Measurement of 1-jettiness in deep-inelastic scattering at HERA

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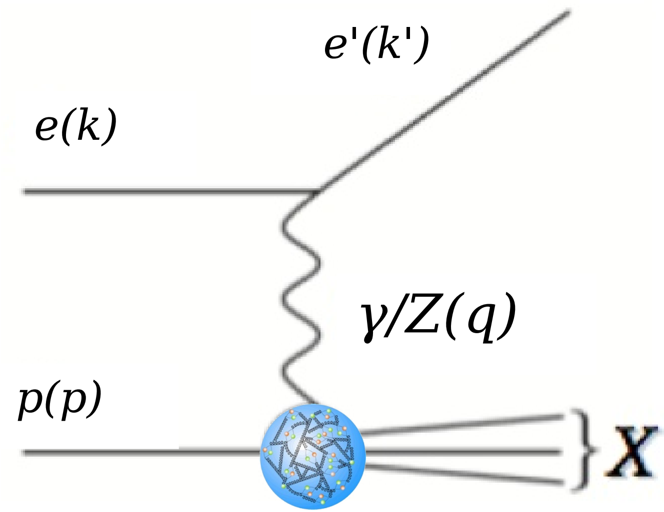
Neutral current deep-inelastic scattering

Neutral current deep-inelastic scattering

- Process: ep → e'X
- Electron or positron



Kinematic variables

- Virtuality of exchanged boson Q^2

$$Q^2 = -q^2 = -(k - k')^2$$

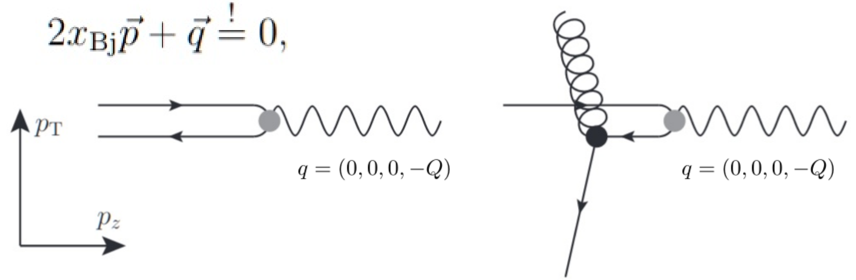
- Inelasticity, Bjorken-x and center-of-mass energy

$$y = \frac{p \cdot q}{p \cdot k} \qquad Q^2 = s \cdot x_{\mathrm{Bj}} \cdot y$$

The Breit frame

- Exchanged virtual boson collides 'head-on' with parton from proton ('brick-wall' frame)

$$2x_{\mathrm{Bj}}\vec{p} + \vec{q} \overset{!}{=} 0,$$



The 1-jettiness event shape

DIS thrust normalised to boson axis

- Normalisation with 2/Q

$$\tau_Q = 1 - \frac{2}{Q} \sum_{i \in \mathcal{H}_\mathcal{C}} P_{z,i}^{\mathrm{Breit}}$$

- Infrared safe, and free of non-global logs

1-jettiness

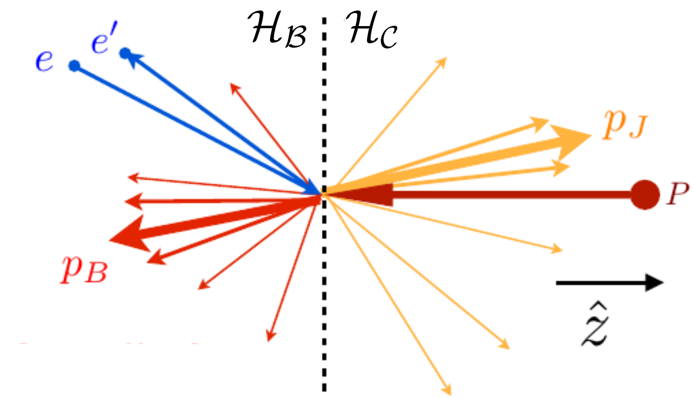
- Axes: incoming parton, and q+xP

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

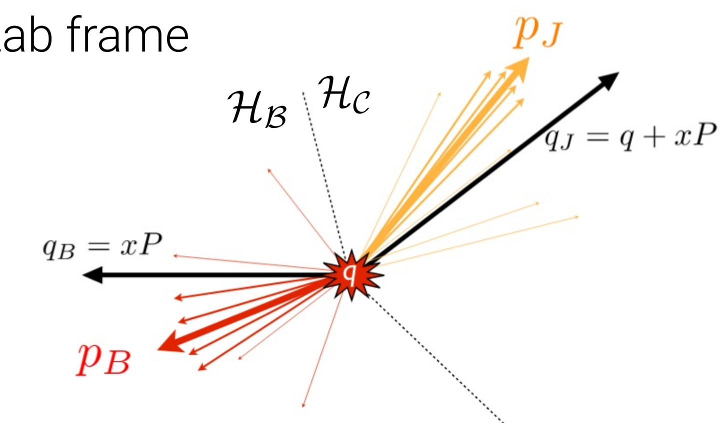
Equivalence

$$\tau_Q = \tau_1^b$$

Breit frame



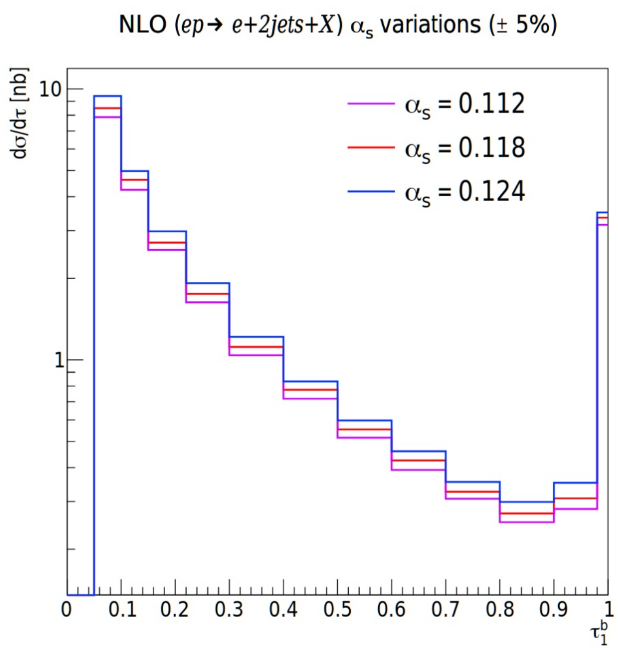
Lab frame



Sketch taken from Kang, Lee, Stewart [Phys.Rev.D 88 (2013) 054004]

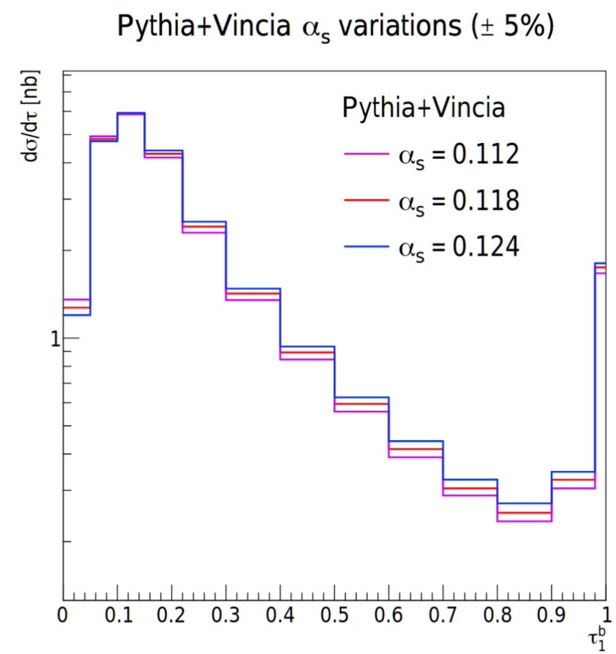
α_s dependence ±5%

Fixed order predictions



- parton level predictions
- NLO QCD for ep → 2 jets
- Calculation invalid for τ→0

