MC4EIC

CTEQ-EICUG workshop on MC event simulation for the EIC

Monte Carlo Data Comparisons and Validation

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Motivation

- Validate the electron-proton collision MC-data generated by three MCEGs
- Determine which MCEG tunings explains the e-p collision physics the best

Content

- Why Monte Carlo Studies?
- The Monte Carlo event generators
- Experimental e-p collision data: HERA
- Deep Inelastic Scattering Kinematics
- Analyses and Results
- Summary, Outlook

Why Monte Carlo studies

- **Underlying physics models for highly complex systems**
- **Event selection and Background estimation**
- **Theory Predictions: discoveries of new particle and interactions**
- **Testing the capabilities of current MCEG**
- **Predictions for future experiments**

Monte Carlo Event Generators: Pythia8

Pythia8

Herwig7

Sherpa2

- ➔ A generator written in modern program language: C++
- ➔ Mainly built for for needs of LHC experiments

For EIC related analyses

- ➔ Default parton shower for DIS-type events: dipole showers
- ➔ Completely new parton-shower model: DIRE.
- ➔ New Photoproduction model
- ➔ Hadronization: Lund string fragmentation
- ➔ Generating events in intermediate Q^2
- ➔ Heavy ion model

https://pythia.org/documentation/

The Monte Carlo Event Generators: Herwig7

Pythia8

Herwig7

Sherpa2

Focus on
- ➔ QCD dynamics for parton shower algorithms
- ➔ Improving the hard processes

Two different parton shower modules
- ➔ Angular-ordered (’QTilde’) algorithm
- ➔ Dipoles stretched by colour charges.

- ➔ Multi parton interaction
- ➔ Cluster hadronization model

https://herwig.hepforge.org/

The Monte Carlo Event Generators: Sherpa2

Pythia8

Herwig7

Sherpa2

- ➔ Two built-in matrix element generators, AMEGIC and COMIX: Merging of leading-order matrix elements with parton showers
- ➔ For the simulation of parton-level events within the Standard Model and beyond,
- ➔ For the decay of heavy resonances
- ➔ Default parton-showering algorithm: CS shower
- ➔ DIRE shower
- ➔ Cluster Hadronization

https://sherpa.hepforge.org/doc/SHERPA-MC-2.2.5.html

Experimental e-p Collision Data: HERA

H1, ZEUS experiments: Testing the MCEG data against these experimental datasets

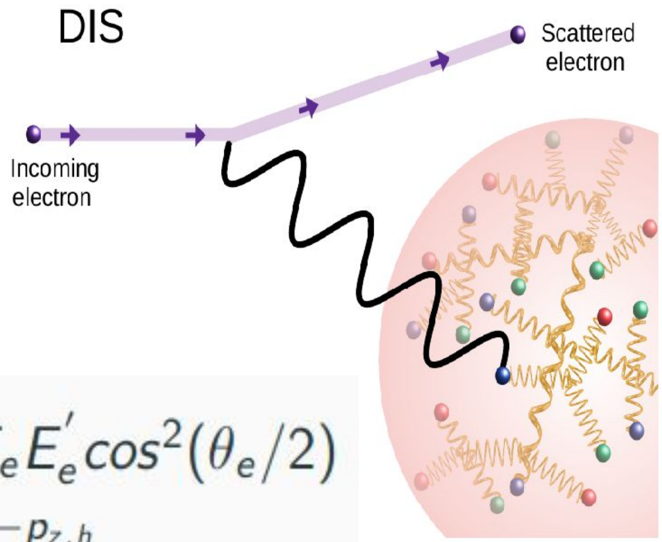
HERA: electron-proton collisions

- Proton structure at small x and high Q^2
- QCD tests provided new insights into strong force
- Study of charm and beauty production
- Diffractive scattering

100+ papers published since 1994 by H1 and ZEUS collaborations

- H1: Five Rivet Analysis
- H1+ZEUS: One Rivet Analysis
- ZEUS: Three Rivet Analysis

DIS Kinematics



DIS is defined by large virtualities

$Q^2 >> \Lambda^2_{QCD}$

Transverse Radius (R_t) and Longitudinal length(L) of the probed region are:

$R_t \simeq \frac{1}{Q}$

$L \simeq \frac{1}{m_{proton}x}$

- $Q^2 = 4E_eE_e^{'}cos^2(\theta_e/2)$
- $y = \Sigma\frac{E_h - p_{z,h}}{2E_e}$
- $x = \frac{Q^2}{ys}$
- $W^2 = m_p^2 + sy - Q^2$

Parton Shower Tests

- Average transverse energy in central and forward regions
- Transverse energy in low and high bjorken x, high and low Q regions
- Transverse energy-energy correlation in high and low bjorken x regions

