Recent ~~HERA~~ H1 Measurements

(restricted to measurements relevant for MC tuning)

Measurements by ZEUS are not included, unfortunately there was not enough time to prepare

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on behalf of the H1 collaboration

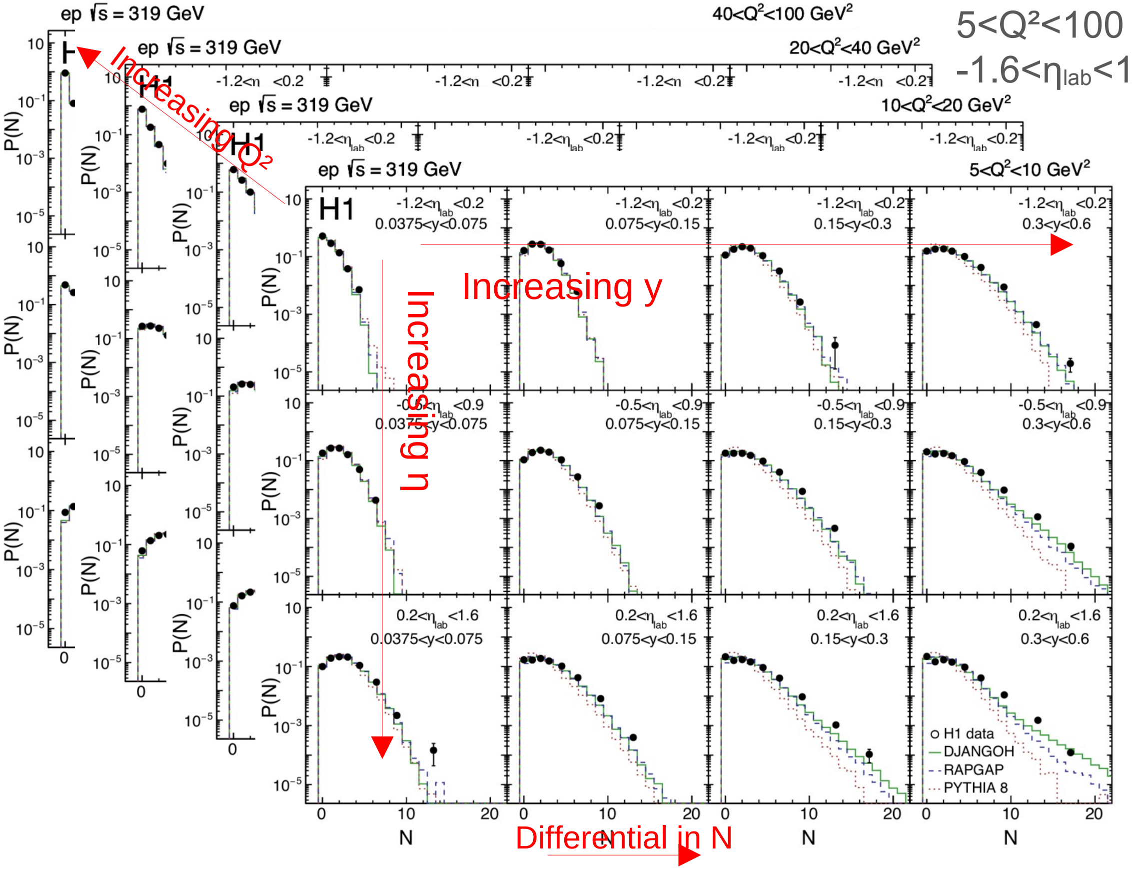
LPCC MCWG Tuning Forum online meeting, March 2026

HERA Collider, Outline of the talk

- HERA collider: operated 1992-2007
- Two collider experiments H1 and ZEUS
- Harvest 0.5fb^{-1} each experiment
- Colliding beams:
  - protons 920 GeV
  - Electrons or positrons 27.6 GeV
  - sqrt(s)=320 GeV
- Kinematic variables
  - Momentum transfer Q^2
    - Low Q^2: $5<Q^2<100$ GeV^2
    - High Q^2: $150<Q^2<10000$ GeV^2
  - Inelasticity y
  - Bjorken x: $Q^2=s\ x\ y$

- Papers discussed in this talk
  - Particle multiplicities
  - 1-jettiness event shape, empty hemisphere events
  - Groomed event shapes
  - Jet substructure
  - Lepton-jet azimuthal correlation
  - Outlook: unbinned unfolding of all particles

Charged particle multiplicity distributions in DIS



Increasing Q²

Increasing y

Increasing η

Differential in N

$5<Q^2<100$ GeV², $0.0375<y<0.6$
$-1.6<\eta_{lab}<1.6$, $p_T>150$ MeV

EPJC81 (2021) 212

- Charged particle multiplicity P(N) is measured **four-differential**, in:

  Q^2, y, η_{lab}, N ($p_{T,track}$>150 MeV)

- Models have difficulties to describe the data at low Q^2, high y, large η_{lab}
- Main scope of the paper is entropy and entanglement, but the underlying particle multiplicities may of high interest for MC tuning
- There is an older H1 publication on pT spectra Eur.Phys.J.C73 (2013) 2406

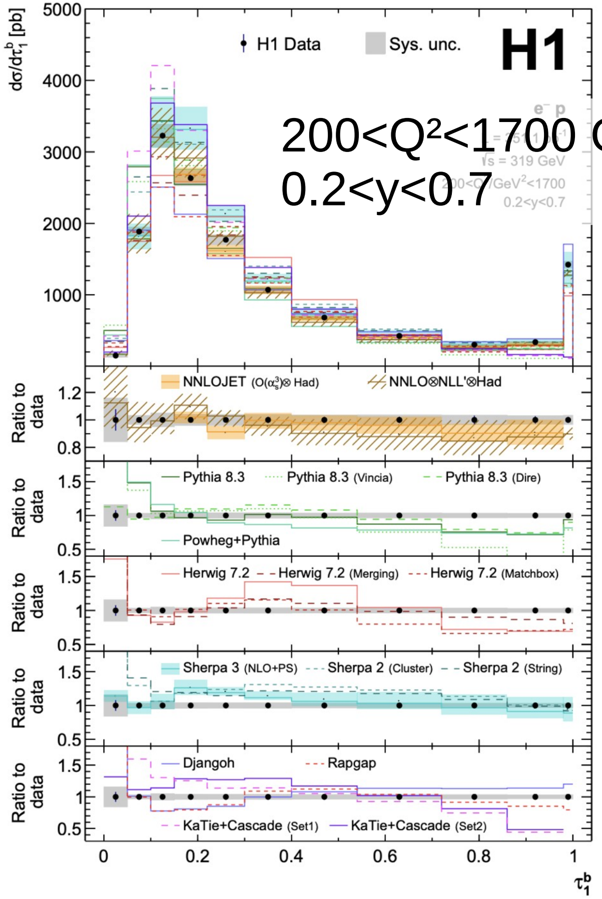
1^{st} measurement of 1-jettiness event shape in DIS ep scattering at HERA

- Observable τ_1^b: equivalent to classical event shape observable thrust normalized with Q/2.

$$\tau_1^b = 1 - 2\cdot\sum_{i\in X}\max\left(0, \frac{q\cdot p_i}{q\cdot q}\right) = 1 - 2\cdot\sum_{i\in\mathcal{H}_C}\frac{q\cdot p_i}{q\cdot q}$$

EPJC84 (2024) 785

- It quantifies how the hadrons are collimated along the exchanged boson direction.
  - Low τ_1^b: fragmentation of a single jet
  - High τ_1^b: hard QCD radiation, multiple jets
- Triple-differential cross section is measured in:
  τ_1^b, Q^2, y
- Shown here: 1-differential measurement in τ_1^b