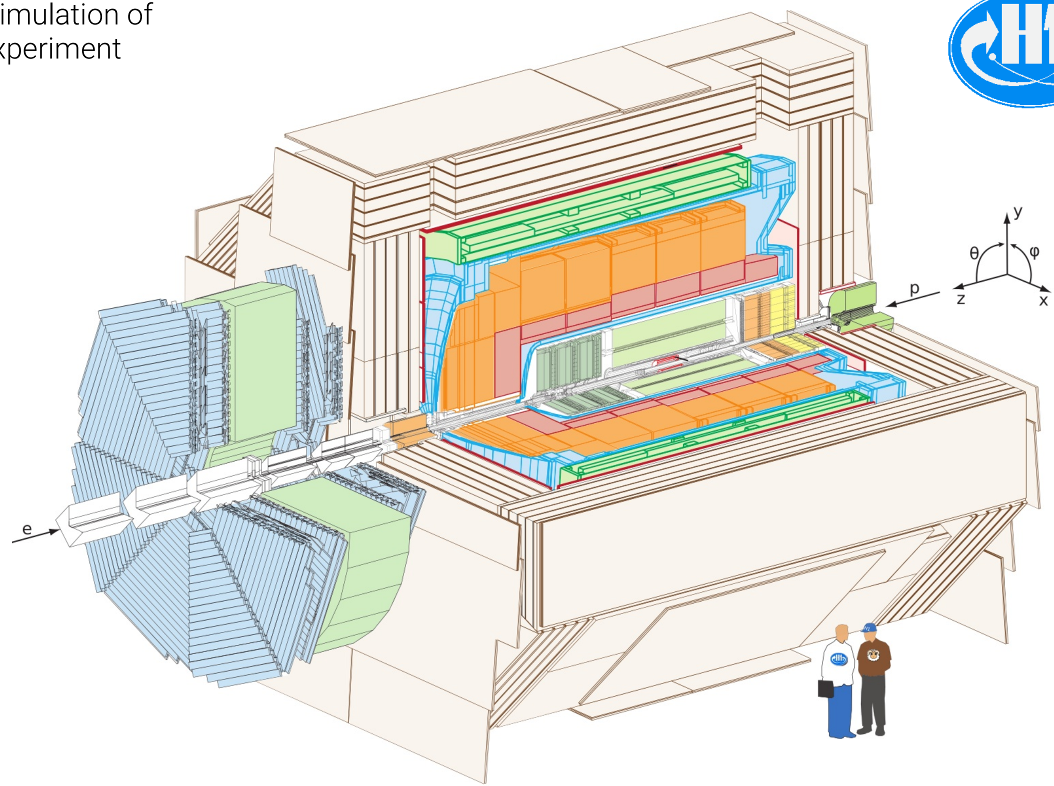
Monte Carlo event generator



- Pythia predictions at particle level
- DIS plus parton shower plus hadronization
- DIS kinematics important at low τ

The H1 experiment at HERA

GEANT simulation of
the H1 experiment



H1 'Multi-purpose' DIS detector

- Asymmetric design with trackers, calorimeters, solenoid, muon-chambers, forward & backward detectors, ...

H1 data preservation and analysis

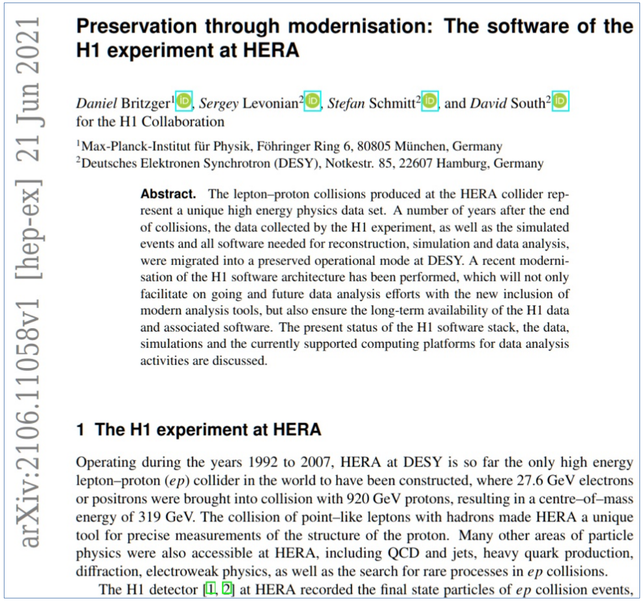
HERA data preservation supported by DESY-IT and MPP

- Data storage, redundancy, access rights, compute power etc... but:
- Experiment specific software, documentation, databases, etc... are in the responsibility of the collaborations

H1 software

- Fortran code(s) → Simulation, reconstruction, data access, event display, analysis
- C++ ROOT-based common analysis framework
  → defines common language how H1 talks about data and processes data

- All H1 software migrated to amd64 architecture (gcc9, C++20, ROOT6, LCG97) and runs natively on CentOS7 at DESY NAF-cluster
- Distributed python-based analysis possible through PyROOT


arXiv:2106.11058v1 [hep-ex] 21 Jun 2021

Preservation through modernisation: The software of the H1 experiment at HERA

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Abstract. The lepton–proton collisions produced at the HERA collider represent a unique high energy physics data set. A number of years after the end of collisions, the data collected by the H1 experiment, as well as the simulated events and all software needed for reconstruction, simulation and data analysis, were migrated into a preserved operational mode at DESY. A recent modernisation of the H1 software architecture has been performed, which will not only facilitate on going and future data analysis efforts with the new inclusion of modern analysis tools, but also ensure the long-term availability of the H1 data and associated software. The present status of the H1 software stack, the data, simulations and the currently supported computing platforms for data analysis activities are discussed.

1 The H1 experiment at HERA

Operating during the years 1992 to 2007, HERA at DESY is so far the only high energy lepton–proton (*ep*) collider in the world to have been constructed, where 27.6 GeV electrons or positrons were brought into collision with 920 GeV protons, resulting in a centre–of–mass energy of 319 GeV. The collision of point–like leptons with hadrons made HERA a unique tool for precise measurements of the structure of the proton. Many other areas of particle physics were also accessible at HERA, including QCD and jets, heavy quark production, diffraction, electroweak physics, as well as the search for rare processes in *ep* collisions.
The H1 detector [1, 2] at HERA recorded the final state particles of *ep* collision events,

vCHEP contribution
EPJ Web Conf. 251 (2021) 03004

Inclusive DIS data

HERA-II data

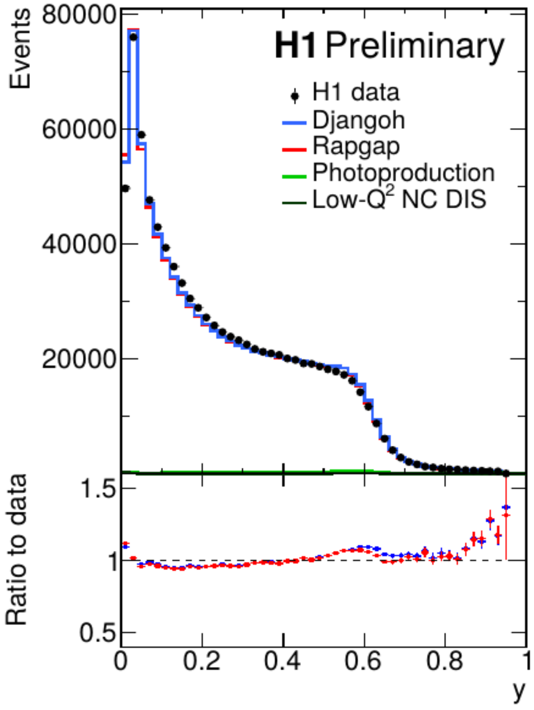
- Luminosity L=351 pb^{-1}
- Trigger requires high-energetic cluster in LAr calorimenter
  → triggered by electron or hadron
  → >99% efficient for y<~0.7
- High-Q^2 region: Q^2>150 GeV^2

