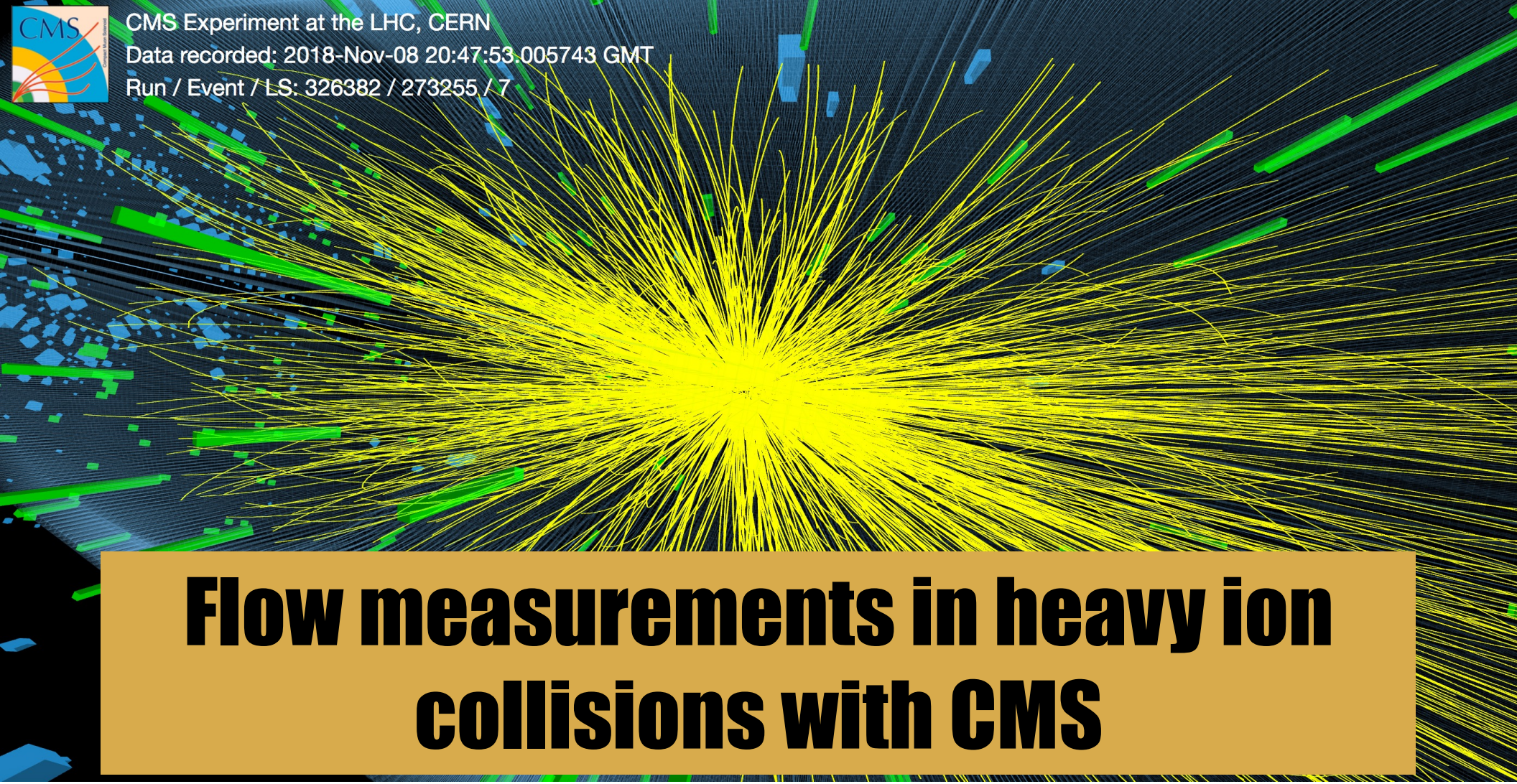


Flow measurements in heavy ion collisions with CMS

Shengquan Tuo
(Vanderbilt University)
for the CMS Collaboration

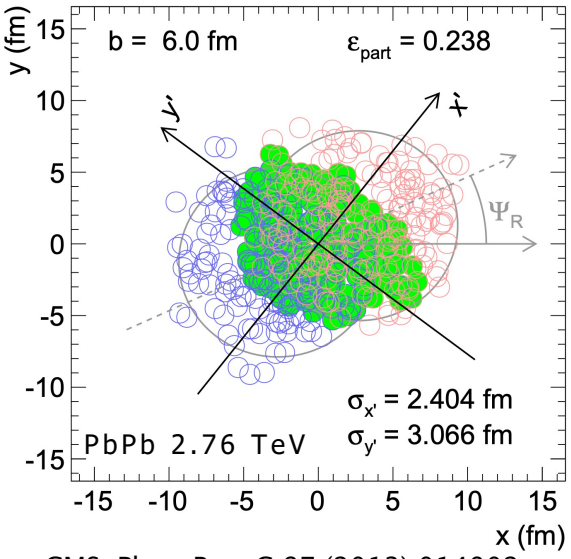
July 8, 2022

U.S. DEPARTMENT OF ENERGY | Office of Science

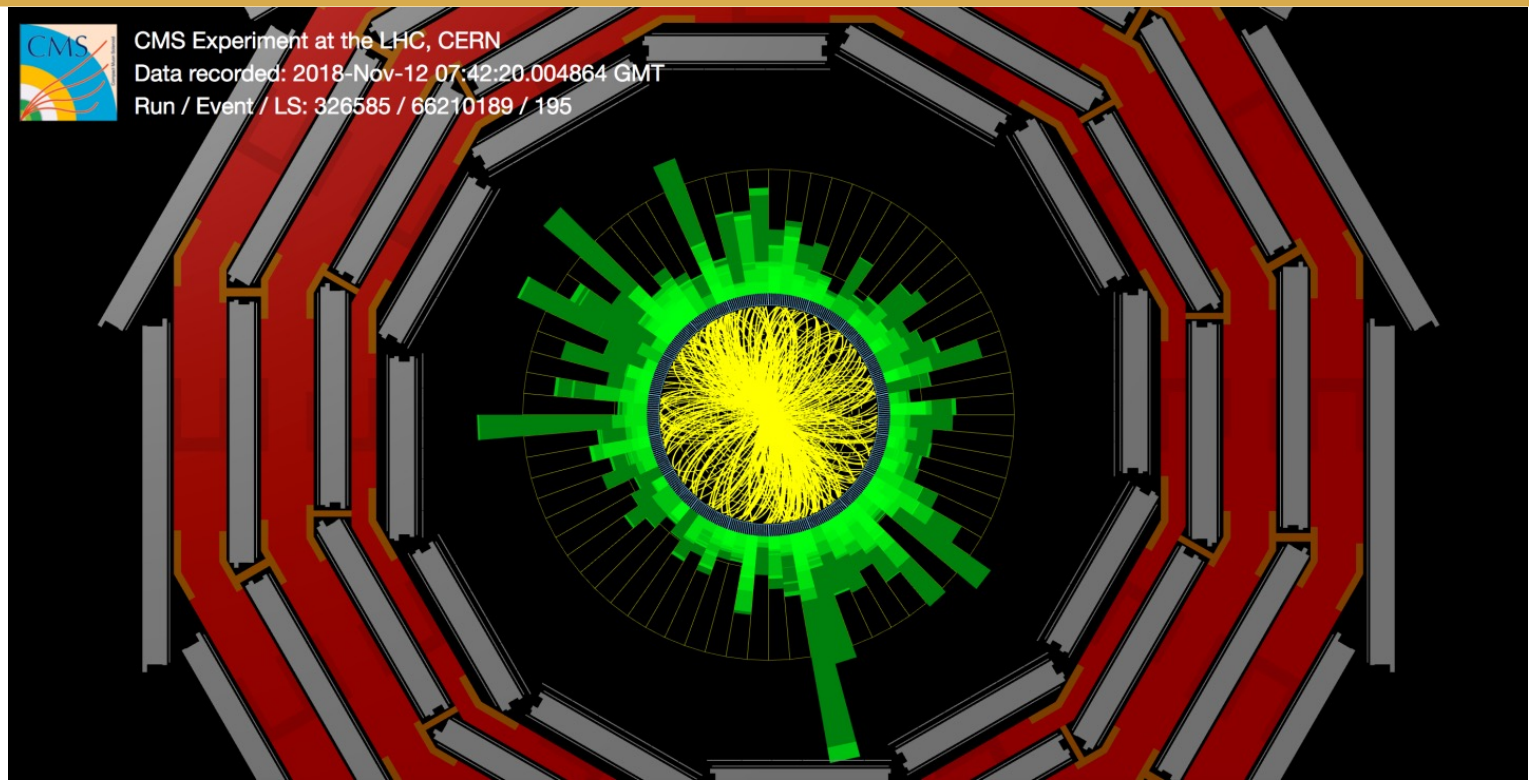
VANDERBILT UNIVERSITY

ICHEP 2022 BOLOGNA

FLOW IN HEAVY ION COLLISIONS



