Diffraction and Low-x 2021

Sept 27th – Oct 1st, La Biolola Italy

# Recent HERA results on vector meson production, particle correlations and particle multiplicity spectra

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# Outline of the talk

**Search for collectivity in DIS and photoproduction**

ZEUS: arXiv:2106.12377 submitted to JHEP, JHEP 04 (2020) 070

H1: H1prelim-20-033

**Charged particles and entanglement**

Eur.Phys.J.C81 (2021), 212

**rho(770) photoproduction**

Eur.Phys.J.C80 (2020), 1189

# H1 and ZEUS @ HERA

**HERA COLLIDER**

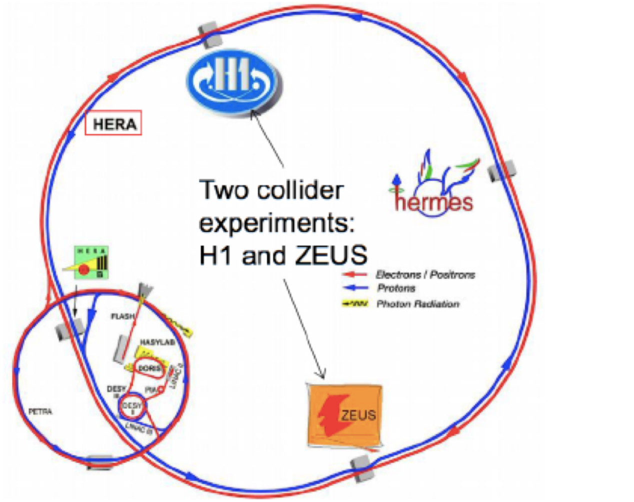
Operated from 1992 to 2007, 500 $pb^{-1}$ to ZEUS/H1

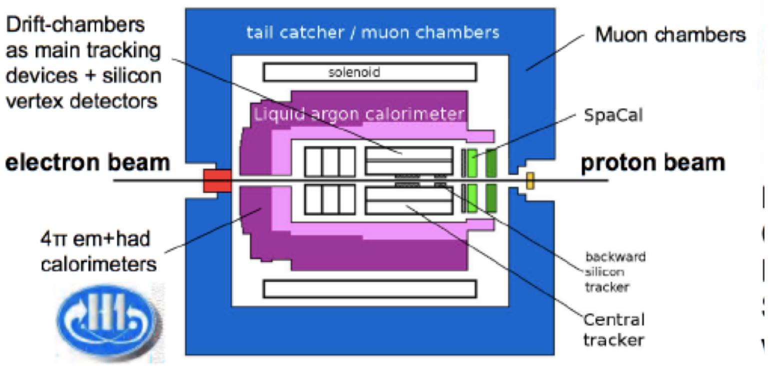
6.3 km circumference

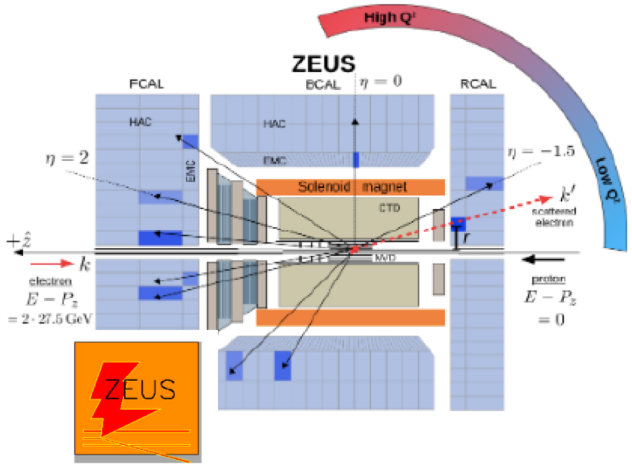
Asymmetric detectors

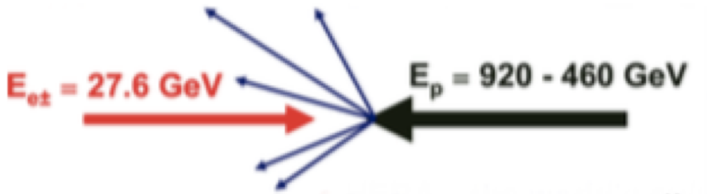
$e^+$ or $e^-$ colliding with p

Center of mass system boosted in p direction → asymmetric detectors



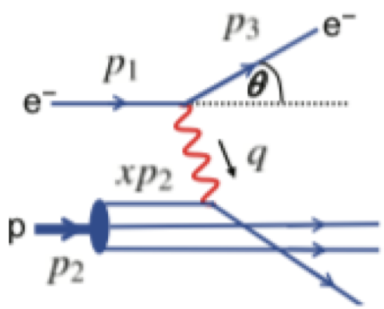




$\Rightarrow \sqrt{s} = 318$ GeV

$$s = (p_1 + p_2)^2 \simeq 2p_1 \cdot p_2, \quad y = \frac{p_2 \cdot q}{p_2 \cdot p_2}, \quad x = \frac{Q^2}{2p_2 \cdot q}$$




**$Q^2 \sim 0$ γproduction**

**$Q^2 > 0$ DIS**

**Search for collectivity in DIS and photoproduction**

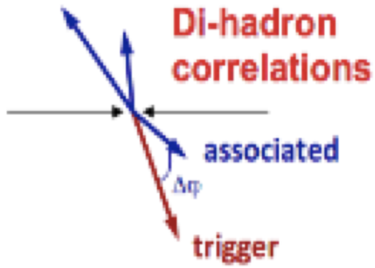
ZEUS: arXiv:2106.12377 submitted to JHEP, JHEP 04 (2020) 070

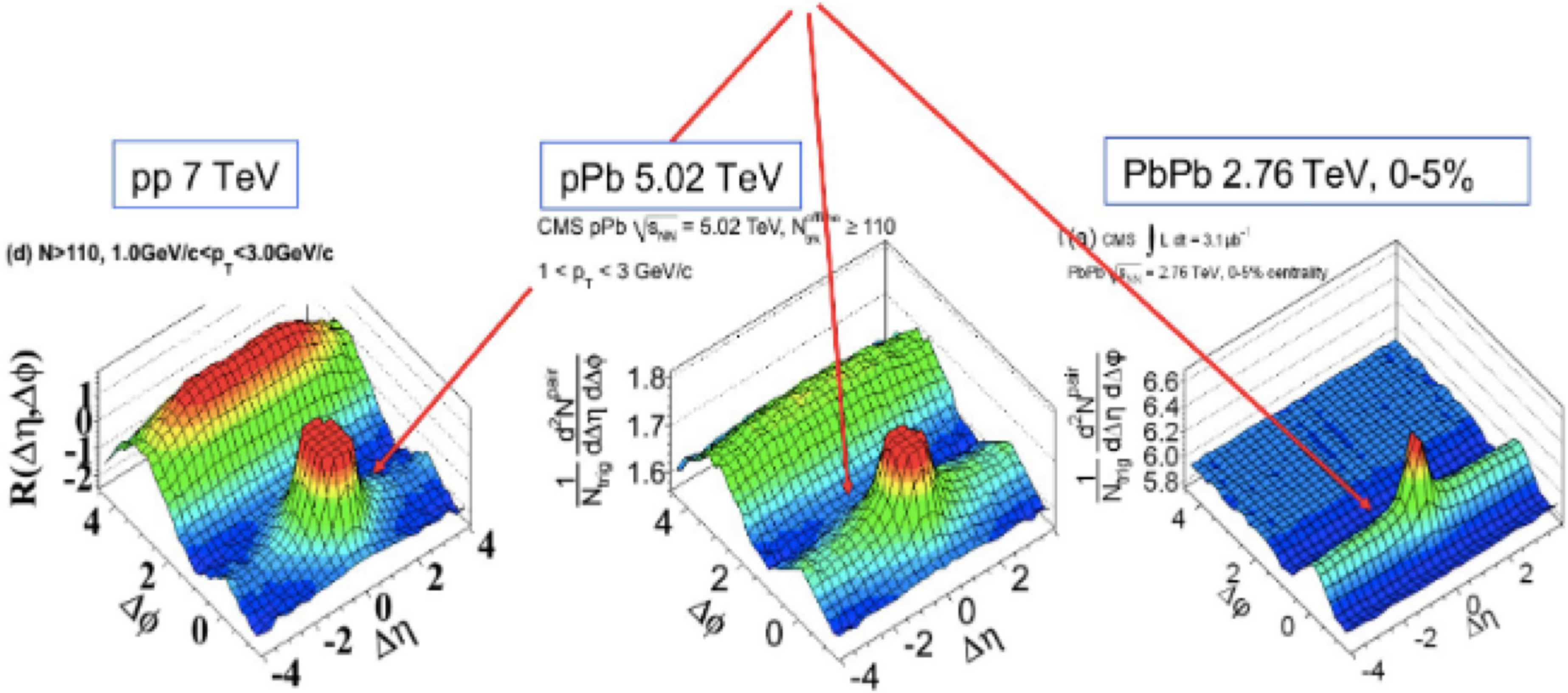
H1: H1prelim-20-033

# "Everything...flows"(?)



- Long-range (2 < |Δη| < 4), near-side (Δφ ≈ 0) angular correlations are seen at LHC at various √s in
  - heavy ions (XeXe and PbPb), **and**
  - "small systems", i.e., high-multiplicity (≳50–60) pPb and pp collisions
- Signs reminiscent of **collective behavior** of a quark-gluon plasma (QGP)

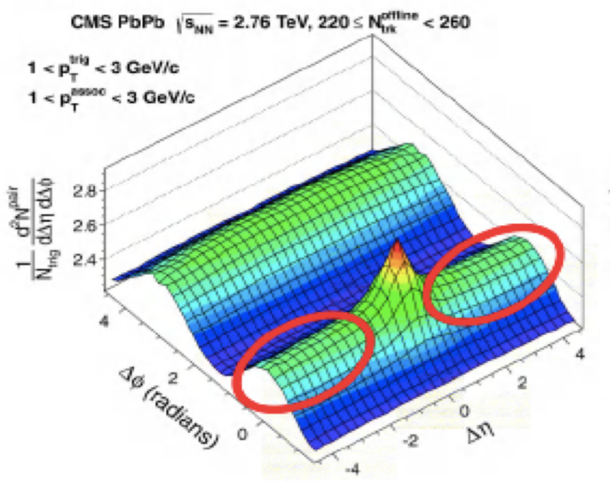


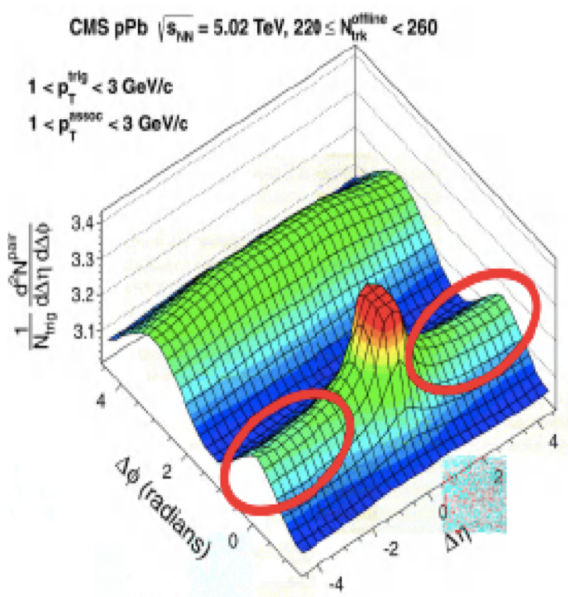

**Slide by G. Krintiras at this workshop**

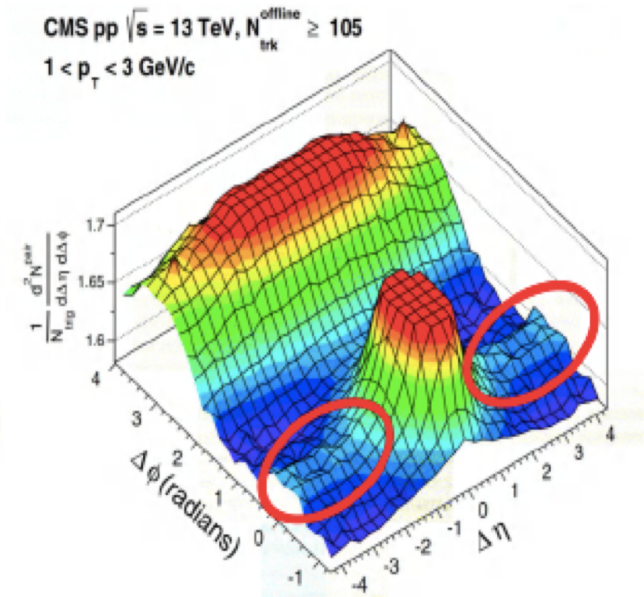
# Motivation

In **heavy ion collisions** evidence of long-range correlation in Δη for particle pairs produced at small $\Delta\phi$ (**ridge**)
→ understood as **fluid-like behaviour (QGP)**




