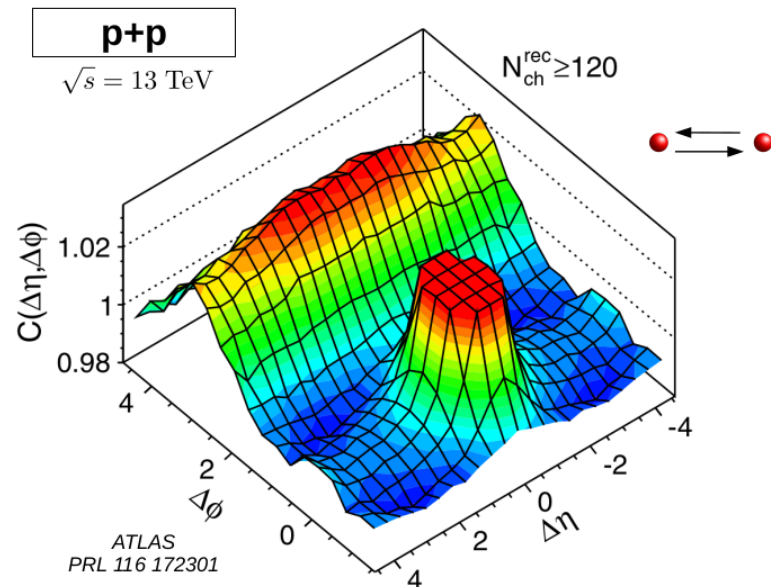
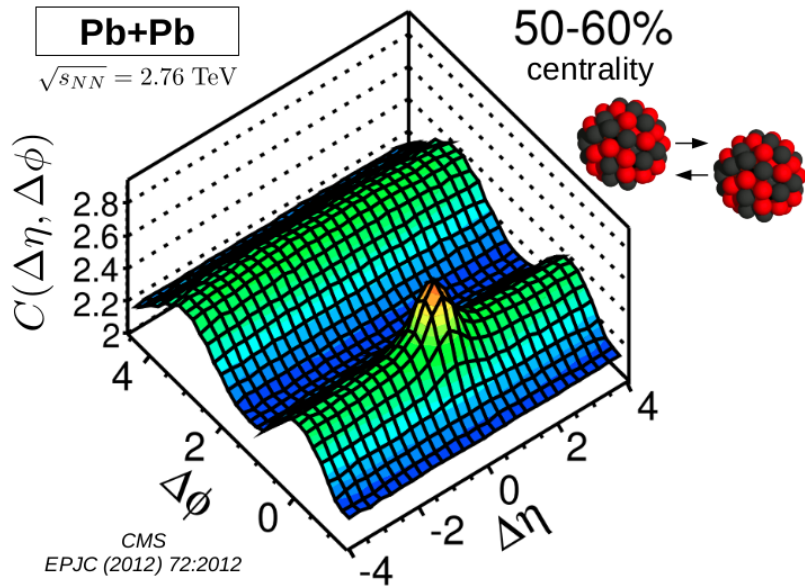


# Azimuthal correlations in photoproduction and deep inelastic $ep$ scattering at HERA

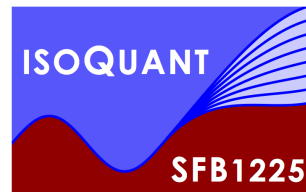
**ZEUS Publication:**  
**JHEP 12 (2021) 102**



