# Measurement of charged particle multiplicity distributions in DIS at HERA and its implication to entanglement entropy of partons

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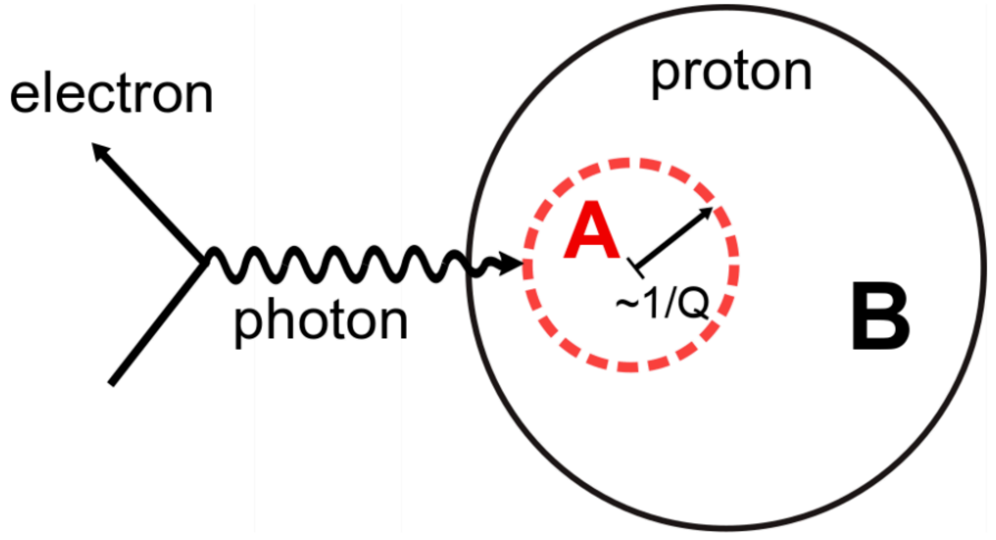
RICE

# Entropy in particle collisions

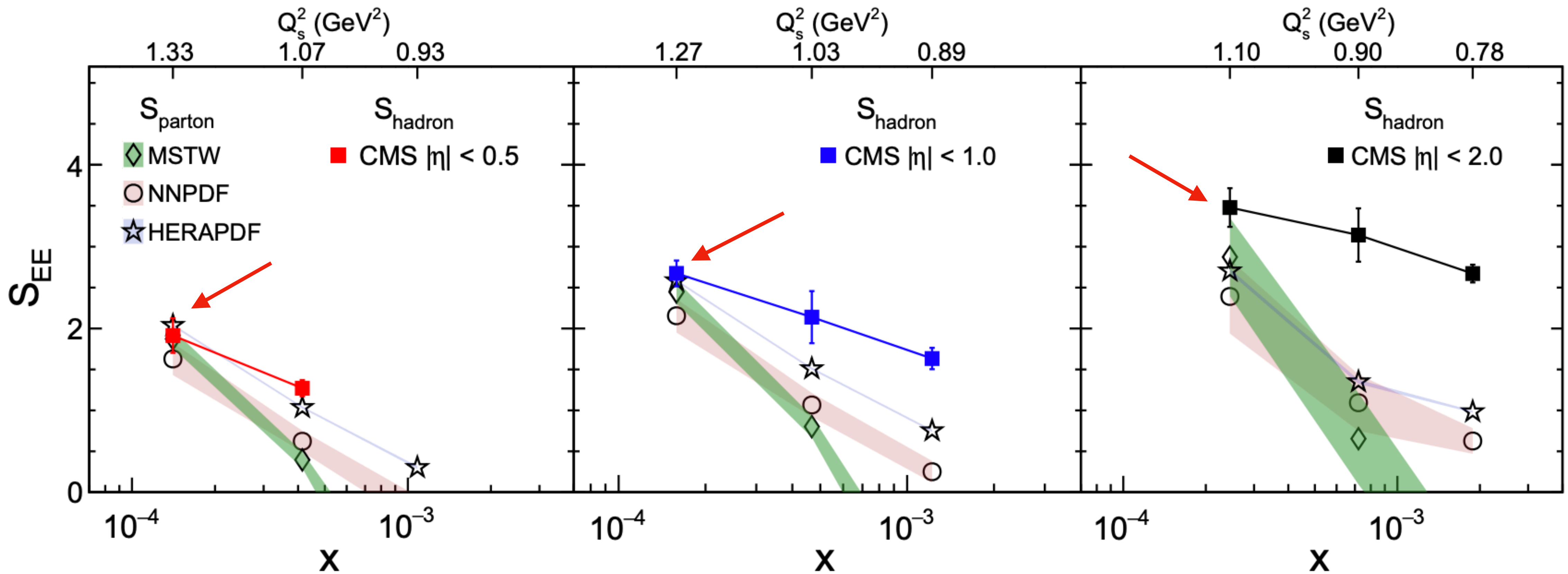
- Partons within a proton are confined and must combine to form a color-singlet state
  - The proton is a pure quantum state, $S_{proton} = 0$
  - How do we reconcile this with detailed proton substructure, i.e. incoherent partons having many potential micro states, so $S_{proton} \neq 0$ ?
- Theory prediction[1] that entanglement entropy of region A, of size ~1/Q, will be related to gluon pdf at sufficiently small x
  - $S_{gluon} = \ln[xG(x, Q^2)]$
- Assuming hadronization doesn't increase entropy much, this is predicted to equal the entropy calculated from the hadron multiplicity probability distribution
  - $S_{hadron} = -\sum P(N)\ \ln[P(N)]$
- Is it true that $S_{gluon} = S_{hadron}$?




