Physics requirements for a Hadron Calorimeter for a 100 TeV proton-proton collider

S. Chekanov (ANL)

Exploration of ~tens TeV jets using calorimeter technologies

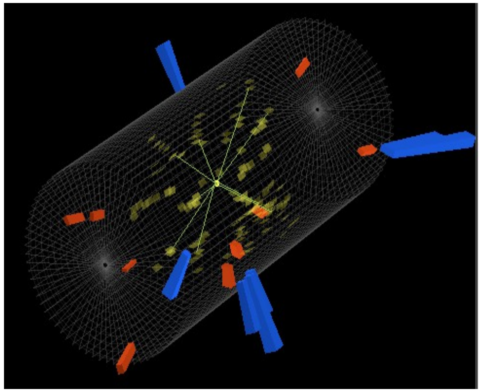
Boost 2015

August, 2015

with contributions from:
J.Proudfoot, J.Dull (ANL SULI2015), D.Dylewsky, C.Doglioni, M. Gouzevitch, A. Henriques, C.Helsens, C.Solans

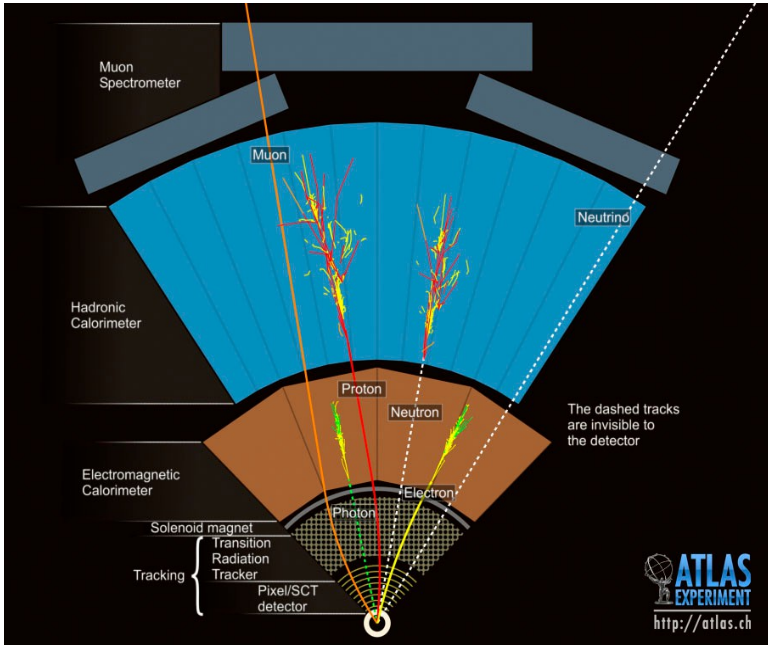
Beyond the LHC

→ Is the mass scale beyond the LHC reach (>5 TeV)?
→ Large masses → large energy of decay products
→ Large energy of decay products means:



- Large jet transverse momentum
- Missing ET
- High-mass, long-lived particles
- Tau decays
- Veto on photons / electrons / jets

} Hadron Calorimeter (HCAL)



For a typical HCAL (λ(HCAL)/λ(total) ~ 0.8):

- Measured average energy fractions for **hadrons**:
  - ~50% for 1 GeV
  - ~70% for 30 GeV
- Measured average energy fractions for **jets**:
  - ~ 30% for pT(jet) =1 TeV
  - ~ 40% for pT(jet) =3 TeV
  - ~ ??% for pT(jet)>30 TeV (FCC)

Requirements for a hadron calorimeter at 100 TeV

- **Physics goals for the FCC-hh HCAL calorimeter:**
  - Measurements of high-pT jets up to ~30 TeV (including b-jets)
  - Missing transverse energy
  - Veto jet events
  - Tau reconstruction
  - BSM particles that may decay in HCAL

- **Physics goals → instrumentation choices**

- Easy study: "technique **A** improves **B** by **X%**"
- It is harder to build a stronger case:
  - Unless technique **A** is improved by **X%**, physics **B** cannot be done!
- **We are at the beginning of such studies**

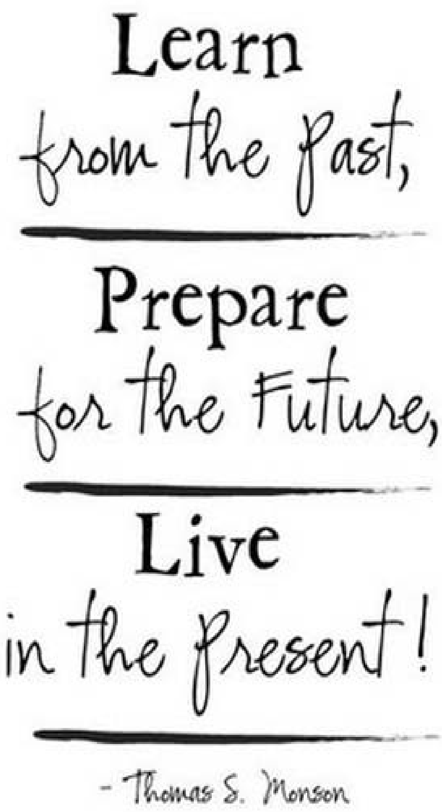
> "All things are difficult before they are easy."
>
> Genesie Keith Sta.Ana
> 22 Jan 2013 9:43 am

Past, Present, Future

SSC, etc.

FCC etc.

LHC



SSC calorimeter (1986)

4π Calorimeter Parameters

Electromagnetic thickness	25 X_0,	~1λ ± 5X_0
Precision Hadronic	5λ	
Total Precision EM + Hadr.	6λ	± 1λ
Hadronic tail catcher	6λ	± 1λ
Total	12λ	± 2λ
Transverse Segmentation		
EM Δy x Δϕ	.03 x .03	± .01
Hadronic Δy x Δϕ	.06 x .06	
Tail Catcher Δy x Δϕ	.06 x .06	
Longtitudional Segmentation		
EM	3	± 1
Hadronic	2	± 1
Tail Catcher	2	± 1

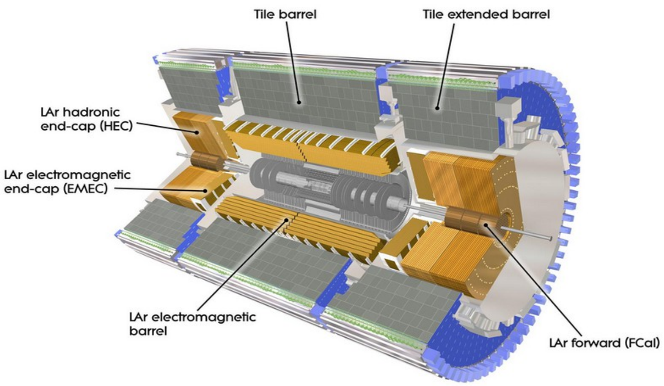
Detectors for the SSC: Summary report - Williams, H.H. In *Snowmass 1986, Proceedings, Physics of the Superconducting Supercollider* 327-349

Other hadron calorimeters:
H1, ZEUS, CDF, D0, DHCAL/Calice

Present: ATLAS & CMS calorimeters

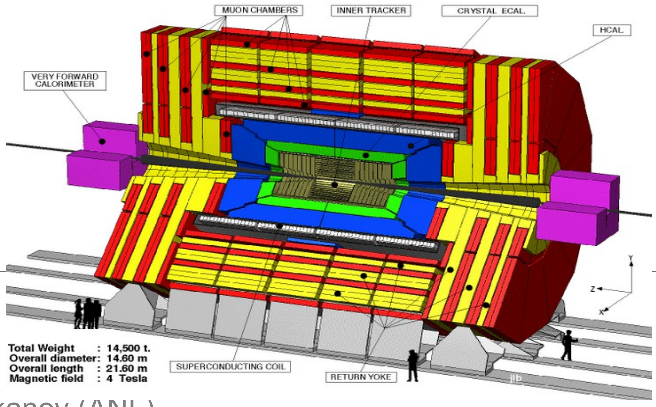
ATLAS

- Location: Behind solenoid
- Longitudinal segmentation
- Angular measurements
- Good energy resolution for jets
- High granular
- Radiation resistance
- Fe + scintillator (HCAL)



CMS

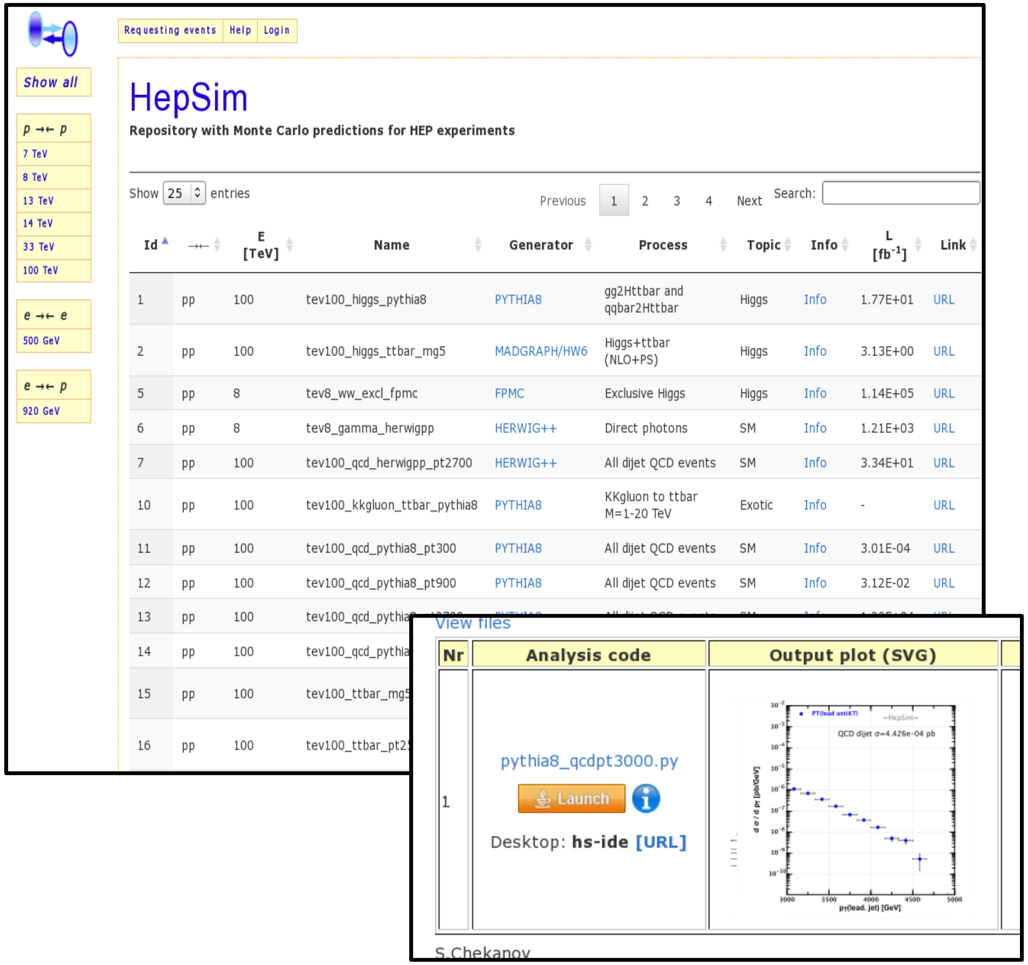
- Location: Before solenoid
- Fast response (<100 ns)
- High granular
- Less radiation resistance
- Good energy resolution (e/γ)
- Brass + scintillator (HCAL)



Public Monte Carlo event samples for 100 TeV

- 50 Monte Carlo event samples for 100 TeV provided by HepSim
- MG5, PYTHIA,HERWIG, NLO etc.
- Includes:
  - Validation, example programs
  - Data streaming technology
  - Pileup mixing
- Integrated with Delphes 3.2 fast simulation
- Many samples for "boosted" signatures (pT(jet,W)>3-10 TeV)
- Jet substructure variables provided by Delphes
- Includes ROOT files with Delphes fast simulations based on FFC geometry card (v2)

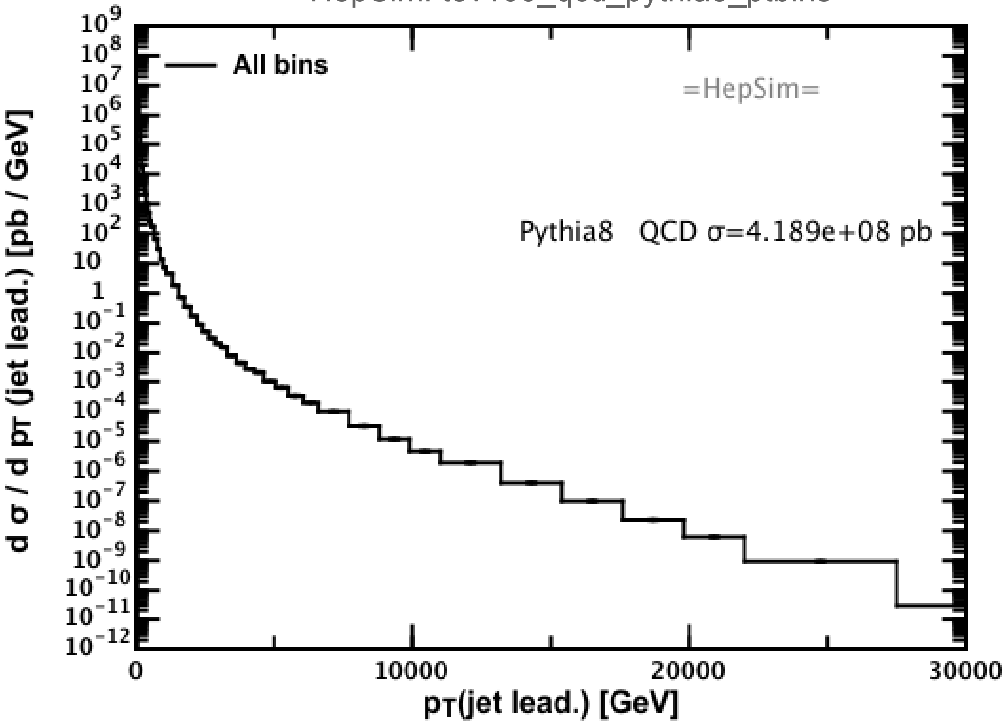
HepSim: http://atlaswww.hep.anl.gov/hepsim/



QCD jets at a 100 TeV collider

Business as usual: Jets with pT>10 TeV

HepSim: tev100_qcd_pythia8_ptbins



10 ab^{-1} :

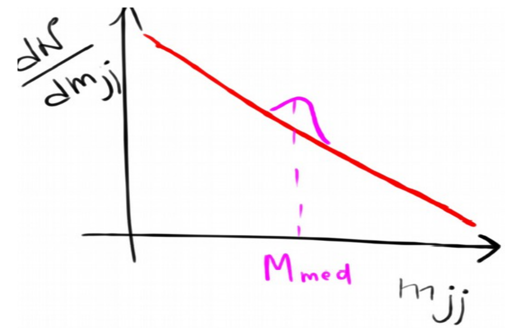
a dozen of events are expected for pT(jet)>20 TeV at LO QCD

Jets p_T [TeV]	1	5	10	20	30	40
Cross section [pb]	3453	0.974	0.0108	1.84e^{-5}	3e^{-8}	3.4e^{-12}

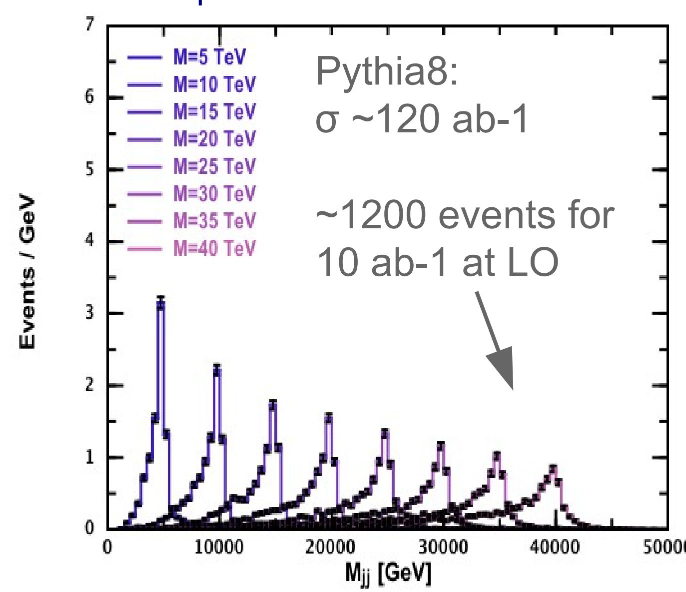
C.Helsens

Be prepared for pathological high-pT events!