200<Q²<1700 GeV²
0.2<y<0.7

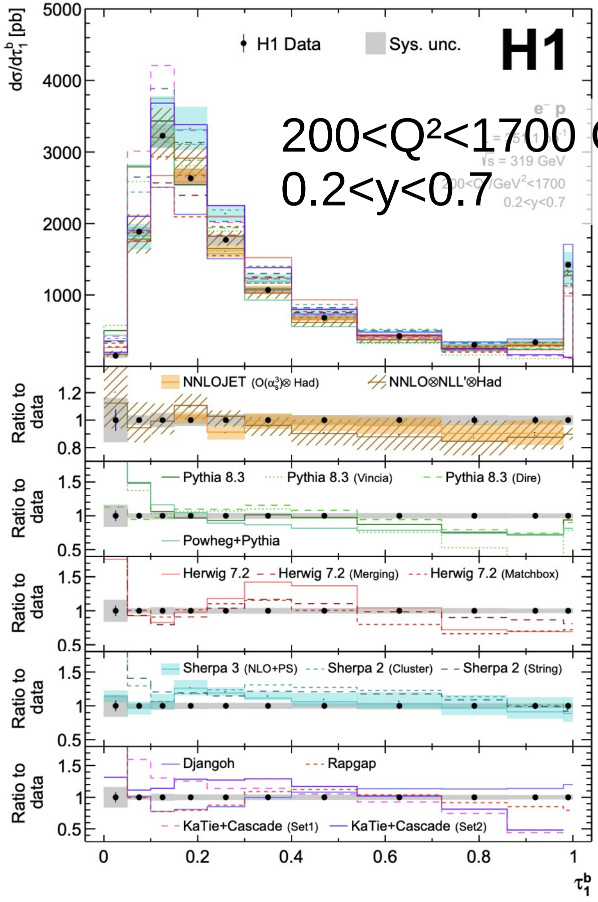
1st measurement of 1-jettiness event shape in DIS ep scattering at HERA

- Observable τ_1^b: equivalent to classical event shape observable thrust normalized with Q/2.

$$\tau_1^b = 1 - 2\cdot\sum_{i\in X}\max\left(0,\frac{q\cdot p_i}{q\cdot q}\right) = 1 - 2\cdot\sum_{i\in\mathcal{H}_\mathcal{C}}\frac{q\cdot p_i}{q\cdot q}$$

EPJC84 (2024) 785

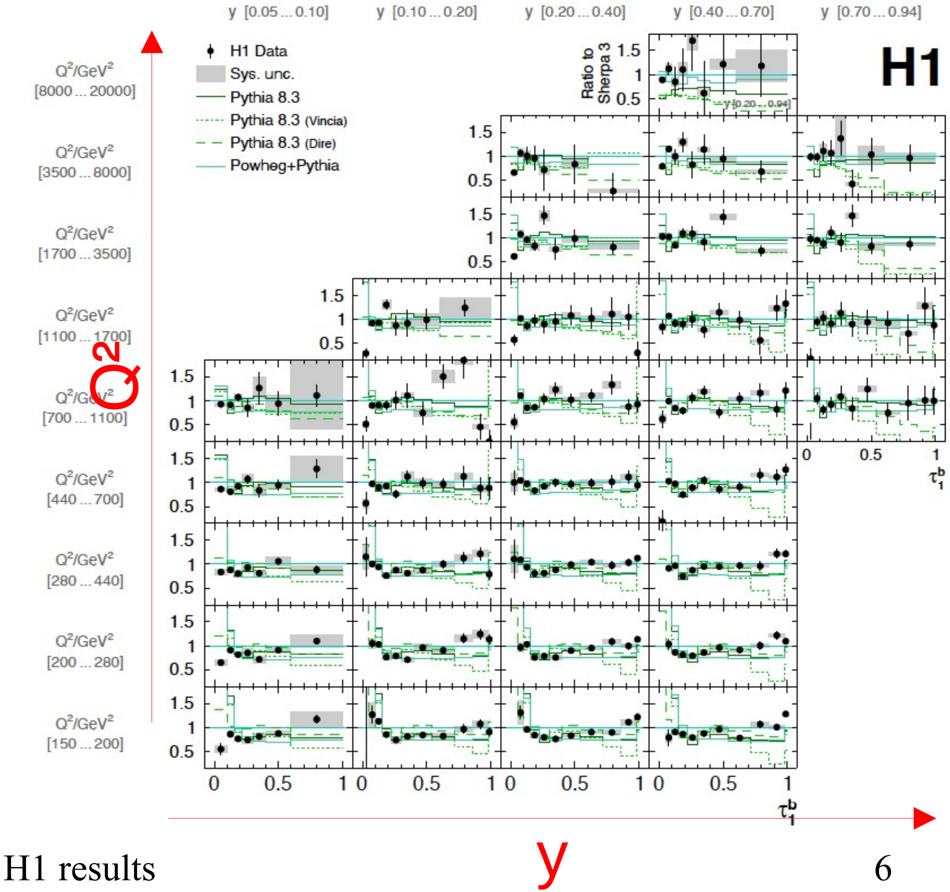
- Models have difficulties to describe all aspects of the measurement.
- Peak in the data at τ_1^b=1 corresponds to events with empty hemisphere — measured in a dedicated H1 paper EPJC84 (2024), 720 (backup slides)
- Comparison is most illusive for triple-differential measurement



200<Q²<1700 GeV²
0.2<y<0.7

Triple-differential: Ratio to models

- 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 also available

Measurement of groomed event shapes

- Groomed 1-jettiness

EPJC84 (2021) 718

$$\tau_1^b = \frac{2}{Q^2} \sum \min\left(p_i \cdot q_B, p_i \cdot q_J\right)$$

$$q_B = xP \quad \text{(incoming parton direction)}$$

$$q_J = xP + q \quad \text{(scattered parton direction)}$$

- Groomed invariant mass (backup)

$$\mathrm{GIM} = \ln\left(\frac{\left(\sum p_i\right)^2}{Q^2_{\mathrm{min}}}\right)$$

The sums Σ run over all particles contained in jets which pass the grooming condition

- Grooming conditions (modified Mass-Drop Tagging algorithm): remove jets and particles failing condition on a distance parameter z_i
- Jet algorithm: Centauro

Phys. Rev. D 104 (2021) 034005, [arXiv:2006.10751]

- Distance parameter:

$$z_i = \frac{P \cdot p_i}{P \cdot q}$$

Grooming condition:

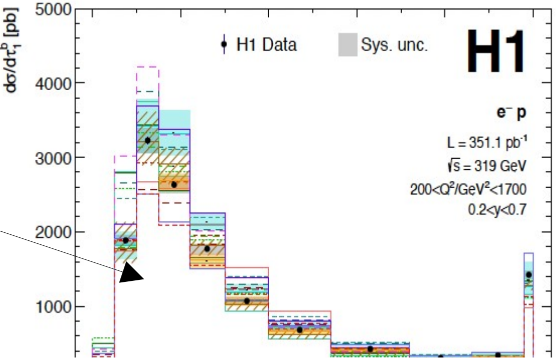
$$\frac{\min\left(z_i, z_j\right)}{z_i + z_j} > z_{\mathrm{cut}}$$

