HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

Measurement of 1-jettiness Event Shapes

and Empty Hemisphere Events in Deep Inelastic Scattering at HERA

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on behalf of the H1 collaboration

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Outline

- The H1 experiment at HERA
- The 1-jettiness event shape
- Empty hemisphere events
- Results

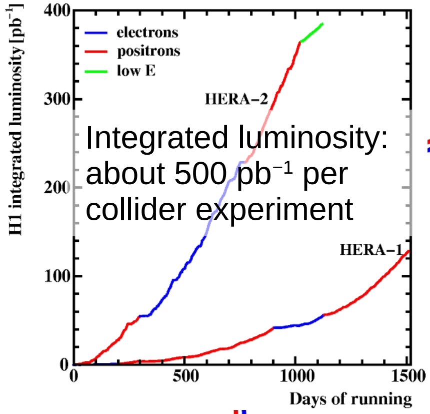
The new results presented here are published in:

Eur.Phys.J.C84 (2024), 785 [arxiv:2403.10109] (1-jettiness)

Eur.Phys.J.C84 (2024), 720 [arxiv:2403.08982] (empty hemisphere events)

The HERA ep collider

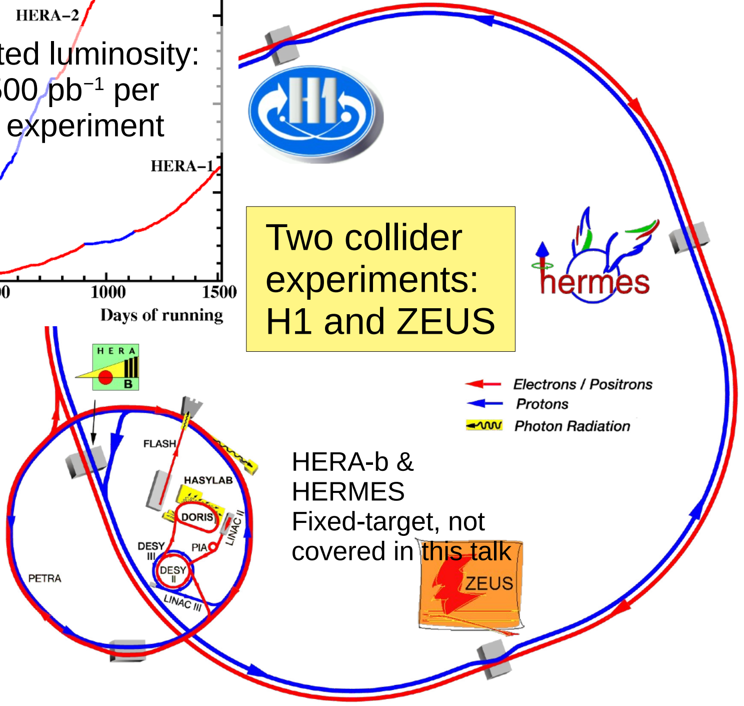
- HERA collider:
  - operated from 1992 to 2007
  - Circumference 6.3 km
  - Electrons or positrons colliding with protons
  - Proton: 460-920 GeV, Leptons 27.6 GeV
  - Peak luminosity ~7×10^{31} cm^{-2}s^{-1}