Example: q* (40 TeV) → $q\bar{q}$



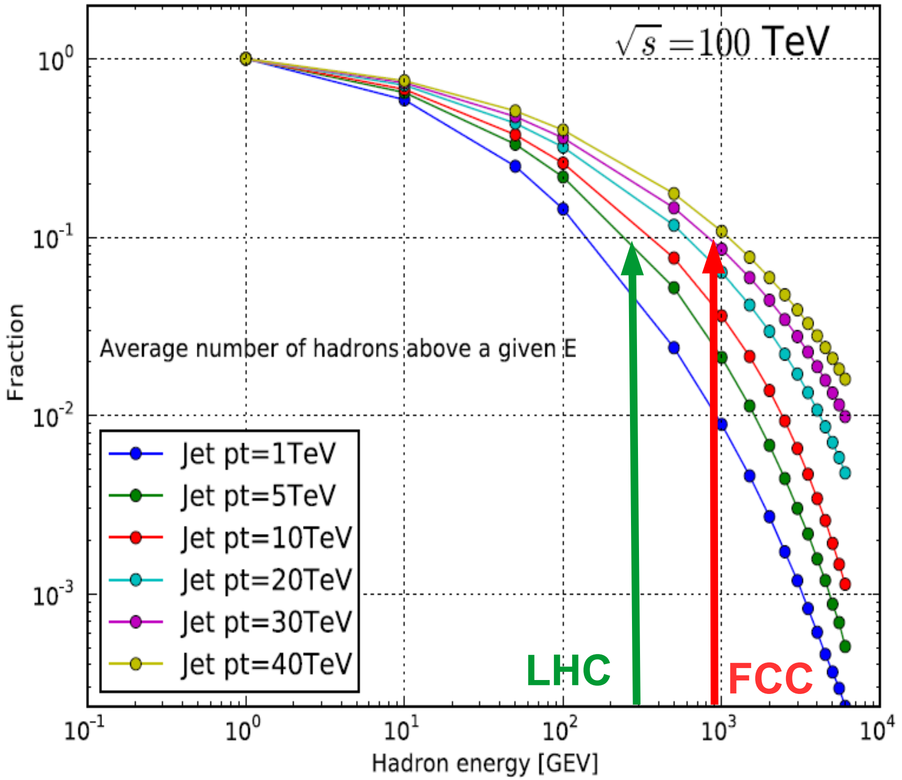
HepSim Monte Carlo database



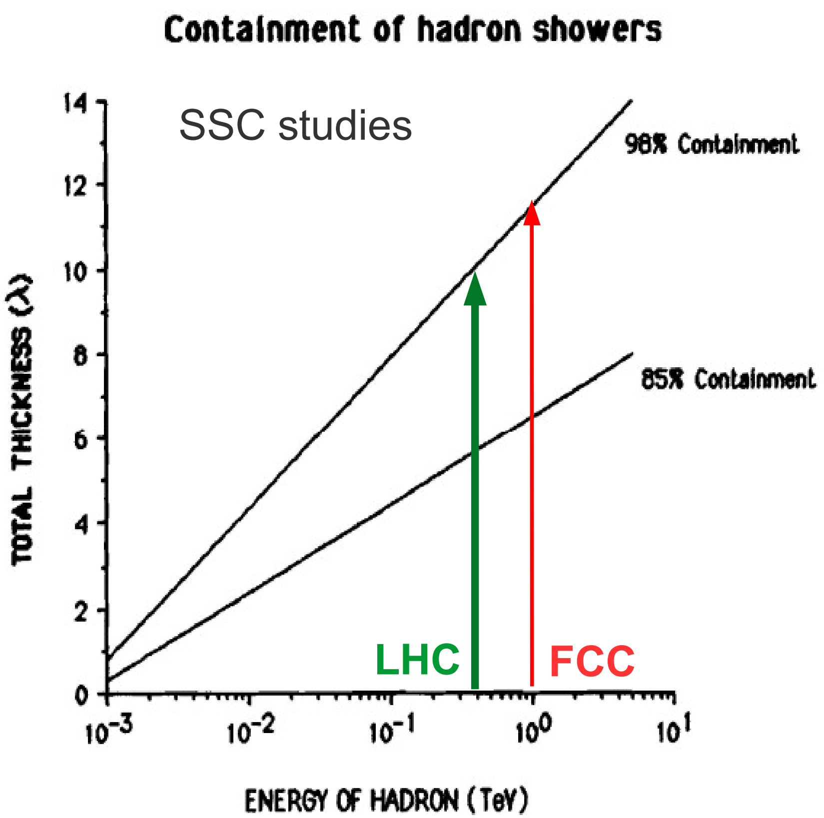
Estimating HCAL depth

Leading particles in high-pT jets

C.Helsens,C.Solans

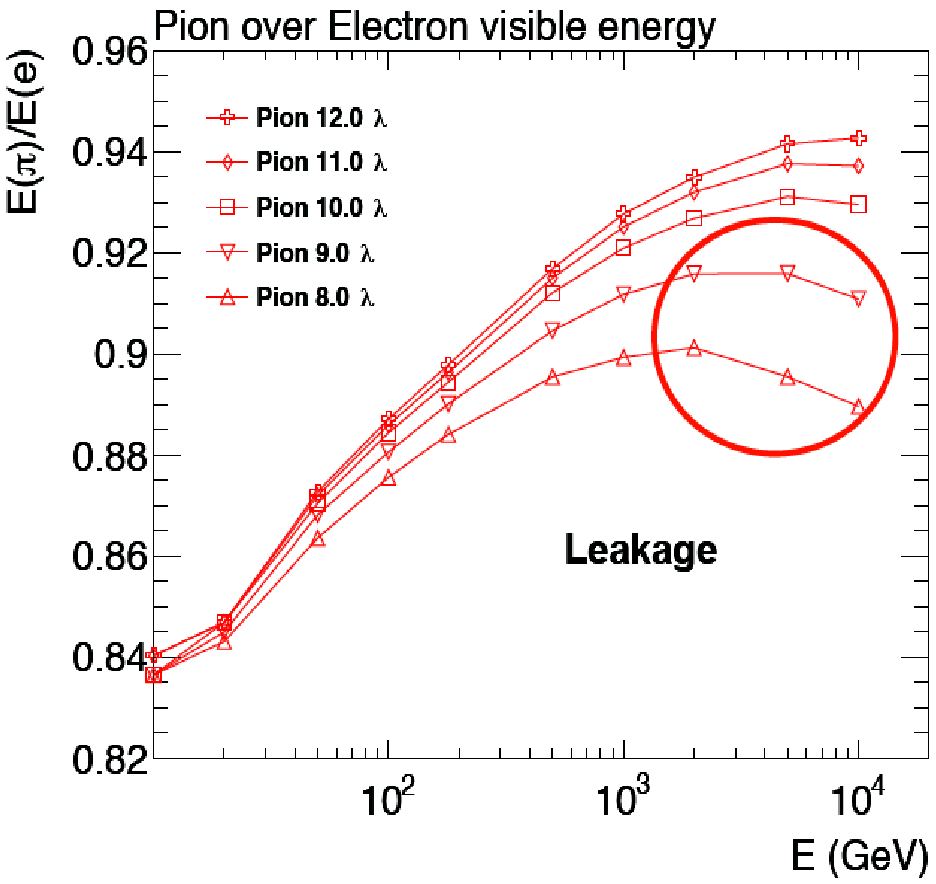


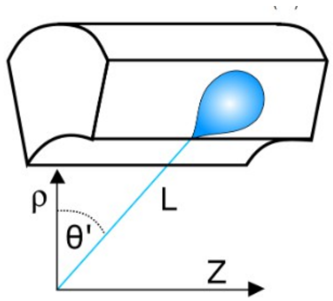
http://lss.fnal.gov/conf/C860623/p355.pdf



pT(jet)>30 TeV: ~10% will be carried by 1 TeV hadrons (~9 hadrons/jet)
12 λ is needed to contain 98% of energy of a 1 TeV hadron
Agrees with SSC estimates

Estimating HCAL depth





- Geant4 TileCal inspired simulation based on FTFP_BERT
- Electrons deposit more energy (e/h>1)
- Leakage for pions when using a shorter calorimeter (ATLAS/CMS)

C.Solans

https://indico.cern.ch/event/404924/

Energy resolution

Performance of calorimeters improves with energy

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a – stochastic/sampling term,
b - electronic noise term
c - constant term

Single hadrons:

ATLAS: $\sigma_E/E \sim 50\%/\sqrt{E} + 3.0\%$

CMS: $\sigma_E/E \sim 100\%/\sqrt{E} + 4.5\%$

(small noise term for both)

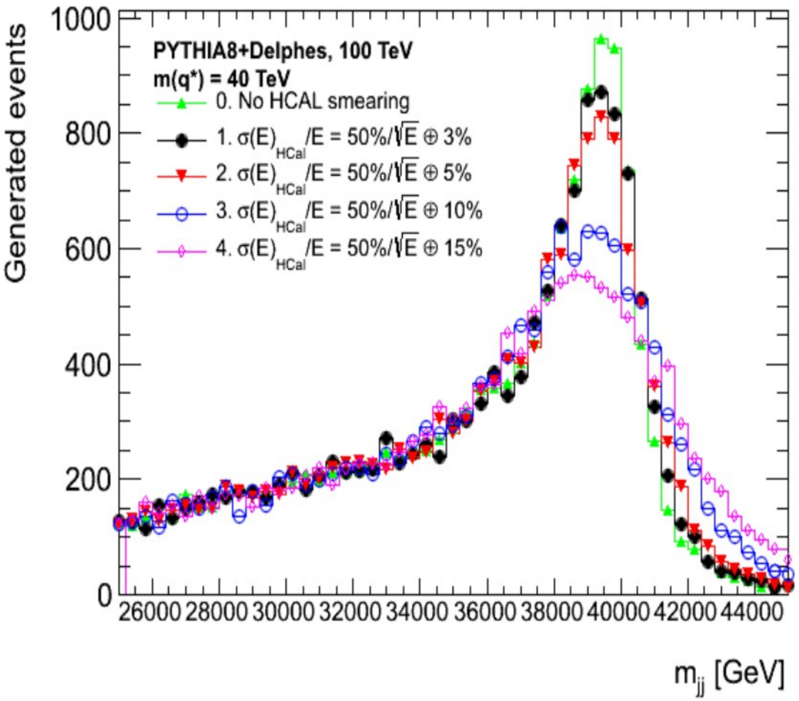
pT(jet)~1 TeV: 50% contribution from the constant term
pT(jet)>5 TeV: Constant term dominates

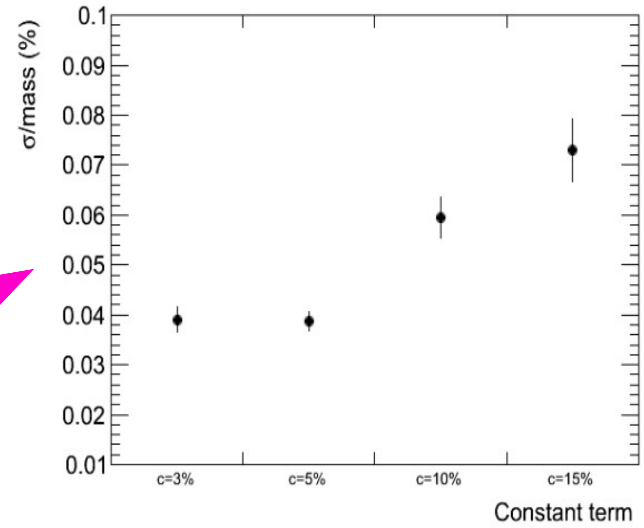
Reduction of the constant term requires solutions for:
dead material, longitudinal and lateral energy leakage, non-uniformity calibration, transition region, etc.

Dijet masses

D.Dylewsky, C.Doglioni, A.Henriques

Excited fermions: q* → jj





→ Smear MC samples (q*) with different calorimeter resolution hypotheses using Delphes

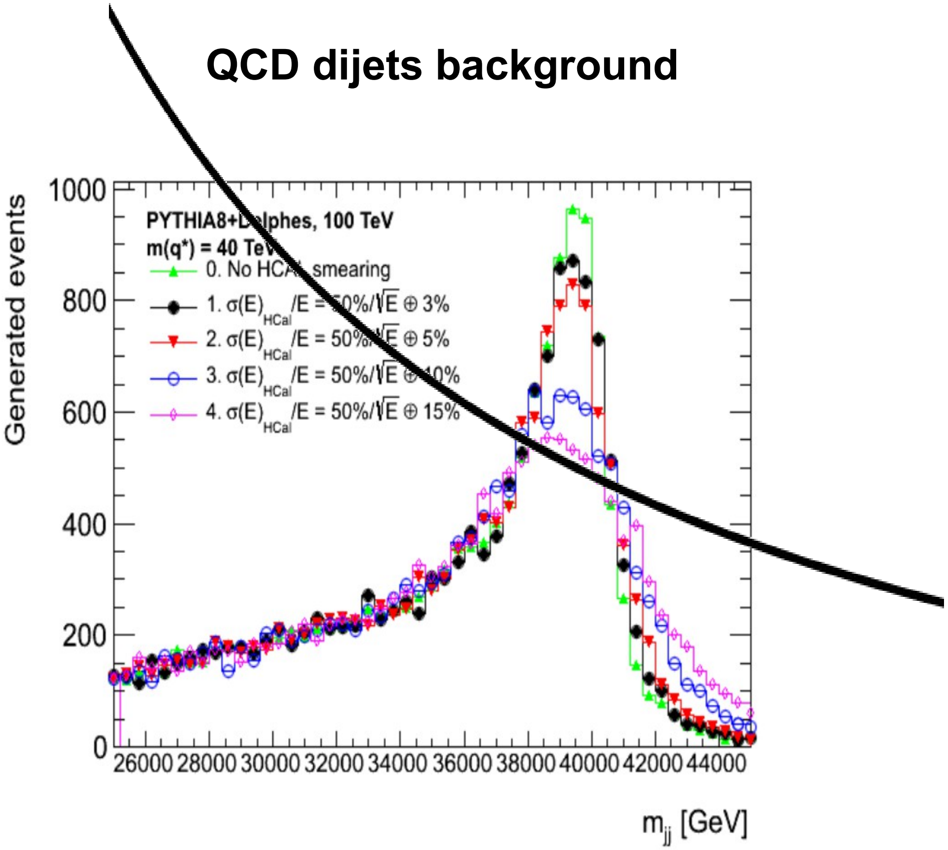
→ Check effect on peak width

Broadening of dijet mass for large E_T depends on the constant term "C"

C=3%, 5%, 10%, 15%

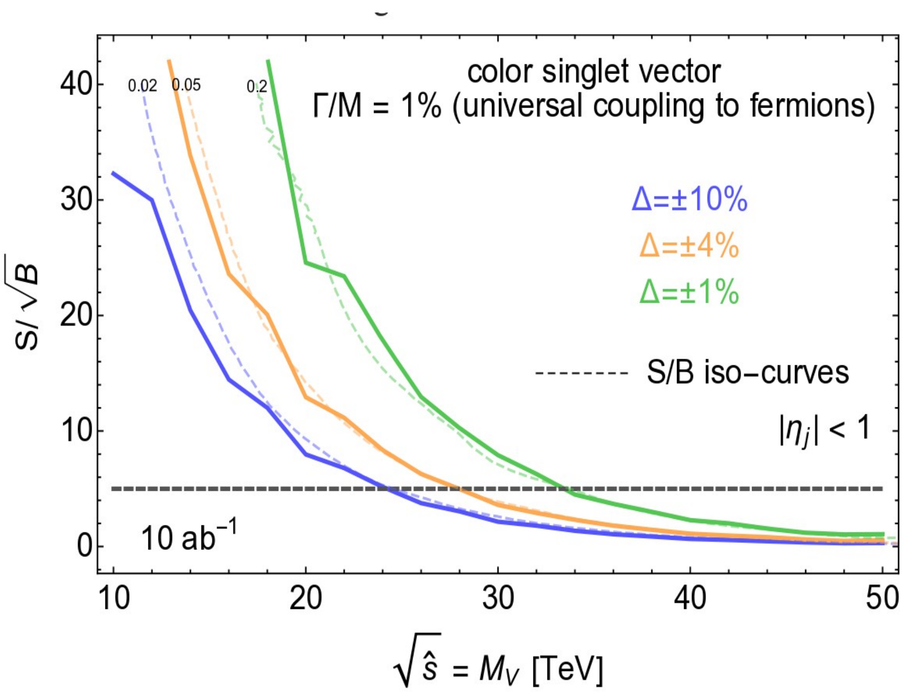
http://indico.cern.ch/event/352868/session/6/contribution/18/material/slides/0.pdf

Dijet mass resolution



But think about the discovery potential when adding QCD background!

