CMS results on High Multiplicity and Small System

MPI@LHC2022: 13th International workshop on Multiple Partonic Interactions at the LHC

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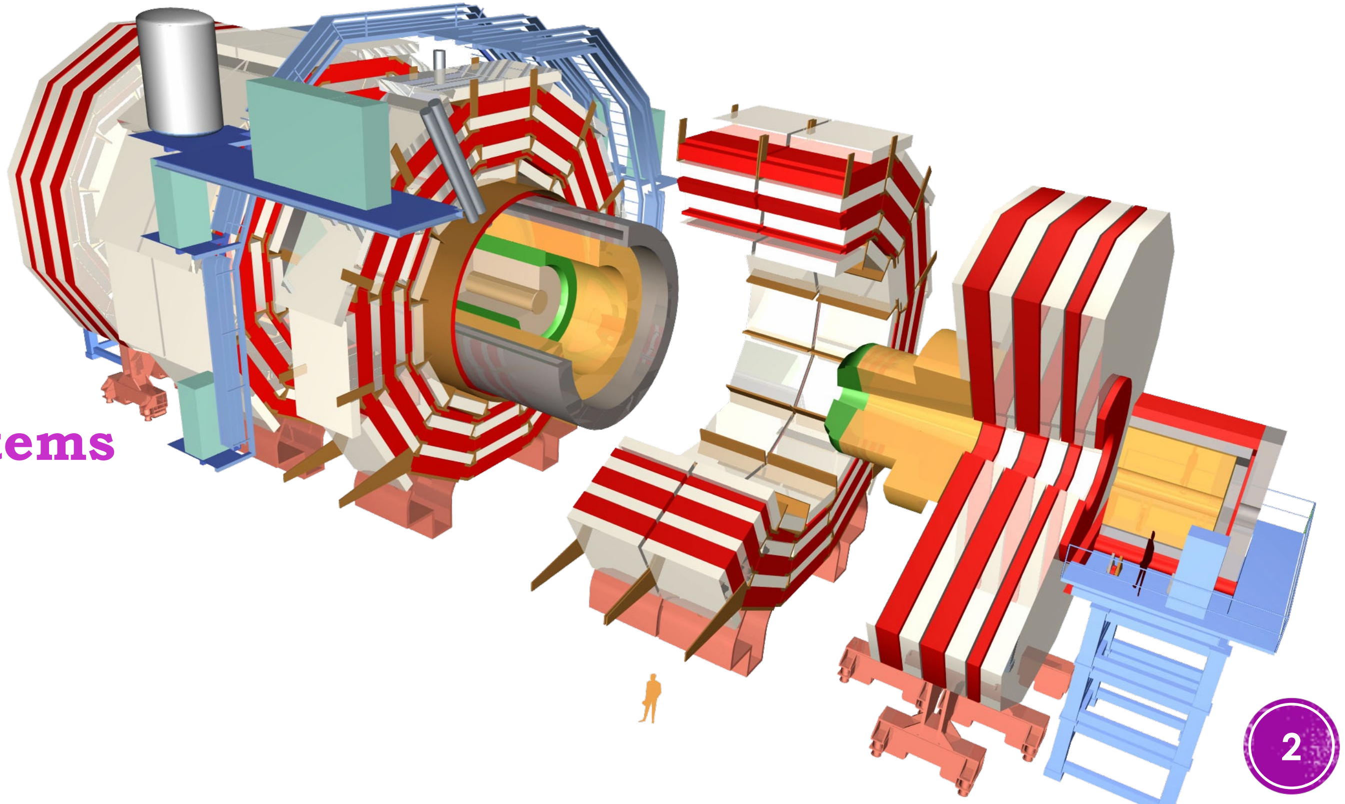
Introduction

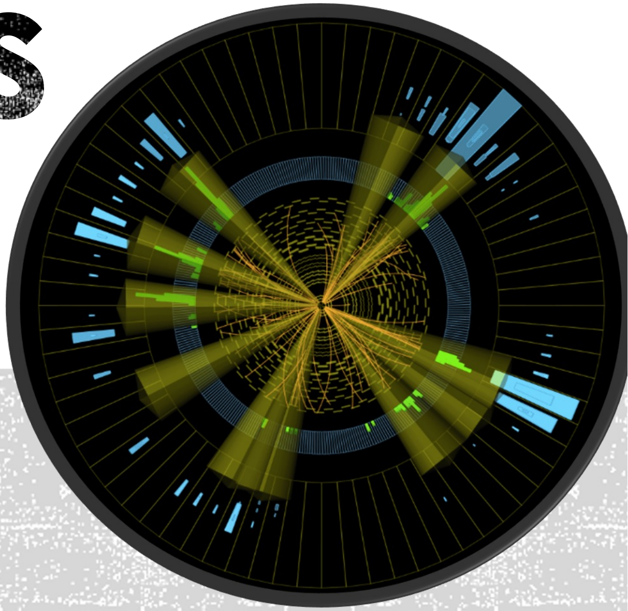
To date, we can take as a truth that **Multi Parton Interaction (MPI) can't be neglected** when describing high multiplicity events.

Experiments at the hadron collider are excelent laboratories for studing QCD and (possible) collectivity effects.



Today, I'll describe the latest results from the CMS Collaboration in **high multiplicity events** and **small systems** from the Run2 of LHC

High multiplicity - MultiJet events



Jet multiplicity in pp collisions

Jet production is described by QCD

- **At LO** two colliding partons from the incident protons scatter and produce two high pT partons in the final state.
  The originating jets are strongly correlated in the transverse plane, and the azimuthal angle difference between them $\Delta\phi_{1,2}$ **should be close to** π
- **Higher-order corrections** to the lowest order process will result in a decorrelation in the azimuthal plane, and $\Delta\phi_{1,2}$ **will significantly deviate from** π.
  These corrections can be due to either hard parton radiation @NLO, or softer multiple parton radiation described by parton showers.

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⇒New measurements of dijet events with rapidity $|y| < 2.5$ and with transverse momenta of the leading jet $p_{T1} > 200$ GeV and the subleading jet $p_{T2} > 100$ GeV, using 2016 data.

The multiplicity of jets with $p_T > 50$ GeV is measured in bins of p_{T1} and $\Delta\phi_{1,2}$.

Jet multiplicity in pp collisions

https://arxiv.org/abs/2210.13557

Generator	PDF	ME	Tune
PYTHIA 8 [23]	NNPDF 2.3 (LO) [25]	LO $2 \to 2$	CUETP8M1 [24]
MADGRAPH+PY8 [4]	NNPDF 2.3 (LO) [25]	LO $2 \to 2, 3, 4$	CUETP8M1 [24]
MADGRAPH+CA3 [4]	PB-TMD set 2 (NLO) [1]	LO $2 \to 2, 3, 4$	—
HERWIG++ [26]	CTEQ6L1 (LO) [27]	LO $2 \to 2$	CUETHppS1 [24]
MG5_aMC+Py8 (jj)	NNPDF 3.0 (NLO) [31]	NLO $2 \to 2$	CUETP8M1 [24]
MG5_aMC+CA3 (jj)	PB-TMD set 2 (NLO) [1]	NLO $2 \to 2$	—
MG5_aMC+CA3 (jjj)	PB-TMD set 2 (NLO) [1]	NLO $2 \to 3$	—

LO Monte Carlo

- Pythia 8 with Tune CUETP8M1 for MPI parametrization
- MadGraph LO & Pythia8 (Tune CUETP8M1) for the showering
- MadGraph LO & Cascade3 for the showering => **no MPI effects simulated**
- Herwig++ with Tune CUEHppS1

NLO Monte Carlo

- MadGraph NLO & Pythia8 (Tune CUETP8M1) for pp->jj
- MadGraph NLO & Cascade3 for pp->jj => **no MPI effects simulated**
- MadGraph NLO & Cascade3 for pp->jjj => **no MPI effects simulated**

Jet multiplicity in pp collisions

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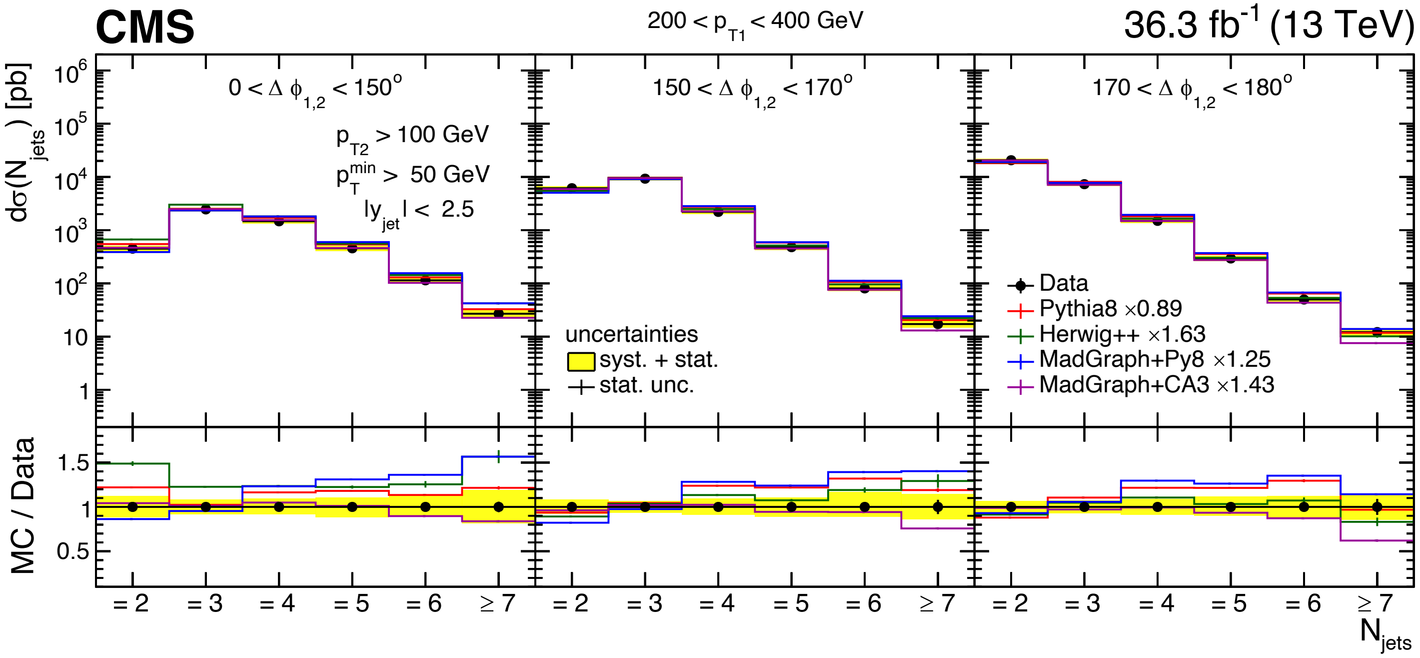
@LO