Also at LHC similar structure in **pPb and pp systems**




**What happens in an even smaller systems, i.e. electron-proton collision?**

# Formalism

- **Two-particle and four-particle azimuthal correlations** defined as

$$C_n\{2\} \equiv \langle \cos\left[n(\varphi_1 - \varphi_2)\right]\rangle ,$$
$$C_n\{4\} \equiv \langle \cos\left[n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\right]\rangle$$

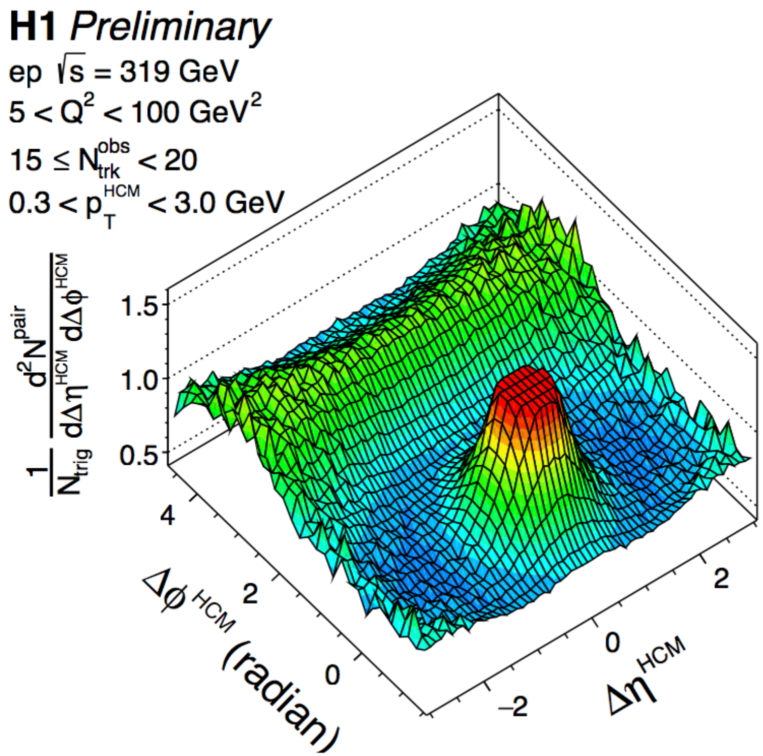
- $\varphi_i$ the azimuthal angle of particle *i*
- *n* the harmonics
- ⟨ ⟩ averages over pairs and quadruplets
  (corrections for non-uniform acceptance taken into account by proper weights)

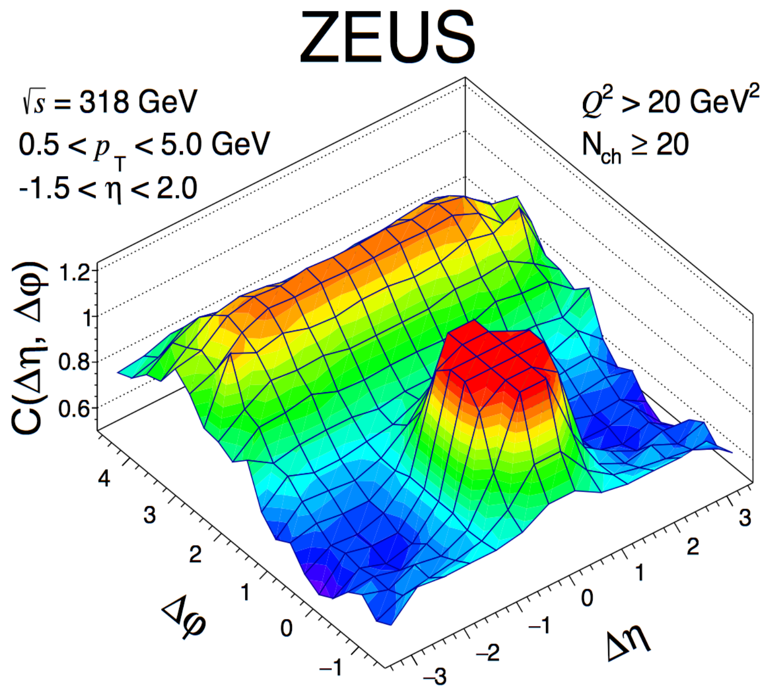
- Also **two-dimensional correlation functions** $C(\Delta\eta, \Delta\varphi) = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$

- S (signal)
- B (background)

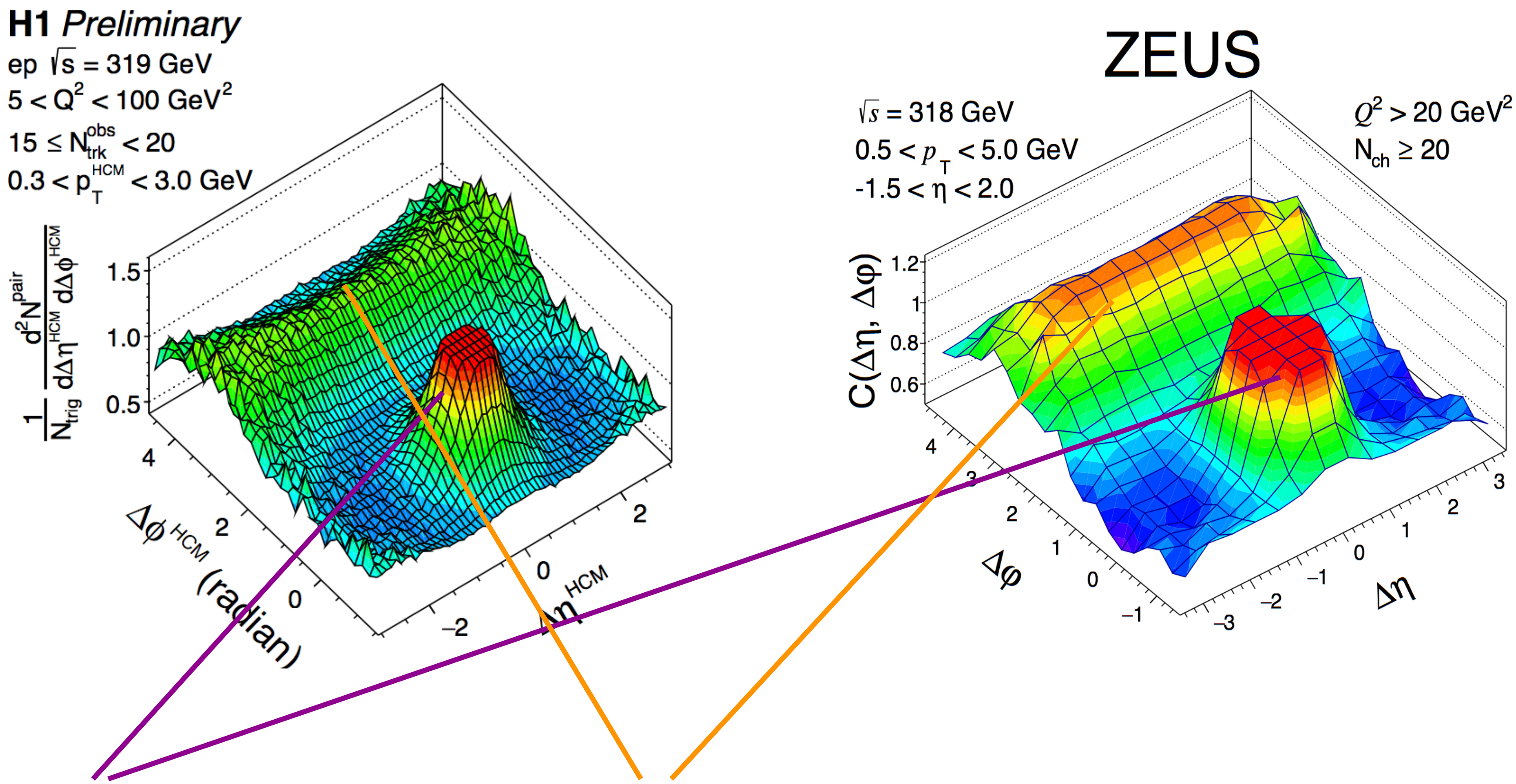
formed with pairs from the same- and mixed- event respectively

# Ridge in DIS?


H1 Preliminary
ep √s = 319 GeV
5 < Q² < 100 GeV²
15 ≤ N_trk^obs < 20
0.3 < p_T^HCM < 3.0 GeV
1/N_trig d²N^pair/dΔη^HCM dΔφ^HCM
Δφ^HCM (radian)
Δη^HCM


ZEUS
√s = 318 GeV
0.5 < p_T < 5.0 GeV
-1.5 < η < 2.0
Q² > 20 GeV²
N_ch ≥ 20
C(Δη, Δφ)
Δφ
Δη

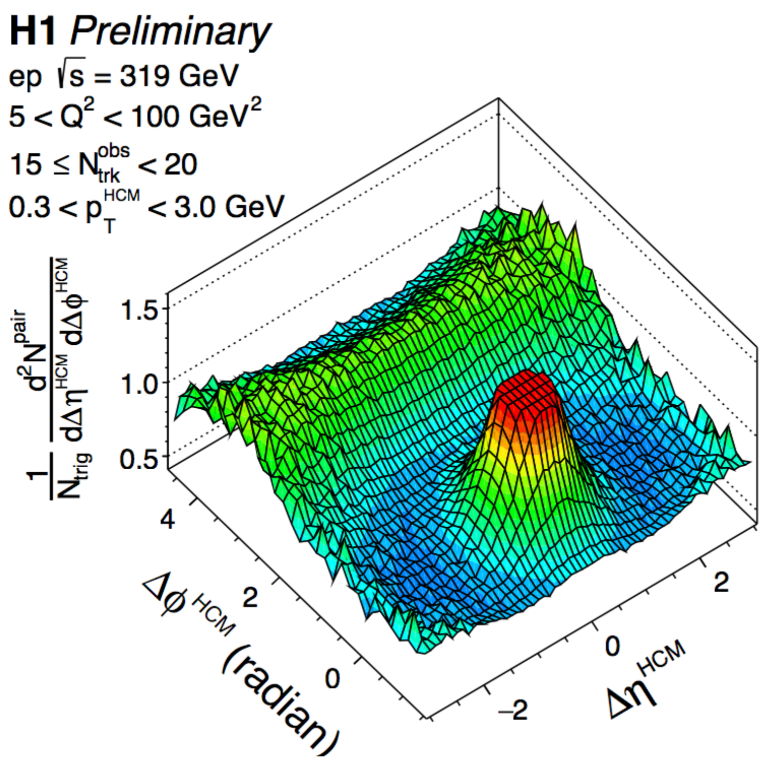
# Ridge in DIS?