Event Selection and Kinematics

p: 820 GeV

e: 26.7 GeV

$\sqrt{s} = 296$ GeV

$Q^2 < 10000 GeV^2$

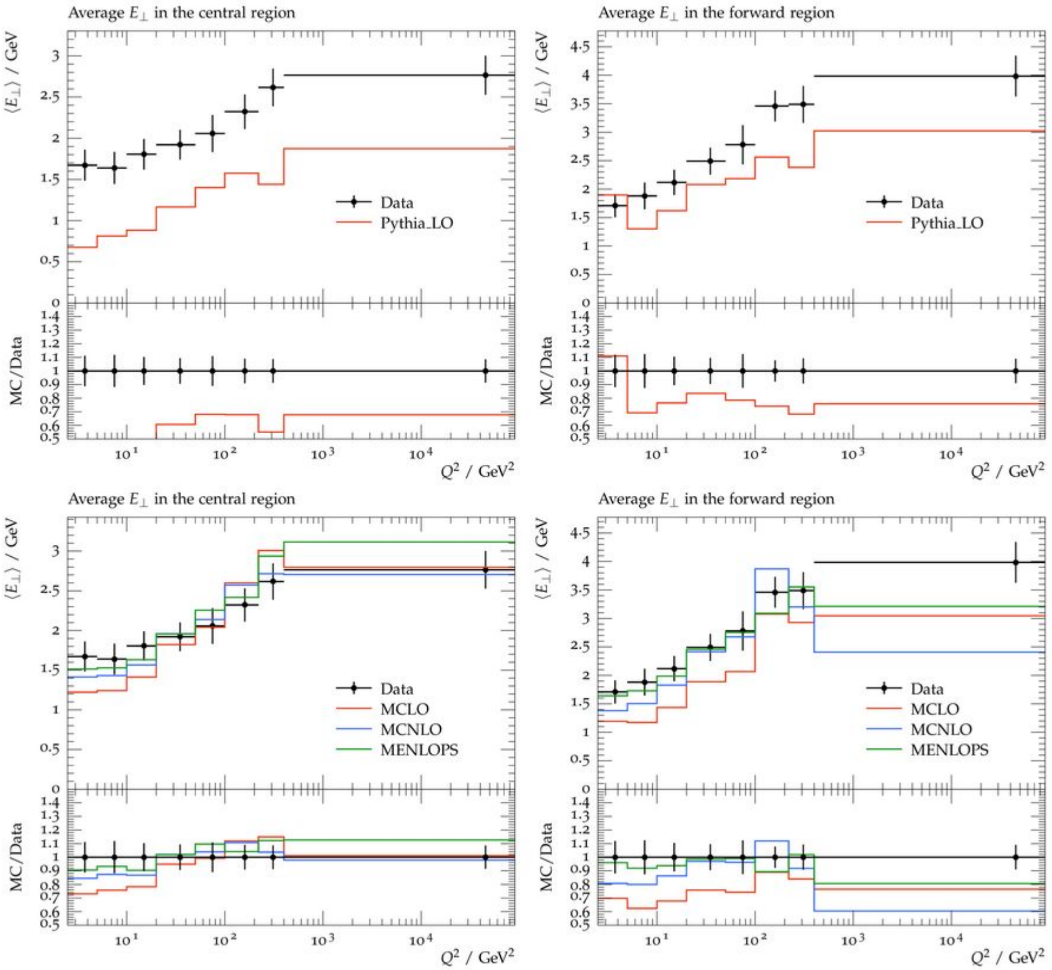
$W^2 > 3000 GeV^2$

$E_F > 0.5 GeV \ (4.4 < \theta < 15)$

$10^{-4} < x < 10^{-2}$

Average Transverse Energy Flow

- Characterize the system at extreme conditions of temperature and energy density.
- Central region: $-0.5 < \eta < 0.5$
- Forward region: $2 < \eta < 3$ (photon fragmentation region
- $E_T = \sum_i E_i \sin(\phi_i)$



Top panel: Pythia8
Bottom Panel: Sherpa2

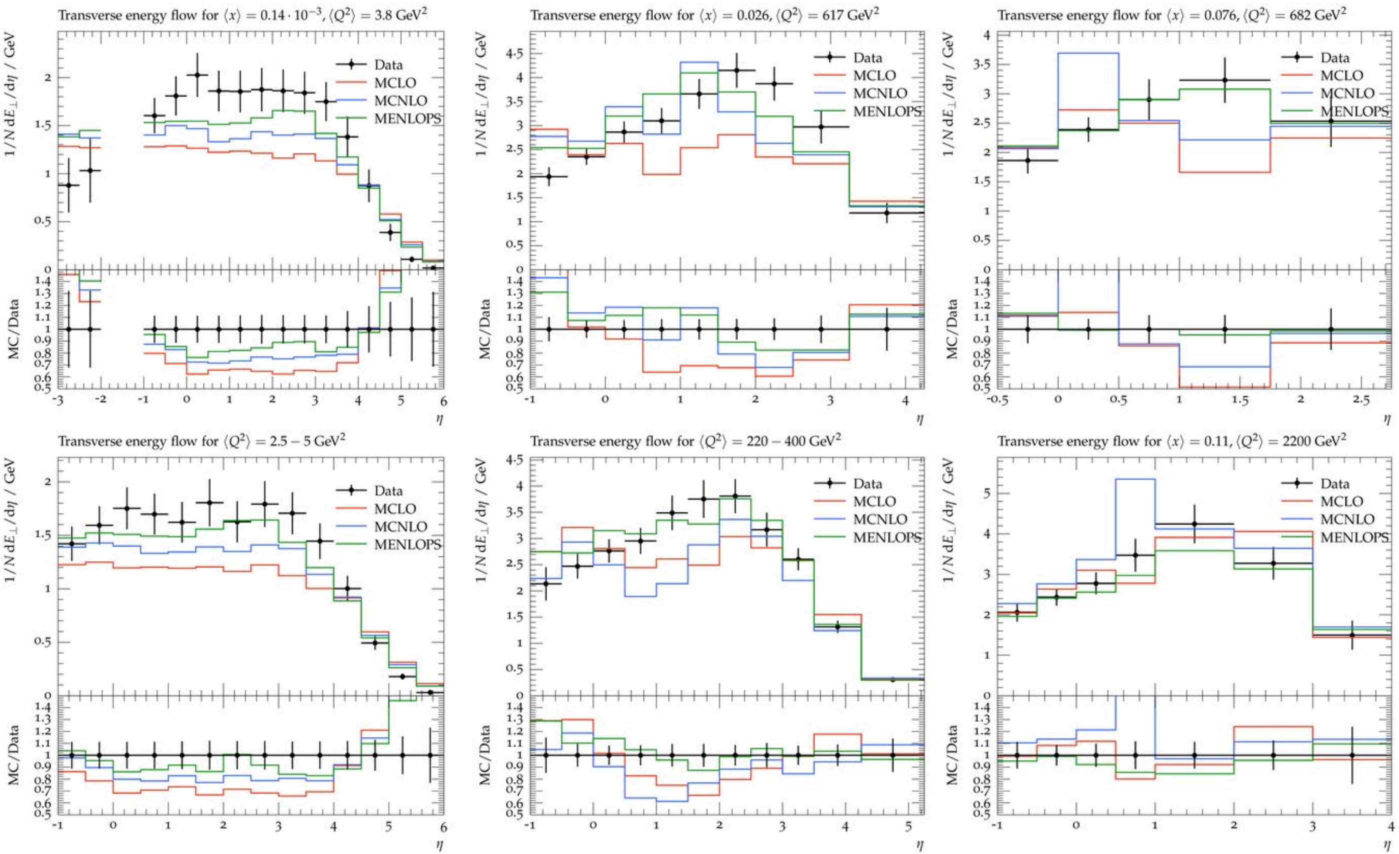
Transverse Energy Flow

Source of transverse energy production:

- Soft multiparticle production
- Hard scattering jets

- Defines the 'explosiveness' of collision event

Sherpa2 tunings

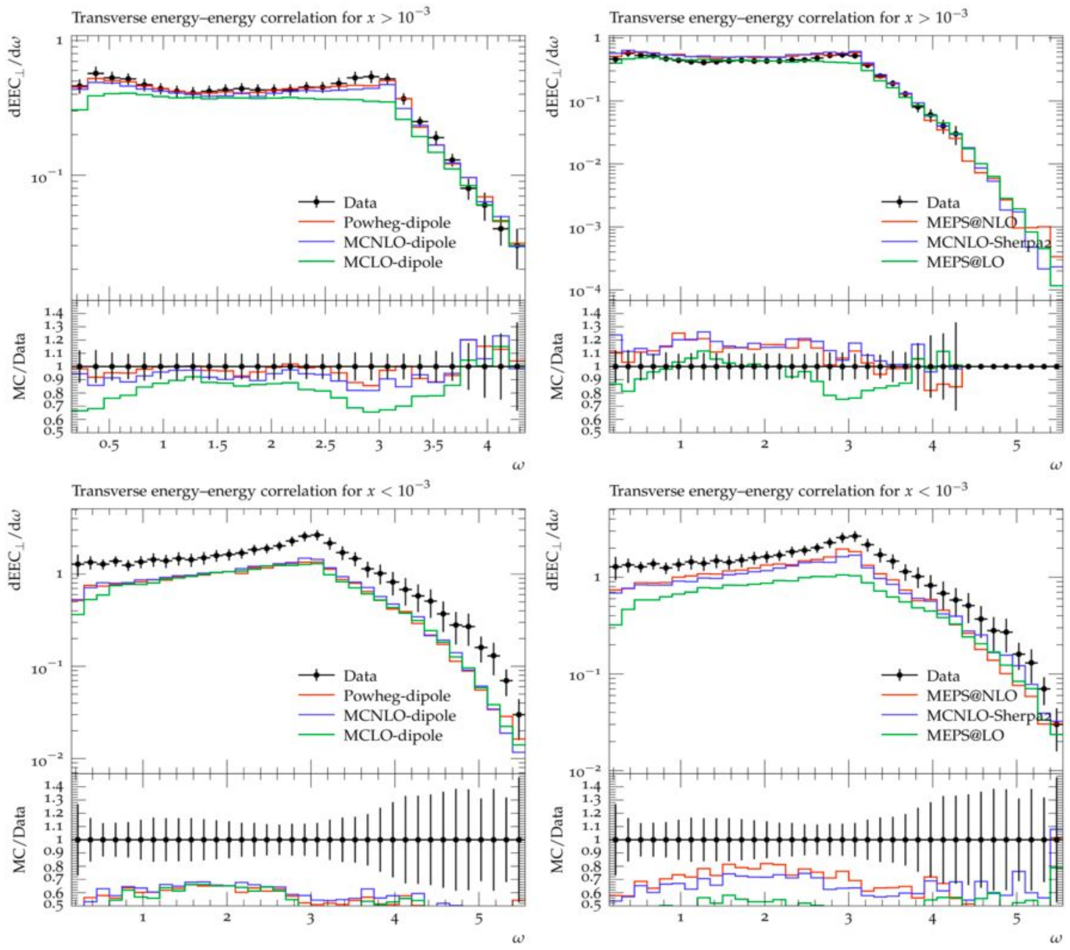


Transverse Energy-Energy Correlation

- An event shape observable- for QCD tests
- The measurements of energy weighted angular distributions of hadron pairs.
- Independent of hadronization of the primary partons

$$\omega^2_{ij} = \left(\eta_i - \eta_j\right)^2 + \left(\phi_i - \phi_j\right)^2$$

$$\frac{1}{N\Delta\omega}\sum_N \sum_{i,j,i!=j} \frac{E_{Ti}E_{Tj}}{p_{Te}^{\ 2}} \int_{\omega-\frac{\Delta\omega}{2}}^{\omega+\frac{\Delta\omega}{2}} \delta\left(\omega' - \omega_{ij}\right) d\omega'$$



Left panel: Herwig7
Right Panel: Sherpa2

Hadronization Tests

- Charged Particle Multiplicity and Associated Observables
- Scaled charged particle spectra
- Average $p_T^{\,2}$ Distribution
- D* Meson Cross section
- ϕ Meson Cross section

Event selection kinematics

p: 820 GeV

e: 27.5 GeV

$\sqrt{s} = 300$ GeV

$e' > 12$ GeV

$10\,GeV^2 < Q^2 < 1000\,GeV^2$

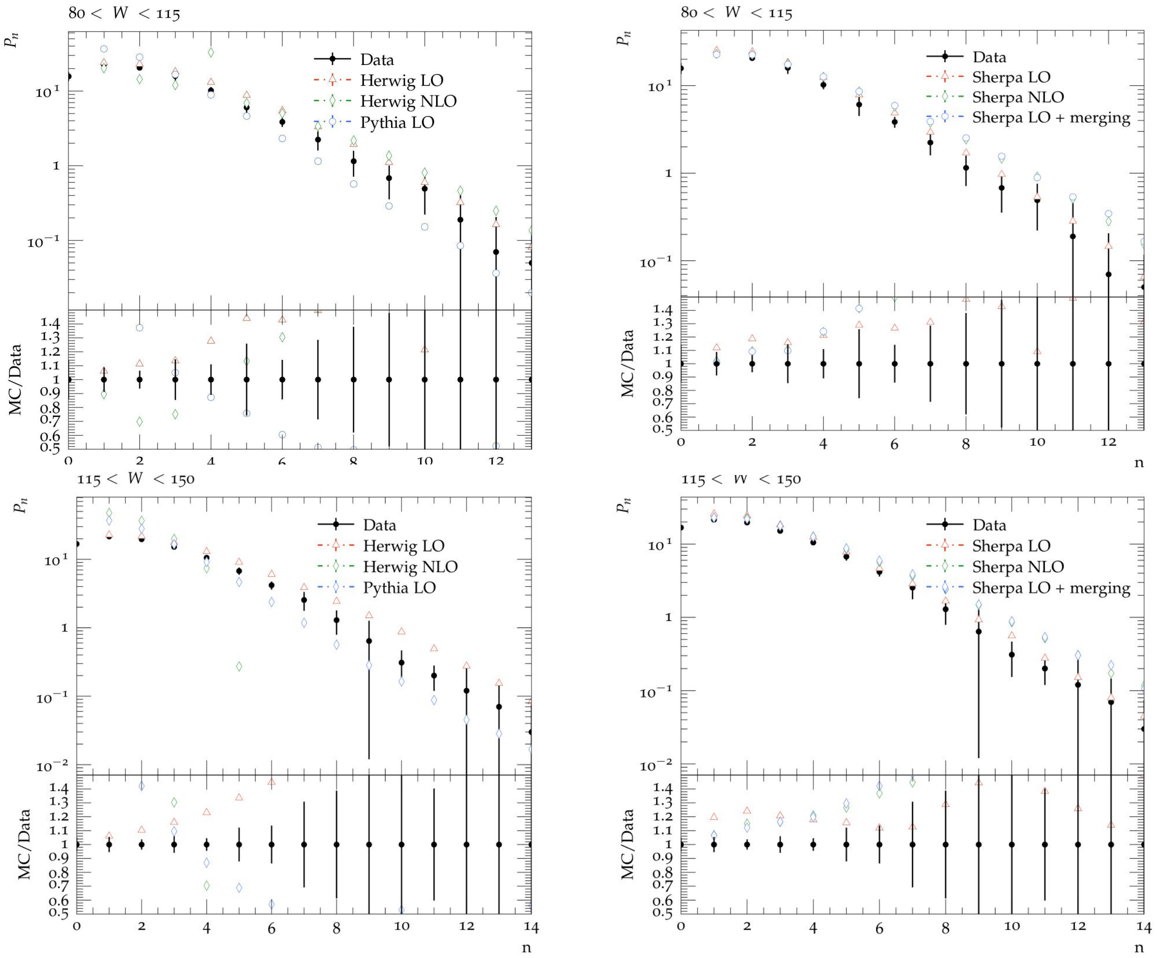
$80\text{ GeV} < W < 220\text{ GeV}$

$E_F > 0.5\text{ GeV}\ (4.4 < \theta < 15)$

$10^{-4} < x < 10^{-2}$

Charged Particle Multiplicity

- Set of probabilities(P_n) associated with the occurrence of the number of hadrons, n, in the phase space region under observation.

