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

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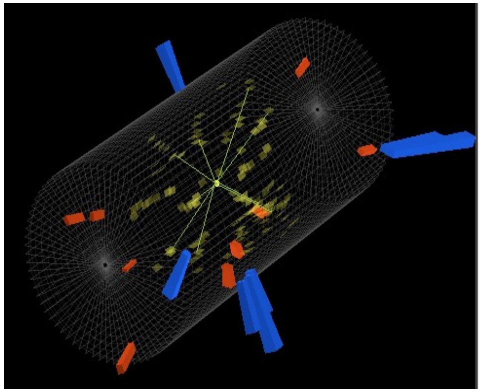
C. Solans, J.Proudfoot

FCC Week 2015
March 23-27, 2015.
Washington D.C.

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:

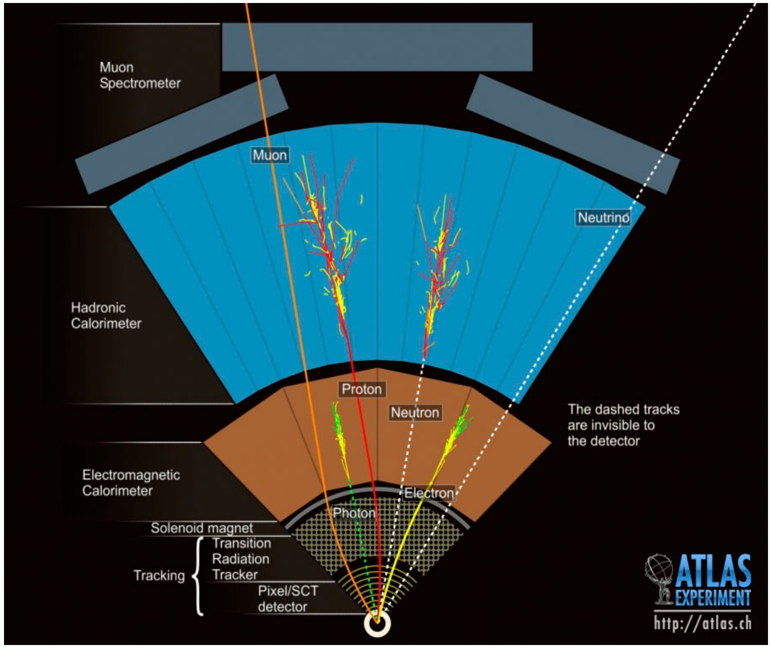


- Large jet transverse momentum
- Missing ET
- High-mass, long-lived particles
- Tau decays
- Veto on photons / electrons

} 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



Physics requirements for a hadron calorimeter

- **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**

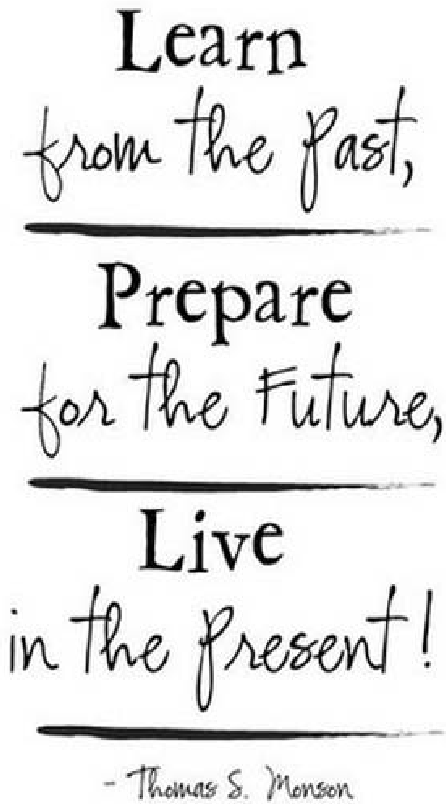
- Easy study: "technique **A** improves **B** by **X%**"
- It is harder to build a stronger case:
  - Unless technique **A** is improved by **X%**, physics **B** cannot be done!
- We are at the beginning of such studies

Past, Present, Future

SSC, etc.

FCC etc.

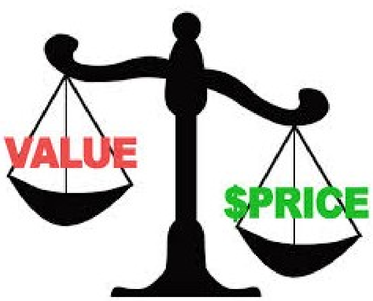
LHC



4π Calorimeter Parameters

Electromagnetic thickness	25 X_0, ~1λ	$\pm$ 5X_0
Precision Hadronic	5λ	
Total Precision EM + Hadr.	6λ	$\pm$ 1λ
Hadronic tail catcher	6λ	$\pm$ 1λ
Total	12λ	$\pm$ 2λ
Transverse Segmentation		
EM $\Delta y \times \Delta\phi$	.03 x .03	$\pm$ .01
Hadronic $\Delta y \times \Delta\phi$	.06 x .06	
Tail Catcher $\Delta y \times \Delta\phi$	.06 x .06	
Longtitudional Segmentation		
EM	3	$\pm$ 1
Hadronic	2	$\pm$ 1
Tail Catcher	2	$\pm$ 1

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



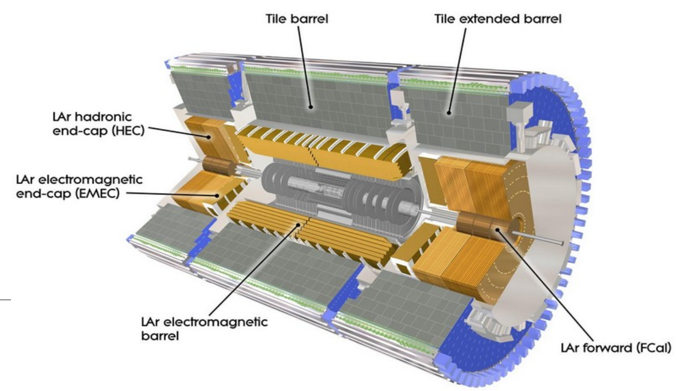
Other hadron calorimeters:

H1, ZEUS, CDF, D0, DHCAL/Calice

Present: ATLAS & CMS calorimeters

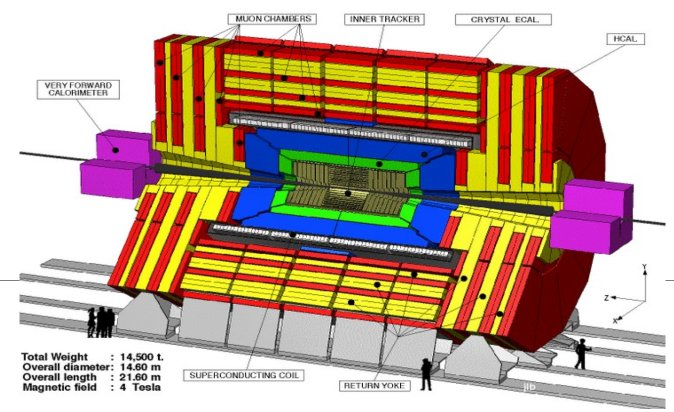
ATLAS

- Location: Before solenoid
- Longitudinal segmentation
- Angular measurements
- Slow (~400 ns)
- High granular
- Radiation resistance
- Good energy resolution
- Fe + scintillator



CMS

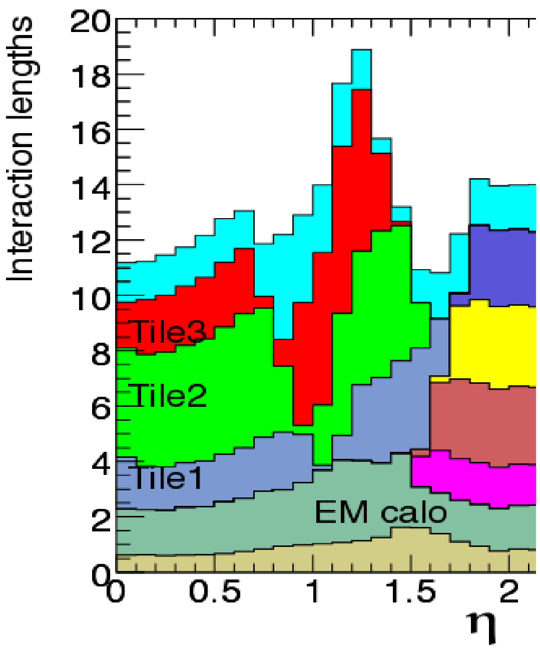
- Location: Behind solenoid
- Fast response (<100 ns)
- High granular
- Less radiation resistance
- Good energy resolution
- Brass + scintillator



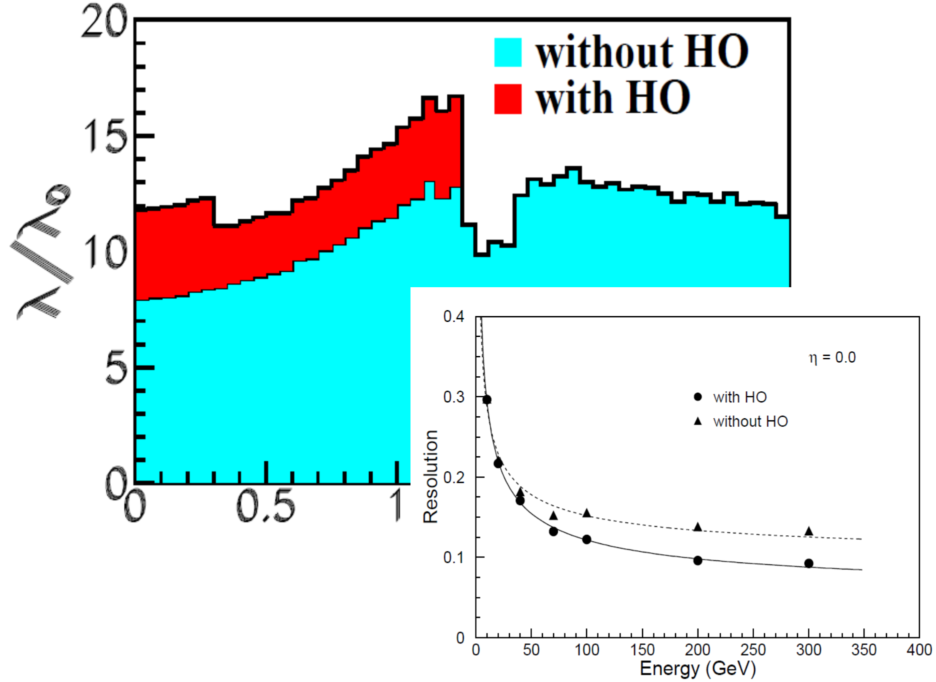
HCAL depth considerations

- 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 (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



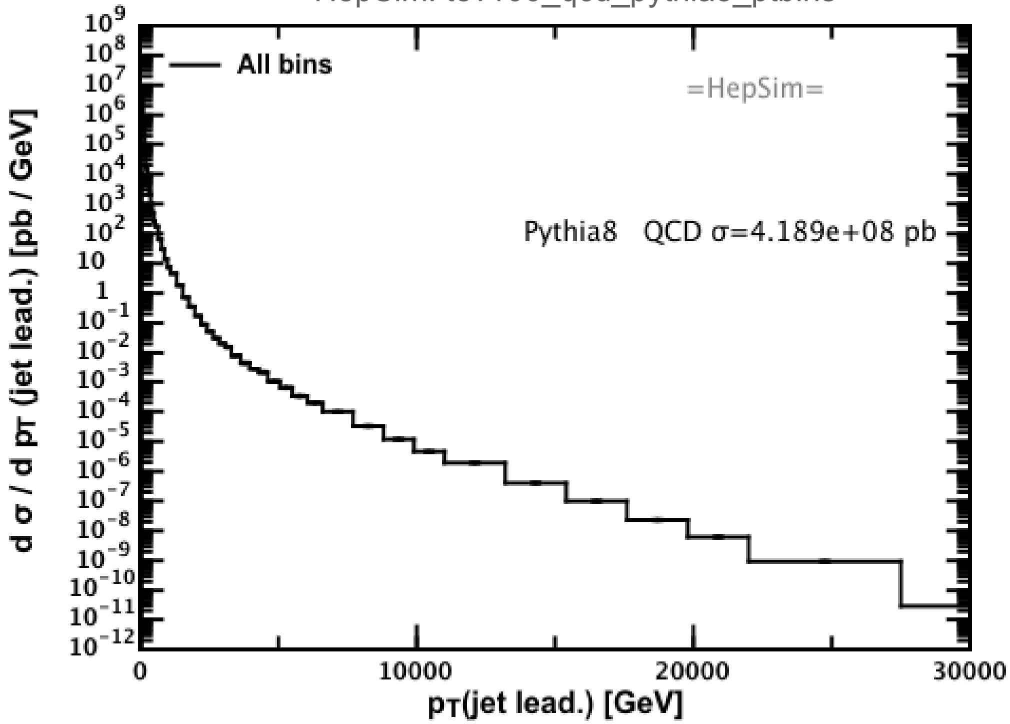
CMS



QCD jets at a 100 TeV collider

Business as usual: Jets with pT>10 TeV

HepSim: tev100_qcd_pythia8_ptbins



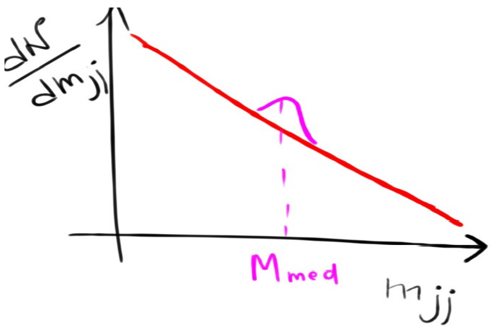
10 ab^{-1} :
few events are expected for pT(jet)>20 TeV at LO QCD

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

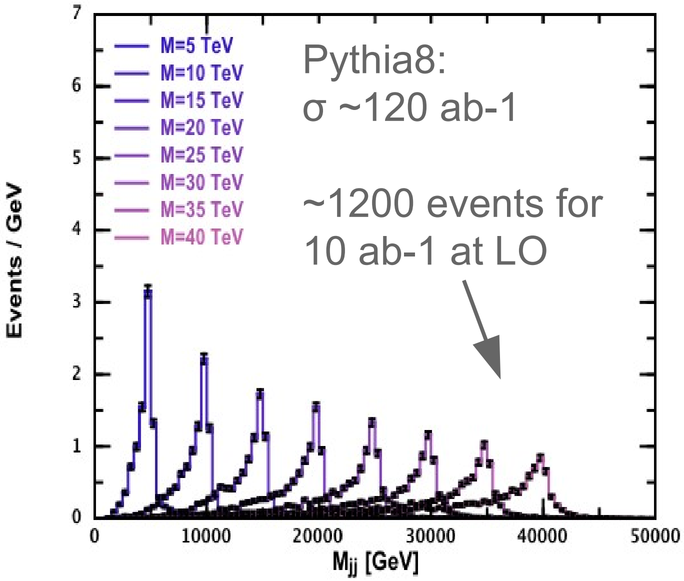
C.Helsens

Be prepared for pathological high-pT events!

