Measurement of Multiplicity Distributions

in Deep Inelastic Scattering at HERA
and its Implications to Entanglement Entropy of Partons

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on behalf of the H1 collaboration

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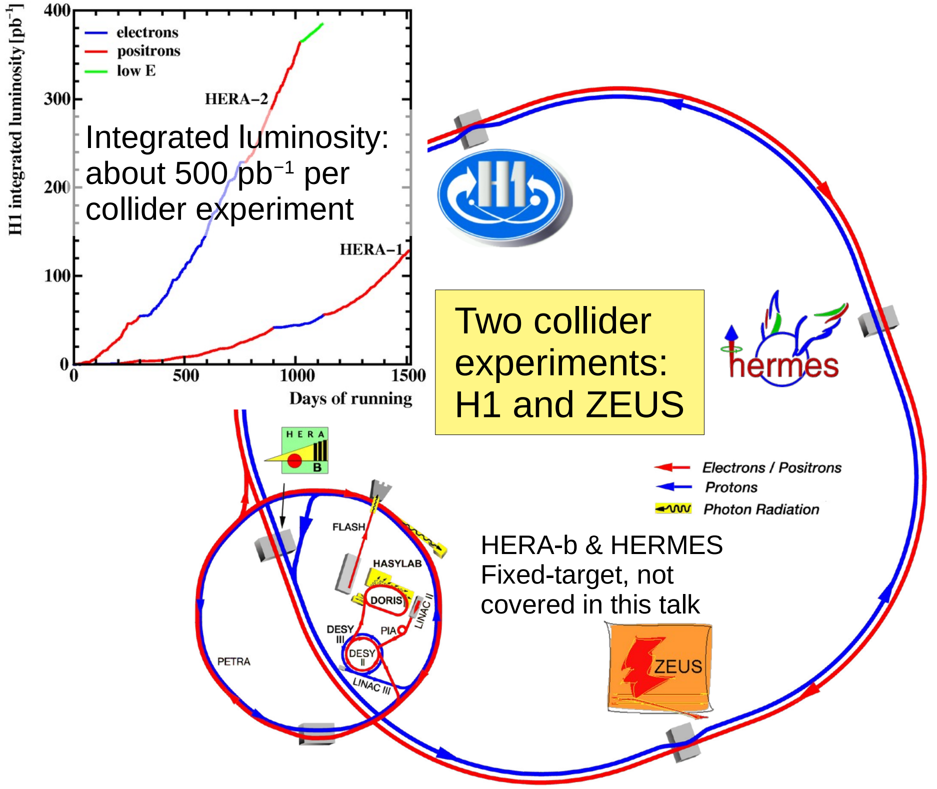
Outline

- Introduction: HERA and the H1 experiment
- Results on particle production in Deep-inelastic scattering
- Comparison to entanglement entropy predictions for partons

Results from: Eur.Phys.J.C81 (2021), 212 [arxiv:2011.01812]

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

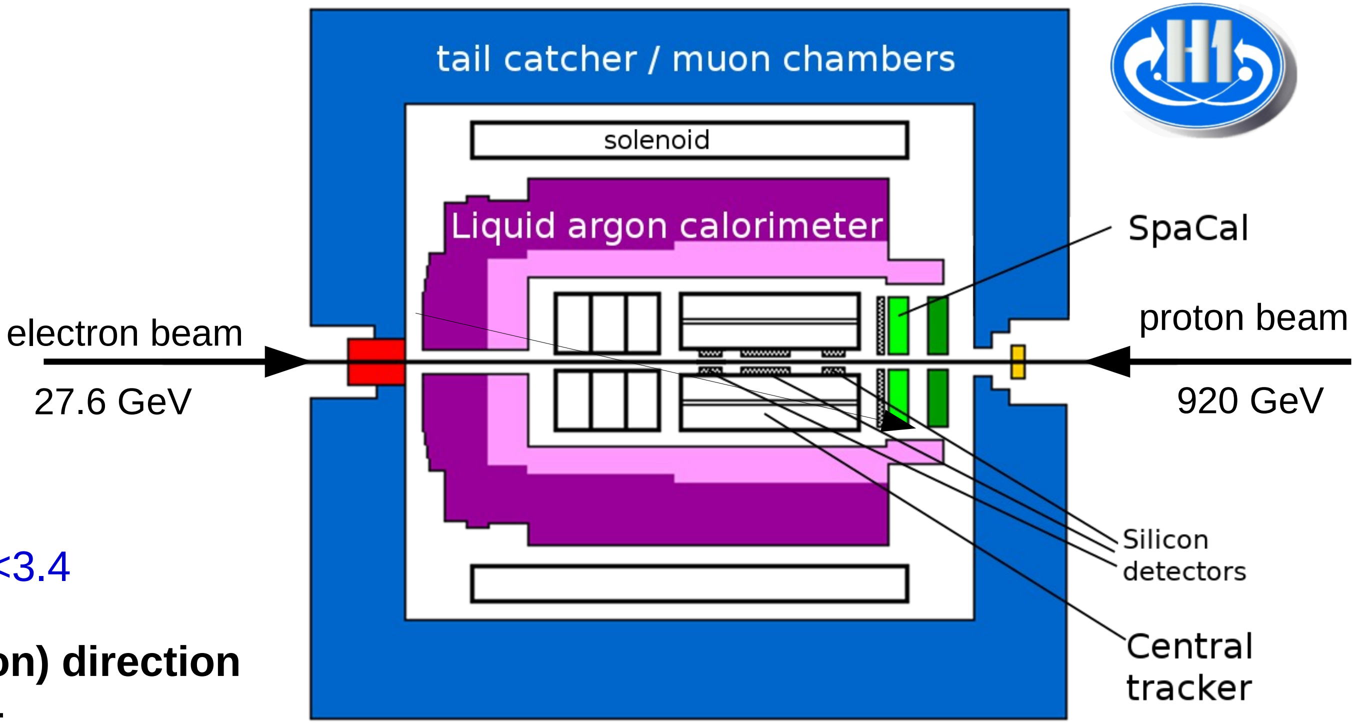

Curved section

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 as 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** (Deep Inelastic Scattering)

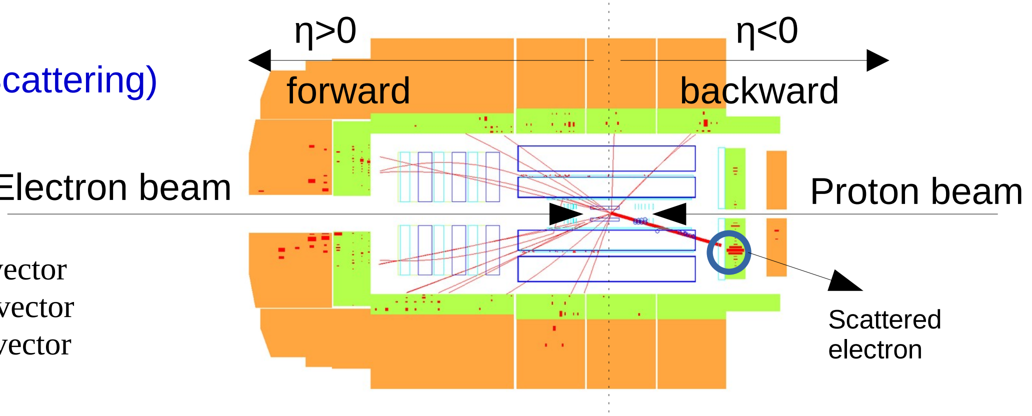
  Momentum transfer: $Q^2 = -q^2 = -(e - e')^2$

