Inclusive DIS Variable Reconstruction at ep Colliders: some thoughts based on HERA

ATHENA Inclusive Group Meeting

24 May 2021

Paul Newman (University of Birmingham)

[With thanks to many colleagues who made the plots shown here]

Similarities and Differences

HERA was:

- A high energy electron-proton collider with polarised electron/positron beams

HERA was not:

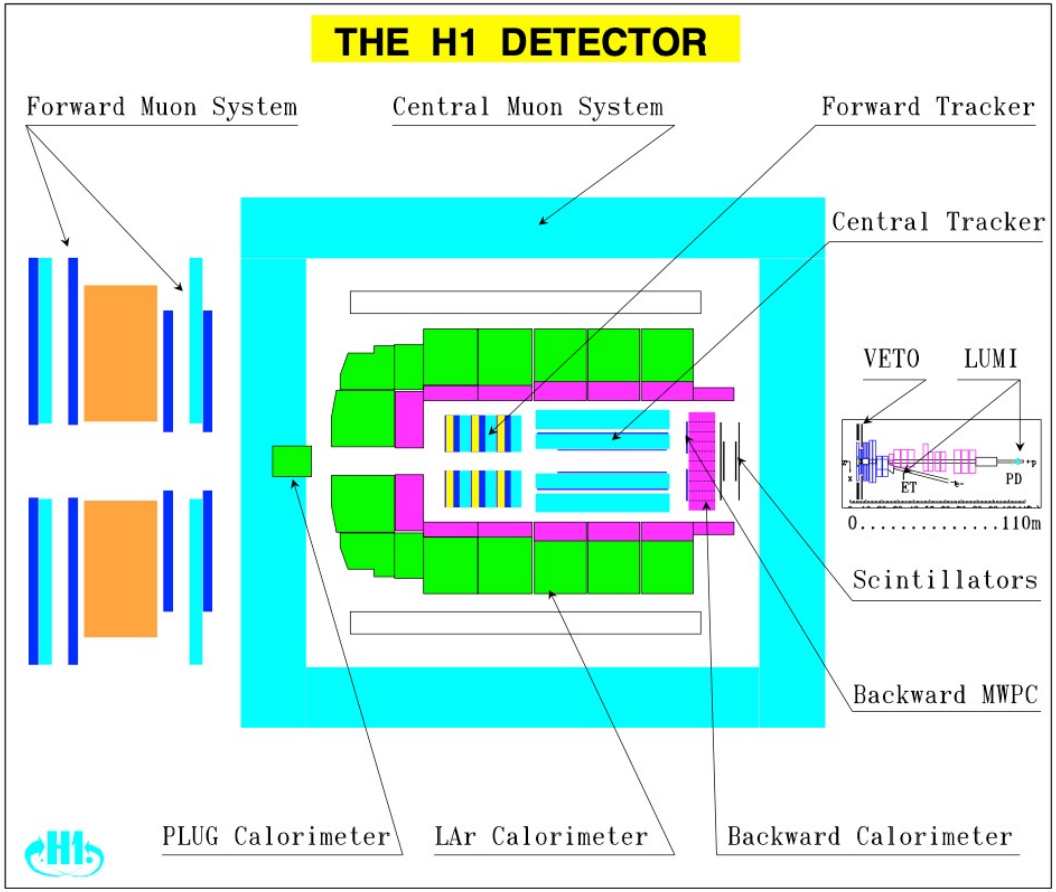
- An electron-ion collider
- A polarised target machine
- A high luminosity collider

... useful to compare but not necessarily to follow ...

