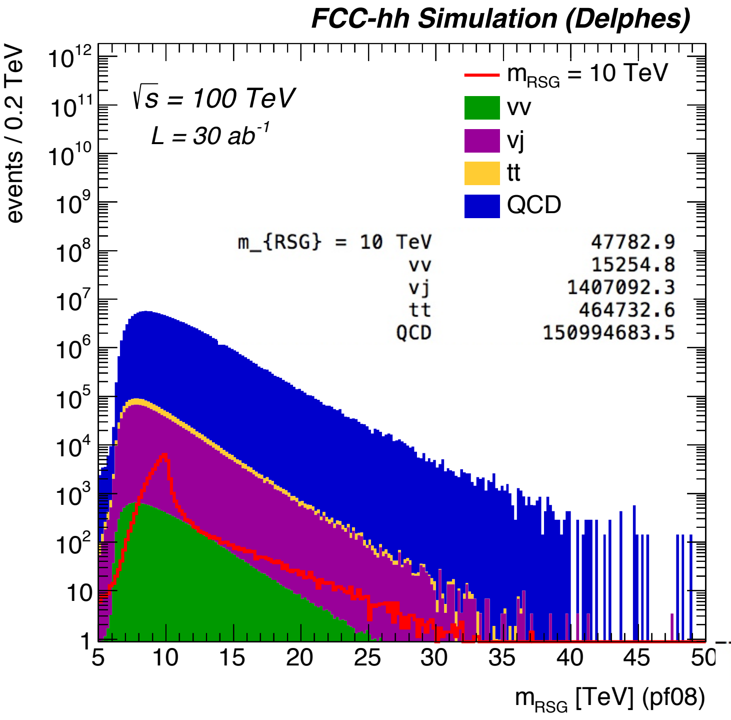
- Norm uncertainties
  - ttbar 20% QCD 50%, VV 20%, VJ 40%

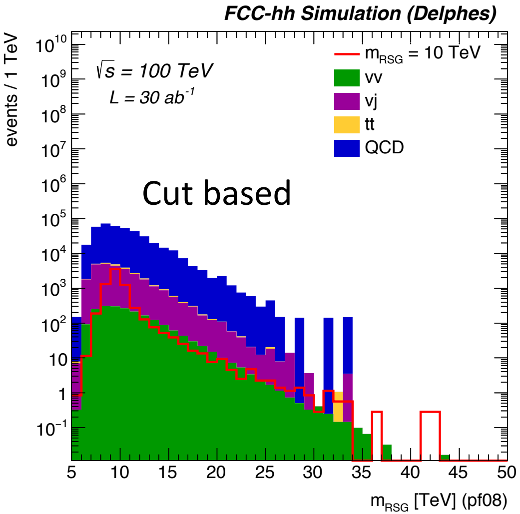
Di-boson res

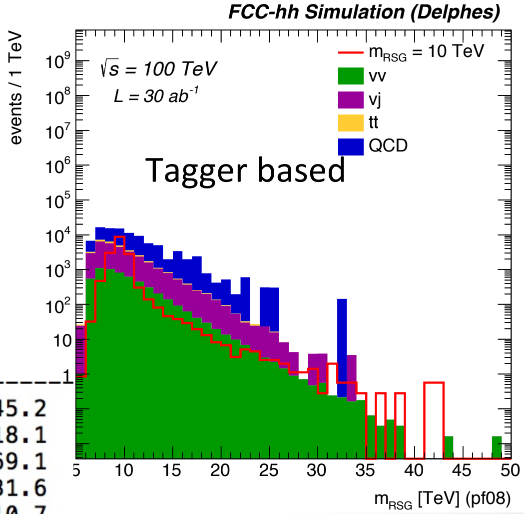
m_{RSG} = 10 TeV	7035.8
vv	2023.4
vj	25824.7
tt	1795.2
QCD	377427.6

Jet1/2 SD 100<m<50GeV
Jet1/2 τ_{21} < 0.6
Jet1/2 Flow45 < 0.07
Jet1/2 Flow55 < 0.07