Signal Monte Carlo models

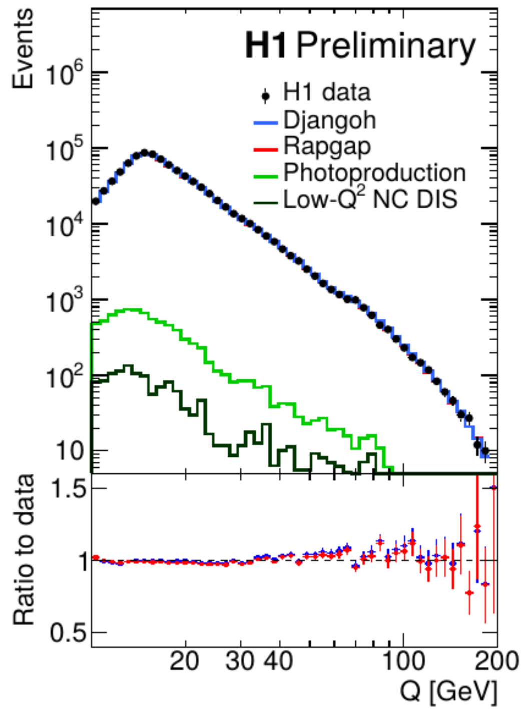
- Rapgap (ME+PS) and
- Djangoh (CDM)

Little background in incl. DIS

- photoproduction
- low-Q^2 NC DIS



$$y = y_\Sigma = \frac{\Sigma}{\Sigma + E_{e'}(1 - \cos\theta_{e'})}$$



$$Q^2 = Q^2_\Sigma = \frac{E^2_{e'} \sin^2\theta_{e'}}{1 - y_\Sigma}$$

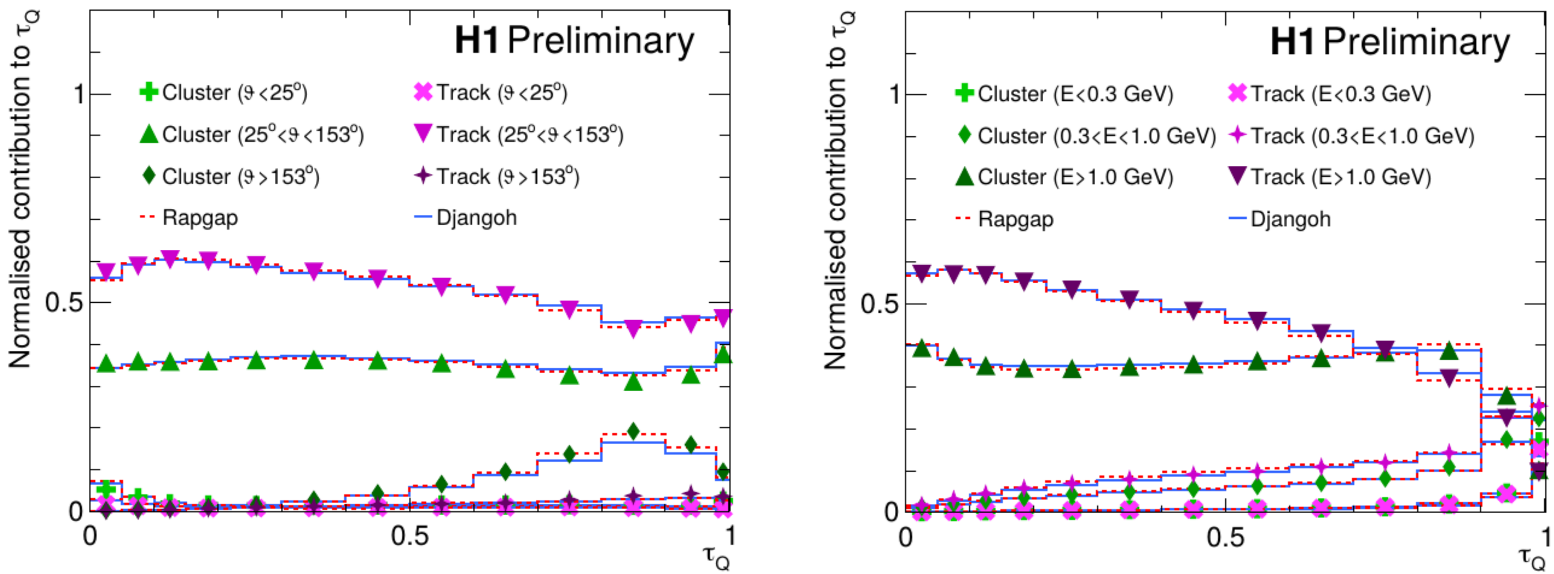
DIS Thrust – a 4π observable

All particle candidates in all DIS events contribute

- Particles are reconstructed using a particle-flow algorithm,
  → combining cluster and track information without double-counting of energy

$$\tau_Q = 1 - \frac{2}{Q} \sum_{i \in \mathcal{H}_C} P_{z,i}^{\mathrm{Breit}}$$

Normalised contribution to τ_Q for different ranges in polar angle θ and energy



- Mainly tracks and clusters in the central part of the detector contribute (25°<θ<153°)
- Mainly particles with high energy contribute (E>1.0GeV)

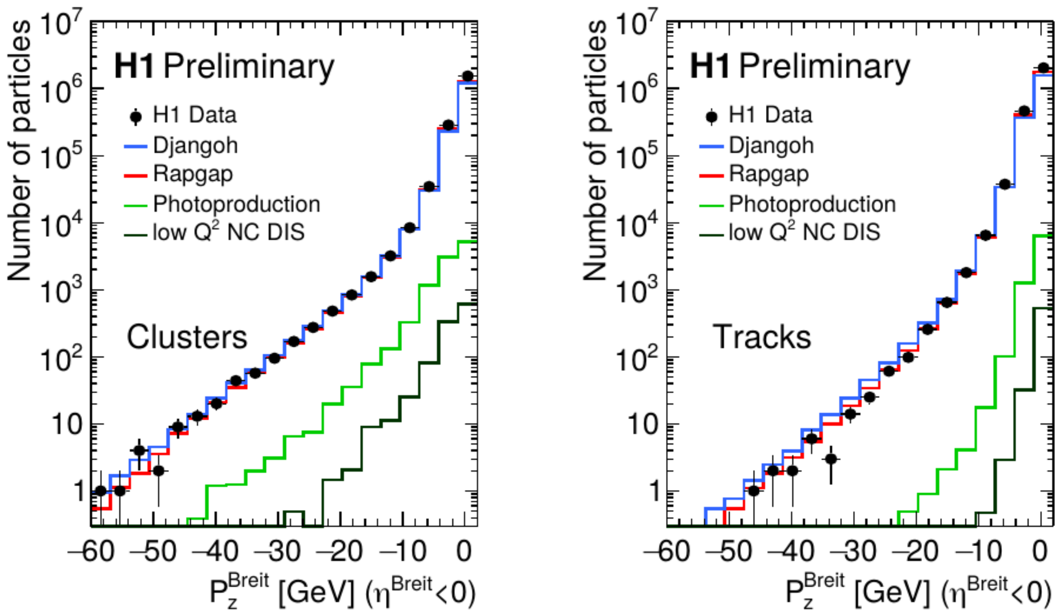
1-jettiness – DIS thrust

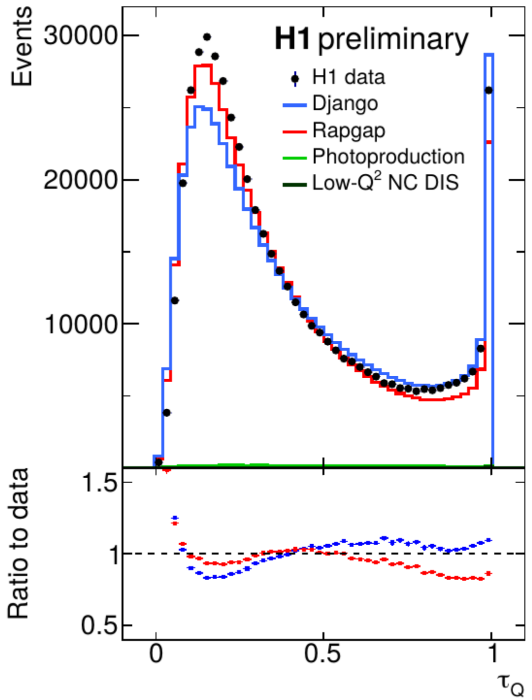
DIS thrust: sum of longitudinal momenta

- Longitudinal momenta in Breit frame are well measured and well modelled by simulation for clusters and tracks