R.Torre & M. Mangano

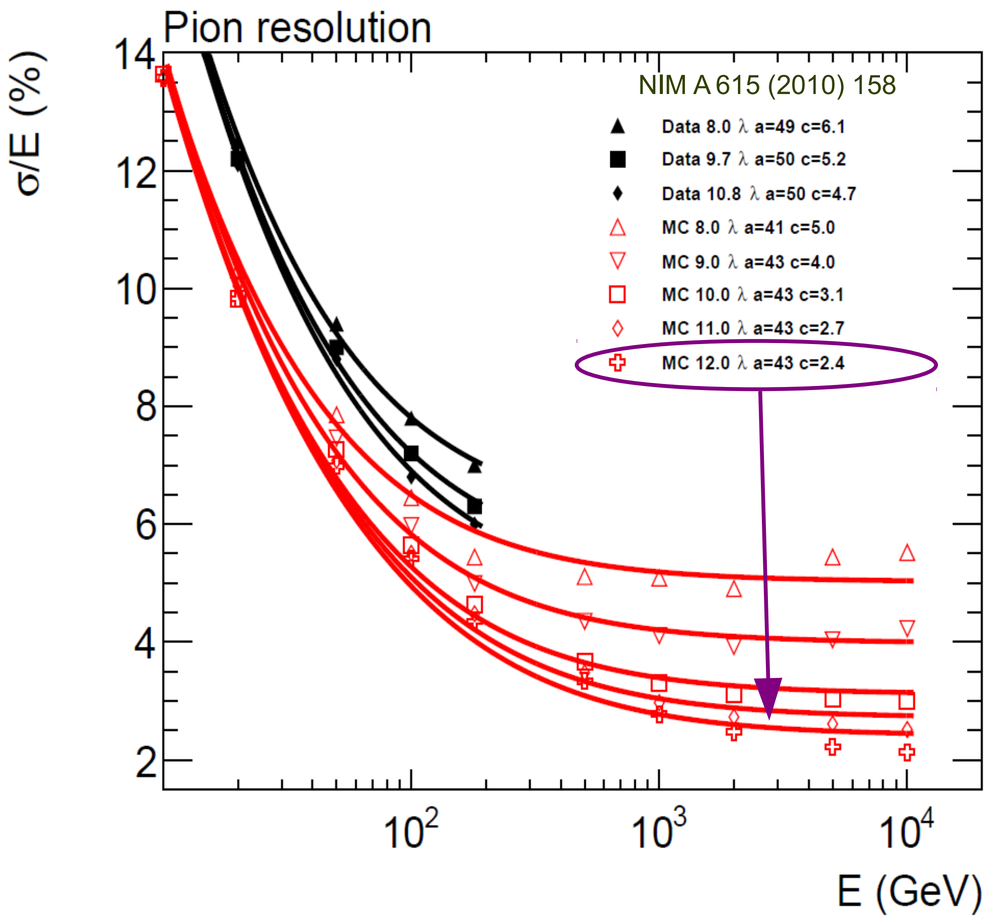


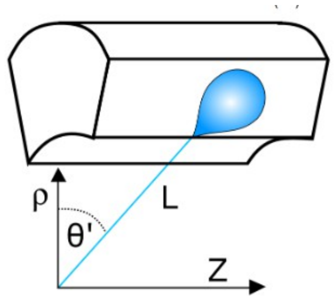
Detector resolution smearing determines the achievable mass reach

http://indico.cern.ch/event/352868/session/6/contribution/18/material/slides/

http://indico.cern.ch/event/352868/session/6/contribution/17/material/slides/

Resolution for single pions





- Geant4 TileCal inspired simulation based on FTFP_BERT
- Calculate single-particle resolution
- Stochastic term is close to 45%/√E
- Constant term improves by ~20% with increase of 1 lambda
- Constant term c~2.5 is achievable

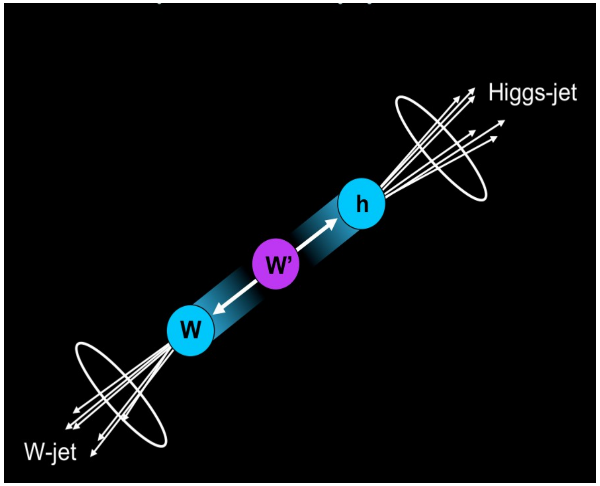
C.Solans

https://indico.cern.ch/event/404924/

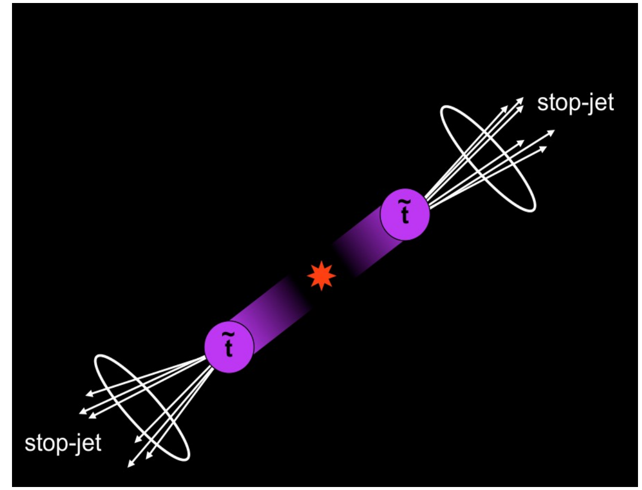
Lateral segmentation. Where does it matter..

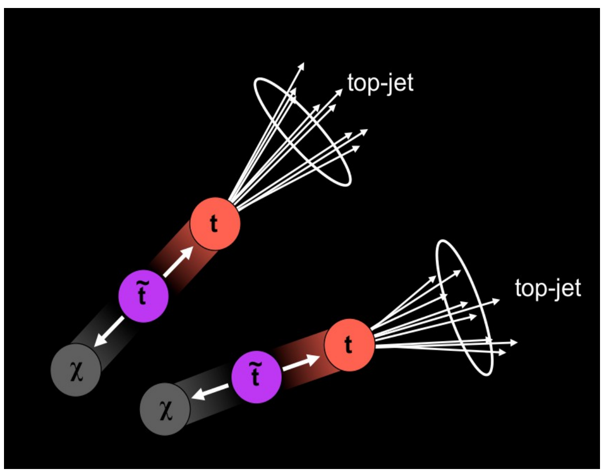
Brock Tweedie. Next steps in the Energy Frontier. LPC@FNAL. Aug. 24, 2014

X → W / Z / Higgs / top

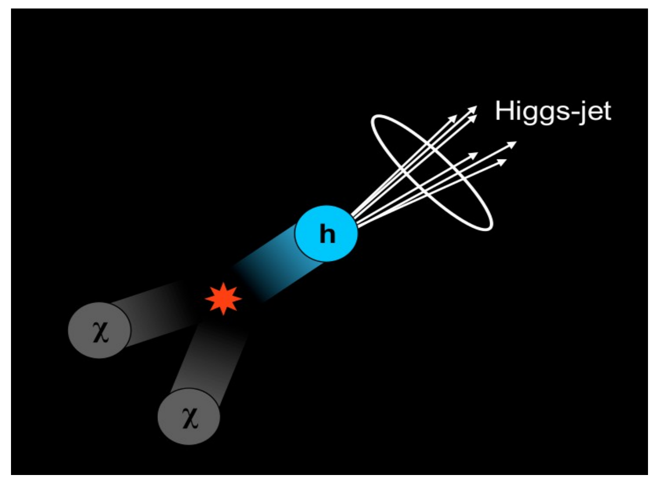


X → quarks/gluons





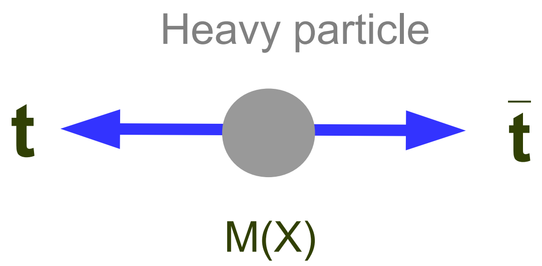
TeV-scale pair-produced

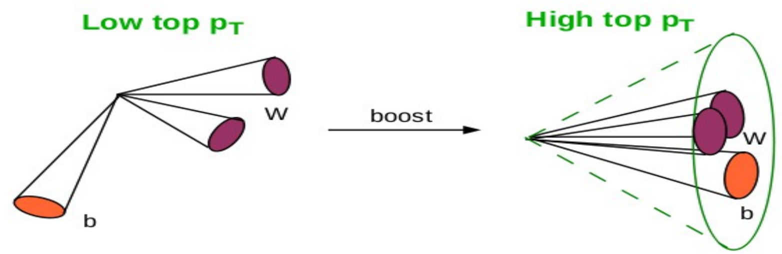


SM + dark matter

- Large mass → large Lorentz boost → large collimation of decay products

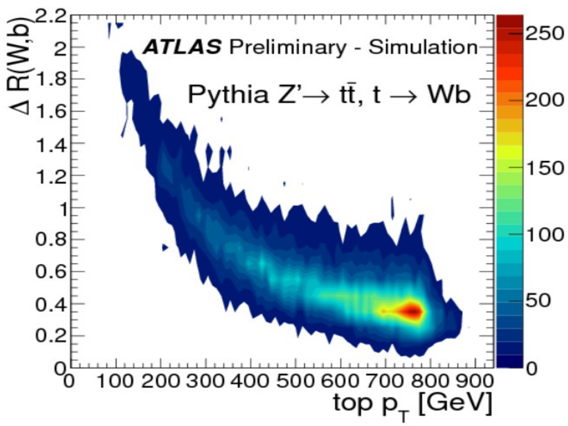
Boosted top from high-mass particles

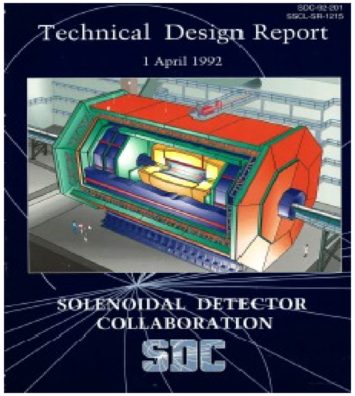




www.quantumdiaries.org

- M(X)~10 TeV → top quarks with pT(top) > 3-5 TeV
- ΔR distance between 2 particles (W,b) from top decay. ΔR ~ 2* pT / m(top)
- SM physics & 10 ab-1 for FCC-hh:
  - 5M top events with pT(top)>3 TeV
- SSC TDR discussed substructure signatures and large R-jets for boosted Z (SSC-SR-1217 TDR 1992 p 3-26)
- FCC detector will be based on boosted signatures for top, Z/W, Higgs + modern techniques

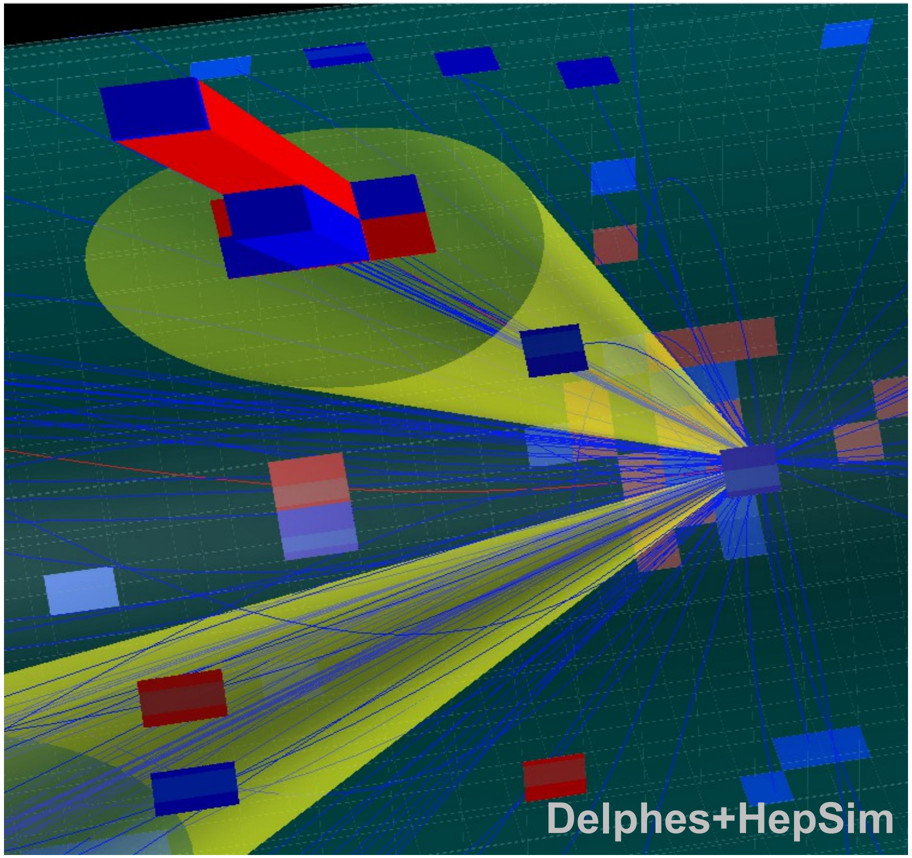


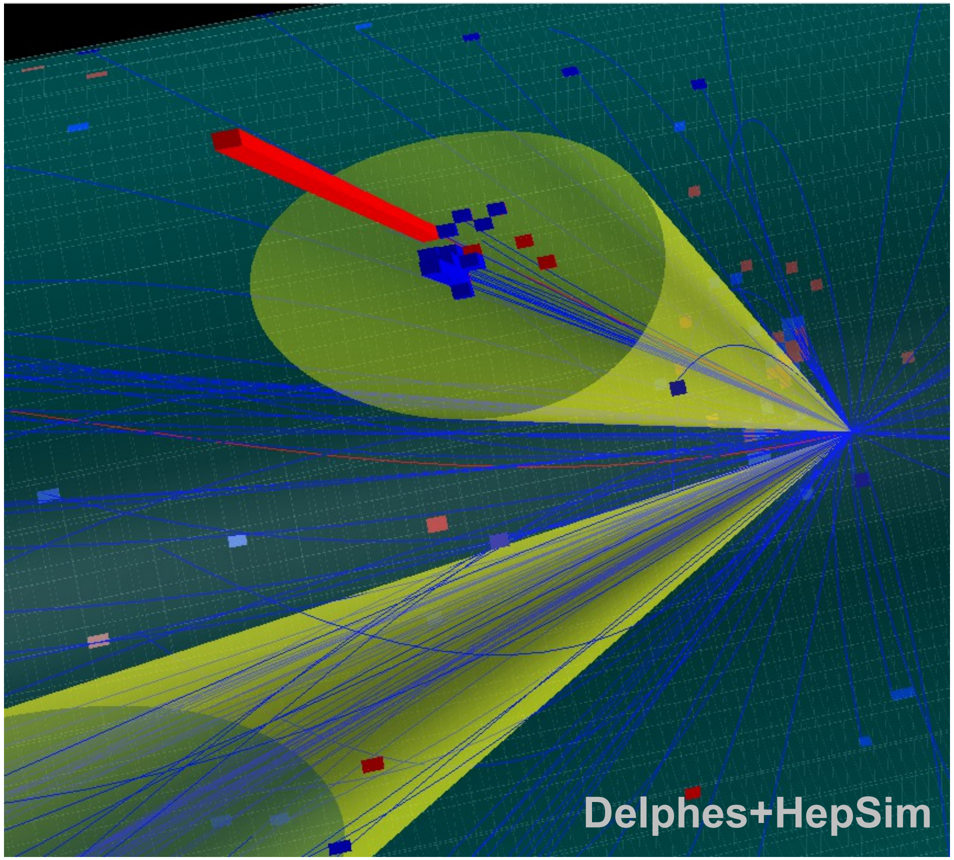


Example: Z'(10 TeV) → $t\bar{t}$ → 2 antiKT05 jets (pT(top)> 3 TeV)