PYTHIA 8 vs HERWIG++:

- PYTHIA 8 shape is different from data
- HERWIG++ shape agrees better

⇒ Different treatment of in parton shower

MADGRAPH+PY8 vs MADGRAPH+CA3 with additional noncollinear high-pT partons supplemented with different parton showering approaches and MPI are shown

- MADGRAPH+PY8 does not agree in shape
- MADGRAPH+ CA3 prediction does, similarly to HERWIG++

N=2 bin is tricky since it has only high pt boosted dijet, without resolvable jets as recoil
=> many softish emissions to add up to the right recoil needed.
Angular ordering from generators like Cascade or herwig might be not optimal in this case, than rather a less restrictive pt-ordering condition

Jet multiplicity in pp collisions

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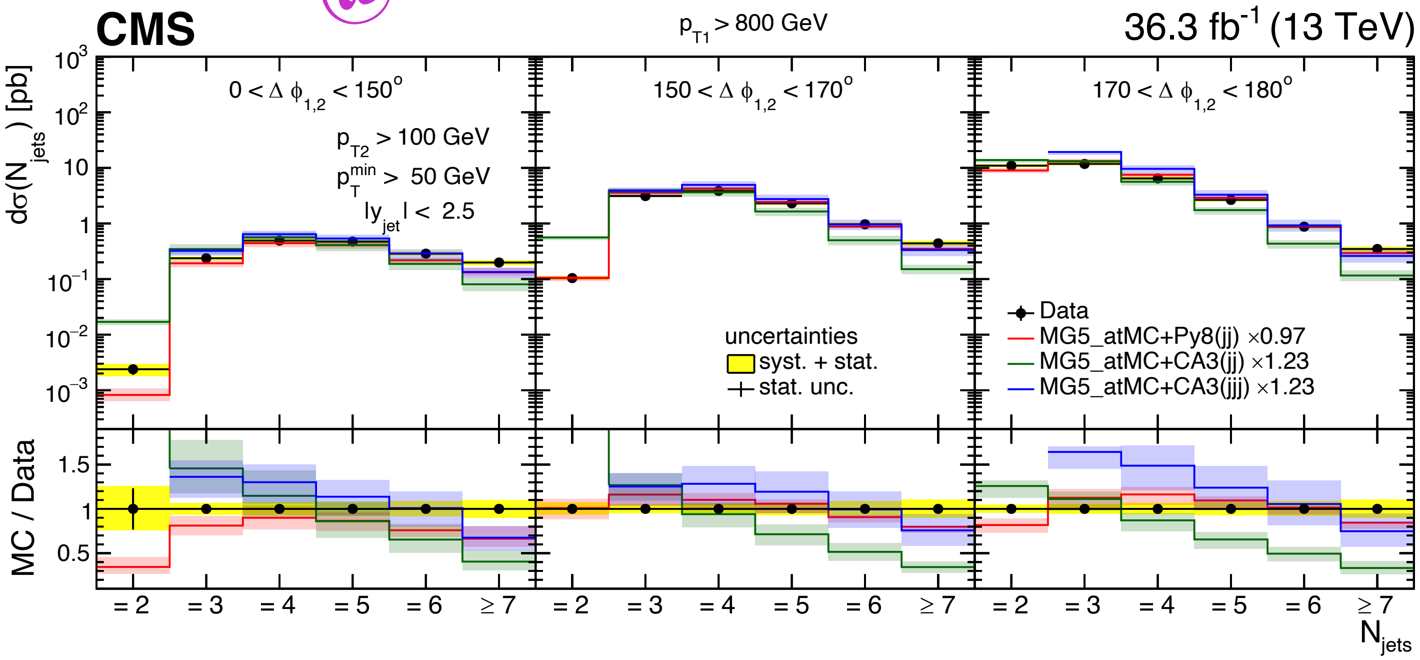
@NLO



Uncertainty bands of the predictions come from the variation of the factorization and renormalization scales by a factor of two up and down

- The normalization of the MG5 aMC+Py8 (jj) calculation is in reasonable agreement with the measured cross section even for 3 jets. For higher jet multiplicities the prediction falls below the measurement.
- MG5 aMC+CA3 (jj) predicts a smaller cross section for more than three jets compared with the measurement.
- The MG5 aMC+CA3 (jjj) NLO calculation (with same normalization factor as for MG5 aMC+CA3 (jj)) predicts a larger three- and four-jet cross section, whereas the higher jet multiplicities are still underestimated

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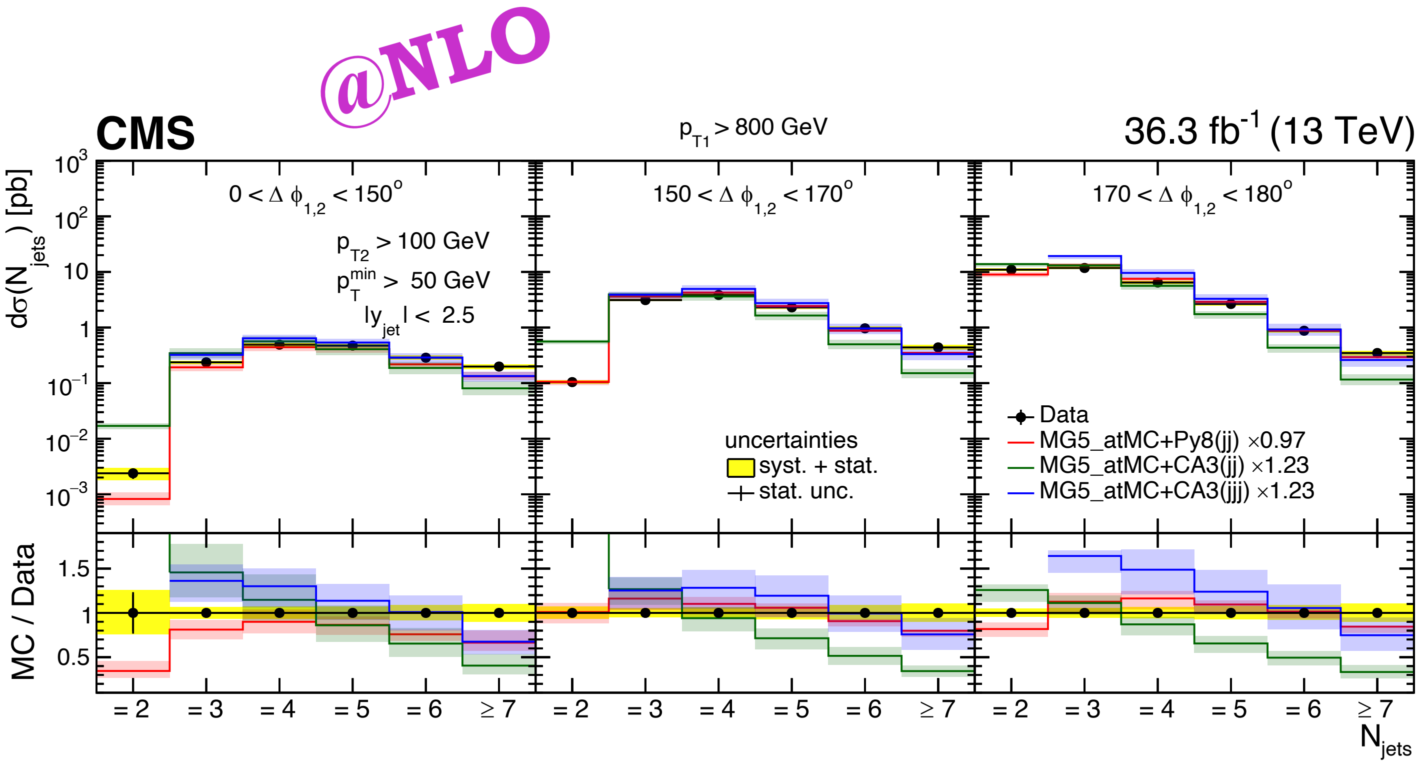

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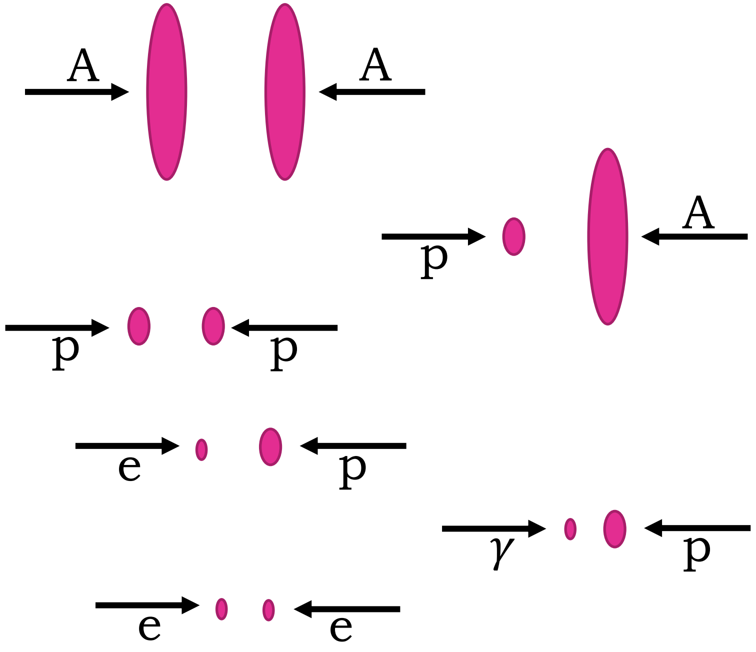
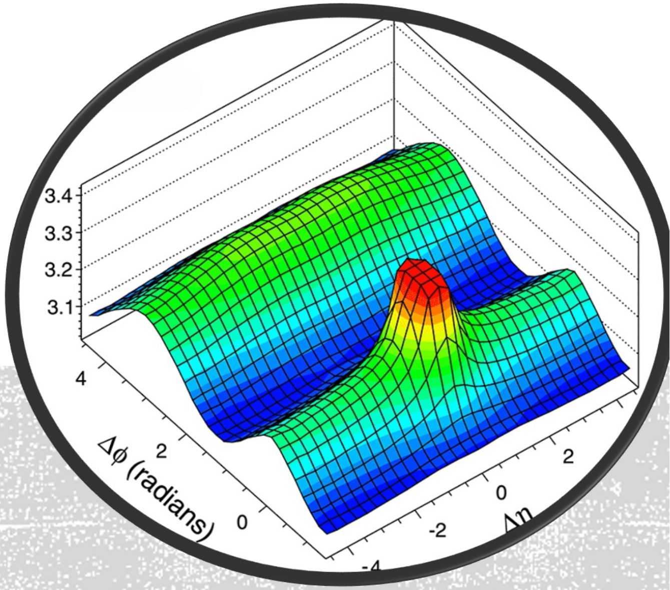
Our predictions still need to be improved for high multiplicity events description!

