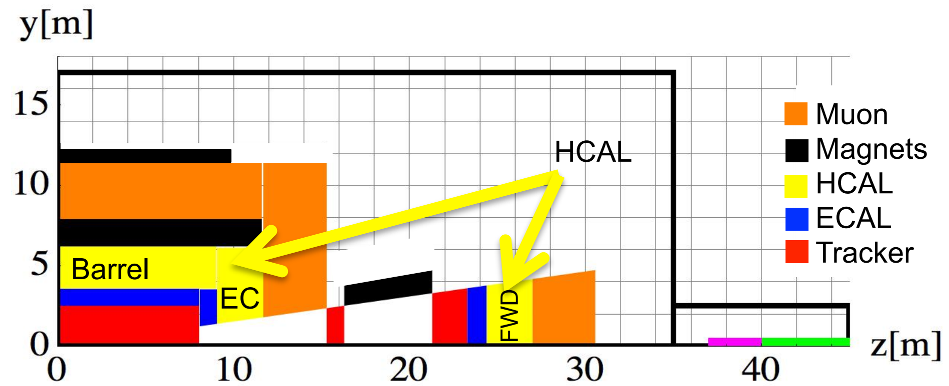
Detector requirements for a Hadronic Calorimeter at the FCC

Carlos Solans
On behalf of many people

16th September 2015

HCAL for a 100 TeV collider

- We expect large energy of decay products at the FCC
  - Large jet P_T
  - Missing E_T signatures
  - High-mass, long-lived particles
  - Tau decays
  - Veto on photons / electrons / jets

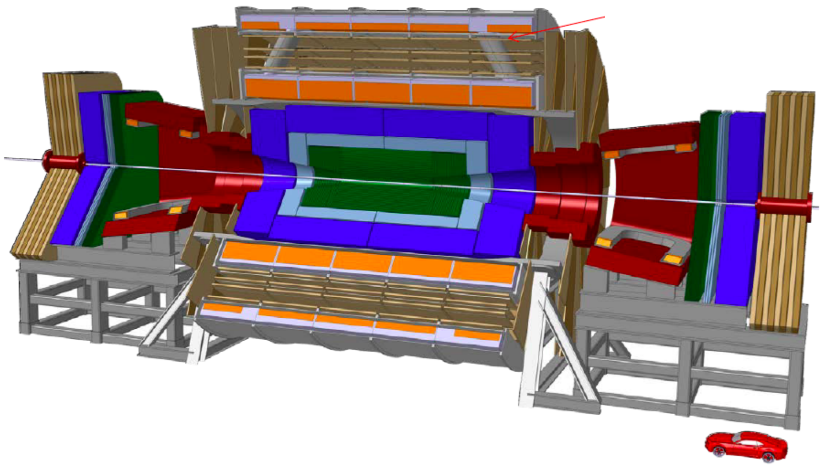


Baseline barrel calorimeter:

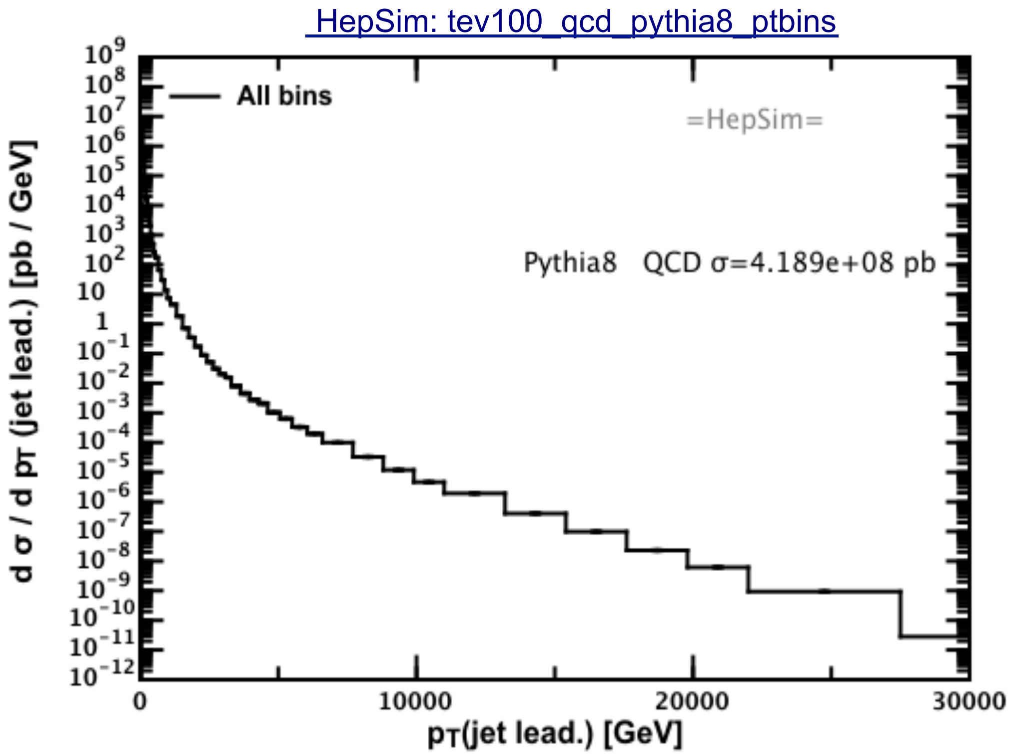
80% Fe, 20% Polystyrene

λ of this mix = 20.6 cm

- Requirements for HCAL
  - Depth
  - Resolution
  - Segmentation
  - Dynamic range
  - Coverage



QCD jets at a 100 TeV collider

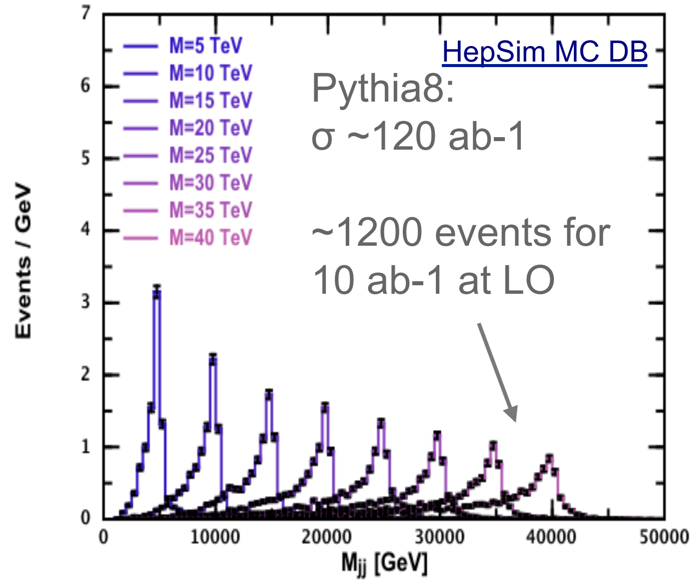


Expect very high-p_T events!
Typical benchmark used is q* because of its high cross section
Example: q* (40 TeV) → qq