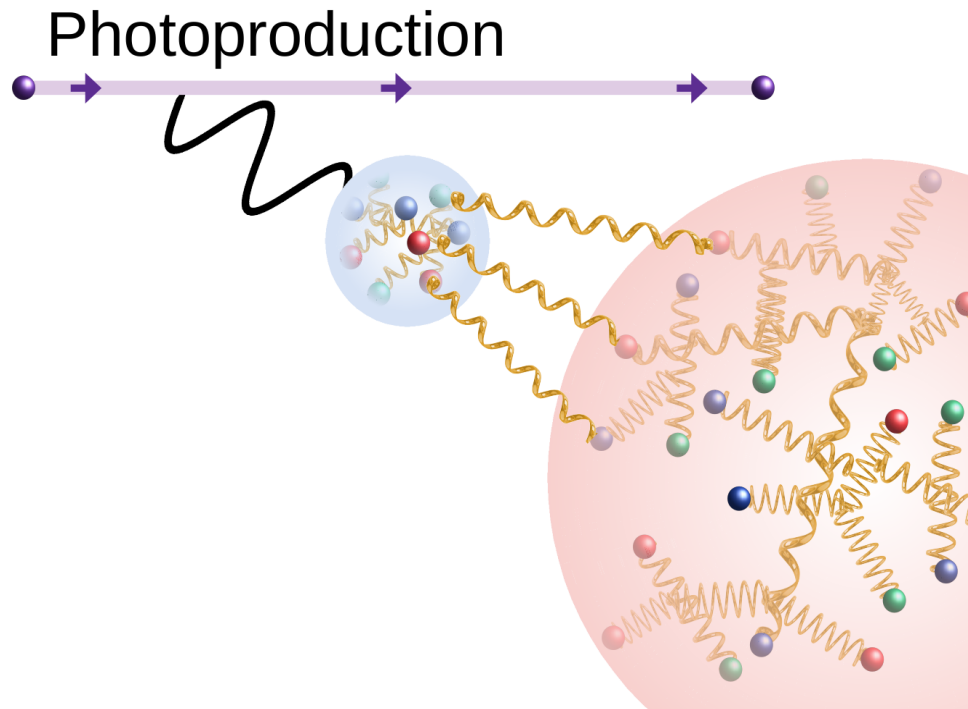
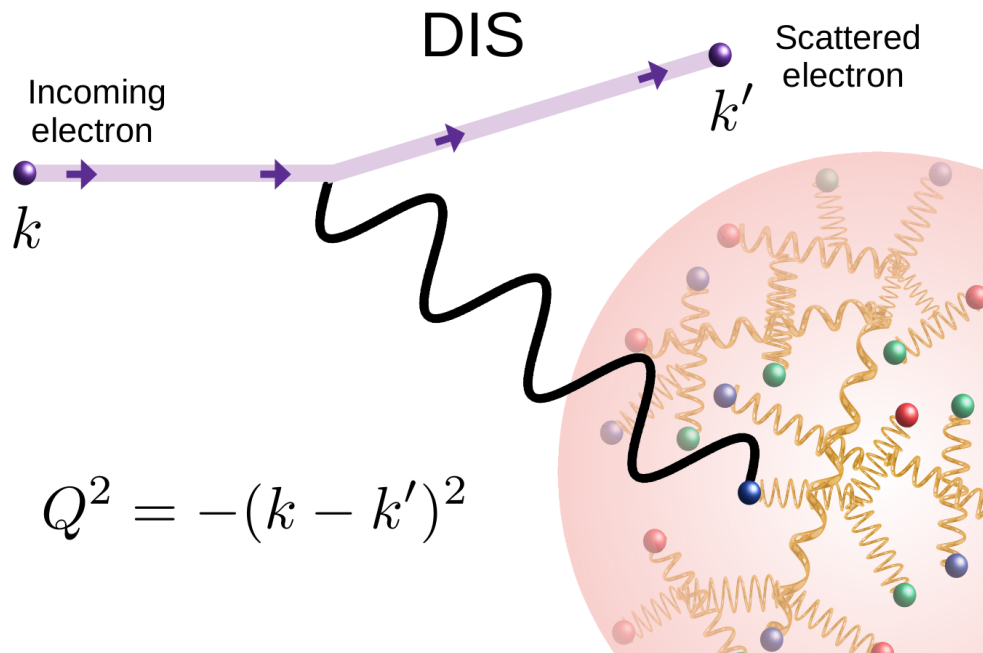
- The double-ridge observed with two-particle azimuthal correlations is evidence for collective behavior, which is typically associated with the formation of a **quark-gluon plasma**.
- It was a surprise to find it in the “small” systems produced in  $pp$  collisions.
- Does it exist in more fundamental  $ep$  collisions such as those recorded by **ZEUS**??