CMS: Phys. Rev. C 87 (2013) 014902



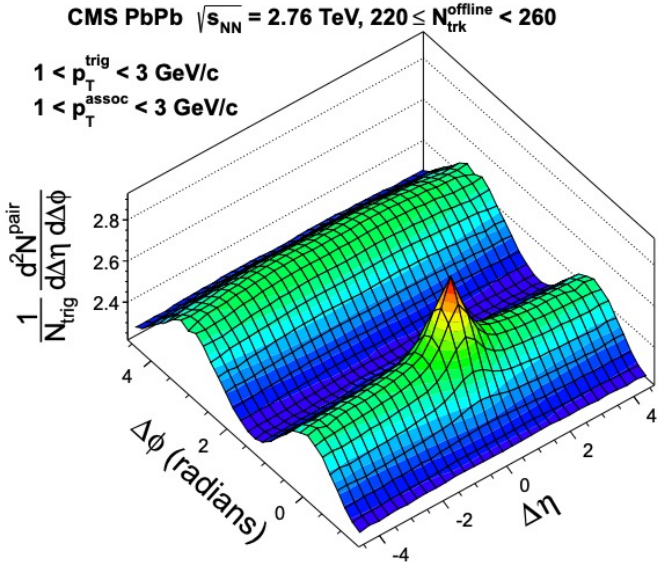
- One PbPb collision -> hundreds of nucleon-nucleon (NN) collisions
- Particles produced in preferred angles from hundreds of NN collisions at the same time -> collective FLOW of the created medium: Quark-Gluon Plasma
  - Initial state geometry, fluctuations
  - Medium properties, parton-medium interactions