Grooming conditions investigated

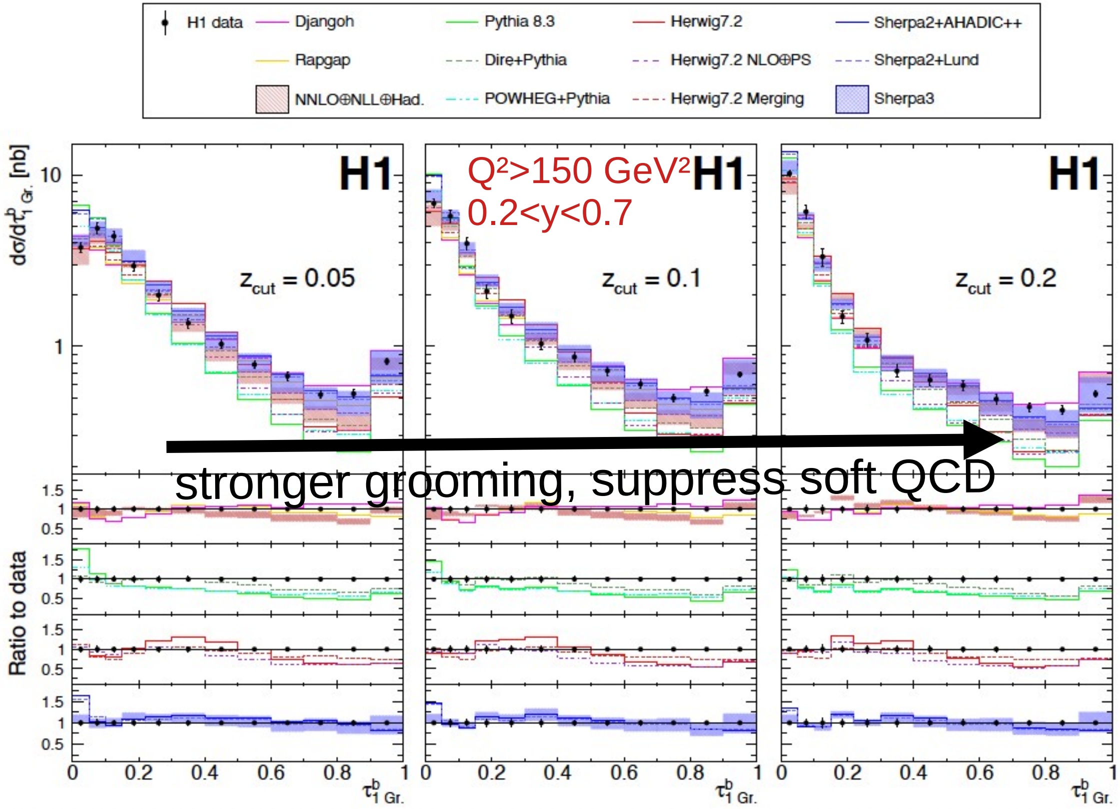
z_{cut}={0.05, 0.1, 0.2}

Results on the groomed 1-jettiness τ_1^b

Measurement of τ_1^b without grooming, similar kinematic selection



Q²>150 GeV²
0.2<y<0.7

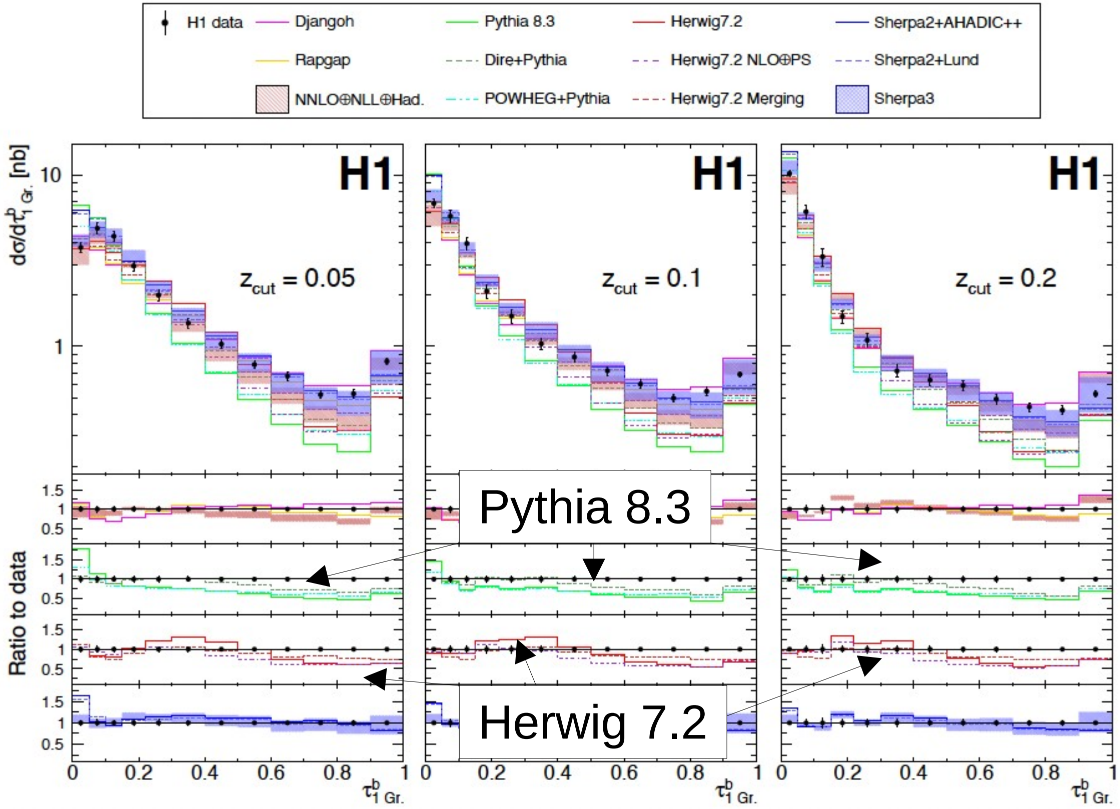


stronger grooming, suppress soft QCD

- Stronger grooming: large shape change near τ_1^b~0.15, corresponding to single-jet events+fragmentation (i.e. soft QCD)
- The pQCD regime τ_1^b>0.2 changes less in shape with changing z_{cut}

Comparison of groomed τ_1^b to models

- Sherpa does very well
- Pythia 8.3 and Herwig 7.2: fail to describe the groomed τ_1^b within the data accuracy
  - Pythia 8.3 fails at small τ_1^b and is low at large τ_1^b
  - Herwig 7.2 is above the data at medium τ_1^b and below at large τ_1^b



Backup: double-differential measurements as a function of Q².
→ can use 2D measurements for tuning

Measurement of jet substructure in DIS

PLB844 (2023) 138101

- Jet substructure: generalized angular moments

$$\lambda_\beta^\kappa = \sum_{i \in \mathrm{jet}} z_i^\kappa \left(\frac{R_i}{R_0} \right)^\beta$$

Phase-space:
Q²>150 0.2<y<0.7

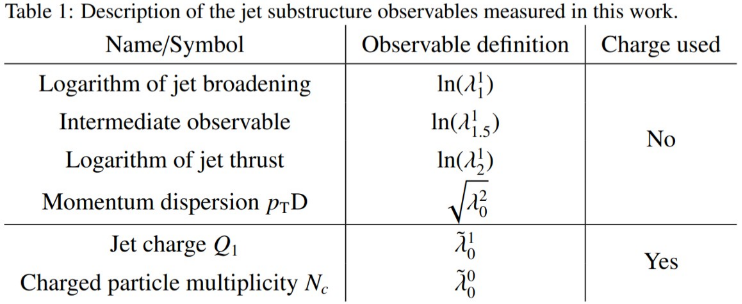
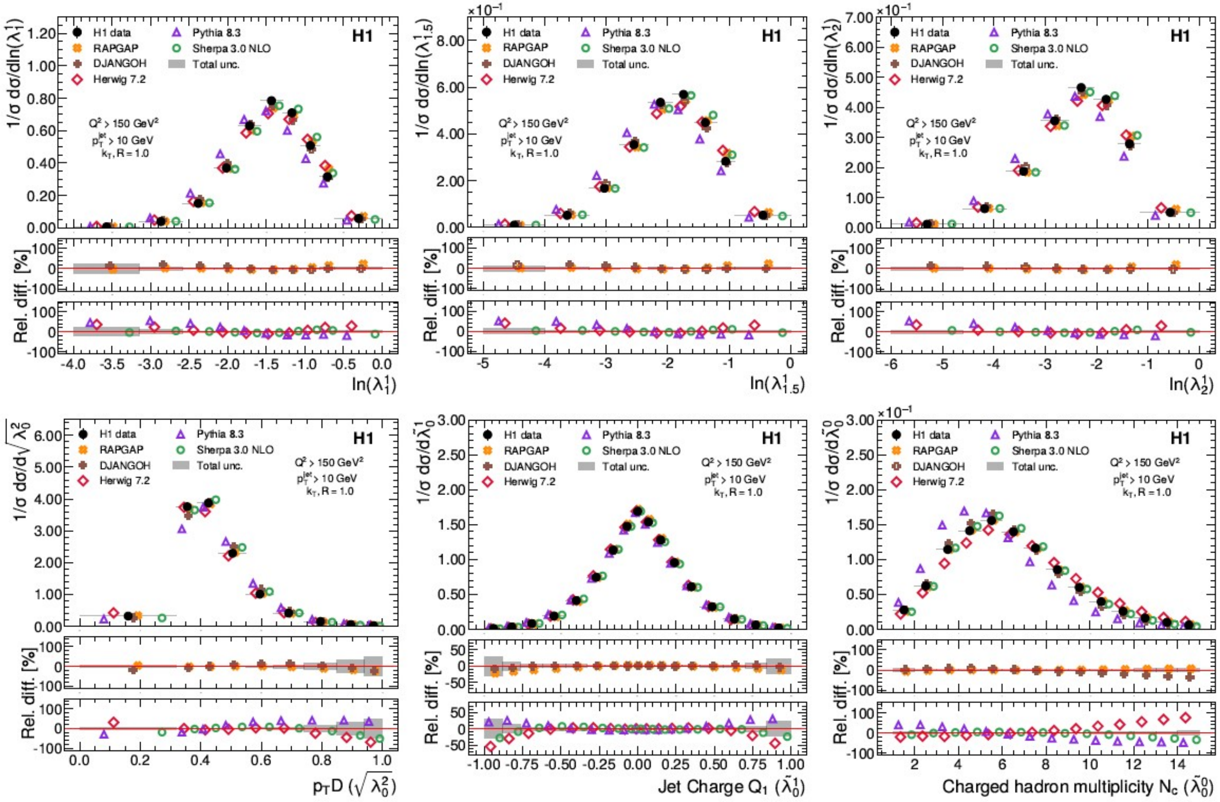


Table 1: Description of the jet substructure observables measured in this work.