Disclaimer:

- I worked on H1, so examples taken from there.
- ZEUS is broadly similar
- HERMES is a different talk entirely

H1 Detector and some immediate comments



- HERA detectors were (initially) built to focus more on high Q^2 / BSM searches and less on low x/Q^2 physics

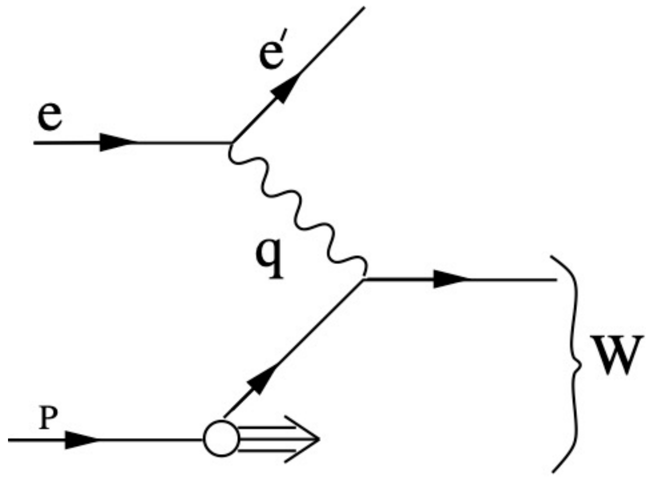
- Reality turned out a bit differently

- 'Backward calorimeter' and MWPC later replaced with SPACAL with electromagnetic and hadronic sections + Backward Drift Chambers

- There was beamline electron tagger ($Q^2 < 0.01$ GeV^2), but then a gap in tagged electron acceptance until $Q^2 \sim 1$ GeV^2, only partially / temporarily fixed later.

- Locating main HCAL inside coil improved hadronic response (obviously limited by magnet bore size)

Inclusive Reconstruction Basics



$$Q^2 = -q^2 \qquad s = (e+p)^2$$

$$x = \frac{-q^2}{2p\cdot q} \qquad Q^2 \simeq sxy.$$

$$y = \frac{p\cdot q}{p\cdot e} \qquad W^2 = (q+p)^2.$$

- x, Q^2 (via y, Q^2) can be reconstructed from any two of E_e, θ_e, E_h, θ_h (see later for details)

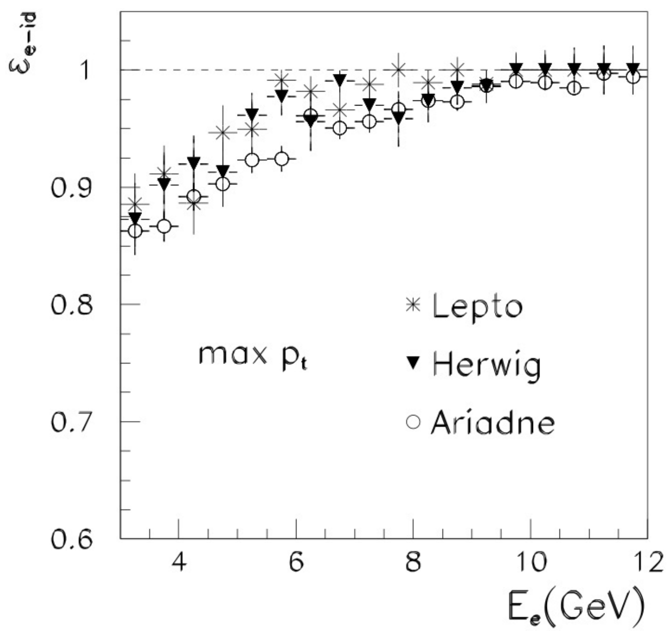
- Hadronic final state kinematics also important for background rejection

