Probing quantum entanglement and collectivity effects in ep collisions at HERA

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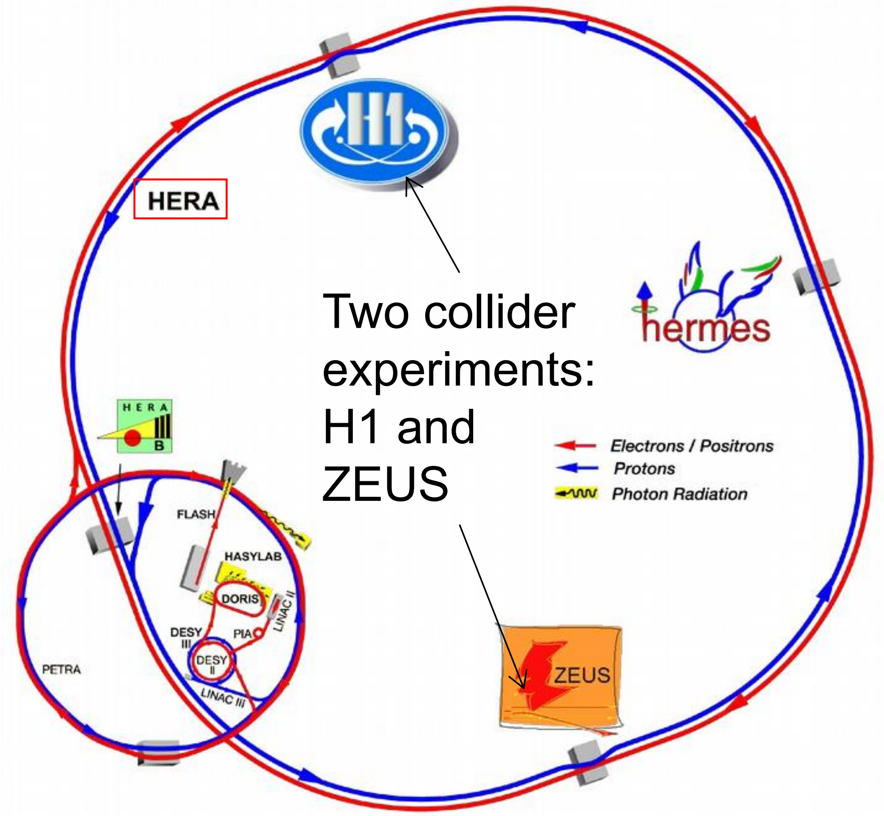
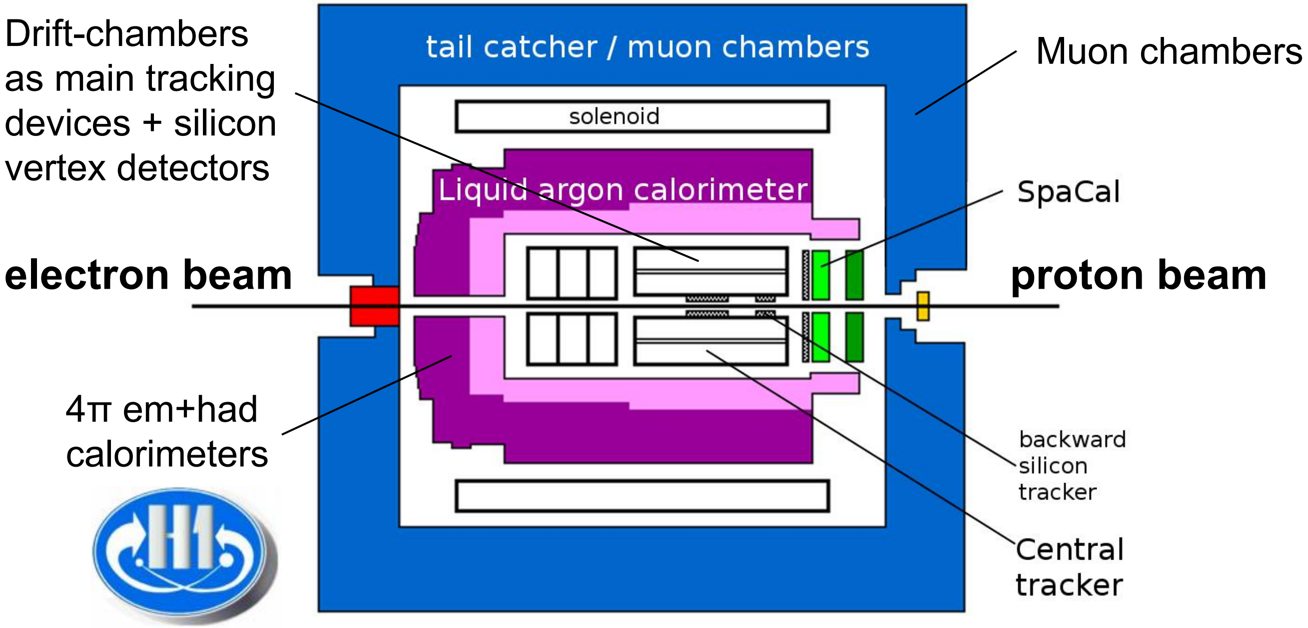
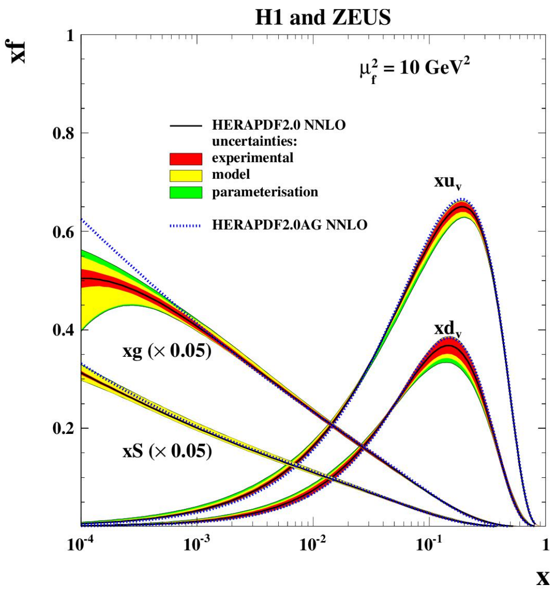
HERA Collider
Operated from 1992 to 2007
Circumference 6.3 km
Asymmetric detectors
Electrons or positrons colliding with protons
E_e=27.6 GeV, E_p=460 - 920 GeV
Centre-of-mass system is boosted to proton-direction

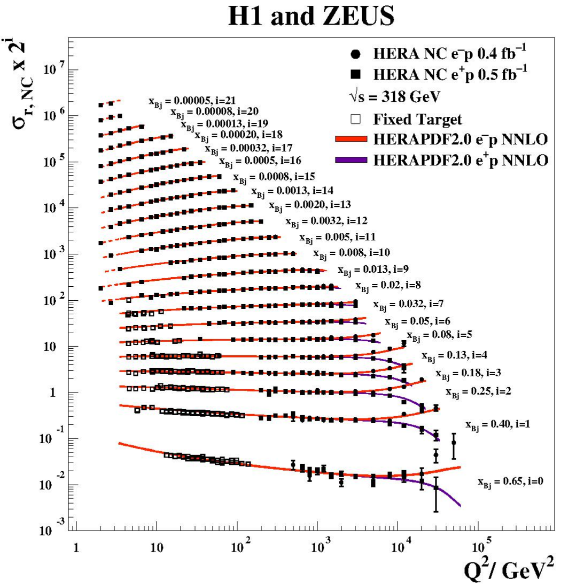




H1 Detector
Central tracker acceptance $|\eta|<1.6$
LAr calorimeter for hadronic final state
SpaCal calorimeter for detecting electrons with $5<Q^2<100$ GeV^2

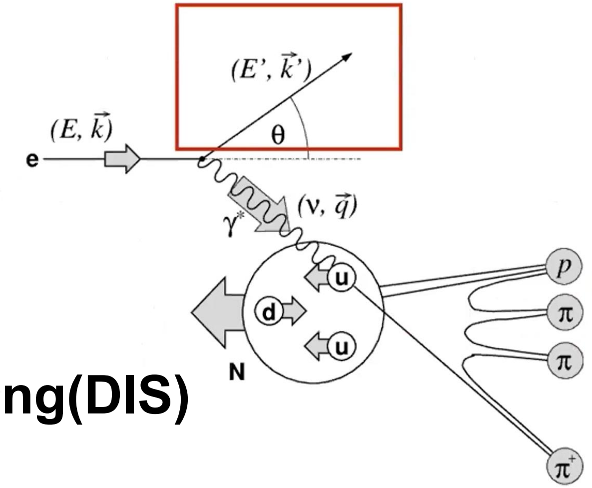
Nucleon Structure





Eur. Phys. J. C (2015)75:580

Our understanding is mostly based on
1D nucleon structure function, Parton Distribution Functions(PDFs)...
Parton correlation, as well as dynamical picture of partons inside nucleon are not well-understood

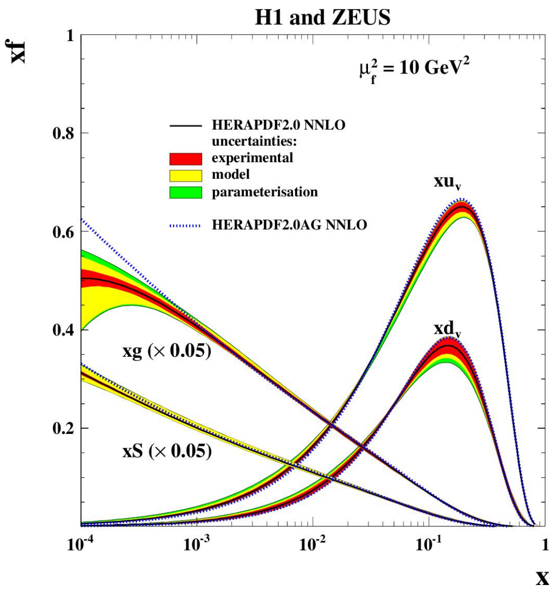


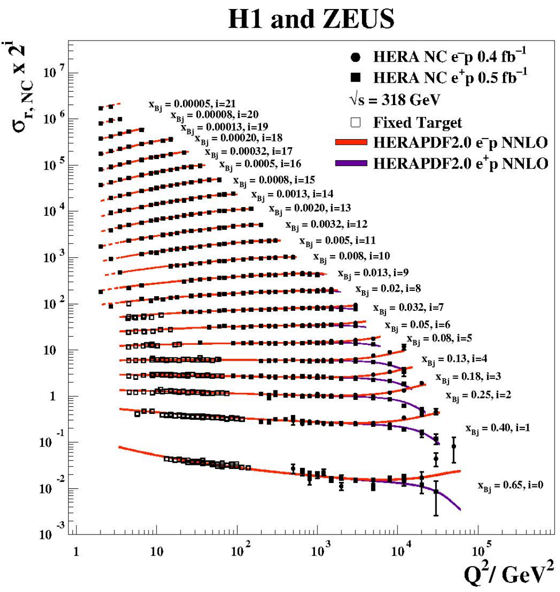
In order to explore parton correlation, two approaches used:
Predictions from quantum entanglement; Collectivity

Dataset
Operated from 2006 - 2007
Beam energy: E_e=27.6 GeV, E_p=920 GeV
Integrated luminosity: 136 pb^{-1}

Deep Inelastic Scattering(DIS) kinematics:
momentum transfer squared: $Q^2=(k-k')^2$
momentum fraction of struck quark: x

Nucleon Structure





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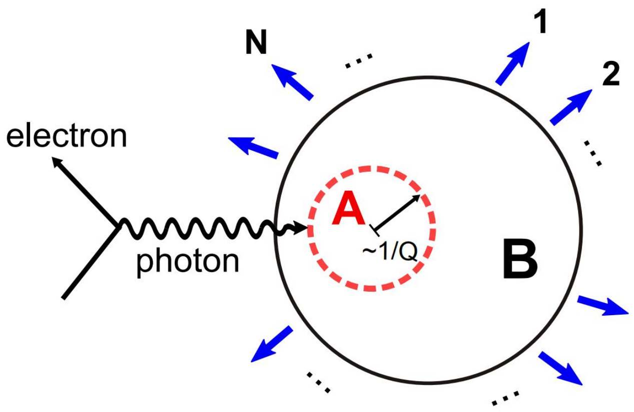
In DIS, **Quantum entanglement** as a probe of parton correlation:



Regions A and B are entangled
-> entropy

Compare $S_{gluon} = \ln[xG]$

PRD 95, 114008 (2017)

gluon density from PDFs

with $S_{hadron} = -\sum P(N) \ln[P(N)]$

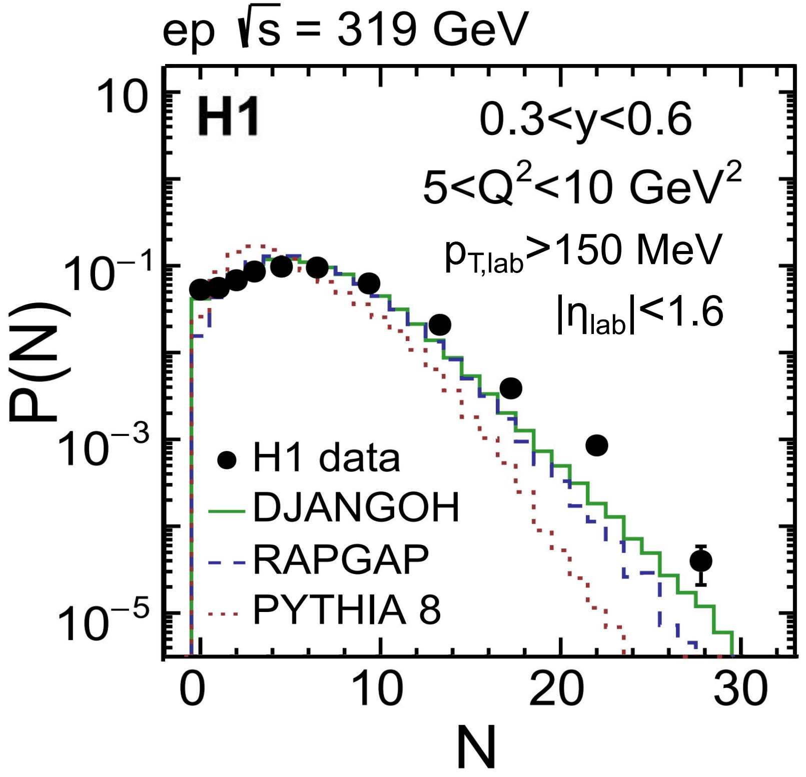
hadron multiplicity distribution P(N)

Theory prediction $S_{gluon} = S_{hadron}$

Quantum entanglement in ep DIS

Charged particle multiplicity distribution P(N)

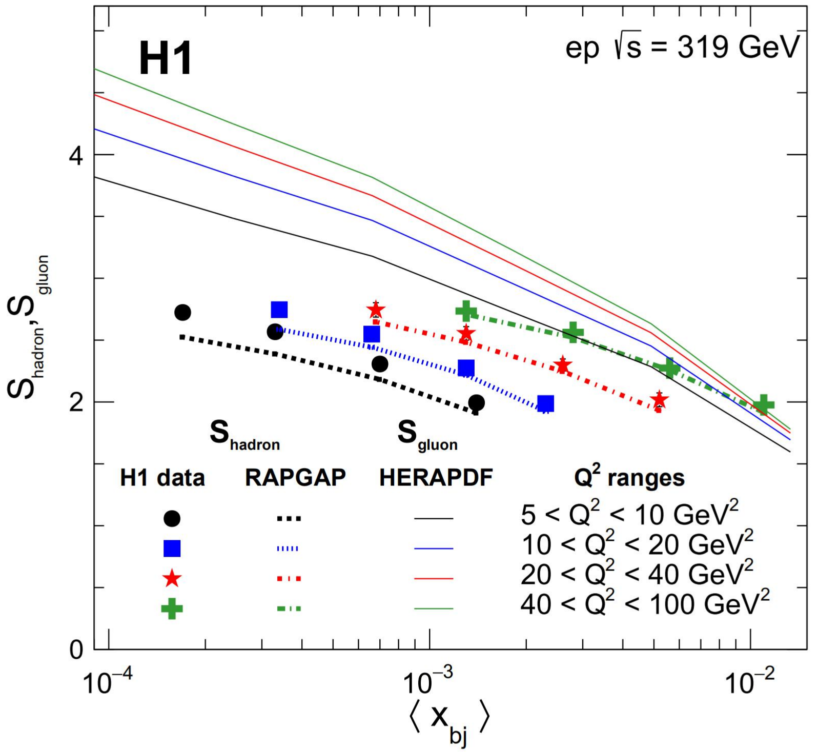
Eur.Phys.J.C 81 (2021) 3, 212



Predictions based on quantum entanglement

$$S_{\text{hadron}} \equiv -\sum P(N) \ln P(N) = \ln[xG(x,Q^2)] \equiv S_{\text{gluon}}$$