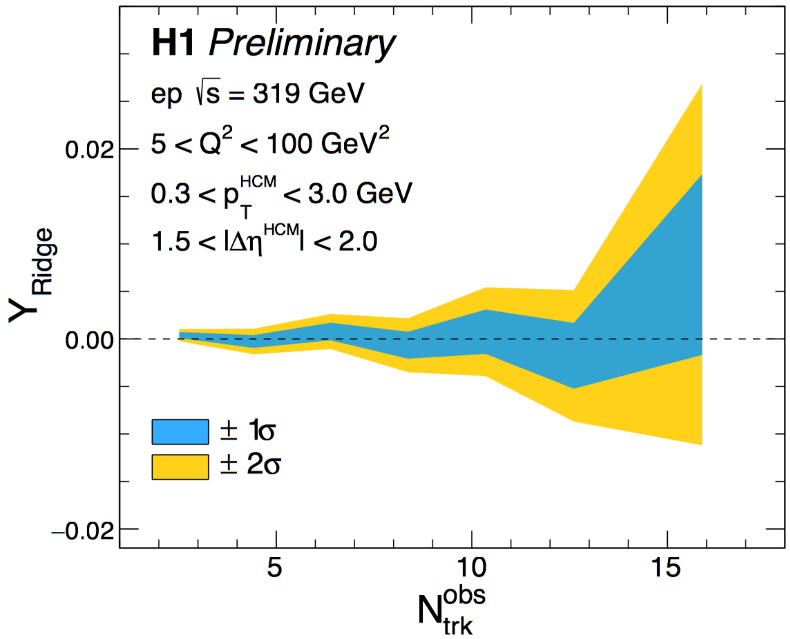


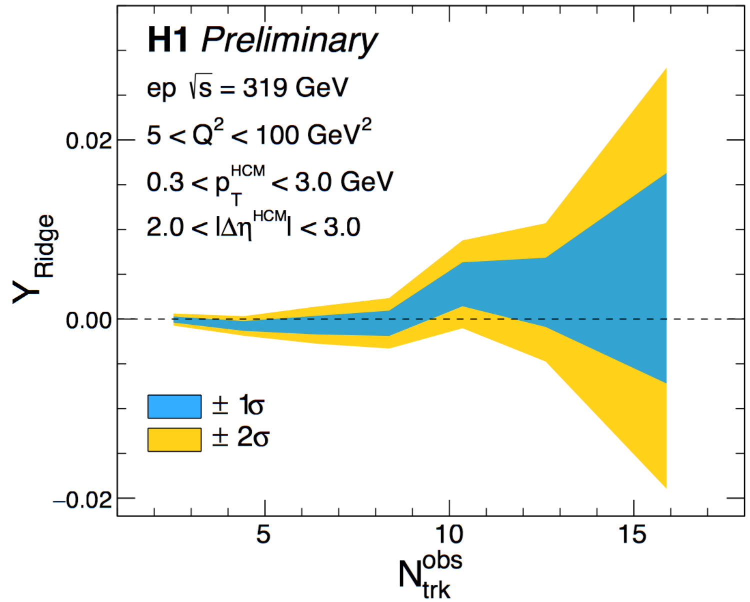

**Near-side ($\Delta\varphi \sim 0$) peak and away-side ridge clearly visible**

**No visible long-range near-side double ridge**

# Ridge in DIS?



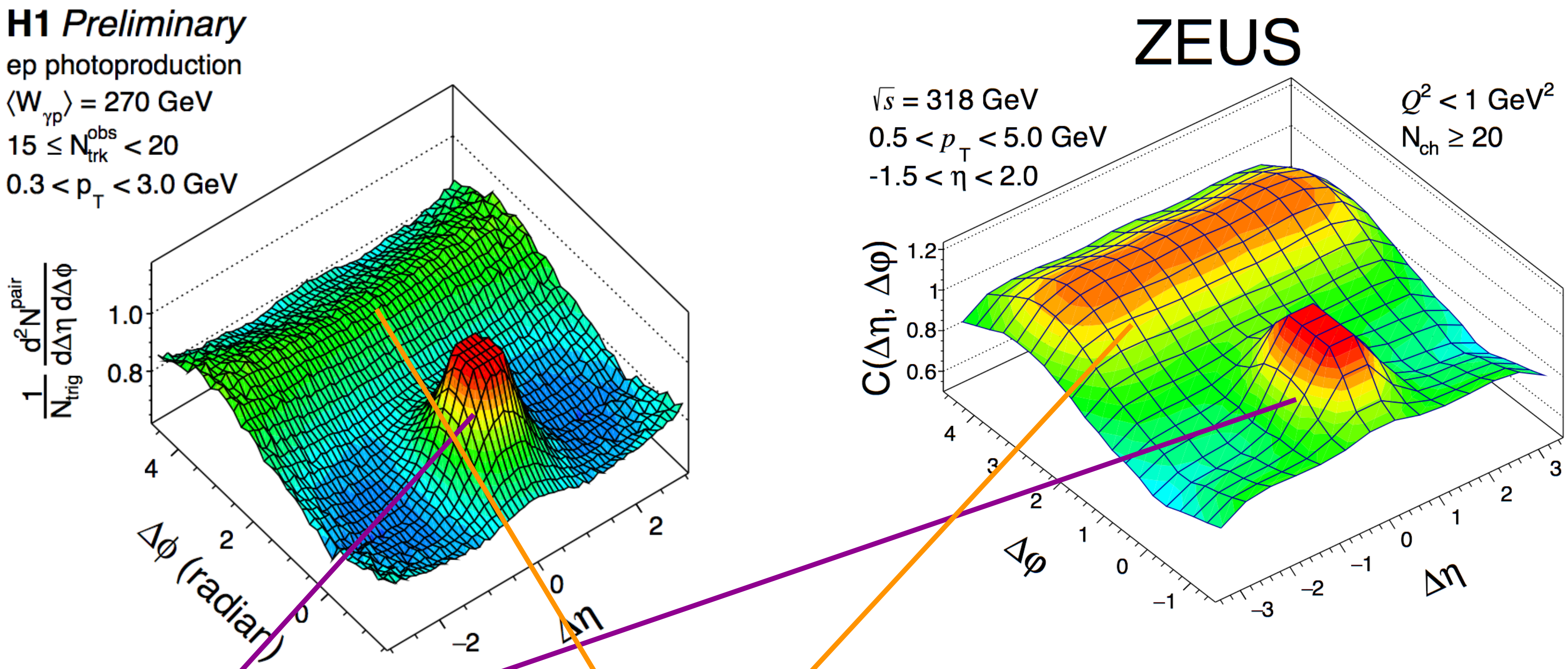




Ridge limits extracted
using a Zero-Yield-At-Minimum assumption
with bootstrap procedure

**→ Limits indicate**
**small room for existence of ridge**

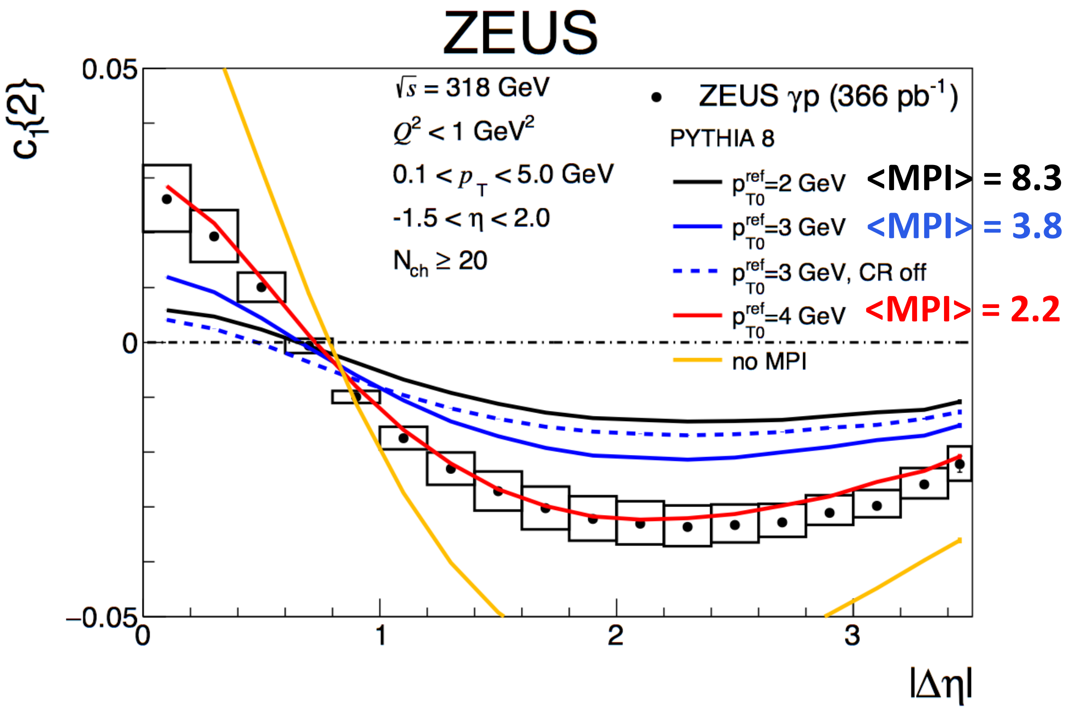
# Ridge in photoproduction?