Integrated luminosity: about 500 pb^{-1} per collider experiment

Maximum centre-of-mass energy: 320 GeV

Two collider experiments: H1 and ZEUS



HERA-b & HERMES Fixed-target, not covered in this talk

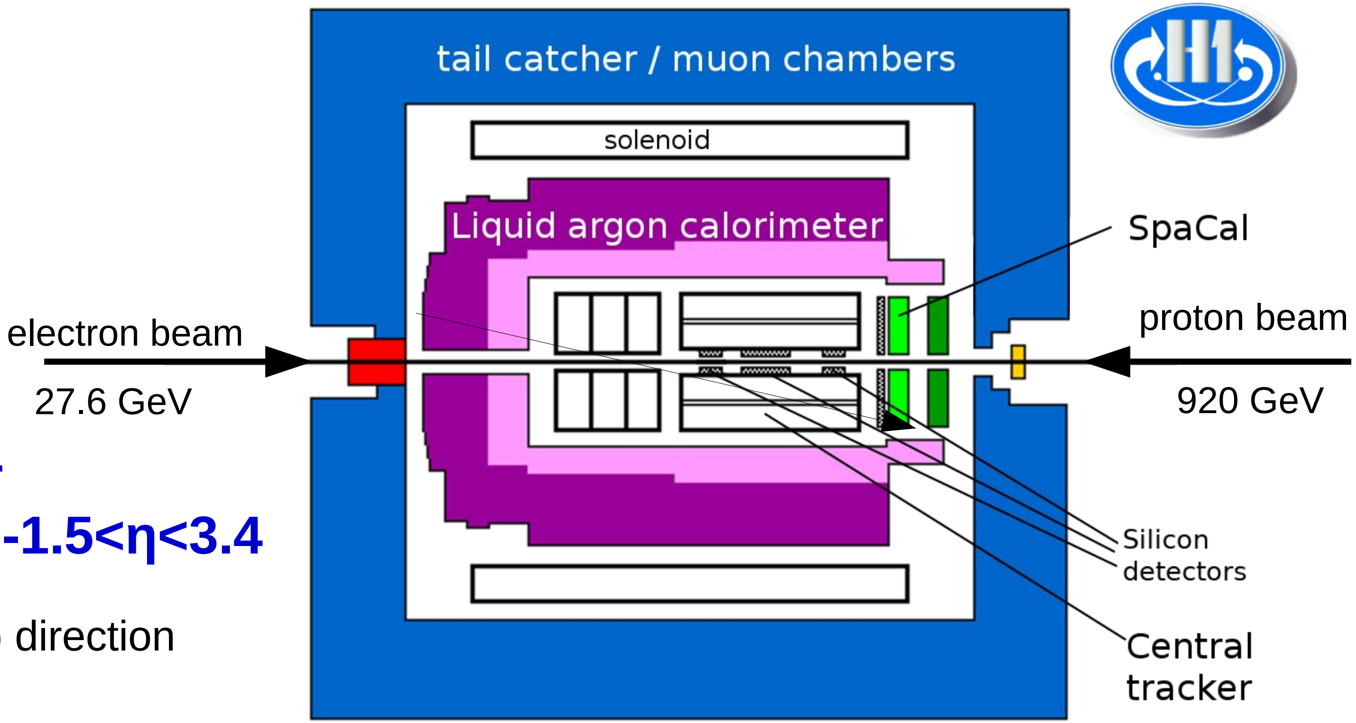

Straight section


Curved section

The H1 Experiment

Asymmetric detector
Centre-of-mass system is boosted to proton-direction
E_e=27.6 GeV, E_p=920 GeV

Drift-chamber: main tracking device 15°<θ<165°



Liquid Argon calorimeter
σ_{had}=0.5/√E, σ_{EM}=0.11/√E, -1.5<η<3.4

Lead+fiber in backward (electron) direction
[SpaCal] σ_{EM}=0.07/√E, -4<η<-1.4

Deep-inelastic scattering at HERA

- Neutral Current DIS

  Momentum transfer: $Q^2 = -q^2 = -(e - e')^2$

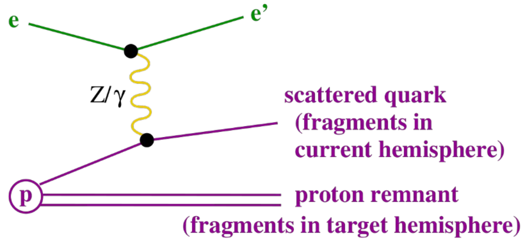
  Inelasticity: $y = \frac{qp}{ep}$

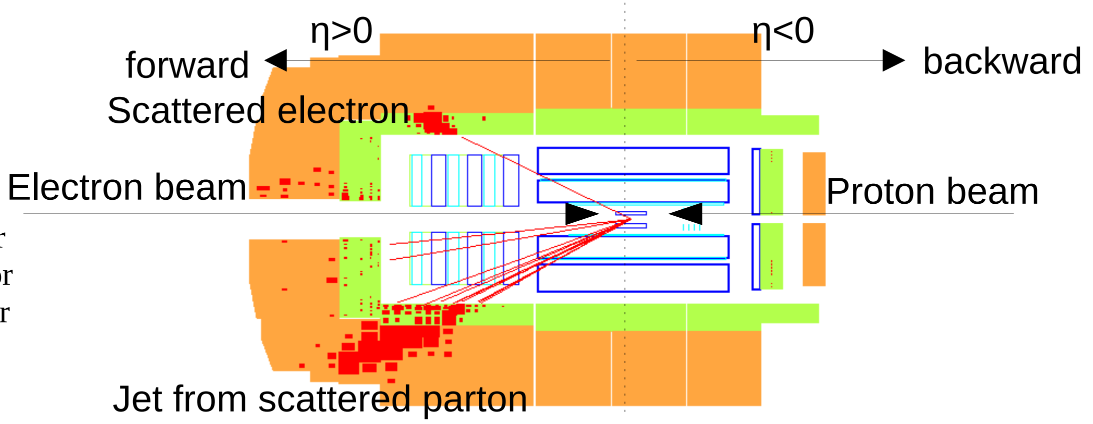
  Bjorken-x: $x = \frac{Q^2}{s\, y}$

  Hadronic mass: $W^2 = (p+q)^2$

  e: incoming lepton 4-vector
  p: incoming proton 4-vector
  e': scattered lepton 4-vector

- Leading order picture





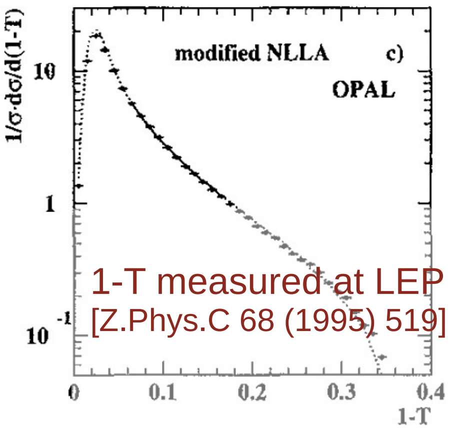
Event at high $Q^2 > 150$ GeV²

- Electron in LAr calorimeter
- Hadrons in the central tracker and LAr (~current hemisphere)
- Proton remnants in forward direction mostly escape detection