Snowmass-like CAL geometry 'ATLAS'-like

x4 smaller CAL cells





~ 5 deg :
Phi ~ 5 deg, Eta ~ 0.1

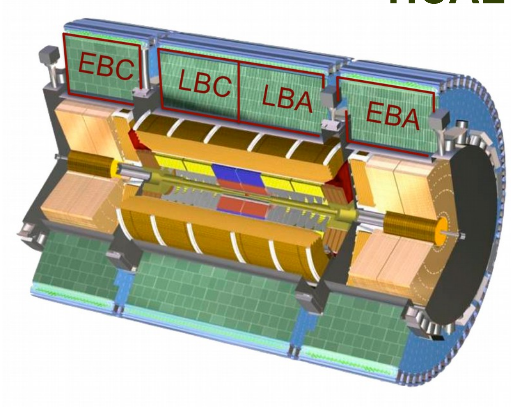
→

~ 1.25 deg :
Phi ~ 1.25 deg, Eta ~ 0.025

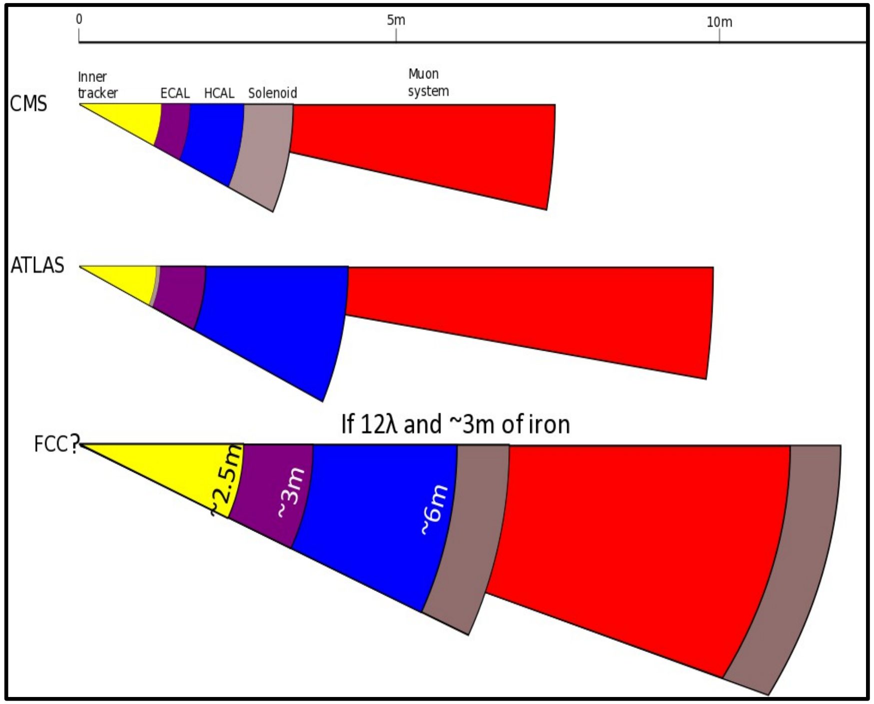
x 4 better segmentation

Calorimeter segmentation: from LHC to FCC

HCAL (Tile)



- **ATLAS:**
  - HCAL (TileCal) has 64 modules in φ (0.1 rad) and η=0.1 in the central region
  - ECAL has x4 better segmentation
  - Cell size ~22 cm (2.28 m from IP)
- **22cm means Δφ=0.06 rad for 3.5 m from IP**
  - ~ x2 better Δφ segmentation
- **Increasing segmentation by x4, x6 or more may require different instrumentation, readout technology, etc.**
  - but interaction length (Fe,Pb<16 cm)!
  - large out-of-cell leakage expected
- **How to make the decision on segmentation?**
  - look at physics with fast det. simulations



C.Barnet, C.Helsens

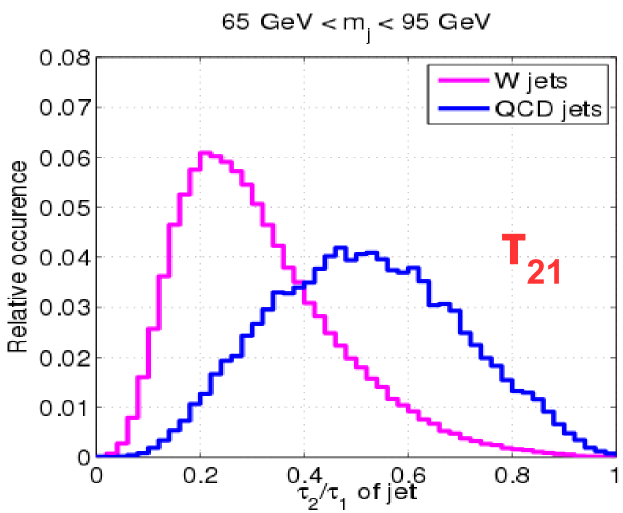
Substructure variables

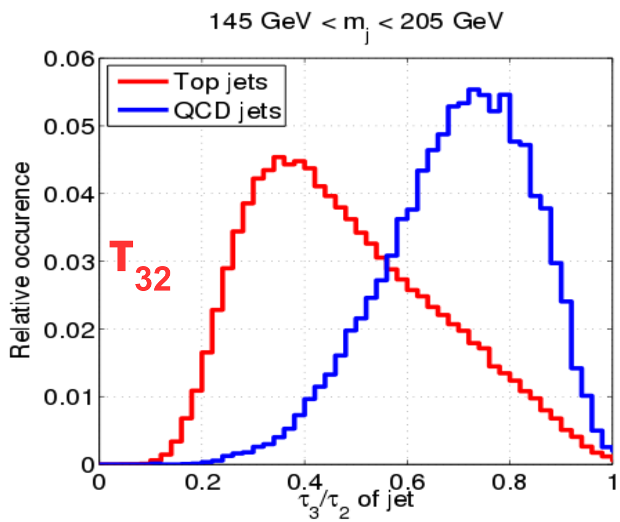
- τ_N-subjettiness - measure of the degree to which a jet can be considered as being composed of N-subjets

J.Thaler and K. Van Tilburg, JHEP 1103 (2011) 015

- $\tau_{21} = \tau_2 / \tau_1$ $\tau_{32} = \tau_3 / \tau_2$

- $\tau_{21} < 0.3$ cut reduces QCD dijet background for boosted Z/W
- $\tau_{32} > 0.75$ cut reduces QCD dijet background for boosted top quarks





See J.Love's talk on highly boosted jets at a 100 TeV

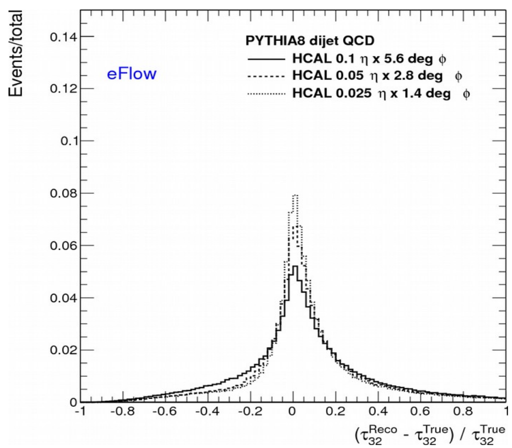
Calorimeter segmentation studies

HepSim

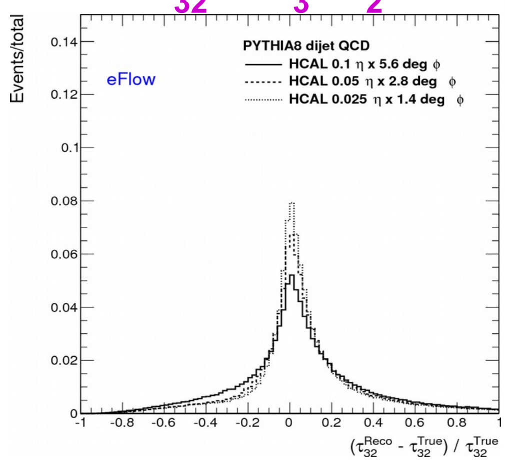
DELPHES
fast simulation

- DELPHES 3.2 $t\bar{t}$ MG5 from HepSim
- pT(jet)>3 TeV. R=0.5
- ECAL has x4 smaller cell size than HCAL
- (1) Reduce HCAL cells by x2 and x4 keeping ECAL the same
- (2) Also reduce HCAL & ECAL cells at the same time
- **Eflow setup:**
  - Charge particles from tracks
  - Photons/electrons in ECAL
  - Rest: 60% of energy in HCAL
- **Improvement in resolution by 15% going from 0.1 to 0.05 cell size**
- **Improvement by 5% going from 0.05 to 0.025 cell size**
- **x2 (x4) better granularity leads to ~30 (35)% improvement in jet mass resolution**

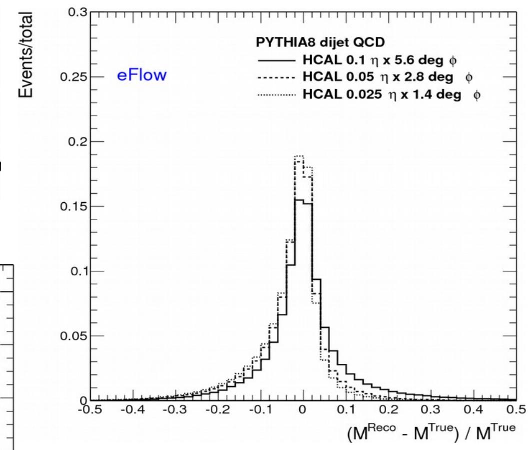
$\tau_{21} = \tau_2 / \tau_1$



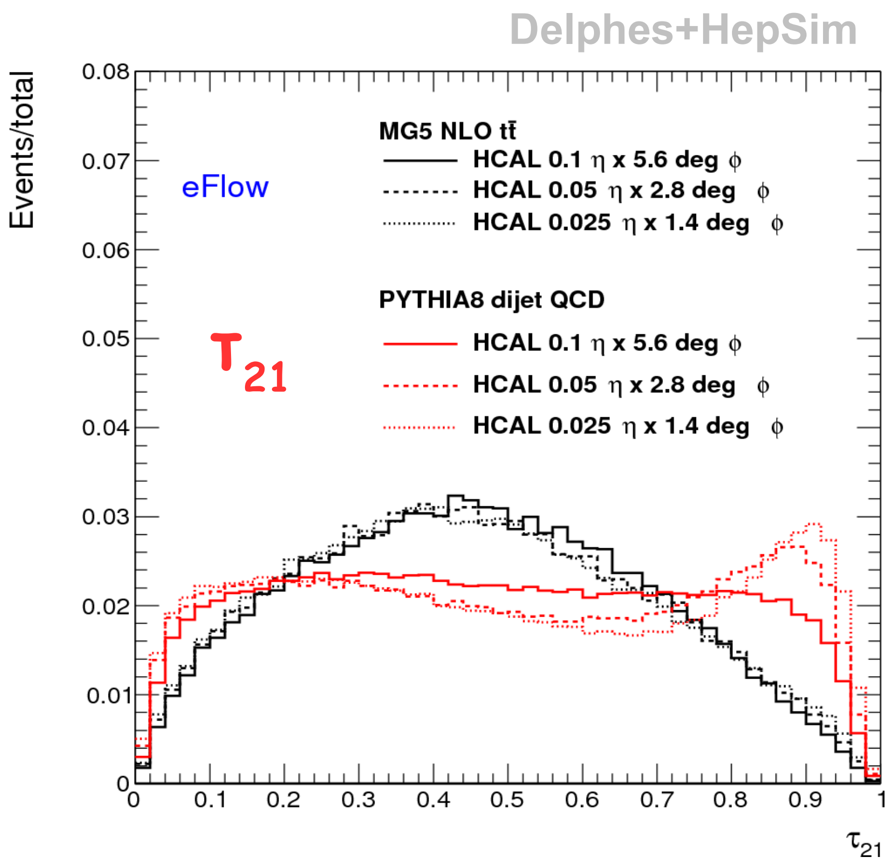
$\tau_{32} = \tau_3 / \tau_2$

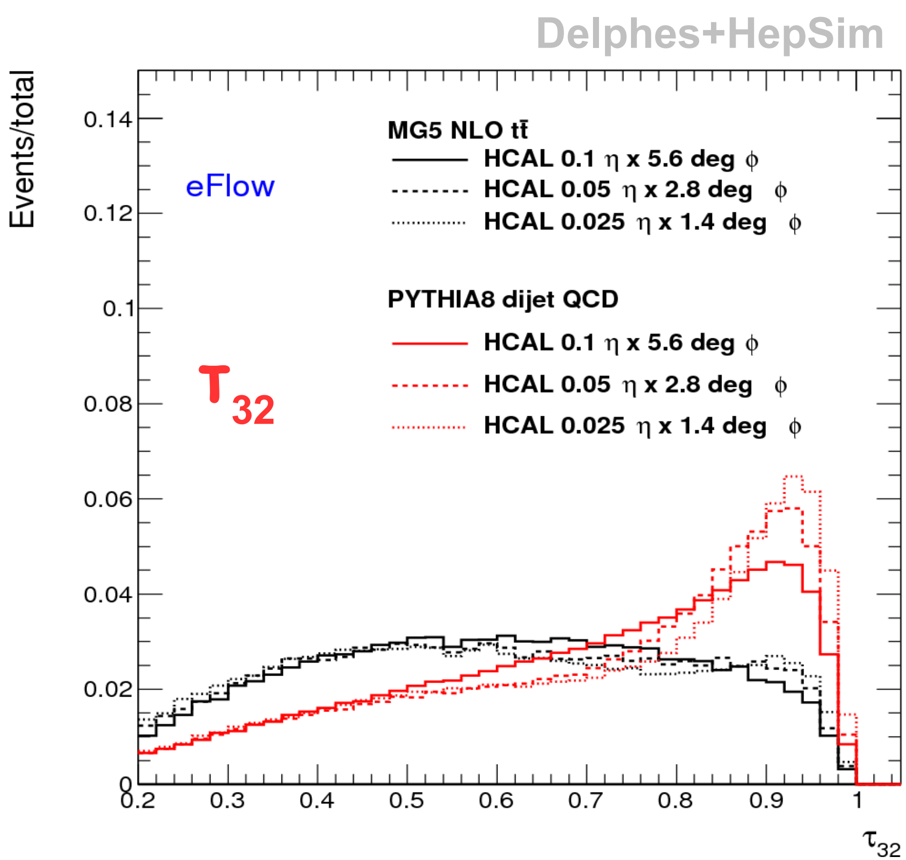


Jet mass



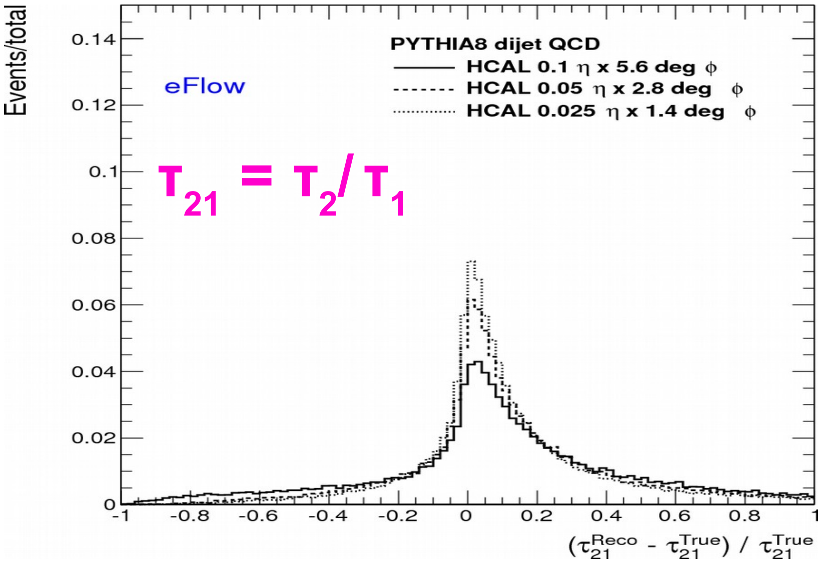
Finer HCAL cells. Boosted top quarks vs QCD dijets

