Center for Frontiers in Nuclear Science Workshop series

Search for collective effects in small system obtained in ep collisions at HERA

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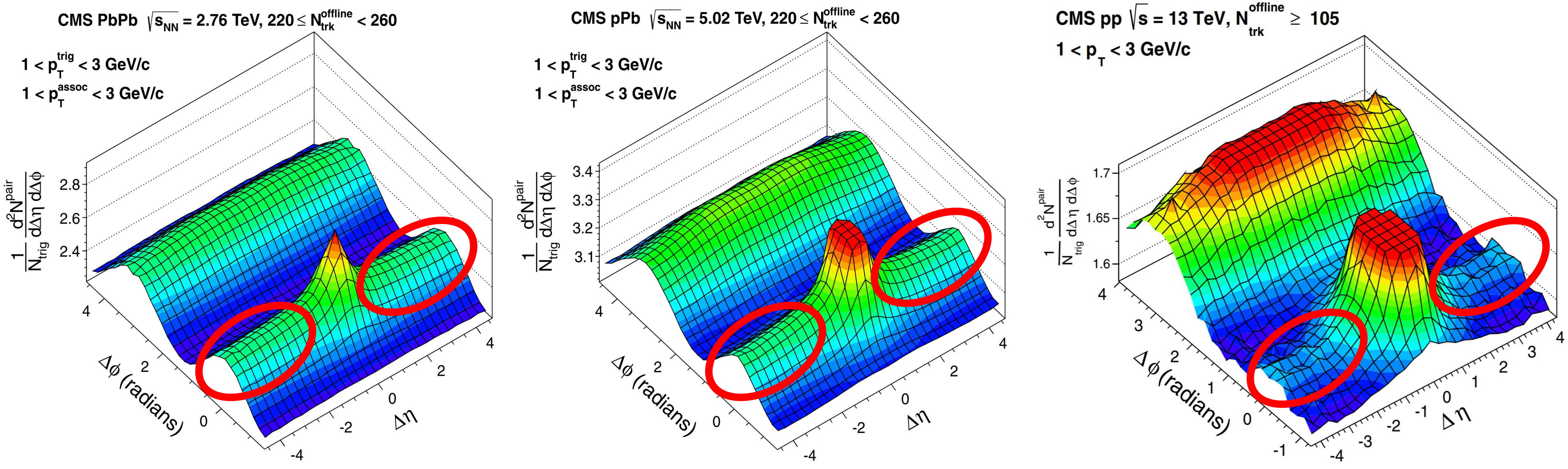
Collectivity in small system

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

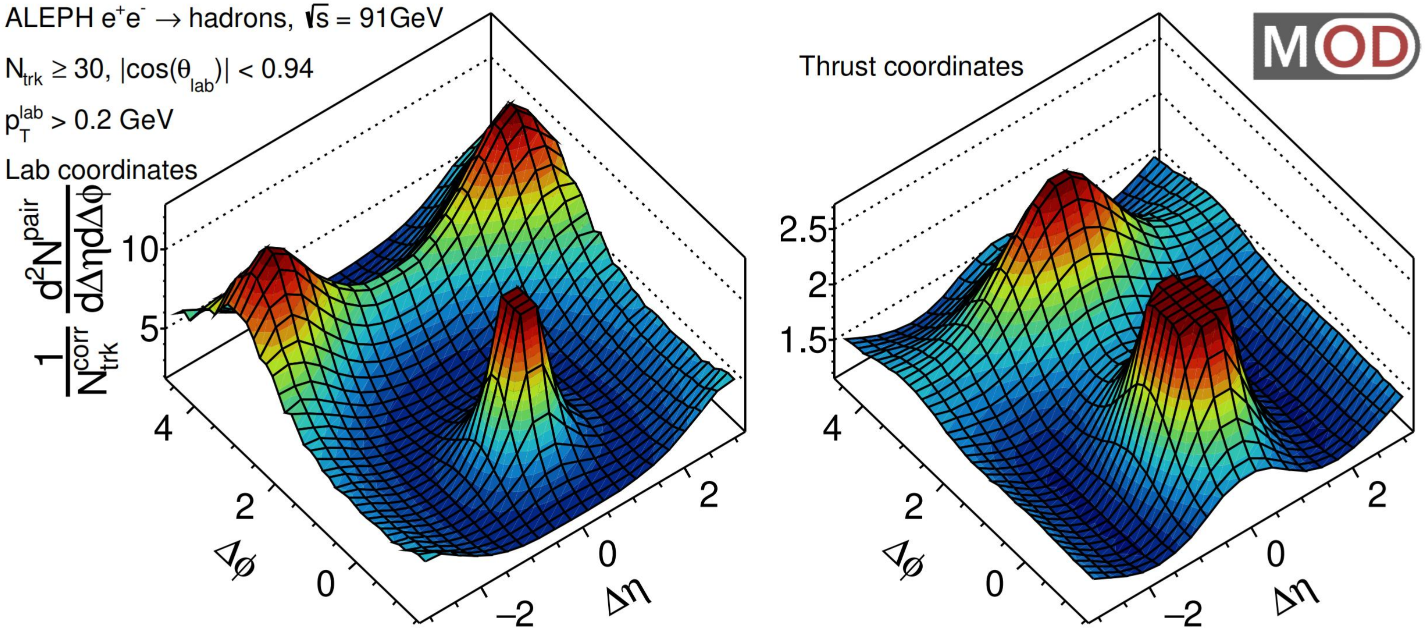


Lots of evidence of collectivity in high multiplicity pp and pPb collisions, similar to heavy-ion collisions attributed to the perfect liquid nature of QGP

What about even smaller system?

Collectivity in small system

PRL 123, 212002 (2019)



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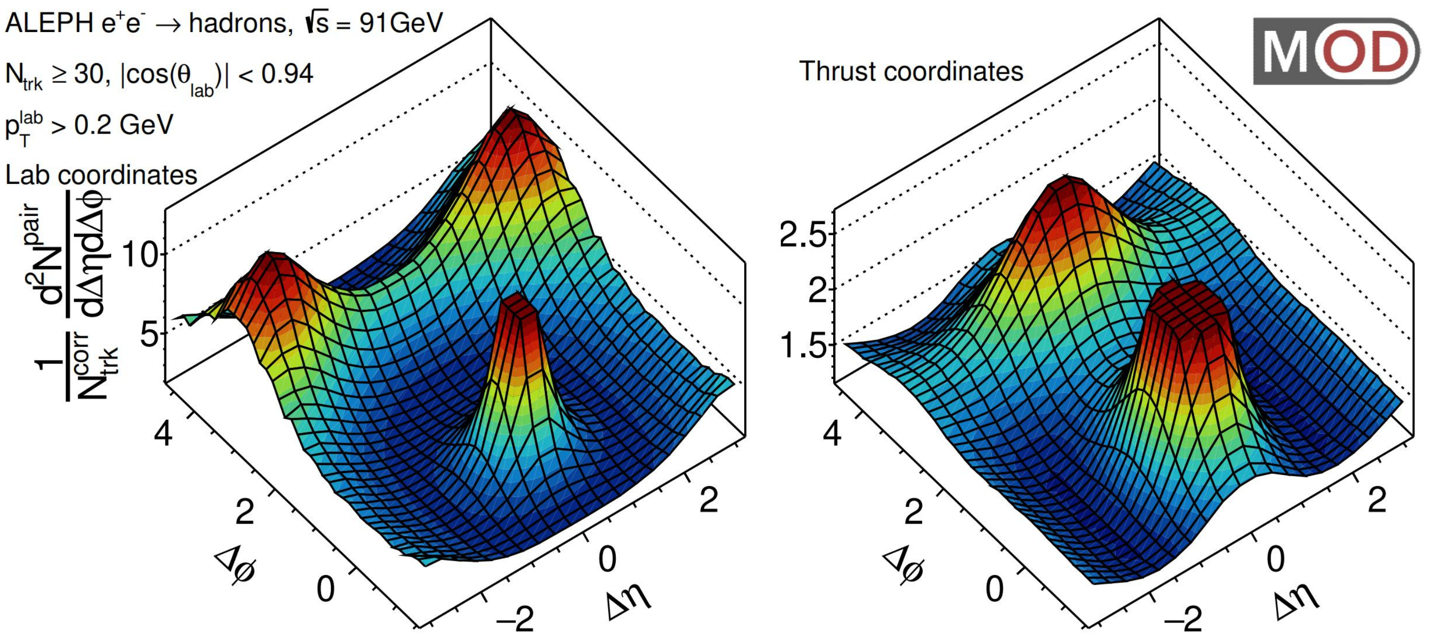


Lots of evidence of collectivity in high multiplicity pp and pPb collisions, similar to heavy-ion collisions attributed to the perfect liquid nature of QGP

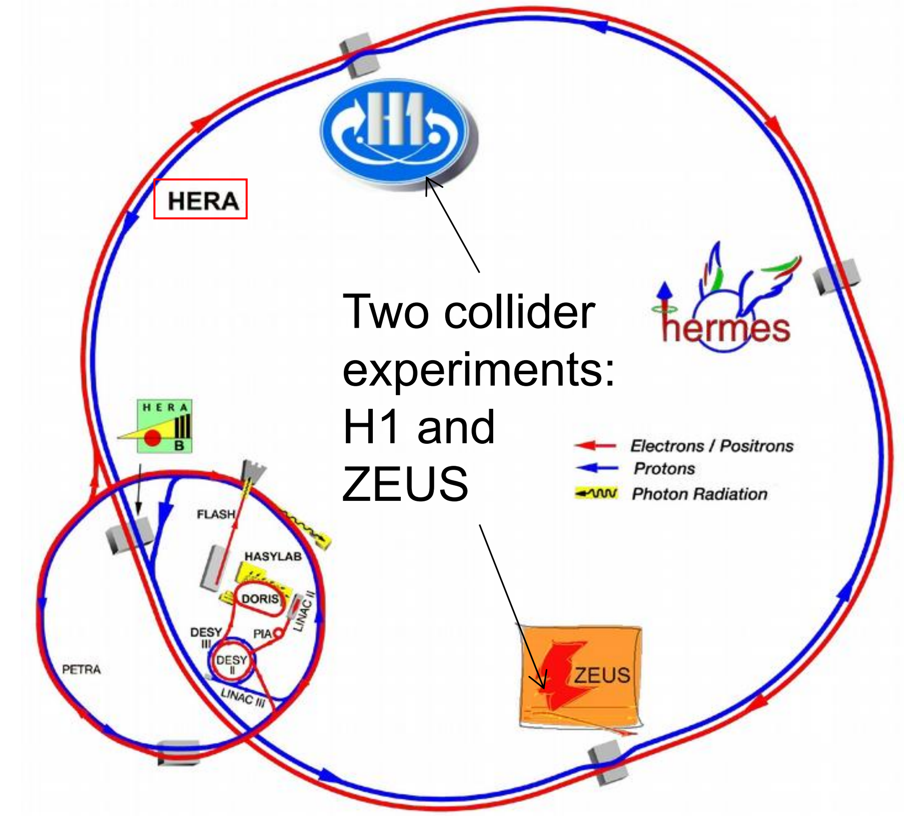
What about even smaller system? in e^+e^- or ep collisions

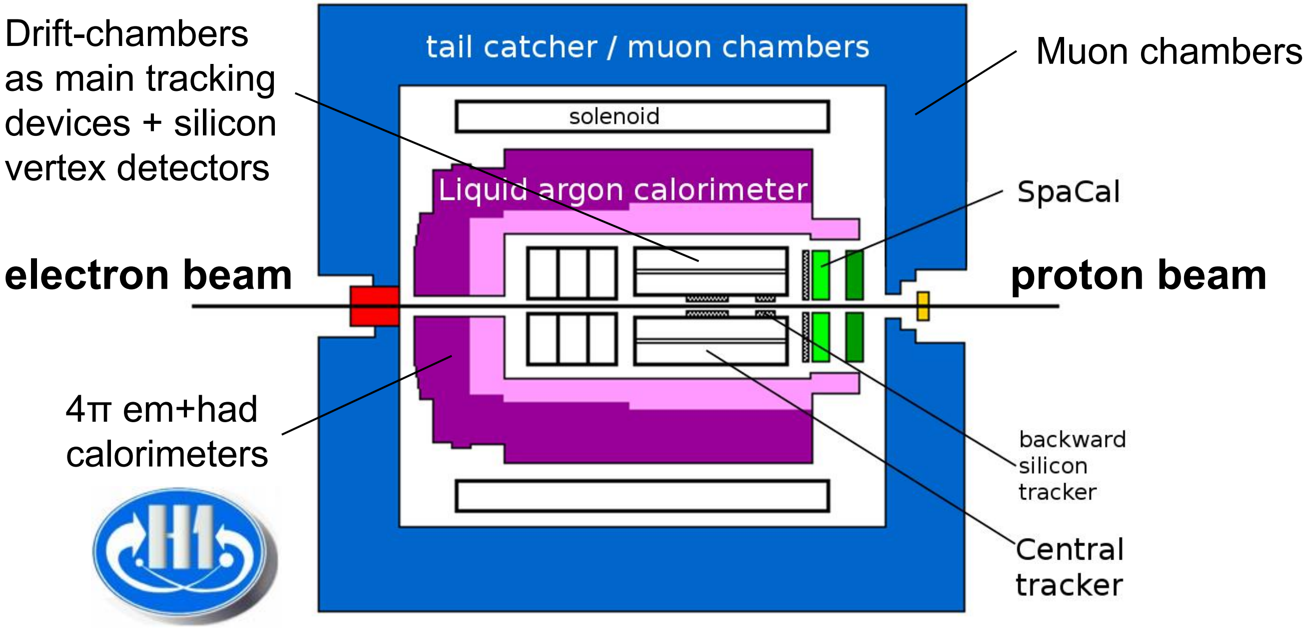
In deep-inelastic scattering(DIS) and photoproduction events:

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

H1 at HERA

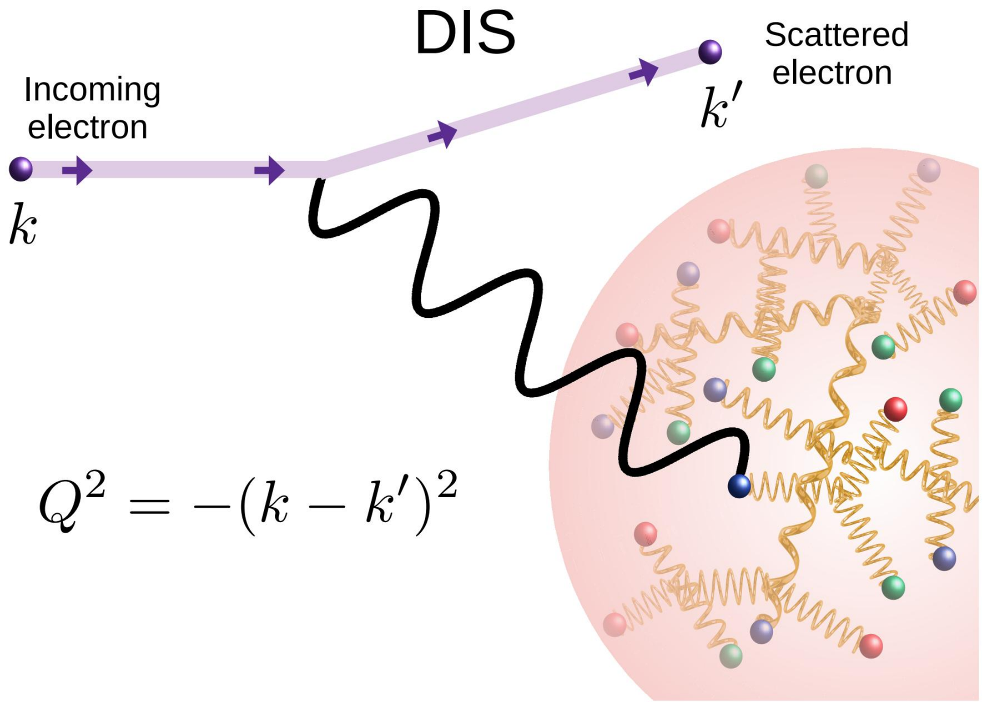
HERA Collider
Operated from 1992 to 2007
Circumference 6.3 km
Asymmetric detectors
Electrons or positrons colliding with protons
E_e=27.6 GeV, E_p=460 - 920 GeV
Centre-of-mass system is boosted to proton-direction

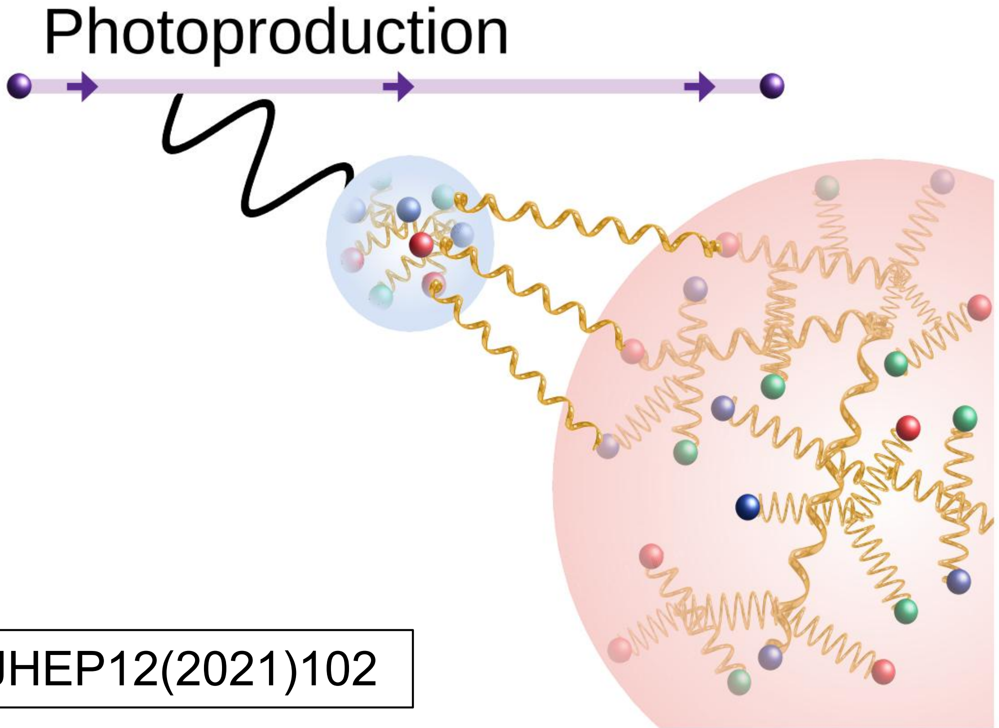




H1 Detector
Central tracker acceptance $|\eta|<1.6$
LAr calorimeter for hadronic final state
SpaCal calorimeter for detecting electrons with $5<Q^2<100$ GeV^2