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

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

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

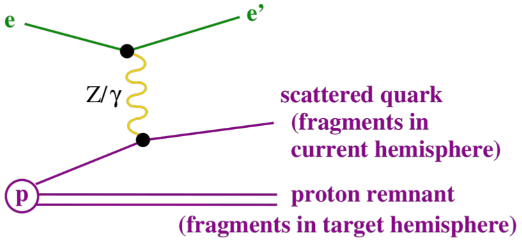
  e: incoming lepton 4-vector
  p: incoming proton 4-vector
  e': scattered lepton 4-vector



Typical event at low Q² and low-x:

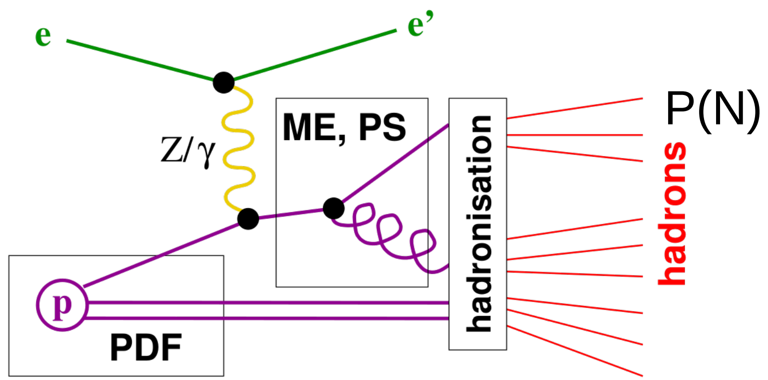
- electron in rear calorimeter
- Hadrons in the central tracker (~current hemisphere)
- Proton remnant in forward direction largely escapes detection

- **Leading order picture**



Particle multiplicity distributions

- Measure number of charged hadrons
- Sensitive to parton shower and hadronisation → MC tuning
- Typical DIS generator: PDF, matrix element, parton shower, hadronisation



- This measurement:
  - Differential in Q^2 and y (or W or x)

    $5<Q^2<100$ GeV² and $0.0375<y<0.6$
  - Hadron transv. momentum: $p_T>150$ MeV

    Hadron pseudorapidity: $|\eta|<1.6$, various subranges studied
  - **Observable: P(N)**

    How frequently do we observe N hadrons?

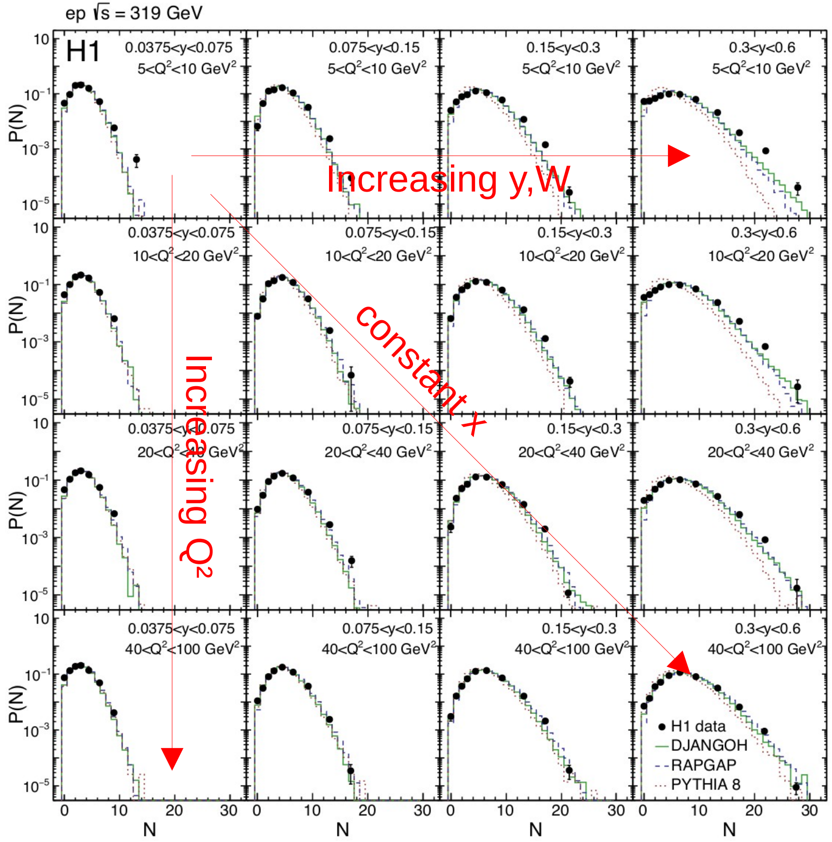
Results on P(N)

BACKUP slides

- Measurements are repeated in different (laboratory) η ranges
  - **Shown here: full range −1.6<η<1.6**
  - Also measured: subranges of size Δη=1.4
  - Also tested: restriction to current hemisphere η*>0
  - MC models tested:
    - DJANGOH (color dipole)
    - RAPGAP (pt ordered)
    - PYTHIA8

4x4 bins in Q^2,y
In each bin, measure distribution P(N)

MC models do a fair job but underestimate the tails at large P(N)



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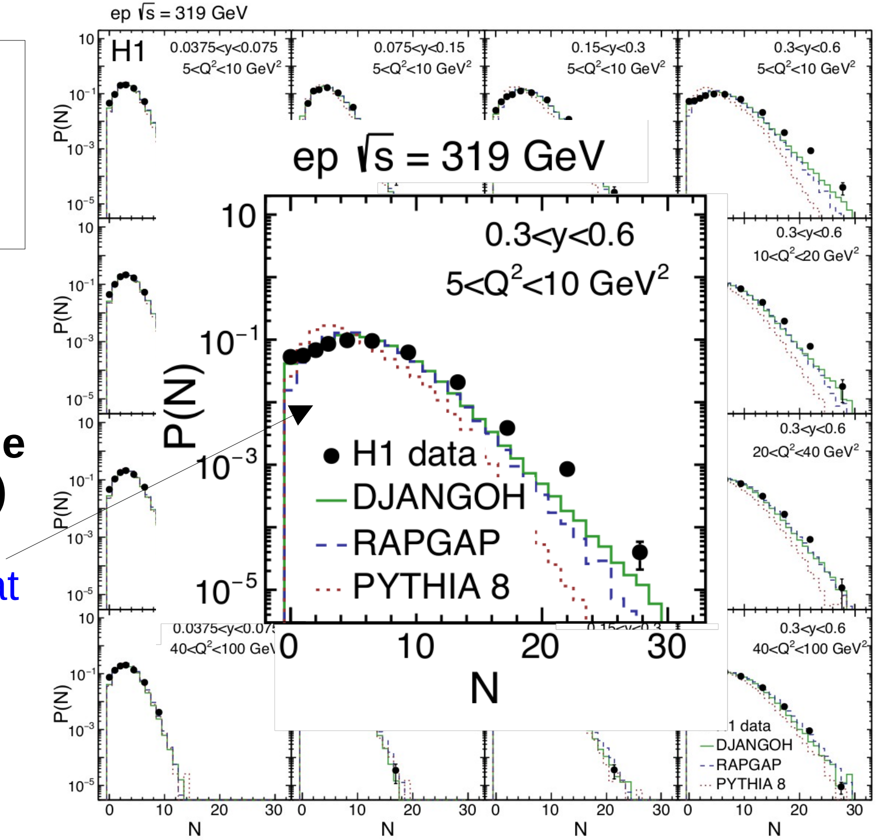
BACKUP slides