$$dN/d\phi \propto 1 + \sum_n v_n \cos(n(\phi - \Psi_n))$$

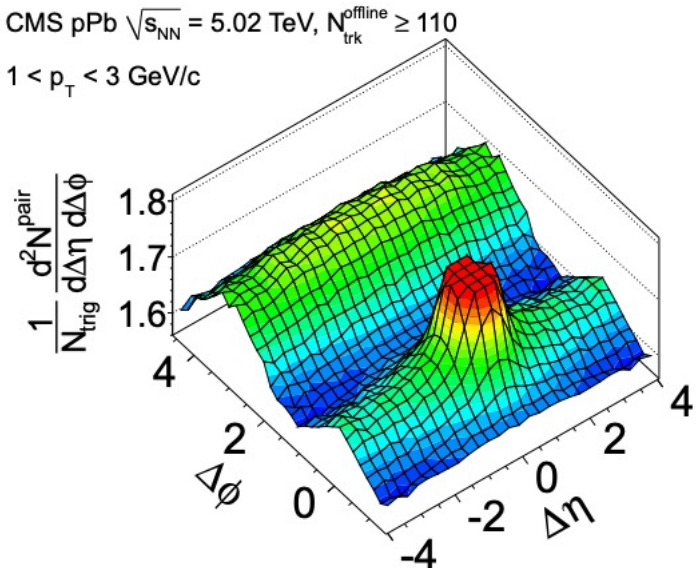
Elliptic flow: v_2

Triangular flow: v_3

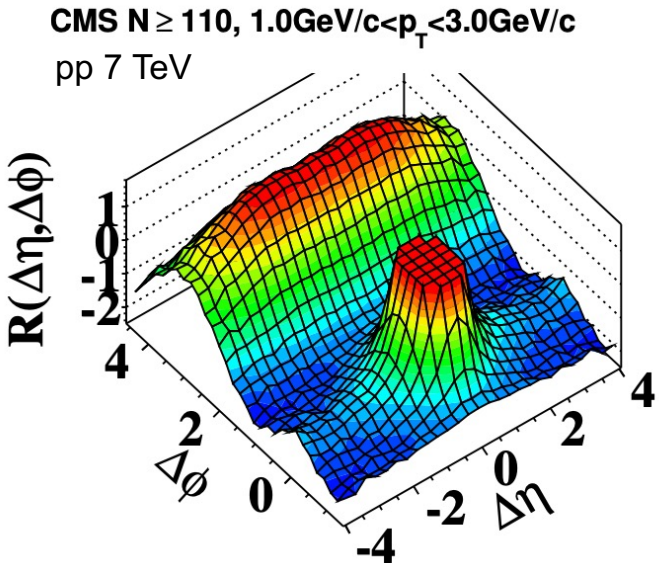
FLOW measurements in CMS



CMS: Phys. Lett. B 724 (2013) 213

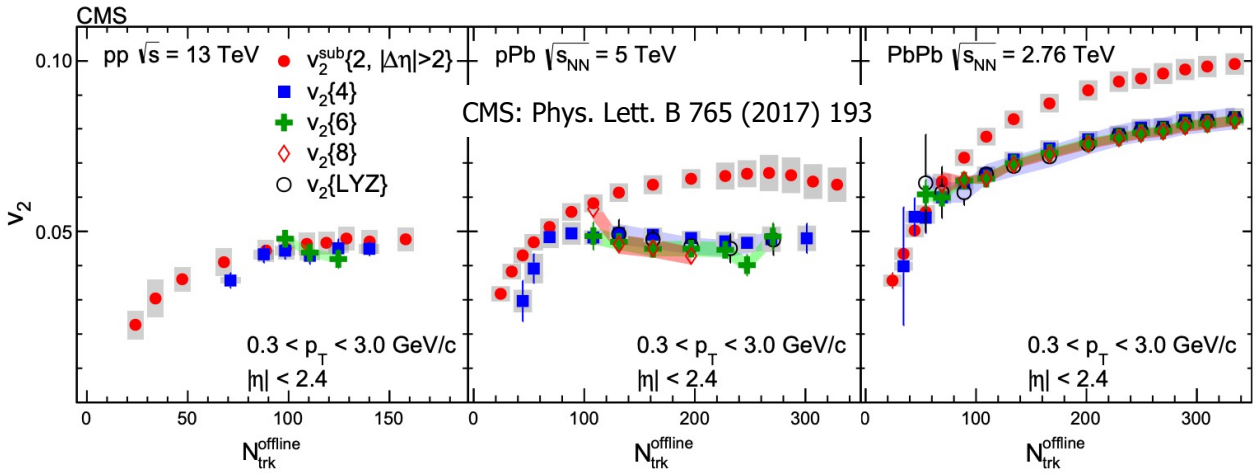


CMS: Phys. Lett. B 718 (2013) 795



CMS: JHEP 1009:091,2010

Evidence of flow in small collision systems



Analysis methods:

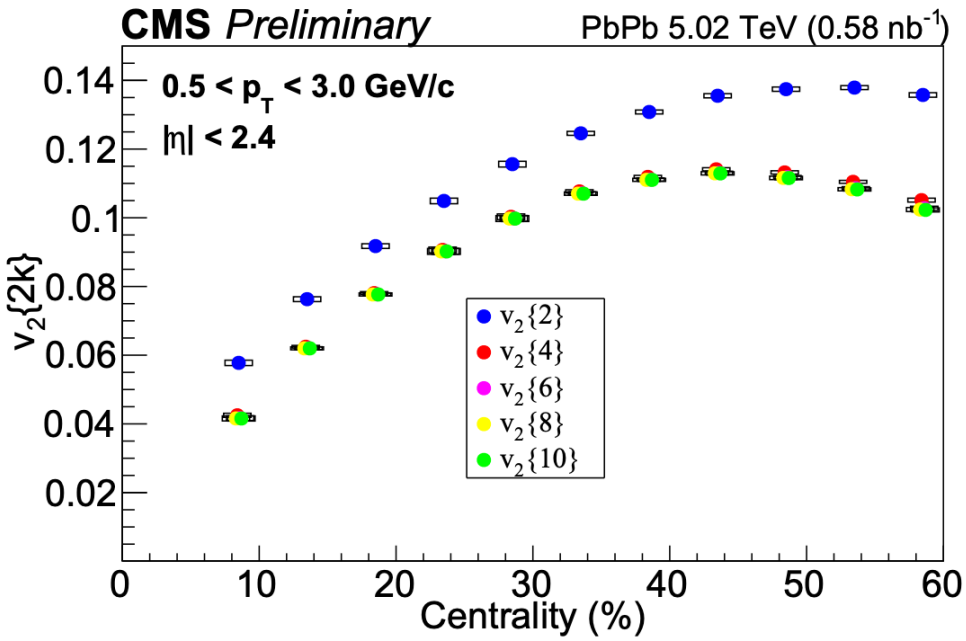
- Two particle correlations
- Multiparticle correlations to remove correlations that are not from collective flow (nonflow)

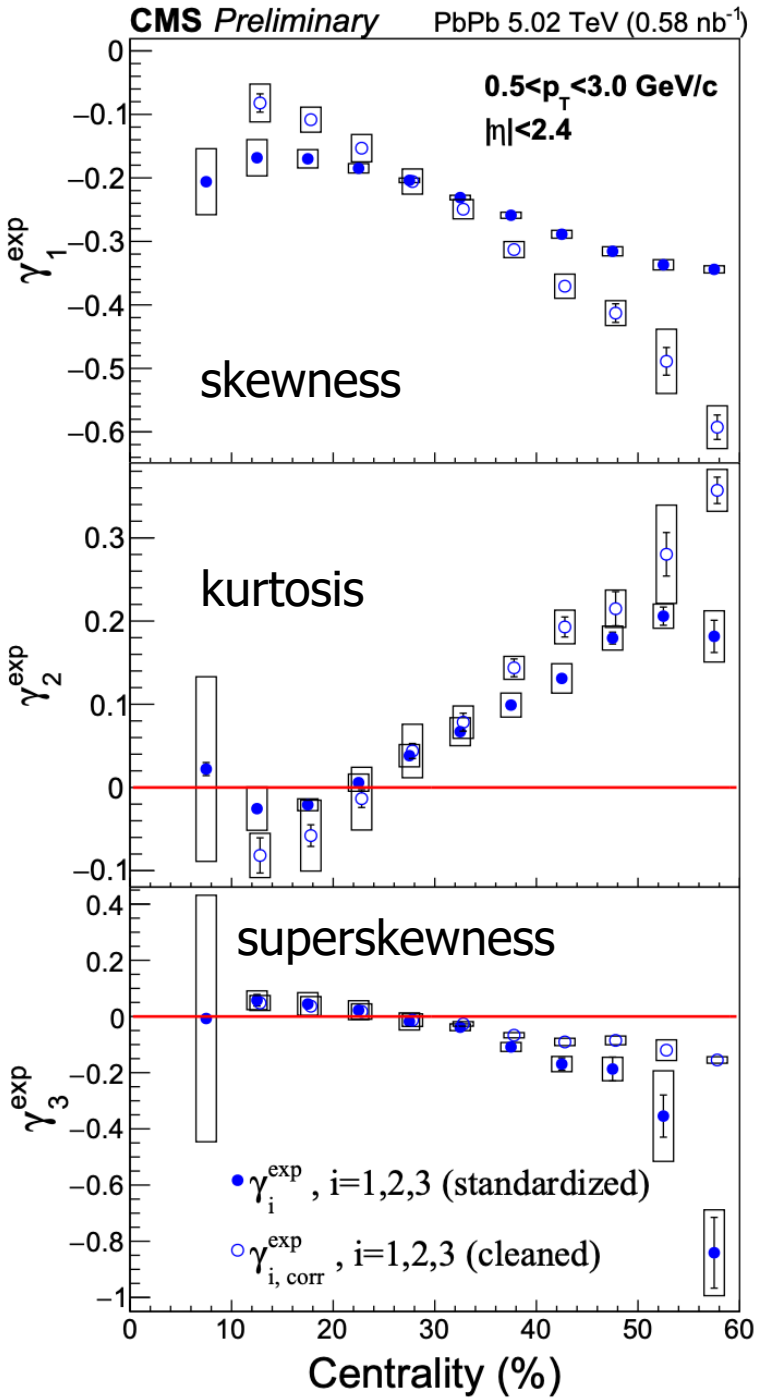
CMS ~~heavy ion~~ flow measurements include

