Recent results from HERA experiments H1 and ZEUS

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(on behalf of the H1 and ZEUS Collaborations)

Diffraction and Low-x

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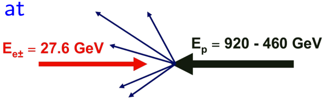
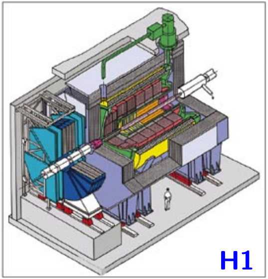
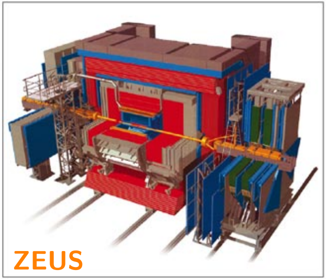
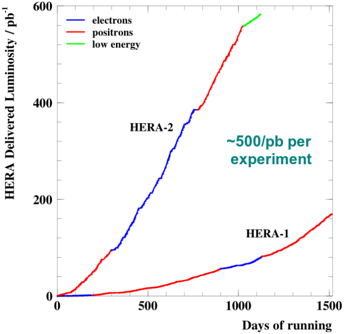
Recent results from H1 and ZEUS - outline

- The azimuthal correlation between the leading jet and the scattered lepton in DIS at HERA, ZEUS Collaboration, arXiv:2406.01430 [hep-ex]
- Observation and differential cross section measurement of NC DIS events with an empty hemisphere in the Breit frame, H1 Collaboration, Eur. Phys. J. C84 (2024) 720
- Measurement of jet production in DIS and NNLO determination of α_s at ZEUS, ZEUS Collaboration, Eur. Phys. J. C83 (2023) 1082
- Measurement of groomed event shape observables in DIS at HERA, H1 Collaboration, Eur. Phys. J. C84 (2024) 718
- Measurement of the 1-jettiness event shape observable in DIS at HERA, H1 Coll., Eur. Phys. J. C84 (2024) 785







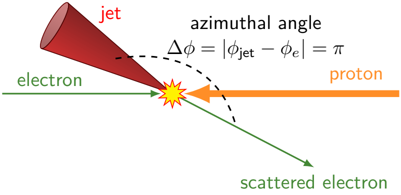


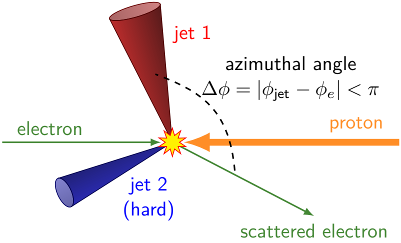
Azimuthal correlation between jet and scattered lepton

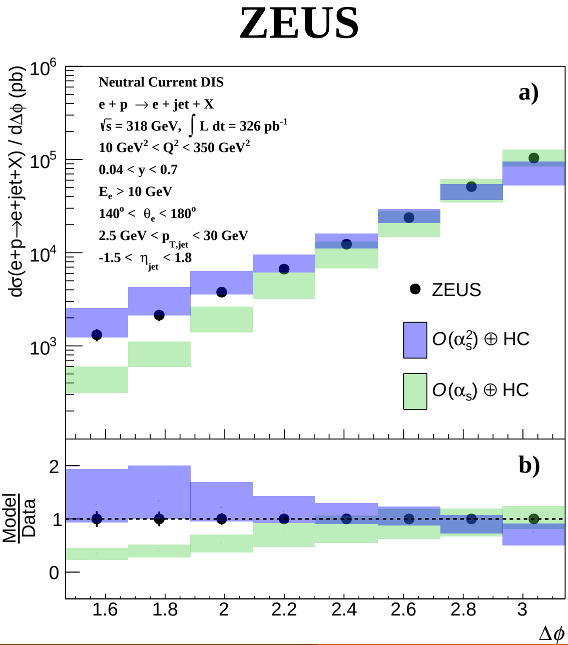
- At the Born limit ($\mathcal{O}(\alpha_s^0)$) of NC DIS, the final state jet is produced in the process:

$$e + p \rightarrow e + \text{jet} + X$$

  in the back-to-back topology with the scattered lepton, $\Delta\phi = |\phi_{\text{jet}} - \phi_e| = \pi$.
- Small deviations from the back-to-back topology arise if soft gluons are emitted and/or if the struck parton carries a non-zero transverse momentum.
- Larger deviations from $\Delta\phi = \pi$ are expected when additional jets are produced through hard gluon radiation.
- Sensitivity to various QCD phenomena, including both soft and hard processes, allows evaluation of theoretical models without explicitly describing the additional jets arising from higher-order processes.