Pre-selection





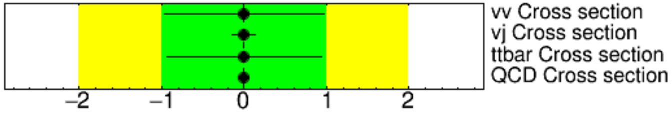


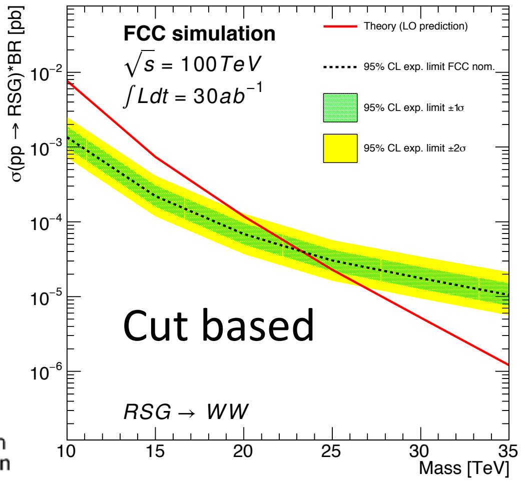
Jet1/2 tagger>0.15
Jet1/2 SD mass > 40GeV

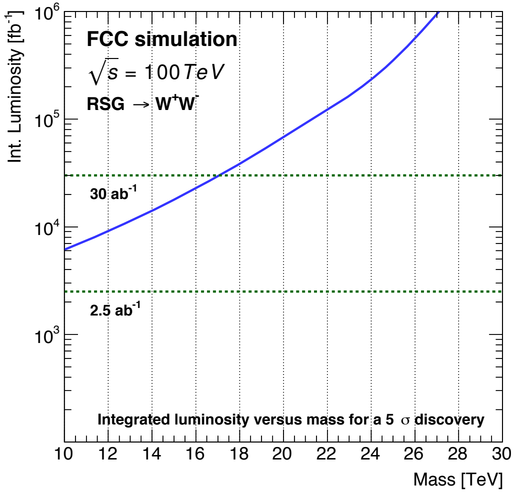
m_{RSG} = 10 TeV	15745.2
vv	5518.1
vj	24969.1
tt	2931.6
QCD	64910.7

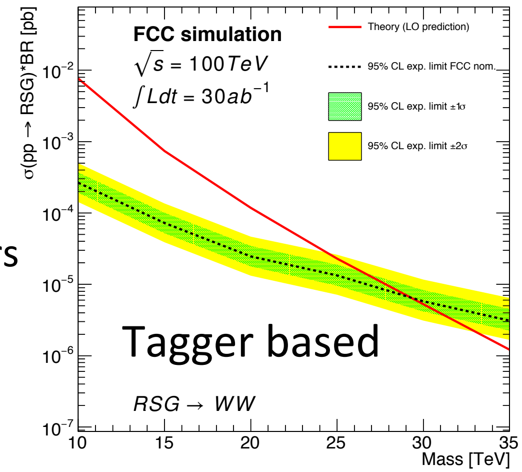
Need more di-jet 1k raw of 50M

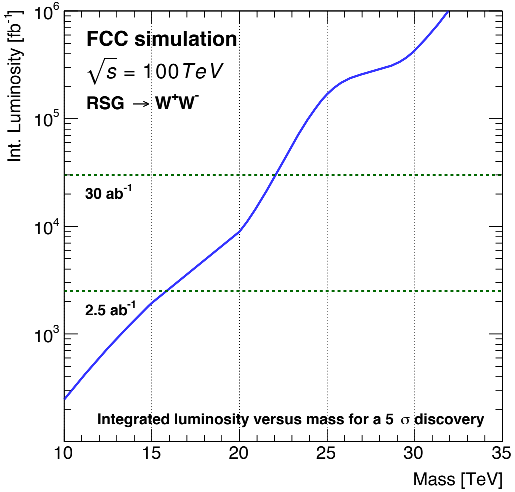
RSG->WW











5σ discovery for RSG:

- 10TeV after 2 years (200fb^{-1})
- 16TeV after 10 years @ baseline
- 22TeV after full operation 25 years

