Noble liquid calorimetry for future high energy collider experiments

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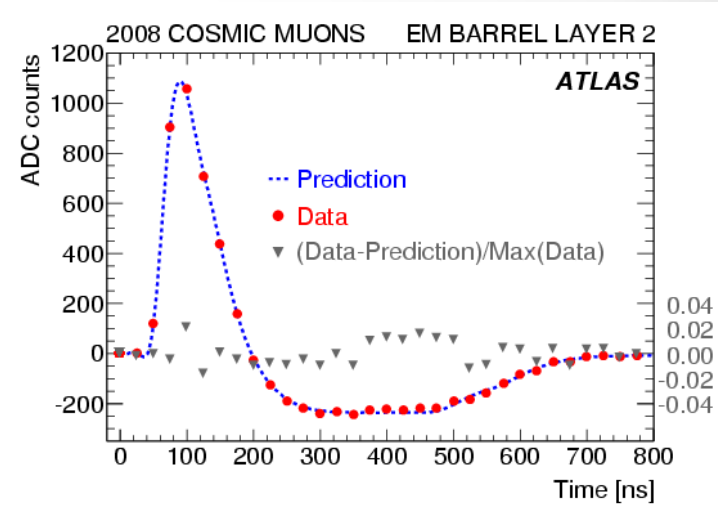
Next steps in the Energy Frontier - Hadron Colliders
Fermilab

Outline

- Noble liquid calorimeters in HEP experiments
- Experiences from ATLAS LAr calorimeter
- Requirements for next generation experiment in hadron colliders
- Thoughts on noble liquid calorimeters for the next generation hadron collider experiments
- Conclusions

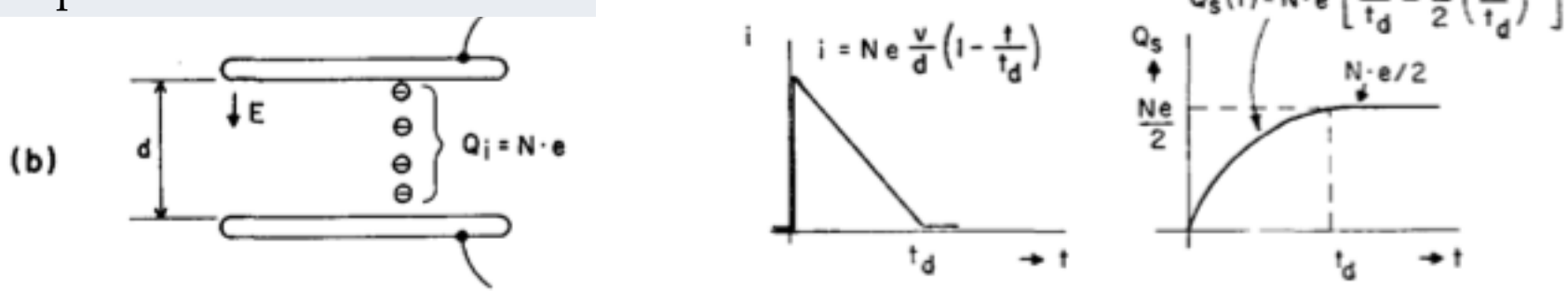
Introduction of principles

- Well-established technique for large calo system
  - High density medium, → ion chamber mode, gain==1.
    - LAr: 1.4g/cm^3, LKr: 2.4g/cm^3
  - Cell-to-cell uniformity ensured by mechanical precision and electronics calibration→ small constant term
  - Ease for segmentation, radiation hard
  - Various configurations have been developed for different applications
- Challenges
  - Inactive material, cryogenics, liquid purity
  - Long drift time, typically 450 ns, reduced for forward calo
  - LKr: cost may be prohibitive for large detector, purity a concern



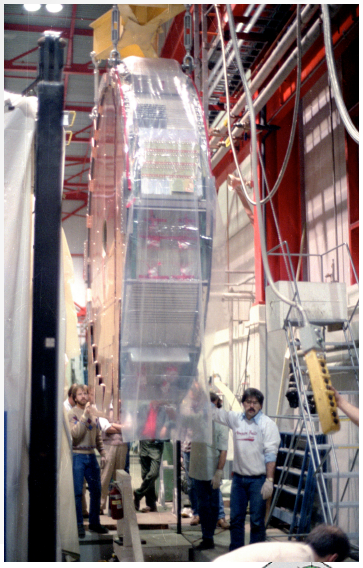
Signal with bipolar shaping and multiple sampling

Principle of ionization detection



Willis & Radeka, NIM 120 (1974)

40 years of LAr Calorimetry



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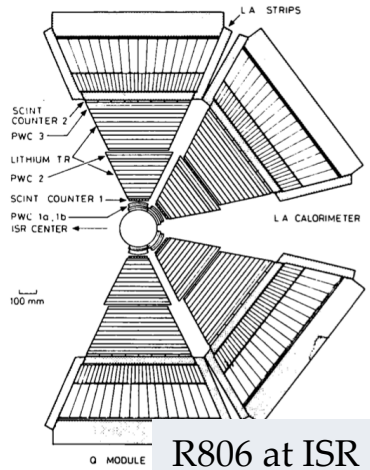
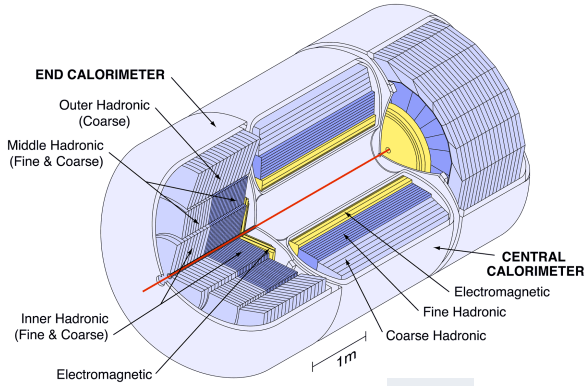


R806 at ISR

Fig. 1. Schematic cross- ular detectors, electrons are identified through transition radiation and electromagnetic showers in the calorimeters.



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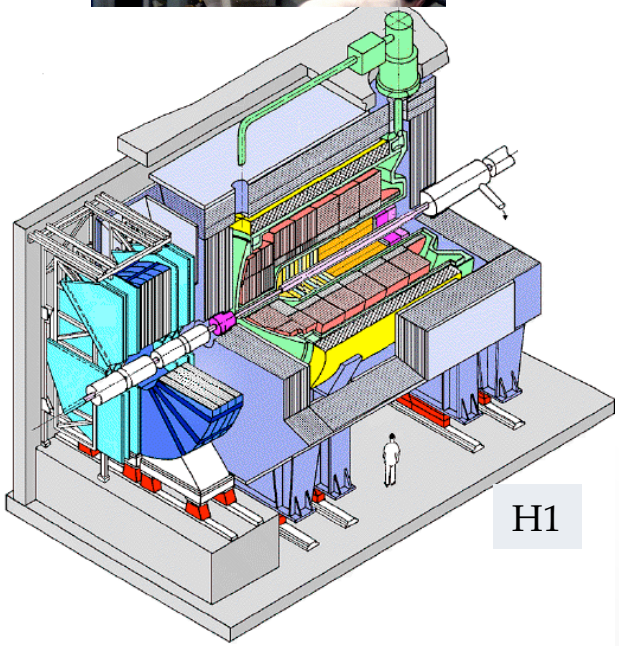
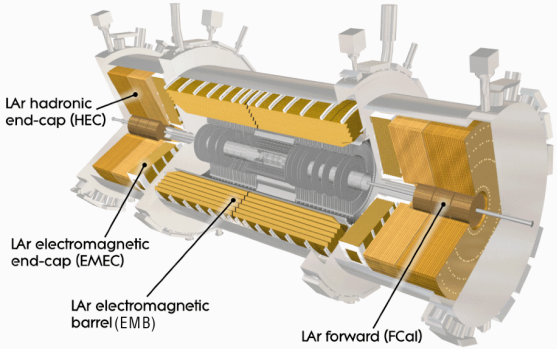
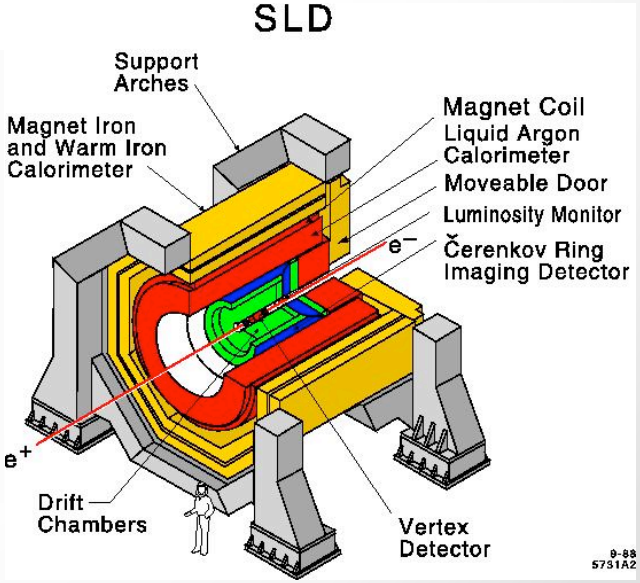