$0 < \eta^* < 4.0$ **HCM frame**



The charged particle multiplicity distributions are measured for particles on a 4x4 grid in x and Q^2

High multiplicity: MC cannot fully explain data

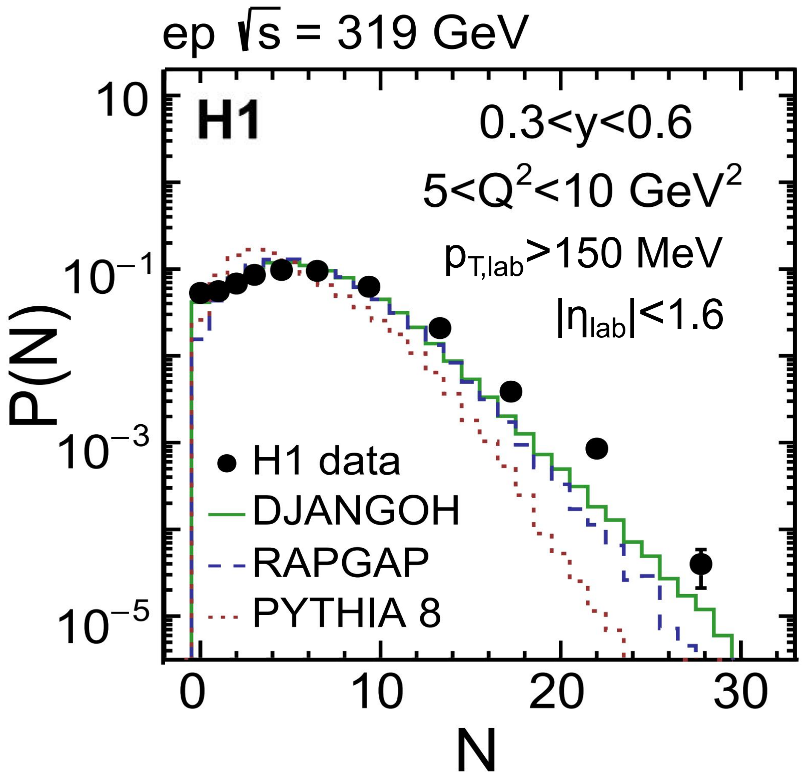
Entropy of gluons disagree with the hadron entropy

Data does not support the prediction

Quantum entanglement in ep DIS

Charged particle multiplicity distribution P(N)

Eur.Phys.J.C 81 (2021) 3, 212



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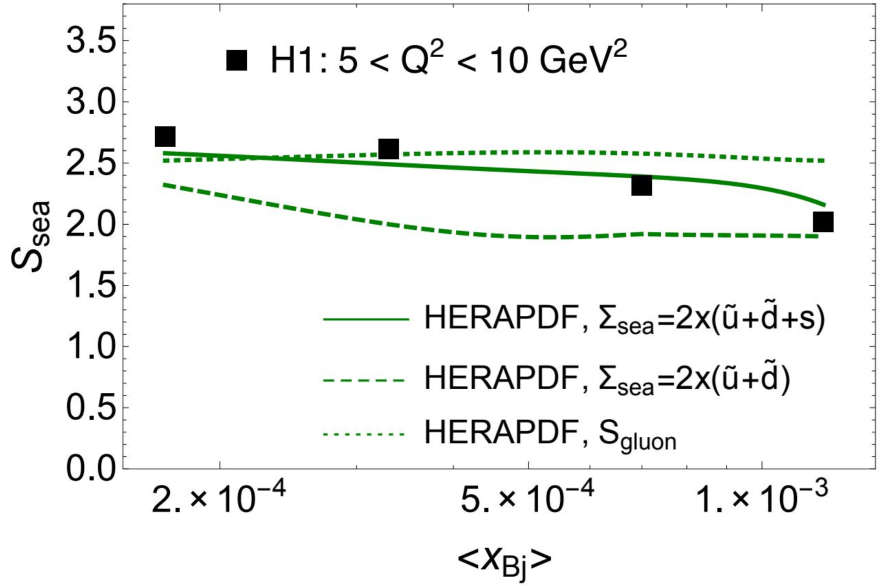
arXiv:2102.09773 [hep-ph]

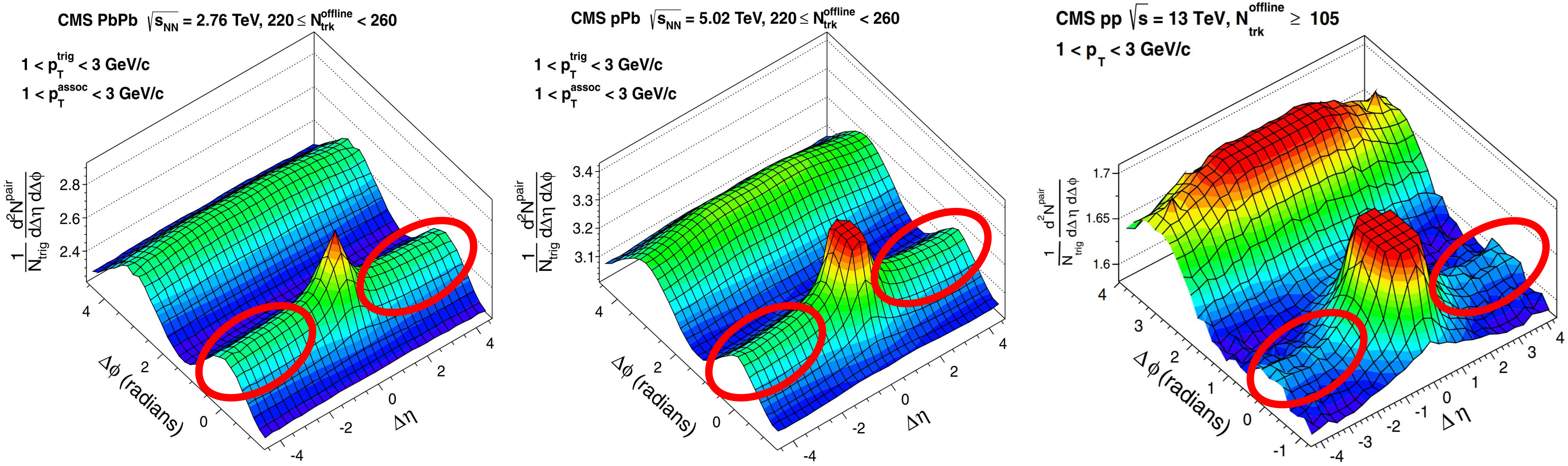
Two effects: Hadron multiplicity N not large; In current fragmentation region, structure function is not gluon but sea quark;



Entropy of sea quark agrees with the hadron entropy

Collectivity in small system

PLB 724 (2013) 213–240; PRL 116, 172302 (2016)



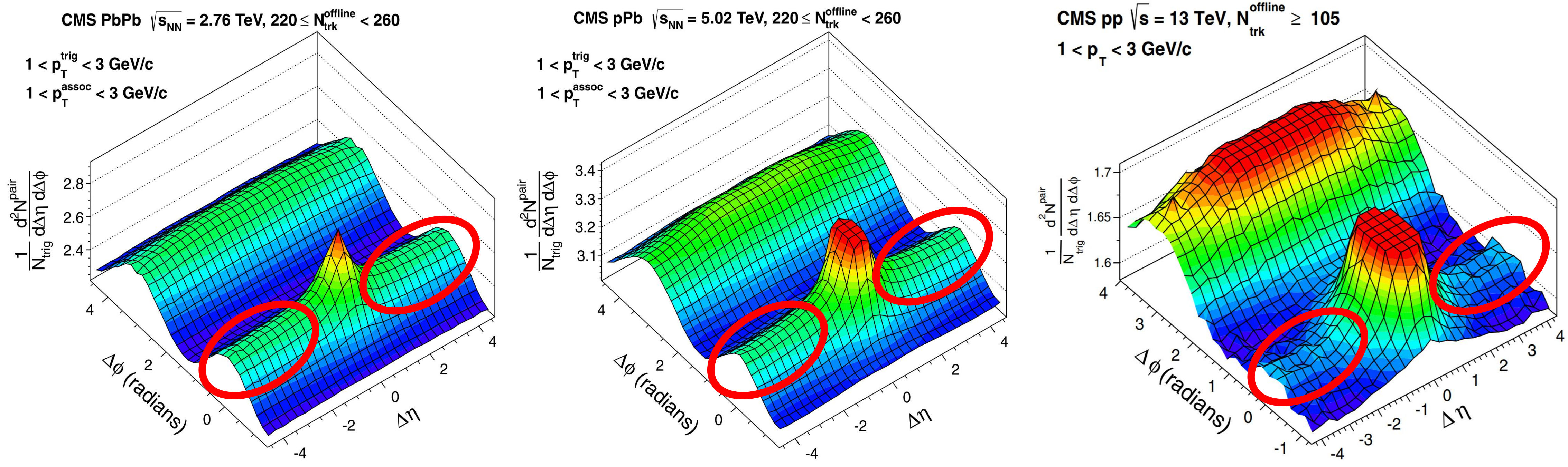
Collectivity as a probe of parton correlation:

Lots of evidence of collectivity in high multiplicity pp and pPb collisions, similar to heavy-ion collisions attributed to the perfect liquid nature of QGP

What about even smaller system?

Collectivity in small system

PLB 724 (2013) 213–240; PRL 116, 172302 (2016)



Collectivity as a probe of parton correlation:

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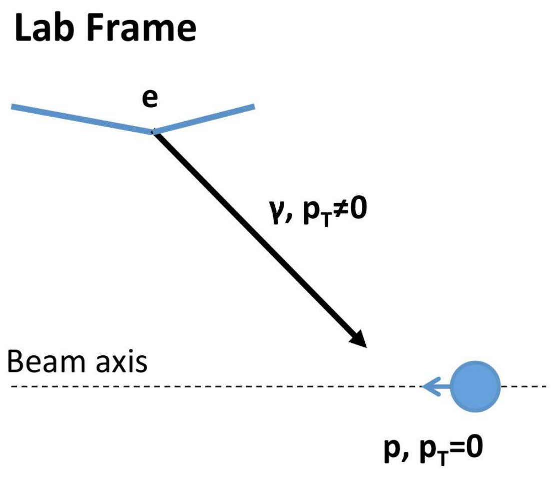
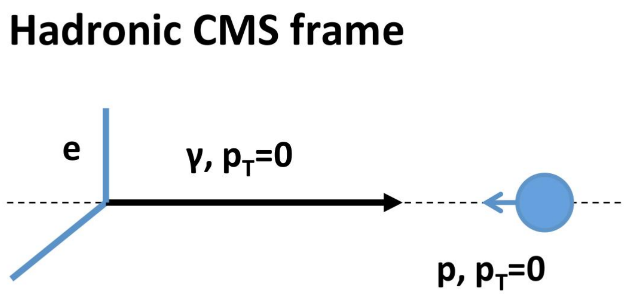
What about even smaller system?

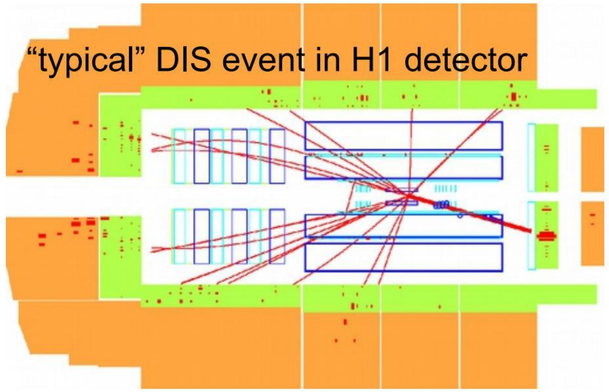
In DIS and photoproduction events:

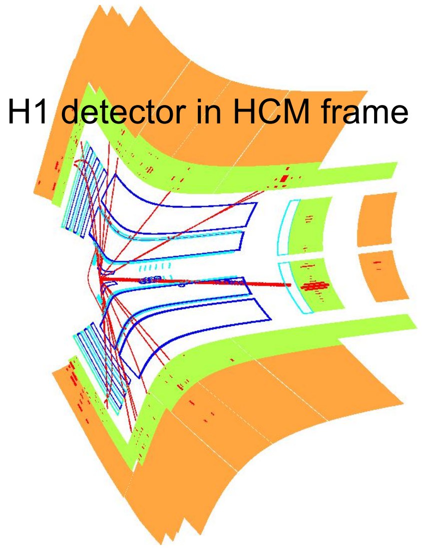
Two-paticle correlation(Ridge, $V_{n\Delta}$), Four-particle correlation($C_2\{4\}$)