DIS thrust at detector level

- Reasonable agreement between data and MC, as expected from the two physics models (ME+PS, CDM)
- Full τ range measurable





Single differential cross sections

1-jettiness cross sections

- Unfolded using bin-by-bin method
- Corrected for QED radiative effects
- range: $0 \leq \tau \leq 1$
- stat. & syst. uncertainties smaller than markers

Comparisons with Monte Carlo models

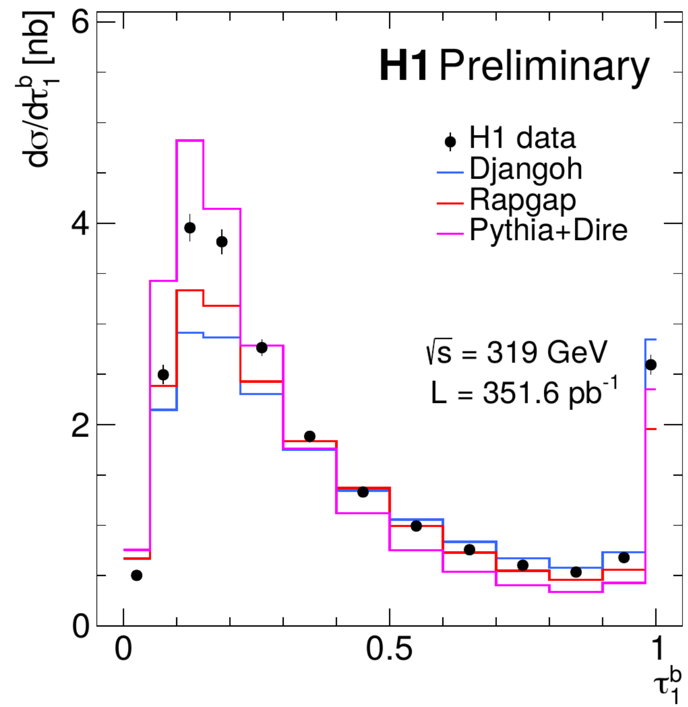
- Djangoh 1.4: Color-dipole-model (CDM)
- Rapgap 3.1: ME + parton shower
- Pythia8.3 + Dire

Resummation region

- Not well described by MC models

Fixed order region

- Djangoh & Rapgap perform well
- Pythia+Dire underestimate data

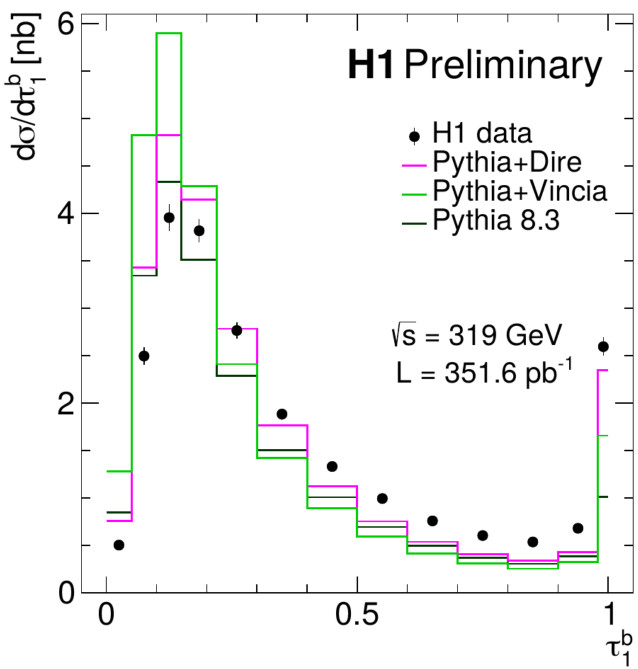


$$150 < Q^2 < 20\,000\,\mathrm{GeV}^2$$
$$0.2 < y < 0.7$$

Single differential cross sections

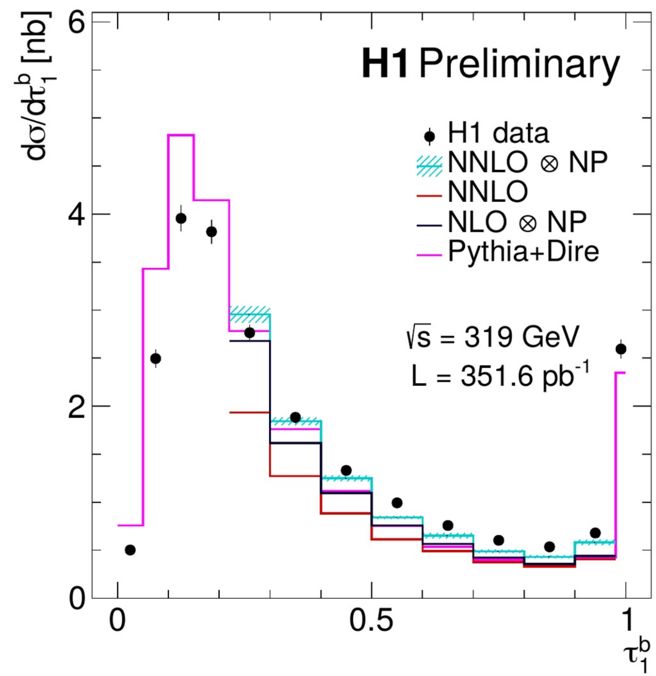
Comparison with Parton shower models

- Resummation region has strong dependence on different parton showers
- No PS model provides a fully satisfactory description
- 'Pythia default' PS underestimates τ=1



γp → 2jets NNLO prediction from NNLOJET

- NP corrections from Pythia8.3 (sizeable)
- NNLO provides reasonable description of fixed-order region
- NNLO improves over NLO



3D cross sections

Large cross section & sizeable data

→ triple-differential cross sections as functions of:

Q^2, y, τ_1

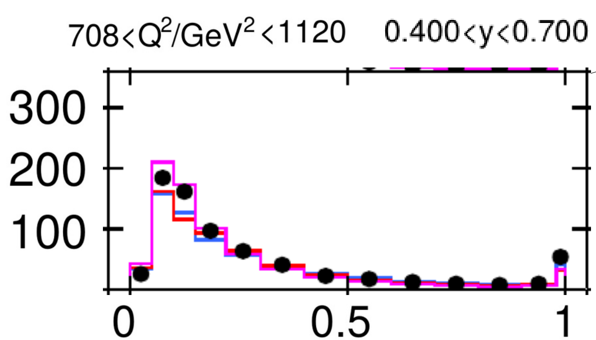
3D cross sections

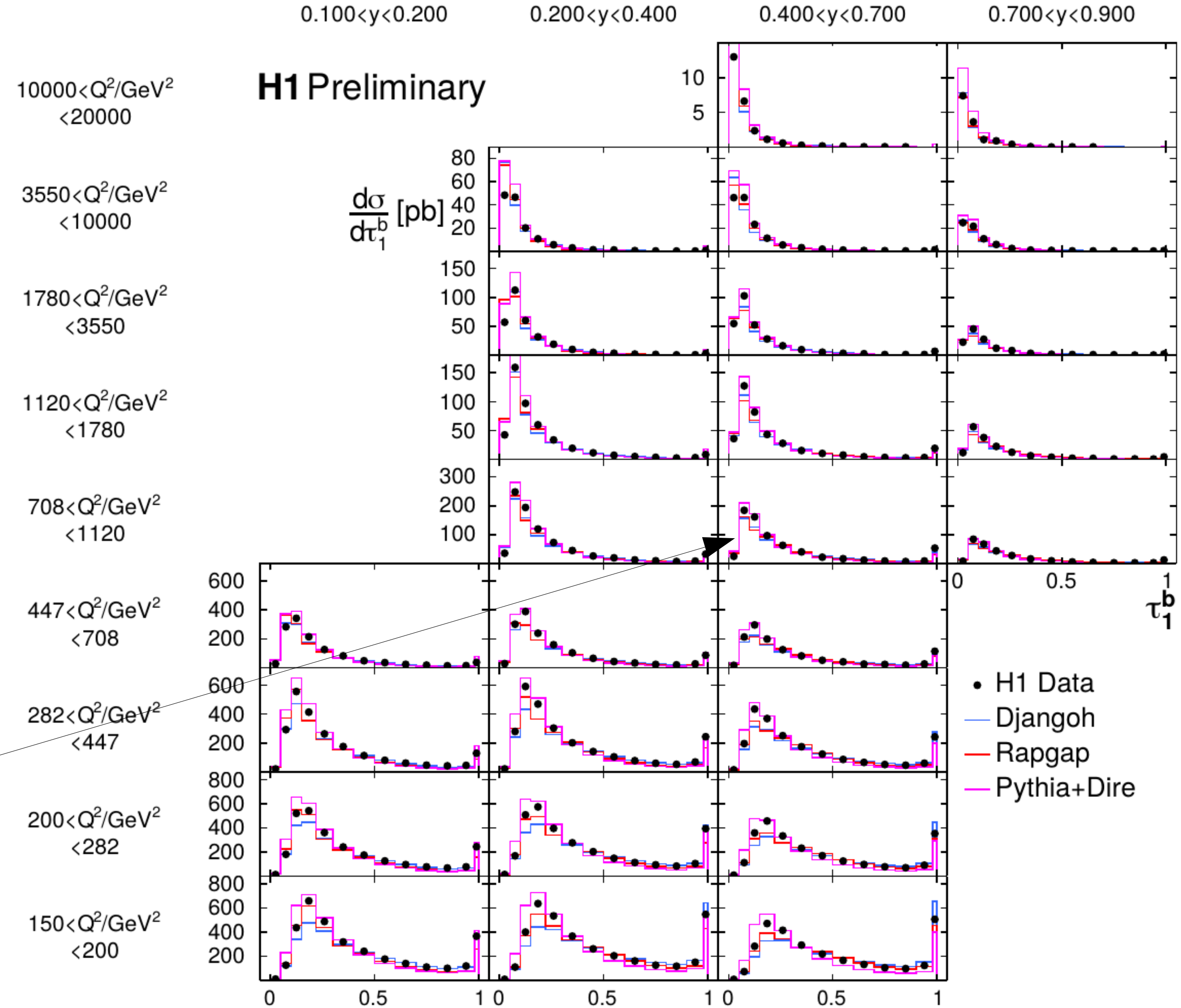
→ higher Q^2

- 'peak' moves to lower τ
- bulk region lowers

→ higher y (lower x)

- τ_1=1 becomes enhanced





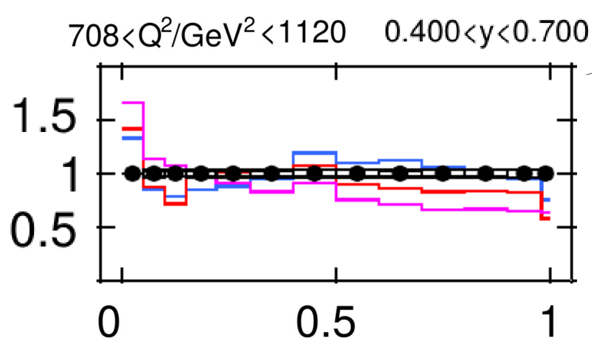
3D cross sections

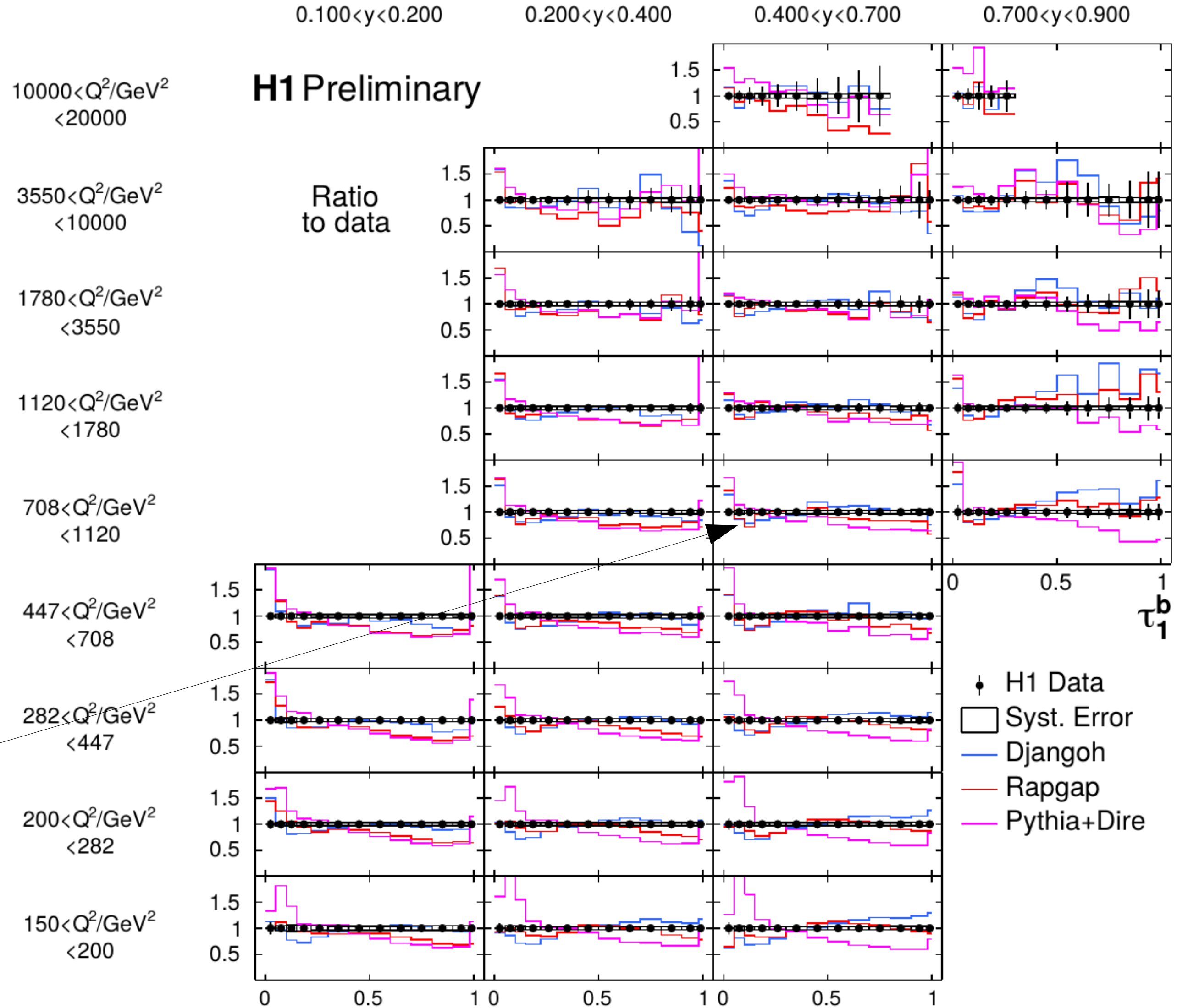
Ratio to data

- Stat. uncertainties of a few to O(10%)
- Syst. uncertainties are of the order of 5%

'classical' MC models

- Perform reasonably well over entire phase space
- Pythia+Dire similar to Rapgap at low y, but too large at low τ