4x4 bins in Q²,y
In each bin, measure distribution P(N)

MC models do a fair job but underestimate the tails at large P(N)

Main differences at low Q² and high y

Backup slides: moments of N, KNO scaling



Entanglement entropy of partons

- Virtual Photon probes a region “A” of the proton, size ~1/Q
- Proton = A+B is a pure quantum state
- Systems “A” and ”B” are expected to be entangled after the collision

  → expect to find non-zero entanglement entropy

  For maximal entanglement: $S=S(A)=S(B)$
- Van Neumann entropy: $S=-\Sigma_N P(N) \ln [P(N)]$
- Prediction: $S_{gluon} \sim \ln[xG(x)]$ where G(x): gluon density

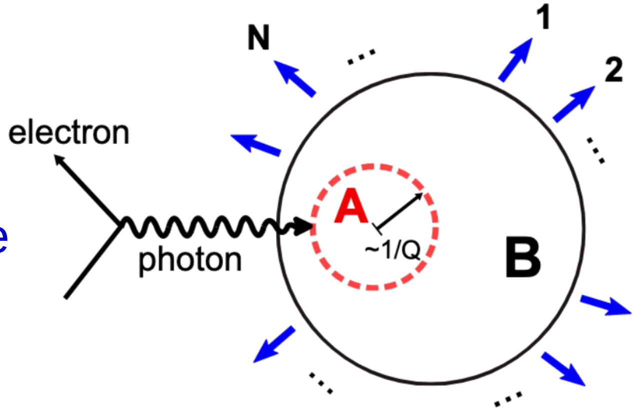


Figure from arXiv:1904:11974

Sum runs over all (partonic) states N with probability P(N)

Kharzeev, Levin, Valparaiso, Phys.Rev.D 95 (2017) 11, 114008 [1702.03489]

Entropy of hadrons

- Virtual Photon probes a region “A” of the proton, size ~1/Q
- Region “B”: proton remnant, can not be measured
- Hadrons from region “A”: select suitable pseudorapidity range
- Two methods tested
  - window of size 1.4 around $\eta_{lab} \sim Y_{beam} + \ln[x]$
  - Restrict to current hemisphere of the hadronic-centre-of-mass frame
- Hadron entropy: $S_{hadron} = -\Sigma_N P(N) \ln [P(N)]$
- Invoke parton-hadron duality and compare to $S_{gluon} = \ln[xG(x)]$ where G(x) is taken at $x = x_{Bjorken}$

$$Y_{beam}(E=920\ \text{GeV}) = \ln\left[\frac{2\times 920}{0.938}\right] = 7.5$$

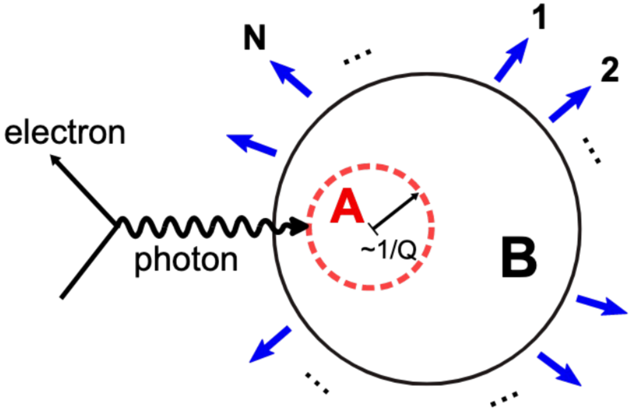
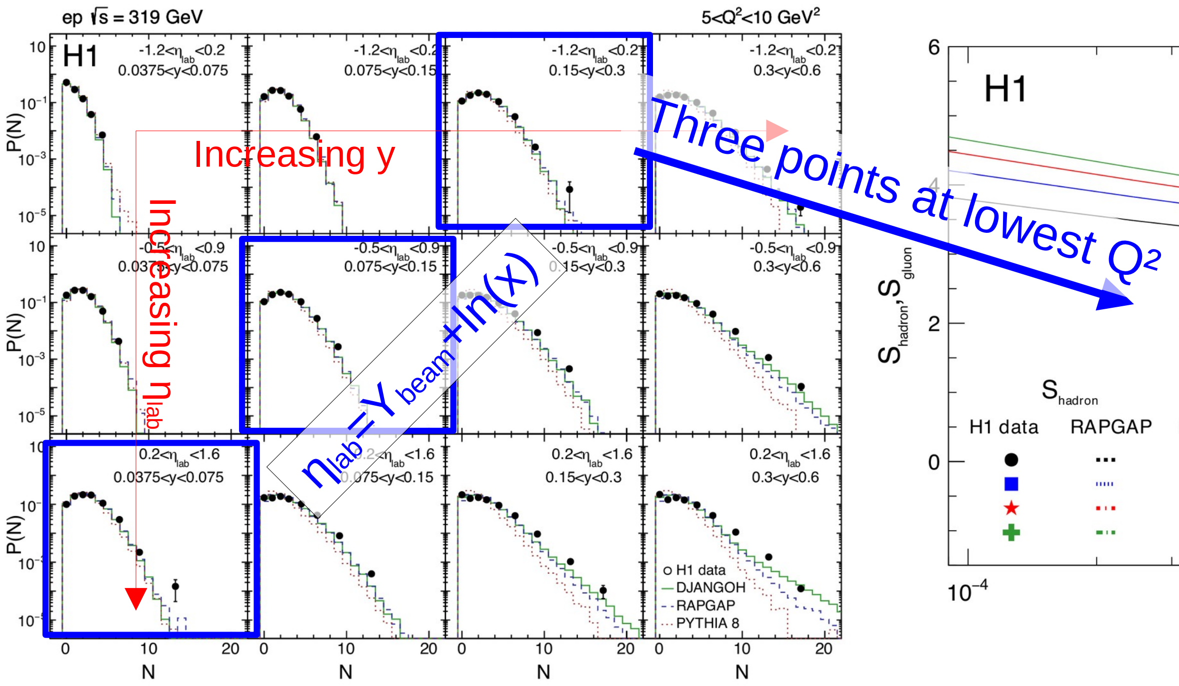
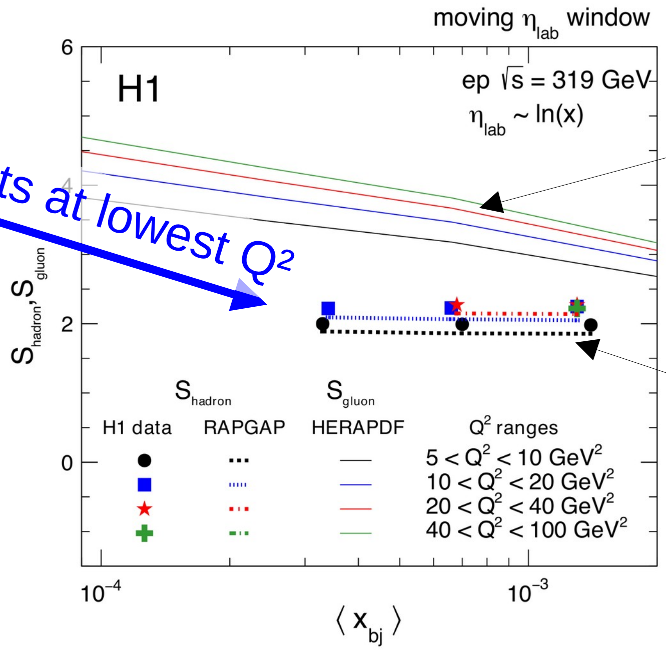