Event shapes in e+e- and ep

- "Classical" event shapes in e+e-: thrust 1-T, jet broadening, etc: extract α_s
- e+e- event: two equivalent hemispheres

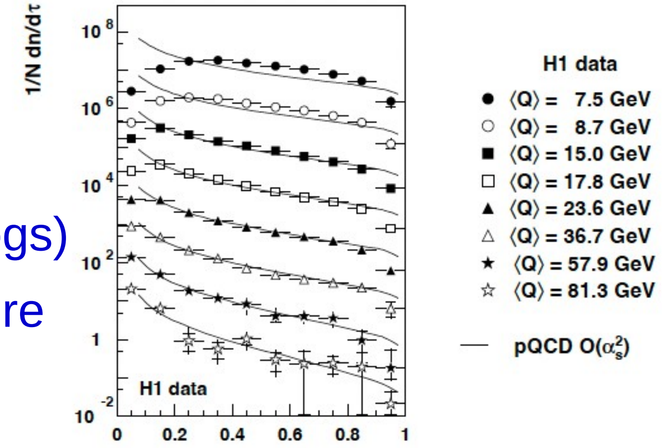
$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |p_i|}$$



1-T measured at LEP
[Z.Phys.C 68 (1995) 519]

- ep scattering: two distinct hemispheres
  - Target hemisphere: proton remnant, limited acceptance
  - Current hemisphere of the Breit frame: good acceptance

- **Event shape measurement in ep**
  - Use only in current hemisphere
  - Cut in polar angle complicates QCD calculations (non-global logs)
  - Bonus for ep: vary Q^2 → measure scale dependence

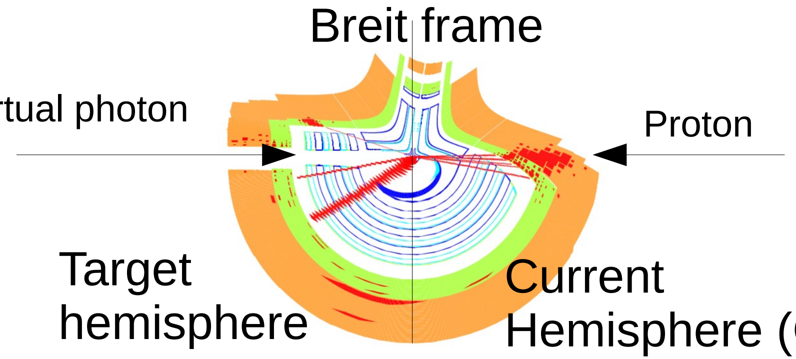


1-T in current hemisphere
[Eur.Phys.J.C14 (2000) 255]

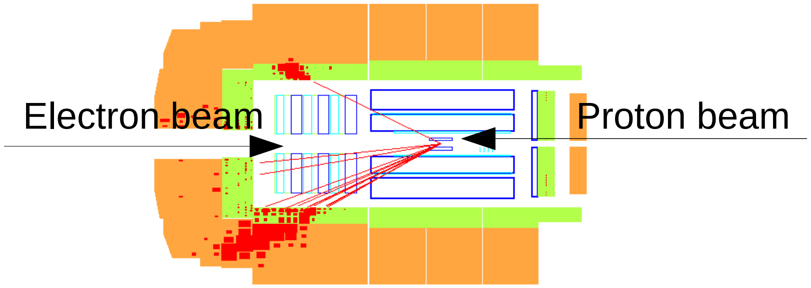
Breit frame (BF) and definition of τ_1^b

- proton along +z axis
- After boost: virtual photon along -z axis with energy=0
- in LO, the quark is scattered along the -z axis

- Current hemisphere: particles with $p_z<0$ in BF
- Target hemisphere: particles with $p_z>0$



Lorentz boost

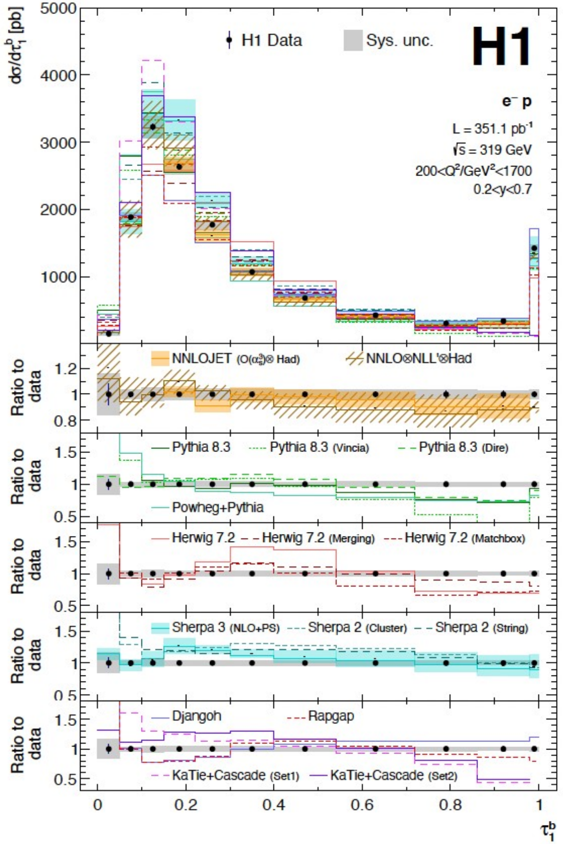


- 1-jettiness τ_1^b: $$\tau_1^b = 1 - 2\sum_{i\in CH} \frac{q\cdot p_i}{q\cdot q}$$
- Can be written as a sum including all particles
- Infrared & collinear save, free of non-global logs