3D cross sections

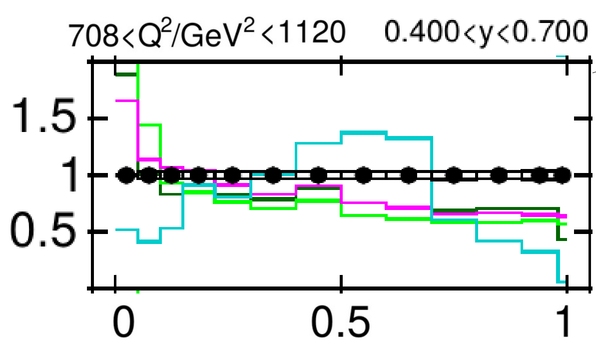
Comparison with further MC models

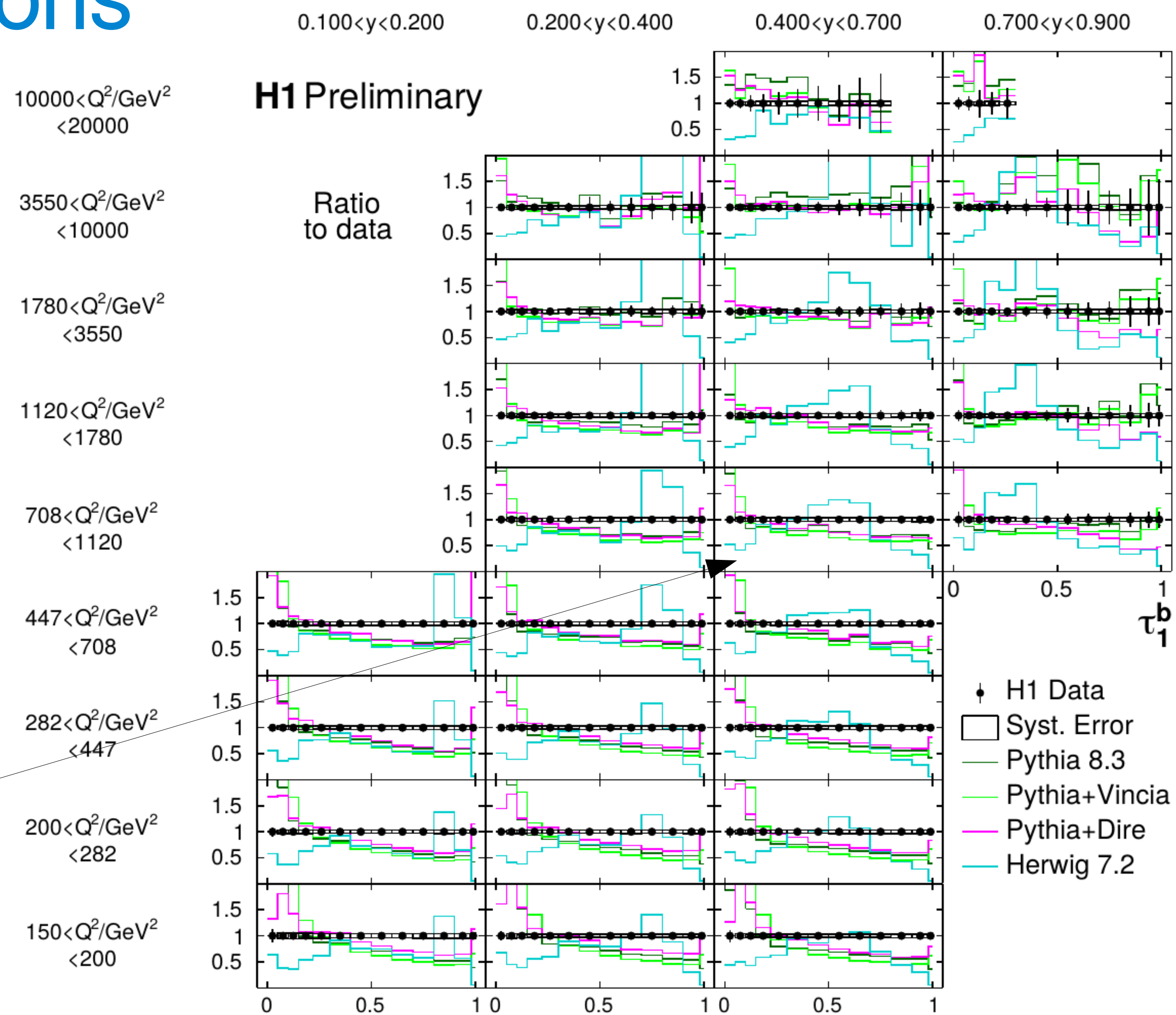
- Pythia + Vincia
- Pythia w/ default shower

Herwig 7.2

- often similar to Pythia, but
- resummation region too low (too low DIS cross section)
- some structure at high τ

→ See talk by H. Klest for updated HERWIG predictions



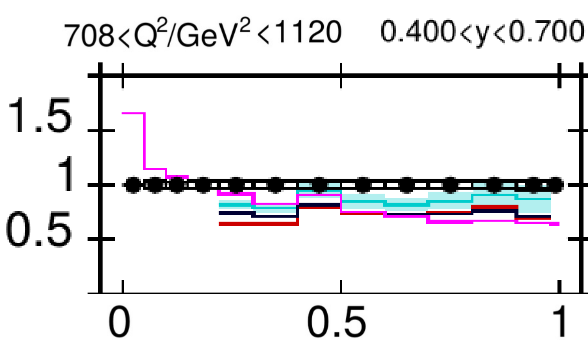


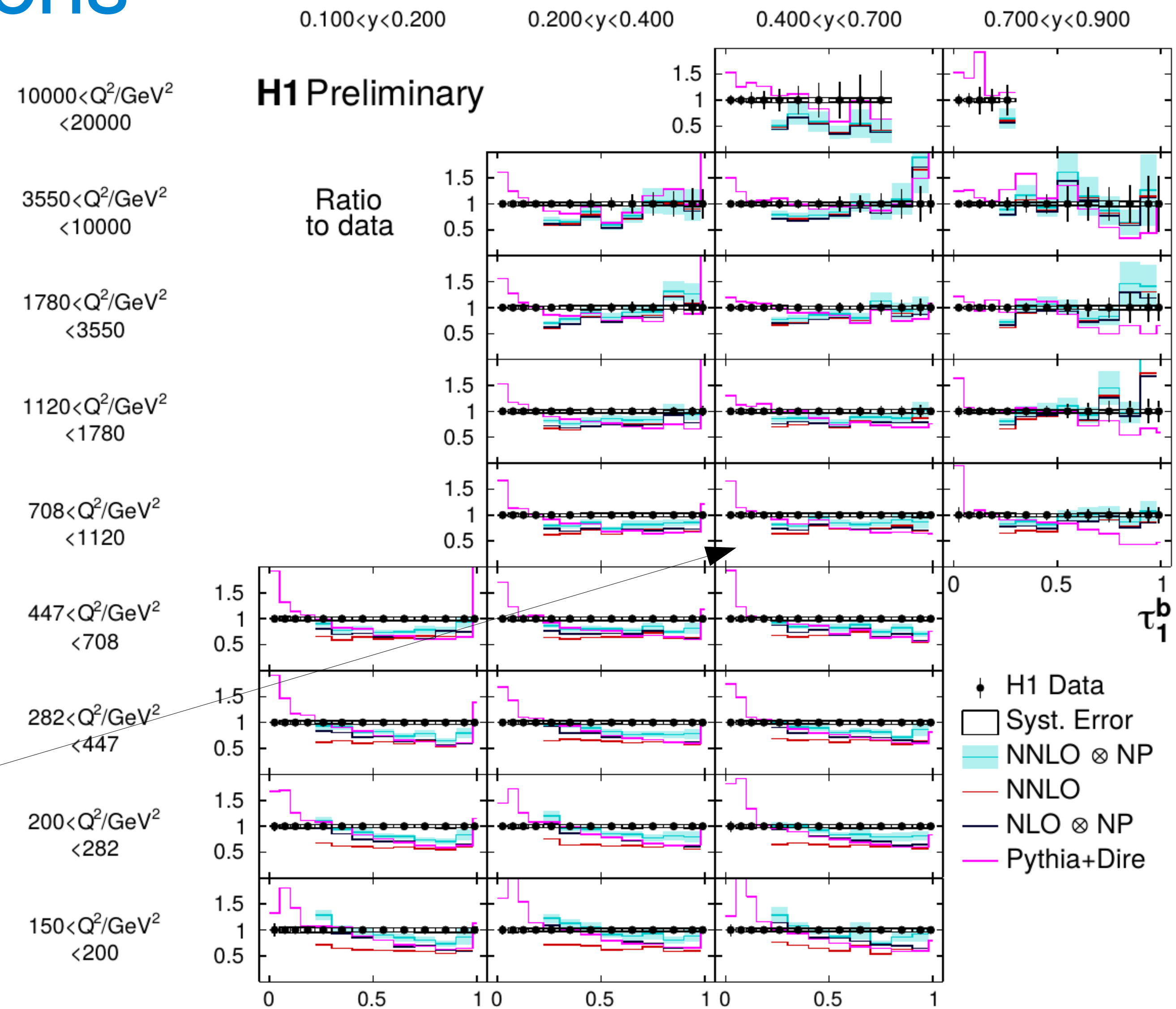
3D cross sections

NNLO pQCD (*ep* → 2 jets)