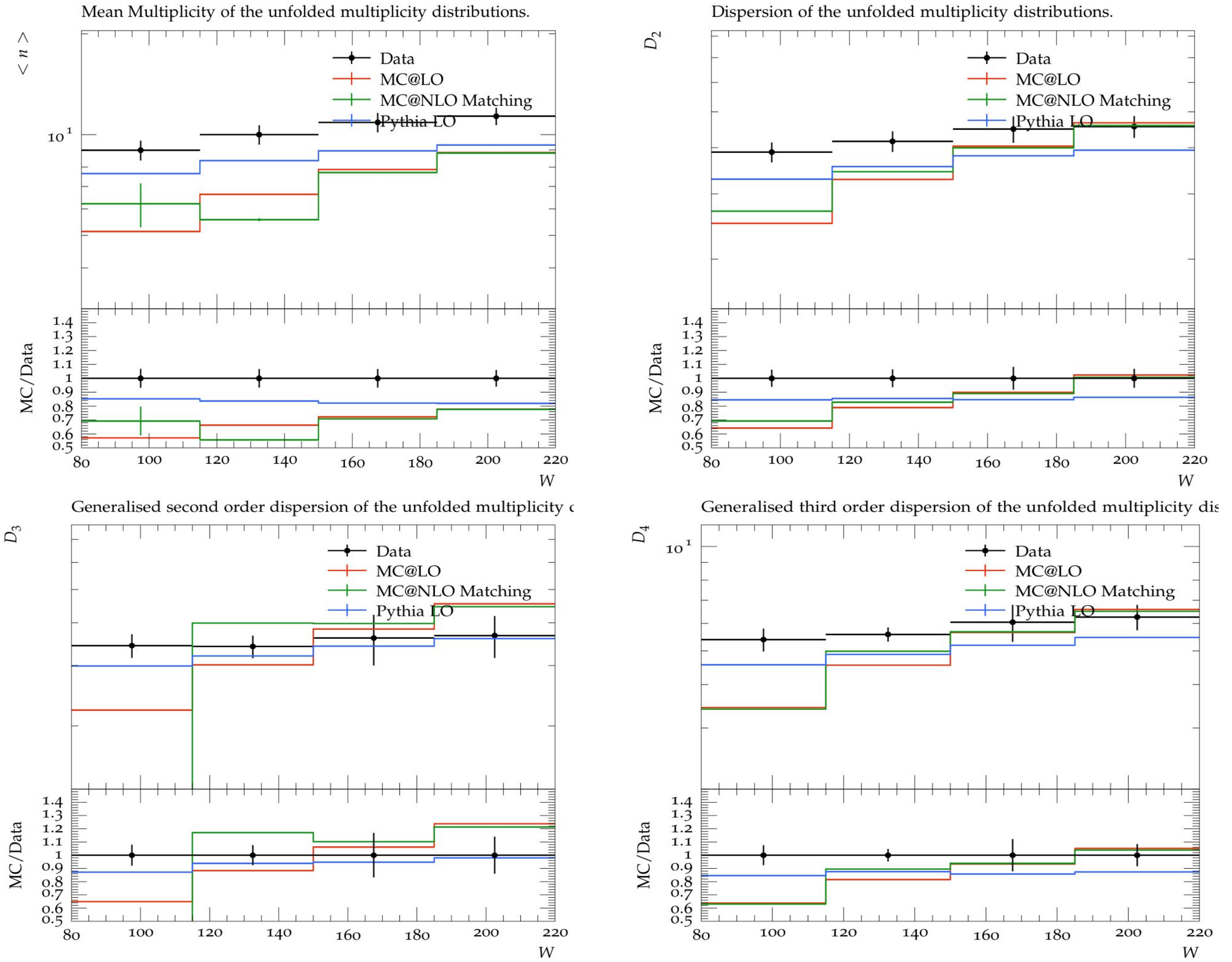


Left panel: Pythia8, Herwig
Right Panel: Sherpa2

Mean of Charged Particle Multiplicity

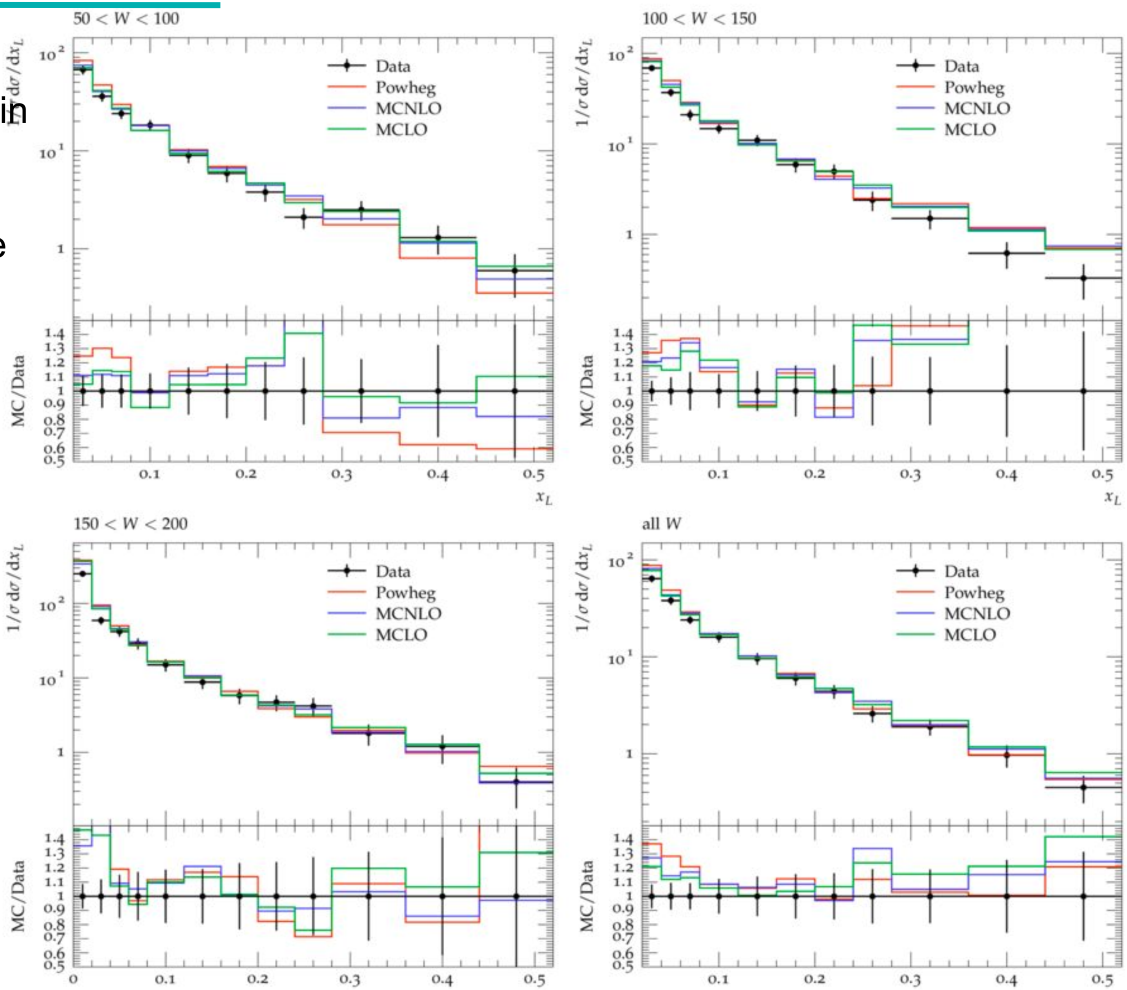
- <n> is mean charged multiplicity
- Generalised Dispersions upto 4th order
- $$D_q = \left[\overline{(n-\bar{n})^q}\right]^{1/q} :$$
- These observables can directly measure the correlation strength among particles