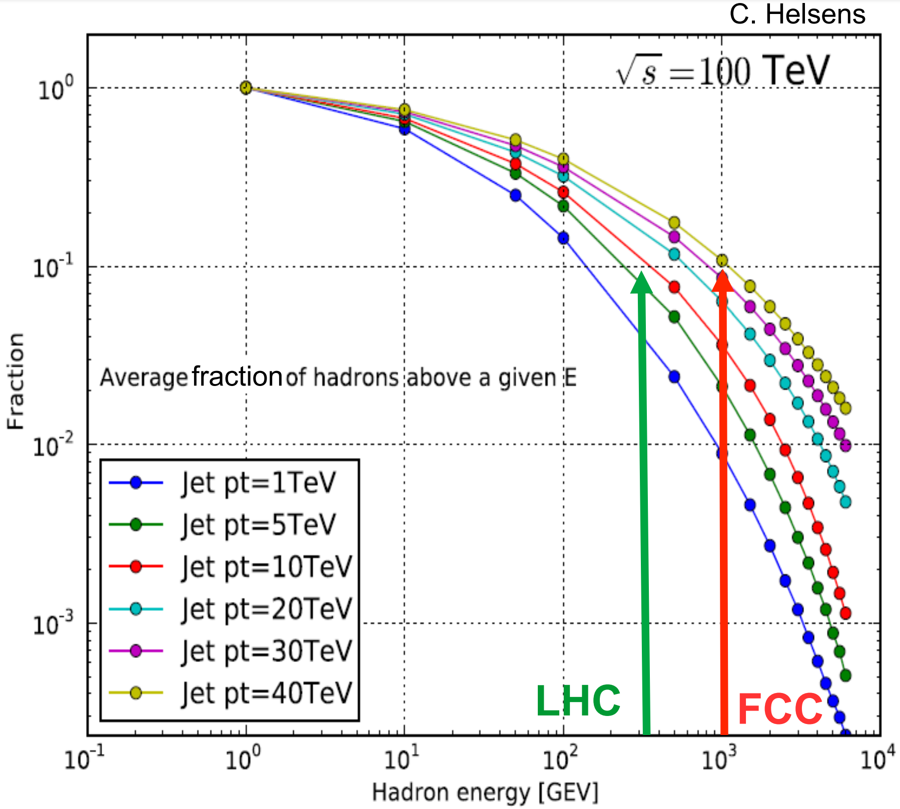
10 ab^{-1} :
a dozen of events are expected for p_T(jet) > 20 TeV at LO QCD

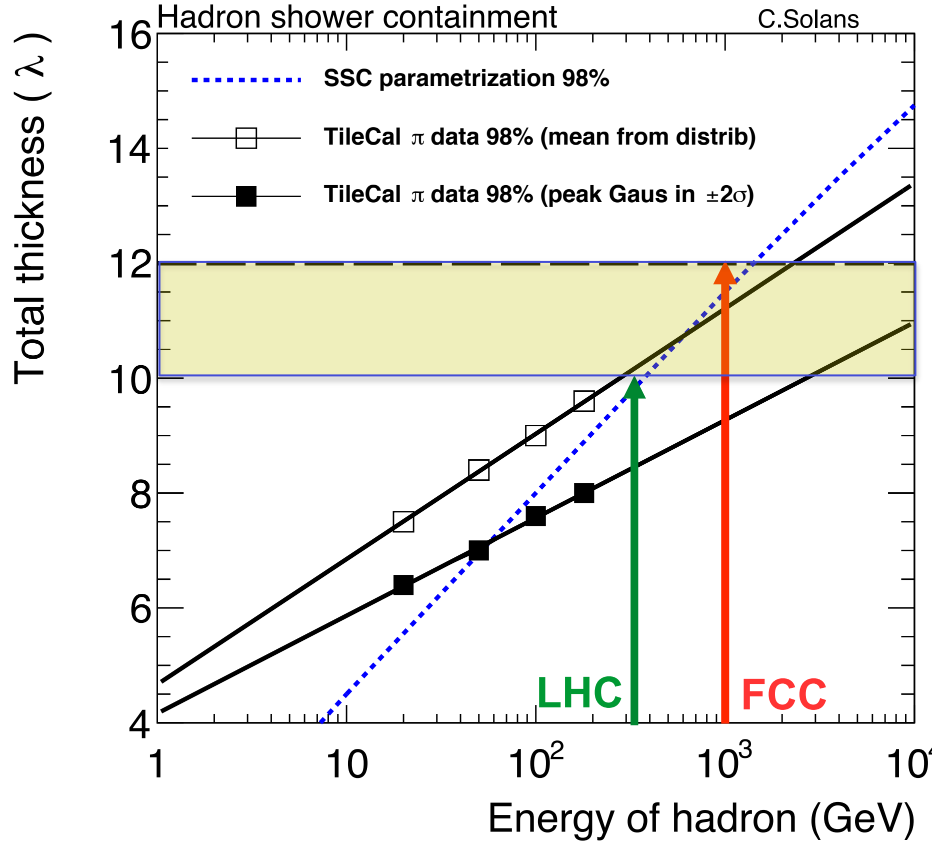
Jets p_T [TeV]	1	5	10	20	30	40
Cross section [pb]	3453	0.974	0.0108	$1.84e^{-5}$	$3e^{-8}$	$3.4e^{-12}$

C.Helsens



HCAL depth





- 10% of energy of a p_T(jet) > 30 TeV carried by 1 TeV hadrons (~9 hadrons/jet)
- ~12 λ is needed to contain 98% of a few TeV single hadron

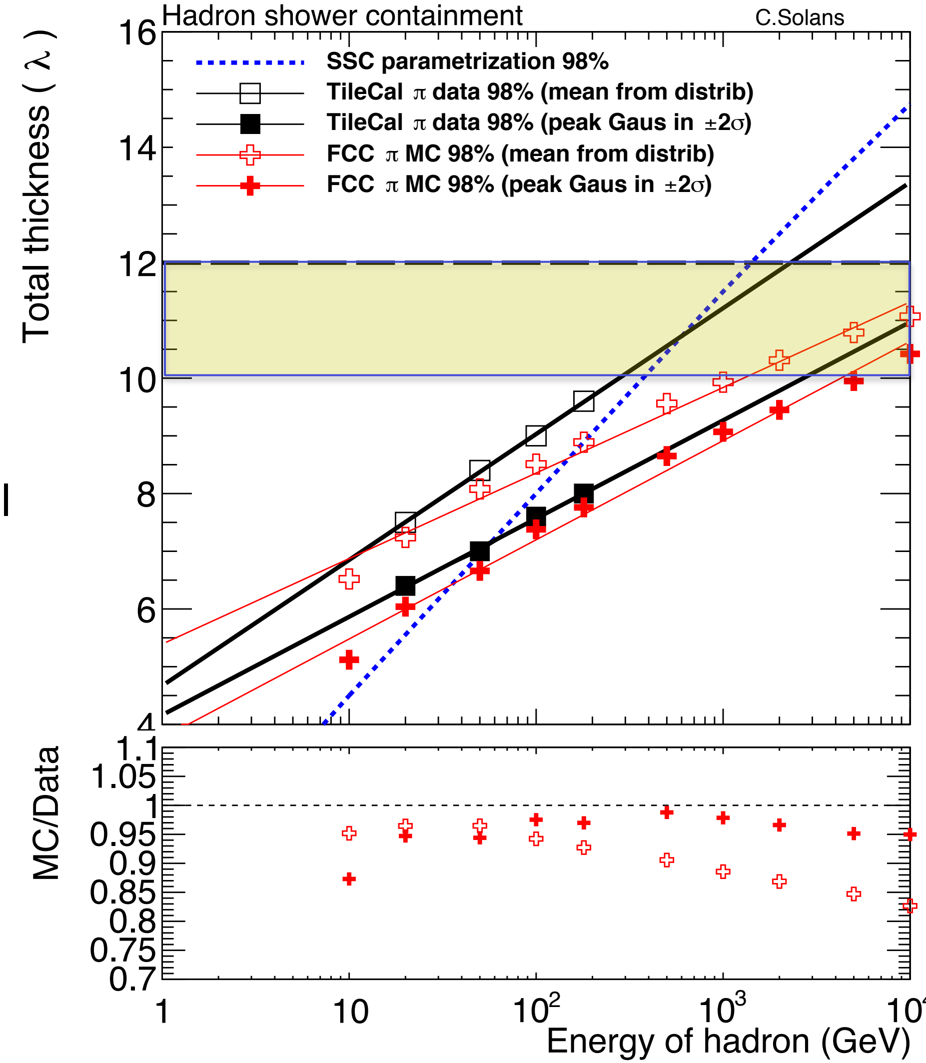
C.Batlay, Calorimetry for SSC detectors, Snowmass 84
Tile calorimeter collaboration, NIM A 615 (2010) 158

