

From RHIC to EIC

At the QCD Frontiers

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

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Stony Brook University/Shandong University

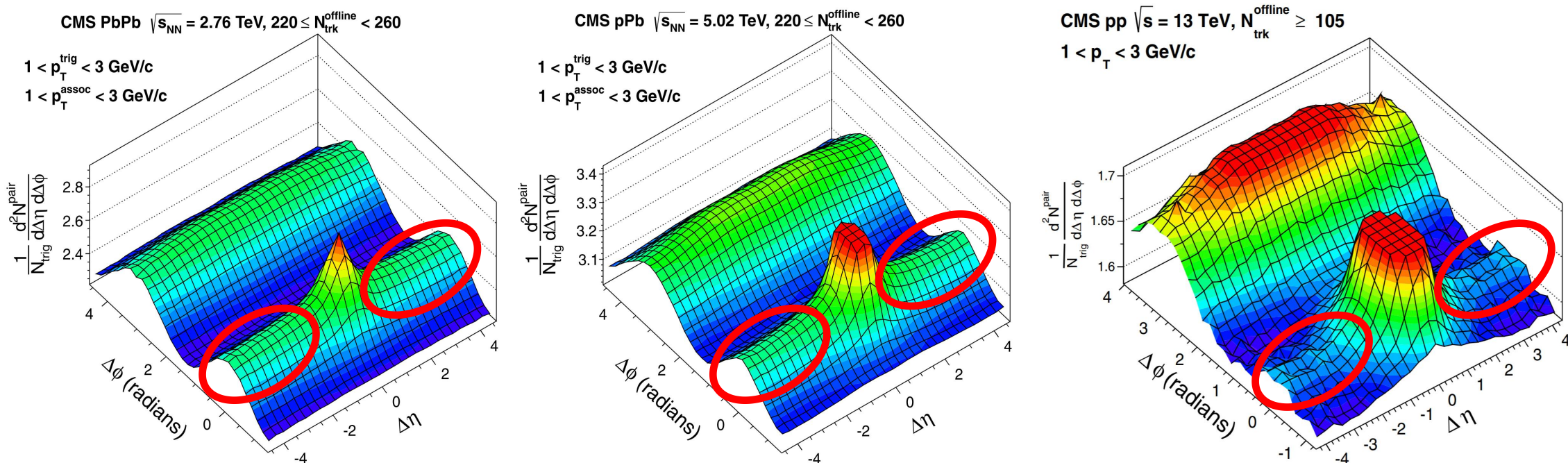


Stony Brook
University



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

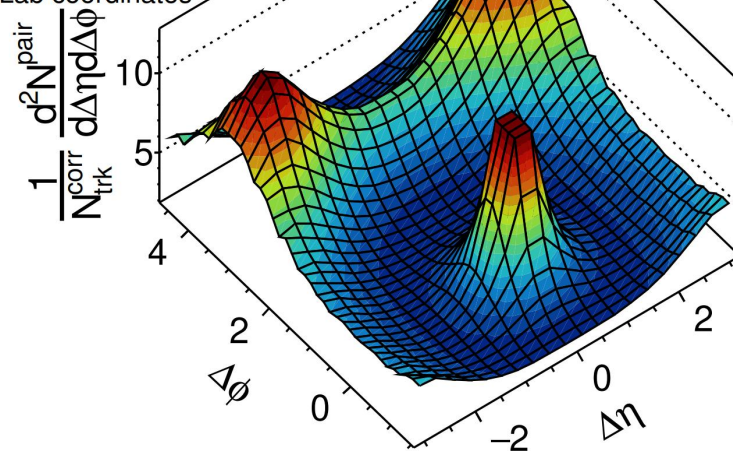
PRL 123, 212002 (2019)

ALEPH $e^+e^- \rightarrow \text{hadrons}$, $\sqrt{s} = 91\text{GeV}$

$N_{\text{trk}} \geq 30$, $|\cos(\theta_{\text{lab}})| < 0.94$

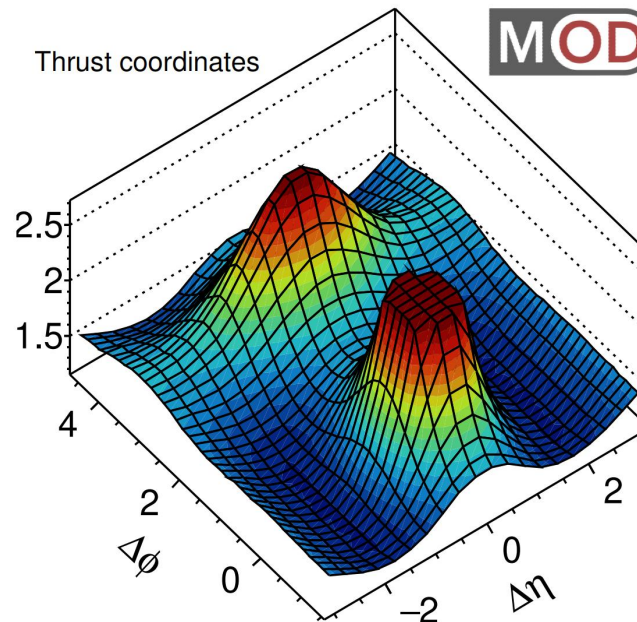
$p_{\text{T}}^{\text{lab}} > 0.2\text{ GeV}$

Lab coordinates



Thrust coordinates

MOD



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What about even smaller system?

Collectivity in small system

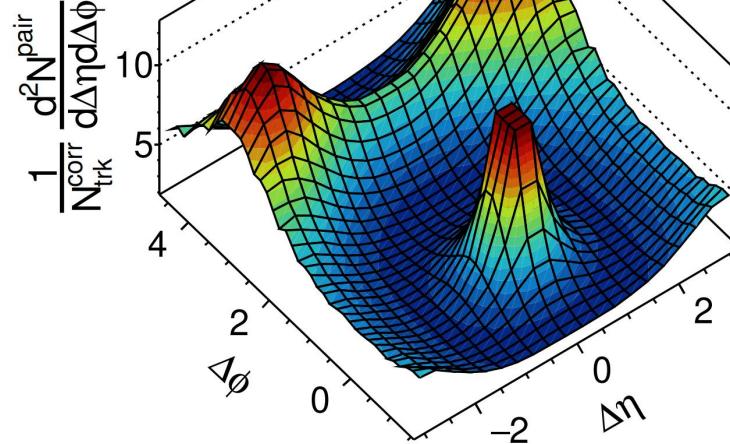
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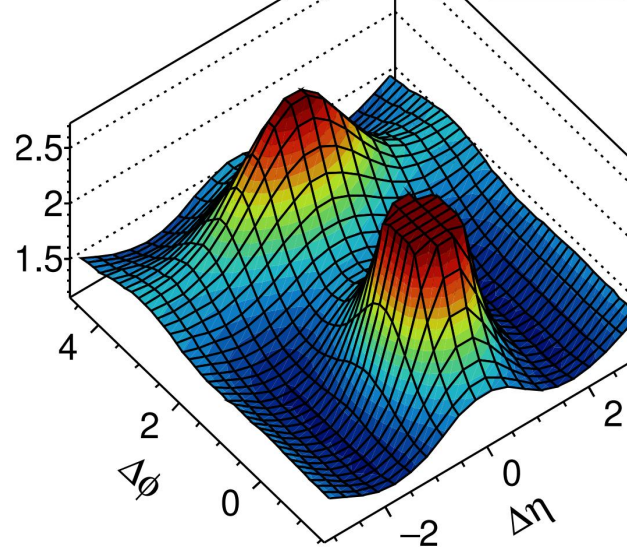
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Lab coordinates



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MOD



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

H1 at HERA

HERA Collider

Operated from 1992 to 2007

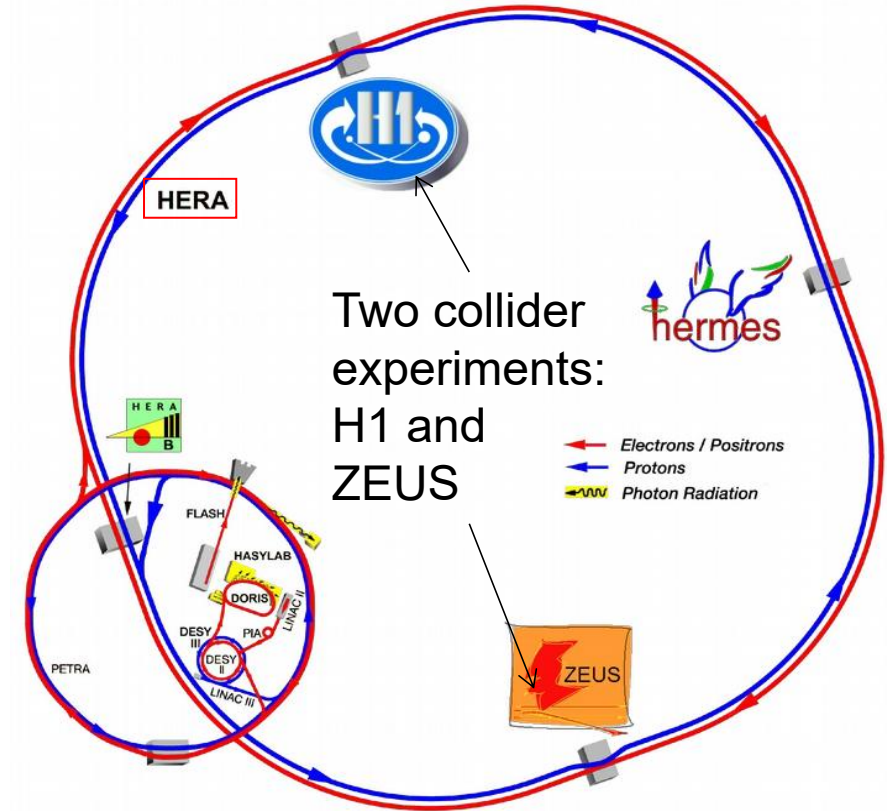
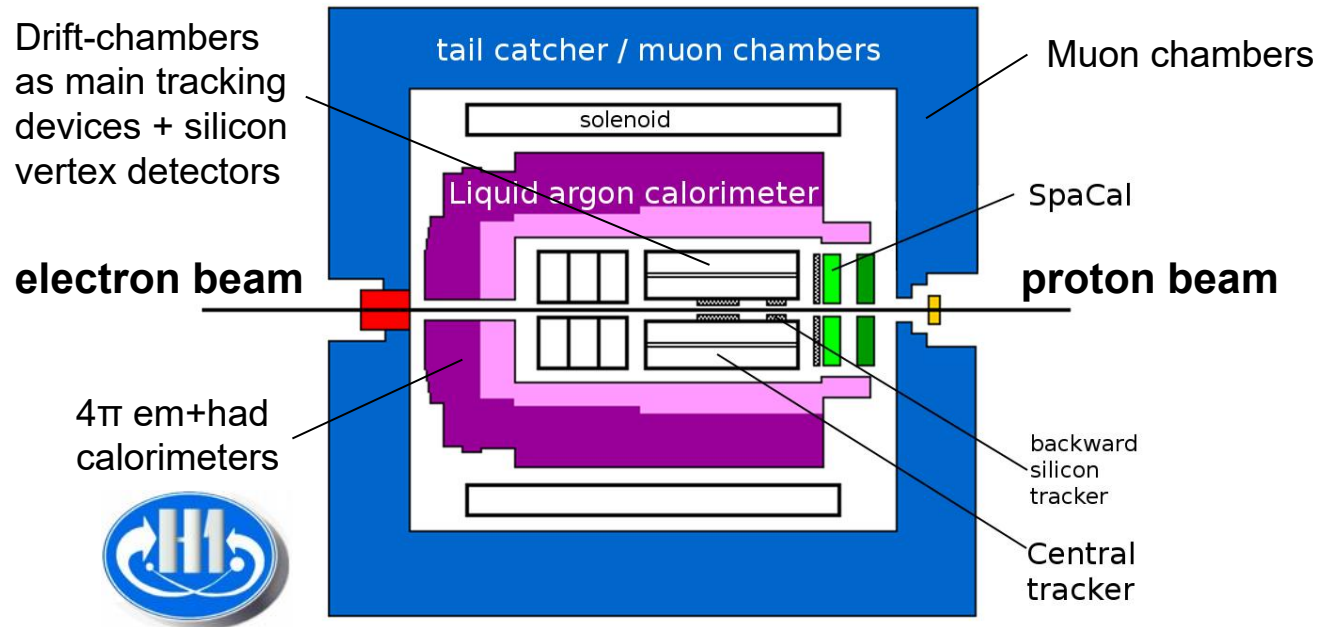
Circumference 6.3 km

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



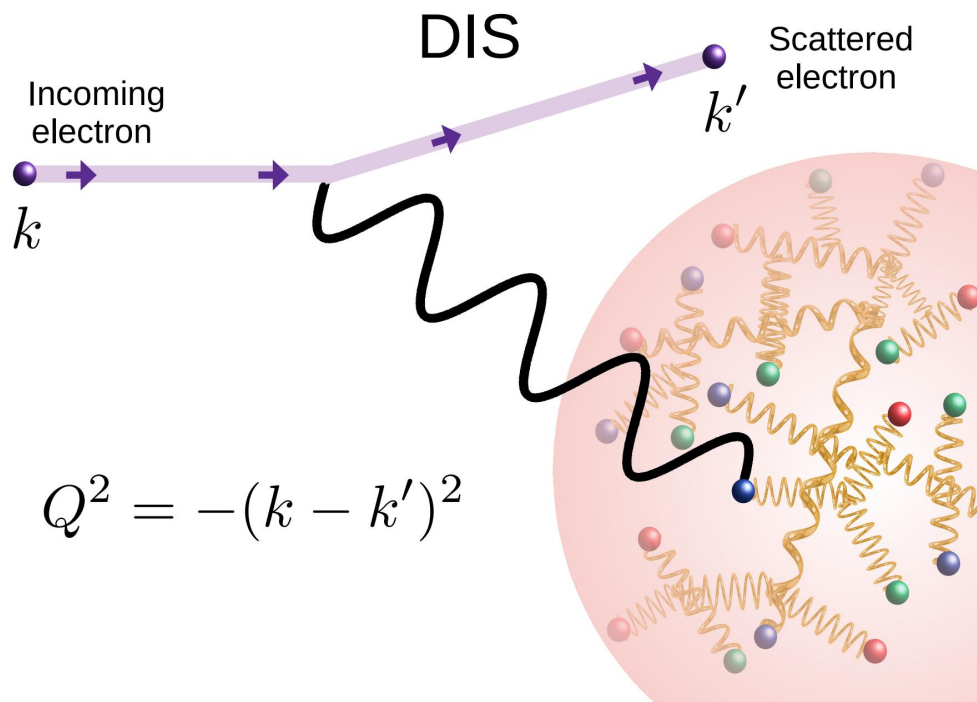
H1 Detector

Central tracker acceptance $|\eta| < 1.6$

LAr calorimeter for hadronic final state

SpaCal calorimeter for detecting electrons with $5 < Q^2 < 100$ GeV²

DIS and photoproduction



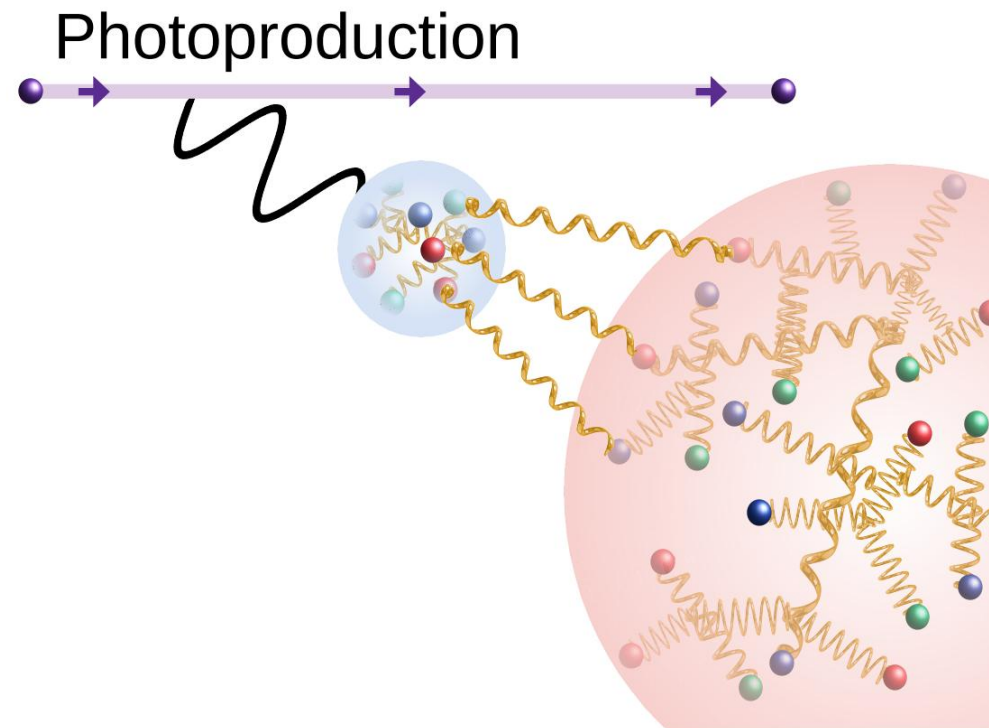
DIS defined by large virtualities:

$$Q^2 \gg \Lambda_{QCD}^2$$

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

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

PRD 95, 114008 (2017)



Photoproduction defined by small virtualities:

$$Q^2 \ll \Lambda_{QCD}^2$$

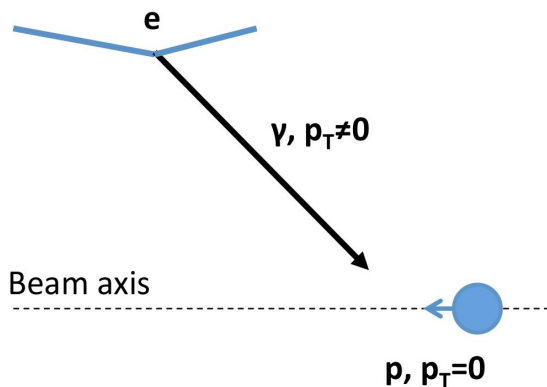
Exchange photon may fluctuate into partons