H1



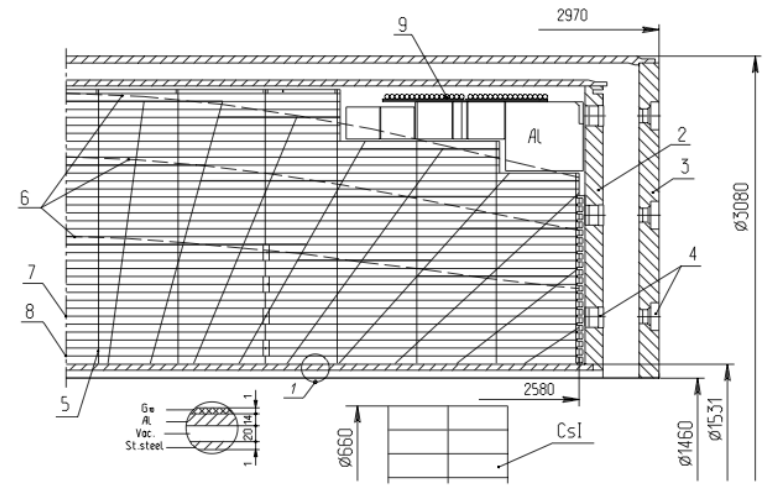
ATLAS
LAr Calorimeter



Liquid Krypton Calorimeters

KEDR

- Highly segmented total absorption LKr EM calorimeter at VEPP-4M (e+e- τ/charm physics)
- Readout with 10×10cm^2 pads and 5mm strips
- Energy resolution: 3% at 1.8GeV
- Spatial resolution: 0.8mm at 1GeV



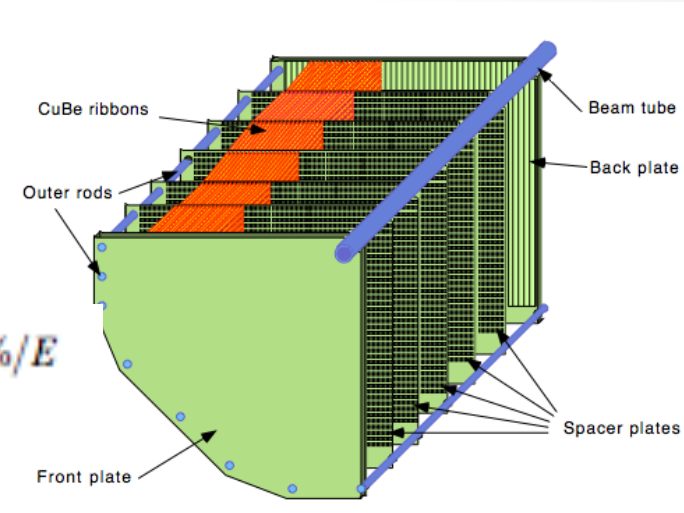
KEDR LKr EM Calo

NA48/NA62

- 10 m^3 of liquid krypton
- 13212 readout towers of 2cm×2cm
- 1cm drift
- Energy resolution

$$\sigma(E)/E = (3.2 \pm 0.2)\%/\sqrt{E} \oplus (9 \pm 1)\%/E \oplus (0.42 \pm 0.05)\%$$

- Position resolution ~1mm, E>25GeV



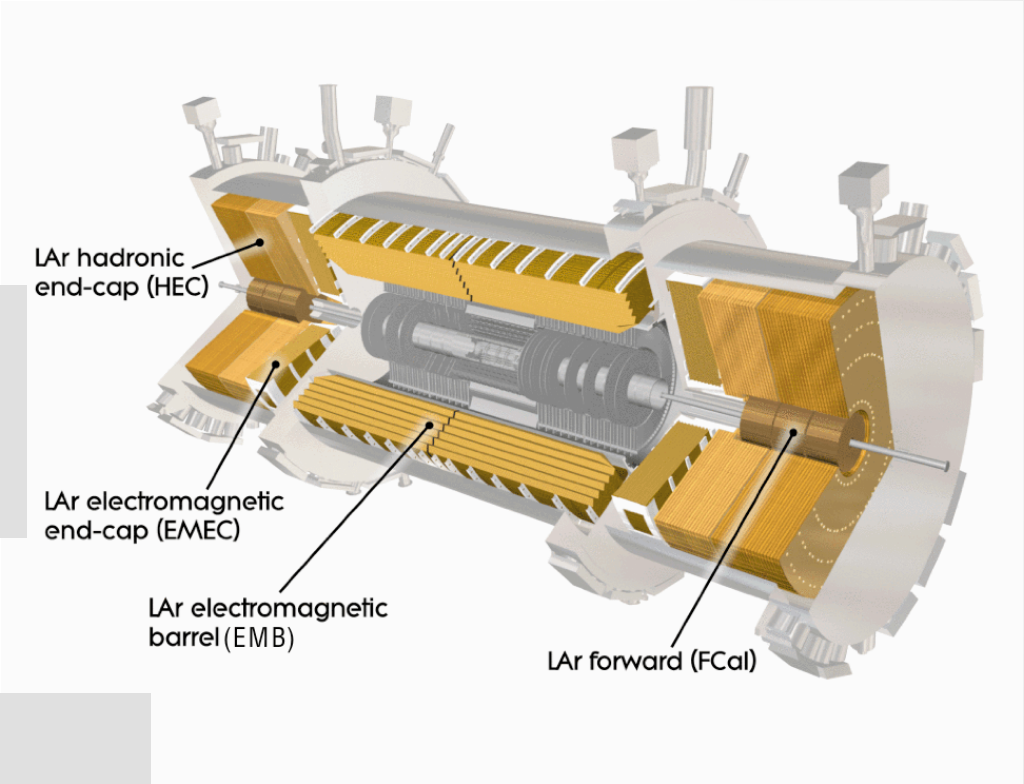
NA48/NA62 LKr Calo

ATLAS LAr calorimeter

Electromagnetic (EMB,EMEC)
Pb absorber, accordion geometry
$|\eta| < 3.2$, ~174k channels
Design $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

Hadronic End-Cap (HEC)
Cu absorber, electrostatic transformer
$1.5 < |\eta| < 3.2$, ~5.6k channels
Design $\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

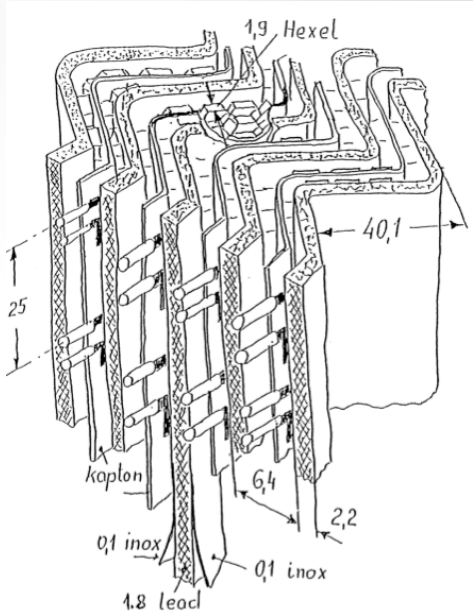
Forward (FCal)
Cu/W for EM/Had, tubes with narrow gaps
$3.1 < |\eta| < 4.9$, ~3.5k channels
Design $\sigma/E \sim 100\%/\sqrt{E} \oplus 10\%$



Techniques invented specifically for high E & Lumi hadron collider experiment

Accordion EM Calorimeter

- Fast shaping can reduce pileup effects, but requires low inductance from detector to preamps.
- Accordion geometry reduces interconnects, and allows this fast rise time even for high granularity.
- Hermetic coverage in ϕ with minimum modulation in response