Single pion containment

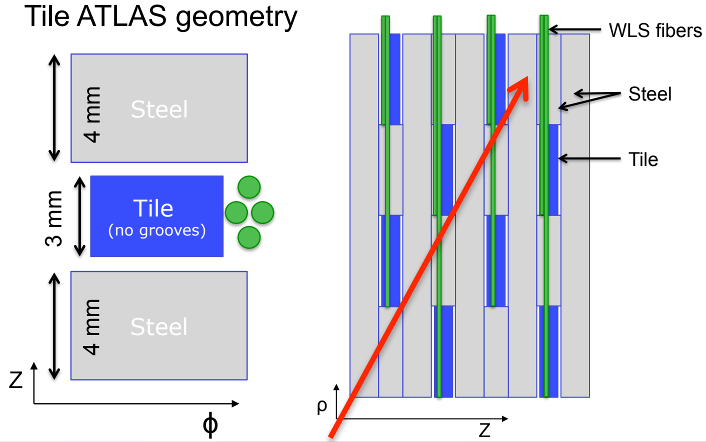
	Data		MC	
Method	a	b	a	b
Mean	0.95	4.7	0.64	5.4
Peak	0.74	4.2	0.75	3.8

Single pion shower containment at 98% parameterization: $\lambda_{98} = a \cdot ln(E) + b$

- Geant4 + FTFP_BERT + Tile ATLAS model
- ~12 λ to contain few TeV single hadron
- MC showers are shorter than data

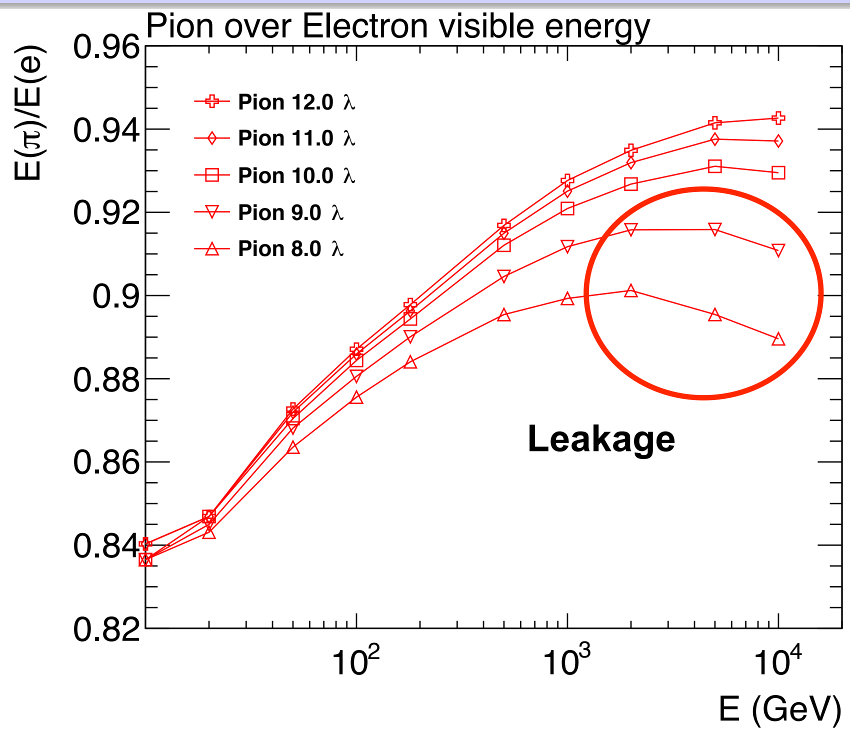


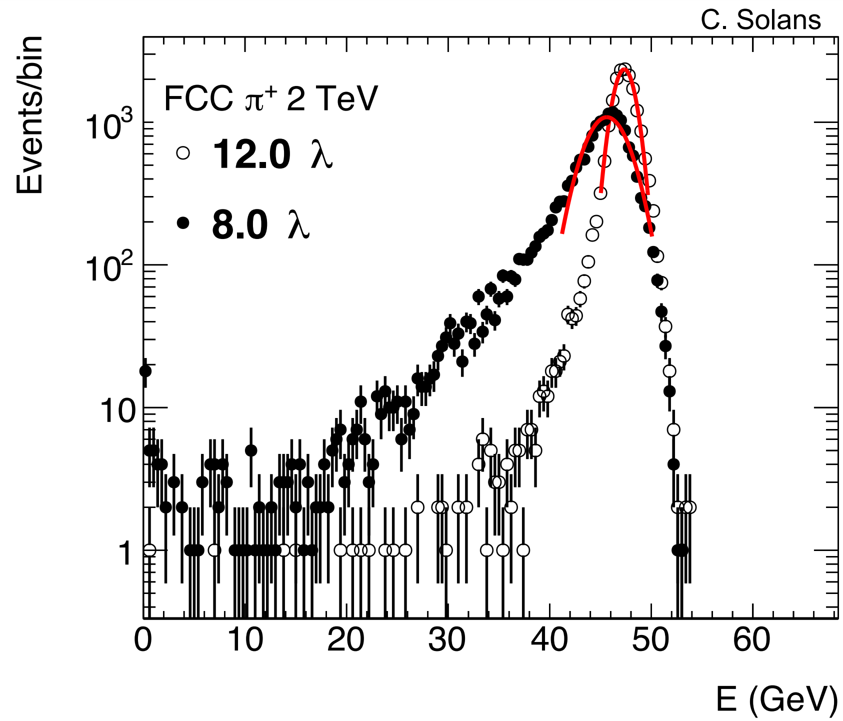
Tile ATLAS geometry



Simulation compatible with ATLAS test-beam

Single pion simulation





- Non compensating calorimeter (e/h ~ 1.27)
  - Implies non linearity for pions over energy
- Leakage enhances low energy tails and non-linearity
  - Response of 2 TeV pion: 8λ/12λ = 96 % , 10λ/12λ = 98 %
  - Percent of events below 3 sigma for 8λ = 11%, 12λ = 3%

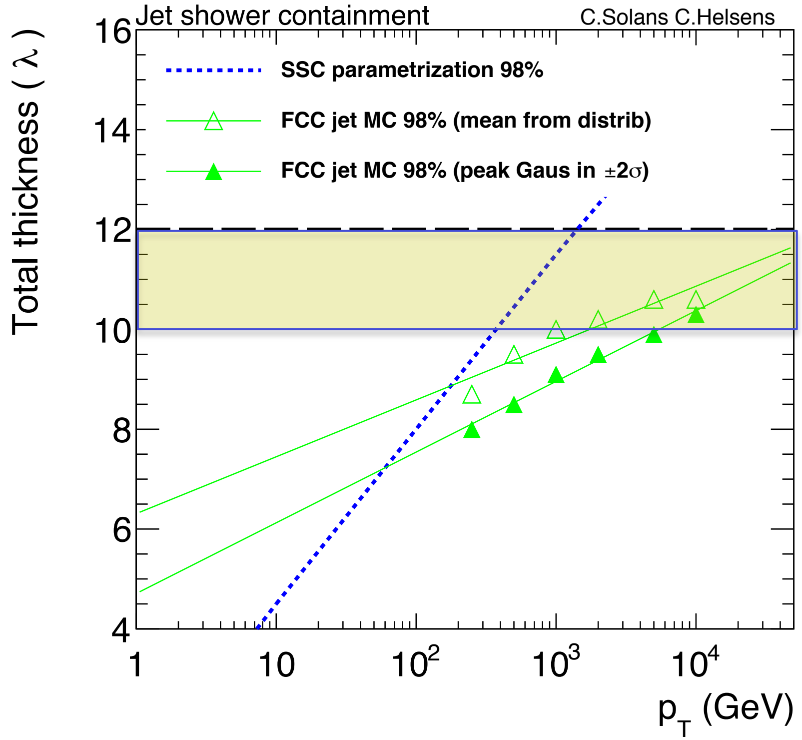
Jet containment at 98% (preliminary)

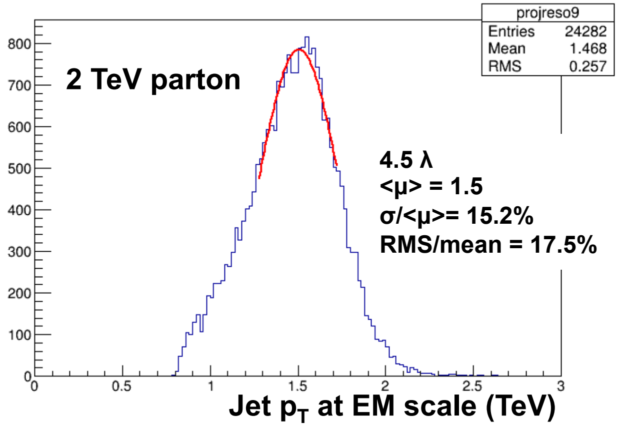
- Fixed p_T parton hadronized in Pythia8
  - Simulated Z' → qq at rest (back to back)
- Reconstruct jets with antiKT jets R=0.5 with different depths
  - Truth matching ΔR (truth, reco) < 0.2
  - Truth jet p_T within 10% of parton jet p_T
- 12 λ needed to contain 20-40 TeV p_T jet