1. D. Kharzeev and E. Levin, Phys. Rev. D 95, 114008 (2017)

# Supported in pp collisions?

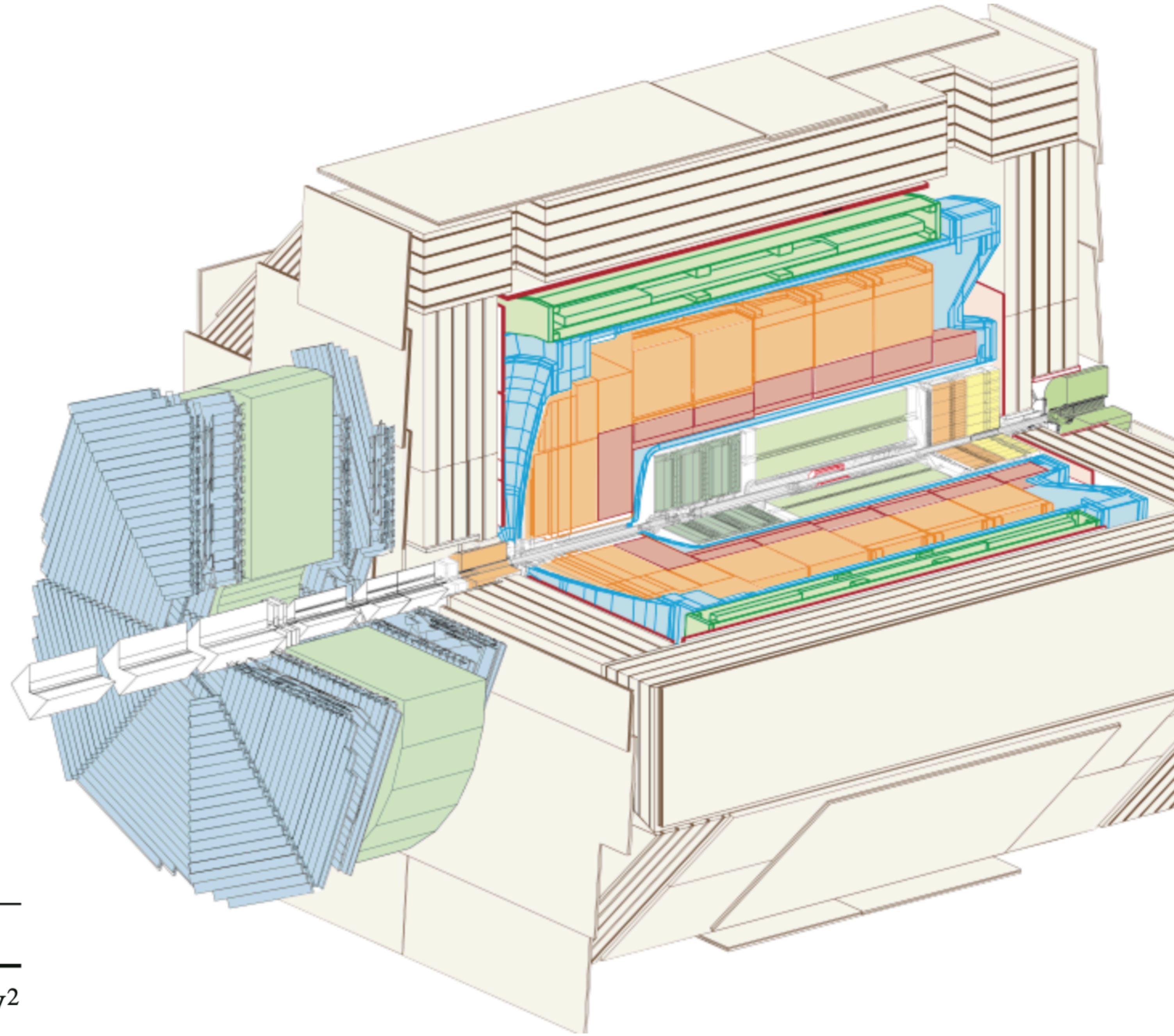
- Previous phenomenology studies using CMS pp multiplicity data indicate that this could be the case at low x
    - ‘Sub-nucleonic EPR paradox’
    - Analysis is complicated by the presence of two protons
- ep collisions can provide a much cleaner test




Phys. Rev. Lett. 124, 062001 (2020)

# H1 Detector

- Using 2006-2007 data
- 136 $pb^{-1}$ of $e^{+}p$ data
    - $\sqrt{s} = 318$ GeV
- DIS variables calculated using ECAL and tracking
- Multiplicity measurement uses both central and forward tracking for large kinematic coverage



| | Laboratory frame | HCM frame |
|---|---|---|
| $Q^2$ | $5 < Q^2 < 100\,\mathrm{GeV}^2$ | $5 < Q^2 < 100\,\mathrm{GeV}^2$ |
| $y$ | $0.0375 < y < 0.6$ | $0.0375 < y < 0.6$ |
| $p_{\mathrm{T,lab}}$ | $p_{\mathrm{T,lab}} > 150\,\mathrm{MeV}$ | $p_{\mathrm{T,lab}} > 150\,\mathrm{MeV}$ |
| $\eta_{\mathrm{lab}}$ | $-1.6 < \eta_{\mathrm{lab}} < 1.6$ | $-1.6 < \eta_{\mathrm{lab}} < 1.6$ |
| $\eta^*$ | – | $0 < \eta^* < 4$ |