Collectivity in small system





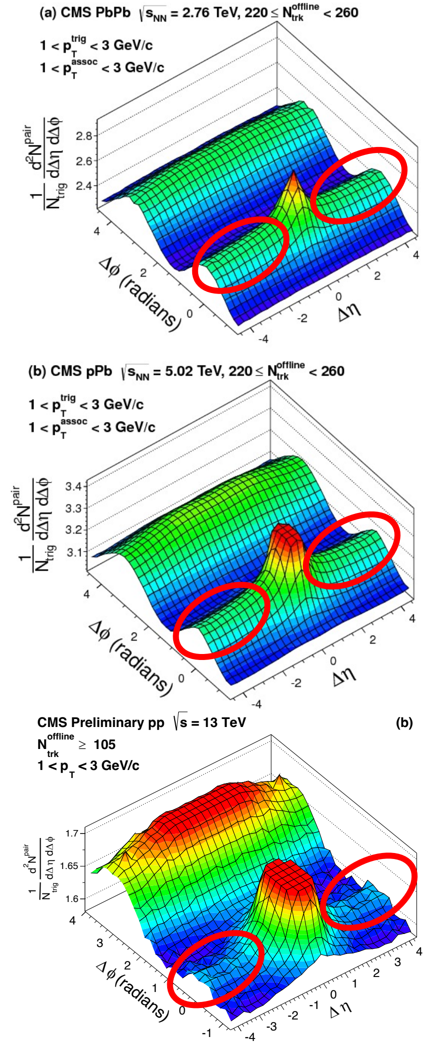
Collectivity in small system

Experimental evidences suggested the **existence of collectivity** in large (A-A) and small (p-A, p-p) systems

⇒ Indication of strongly interacting quark-gluon plasma (QGP)

⇒ Collectivity is observed via the azimuthal correlations of particles that are far apart in rapidity => "**ridge effect**"

The two-particle azimuthal correlations can be characterized by their Fourier components $V_{n\Delta}$.



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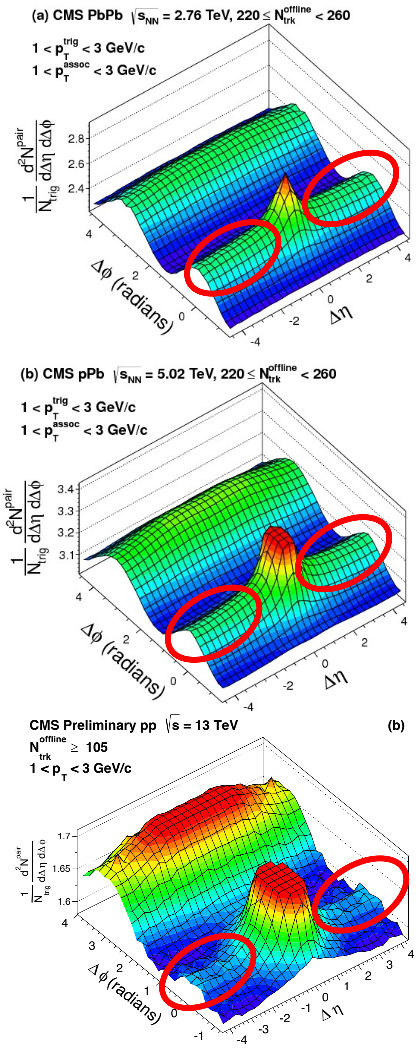
If the two-particle correlations can be factorized into the product of the corresponding single particle azimuthal distributions, the single-particle azimuthal anisotropy Fourier coefficients is $\boldsymbol{v_n = \sqrt{V_{n\Delta}}}$

- v_2 is the elliptic flow
- v_3 is the triangular flow

$\Big\}$ directly related to the initial collision geometry



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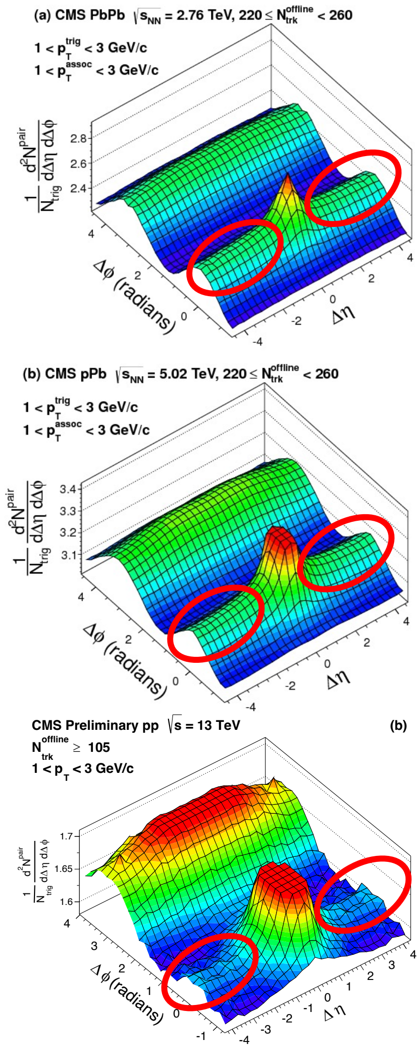


In high-multiplicity events, v_2 and v_3 depend on hadron species and scale with the number of valence quarks => **common origin of the collectivity** seen in PbPb and in high-multiplicity pp and pPb events

Collectivity in small system

Two-particle azimuthal correlations in γp interactions with pPb collisions

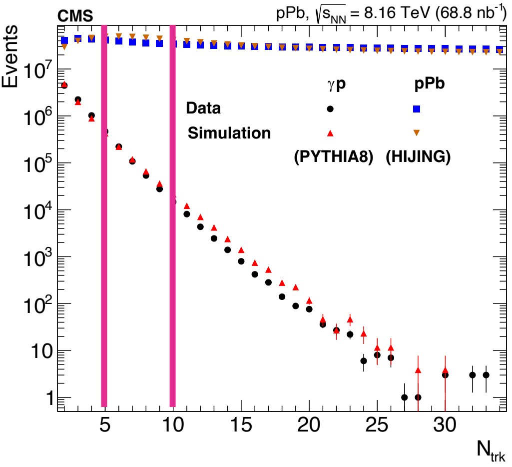
- Pb generate a large quasi-real photon flux, ideal to study long-range correlation in γp collisions (E_γ~80 GeV)
- Complementary to ep two particle correlation measured by ZEUS,
  γp collisions used for the first time to study long-range particle correlation!
- The γp results are compared to both hadronic minimum bias pPb collisions and MC predictions

Studies of charm and beauty hadron long-range correlations in pp and pPb collisions

- Measurements of v_2 of the azimuthal distributions of prompt & nonprompt D^0 in pp and pPb collisions
- v_2 for open beauty extracted for the first time via nonprompt D^0 mesons in pPb collisions.
- Elliptic flow observed already in PbPb and AuAu && recently in pPb
  => **charm develop significant collective behavior** via their strong interactions with the bulk of QGP.

Two-particle azimuthal correlations in γp interactions

https://arxiv.org/abs/2204.13486



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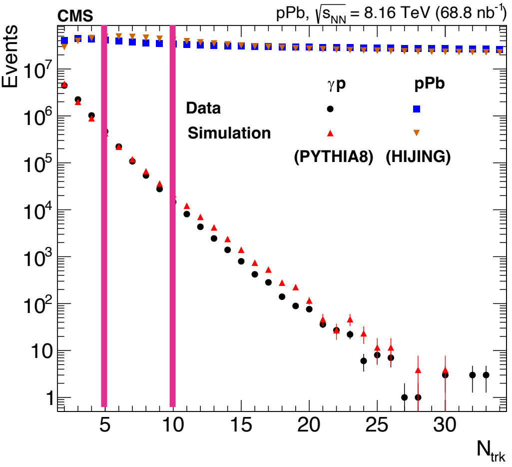
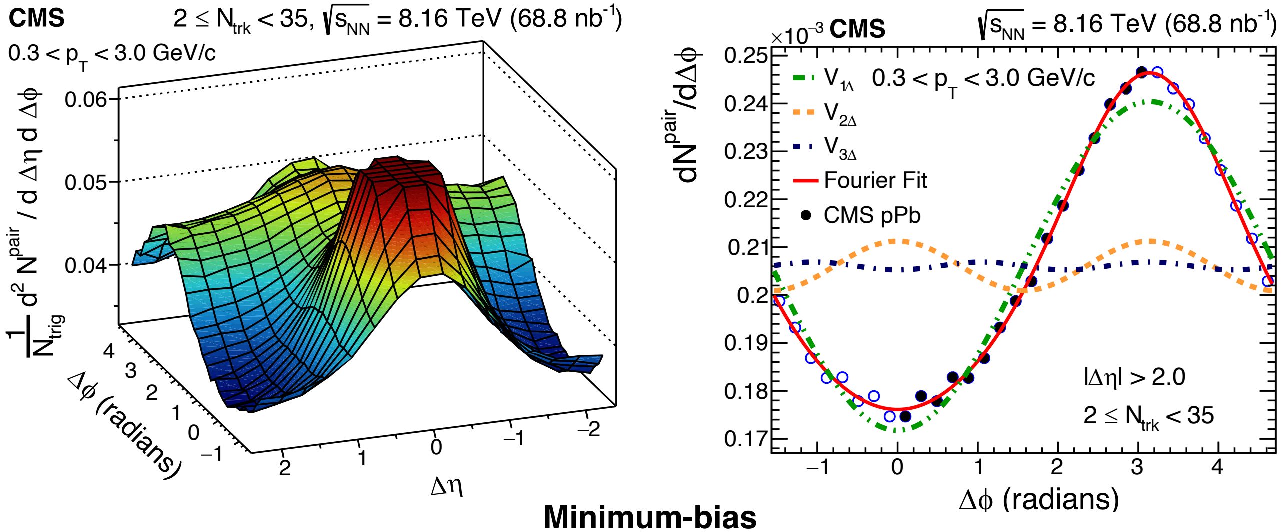