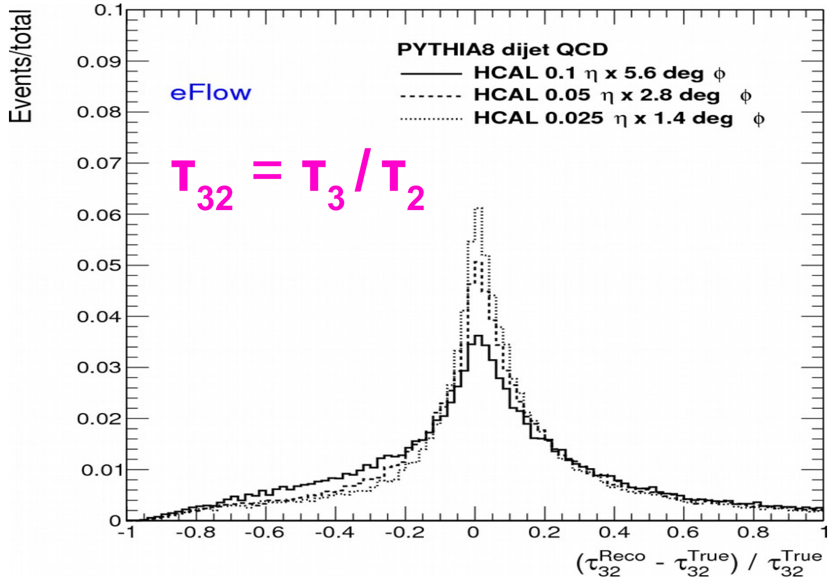


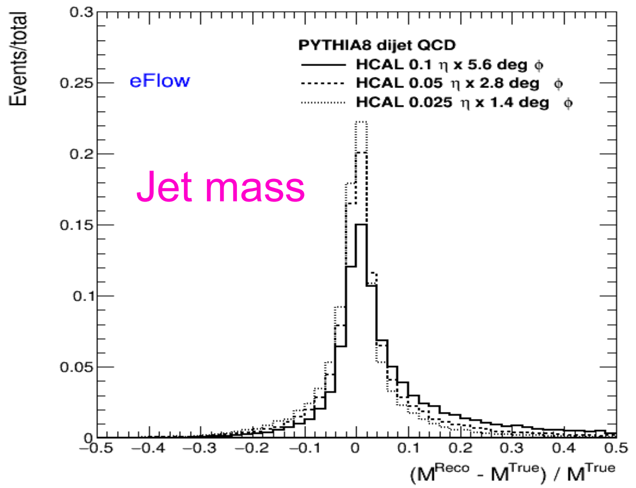


- **0.1 → 0.05 cell size reduction improves QCD background rejection**
- **0.05 → 0.025 cell size reduction shows smaller improvement**
- **Same conclusion for smaller cell size**

Extreme case: resolution for pT(jet)>10 TeV







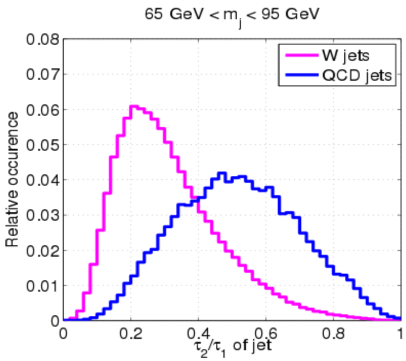
Decrease in RMS compared to $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

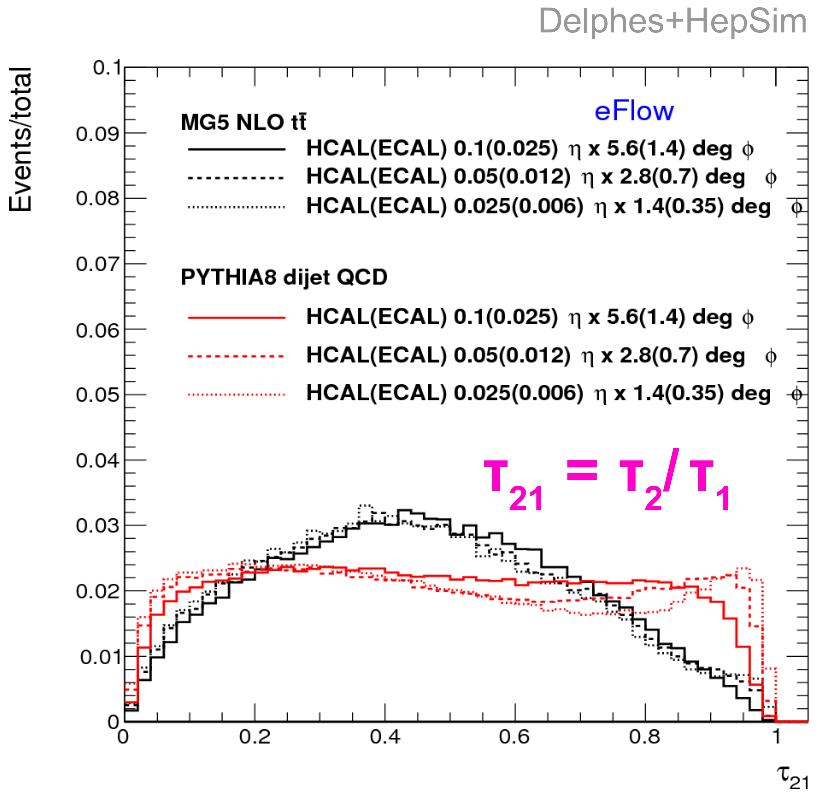
	$\Delta\eta \times \Delta\varphi = 0.05 \times 0.05$	$\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$
tau21	18%	28%
tau32	9%	13%
jet mass	80%	120%

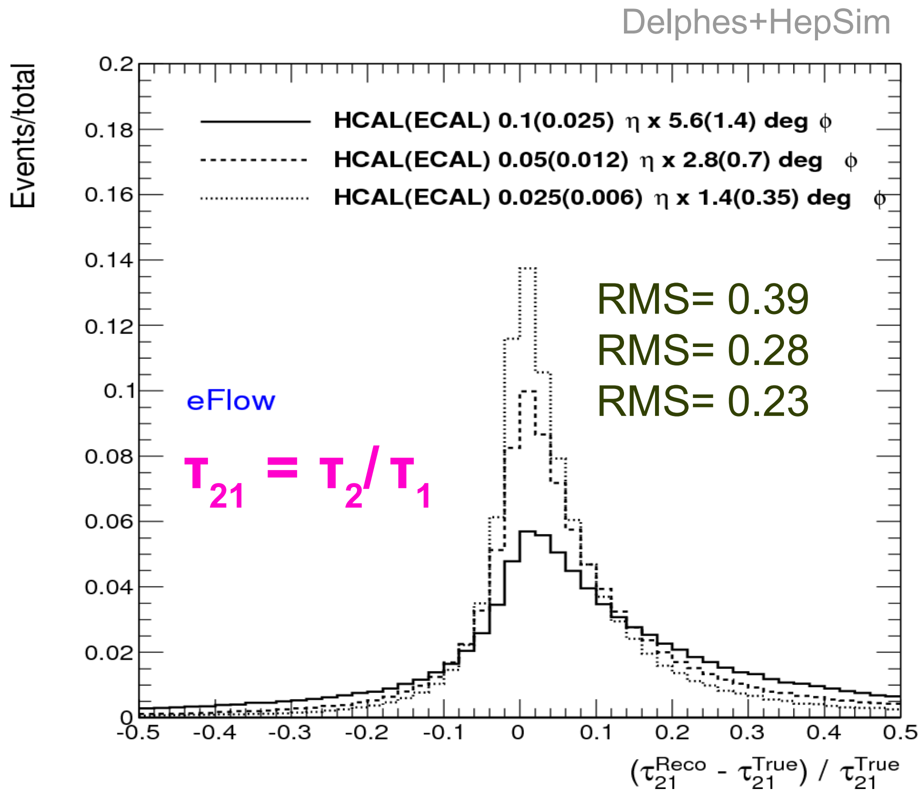
Large improvement in resolution for $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$

τ_{21}. Finer HCAL & ECAL cells. Delphes fast simulation

- pT(jet)>3 TeV
- Assume x2 and x4 finer granularity of **both ECAL and HCAL**
- x2 (x4) increase in granularity leads to 36% (67%) improvement in resolution

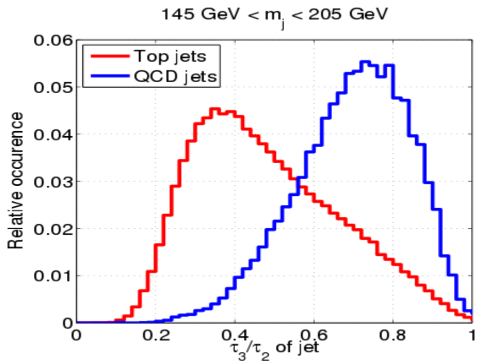




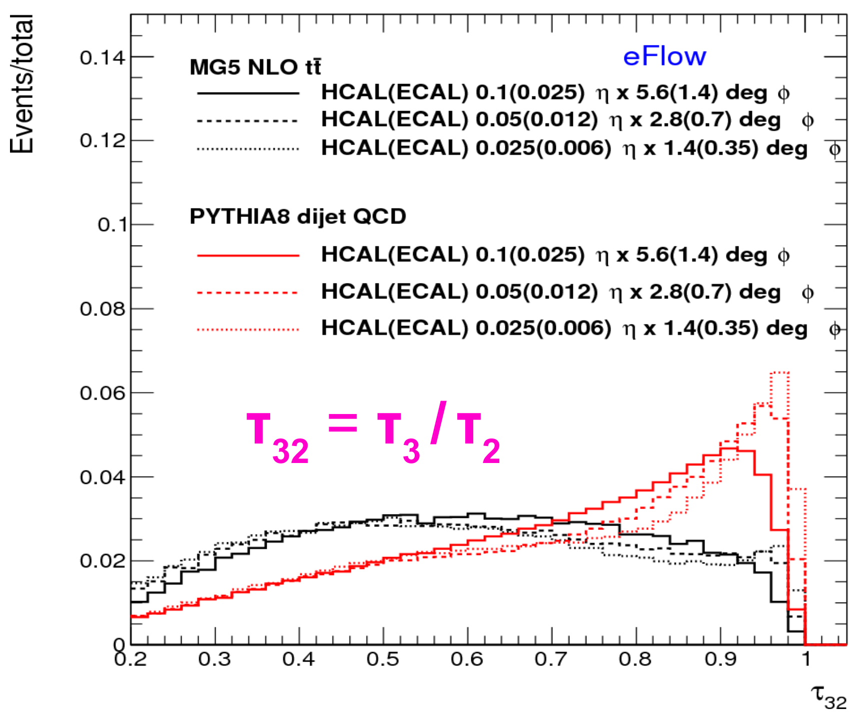


τ_{32}. Finer HCAL and ECAL cells

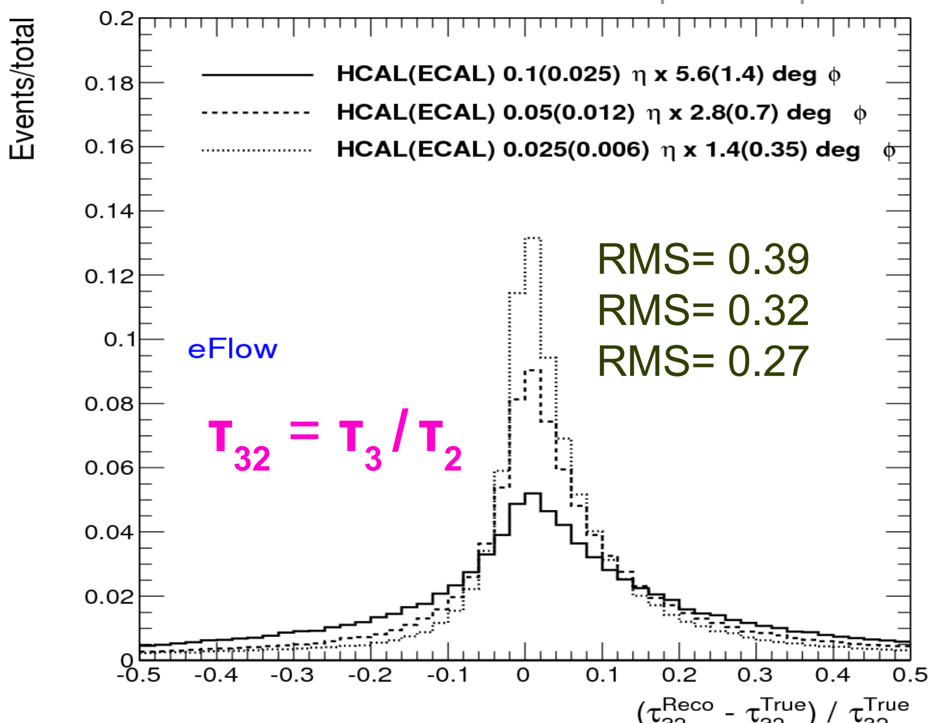
- pT(jet)>3 TeV
- Assume x2 and x4 finer granularity for both ECAL and HCAL
- x2 (x4) increase in granularity leads to 20% (40%) improvement in resolution



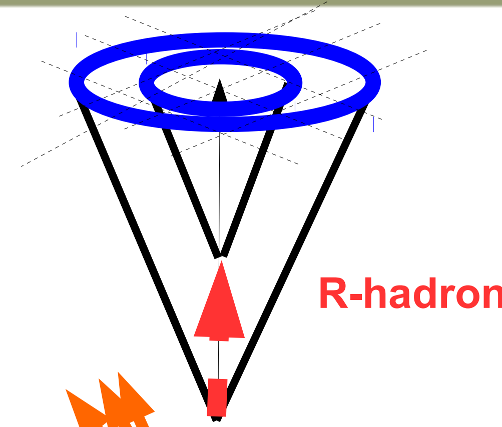
Delphes+HepSim



Delphes+HepSim



Energy range of cells



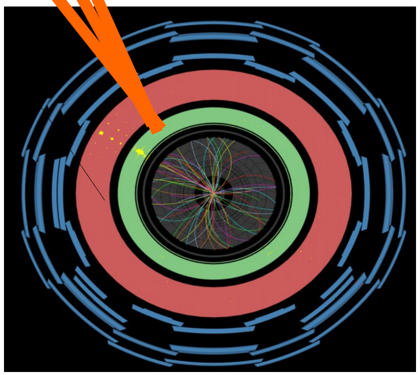
- Dynamic range of cell readout determined by cell sizes
- **Large cell size → large dynamic range →**

expensive readout

Dynamic range of the existing experiments **~ 10^4**

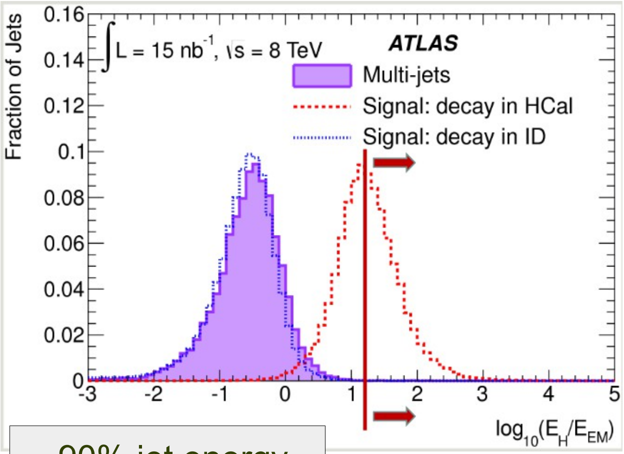
- Example: ATLAS HCAL dynamic range of cells is 0.22 GeV (muons) – 1.5 TeV (jets)

FCC HCAL cells should accommodate ~20 TeV SM jets



But assume safe margin:

BSM scenario with long-lived jets:
→ Jets start close to HCAL
→ Stronger energy collimation around a few cells
→ Large energy in cells