Example: q* (40 TeV) → $q\bar{q}$



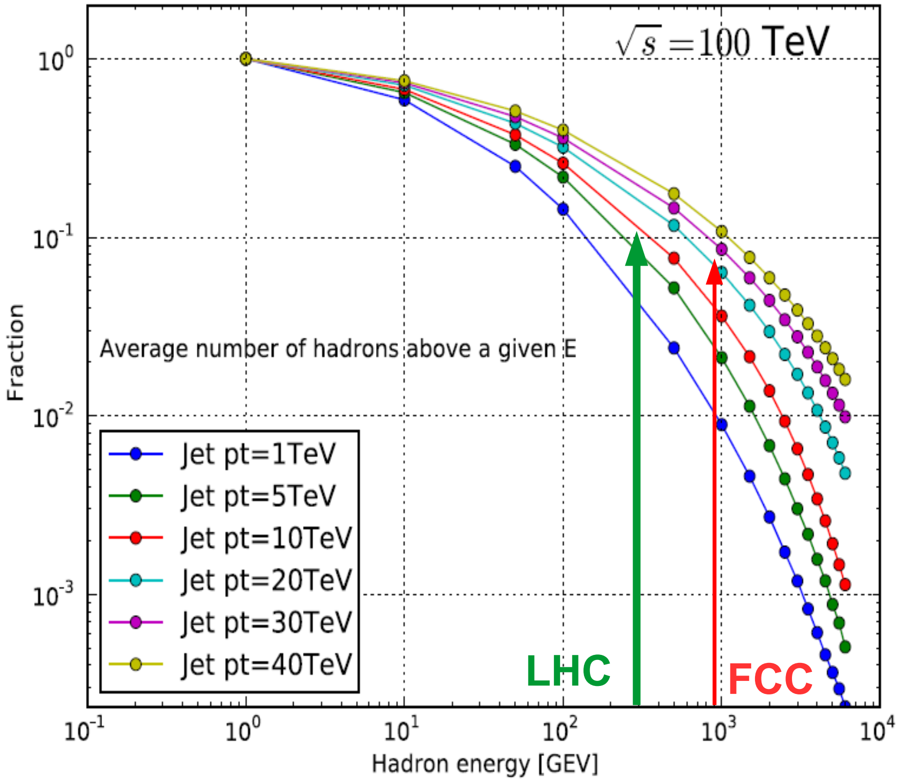
HepSim Monte Carlo database



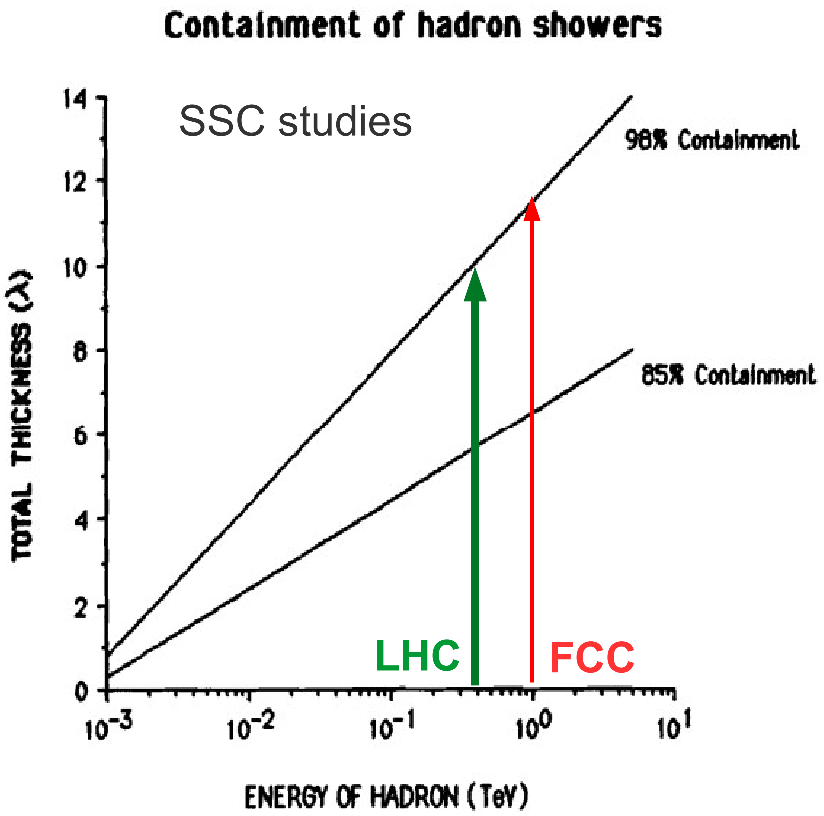
Estimating HCAL depth

Leading particles in high-pT jets

C.Helsens



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

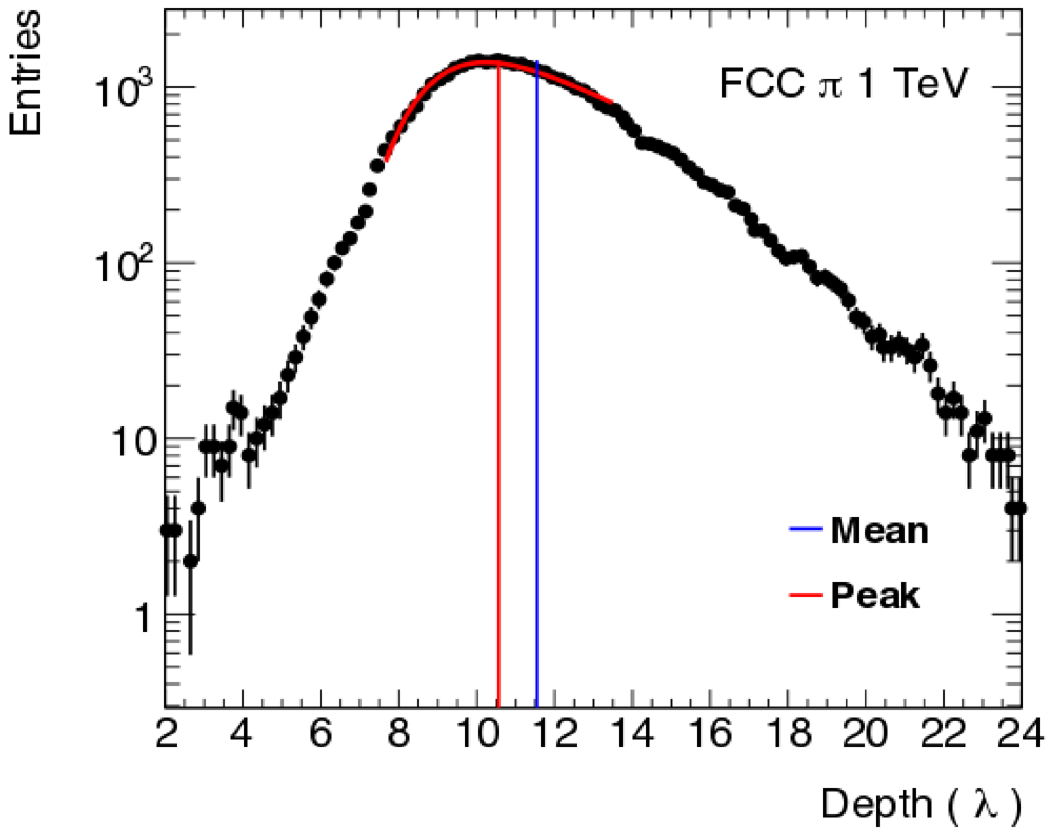


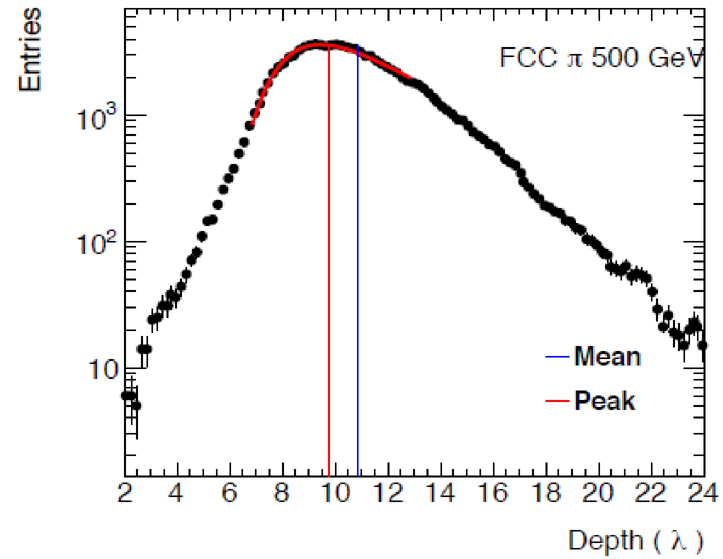
pT(jet)>30 TeV: ~10% will be carried by 1 TeV hadrons (~9 hadrons/jet)
12 λ is needed to contain 98% of energy of a 1 TeV hadron

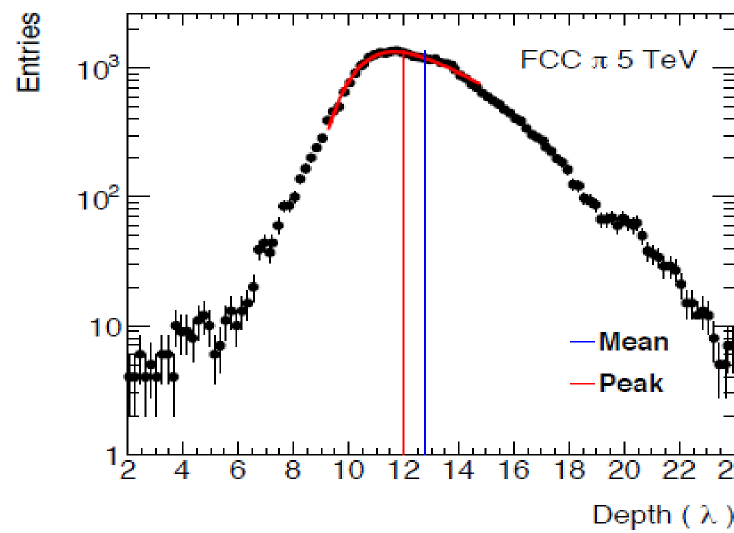
Estimating HCAL depth.   98% π containment depth

GEANT4 simulation: ATLAS-inspired calorimeter concept
Average value of λ needed to contain 98% energy:

C.Solans







12 λ is well motivated

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)

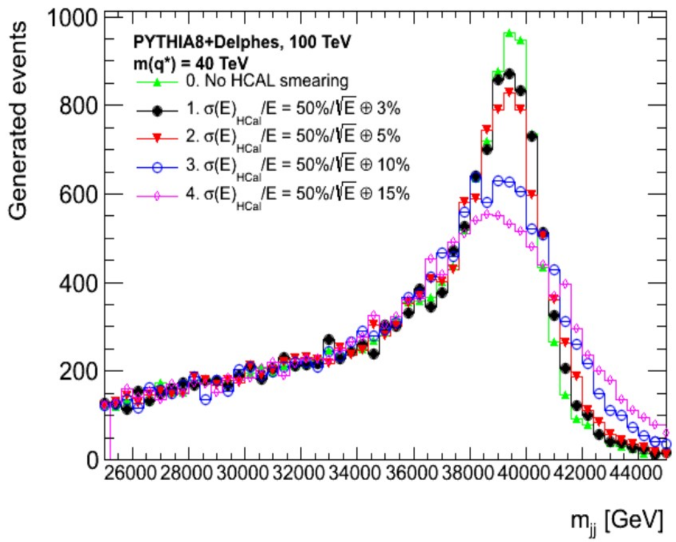
pT(jet)~1 TeV: Contribution of sampling term ~50% of that of the constant term
pT(jet)>5 TeV: Constant term dominates

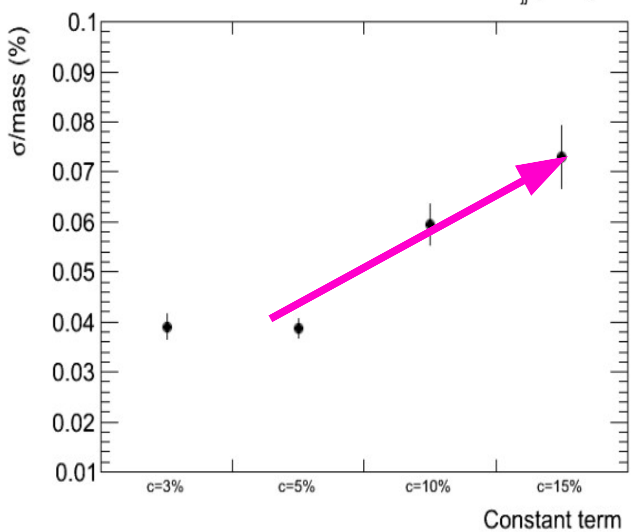
Reduction of constant term needs solutions for:
dead material, longitudinal and lateral energy leakage, non-uniformity calibration, transition region, etc.