- Reasonable description in entire phase space:
- Improved description with increasing Q^2
- small scale uncertainites

- Altogether:
  NNLO improves over NLO
  NP corrections are Q^2 dependent



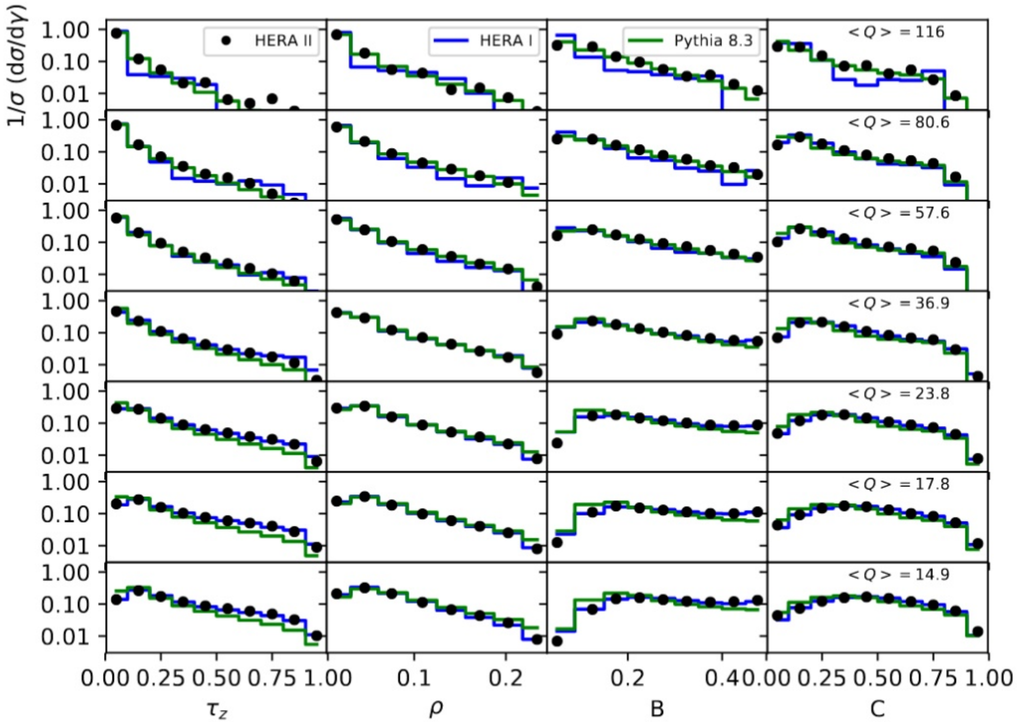


Classical event shape observables

Classical event shapes

- Measured at HERA-I by H1 and ZEUS
- No public measurement in HERA-II

Master thesis J. Hessler, TUM, 2021
https://www-h1.desy.de/psfiles/theses/h1th-920.pdf
https://inspirehep.net/literature/2010833



Definitions

- Thrust τ_z
- Jet broadening B
- Squared jet mass ρ
- C-parameter

$$\tau_z = 1 - \frac{\sum_{h\in\mathcal{H}_c} |p_{z,h}|}{\sum_{h\in\mathcal{H}_c} |\vec{p}_h|}$$

$$B = \frac{\sum_{h\in\mathcal{H}_c} |p_{t,h}|}{2\sum_{h\in\mathcal{H}_c} |\vec{p}_h|}$$

$$\rho = \frac{(\sum_{h\in\mathcal{H}_c} |p_h|)^2 - (\sum_{h\in\mathcal{H}_c} \vec{p}_h)^2}{(2\sum_{h\in\mathcal{H}_c} |\vec{p}_h|)^2}$$

$$C = \frac{1}{2} \cdot \frac{3\sum_{h,h'\in\mathcal{H}_c} |\vec{p}_h||\vec{p}_{h'}| \sin^2\vartheta_{hh'}}{(\sum_{h\in\mathcal{H}_c} |\vec{p}_h|)^2}$$

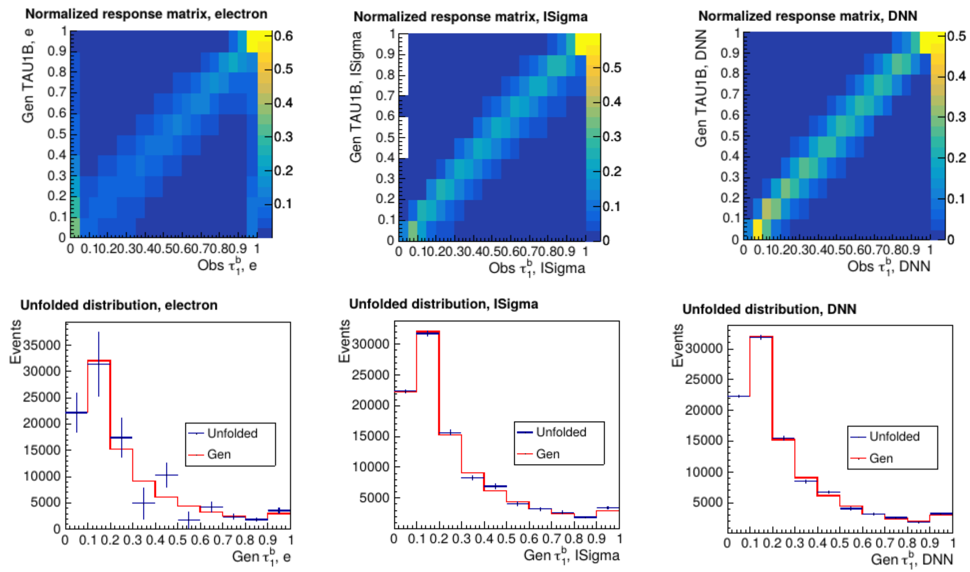
→ only particles in the current hemisphere contribute

→ Additional cut to ensure infrared safety of observables

$$E_c = \sum_h E_h > Q/10$$

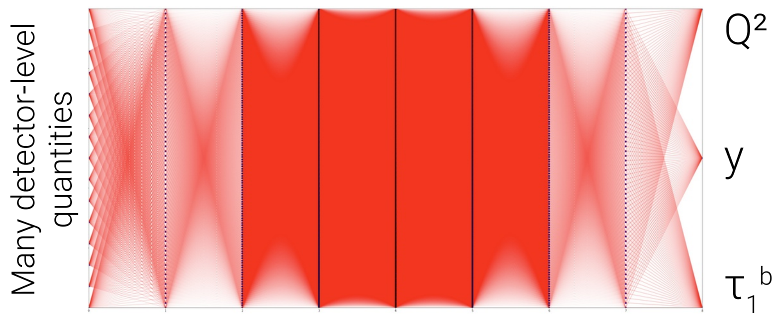
Further improvements using Machine Learning