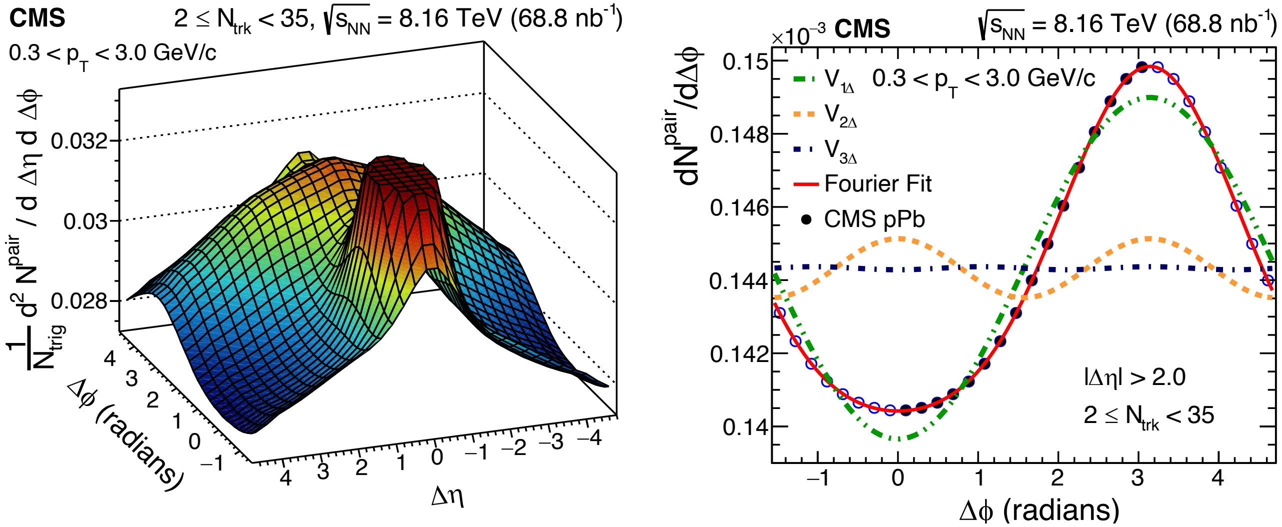
2D correlation function

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

γp enhanced



Minimum-bias



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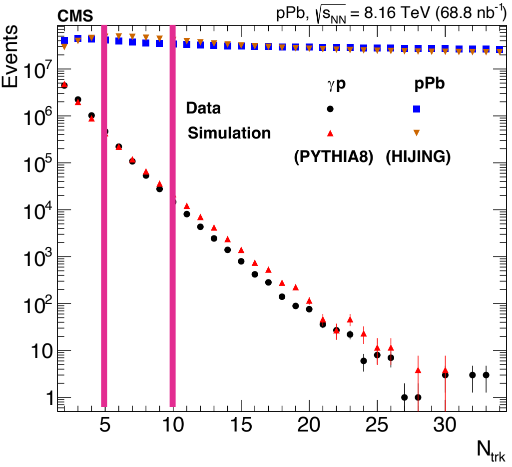

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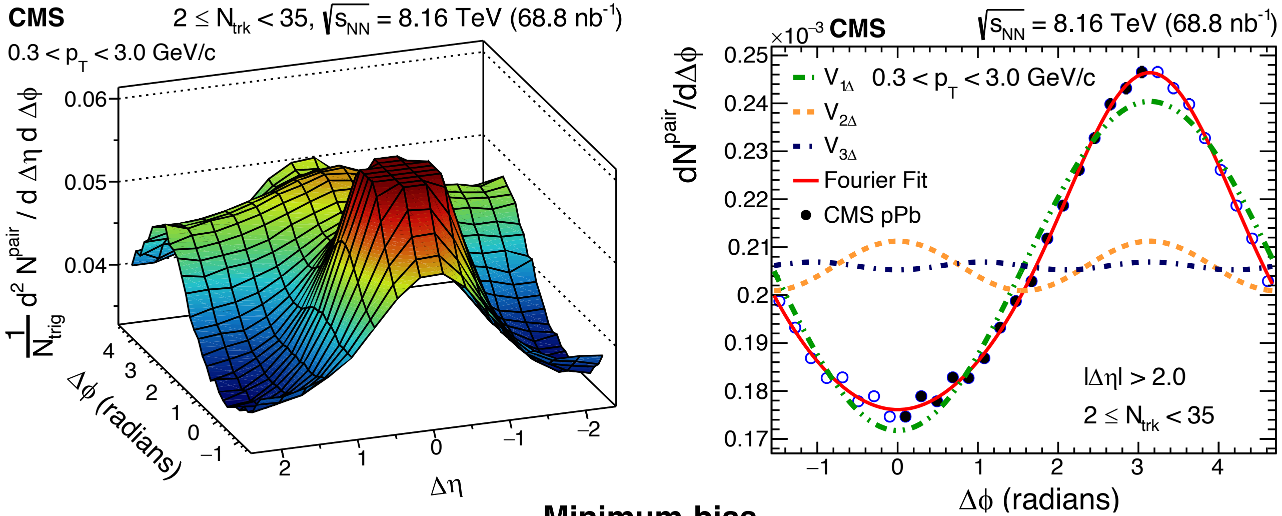

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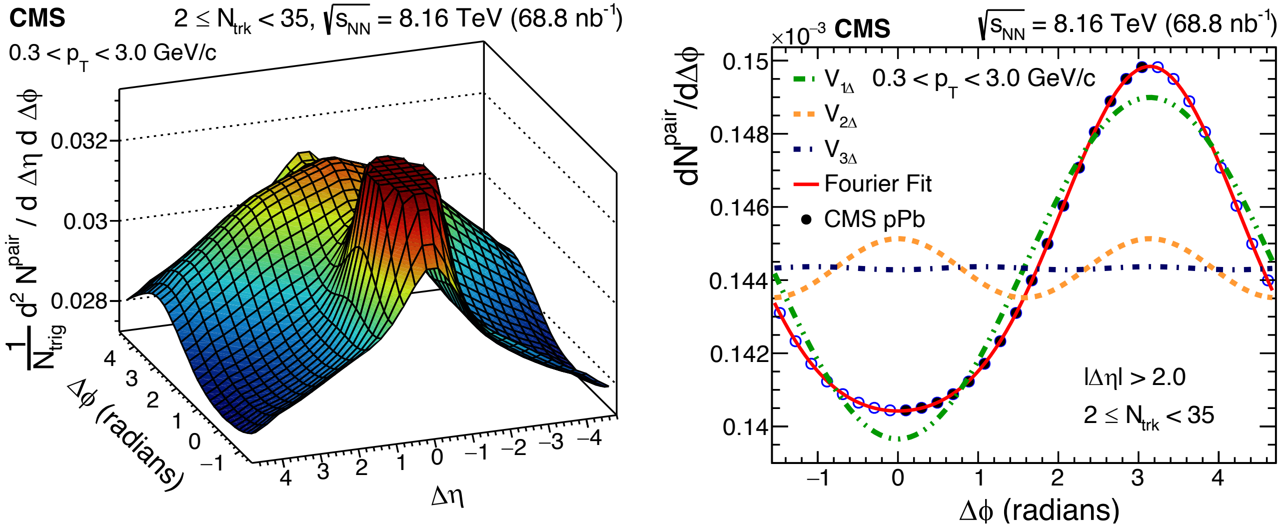

No “ridge”-like structure appears at $|\Delta\phi|$~0 for $|\Delta\eta|$ > 2

1D correlation -> Fourier fit is shown taking into accounts the first three terms of the Fourier expansion $\propto 1 + \sum_n 2V_{n\Delta}$

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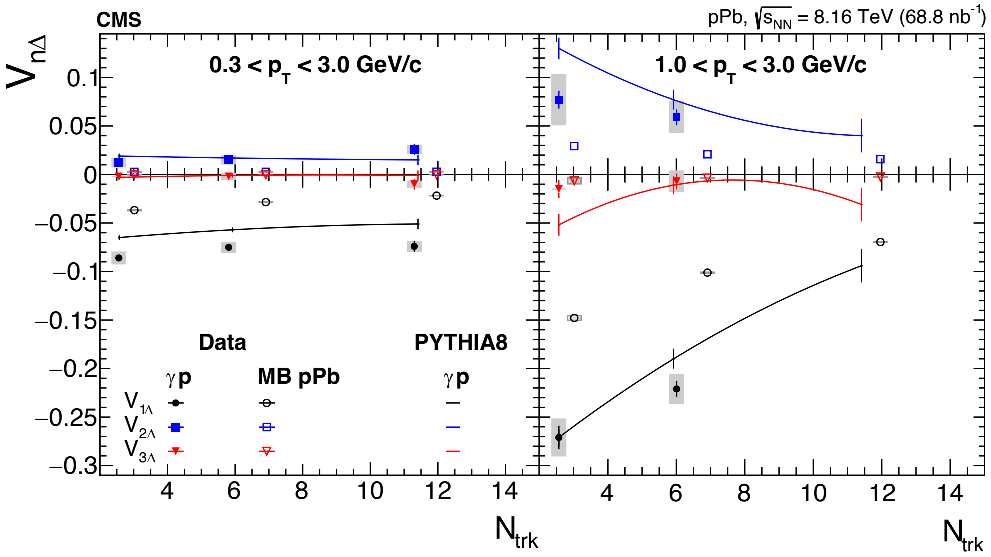

Measured $V_{n\Delta}$ **coefficients as a function of N_{trk}**:

$V_{1\Delta}<0$, $V_{2\Delta} > 0$ (with smaller magnitude than $V_{1\Delta}$) and $V_{3\Delta} \sim 0$. For a given N_{trk} and p_T range, both $V_{1\Delta}$ and $V_{2\Delta}$ are larger in γp than in MB. Magnitude of $V_{1\Delta}$ and $V_{2\Delta}$ increase with pT => also in e-p collisions.

$\Rightarrow$ predictions from PYTHIA8 in γp collisions well reproduce $V_{2\Delta}$ and $V_{3\Delta}$, while are smaller in magnitude for $V_{1\Delta}$

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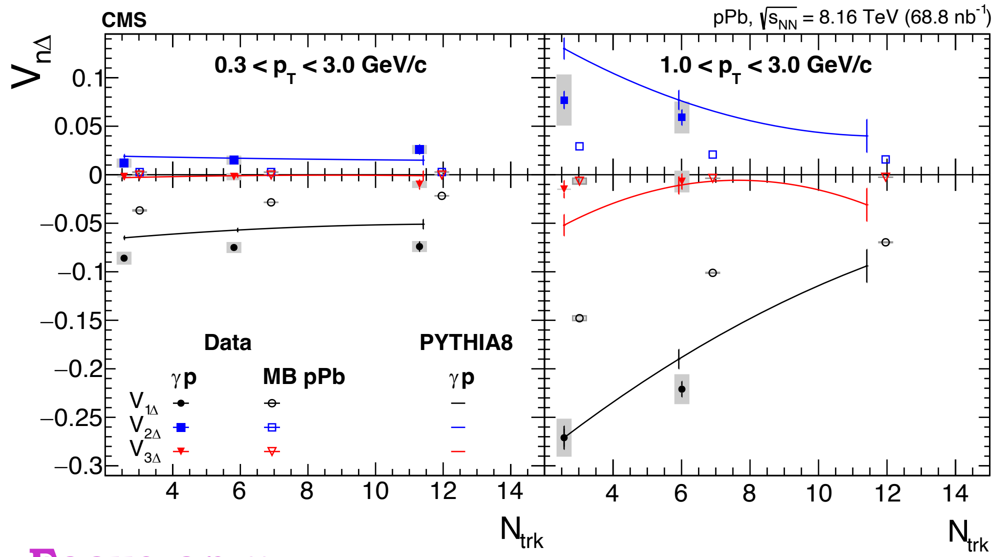