Figure from arXiv:1904:11974

Sum runs over states with charged hadron multiplicity N, produced with probability P(N)

Hadron Entropy in moving η window



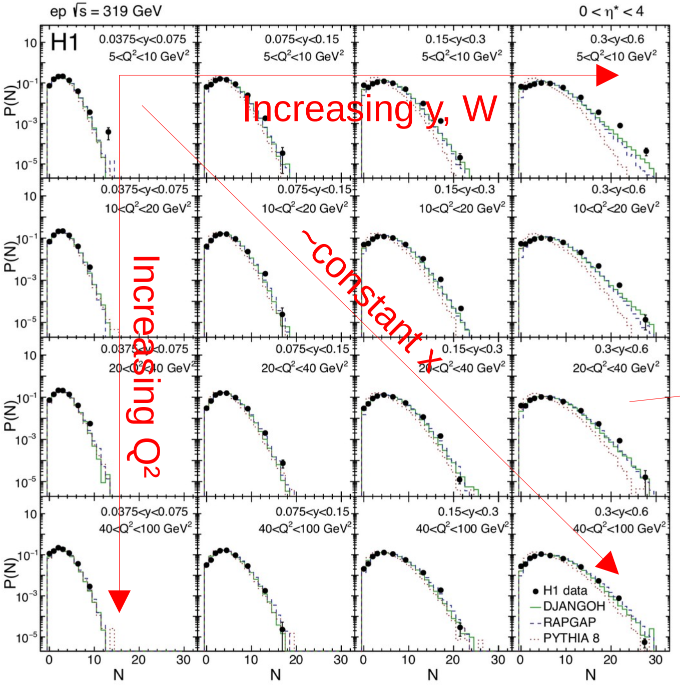


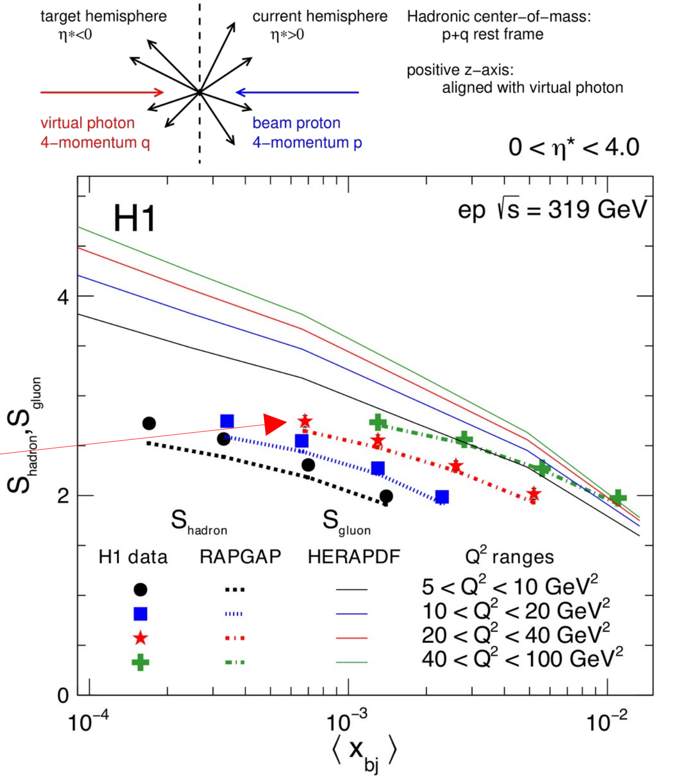
Prediction for S_{gluon} is far from data on S_{hadron}

Reasonable description of S_{hadron} by MC

Multiplicity distribution P(N) measured in 4x3 bins of y x η, shown here for $5<Q^2<10$ GeV² → extract S_{hadron} . Repeat this procedure for other Q² ranges (P(N) data in backup).

Hadron entropy in current hemisphere





S_{gluon} not compatible with S_{hadron}

Updated theory paper gives improved description of H1 data [arXiv:2102.09773] → next slide

C.f. Predictions by other groups, e.g. Phys. Rev. D 101, 074040 (2020) arXiv:2003.05008

S_{hadron} described by MC, except for low Q² and low-x

Multiplicities with restriction η*>0 on 4x4 bins of Q² and y → calculate entropy in Q²,x plane

Updated theory paper 2102.09773

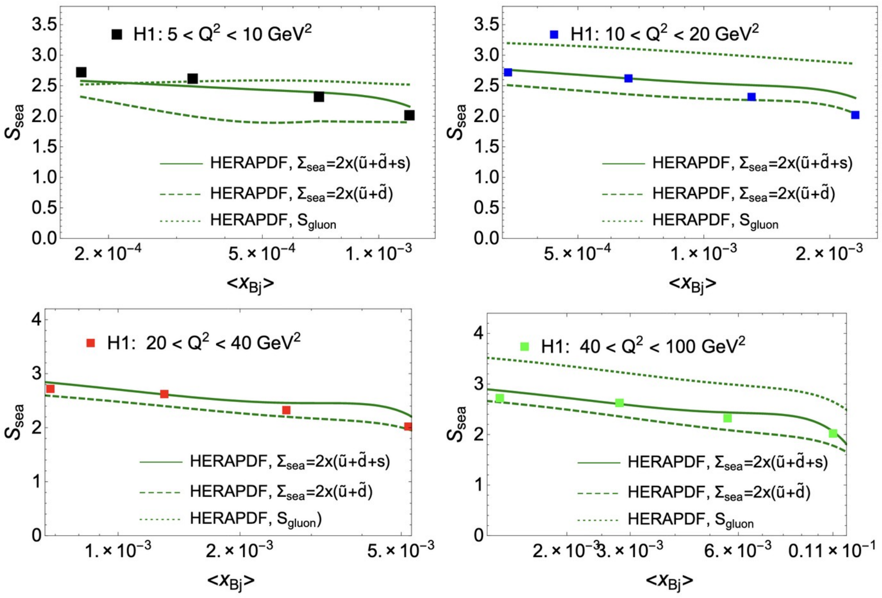


Figure taken from arXiv:2102.09773 (Kharzeev, Levin)

