Shower library technique for fast simulation of showers in calorimeters of the H1 experiment

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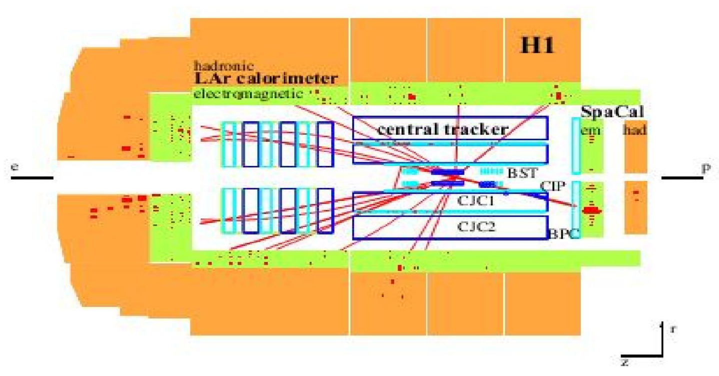
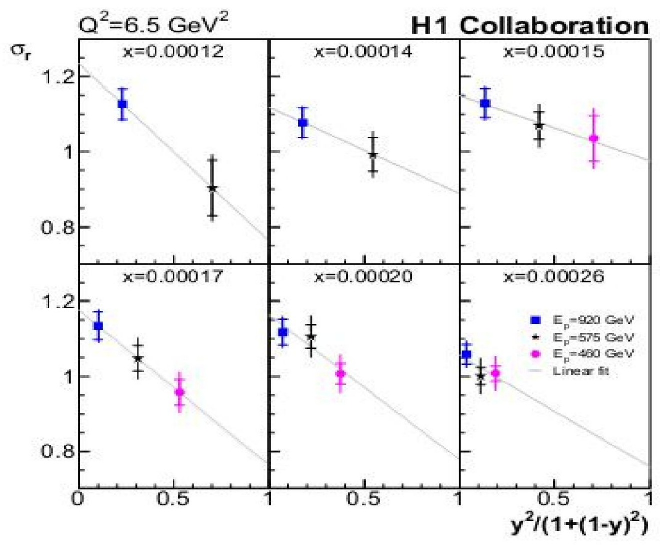
H1 detector and physics analysis requirements



- ❑ H1 experiment – study of e±p DIS from HERA collider in Hamburg , E_p = 920 GeV, E_e = 27.5 GeV
- ❑ Calorimeters are used for event kinematics reconstruction and identification of scattered electron



❖ Neutral current reduced cross section at low photon virtuality Q^2

$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \quad Y_\pm = 1 \pm (1-y)^2$$

x – Bjorken variable

$y \sim E'_e/E_{e,beam}$ – event inelasticity

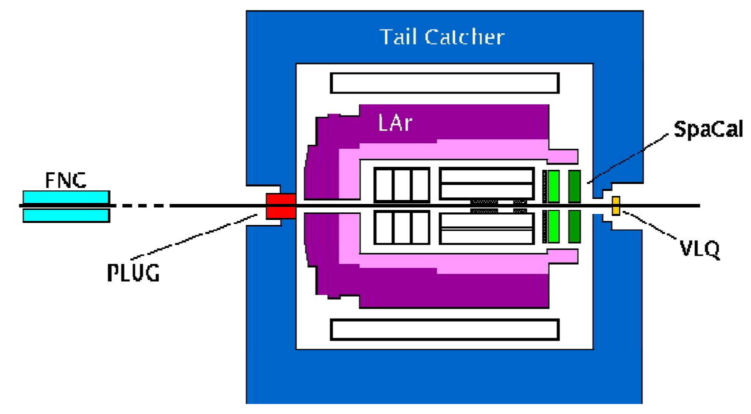
→ Extension to lowest E'_e allows to measure at highest y, which is important for measuring of structure function F_L **directly related to the gluon distribution in the proton**

Simulation of showers

❑ Shower simulation typically takes significant amount of the simulation time → speedup of shower simulation important point in HEP analysis

Methods used to speedup shower simulation:

- ❖ GFLASH parameterization of higher energy showers (becomes less efficient for detectors with a large amount of material in front of the calorimeter)
- ❖ Shower libraries, pre-simulated sets of showers (limited to calorimeters with translational symmetry of readout elements)
- ❖ "Frozen showers" (ATLAS), libraries of GEANT hits for soft particles.