DIS and photoproduction





JHEP12(2021)102

DIS defined by large virtualities:

$Q^2 \gg \Lambda^2_{QCD}$

Transverse radius(R_t) of the probed region are given by:

$R_t \backsim \frac{1}{Q}$

PRD 95, 114008 (2017)

Photoproduction defined by small virtualities:

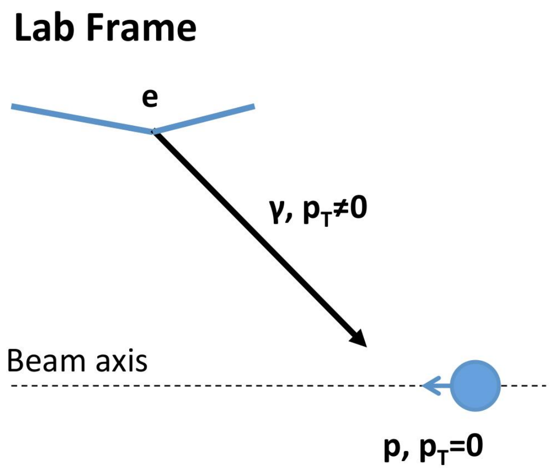
$Q^2 \ll \Lambda^2_{QCD}$

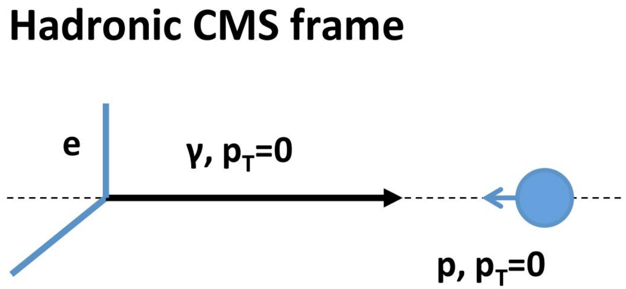
Exchange photon may fluctuate into partons

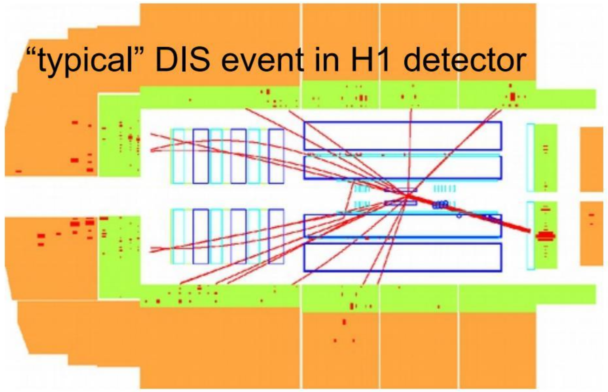
Large interaction regions probed

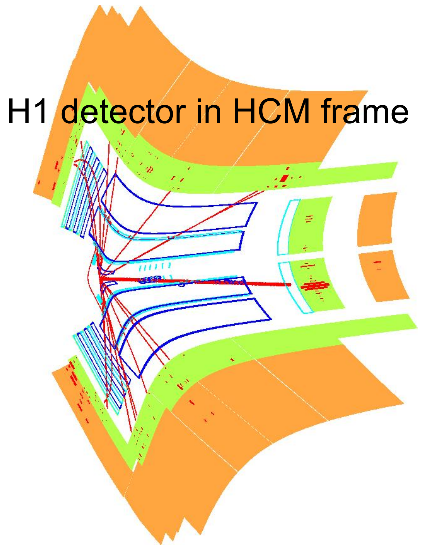
Scattering may be hadron-like

Search for collectivity in ep DIS









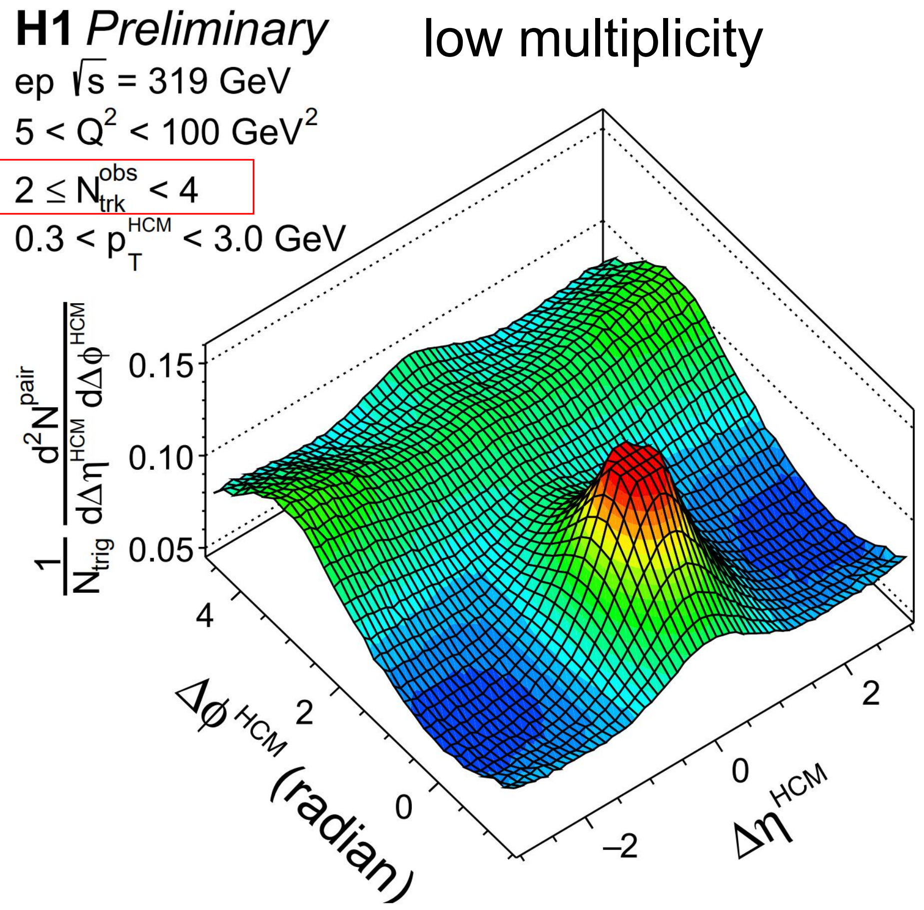
lab frame:
inhomogeneous p_T space

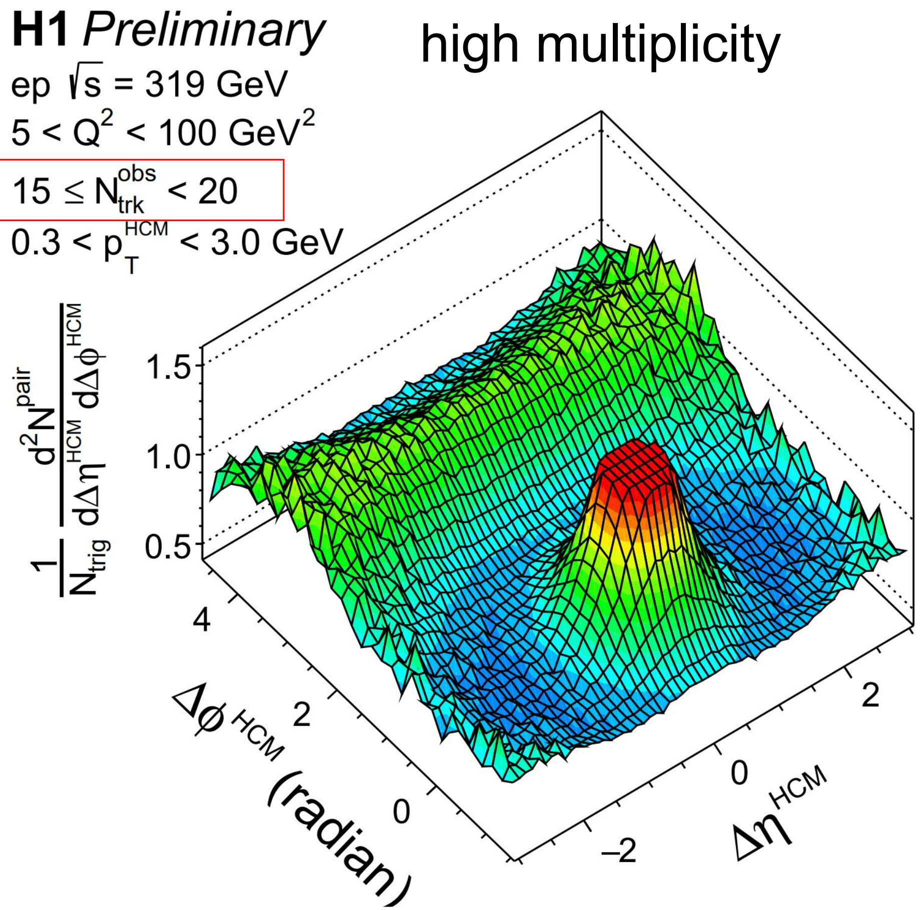
HCM frame:
homogeneous p_T space

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

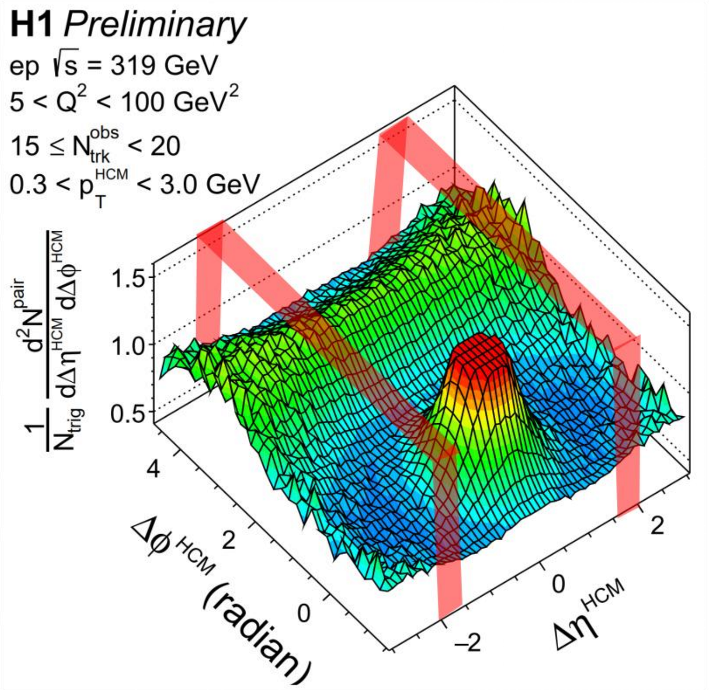
Extract ridge yield limits through ZYAM and bootstrap procedure

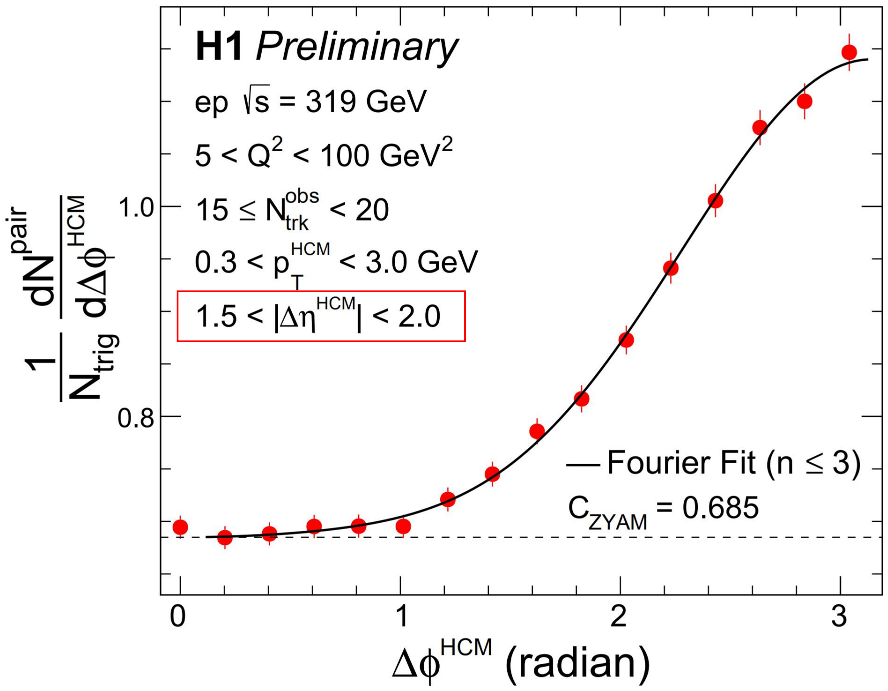
DIS HCM

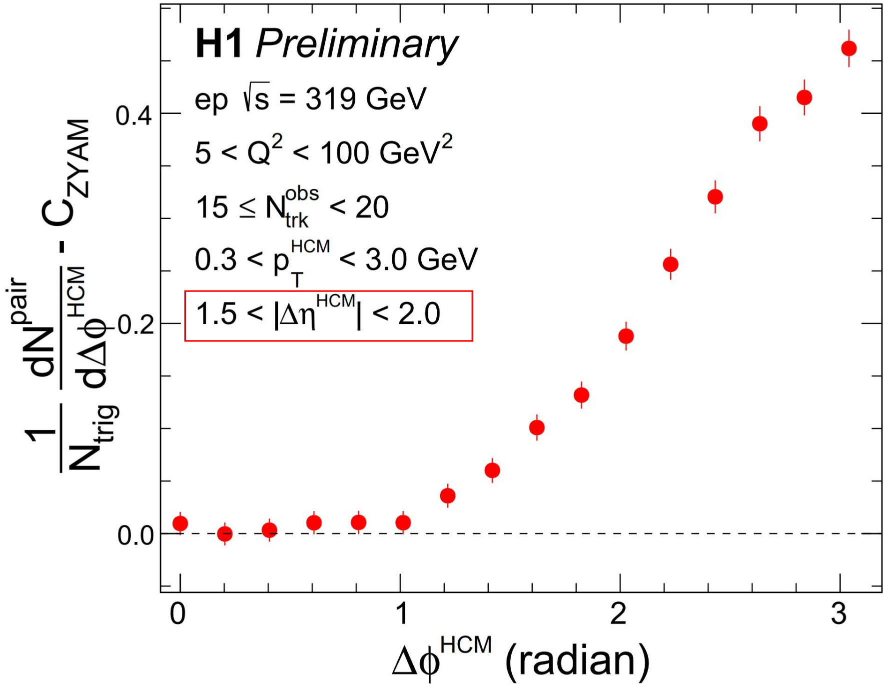
Ridge yield extraction procedure

Zero-yield-at-minimum(ZYAM)

PRC 81 014905 (2010)