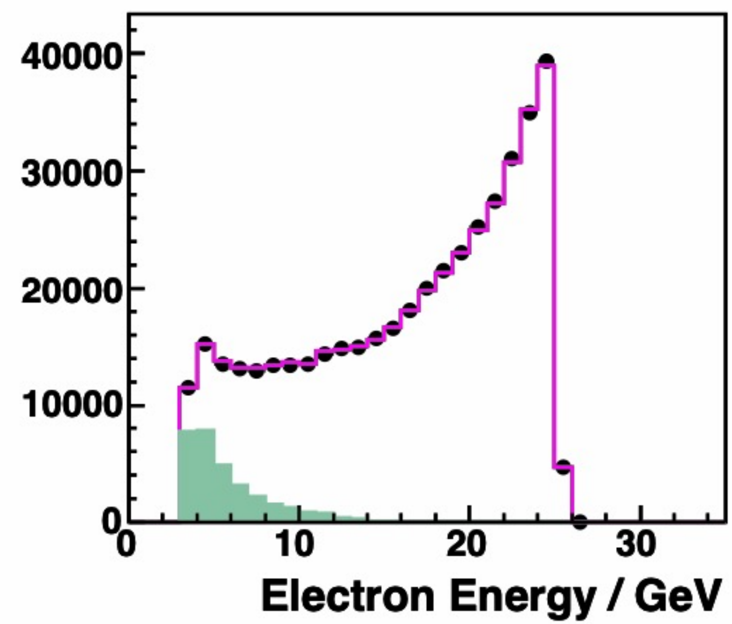
- Starting point is therefore electron identification & reconstruction, plus inclusive hadronic final state measurement.

Scattered Electron Identification

- For high electron energies (>~ 10 GeV or 1/3 beam energy), choosing highest energy or highest p_T electromagnetic calo cluster is already efficient and almost background free

- At smaller energies, misidentification and 'photoproduction' background become important.





[Plots from inclusive measurements focused on high y (low Ee, low x)]

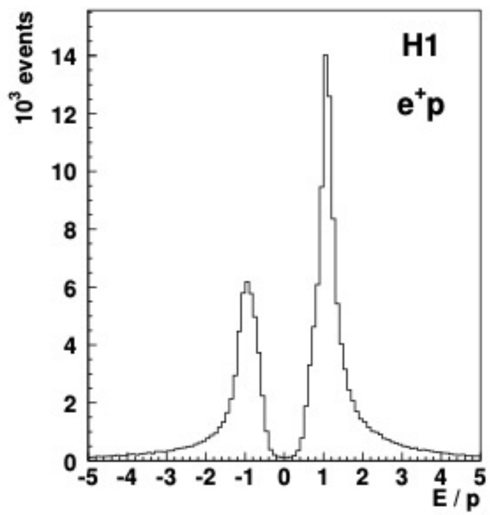
Scattered Electron Identification

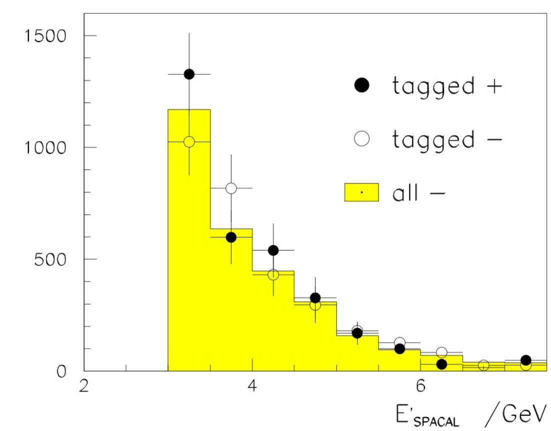
- Particle ID at H1 was very limited (basically only dE/dx of tracker)

- Additional requirements improve selection efficiency and suppress most of the background:
  - … compactness & isolation of cluster (radius, depth, HCAL fraction)
  - … link to inner track (spatially and in E/p ratio)
  - … overall event kinematics: total E-pz (electrons+hadrons) = $2E_e$

Energy E_e' of scattered electron candidate	> 3.4 GeV
Transverse size R_{log} of candidate cluster	< 5 cm
Hadronic energy fraction behind the cluster	$< 15\,\%$ of E_e'
Transverse distance between cluster and linked track	< 6 cm
$E - p_z$	> 35 GeV
z position of interaction vertex	$\lvert z_v \rvert < 35$ cm

Table 1: Criteria applied to select DIS events at high inelasticity y.