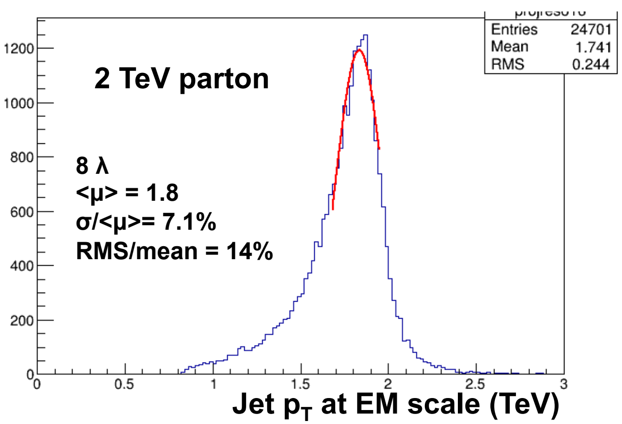
Method	a	b
Mean	0.495	6.3
Peak	0.615	4.7

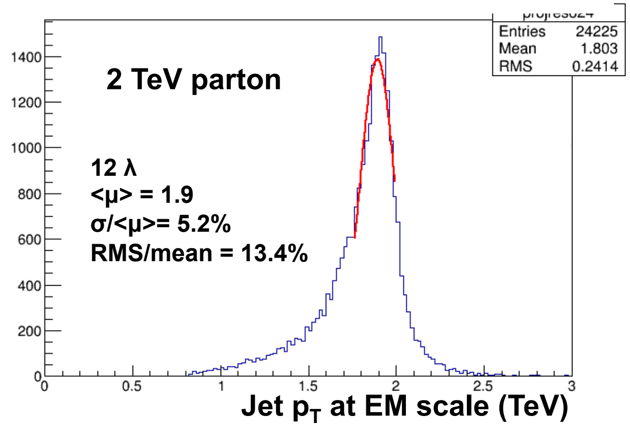
Jet containment at 98% :

$$\lambda_{98} = a \cdot ln(p_T) + b$$









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

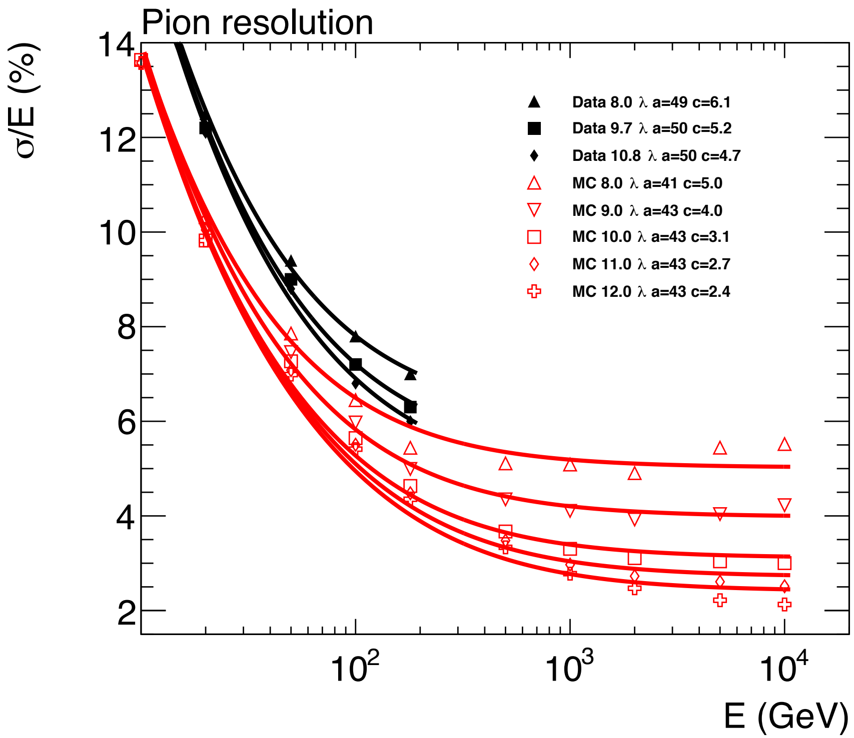
CMS: $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 4.5\%$

(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.

Single pion energy resolution



C. Solans

	Gaussian sigma		RMS	
λ	a (GeV$^{-1/2}$)	c (%)	a (GeV$^{-1/2}$)	c (%)
8	41	5.0	42	6.9
9	43	4.0	43	5.3
10	43	3.1	45	4.0
11	43	2.7	45	3.4
12	43	2.4	45	2.9

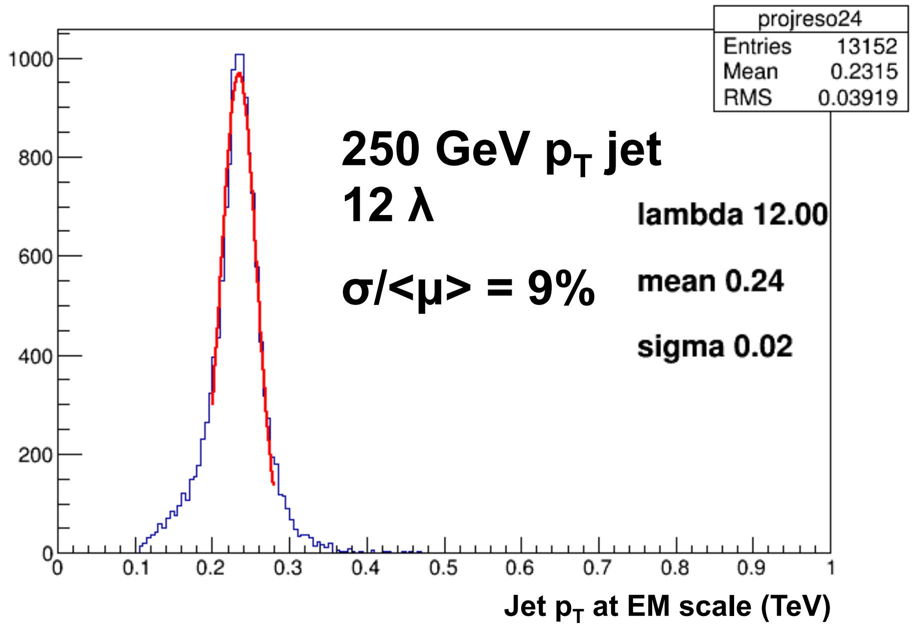
Energy resolution assuming noise (b) = 0

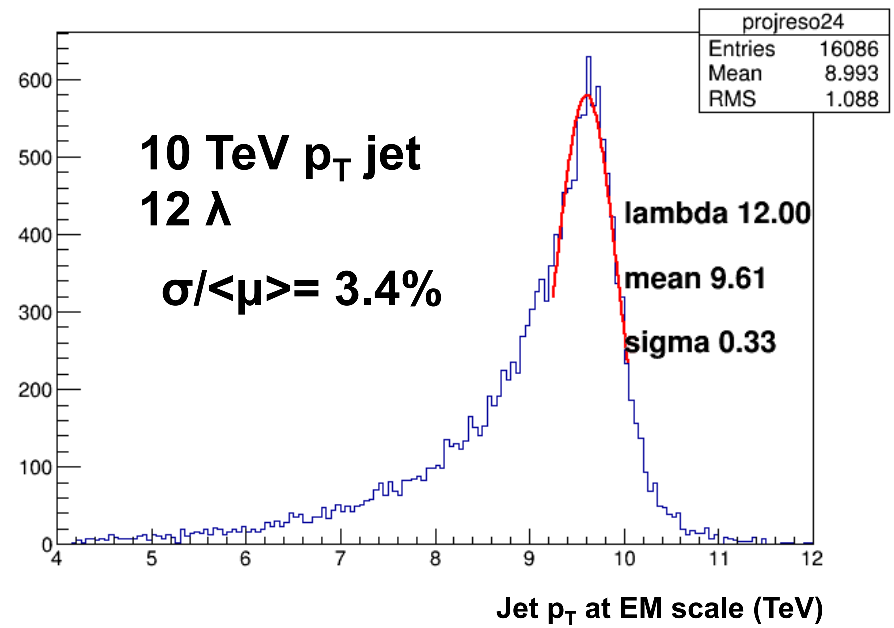
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- By increasing the depth of the calorimeter we reduce the constant term
  - Single pion simulations are comparable with ATLAS test-beam data
- Energy resolution achievable at 12 λ: $\sigma_E/E \sim 43\%/\sqrt{E} \oplus 2.4\%$