Step1: long-range 1D projection

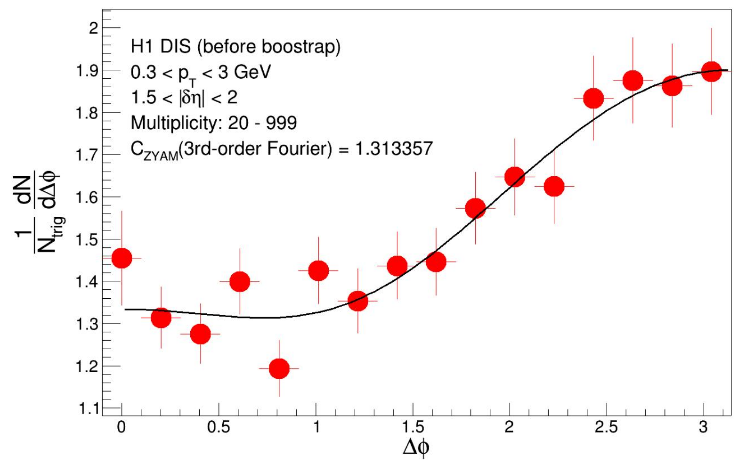
Step2: third-order Fourier fit

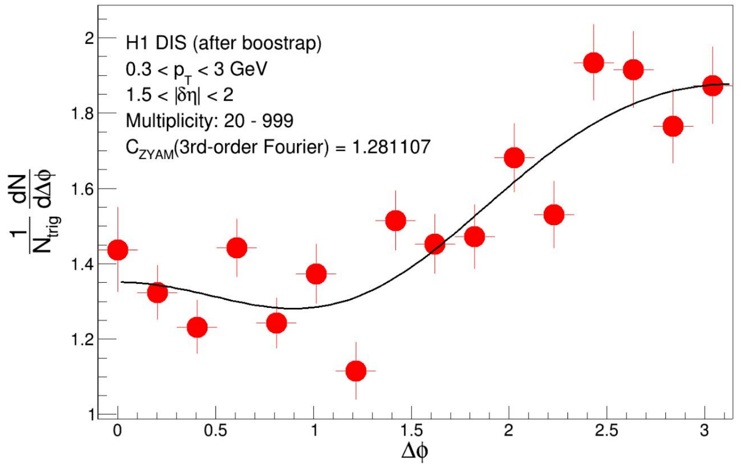
Step3: subtraction

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

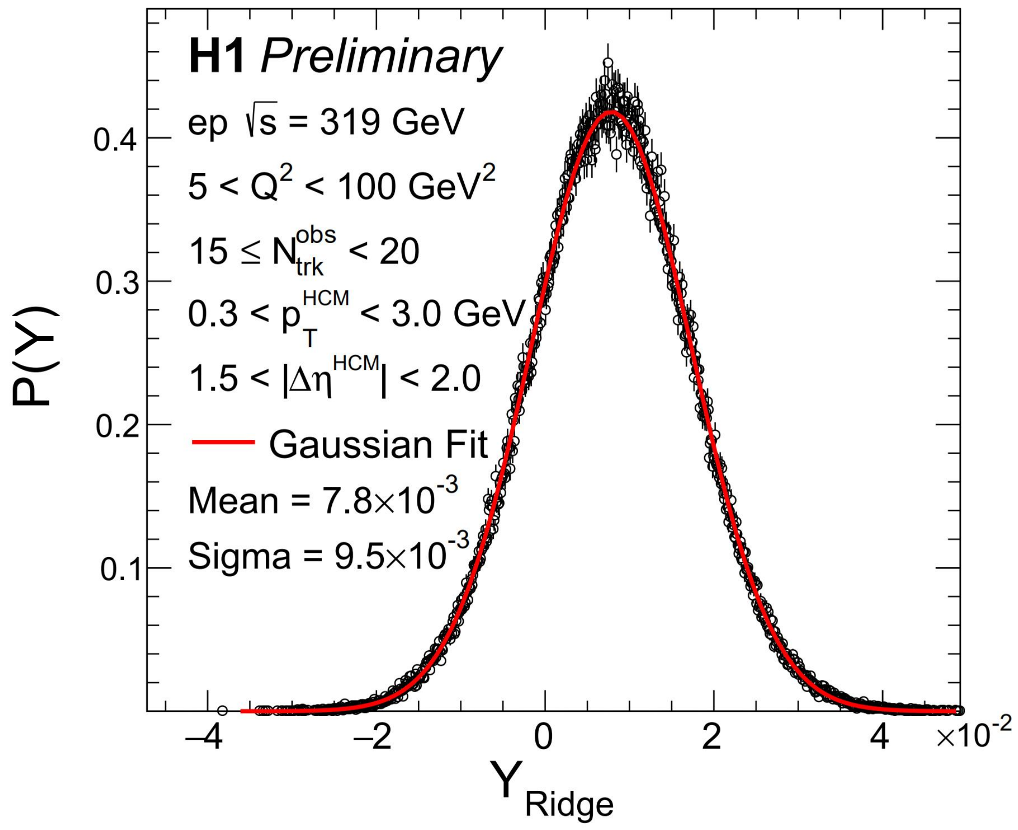
Bootstrap procedure

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



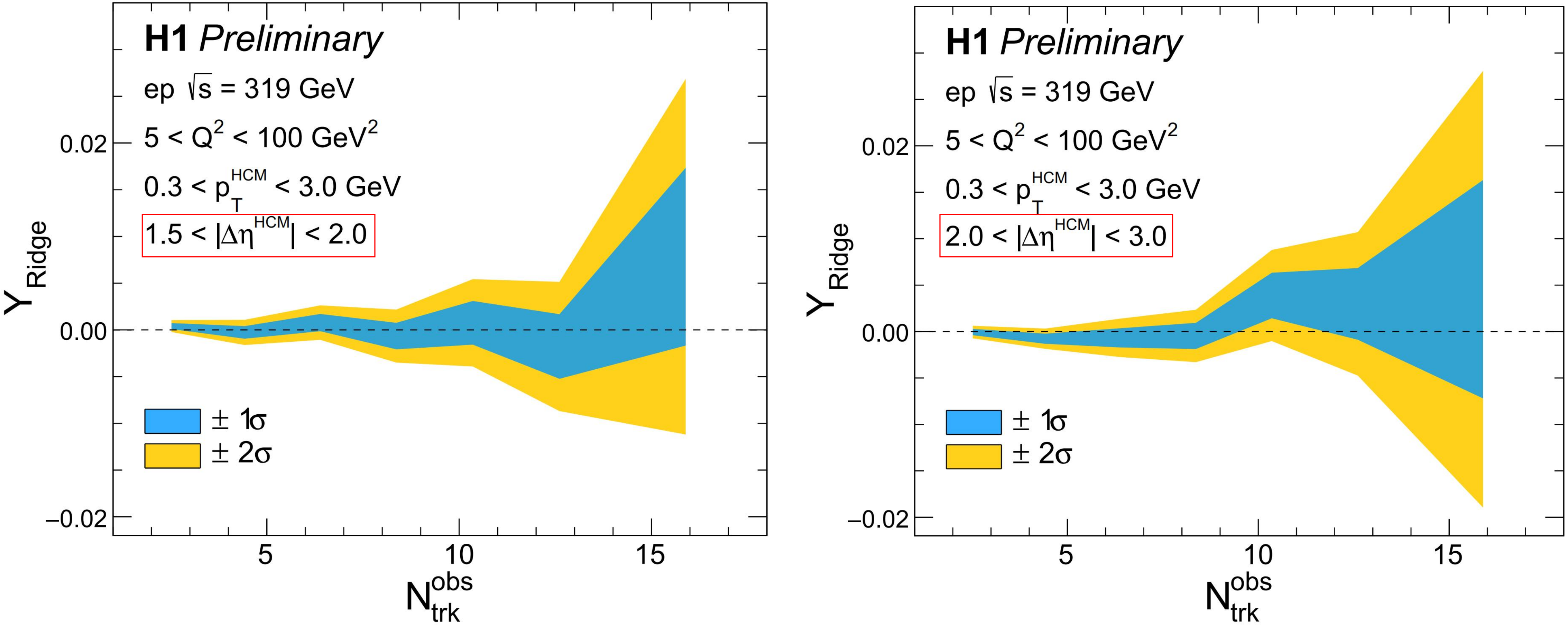


Each yield distribution is sampled 2.5x10[5] times



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

Ridge yield limits in ep DIS



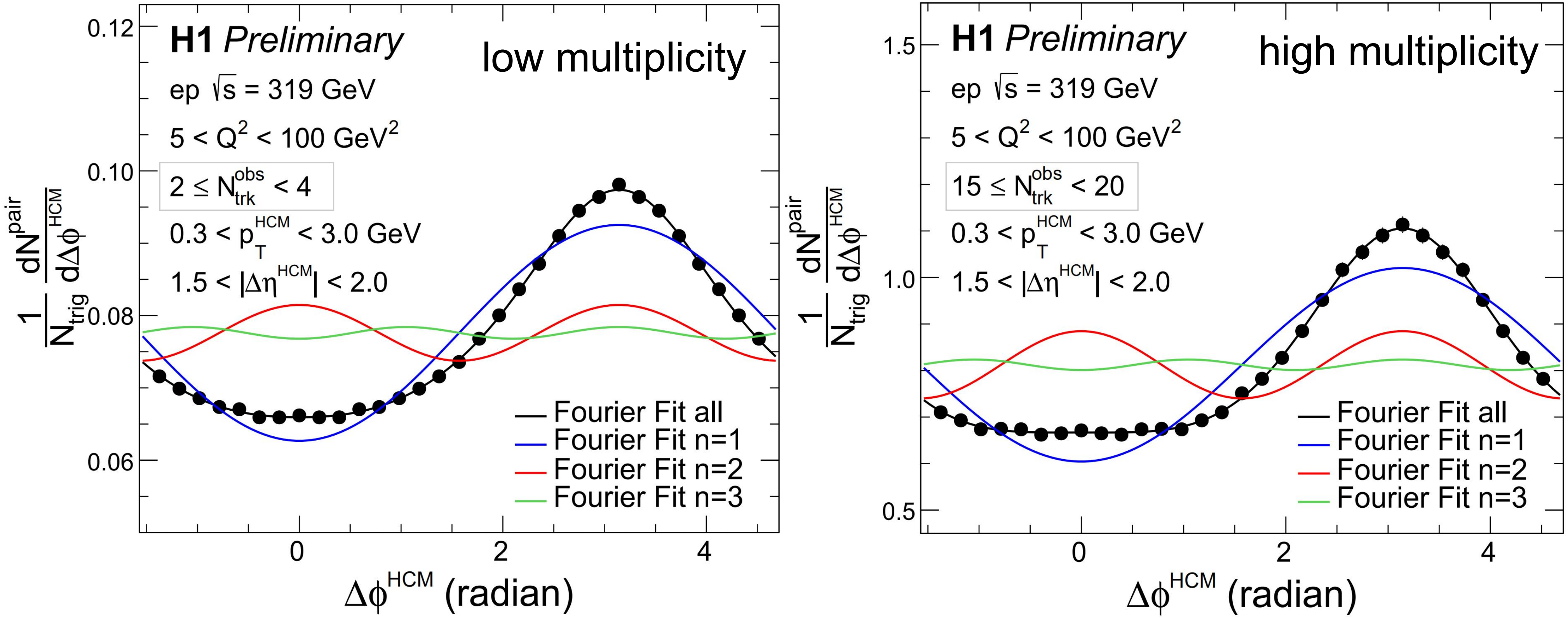
Limits set for ridge yield
Small room for existence of ridge

DIS HCM

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

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

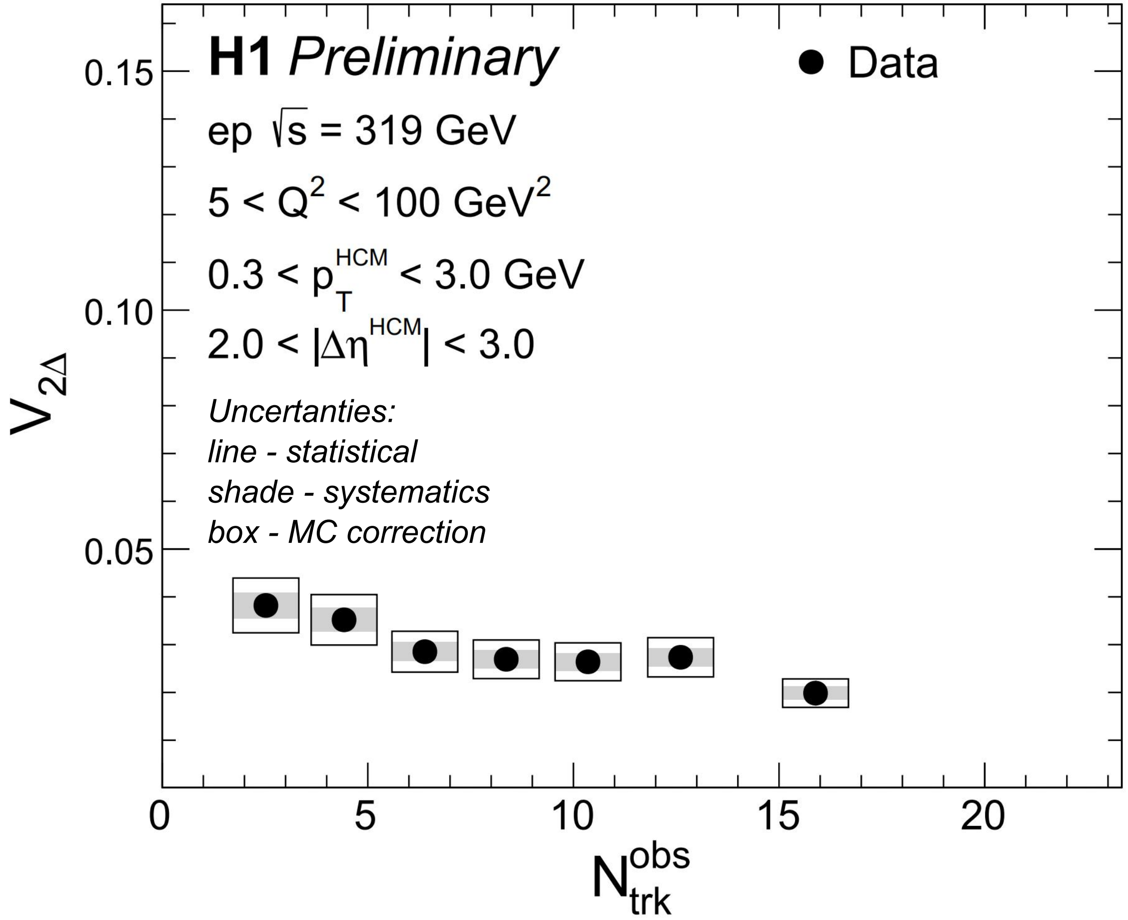
$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left(1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right)$$