- Residual background subtraction controlled through comparisons with ‘wrong-charge’ clusters & subsample with tagged photoproduction electron

- Measurements down to E_e ~ 3 GeV (1/10 beam energy) were made.

Inclusive Hadronic Final State Reconstruction

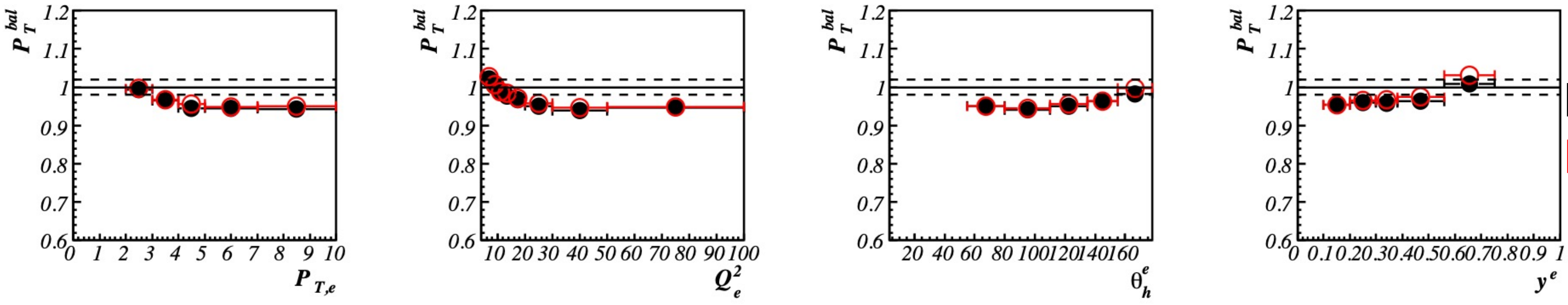
- Reconstructing the inclusive hadronic final state (in general - not only high p_T jets) essential for photoproduction background rejection and kinematic reconstruction beyond electron-only methods.

- Use of hadronic final state p_T and E-pz as basic variables minimises impact of missing energy from proton remnant (which has $E \approx pz$)

- Energy flow algorithms developed to reconstruct hadronic final state by combining calorimeter and tracking information making optimal use of both

- Suppression of calorimeter noise at low energies is very important

- Hadronic final state measurements `easily' calibrated using pT and E-pz balance versus scattered electron in NC events



Black: data
Red: MC

Why not just reconstruct NC kinematics using the electron method?

$$y_e = 1 - \frac{E'_e}{E_e} \sin^2 \frac{\theta}{2}$$

Electron method resolution in y (~1/x) degrades as 1/y … [E_e' getting large, towards the 'kinematic peak']

