Measurement of Groomed Event Shapes

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
- Definition of the Breit Frame
- The Centauro jet algorithm
- Event shapes studied: 1-jettiness and groomed invariant mass
- Comparison to MC predictions and analytic predictions

→not discussed in detail, see H1 talk earlier in this session

The new H1 results presented here are published in:

Eur.Phys.J.C84 (2024), 718 [arxiv:2403.10134]

The Centauro jet algorithm

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

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

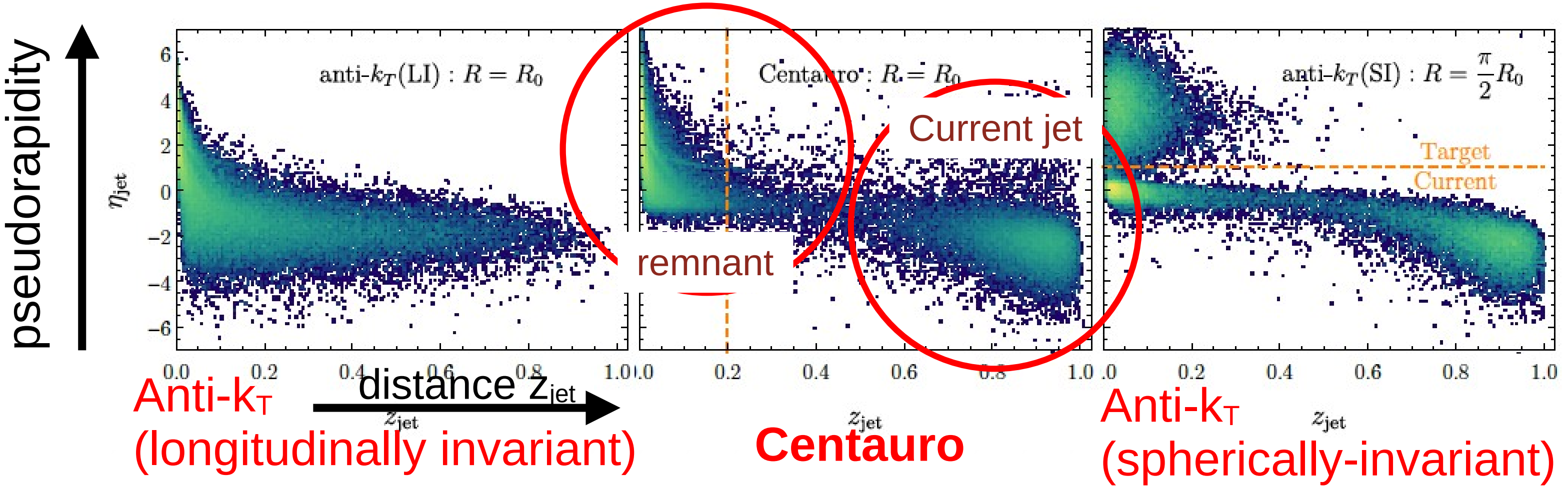
  Incoming proton: ($Q/2x_{Bj}$;0,0,+$Q/2x_{Bj}$)

  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



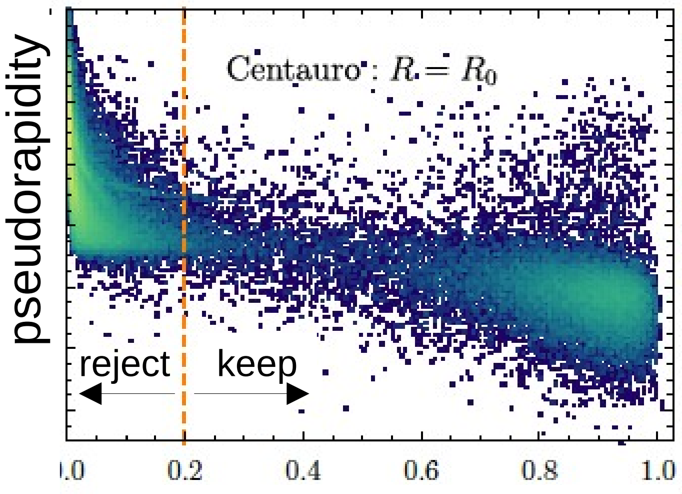
Asymmetric jet clustering in deep-inelastic scattering

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



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

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

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

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

Grooming condition:

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

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

Groomed event shapes studied here

- Groomed 1-jettiness
  - 1-jettiness is designed to measure properties of the current hemishpere
  - Particles are projected onto the direction of either the incoming or the scattered parton
  - Expect to have only moderate effects from grooming in the regime of pQCD