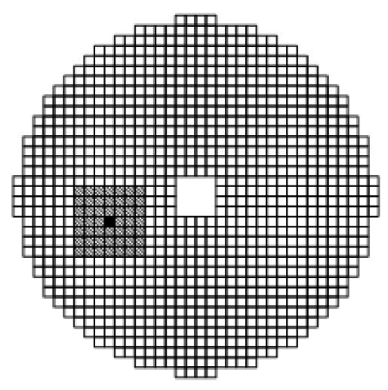


At H1:

- ❖ MC simulation of showers using shower library first implemented for the backward SpaCal calorimeter → speedup vs GEANT simulation up to factor of 10 depending on event topology
- ❖ After SpaCal, Shower library simulation tested for Forward Neutron calorimeter (FNC)

Shower library simulation

❑ Shower library - presimulated sets of showers - to improve and speedup simulation of showers in calorimeters



- ➢ Contains energies in a box around the hottest cell
- ➢ Binned logarithmically in energy , linearly in impact position inside the hottest cell and impact angle
- ➢ Translational invariance used to place showers for different hottest cell

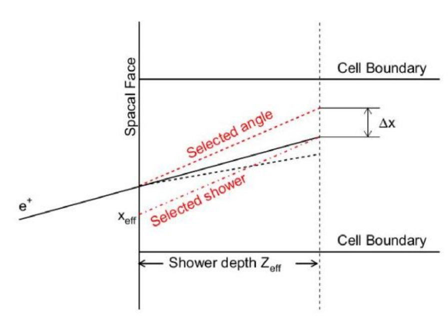
❑ Shower libraries are used for compact electromagnetic and broad hadronic showers.

Energy and position interpolation

- ❑ The library contains energy bins binned logarithmically
- ❑ During simulation a shower is selected from the library

The energy bin selection:

- ❖ Select two bins $E_l < E \le E_h$
- ❖ Randomly pick bin l or h with probability based on logarithmic distance: $p = \frac{\log \frac{E_h}{E}}{\log \frac{E_h}{E_l}}$
- ❖ The variation of energy resolution vs E is reproduced correctly up to first order in log E_h/E_l



- ❖ The shower library is used at the calorimeter face
- ❖ The shower position is corrected for the difference between the incident angle and the shower library angular bin using effective shower depth Z_{eff} (measured in full simulation)

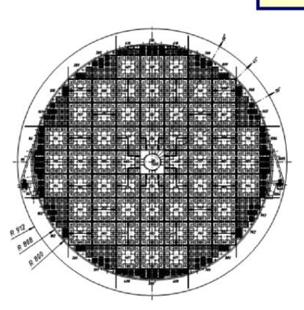
Library packing

5	5	6	8	6	5	5
5	10	10	12	10	10	5
6	10	20	20	20	10	6
8	12	20	24	20	12	8
6	10	20	20	20	10	6
5	10	10	12	10	10	5
5	5	6	8	6	5	5

- ❖ Store showers as total energy and fractional energy in each cell
- ❖ Use bit packing for fractional energy (optionally: in log E_{cell}/E_{shower})
- ❖ Fraction of the shower energy contained in the cell at the shower centre is stored with the highest precision
- ❖ Keep packed showers in memory, unpack only during usage of the shower

- ❖ Group showers in buffers. A buffer contains several copies of complete shower library. Keep one buffer in memory, read new one after recycling same showers few times
- ❖ The packing of the energy information significantly reduces the size for one buffer

Shower library for the SpaCal



SpaCal is lead/ scintillator-fiber calorimeter, backward in H1

- ➢ Electromagnetic section with 1192 cells of 4.05×4.05×25 cm³ size each, 27.5 radiation length.
- ➢ Hadronic section with 136 cells of 12×12×25 cm³ size each. Total nuclear interaction length: λ = 2.