Search for collectivity in ep DIS









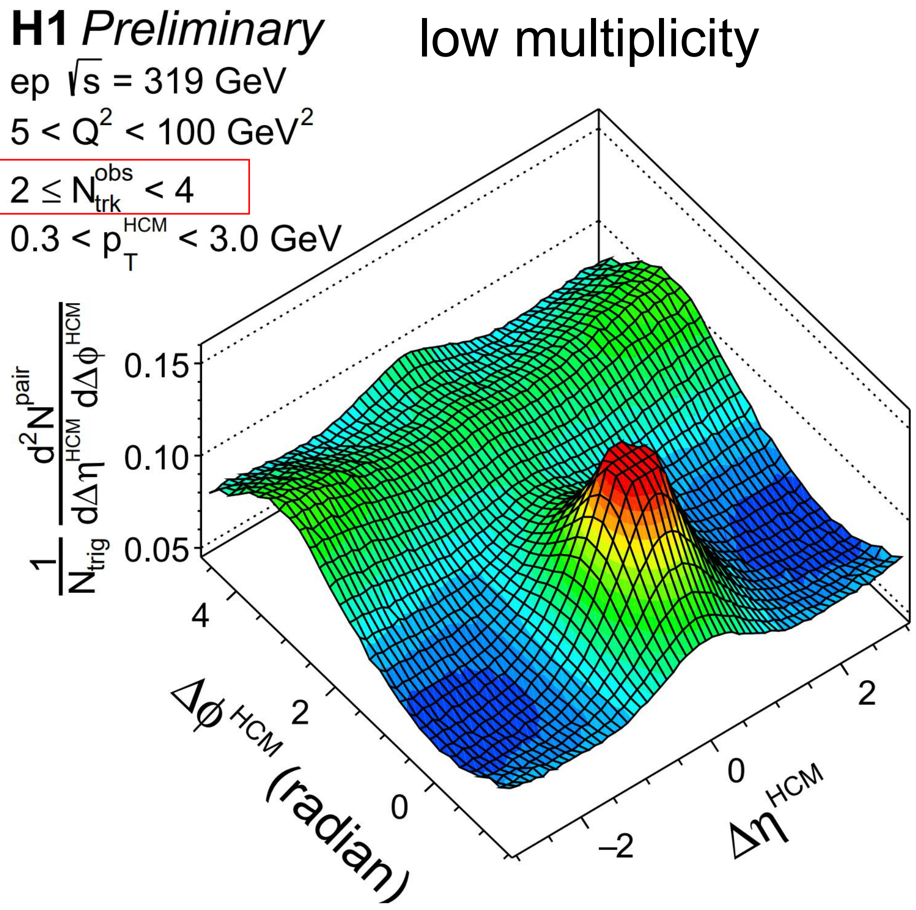
lab frame:
inhomogenious p_T space

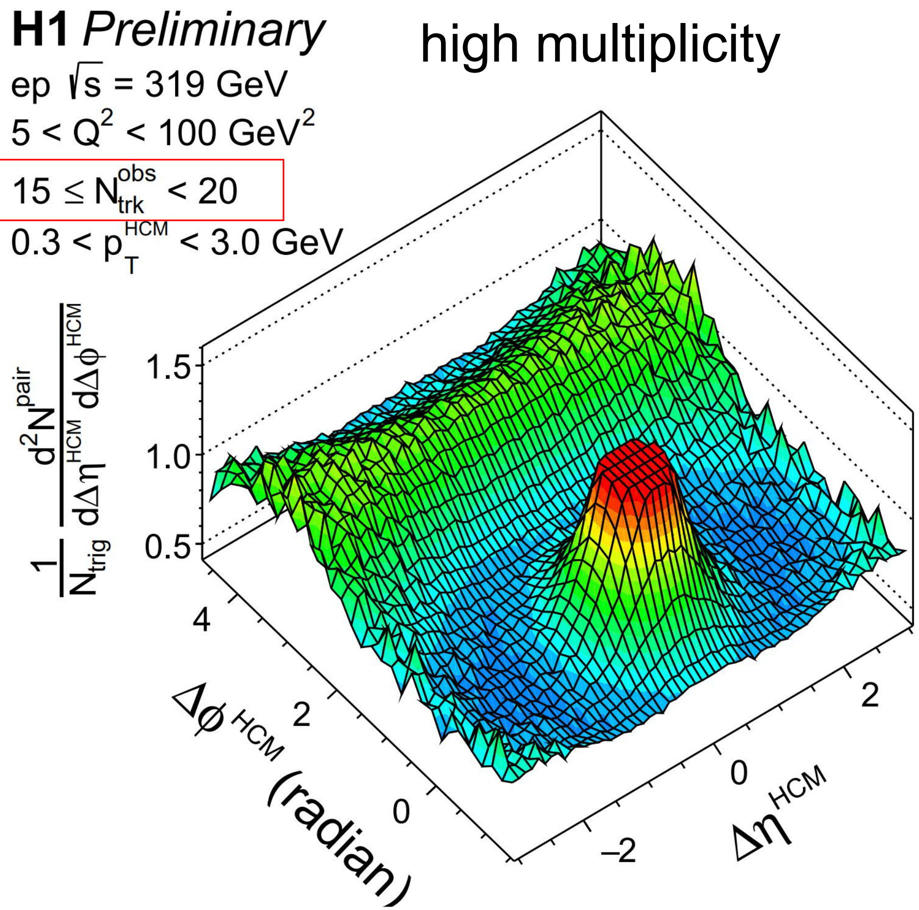
HCM frame:
homogenious p_T space

Search for collectivity with H1 data in HCM frame

Two-particle correlation functions in ep DIS

H1prelim-20-033: https://www-h1.desy.de/publications/H1preliminary.short_list.html



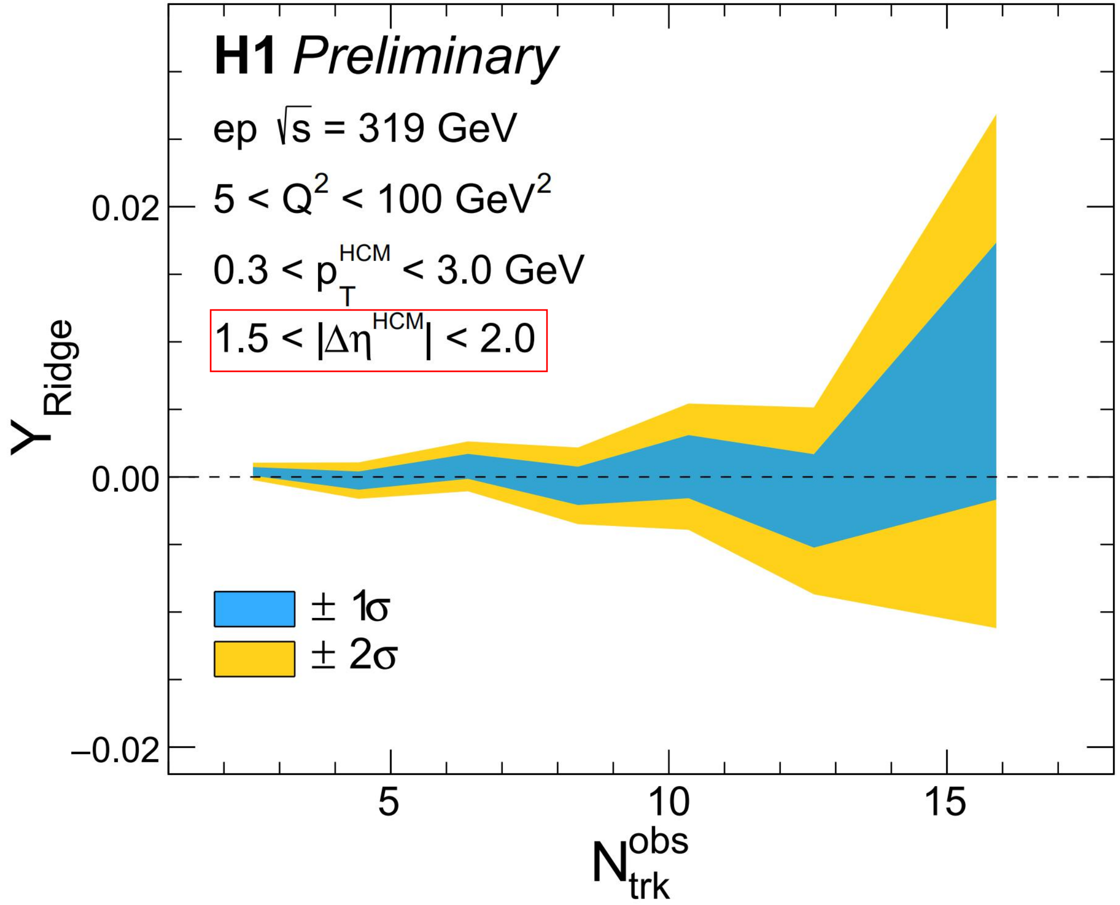


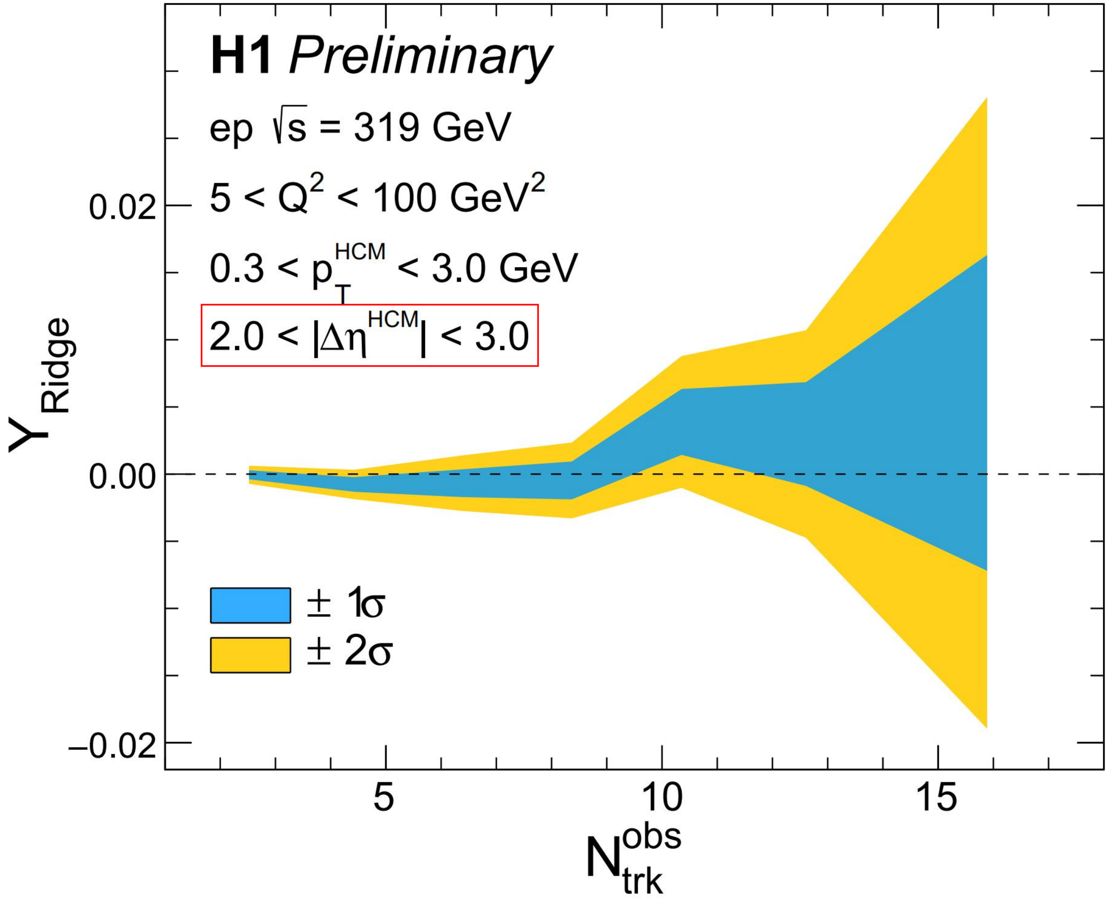
No near-side long-range ridge with H1 DIS data

Extract ridge yield limits through ZYAM and booststrap procedure

DIS HCM

Ridge yield limits in ep DIS





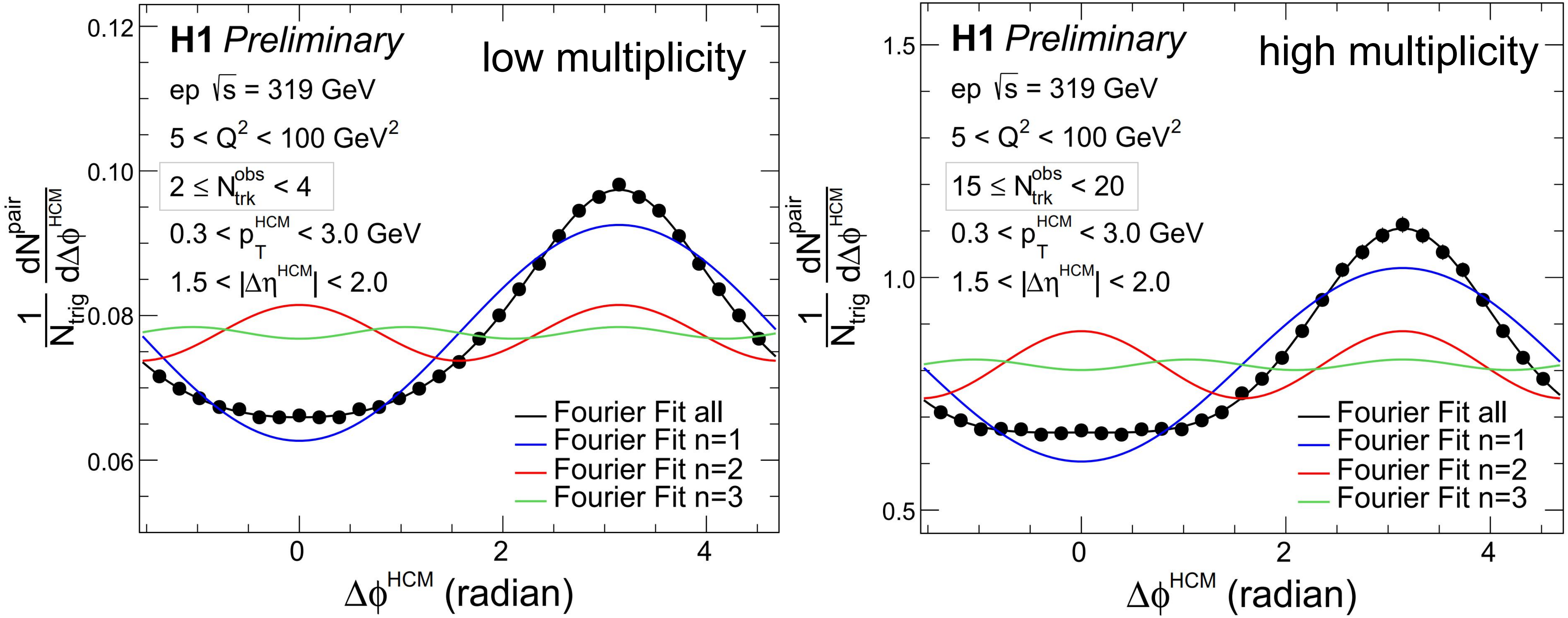
Limits set for ridge yield
Small room for existence of ridge

DIS HCM

Fourier coefficient $V_{n\Delta}$ extraction procedure

Long-range 1-D projections of 2PC functions on Δφ direction

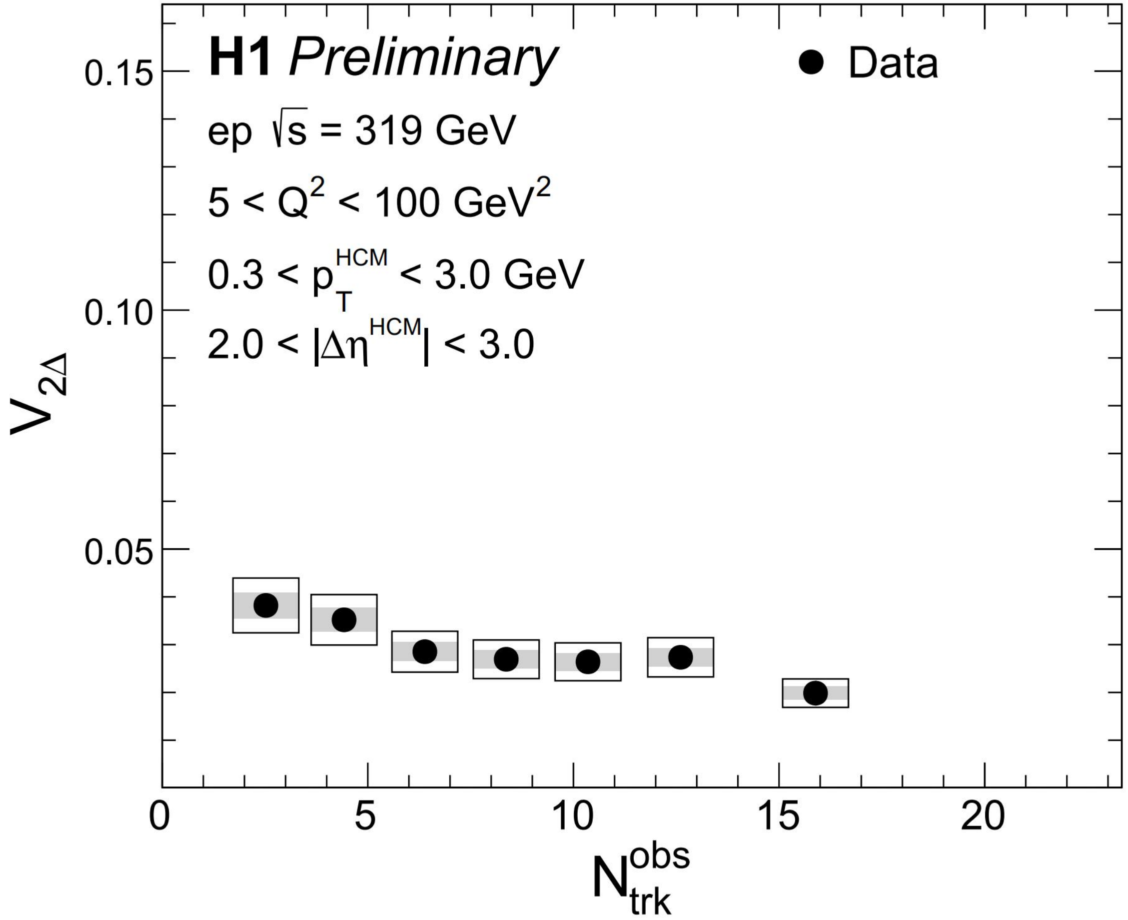
$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left(1+\sum_{n} 2V_{n\Delta}\cos(n\Delta\phi)\right)$$