RD3, CERN/DRDC/90-31

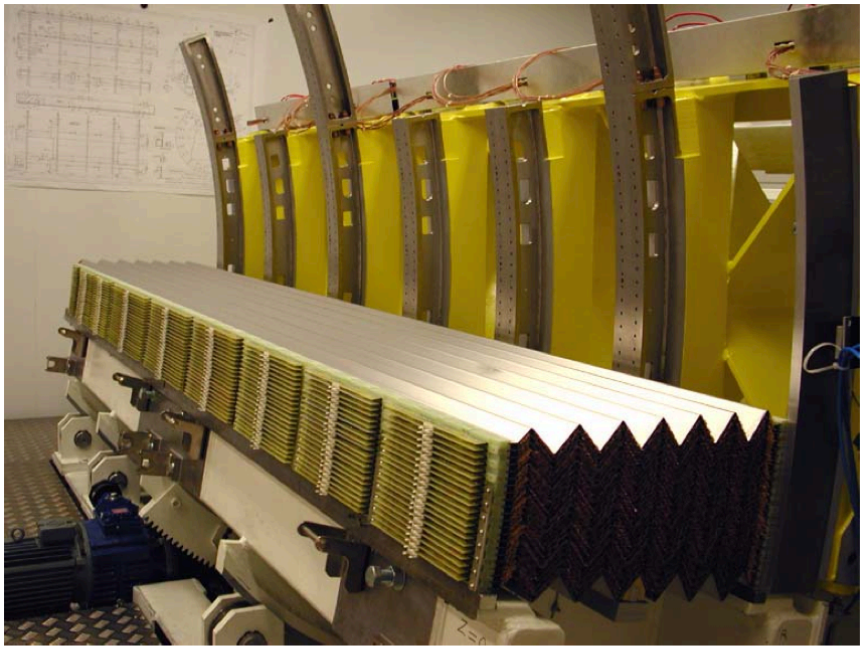
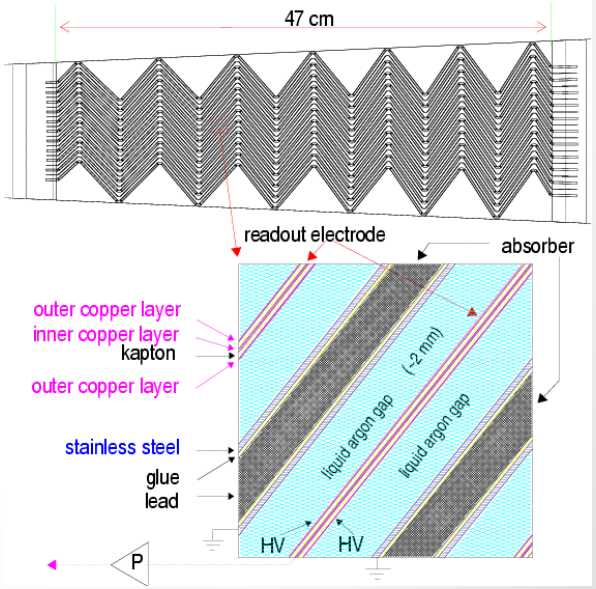


Fig. 2. One partly stacked module. The 6 outer rings on which are screwed the absorbers can be seen. Also the backbone (yellow part) and the assembling bench



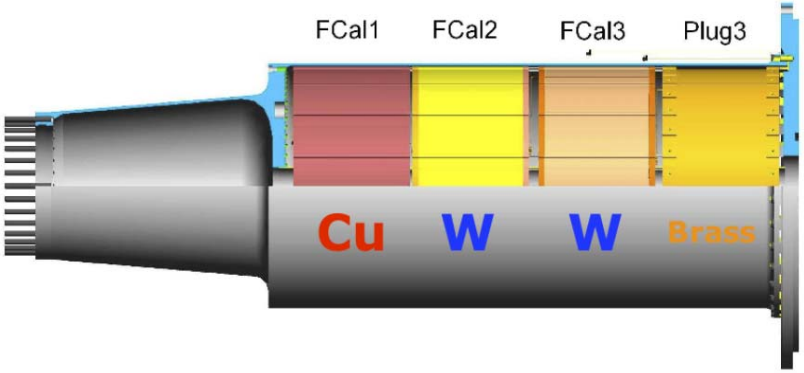
ATLAS EM Barrel

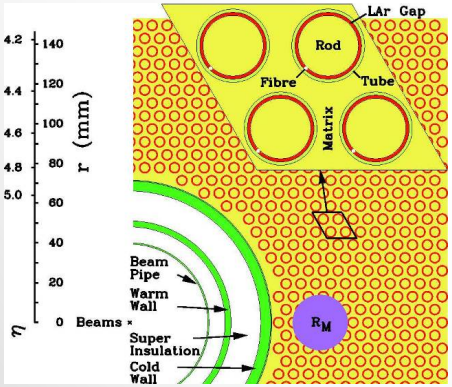
Forward calorimeter

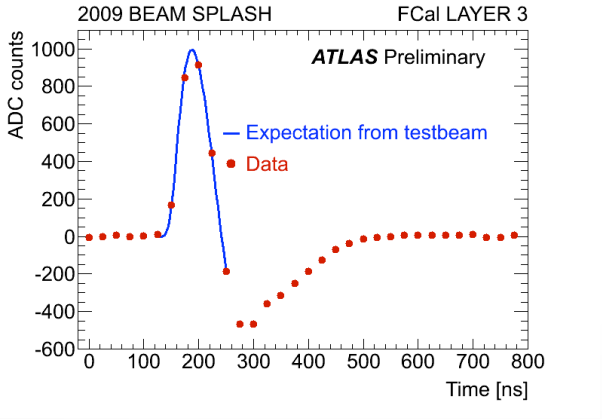
- Designed to operate in the harsh radiation environment
- Thinner LAr gap: less ion buildup and faster response
- Excellent performance in ATLAS physics program
  - Forward jets for VBF/VBS processes
  - Forward electrons
  - Heavy Ion centrality measurements
  - HV current→ Lumi measurements

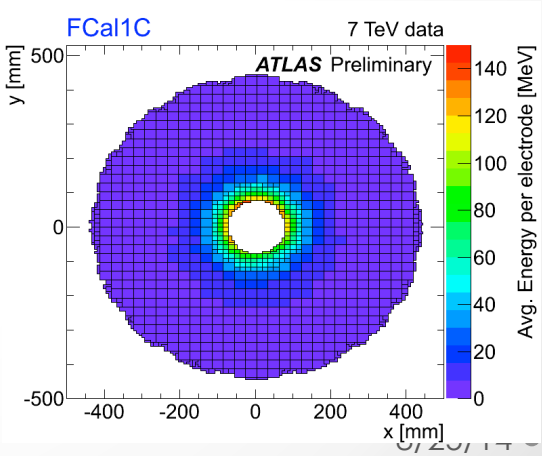
Liquid Argon Forward Calorimeter

Layer	Absorber	LAr gap	$N_{electrodes}$	$N_{channels}$
FCal1	Cu	269 μm	24,520	2,016
FCal2	W	376 μm	20,400	1,000
FCal3	W	508 μm	16,448	508