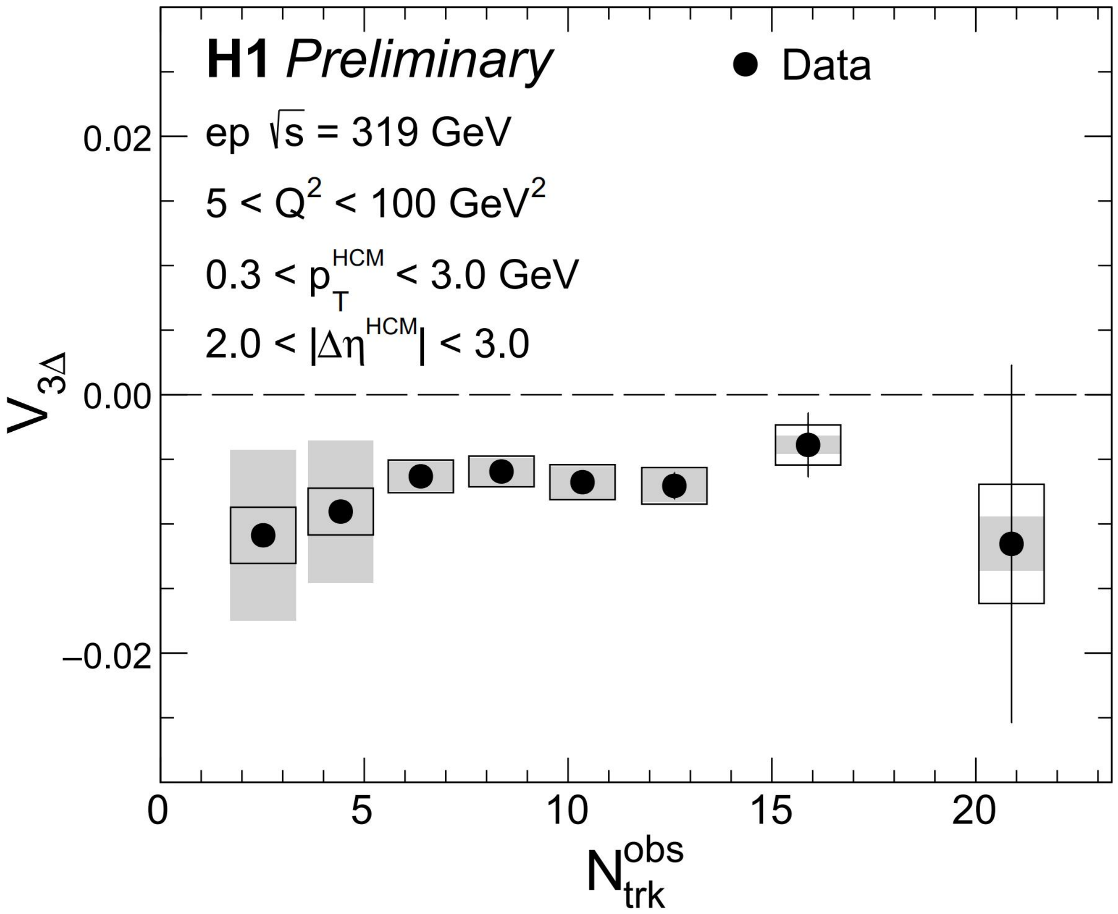


Similar shapes in low and high multiplicity

DIS HCM

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



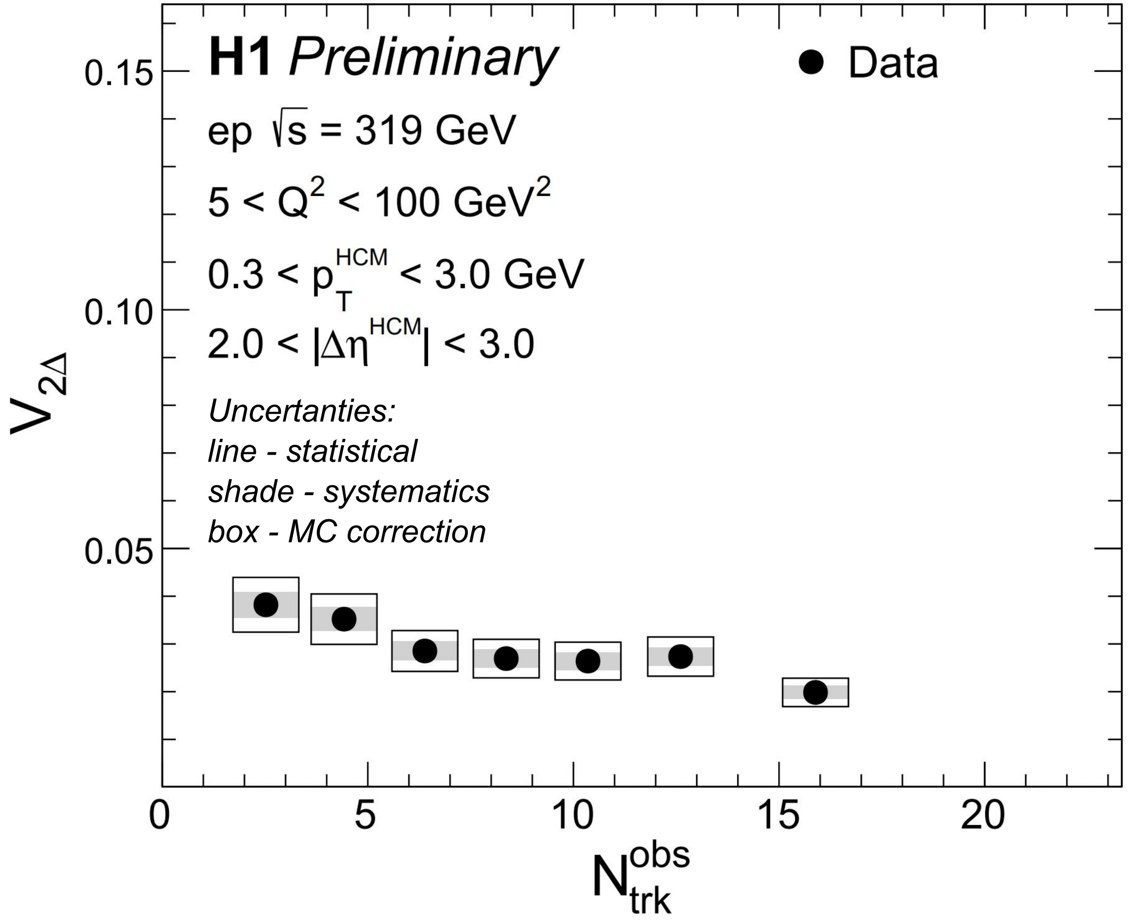


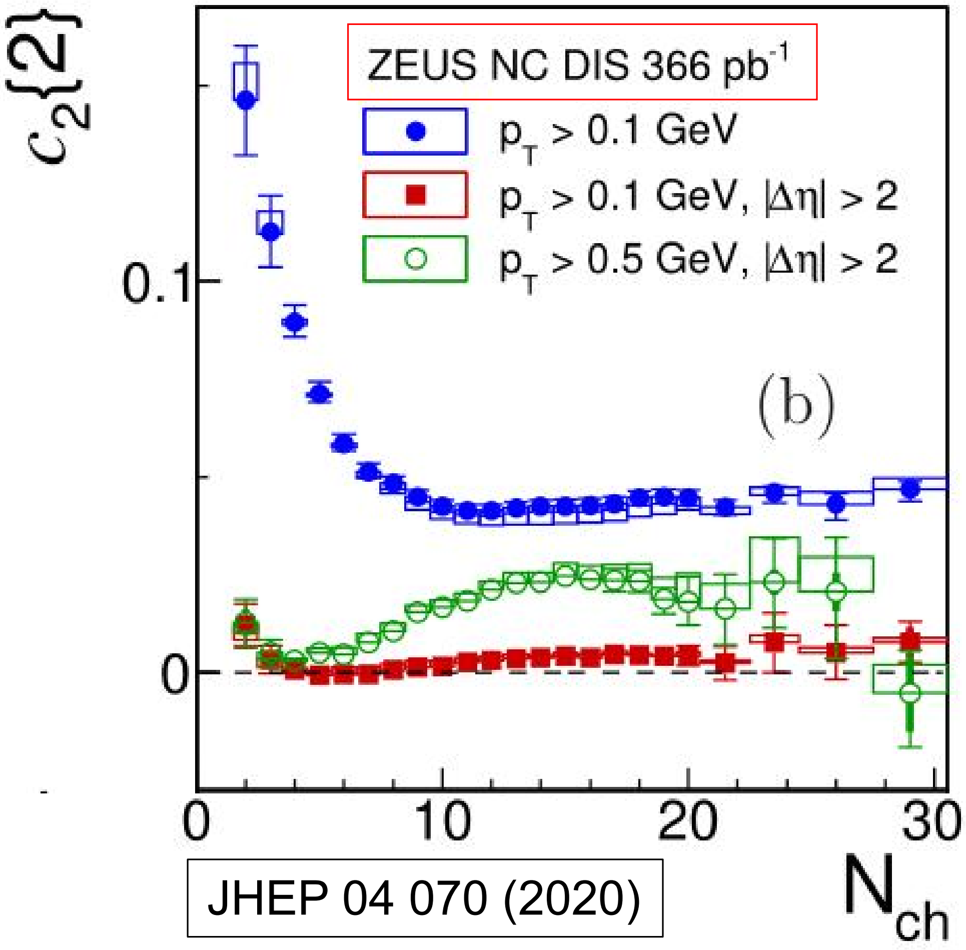
$V_{2\Delta}$ value drops in high multiplicity

Negative $V_{3\Delta}$ means it dominated by non-flow correlation

DIS HCM

Fourier coefficient $V_{n\Delta}$ in ep DIS (Compared with ZEUS)



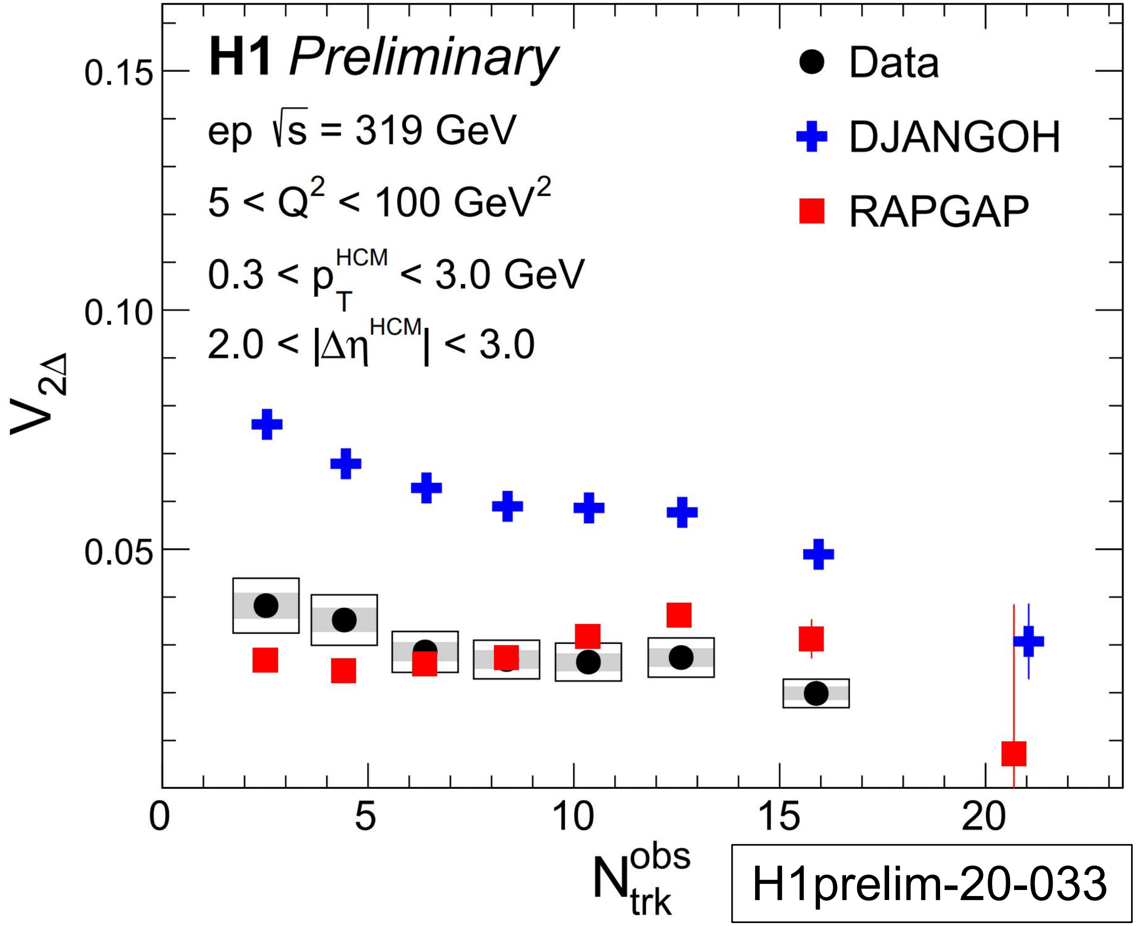


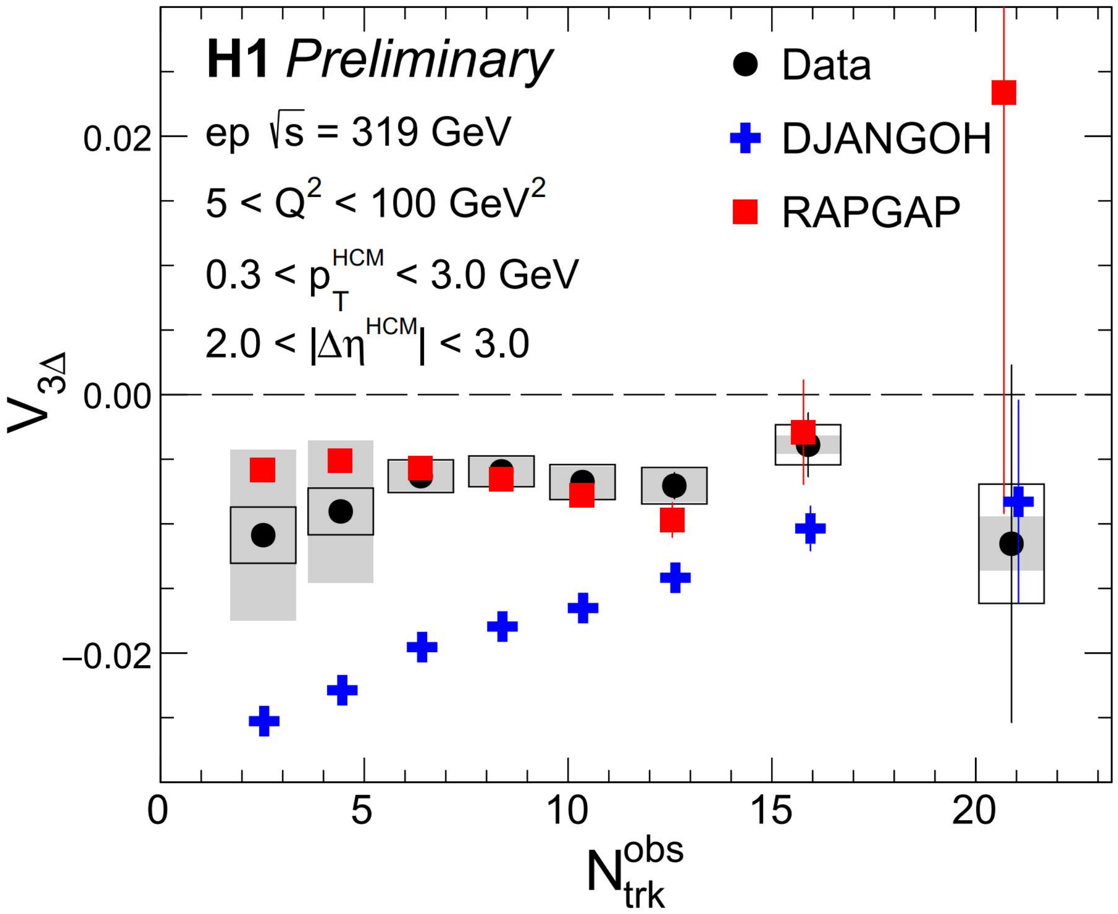
JHEP 04 070 (2020)

$V_{2\Delta}$ has similar trend as ZEUS result

DIS HCM

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

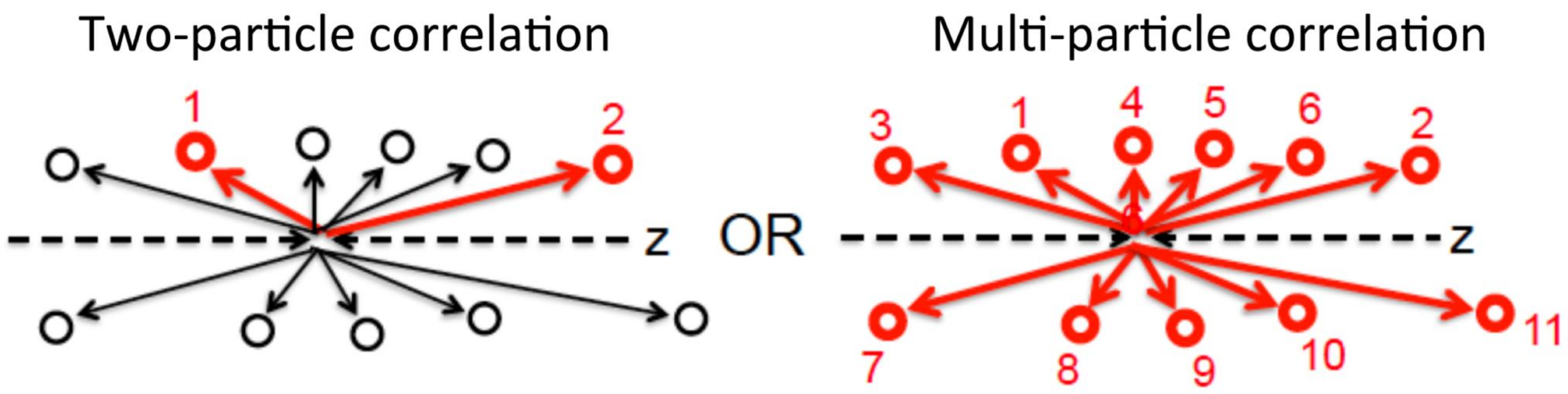




RAPGAP has better description on DIS data than DJANGOH
Data can be described by MC(RAPGAP) w/o collectivity

DIS HCM

Multi-particle correlation



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

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

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

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

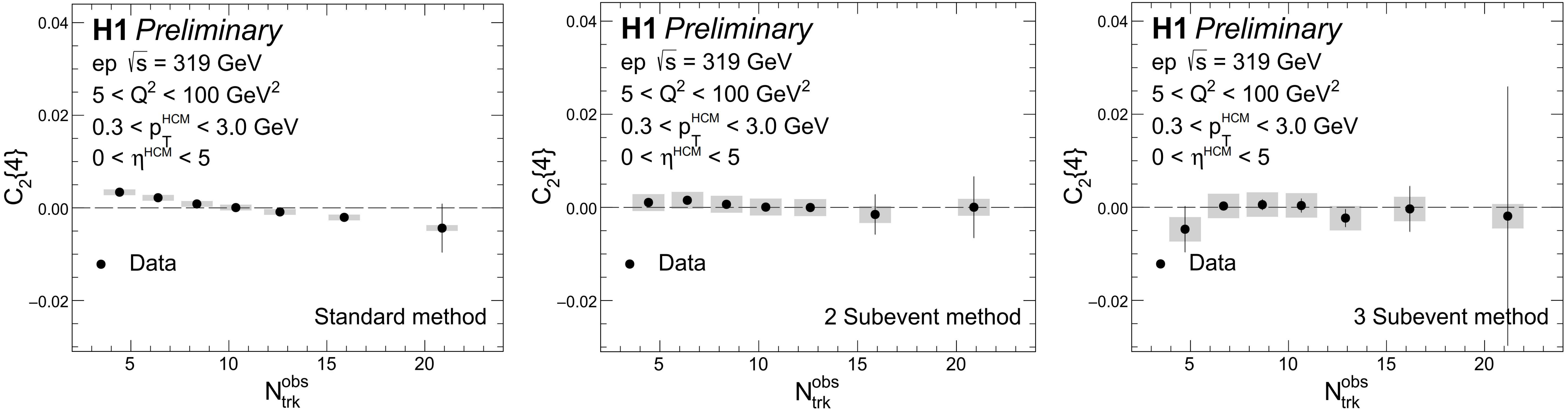
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Few particle correlation is suppressed
Collective behavior leads to negative $C_n\{4\}$
Subevent cumulants also investigated to further suppress non-flow

PRC 83, 044913 (2011)

PRC 96, 034906 (2017)

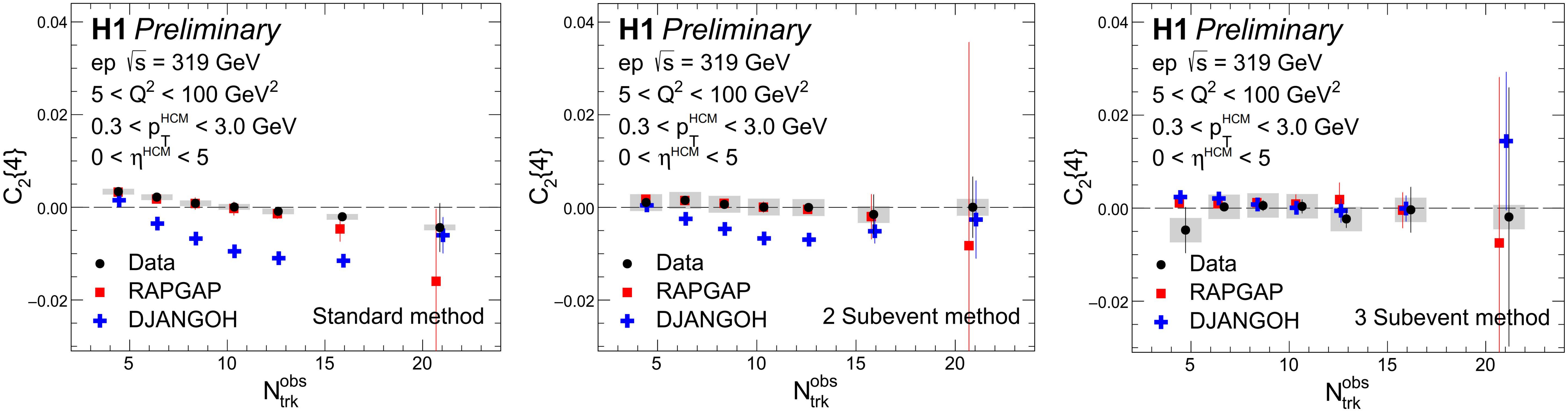
Multi-particle correlation in ep DIS



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

DIS HCM

Multi-particle correlation in ep DIS

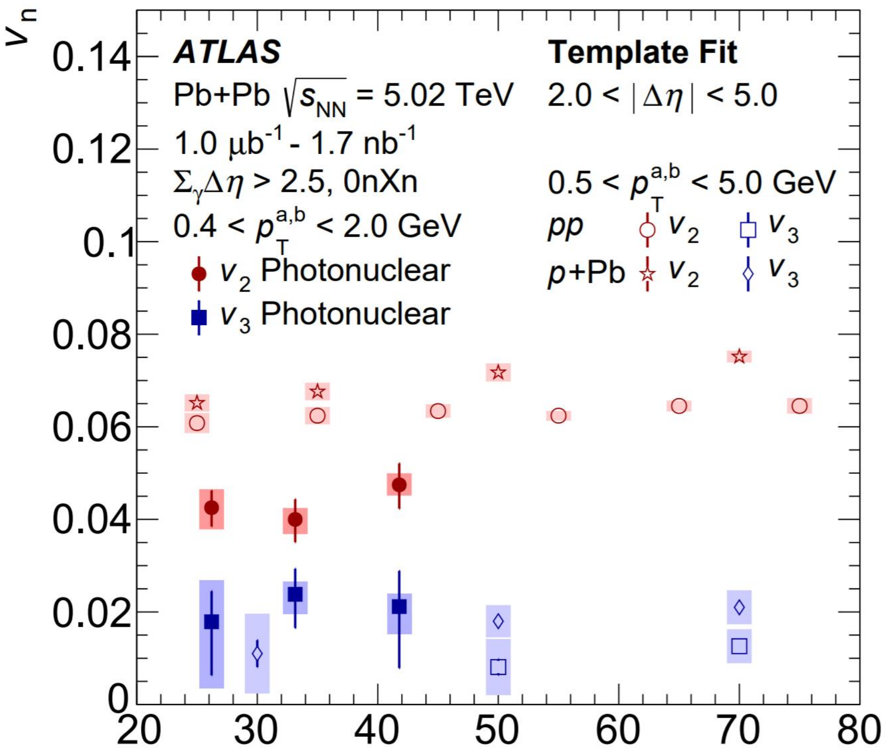


No obvious negative $C_2\{4\}$ in DIS

RAPGAP can describe data

DIS HCM

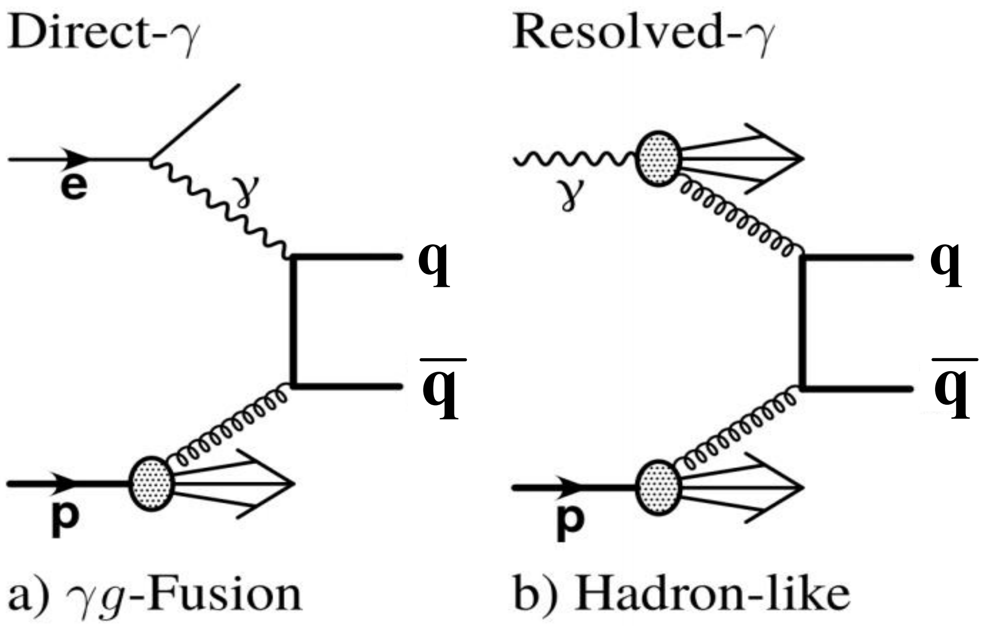
Search for collectivity in ep photoproduction