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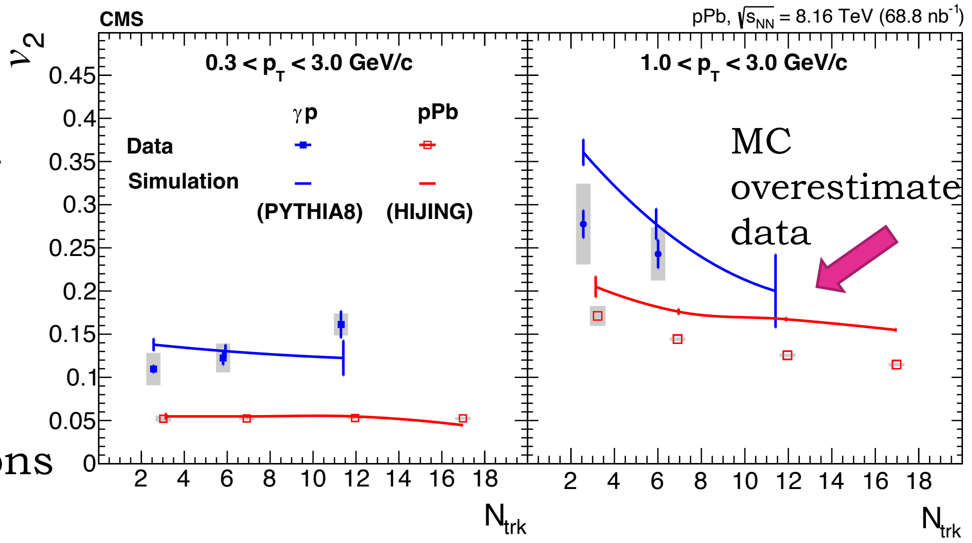
Focus on v_2 :
PYTHIA8 and HIJING predictions shown => no collective effects included.

For both data and simulations, v_2 varies slowly with track multiplicity

At a given p_T and N_{trk}, v_2 is higher for γp than for pPb interactions

At a given N_{trk}, v_2 is larger in the higher p_T range => similar in e-p collisions



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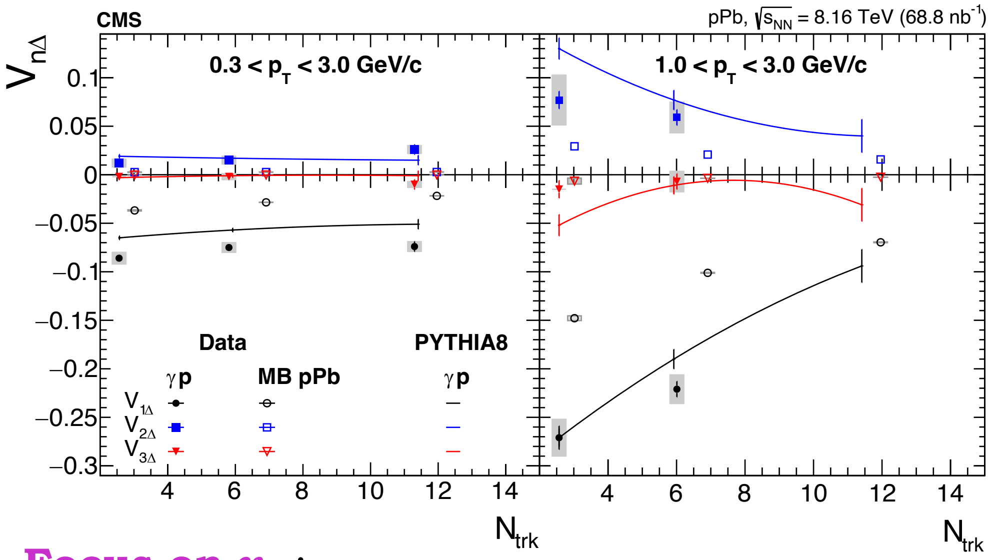

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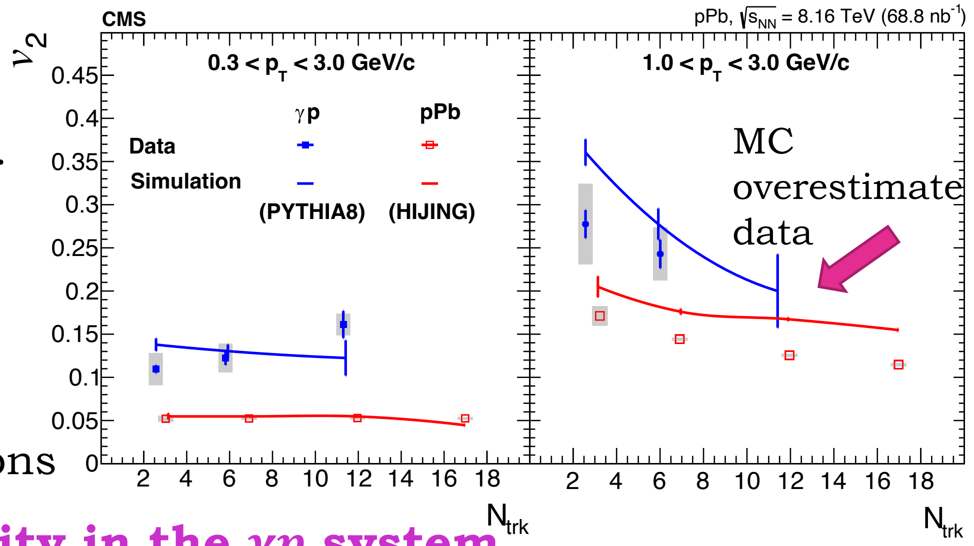
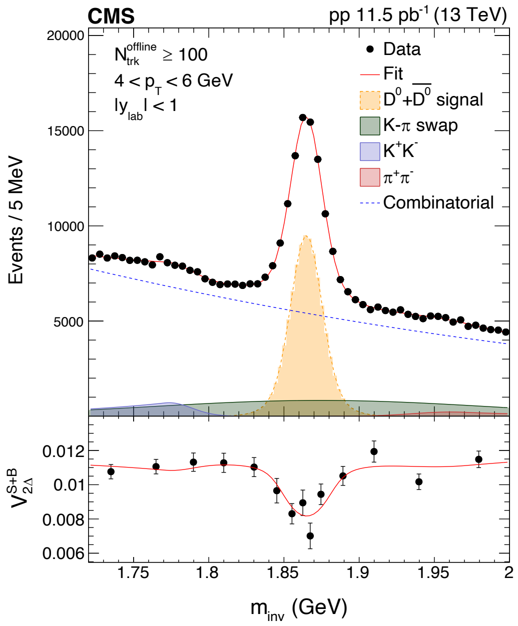


Data consistent with absence of collectivity in the γp system over the multiplicity range explored.

Charm and Beauty long-range correlations

https://www.sciencedirect.com/science/article/pii/S037026932030839X?via%3Dihub



D^0 candidate invariant mass fitted with different contributions is shown together with the $V_{2\Delta}^{S+B}$ distribution fitter with both signal and background components.

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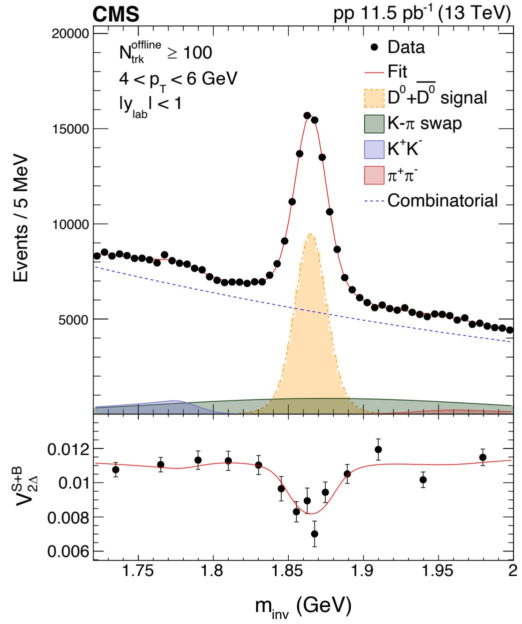

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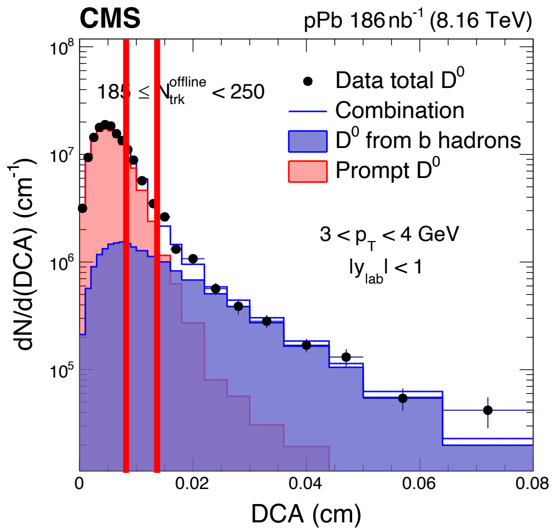
Nonprompt D^0 are evaluated by the DCA distribution



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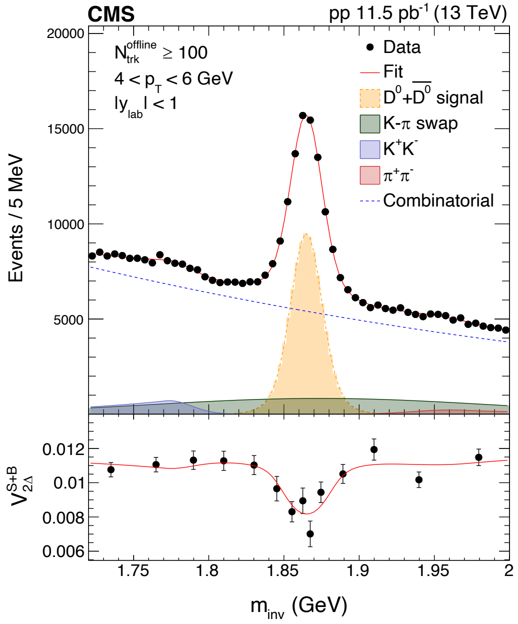