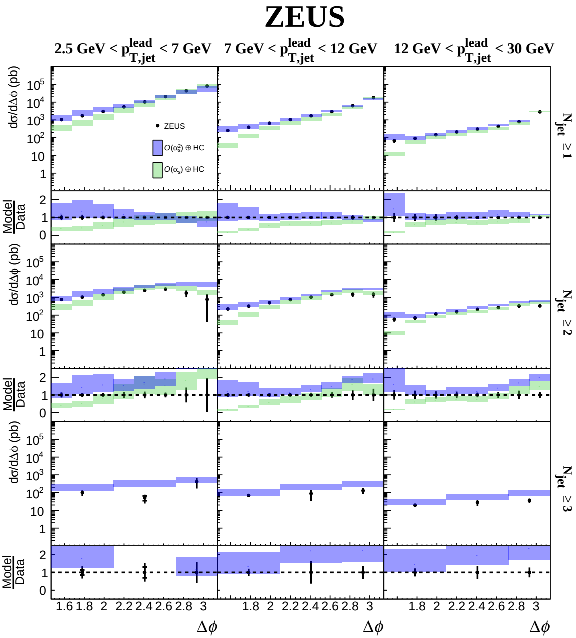






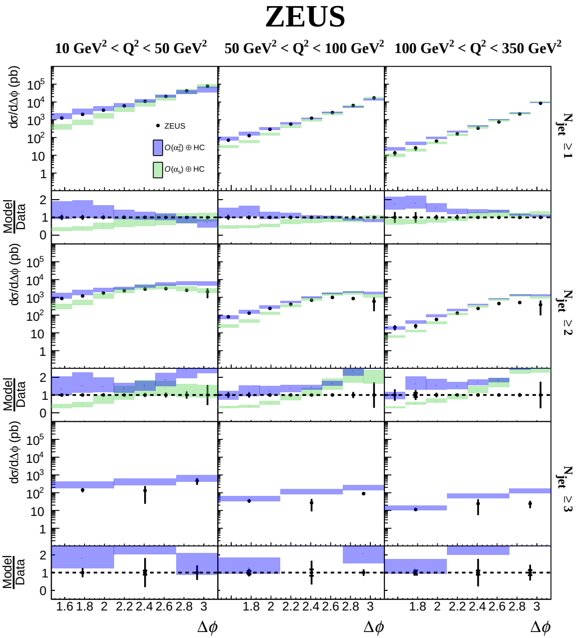
- Measurement of azimuthal correlation, $\Delta\phi = |\phi_{\text{jet}} - \phi_e|$, in the fiducial region:
  $10 < Q^2 < 350$ GeV^2,
  $0.04 < y < 0.7$,
  $E_e > 10$ GeV,
  $140^\circ < \theta_e < 180^\circ$,
  $2.5 < p_{\text{T, jet}} < 30$ GeV,
  $-1.5 < \eta_{\text{jet}} < 1.8$
- Jets were reconstructed in the LAB frame using the k_{T}-clustering algorithm with E-recombination scheme and the radius parameter $R = 1$.
- Measured cross section compared with $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ predictions corrected for hadronization effects.

Azimuthal correlation between jet and scattered lepton



- Differential cross sections for various ranges of $p_{\text{T, jet}}^{\text{lead}} \otimes N_{\text{jet}}$
- In all cases, the $\mathcal{O}(\alpha_s^2)$ corrections significantly improve agreement with the data in the region $\Delta\phi < 3\pi/4$, which is sensitive to additional hard jet production.
- An enhancement of events displaying a reduced azimuthal correlation angle with increasing jet multiplicity is observed. (Also observed in pp collisions, CMS EPJC78 (2018) 566).

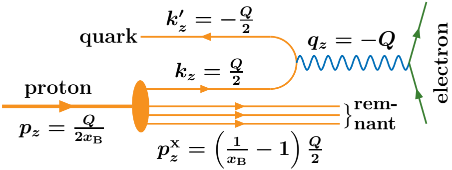
Azimuthal correlation between jet and scattered lepton



- Differential cross sections for various ranges of $Q^2 \otimes N_{\text{jet}}$
- $\mathcal{O}(\alpha_s^2)$ corrections significantly improve agreement with data in the region $\Delta\phi < 3\pi/4$, which is sensitive to additional hard jet production.
- The slope of the measured cross section increases as a function of Q^2, as the HO contributions are suppressed for $N_{\text{jet}} \geqslant 1$. For $N_{\text{jet}} \geqslant 2$, the slope only increases with Q^2 for $\Delta\phi < 3\pi/4$.
- Similar trend is observed at hadron colliders in the dijet cross section growing with increasing p_{T} of the highest-p_{T} jet.

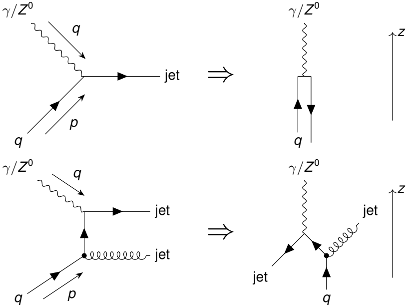
DIS in Breit frame

- DIS in the Breit frame ($M_p^2/Q^2 \ll 1$):
  - The scattered parton is well separated from the proton's remnant.
  - The separation in momentum increases with increasing Q^2 and decreasing x_B.



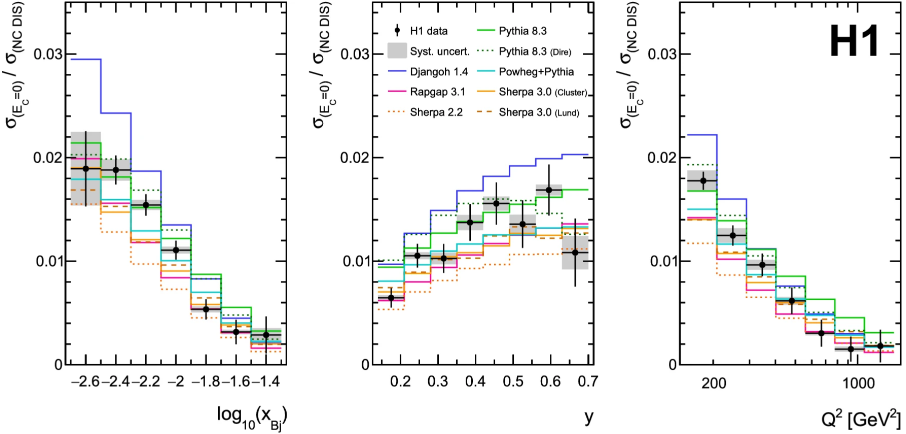
  - Hadrons are produced all along the intermediate momenta because of the color flux between scattered parton and the remnant.

- Breit frame has several advantages for the study of QCD processes in DIS:
  - The exchanged virtual boson $V^\star$ (γ or Z) collides collinearly with an incoming parton.
  - The single-jet production process ($V^\star q \to q$, referred to as QPM-like) is predominantly of zeroth order in α_s.
  - In dijet (or multi-jet) production processes, which involve hard QCD interactions $\mathcal{O}(\alpha_s)$ or higher, jets have in general a non-zero transverse momentum in the Breit frame.
  - The leading-order contributions are from QCD-Compton and boson-gluon fusion.