Jet energy resolution (preliminary)

C. Helsens



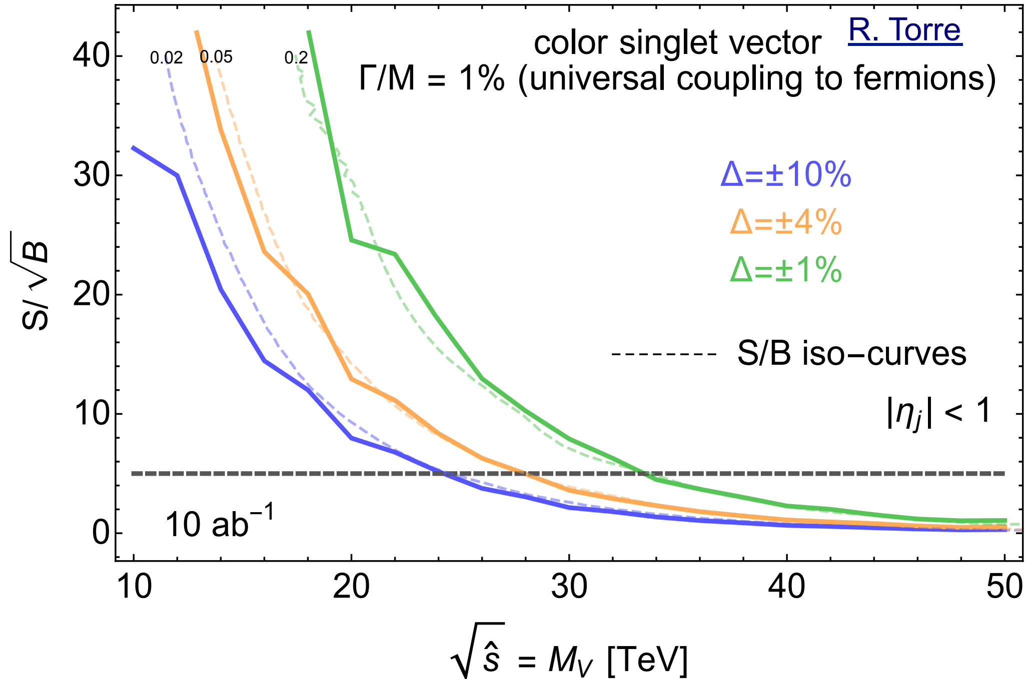


- Very preliminary results from jet energy resolution
- Resolution is very large in medium p_T range compared to ATLAS
  - To be investigated
- Need to understand the big tails at high p_T with 12λ

Impact on di-jet search sensitivity

Dijet observable

Dijet invariant mass



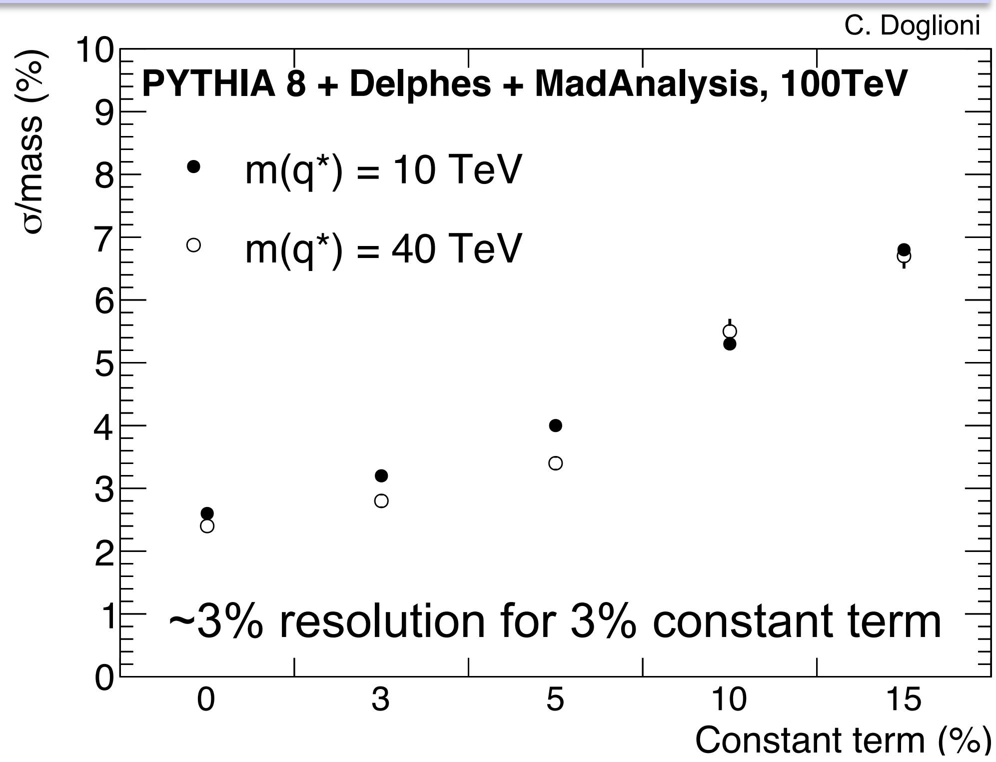
- Excited quark(q*) benchmark
  - PDF MSTW208LO
  - AntiKT jets with R=0.5 (Delphes FCC default)
  - https://cds.cern.ch/record/1750237

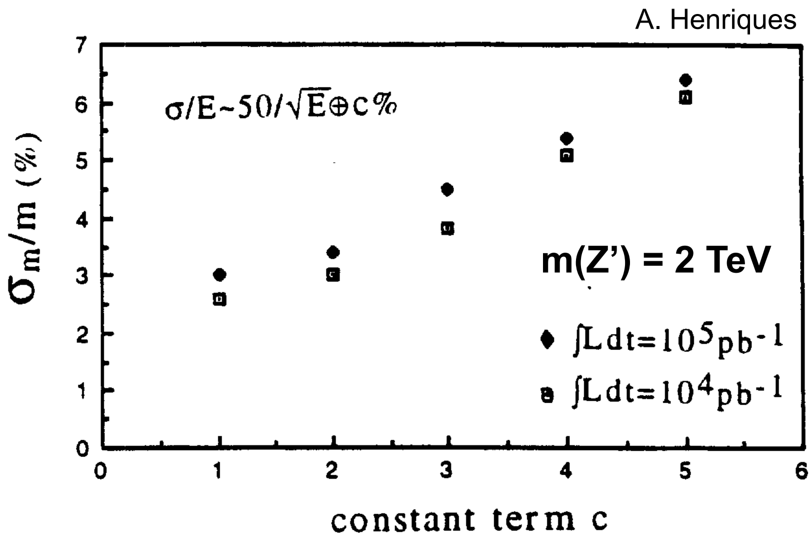
- Using HepSim samples and MadAnalysis 5 (arXiv:1206.1599)
  - Check signal width for different constant terms