Pythia8, Herwig7



Scaled Charged Particle Spectra

- This observable is presented in hadronic CoM frame
- Minimised effect of transverse boost from virtual photon
- z* is direction of the virtual photon
- $x_L = \frac{2p_z^*}{W}$



Herwig7

Average p_T^2 Distribution

- Hadronization is expected at lower pT values
- Higher pT- hard parton radiation

$$x_L = \frac{2p_z^*}{W}$$

p: 820 GeV

e: 26.7 GeV

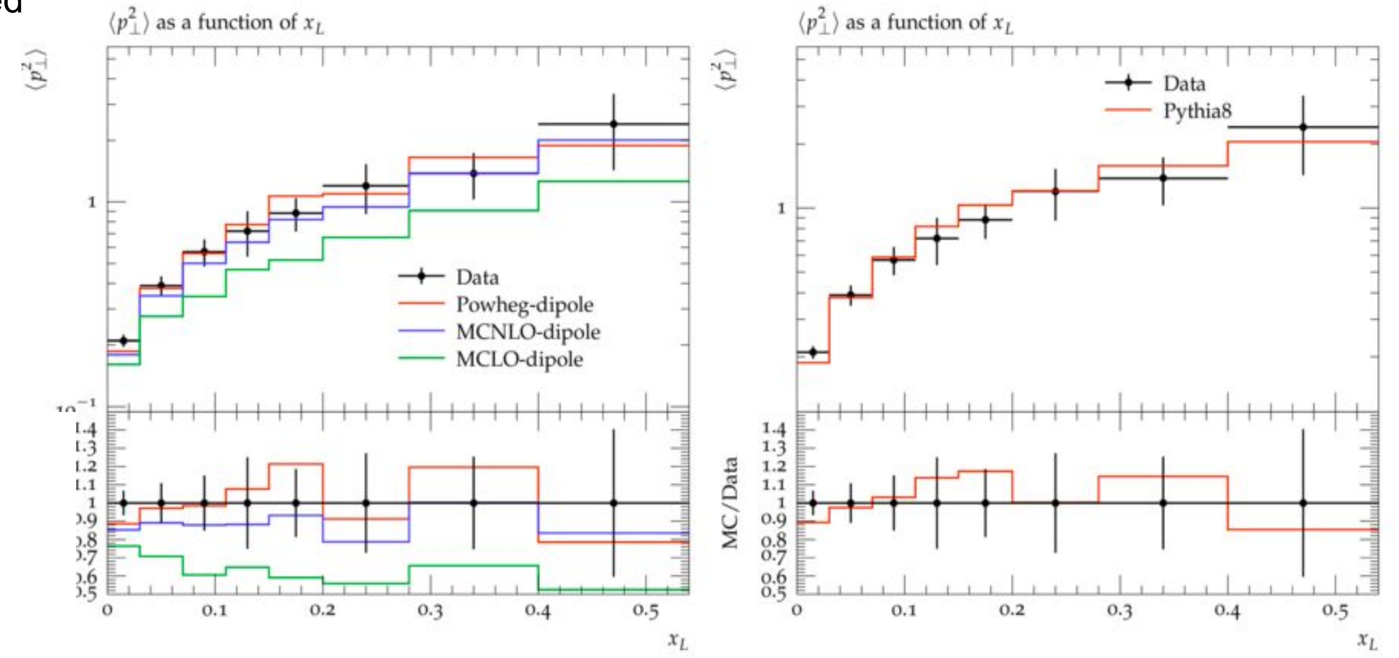
$\sqrt{s} = 296$ GeV

$Q^2 < 100 GeV^2$

$W^2 > 3000 GeV^2$

$E_F > 0.5 GeV (4.4 < \theta < 15)$

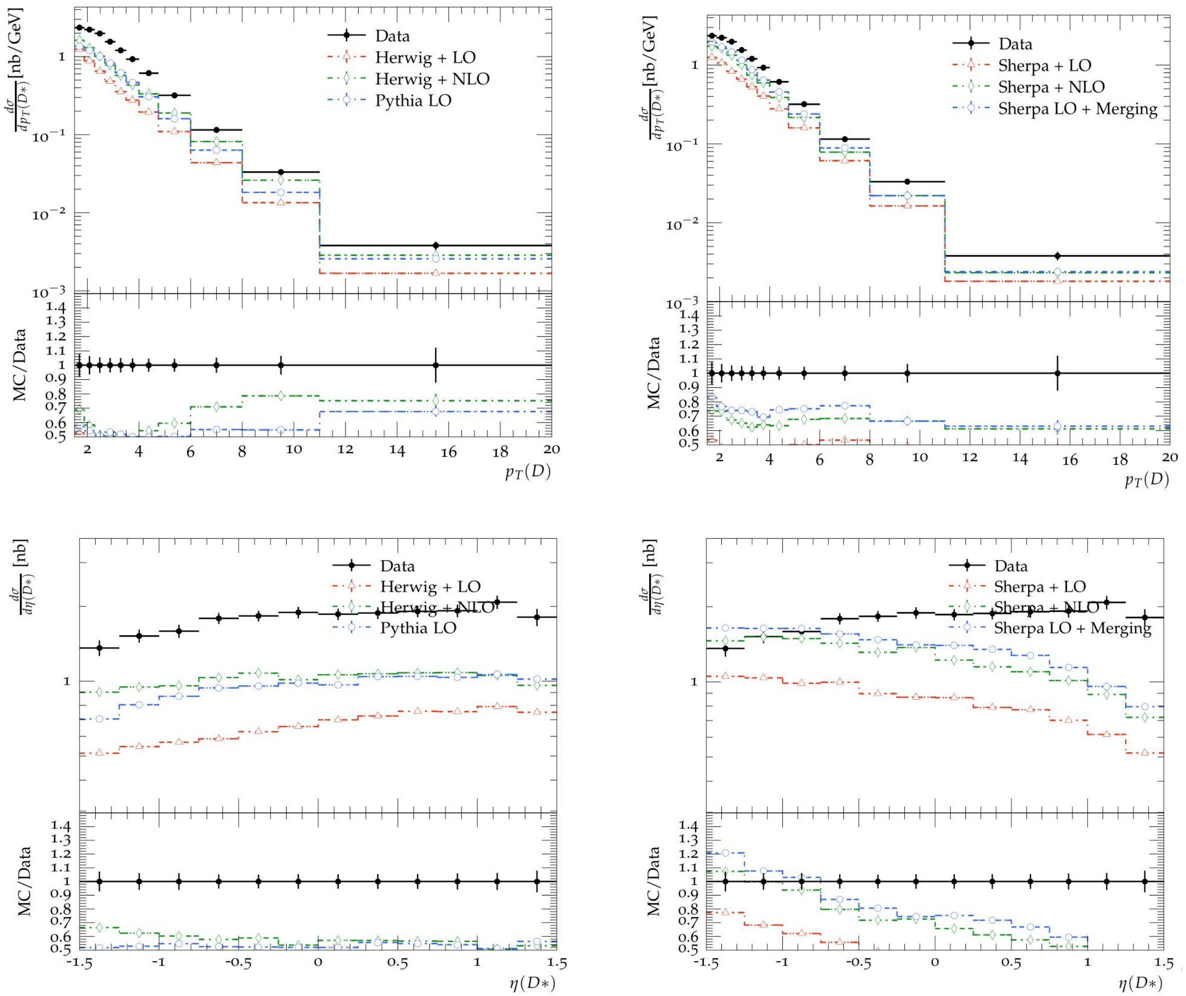
$10^{-4} < x < 10^{-2}$



Left:Herwig7
RightI: Pythia

D* Meson Cross-section

- Charm production: involves gluon-gluon fusion
- Studying gluon distribution inside proton
- Testing QCD predictions