- Collision system size scan: PbPb, pPb, pp, γp collisions
- Particle species scan: Charged hadrons (mostly light quark), strange /charm /bottom hadrons, Jets, Z boson

CHARGED HADRONS – CUMULANTS IN PBPB

CMS-PAS-HIN-21-010





- Measurements of v_2 with up to 10 particle correlations from the cumulant method
- Splittings between cumulant of different orders are sensitive to non-Gaussian fluctuations of v_2
- Hydrodynamics and initial state models can be tested with the moments: skewness, kurtosis, and superskewness

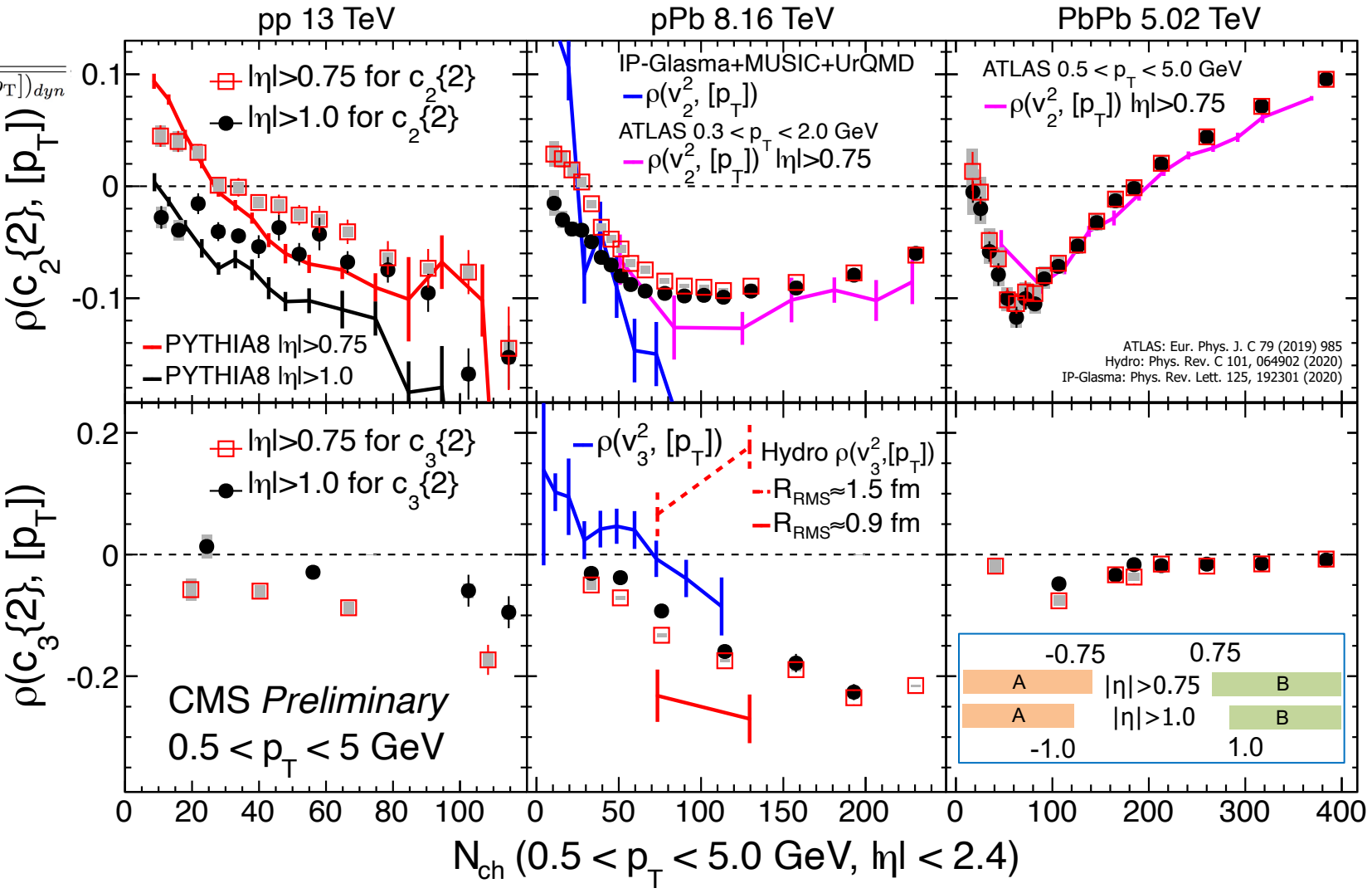
FLOW-MEAN PT CORRELATIONS

CMS-PAS-HIN-21-012

$$\rho(v_2^2, [p_T]) = \frac{\mathrm{cov}(v_2^2, [p_T])}{\sqrt{\mathrm{Var}(v_2^2)_{dyn}}\sqrt{\mathrm{Var}([p_T])_{dyn}}}$$