Precision measurement of τ_1^b at high Q^2

- Measurement phase space:
  - $200<Q^2<1700$ GeV² and $0.2<y<0.7$
- Results are unfolded to particle level
- Only depends on current hemisphere particles → free of acceptance corrections, high precision <5% in most bins
- Peak structure around 0.15: single jet events
- Tail towards larger τ_1^b: higher orders, hard QCD radiation
- Peak at $\tau_1^b=1$: events where the current hemisphere is empty
- Test against a variety of models → next slide

$$\tau_1^b = 1 - 2\sum_{i\in \mathrm{CH}} \frac{q\cdot p_i}{q\cdot q}$$

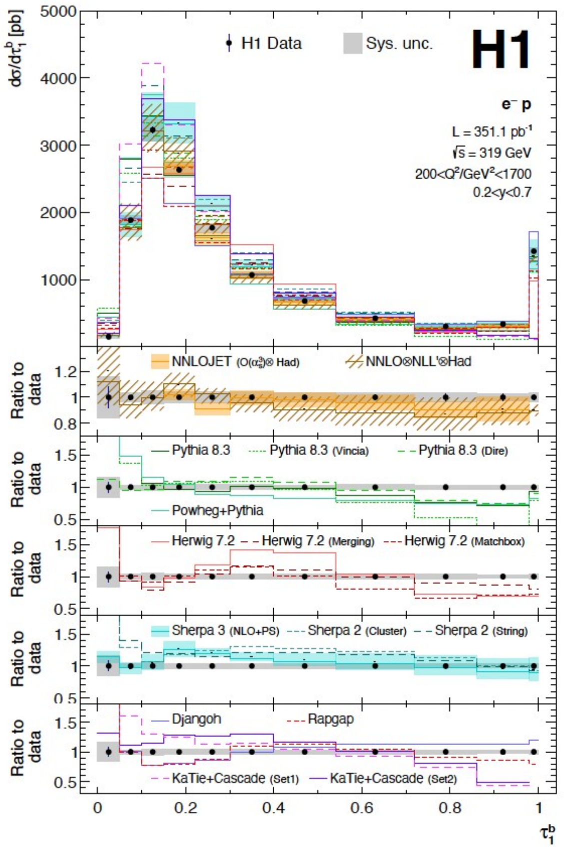


Precision measurement of τ_1^b at high Q^2

- Measurement phase space:
  - $200 < Q^2 < 1700$ GeV² and $0.2 < y < 0.7$
- Results are unfolded to particle level
- Comparison to
  - NNLOJET: NNL QCD (only for sufficiently high τ_1^b)
  - Pythia 8.3
  - Powheg+Pythia
  - Herwig 7.2
  - Sherpa 2, Sherpa 3
  - Rapgap. Djangoh

$$\tau_1^b = 1 - 2 \sum_{i \in \mathrm{CH}} \frac{q \cdot p_i}{q \cdot q}$$

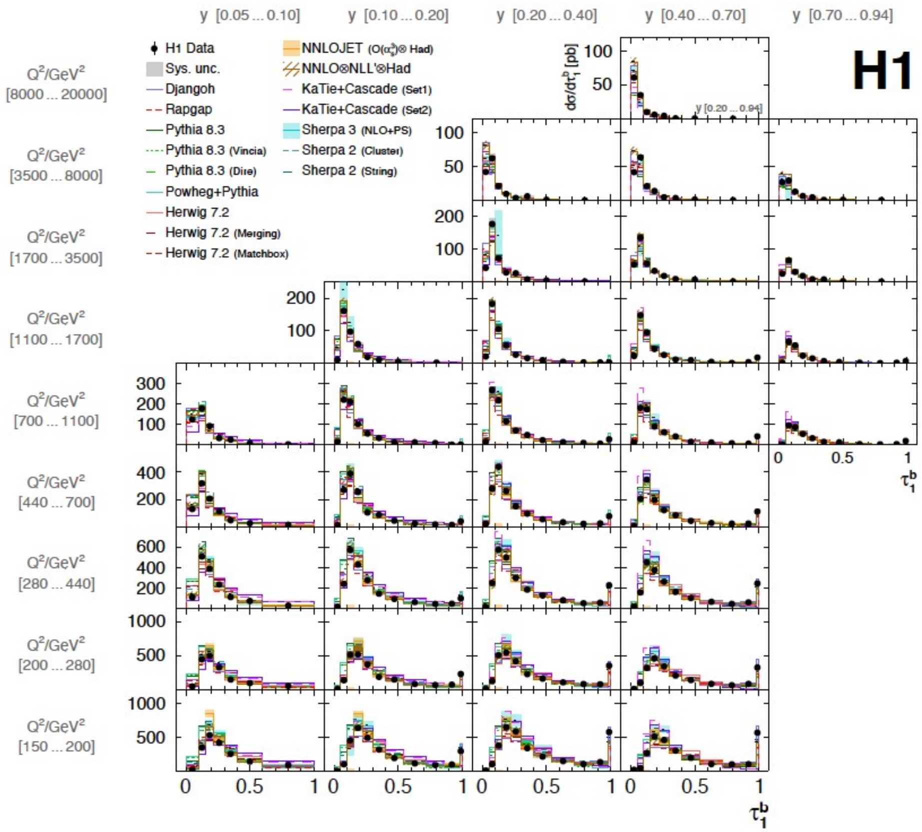
NNLO calculation works well
None of the models is perfect
→ room for tuning



