Fast simulation of electromagnetic and hadronic showers in SpaCal calorimeter at the H1 experiment

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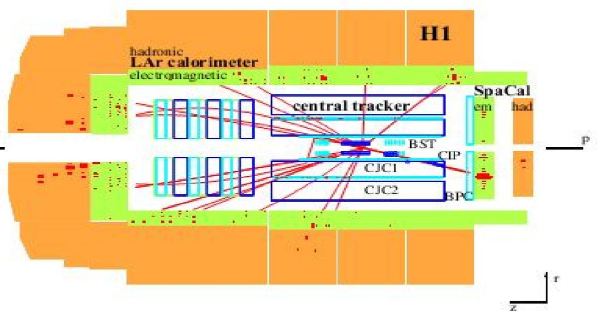
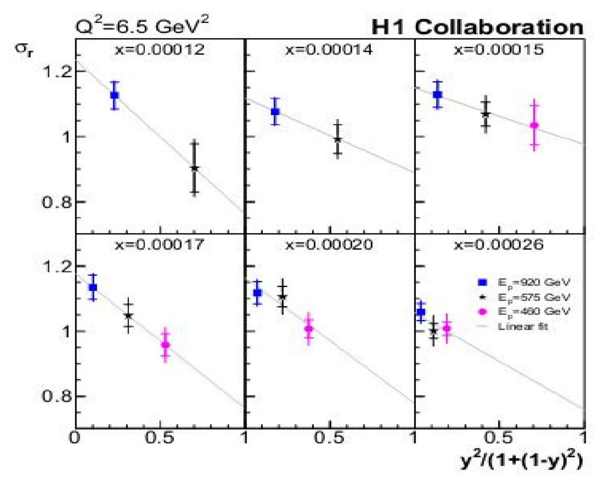
H1 detector and physics analysis requirements





- ❑ 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

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

x – Bjorken variable

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

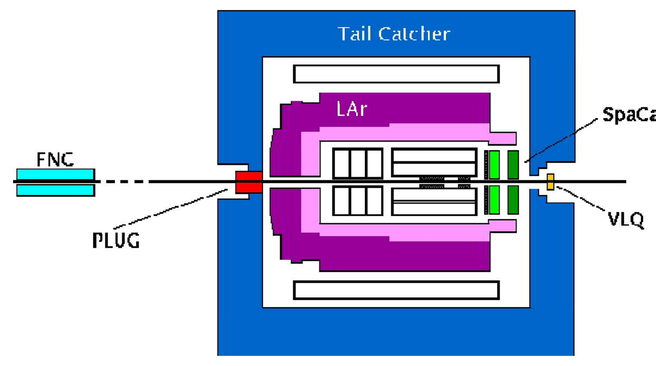
→ Extension to lowest E'_e allows to measure at highest y, which is important for measuring of structure function F_L **directly related to the gluon distribution in the proton**

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.

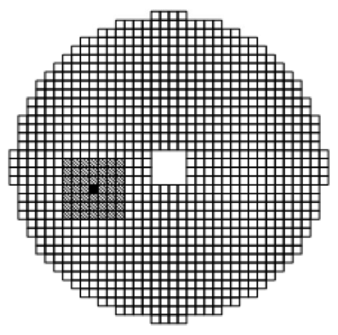


At H1:

- ❖ 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

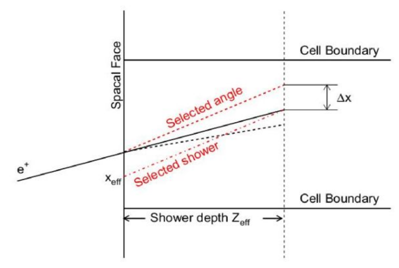
- ❑ Shower libraries are used for compact electromagnetic and broad hadronic showers.