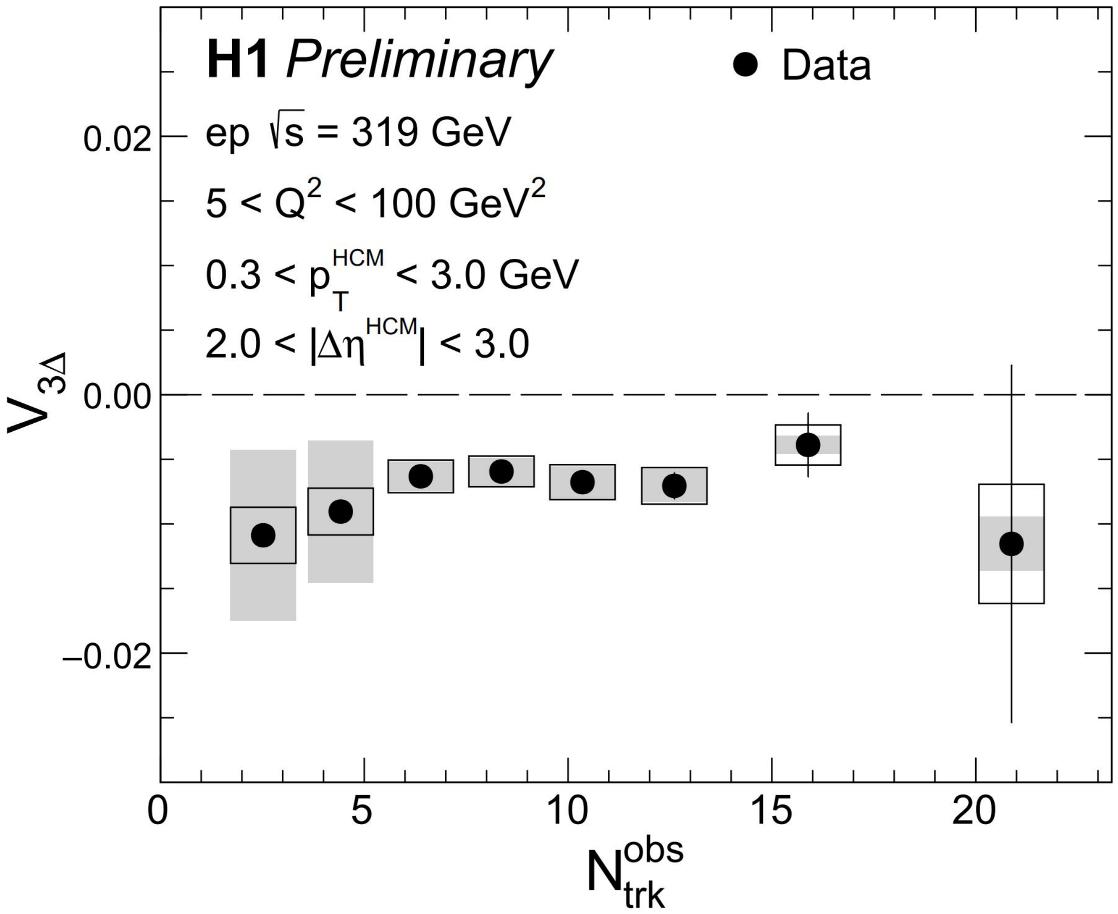


Similar shapes in low and high multiplicity

DIS HCM

Fourier coefficient $V_{n\Delta}$ in ep DIS





$V_{2\Delta}$ value drops in high multiplicity

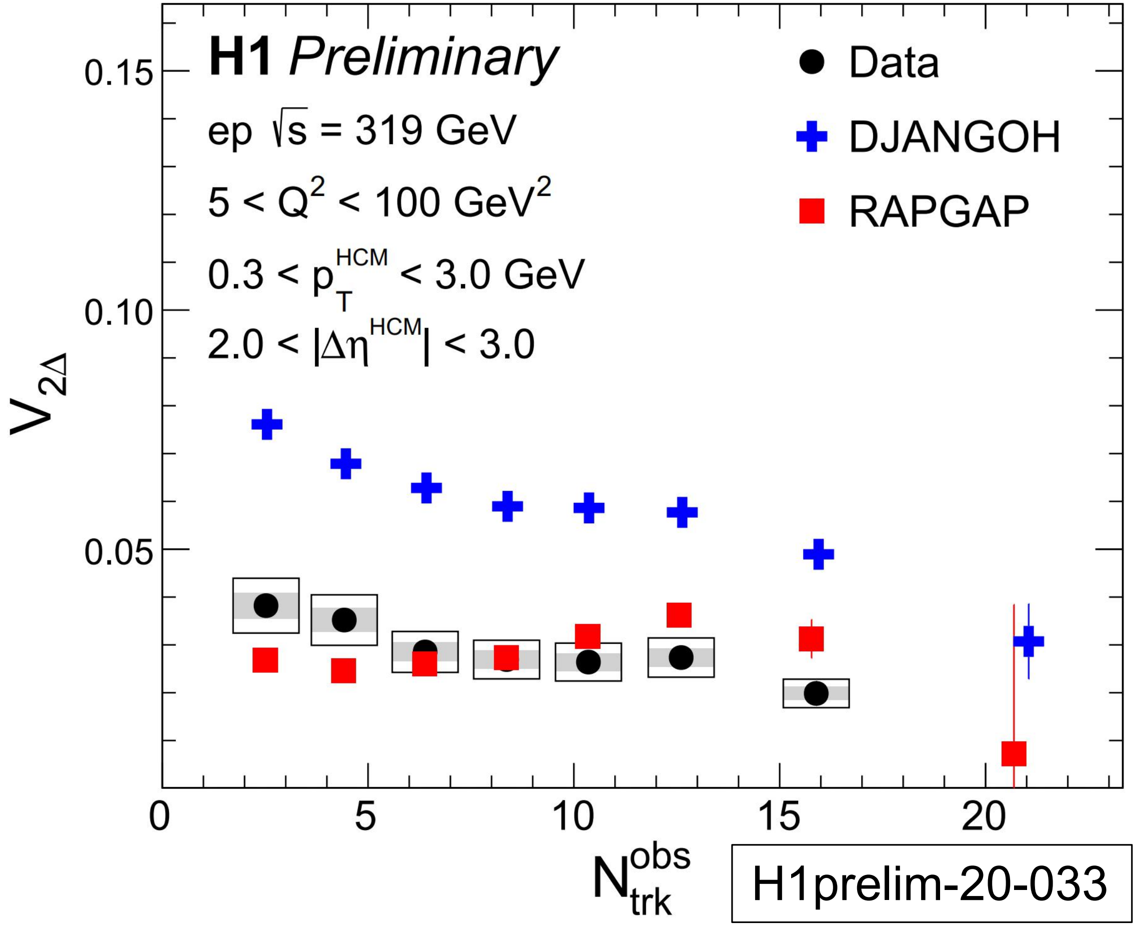
$V_{3\Delta}$ remains negative, indicating no collectivity

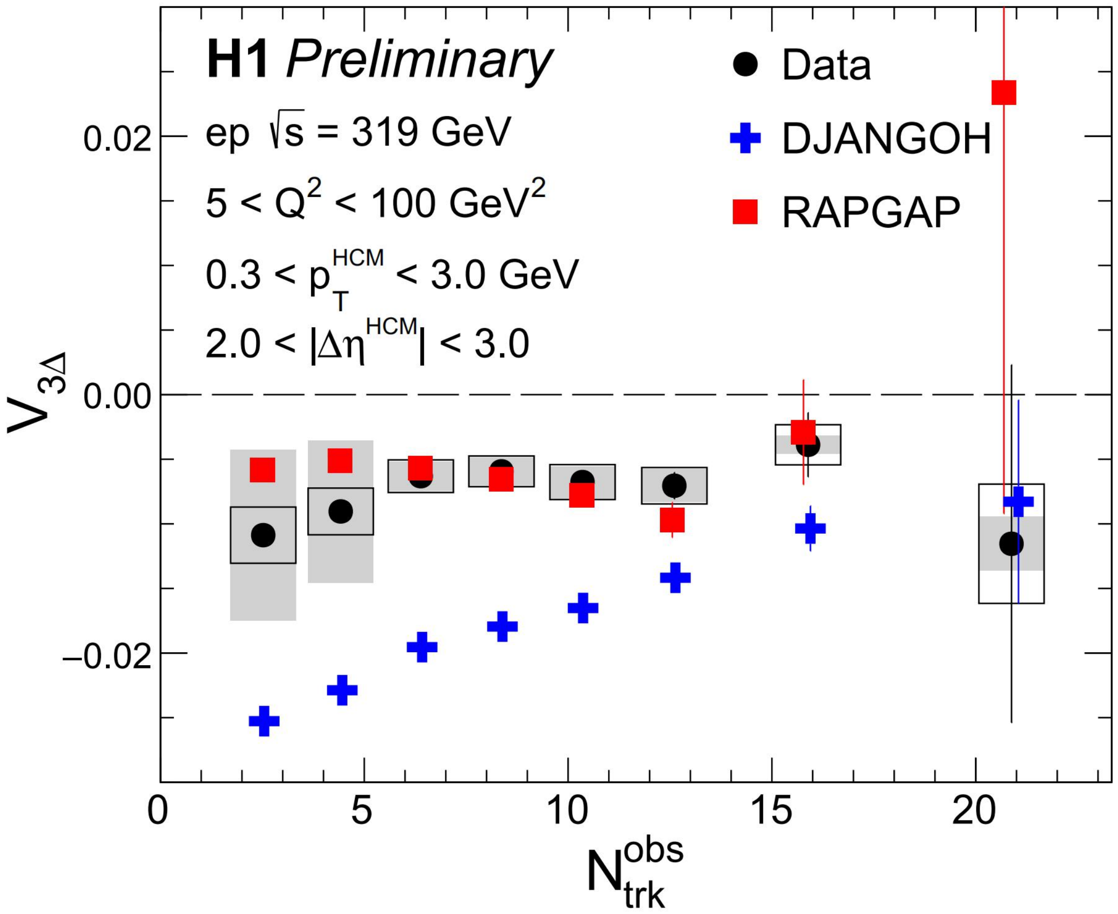
Similar trend as ZEUS result

talk 616# D. Gangadharan Wed 8:36

DIS HCM

Fourier coefficient $V_{n\Delta}$ in ep DIS

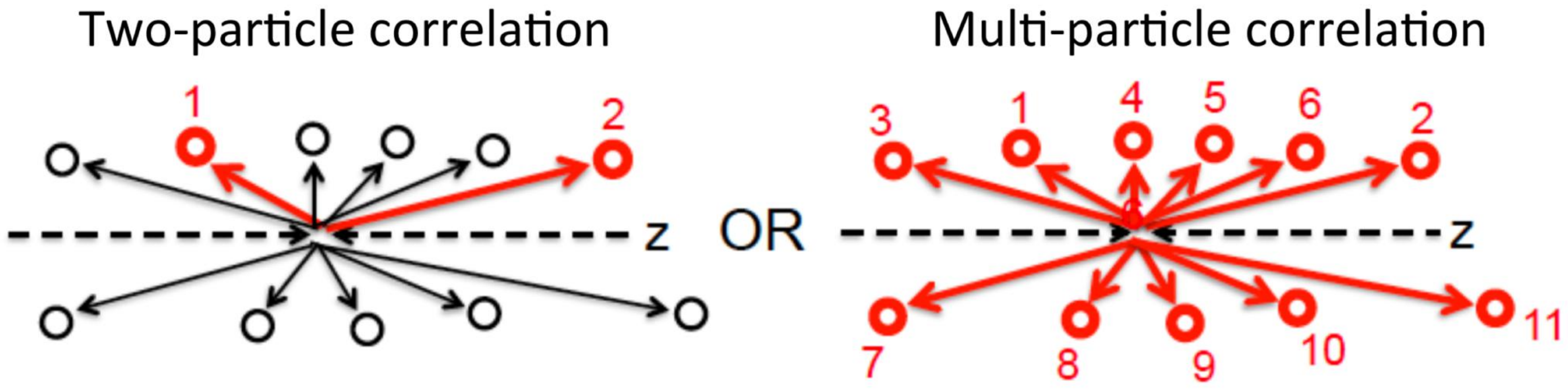




RAPGAP has better description on DIS data than DJANGOH
The difference between RAPGAP and DJANGOH is still under investigation
Data can be described by MC(RAPGAP) w/o collectivity

DIS HCM

Multi-particle correlation



$$\langle 2\rangle = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle = \frac{Q_n^2 - M}{M(M-1)}$$

$$\boxed{Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}}$$

$$\langle 4\rangle = \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle = \frac{Q_n^4 - 2\mathrm{Re}[\boldsymbol{Q}_{2n}\boldsymbol{Q}_n^{*2}] - 4(M-2)Q_n^2 + 2M(M-3) + Q_{2n}^2}{M(M-1)(M-2)(M-3)}$$

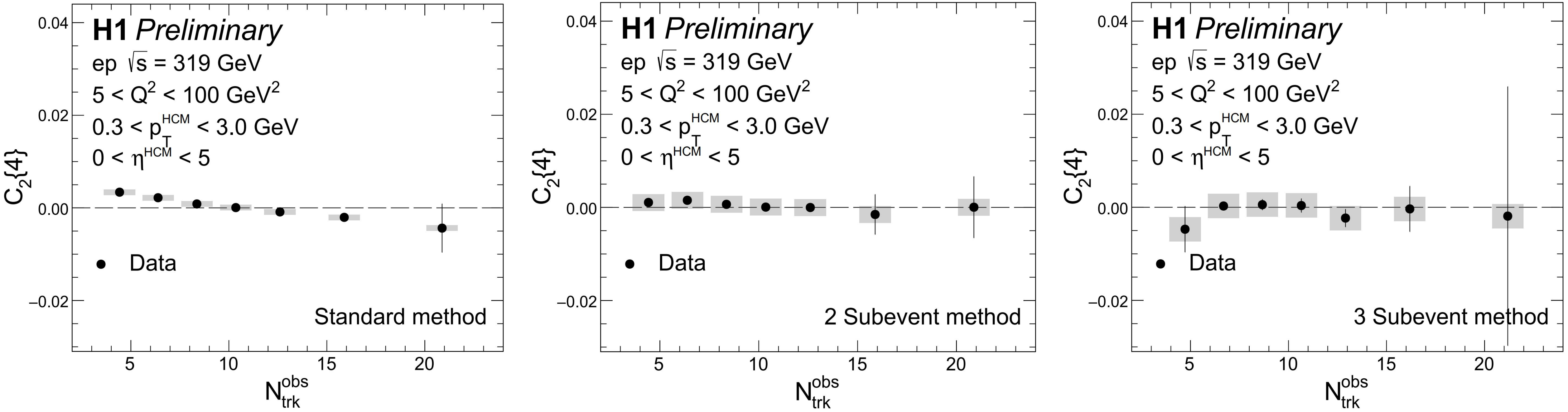
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Phys. Rev. C 83, 044913
Phys. Rev. C 96, 034906

Few particle correlation suppressed
Collective behavior leads to negative $C_n\{4\}$
Subevent cumulants also investigated, providing more reliable results on collectivity