Large interaction regions probed

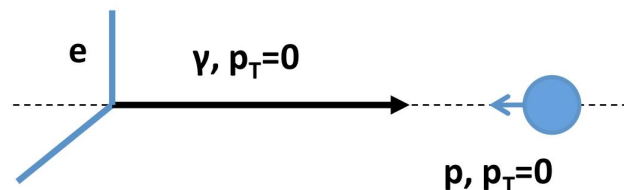
Scattering may be hadron-like

Search for collectivity in ep DIS

Lab Frame

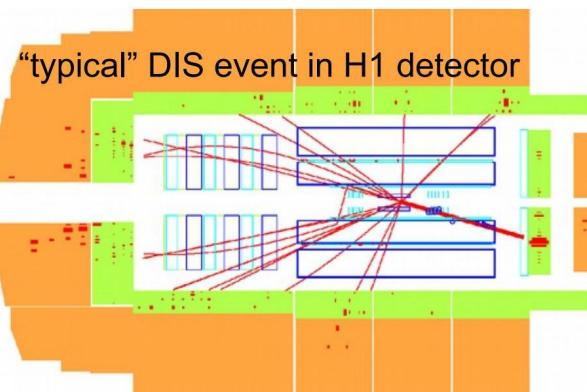


Hadronic CMS frame

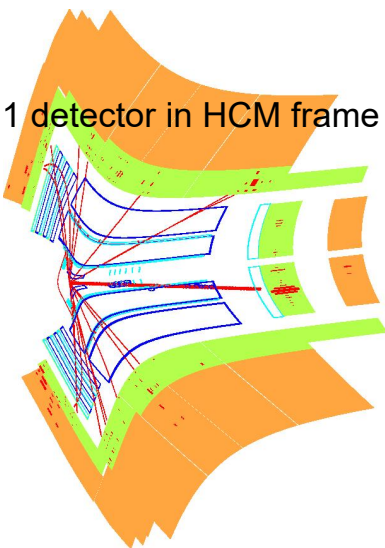


lab frame:
inhomogeneous p_T space

HCM frame:
homogeneous p_T space



H1 detector in HCM frame



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

H1 Preliminary

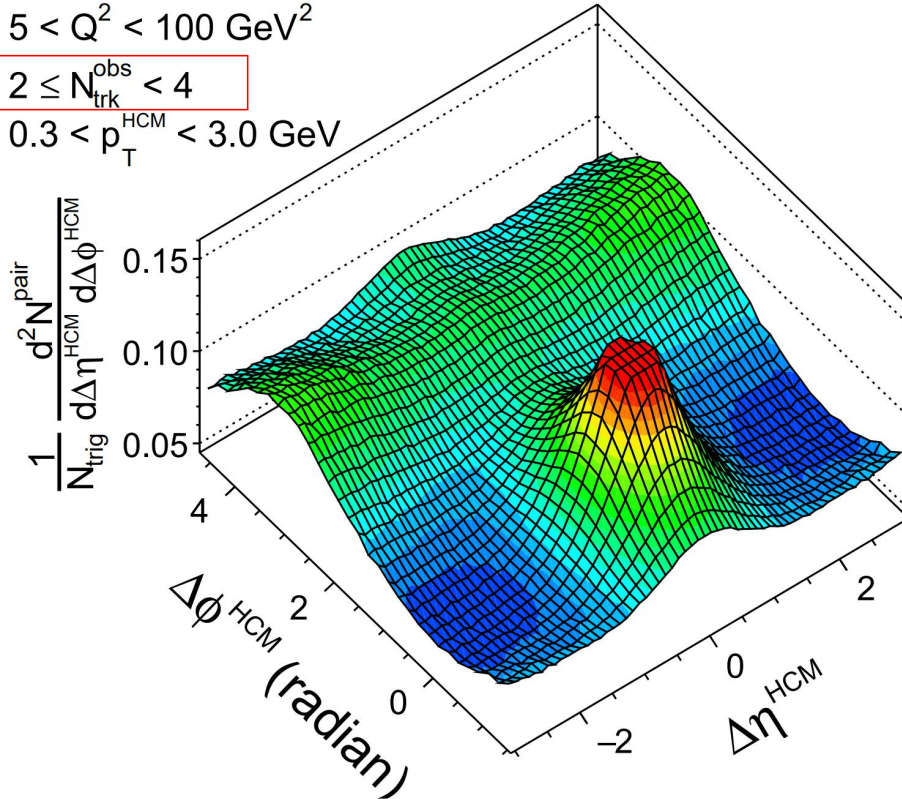
ep $\sqrt{s} = 319$ GeV

$5 < Q^2 < 100$ GeV²

$2 \leq N_{\text{trk}}^{\text{obs}} < 4$

$0.3 < p_{\text{T}}^{\text{HCM}} < 3.0$ GeV

low multiplicity



H1 Preliminary

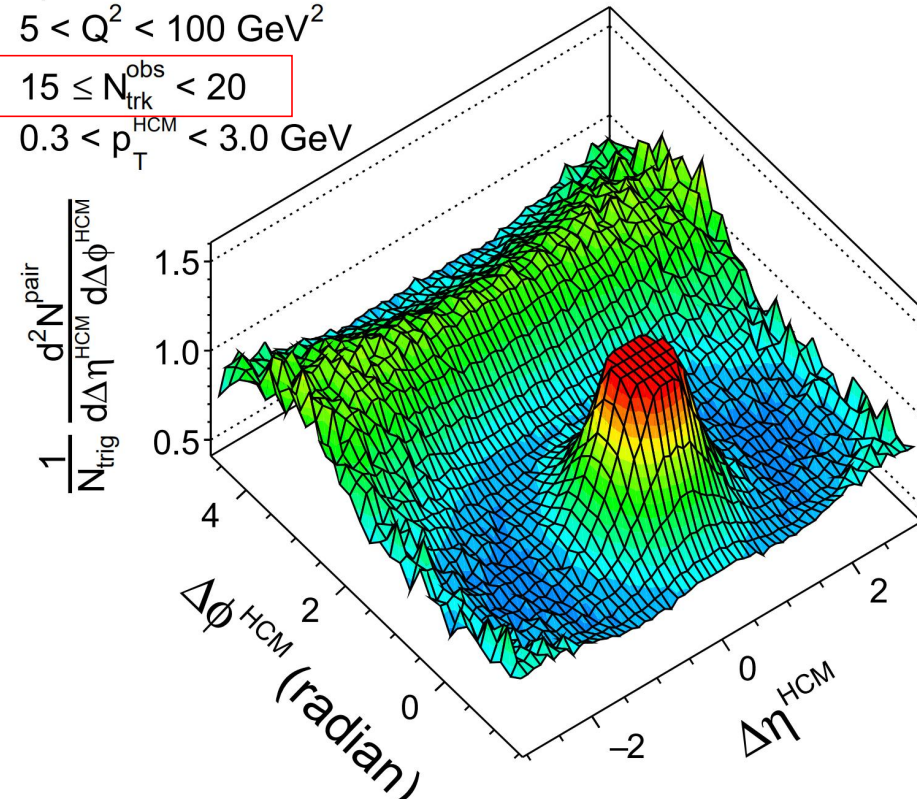
ep $\sqrt{s} = 319$ GeV

$5 < Q^2 < 100$ GeV²

$15 \leq N_{\text{trk}}^{\text{obs}} < 20$

$0.3 < p_{\text{T}}^{\text{HCM}} < 3.0$ GeV

high multiplicity



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)

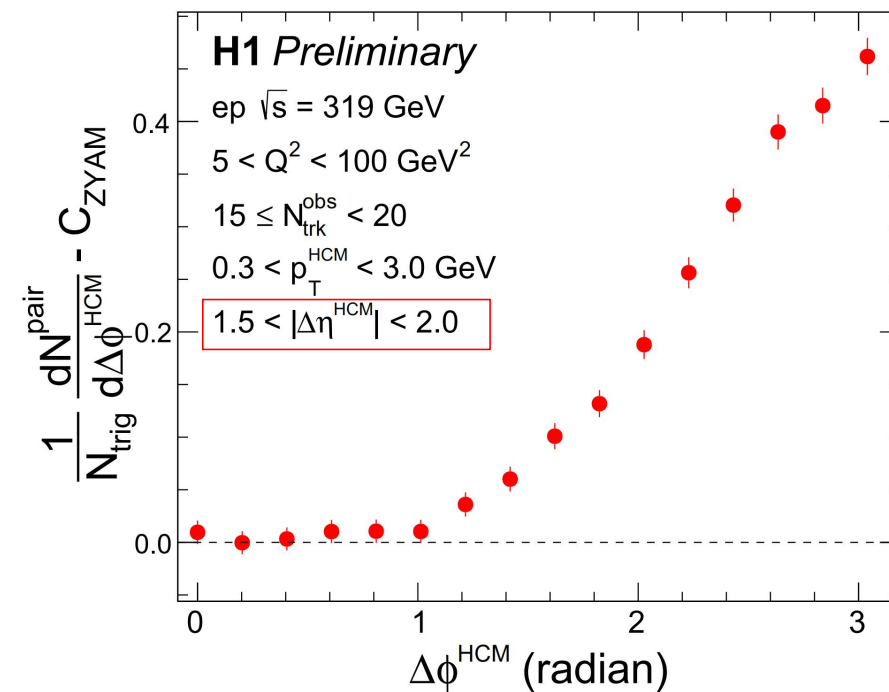
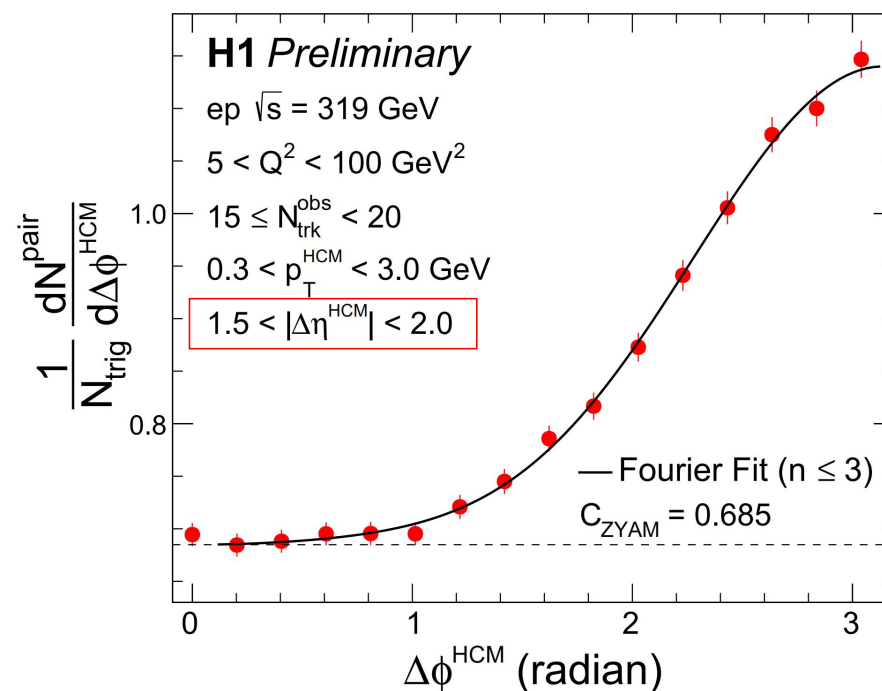
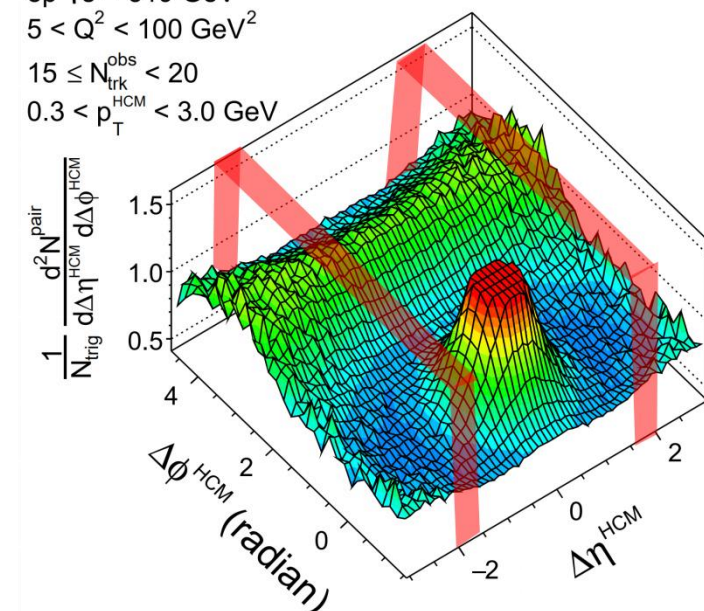
H1 Preliminary

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Step1: long-range 1D projection

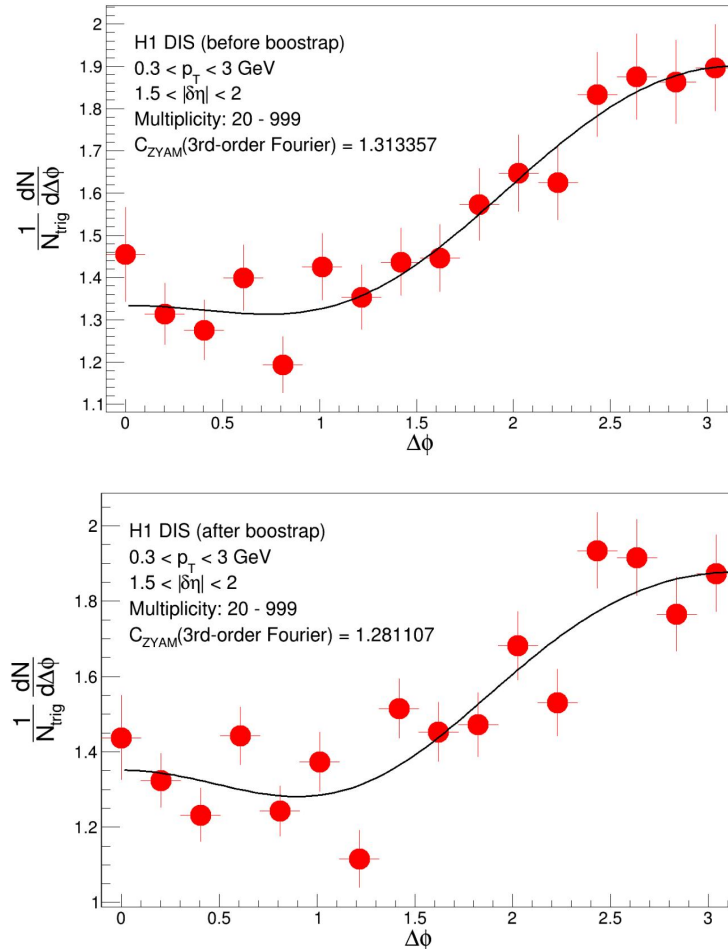
Step2: third-order Fourier fit

Step3: subtraction

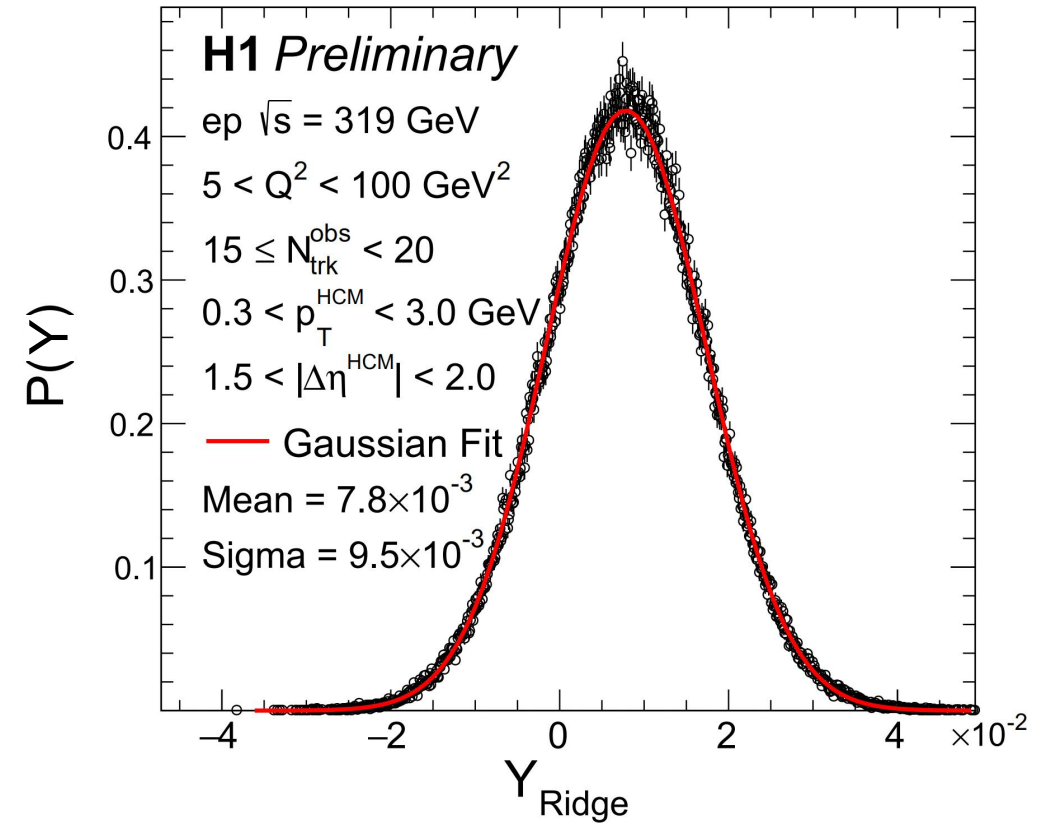
Then integrate from $\Delta\Phi=0$ to where the minimum value of ZYAM occurs as the ridge yield value

Bootstrap procedure

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

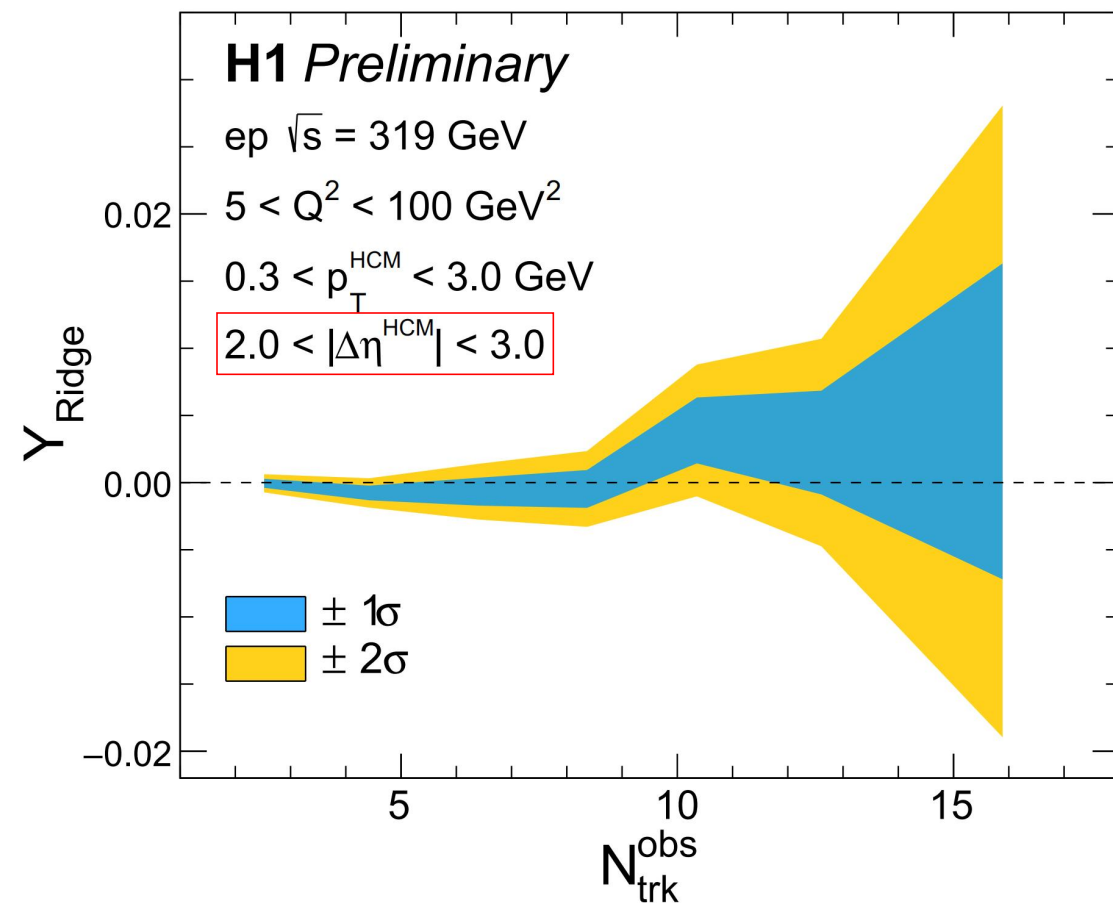
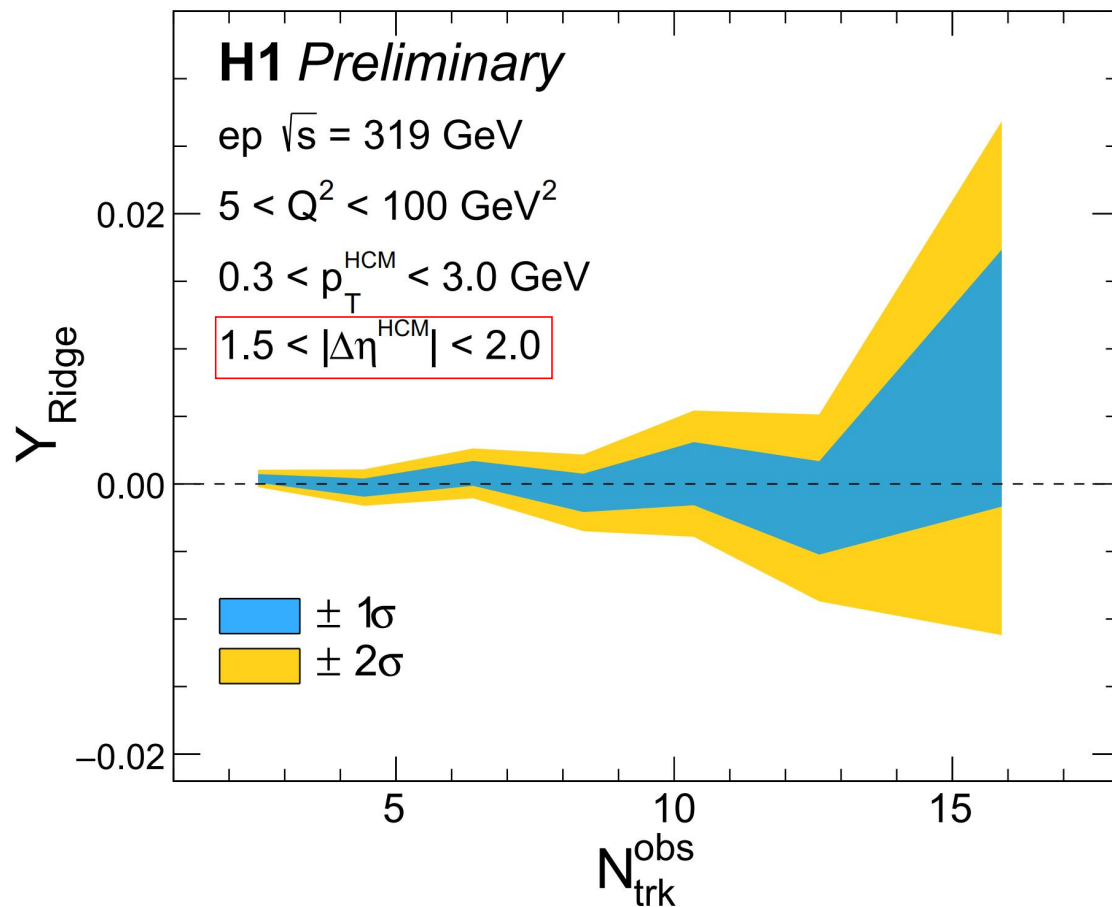