Name/Symbol	Observable definition	Charge used
Logarithm of jet broadening	$\ln(\lambda_1^1)$	No
Intermediate observable	$\ln(\lambda_{1.5}^1)$	
Logarithm of jet thrust	$\ln(\lambda_2^1)$	
Momentum dispersion p_{T}D	$\sqrt{\lambda_0^2}$	
Jet charge Q_1	$\tilde{\lambda}_0^1$	Yes
Charged particle multiplicity N_c	$\tilde{\lambda}_0^0$	

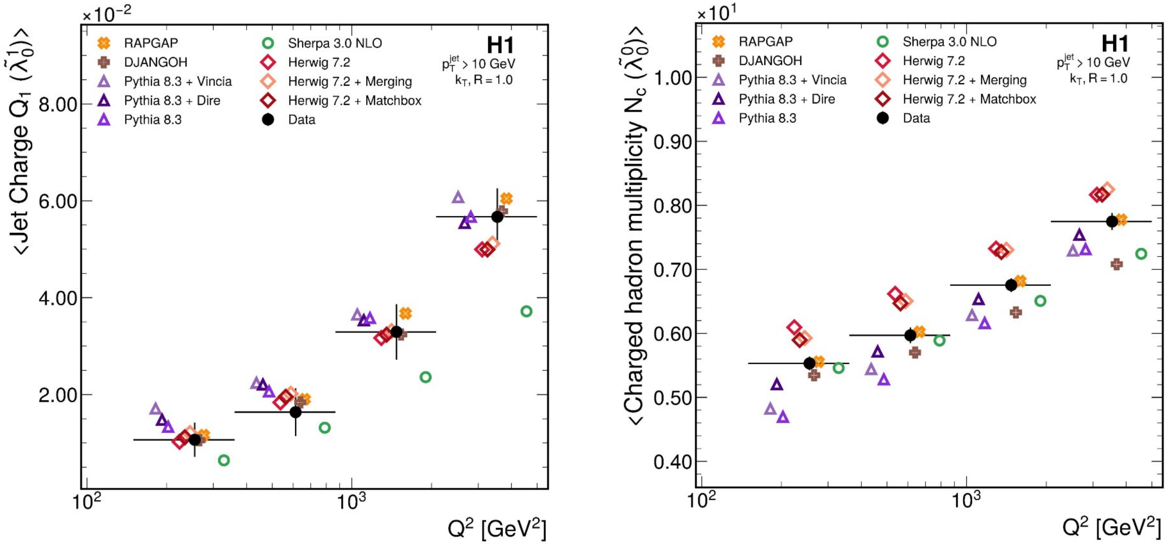
Comparisons to models: definitely there is room for improvements



Jet substructure: extraction of moments

PLB844 (2023) 138101

- Shown here: first moment as a function of Q^2 for jet charge and charged particle multiplicity
- Sizable difference to Models → room for tuning
- Extraction of first moments is free of binning effects due to the unbinned unfolding

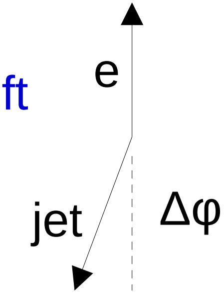


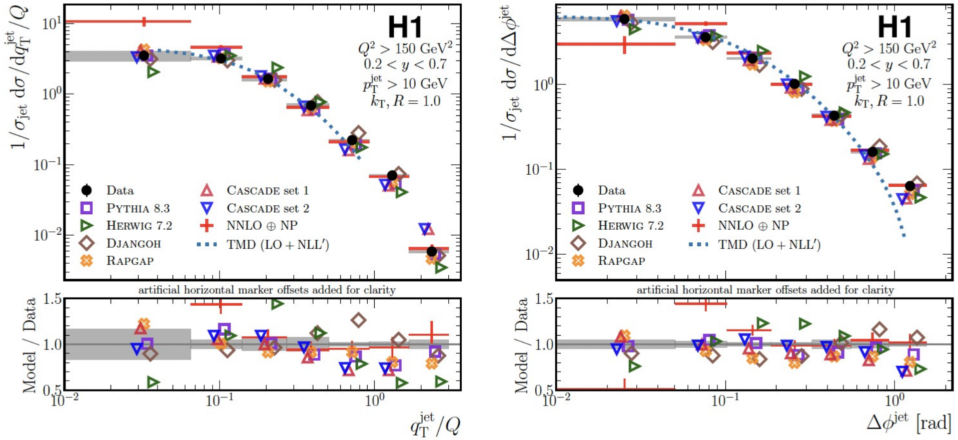
Orther substructure variables: see paper

Lepton-jet azimuthal correlation

- Size of lepton-jet azimuthal (de-)correlation is sensitive to soft gluon radiation and intrinsic pT

PRL 128 (2022), 132002

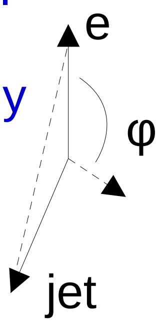


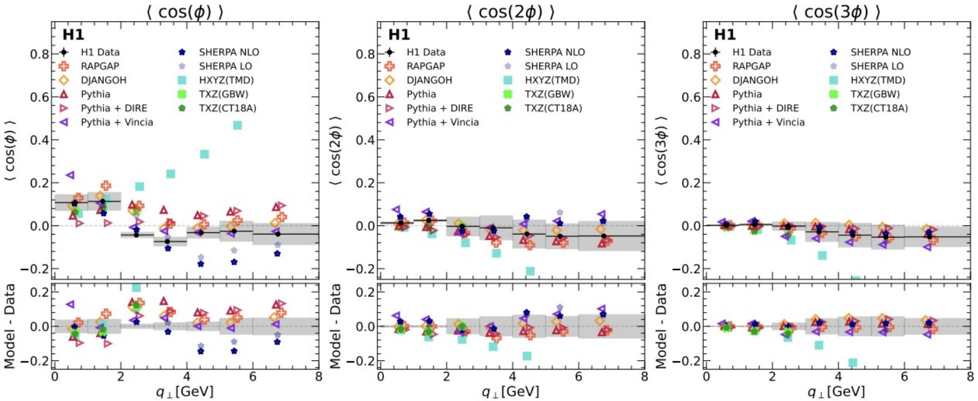


- Azimuthal direction of the momentum difference (moments of “azimuthal asymmetry”) is less sensitive to intrinsic pT – complementary study