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

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

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

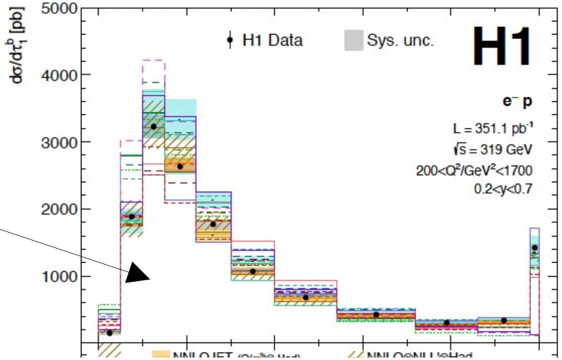
- Groomed invariant mass
  - Invariant mass collects all particles
  - Without grooming, this is very sensitive to acceptance limitations and proton remnants

    → not usable without grooming
  - Expect to see large effects from grooming

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

Results on the groomed 1-jettiness τ_1^b

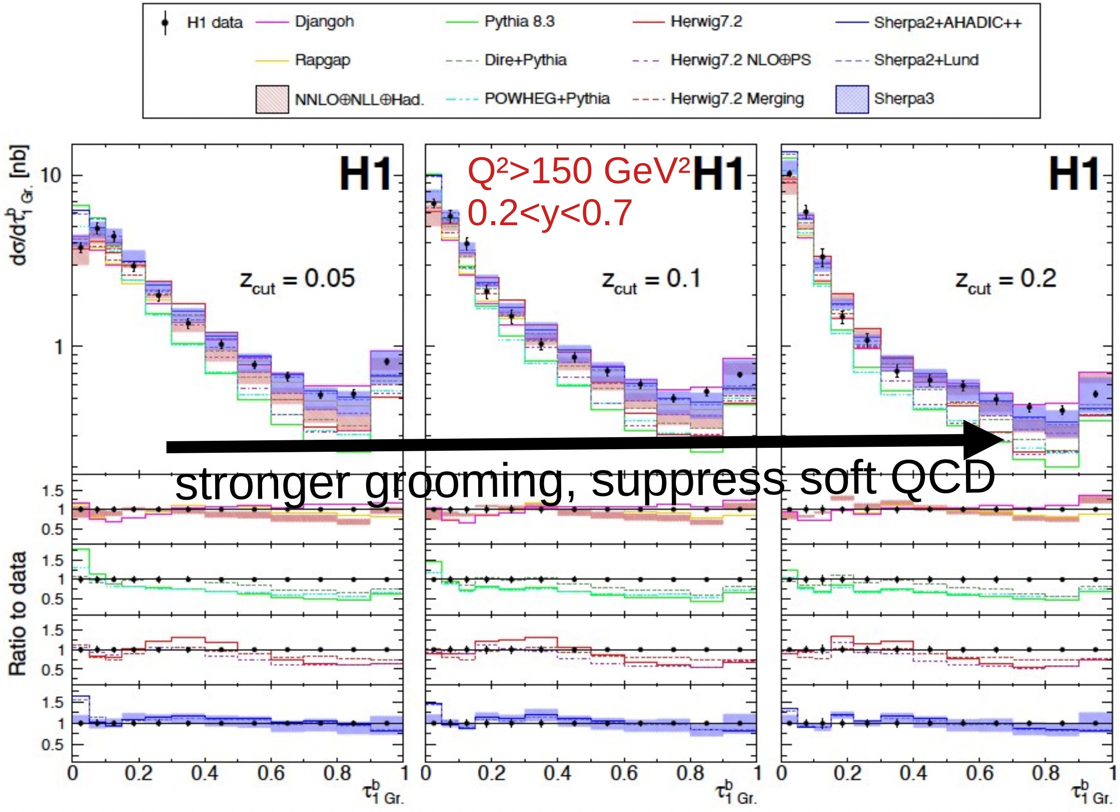
Measurement of τ_1^b without grooming, similar kinematic selection



- Study three grooming conditions:

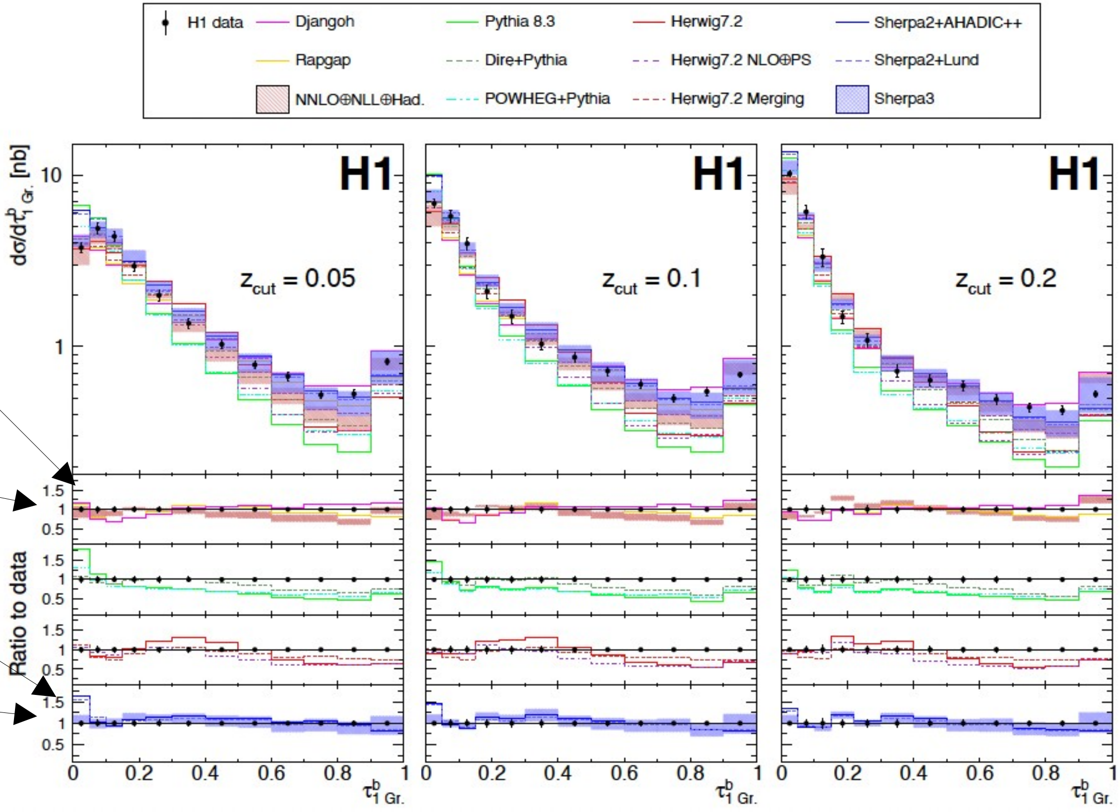
  z_{cut}={0.05, 0.1, 0.2}

- 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}



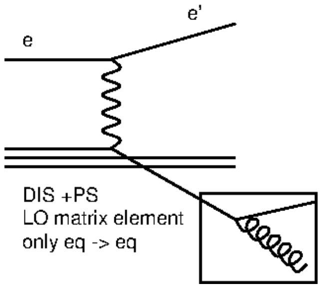
Comparison of groomed τ_1^b to models (1)

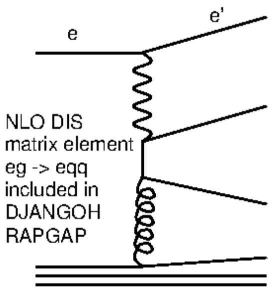
- NLLO+NLL+Had prediction is performing very well
- “Traditional” HERA MC generators RAPGAP and DJANGOH do a reasonable job
- Sherpa 3 performs very well
- Sherpa 2 fails only in the very first bin



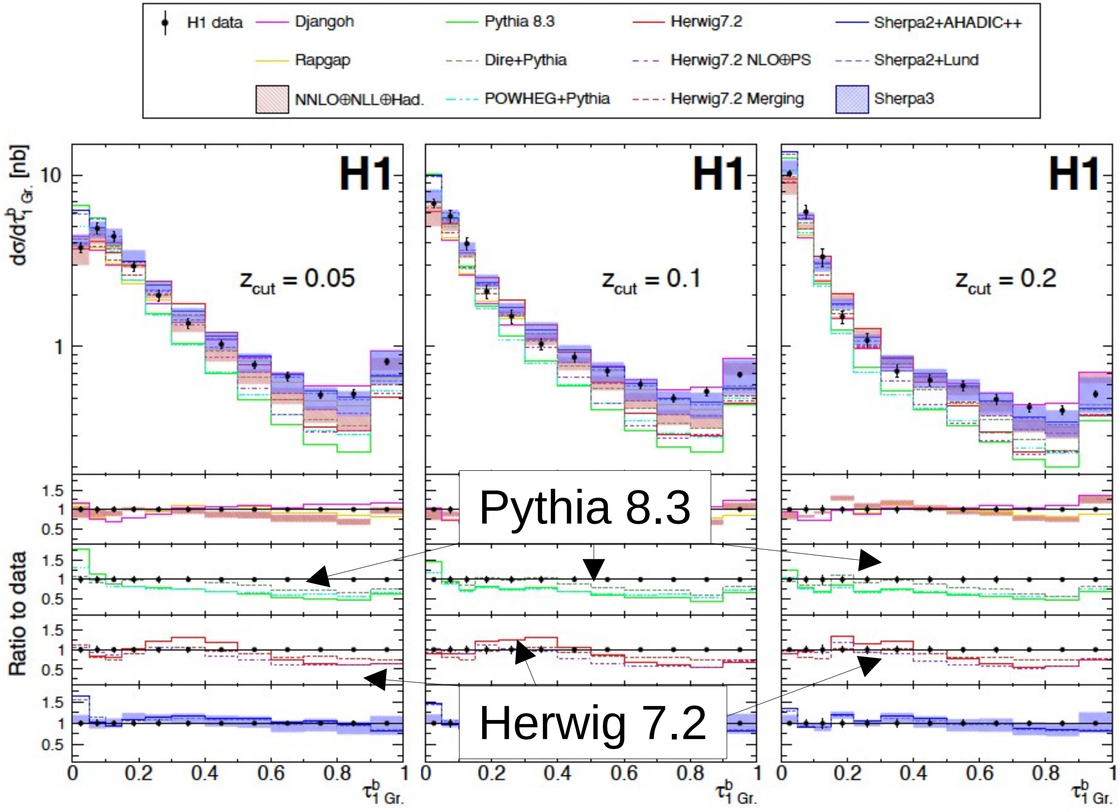
Comparison of groomed τ_1^b to models (2)