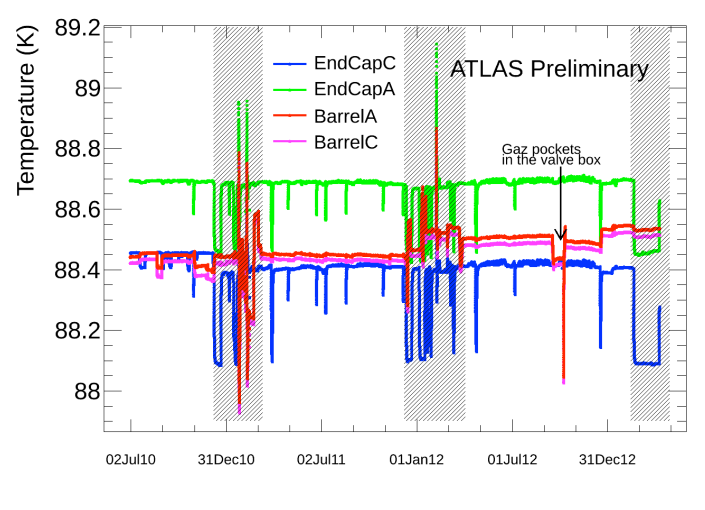


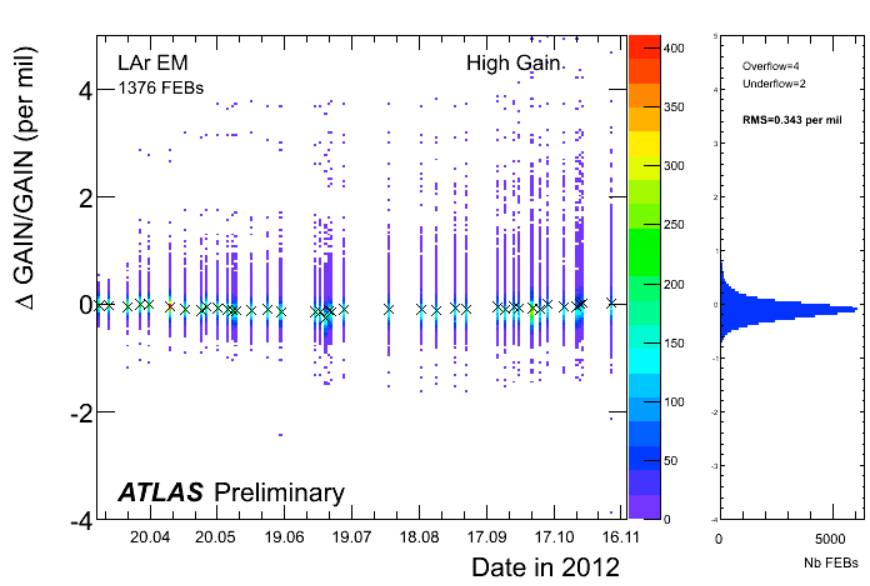


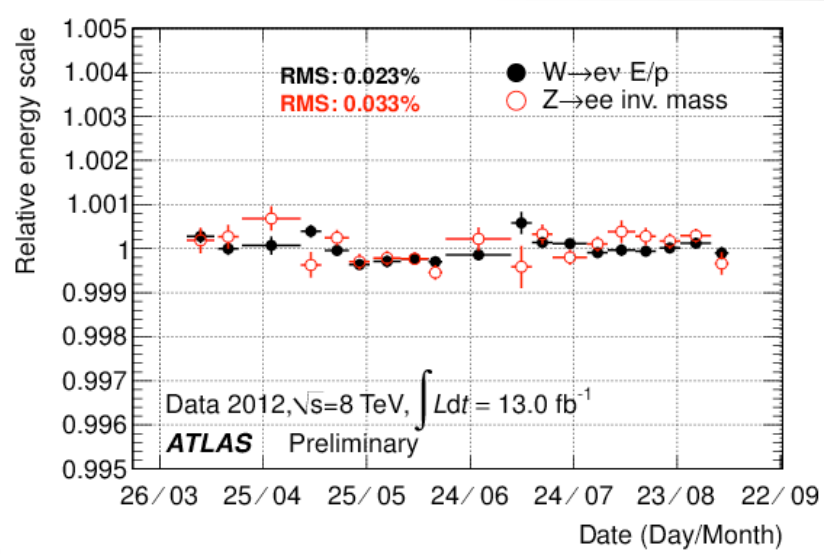


Excellent stability of ATLAS LAr Calo

- Temperature stability
  - ~ 5mK
- Electronic calibration:
  - a few per mil
- Energy scale stable
  - ~ per mil, vs time and pileup

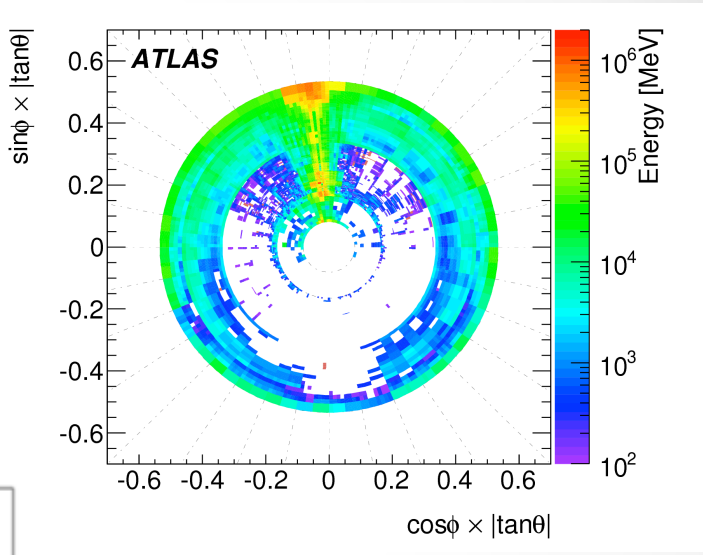






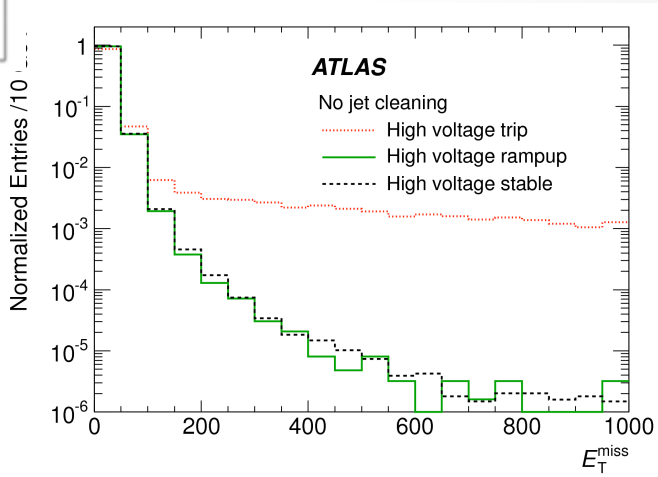
Challenges in operations

- A few operational challenges are mitigated by sophisticated data quality monitoring
  - Short noise bursts: time veto
  - HV trips: recover data during ramp



	Total	Data corruption	Missing condition data	High voltage trips	Coverage	Noise bursts	Noisy channels
2011	3.20%	0.04%	0.11%	0.96%	0.70%	1.24%	0.15%
2012	0.88%	0.01%	0.02%	0.46%	0.28%	0.06%	0.05%

Monitoring and data quality assessment of the ATLAS liquid argon calorimeter
Published in JINST 9 P07024



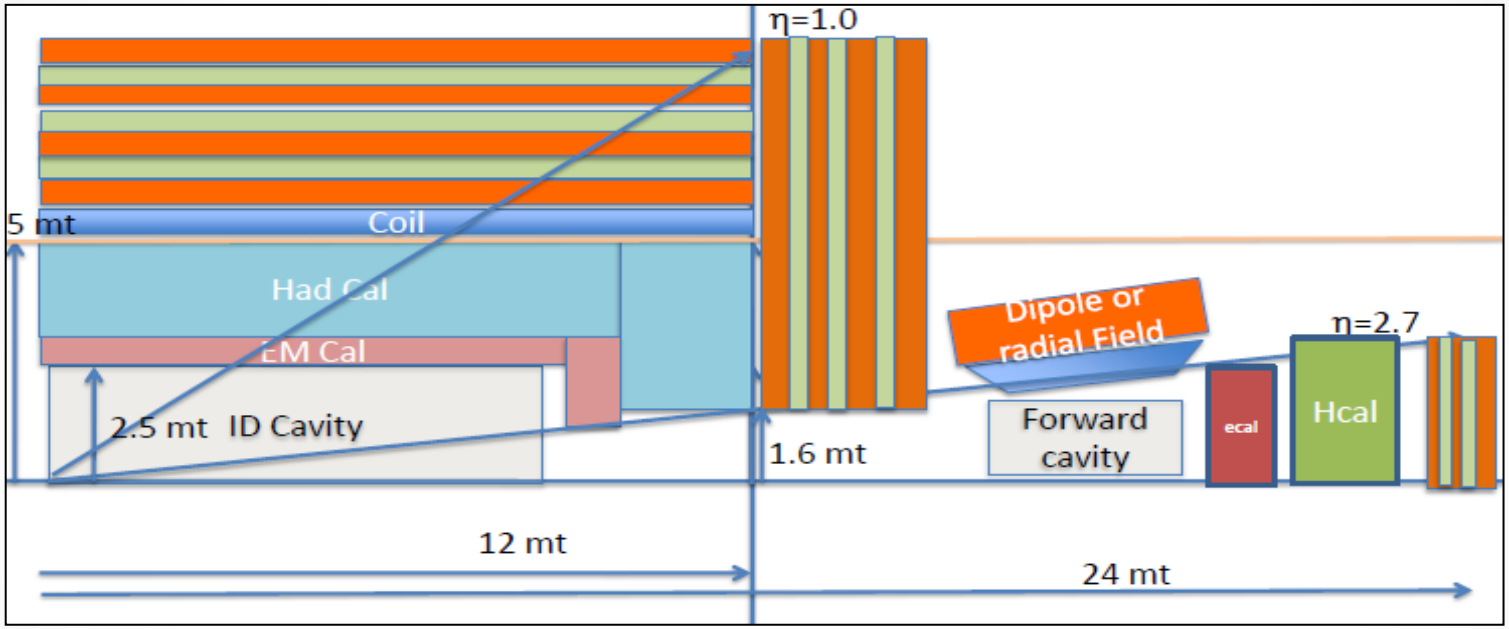
- Loss due to data quality in LAr < 1% during 2012.