Left panel: Pythia8, Herwig
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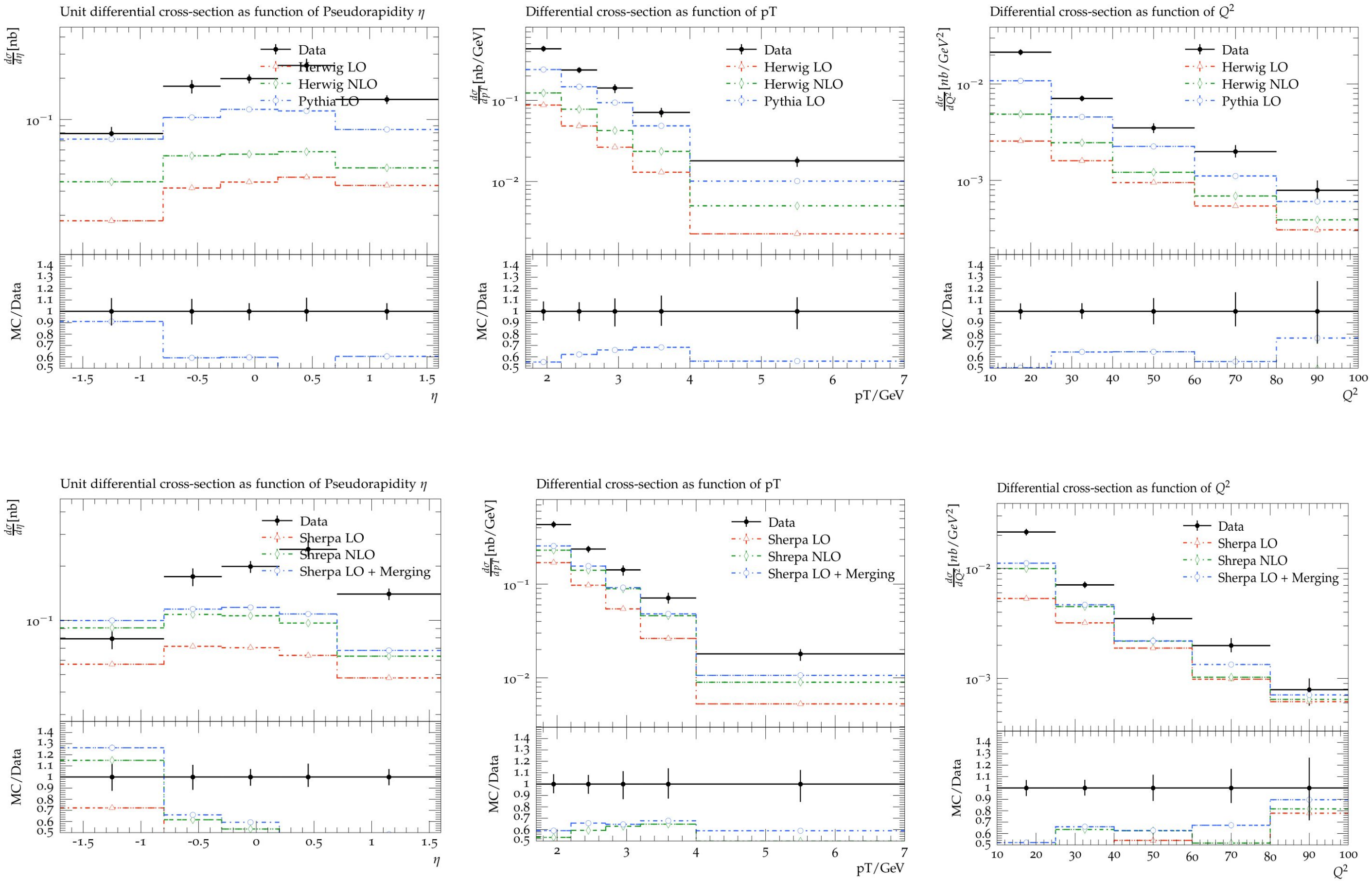
ϕ Meson Production

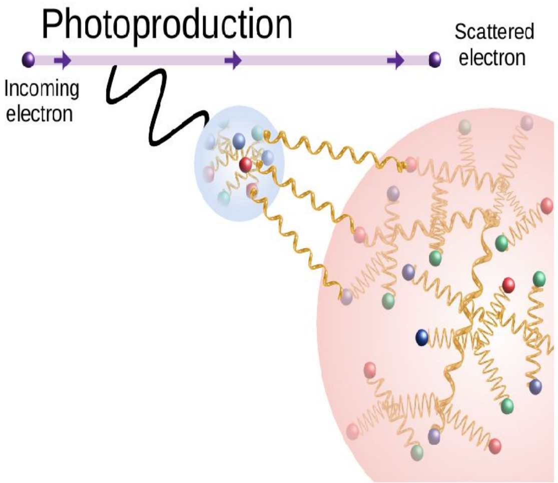
- Strange quark production and hadronization
- Production through gluon-gluon fusion also possible
- Testing QCD theories in neutral current DIS