n=2

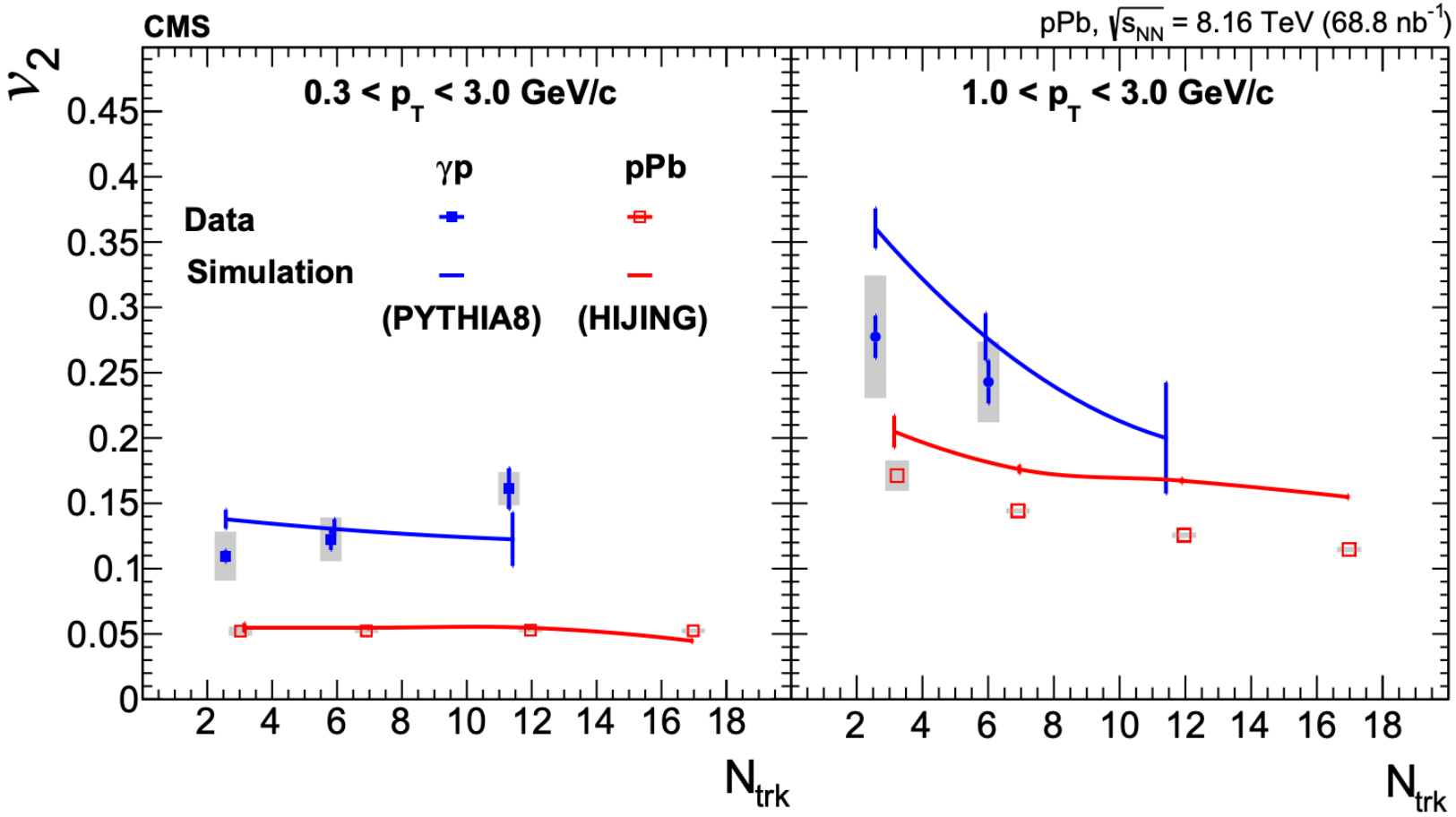
n=3



- Apparent sign change for $\rho(c_2\{2\}, [p_T])$ in pPb -> agree with IP-Glasma+hydrodynamics
- However, no sign change is observed when using $|\eta|>1.0$ for $c_2\{2\}$
- After removing nonflow with larger η gap, no evidence of CGC in data
- Data better described by the smaller initial fireball $R_{RMS}=0.9$ fm in hydrodynamics

FLOW IN PHOTON-P COLLISIONS

arXiv:2204.13486

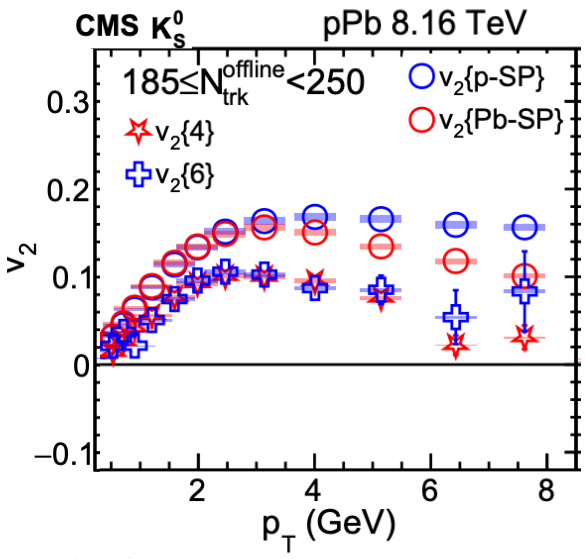


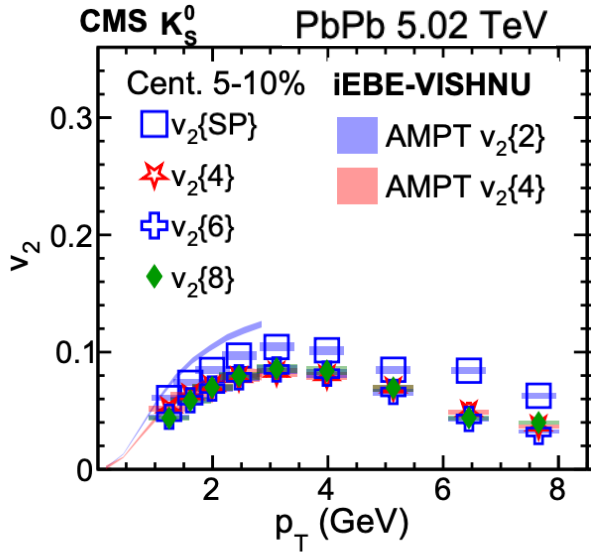
- Search for azimuthal anisotropy in γp interactions with pPb UPC
- Nonflow peripheral subtraction not applied
- Consistent with simulations without collective effects for both γp and pPb in the N_{trk} range