arXiv:2412.14092

Moments of azimuthal difference between momentum sum and momentum difference

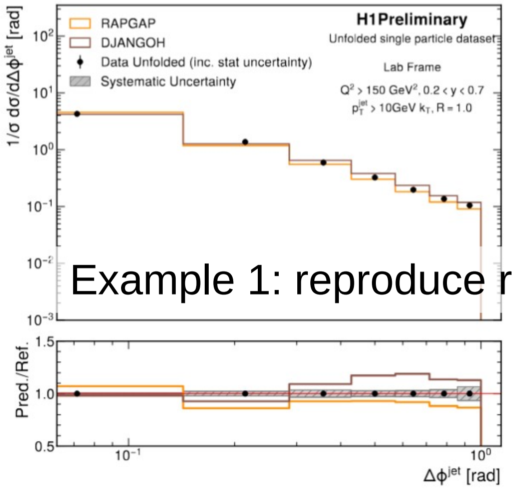


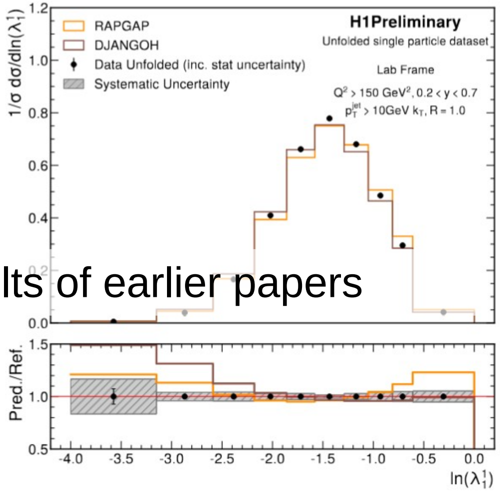


Outlook: unfolding of all particles

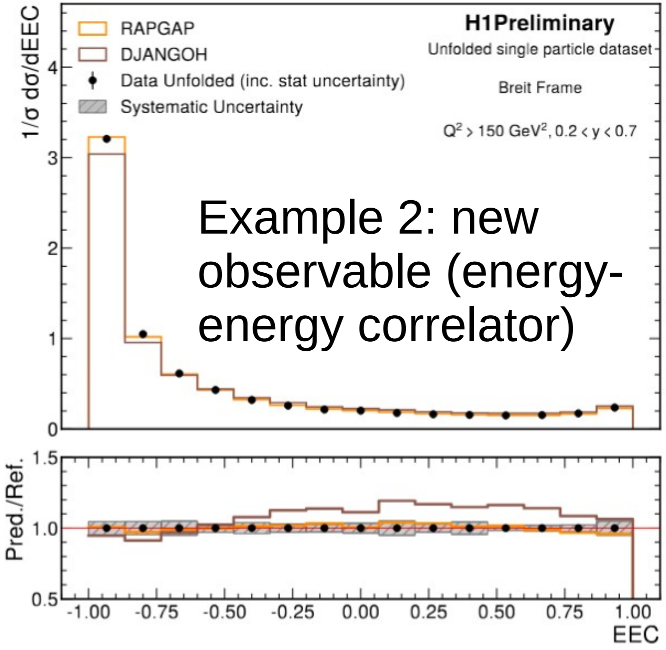
- Idea to unfold all particles of the final state using Omnifold
- User can decide which variables to study
- Flexible jet algorithm, no predefined binning, etc
- Preliminary results show that this goal is in reach

H1prelim-25-031





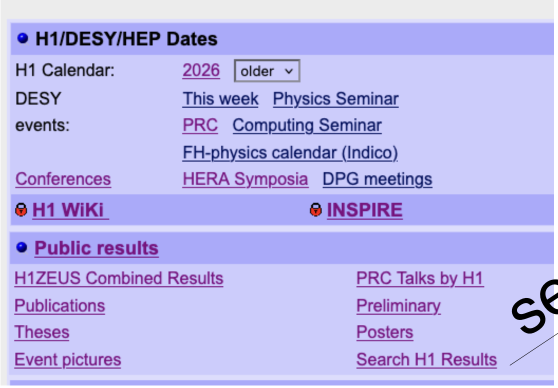
Example 1: reproduce results of earlier papers



Example 2: new observable (energy-energy correlator)

More H1 results

- Have a look at the H1 list of papers – also searchable by physics topics
  http://www-h1.desy.de/



H1/DESY/HEP Dates

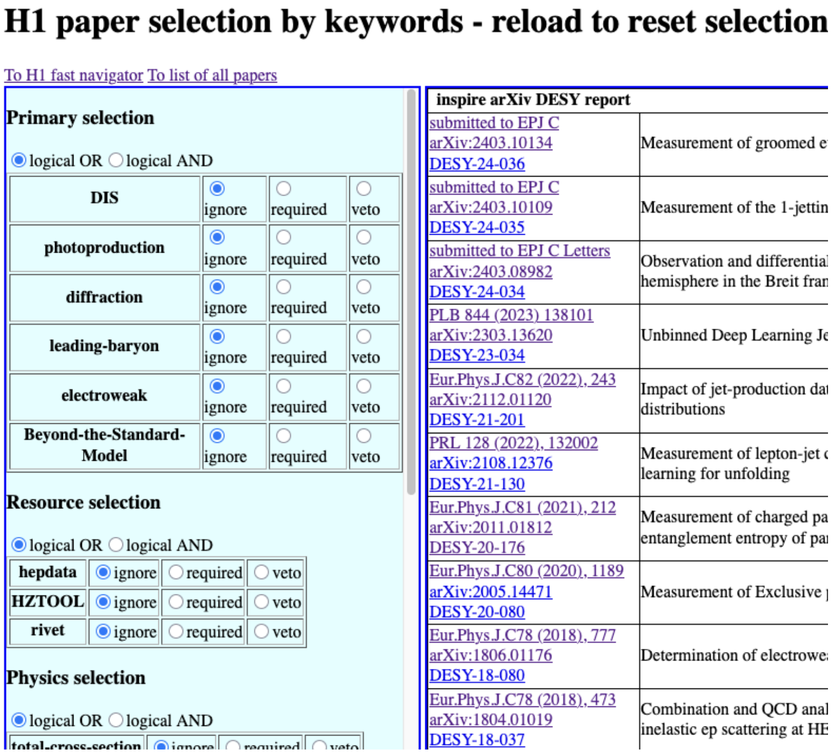
H1 Calendar:	2026 older
DESY events:	This week Physics Seminar PRC Computing Seminar FH-physics calendar (Indico)
Conferences	HERA Symposia DPG meetings

H1 WiKi **INSPIRE**

Public results

H1ZEUS Combined Results	PRC Talks by H1
Publications	Preliminary
Theses	Posters
Event pictures	Search H1 Results

search by topic



H1 paper selection by keywords - reload to reset selection

To H1 fast navigator To list of all papers

Primary selection

● logical OR ○ logical AND

DIS	● ignore	○ required	○ veto
photoproduction	● ignore	○ required	○ veto
diffraction	● ignore	○ required	○ veto
leading-baryon	● ignore	○ required	○ veto
electroweak	● ignore	○ required	○ veto
Beyond-the-Standard-Model	● ignore	○ required	○ veto

Resource selection

● logical OR ○ logical AND

hepdata	● ignore	○ required	○ veto
HZTOOL	● ignore	○ required	○ veto
rivet	● ignore	○ required	○ veto

Physics selection

● logical OR ○ logical AND

total-cross-section	● ignore	○ required	○ veto

inspire arXiv DESY report	
submitted to EPJ C arXiv:2403.10134 DESY-24-036	Measurement of groomed e
submitted to EPJ C arXiv:2403.10109 DESY-24-035	Measurement of the 1-jettin
submitted to EPJ C Letters arXiv:2403.08982 DESY-24-034	Observation and differential hemisphere in the Breit fran
PLB 844 (2023) 138101 arXiv:2303.13620 DESY-23-034	Unbinned Deep Learning Je
Eur.Phys.J.C82 (2022), 243 arXiv:2112.01120 DESY-21-201	Impact of jet-production dat distributions
PRL 128 (2022), 132002 arXiv:2108.12376 DESY-21-130	Measurement of lepton-jet c learning for unfolding
Eur.Phys.J.C81 (2021), 212 arXiv:2011.01812 DESY-20-176	Measurement of charged pa entanglement entropy of pai
Eur.Phys.J.C80 (2020), 1189 arXiv:2005.14471 DESY-20-080	Measurement of Exclusive
Eur.Phys.J.C78 (2018), 777 arXiv:1806.01176 DESY-18-080	Determination of electrowea
Eur.Phys.J.C78 (2018), 473 arXiv:1804.01019 DESY-18-037	Combination and QCD anal inelastic ep scattering at HE

A request to the community

- Classical HERA generators, used for data unfolding and QED corrections:
  - “Leading-order” QCD, including boson-gluon-fusion for scattering off gluons in the proton
  - RAPGAP (leading-log) and DJANGOH (color-dipole) for parton showers, both generators include HERACLES for LO QED+EW effects

- For HERA analyses, QED radiative and EW corrections are of high importance
- All results shown here are “corrected” for radiative effects.
- We are missing state-of-the-art generators with both
  - NLO QCD+PS and
  - Full QED+EW