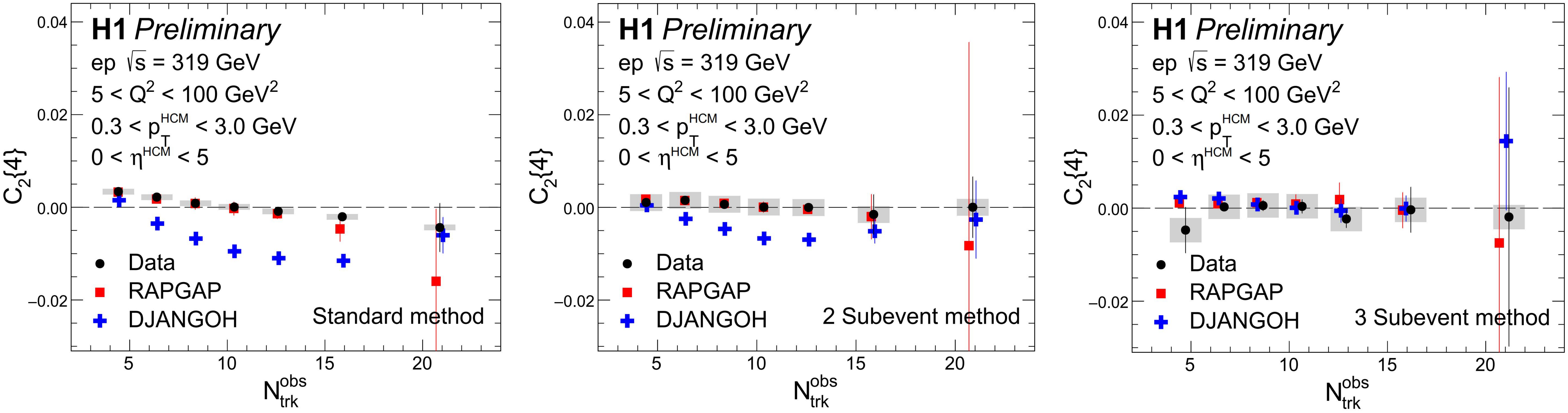
Multi-particle correlation in ep DIS



No obvious negative $C_2\{4\}$ in DIS

DIS HCM

Multi-particle correlation in ep DIS

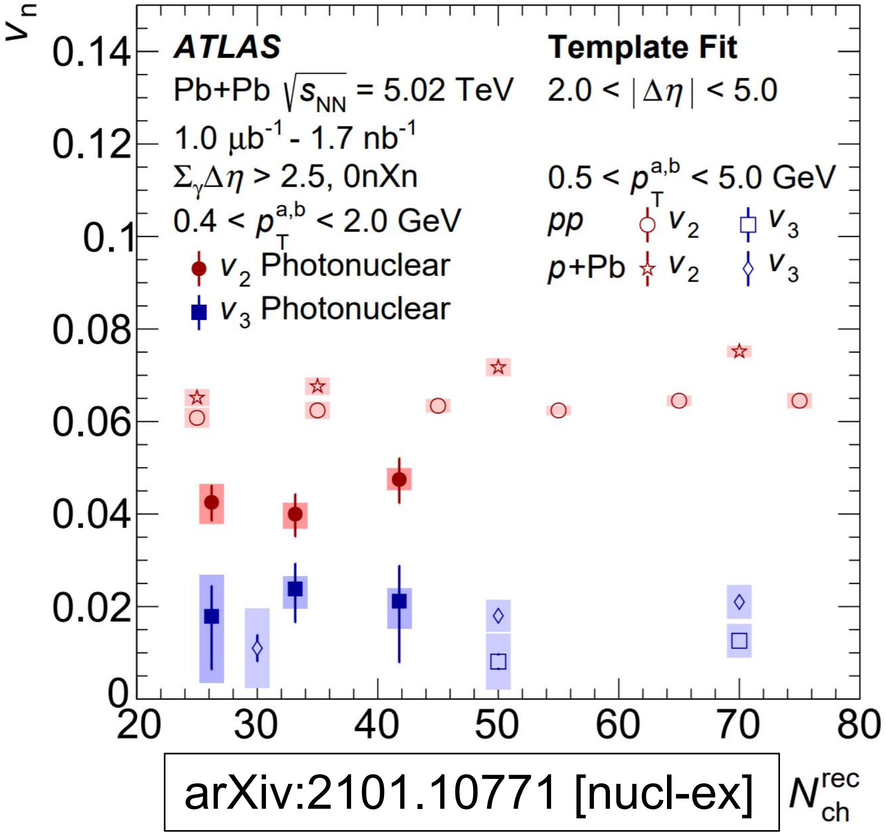


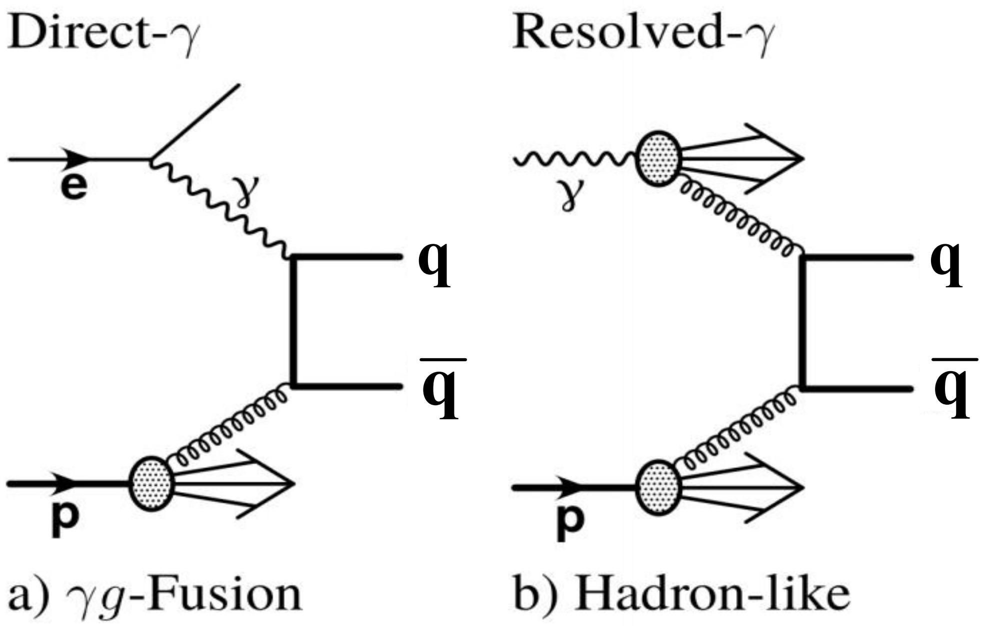
No obvious negative $C_2\{4\}$ in DIS

RAPGAP has better agreement with data

DIS HCM

Search for collectivity in ep photoproduction





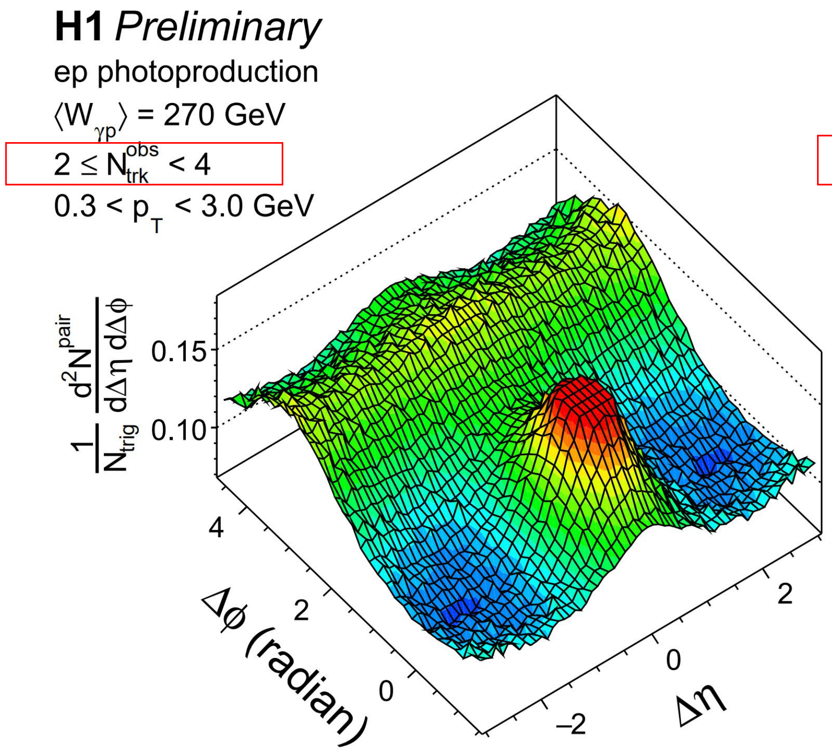
Non-zero v_2 values observed in PbPb ultra-peripheral collisions(photo-nuclear collisions)

Evidence of collectivity in hadron-like collisions

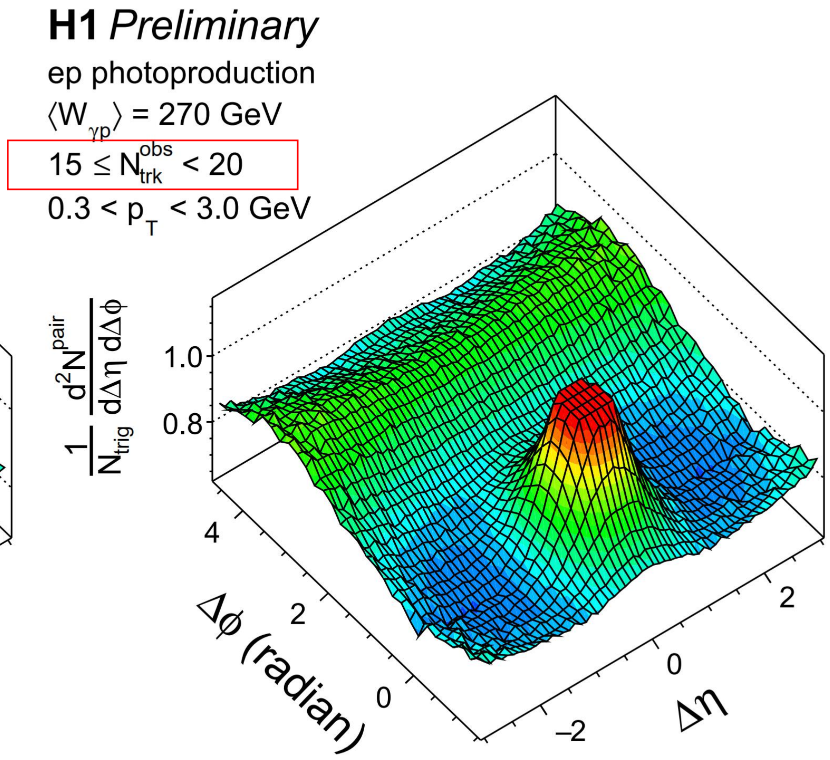
The resolved photoproduction process in ep collisions can be regarded as hadronic collisions

Collectivity in ep photoproduction?

Ridge yield limit in ep photoproduction



low multiplicity

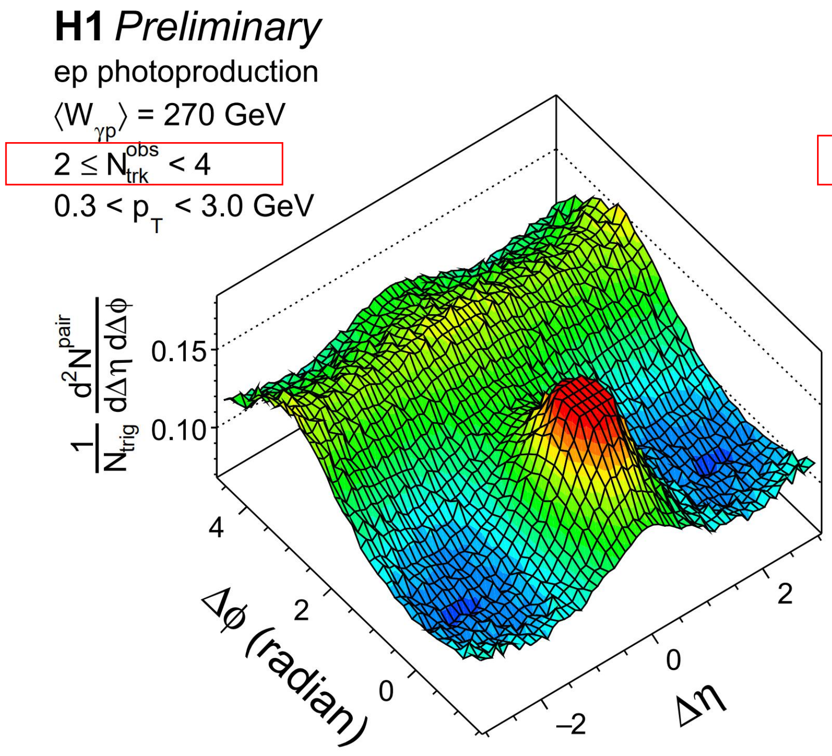


high multiplicity

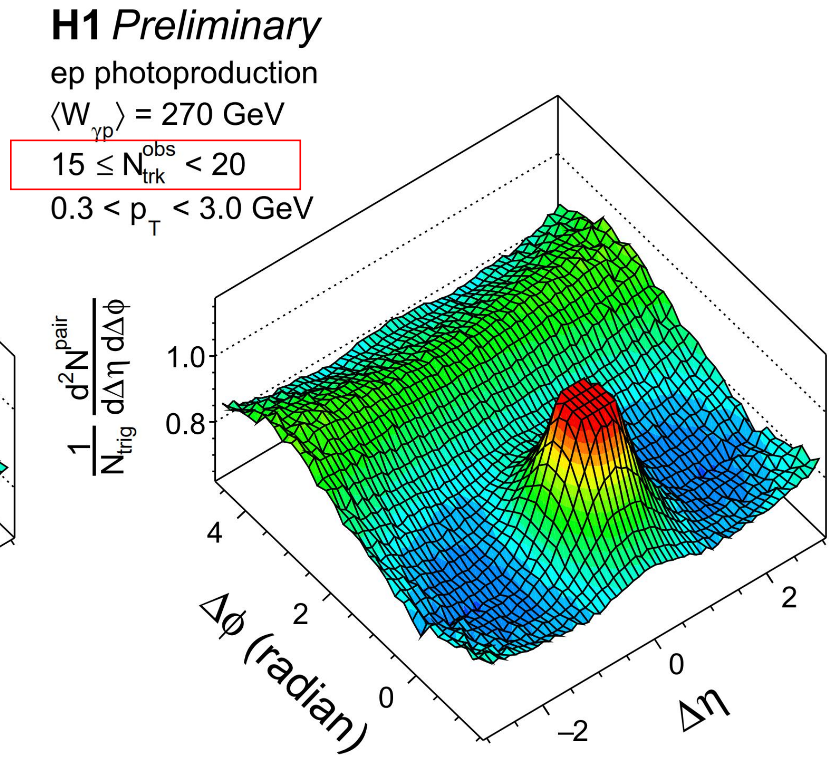
No near-side long-range ridge with H1 photoproduction data