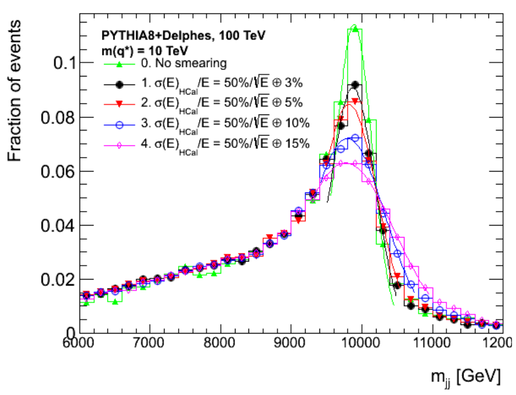
C.Doglioni Higgs and BSM @100 TeV 2015

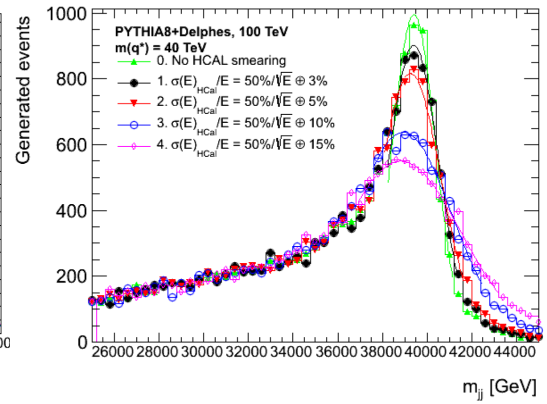
Di-jet mass resolution

- Worsening calorimeter resolution broadens mass peak
  - With from gaussian fit
- Comparable with early LHC/SSC studies (phys-92-010)









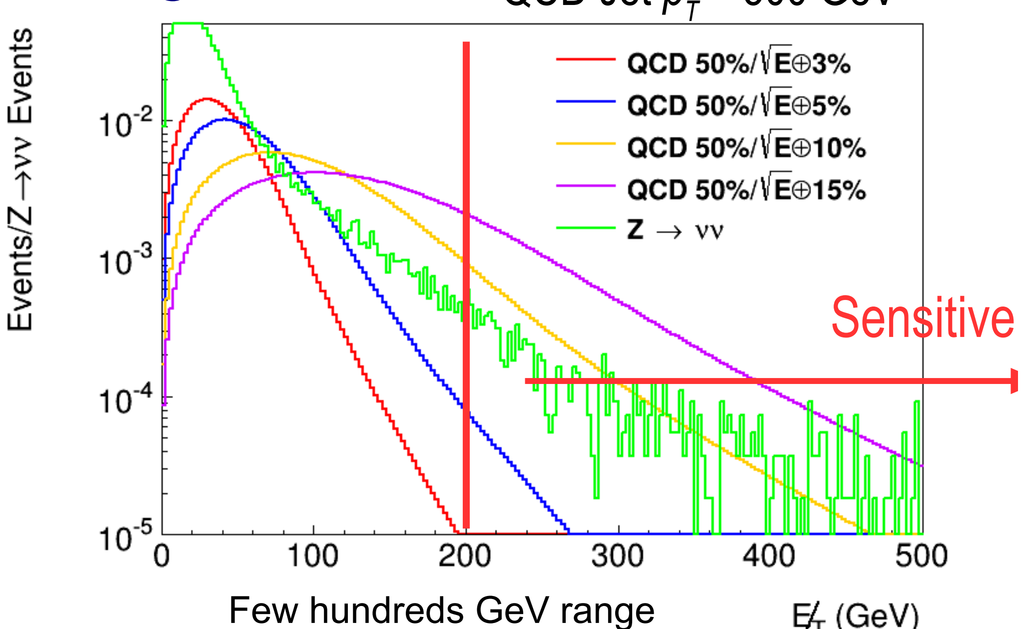
Resolution effect on MET (DM reach)

- Check kinematics of signal at parton level
  - Signal sample is from ATLAS/CMS DM [forum]
- MET observable vs resolution
  - Notable difference between results
- Working on understanding results and continuing on relevant signals for FCC

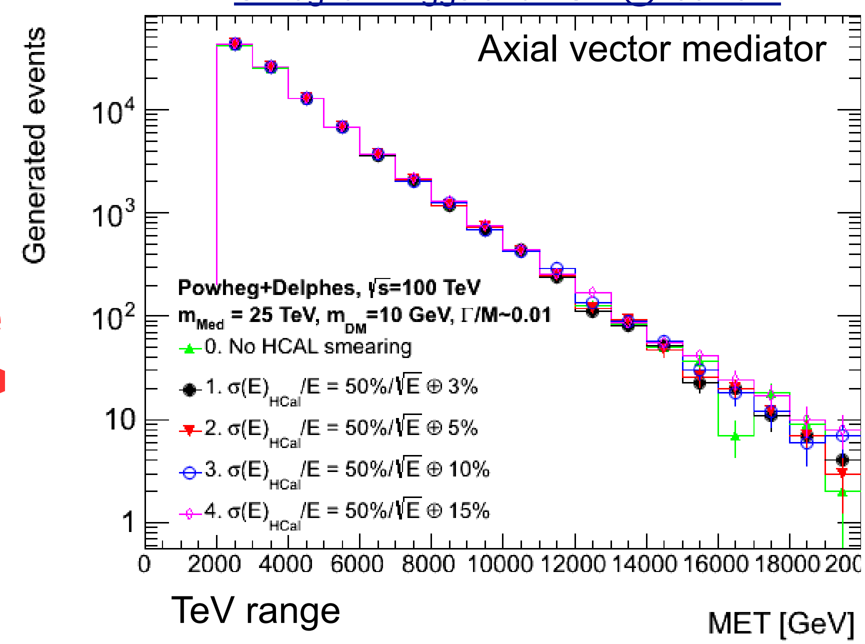
MET+X selection

Signal region:
>1 high-pT jet
pT/MET cut ("monojet")
Lepton veto
Control regions:
Lepton selection (W/Z CR)
Jet selection: same as CR