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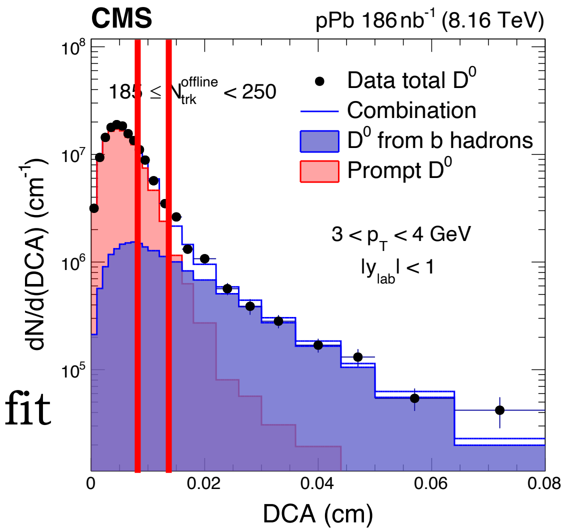
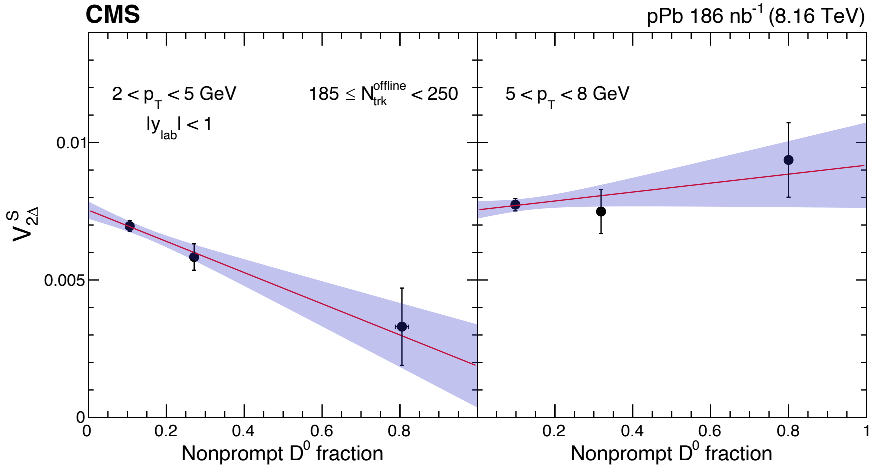
Nonprompt D^0 are evaluated by the DCA distribution and the inclusive D^0 $V_{2\Delta}$ values from the three DCA regions are plotted as a function of the corresponding nonprompt D^0

➢ measurements are well described by a linear-function fit





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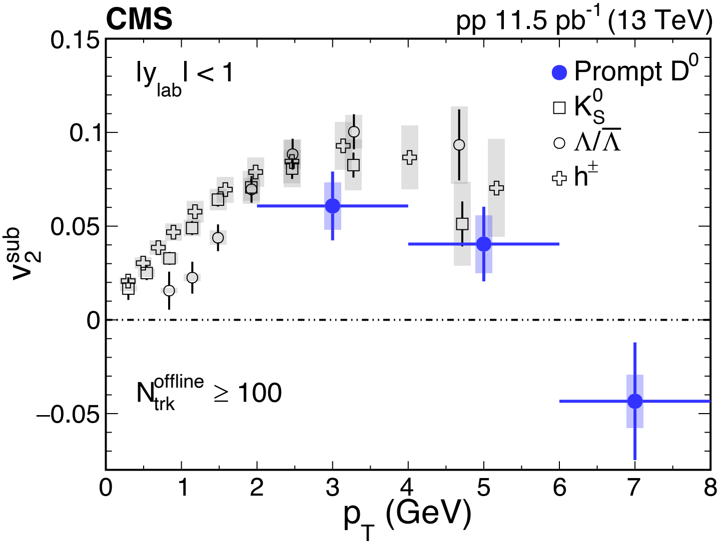

The positive v_2 signal (0.061 ± 0.018 (stat) ± 0.013 (syst)) over a pT range of 2–6 GeV for prompt charm hadrons provides **indications of collectivity of charm quarks in pp collisions**

v_2 magnitude for prompt D^0 mesons is compatible with light-flavor hadron species, though slightly smaller by ~1σ

⇒ collectivity is being developed for charm hadrons in pp collisions, comparable (or slightly weaker) than that for light-flavor hadrons.

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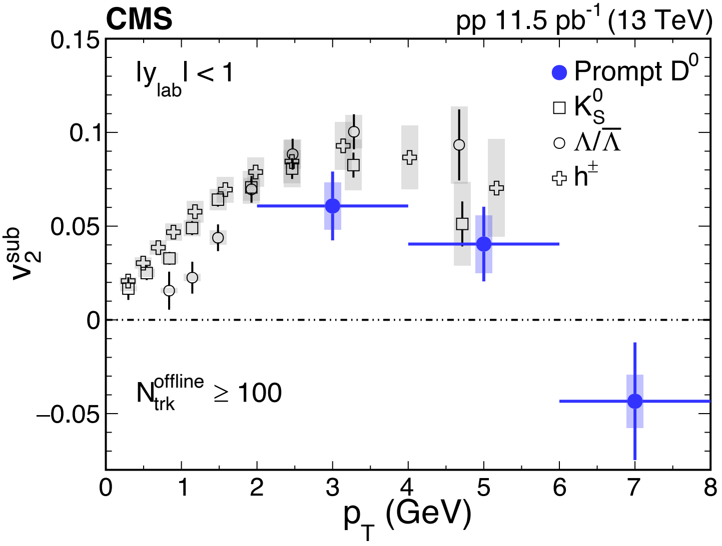

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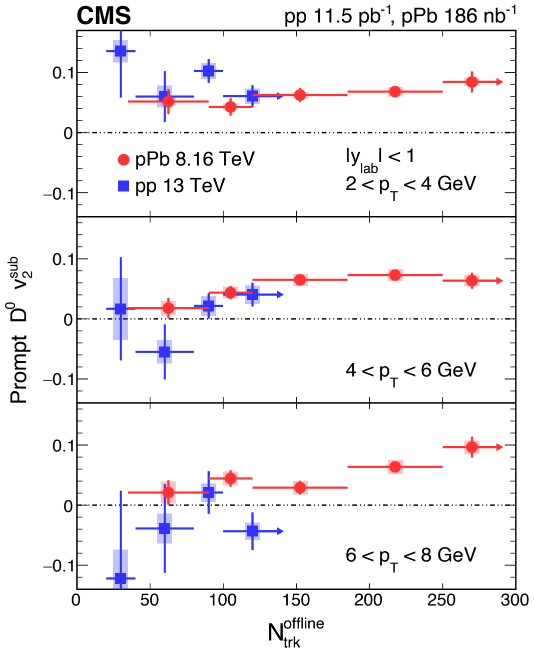
Measuring v_2 in pp and pPb collisions as a function of $N_{track}^{offline}$ we see:

- In $N_{track}^{offline}$ ~100, the prompt D^0 v_2 values are comparable in pp and pPb
- In all the pT range positive v_2 down to $N_{track}^{offline}$ ~ 50 in pPb collisions



No clear multiplicity dependence can be determined for pp data due to large errors

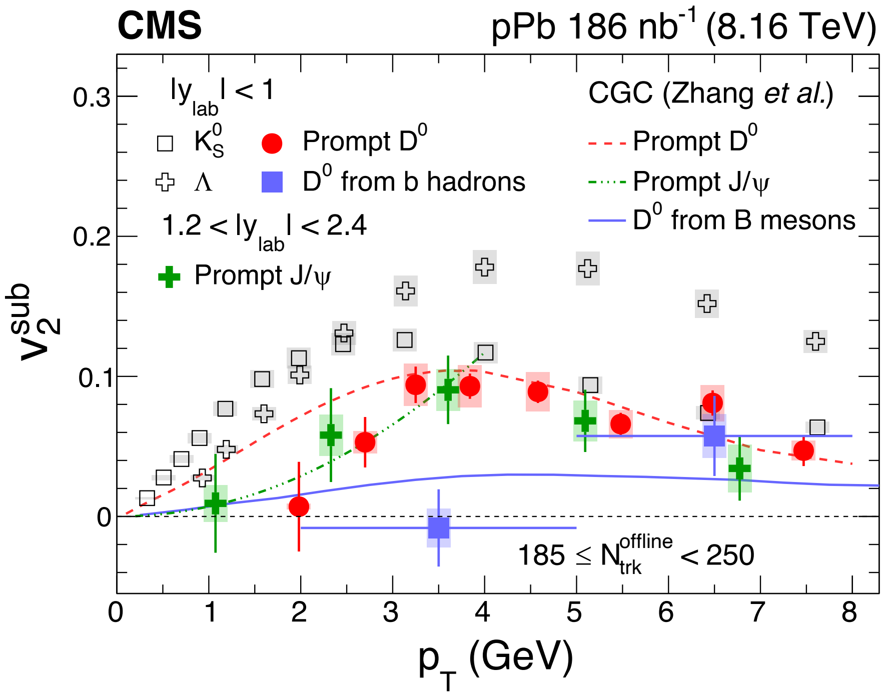
Charm and Beauty long-range correlations

v_2 for nonprompt D^0 measured for the first time!

At low pT, the nonprompt D^0 v_2 is consistent with zero, while at high pT, a hint of a positive v_2 value for beauty mesons is suggested but not significant within uncertainties.

Color Glass Condensate (CGC) are also shown with a qualitative agreement to data => initial-state effects may play an important role in the generation of collectivity in pPb collisions.

CGC framework also predicts a **flavor hierarchy** between prompt and nonprompt D^0 for pT ~ 2–5 GeV, consistent with the data.



Conclusion

- **High multiplicity events** still suffer a suboptimal description from simulations
  - Both with and without MPI modeling included

Collectivity studies shown interesting and promising results

- For the first time long-range correlations have been studied in γp **collisions,** identified from pPb collisions and studied

  $\Rightarrow$No collectivity effect shown so far

- **Collectivity in D^0 mesons** studied: for the first time for prompt D^0 in pp and nonprompt D^0 in pPb

  $\Rightarrow$ measurement of charm hadron v_2 in the pp system and the indications of mass dependence of heavy-flavor hadron v_2 in the pPb system provide insights into the origin of heavy-flavor quark collectivity in small colliding systems.

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Run 3 with $\sqrt{s}$=13.6 TeV is just started and new interesting results are coming!

STAY TUNED!

backup

Jet multiplicity – event selection

All events that contain jets clustered using the anti-kT algorithm with a distance parameter of R = 0.4 and reconstructed with $|\eta| < 3.2$ and transverse momentum pT > 20 GeV are preselected.

From these events, the ones with at least a pair of jets with pT1 > 200 GeV, pT2 > 100 GeV and $|y^{1,2}| < 2.5$ are selected (events with one of the leading two jets with $|y| > 2.5$ are vetoed).