Each yield distribution is sampled 2.5×10^5 times



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

Ridge yield limits in ep DIS



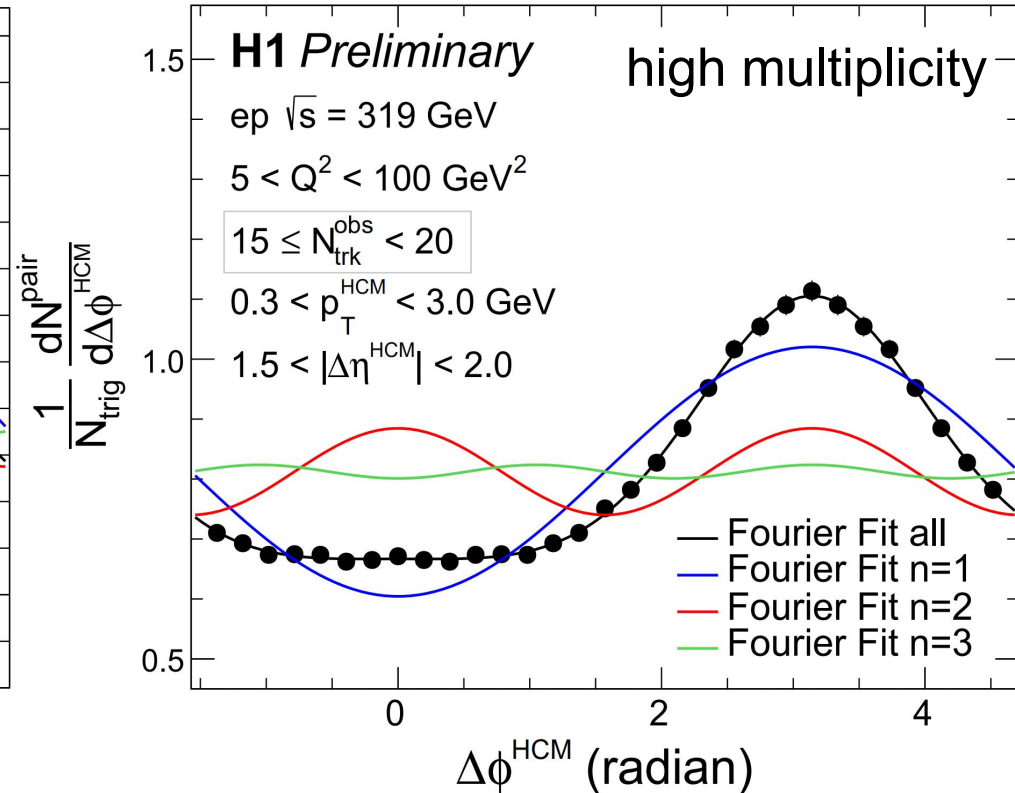
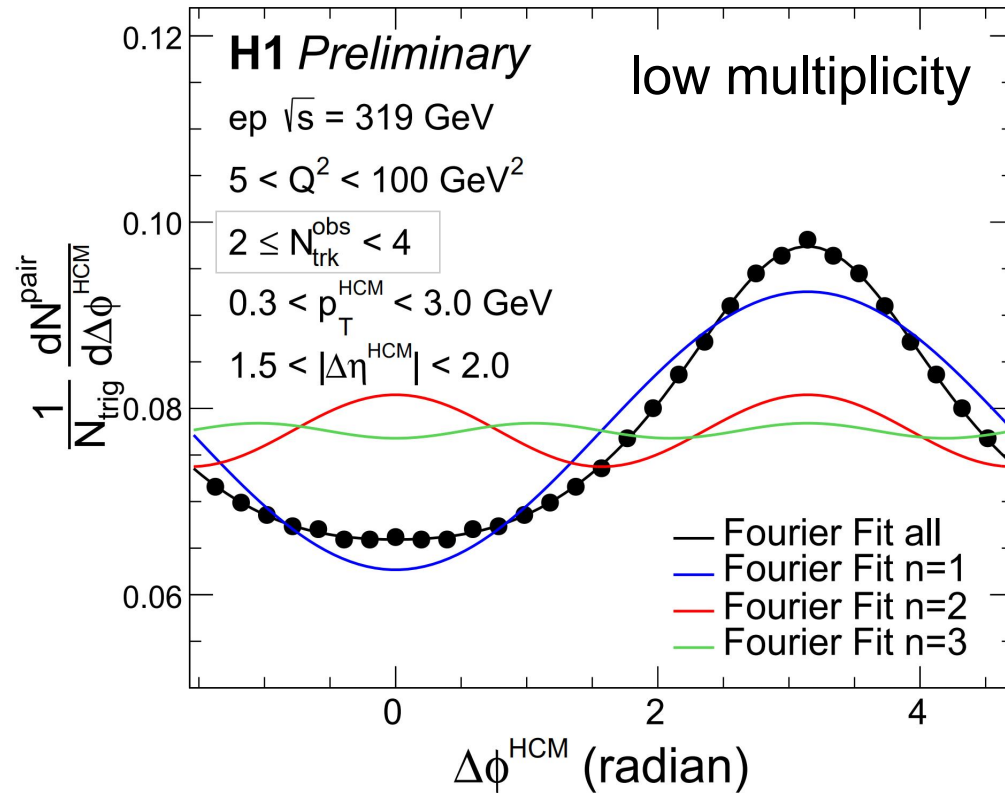
Limits set for ridge yield
Small room for existence of ridge

DIS HCM

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

Long-range 1-D projections of 2PC functions onto $\Delta\phi$ direction

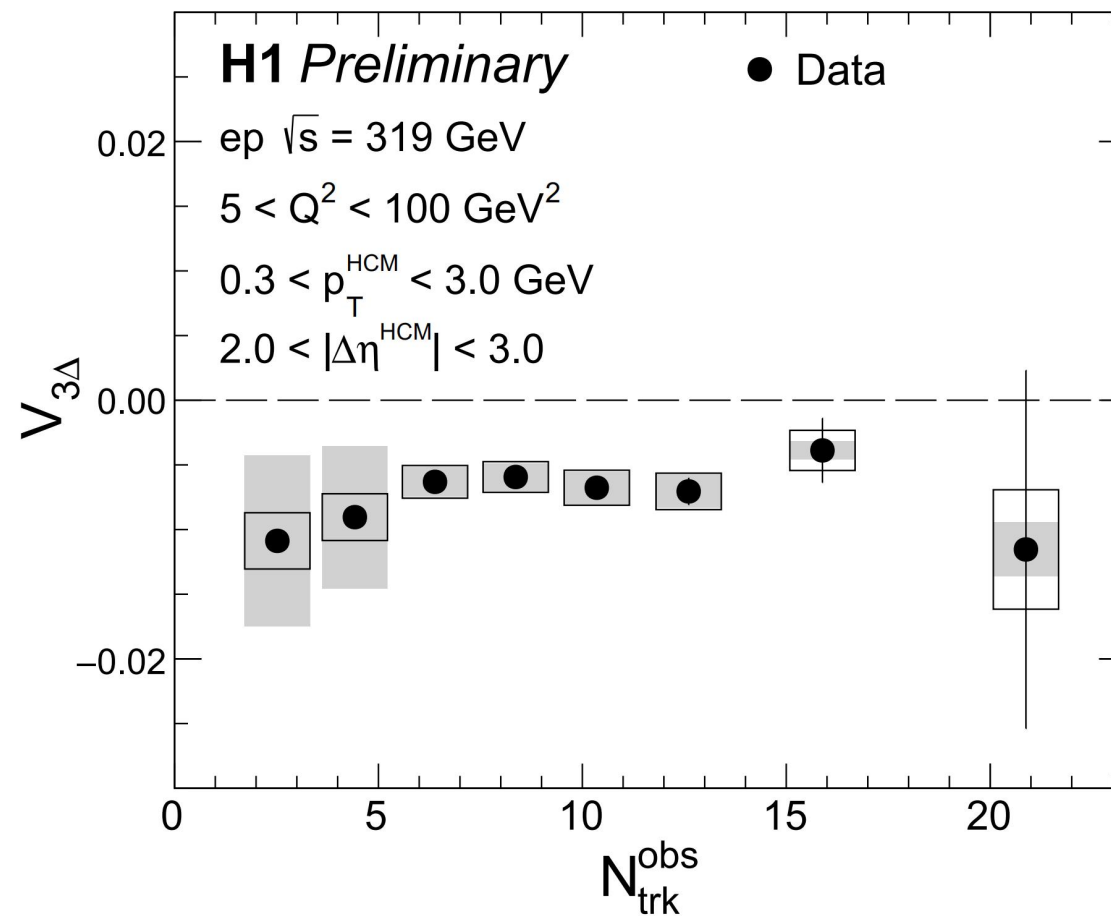
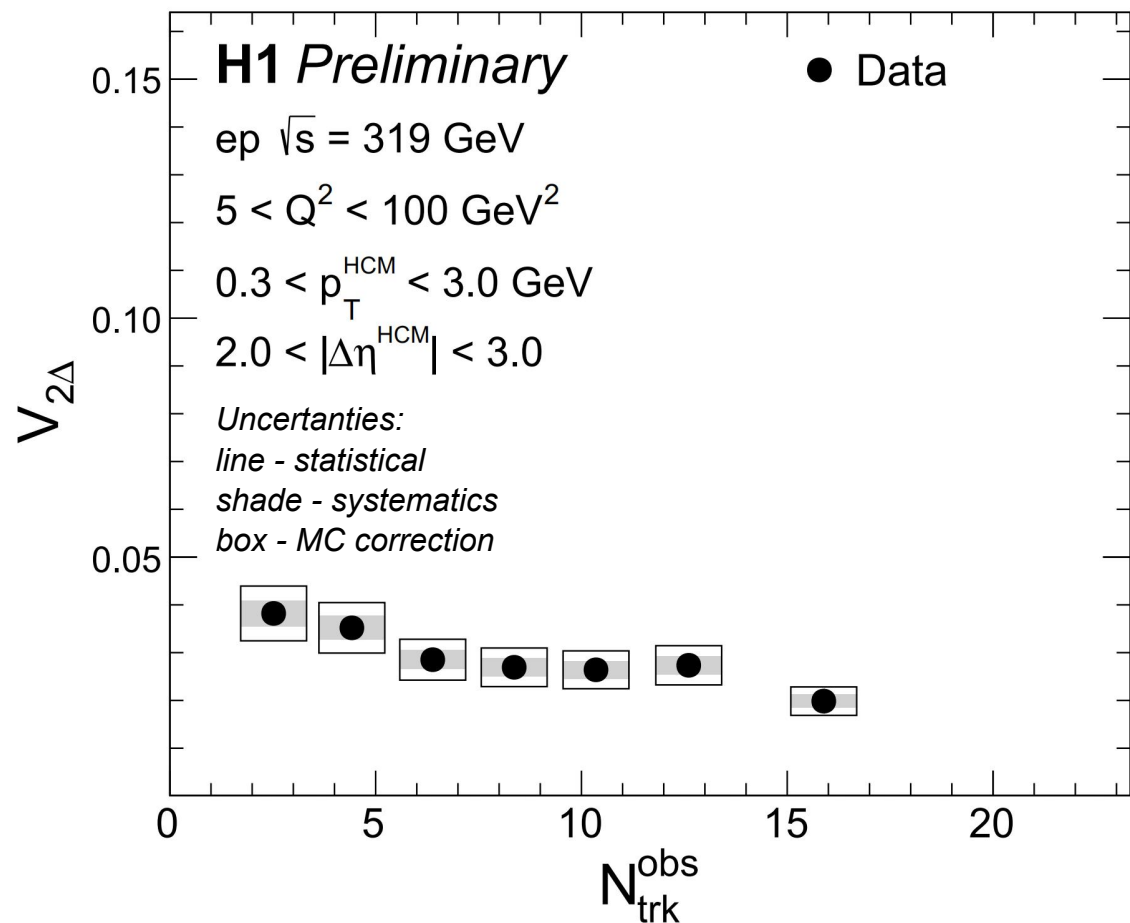
$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi} \left(1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right)$$



Similar shapes in low and high multiplicity

DIS HCM

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

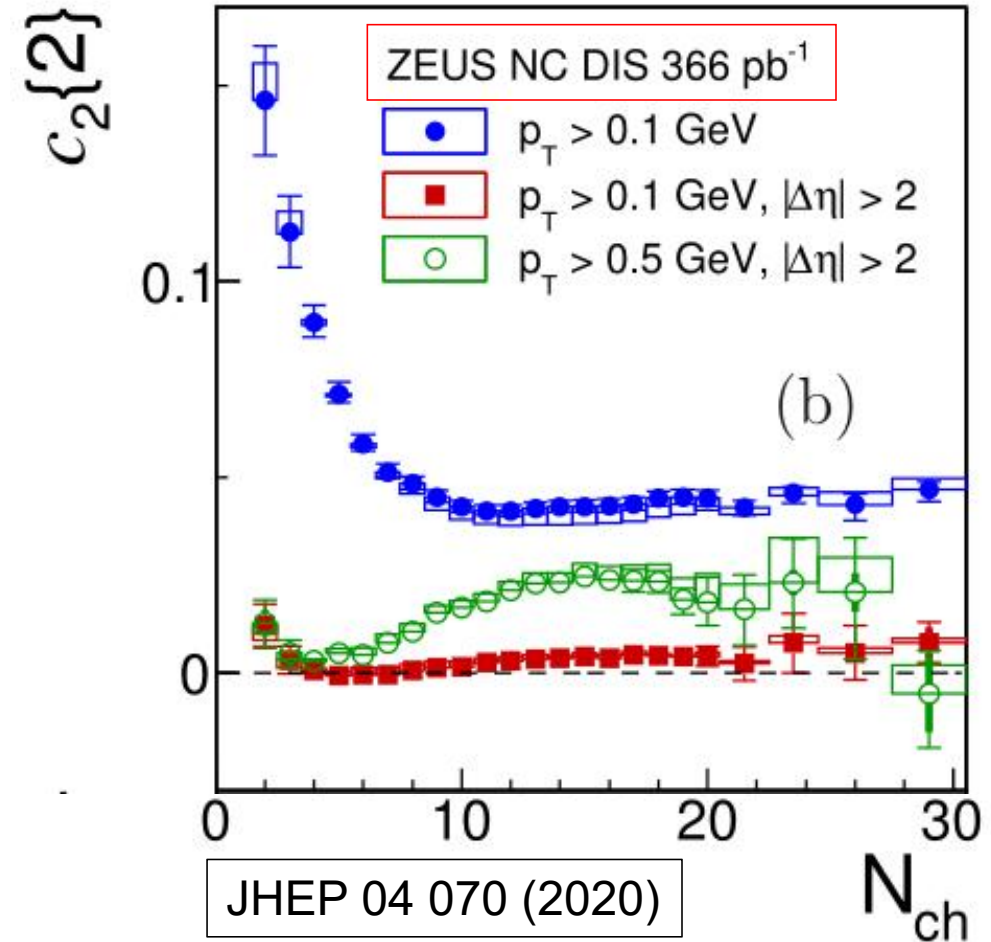
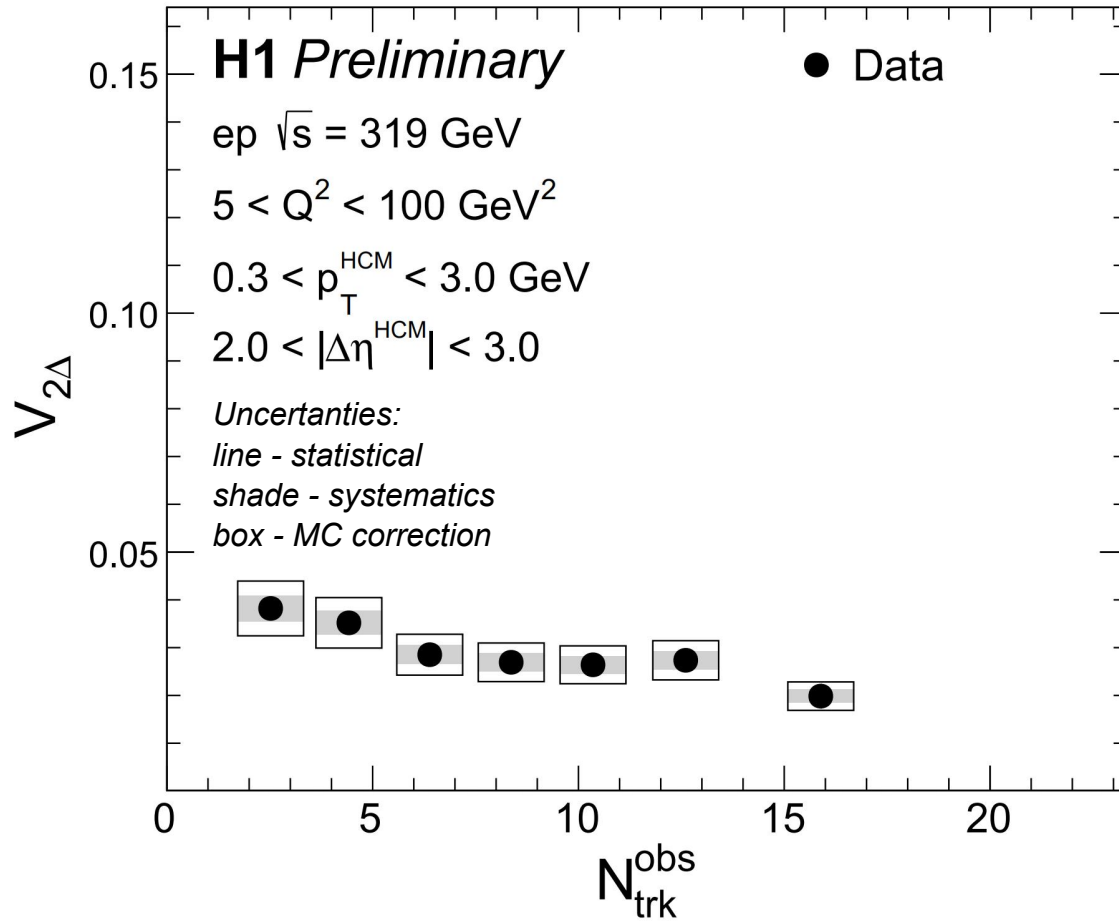