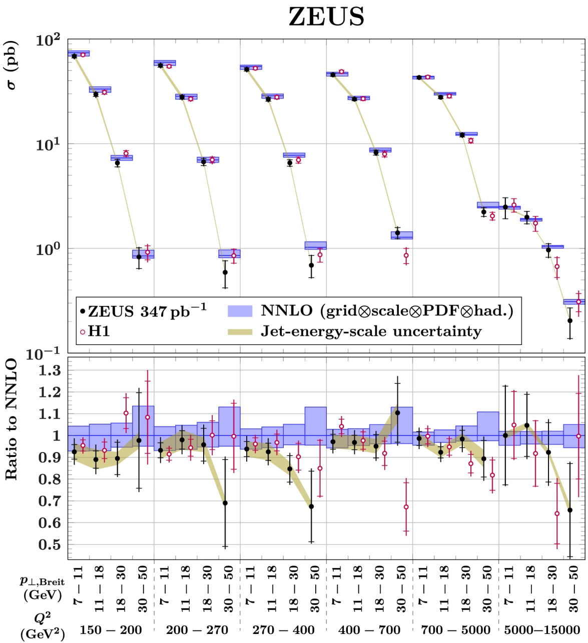


DIS events with empty current hemisphere in Breit frame

- At $\mathcal{O}(\alpha_s)$ (or higher) for $x_B < 0.5$ configurations are kinematically accessible where all outgoing partons are scattered into the target hemisphere, such that the current hemisphere remains empty (Z. Phys. C2 (1979) 237).
- H1 measured the total probability of such configuration for $150 < Q^2 < 1500$ GeV^2 and $0.14 < y < 0.7$ to be $0.0112 \pm 6.2\%$ and also differentially.
- The measurement can help to improve parton shower and hadronization models.



Measurement of inclusive-jet cross sections



- Double differential inclusive jet cross sections have been measured in the fiducial region:

  $0.2 < y < 0.7$,
  $Q^2 > 150$ GeV^2
  $p_{\perp,\mathrm{Breit}} > 7$ GeV,
  $-1 < \eta_{\mathrm{jet}}^{\mathrm{lab}} < 2.5$.

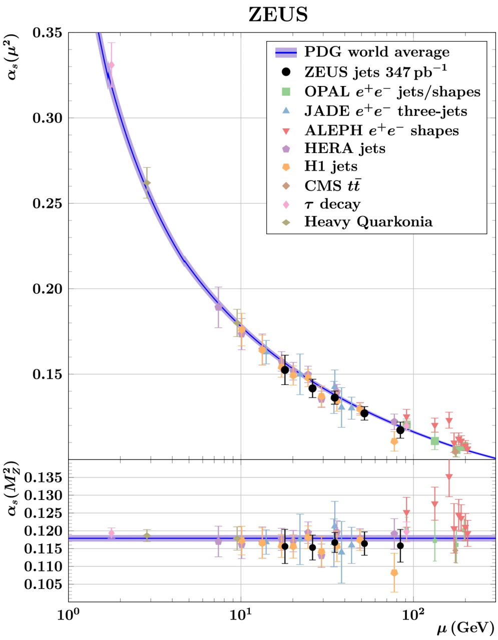
- Compatible with H1 results (EPJC75 (2015) 65) and with QCD predictions:

  - Matrix elements: NNLOJet (JHEP7 (2017) 18),

  - PDFs: HERAPDF2.0Jets NNLO (EPJC82 (2022) 243)

- Inner error bars: unfolding uncertainty; outer error bars: total uncertainty; shaded band: uncertainty associated with the jet-energy scale.

Extracting α_s from inclusive-jet cross sections



- The measured cross sections were used in a QCD analysis at NLO ($\mathcal{O}(\alpha_s^2)$) and NNLO ($\mathcal{O}(\alpha_s^3)$) to perform simultaneous determination of the proton's PDFs and α_s:

$$\alpha_s(M_Z^2) = 0.1142 \pm 0.0017(\text{exp./fit}) \, ^{+0.0006}_{-0.0007}(\text{model/param.}) \, ^{+0.0006}_{-0.0004}(\text{scale})$$

- The dependence of α_s on the energy scale was determined using subsets of measured jet cross sections centered around a certain value of the scale $\langle\mu\rangle$.

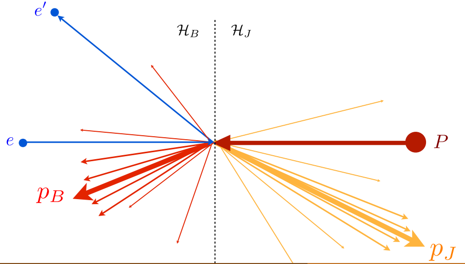
  It was found to be consistent with previous measurements and the perturbative QCD expectations.

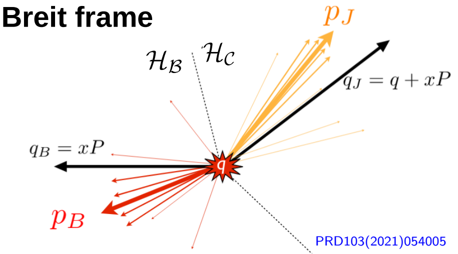
1-jettiness event shape observable

- 1-jettiness is defined as (q_B , q_J are massless four-vectors chosen to lie along the beam and jet directions):

$$\tau_1^b = \frac{2}{Q^2} \sum_{i \in X} \min \{q_B \cdot p_i,\, q_J \cdot p_i\} = \frac{2}{Q^2} \sum_{i \in X} \min \{xP \cdot p_i,\, (q + xP) \cdot p_i\}$$

- Important features of 1-jettiness from theory point of view:
  - infrared safe and free of non-global logs,
  - sensitive to α_s and parton shower models.
- 1-jettiness is experimentally robust and provides clear insight into QCD dynamics, making it a superior choice for detailed studies of event shapes in the context of electron-proton collisions.