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 $E_l < E \leq E_h$
- ❖ Randomly pick bin l or h with probability $p = \frac{\log \frac{E_h}{E}}{\log \frac{E_h}{E_l}}$ based on logarithmic distance:
- ❖ 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)

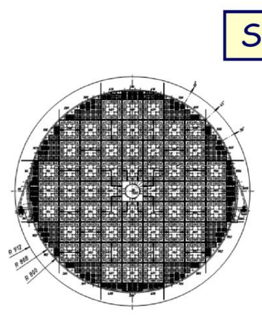
Library packing

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)

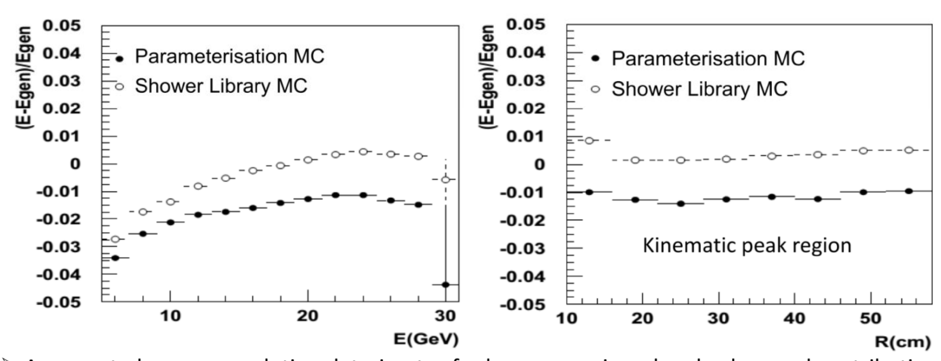
Library for hadrons

- ❑ 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

Linearity and uniformity of e⁻/e⁺ cluster energy in EM section of Spacal

- ❑ Shower library simulation is compared with MC simulation using the shower parametrisation based on GFLASH which was used in H1 collaboration before Shower library implementation
- ❑ To select as clean as possible sample of e-/e+ candidates strong cuts were put on standard DIS selection criteria (apart for requiring high energy cluster when studying linearity)
- ❑ The simulation of e±p collisions uses the DJANGO event generator



- ➢ As expected energy resolution deteriorates for lower energies when background contribution (mainly from hadrons) is larger
- ➢ Shower library provides improvement in simulation of the energy sharing in SpaCal cells

Cluster profile description

- ❑ 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:

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

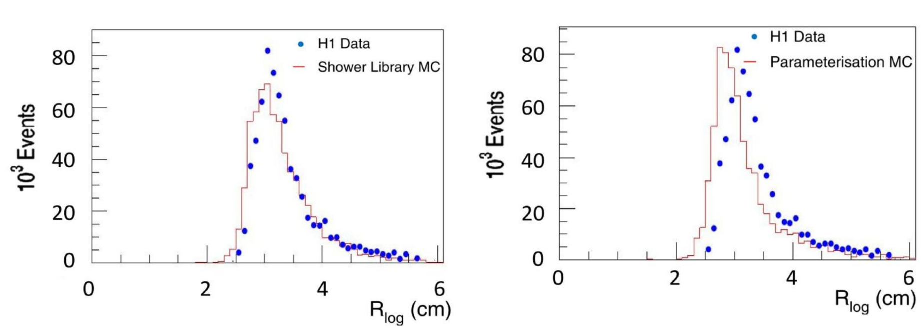
- ❑ Estimation of transverse size radius $R_{\log} = \sqrt{\Sigma_i (R_i w_{i,\log})^2} \quad ECRA = \Sigma_i R_i w_{i,sqrt}$

Selection criteria for photon and hadron candidates

- ❑ Properties of photon and hadron clusters in Spacal are studied using PHOJET 1.6 event generator which is used to generate photoproduction background for e±p scattering
- ❑ To select photoproduction sample in data, specific requirements were applied and responses of two electromagnetic crystal calorimeters, a photon tagger (PT) and an electron tagger (ET) were used. The PT and ET were located downstream of the incoming lepton beam to monitor the luminosity via the measurement of the Bethe-Heitler process ep → γep
- ❑ To eliminate the DIS, events with the scattered electron reconstructed in the ET are used
- ❑ The residual DIS and Bethe-Heitler overlaps are reduced by requiring: no energy deposition in the PT, energy in the ET is greater than 7 GeV and by applying energy/momentum conservation cuts.