PRC 104, 014903 (2021)

Non-zero v_2 values observed in PbPb ultra-peripheral collisions

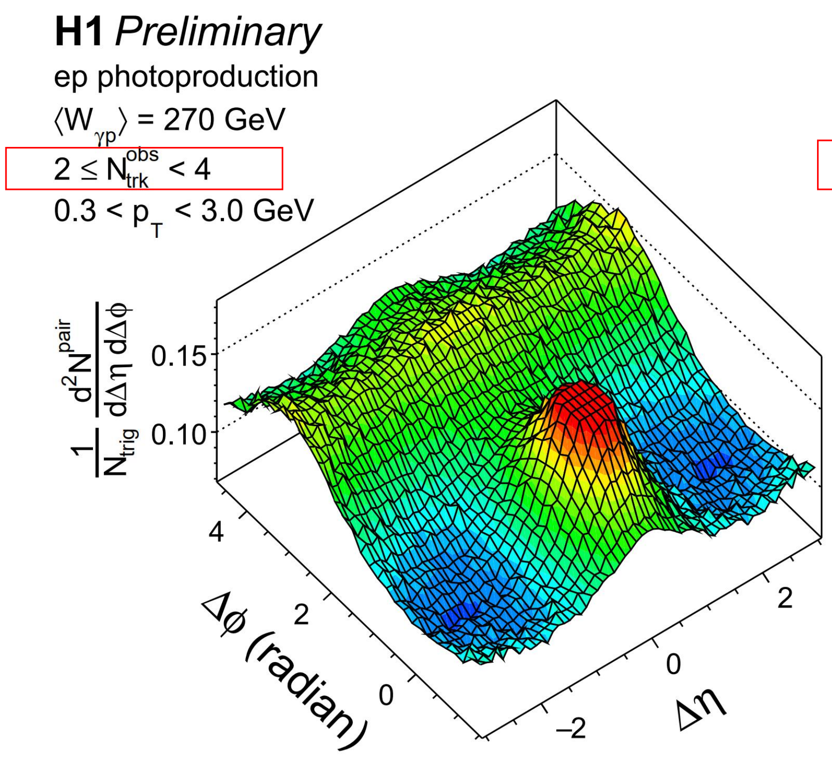
Evidence of collectivity in photo-nuclear collisions



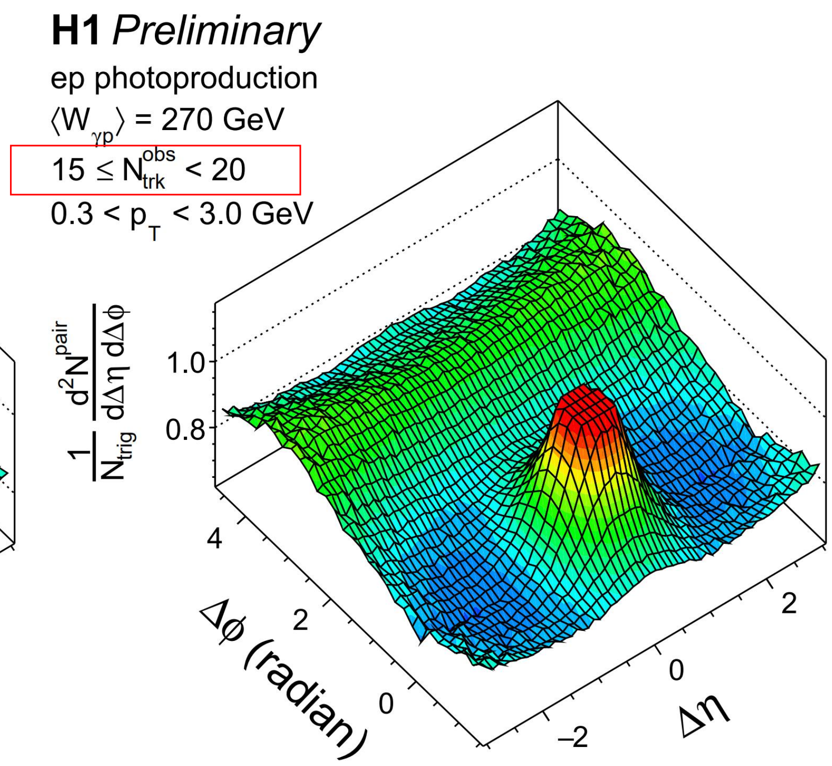
The resolved photoproduction process in ep collisions can be regarded as hadronic collisions

Collectivity in high multiplicity ep photoproduction?