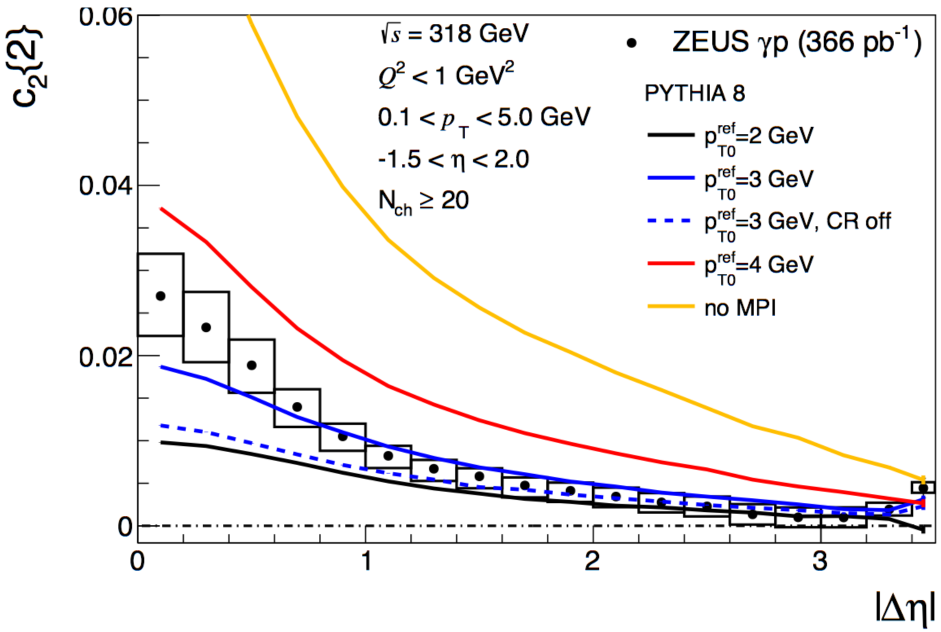



**Near-side ($\Delta\varphi \sim 0$) peak and away-side ridge visible**

**No visible long-range near-side double ridge**

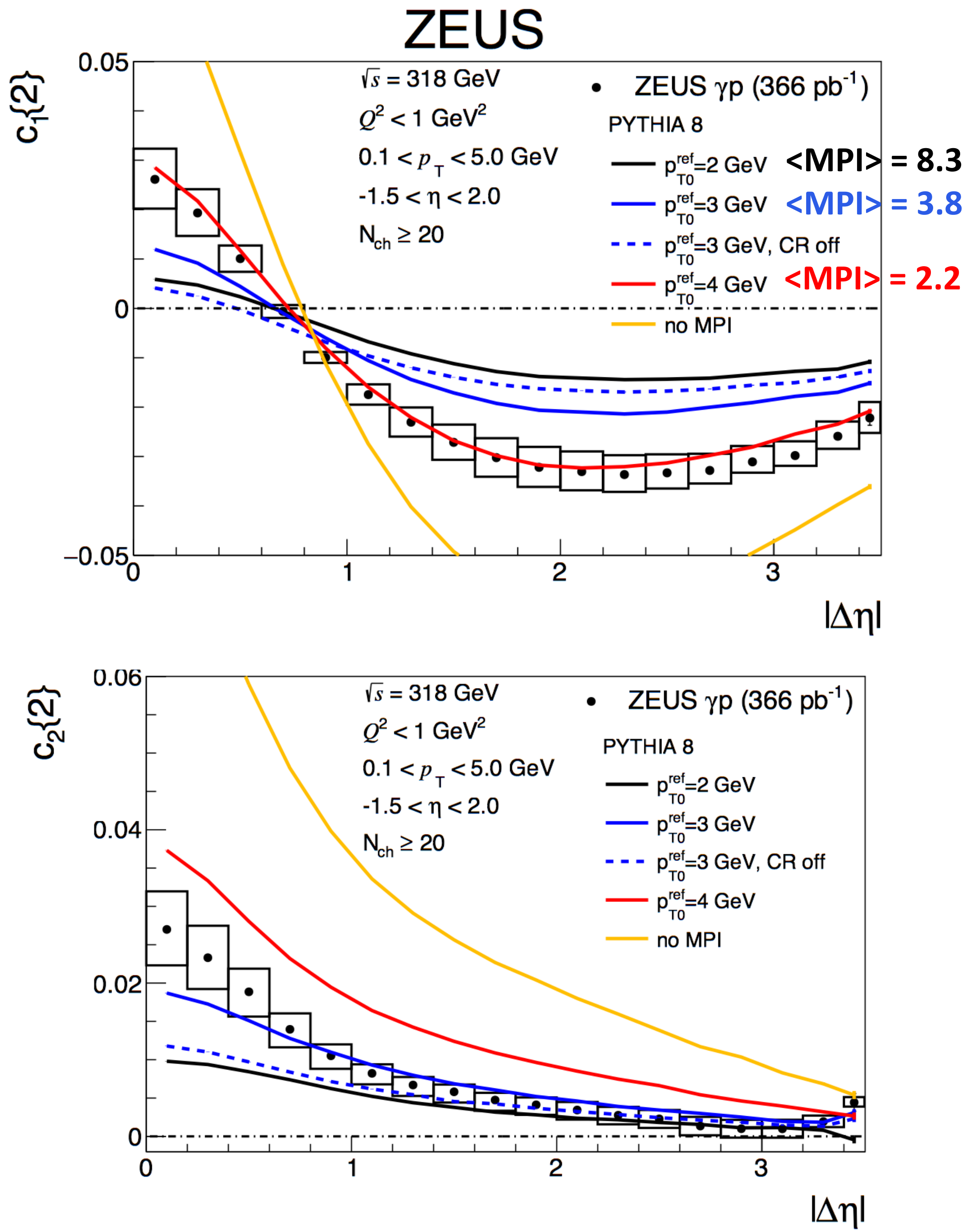
# 2-particle cumulants in photoproduction




**$C_1$ negative much more than $C_2$ is positive, in constrast to heavy-ion collisions**

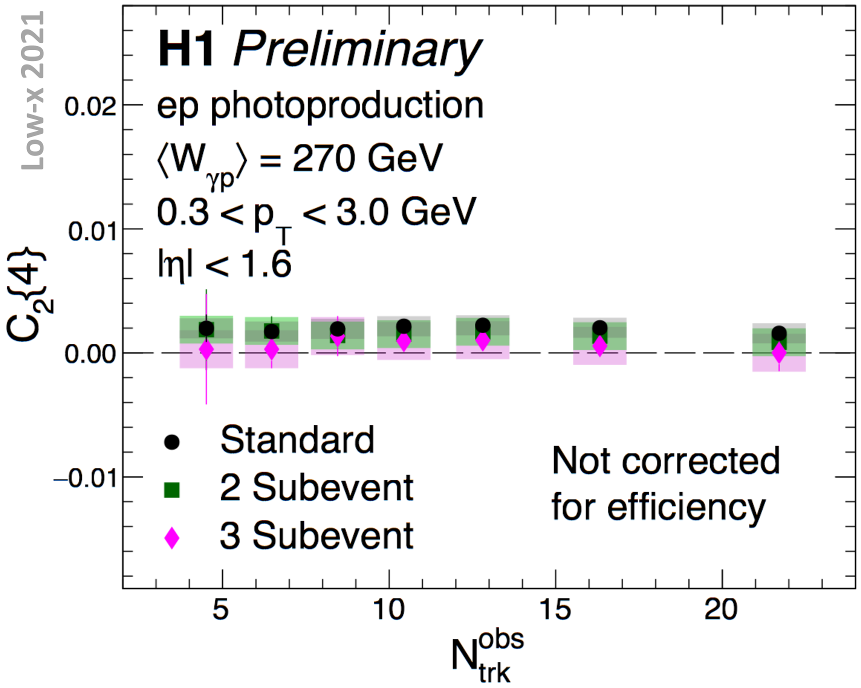
# 2-particle cumulants in photoproduction

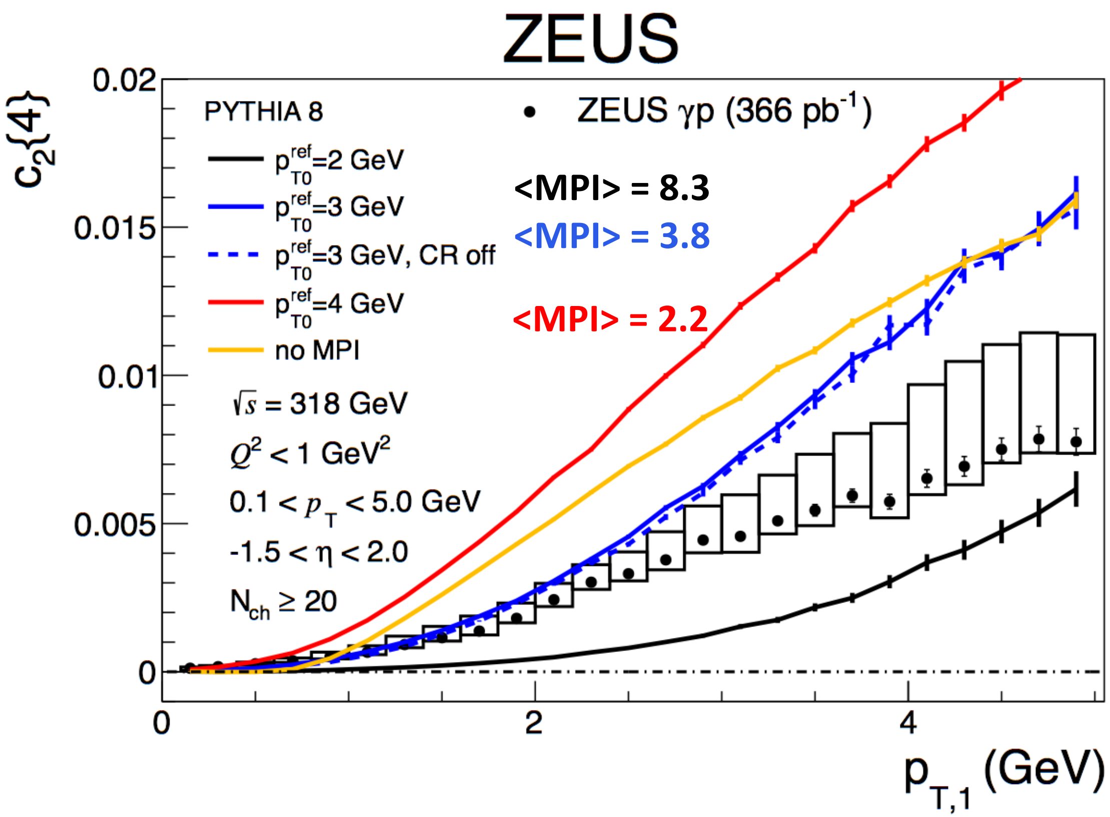



2 → 2 MPI in PYTHIA 8 ranges from 2 to 8

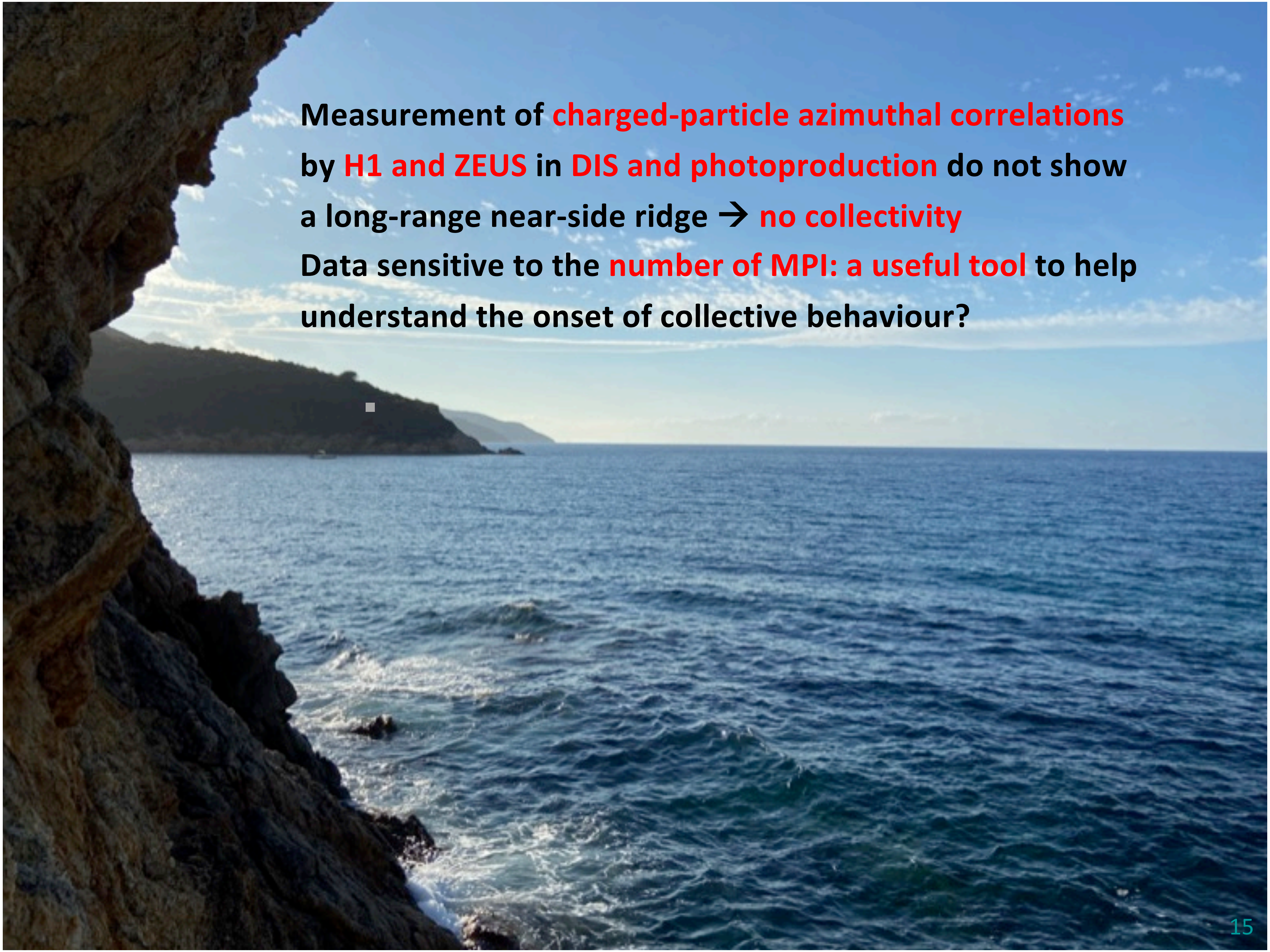
**NO-MPI and many MPI disfavoured**

# 4-particle cumulants in photoproduction




4-particle cumulant is positive, in contrast to heavy-ion collisions



Measurement of charged-particle azimuthal correlations by H1 and ZEUS in DIS and photoproduction do not show a long-range near-side ridge → no collectivity

Data sensitive to the number of MPI: a useful tool to help understand the onset of collective behaviour?