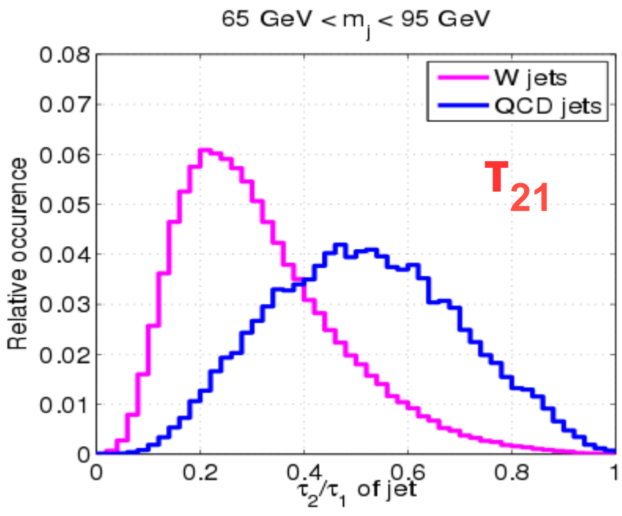
P. Harris @ FCC week 2015

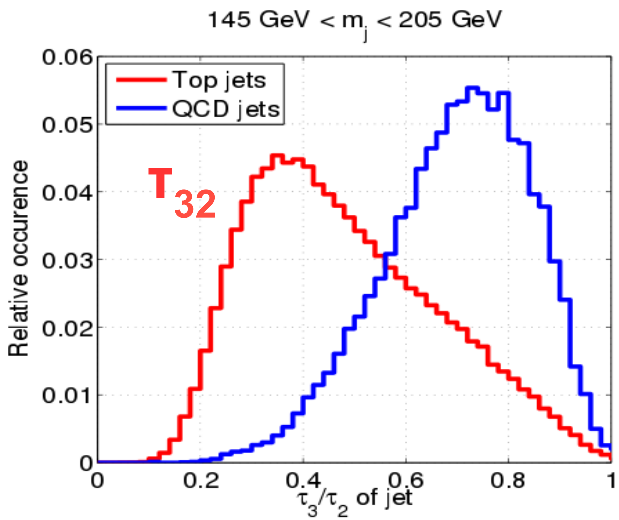


C.Doglioni Higgs and BSM @100 TeV

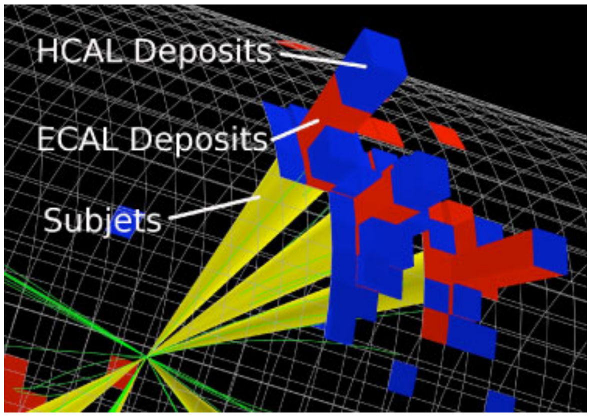


HCAL transversal segmentation





Delphes Towers



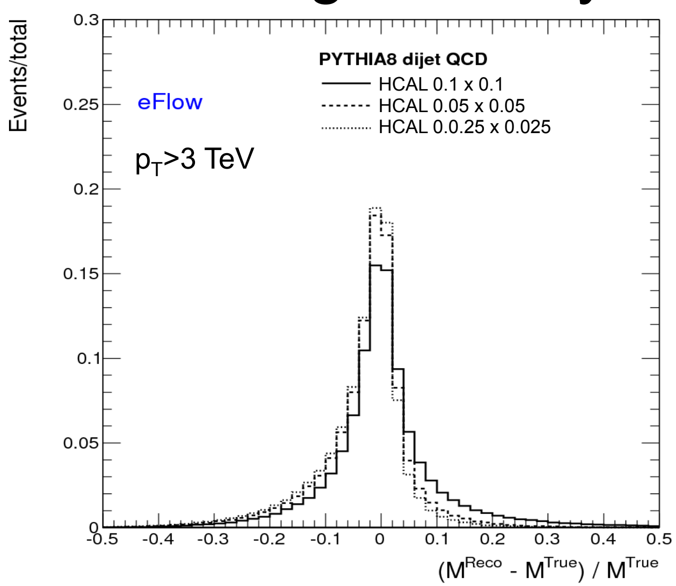
- Assess transversal segmentation through jet sub-structure
- τ_N-subjettiness measures the degree to which a jet can be considered as being composed of N subjets
  - $\tau_{21} = \tau_2 / \tau_1 < 0.3$: reduces QCD dijet bkg for boosted Z/W
  - $\tau_{32} = \tau_3 / \tau_2 > 0.75$: reduces QCD dijet bkg for boosted top quarks

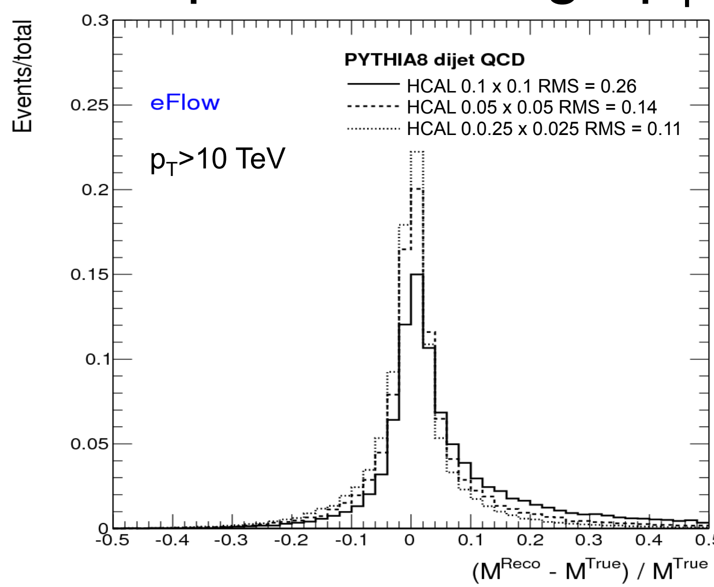
S.Chekanov @ BOOST 2015

Impact on jet sub-jettiness variables

Improvement (%) of sub-jettiness variables for based on distribution RMS							
		P_T>3 TeV			P_T>10 TeV		
Granularity	wrt ATLAS	τ_{32} (%)	τ_{21} (%)	**RMS(M_{jet}) (%)**	τ_{32} (%)	τ_{21} (%)	**RMS(M_{jet}) (%)**
0.1 x 0.1	1	1	1	**1**	1	1	**1**
0.05x0.05	1/2	18	28	**30**	9	18	**80**
0.025x0.025	1/4	30	41	**35**	13	28	**120**

Transversal granularity is more important for high-p_T jets





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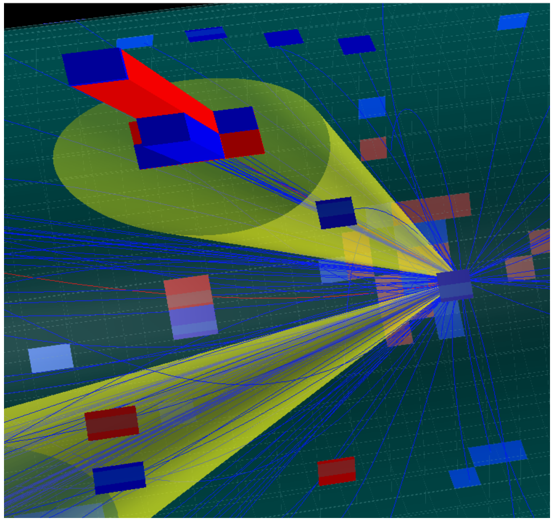
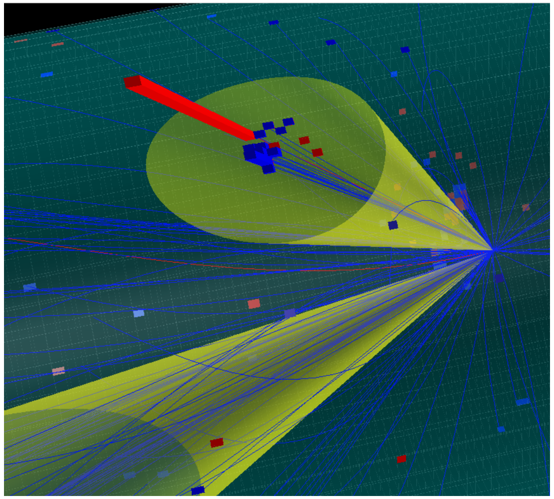
Impact on read-out dynamic range

S. Chekanov

- Dynamic range is important for electronics specifications
  - The bigger the cell the more energy collected
- In ATLAS we achieve 10^6 resolution with 2 gains of 10^3 (2^{10})
  - High resolution 200 MeV muon deposits
  - Low resolution for 1TeV jet deposits
- If we have 10 times more energy and 4 times smaller cells we get 2.5 times more energy per cell
  - We want to keep the high resolution threshold
- We require a 10^7 resolution
  - Achievable with existing technologies



HepSim + Delphes with ATLAS segmentation



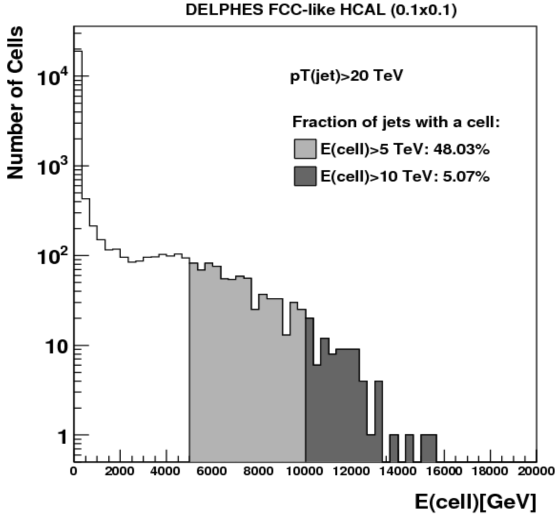
HepSim + Delphes with x4 ATLAS segmentation