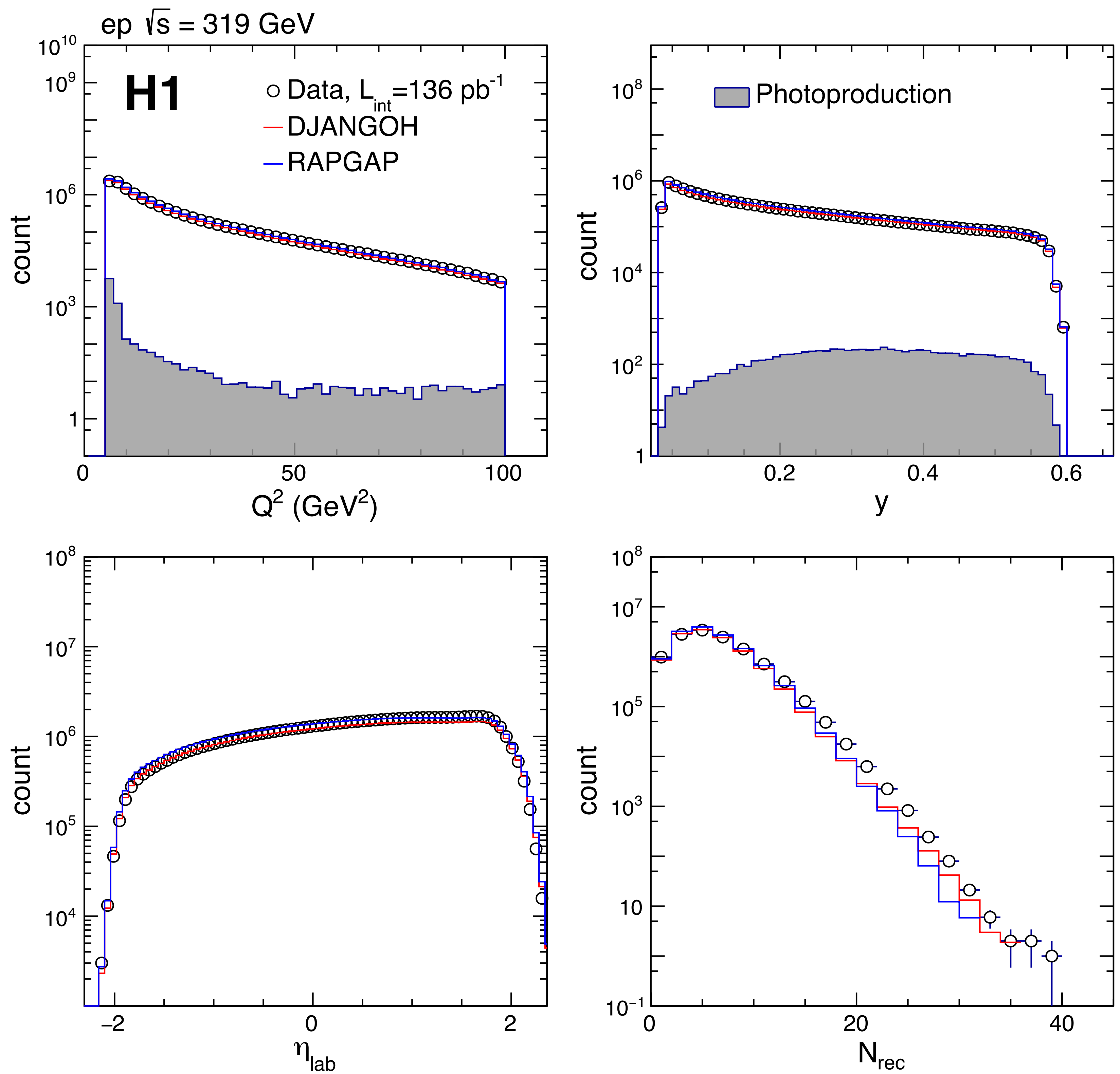
# MC Comparisons

- DIS variables calculated with ‘e-Σ’ method:

$$Q^2 = 4E_e E_e' \cos\frac{\theta_e}{2}^2,$$

$$y = 2E_e \frac{\Sigma}{[\Sigma + E_e'(1-\cos\theta_e)]^2}$$

$$x_{\mathrm{bj}} = \frac{Q^2}{sy}.$$

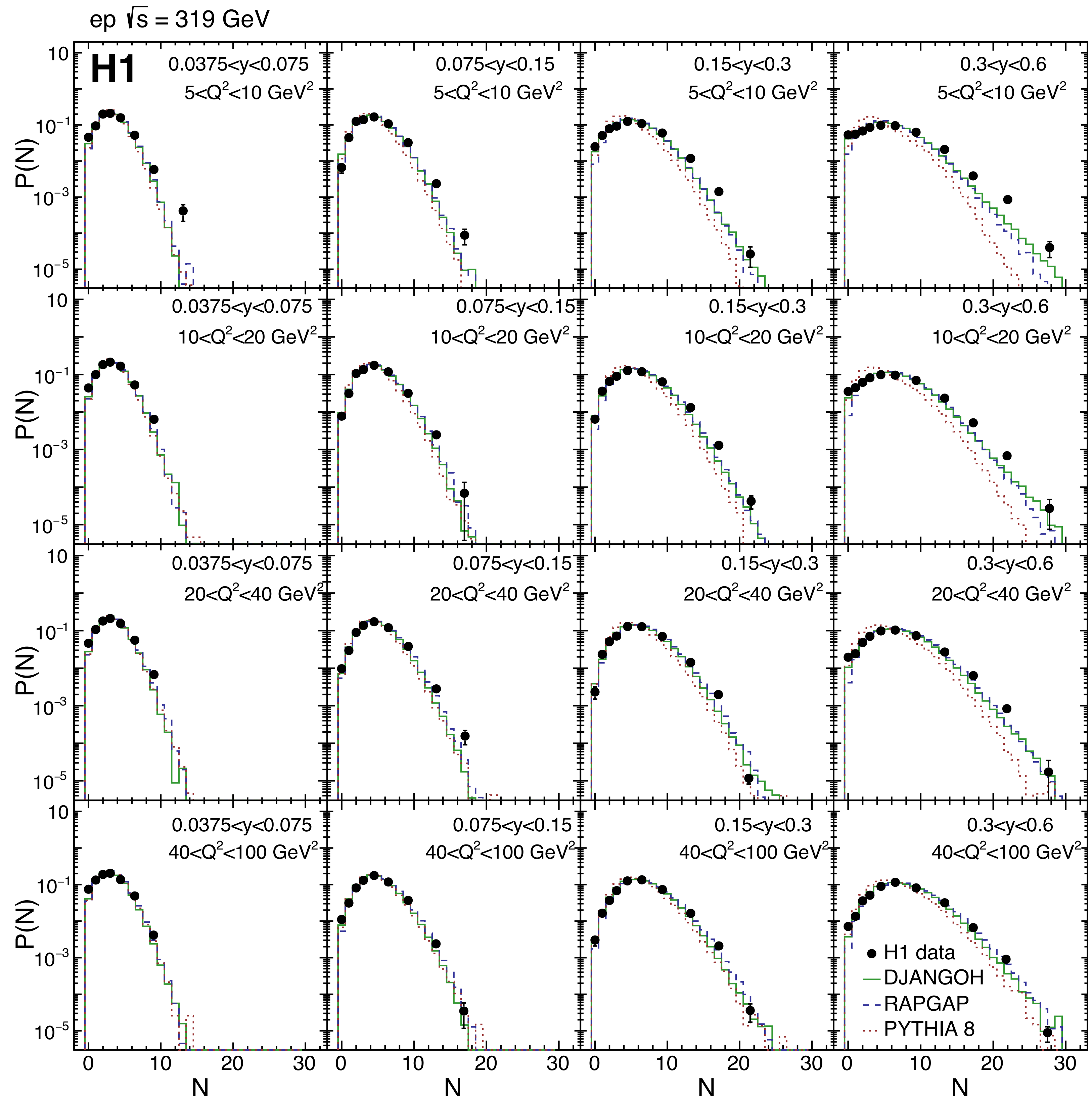



- Very good agreement for basic event reconstruction variables between data and MC