photoproduction

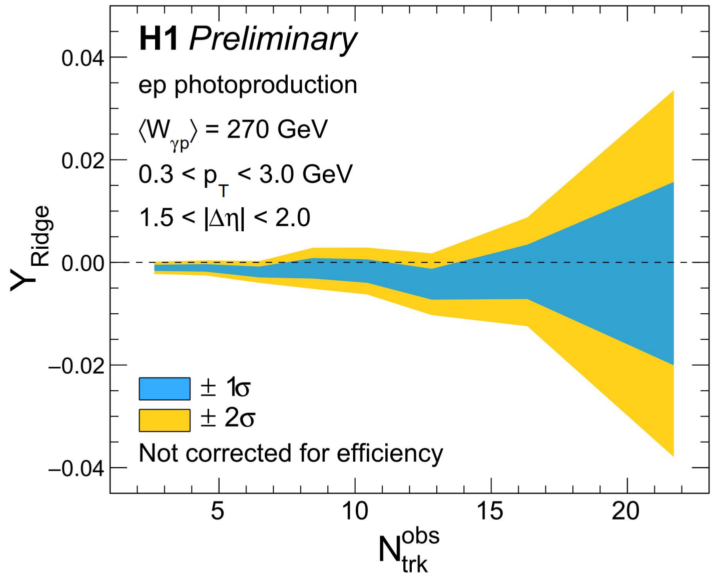
Ridge yield limit in ep photoproduction

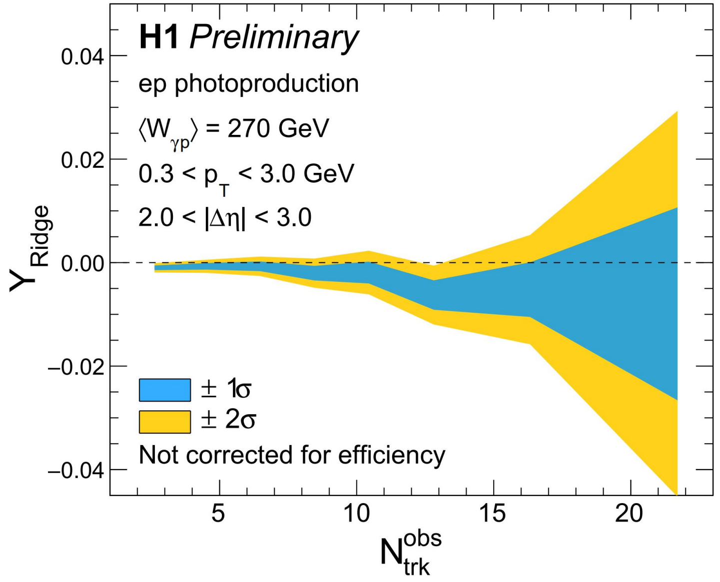


low multiplicity



high multiplicity

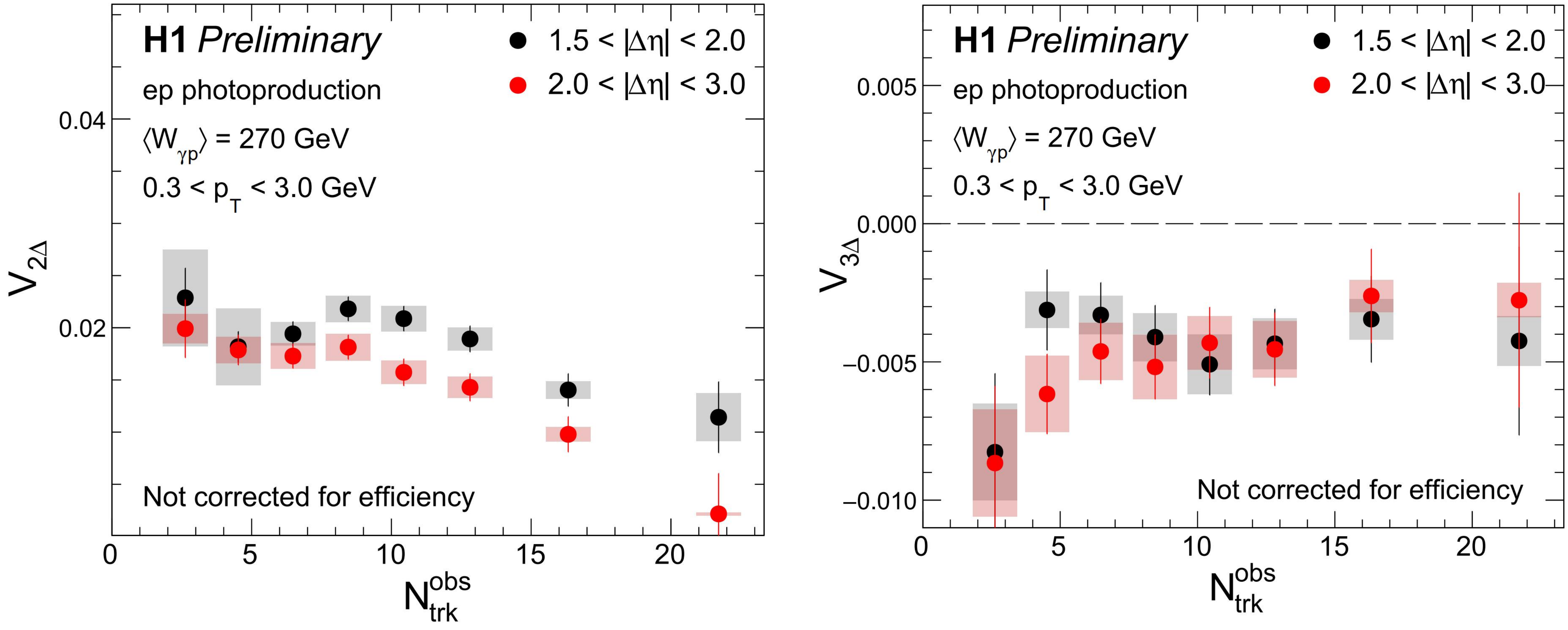




No near-side long-range ridge with H1 photoproduction data
Limits indicate small room for existence of ridge

photoproduction

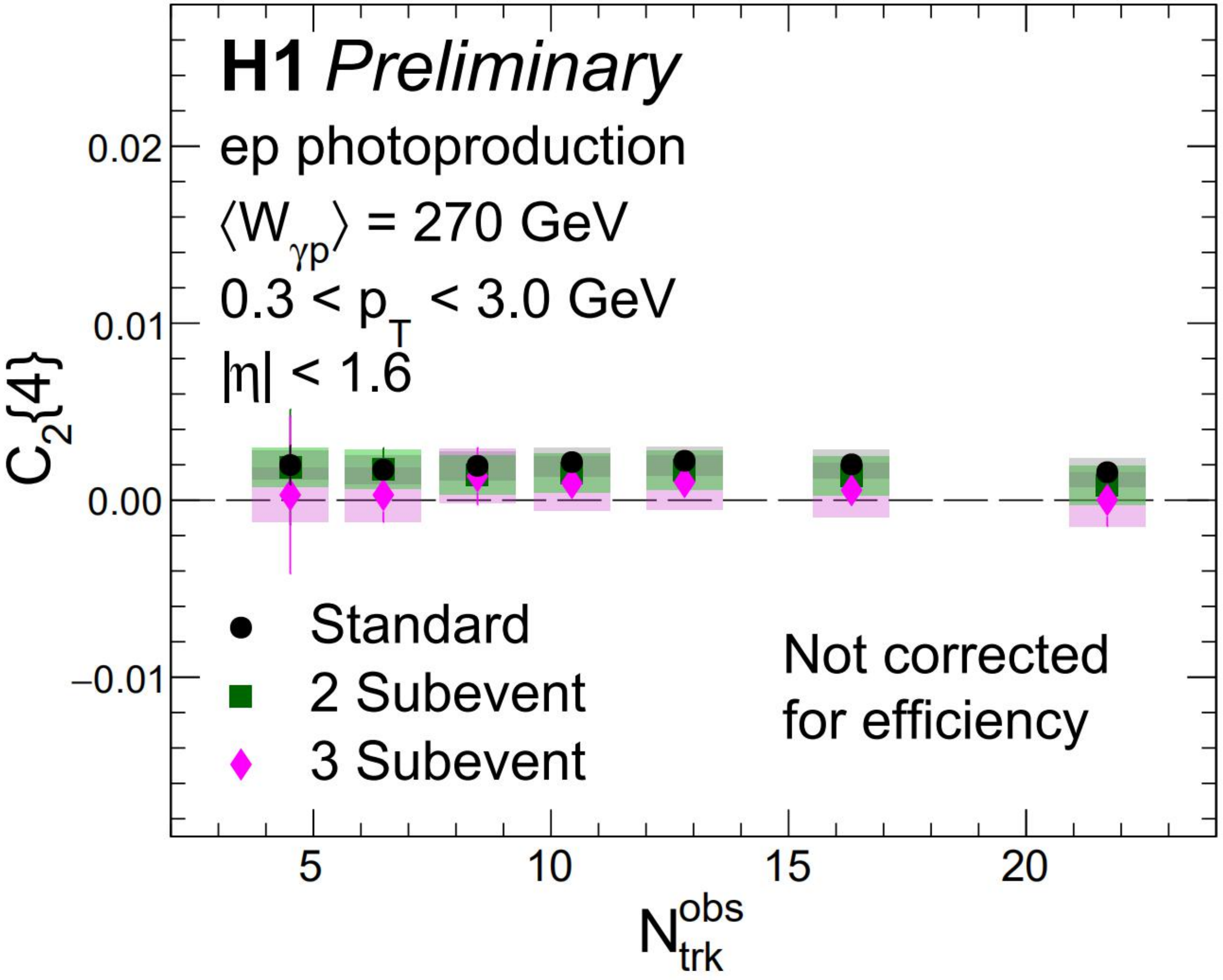
Fourier coefficient $V_{n\Delta}$ in ep photoproduction



Similar behavior in photoproduction data as in DIS

photoproduction

Multi-particle correlation in ep photoproduction



No evidence of negative $C_2\{4\}$, no sign of collectivity

photoproduction

Test of the predictions based on quantum entanglement in DIS H1 ep collisions

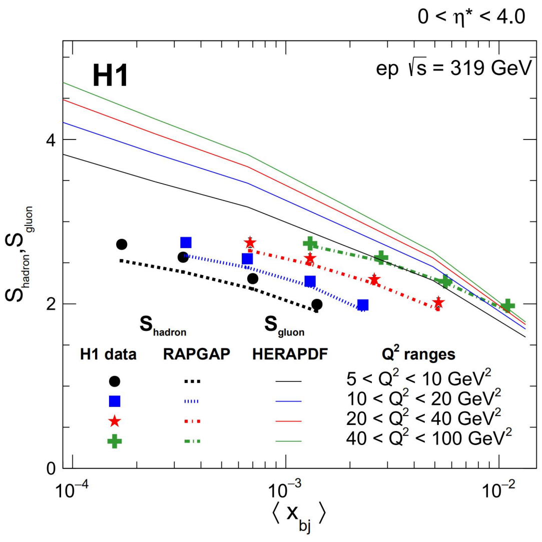
The predictions from the entropy of gluons disagree with the hadron entropy obtained from the multiplicity measurements

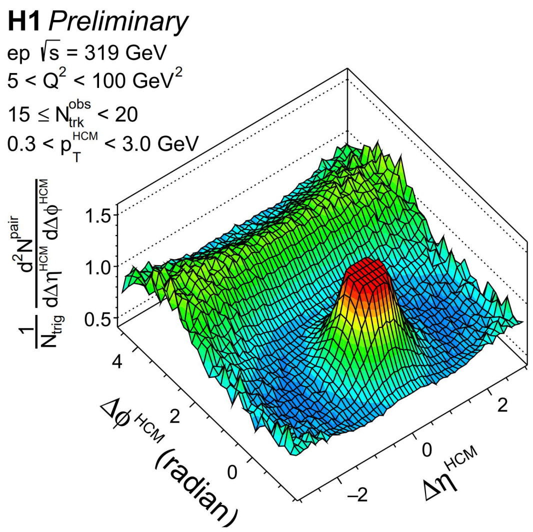
No collectivity observed in either DIS or photoproduction in H1 ep collisions

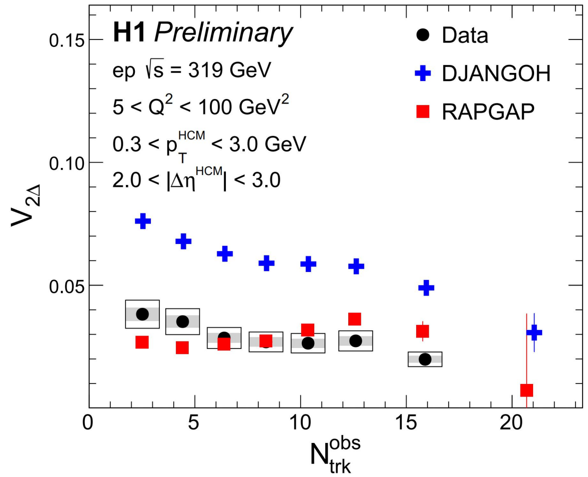
No long-range near-side ridge

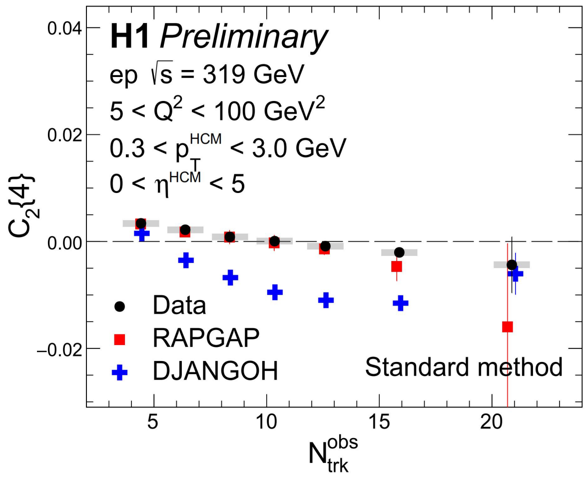
$V_{2\Delta}, V_{3\Delta}$ in DIS can be described by RAPGAP w/o collectivity

No negative $C_2\{4\}$, and $C_2\{4\}$ can also be described by RAPGAP w/o collectivity









Summary

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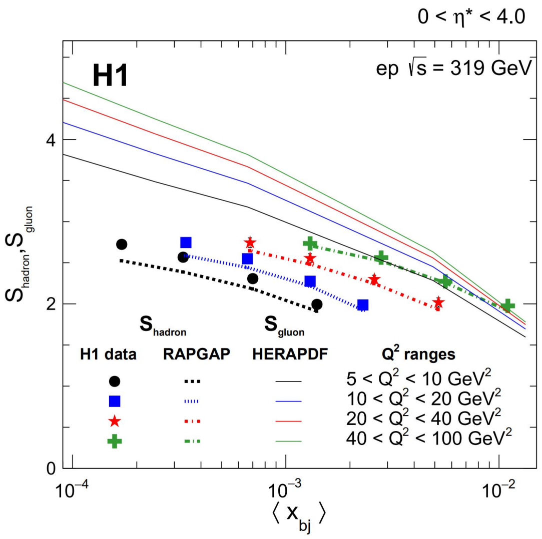
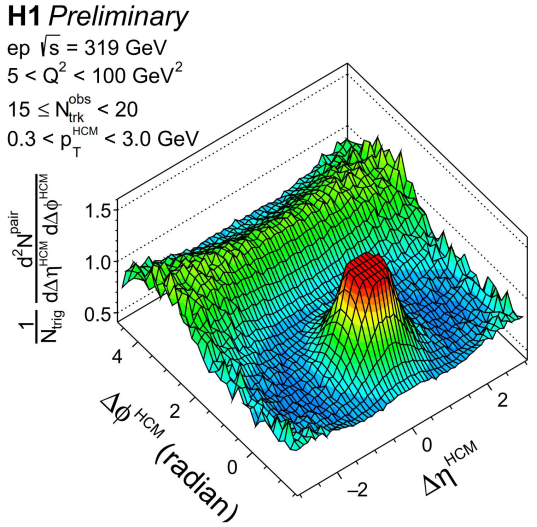
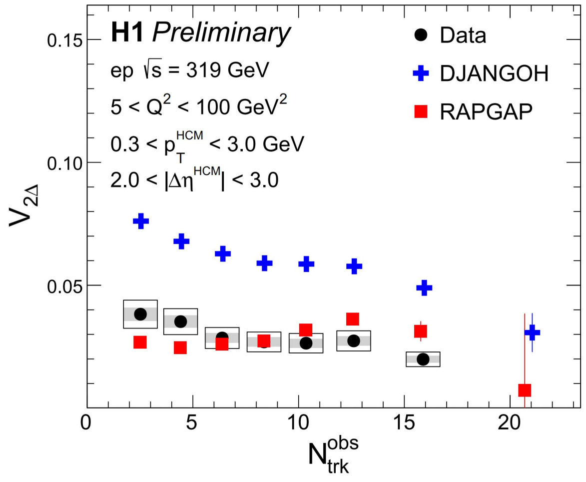
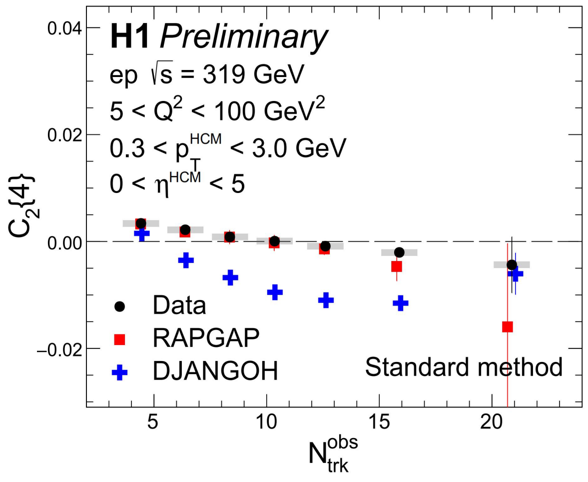
Are there any ridge structure in high multiplicity eA collisions? Stay tuned for EIC