- 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
- Does the poor description at high τ_1^b have a common cause for Pythia & Herwig?



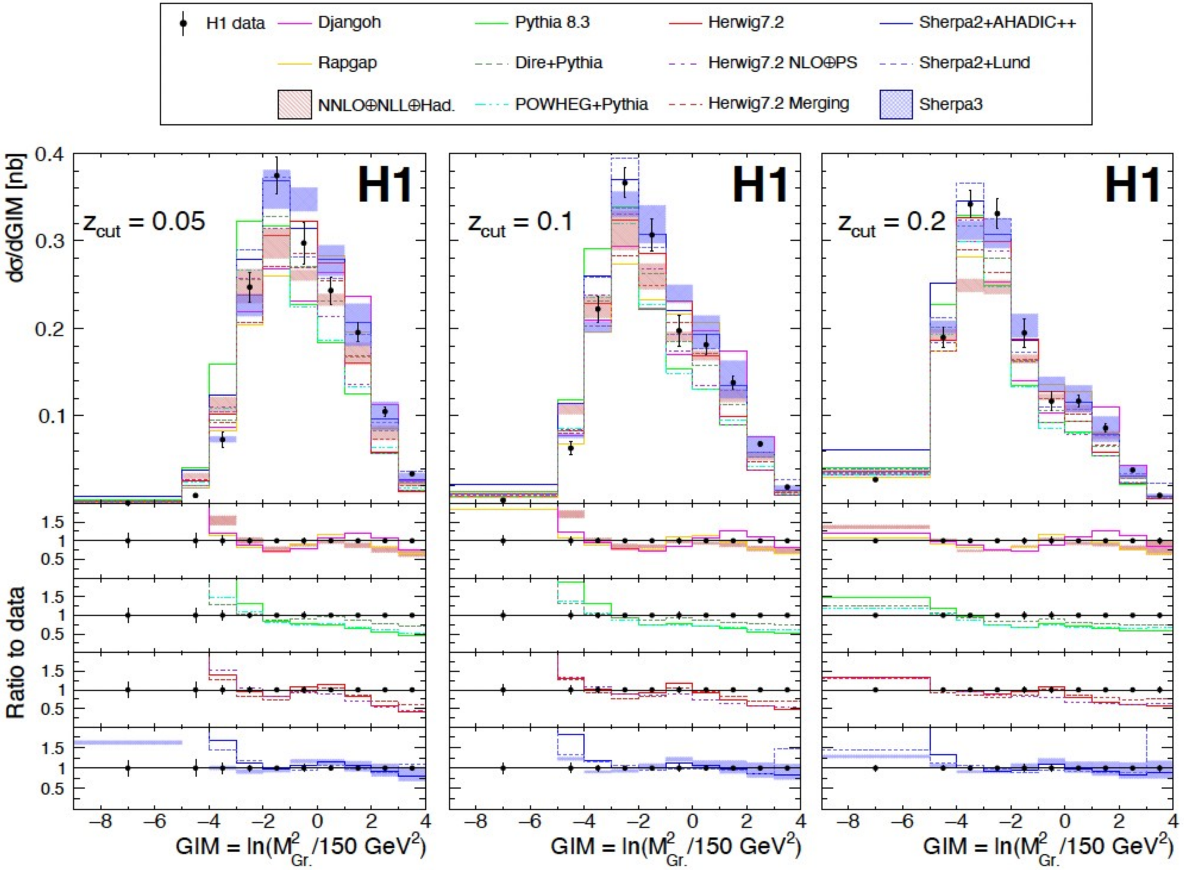


This graph was not included in Pythia or HERWIG at the time HERA started ~1990
→ reason to have dedicated DIS event generators. Is this "fixed" now?