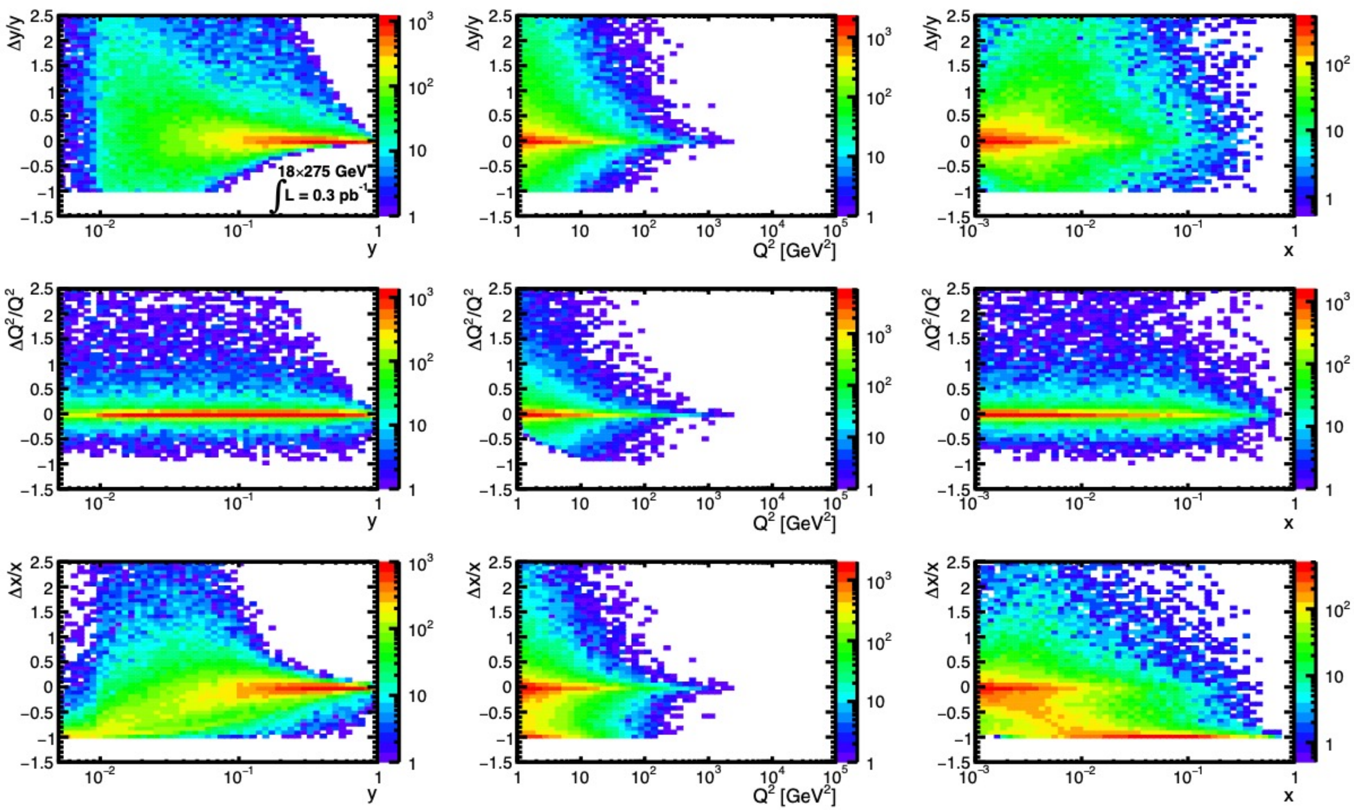


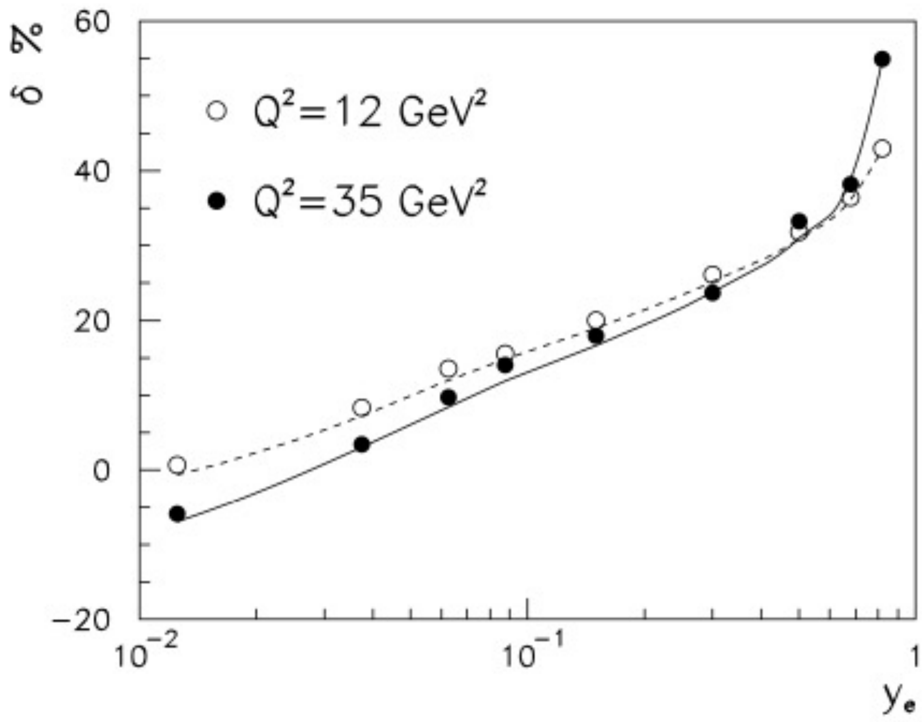
Figure 8.17: Resolutions, defined as (reconstructed - true)/true, for kinematic variables in NC 18x275 GeV events. The ineleasticity is require to be $y < 0.95$