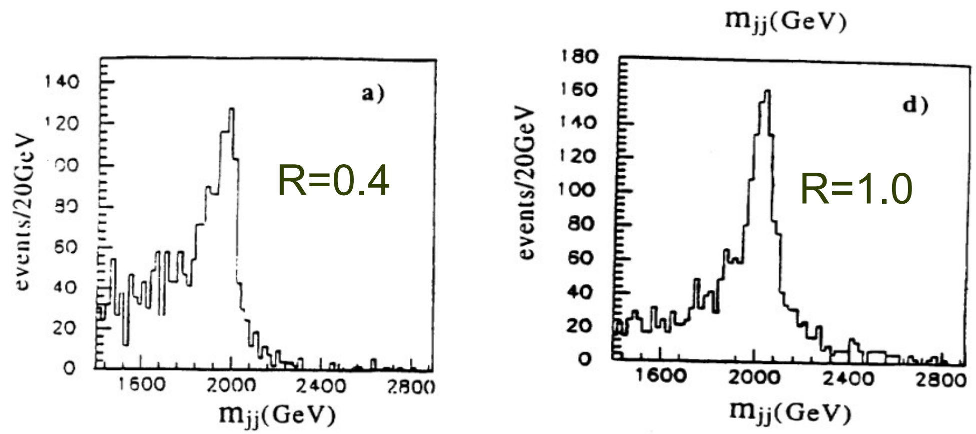
Dijet masses

D.Dylewsky, C.Doglioni, A.Henriques

excited fermions: q* → jj







ATLAS simulation 1992. A.Henriques, L.Poggioli

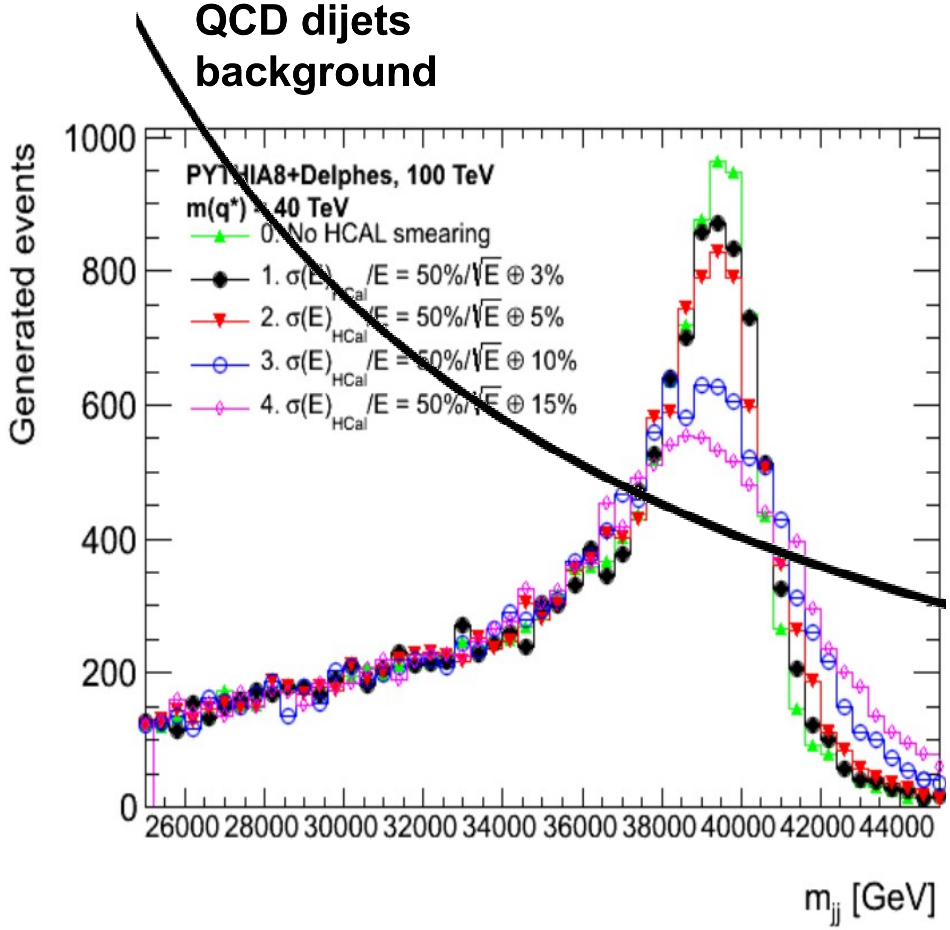
Smear MC samples (q*) with different calorimeter resolution hypotheses using Delphes & check effect on peak width

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

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

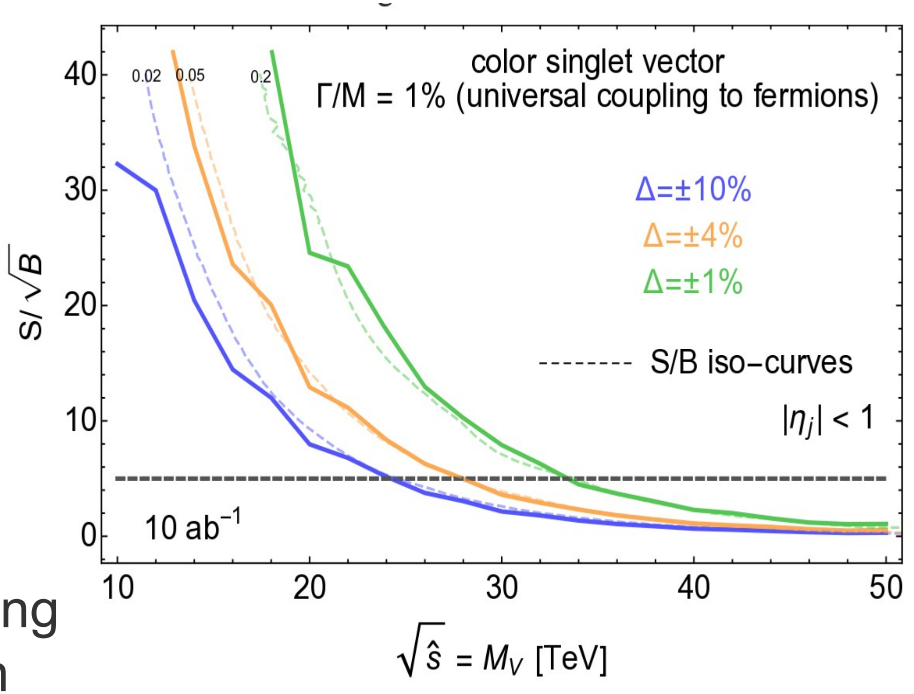
http://indico.cern.ch/event/352868/session/6/contribution/18/material/slides/0.pdf

Dijet mass resolution



But think about the discovery potential when adding QCD background!

R.Torre & M. Mangano



Shower and detector resolution smearing determine the achievable mass reach

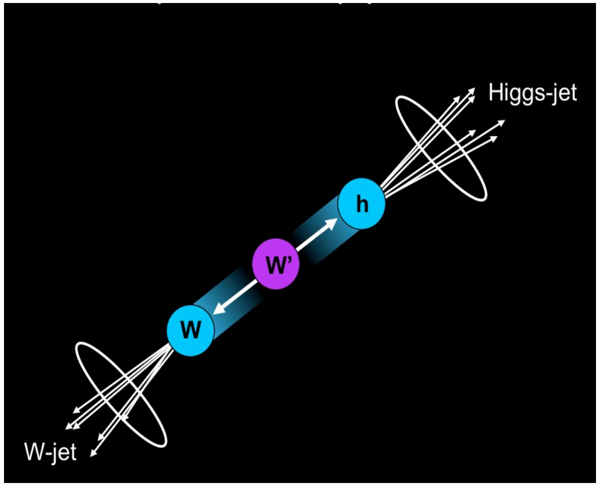
http://indico.cern.ch/event/352868/session/6/contribution/18/material/slides/

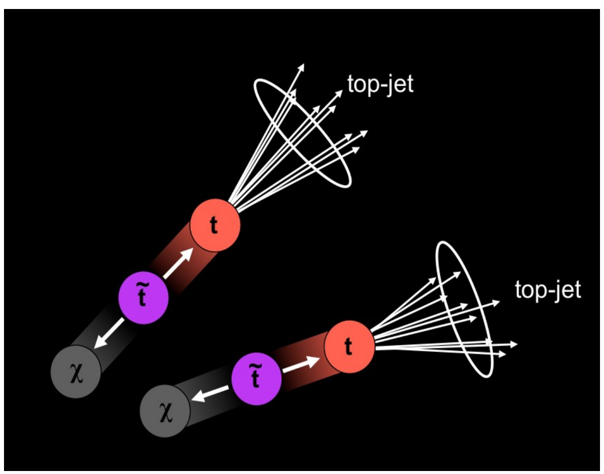
http://indico.cern.ch/event/352868/session/6/contribution/17/material/slides/

Lateral segmentation. Where does it matter..

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

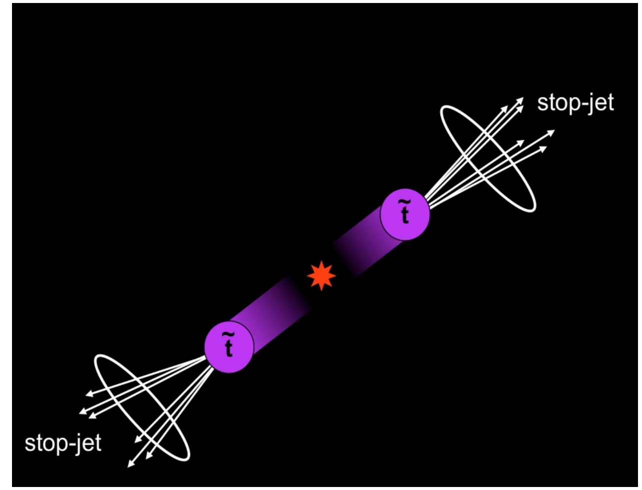
X → W / Z / Higgs / top

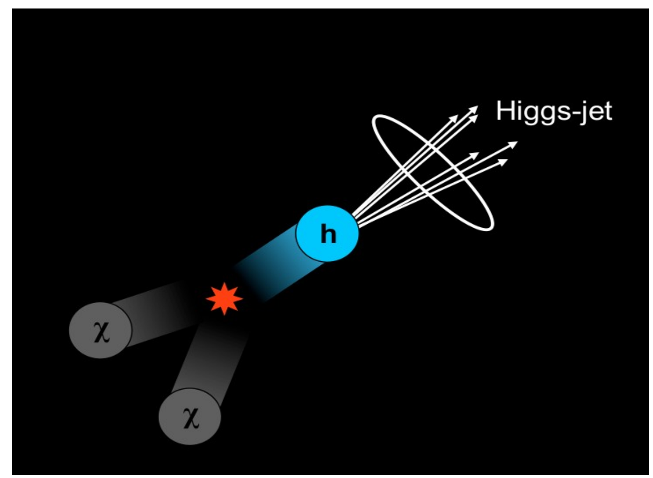




TeV-scale pair-produced

X → quarks/gluons

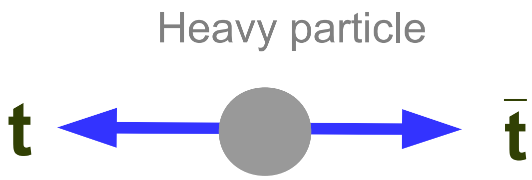


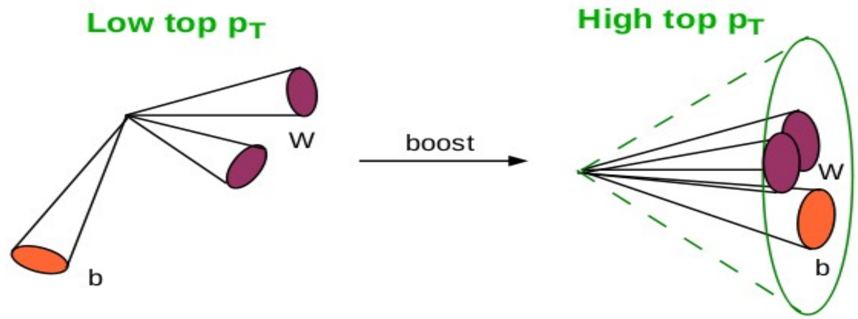


SM + dark matter

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

Boosted top from high-mass particles



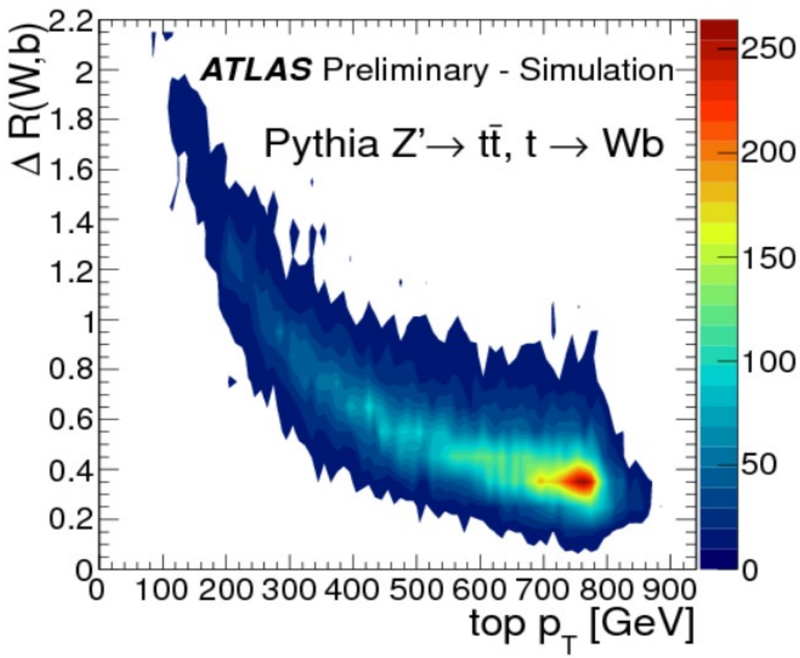


www.quantumdiaries.org

- M ~ 10 TeV corresponds to top quarks with pT(top) > 3-5 TeV
- ΔR distance between 2 particles (W,b) from top decay
- ΔR ~ 2* pT / m(top)