Triple-differential measurement of τ_1^b

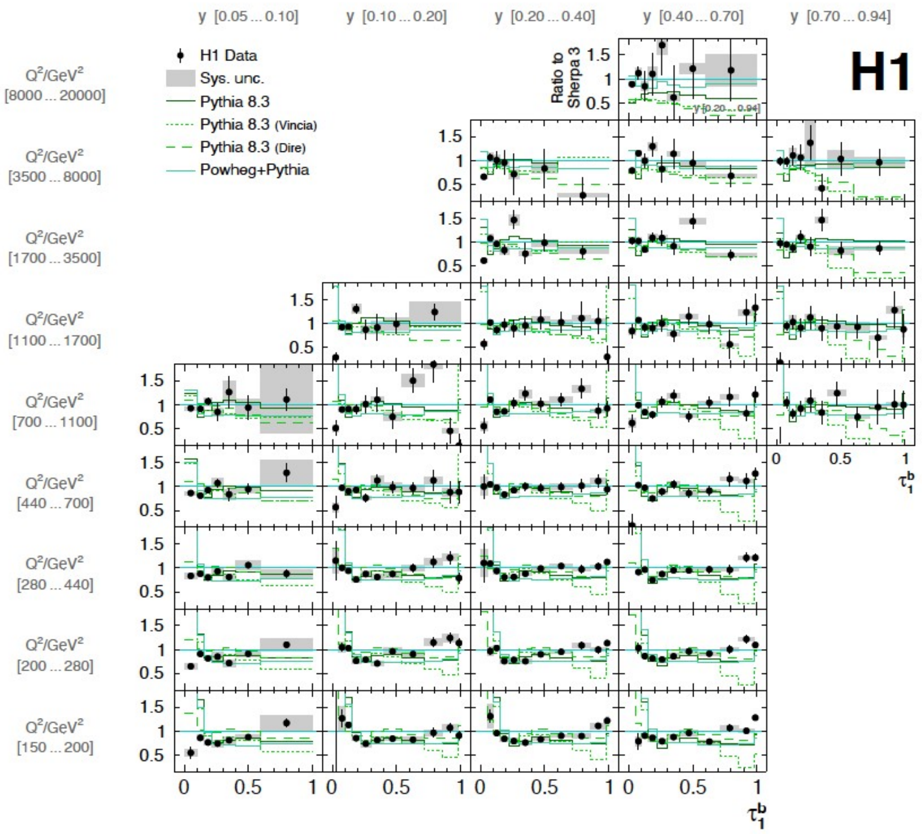
- Measurement of τ_1^b in Q^2 and y bins
- With increasing Q^2: peak shifts and is less broad, tail towards high τ_1^b is reduced

  → QCD evolution with the scale
- Peak position also shifts with y: could be related to varying contributions from quark or gluon induced scattering
- Detailed comparison to models → ratio plots (next slide)



Triple-differential: Ratio to Pythia 8.3

- Example of triple-differential model comparison: Sherpa3 and PYTHIA 8.3
- Dots: ratio of Data/Sherpa3
- Line at unity: Sherpa 3, describes the data well
- Green lines: ratio Pythia8.3/Sherpa3
- Pythia 8.3: difficulties to describe the data at very low τ_1^b – already evident from 1D distribution
- Additional feature: high τ_1^b is not described accurately by Pythia and Pythia variants. At high y, Vinca and Dire definitely do not perform well, Powheg and "plain" Pythia are doing better.



Sherpa2, NNLOJET, HERWIG7.2 in backup

Recent calculations confronted to data

- A recent paper confronts N3LL calculations with the H1 data
- Accurate predictions over the full τ_1^b range (c.f. NNLO jet predictions only down to ~0.15)
- Can we use triple-differential HERA data (Q^2,y,τ_1^b) for PDF+α_s fits in the future?