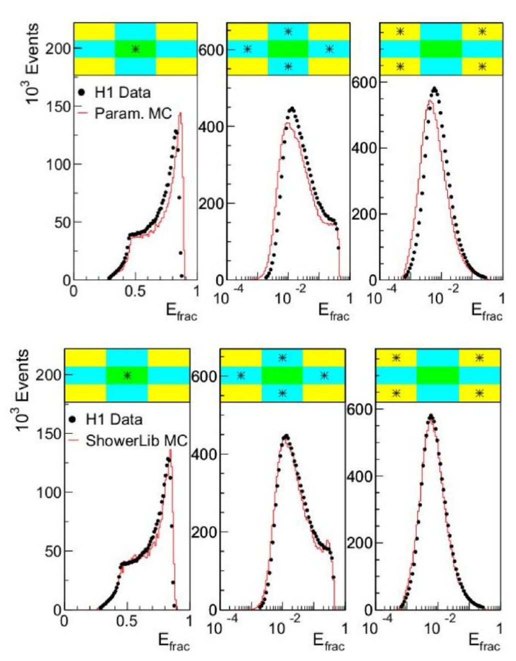
- ❑ The library contains 12 energy bins, binned logarithmically from 0.1 GeV to 32 GeV
- ❑ Incident angles for the particles from IP are $|\theta_{max}| < 25°$
- ❑ Position resolution of the SpaCal is ~3 mm → 8×8 bins in θ_x, θ_y and 10×10 bins in x, y
- ❑ Two bins for particle type (electron/positron and photon)

Library for hadrons

- ❑ 5×5 position bins and 4×4 angular bins
- ❑ Energy binning: 10 bins, 0. 1 –20 GeV
- ❑ 9 bins in particle type ($\pi^\pm, K^\pm, K^0, n, \bar{n}, p, \bar{p}$)

Packing: Info from complete SpaCal calorimeter, for cells with non-zero energy

Energy sharing in the SpaCal

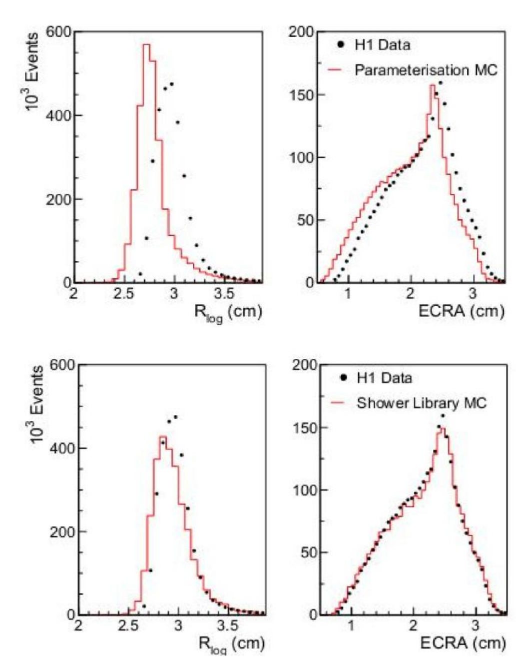


Use shower from scattered electrons with 15 < E'$_e$ < 30 GeV, for 30 < R'$_e$ < 60 cm (clean DIS sample) to compare data with two simulations:

- ▪ MC simulation using the shower parametrisation based on GFLASH
- ▪ MC simulation using the shower library

- ➢ Shower library provides significant improvement in simulation of the energy sharing
- ➢ The quality of shower library simulation is the same as in the full GEANT simulation, BUT the CPU time for MC based on shower library is reduced compared to the full GEANT simulation by about factor of 10 depending on event topology.

Shower profile in the SpaCal



▪ Estimation of shower center-of-gravity

$$X_{cluster} = \Sigma_i x_i w_i \quad Y_{cluster} = \Sigma_i y_i w_i$$

with square root or logarithmic weighting

$$w_{i,sqrt} = \frac{\sqrt{E_i}}{\Sigma_j \sqrt{E_j}}$$

$$w_{i,log} = \frac{\max(0, W_{cut} + \log(E_i / E_{cluster}))}{\Sigma_j \max(0, W_{cut} + \log(E_j / E_{cluster}))}$$

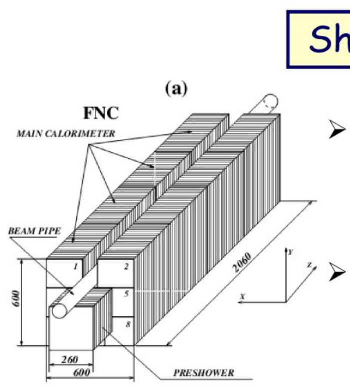
▪ Estimation of transverse size radius

$$R_{log} = \sqrt{\Sigma_i (R_i w_{i,log})^2}$$

$$ECRA = \Sigma_i R_i w_{i,sqrt}$$

➢ Shower library provides significant improvement in simulation of the shower profile