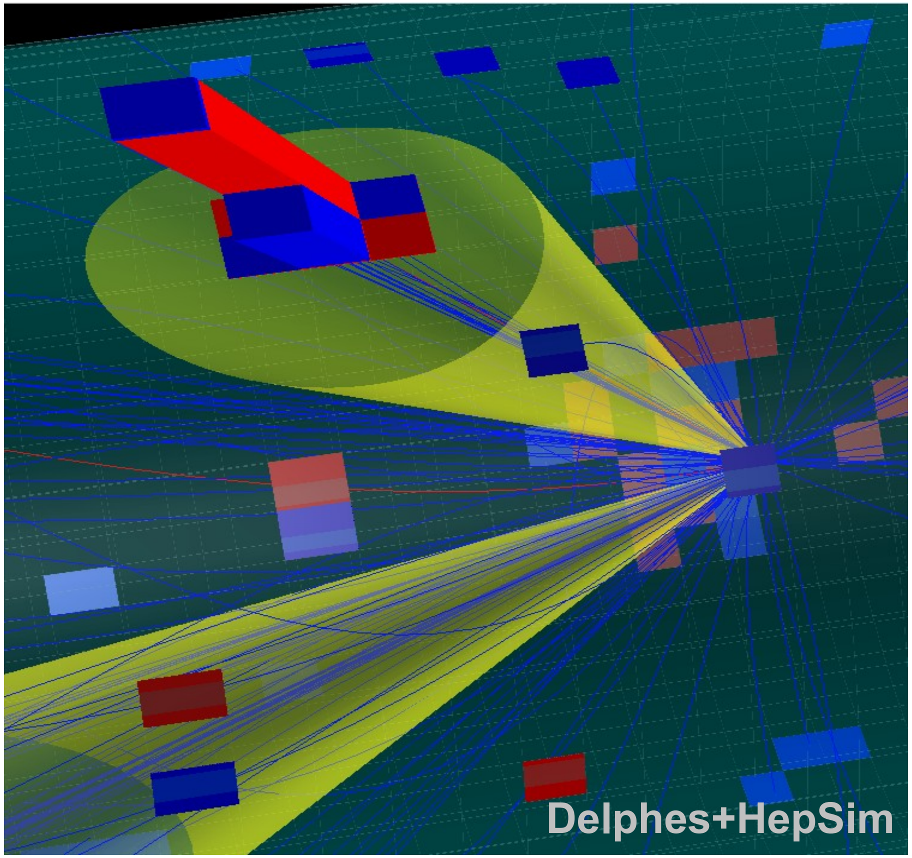
SM physics & 10 ab-1:

> 5M top events with pT(top)>3 TeV



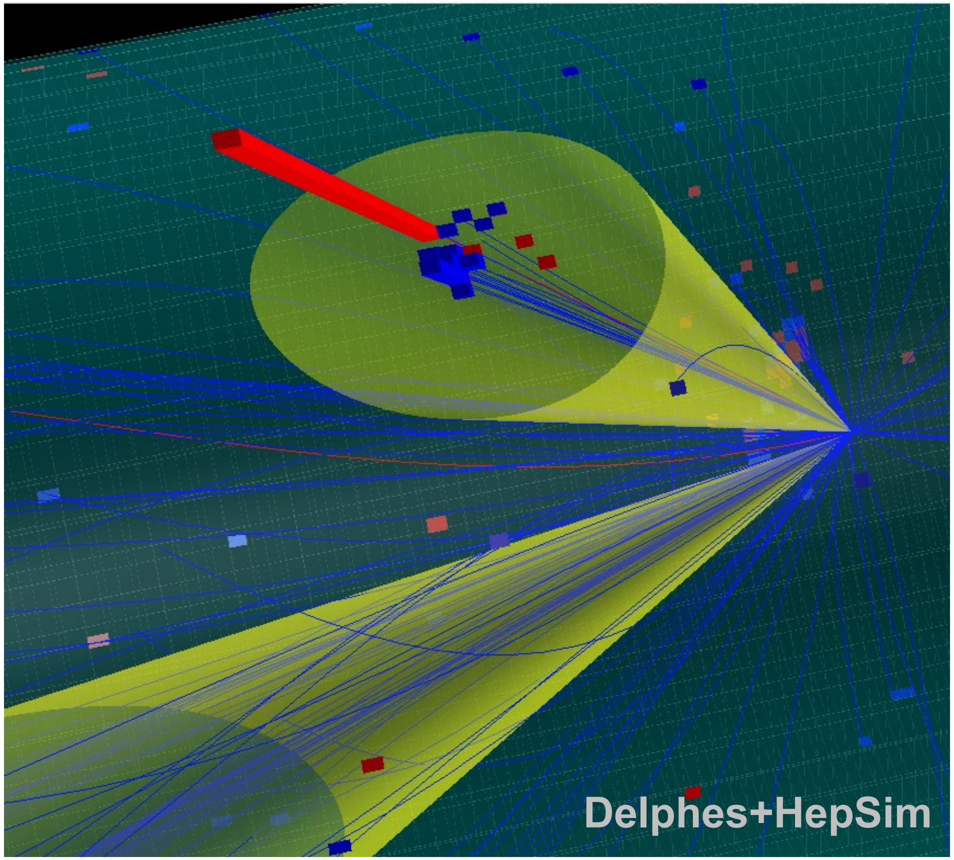
Example: Z'(10 TeV) → $t\bar{t}$ → 2 antiKT05 jets (pT(top)> 3 TeV)

Snowmass-like CAL geometry 'ATLAS'-like



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

x4 smaller CAL cells



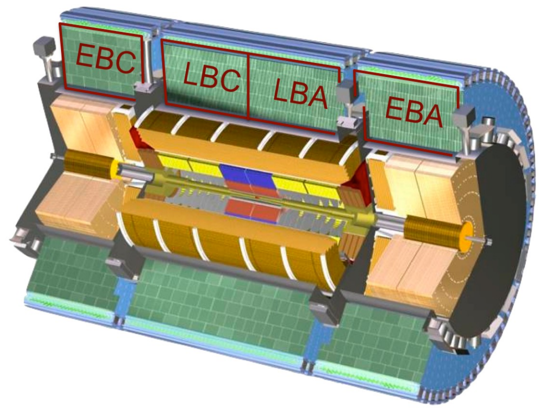
~ 1.25 deg :
Phi ~ 1.25 deg, Eta ~ 0.025

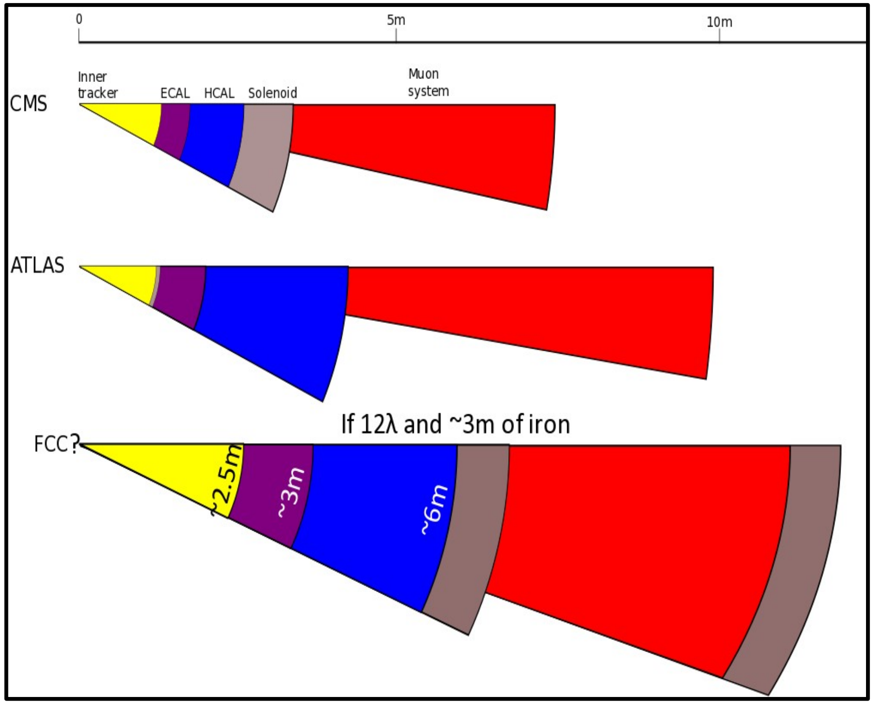
x 4 better segmentation

Calorimeter segmentation

- **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 and technology**
  - → look at physics with fast det. simulations
- **Better segmentation in η can be done with different readout**
- **But watch the Molière radius (Fe,Pb<2 cm)**

HCAL (Tile)





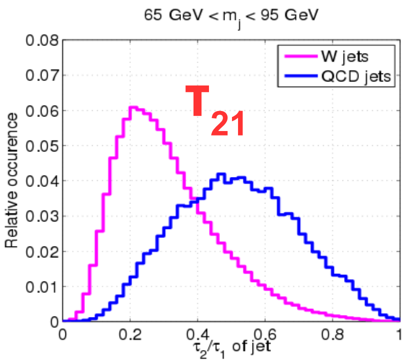
C.Barnet, C.Helsens

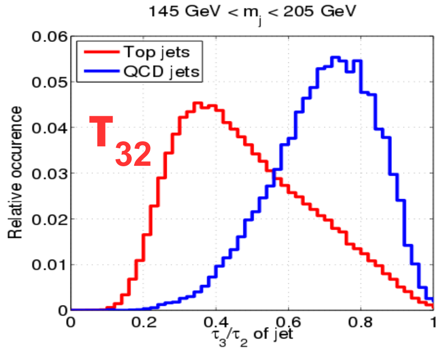
Substructure variables

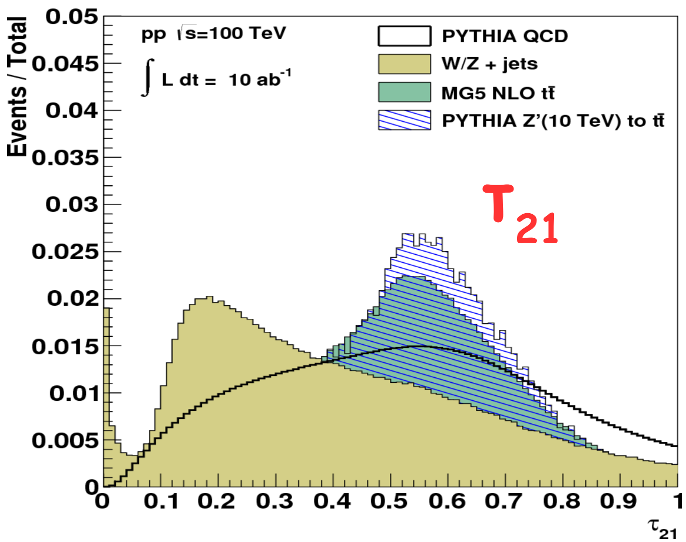
- τ_N-subjettiness - measure of the degree to which a jet can be considered as being composed of N-subjets
- $\tau_{21} = \tau_2 / \tau_1 \qquad \tau_{32} = \tau_3 / \tau_2$

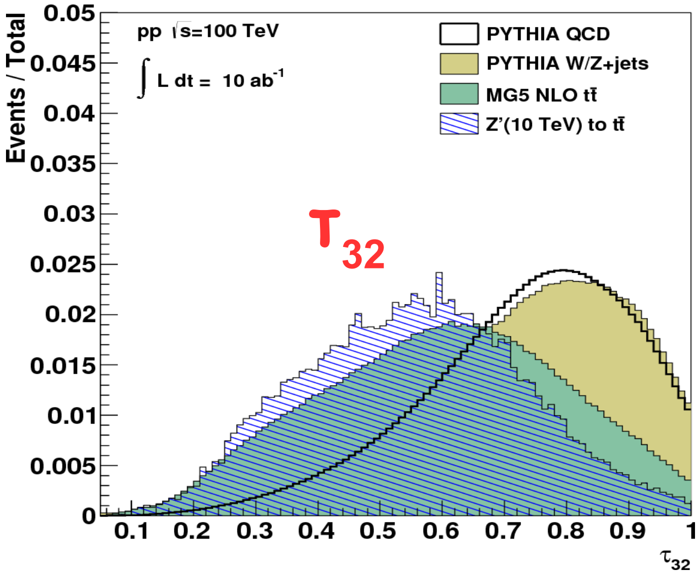
J.Thaler and K. Van Tilburg, JHEP 1103 (2011) 015

- τ_{21} **<0.3** cut reduces W/Z bkg.
- τ_{32} **>0.75** cut reduces QCD & W/Z bkg.