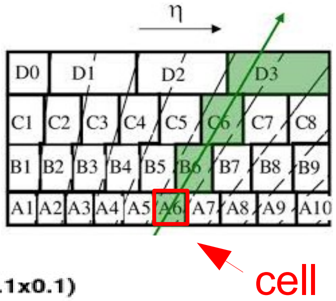
~90% jet energy in HCAL

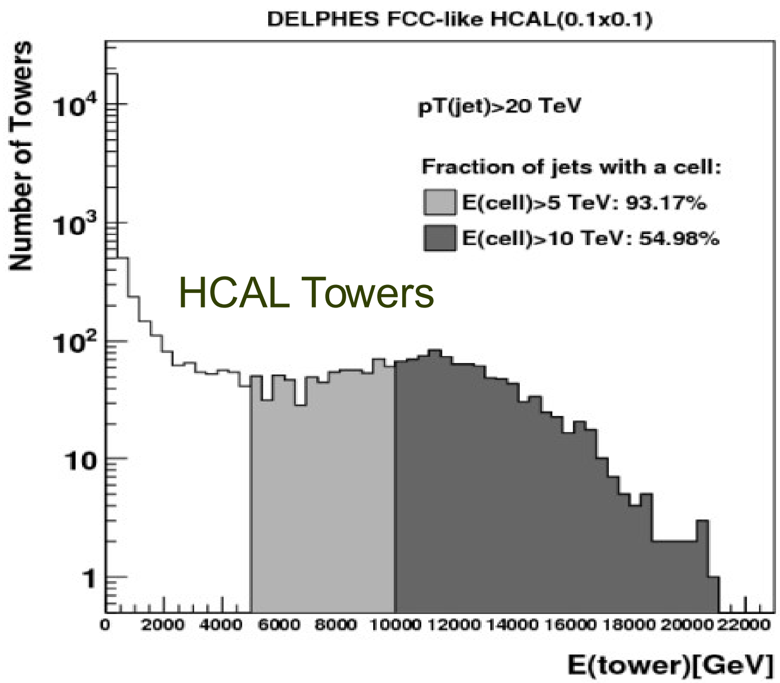
Energy range of HCAL cells using Delphes

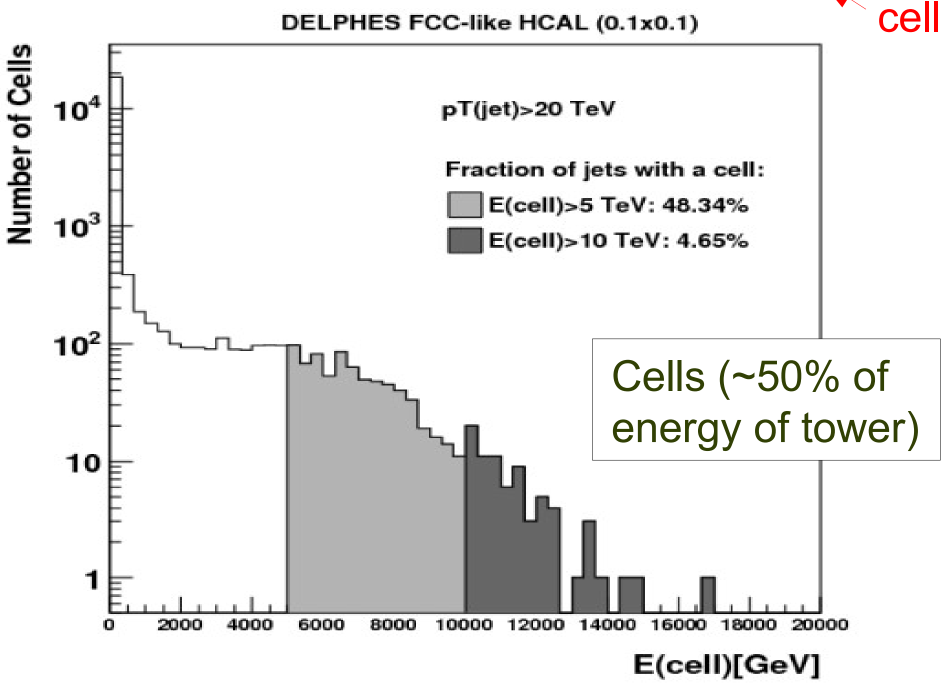
J.Dull.
ANL summer student

Energy sharing between ECAL and HCAL, and energy sharing between different layers of HCAL were tuned to ATLAS Geant4

Look at cell energy of jets using ATLAS-like HCAL with pT > 20 TeV





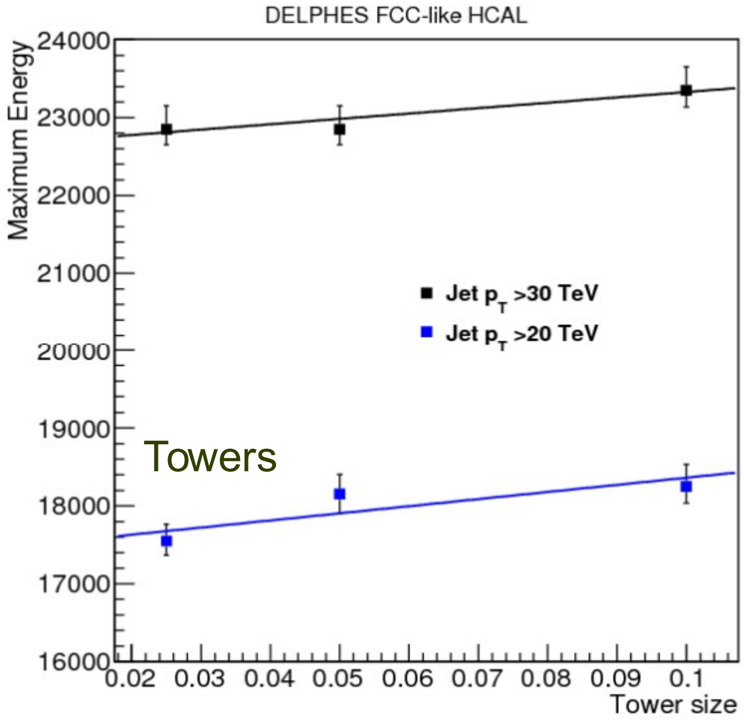


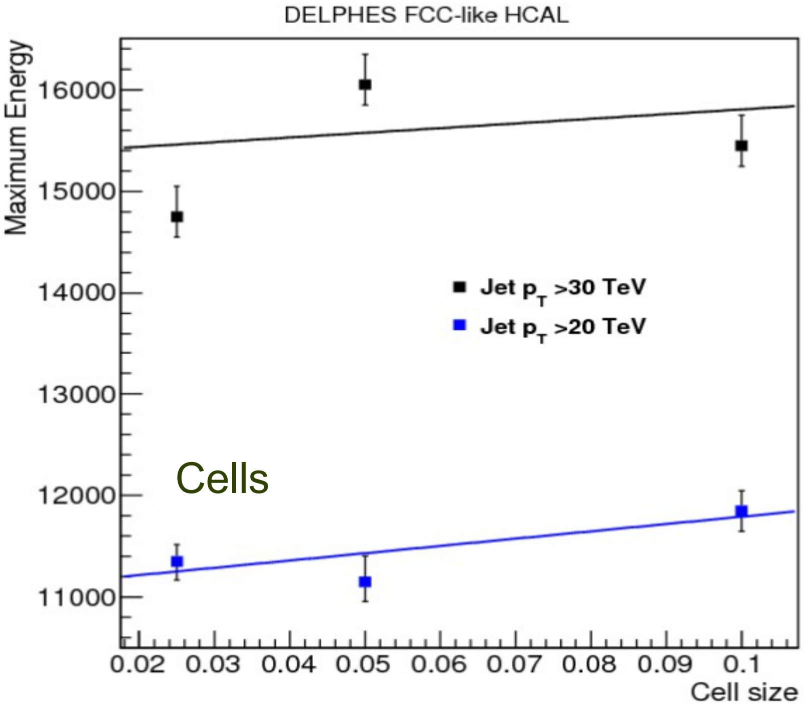
- Energy range 0.2~15000 GeV for 0.1x0.1 cells for jets above 20 TeV
- Technical challenges (~10^5 cell dynamic range)

Energy range of HCAL cells

(J.Dull. ANL SULI)

Maximum value of energy seen by towers and cells for 20 and 30 TeV jets
Defined as a range of energy that fully contains all jet cells (or towers) for 99% of SM jets

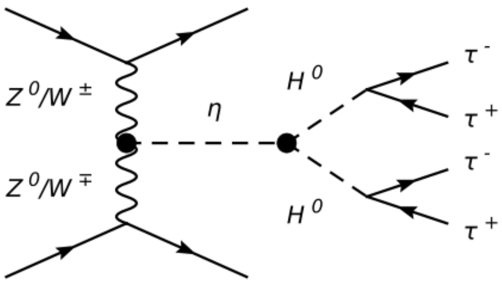




Maximum energy per cell drops with decrease of the cell size
But the decrease is a slow function.
Can it be used to extrapolate to a smaller cell sizes?

Forward η coverage

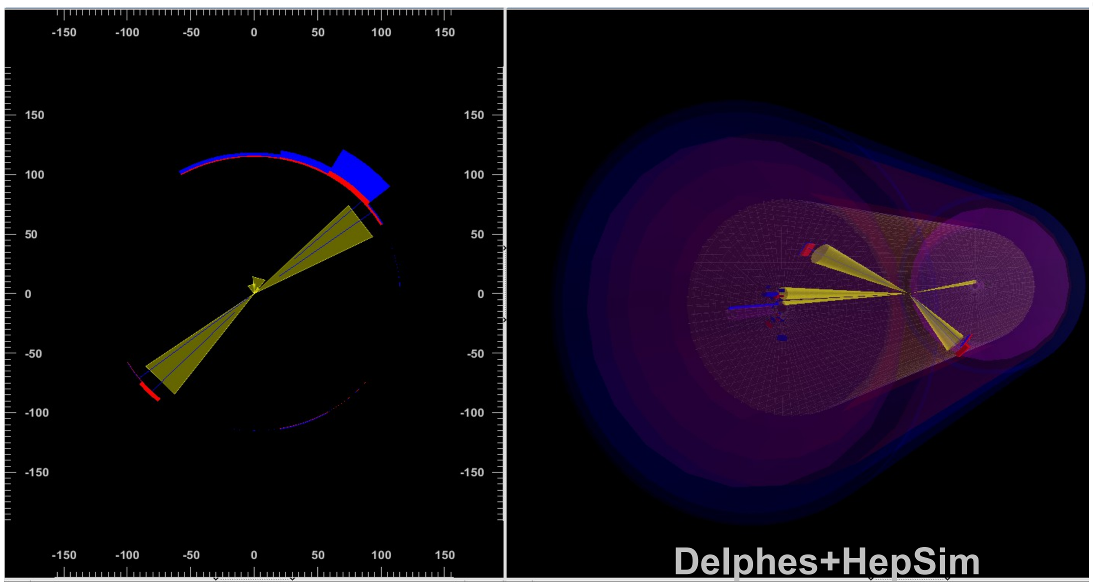
- Many SM channels will benefit in opening up the η range
  - VBF-Higgs production, WW → WW, WW → HH, $t\bar{t}H$ production
- BSM channels: High-mass resonances in vector-boson scattering & Higgs decay:

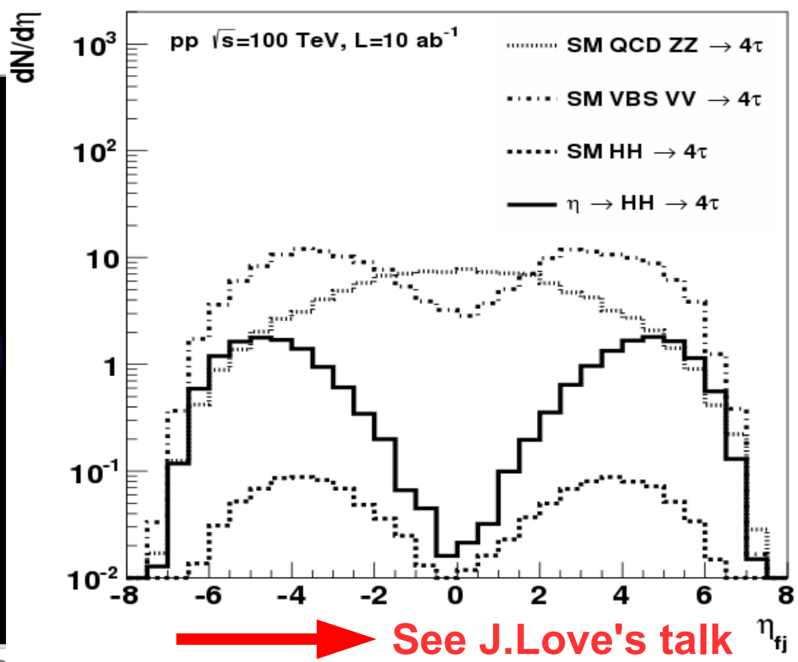


A. V. Kotwal, S.C., M. Low
Phys. Rev. D 91, 114018 (2015)

~ 50% of events in the region η~4-6
Typical requirement coverage: ~ 6

h → 2H → 4 τ

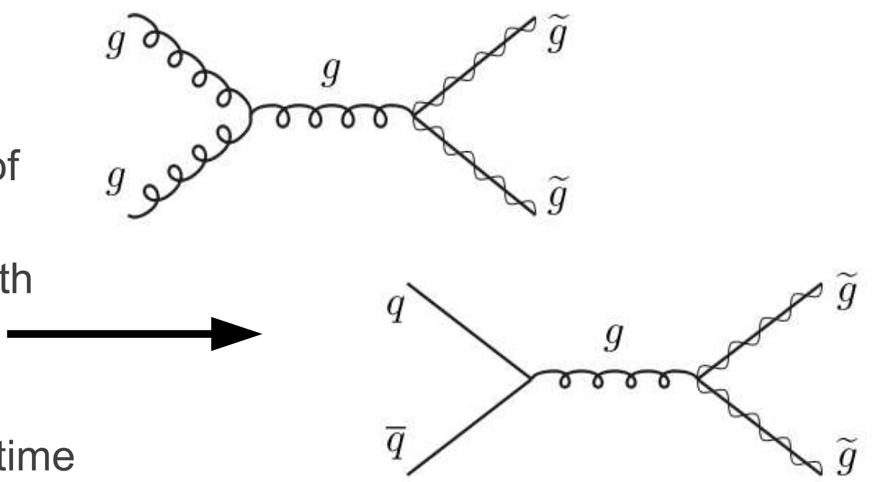




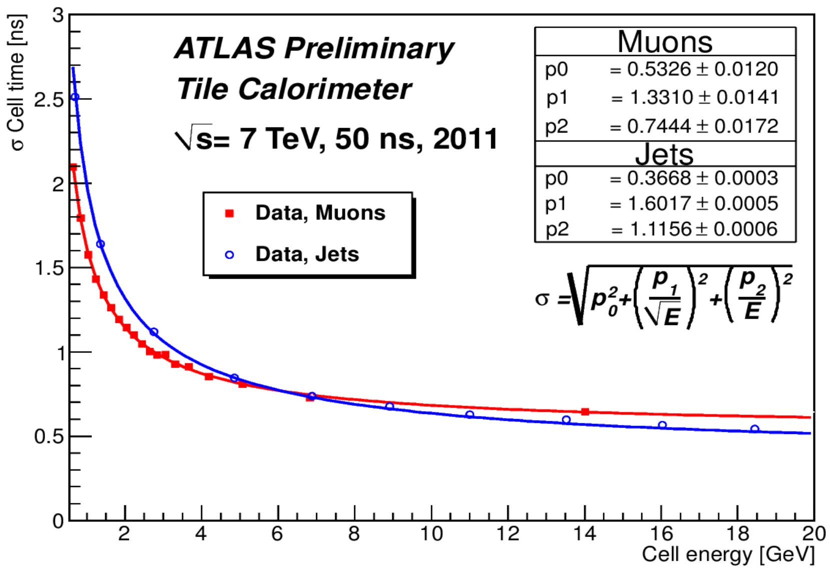
See J.Love's talk

Time reconstruction

- Several SUSY scenarios predict existence of Long-Lived Particles (LLP)
  - split SUSY scenarios: Heavy gluinos with long lifetime → R-hadrons
- "Hidden Valley" models
- Extra-dimension models with detectable lifetime of graviton (G*)



Required:
- precise time-of-flight measurement
- longitudinal segmentation



ATLAS HCAL example:
- Independent measurement up to 6 cells
- Time resolution ~0.5 ns for E>10 GeV

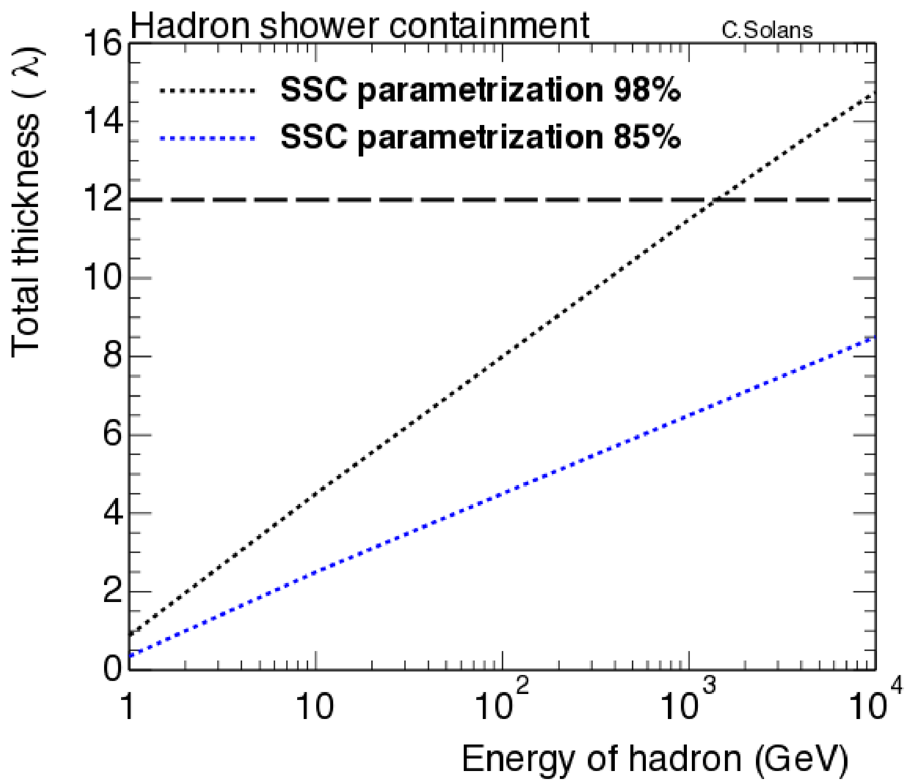
Limitations: constant term ~0.4 ns. Can it be reduced?