Shower library for the FNC



- ➢ The Main Calorimeter of the FNC consists of four identical sections. Each section is 51.5 cm long with transverse dimensions of 60x60 cm² and consists of 25 lead absorber plates of 14 mm thickness and 25 active boards with 3 mm thick scintillators
- ➢ The Preshower Calorimeter is a 40 cm long lead-scintillator sandwich calorimeter, corresponding to about 60 radiation lengths or 1.6 hadronic interaction lengths. It is composed of 24 lead-scintillator planes

Library for hadrons

- ❑ 50×50 bins in x, y (all front of the preshower surface), no bining in θ_x, θ_y
- ❑ Energy binning: 100 bins, 25–1040 GeV

Electromagnetic shower library

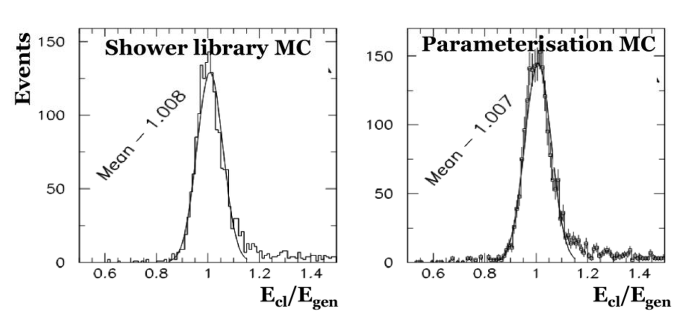
- ❑ 50×50 bins in x, y (all front of the preshower surface), no bining in θ_x, θ_y
- ❑ Energy binning: 50 bins, 0.5–700 GeV

The energy response of all 50 cells (9+9 (preshower) + 32 (FNC main)) of calorimeter is recorded. The hadronic library includes 3 buffers generated with neutrons. The electromagnetic library includes 24 buffers with photons.

Energy reconstruction in the FNC

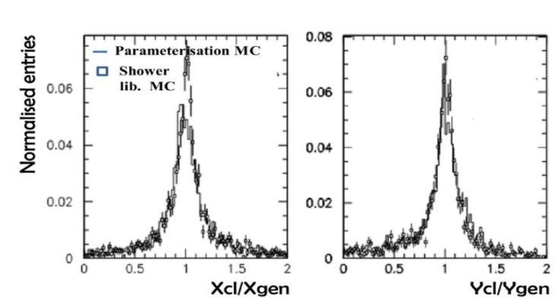
❑ Cuts for selection of a clean sample of DIS events with additional cuts on deposited energy in the preshower and in the main FNC section are applied for selection of high energy neutrons to compare between the two simulations:

- MC simulation using the shower parametrisation based on GFLASH
- MC simulation using the shower library

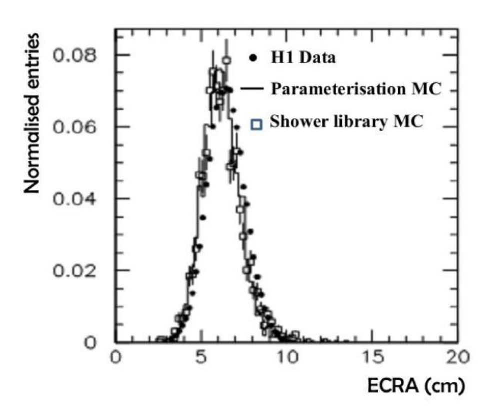


- ❑ Mean and RMS for ratio of reconstructed cluster energy to generated energy similar for the two simulations
- ❑ Simulation time for shower library shorter about 25% taking into account tracing of particles from the IP through the forward detector elements (which takes most of the time) up to the FNC

Shower profile in the FNC



❑ Dstrbutions for ratio of reconstructed to generated X, Y cluster positions in the FNC similar for the two simulations



- ❑ Shower profile distributions similar for the two simulations
- ❑ For the FNC, both simulations provide fair description of the shower profile from data

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- ➢ MC simulation based on shower library provides good description of the shower profile in SPACAL, better than MC simulation using the GFLASH based shower parameterisation
- ➢ For SpaCal, the quality of shower library simulation is the same as in the full GEANT simulation, BUT the CPU time for MC based on shower library is significantly reduced → speedup vs GEANT simulation up to factor of 10 depending on event topology
- ➢ For the FNC, simulations based on shower library and GFLASH provide similar description of cluster properties, but the CPU time used by shower lib simulation is significantly shorter
- ➢ For the FNC, both simulations provide fair description of the shower profile
- ➢ Shower libraries are simple to implement in the GEANT environment