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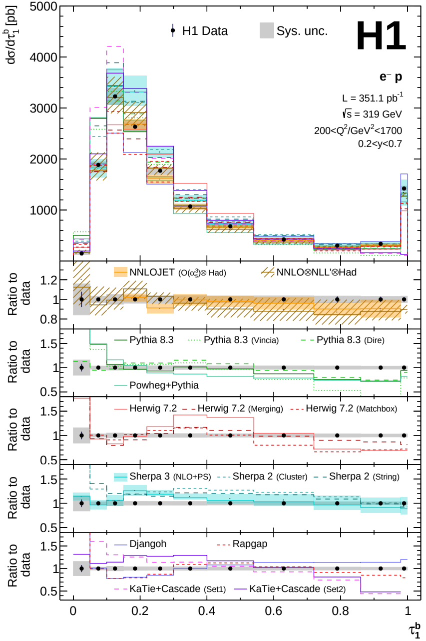
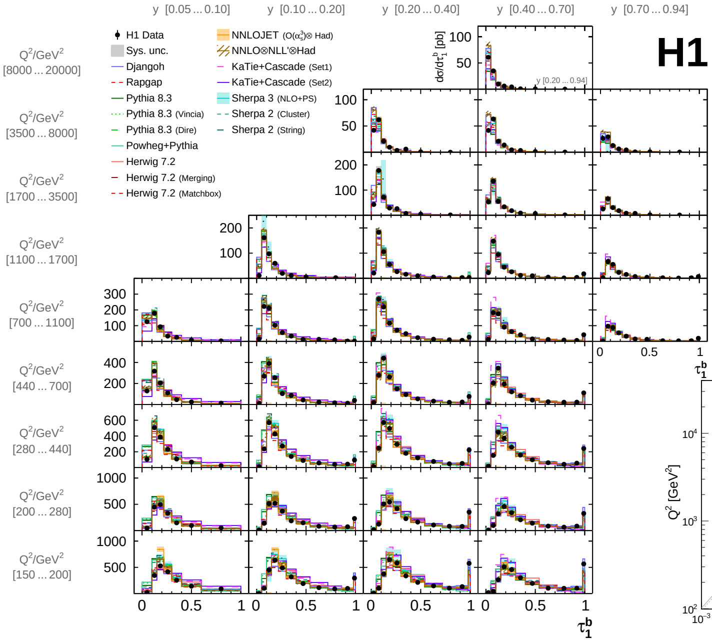
1-jettiness cross section in DIS

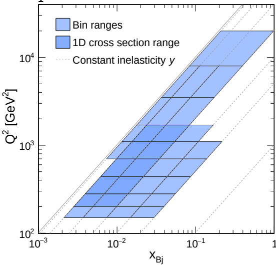


- Measurement of differential 1-jettiness cross section in fiducial region: $0.2 < y < 0.7$ and $200 < Q^2 < 1700$ GeV^2
- No significant differences between the e^-p and e^+p cross sections.
- Features of the cross section:
  - A peak populated by DIS Born-level kinematics with a single hard parton, the position and shape of which are dominated by hadronization and resummation effects.
  - Tail region populated by events with hard radiation, including two-jet topologies.
  - Events with empty current hemisphere peak at $\tau_1^b = 1$.
- None of the MC models works perfectly, now have precision data for tuning.
- Exact QCD predictions have sizeable scale uncertainties and hadronization corrections.

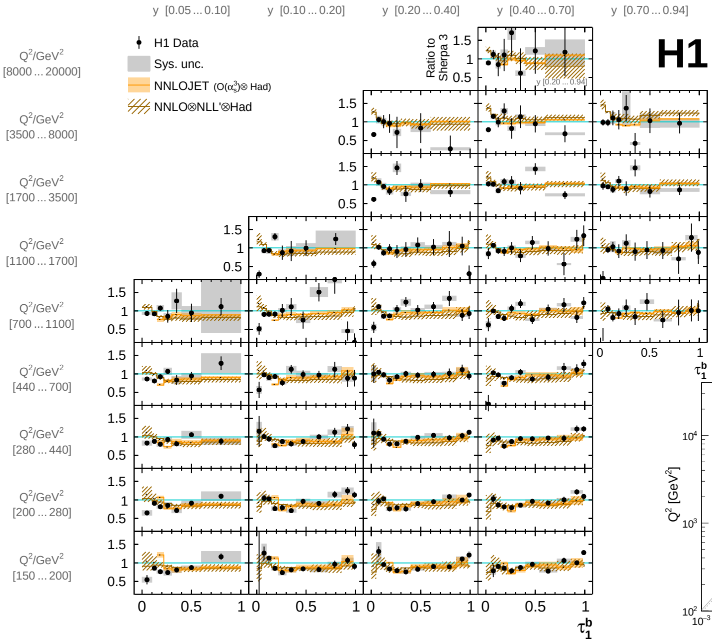
Triple-differential 1-jettiness cross section



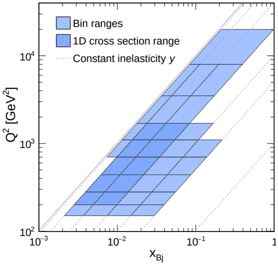
- Study change in shape of the τ_1^{b} distributions:
  - increasing Q^2 $\Rightarrow$ tail lowers,
  - increasing y $\Rightarrow$ $\tau = 1$ more pronounced.
- Reasonable description by various models.



1-jettiness in DIS



- Uncertainties:
  Stat: few-$\mathcal{O}(10\%)$
  Syst: 5-10%
- Ratio to Sherpa 3: Fixed order calculations provide satisfactory description in region of validity.

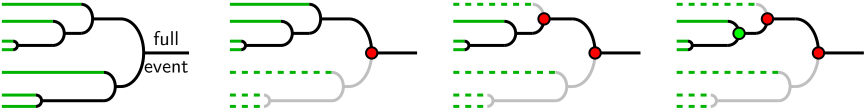


Grooming procedure in DIS

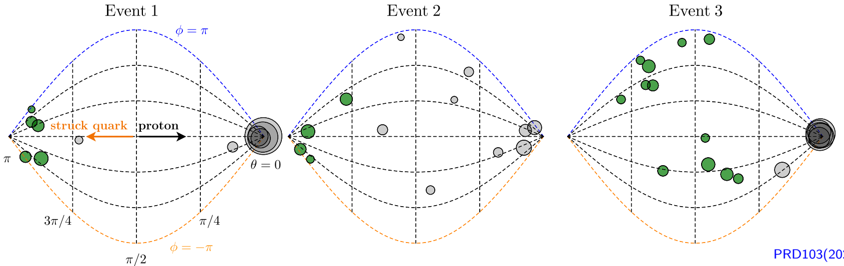
- All four-vectors in the event are clustered in the Breit frame by the Centauro algorithm.
- The tree is then iteratively declustered in reverse order, and at each declustering step the z_i values of the branches are compared to the grooming condition:

$$z_i = \frac{P \cdot p_i}{P \cdot q} \xrightarrow[\text{frame}]{\text{Breit}} \frac{p_i^+}{Q} \qquad\qquad \frac{\min(z_i, z_j)}{z_i + z_j} > z_{\text{cut}}$$

- If the grooming condition is not met, the branch with smaller z_i is removed and the remaining branch is again subdivided and compared to the grooming condition.