STRANGE PARTICLE FLOW

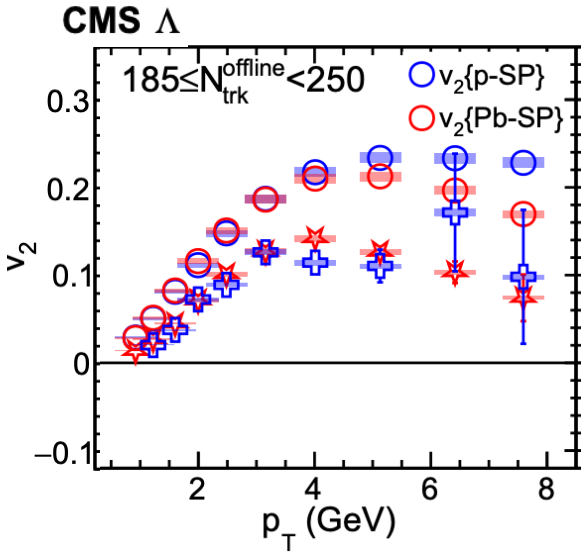
arXiv:2205.00080

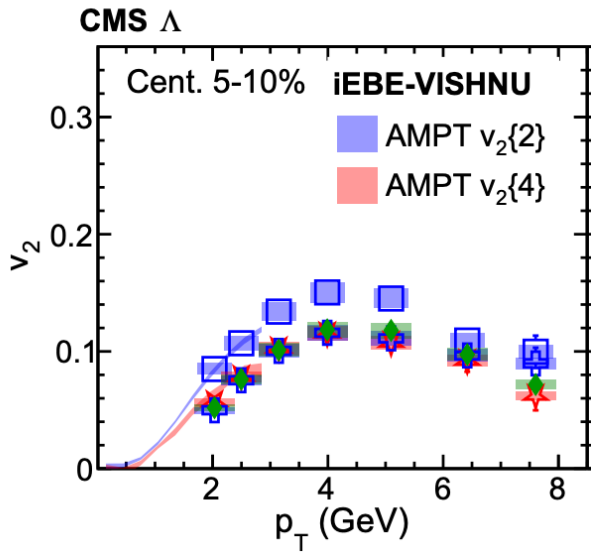
K^0_S





Λ





K^0_S/Λ pPb/PbPb

⬇

J/Ψ PbPb pPb

⬇

D^0 PbPb pp/pPb

⬇

Y(1S/2S) pPb/PbPb

⬇

Dijet PbPb

⬇

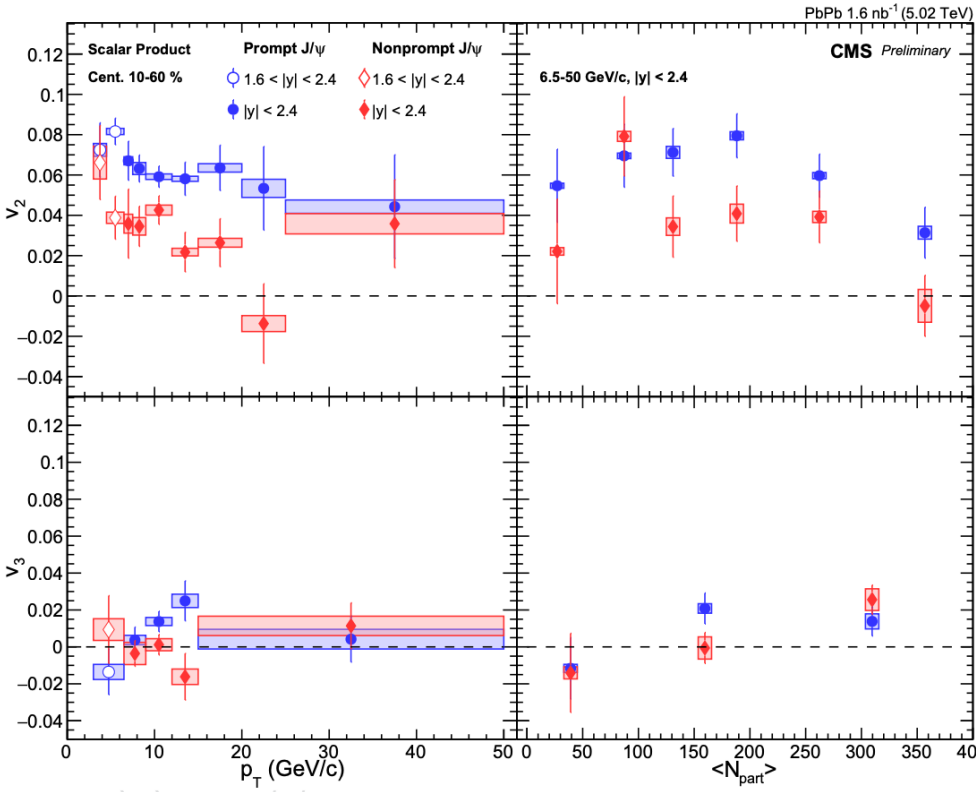
Z boson PbPb

- K^0_S and Λ flow studied with multiparticle correlations
- Four and six particle correlations are nearly identical
- Compared with PbPb to illustrate the system size dependence of event-by-event fluctuations

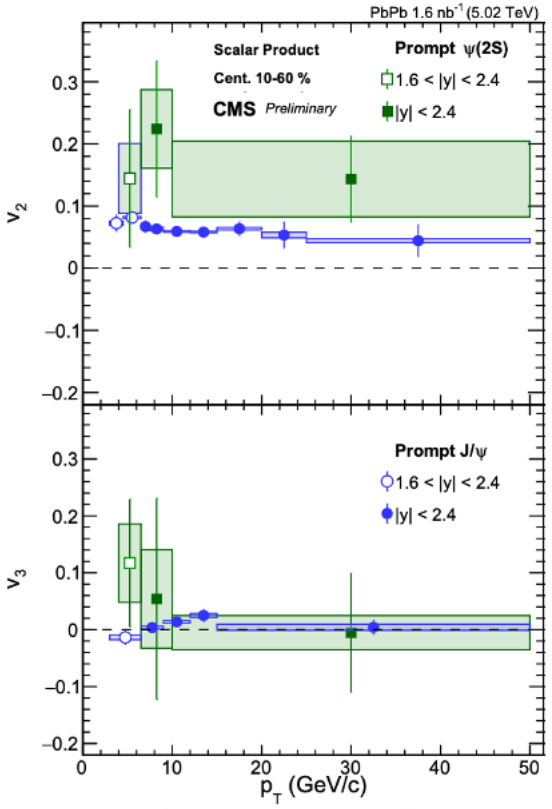
J/Ψ AND Ψ(2S) FLOW IN PBPB

CMS-PAS-HIN-21-008

Prompt J/ψ and b→J/ψ



Prompt Ψ(2S)