Paper: **Precision DIS thrust predictions for HERA and EIC**

June-Haak Ee, Daekyoung Kang, Christopher Lee, Iain W. Stewart

arXiv:2504.05234

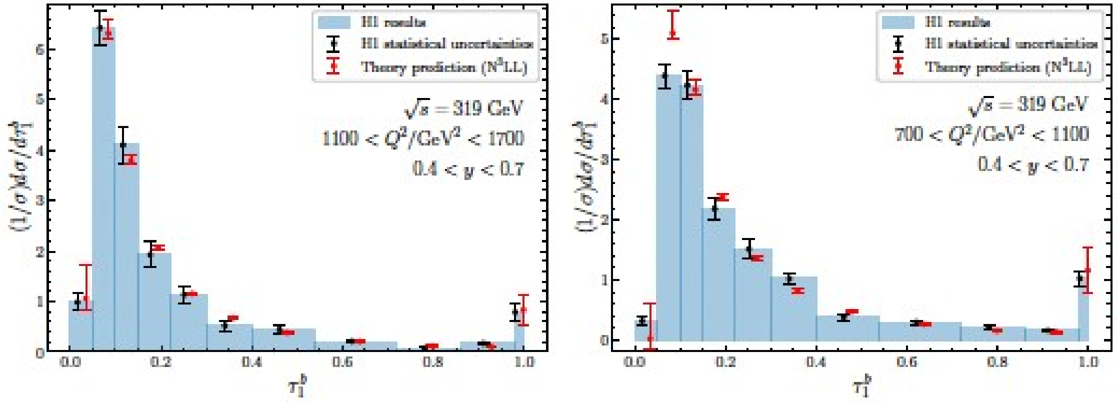
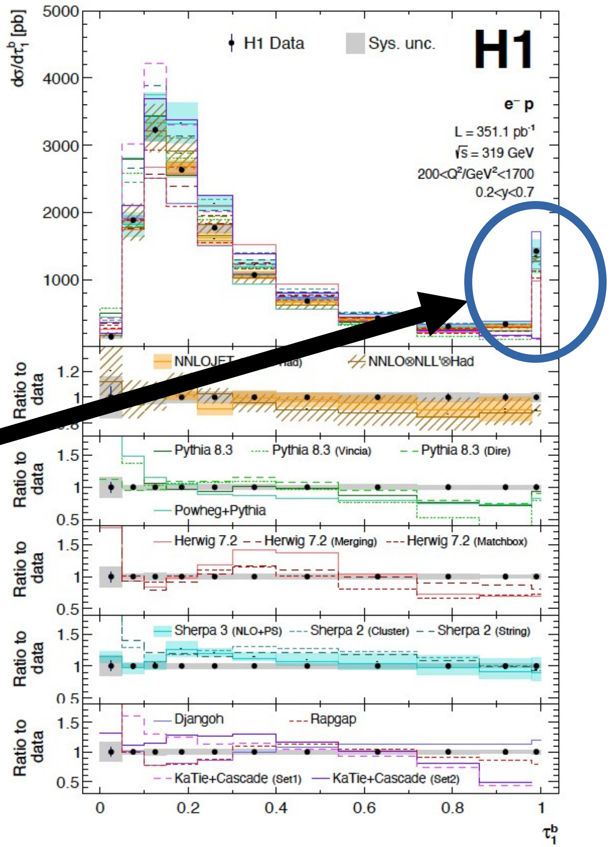


Figure 17. Comparison of differential cross section measurements from the H1 collaboration at HERA [26] (black points) with our theoretical predictions (red points). The left and right panels show results from two different bins in Q^2 with the same bin in y.

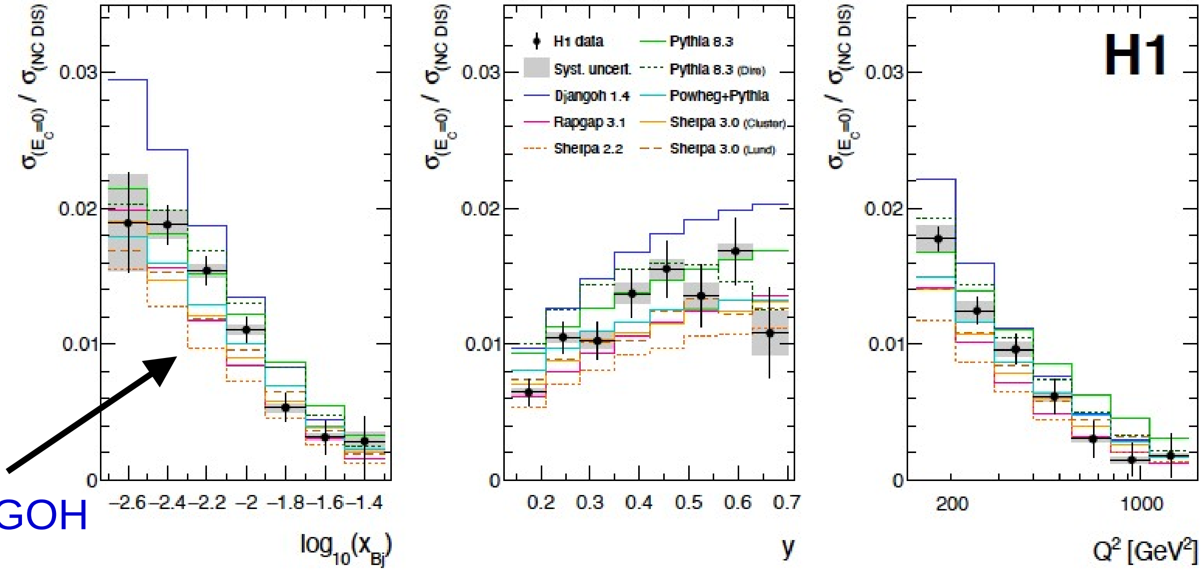
Empty hemisphere (EH) events

- Empty hemisphere events are predicted at NLO: dijet events can have both jets in the target hemisphere
  - Leading order: scattered parton is massless
  - Next order: dijet system with finite mass
  - Boost to Breit Frame can bring both jets into the target hemisphere (given certain kinematic conditions)
- **The current hemisphere can be empty, τ_1^b=1**
- Exact predictions are difficult, as this is a pure higher-order effect. At even higher orders (third jet), or with hadronisation, the rate of these events may be smaller than expected from the lowest order parton-level dijet prediction



