Reconstructing the Kinematics of Deep Inelastic Scattering with Deep Learning

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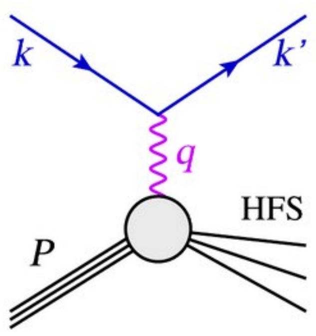
Digest

We introduce a method to reconstruct the kinematics of neutral-current deep inelastic scattering (DIS) using a deep neural network (DNN). Unlike traditional methods, it exploits the full kinematic information of both the scattered electron and the hadronic-final state, and it accounts for QED radiation by identifying events with radiated photons and event-level momentum imbalance. The method is studied with simulated events at HERA and the future Electron-Ion Collider (EIC). We show that the DNN method outperforms all the traditional methods over the full phase space, improving resolution and reducing bias. Our method has the potential to extend the kinematic reach of future experiments at the EIC, and thus their discovery potential in polarized and nuclear DIS.

DIS kinematic reconstruction

The DIS scattering process is characterized by three kinematic variables:

$$Q^2 = -q^2 \qquad y = \frac{q \cdot P}{k \cdot P} \qquad x = Q^2/(sy)$$



Due to longitudinal and transverse momentum-conservation their calculation in experiment is overconstrained, and many equation were proposed in literature. Every method has its pros and cons and no single method is preferred over the entire kinematic range.

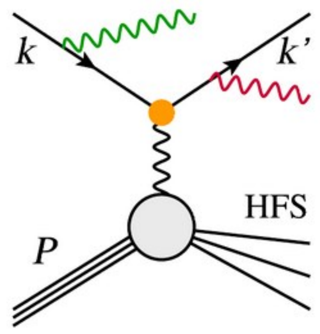
Method name	Observables	y	Q^2	$x \cdot E_p$
Electron (e)	$[E_0,E,\theta]$	$1-\frac{\Sigma_e}{2E_0}$	$\frac{E^2\sin^2\theta}{1-y}$	$\frac{E(1+\cos\theta)}{2y}$
Double angle (DA) [6, 7]	$[E_0,\theta,\gamma]$	$\frac{\tan\frac{\gamma}{2}}{\tan\frac{\gamma}{2}+\tan\frac{\theta}{2}}$	$4E_0^2\cot^2\frac{\theta}{2}(1-y)$	$\frac{Q^2}{4E_0 y}$
Hadron (h, JB) [4]	$[E_0,\Sigma,\gamma]$	$\frac{\Sigma}{2E_0}$	$\frac{T^2}{1-y}$	$\frac{Q^2}{2\Sigma}$
ISigma (IΣ) [9]	$[E,\theta,\Sigma]$	$\frac{\Sigma}{\Sigma+\Sigma_e}$	$\frac{E^2\sin^2\theta}{1-y}$	$\frac{E(1+\cos\theta)}{2y}$
IDA [7]	$[E,\theta,\gamma]$	y_{DA}	$\frac{E^2\sin^2\theta}{1-y}$	$\frac{E(1+\cos\theta)}{2y}$
$E_0E\Sigma$	$[E_0,E,\Sigma]$	y_h	$4E_0E-4E_0^2(1-y)$	$\frac{Q^2}{2\Sigma}$
$E_0\theta\Sigma$	$[E_0,\theta,\Sigma]$	y_h	$4E_0^2\cot^2\frac{\theta}{2}(1-y)$	$\frac{Q^2}{2\Sigma}$
$\theta\Sigma\gamma$ [8]	$[\theta,\Sigma,\gamma]$	y_{DA}	$\frac{T^2}{1-y}$	$\frac{Q^2}{2\Sigma}$
Double energy (A4) [7]	$[E_0,E,E_h]$	$\frac{E-E_0}{(xE_p)-E_0}$	$4E_0y(xE_p)$	$E+E_h-E_0$
Sigma (Σ) [9]	$[E_0,E,\Sigma,\theta]$	$y_{I\Sigma}$	$Q^2_{I\Sigma}$	$\frac{Q^2}{4E_0 y}$
eSigma ($e\Sigma$) [9]	$[E_0,E,\Sigma,\theta]$	$\frac{2E_0\Sigma}{(\Sigma+\Sigma_e)^2}$	$2E_0E(1+\cos\theta)$	$\frac{E(1+\cos\theta)(\Sigma+\Sigma_e)}{2\Sigma}$

Five quantities are used: E_0 (electron-beam energy), E and θ (scattered electron energy and polar angle), Σ and γ (longitudinal energy-momentum balance, $\Sigma = \Sigma_{HFS}(E_i - p_{z,i})$, and the inclusive angle of the HFS).
A shorthand notation is: $\Sigma_e=E-p_{z,e}$. The transverse momenta of the electron and HFS are $p_{T,e}$ and T, respectively.