Requirements at 100 TeV collider

The detector has to cover wide range of signatures

- Detection of high mass states
  - Dijet resonances or compositeness, M_{q*} ~ 50 TeV
  - Z' or W' to leptons, $m_{Z'}$ ~ 30 TeV
  - → Deeper calorimeters, higher dynamic range
- Precision measurements of the Higgs boson properties, and Higgs in BSM production
  - Precision lepton/photon in complex events, b, c, tau tagging
  - → at least comparable to CMS/ATLAS in EM resolution and PID
- Vector boson fusion and scattering
  - Forward jets → more forward coverage, up to η=6
- Boosted jets from Z, W, top and H
  - Jet substructures
  - → More granular calorimeters

Large Solenoid Detector



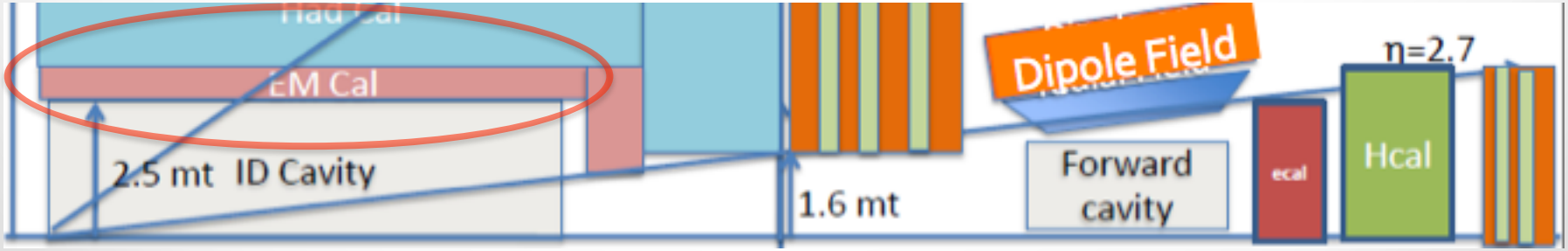
Barrel	$0 < \|\eta\| < 1.5$	16 m long, 2.5 m radius	$250 m^2$
Ext barrel	$1.5 < \|\eta\| < 2.7$		$20 m^2$ X 2
Endcap	$2.7 < \|\eta\| < 4.0$	3m outer radius	$25 m^2$ X2
FCal	$4.0 < \|\eta\| < 6.0$	1m outer radius	$3 m^2$ X2

One of possible detector layouts, used in this talk as an example
other more compact designs are also being studied

D. Fournier, overview at FCC Kick-off meeting in Feb 2014
M. Mannelli, ECAL summary; C. Helsens, HCal summary, FHC workshop, May 2014

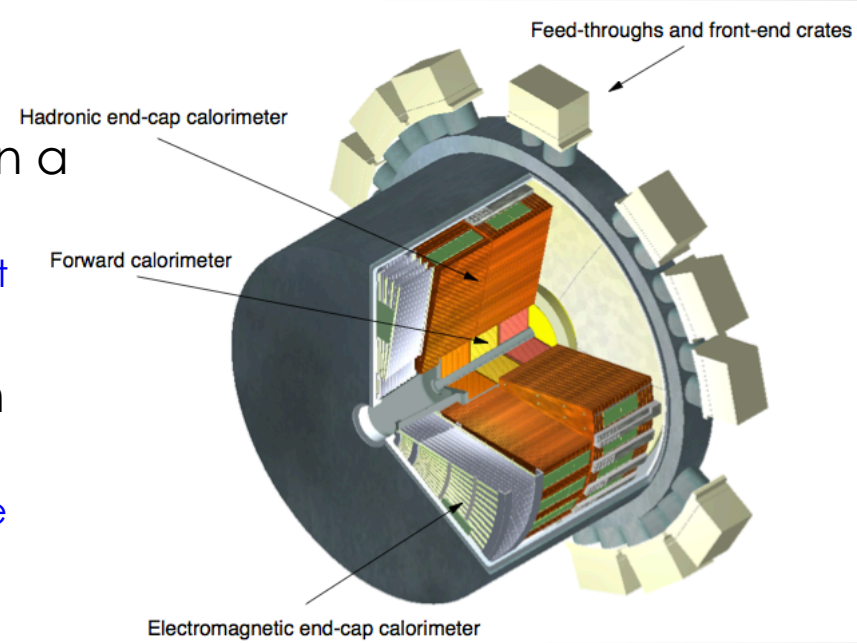
Barrel EM calorimeter

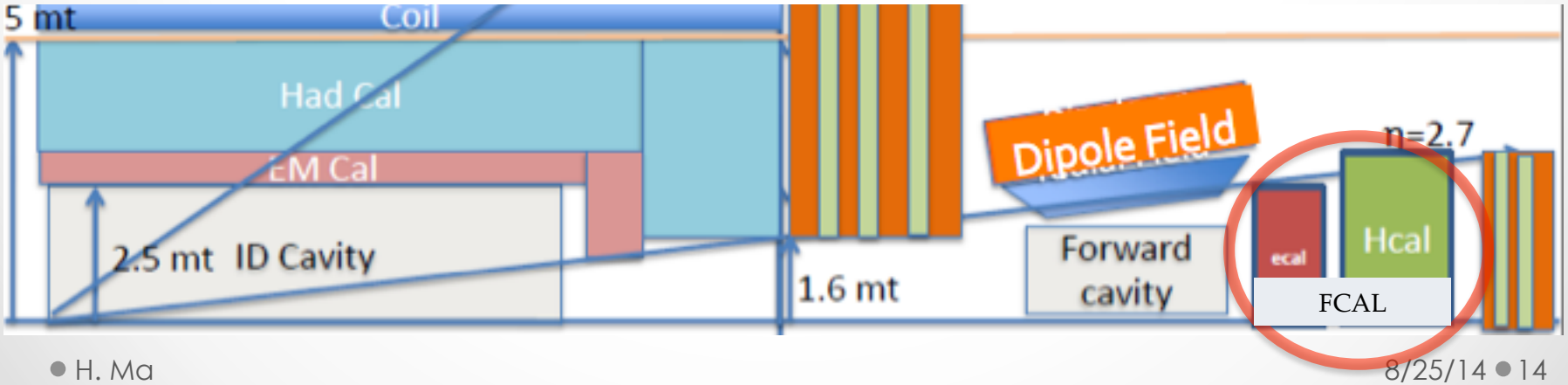
- Accordion EM calorimeter, a larger version of ATLAS EM barrel
  - Radiation levels and rates should be ok
  - Longitudinal shower containment→ depth ~ $30X_0$, (ATLAS >24 X_0)
  - Inner radius: 2.5 m, (ATLAS 1.15m), Barrel length 16m, (ATLAS 6.7m)
  - ATLAS physical cell size of middle layer → 0.015 x 0.015 in $\Delta\eta$ x $\Delta\phi$
  - Cost may scale with size, volume ratio: ~ 6
- Comparable resolution: $\sigma_E/E \sim 10\%/\sqrt{E} + 1\%$
  - Good stochastic and constant energy resolution term
  - Need to maintain the mechanical precision in a much larger system
- Good transverse granularity and longitudinal segmentation
  - Shower shape analysis for EM shower ID
  - ATLAS: 3 longitudinal layers, Could be extended to 4, going beyond this would require substantial new development of the read-out electrodes



Combined Endcap Calorimeters

- A combined LAr EM, hadronic and forward calorimeter system offers radiation hard and robust detector in a hostile environment
  - Space for feed-throughs is not a constraint
- Similar concept to ATLAS endcap calorimeter can be considered, with higher η coverage
  - Higher η →high radiation →larger distance
  - What is the limitation for operation?