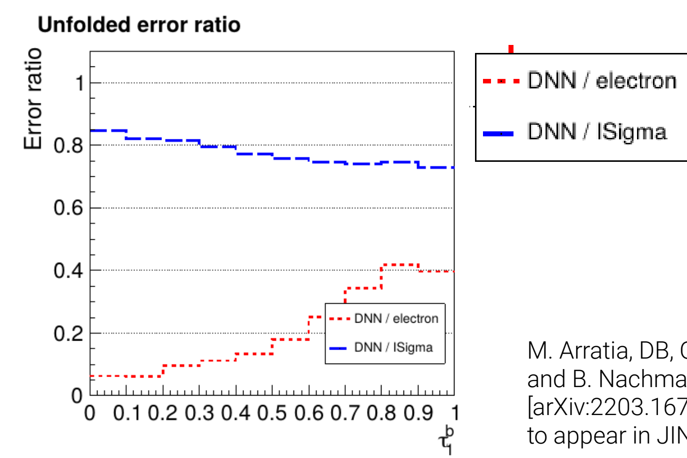
- Triple differential measurement of Q^2, y and τ_1^b
  → requires precise measurement of electron and the entire hadronic final state (and also *x* for the boost vector)
- With lower y these measurements become increasingly difficult



Possible improvement with a deep neural network

Use a deep neural network to reconstruct Q^2, y and τ_1^b using the entire event information in an optimal way





M. Arratia, DB, O. Long, and B. Nachman [arXiv:2203.16722] to appear in JINST

→ Possibility to enlarge the accessible phase space
→ Lower uncertainties of unfolded cross sections

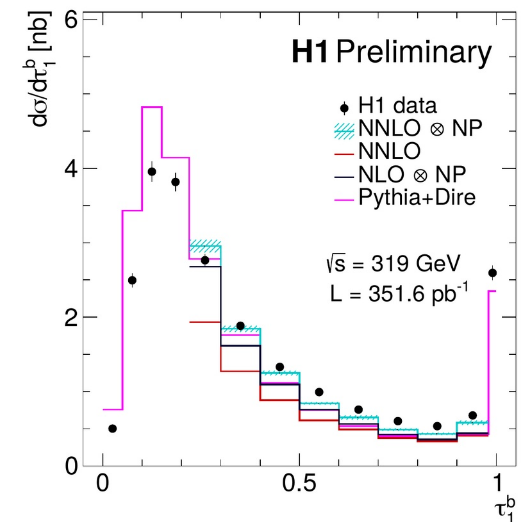
More details about the DNN by O. Long on Friday

Summary and outlook

- A first measurement of the 1-jettiness event shape observable in NC DIS was presented: $\sqrt{s}$=319 GeV, Q^2>150GeV^2, 0.1 < y < 0.9, 0 ≤ τ ≤ 1
- 1-jettiness is equivalent to DIS thrust normalised with 2/Q
  → τ_1^b is defined for every NC DIS event

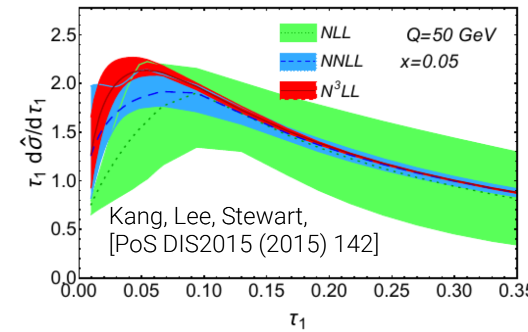
- 'Classical' Monte Carlo models provide a good description of the data
- Modern Monte Carlo models provide a reasonable description

- NNLO fixed order predictions (ep→2jets) provide good description in the region of validity, but hadronisation corrections are large



Outlook

- N3LL and N3LO DIS predictions need to be confronted with data
- sensitivity to α_s and PDFs need to be explored
- Data will become useful for improving (DIS) MC genererators
- Determine the generalized structure functions $F_1(Q^2,x,\tau)$ and $F_L(Q^2,x,\tau)$
- Many more event shape quantities can be measured (τ_1^a, τ_1^c, τ_2, jet mass, …)
- Measurements in diffractive DIS or charged current DIS can be performed



H1prelim-21-032
July 2021
Submitted to ISMD2021 and EPS-HEP21 conferences

Measurement of the 1-jettiness event shape observable in deep-inelastic electron-proton scattering at HERA

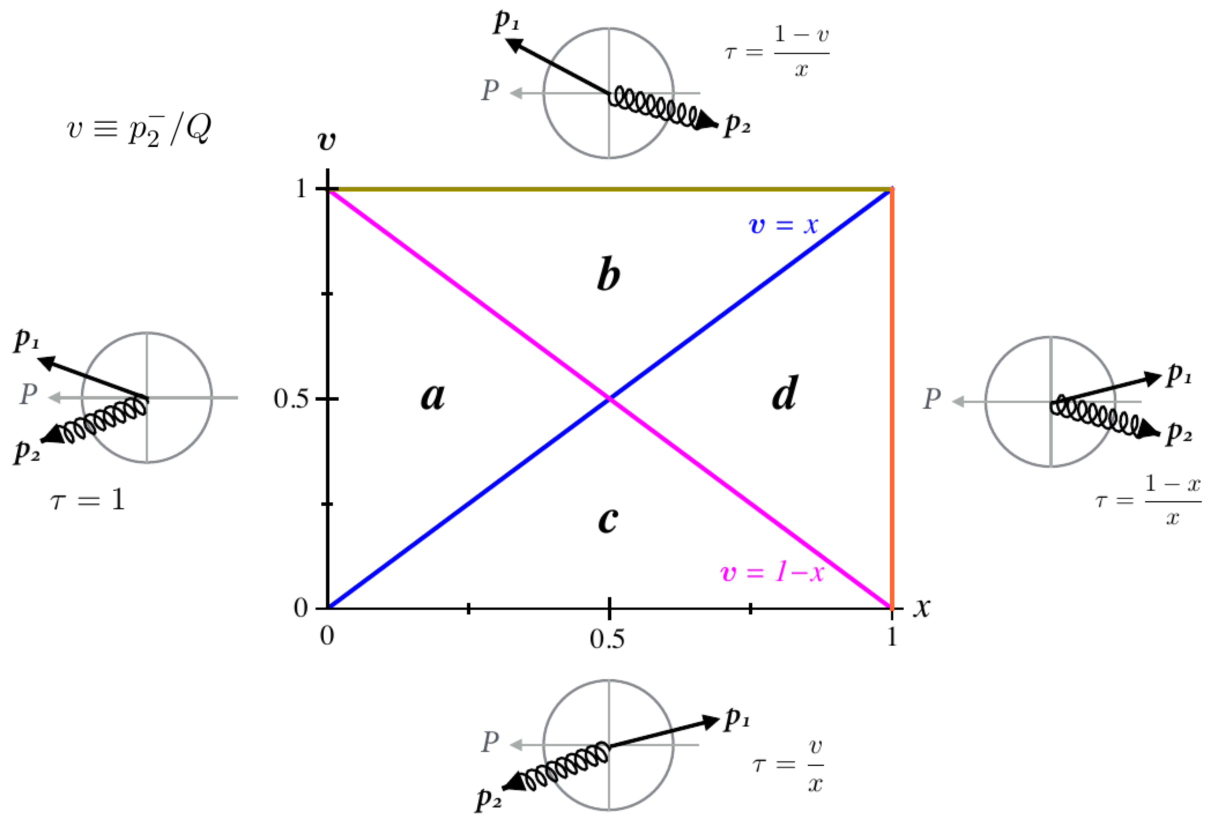
H1 Collaboration

Abstract

A first measurement of the 1-jettiness event shape observable in neutral-current deep-inelastic electron-proton scattering is presented. The 1-jettiness observable τ_b^1 is defined such that it is equivalent to the thrust observable defined in the Breit frame. The data were taken in the years 2003 to 2007 with the H1 detector at the HERA ep collider at a center-of-mass energy of 319 GeV and correspond to an integrated luminosity of $351.6\,\mathrm{pb}^{-1}$. The triple-differential cross sections are presented as a function of the 1-jettiness τ_b^1, the event virtuality Q^2 and the inelasticity y in the kinematic region $Q^2 > 150\,\mathrm{GeV}^2$. The data have sensitivity to the parton distribution functions of the proton, the strong coupling constant and to resummation and hadronisation effects. The data are compared to selected predictions.

https://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-21-032.long.html

Regions of two-body phase space in Breit frame



D. Kang, Ch. Lee,, I. W. Stewart
JHEP 11 (2014) 132 [arXiv:1407.6706]