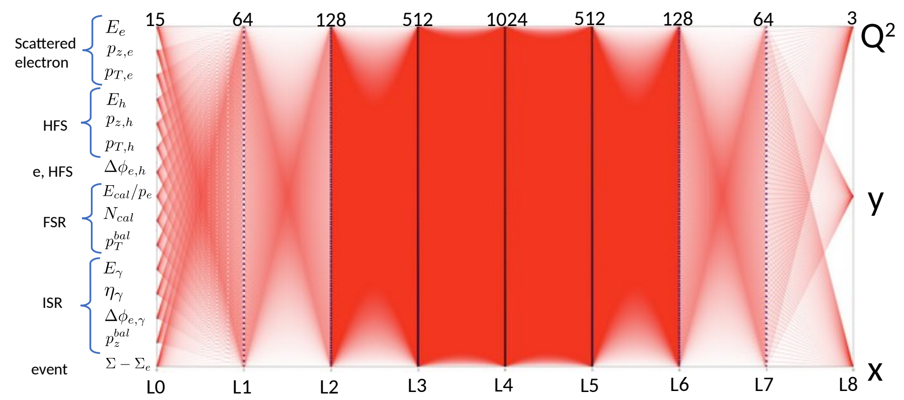
QED radiation & DNN architecture

The presence of QED radiative effects at the leptonic vertex invalidates the two conservation laws and biases the measurement of Q², y and x. We introduce two variables to quantify the strength of QED radiation

$$p_T^{\rm bal} = 1 - \frac{p_{T,e}}{T} \qquad p_z^{\rm bal} = 1 - \frac{\Sigma_e + \Sigma}{2\,E_0}$$



These variables cannot be measured, but are determined by us from 15 selected measured quantities using a regression DNN.

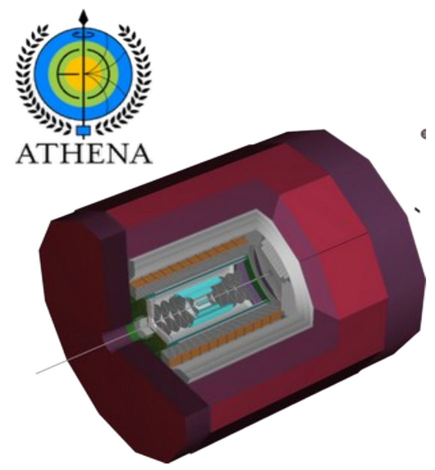


Next, we use a similar regression DNN to determine Q², y and x. The inclusion of the QED variable p_T^{bal} and p_z^{bal} does not improve the regression, and we conclude that this is done internally by the DNN.

Studied experiments

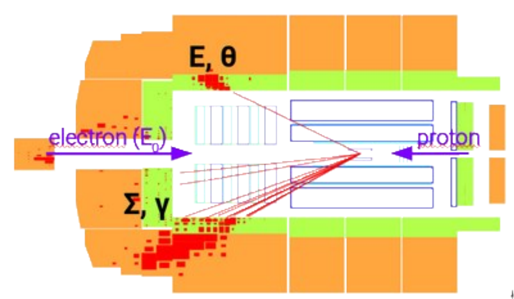
ATHENA @ EIC (fast DELPHES sim.)

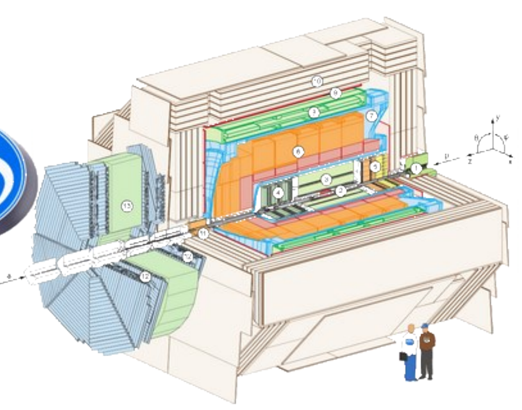
- EIC: √s = 141GeV, Q²>200GeV²
- 3T solenoid
- All silicon tracker
- Excellent momentum resolution



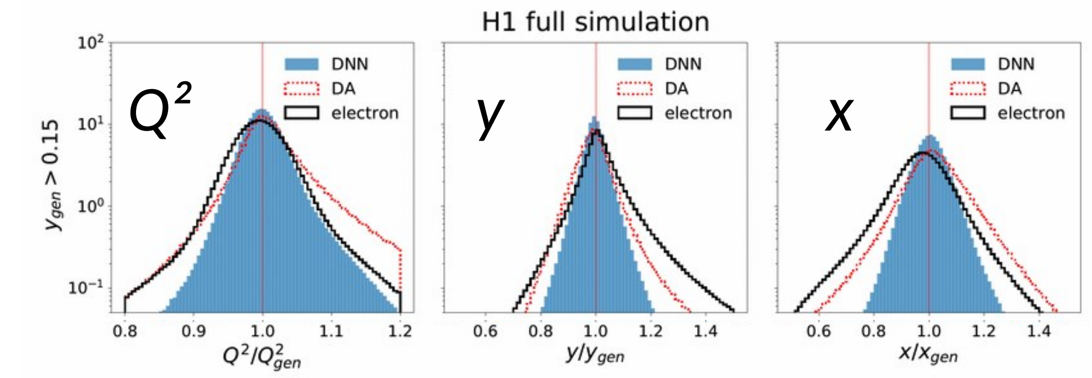
H1 @ HERA (full GEANT sim.)