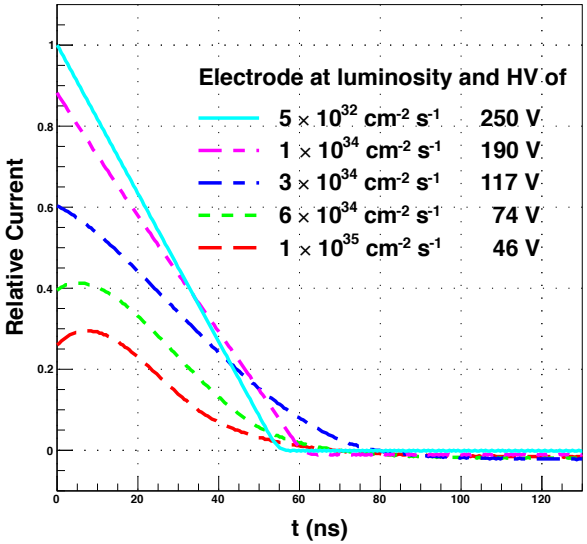
Forward calorimetry

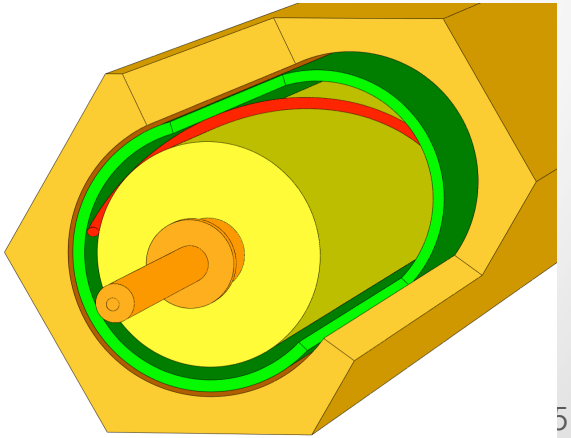
- ATLAS FCal at L > $10^{34}/cm^2/s$
  - HV drop due to higher current on protection resistors
  - Positive ion charge build-up leading to degraded signal response
  - Potential heating due to energy deposits
  - On-going studies to quantify the effects
- R&D on sFCal:
  - Reduce the LAr gap to 120μm
    - Raise significantly critical ionization rate
    - Shortens the drift time to 23ns
  - Smaller protection resistance
  - One of the options for ATLAS LAr Phase-II
  - ATLAS Phase-II LoI CERN-LHCC-2012-022

$$D_c \equiv \frac{n_c}{\tau} = \frac{4V_0^2 \varepsilon \mu_+}{e a^4}$$

J. Rutherfoord, NIM A 482 (2002)

Expected current in FCAL at high lumi





Beam Test Results from HiLum

- Measuring LAr response using 50 GeV proton beam at Protvino
  - 10^6 p/s up to 10^{12} p/s
- Detectors similar to ATLAS EMEC, HEC, FCAL and sFCAL were tested
  - Critical intensity points were measured
- More results are expected

A. Glatte et al, NIMA 669 (2012)

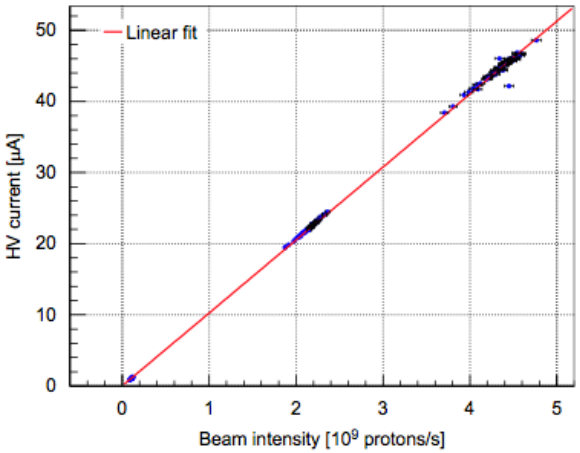


Fig. 24. Total FCal HV current compared with the spill-based beam intensity measurement provided by the ionization chamber. The line shows the result of a linear fit to the data points.

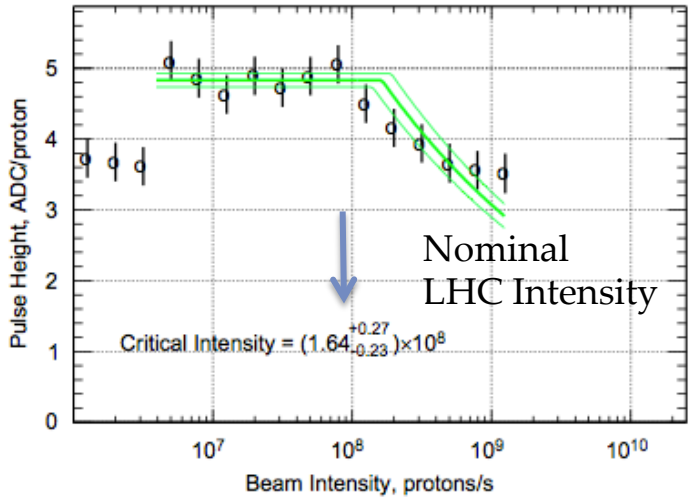


Fig. 30. Dependence of the EMEC signal (at 1.2 kV) on beam intensity. The solid line shows a fit to the data (see text), but ignoring the very low intensity region.

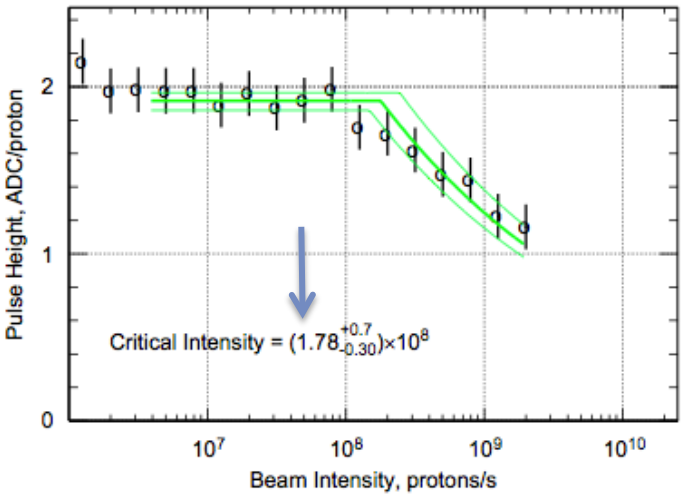


Fig. 31. Dependence of the HEC signal (at 1.2 kV) on beam intensity. The solid line shows a fit to the data (see text), but ignoring the very low intensity region.

sFCal for a 100 TeV Detector?

- Compared to ATLAS FCal (z=4.7m, η_{max}=4.78)
  - dE_T/dR increase 14TeV →100TeV: 2.6
    - inelastic cross section increase: 1.3
    - Mean p_T increase: 2
  - η_{max} (4.87→6), Z (4.7m →20 m) : 1.6
    - $dE/dxdy \sim 1/(Z^2\theta^3) \times dE_T/dR$
  - Energy density increase ~ 4,
  - Large uncertainty because of extrapolation to η=6
- At 100TeV and L=5×10^{34}/cm^2/s, "sFCal" will be operated at ~20 times higher intensity than the ATLAS FCal at nominal LHC Lumi
  - First HiLum results are promising
  - Data with higher intensity will give more definitive answers soon
- Engineering issues for high current and heat dissipation need to be studied

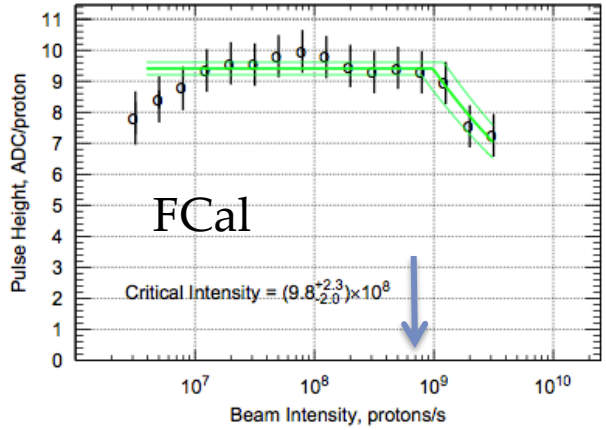


Fig. 32. Dependence of the FCal(269) signal on beam intensity. The solid line shows a fit to the data (see text), but ignoring the very low intensity region.