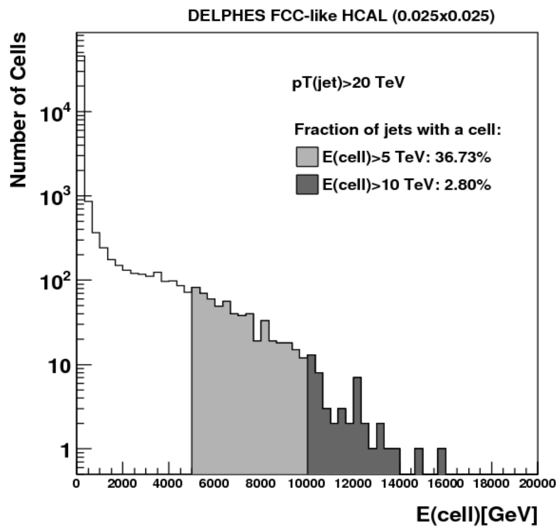
Impact of cell size in occupancy

J. Dull S. Chekanov

Granularity	P_T^{th} (TeV)	E_{cell}^{th} (TeV)	Prob (%)	Sim
0.1 x 0.1	3	1.2	4.14	Geant4
0.1 x 0.1	3	1.5	1.45	Geant4
0.1 x 0.1	3	1.2	4.77	Delphes
0.1 x 0.1	3	1.5	0.81	Delphes
0.1 x 0.1	20	5	48.03	Delphes
0.1 x 0.1	**20**	**10**	**5.07**	**Delphes**
0.025 x 0.025	20	5	36.73	Delphes
0.025 x 0.025	**20**	**10**	**2.8**	**Delphes**

x4 reduction of cell size reduces number of cells above threshold by a factor of ~1.5





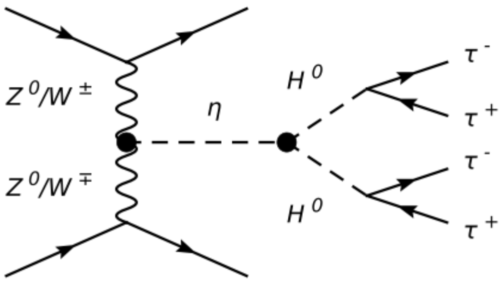
Dynamic range of cells for 100 TeV, Standard Model events. Jet p_T > 20 TeV

HCAL η coverage

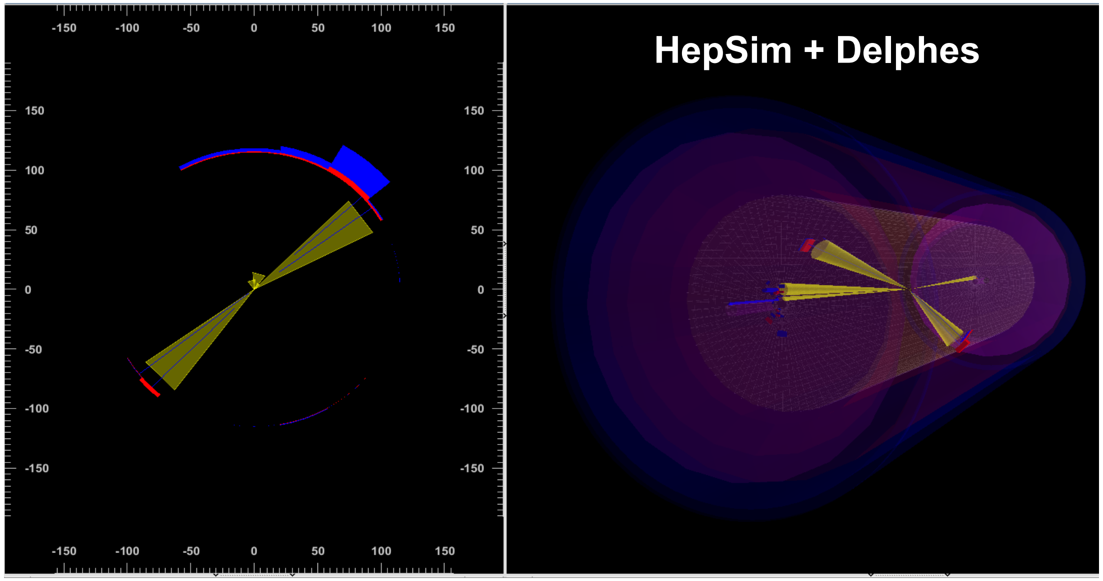
- Many SM channels will benefit in opening up the η range
- VBF-Higgs production, WW → WW, WW → HH, ttH production
- BSM channels: High-mass resonances in vector-boson scattering & Higgs decay:

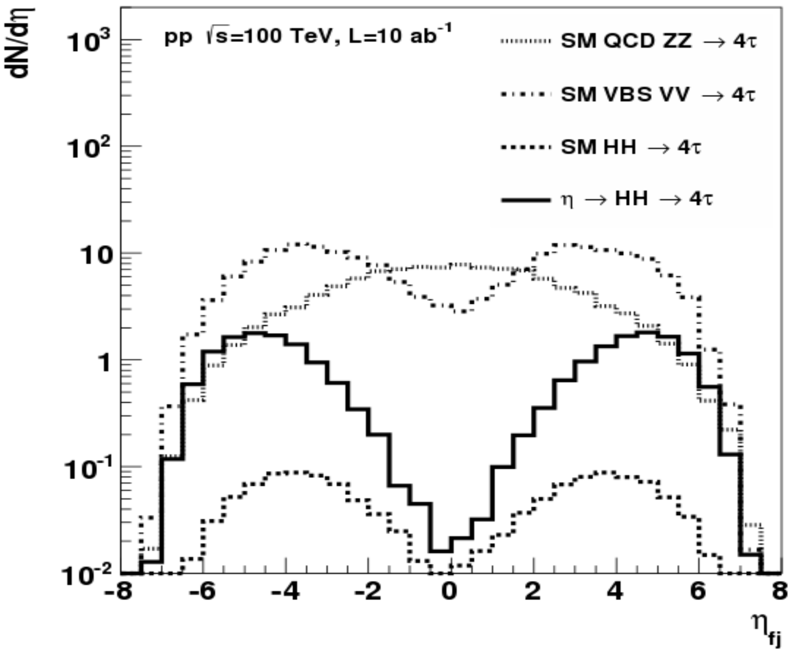
~ 50% of events in the region η~4-6
Coverage requirement up to η~6

S. Chekanov



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





Summary

- Calorimeter depth of 12 λ
- Energy resolution constant term ~3% or smaller
  - Small note in progress to summarize jet and pion simulations
- 4 times more transversal granularity than LHC
  - $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$ (Delphes baseline is 0.5×0.5)
- Longitudinal segmentation to improve calibration
  - No detailed study yet
- Cell energy range extended by a factor 10
- Extended coverage up to $\eta \sim 6$

Bonus

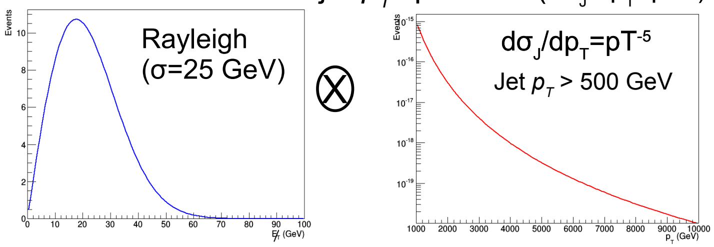
MET spectrum difference

From Philip Harris

1. Assume no neutrinos are in the di-jet
2. Assume the MET resolution follows the form of a rayleigh distribution (ie the MET is gaussian)
    1. Take the MET resolution to be sqrt(2) the jet resolution (these are di-jet events)
3. Take a form for the jet p_T spectrum
    1. p_T^{-5} is reasonable
4. Take multiple hypotheses for the jet resolution
    1. sigma(p_T) = Const + stochastic/sqrt(E)
5. Sample the pT spectrum, compute the jet resolution and construct a rayleigh of this form, sum all rayelieghs together

Expected QCD Shape

- Compute QCD *MET* by scanning same jet res
    - Using resolution above
- Resulting *MET* shape is a rayleigh distribution
    - Rayleigh : f(*MET*)=*MET*/σ^2exp(-*MET*^{2}/σ^2)
        - Sigma is the jet resolution
- Convolve this with jet p_T spectrum ($d\sigma_J/dp_T$=pT^{-5})



[P. Harris @ FCC week 2015]