- HERA: √s = 319 GeV, Q²>200GeV²
- Full sim with real noise & run-dependent effects
- Calibrated sim.& full reconstruction



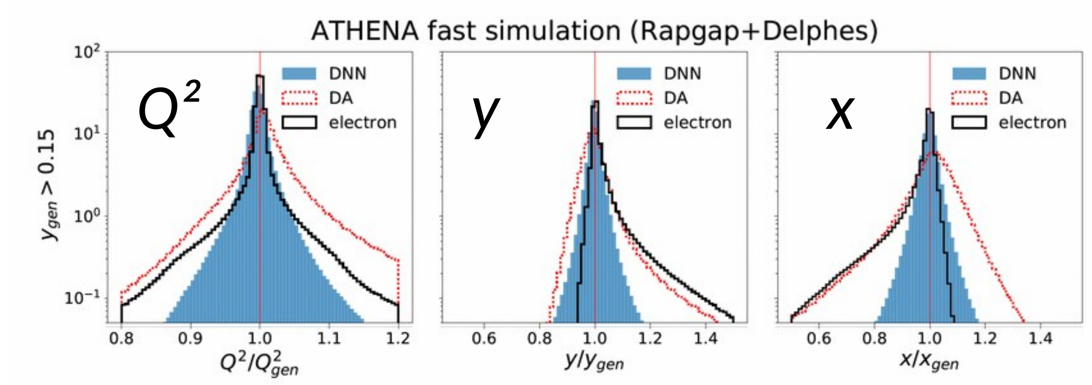


H1: Q², y and x from DNN

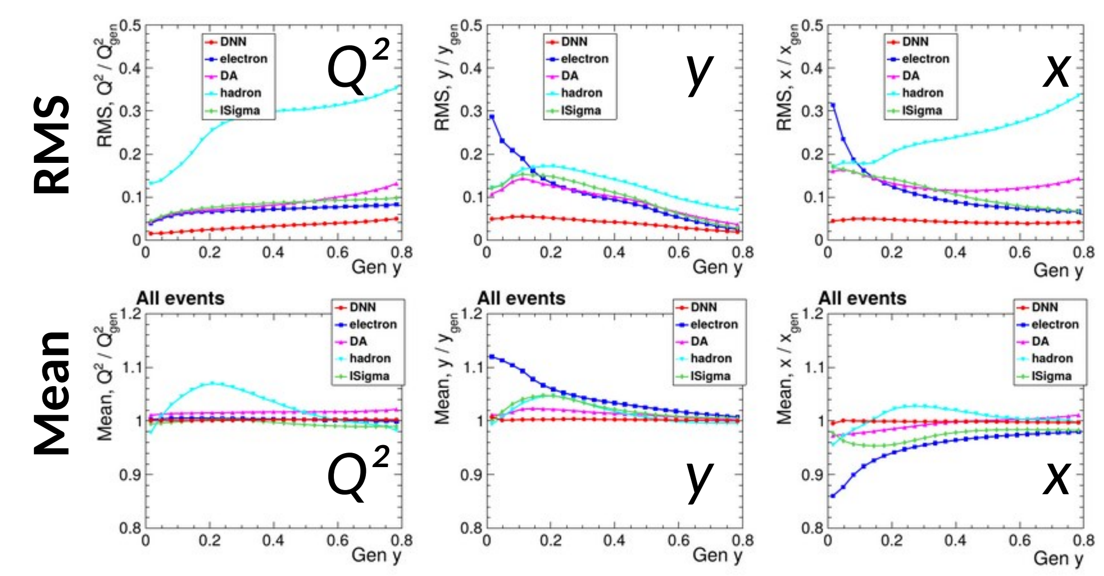


DNN has better core resolution than best conventional method ('electron' at high y, 'DA' at low y). DNN distributions are much more symmetric, and free of large QED radiation tails.

Athena: Q², y and x from DNN



DNN has similar core resolution to best conventional method Large tails from QED radiation are absent in DNN.
The mean and RMS of the distributions as a function of y are:



The DNN reconstruction has the smallest RMS among all methods, for all three kinematic variables and all y intervals. The mean distributions are unbiased for Q2 , y and x for all y intervals, while the classical methods exhibit large biases