B. Auerbach, S. C., J. Love, J. Proudfoot, A.V. Kotwal. Phys. Rev. D 91 (2015) 034014

Calorimeter segmentation studies

HepSim

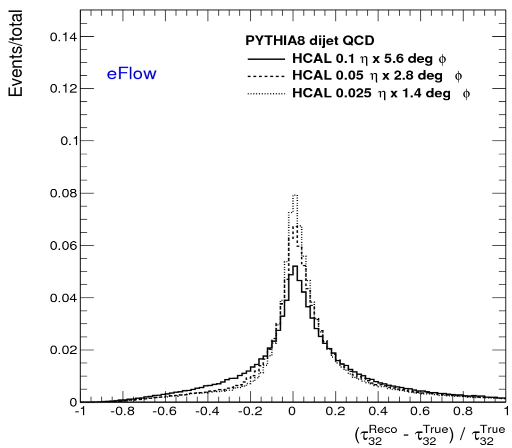
DELPHES
fast simulation

- 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

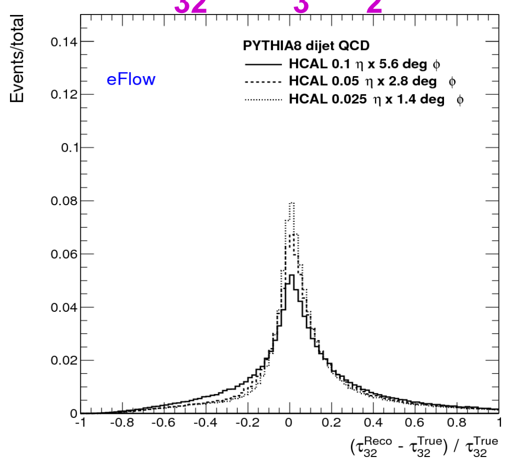
- **Eflow setup:**
  - Charge particles from tracks
  - Photons/electrons in ECAL
  - Rest: 60% of energy in HCAL

- **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 ~40 (45)% improvement in jet mass resolution**

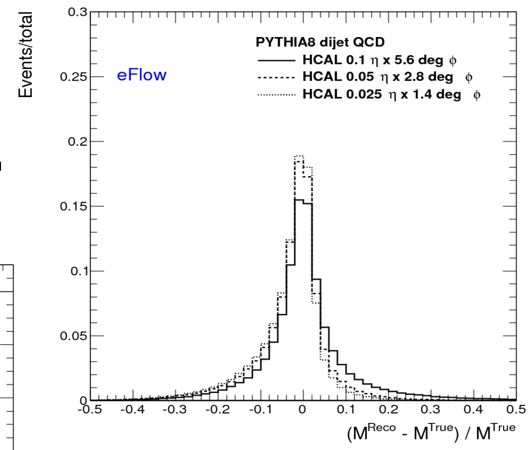
$\tau_{21} = \tau_2 / \tau_1$



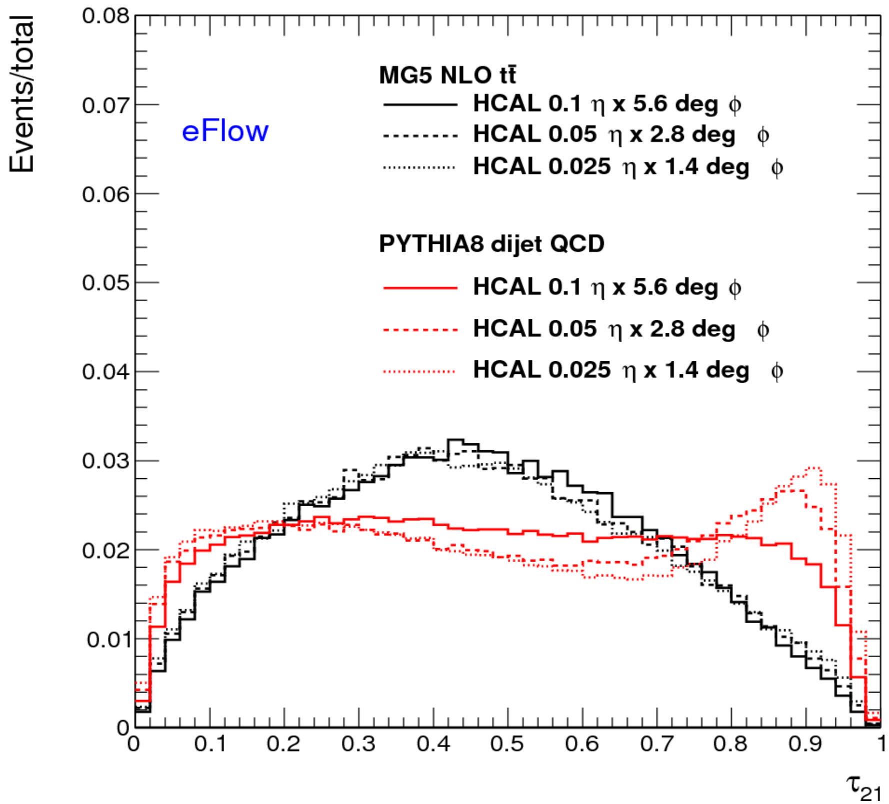
$\tau_{32} = \tau_3 / \tau_2$

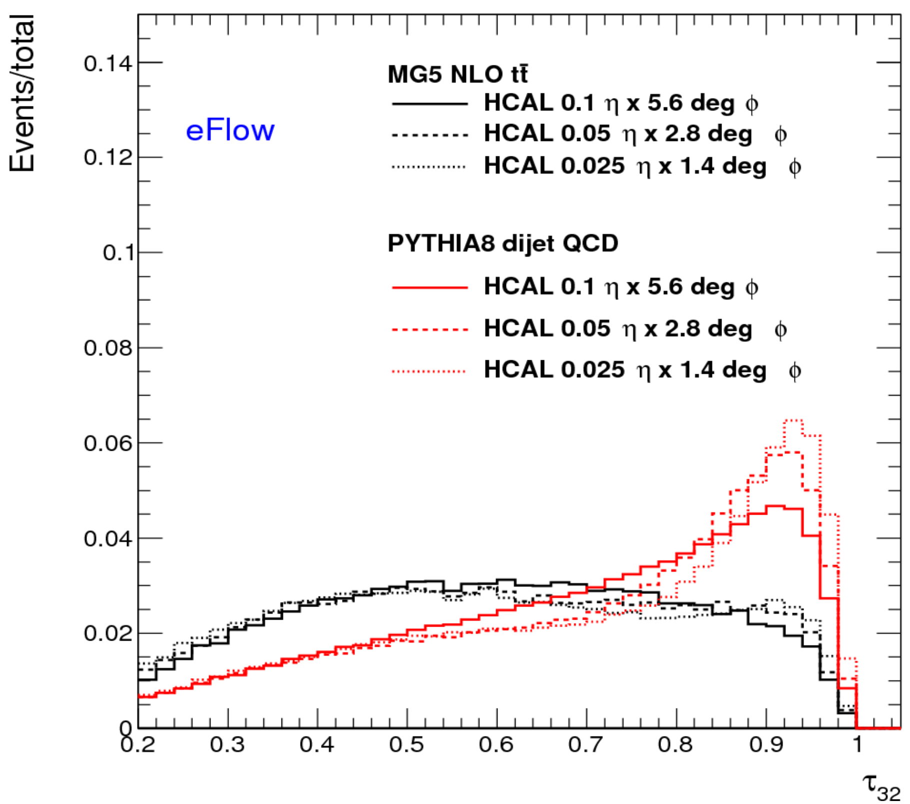


Jet mass



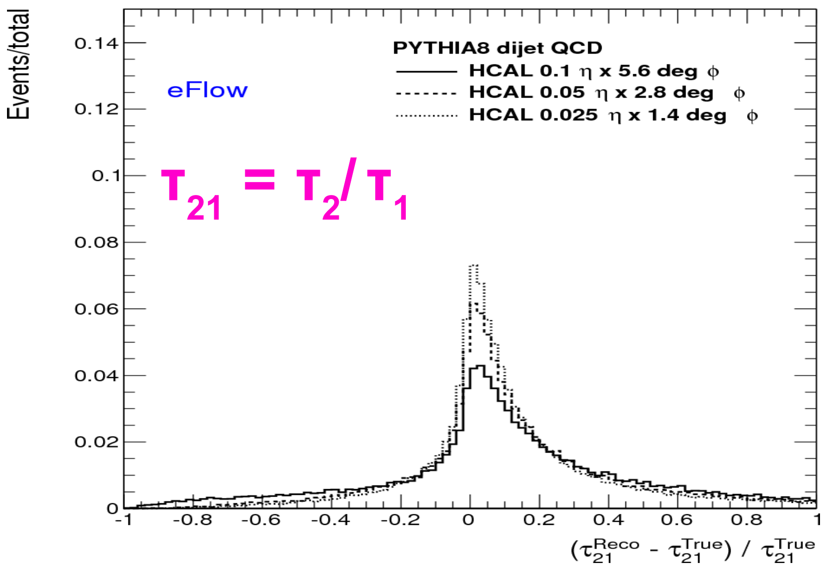
Finer HCAL cells. Boosted top quarks & QCD dijets

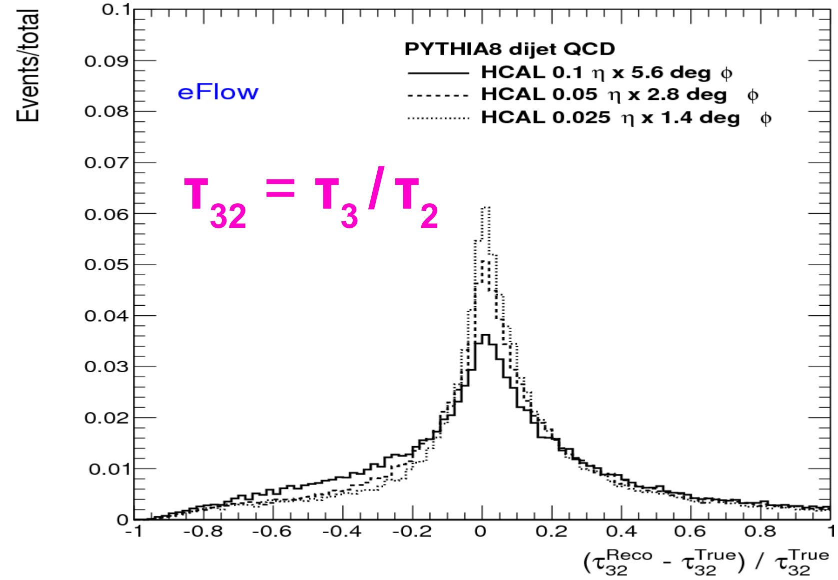


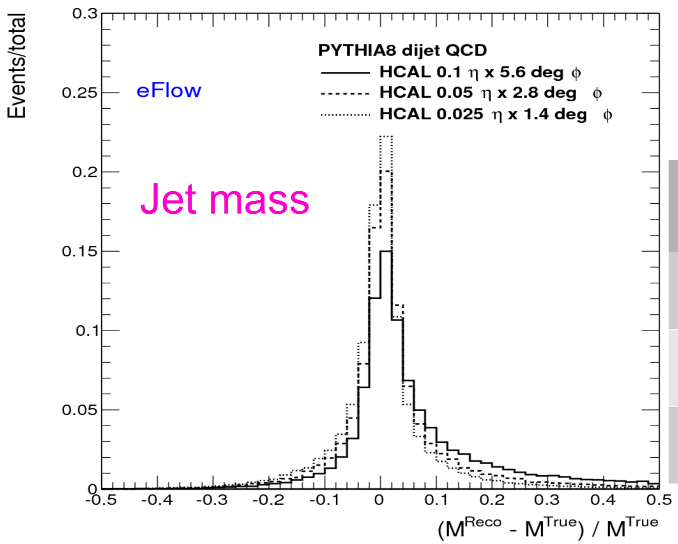


- **0.1 → 0.05 cell size reduction improves QCD background rejection**
- **0.05 → 0.025 cell size reduction shows smaller improvement**
- **Same conclusion for smaller cell size**

Resolution for pT(jet)>10 TeV







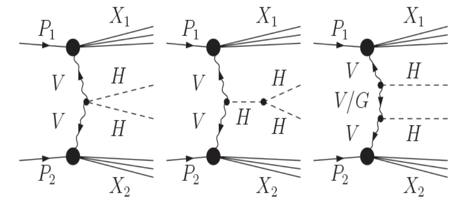
Decrease in RMS compared to $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

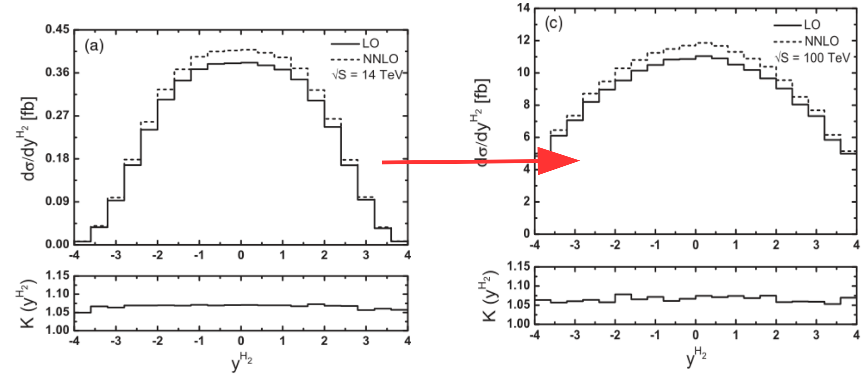
	$\Delta\eta \times \Delta\varphi = 0.05 \times 0.05$	$\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$
tau21	18%	28%
tau32	9%	13%
jet mass	80%	200%