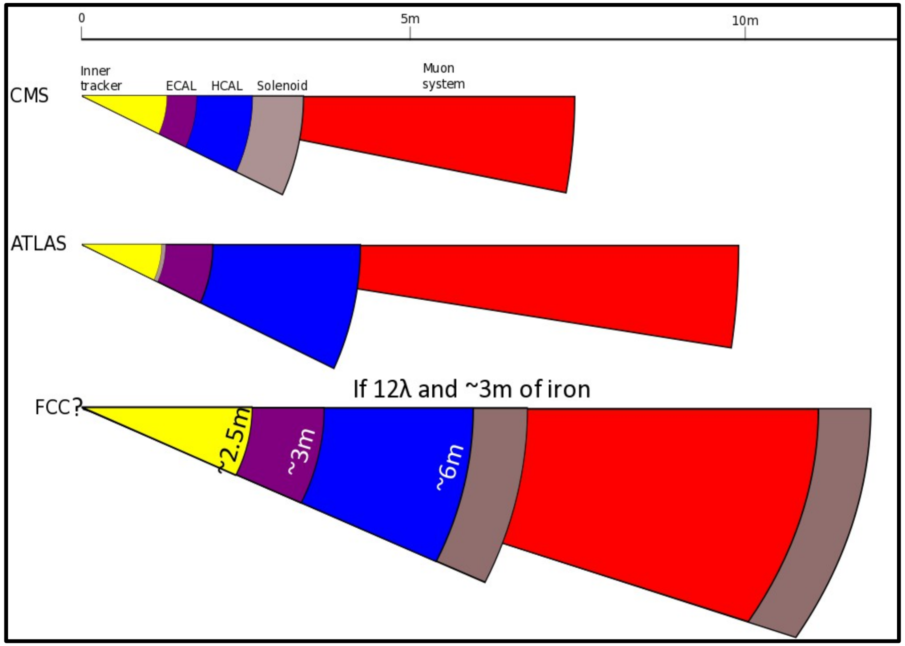
Summary

- **12 λ in depth**
- **Energy resolution with C~3% and below**
- **Longitudinal segmentation for 3D clusters**
- **Should be designed keeping in mind boosted signatures**
- **$\Delta\eta \times \Delta\varphi$ = 0.05 x 0.05 (and smaller) for pT(jet)>3 TeV**
- **$\Delta\eta \times \Delta\varphi$ = 0.025 x 0.025 (and smaller) for pT(jet)~10 TeV**
  - ~4 better than for ATLAS/CMS
  - x2 → increase of the distance from IP
  - x2 → improvement in instrumentation
- **Cell energy range must be extended by a factor 10**
- **Extended coverage η~6 is designed**
- **Ongoing work on full detector simulation in Europe, USA & China**

Backup

Estimating HCAL depth



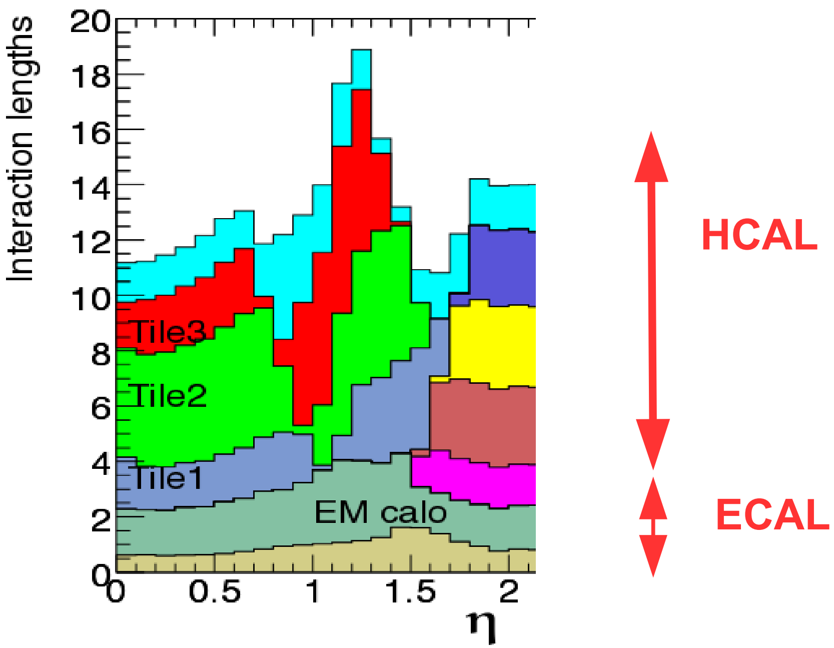


Missing part: Realistic Geant4 simulation of jets up to pT(jet)~30 TeV
Estimation of punch-through events
Missing ET is missing study! (important for transverse and η containment)

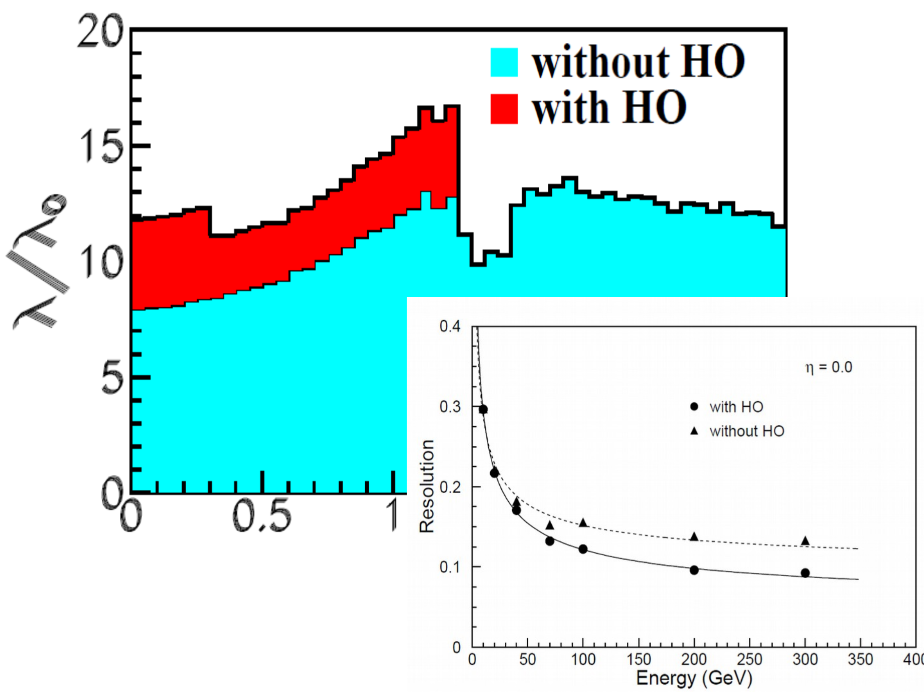
HCAL depth considerations

- Important for longitudinal shower development
  - fully contain the development of showers. No punch-through
- Formulated in terms of nuclear interaction length (λ)
- ATLAS HCAL active thicknesses of 7.6 λ (layers 1.9, 4.2 and 1.5 λ)
- Thickness of CMS HCAL calorimeter 5.3 λ (inside the solenoid)
  - + tail catcher (2.1 λ)

ATLAS



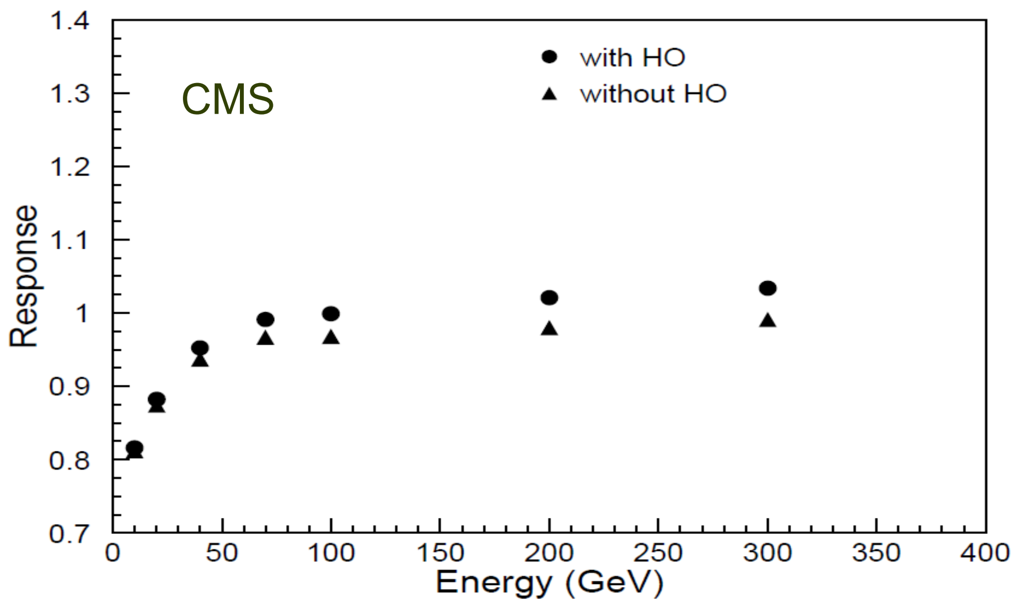
CMS

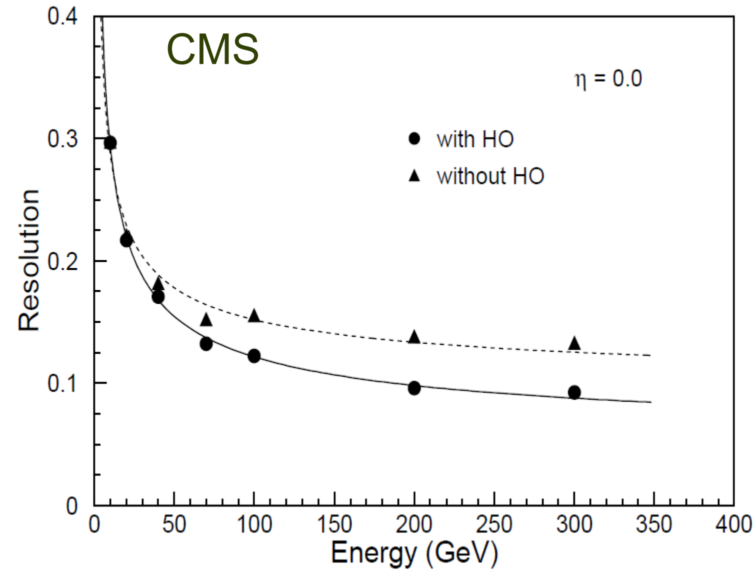


LHC Calorimeters

- Both calorimeters are designed to measure jets in the range 1-3 TeV
- An example: How reconstruction changes by adding additional 2.1 λ0

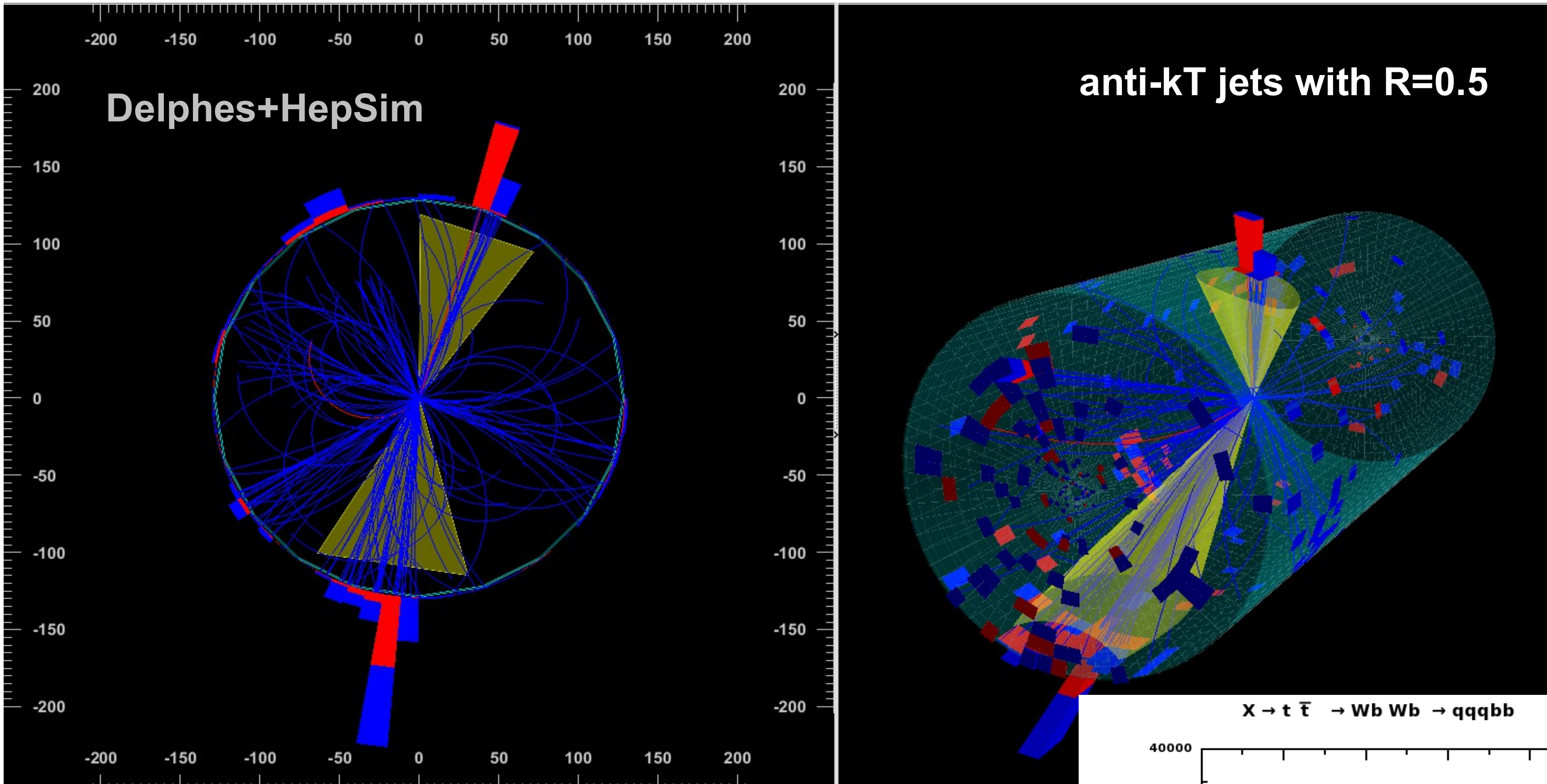
<E>/E(ins)