$V_{2\Delta}$ value drops in high multiplicity

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

DIS HCM

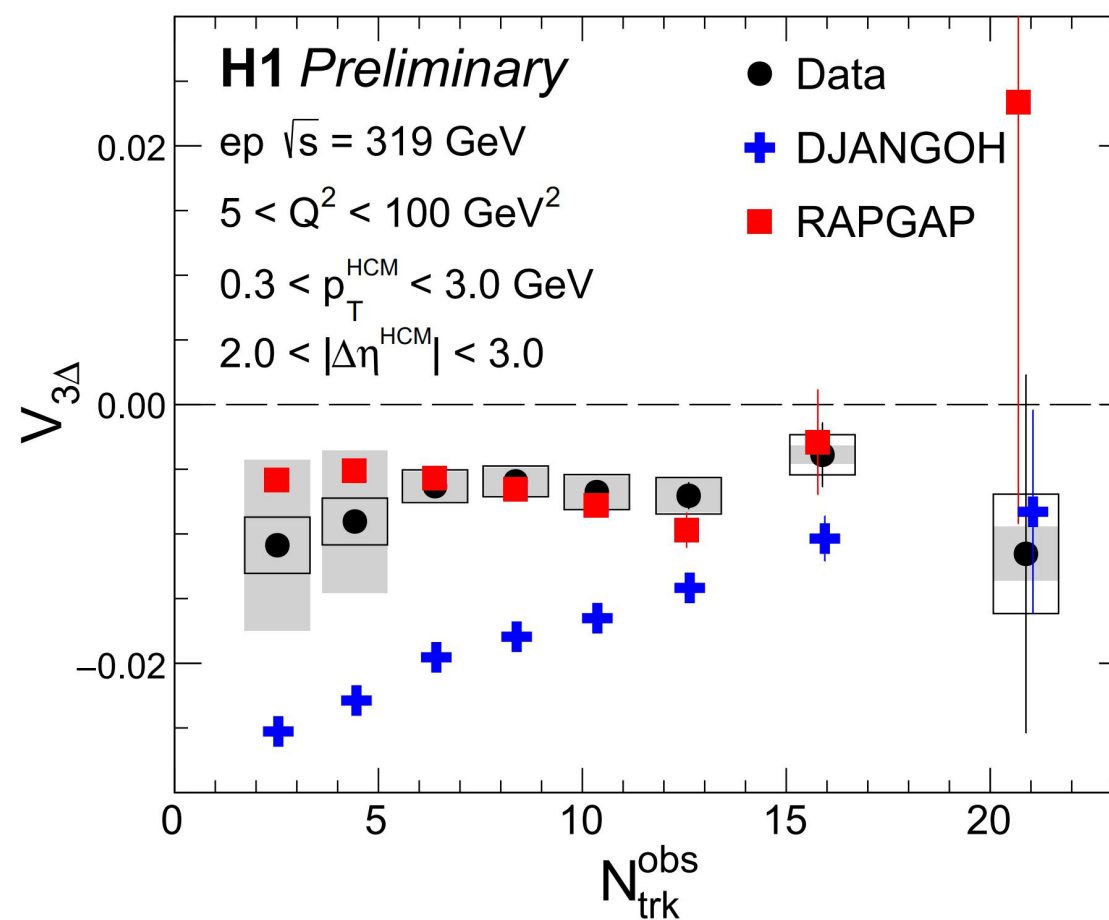
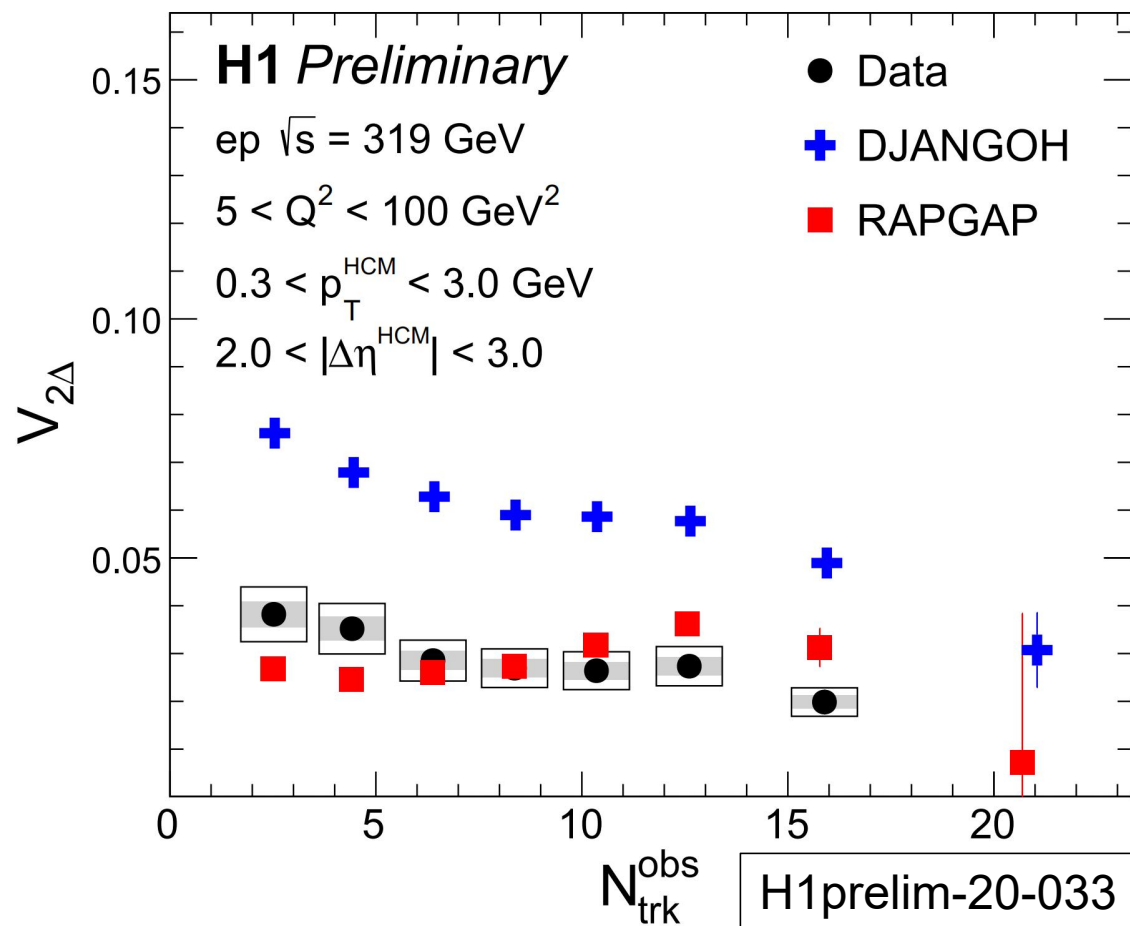
Fourier coefficient $V_{n\Delta}$ in ep DIS (Compared with ZEUS)



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

DIS HCM

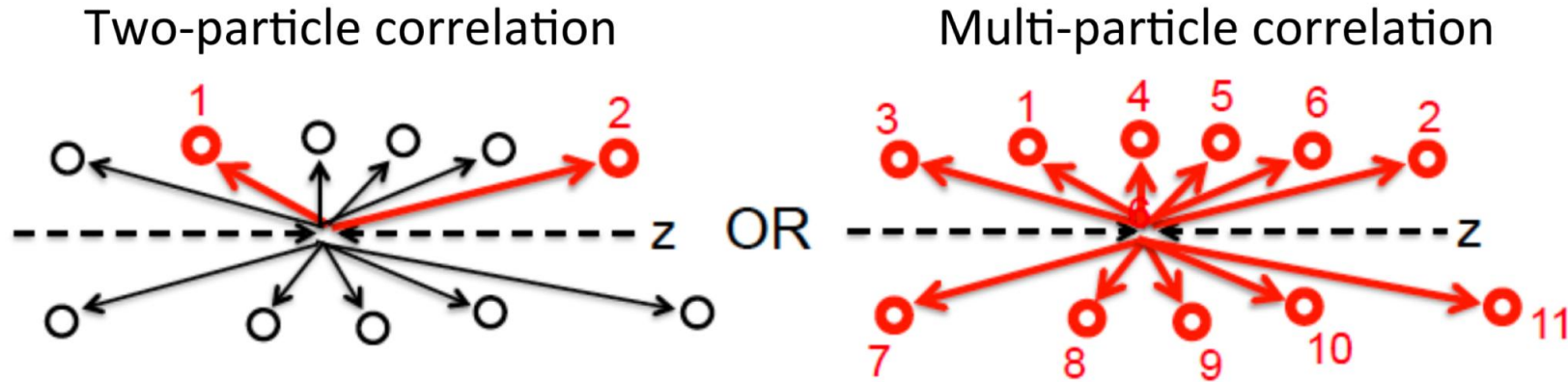
Fourier coefficient $V_{n\Delta}$ in ep DIS



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

DIS HCM

Multi-particle correlation



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

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

$$\langle 4 \rangle = \langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle = \frac{Q_n^4 - 2\text{Re}[Q_{2n}Q_n^{*2}] - 4(M-2)Q_n^2 + 2M(M-3) + Q_{2n}^2}{M(M-1)(M-2)(M-3)}$$

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

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

Few particle correlation is suppressed

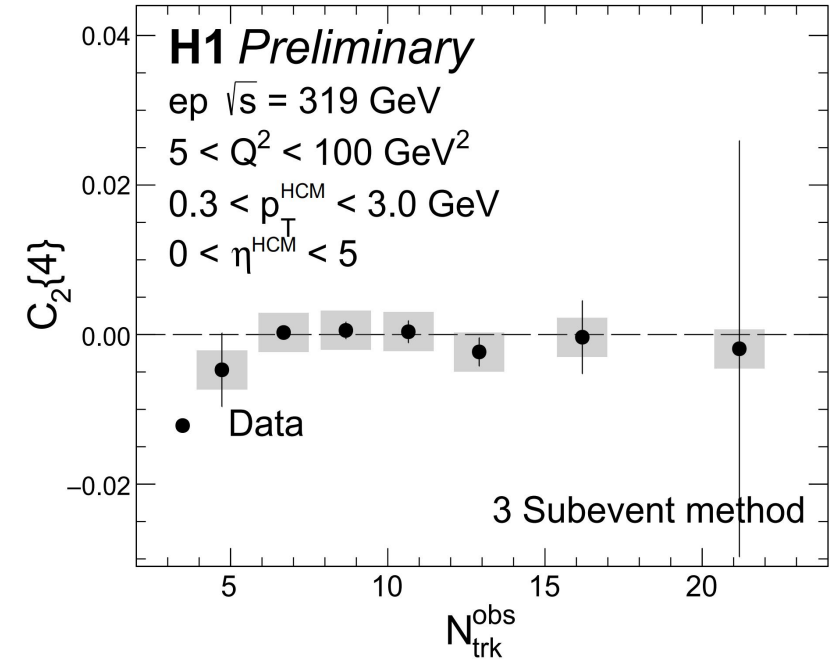
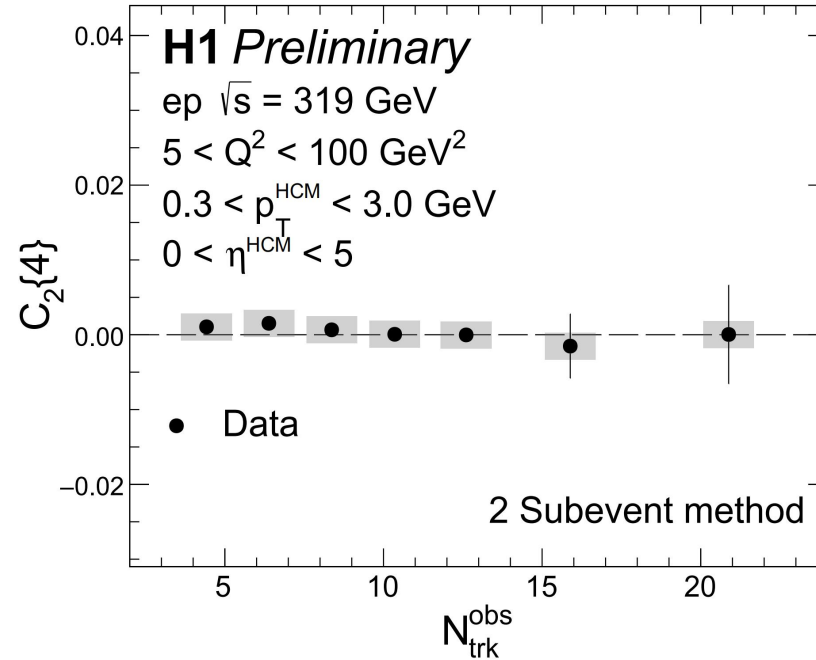
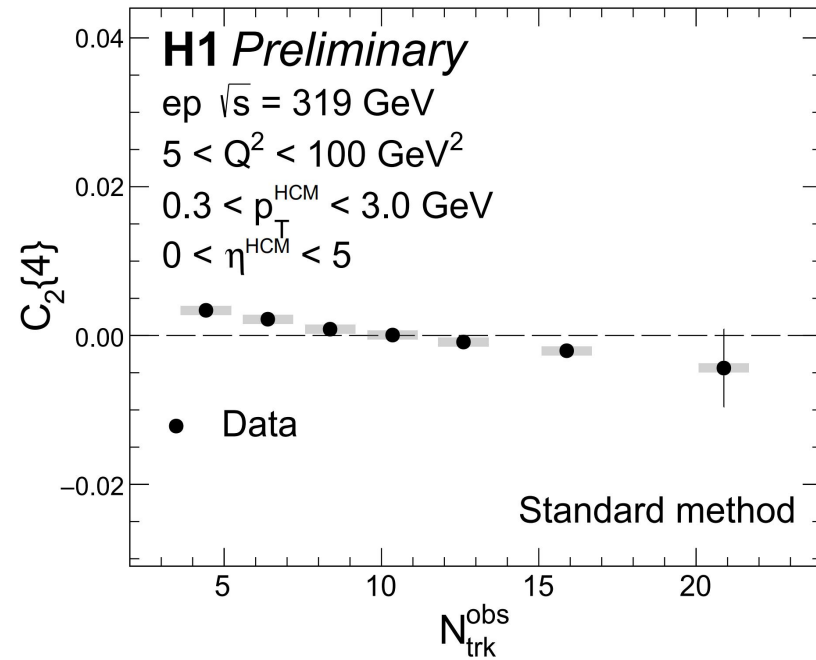
Collective behavior leads to negative $C_n\{4\}$

Subevent cumulants also investigated to further suppress non-flow

PRC 83, 044913 (2011)

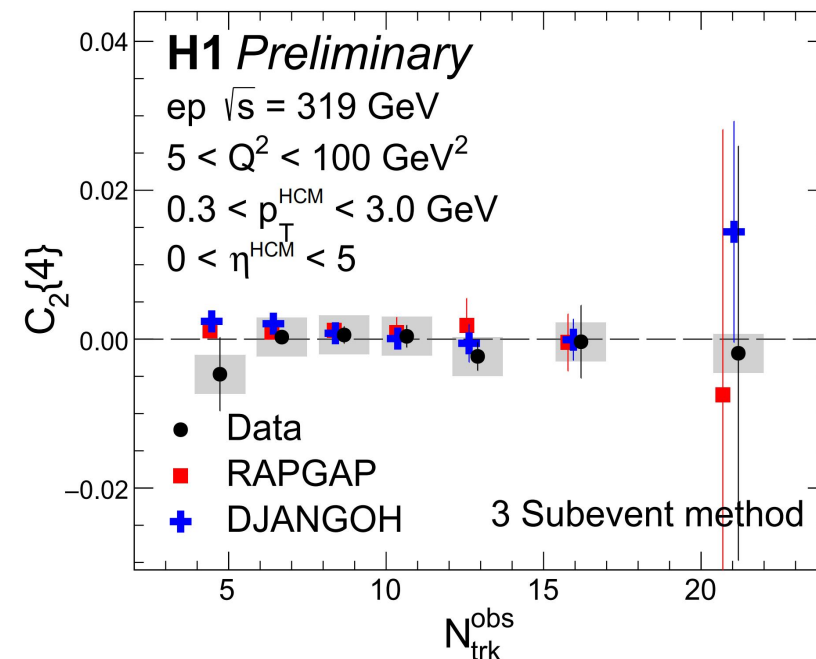
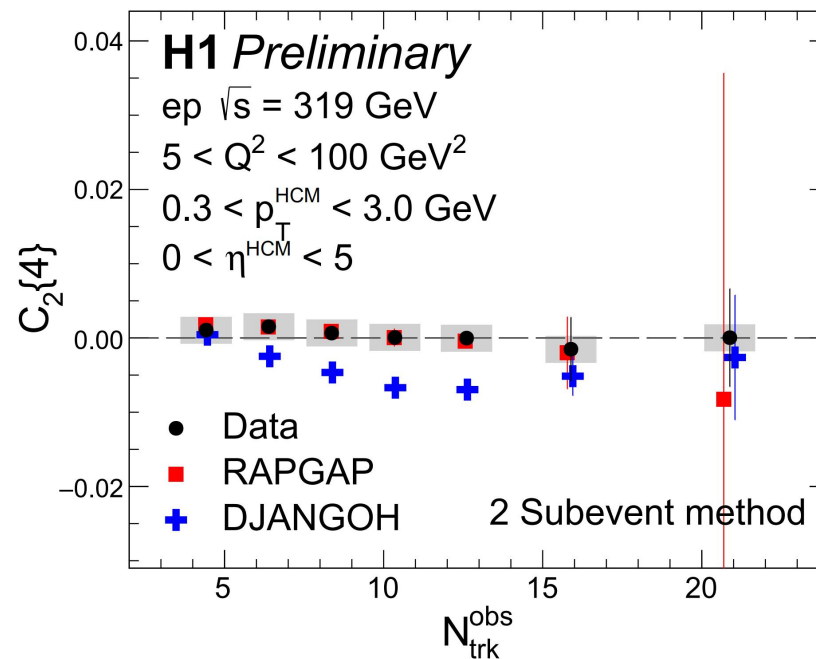
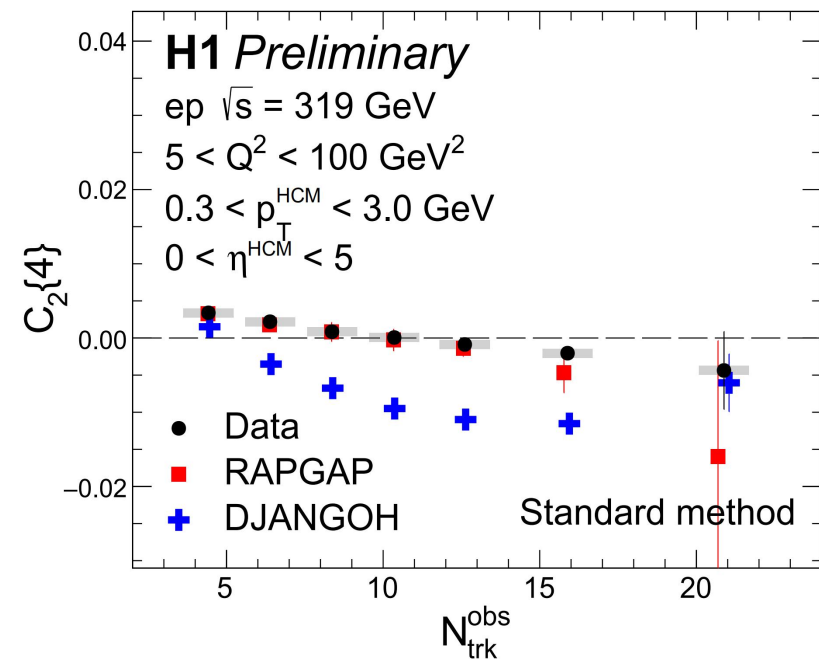
PRC 96, 034906 (2017)