Kinematic properties of EH events

- The rate of empty hemisphere events is measured at the particle level
- Measurement phase space $150<Q^2<1500$ GeV^2, $0.14<y<0.7$
- The rate is measured as a function of $\log(x_{Bj})$, y, Q^2
- Confronting with MC models, the data have discriminative power
- The "traditional" HERA models DJANGOH and RAPGAP bracket the data:



→ estimate model uncertainties from DJANGO-RAPGAP differences. Unfolding uses extra bins (=extra nuisance parameters) to obtain results with small model uncertainties

Result integrated over full phase space: $r = 0.0112 \pm 3.9\,\%_{\rm stat} \pm 4.5\,\%_{\rm syst} \pm 1.6\,\%_{\rm mod}$

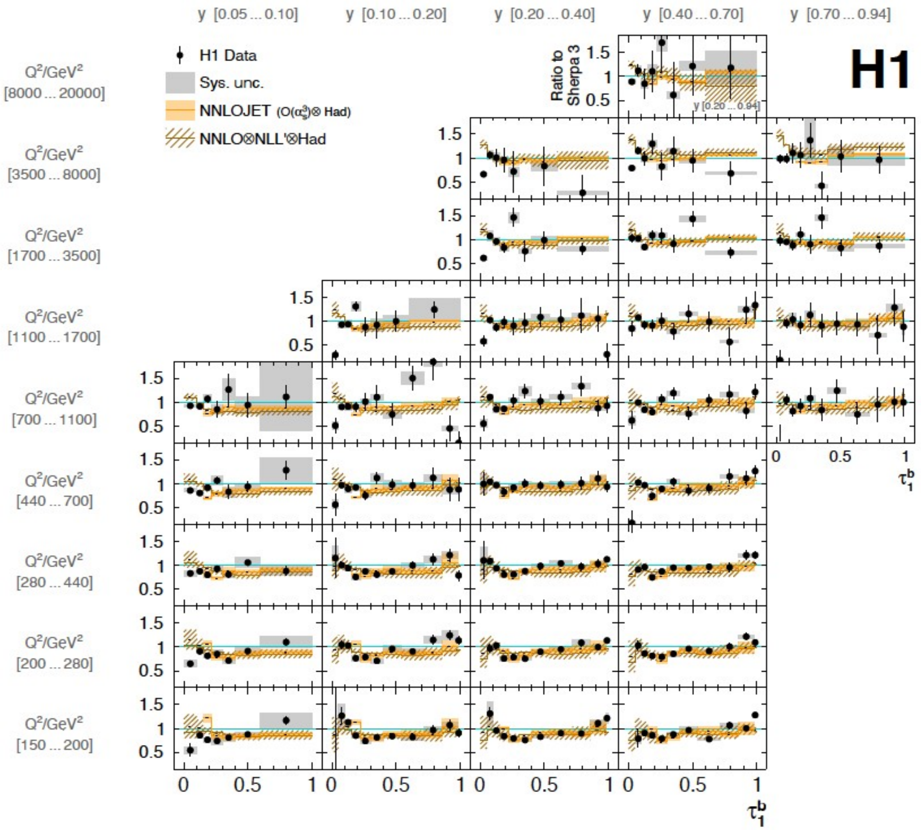
Summary

- The H1 collaboration presents new precision data on the 1-jettiness event shape variable τ_1^b
- The data are measured triple-differential and “inclusive”, such that for a given Q^2,y all possible hadronic final state are quantified in terms of τ_1^b (there is no acceptance limitation in τ_1^b) - see backup for inclusive τ_1^b integrated cross sections in (Q^2,y)
- Modern ep MC generators do a good job in describing τ_1^b , but there is also room for further improvements
- At τ_1^b=1 there is a special event topology with an empty hemisphere. The kinematic properties of these events are studied in detail. In particular the x-dependence is very sensitive to details of MC models