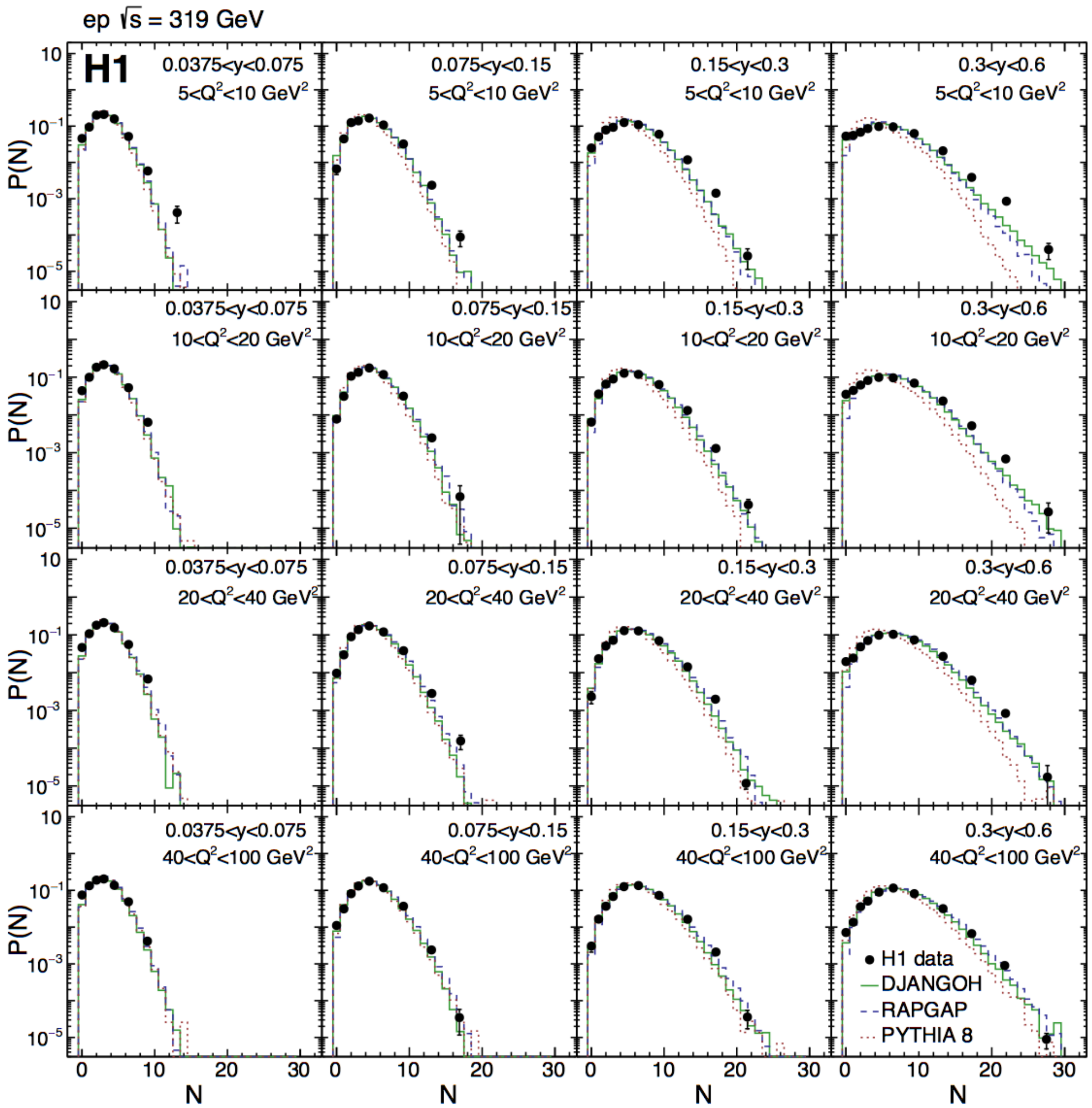
**Charged particle multiplicity and entanglement entropy of partons**

Eur.Phys.J.C81 (2021), 212

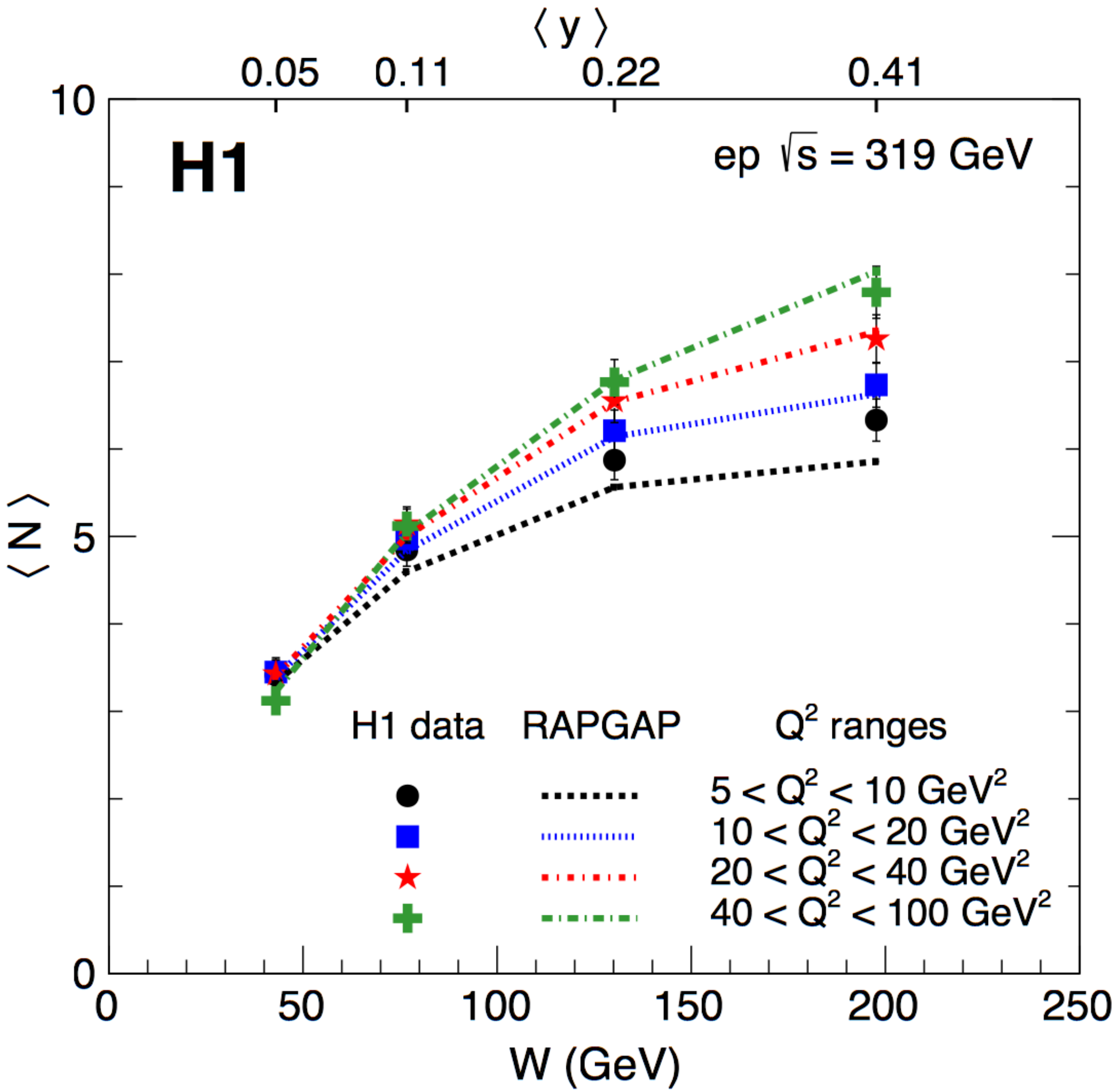
# Multiplicity distributions

Charged particle multiplicity distributions measured on a 4x4 grid in Q2 and y

**MC models underestimate the tails at large N**



# Mean multiplicity as a function of energy



# Entanglement entropy

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

*Theory prediction* **[PRD 95,114008 (2017)]**

$S_{hadron}$ → final state hadron entropy calculated from particle multiplicity distributions

$S_{gluon}$ → entanglement entropy for gluons at low x

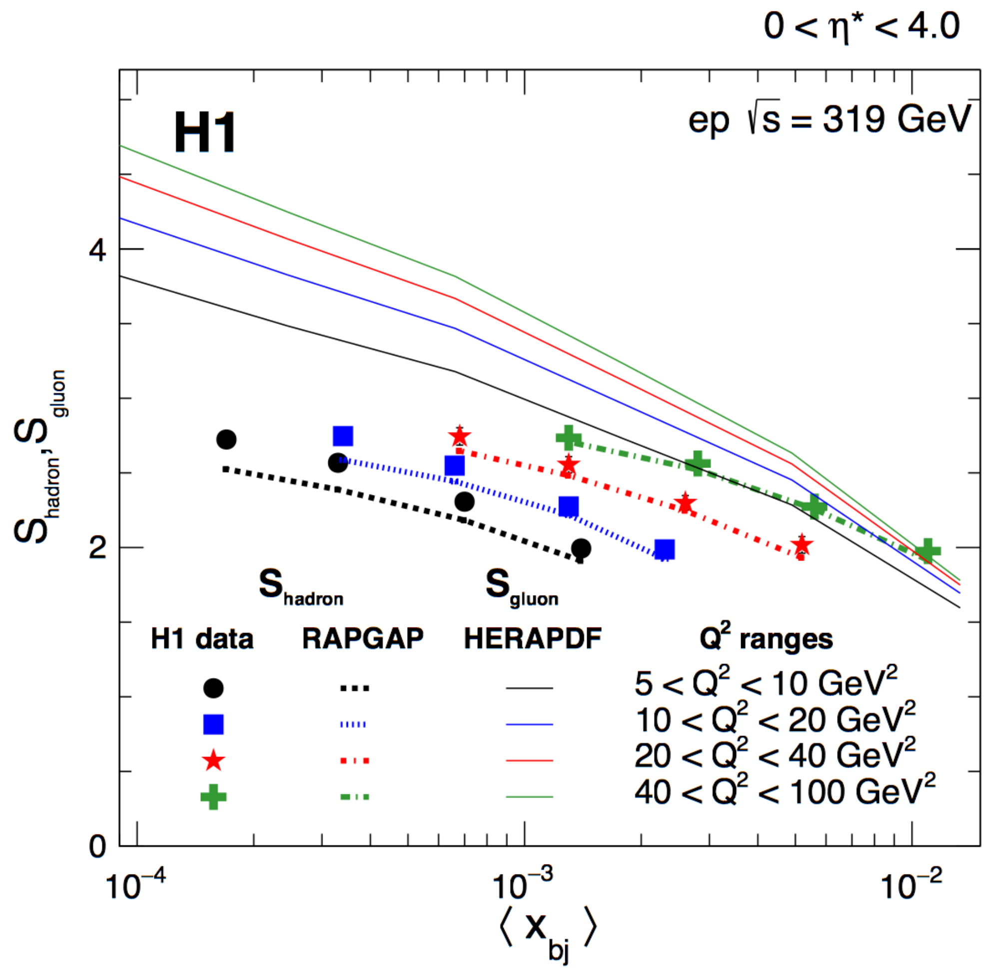
**Are the data compatible with $S_{gluon}$ = $S_{hadron}$ ?**

# Test of quantum entanglement in DIS

**Multiplicity distribution converted to the hadron entropy $S_{hadron}$**

**$S_{gluon}$ from HERAPDFs not compatible with $S_{hadron}$**

*Update in theory:* arXiv:2102.09773



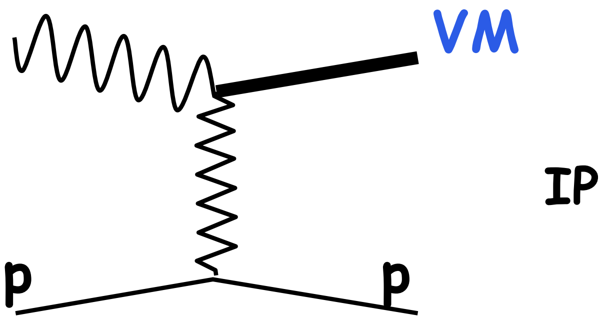
- **Predictions for the entropy of gluons disagree with hadron entropy obtained from multiplicity measurements**