- Effects of photoproduction are found to be less than 0.5% in this analysis

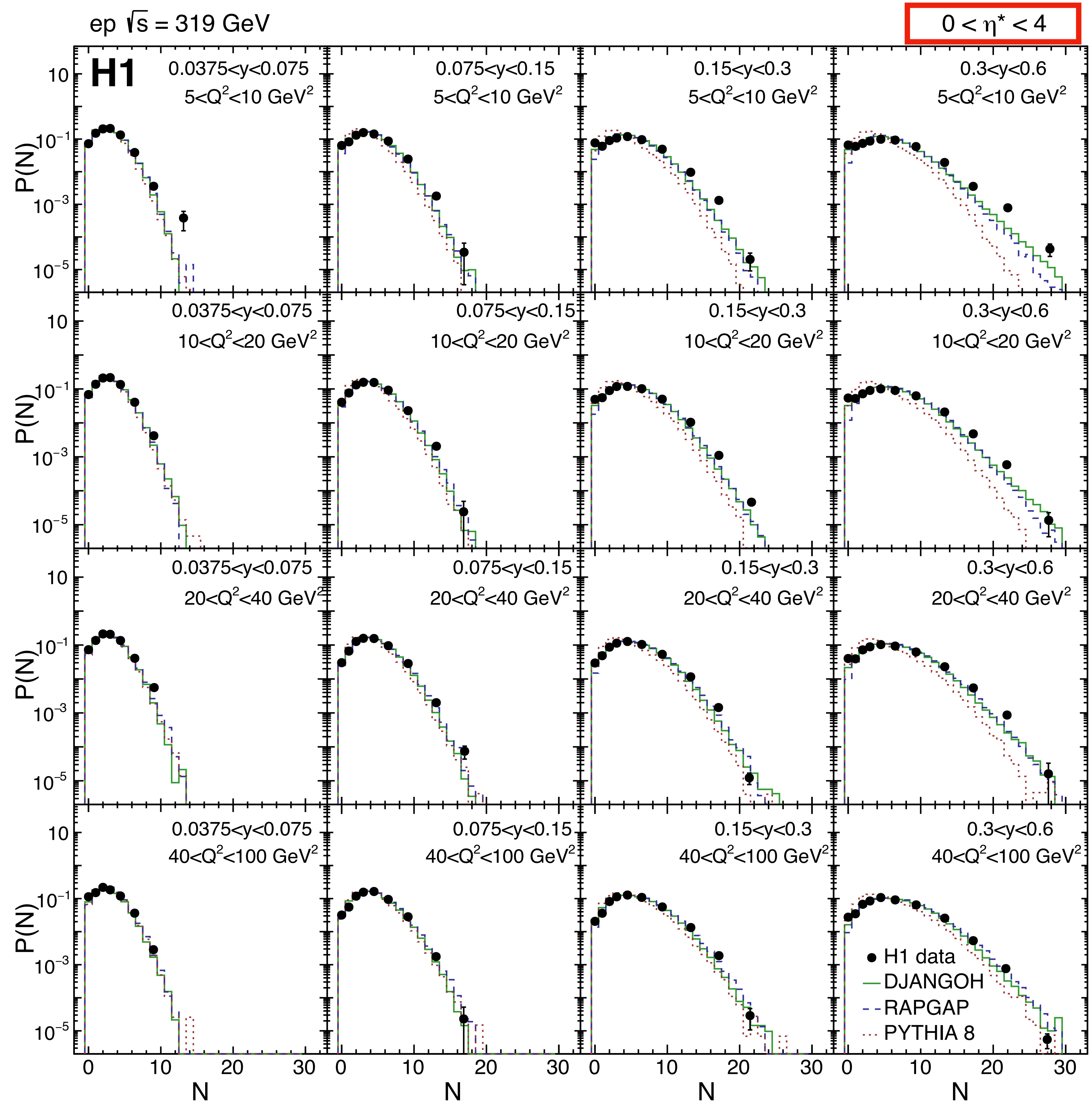
# Lab frame Multiplicity

- Measure multiplicity distribution P(N) vs Q², y
- Also measured in differential $\eta_{lab}$ windows (not shown)
- Large y leads to broader distribution of P(N)
  - Little Q² dependence
- MC matches data well around peak of distribution but under predict at high and low multiplicity
- RAPGAP and DJANGOH seem to agree better than PYTHIA 8