**Dhevan Gangadharan**  
University of Houston  
Quark Matter 2022



# Regimes of scattering in $ep$



## Deep Inelastic Scattering (DIS)

- DIS is defined by large virtualities:

$$Q^2 \gg 1 \text{ GeV}^2$$

- Probed size of transverse region:

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

- Neutral current DIS is studied:  
 $\Upsilon$  or Z exchange

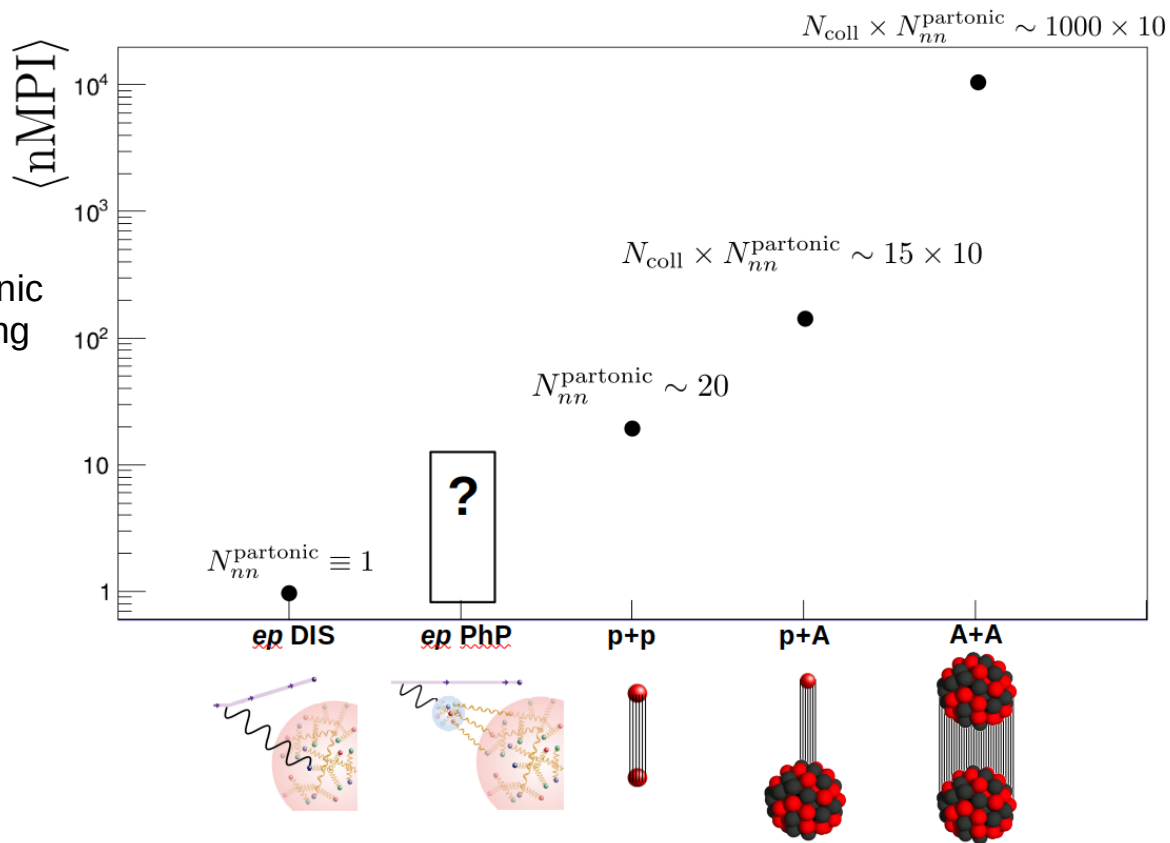
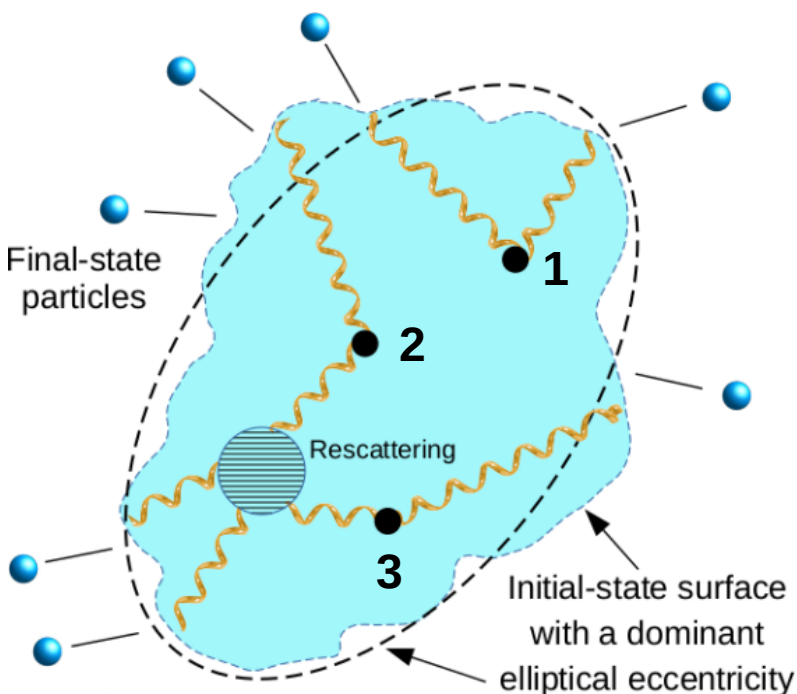
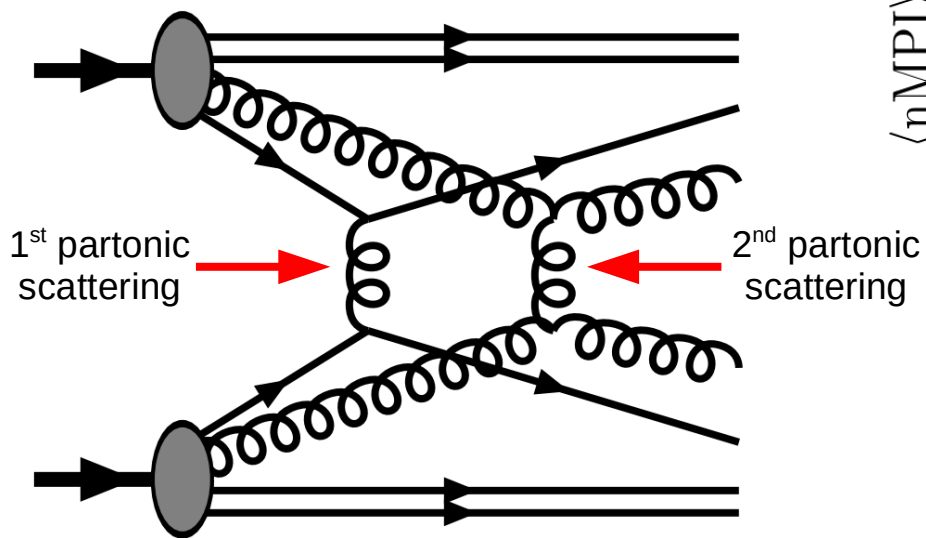
## Photoproduction (PhP)