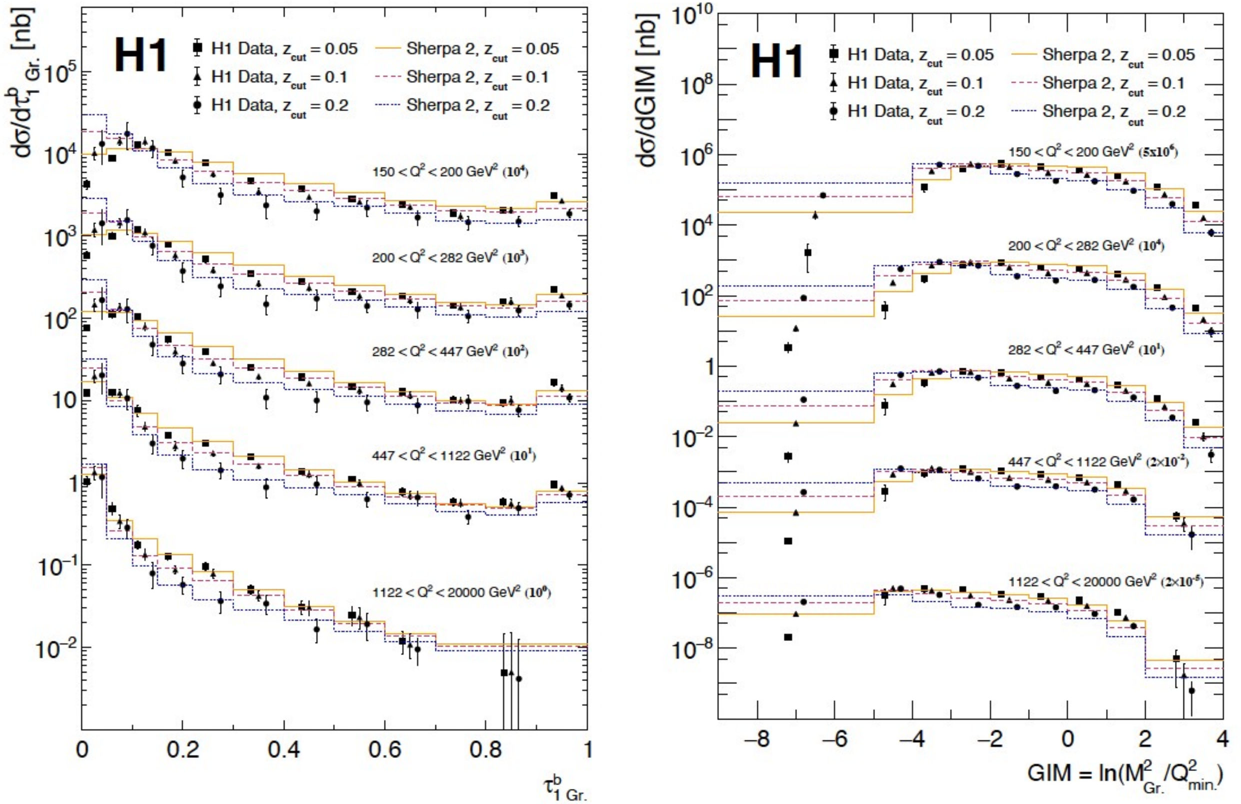
Groomed invariant mass GIM

- 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



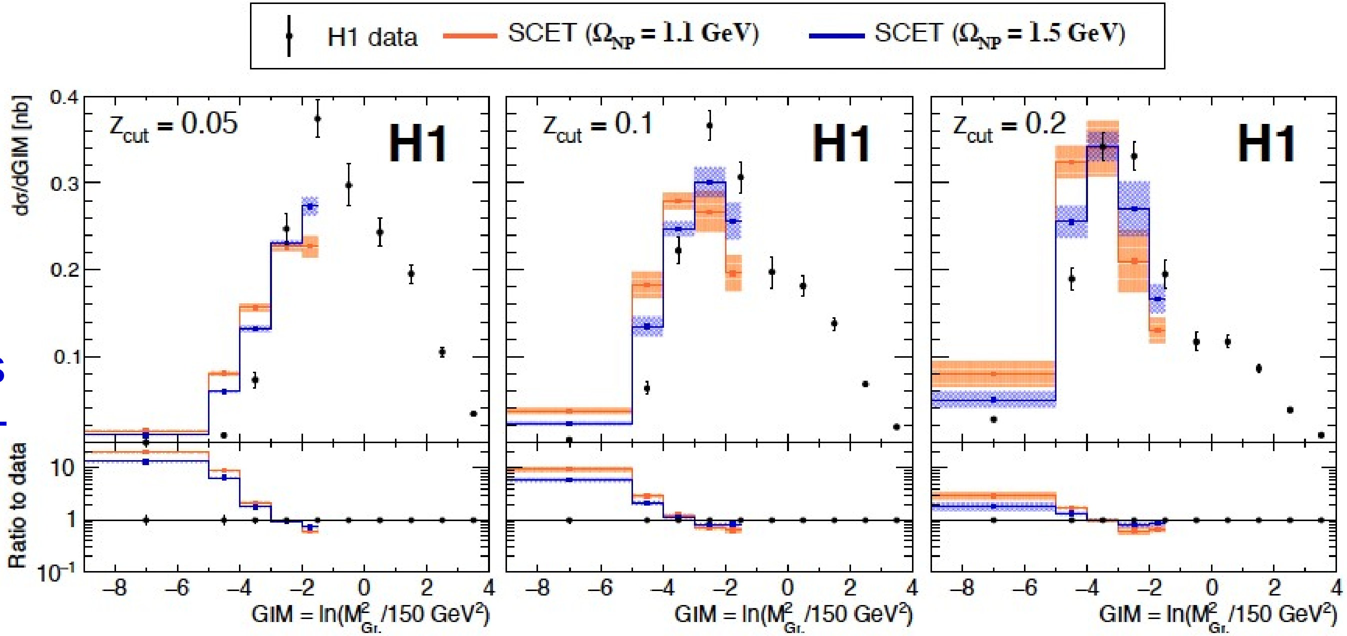
Double-differential measurements

- 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}



Comparison of GIM to SCET predictions

- SCET (Soft Collinear Effective Theory) predictions address the region of small GIM
- At large GIM, the theory is not expect to work (single-jet approximation)

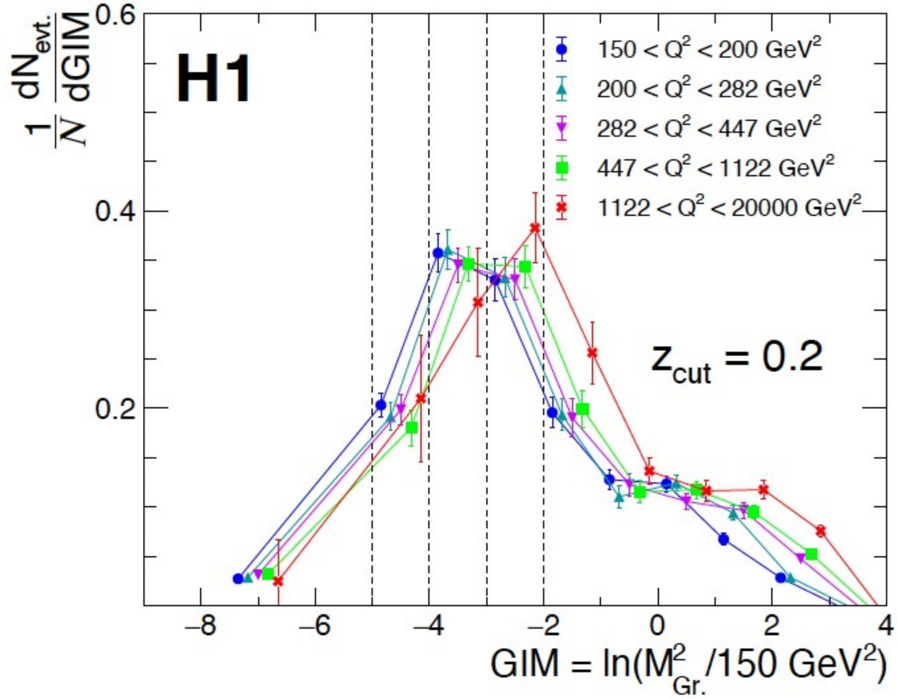


- SCET does not describe the data well, not even at small GIM
- The data seem to prefer large settings for the non-perturbative parameter Ω_{NP} - perhaps even larger than was tested here

SCET predictions:
Phys. Rev. D 103 (2021) 054005
[arXiv:2101.02708]

Test of GIM shape universality

- Within SCET, the shape of the GIM distribution is predicted to be scale-independent at low GIM
- Shown here: GIM distribution measured in different Q^2 regions
- Within data uncertainties, the scale-independence of the GIM shape is confirmed



SCET predictions: Phys. Rev. D 103 (2021) 054005 [arXiv:2101.02708]