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

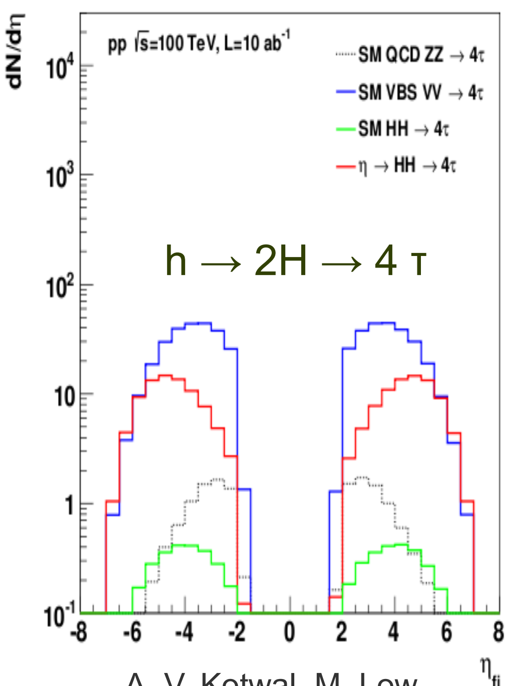
Forward η coverage. Physics cases

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

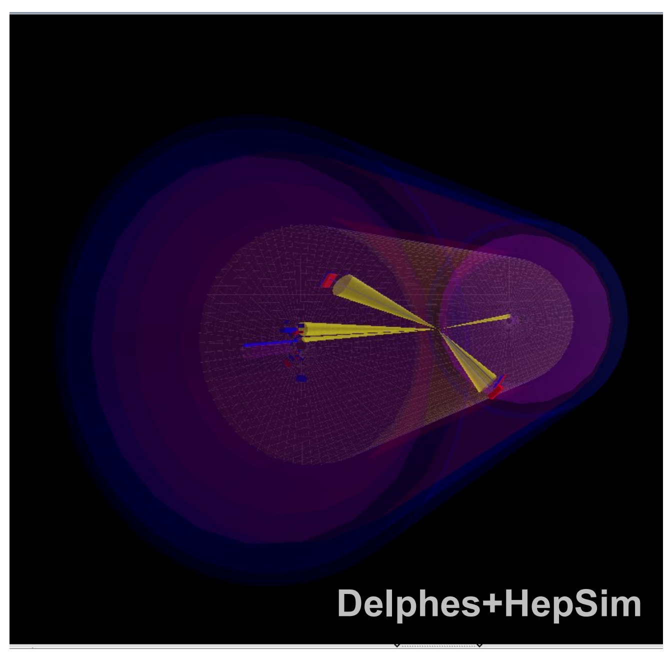




Typical requirement for η coverage: ~ 6



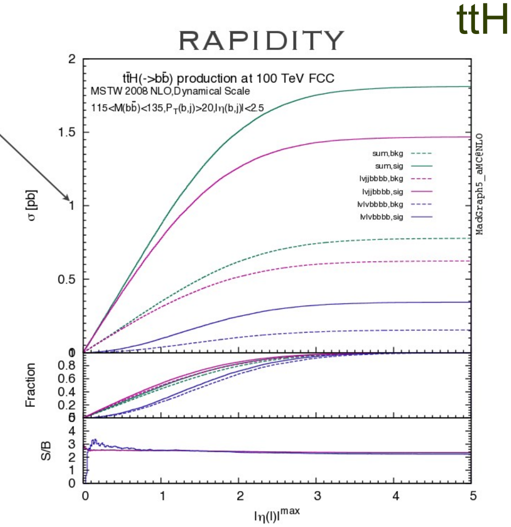
A. V. Kotwal, M. Low



Phys. Rev. D 89, 073001, Liu-Sheng Ling, Ren-You Zhang, Wen-Gan Ma, Lei Guo, Wei-Hua Li, and Xiao-Zhou Li

$t\bar{t}H$

10 M events with 10 ab-1



Hua-Sheng Shao

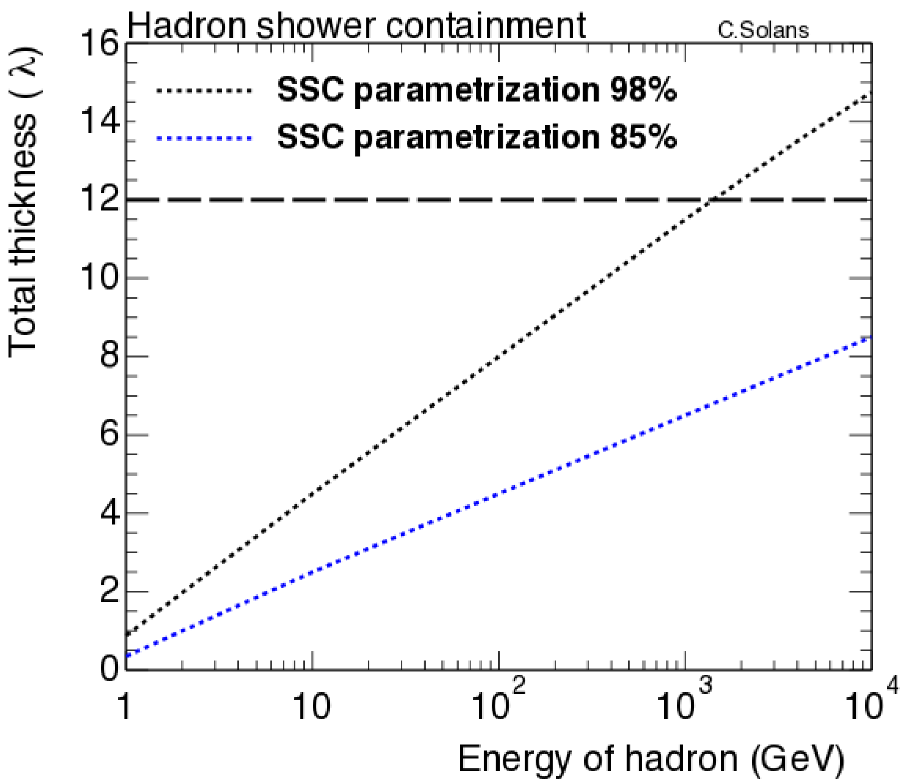
https://indico.cern.ch/event/356664/contribution/5/material/slides/0.pdf

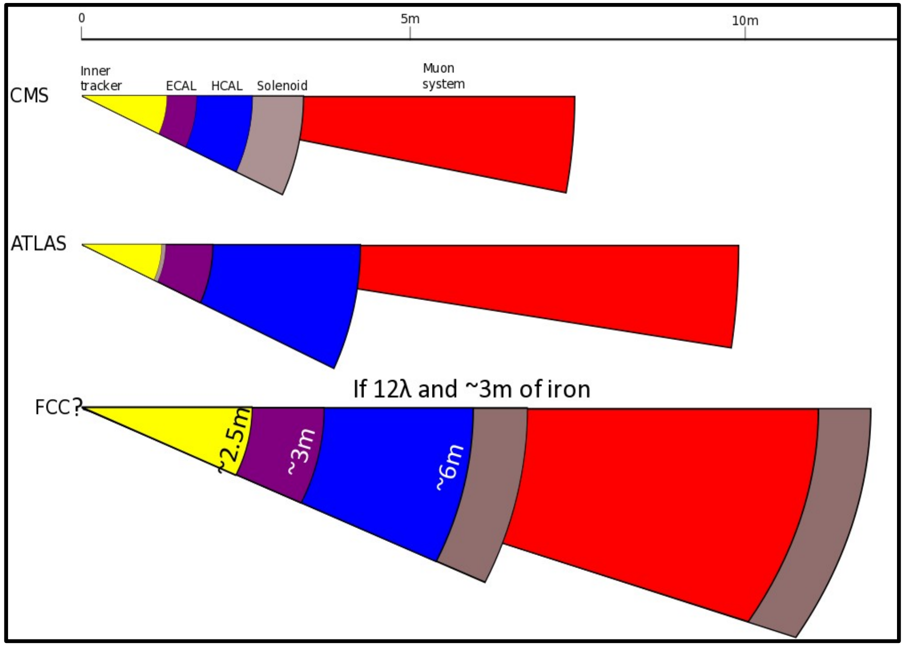
Summary. HCAL characteristics

- **12 λ in depth**
- **Energy resolution with C~3% and below**
- **Longitudinal segmentation for 3D clusters**
- **Δη x Δφ = 0.05 x 0.05 (and smaller)**
  - Based on resolution studies of substructure variables
- **Δη x Δφ = 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
- **New technology is needed to achieve x4 better segmentation**
- **Extended coverage η~6 is designed**

Backup

Estimating HCAL depth



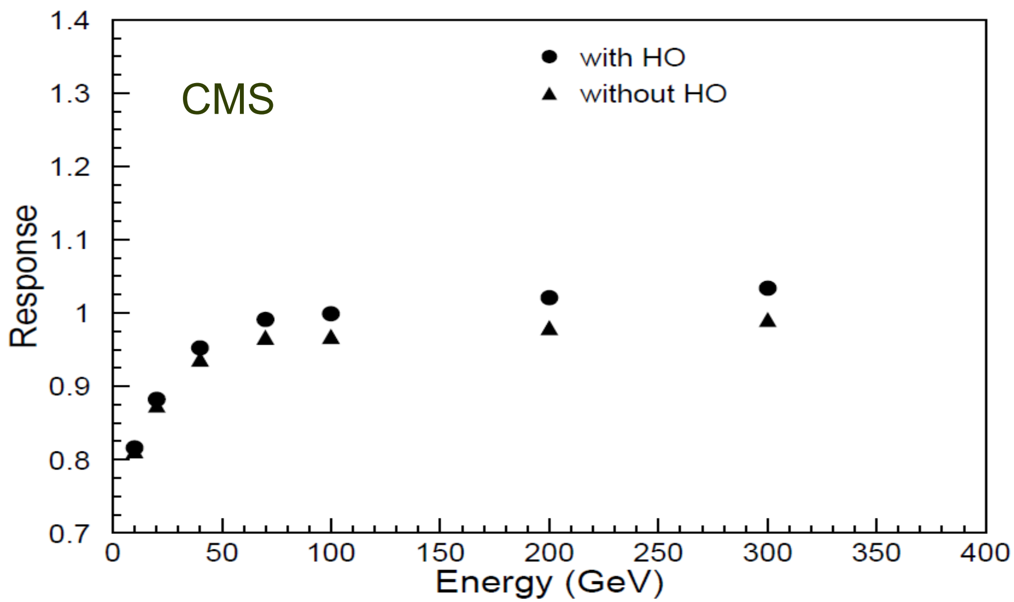


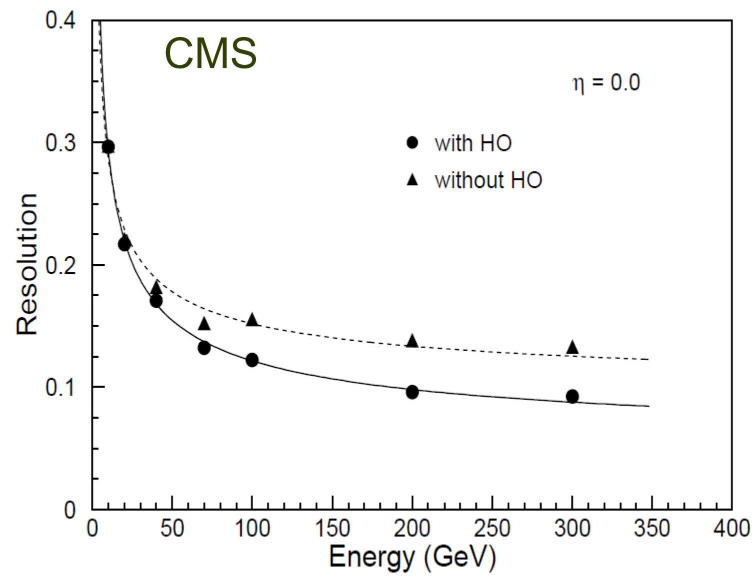
Missing part: Realistic Geant4 simulation of jets up to pT(jet)~30 TeV
Estimation of punch-through events
Missing ET is missing study! (important for transverse and η containment)