- Photoproduction is defined by small virtualities

$$Q^2 \lesssim 1 \text{ GeV}^2$$

- Exchanged photon may fluctuate into quarks and gluons.
- Larger interaction regions are probed.
- multiparton interactions (MPI) are possible.
- Scattering is hadron-like

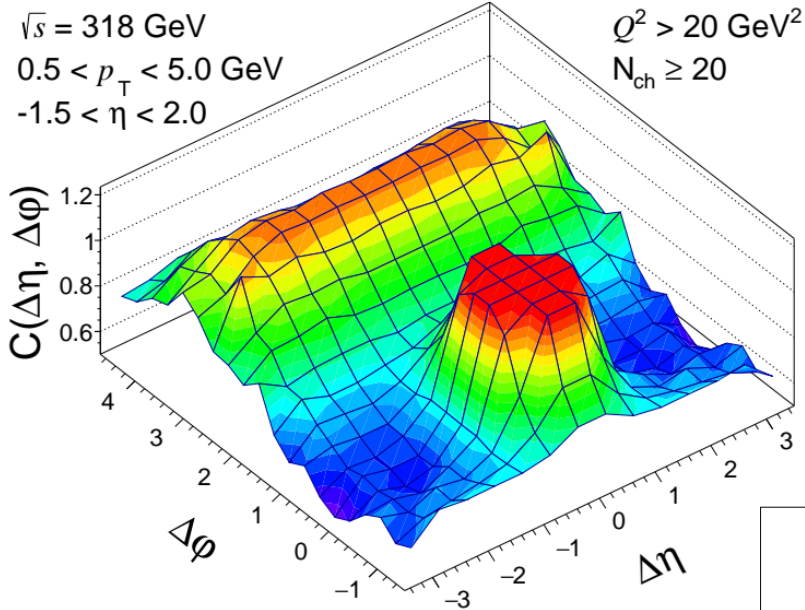
# Multiparton Interactions (MPI) and a possible route to collective behavior in $ep$ photoproduction



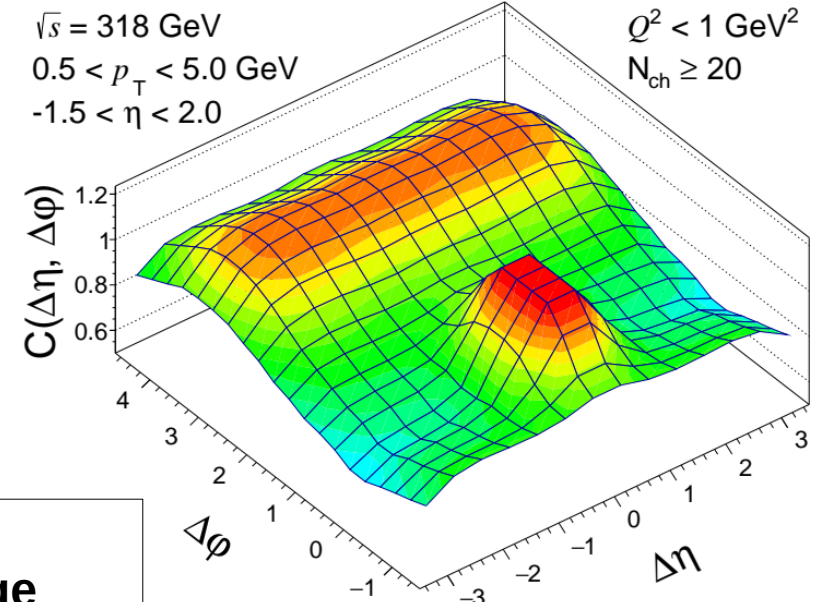
- ZEUS photoproduction data will be compared to PYTHIA 8.3 with varying amounts of MPI.
- This will form our estimation of how many partonic scatterings occur on average in  $ep$  photoproduction at high multiplicity.