[Plots from Yellow Report]

… serious limitation on measurements at high x, where PDFs poorly known → important part of EIC programme

A further complication: Initial State Radiation corrections

ISR corrections explode as y→1 (i.e. at low x)



… calculable in principle, but with uncertainties due to PDFs etc

Kinematic Variable Reconstruction Methods

Any combination of $E_e, \theta_e,\ E_h, \theta_h$ can be used

1) Electron only method (NC)

2) Hadron only method (CC)

Even for inclusive NC processes, it is possible to do better by mixing 1) and 2).

3) Double Angle and 'DA-pT' methods $(\theta_e,\ \theta_h)$

→ insensitive to calorimeter energy resolution

4) Sigma method and e-Sigma method $(E_e, \theta_e,\ (E - p_z)_h\ )$

→ insensitive to initial state radiation

The best choice depends on kinematic region and details of detector performance. Common feature is improved resolution at low y

Sigma Method

$$y_\Sigma = \frac{\Sigma_h}{E - P_Z}\,, \qquad Q^2_\Sigma = \frac{P^2_{T,e}}{1 - y_\Sigma}\,, \qquad x_\Sigma = \frac{Q^2_\Sigma}{s y_\Sigma}\,.$$

where $\Sigma_h = (E - p_z)$ of hadrons

$$E - P_Z = E'_e(1 - \cos\theta_e) + \sum_i (E_i - p_{Z,i}) = \Sigma_e + \Sigma_h\,,$$

e-Sigma Method

$$y_{e\Sigma} = \frac{Q^2_e}{s x_\Sigma} = \frac{2E_e}{E - P_Z} y_\Sigma\,, \qquad Q^2_{e\Sigma} = Q^2_e\,, \qquad x_{e\Sigma} = x_\Sigma\,.$$

Double Angle Method

$$y_{DA} = \frac{\tan(\theta_h/2)}{\tan(\theta_e/2) + \tan(\theta_h/2)}\,, \qquad Q^2_{DA} = 4E_e^{\,2} \cdot \frac{\cot(\theta_e/2)}{\tan(\theta_e/2) + \tan(\theta_h/2)}\,, \qquad x_{DA} = \frac{Q^2_{DA}}{s y_{DA}}\,.$$