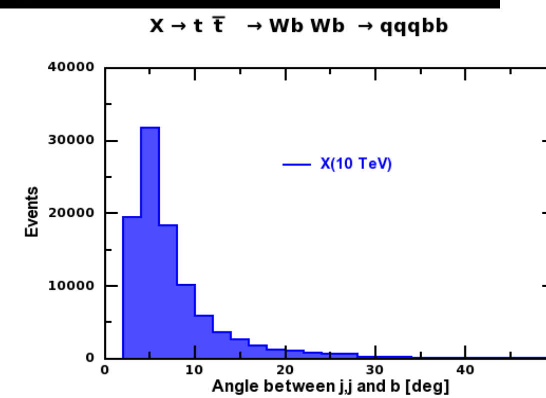




CMS NOTE 1999/063

Zprime (10 TeV)→ $t\bar{t}$. Fast detector simulation using Delphes





- For ~10 TeV object, typical opening angle between q, $\bar{q}$ and b from t ($\bar{t}$) is 5 degree
- "Highly boosted" regime: decay products are inside "standard" jets with R=0.5
- Event kinematics → "back-to-back" jets"

Calorimeter segmentation studies

HepSim → DELPHES fast simulation

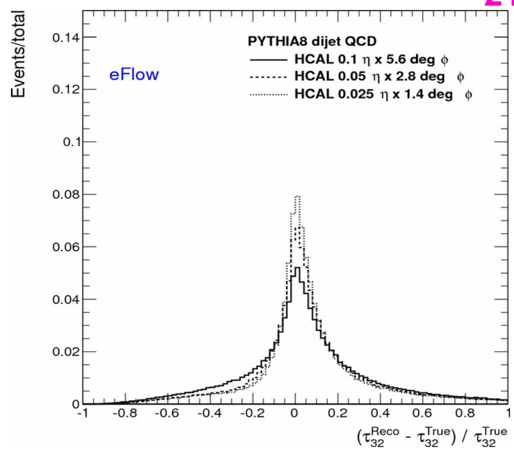
- DELPHES 3.2
- $t\bar{t}$ MG5 from HepSim
- pT(jet)>3 TeV. R=0.5
- Same ECAL.
- Reduce HCAL cells by x2 and x4

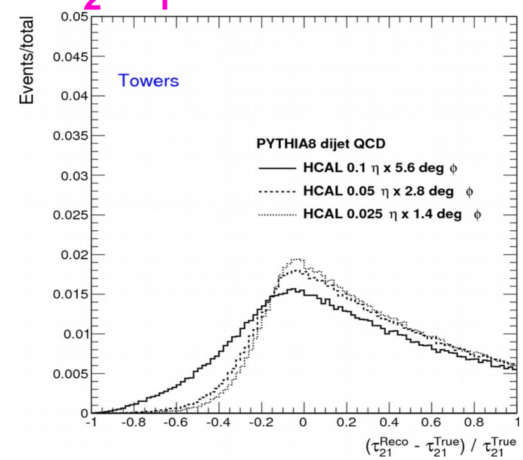
- EFlow:
  - Charge particles from tracks
  - Photons/electrons in ECAL
  - 60% of measured in HCAL
- Towers:
  - Photons/electrons in ECAL
  - 60% of other particles in HCAL

- **Improvement in resolution by 10-15% going from 0.1 to 0.05 cell size**
- **Improvement by 4-5% going from 0.05 to 0.025 cell size**

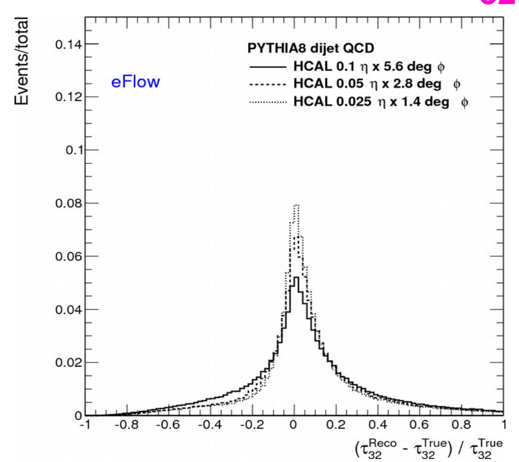
resolution studies

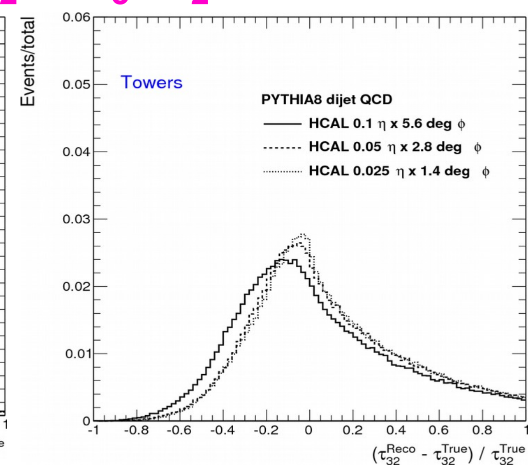
$\tau_{21} = \tau_2 / \tau_1$





$\tau_{32} = \tau_3 / \tau_2$

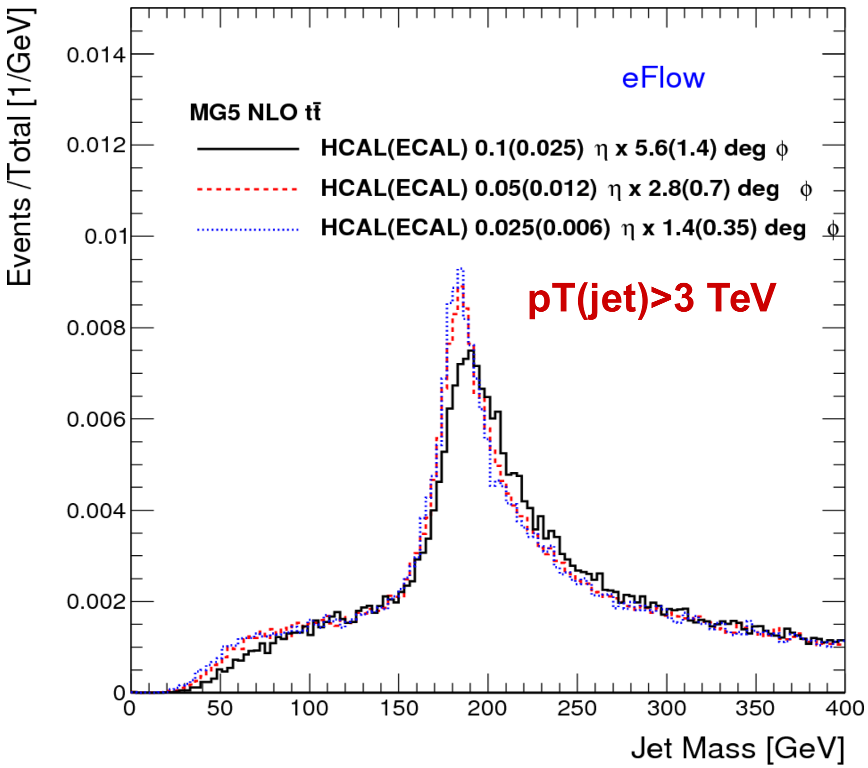


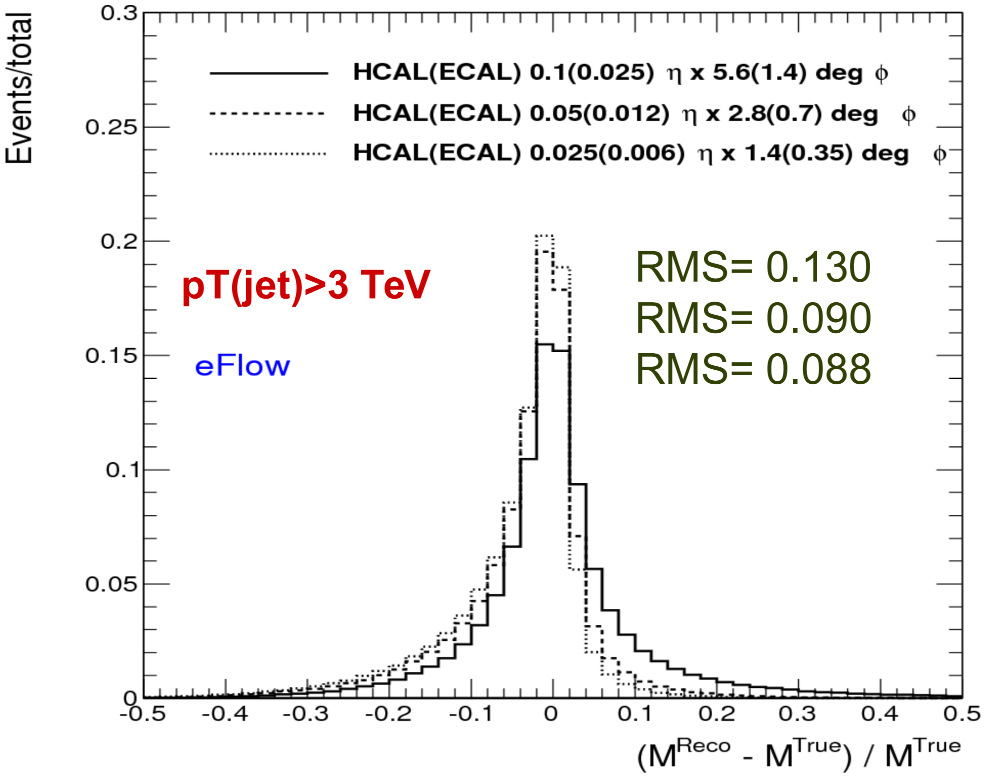


Jet mass. Finer HCAL & ECAL cells

- Assume x2 and x4 finer granularity of both ECAL and HCAL
- x2 (x4) granularity leads to 44% (48%) improvement in resolution

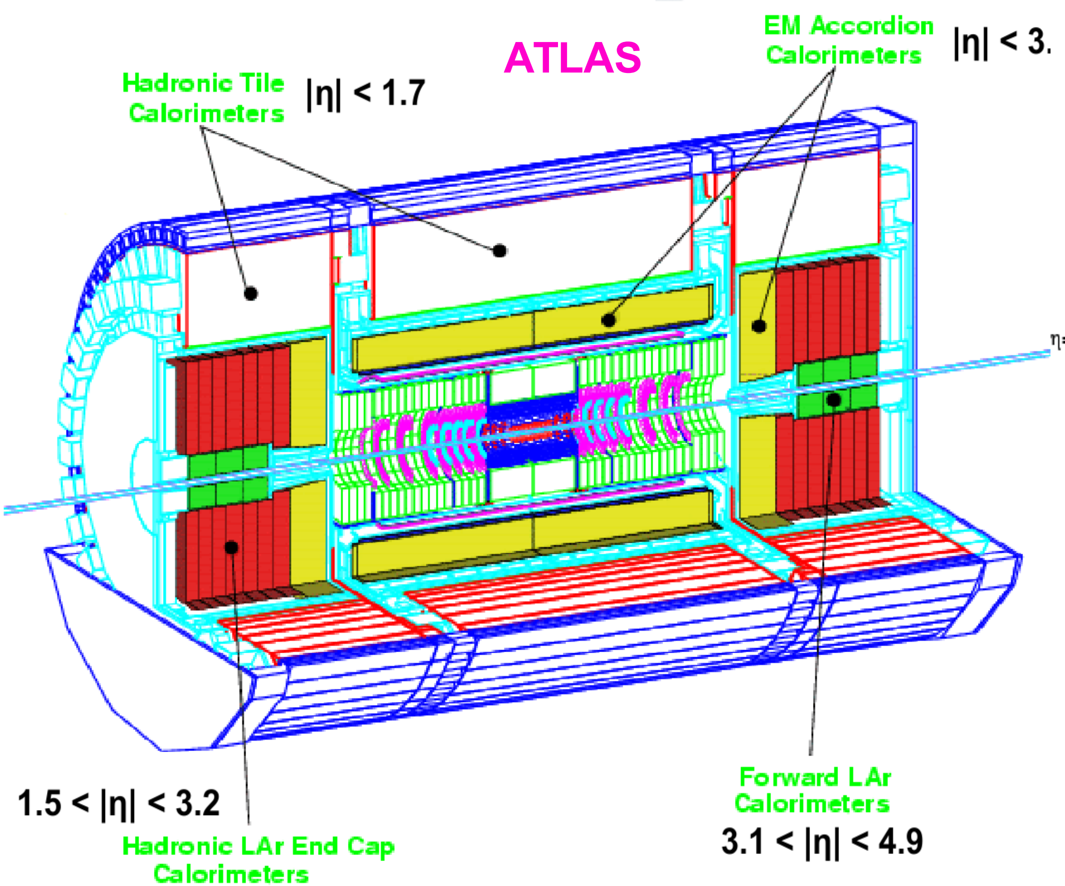
HepSim MC input + Delphes 3.2

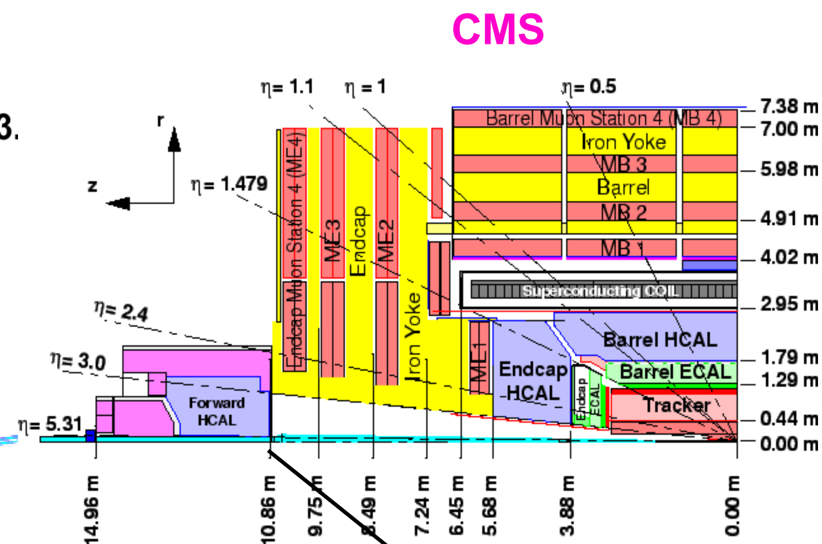


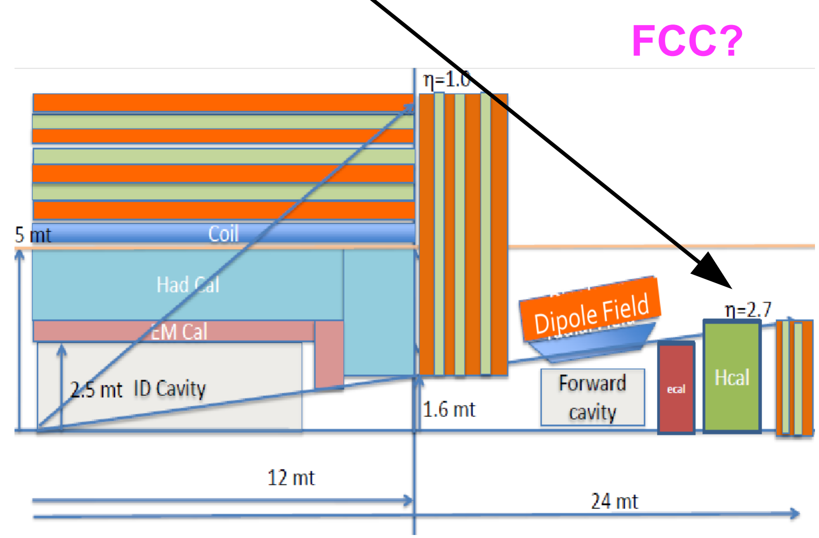


LHC

- Typical coverage of the LHC experiments in η ~ 5
- Usage of this region for physics is still a challenge
  - large radiation, coarse segmentation







Credits to P.Krieger