Summary

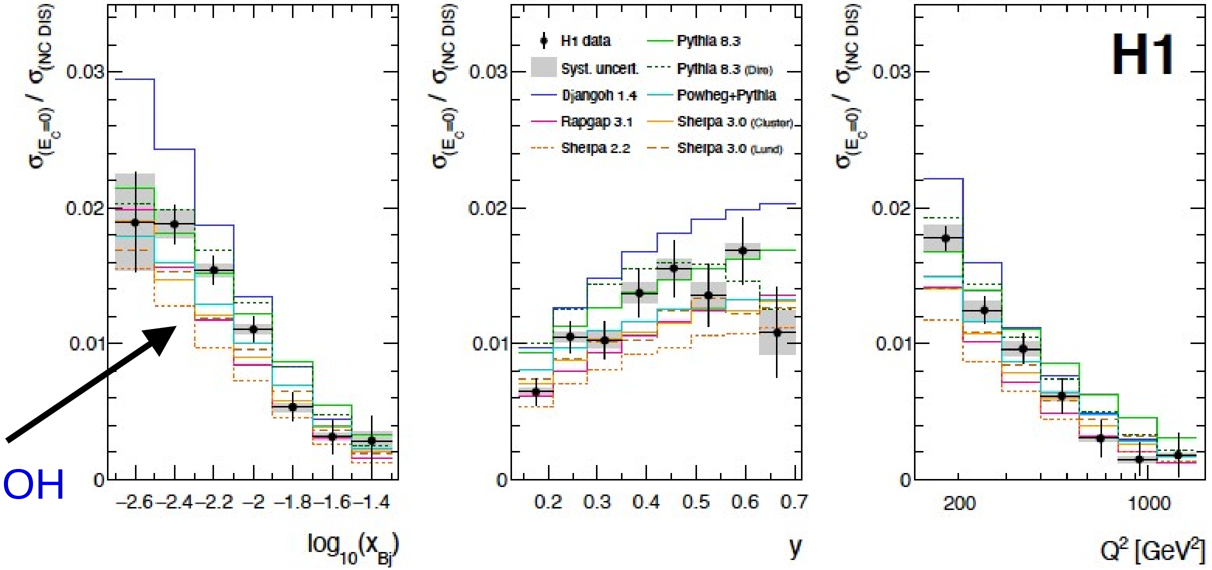
- Surprising enough, HERA experiments produce new results ~20 years after end of data taking
- Can use modern techniques (unfolding) and new observables (1-jettiness, grooming) not available at the time of operation
- Availability of H1 data on HEPdata/RIVET often is delayed – limited personpower
  - Best is to contact the H1 managements and set priorities with urgent requests on HEPDATA and RIVET

Backup

Kinematic properties of EH events

EPJC84 (2024) 720

- The rate of empty hemisphere events is measured at the particle level
- Measurement phase space $150 < Q^2 < 1500$ GeV², $0.14 < y < 0.7$
- 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: $r = 0.0112 \pm 3.9\,\%_{\text{stat}} \pm 4.5\,\%_{\text{syst}} \pm 1.6\,\%_{\text{mod}}$

The Centauro jet algorithm

- Study final state in DIS: Breit Frame (BF)

  Incoming photon: (0;0,0,-Q/2)

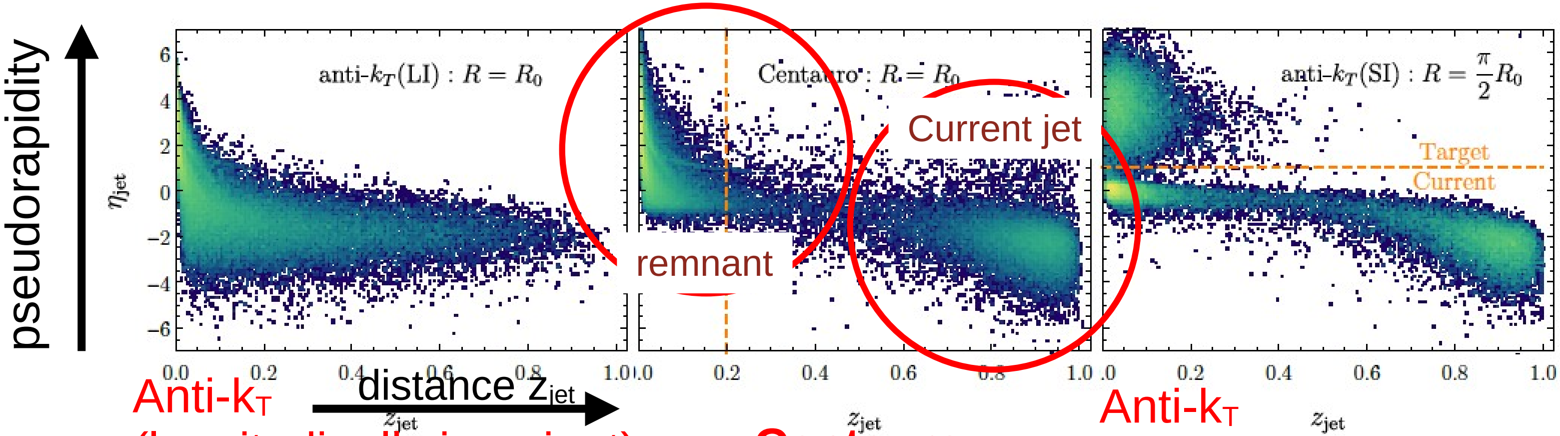
  Incoming proton: ($Q/2x_{Bj}$;0,0,+$Q/2x_{Bj}$)

  Scattered parton: (Q/2;0,0,-Q/2)

- At leading order, no P_T in the BF:

  → k_T type jet algorithms not optimal

- **Centauro**: hybrid of longitudinally- and spherically-invariant jet algorithms



Anti-k_T (longitudinally invariant)

Centauro

Anti-k_T (spherically-invariant)

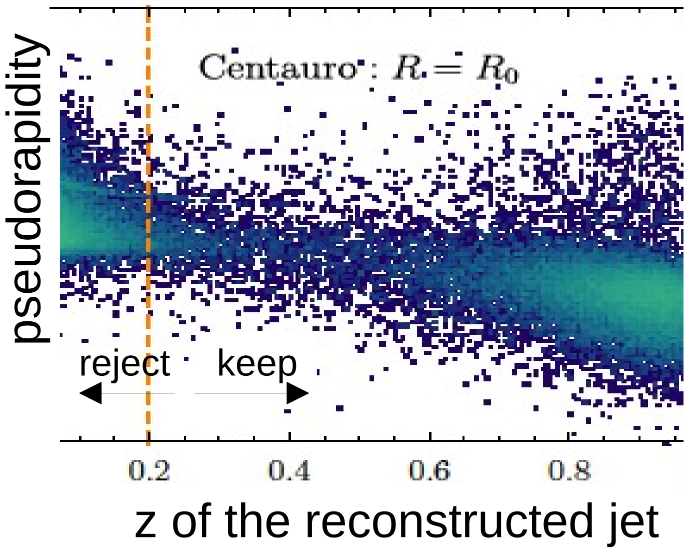
Asymmetric jet clustering in deep-inelastic scattering

M. Arratia, Y. Makris, D. Neill, F. Ringer, N. Sato

Phys. Rev. D 104 (2021) 034005, [arXiv:2006.10751]

Grooming techniques

- Grooming: suppress particles attributed to soft QCD processes
  - Widely used in pp to reconstruct jet final states
  - This analysis: test grooming in ep events
  - Grooming procedure (modified Mass-Drop Tagging algorithm): remove jets and particles failing condition on a distance parameter z_i



P : incoming proton
q : virtual photon
p_i : particle or jet

$$z_i = \frac{P \cdot p_i}{P \cdot q}$$

Grooming condition:

$$\frac{\min(z_i, z_j)}{z_i + z_j} > z_{\mathrm{cut}}$$

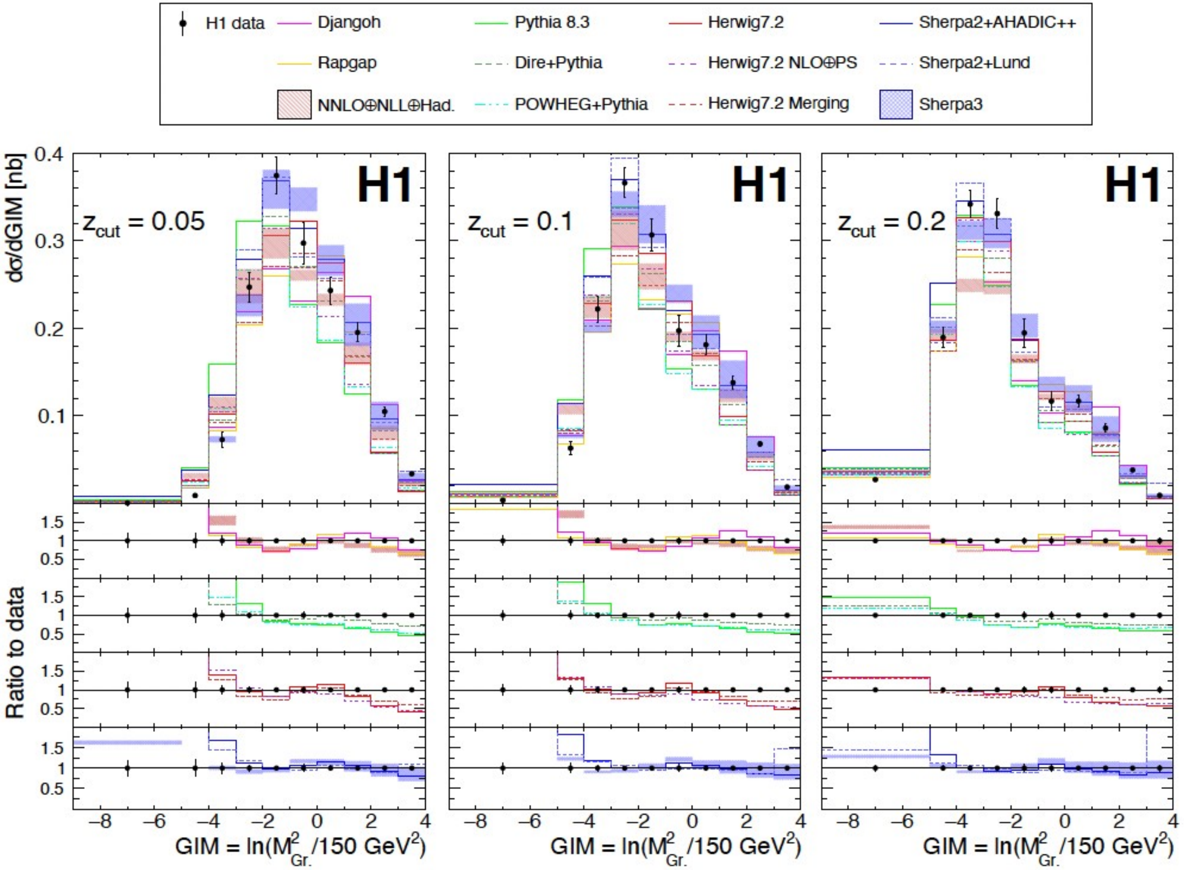
reject “soft” particles/jets with $z<z_{\mathrm{cut}}$

Example result from Centauro paper: Suppress proton remnant for z>0.2

Phys. Rev. D 104 (2021) 034005, [arXiv:2006.10751]

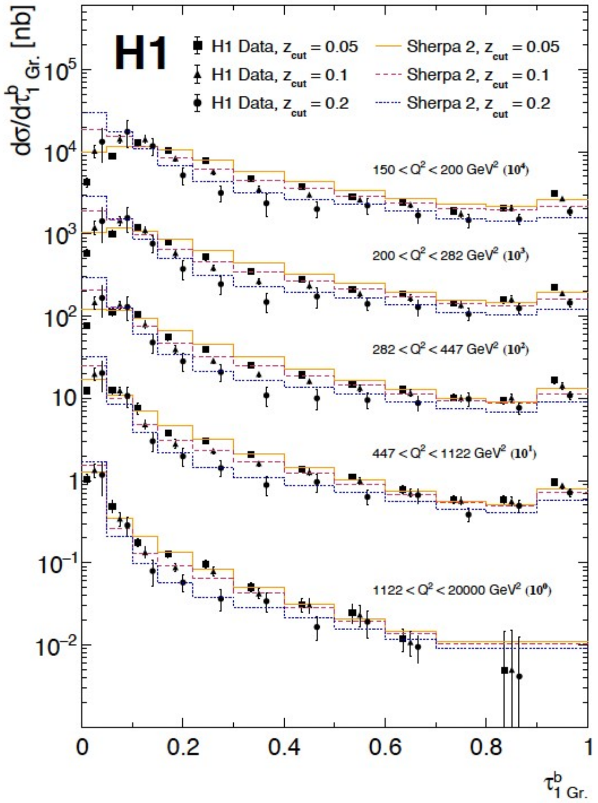
Groomed invariant mass GIM

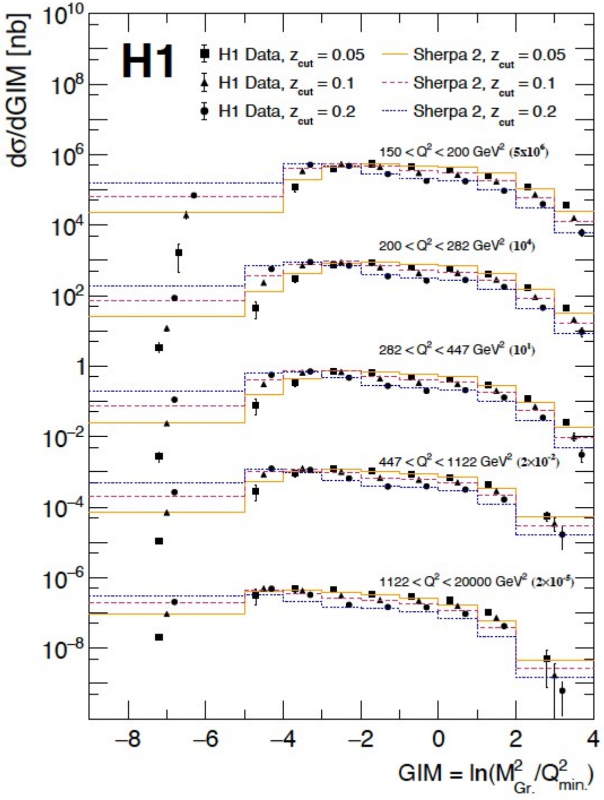
- Small GIM: single, collimated jet
- Large GIM: multijet events
- None of the model is able to describe the first two bins
- Reasonable description by models for larger GIM, and improving with increasing z_{cut}
- Similar to large τ_1^b, Pythia and Herwig have difficulties to describe the region of large GIM



Double-differential measurements

- Measurements are repeated double-differentially in Q^2 and the groomed event shapes, each for three choices of z_{cut}
- Very detailed comparisons to models are possible using these data → tune your MC
- For example: double-differential comparison to Sherpa3 shows that the description at small τ_1^b is difficult but improves significantly with increasing Q^2 and increasing z_{cut}