Ridge yield limit in ep photoproduction



low multiplicity

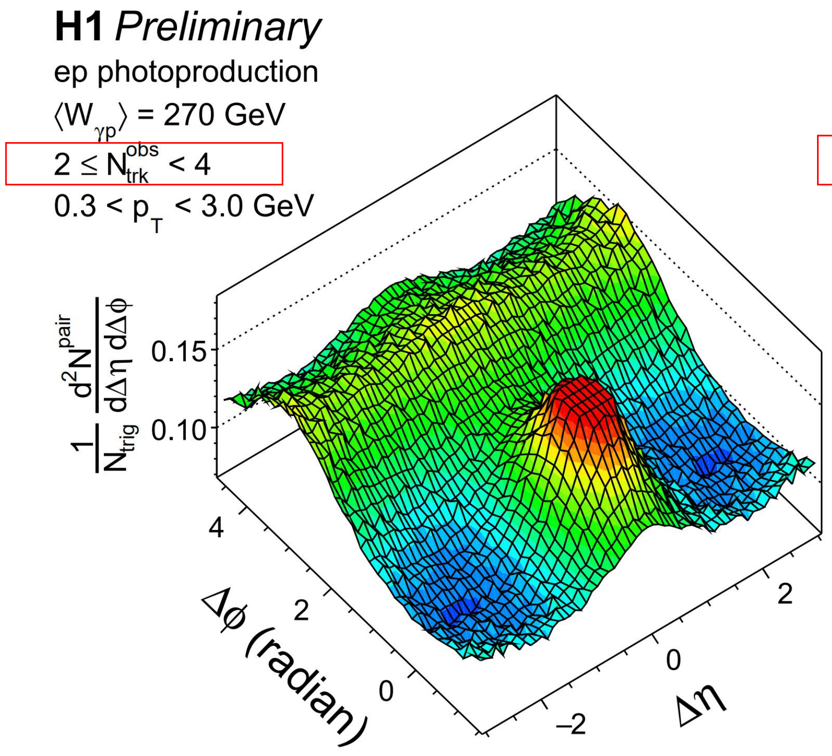


high multiplicity

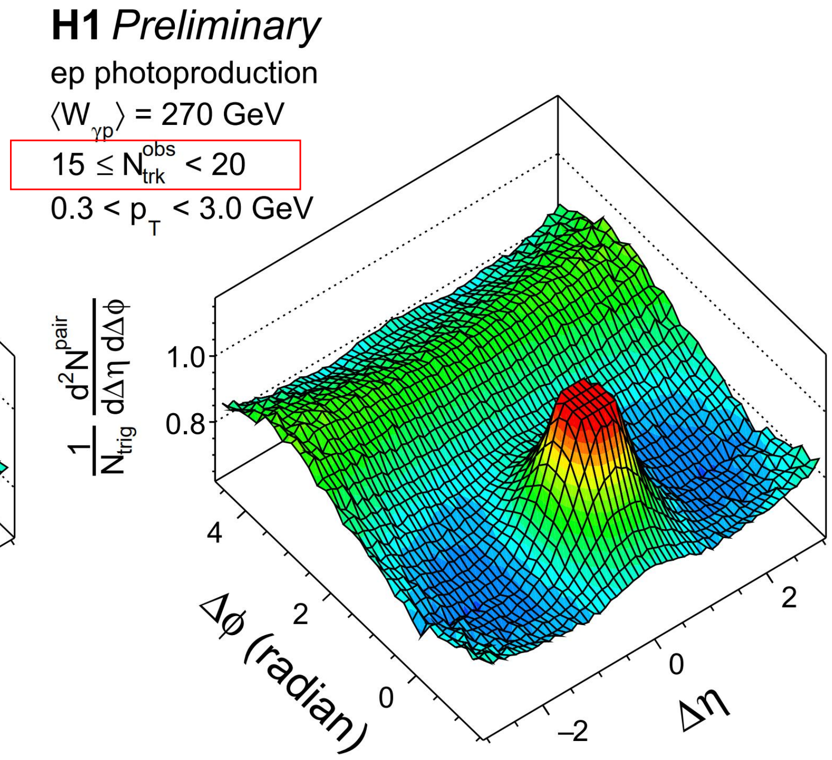
No near-side long-range ridge observed

photoproduction

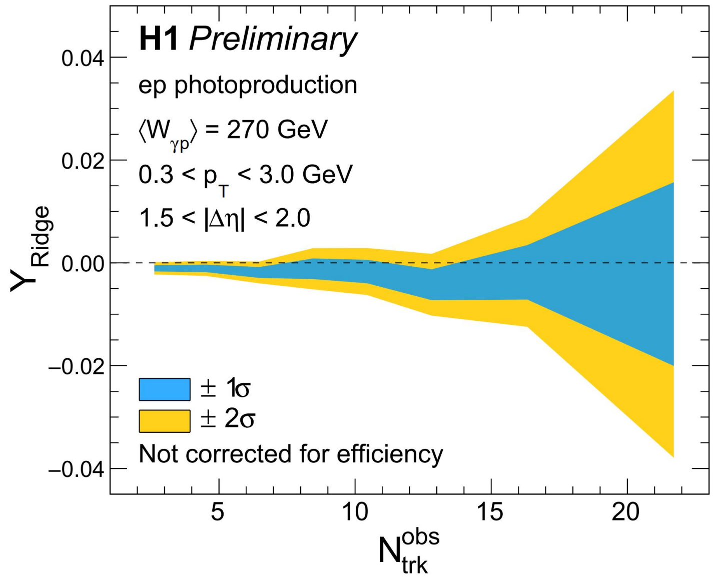
Ridge yield limit in ep photoproduction

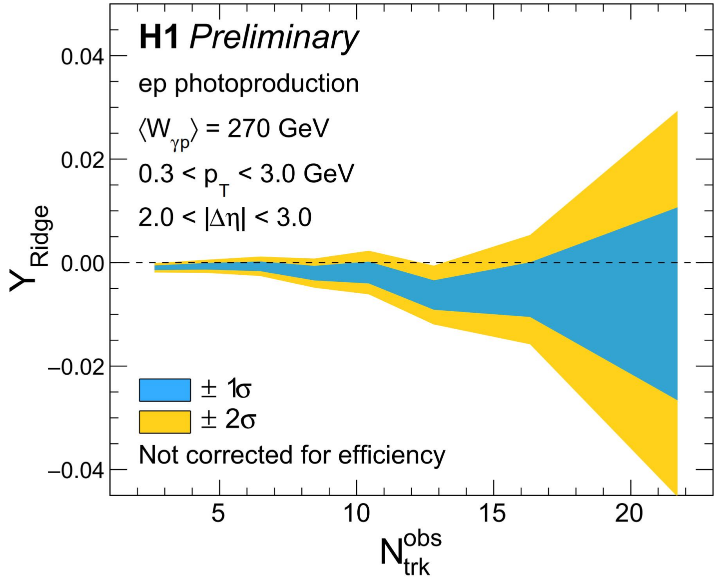


low multiplicity



high multiplicity

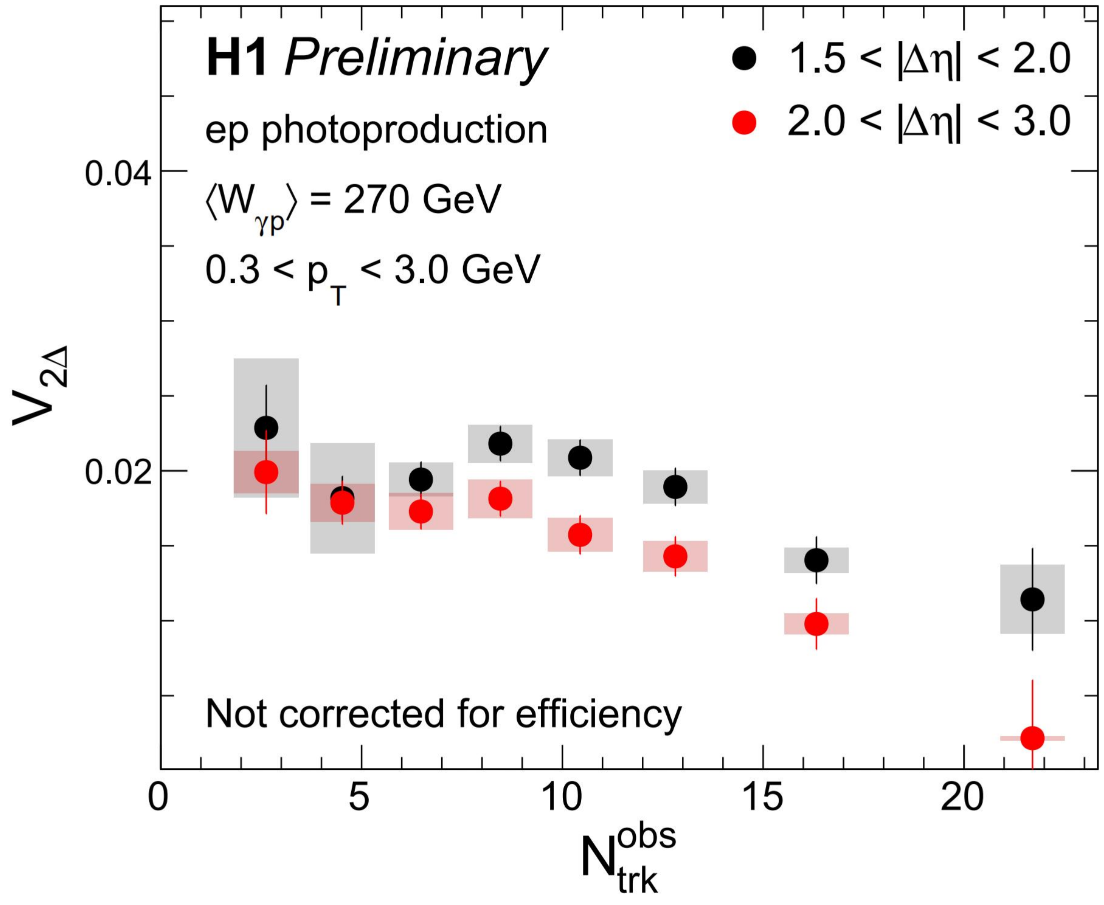


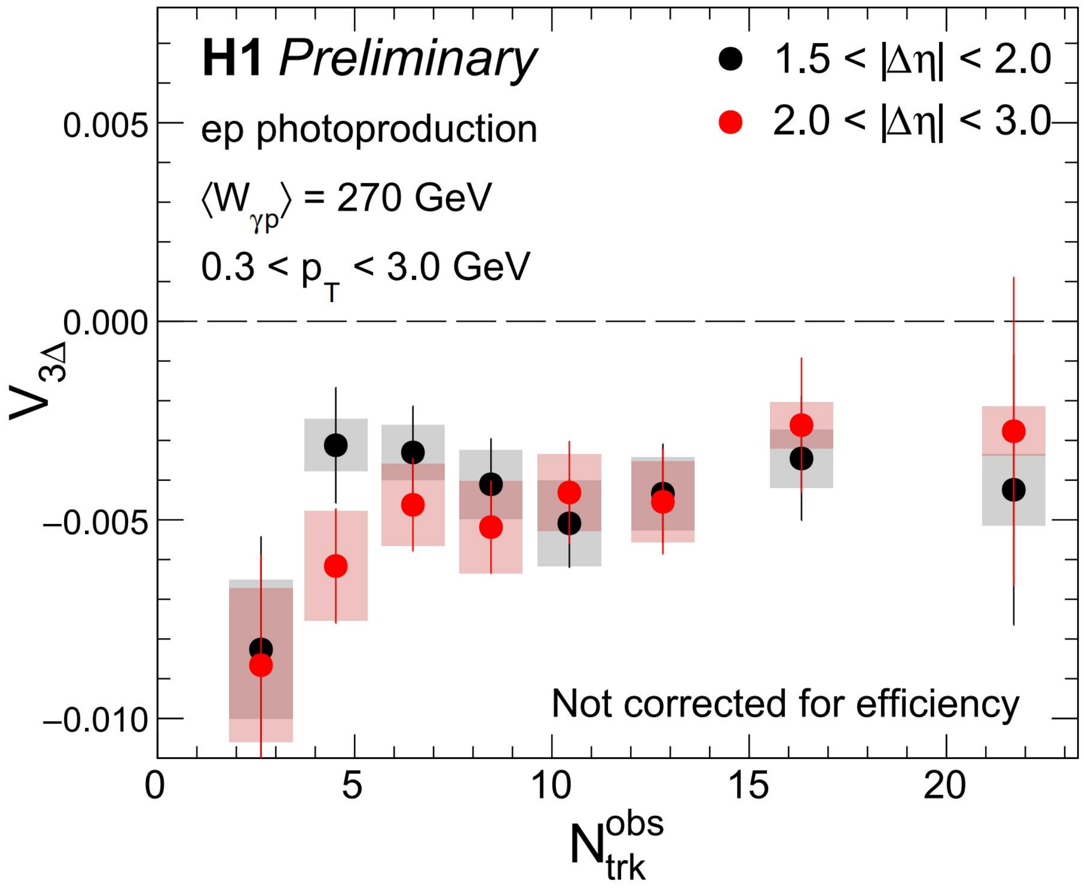


No near-side long-range ridge observed
Small room for existence of ridge

photoproduction

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





photoproduction

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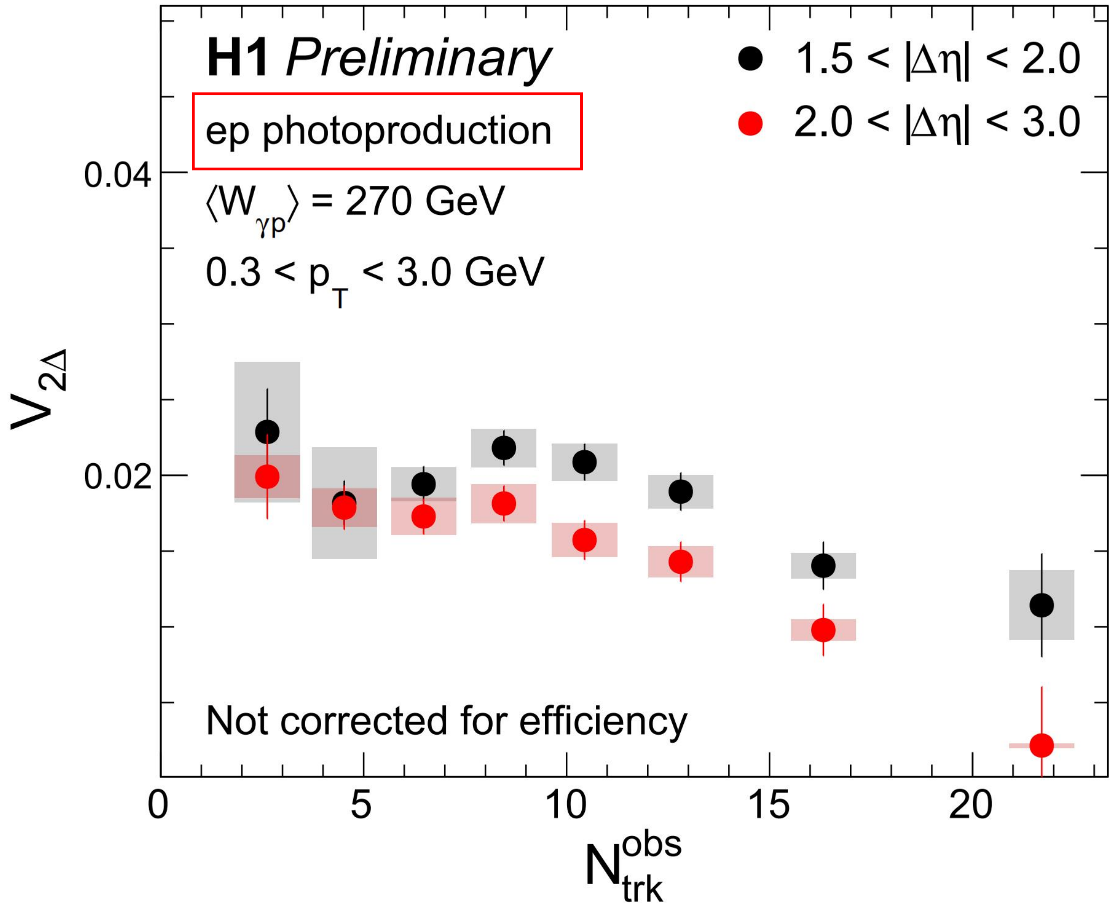
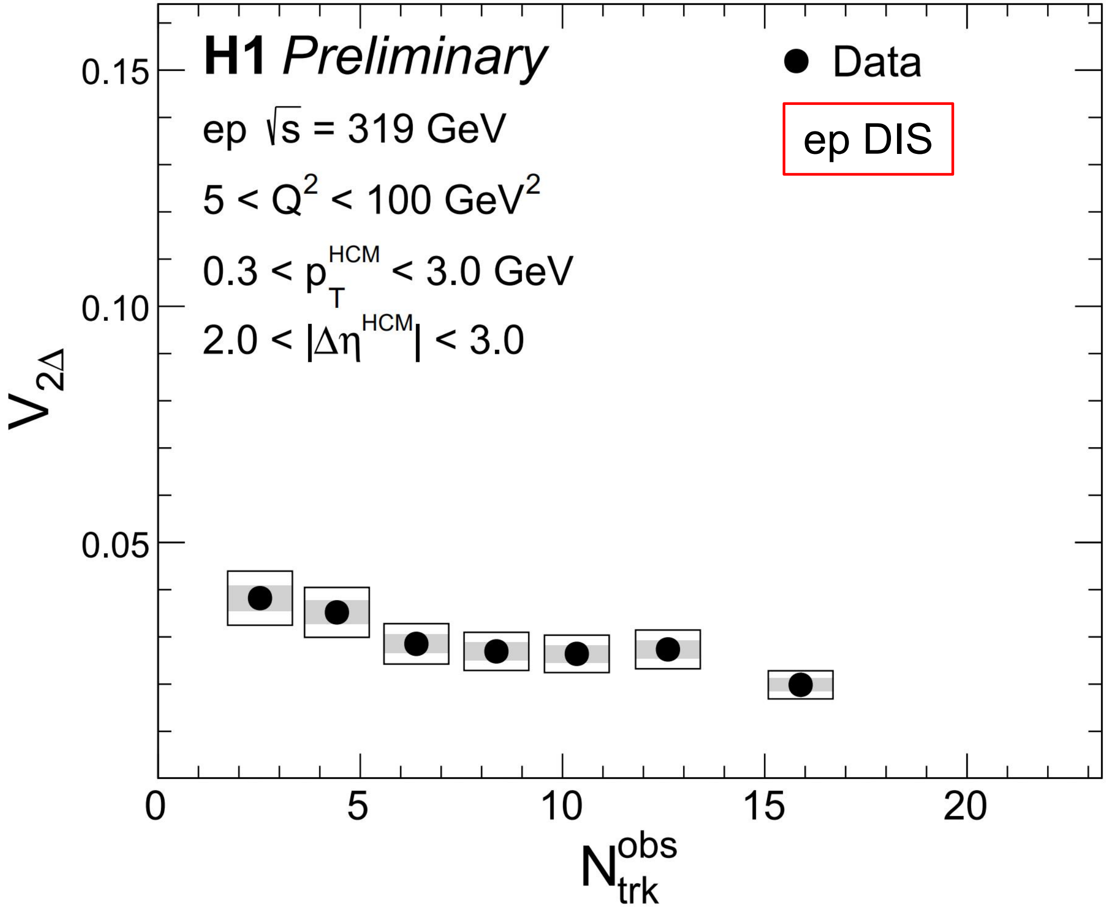
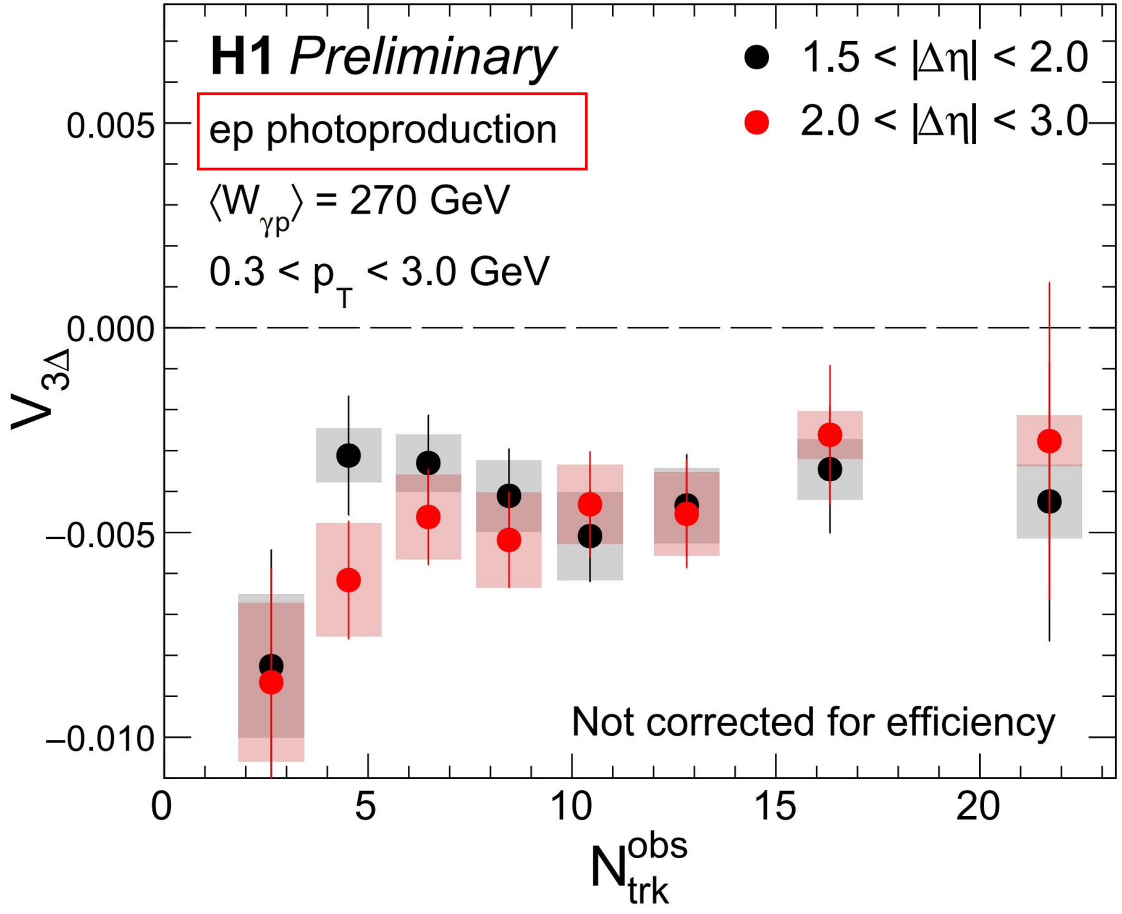


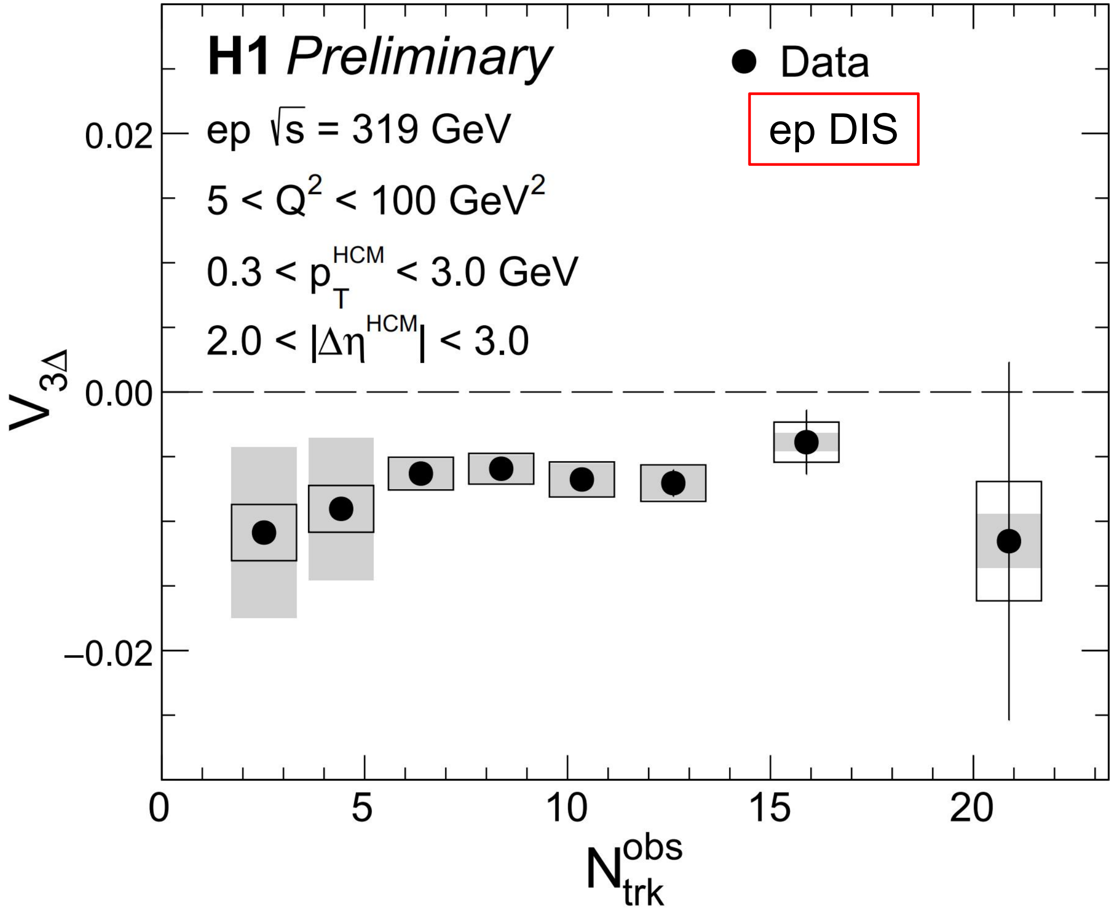


Similar $V_{2\Delta}$ behavior in photoproduction data as in DIS

photoproduction

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

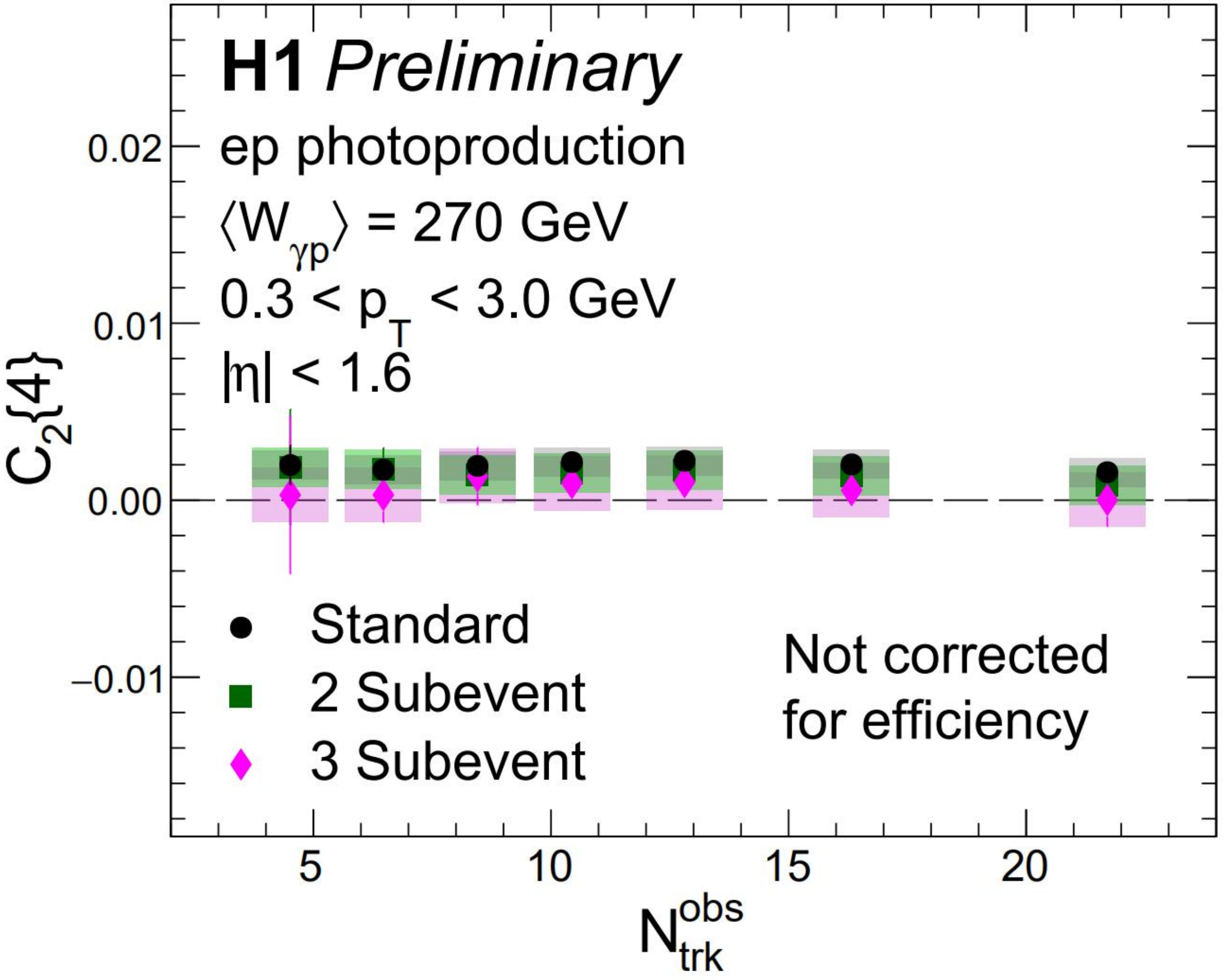




Similar $V_{3\Delta}$ behavior in photoproduction data as in DIS

photoproduction

Multi-particle correlation in ep photoproduction



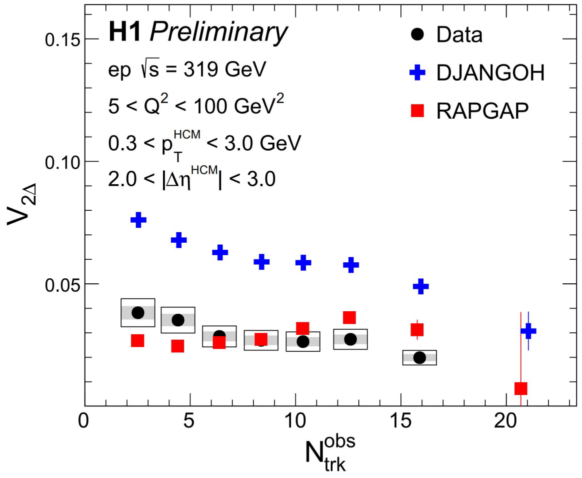
No evidence of negative $C_2\{4\}$, no sign of collectivity