- Significant v_2 for Prompt J/ψ and b→J/ψ
  - Different dynamics for c and b quark
- First separation of v_3 for prompt and b→J/ψ
- First Ψ(2S) with v_2>0; consistent with 0 for v_3

K^0_S/Λ
pPb/PbPb

⬇

J/Ψ
PbPb
pPb

⬇

D^0
PbPb
pp/pPb

⬇

Y(1S/2S)
pPb/PbPb

⬇

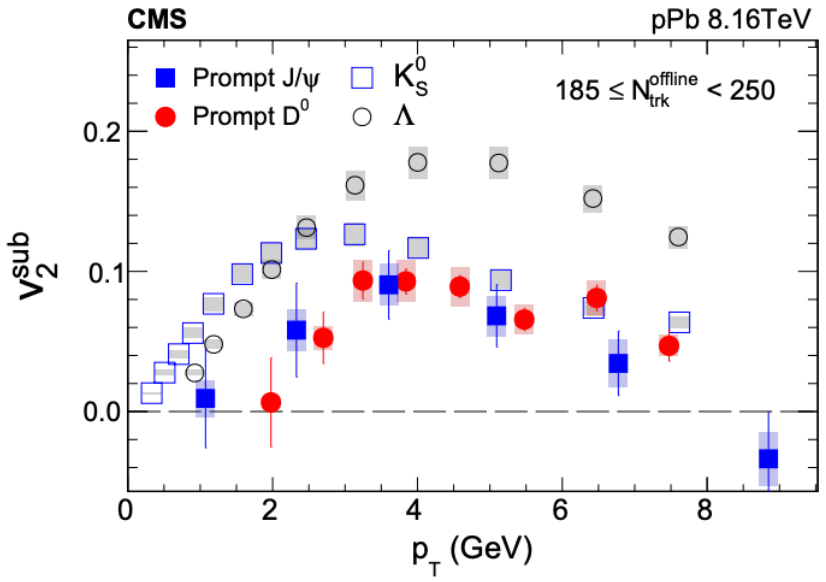
Dijet
PbPb

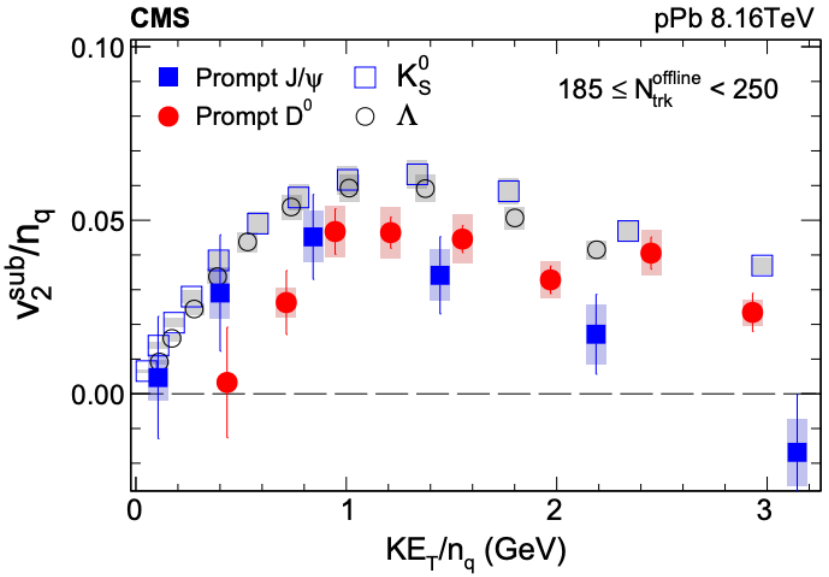
⬇

Z boson
PbPb

J/PSI AND D⁰ IN PPB

arXiv:1810.01473





- Evidence of charm quark collectivity in high multiplicity pPb
- Heavy quarks exhibit weaker collective behavior