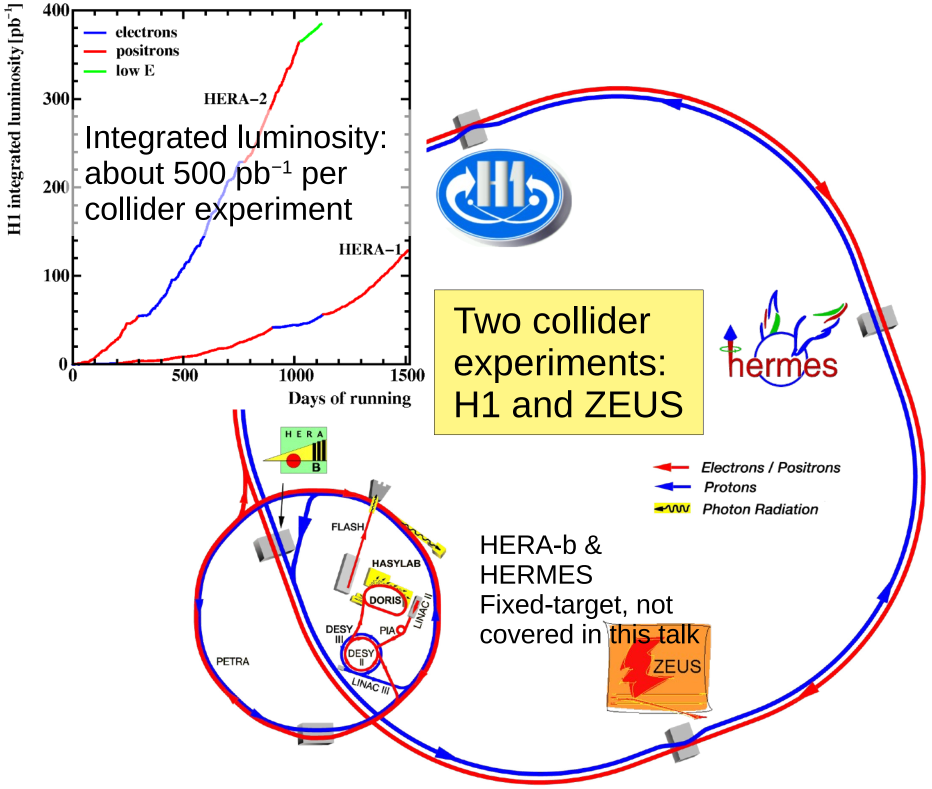


The HERA ep collider

- 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}


Straight section


Curved section



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

Two collider experiments: H1 and ZEUS

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

The H1 Experiment

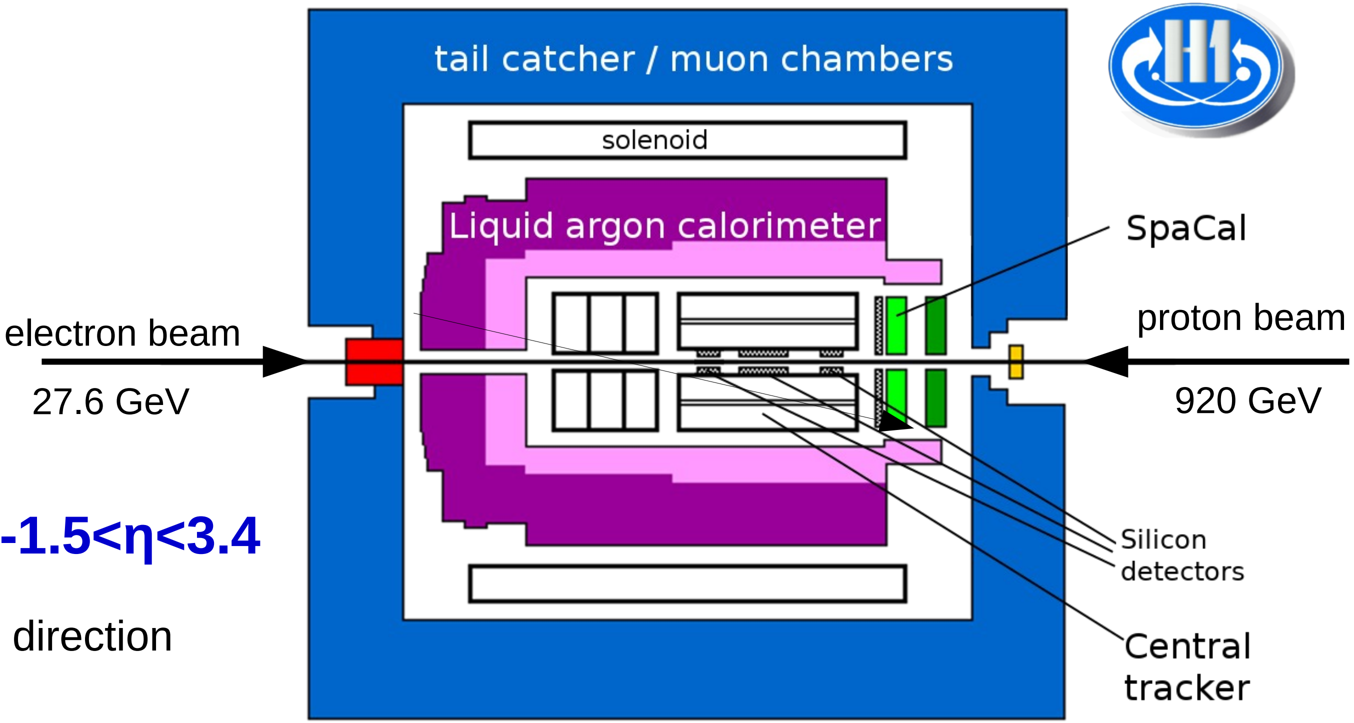
Asymmetric detector
Centre-of-mass system is boosted to proton-direction
E_e=27.6 GeV, E_p=920 GeV

Drift-chamber: main tracking device

15°<θ<165°

Liquid Argon calorimeter
$\sigma_{had}=0.5/\sqrt{E}$, $\sigma_{EM}=0.11/\sqrt{E}$, $-1.5<\eta<3.4$

Lead+fiber in backward (electron) direction
[SpaCal] $\sigma_{EM}=0.07/\sqrt{E}$, $-4<\eta<-1.4$



Deep-inelastic scattering at HERA

- Neutral Current DIS

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

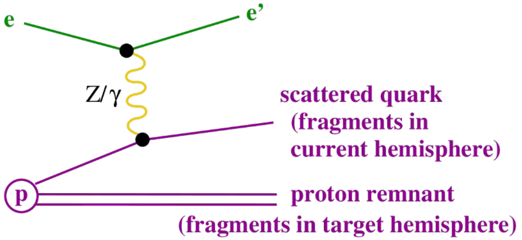
Inelasticity: $y = \frac{qp}{ep}$

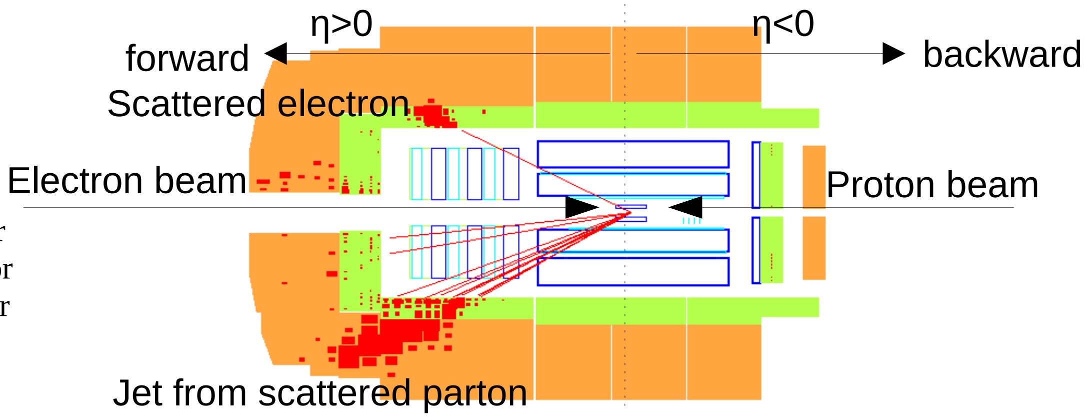
e: incoming lepton 4-vector
p: incoming proton 4-vector
e': scattered lepton 4-vector

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

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

- Leading order picture





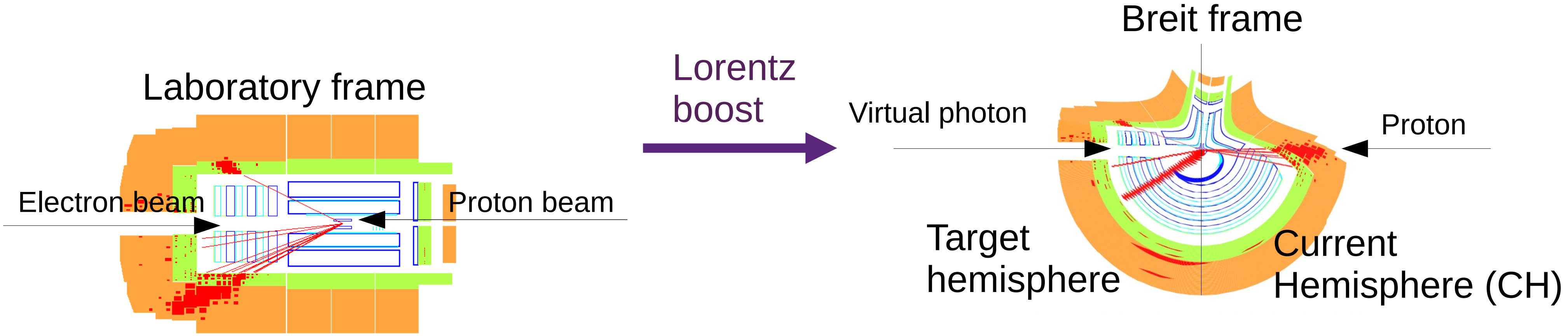
Event at high Q^2>150 GeV^2

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

The Breit frame (BF)

- proton along +z axis
- virtual photon along -z axis with energy=0
- in LO, the quark is scattered along the -z axis of the BF

- Current hemisphere: particles with $p_z<0$ in BF (scattered parton, full acceptance)
- Target hemisphere: particles with $p_z>0$ (proton remnants, limited acceptance)



Laboratory frame

Electron beam

Proton beam

Lorentz boost

Breit frame

Virtual photon

Proton

Target hemisphere

Current Hemisphere (CH)