Backup

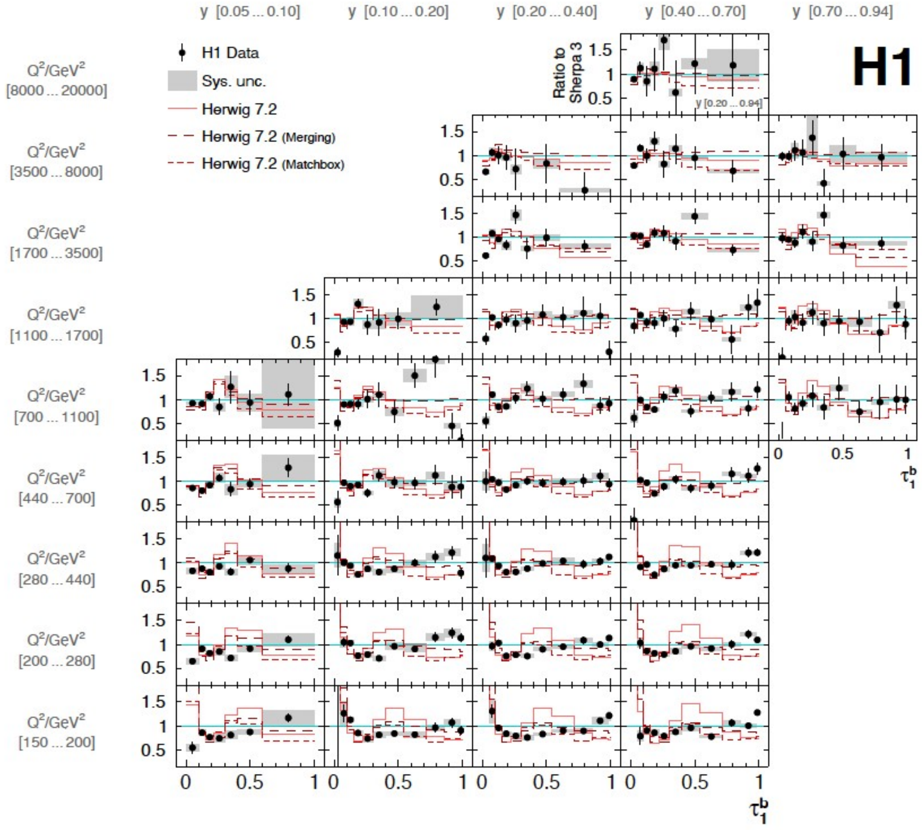
Triple-differential: Ratio to NNLOJET

- Example of triple-differential model comparison: NNLOJET
- Line at unity: Sherpa 3
- Dots: ratio of Data/Sherpa3
- Orange band: ration NNLOJET/Sherpa3
- Overall good description, however prediction is not available at low τ_1^b
- In large parts of the phase space, the data are more precise than the theory within scale uncertainties



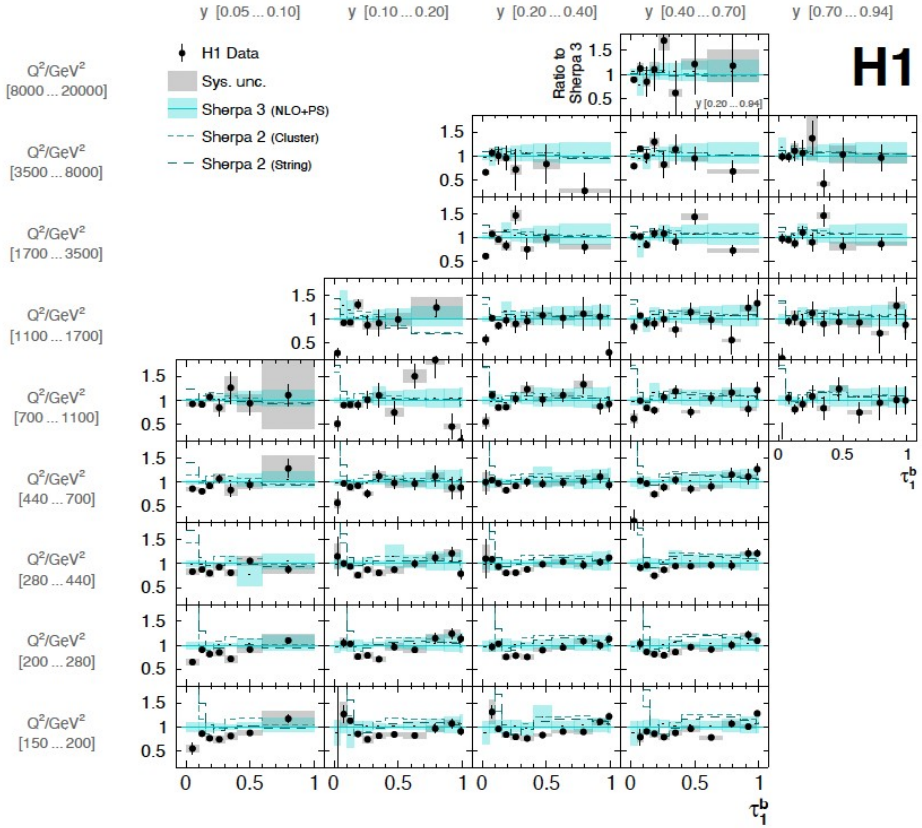
Triple-differential: Ratio to HERWIG7.2

- Example of triple-differential model comparison: NNLOJET
- Line at unity: Sherpa 3
- Dots: ratio of Data/Sherpa3
- Red lines: ratio HERWIG7.2/Sherpa3
- Test: default, mering, matchbox
- In most cases, merging and matchbos are superior to plain HERWIG, but there is room for improvenet in all cases



Triple-differential: Ratio to SHERPA

- Example of triple-differential model comparison: NNLOJET
- Line at unity: Sherpa 3
- Dots: ratio of Data/Sherpa3
- Blue band: Sherpa3 NLO+PS with scale uncertainty
- Dashed lines: Sherpa 2 variants
- Overall very reasonable description
- Sherpa 3 is superior to Sherpa 2



Inclusive cross sections in (Q^2,y)

- By integrating cross sections over τ_1^b one obtains double-differential cross sections measured in (Q^2,y)
- These complement traditional double-differential measurements of structure functions
  - Structure functions: good for fits of analytics predictions
  - Cross sections measured in bins: good for confronting MC predictions