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

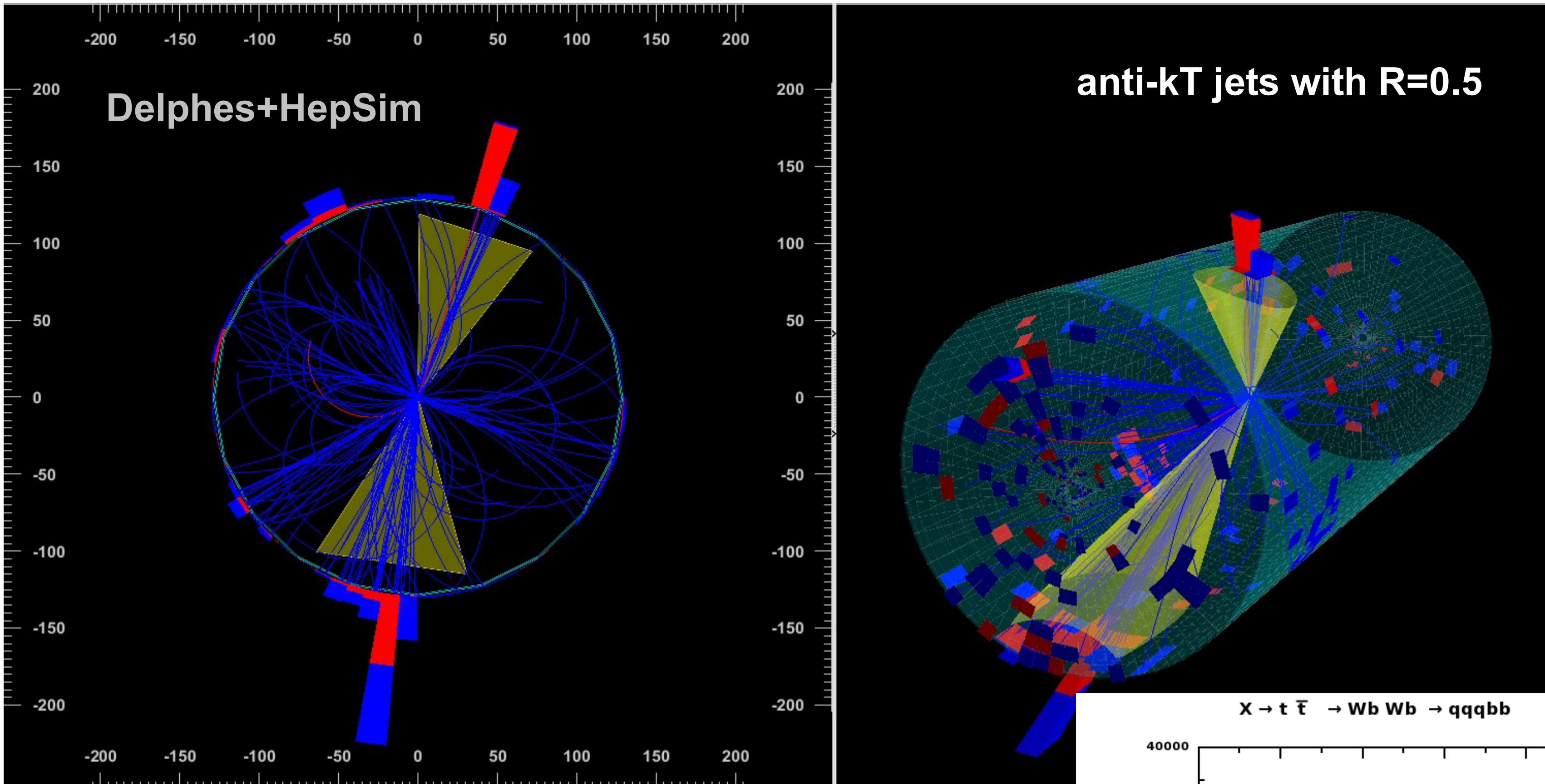
<E>/E(ins)

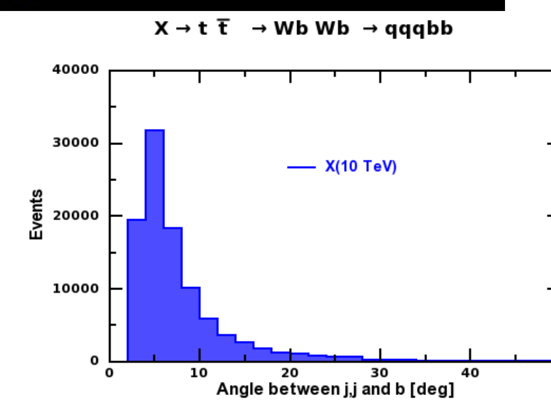




CMS NOTE 1999/063

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

- 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

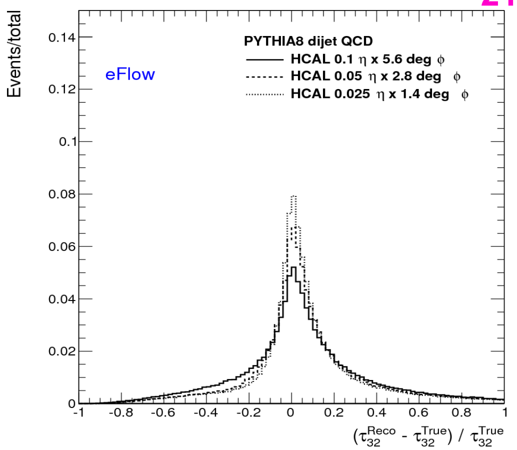
- **EFlow:**
  - Charge particles from tracks
  - Photons/electrons in ECAL
  - 60% of measured in HCAL
- **Towers:**
  - Photons/electrons in ECAL
  - 60% of other particles in HCAL

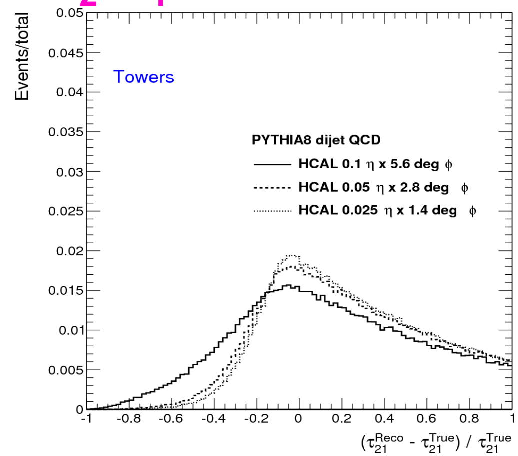
- **Improvement in resolution by 10-15% going from 0.1 to 0.05 cell size**
- **Improvement by 4-5% going from 0.05 to 0.025 cell size**