# Results: Ridge plots & 4-particle cumulant

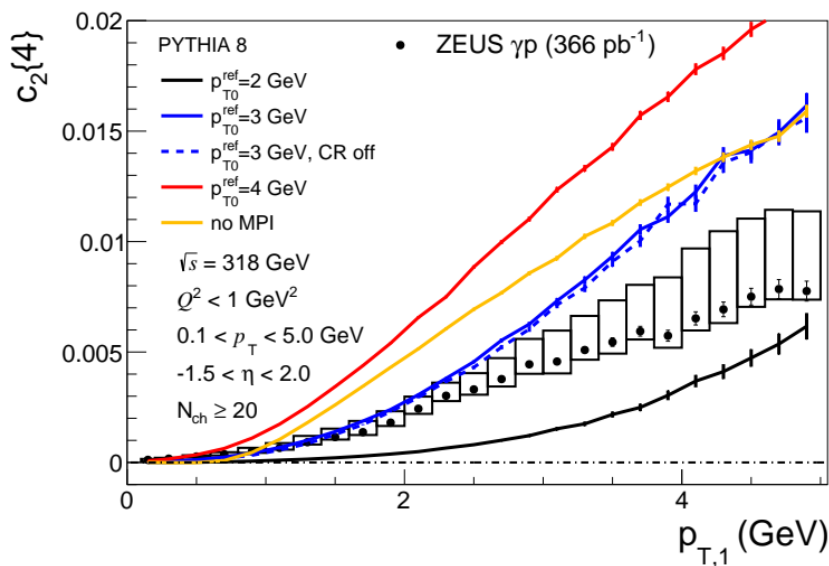
## DIS



## Photoproduction



**No visible double ridge**



$$C_n\{2\} = \langle \cos n(\varphi_1 - \varphi_2) \rangle$$

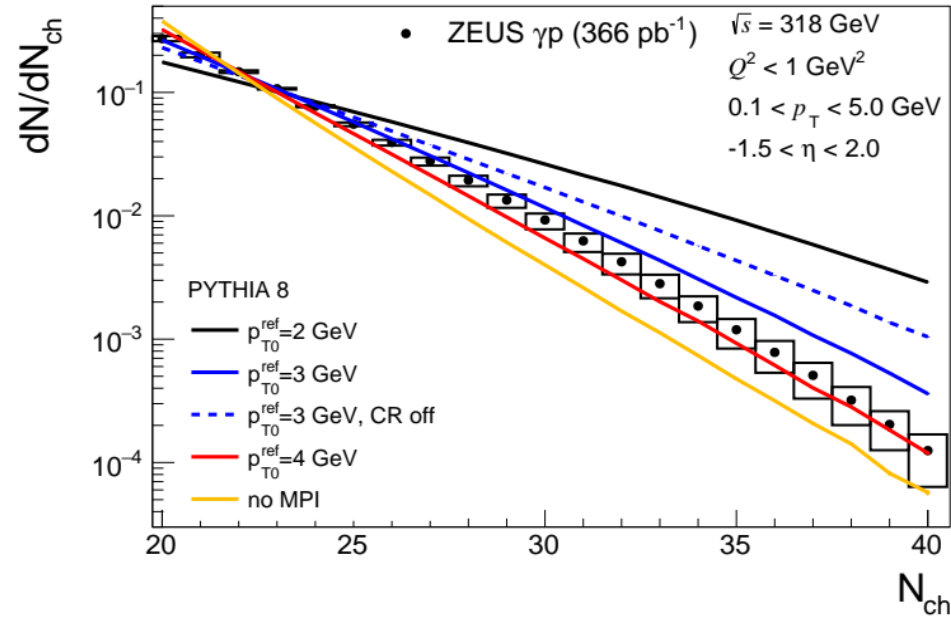
$$C_n\{4\} = \langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle$$