**Exclusive $\pi^+ \pi^-$ and $\rho(770)$ photoproduction**

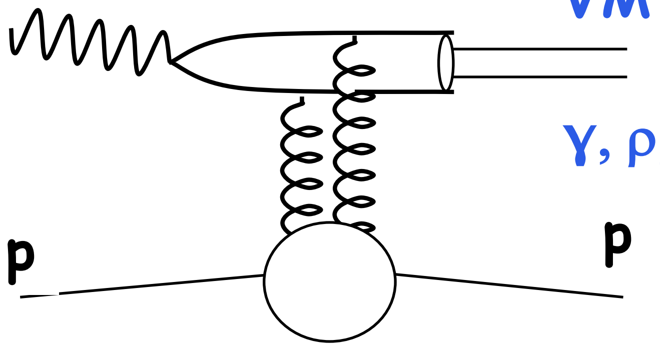
Eur.Phys.J.C80 (2020), 1189

# Transition soft → hard

**Soft - Regge**




**Hard - QCD**

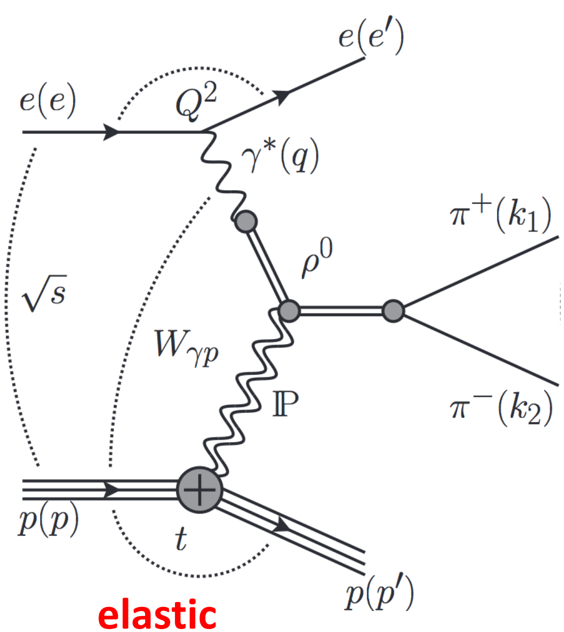



**VM ($J^{PC}=1^{--}$):**

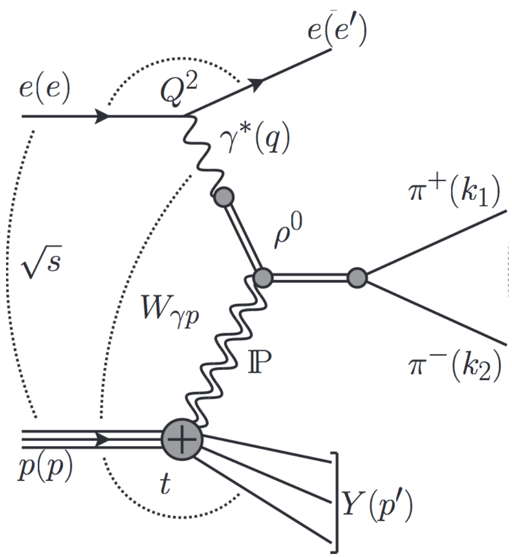
**γ, ρ, φ, J/ψ, Υ,...**

**With increasing scale ($Q^2$, $M_{VM}$, t)**

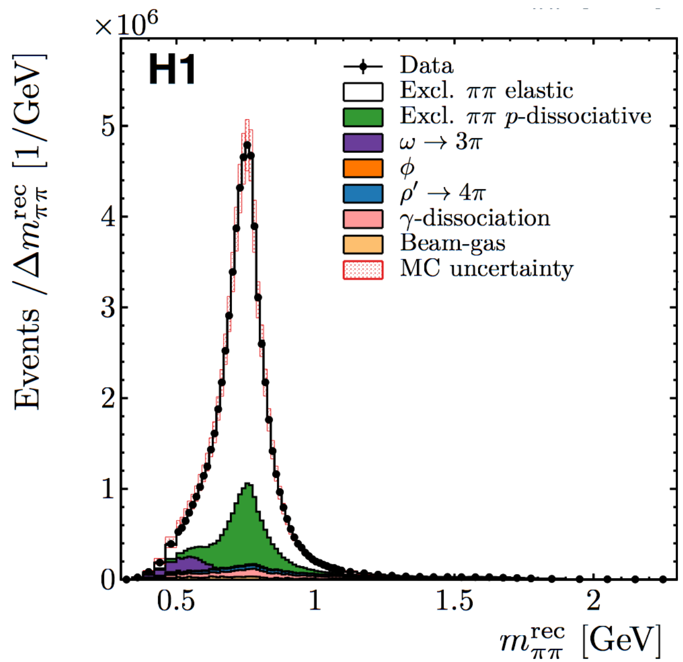
## VM = $\rho^0$




**elastic**

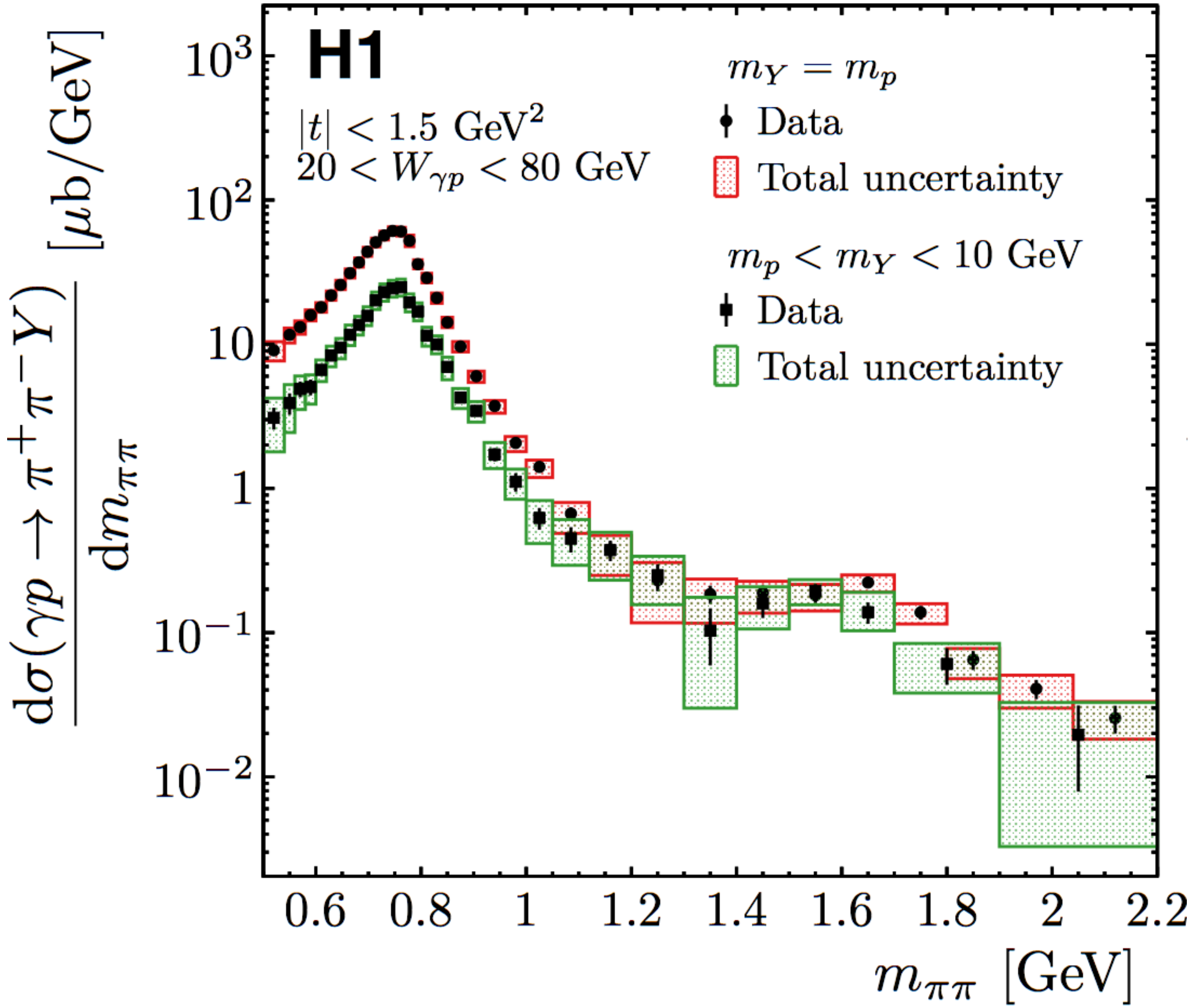



**proton-dissociative (hereafter pdiss)**

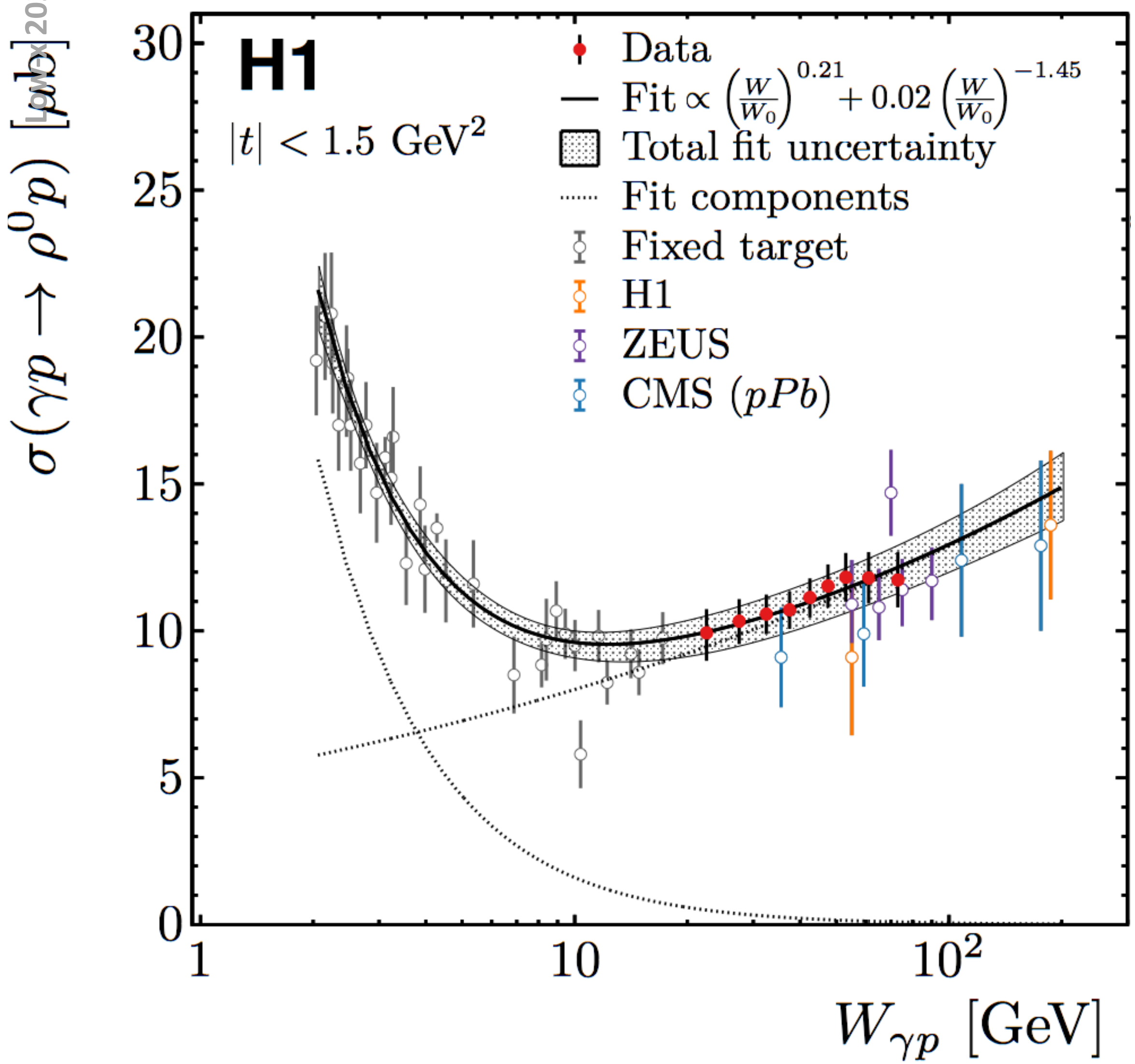


# Differential cross section $d\sigma(\gamma p \rightarrow \pi^+ \pi^- Y)$

elastic and pdiss



# Energy dependence of $\rho^0$ cross section




- **Fit to H1 elastic and pdiss data**

$$\sigma_\rho(W_{\gamma p}) = \sigma_\rho(W_0)\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta}$$