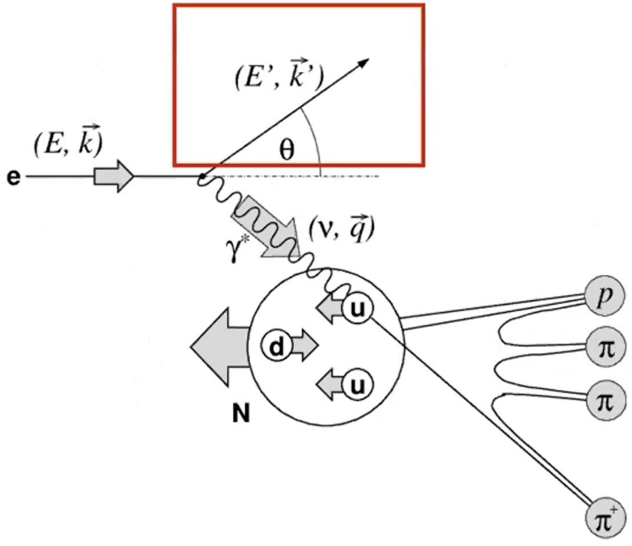




Thanks for attention!

Back up

Kinematics in DIS



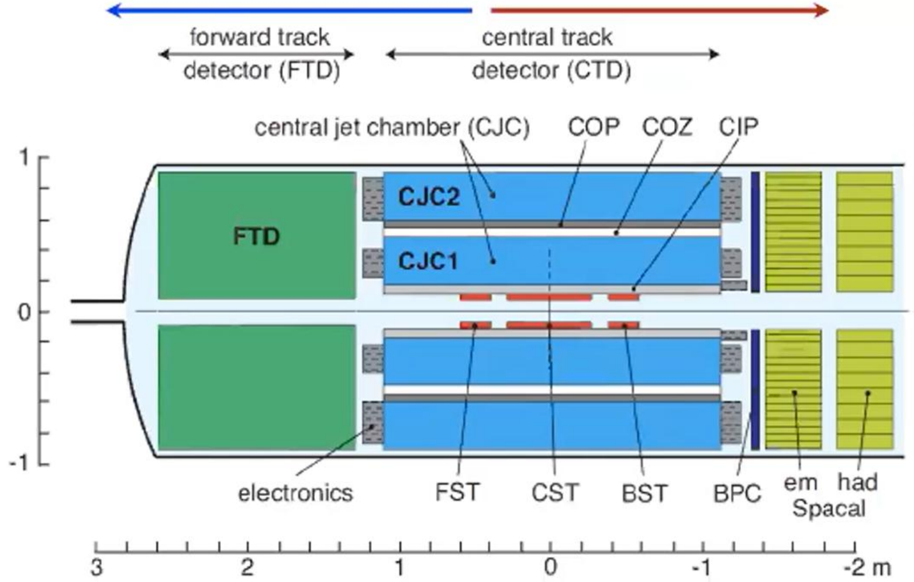
$$Q^2 = -q^2$$

$$y = \frac{\nu}{E_e} = \frac{E_e - E_{e'}}{E_e}$$

$$s = (k + P)^2$$

$$x = \frac{Q^2}{sy}$$

H1 at HERA



Textbook: we only need to measure scattered electron for kinematics.
However, at HERA, there are as least 4-6 different methods to construct kinematics, and each method has its pros and cons. Not only electron is used.

SpalCal, EM Calorimeter to detect scattered electrons in degrees.
CTD covers from 25-155 degrees. (backward~-1.5unit)
FTD+FST covers 5-25 degrees.(forward~3unit)

Two-particle correlation method

In our analysis, the 2PC functions are filled with the difference Δη, ΔΦ of particle pairs. The trigger particle is the charged particles in an event passing track selections. So in the same event, the signal distribution is per-trigger-particle yield of correlated pairs, including detector acceptance effects:

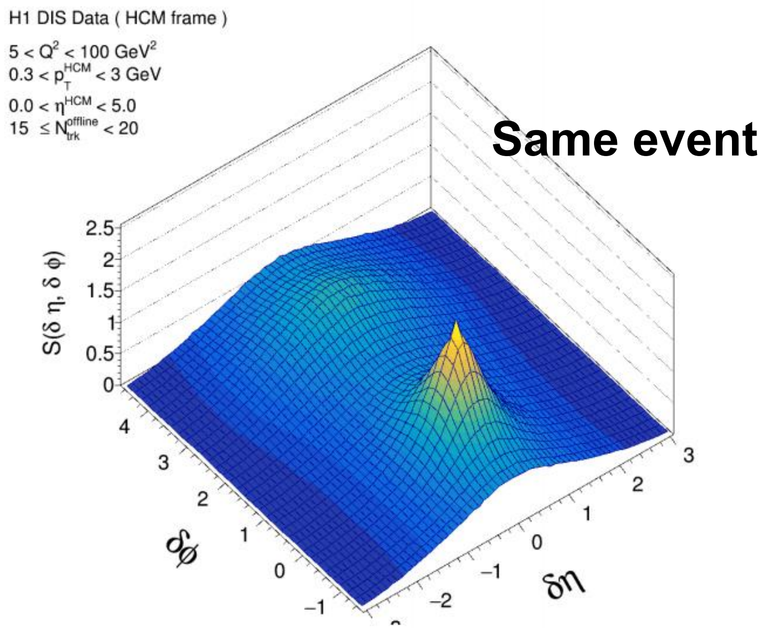
$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{same}}{d\Delta\eta d\Delta\phi}$$

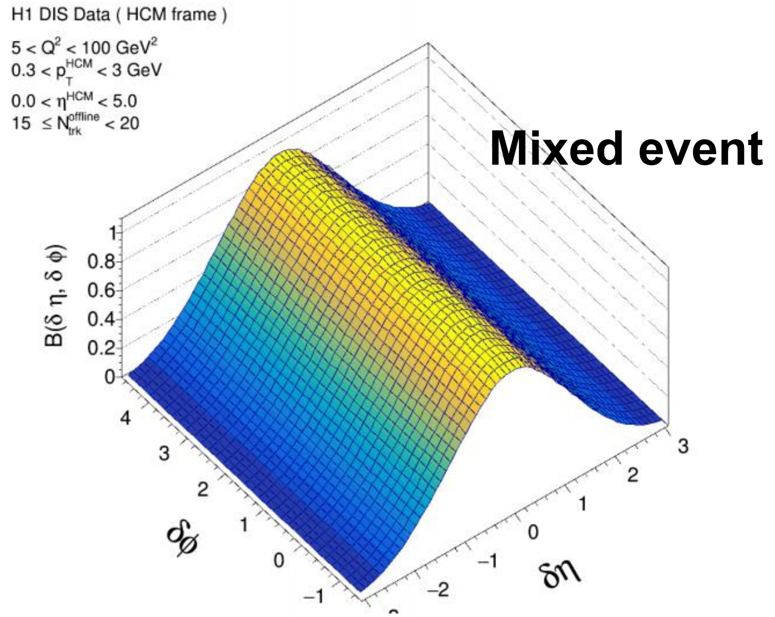
The mix-event background distributions is constructed with trigger particles from one event are correlating with all of the associated particles from different events within $|Z_{VTX}|$ < 2cm. In this analysis, each event is paired with 5 randomly chosen events. The result is given by

$$B(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{mix}}{d\Delta\eta d\Delta\phi}$$

The signal distribution, divided by the background distribution, is the final 2PC function. The pair acceptence of the detector can be corrected.

$$\frac{1}{N_{trig}} \frac{d^2 N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

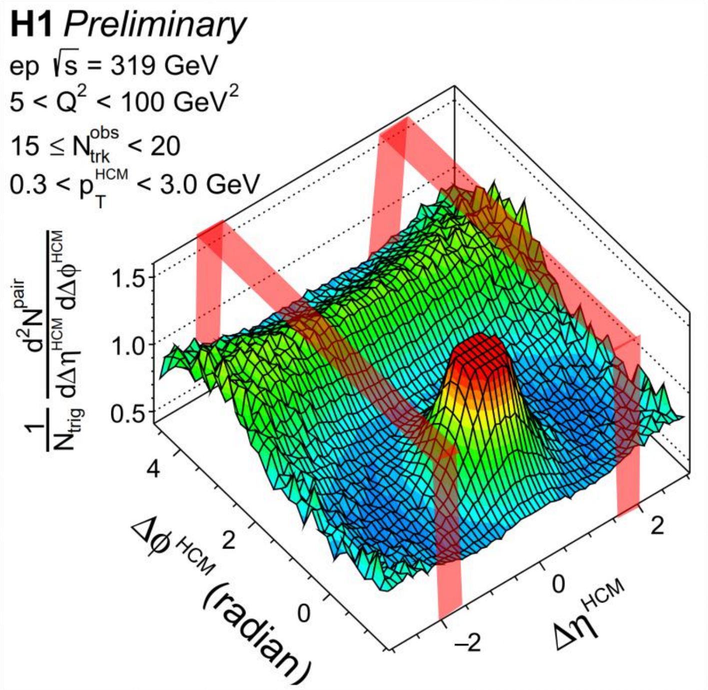


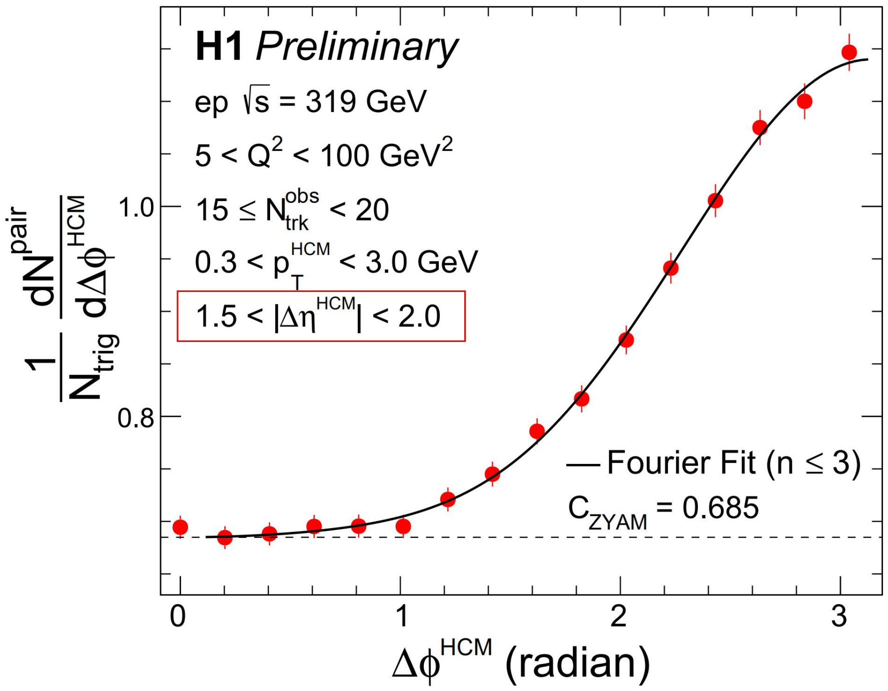


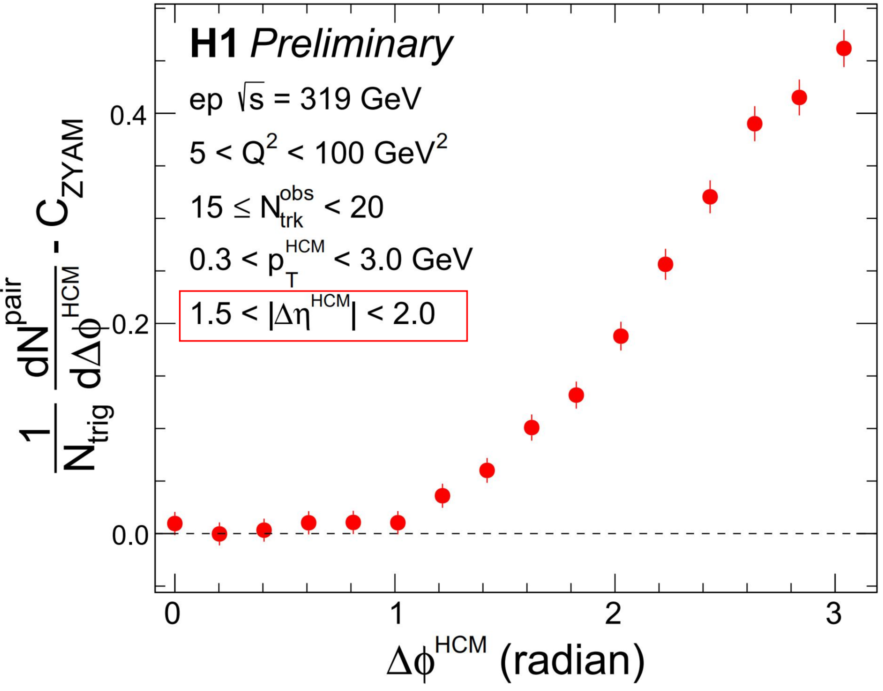
Ridge yield extraction procedure

Zero-yield-at-minimum(ZYAM)

Phys.Rev.C 81 (2010) 014905







Step1: long-range 1D projection

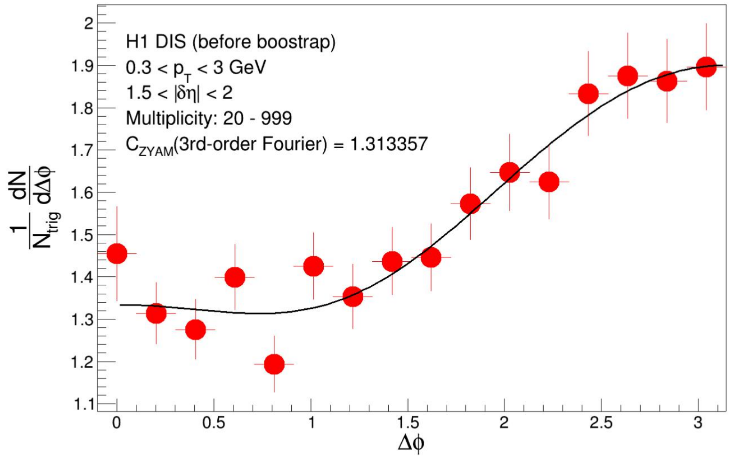
Step2: third-order Fourier fit

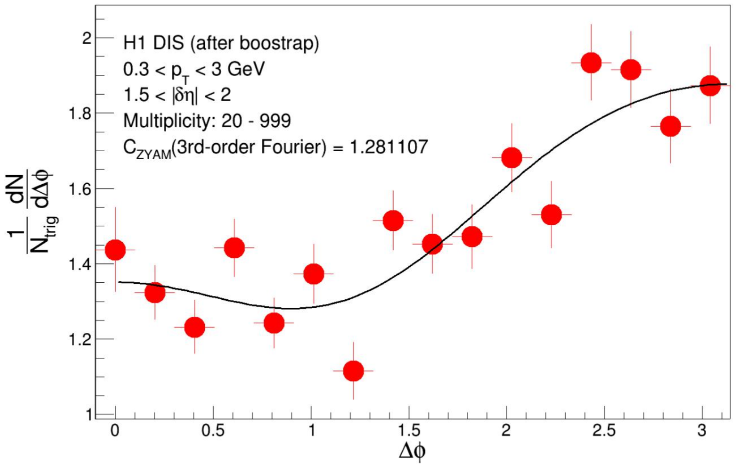
Step3: subtraction

Then integrate from $\Delta\Phi=0$ to where the minimum value of ZYAM occurs as the ridge yield value