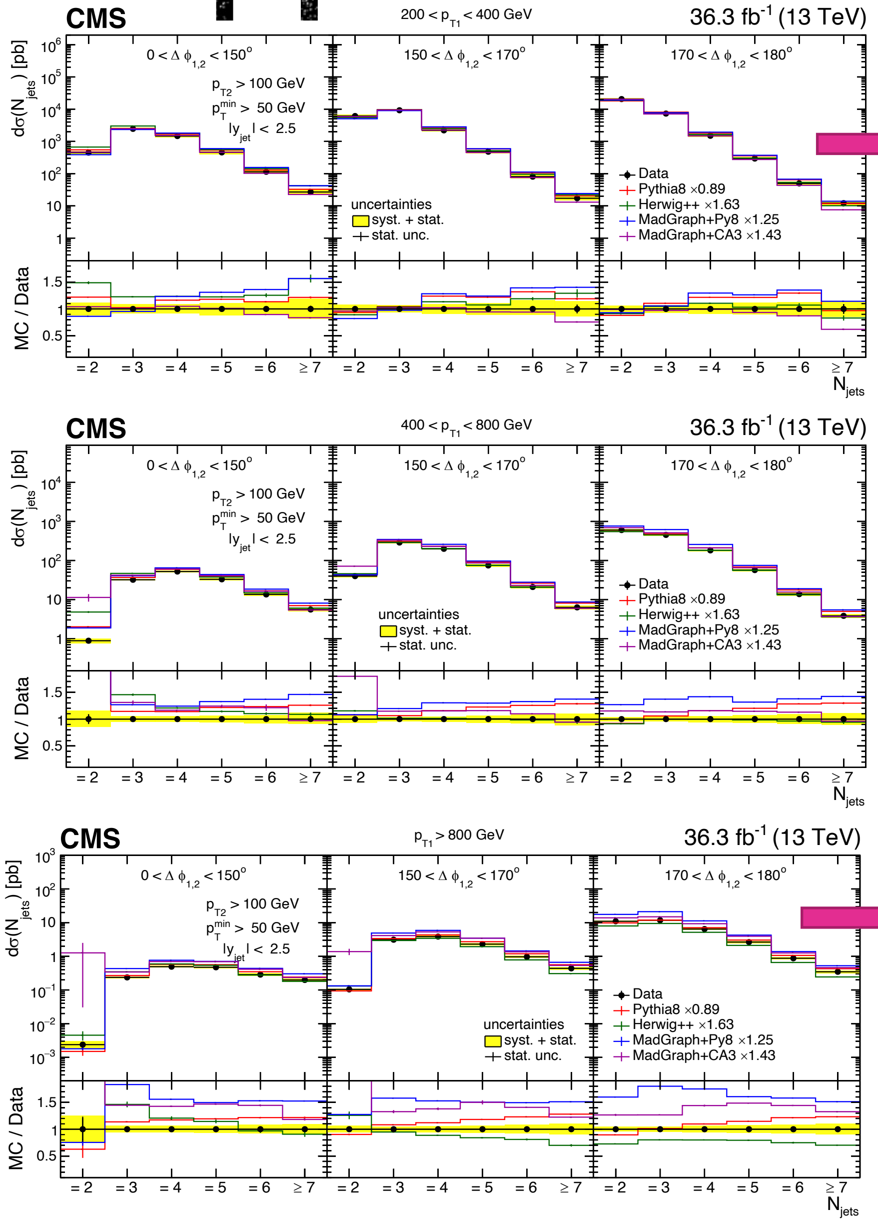
Additional jets must have pT > 50 GeV and $|y| < 2.5$.

Jets must satisfy quality criteria based on the jet constituents, in order to reject misidentified jets.

The selected events must have a missing transverse energy fraction smaller than 0.1

Jet multiplicity in pp collisions

A large number of additional jets The production rate between 3 and 7 jets changes by two orders of magnitude.

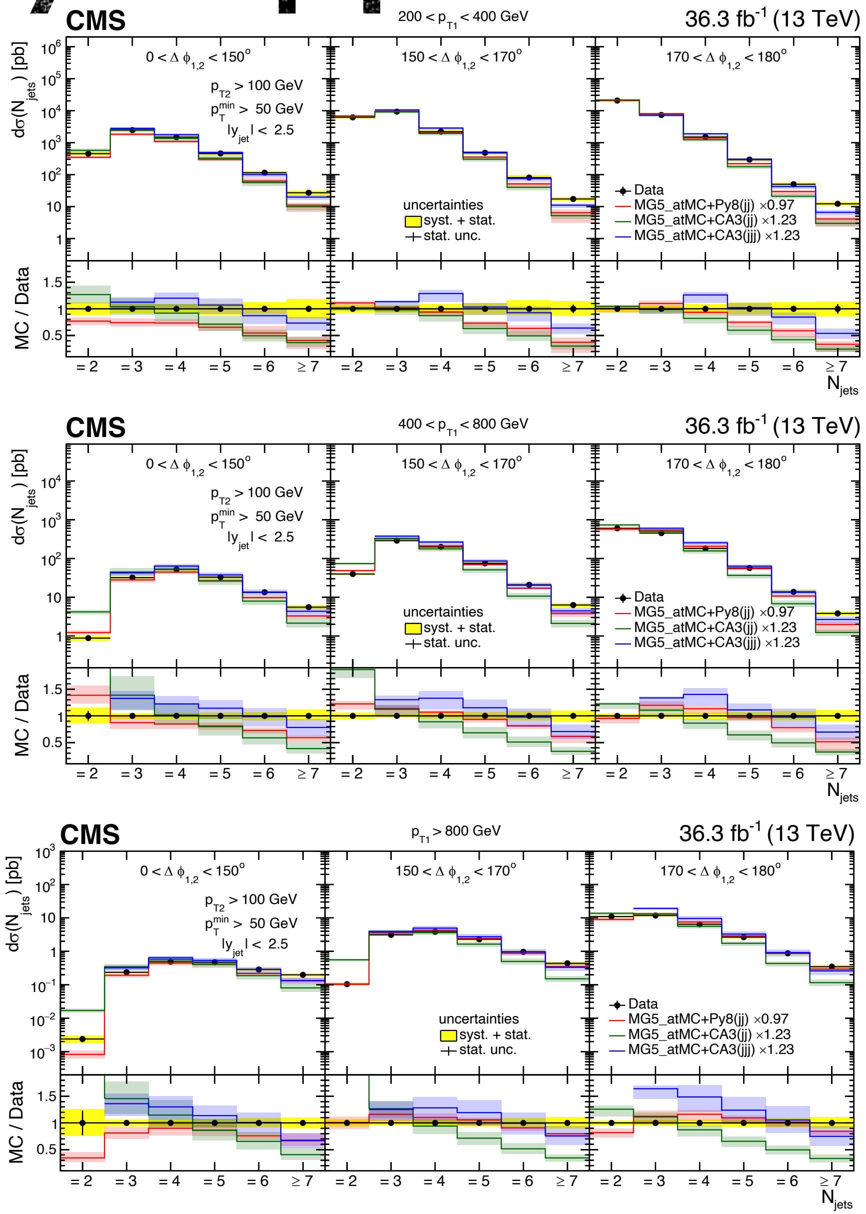


Leading jets are ~back-to-back, the production rate for 3 to 7 jets changes by three orders of magnitude. A large number of additional jets are observed that do not contribute significantly to the momentum imbalance of the two leading jets.

The rate of additional jets is ~ constant => many jets participate in the compensation of the $\Delta\phi_{1,2}$ decorrelation

The rate between 3 and 7 jets changes by less than 2 orders of magnitude, in contrast to the low-p_{T1} region.

Jet multiplicity in pp collisions



Two-particle azimuthal correlations in γp interactions

https://arxiv.org/abs/2204.13486

HLT requires the presence of at least one charged particle (track) with pT > 0.4 GeV/c in the pixel tracker && Only high purity tracks used

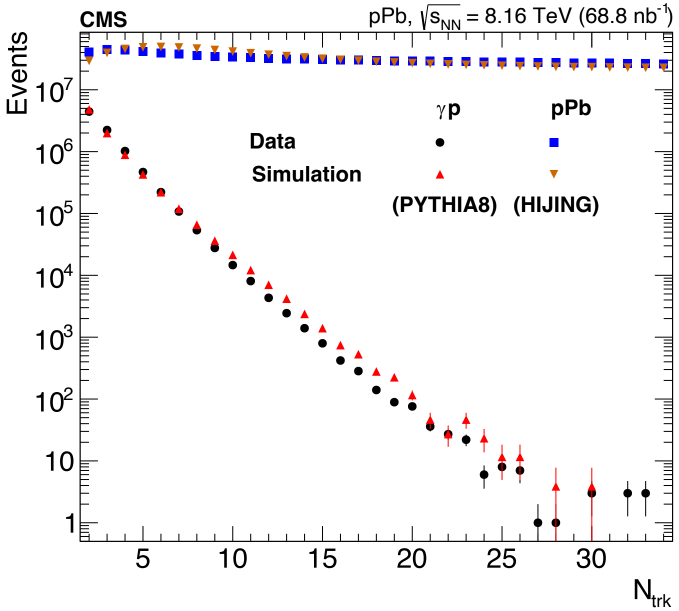
Typically pPb collisions produce particles at both positive and negative rapidity but γp events are expected to be very asymmetric in the lab frame since the $E_\gamma << E_p$

A γp-enhanced selection is designed to capture events with an intact Pb nucleus, particle production in the positive region, and a large rapidity gap η ($5.0 < \Delta\eta^F < 7.5$ where $\Delta\eta^F$ is defined as the difference from η=-5.0 to the lower edge of the first non-empty η bin) == not having a particle within the negative-η region.

N_{trk} = the number of tracks from the PV with pT > 0.4 GeV/c and $|\eta|<2.4$

- the γp-enhanced spectrum drops very rapidly with multiplicity up to 34
- The γp-simulated sample shows a shape and range that is consistent with data
- Three N_{trk} bins are used to analyze the γp-enhanced events:

$2 < N_{trk} < 5$, $5 < N_{trk} < 10$, $10 < N_{trk} < 35$



Two-particle azimuthal correlations in γp interactions

N_{trig} = number of "trigger particles" => tracks those whose p_T, labeled as p_T^{trig} , is within a given range

Particle pairs are then formed by associating each trigger particle with the remaining tracks within a specified $p_T = p_T^{assoc}$ interval

- Identical range for p_T^{trig} and p_T^{assoc}
- Two different p_T ranges are studied, [0.3, 3.0] and [1.0, 3.0] GeV/c.

The two-dimensional correlation function is defined as $\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta \, d\Delta\phi} = B(0,0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$

- $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of the pair and N_{pair} is the number of pairs
- same-event pair distribution, $S(\Delta\eta, \Delta\phi)$, represents the yield of particle pairs from the same event in a given $(\Delta\eta, \Delta\phi)$ bin.
- mixed-event pair distribution $B(\Delta\eta, \Delta\phi)$ is constructed by pairing the trigger particles in each event with the associated charged particles from 100 different randomly selected events in the same 0.5 cm wide vertex range and from the same track multiplicity class.