$\delta_{el} = +0.171 \pm 0.009 \ ^{+0.039}_{-0.026}$

$\delta_{pd} = -0.156 \pm 0.026 \ ^{+0.081}_{-0.079}$

- **Simultaneous fit to all elastic data**

$$\sigma_\rho(W_{\gamma p}) = \sigma_\rho(W_0)\left(\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta_{\mathbb{P}}} + f_{\mathbb{R}}\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta_{\mathbb{R}}}\right)$$

$\delta_{\mathbb{P},el} = +0.207 \pm 0.015 \ ^{+0.033}_{-0.033}$

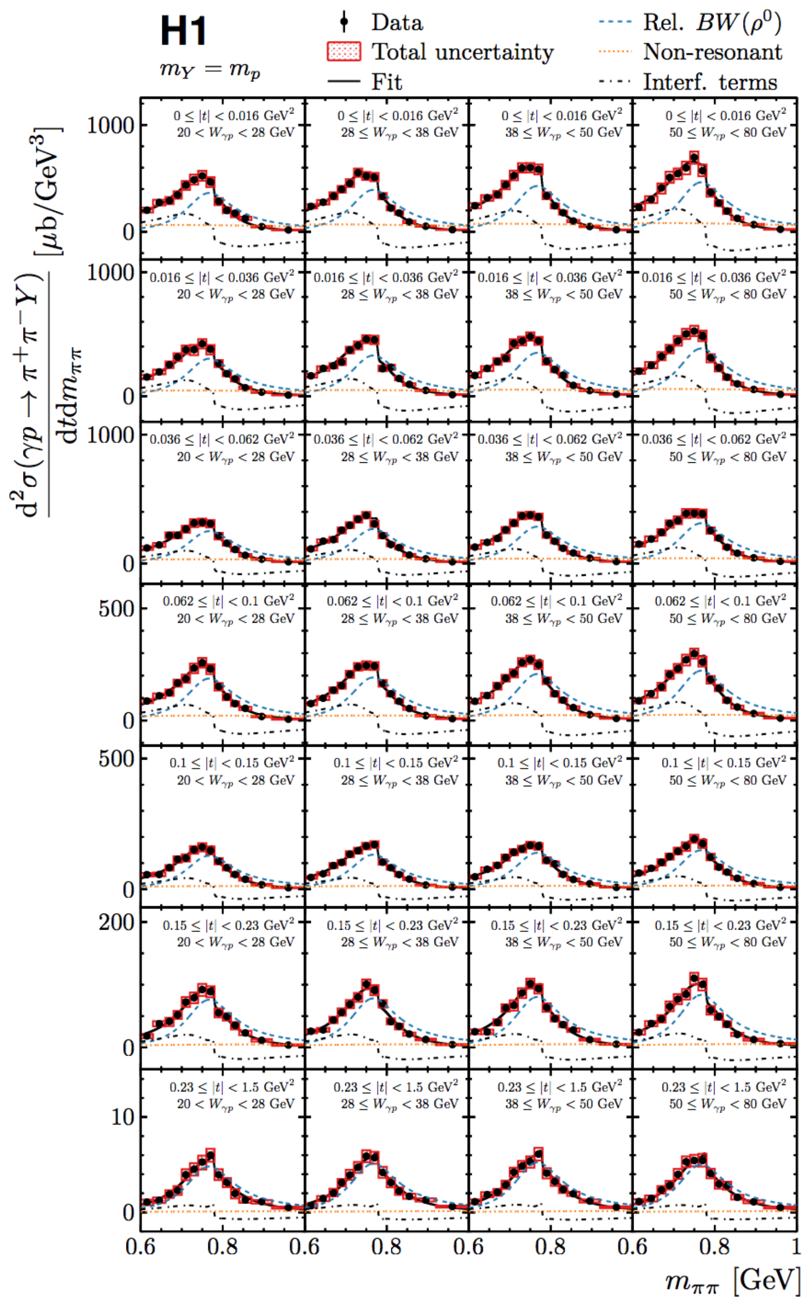
$\delta_{\mathbb{R},el} = -1.45 \pm 0.12 \ ^{+0.35}_{-0.21}$

$f_{\mathbb{R}} = [2.0 \pm 0.7\ (\text{stat.})\ ^{+2.9}_{-1.3}\ (\text{syst.})]\%$

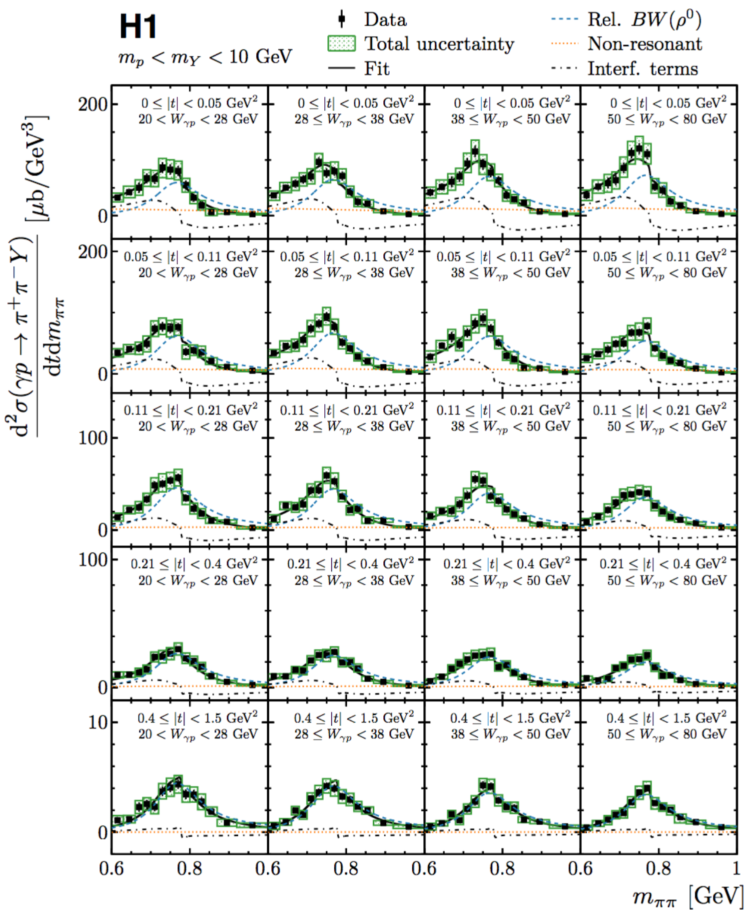
→ **Small IR contribution**

# Double differential cross section dσ(γp→ π⁺ π⁻ Y)

**elastic**

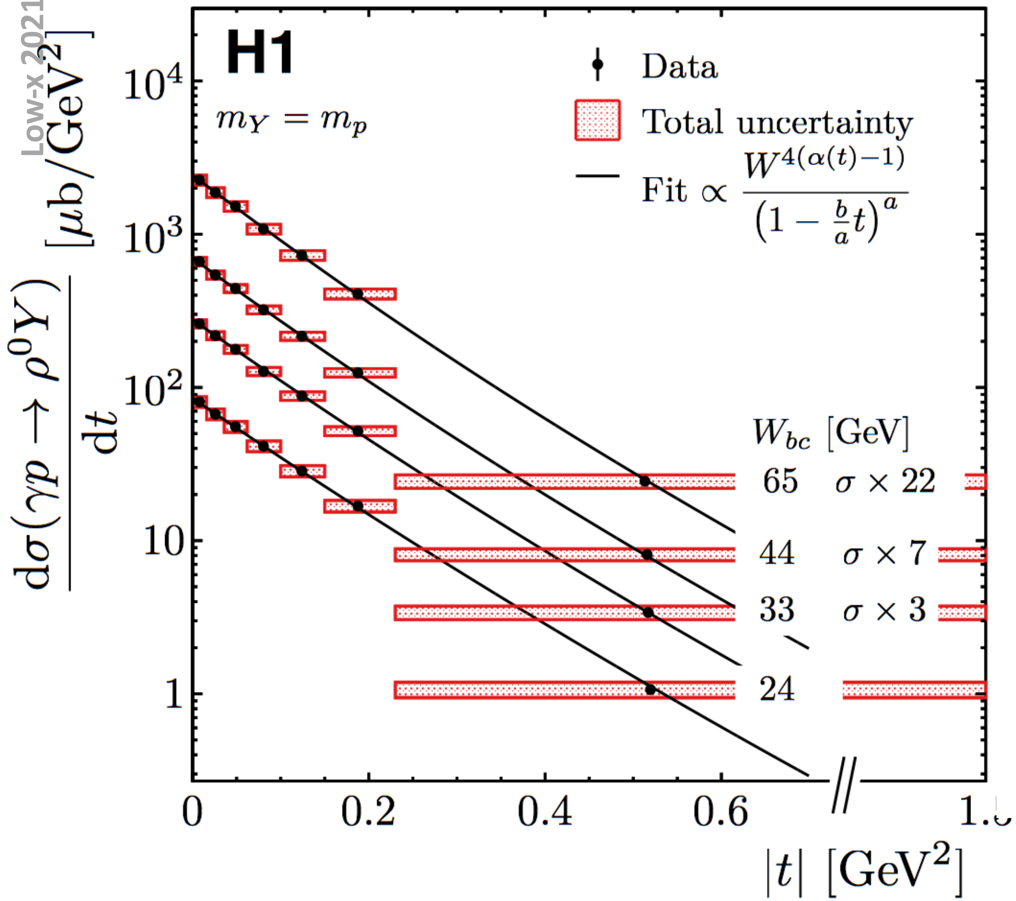



**pdiss**

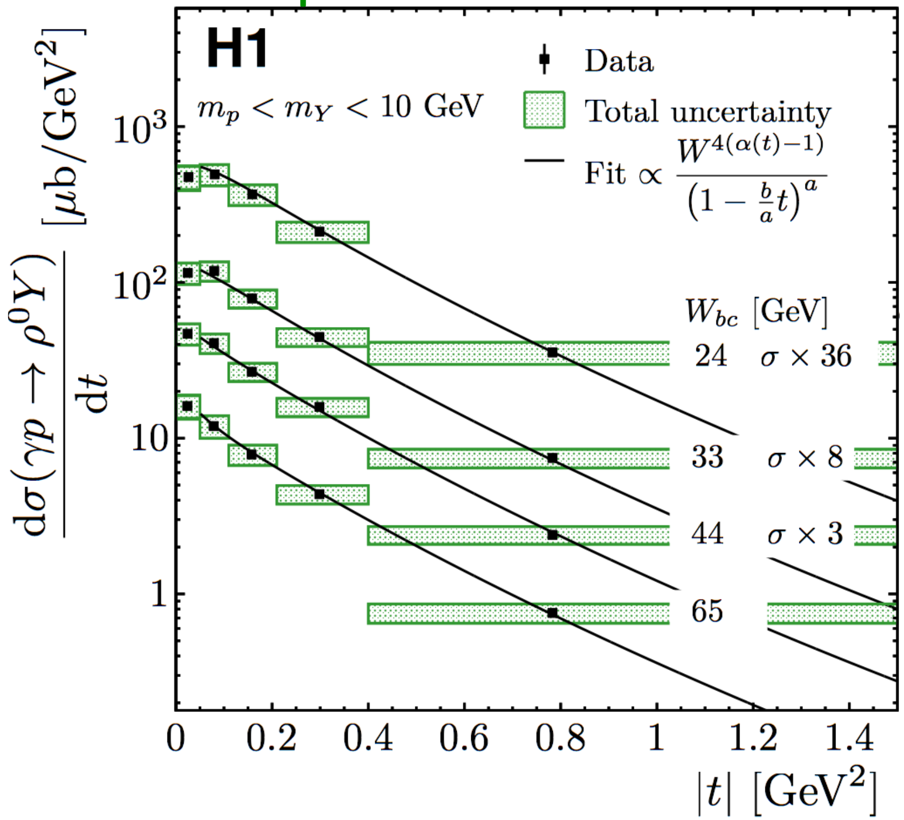


# t dependence of $\rho^0$ cross section

elastic




pdiss




- **Fit t dependence elastic and pdiss simultaneously**

$$\frac{d\sigma_\rho}{dt}(t) = \frac{d\sigma_\rho}{dt}(t=0)\left(1 - \frac{b\,t}{a}\right)^{-a}.$$