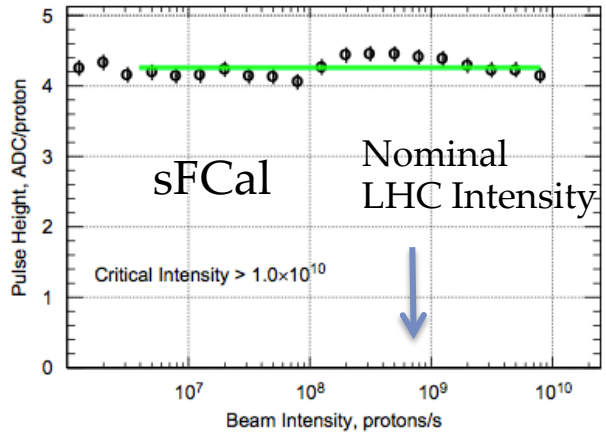
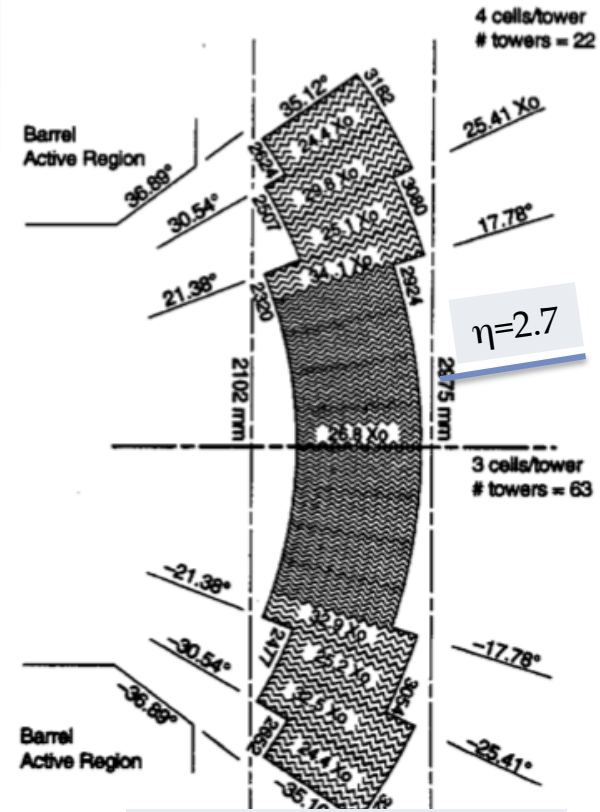


Fig. 33. Dependence of the FCal(119) signal on beam intensity. The solid line shows a fit to the data (see text), but ignoring the very low intensity region.

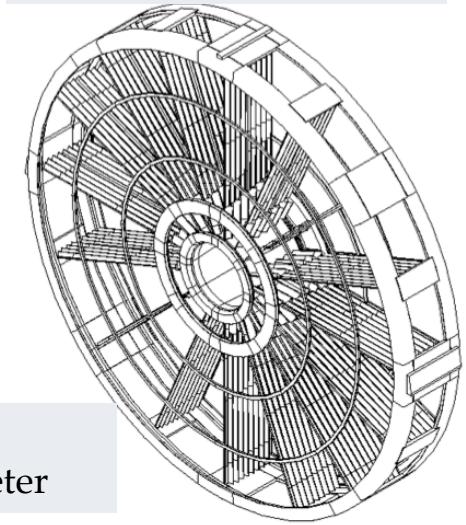
A. Glatte et al, NIMA 669 (2012)

EM Endcap

- Two possible accordion configurations
  - GEM: Vertical barrel-like, symmetry around-y projective and constant sampling fraction, steps to approximate flat front face
  - ATLAS: Spanish fan, phi-symmetric, varying sampling fraction, mechanically complicated.
- For small angular coverage (η=2.7, θ<7.7 deg) the design can be simpler:
  - Sagitta for Z=20m: 18cm. No steps needed!
- Maintaining a transverse segmentation of $\Delta\eta X \Delta\phi$ =0.025X0.025 at η=4 and Z=20m is still feasible: ~ 1.8cm X 1.8cm
- Ion buildup is not likely a problem
  - Energy density may be slightly lower than ATLAS EMEC at η = 3.2, Z=3.7m (see slide 16)
- Pileup noise dominates in endcap. can smaller LAr gap be used in accordion?



GEM EM Endcap @ SSC

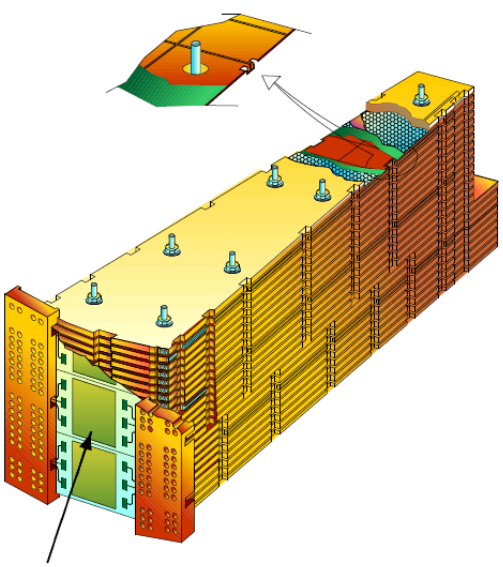


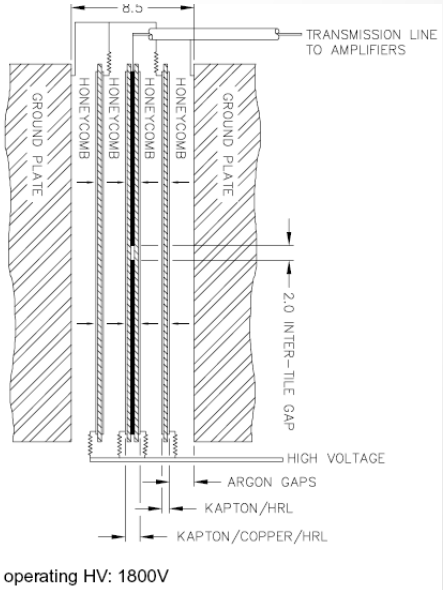
ATLAS EM
Endcap Calorimeter

Hadron Calorimetry

- Main advantage of LAr hadron calorimeter is its robustness and radiation resistance.
- ATLAS Hadronic Endcap design
  - Electrostatic Transformer: low C(faster), lower HV
  - Active pads: cold preamps for every 2 gaps, better S/N.
  - $\Delta\eta\times\Delta\phi$=0.1 × 0.1- 0.2 × 0.2, with 4 longitudinal segmentations

- Can faster response and finer segmentation be explored?
- On-going ATLAS studies on boosted jets and jet sub-structures
  - Public Results
- Jet substructure studies for FCC have also been started
  - See talks by M. Pierini at FCC Kickoff meeting, & B. Tweedie this workshop on Tuesday.

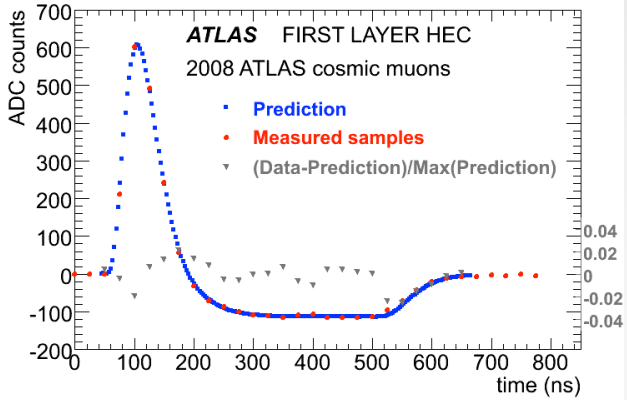




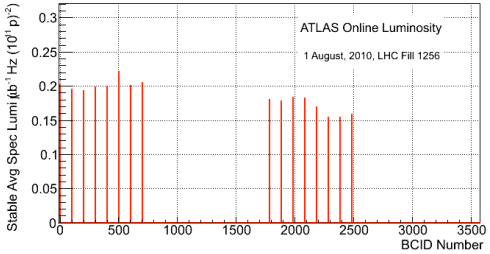
ATLAS Hadronic Endcap

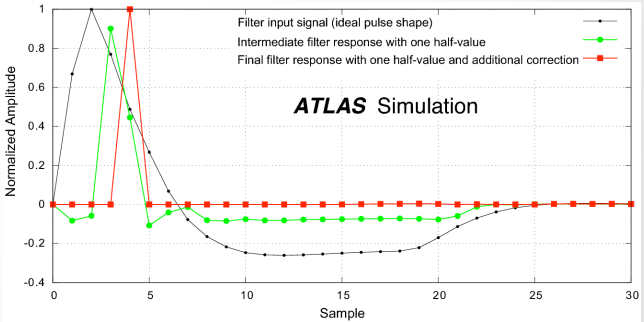
Mitigating Pileup

- Current ATLAS LAr readout electronics and signal processing:
  - Bipolar shaping, t_p ~ 50ns
  - Analog pipeline + digitization after L1 trigger
  - Online energy & time measurements: Optimal Filtering using 5 samples
  - Offline correction: average energy offset based on bunch crossing luminosity, due to finite bunch train length
- Upgraded full digital pipeline readout
  - Digital sampling at 40MHz
  - Online digital signal processing
    - Event-by-event corrections using prior measurements
    - Need to develop fast and smart algorithms
  - First implementation for trigger readout in Phase-I upgrade, CERN-LHCC-2013-017
  - All readout channels in Phase-II upgrade
- Advanced electronics and signal processing can reduce the pileup effects