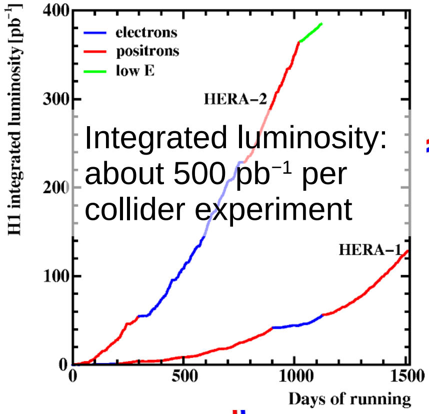
Summary

- Grooming techniques are widely used in pp collisions
- A first measurement of groomed events shapes in ep collisions is presented by the H1 collaboration
- The grooming is performed in the Breit frame, with the help of the Centauro jet clustering algorithm
- Event shapes studied: groomed 1-jettiness τ_1^b and groomed invariant mass GIM
- Groomed τ_1^b is well described by an analytic prediction and by Sherpa 3, with the exception of very low τ_1^b at the lowest Q^2. Pythia and HERWIG match less well
- MC models do not describe the region of very small GIM accurately
- Predictions for GIM using SCET are not yet at the same level as MC models, however the predicted shape universality is confirmed by data

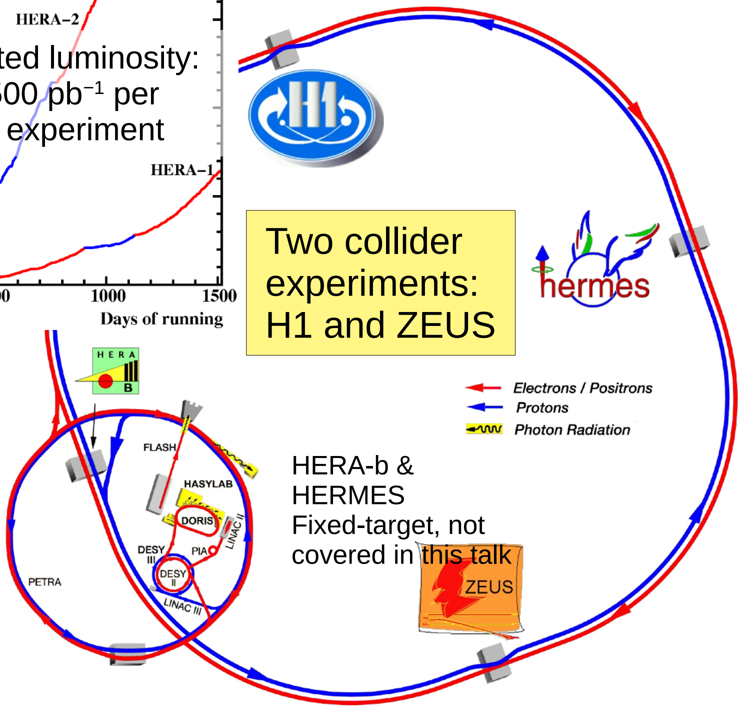
Backup

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



Two collider experiments: H1 and ZEUS