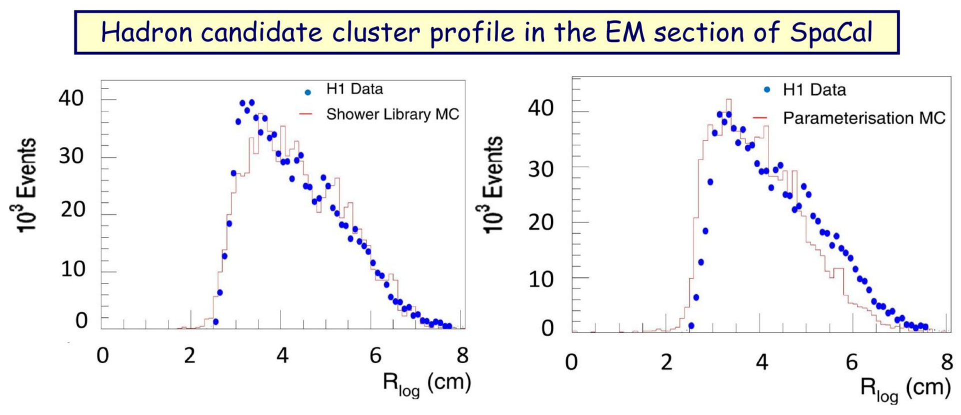
Photon candidate cluster profile in the EM section of SpaCal

- ❑ Photon-like and hadron-like clusters separation based on absence/presence of the signal in a proportional chamber, Central Inner Proportional Chamber (CIP) along the calculated particle trajectory connecting the primary vertex and the selected cluster in the EM section of SpaCal
- ❑ Photon candidate clusters have no match in CIP while hadron candidate clusters have a CIP signal match.



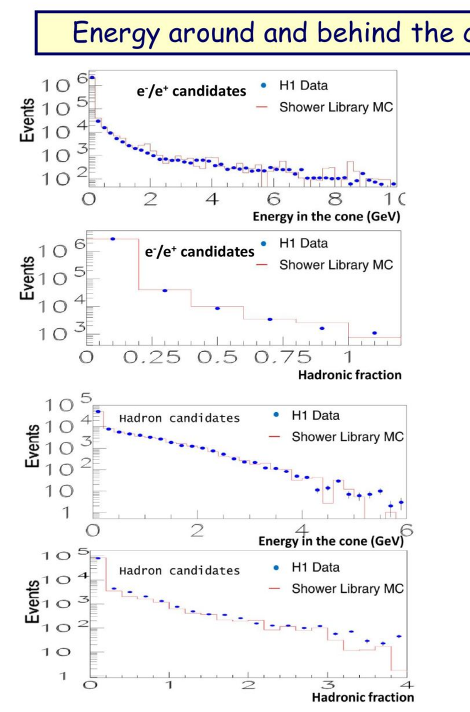
- ➢ Description of photon candidate cluster profile improved with Shower library implementation

Hadron candidate cluster profile in the EM section of SpaCal



- ➢ Description of hadron candidate cluster profile improved with Shower library implementation
- ❑ The separation between photons and hadrons is not 100 % pure. Defined this way photon clusters may have small contamination from hadrons because of CIP inefficiency, whereas hadron clusters in fact also include electrons from photon conversions before the CIP
- ❑ The differences between data versus MC may arise also because of:
  (i) not properly described conversions in the detector material before CIP,
  (ii) not properly described ratio of hadrons to photons in PHOJET,
  (iii) wrong simulation of the energies for the hadronic clusters

Energy around and behind the cluster in the EM section of SpaCal



- ○ Energy in the cone – energy around the selected cluster
- ○ Hadronic fraction - the cluster energy fraction contained in the hadronic section behind the selected cluster
- ➢ Good description of data with Shower library simulation

- ➢ The results on linearity and uniformity of the reconstructed e–/e+ cluster energy in Spacal show that shower library provides accurate and uniform measurement of the selected cluster energy
  → in the kinematic peak region it is within 3 per-mil
- ➢ Monte Carlo simulation using the shower library provides fair description of the photon and hadron cluster shapes observed in data
- ➢ Shower library based simulation provides better description of the SpaCal data than Monte Carlo simulation using GFLASH based shower parametrization for all analysed variables
- ➢ Shower library based simulation also provides a good description of Spacal response around and behind the selected e⁻/e⁺, photon and hadron candidate clusters