- Modified theory (my simplified view, please consult their paper for further details)
  - Small multiplicities at HERA: corrections ~1/N
  - Leading order: have to use sea quarks, not gluon density

Summary

- New data by H1 on multiplicity distributions in Deep-inelastic scattering
- Reasonable description by “standard” HERA simulations, less so by modern generators (PYTHIA8, not yet tuned to DIS data)
- Differential measurement in Q^2, y, η, N → valuable input for MC tuning in view of the planned EIC collider. Data are on HEPDATA. About to release a rivet analysis

- Test of theory on quantum entanglement by means of the hadron entropy

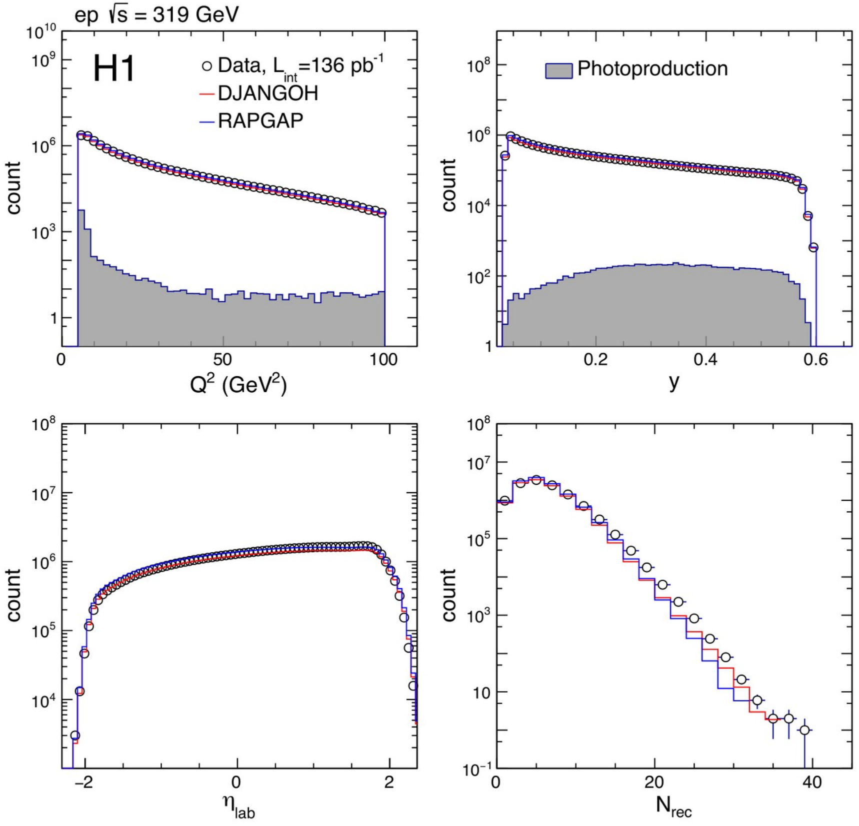
  → original predictions are not compatible with data

  → H1 data have been used to improve the theory

Backup slides

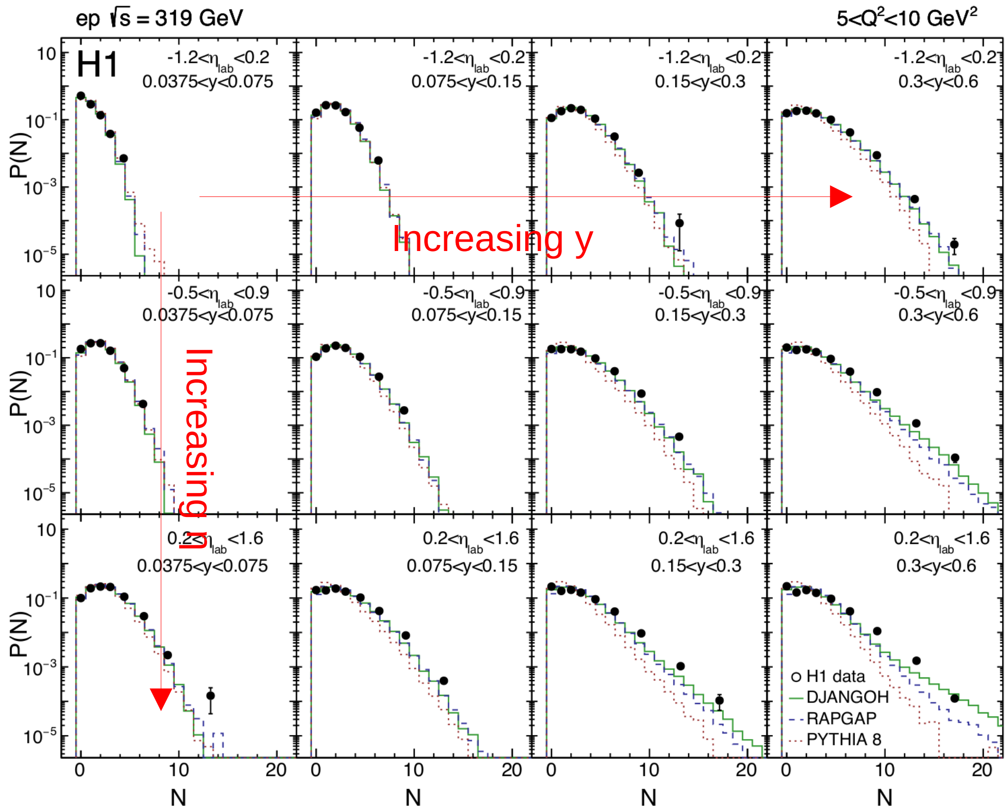
Data unfolding and control plots

- Control distributions well described
- Unfolding with TUnfold
- Binning in 3 dimensions: Q^2, y, N
- Fine binning for detector-level quantities as compared to truth
- Extra bins to control migrations from outside
- Repeated for different η regions