- The procedure continues until the grooming condition is met (or the event is removed).



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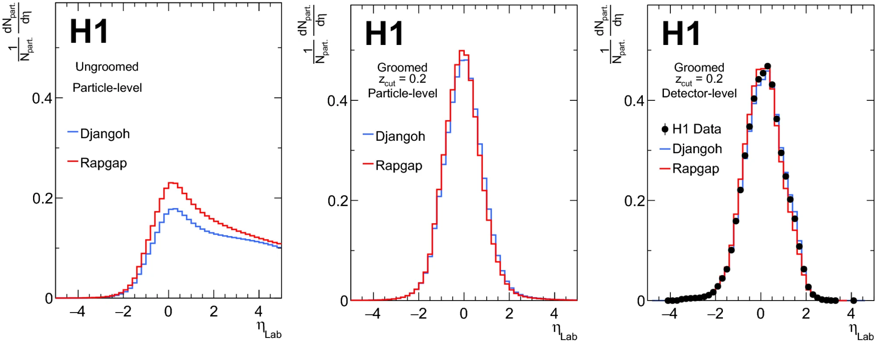
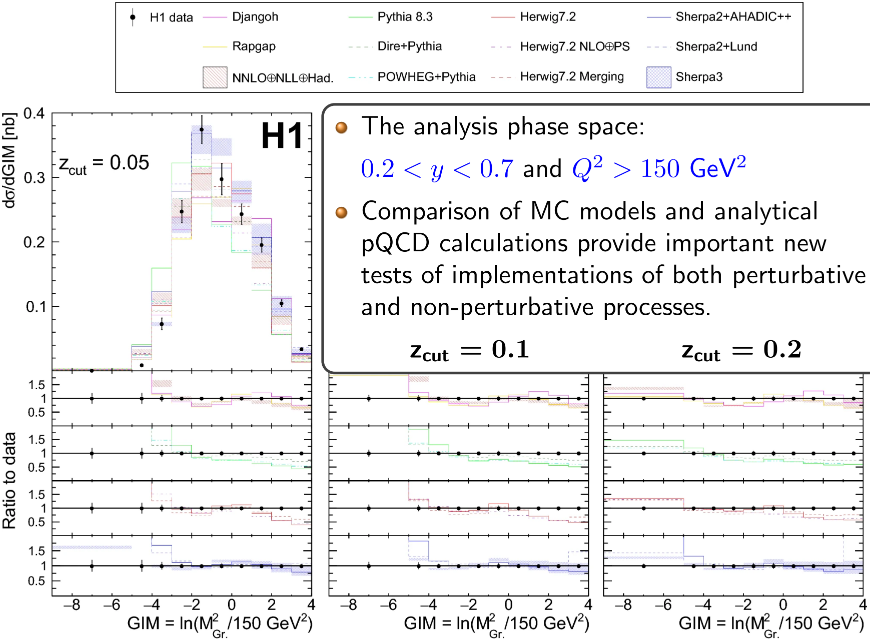
Benefits of groomed event shapes in DIS

- Classical global event shape observables incorporate summation over all particles in an event icluding those escaping the detector acceptance at small angles.
- Event grooming suppresses non-perturbative contributions to event shape distributions in a theoretically well-controlled way.
- Not groomed detector-level distributions can show significant differences from particle-level ones due to detector acceptance and efficiency.
- Grooming procedure applied in DIS at high-Q^2 removes most of the particles produced outside the detector acceptance and brings distributions at particle and detector levels into much better agreement.



Measurement of groomed invariant mass in DIS



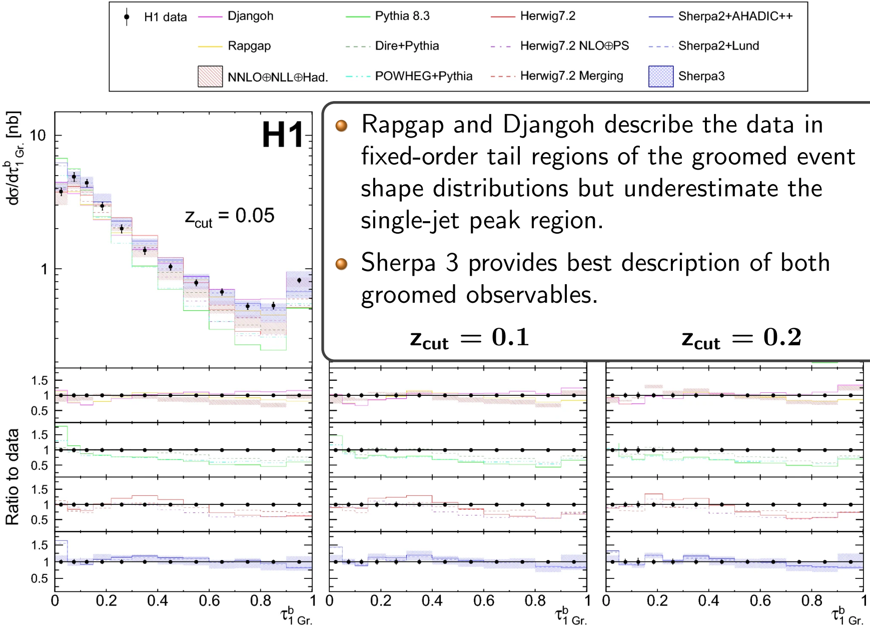
- The analysis phase space:

  $0.2 < y < 0.7$ and $Q^2 > 150$ GeV^2

- Comparison of MC models and analytical pQCD calculations provide important new tests of implementations of both perturbative and non-perturbative processes.