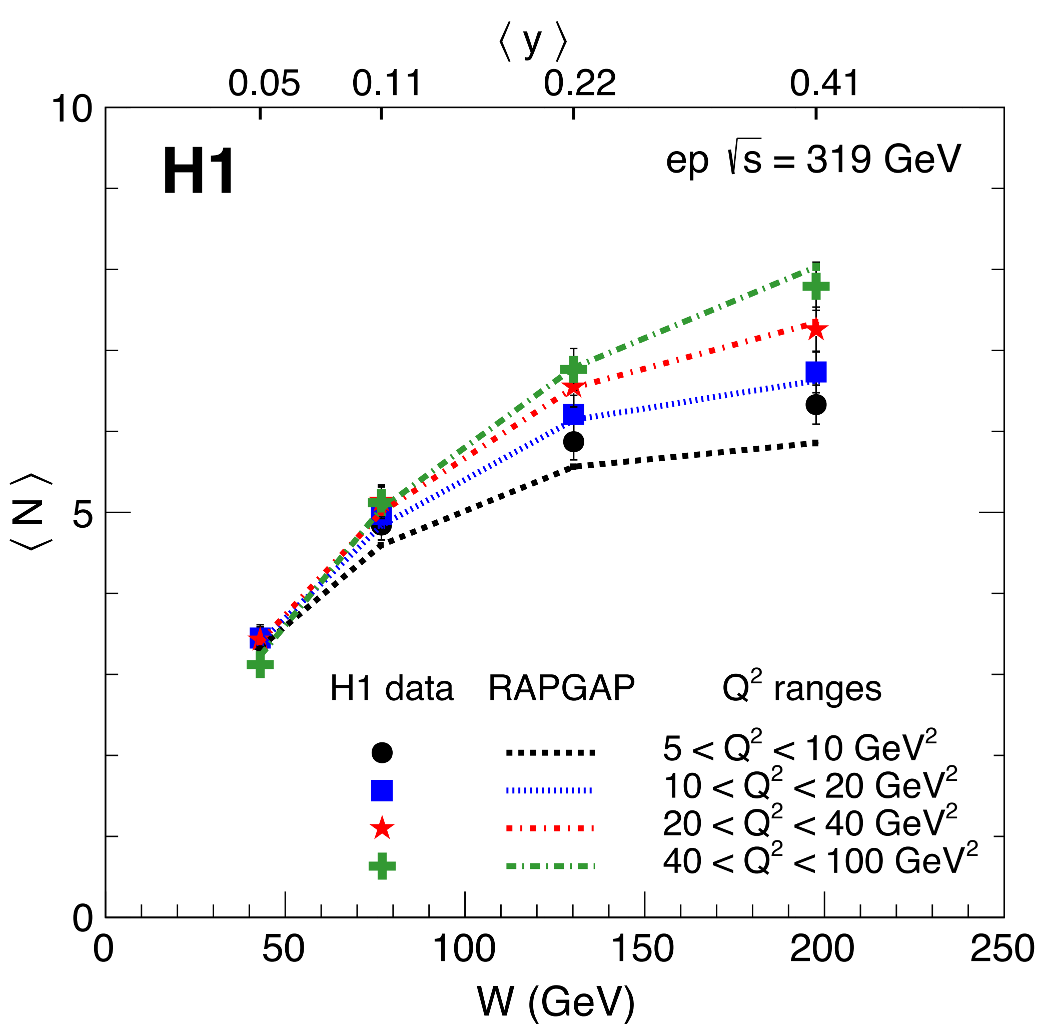
# HCM Multiplicity

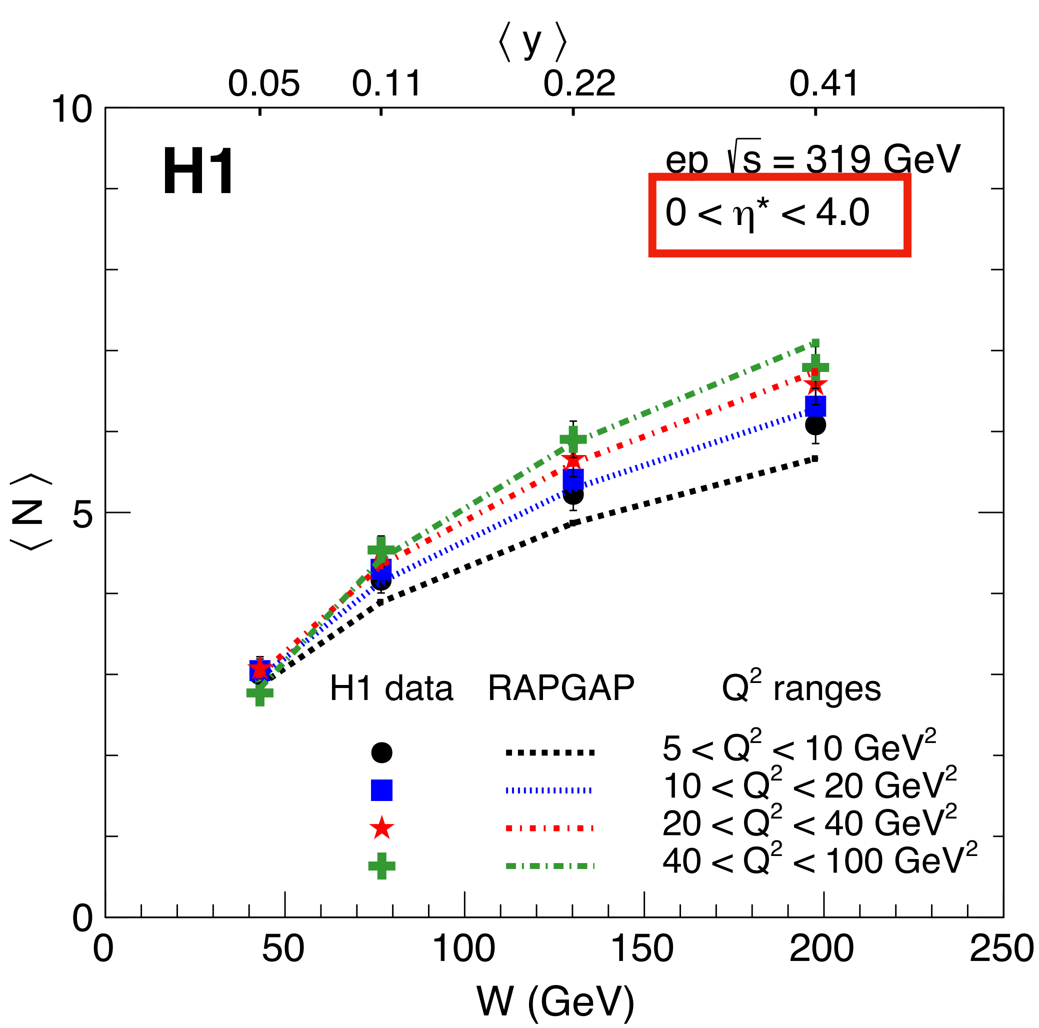
- Hadronic Center of Mass (HCM) frame defined by: $p + q = 0$
- Define positive $\eta^*$ as photon-going hemisphere in HCM frame
  - Similar conclusions as lab frame
- In further plots, only RAPGAP is shown but DJANGOH gives similar results