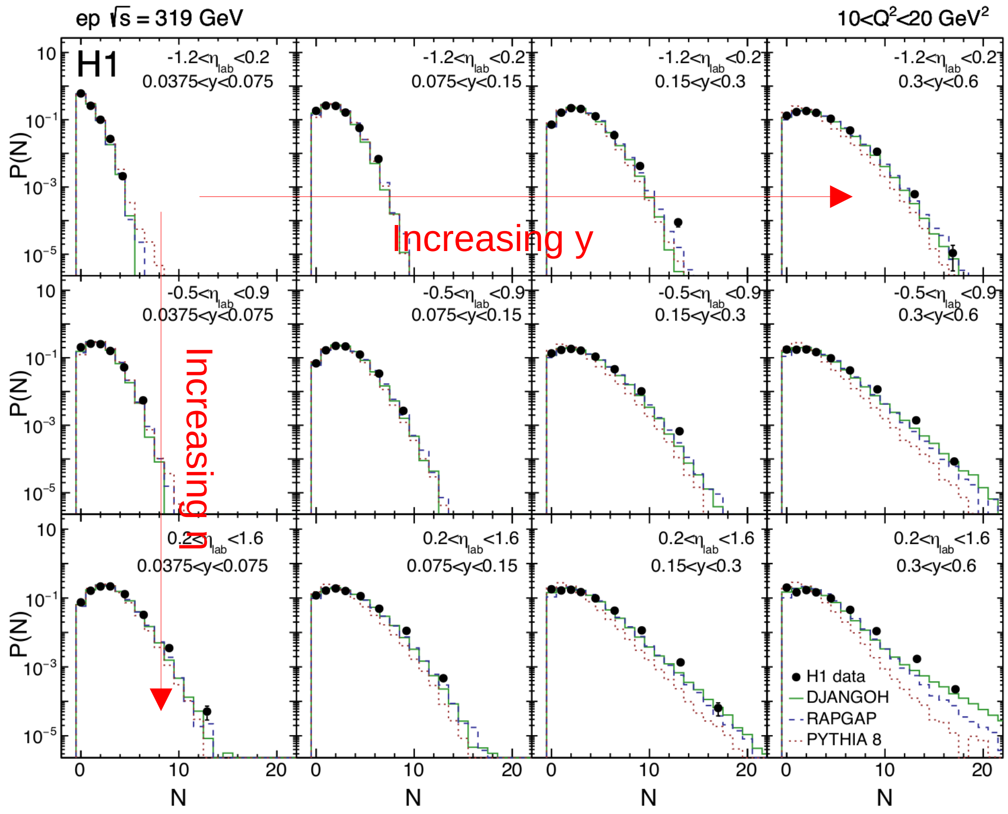
Measurements in η ranges, $5<Q^2<10$ GeV²

- P(N) is measured 4-differential in Q², y, η, N
- The η ranges overlap, to have sufficiently large bins (sufficiently large N)
- Four plots (4 Q² ranges)
- **Here: 5<Q²<10 GeV²**
- MCs have difficulties at high y and high η (forward region)



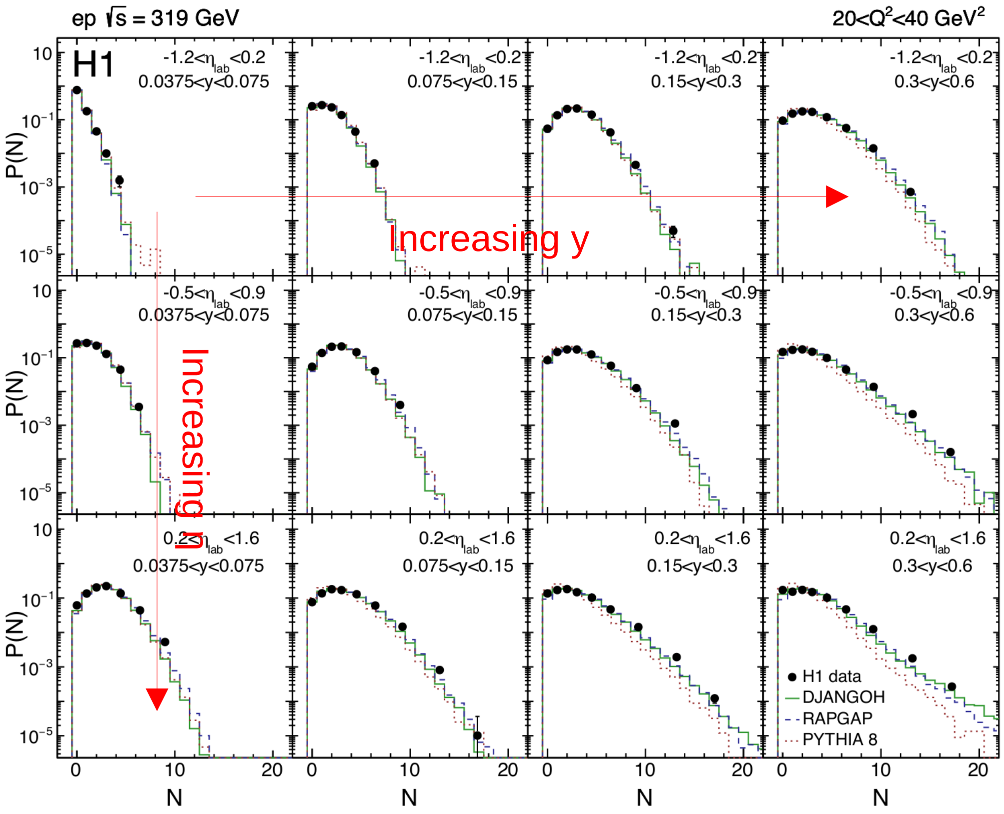
Measurements in η ranges, $10<Q^2<20$ GeV²

- P(N) is measured 4-differential in Q^2, y, η, N
- The η ranges overlap, to have sufficiently large bins (sufficiently large N)
- Four plots (4 Q^2 ranges)
- **Here: $10<Q^2<20$ GeV²**



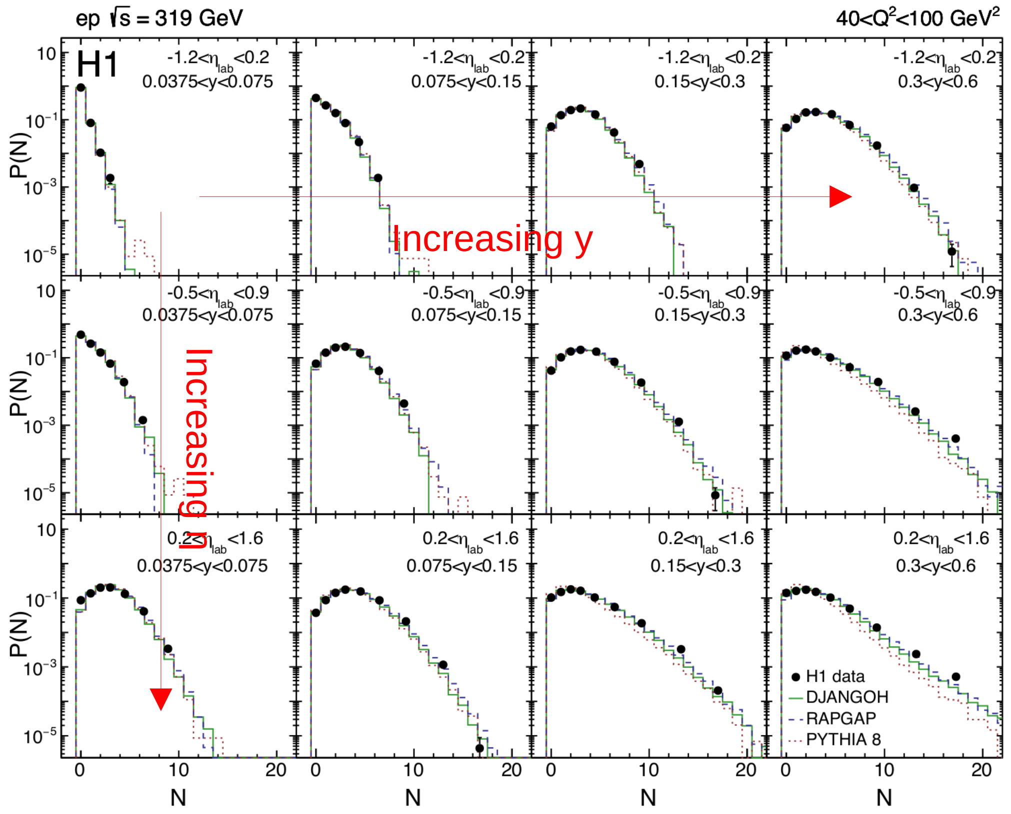
Measurements in η ranges, $20<Q^2<40$ GeV²