photoproduction

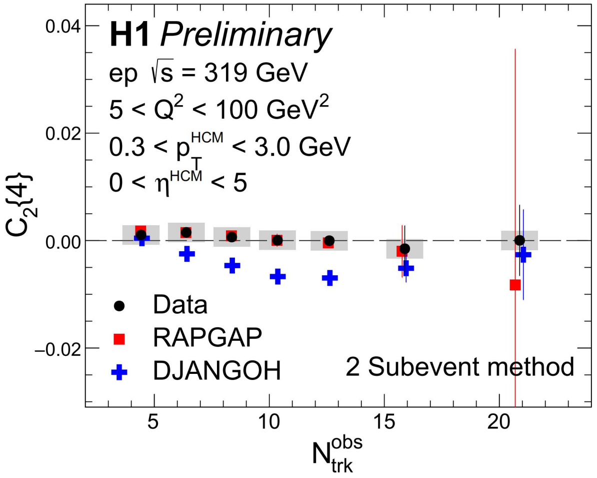
Summary

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

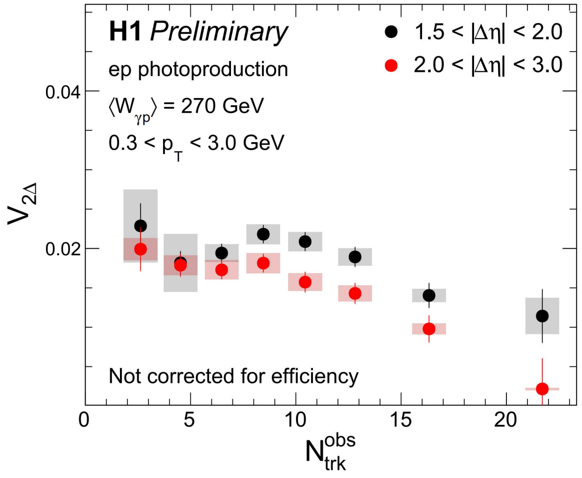
- No long-range near-side ridge
- Decreasing $V_{2\Delta}$ and negative $V_{3\Delta}$
- No negative $C_2\{4\}$
- Compared with MC simulation:
  - $V_{2\Delta}$ and $V_{3\Delta}$ in DIS can be described by RAPGAP w/o collectivity
  - $C_2\{4\}$ can also be described by RAPGAP w/o collectivity



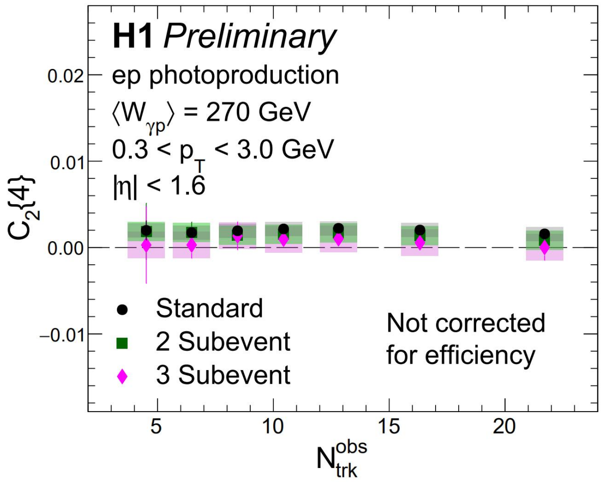
DIS $V_{2\Delta}$



DIS $C_2\{4\}$



photoproduction $V_{2\Delta}$



photoproduction $C_2\{4\}$

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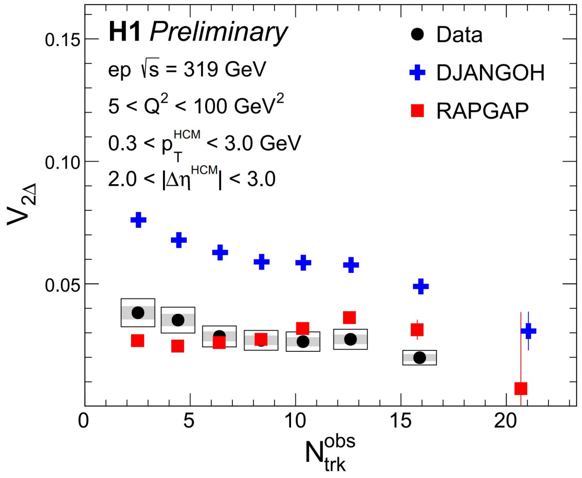
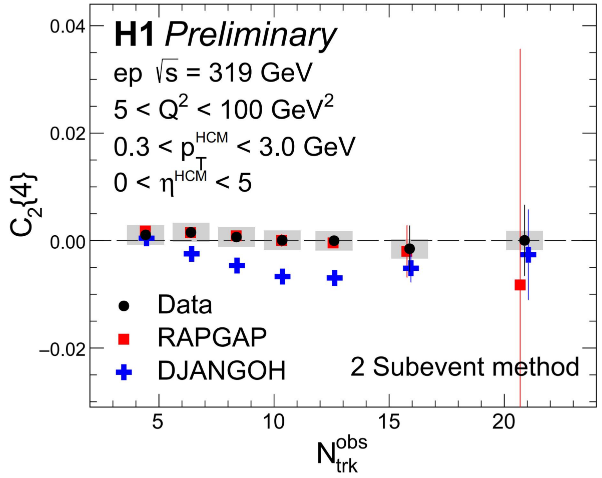
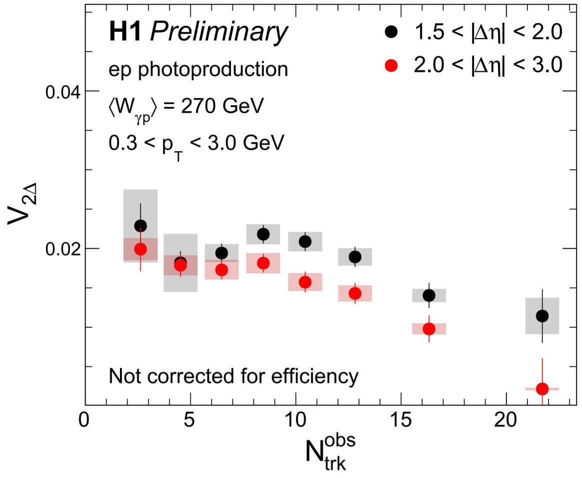
Is there any collectivity in high multiplicity eA collisions? Stay tuned for EIC



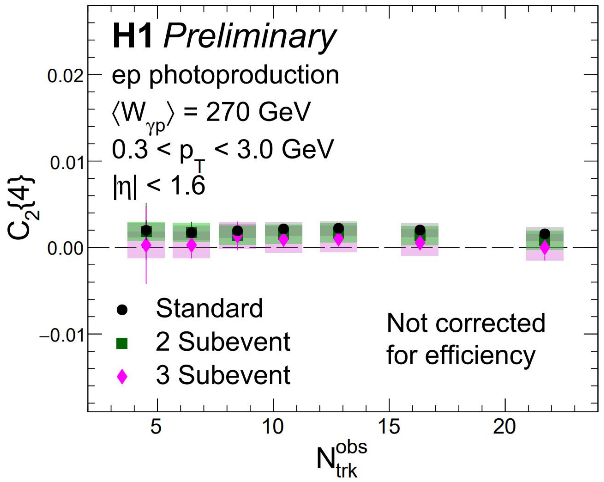
DIS $V_{2\Delta}$



DIS $C_2\{4\}$



photoproduction $V_{2\Delta}$



photoproduction $C_2\{4\}$

Thanks for attention

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

No long-range near-side ridge

Decreasing $V_{2\Delta}$ and negative $V_{3\Delta}$

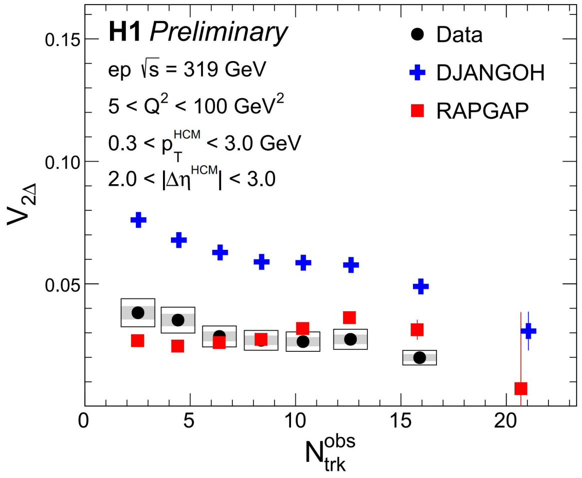
No negative $C_2\{4\}$

Compared with MC simulation:

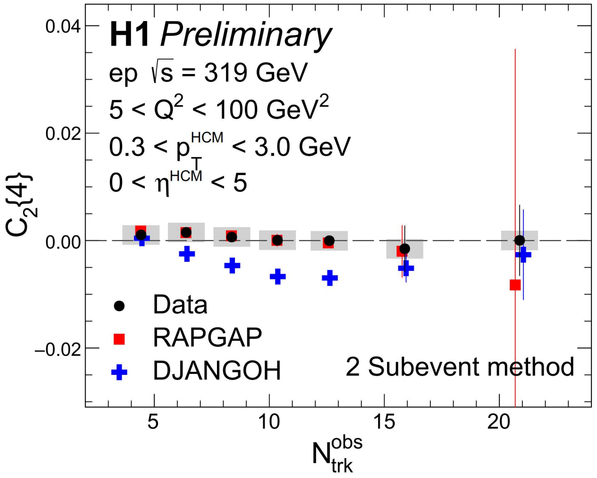
$V_{2\Delta}$ and $V_{3\Delta}$ in DIS can be described by RAPGAP w/o collectivity

$C_2\{4\}$ can also be described by RAPGAP w/o collectivity

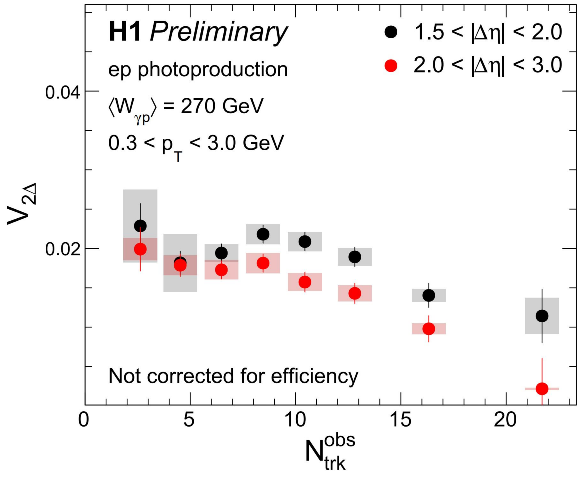
Is there any collectivity in high multiplicity eA collisions? Stay tuned for EIC



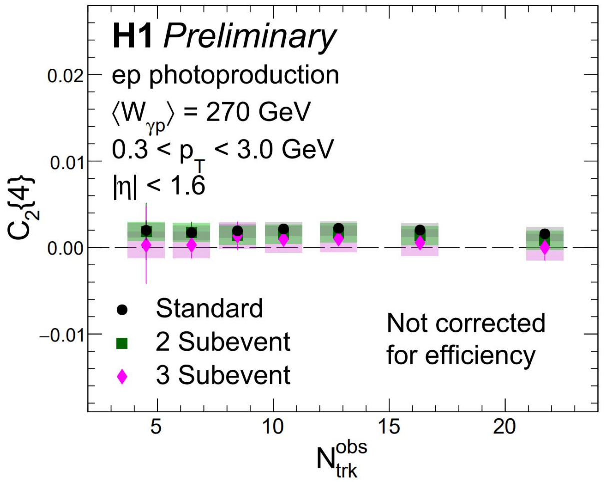
DIS $V_{2\Delta}$



DIS $C_2\{4\}$



photoproduction $V_{2\Delta}$

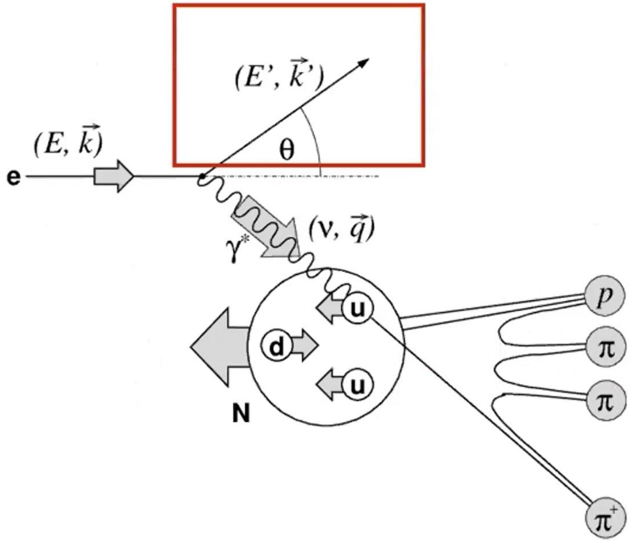


photoproduction $C_2\{4\}$

Thanks for your attention!

Back up

Kinematics in DIS

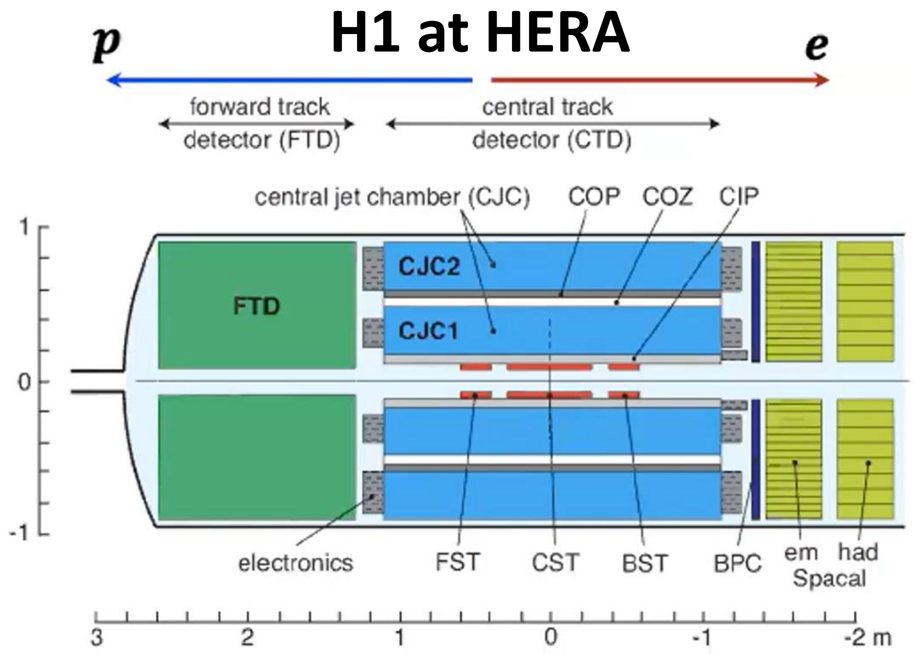


$$Q^2 = -q^2$$

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

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

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



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:

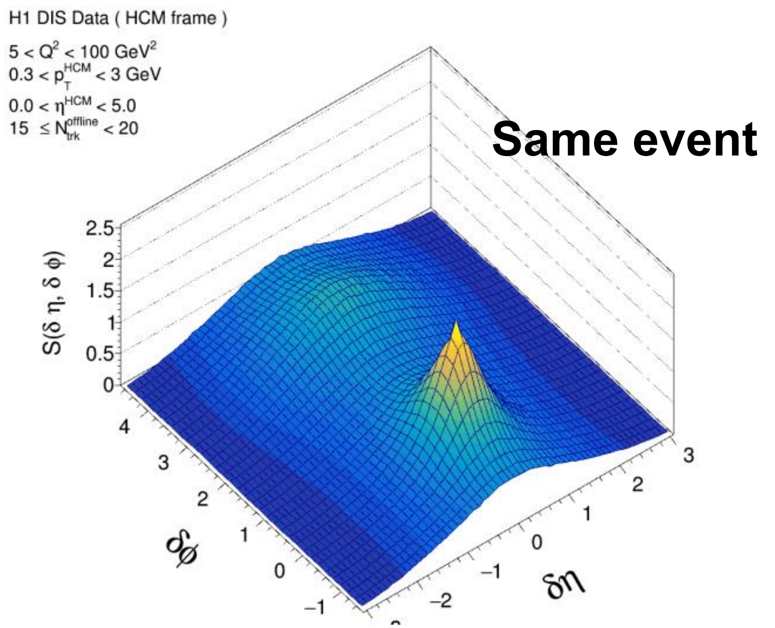
$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{same}}{d\Delta\eta d\Delta\phi}$$