# Average Multiplicity

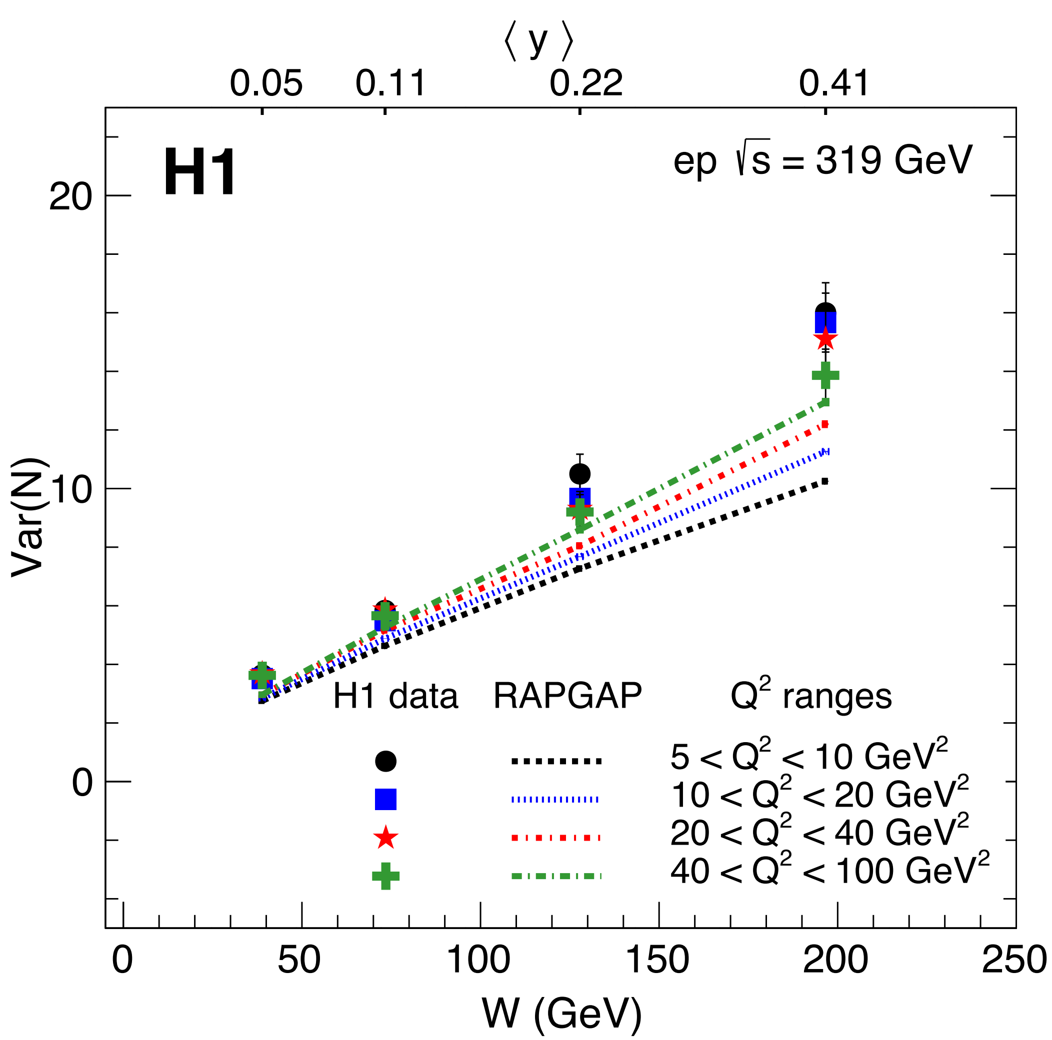
- $\langle N \rangle$ calculated as a function of $W = \sqrt{sy - Q^2 + M_P^2}$, hadronic CoM energy
- More particles produced with higher W, as expected
  - Larger $Q^2$ causes quicker increase vs W
- Reasonable agreement between data and RAPGAP