Top panel: Pythia8, Herwig
Bottom Panel: Sherpa2

Photoproduction

- Photoproduction
- Diffractive dijet production



Photoproduction (γp) is defined by small virtualities: $Q^2 << \Lambda^2_{QCD}$

Exchanged photon may fluctuate into quarks and gluons

Larger interaction regions are probed

Event selection kinematics

p: 920 GeV

e: 27.5 GeV

$\sqrt{s} = 318$ GeV

$Q^2 < 1 GeV^2$

142 GeV $< W <$ 293 GeV

$E_T^{jet} < 17$ GeV

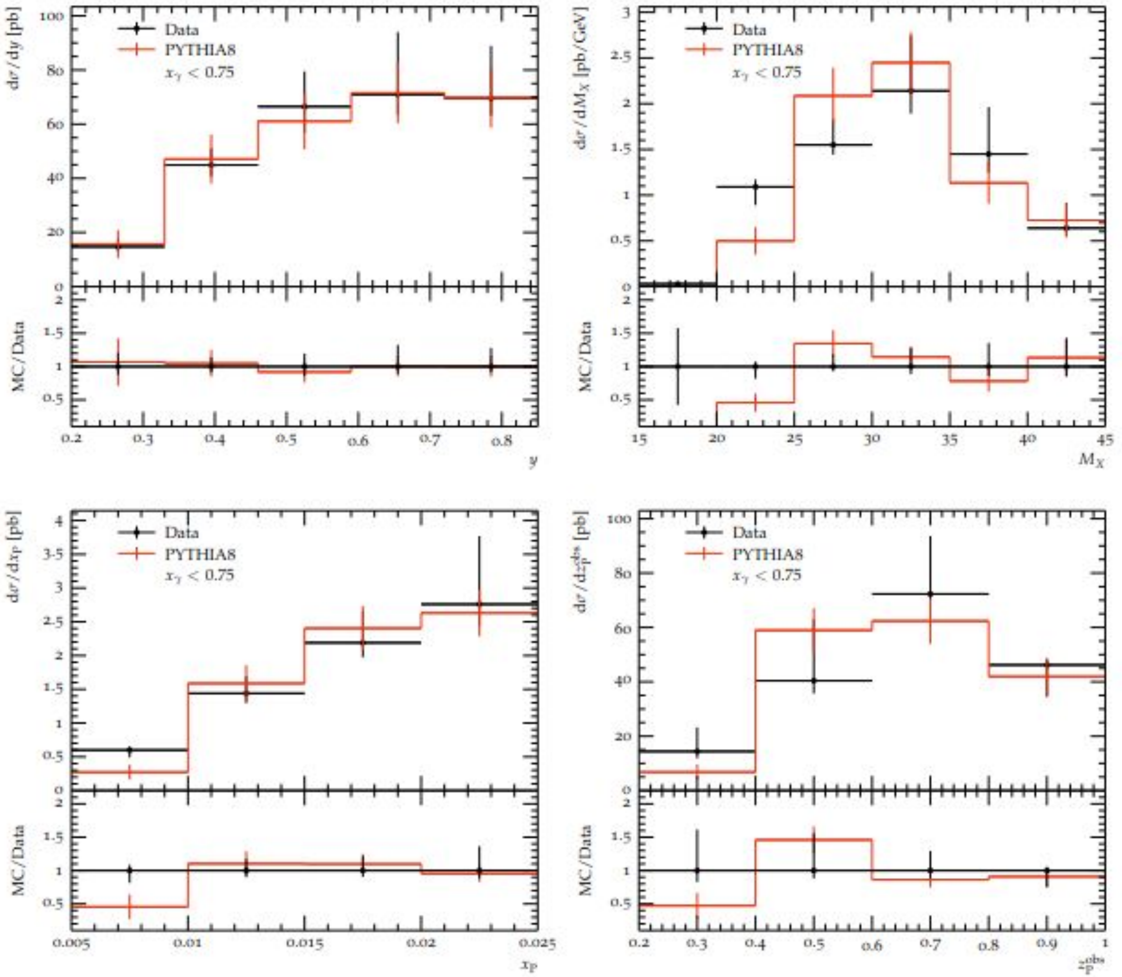
$1.0 < \eta_{jet} < 1.5$

$0.003 < x < 0.9$

$0.2 < y < 0.85$

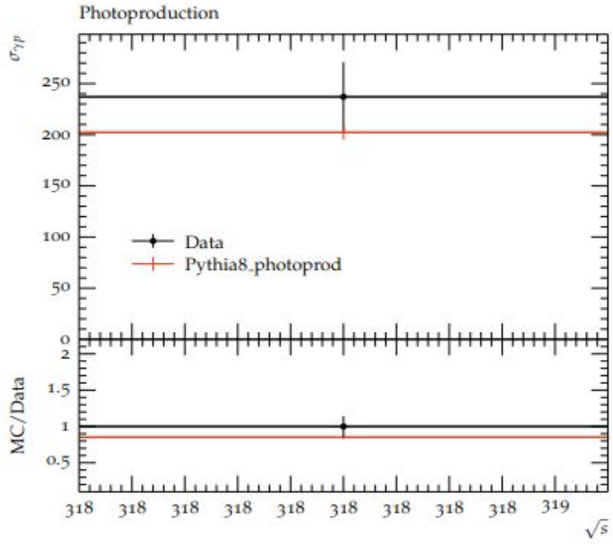
Diffractive Photoproduction of Dijets in ZEUS

- $ep \to e\gamma p \to eX$ (Photoproduction)
- $ep \to eXY$ or epX
  –large rapidity gap
  –rapidity gap survival probability calculated event-by-event for diffractive dijets
- Resolved photon dijet photoproduction

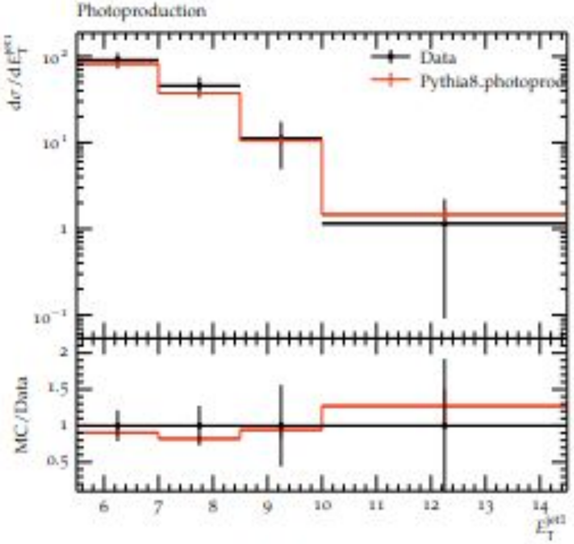


Diffractive Dijet in Photoproduction in H1

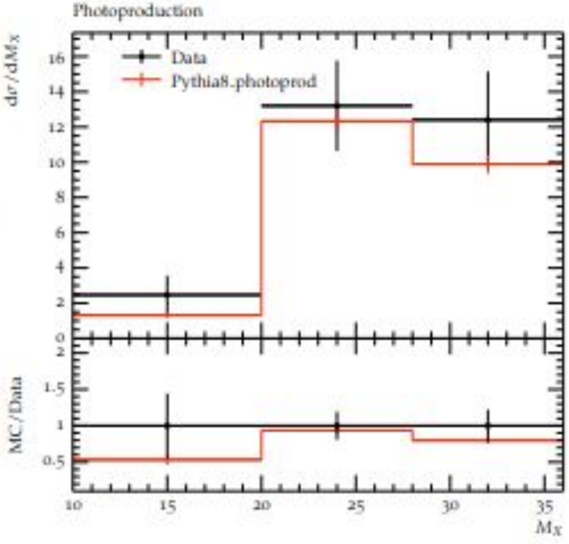
- Total Crossection of photoproduction



- Transverse energy of leading jet



- Invariant mass of the remnant



- H1: 237 pb
- Pythia: 200 pb

Summary

Transverse Energy Flow and Correlation

- Sherpa and Herwig shows better results compared to Pythia
- All MC tunings perform relatively better in the higher bjorken x than in lower x regions

Charged Particle Multiplicity

- Pythia-LO shows better results in comparison to Herwig NLO and LO tunings for mean multiplicity and generalised dispersion measurements

Scaled Charged Particle spectra

- Herwig NLO and Powheg comes closest at explaining the HERA data

Average Momentum distribution

- Sherpa tunings shows a large scaling difference between MCEG data and HERA data

D Meson Production

- Relatively, Herwig NLO best explains the data.
- Sherpa tunings deviates from the data structure for certain measurements

φ Meson Production

- The shape of the data is explained well by all MCs, but none of the MCs fit the data exactly well.