Q*->jj

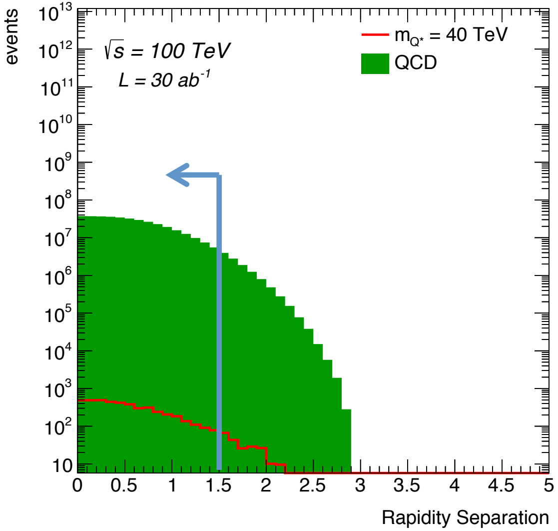
- Q* model
  - Spin ½
  - Same coupling constant as SM quarks
  - No interference considered, no k-factor
  - Decays only to gluon, up, down
  - Scale Λ to Q* mass

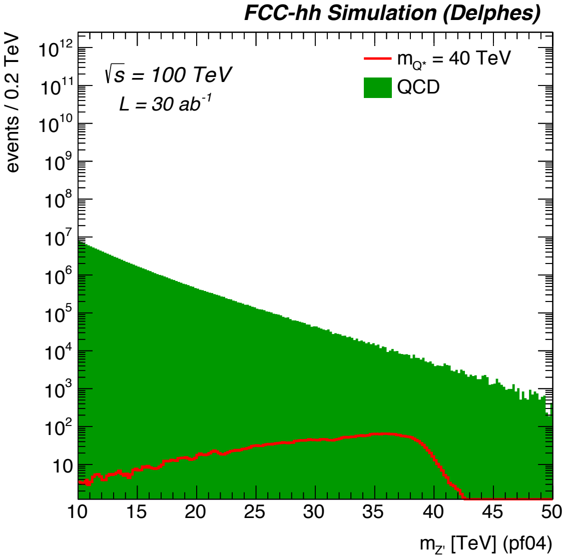
- Analysis selection
  - $p_T(j1)$ and $p_T(j2)$>3TeV
  - Y*=|yjet1-yjet2|/2 < 1.5

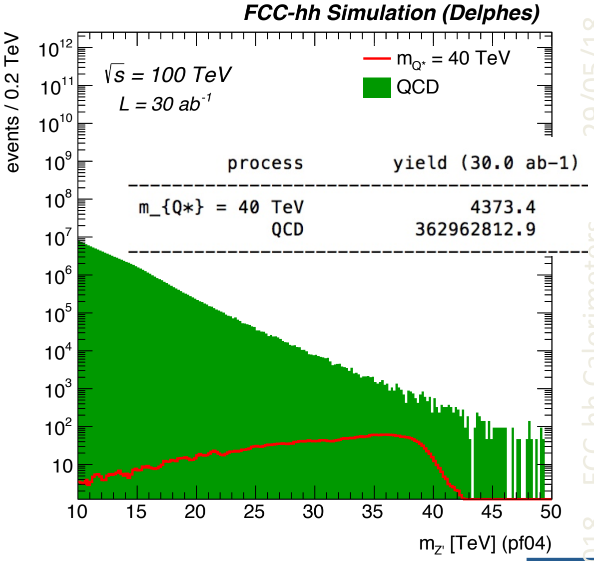
- Uncertainties
  - 50% uncertainty on the Di-jet normalization