$$c_n\{4\} = C_n\{4\}(p_{T,1}) - 2c_n\{2\}(p_{T,1}) \times c_n\{2\}$$

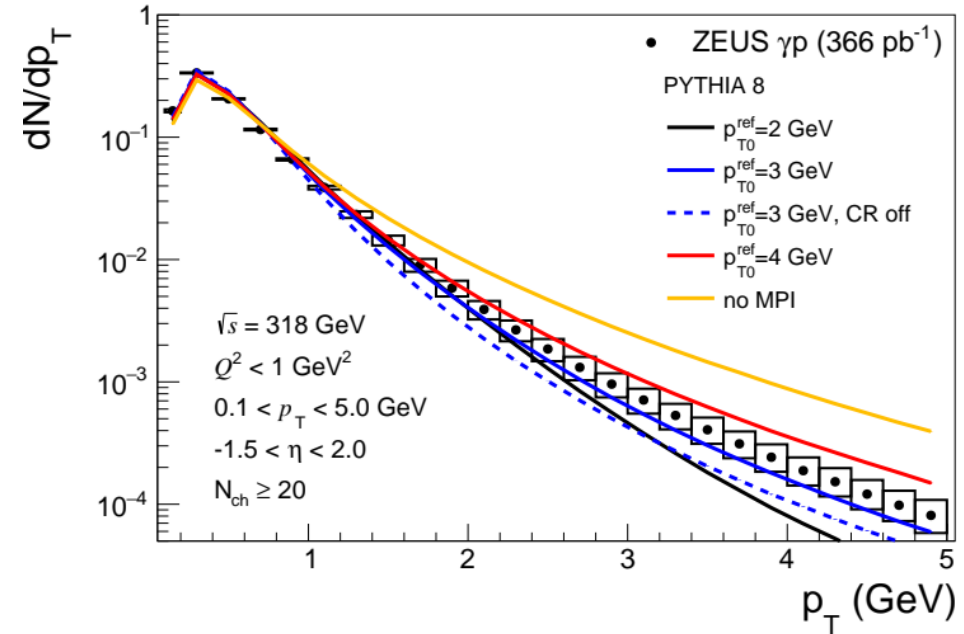
4-particle cumulant is **positive** in ep photoproduction while it is **negative** in non-central heavy-ion collisions where collective behavior is observed.

# Results: Assessment of MPI in ep photoproduction

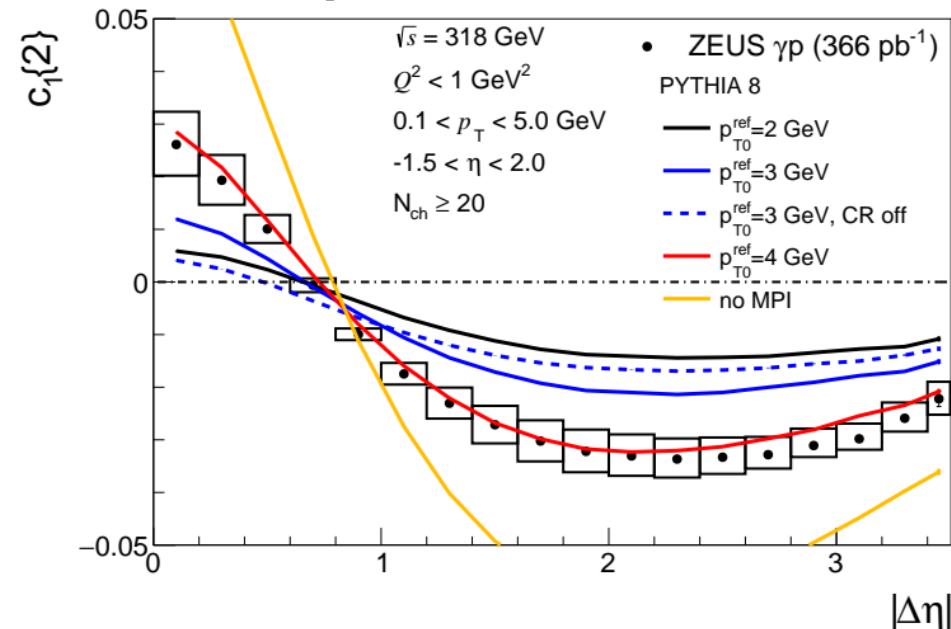
## Multiplicity distribution



## $p_T$ distribution



## 2-particle correlation



## PYTHIA parameter choices

	$p_{T0}^{\text{ref}} = 2$	$p_{T0}^{\text{ref}} = 3$	$p_{T0}^{\text{ref}} = 4$
$\langle n_{\text{MPI}} \rangle$	8.3	3.8	2.2

- The “no MPI” scenario is strongly disfavored.
- Comparisons of data with PYTHIA suggest that  $\sim 3$  MPI occur per  $\gamma p$  event on average.