- P(N) is measured 4-differential in Q², y, η, N
- The η ranges overlap, to have sufficiently large bins (sufficiently large N)
- Four plots (4 Q² ranges)
- **Here: $20<Q^2<40$ GeV²**



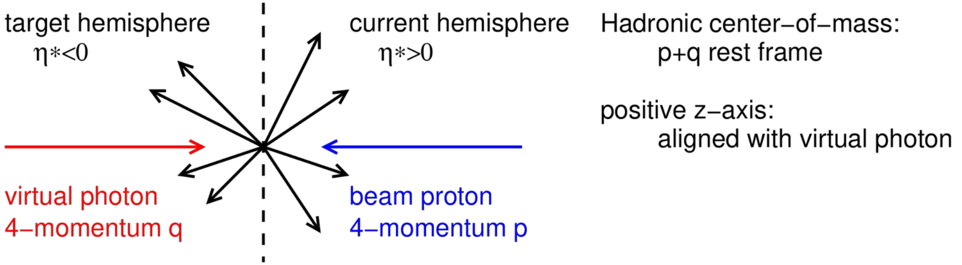
Measurements in η ranges, $40<Q^2<100$ GeV²

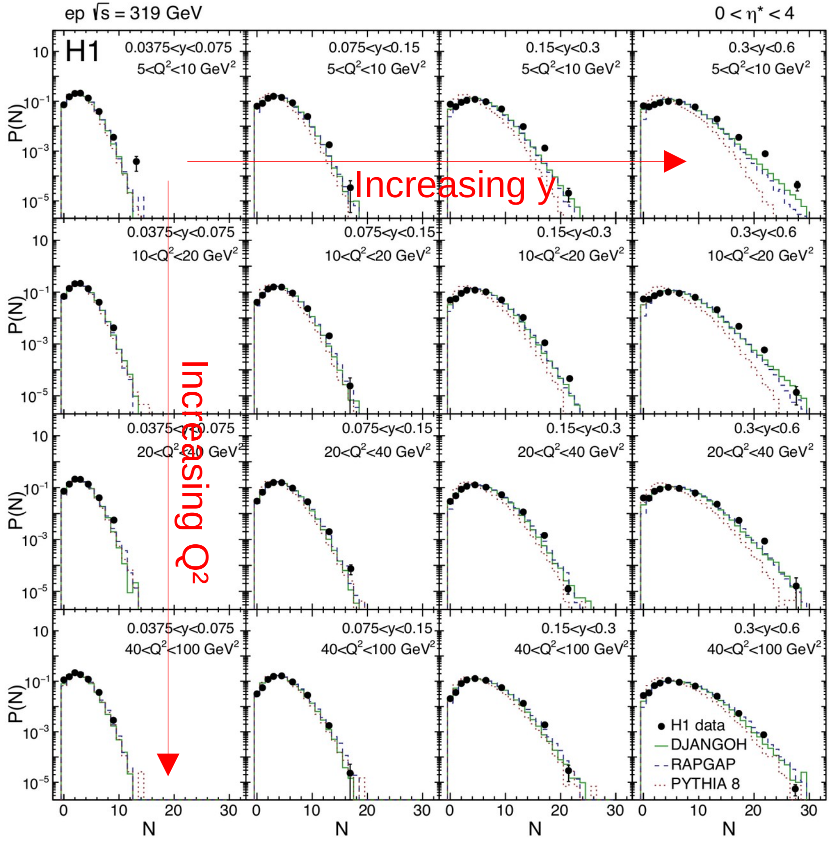
- P(N) is measured 4-differential in Q², y, η, N
- The η ranges overlap, to have sufficiently large bins (sufficiently large N)
- Four plots (4 Q² ranges)
- **Here: $40<Q^2<100$ GeV²**



Measurement with restriction on η*

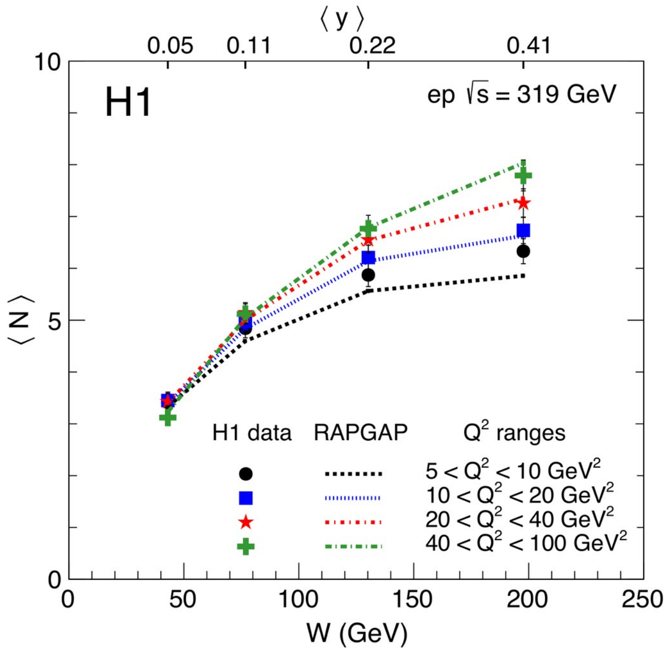
- Measurement with full range in laboratory frame, but restricted to the current region of the hadronic centre-of-mass frame
- Select η*>0 (sign of η* is ~opposite to η in laboratory frame)
- Results are similar to laboratory frame
- MC data agreement is poor at low Q^2 and high y (corresponds to high W & low-x)