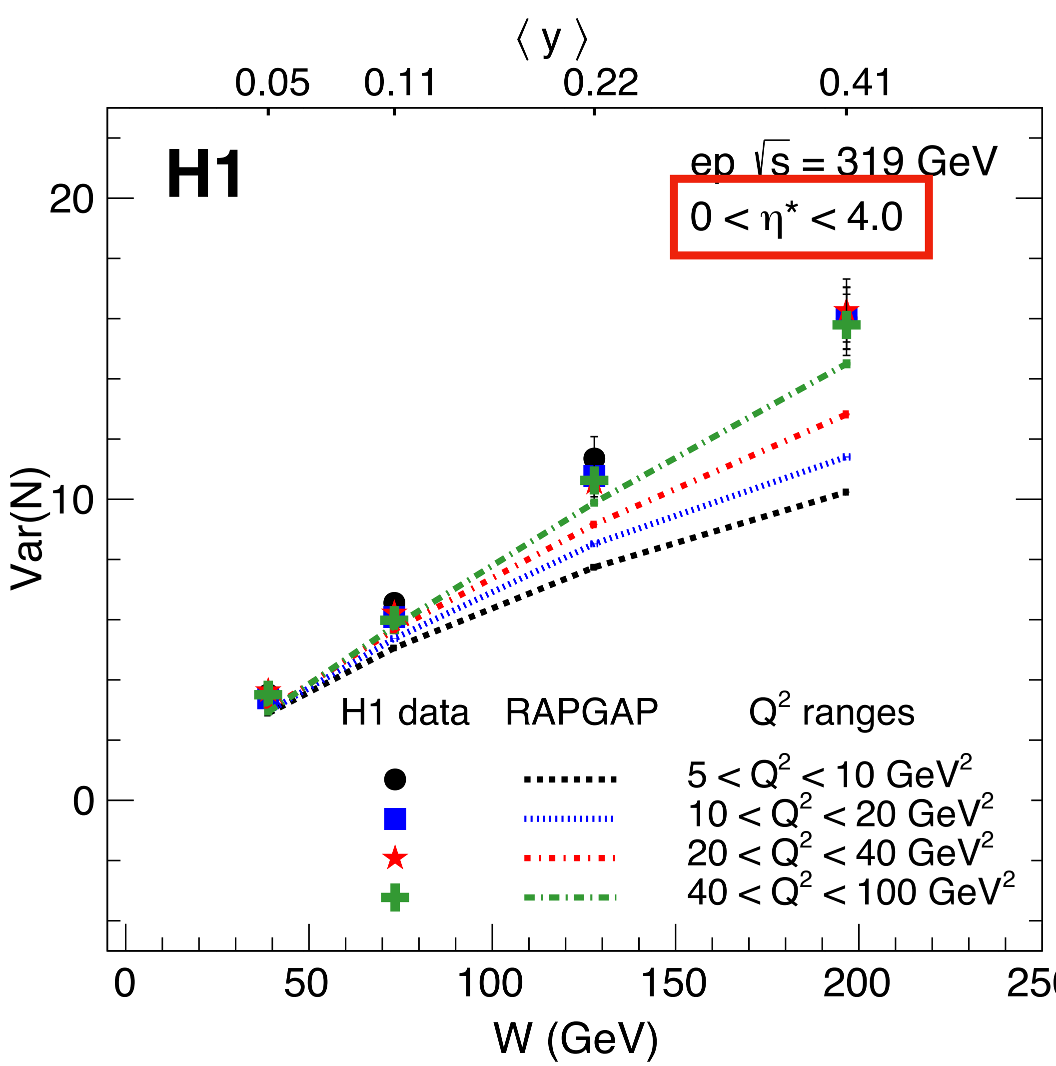


# Multiplicity variance

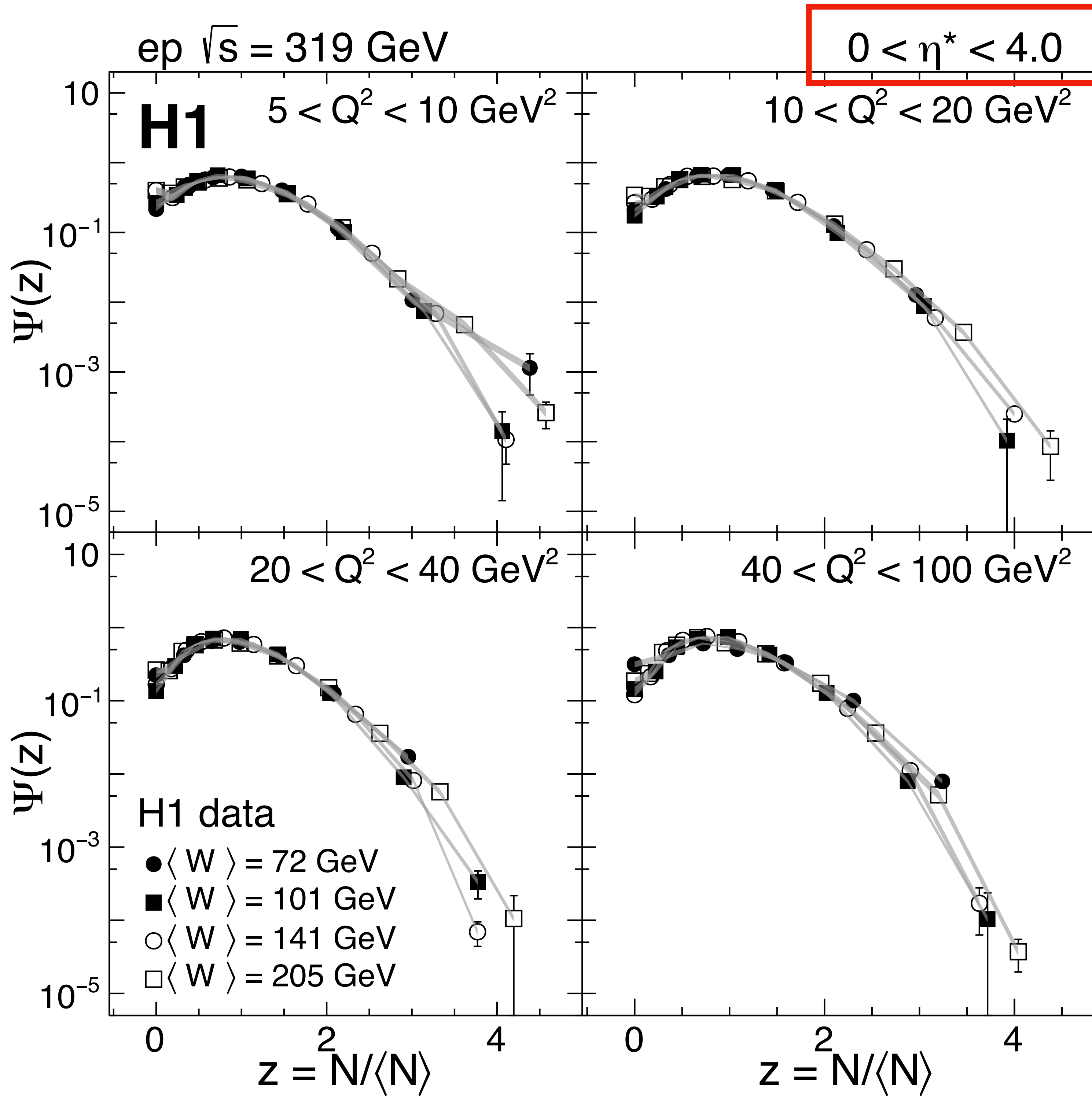
- Variance of N vs W
- Variance strongly rises with W, very little $Q^2$ dependence observed.
- Hemisphere restriction does not affect Var(N) much
- MC does a good job for high $Q^2$ but seems to under predict data at lower $Q^2$