$\mathbf{z_{cut} = 0.1}$ $\mathbf{z_{cut} = 0.2}$

Measurement of groomed 1-jettiness in DIS



- Rapgap and Djangoh describe the data in fixed-order tail regions of the groomed event shape distributions but underestimate the single-jet peak region.
- Sherpa 3 provides best description of both groomed observables.

$\mathbf{z_{cut} = 0.1}$ $\mathbf{z_{cut} = 0.2}$

Summary

- Azimuthal correlations between the scattered lepton and the leading jet in NC DIS have been measured at the hadron level inclusively and differentially in bins of $p_{\mathrm{T,\,jet}}^{\mathrm{lead}} \otimes N_{\mathrm{jet}}$ and $Q^2 \otimes N_{\mathrm{jet}}$.
- First measurement of the fraction of NC DIS events with an empty hemisphere in the Breit frame both inclusively and differentially as functions of x_B, y and Q^2.
- The higher-order pQCD corrections show a significant improvement in describing regions that are driven by hard jet production. The LO+PS predictions by ARIADNE also describe the data well.
- First measurement of the 1-jettiness event shape observable in NC DIS. Cross sections measured inclusively and in bins of x_B and Q^2.
- The groomed event shape distributions provide new, differential constraints for the tuning of MC models and offer the possibility for extracting PDFs and α_s.
- Precise MC modeling of the DIS hadronic final state will be crucial for the future facilities like EIC or FCC-eh to achieve their physics goals.

Thank you for your attention!

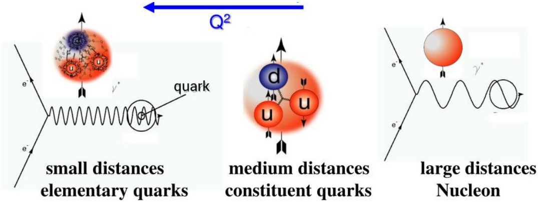
Backup slides

Deep Inelastic electron-proton(nucleon) Scattering (DIS)

- Virtuality of the probe - measure of resolution power:

$$Q^2 \equiv -q^2 = -(k-k')^2 \qquad \lambda \propto \frac{1}{\sqrt{Q^2}}$$

$$Q^2 = 2E_e E'_e(1-\cos\theta_e)$$



- Relative lepton energy loss (inelasticity):

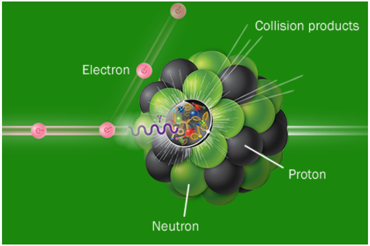
$$y = \frac{p\cdot q}{p\cdot k} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta_e}{2}\right)$$

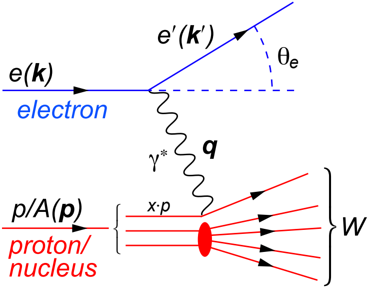
- Momentum fraction of struck quark:

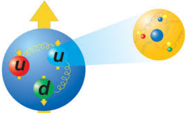
$$x = \frac{Q^2}{2\,p\cdot q} = \frac{Q^2}{sy} \approx \frac{Q^2}{W^2+Q^2}$$

- CMS energies squared in ep and γp frames:

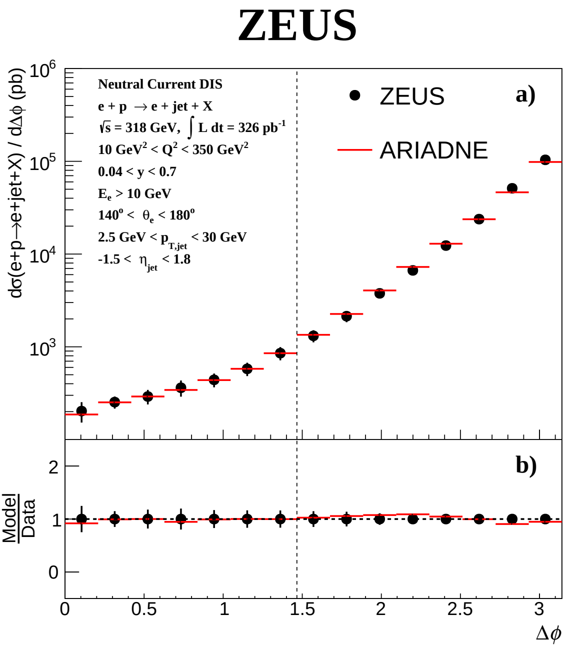
$$s = (k+p)^2 = 4E_eE_p \qquad W^2 = (q+p)^2$$





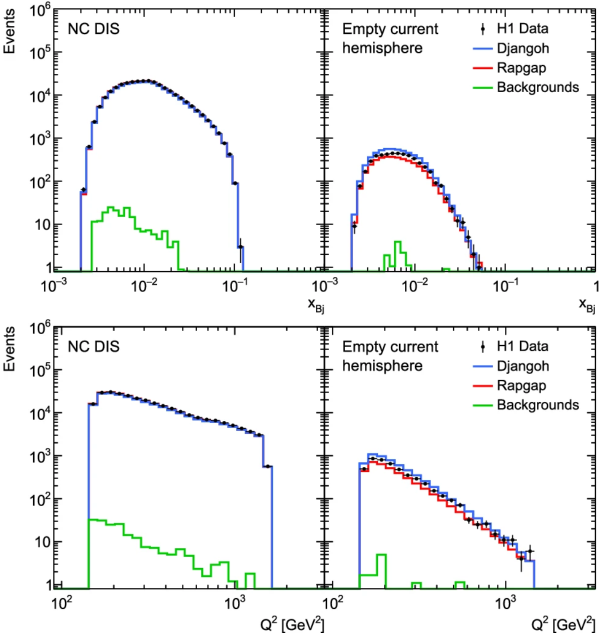


Azimuthal correlation between jet and scattered lepton

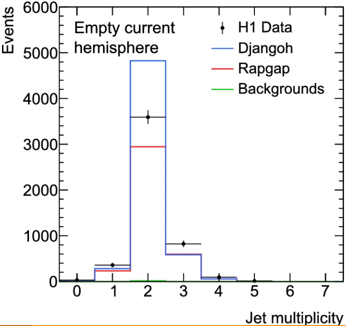


- The LO+PS prediction from ARIADNE is compared to the inclusive measurement of $\Delta\phi$.
- The LO+PS approach describes well HO processes characterised by $\Delta\phi < 3\pi/4$ and $\Delta\phi \approx \pi$, even though they are not fully represented in the LO matrix elements.
- The double differential cross sections, $p_{\text{T, jet}}^{\text{lead}} \otimes N_{\text{jet}}$ and $Q^2 \otimes N_{\text{jet}}$, compared with ARIADNE provide additional information on how PS could be improved to describe HO processes better.