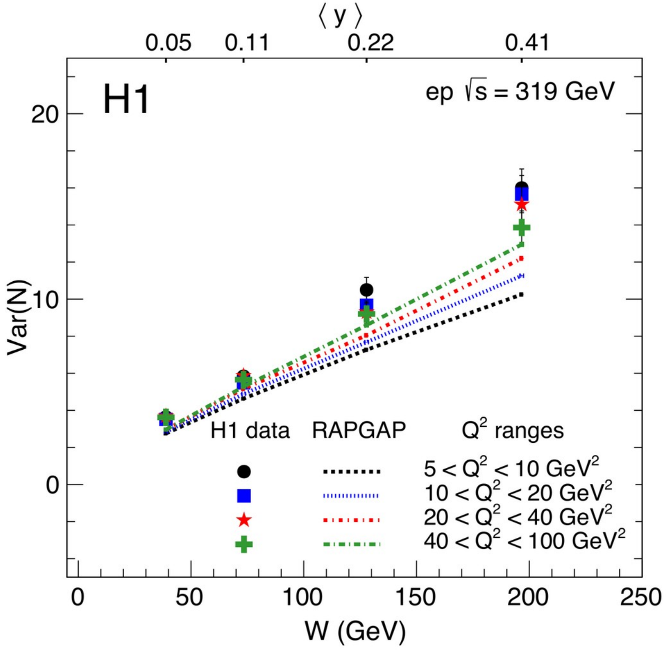


Moments of P(N)

- P(N) distribution measured: can also extract first and second moments
- Shown here as a function of Q^2 and W
- MC prediction underestimates average multiplicity and variance, in particular for low Q^2 and high W
- Similar results with restriction $\eta^*>0$ → paper



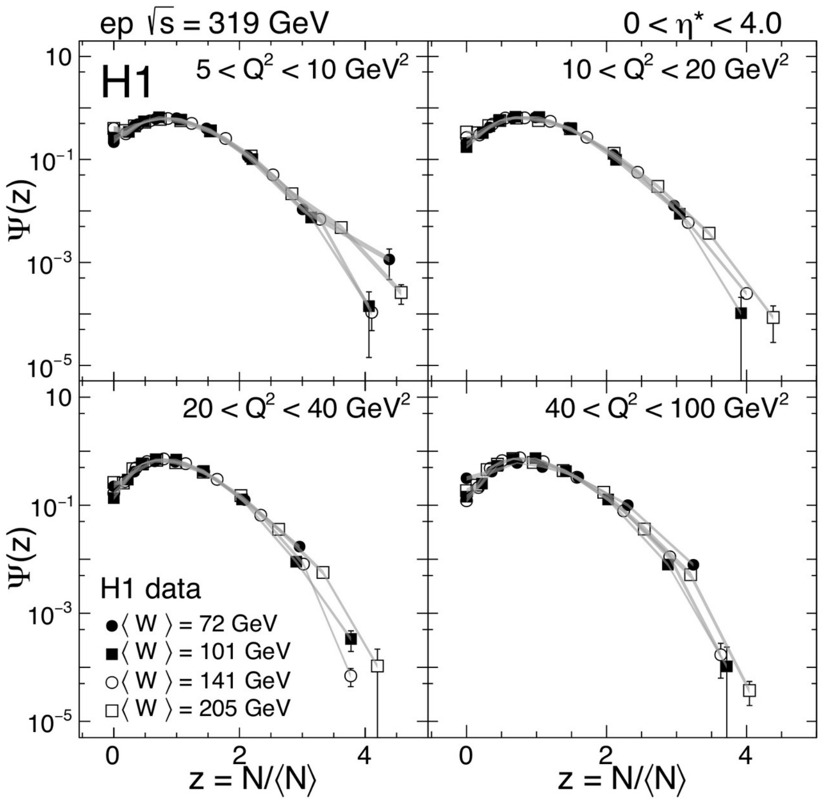
Average multiplicity



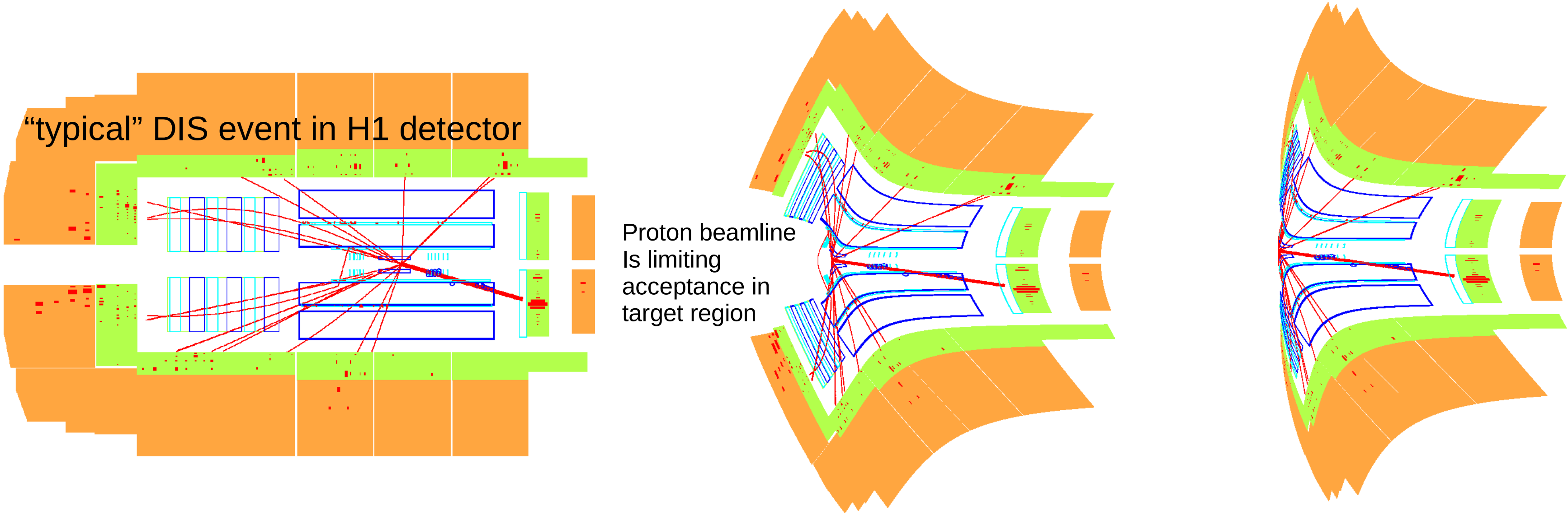
Variance of P(N)

KNO scaling

- KNO scaling: the shape of the multiplicity distribution, expressed as a function of z=N/<N> does not depend on the energy W
- For this experiment, KNO scaling is confirmed



HERA boost visualized



E_e=27.6 GeV E_p=920 GeV

Laboratory system

E_e=160 GeV E_p=160 GeV

ep center-of-mass system

E_e=54000 GeV

Proton rest-frame
c.f. fixed-target
experiment

Accelerators for particle physics at DESY

- DESY was founded in 1959
- German national laboratory for particle physics, accelerators, synchrotron sources
- Accelerators for particle physics
  - DESY 1964-1978 [6 GeV]
    Since 1978: used as pre-accelerator only
  - DORIS 1974-1992 [e^+e^- $\sqrt{s}$=12 GeV]
    1992-2012: used as synchrotron source
  - PETRA 1978-1986 [e^+e^- $\sqrt{s}$=45 GeV]
    1990-2007: pre-accelerator, since 2009 synchrotron source
  - **HERA 1992-2007 [$e^{\pm}p$ $\sqrt{s}$=320 GeV]**
- DESY accelerators in 2020

  → photon science

~8 km to city center