Multi-particle correlation in ep DIS



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

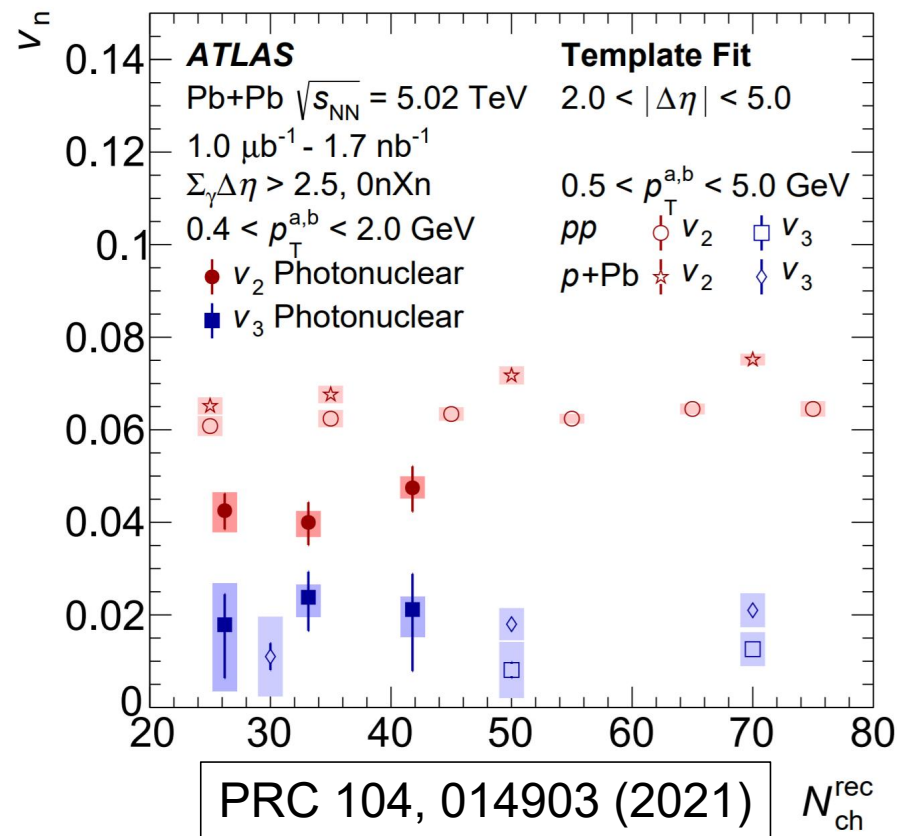
Multi-particle correlation in ep DIS



No obvious negative $C_2\{4\}$ in DIS
RAPGAP can describe data

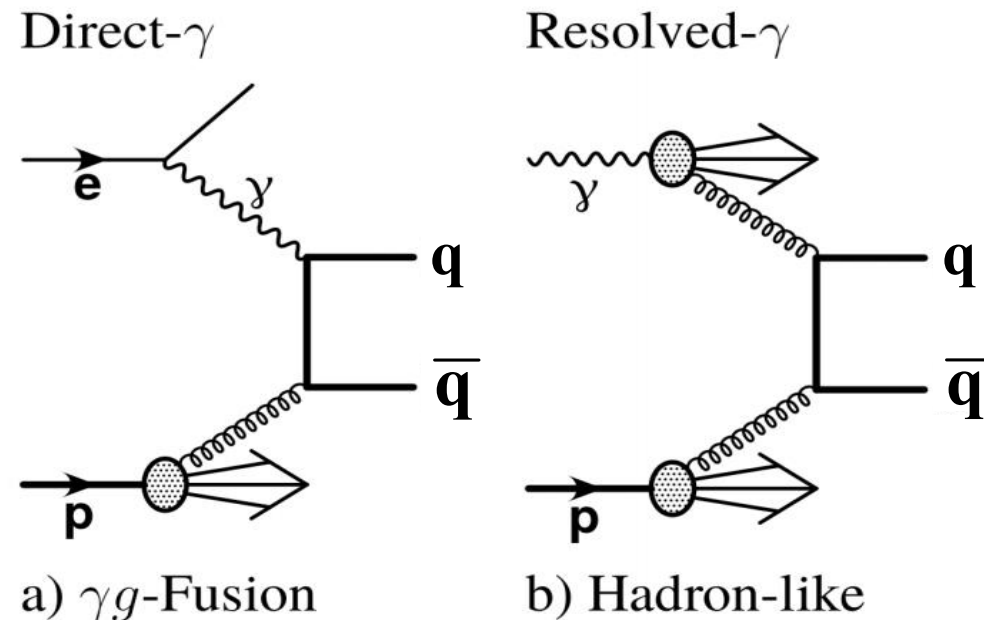
DIS HCM

Search for collectivity in ep photoproduction



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

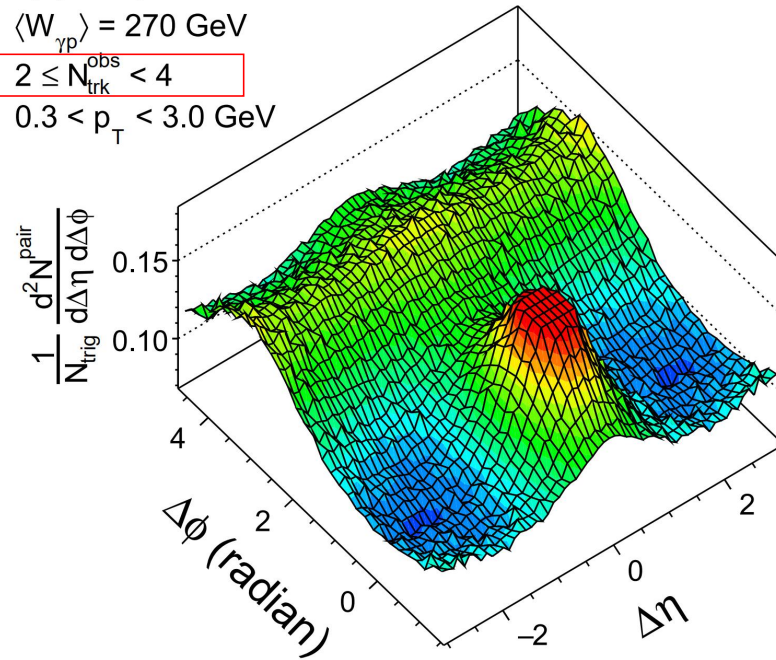
H1 Preliminary

ep photoproduction

$\langle W_{\gamma p} \rangle = 270 \text{ GeV}$

$2 \leq N_{\text{trk}}^{\text{obs}} < 4$

$0.3 < p_T < 3.0 \text{ GeV}$



low multiplicity

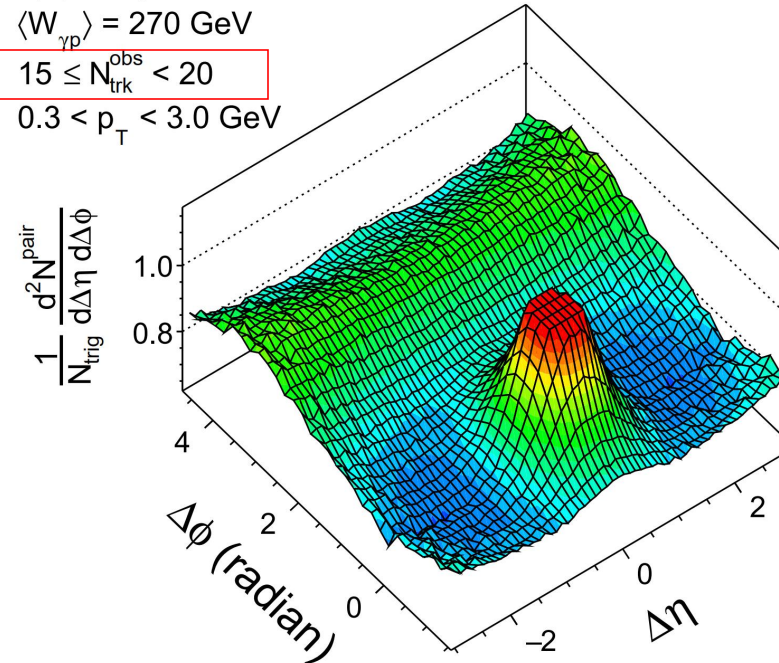
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high multiplicity

No near-side long-range ridge observed

photoproduction

Ridge yield limit in ep photoproduction

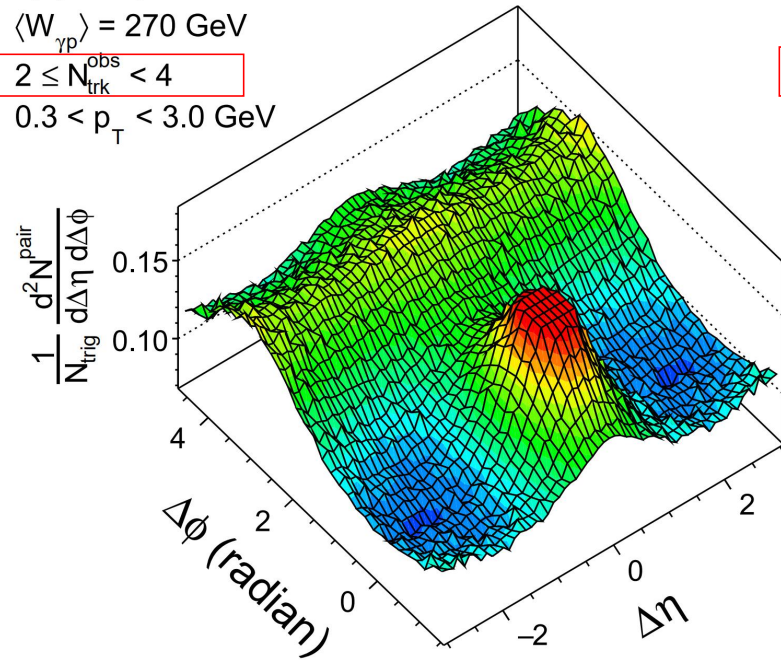
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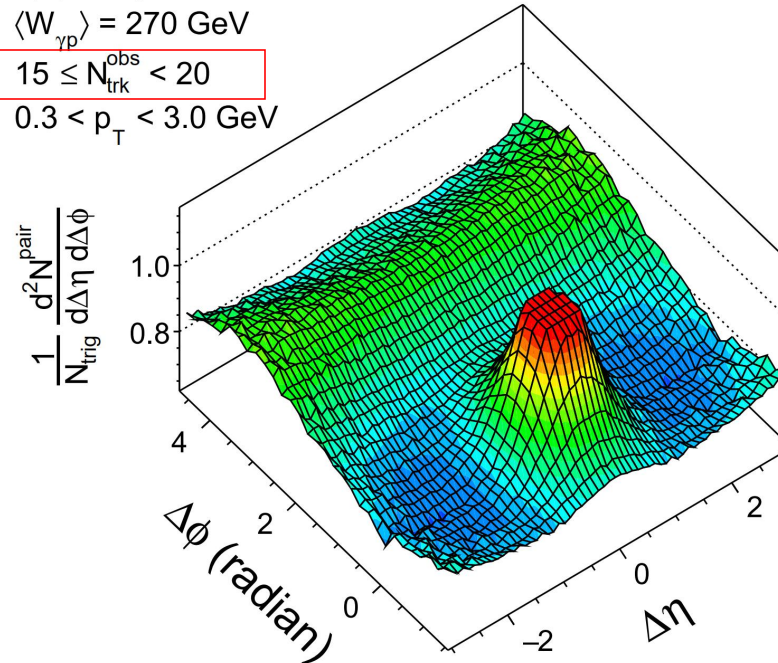
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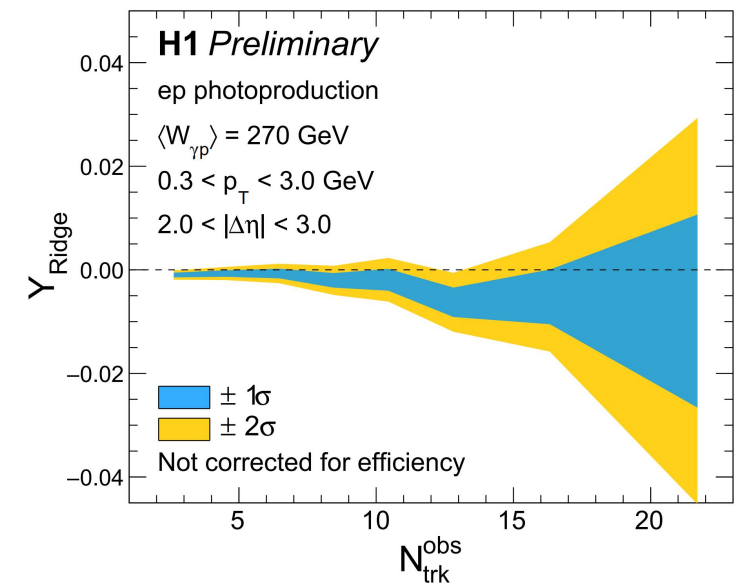
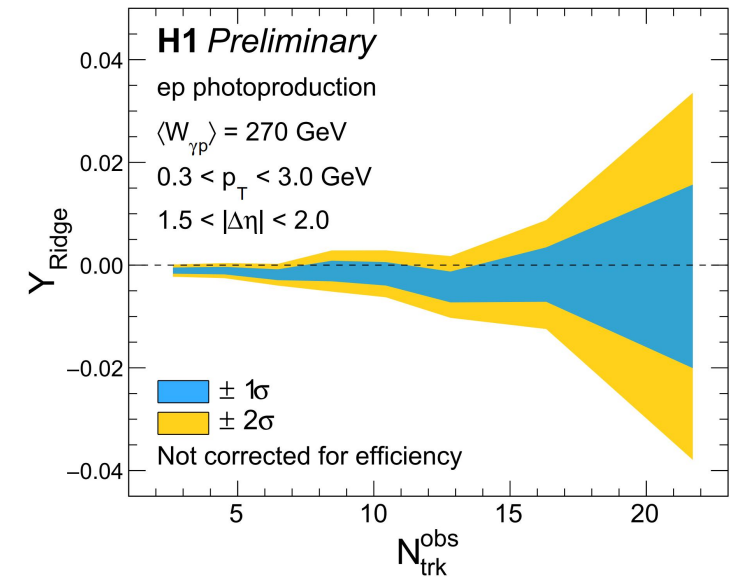
$0.3 < p_T < 3.0$ GeV



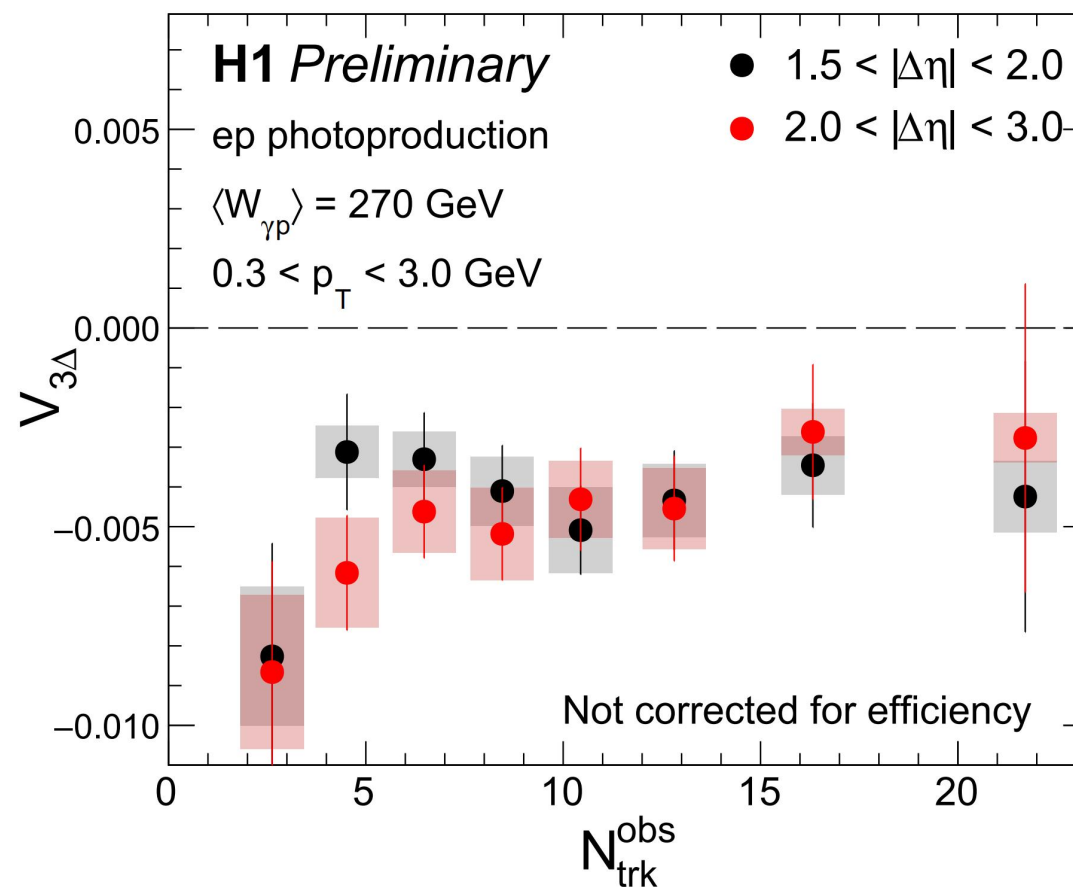
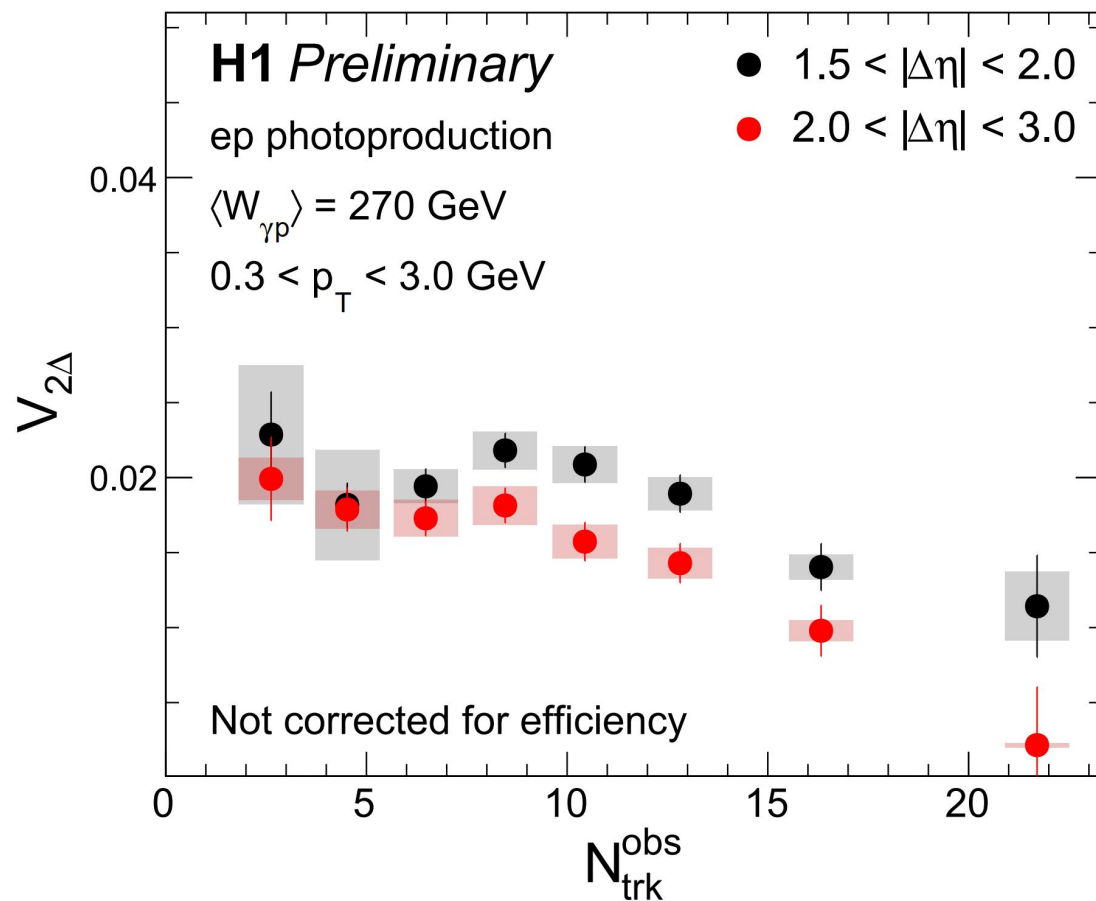
high multiplicity