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

The H1 Experiment

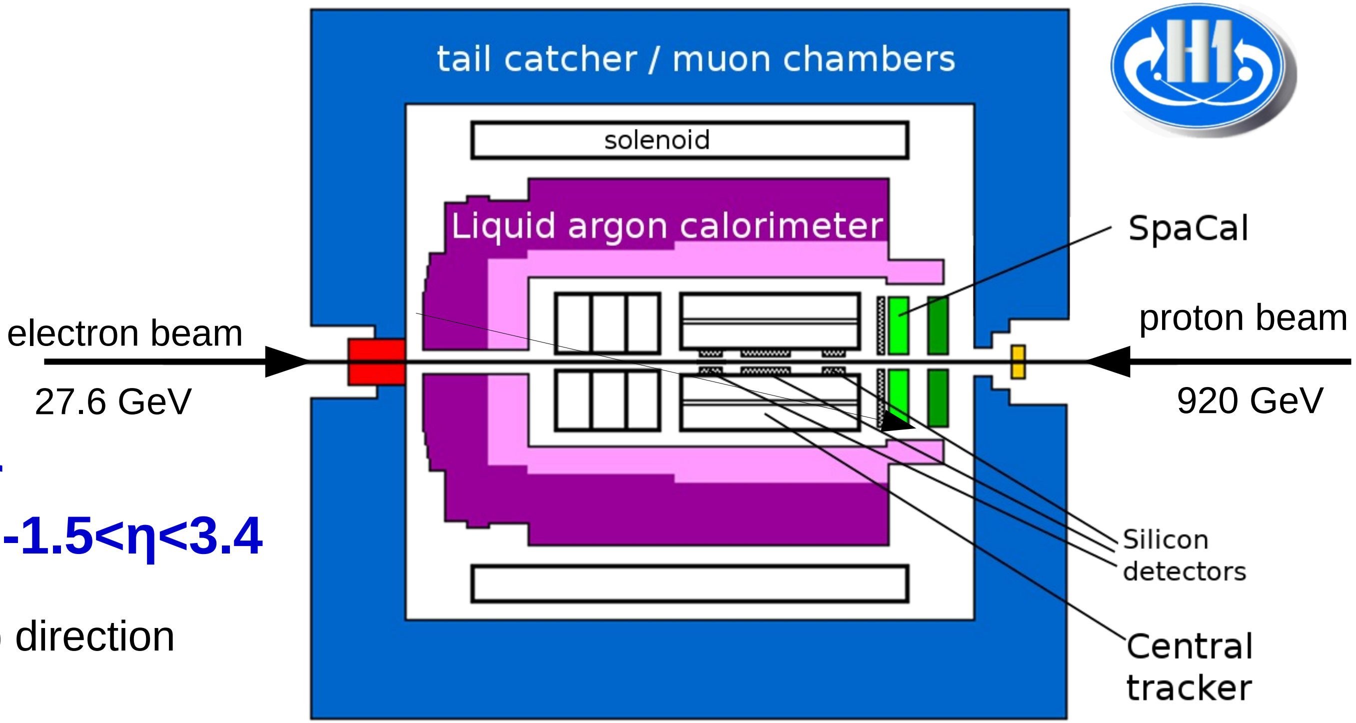
Asymmetric detector
Centre-of-mass system is boosted to proton-direction
E_e=27.6 GeV, E_p=920 GeV

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

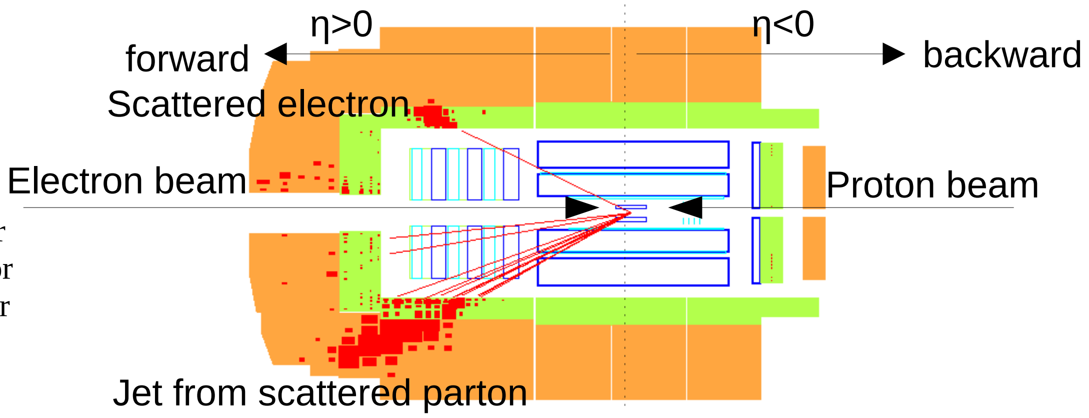
Momentum transfer: $Q^2 = -q^2 = -(e - e')^2$

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

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

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

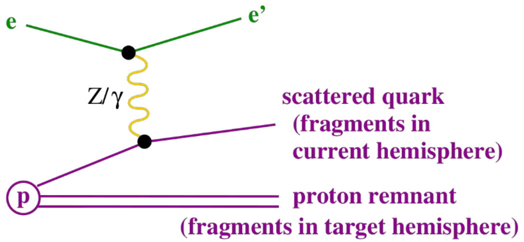
e: incoming lepton 4-vector
p: incoming proton 4-vector
e': scattered lepton 4-vector



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

- ## Leading order picture

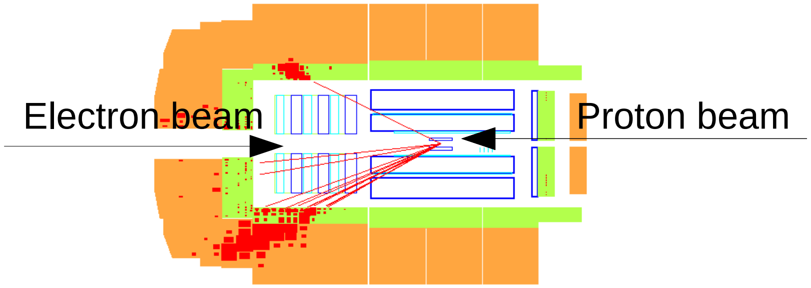


The Breit frame (BF)

- 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



Lorentz boost

Breit frame