HepSim → DELPHES fast simulation

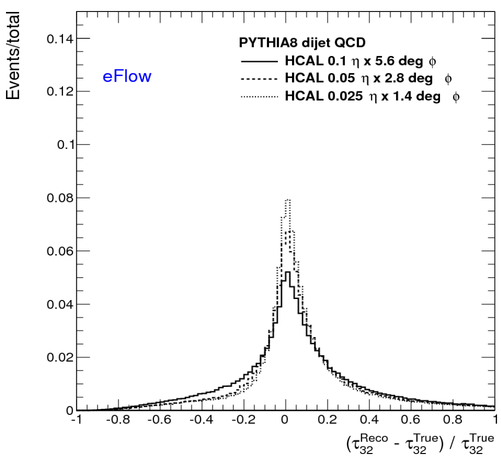
resolution studies

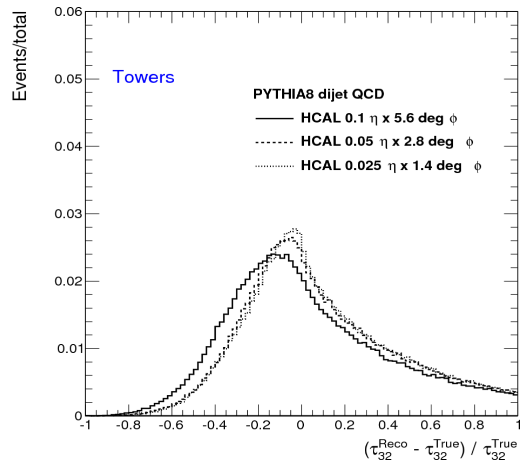
$\tau_{21} = \tau_2 / \tau_1$





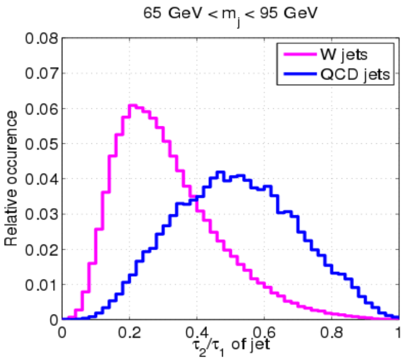
$\tau_{32} = \tau_3 / \tau_2$

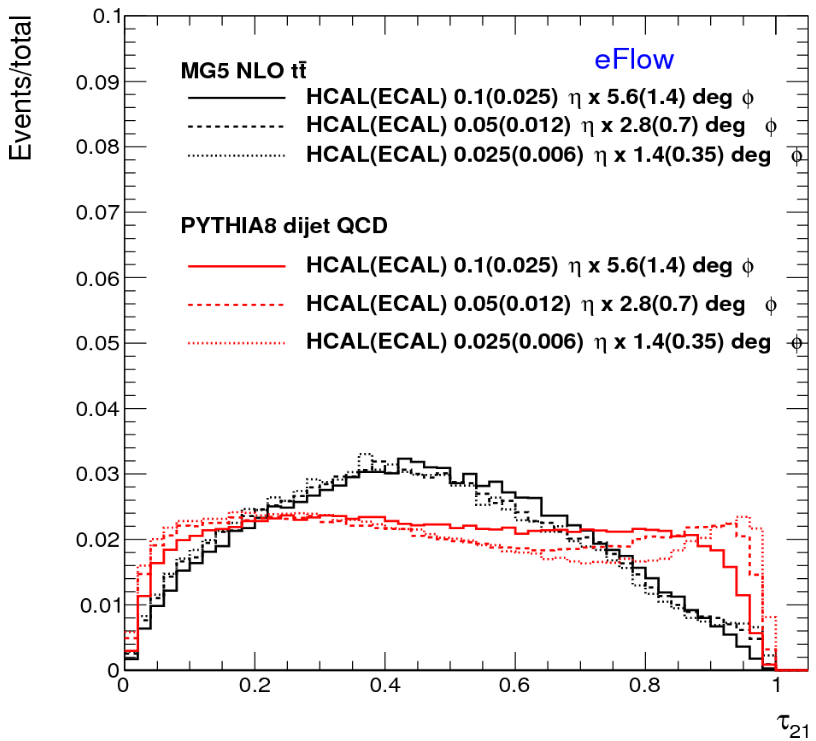


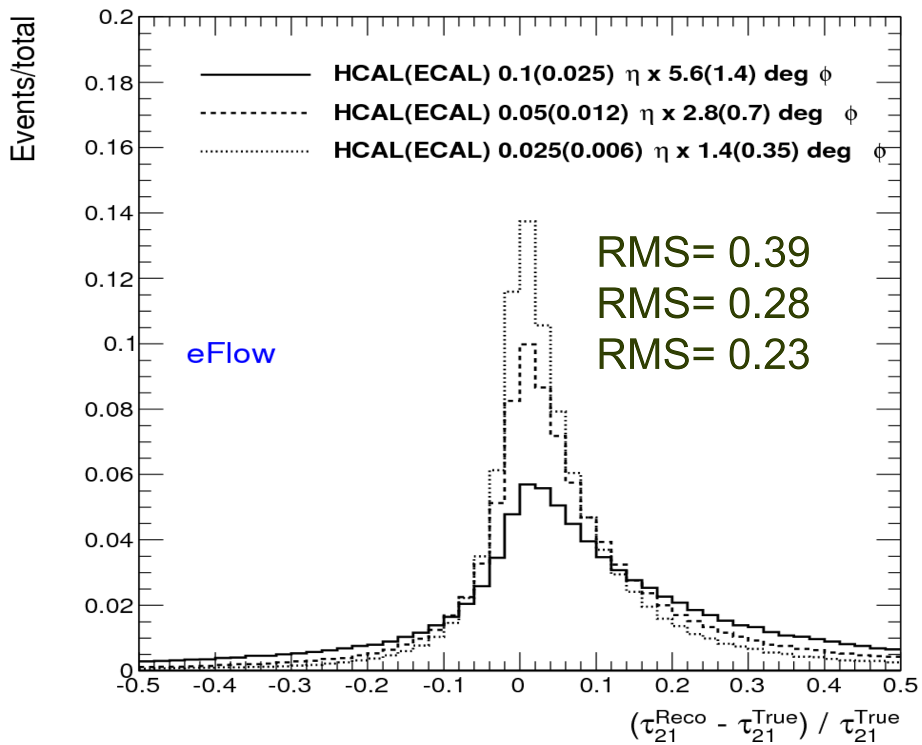


τ_{21}. Finer HCAL & ECAL cells. Delphes fast simulation

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



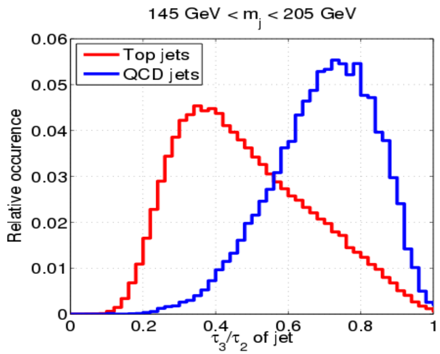


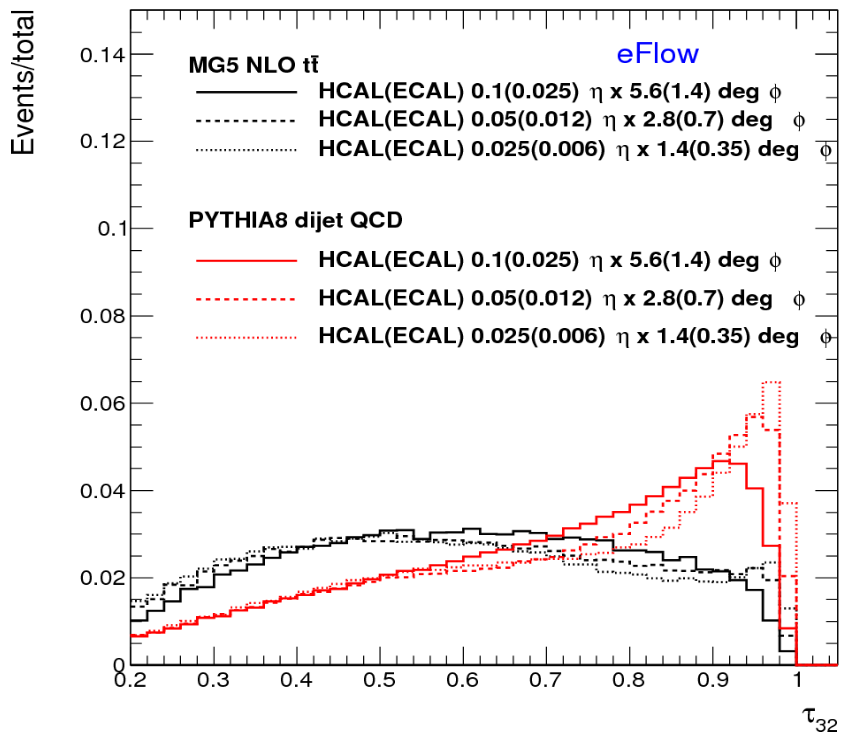


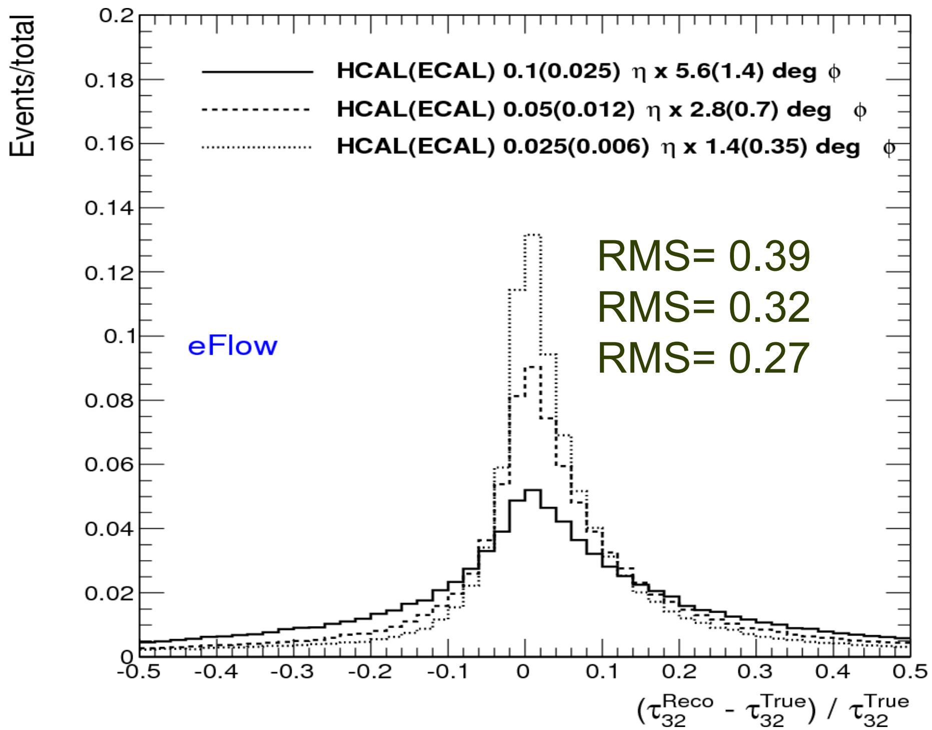
HepSim MC input + Delphes 3.2

τ_{32}. Finer HCAL & ECAL cells. Delphes fast simulation

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





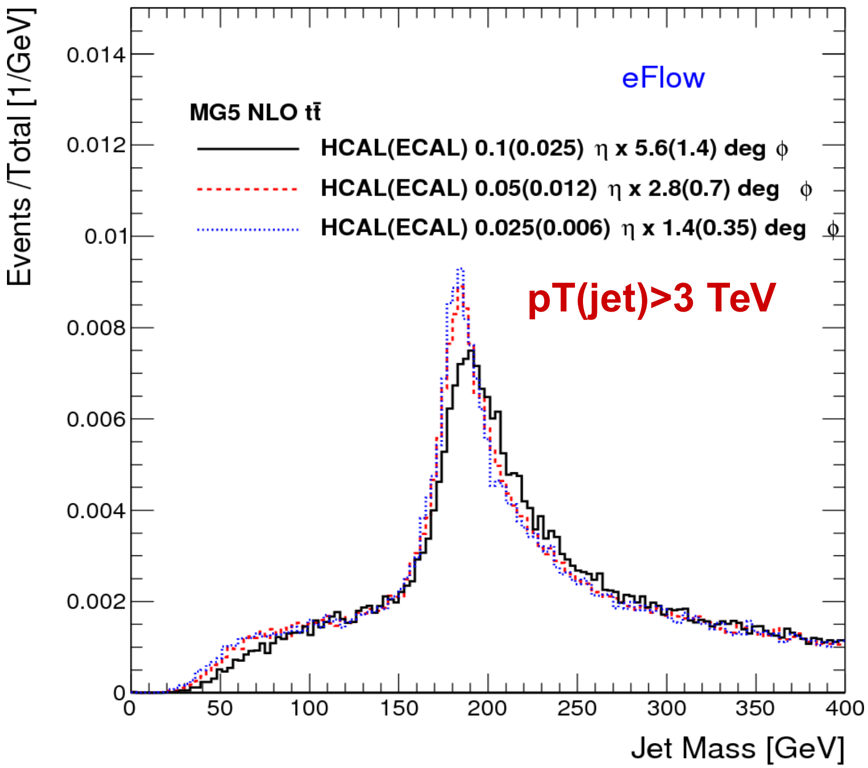


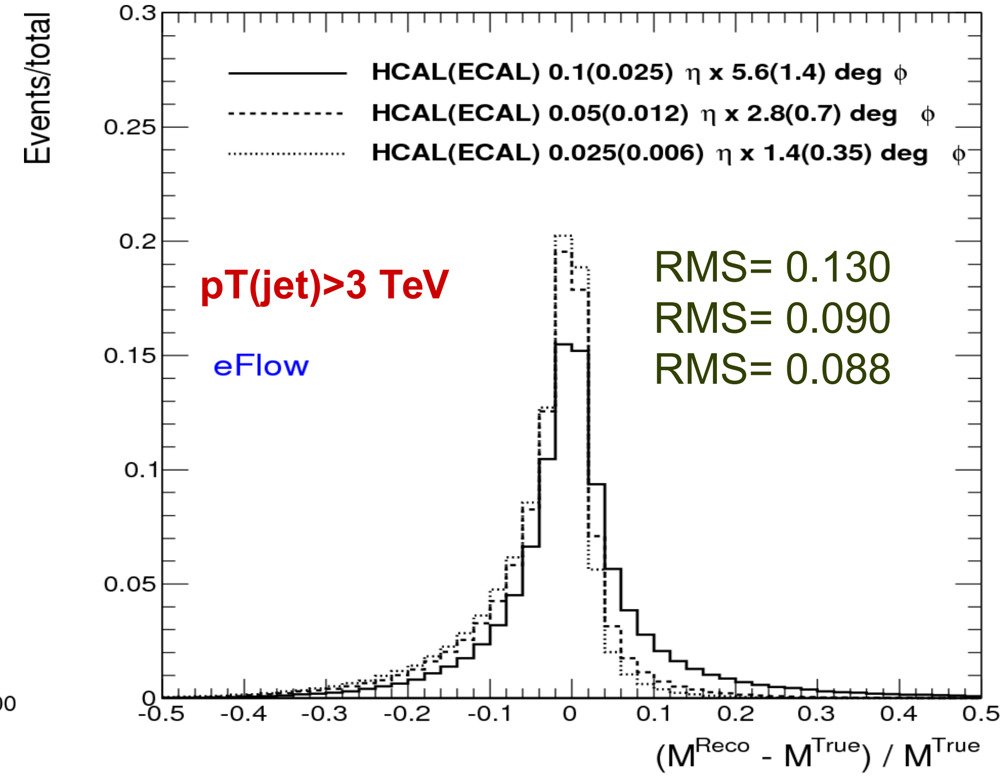
HepSim MC input + Delphes 3.2

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





HCAL coverage

η coverage

Important for forward jets

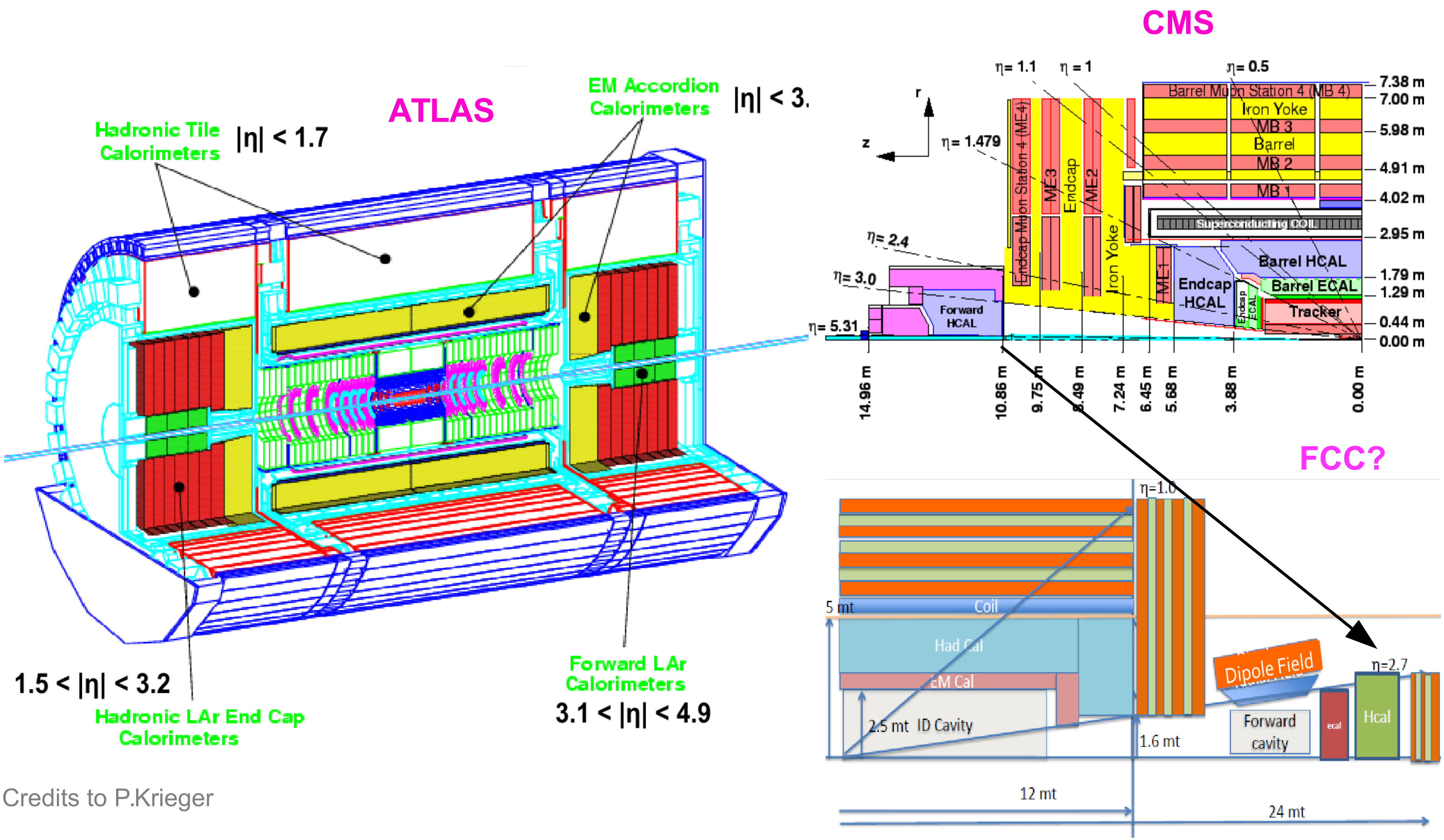
Hermetic coverage

- No cracks in azimuth
- small transition gap between endcap & forward

Important for missing ET reconstruction

LHC

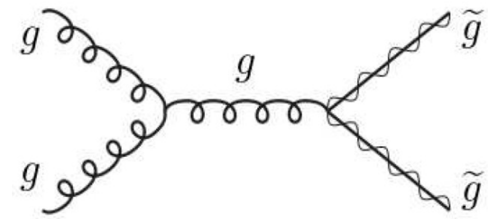
- Typical coverage of the LHC experiments in η ~ 5
- Usage of this region for physics is still a challenge
  - large radiation, coarse segmentation

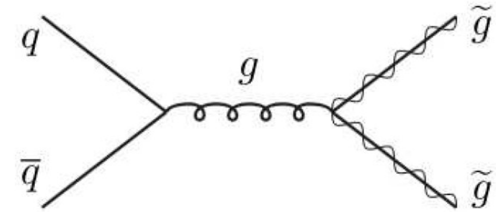


Credits to P.Krieger

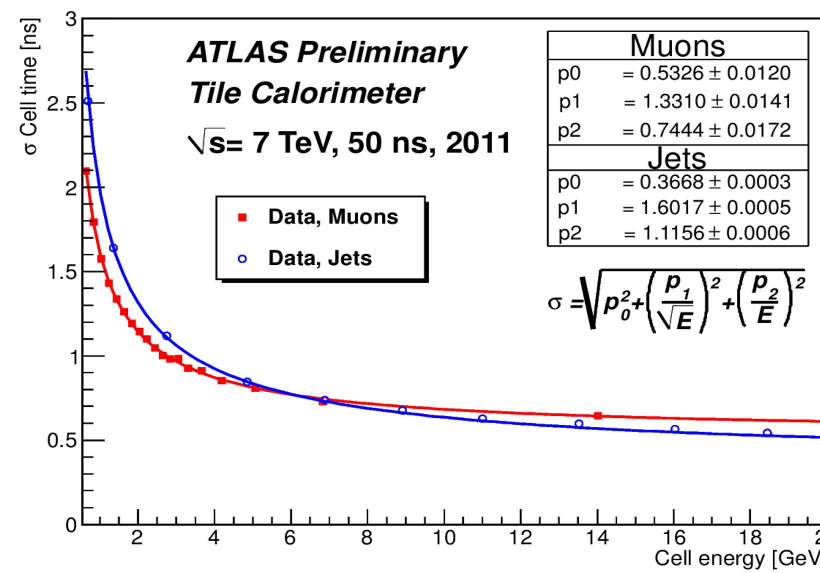
Time reconstruction

- 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?