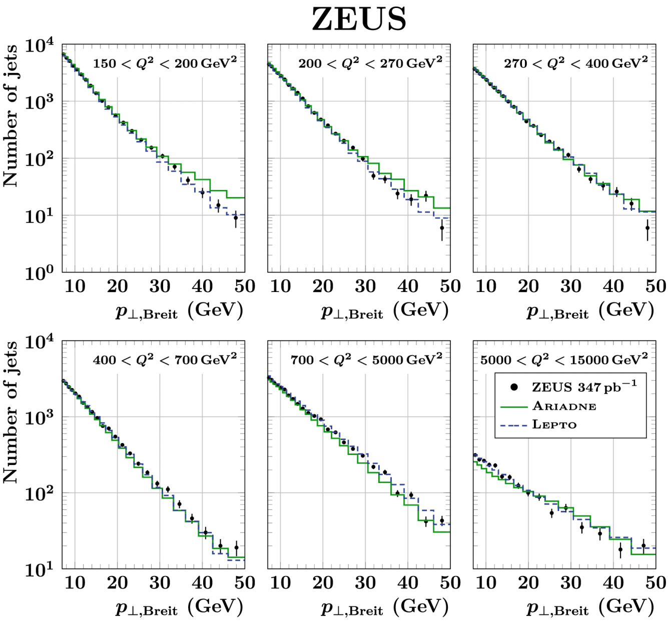
NC DIS events with empty hemisphere in the Breit frame



- Inclusive NC DIS sample is two orders of magnitude larger than the EHE one.
- Jet multiplicity at detector level confirms that EHEs are predominantly two-jet events (jets reconstructed using kt algorithm with a radius parameter of $R = 1$).



Measurement of inclusive-jet cross sections



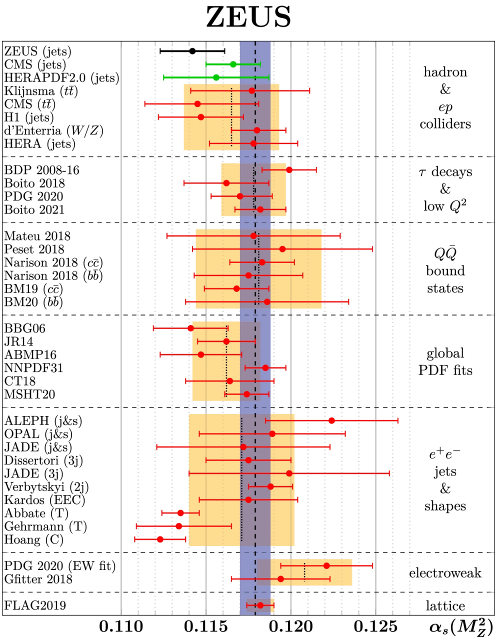
- Reconstructed jets are corrected to hadron level using two-dimensional unfolding with response matrices obtained from MC samples: Ariadne (color-dipol model) and LEPTO (LO parton shower).
- After reweighting, both models give a good description of the data across the entire phase space.

Inclusive-jet cross section - determination of α_s

- The measured inclusive-jet cross sections were used in a QCD analysis at NLO ($\mathcal{O}(\alpha_s^2)$) and NNLO ($\mathcal{O}(\alpha_s^3)$) to perform simultaneous determination of the proton's PDFs and α_s.
- The fit was performed similarly to HERAPDF analyses, using the xFitter program.
- Obtained value (NNLO):

$$\alpha_s(M_Z^2) = 0.1142 \pm 0.0017(\text{exp./fit}) {}^{+0.0006}_{-0.0007}(\text{model/param.}) {}^{+0.0006}_{-0.0004}(\text{scale})$$

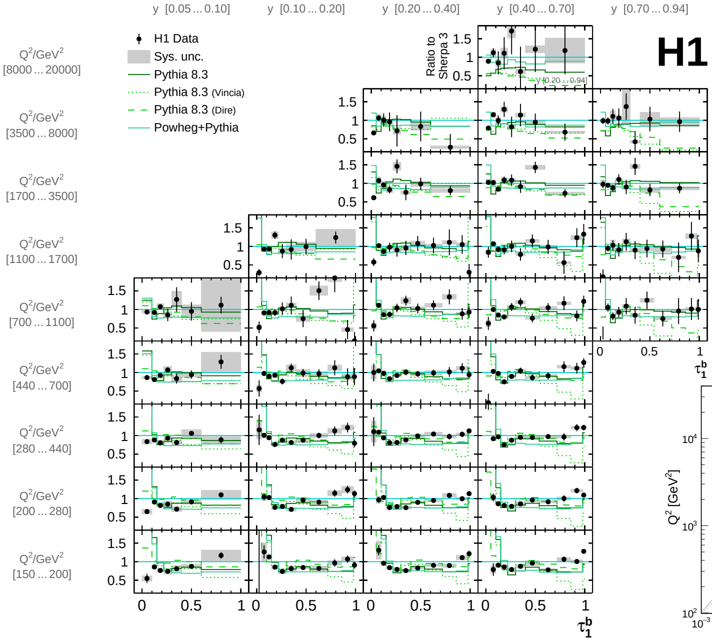
is compared with other measurements.