Two-particle azimuthal correlations in γp interactions

p_T range		$2 \leq N_{trk} < 5$	$5 \leq N_{trk} < 10$	$10 \leq N_{trk} < 35$
	$V_{1\Delta}$	-0.086 ± 0.006	-0.075 ± 0.005	-0.074 ± 0.007
$0.3 < p_T < 3.0\,\mathrm{GeV}/c$	$V_{2\Delta}$	0.012 ± 0.004	0.015 ± 0.004	0.026 ± 0.006
	$V_{3\Delta}$	-0.002 ± 0.001	-0.002 ± 0.004	-0.010 ± 0.006
		$2 \leq N_{trk} < 5$	$5 \leq N_{trk} < 35$	
	$V_{1\Delta}$	-0.271 ± 0.021	-0.221 ± 0.017	
$1.0 < p_T < 3.0\,\mathrm{GeV}/c$	$V_{2\Delta}$	0.077 ± 0.027	0.059 ± 0.017	
	$V_{3\Delta}$	-0.015 ± 0.009	-0.007 ± 0.013	

Charm and Beauty long-range correlations

The D^0/anti D^0 mesons are reconstructed through the hadronic decay channel D0 -> K-p+ and cc.

The invariant mass of D^0 candidates is required to be from 1.725–2.000 GeV to cover the world-average D^0 mass

High purity tracks are used with pT>0.7 GeV and |eta|<2.4

For each pair of tracks two D0 candidates are reconstructed: the correct sign and the wrong sign

The D0 candidates are selected using a BDT, with separate optimization for pp e pPb and for all the pT ranges
The training variables related to D0 mesons include: χ^2 probability for D0 vertex fitting, the t3D distance between PV and SV, and the 3D pointing angle
The training variables related to the decay products are: pT; eta and the track IP_{xy} and IP_z significance.

The optimal selection criterion is the working point with the highest signal significance of prompt and nonprompt D0 signals

Charm and Beauty long-range correlations

The azimuthal anisotropies of D0 mesons are extracted from their long-range ($|\Delta\eta| > 1$) two particle azimuthal correlations of D0 candidates with charged particles

The 2D correlation function is constructed by pairing each D0 candidate with reference primary charged-particle tracks with $0.3 < pT < 3.0$ GeV

$$\frac{1}{N_{D0}} \frac{d^2 N^{pair}}{d\Delta\eta \, d\Delta\phi} = B(0,0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)},$$

$\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity azimuthal angle of each pair.

The same-event pair distribution, $S(\Delta\eta, \Delta\phi)$, represents the yield of particle pairs normalized by the number of D0 candidates (N_{D0}) from the same event.

The mixed-event pair yield distribution, $B(\Delta\eta, \Delta\phi)$, is constructed by pairing D0 candidates in each event with the reference primary charged-particle tracks from 10 different randomly selected events

B(0, 0) represents the value of $B(\Delta\eta, \Delta\phi)$ at $\Delta\eta = 0$ and $\Delta\phi = 0$.

Charm and Beauty long-range correlations

The $\Delta\phi$ correlation functions averaged over $|\Delta\eta|$ > are obtained from the projection of 2D correlation functions and fitted by the first three terms of a Fourier series: $$\frac{1}{N_{\mathrm{D}^0}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left[1+\sum_{n=1}^{3} 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

$V_{n\Delta}$ are the Fourier coefficients and N_{assoc} represents the total number of pairs per D0 candidate.

By assuming $V_{n\Delta}$ to be the product of single-particle anisotropies $V_{n\Delta}(\mathrm{D0, ref}) = v_n(\mathrm{D0})v_n(\mathrm{ref})$, the v_n anisotropy harmonics for D0 candidates can be extracted from the equation:

$$v_n(\mathrm{D}^0) = V_{n\Delta}(\mathrm{D}^0, \mathrm{ref}) \Big/ \sqrt{V_{n\Delta}(\mathrm{ref}, \mathrm{ref})}.$$

Since the limited statistical data, only the elliptic anisotropy harmonic results are reported

To extract the $V_{2\Delta}$ values of the inclusive D0 meson signal ($V_{2\Delta}^{S}$), a two-step fit to the invariant mass spectrum of D0 candidates and their $V_{2\Delta}$ as a function of the invariant mass, $V_{2\Delta}^{S+B}(m_{\mathrm{inv}})$, is performed in each pT interval.

Charm and Beauty long-range correlations

$$V_{2\Delta}^{S+B}(m_{inv}) = \alpha(m_{inv})\, V_{2\Delta}^{S} + [1-\alpha(m_{\mathrm{inv}})]\, V_{2\Delta}^{B}(m_{\mathrm{inv}}),$$

where

$$\alpha(m_{\mathrm{inv}}) = \frac{S(m_{\mathrm{inv}}) + SW(m_{\mathrm{inv}}) + S(m_{\mathrm{K^+K^-}}) + S(m_{\pi^+\pi^-})}{S(m_{\mathrm{inv}}) + SW(m_{\mathrm{inv}}) + S(m_{\mathrm{K^+K^-}}) + S(m_{\pi^+\pi^-}) + B(m_{\mathrm{inv}})}.$$

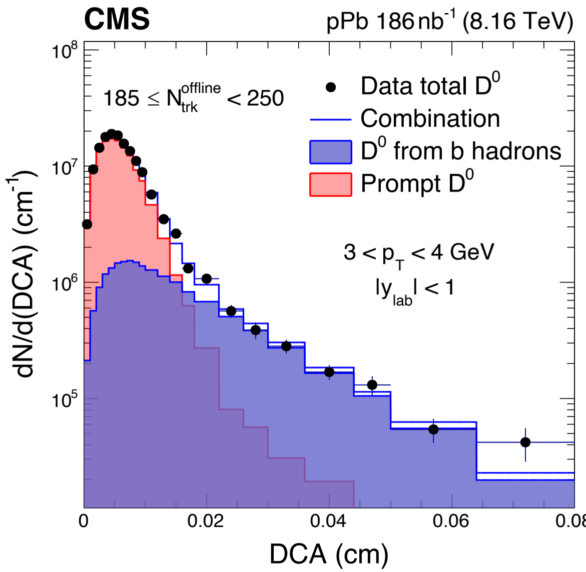
The $V_{2\Delta}^{S+B}(\mathrm{m_{inv}})$ distribution is fit with

$V_{2\Delta}^{B}$ for bkg D0 candidates is modeled as a linear function of the invariant mass, and $\alpha(\mathrm{m_{inv}})$ is the D0 signal fraction.
The K-p swapped, D0 ->pi+pi- and D0 -> K+K- components are included in the signal fraction because these candidates are from genuine D0 mesons

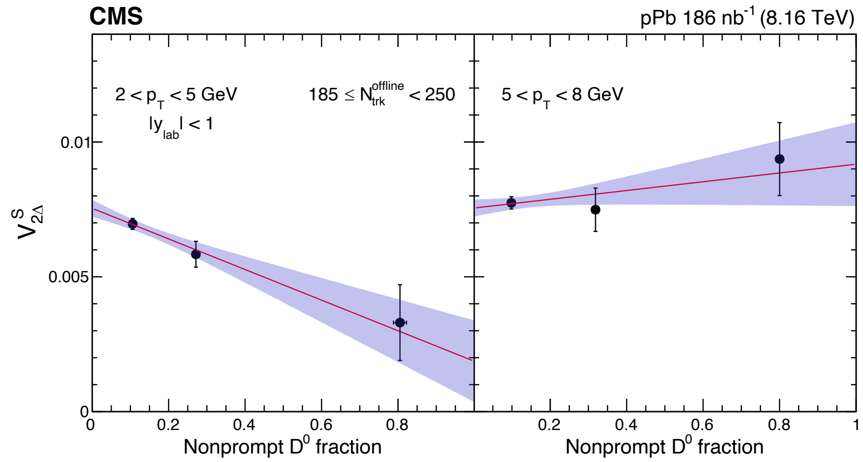
For extracting the $V_{2\Delta}$ values of nonprompt D0 mesons, the measurement and fitting procedure are repeated in three separate DCA ranges.
A linear fit by the functional form $V_{2\Delta}^{S} = f^{\mathrm{b}\to\mathrm{D}} V_{2\Delta}^{\mathrm{b}\to\mathrm{D}} + (1 - f^{\mathrm{b}\to\mathrm{D}}) V_{2\Delta}^{\mathrm{prompt\,D}}$,
to the measured D0 $V_{2\Delta}$ values as a function of nonprompt D0 fraction is performed to extrapolate to the $V_{2\Delta}$ value at a nonprompt fraction of 100%.

Charm and Beauty long-range correlations

Inclusive D0 meson yields, extracted as a function of DCA, by fitting the invariant mass distribution in each DCA bin



A template fit to the DCA distribution is performed using template distributions of prompt and nonprompt mesons obtained from MC



The inclusive D0 $V_{2\Delta}$ values from the three DCA regions are plotted as a function of the corresponding nonprompt D0 fraction => measurements are well described by a linear-function

Charm and Beauty long-range correlations

The Fourier coefficients, $V_{n\Delta}$, extracted from $\frac{1}{N_{D^0}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1+\sum_{n=1}^{3} 2V_{n\Delta}\cos(n\Delta\phi)\right]$ for $N_{track}^{offline} < 35(20)$ in pPb (pp) collisions, are subtracted from the $V_{n\Delta}$ coefficients obtained in the high-multiplicity region, with

$$V_{n\Delta}^{sub} = V_{n\Delta} - V_{n\Delta}(N_{trk}^{offline} < 35)\,\frac{N_{assoc}(N_{trk}^{offline} < 35)}{N_{assoc}}\,\frac{Y_{jet}}{Y_{jet}(N_{trk}^{offline} < 35)}.$$

where Y_{jet} represents the jet yield, and the ratio in the last term is introduced to account for the enhanced jet correlations resulting from the selection of higher-multiplicity events.

Elliptic flow v_n^{sub}, corrected for residual jet correlations, is obtained from $V_{n\Delta}^{sub}$ $v_n(D^0) = V_{n\Delta}(D^0, ref)\Big/\sqrt{V_{n\Delta}(ref, ref)}.$

Charm and Beauty long-range correlations

Source	Prompt D^0 in pPb collisions	Nonprompt D^0 in pPb collisions	Prompt D^0 in pp collisions
Nonprompt D^0 contamination	0.003–0.008	—	0.004–0.005
Nonprompt D^0 fraction estimation	—	0.001–0.007	—
Background $V_{2\Delta}$ PD	0.002–0.004	0.002	0.002–0.005
Efficiency correction	0.0001–0.013	0.0002-0.0006	0.0008–0.013
Trigger bias	0.0006–0.001	0.0001–0.001	0.0004–0.002
Effect from pileup	0.002–0.005	0.002–0.005	0.004–0.01
BDT selection	0.002–0.005	0.002	0.003–0.008
Jet subtraction	0.002–0.007	0.014–0.016	0.005–0.049
Total	0.005–0.018	0.016–0.017	0.013–0.052