where $\tan\frac{\theta_h}{2} = \frac{\Sigma_h}{P_{T,h}}\,.$

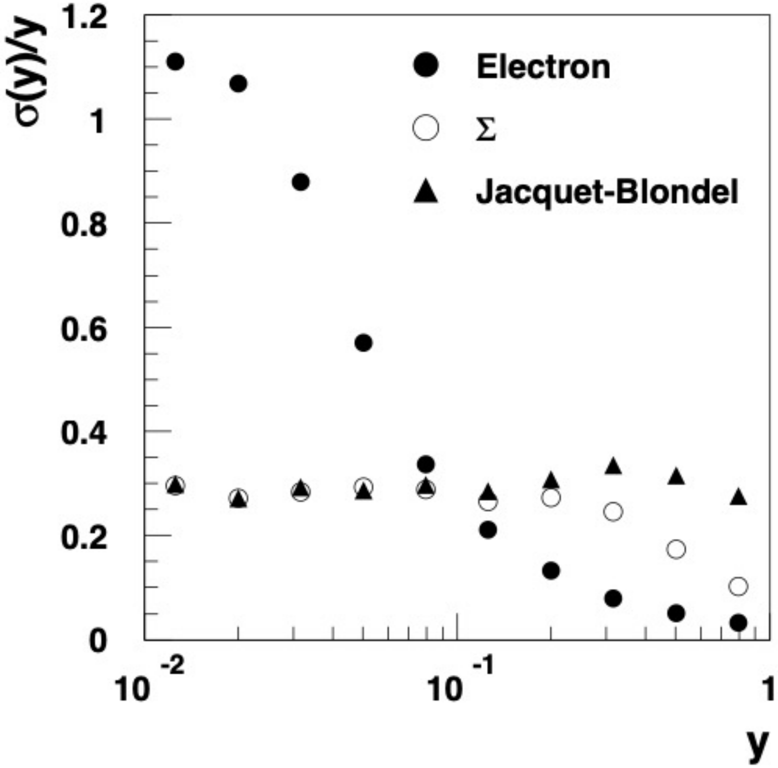
Double Angle / pT Method

Replace θ_h with θ_{PT} where

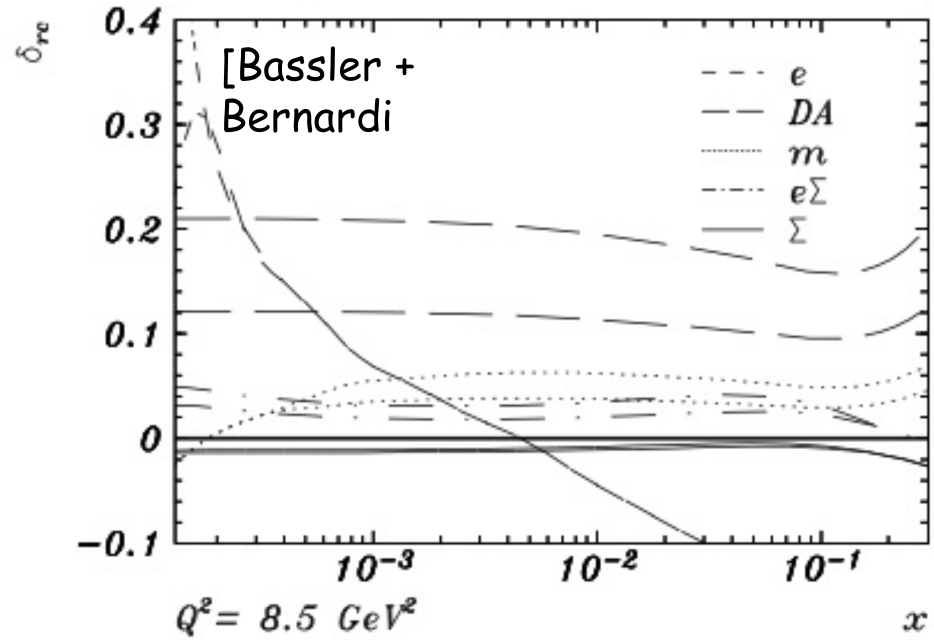
$$\tan\frac{\theta_{PT}}{2} = \frac{\Sigma_{PT}}{P_{T,e}}\,, \quad \text{where} \quad \Sigma_{PT} = 2E_e \frac{C(\theta_h, P_{T,h}, \delta_{PT}) \cdot \Sigma_h}{\Sigma_e + C(\theta_h, P_{T,h}, \delta_{PT}) \cdot \Sigma_h}\,.$$