1-jettiness as a valuable tool for precision QCD studies

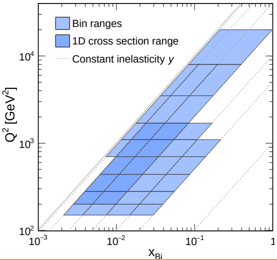
- Infrared safe - it is unaffected by soft or collinear emissions, making it a reliable and stable observable for theoretical predictions and experimental measurements.
- Being free of non-global logs simplifies the calculation of 1-jettiness and ensures that it reflects the global structure of the event without being overly sensitive to soft radiation in limited regions.
- Sensitivity to α_s - 1-jettiness directly probes the strength of the strong force, as it reflects the amount and pattern of QCD radiation in an event.
- Sensitivity to parton shower models - 1-jettiness is influenced by how well MC simulations describe the parton evolution and radiation, making it useful for tuning and validating these models.
- 1-jettiness is designed to quantify how much the event resembles a single jet, making it particularly sensitive and effective in scenarios where one expects a dominant jet structure.
- 1-jettiness is relatively straightforward to measure. It relies on summing over final-state particle momenta in a way that is less susceptible to detector effects like resolution and acceptance compared to some other event shape variables that might require more intricate particle or jet reconstructions.

H1 measurement of 1-jettiness in DIS

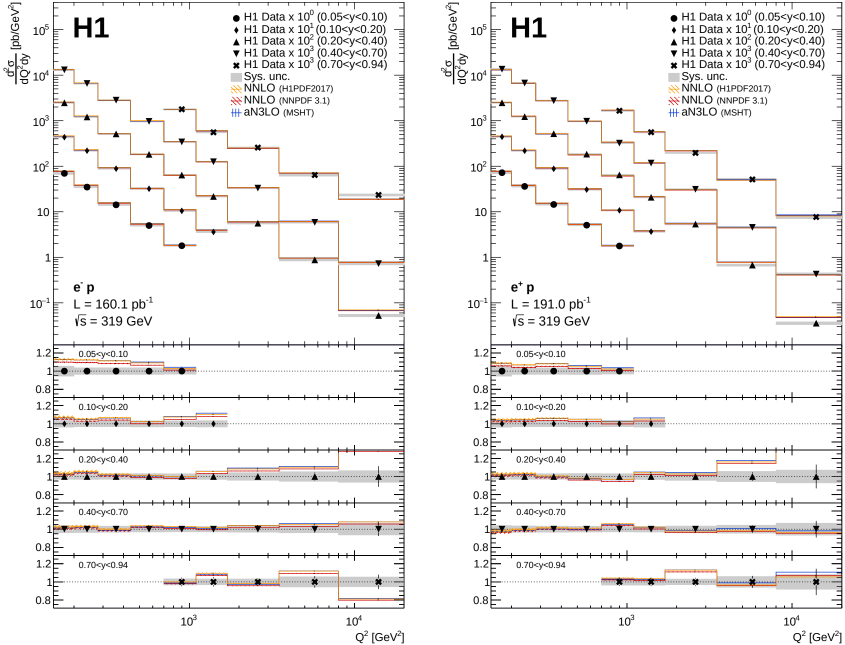


- Comparison to Pythia models.
- Ratio to Sherpa 3:

All three Pythia predictions are similar in the parton-shower region but tend to underestimate the data in the tail region.

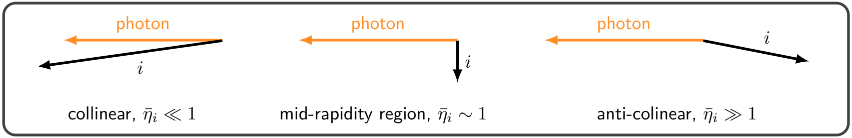


Double differential DIS cross sections - integrated over τ_1^b

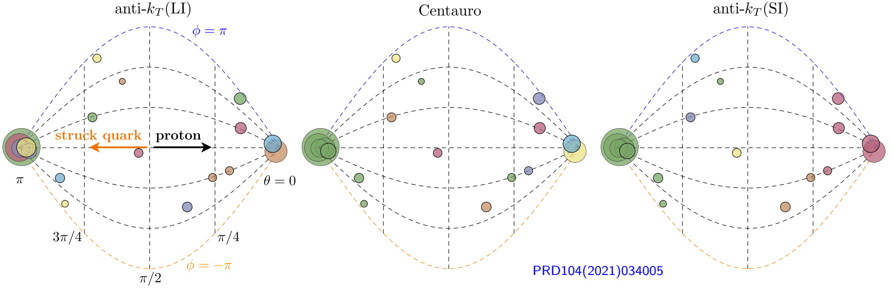


- Particles are combined according to the following distance measure:

$$d_{ij} = (\Delta\bar{\eta}_{ij})^2 + 2\bar{\eta}_i\bar{\eta}_j(1-\cos(\Delta\phi_{ij})), \quad d_{iB} = 1, \qquad \bar{\eta}_i \equiv 2\sqrt{1+\frac{q\cdot p_i}{x_{\mathrm{B}}P\cdot p_i}} \xrightarrow[\text{frame}]{\text{Breit}} \frac{2p_i^{\perp}}{p_i^{+}}$$



- Comparison of jet clustering in the Breit frame using the longitudinally-invariant anti-k_{T}, Centauro, and spherically-invariant anti-k_{T} algorithms:



Groomig in Deep Inelastic Scattering

- The grooming procedure in DIS events serves as a powerful tool to refine the analysis of jets by selectively removing contributions from soft radiation and other non-perturbative effects.
- Grooming isolates the perturbative aspects of QCD dynamics by focusing on the hardest part of the jet, which originates from the parton involved in the hard scattering.
- By focusing on the core components of jets, grooming enhances the sensitivity to the hard scattering process, reduces the impact of non-perturbative effects, improves the resolution of jet observables, and increases the theoretical predictability of the measurements.
- This leads to a more accurate and reliable understanding of the underlying QCD processes in DIS, making grooming an essential technique in modern HEP analyses.

Double differential groomed cross sections

- A reasonable agreement between Sherpa prediction and data is found also in double differential distributions in bins of GIM $\otimes Q^2$ and $\tau_1^{\mathrm{b}}{}_{\mathrm{Gr}} \otimes Q^2$.
- At higher Q^2, the mean values of the event shape distributions decrease, in accordance with the expectations from QCD.