$b_{el} = 9.59 \pm 0.10\,^{+0.17}_{-0.12}$ GeV$^{-2}$

$a_{el} = 19.8 \pm 2.7\,^{+4.9}_{-4.7}$

$b_{pd} = 4.79 \pm 0.19\,^{+0.37}_{-0.39}$ GeV$^{-2}$

$a_{pd} = 9.1 \pm 1.5\,^{+3.1}_{-2.4}$

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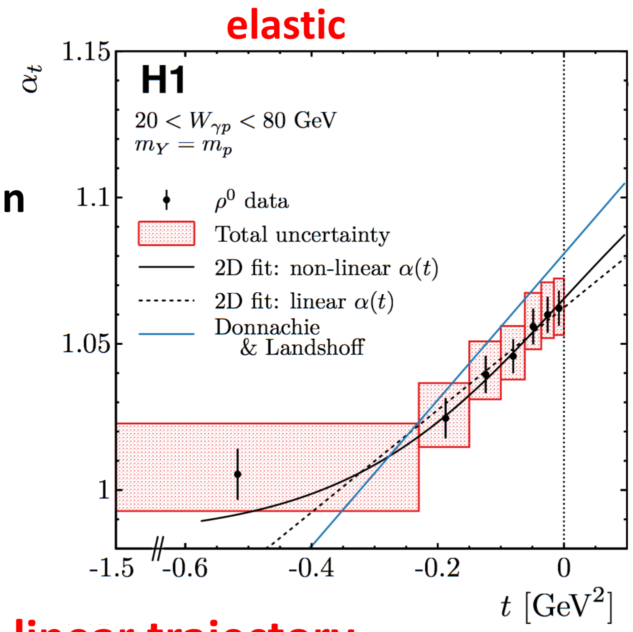
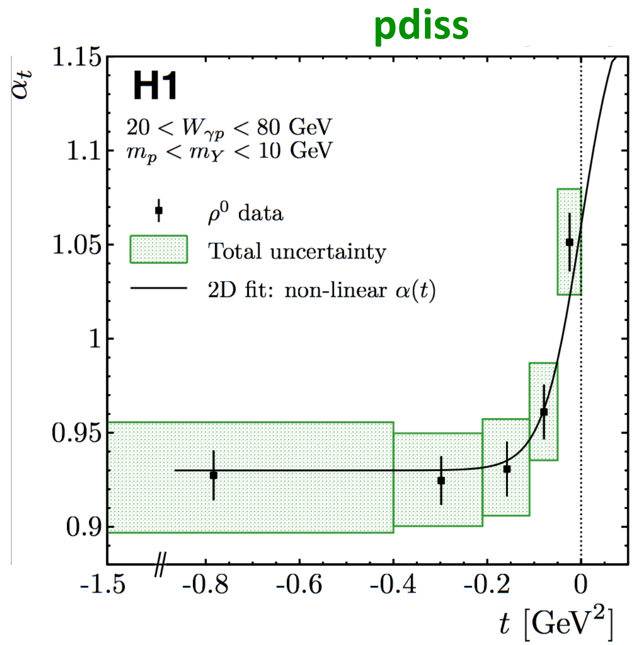
# IP trajectory

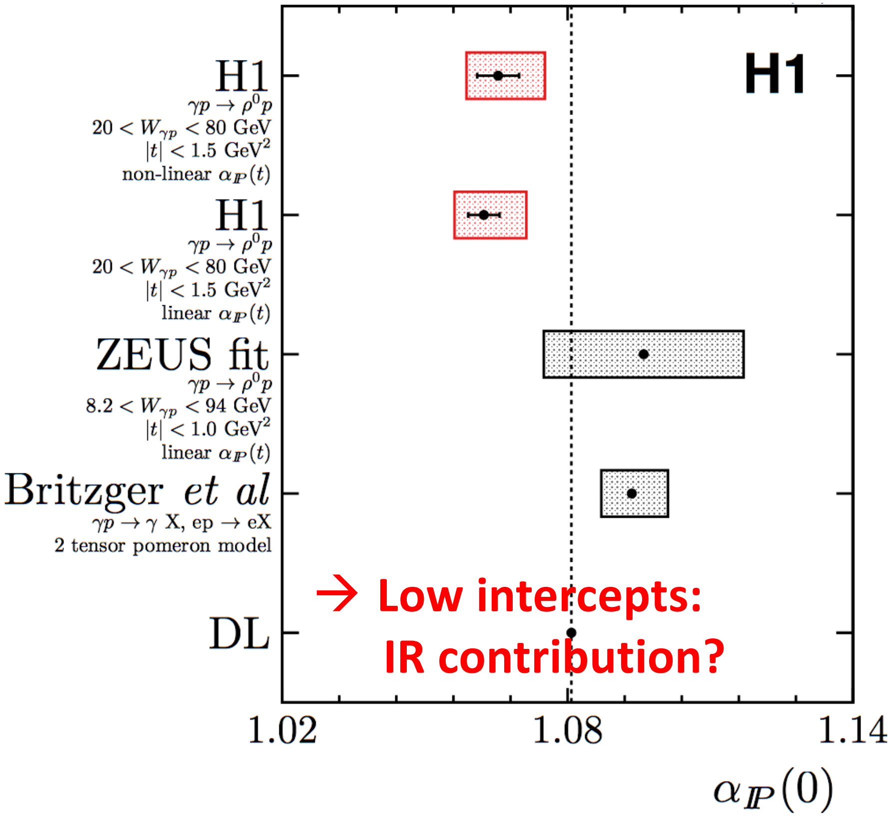
- **Fitting trajectory in each t bin**

$$\alpha(t) = \alpha_0 + \beta\left(\left(e^{-\frac{4\alpha_1 t}{\beta}}+1\right)^{-1} - \frac{1}{2}\right)$$

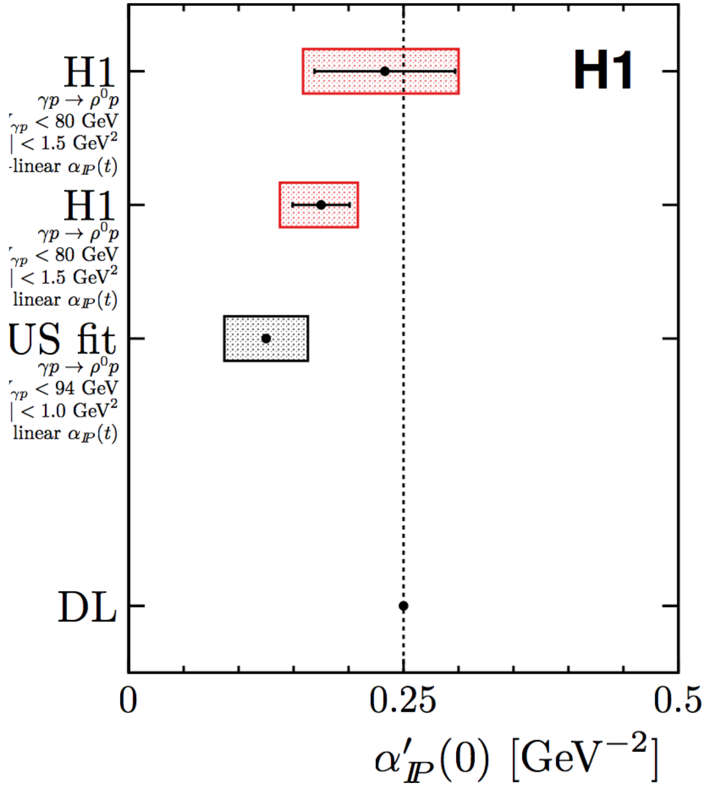


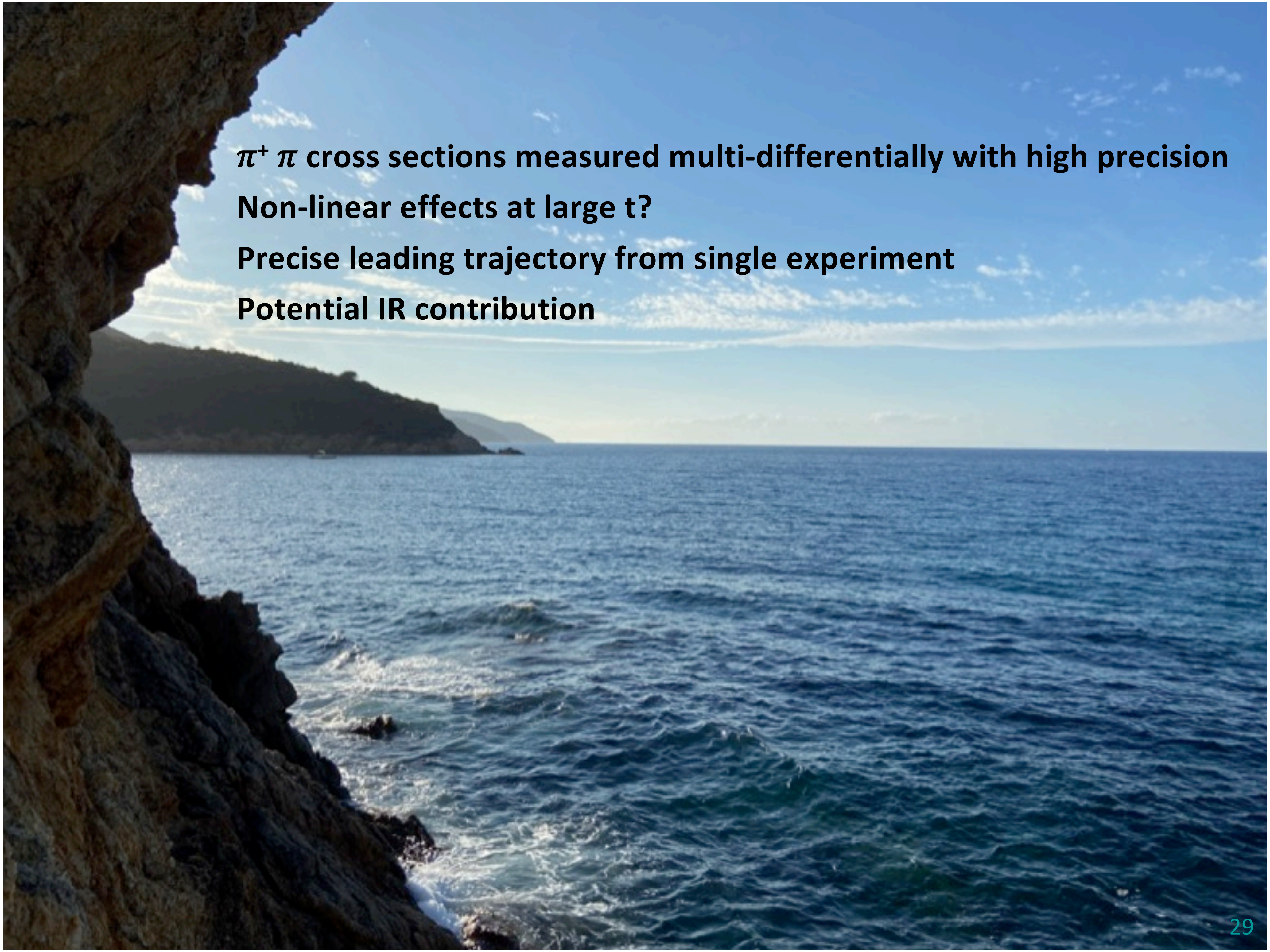




→ pdiss data suggest non-linear trajectory




→ Low intercepts: IR contribution?




$\pi^{+}\,\pi$ cross sections measured multi-differentially with high precision
Non-linear effects at large t?
Precise leading trajectory from single experiment
Potential IR contribution