Examples of Improved Performance

Low y resolution



High y radiative corrections



[Duplicated curves are for Ee>4 and Ee>8]

Data used in Final HERA paper

Data Set		x_{Bj} Grid from	x_{Bj} Grid to	Q^2[GeV^2] Grid from	Q^2[GeV^2] Grid to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	x_{Bj},Q^2 from equations	Ref.
HERA I E_p = 820 GeV and E_p = 920 GeV data sets										
H1 svx-mb [2]	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319	13,17,18	[3]
H1 low Q^2 [2]	96-00	0.0002	0.1	12	150	22	e^+p	301, 319	13,17,18	[4]
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301	19	[5]
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301	14	[5]
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319	19	[6]
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319	14	[6]
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319	13	[7]
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319	19	[7]
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319	14	[7]
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300	13	[11]
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300	13, 19	[12]
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300	13	[13]
ZEUS NC [2] high/low Q^2	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300	21	[14]
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300	14	[15]
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318	20	[16]
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318	14	[17]
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318	20	[18]
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318	14	[19]
HERA II E_p = 920 GeV data sets										
H1 NC $^{1.5p}$	03-07	0.0008	0.65	60	30000	182	e^+p	319	13, 19	[8][1]
H1 CC $^{1.5p}$	03-07	0.008	0.40	300	15000	182	e^+p	319	14	[8][1]
H1 NC $^{1.5p}$	03-07	0.0008	0.65	60	50000	151.7	e^-p	319	13, 19	[8][1]
H1 CC $^{1.5p}$	03-07	0.008	0.40	300	30000	151.7	e^-p	319	14	[8][1]
H1 NC med Q^2 $^{*y.5}$	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319	13	[10]
H1 NC low Q^2 $^{*y.5}$	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319	13	[10]
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318	13,14,20	[22]
ZEUS CC $^{1.5p}$	06-07	0.0078	0.42	280	30000	132	e^+p	318	14	[23]
ZEUS NC $^{1.5}$	05-06	0.005	0.65	200	30000	169.9	e^-p	318	20	[20]
ZEUS CC $^{1.5}$	04-06	0.015	0.65	280	30000	175	e^-p	318	14	[21]
ZEUS NC nominal ^{*y}	06-07	0.000092	0.008343	7	110	44.5	e^+p	318	13	[24]
ZEUS NC satellite ^{*y}	06-07	0.000071	0.008343	5	110	44.5	e^+p	318	13	[24]
HERA II E_p = 575 GeV data sets										
H1 NC high Q^2	07	0.00065	0.65	35	800	5.4	e^+p	252	13, 19	[9]
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252	13	[10]
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251	13	[24]
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251	13	[24]
HERA II E_p = 460 GeV data sets										
H1 NC high Q^2	07	0.00081	0.65	35	800	11.8	e^+p	225	13, 19	[9]
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225	13	[10]
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225	13	[24]
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225	13	[24]

Input data to final HERA combination

Executive NC summary:

- e-method (13) used in limited phase space regions only

– Σ, eΣ (17,18, 19) used extensively by H1 at low y (<~ 0.1-0.2)

- DA, pT (20,21) used extensively by ZEUS

Summary / Questions

Beyond the (excellent) material in the Yellow Report… some thoughts on things we may still want to investigate in ATHENA inclusive group …

[all depend on details of detector; requires simulation of proposed solutions and reconstruction algorithms based on multiple components]

- What can be gained in scattered electron selection / background rejection from sophisticated requirements including cluster compactness, isolation, overall event E-pz etc?

- What level of performance is needed / can be obtained in overall hadronic final state reconstruction (via energy flow algorithms using multiple detector components)

- How much can we improve on NC kinematic reconstruction by trying sigma and double-angle methods?

→ Possibly significant implications for detector design …