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

photoproduction

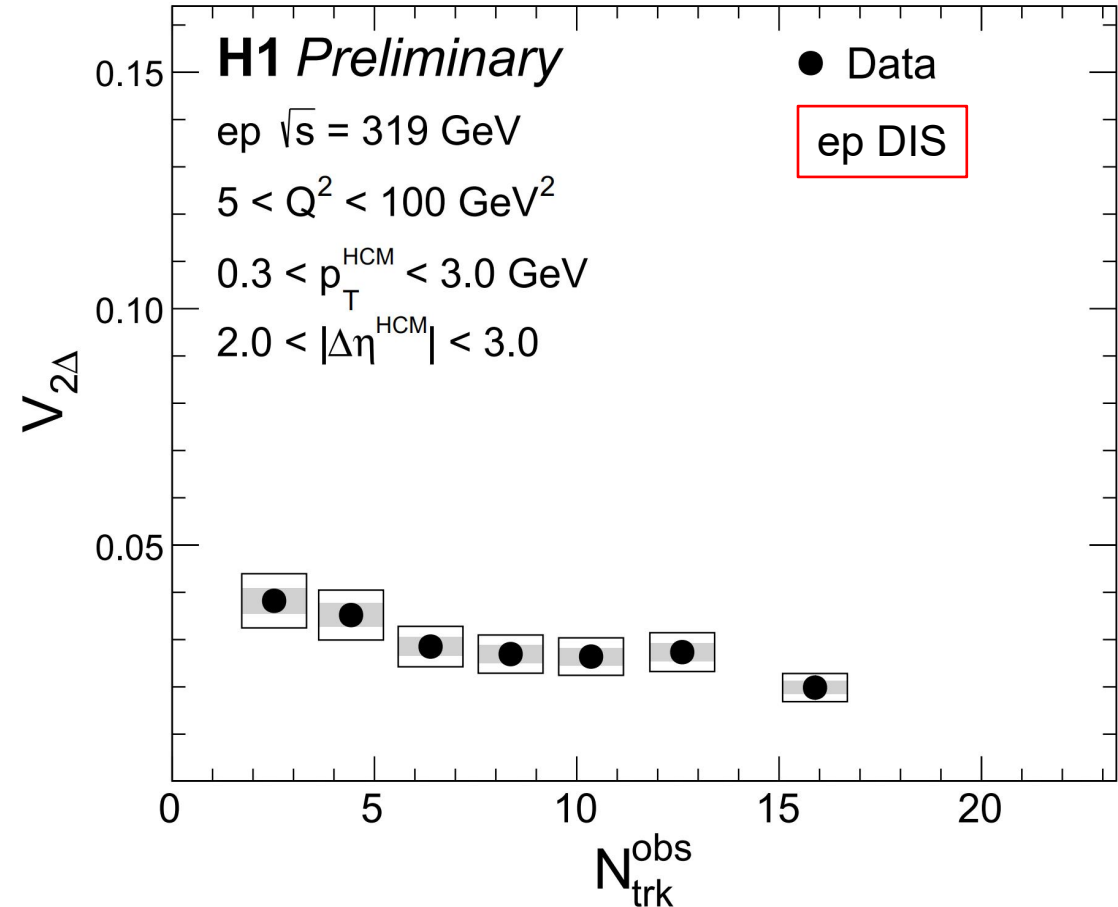
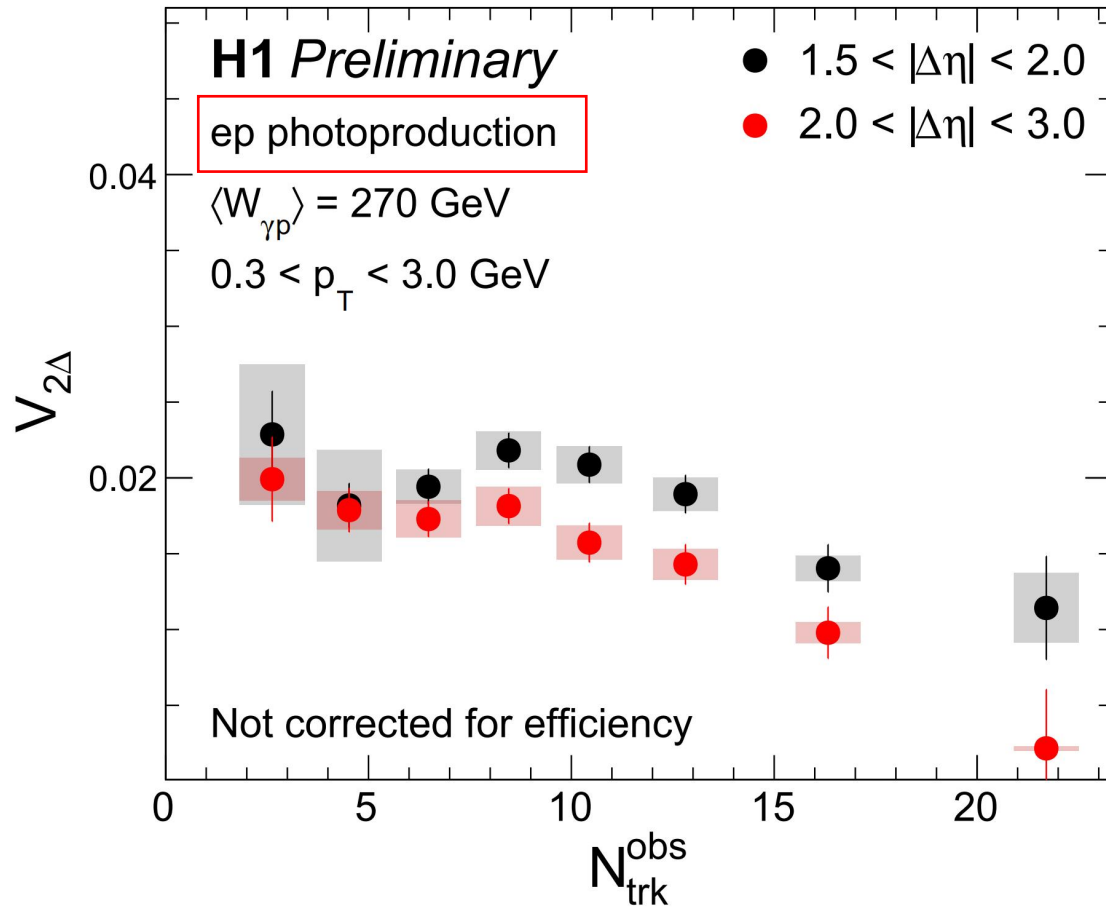


Fourier coefficient $V_{n\Delta}$ in ep photoproduction



photoproduction

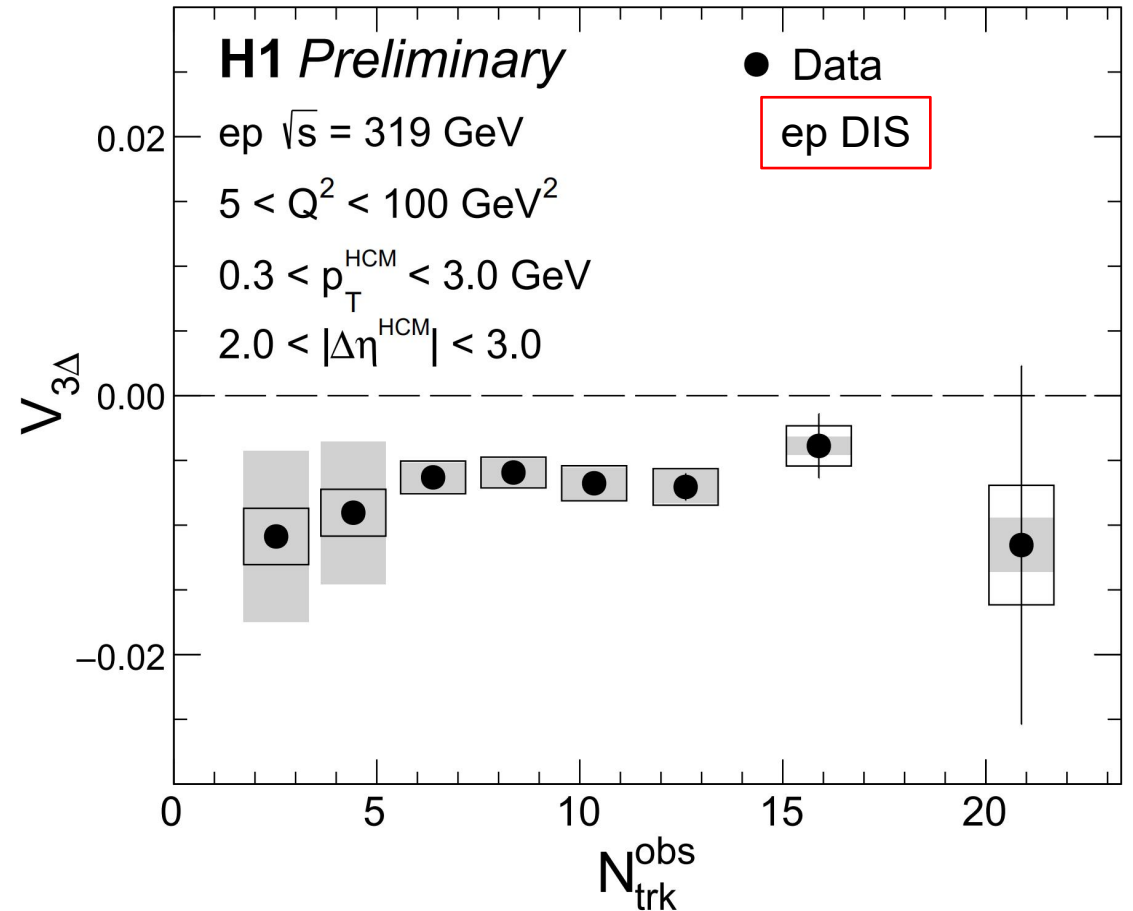
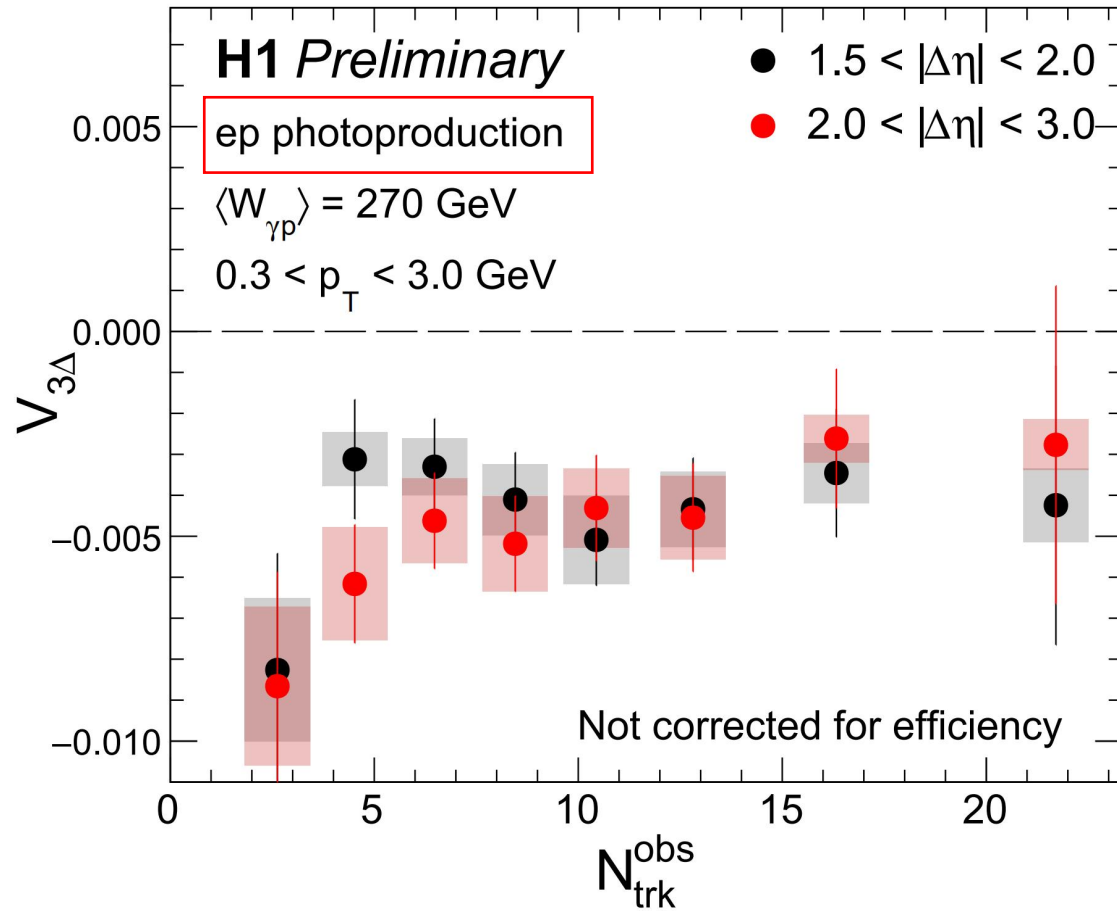
Fourier coefficient $V_{n\Delta}$ in ep photoproduction



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

photoproduction

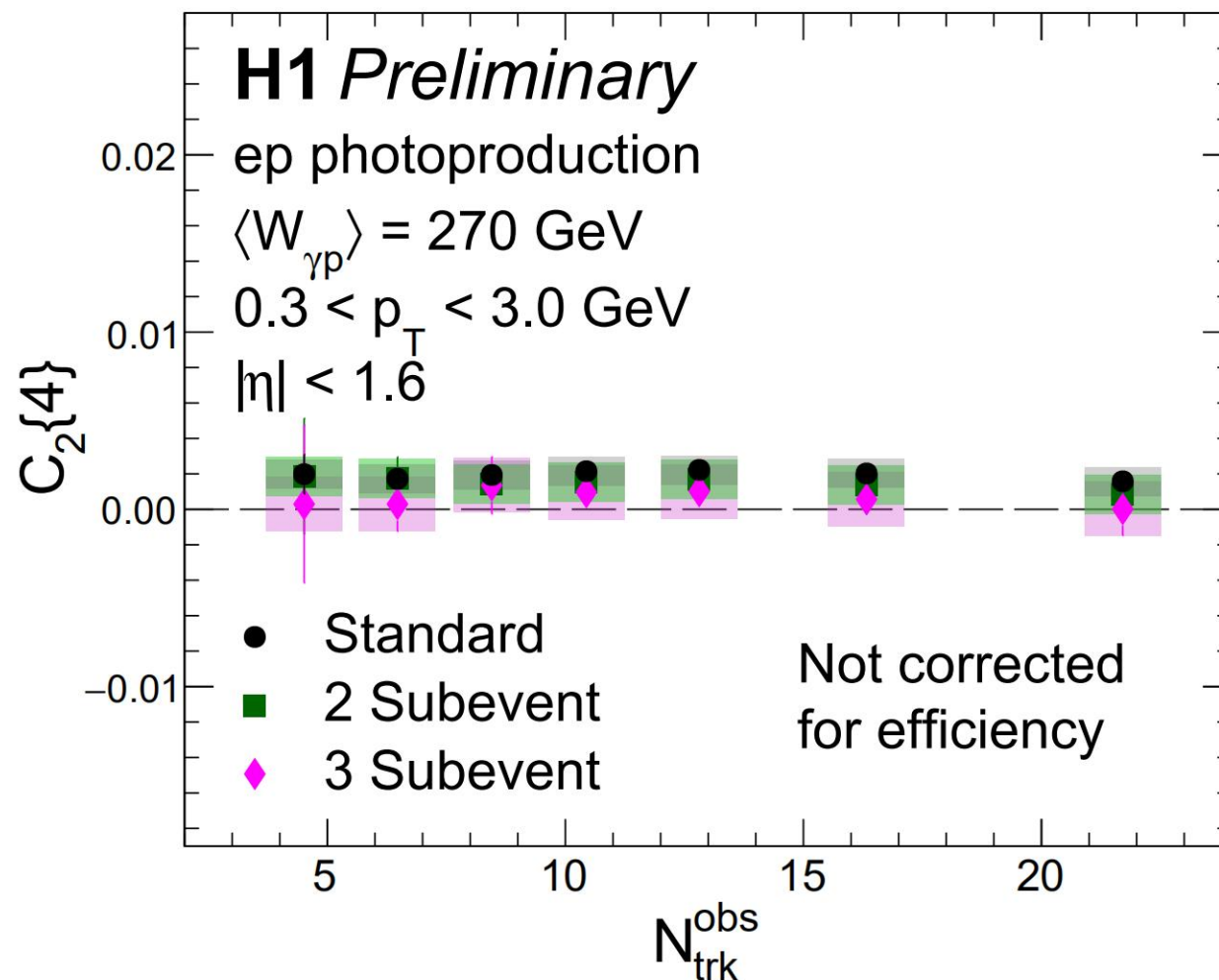
Fourier coefficient $V_{n\Delta}$ in ep photoproduction