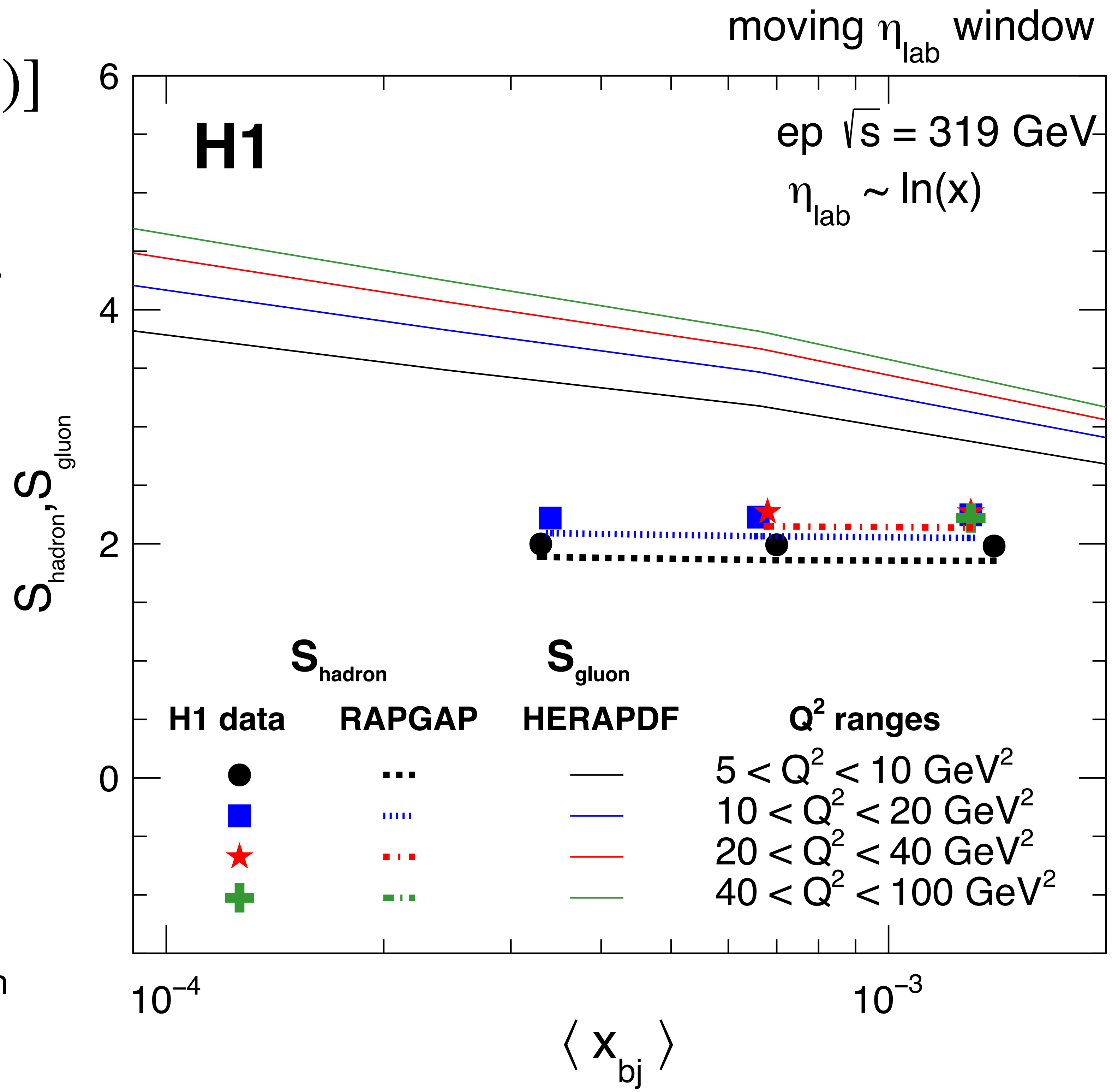
# KNO Scaling

- $\Psi(z) = \langle N \rangle P(N)$
    - Predicted to only be a function of z and not other variables 'KNO scaling'
- Calculated in the HCM frame
- KNO scaling observed, as seen in many previous experiments



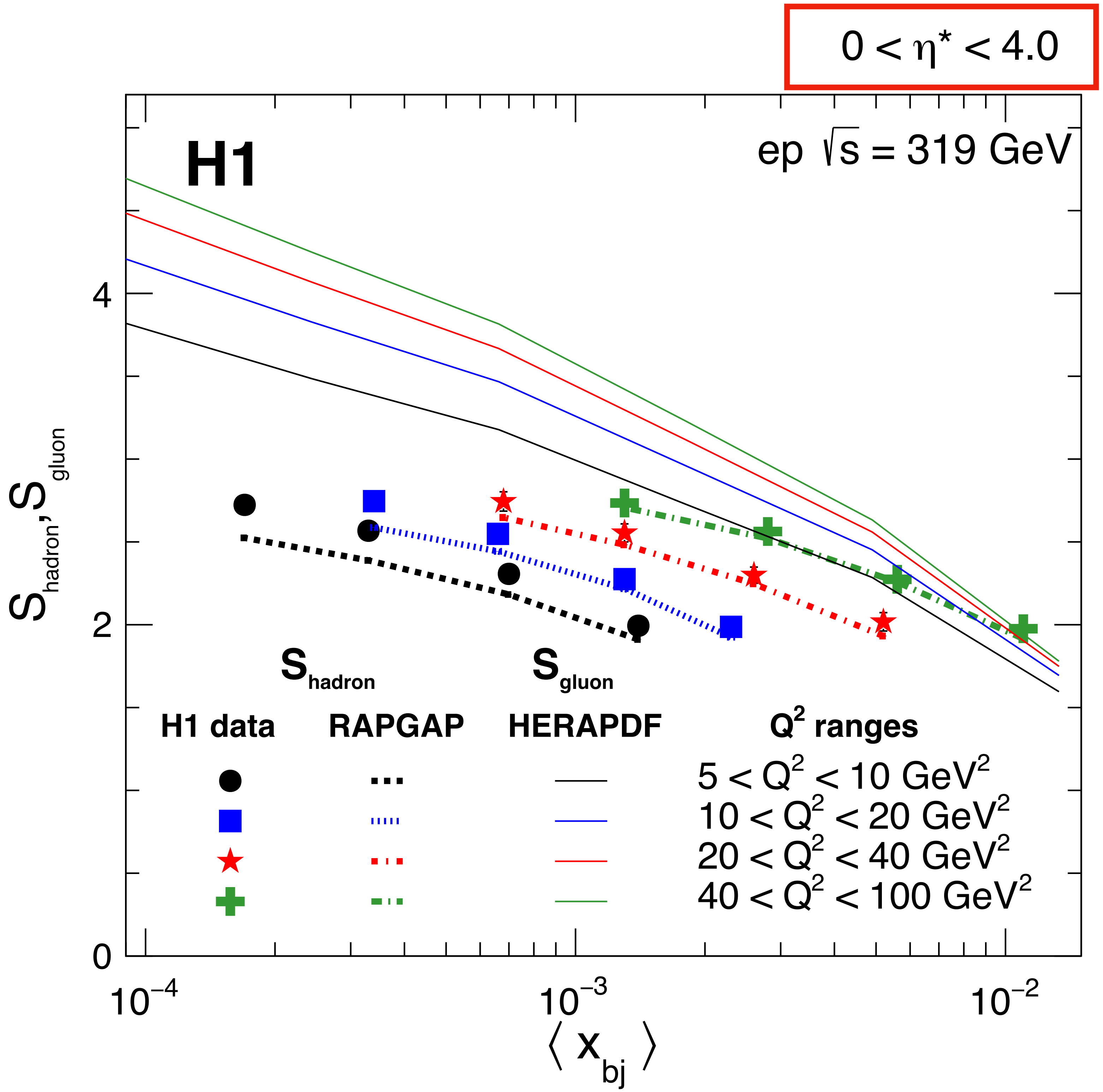
# $S_{hadron}$ vs. <x>

- $$S_{hadron} = -\sum P(N)\ \ln[P(N)]$$
  - Multiplicity calculated in $\eta_{lab}$ window based on <x> using LO Quark Parton Model (QPM)
  - Very little x dependence, slight increase with $Q^2$
- $$S_{gluon} = \ln[xG(x, Q^2)]$$
  - Data do not agree with $S_{gluon}$ from HERAPDF



# HCM frame

- No sliding $\eta_{lab}$ cut applied in HCM frame
- Similar rising behavior seen for different $Q^2$
- RAPGAP generally agrees with data
    - Slight deviations related to differences seen in P(N) distributions
- $S_{gluon}$ predictions from HERAPDF do not match $S_{hadron}$



# Conclusions

- P(N) distributions measured vs Q², y, $\eta$
  - MC generally matches data well
- P(N) moments measured vs Q², W
- KNO scaling seen in these data
- Data do not support $S_{hadron} = S_{gluon}$
- Important data for understanding particle production and entanglement at sub-nucleonic scales

Full paper at:
Eur. Phys. J. C 81 (2021), 212