PhotoProduction

- Pythia-LO model performs quite well in terms on explaining the values and structure of Photoproduction related measurements

Outlook

- ➔ The HERA analyses have been compared to different MCEGs
- ➔ Several comparisons studies are now available and would be published very soon

- ➔ Interpretation of these analyses
- ➔ Explaining the performance of different MCEGs
- ➔ Consecutive improvements in MCEGs’ performance for ep collisions remains

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RIVET Analysis

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- H1_2015_I1343110
- HERA_2015_I1353667
- ZEUS_2001_I568665

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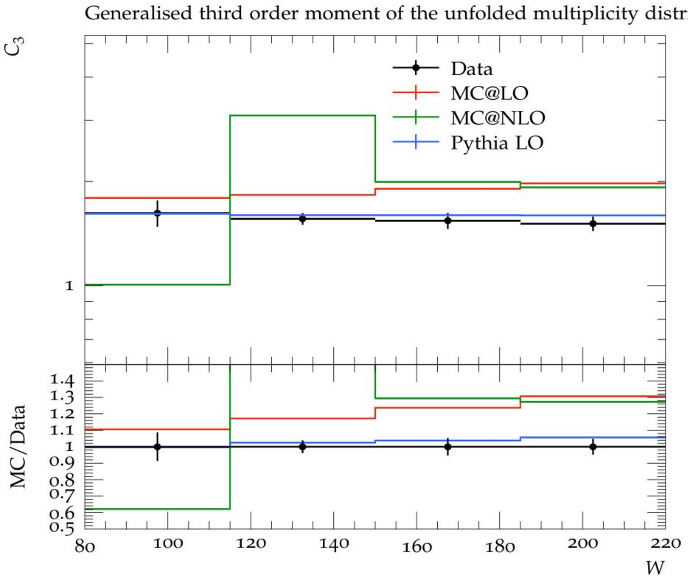
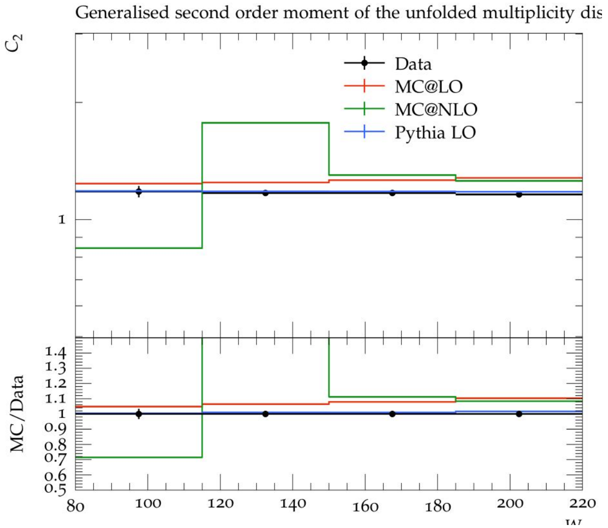
THANK YOU!

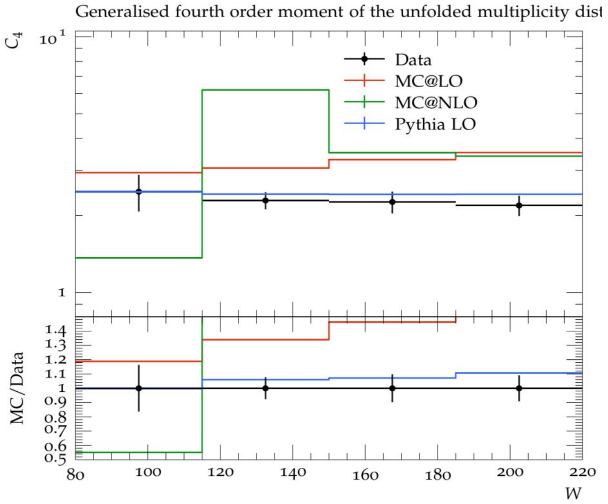
BACKUP

Generalised Moments Distribution

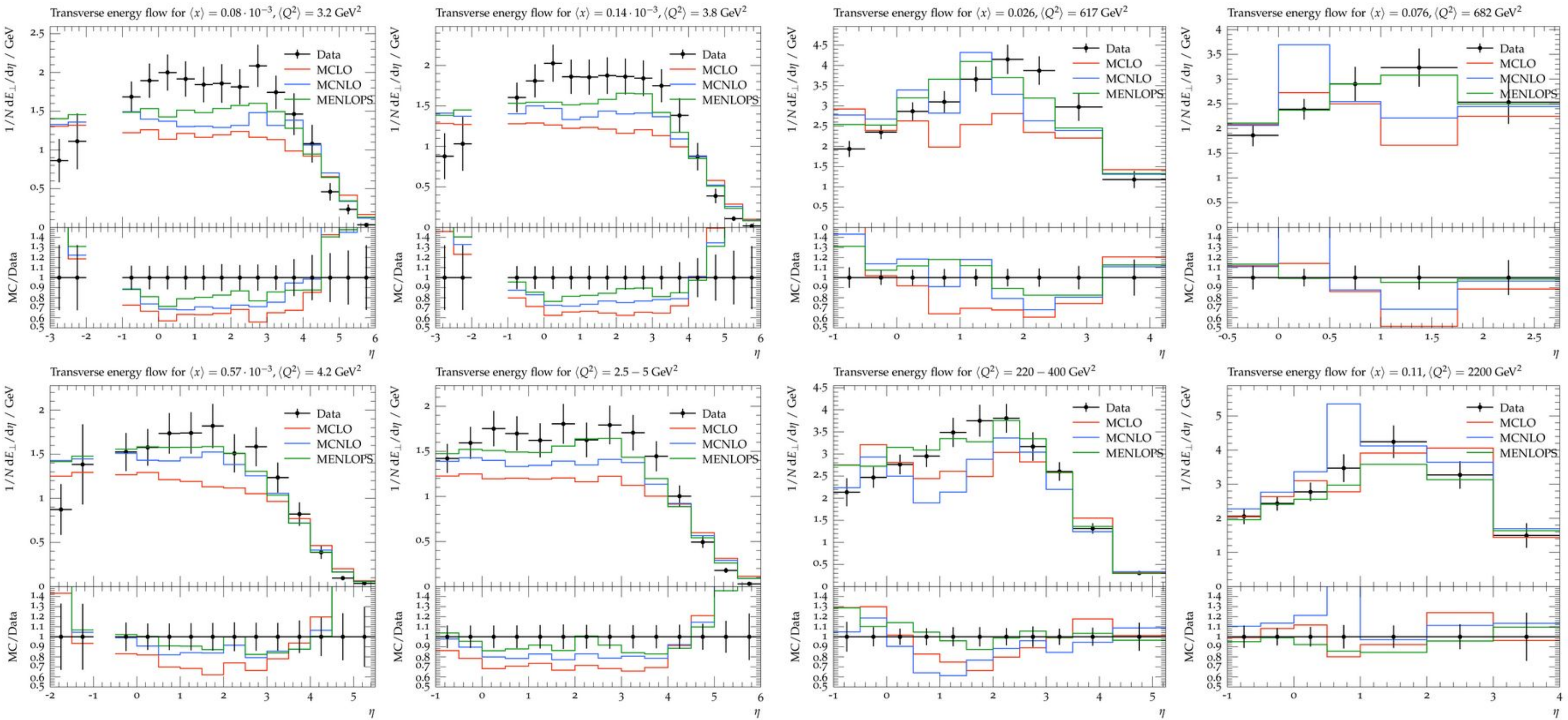
$$C_q = \langle n^q \rangle \,/\, \langle n \rangle^q .$$







Average Transverse Energy Flow



Photoproduction and Diffractive Dijet Production in H1 and Zeus