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

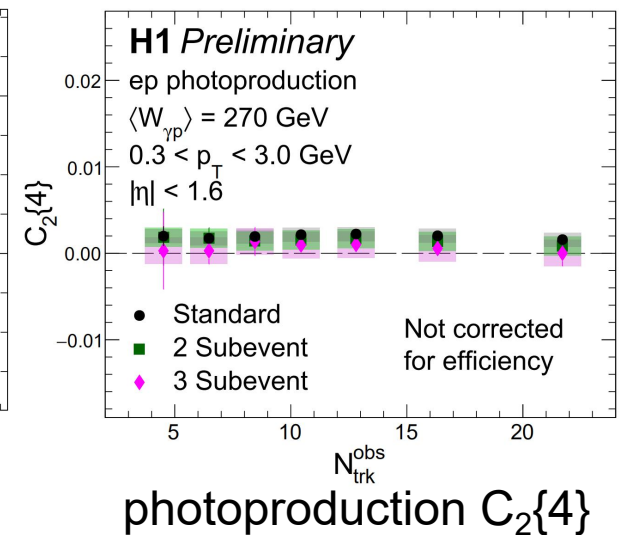
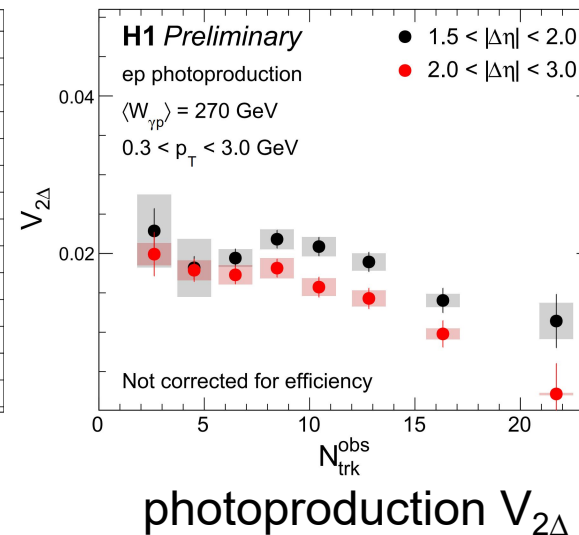
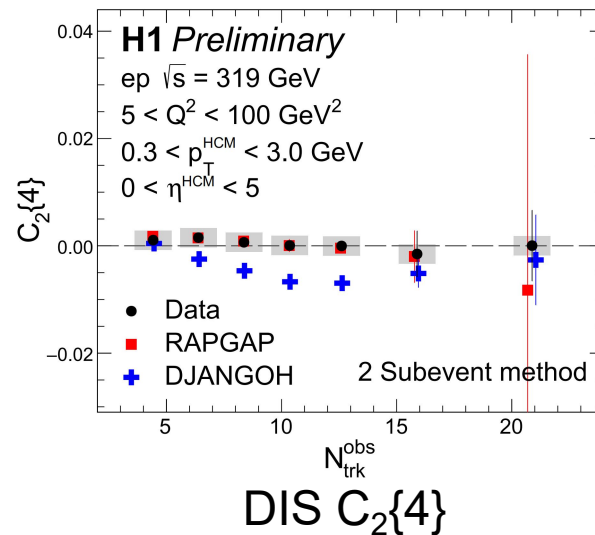
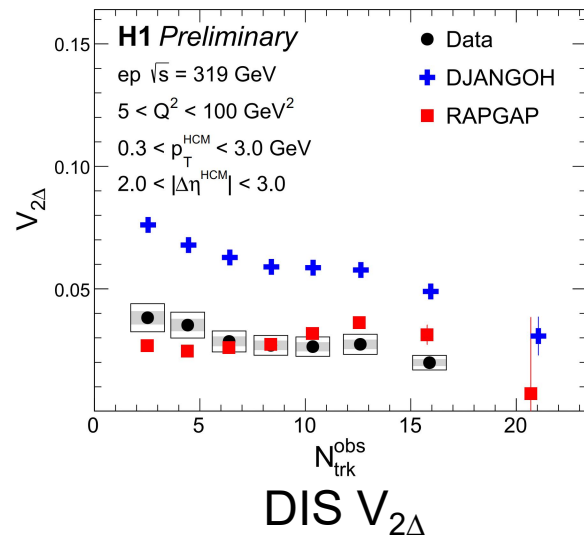
Decreasing $V_{2\Delta}$ and negative $V_{3\Delta}$

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



Summary

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

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

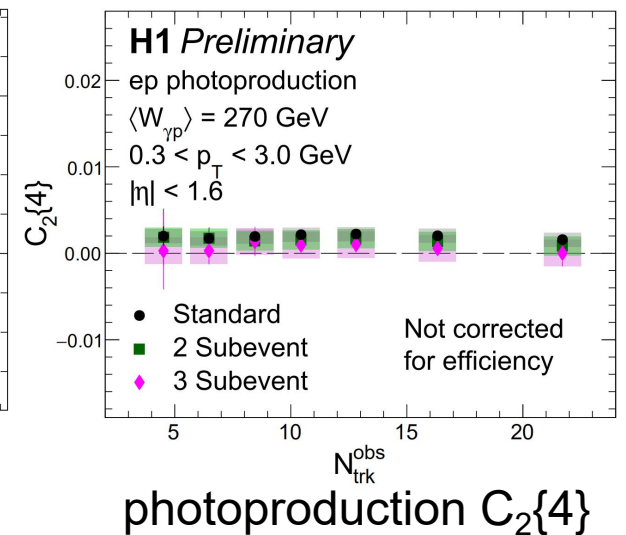
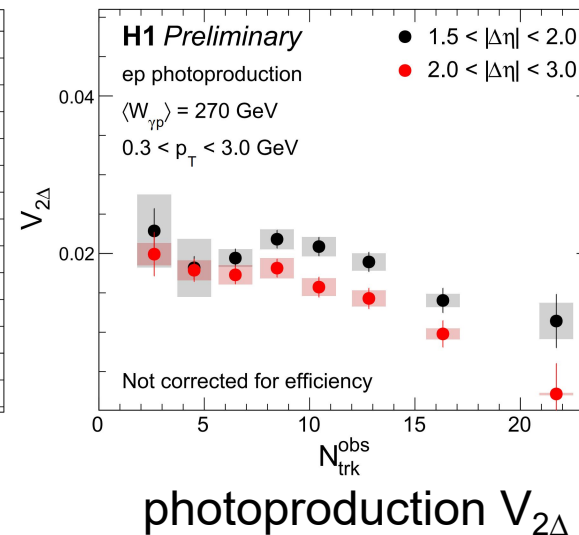
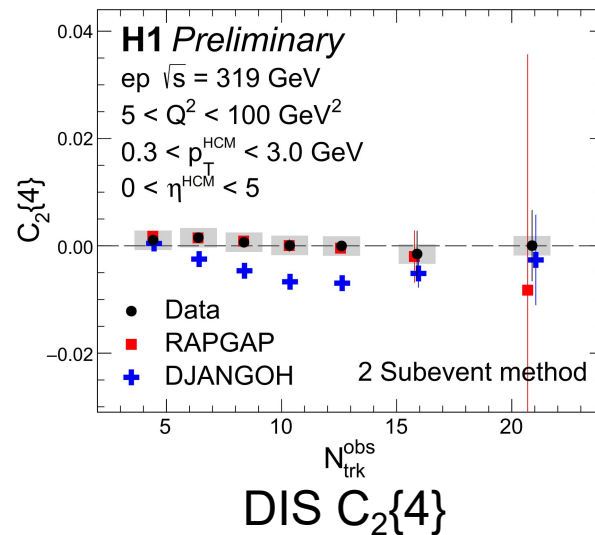
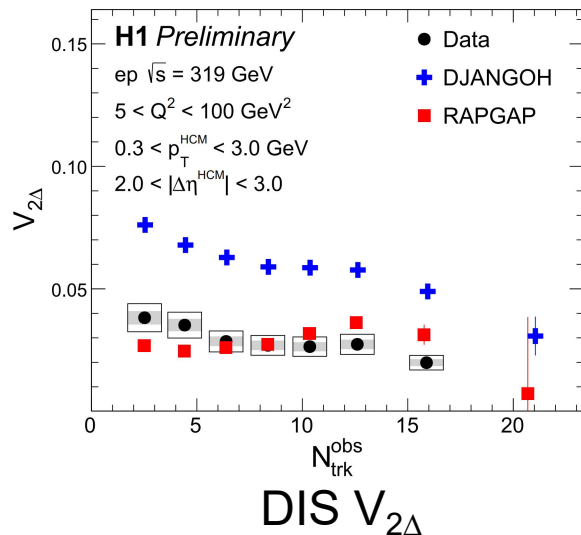
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$C_2\{4\}$ can also be described by RAPGAP w/o collectivity

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



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 $V_{3\Delta}$

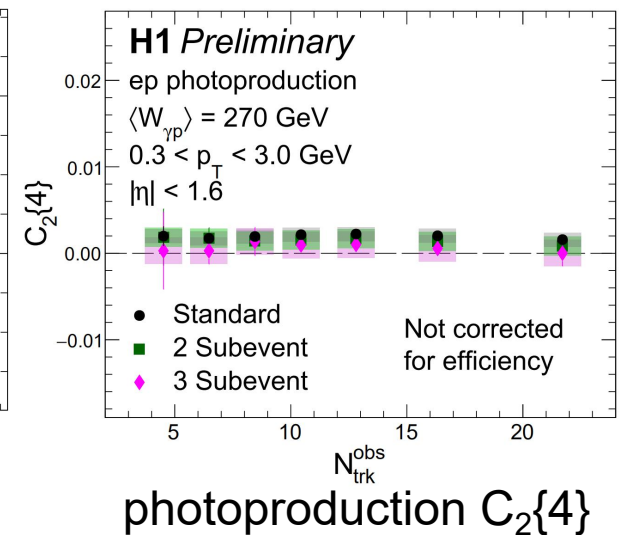
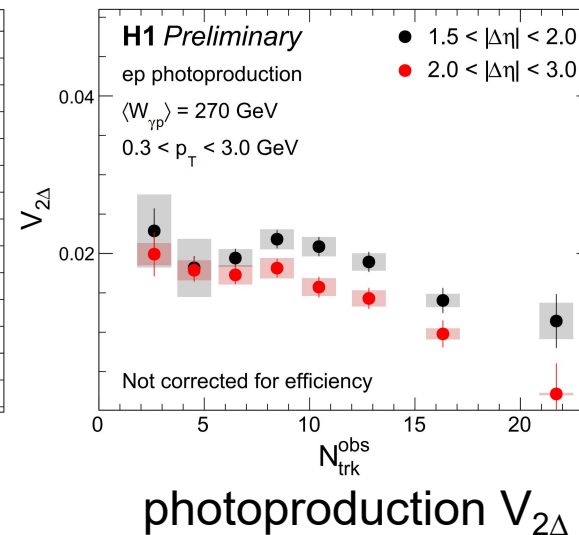
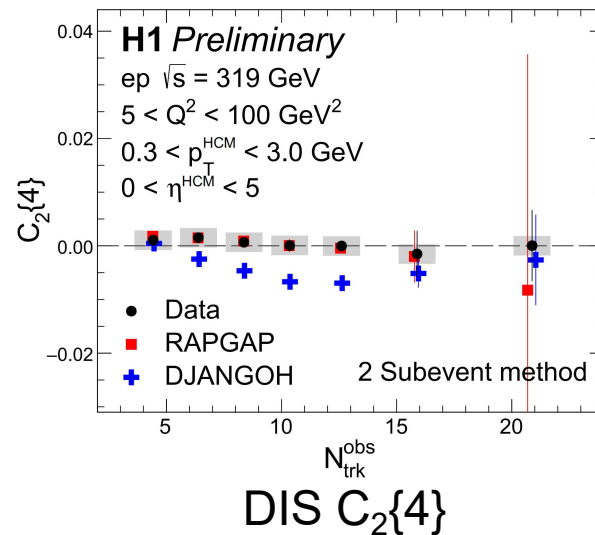
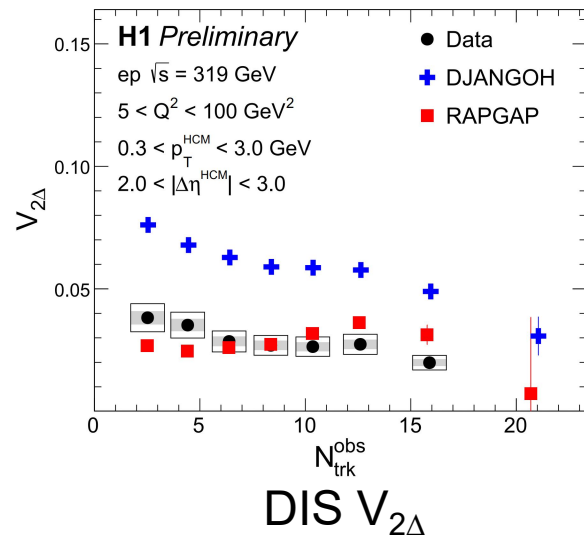
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$V_{2\Delta}$ and $V_{3\Delta}$ in DIS can be described by RAPGAP w/o collectivity

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

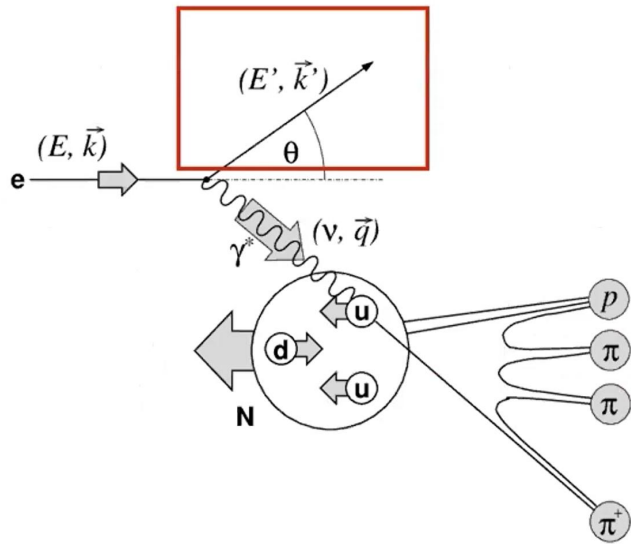
Is there any collectivity in high multiplicity eA collisions? Stay tuned for EIC



Thanks for your attention!

Back up

Kinematics in DIS

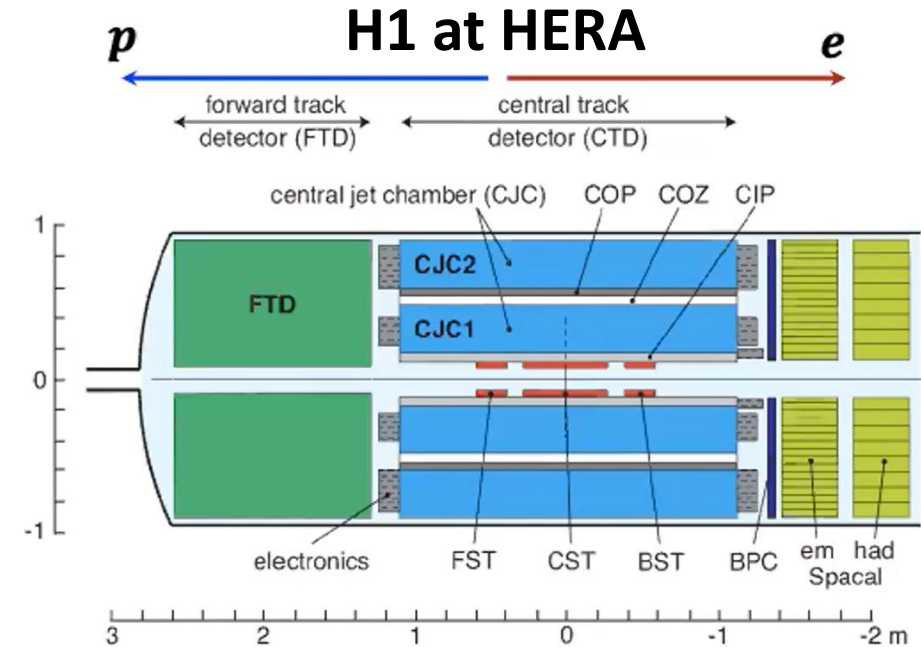


$$Q^2 = -q^2$$

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

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

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



Textbook: we only need to measure scattered electron for kinematics. However, at HERA, there are at 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 $\Delta\eta$, $\Delta\phi$ 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 $|Z_{VTX}| < 2\text{cm}$. In this analysis, each event is paired with 5 randomly chosen events. The result is given by

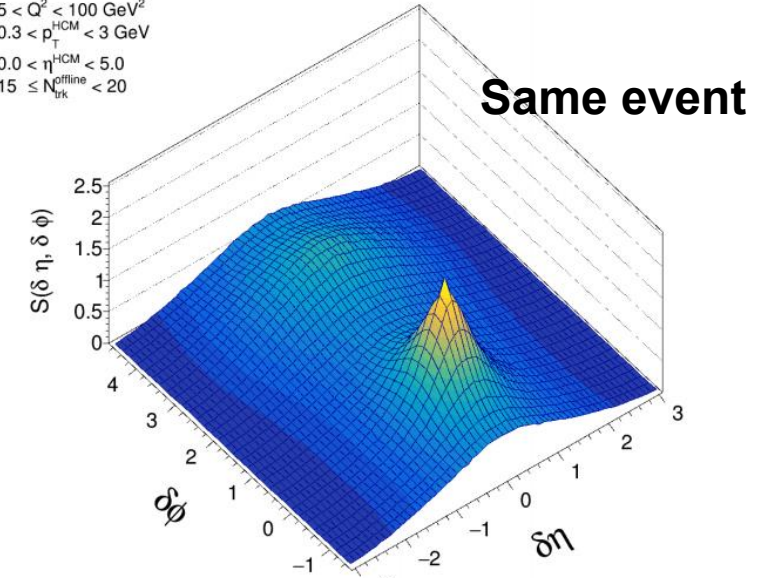
$$B(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N^{mix}}{d\Delta\eta d\Delta\phi}$$

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

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

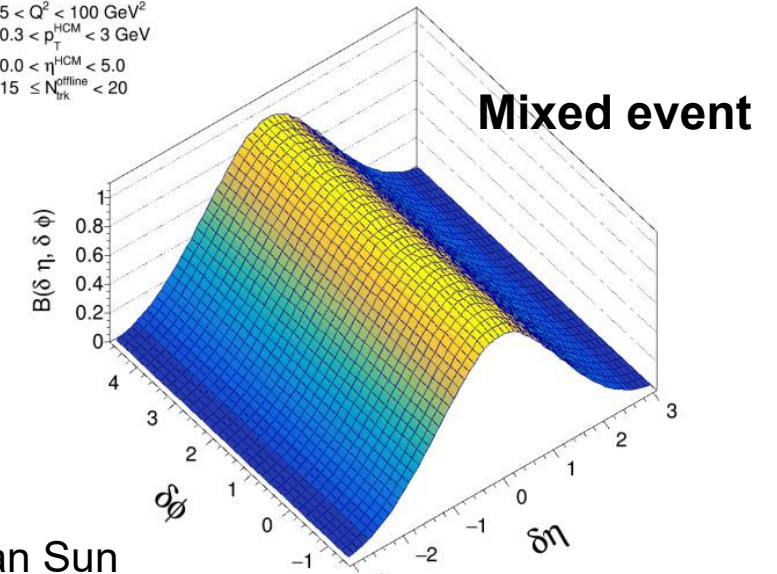
H1 DIS Data (HCM frame)