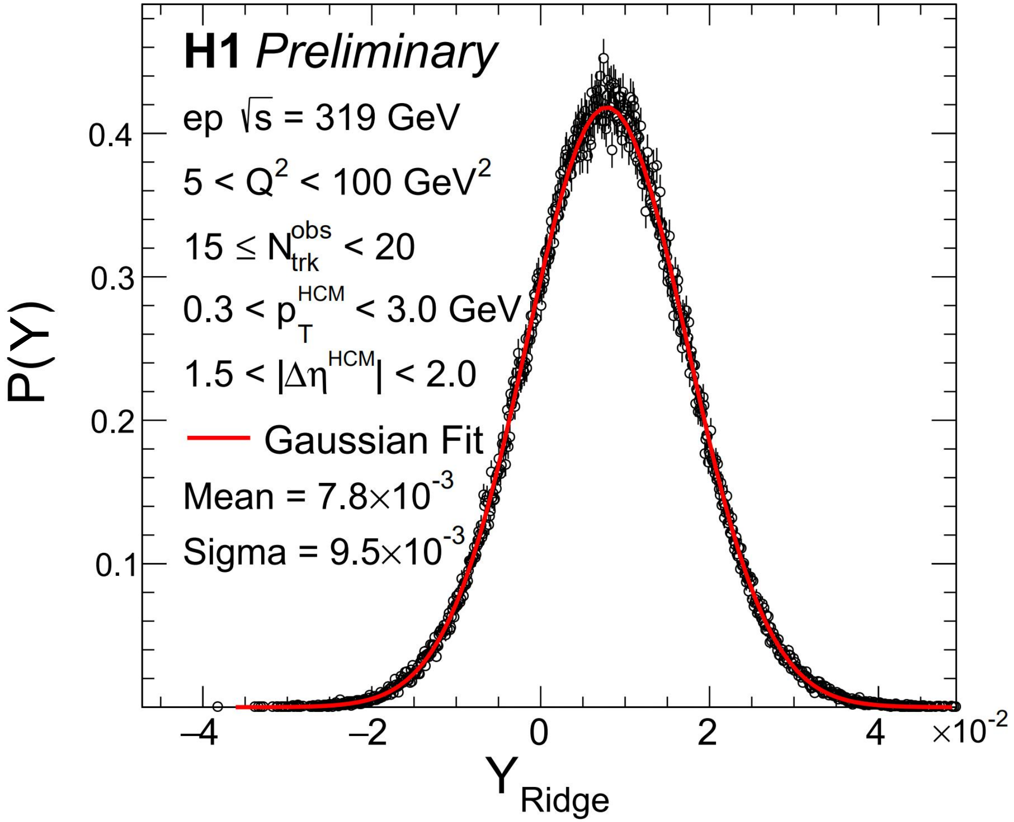
Bootstrap procedure

Each azimuthal differential yield distribution is varied according to their statistical and systematic uncertainties
One time bootstrap, one new ridge yield value





Each yield distribution is sampled 2.5×10^5 times

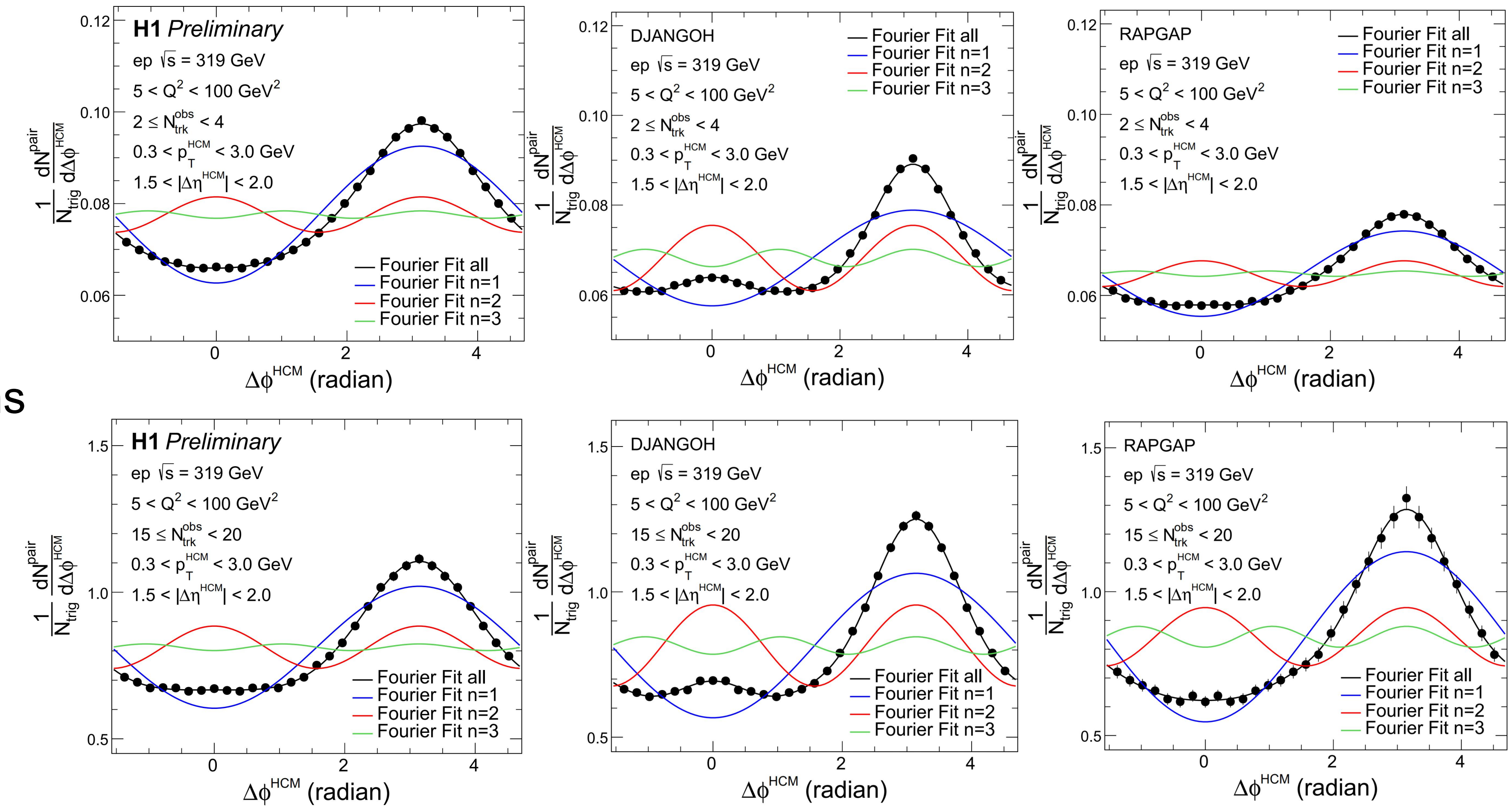


Ridge yield limit extracted from the mean and sigma value of the Gaussian function

Fourier coefficient $V_{n\Delta}$ extraction procedure

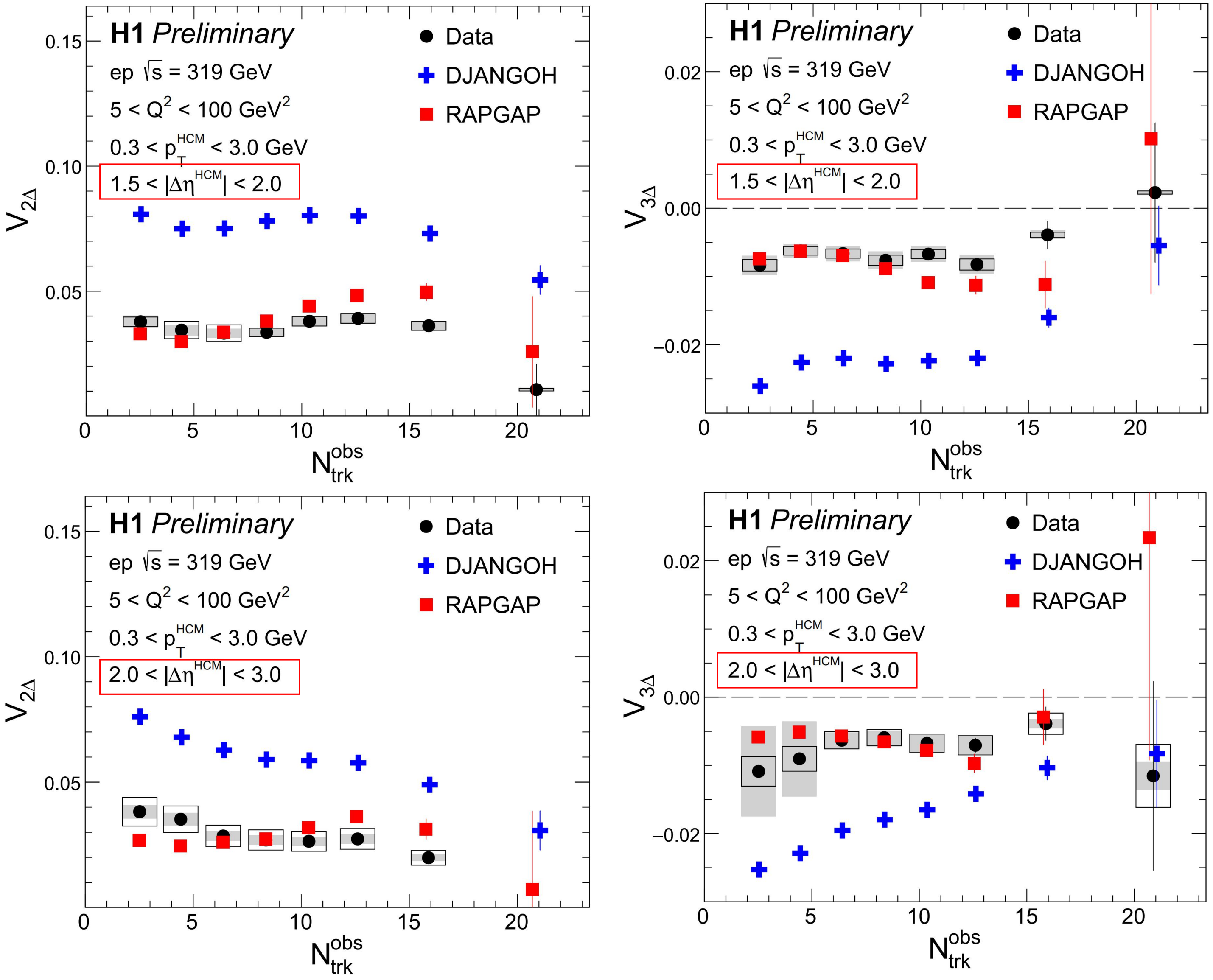
The azimuthal anisotropy harmonics are determined from a Fourier decompositons of long-range two-particle correlation functions on $\Delta\varphi$ direction.

1-D comparisons



The comparison between data and MCs.
Similar shapes in high and low multiplicity.

Fourier coefficient $V_{n\Delta}$



MC RAPGAP has better description on DIS data than MC DJANGOH
Data can be described by MC w/o collectivity

Mechanism in RAPGAP and DJANGOH

Comput.Phys.Commun. 86 (1995) 147-161
Sov.J.Nucl.Phys. 15 (1972) 438-450, Yad.Fiz. 15 (1972) 781-807

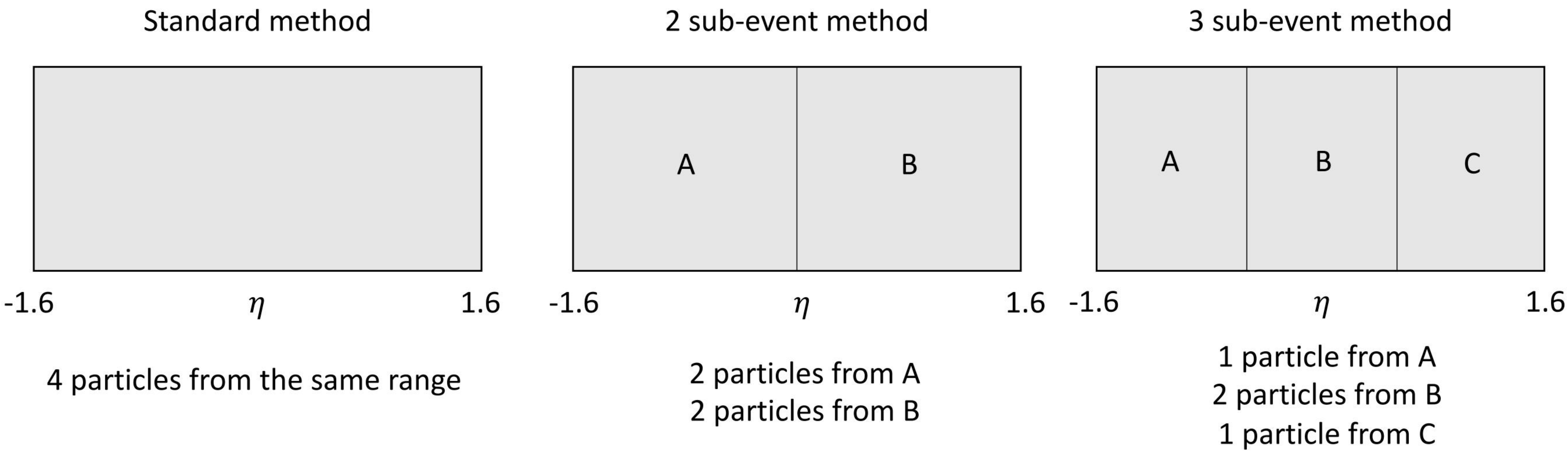
The RAPGAP 3.1

MC event generator matches first order QCD matrix elements to the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) parton showers with strongly ordered transverse momenta of subsequently emitted partons. The factorisation and renormalisation scales are set to $u_f = u_r = \sqrt{Q^2 + \hat{p}_T^2}$, where $\hat{p}_T$ is the transverse momentum of the outgoing hard parton from the matrix element in the center-of-mass frame of the hard subsystem. The CTEQ 6L leading order parametrisation of the parton density function (PDF) is used.

The DJANGOH 1.4

MC event generator used the Color Dipole Model (CDM) as implemented in ARIADNE, which models first order QCD processes and creates dipoles between colored partons. Gluon emission is treated as radiation from these dipoles, and new dipoles are formed from the emitted gluons from which further radiation is possible. The radiation pattern of the dipoles includes interference effects, thus modelling gluon coherence. The transverse momenta of the emitted partons are not ordered in transverse momentum with respect to rapidity, producing a configuration similar to the Balitsky-Fadin-Kuraev-Lipatov (BFKL) treatment of parton evolution. The CTEQ 6L at leading order is used as the PDF.

Multi-particle correlation



More advanced sub-event methods can further suppress few particle correlation

Method paper: Phys. Rev. C **96**, 034906, arXiv.1701.03830

2 and 3-subevent methods provide more reliable results on collectivity