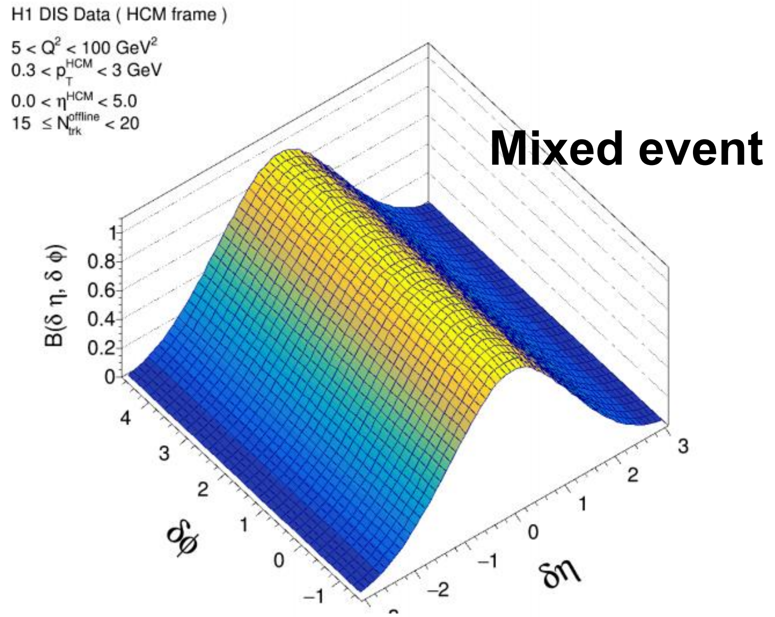
The mix-event background distributions is constructed with trigger particles from one event are correlating with all of the associated particles from different events within $|Z_{VTX}| < 2$cm. In this analysis, each event is paired with 5 randomly chosen events. The result is given by

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

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

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

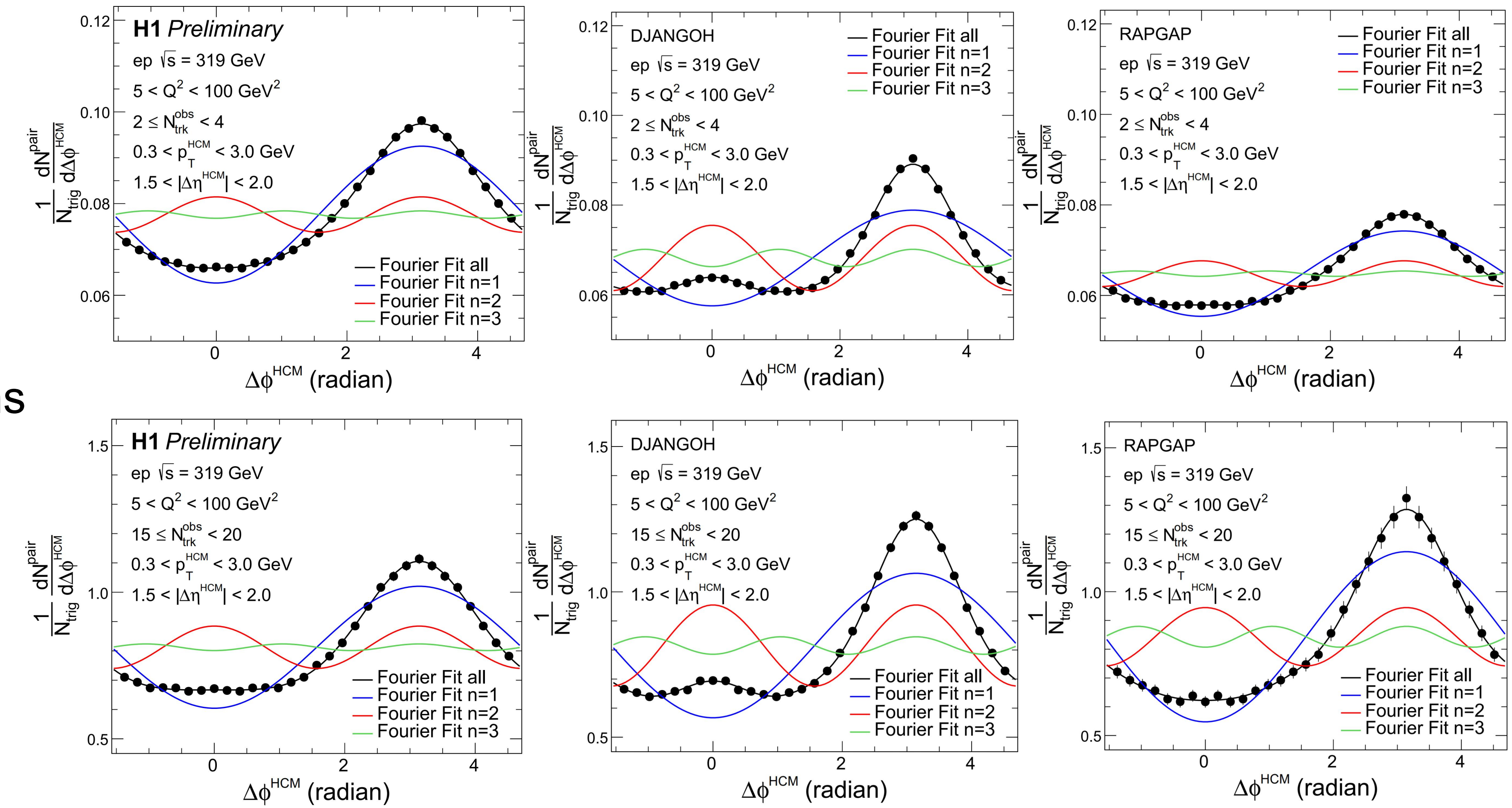




Fourier coefficient $V_{n\Delta}$ extraction procedure

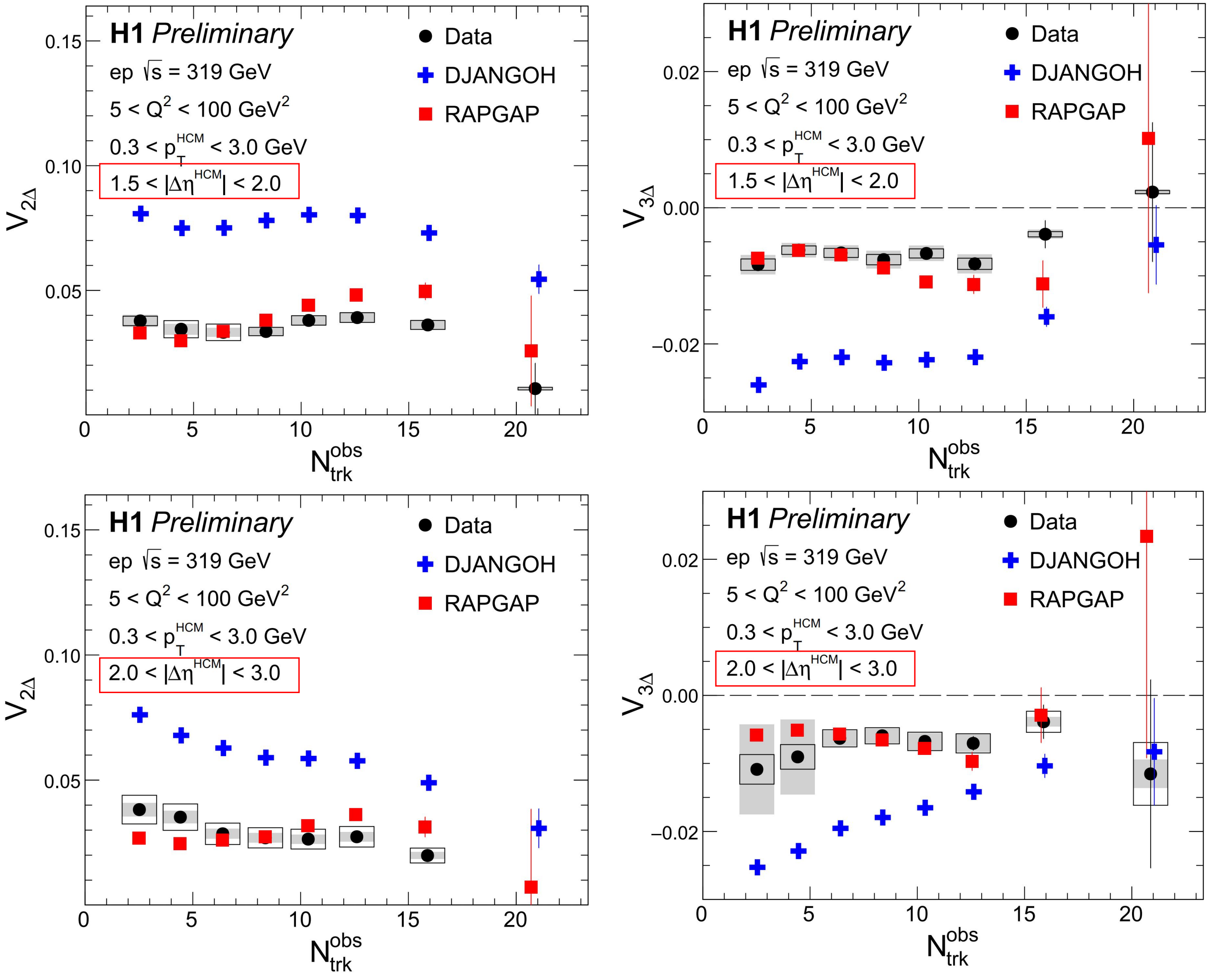
The azimuthal anisotropy harmonics are determined from a Fourier decompositons of long-range two-particle correlation functions on $\Delta\varphi$ direction.

1-D comparisons



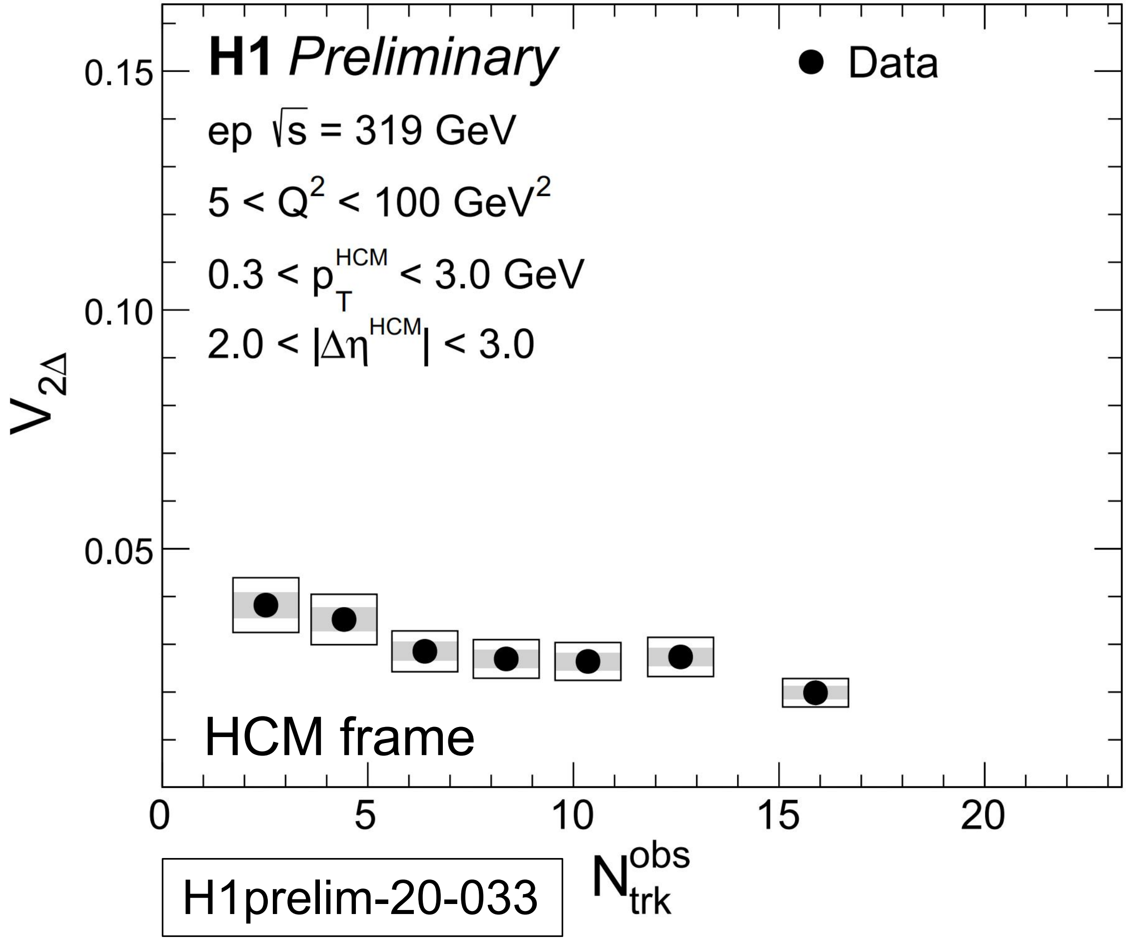
The comparison between data and MCs.
Similar shapes in high and low multiplicity.

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

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



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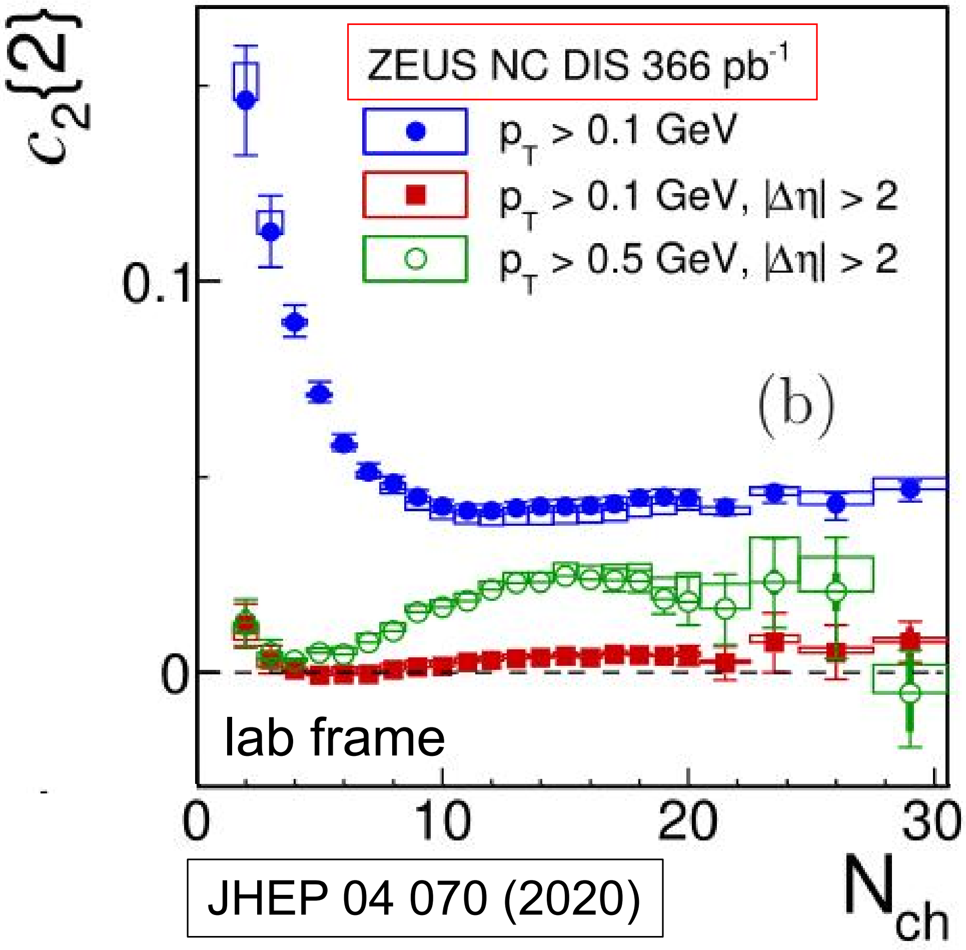

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Similar trend as ZEUS result

DIS HCM

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

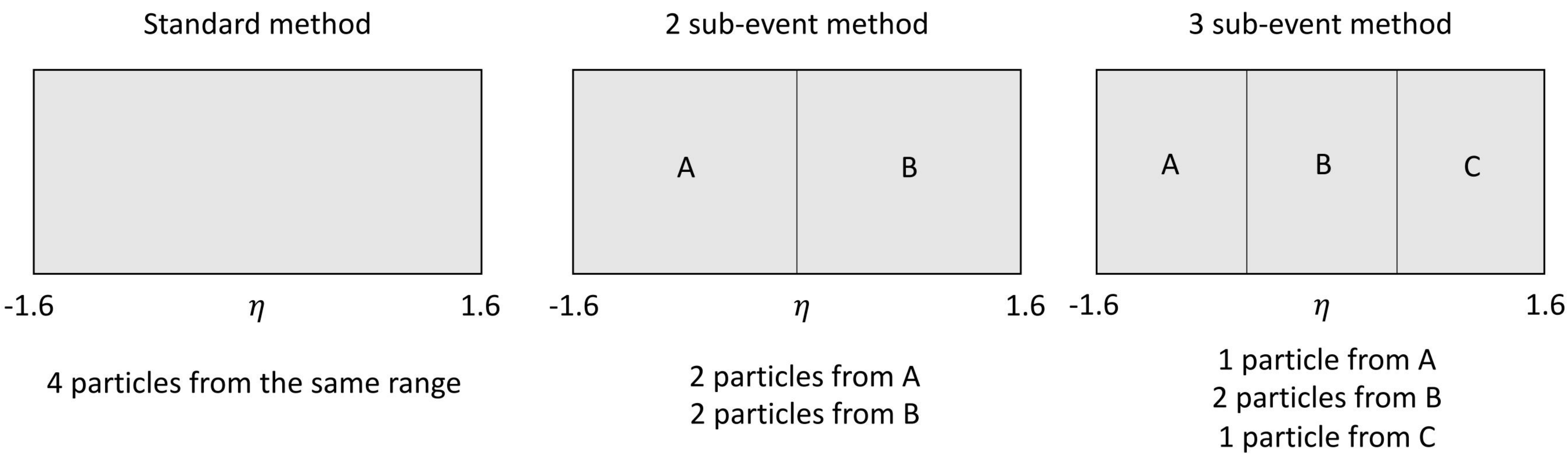
The RAPGAP 3.1

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