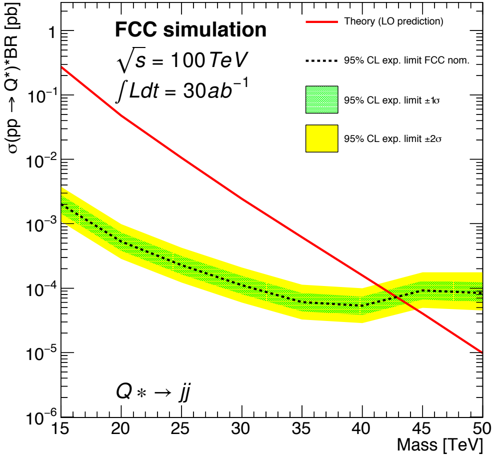
Q*->jj

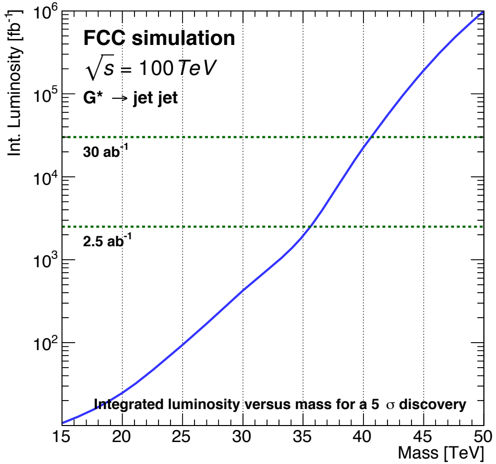
process	yield (30.0 ab-1)
m_{Q*} = 40 TeV	4588.9
QCD	374687859.9