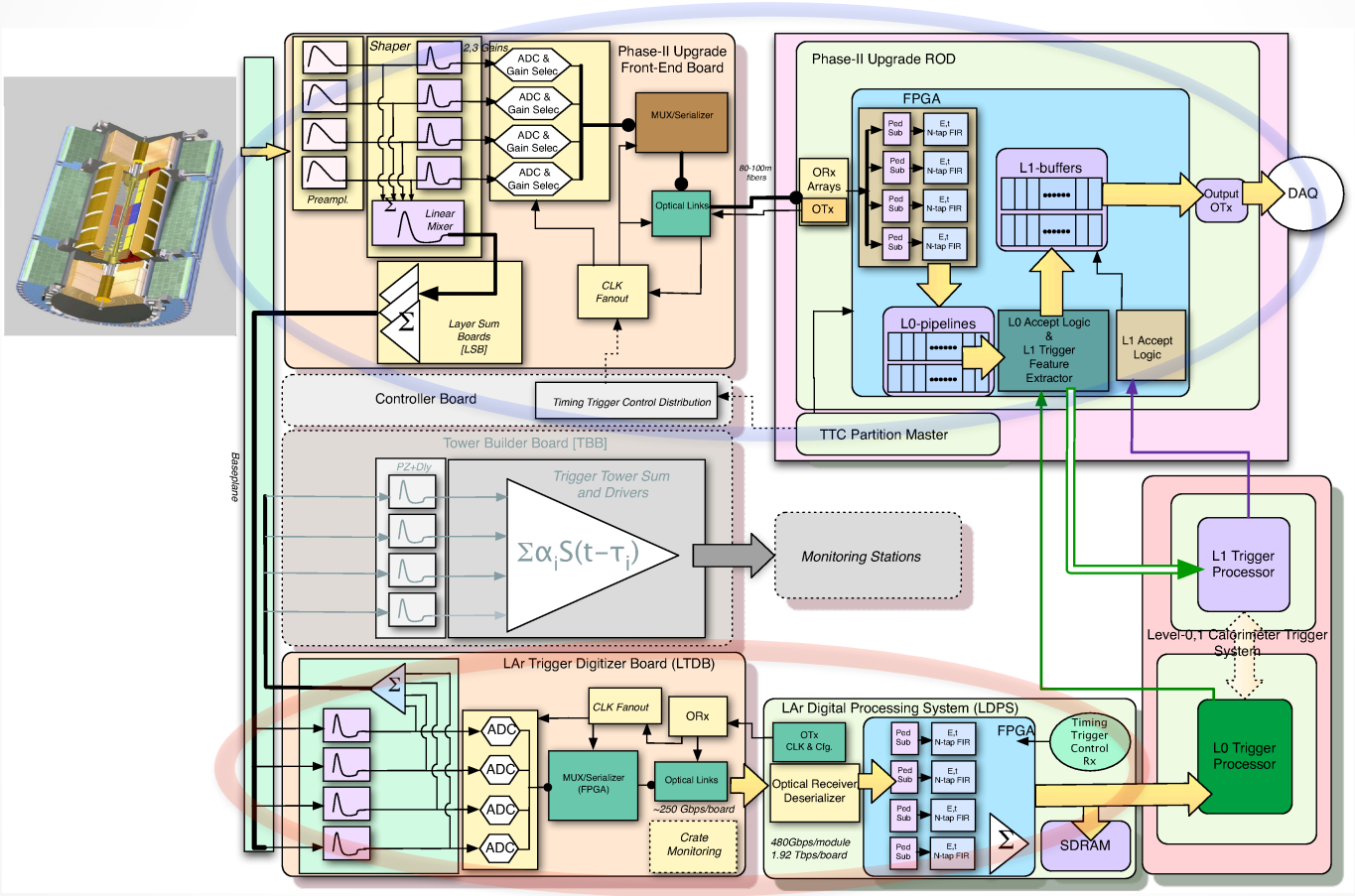
$$A = \sum_{i=1}^{5} (a_i s_i - p), A\tau = \sum_{i=1}^{5} (b_i s_i - p)$$





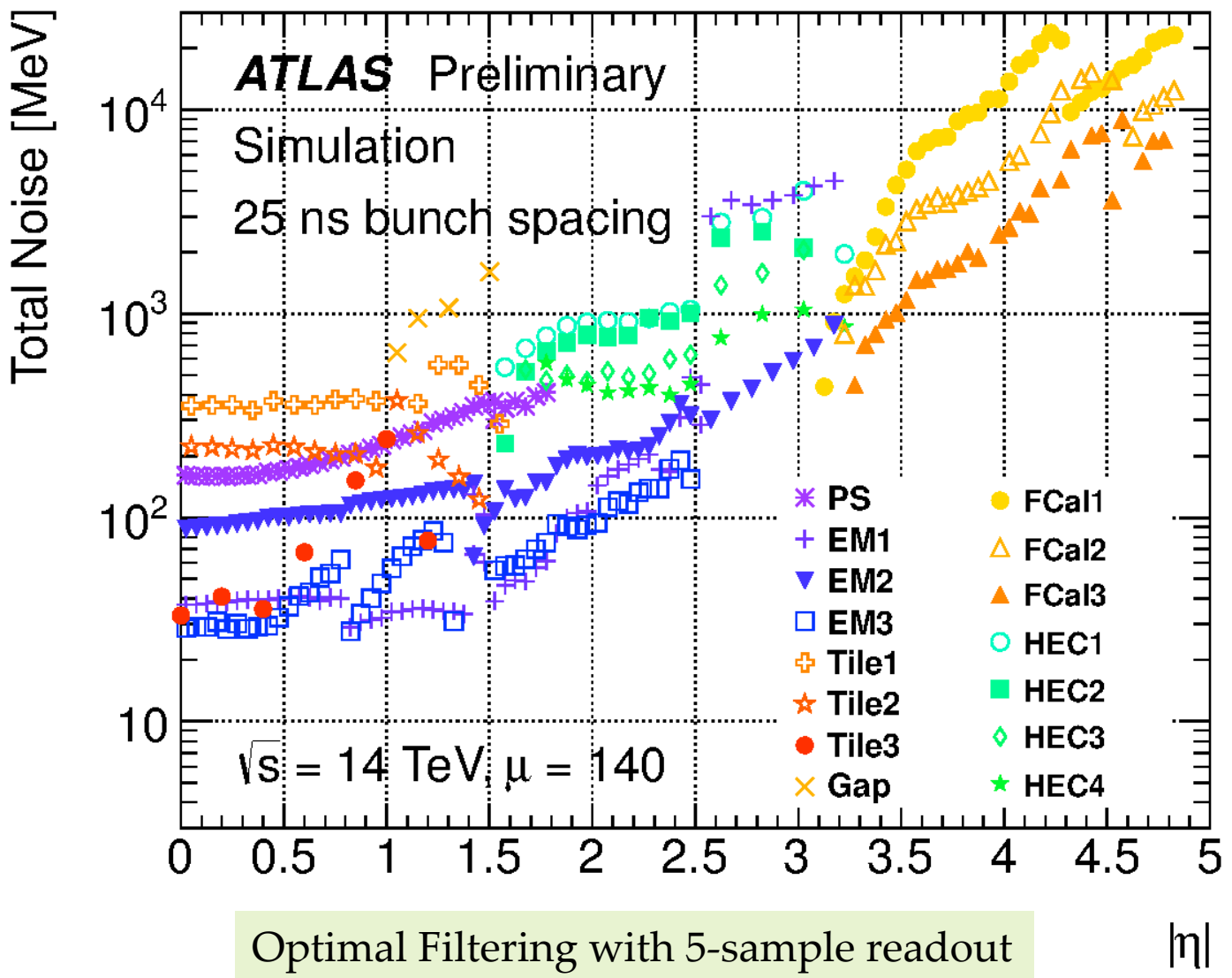
ATLAS LAr Readout Upgrade

Phase-II upgrade: digital sampling for all readout channels



Phase-I upgrade: 40MHz digital sampling for trigger readout

Expected noise at 14 TeV, μ=140



Optimal Filtering with 5-sample readout

Summary

- Experiences with and performance of the ATLAS LAr calorimeters have reinforced the notion that noble liquid calorimetry is an excellent technology for high energy hadron colliders
- Detector concepts are illustrated by extrapolating from the existing calorimeters and detector R&D for the upgrade.
- ATLAS Phase-I upgrade project and R&D efforts for Phase-II upgrade are all relevant for possible design for calorimeters for future hadron collider experiments.
- More quantitative analysis should be done using simulation, in the framework set up in FCC calo group and physics studies.

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