$5 < Q^2 < 100 \text{ GeV}^2$
 $0.3 < p_T^{HCM} < 3 \text{ GeV}$
 $0.0 < \eta^{HCM} < 5.0$
 $15 \leq N_{trk}^{offline} < 20$



H1 DIS Data (HCM frame)

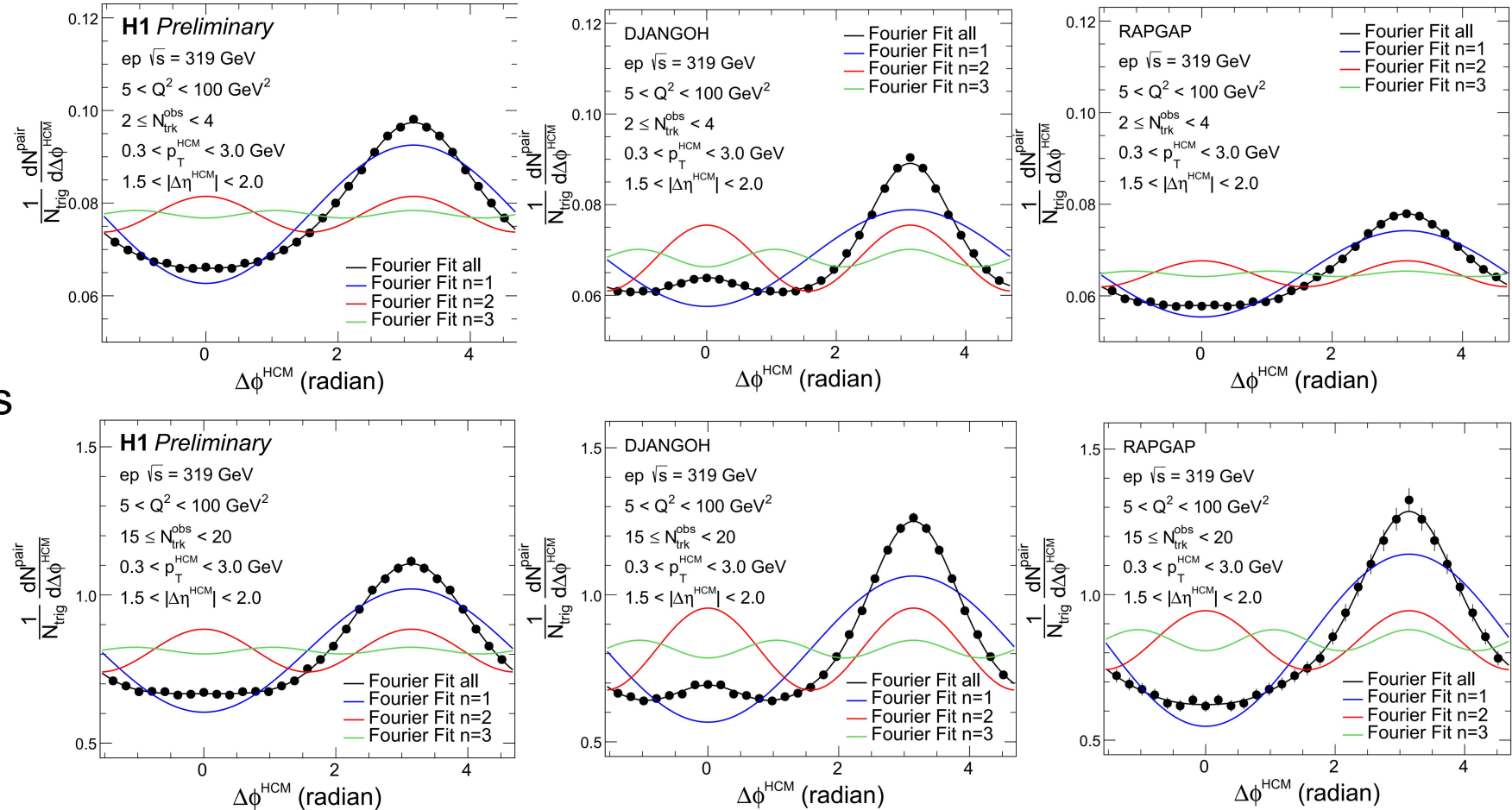
$5 < Q^2 < 100 \text{ GeV}^2$
 $0.3 < p_T^{HCM} < 3 \text{ GeV}$
 $0.0 < \eta^{HCM} < 5.0$
 $15 \leq N_{trk}^{offline} < 20$



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

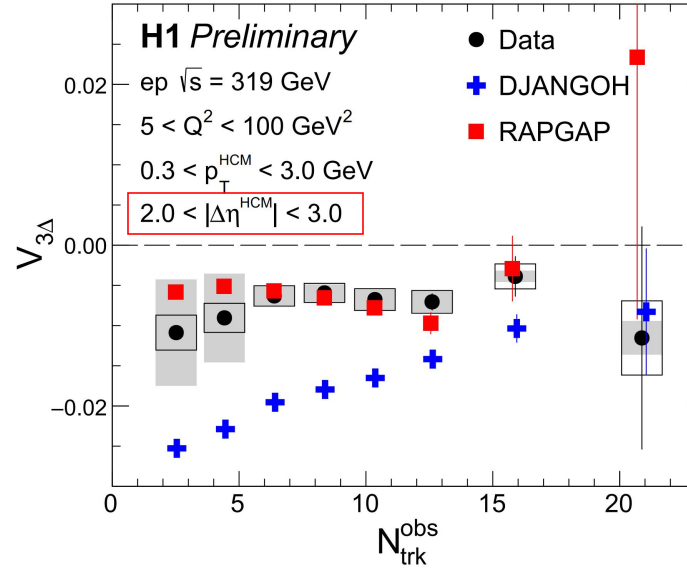
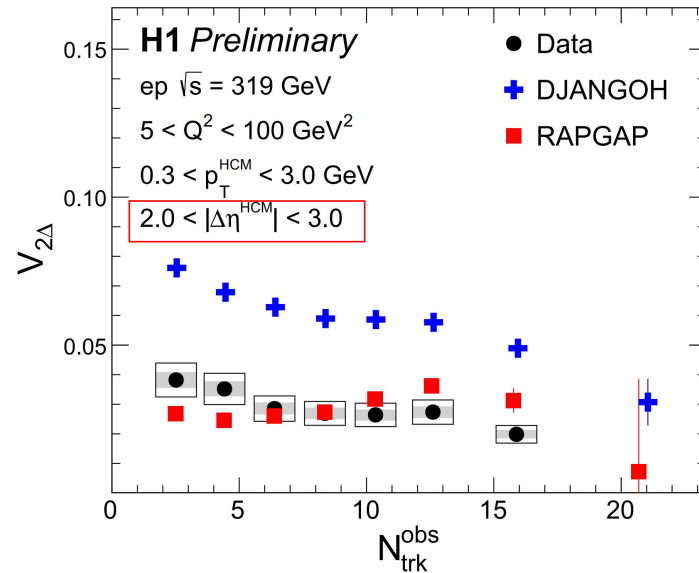
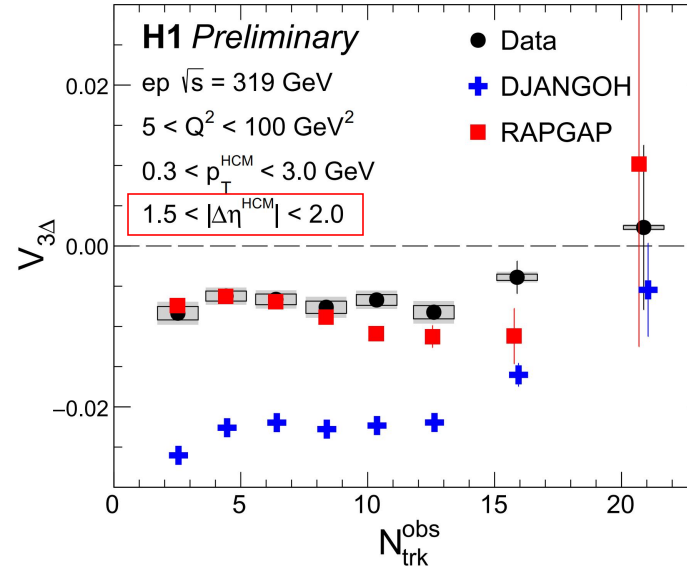
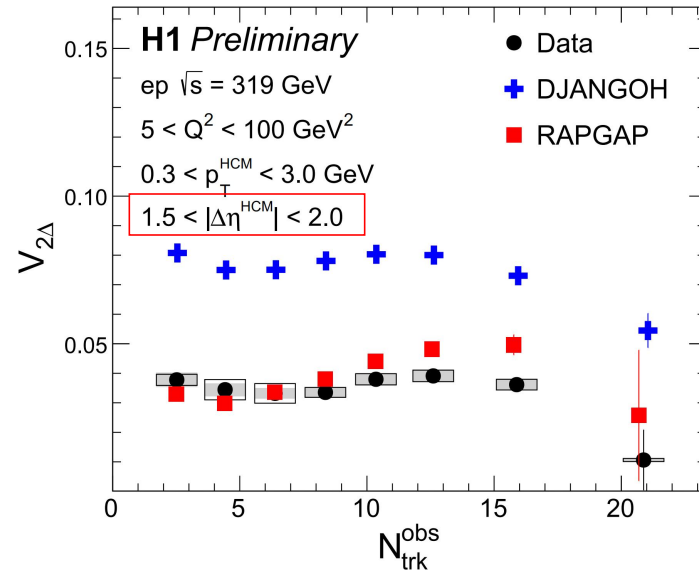
The azimuthal anisotropy harmonics are determined from a Fourier decomposition of long-range two-particle correlation functions on $\Delta\phi$ direction.

1-D comparisons



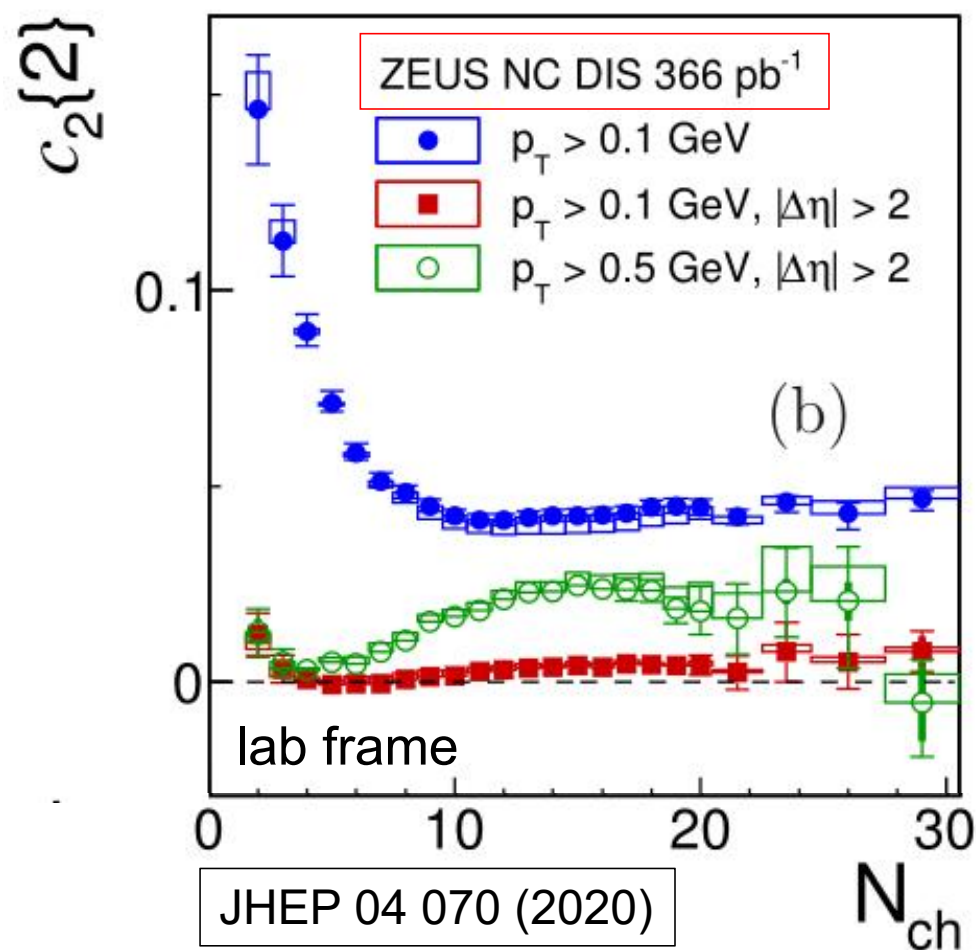
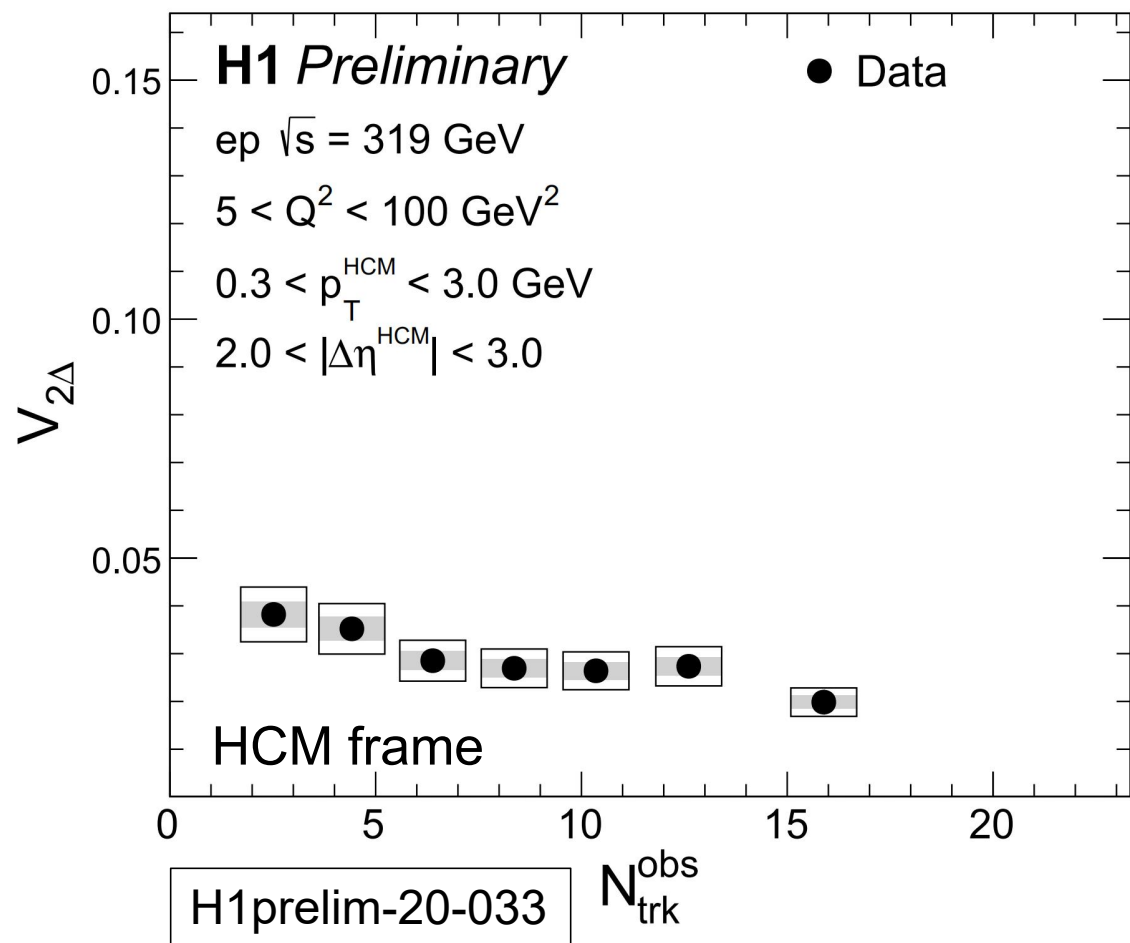
The comparison between data and MCs.
 Similar shapes in high and low multiplicity.

Fourier coefficient $V_{n\Delta}$



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

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



Similar trend as ZEUS result

DIS HCM

Mechanism in RAPGAP and DJANGO

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

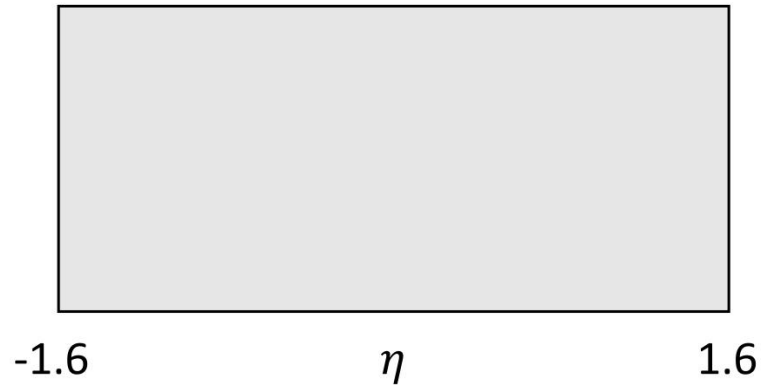
MC event generator matches **first order QCD matrix elements to the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) parton showers** with strongly ordered transverse momenta of subsequently emitted partons. The factorisation and renormalisation scales are set to $u_f = u_r = \sqrt{Q^2 + \hat{p}_T^2}$, 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 DJANGO 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.

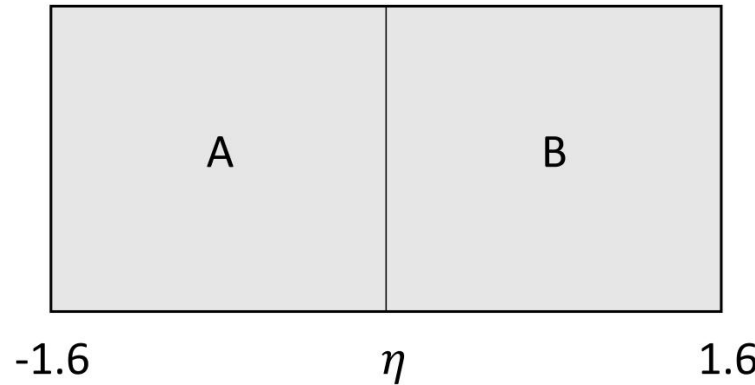
Multi-particle correlation

Standard method



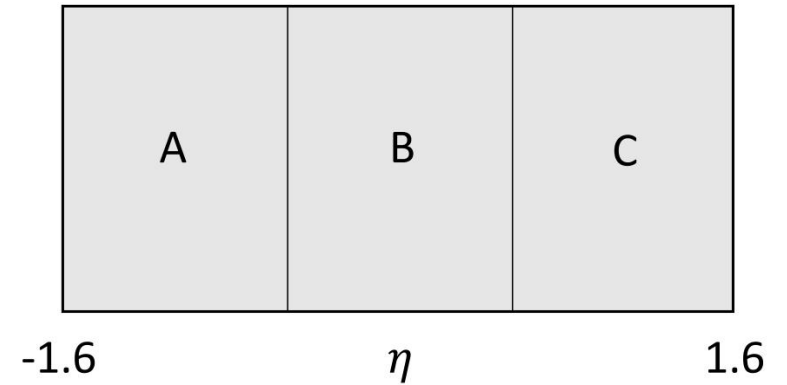
4 particles from the same range

2 sub-event method



2 particles from A
2 particles from B

3 sub-event method



1 particle from A
2 particles from B
1 particle from C

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