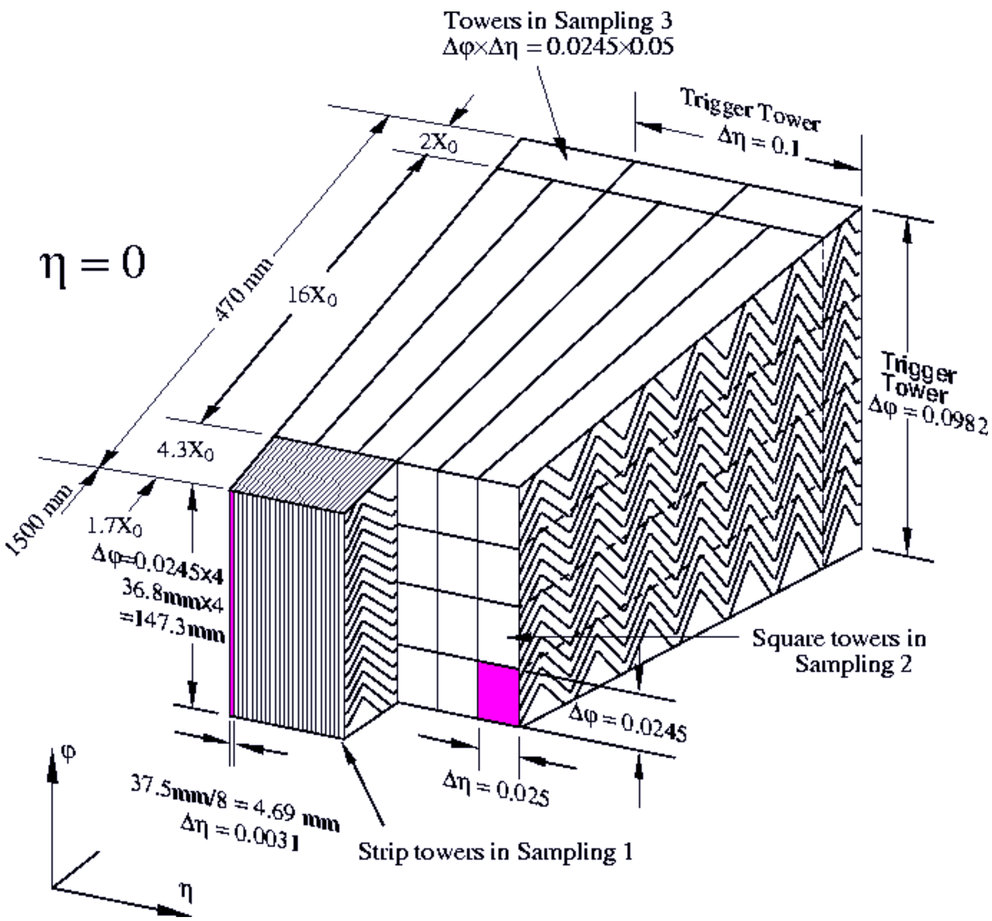




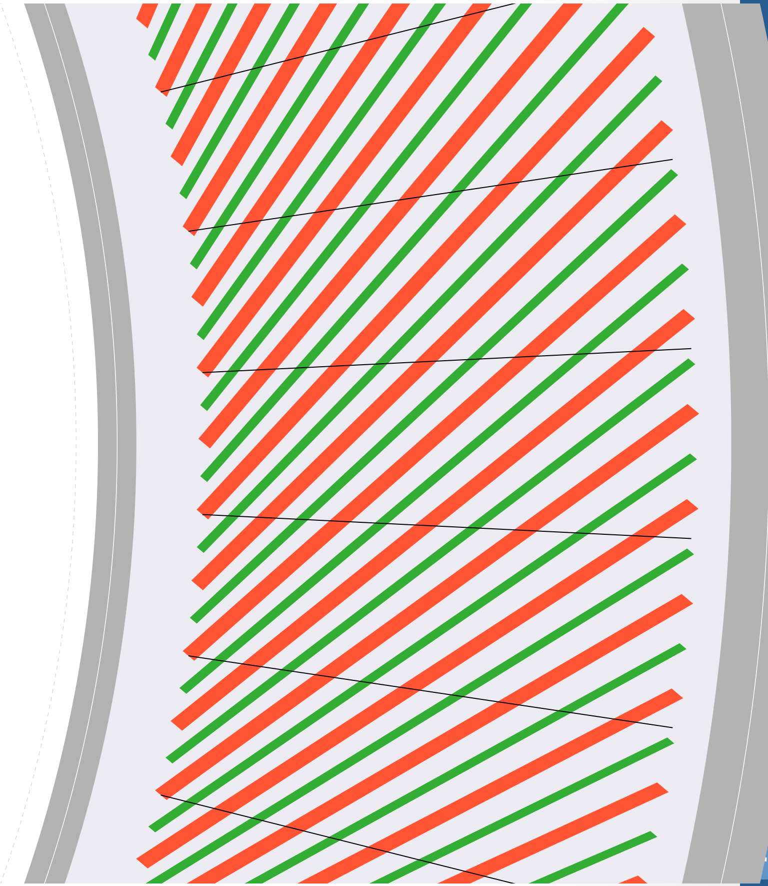


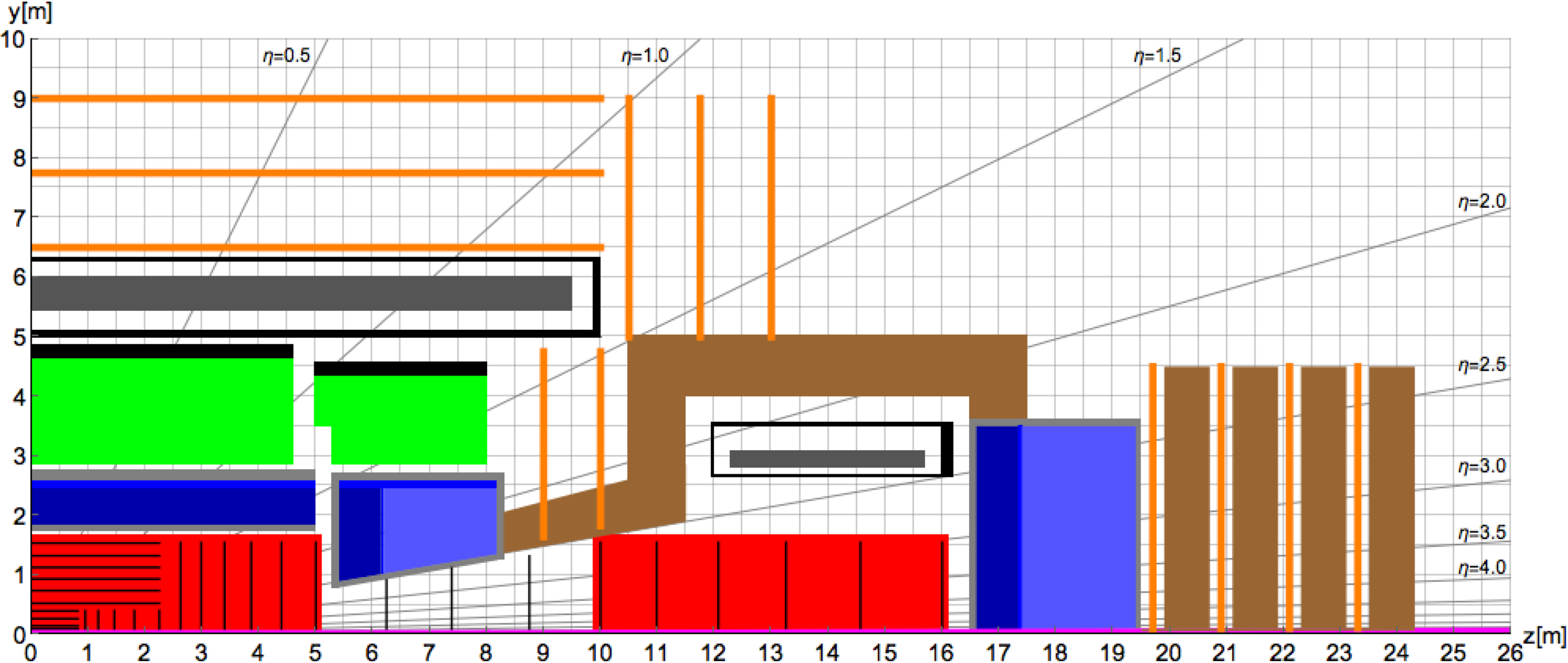
5σ discovery for Q*:

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



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

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z[m]
η=0.5
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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
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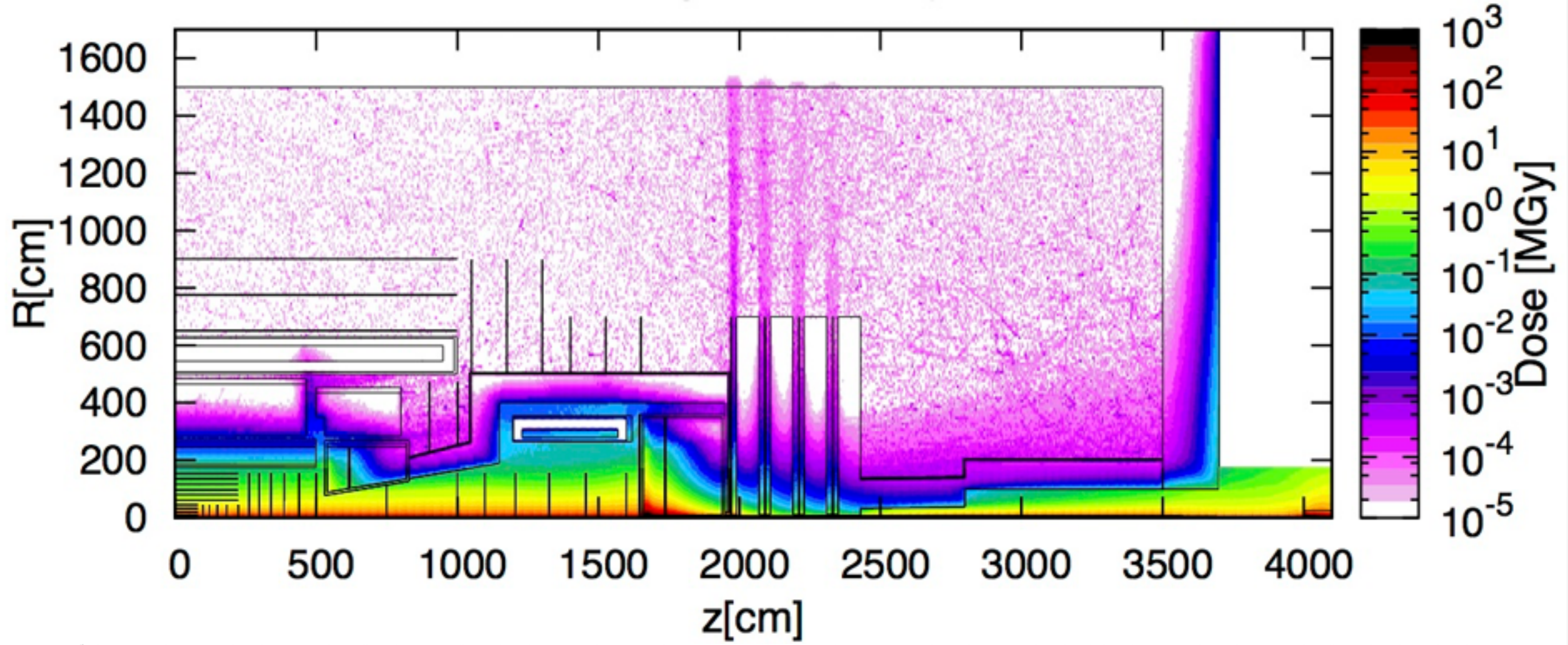
Radiations



	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}