K^0_S/Λ
pPb/PbPb

⬇

J/Ψ
PbPb
pPb

⬇

D^0
PbPb
pp/pPb

⬇

Y(1S/2S)
pPb/PbPb

⬇

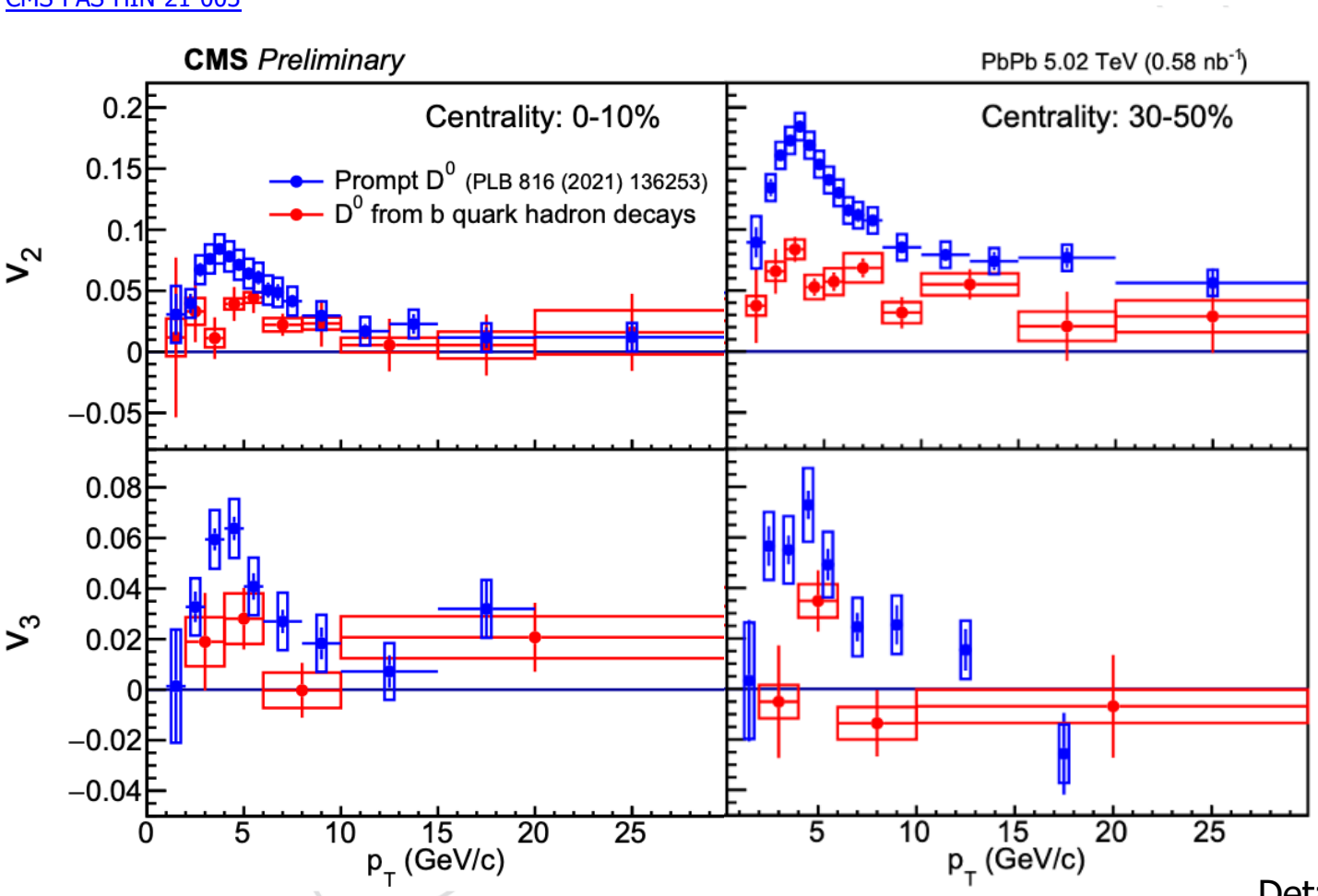
Dijet
PbPb

⬇

Z boson
PbPb

PROMPT D^0 AND B→ D^0 FLOW IN PBPB

CMS-PAS-HIN-21-003



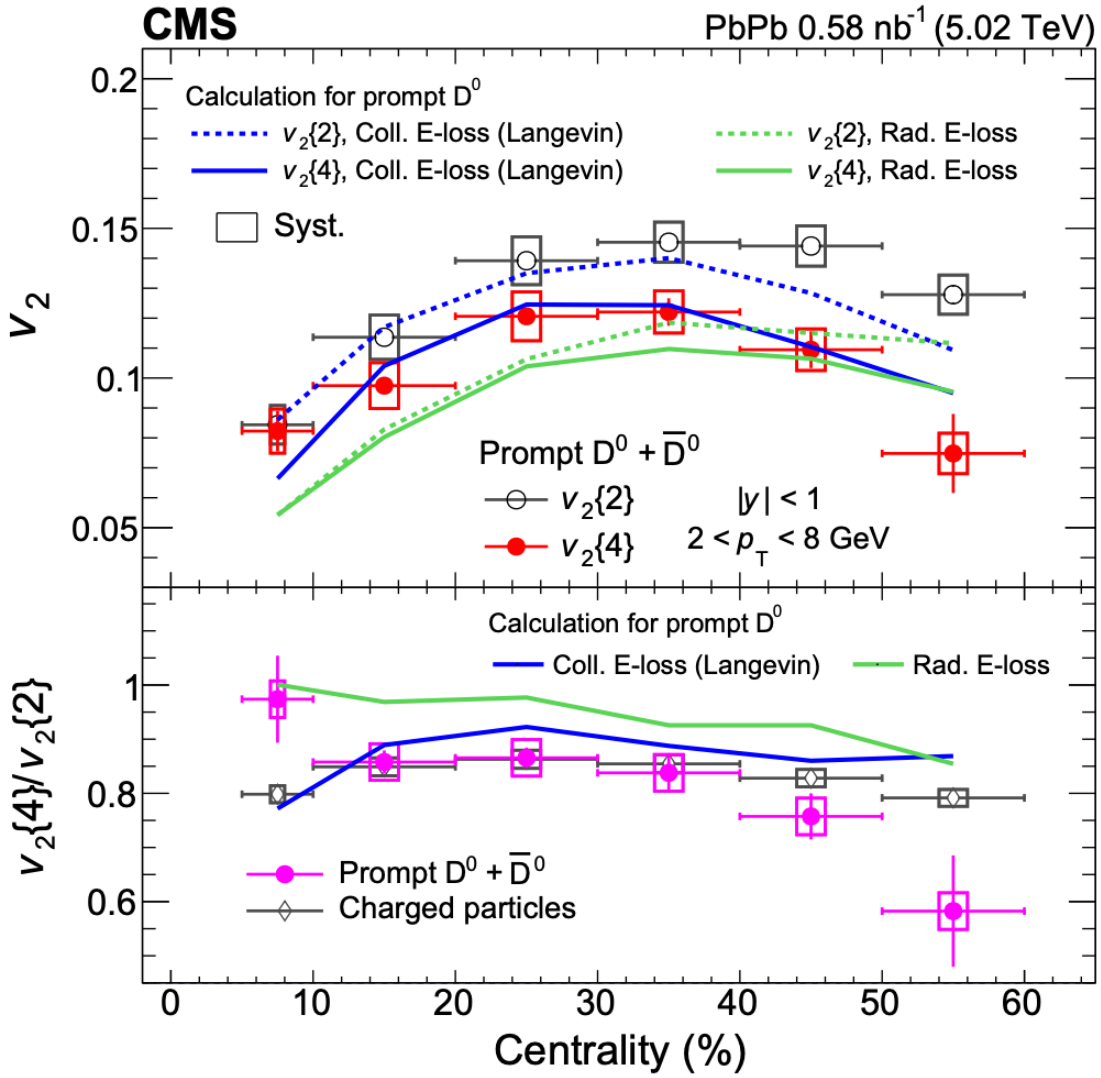
Details in Milan's talk:
Thursday 15:00

- (b→D^0) v_n significantly lower than prompt D^0 v_n
- (b→D^0) v_2, less centrality dependence compared to prompt D^0 v_2
  - b quark collectivity affected by fluctuations

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Y(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

D^0 WITH MULTIPARTICLE CORRELATIONS

arXiv:2112.12236



- Probe event-by-event fluctuations
- $v_2\{4\} < v_2\{2\}$ for D^0
- Indications of possible differences in energy loss fluctuations between D^0 and charged hadrons

K^0_S/Λ
pPb/PbPb

⬇

J/Ψ
PbPb
pPb

⬇

D^0
PbPb
pp/pPb

⬇

Υ(1S/2S)
pPb/PbPb

⬇

Dijet
PbPb

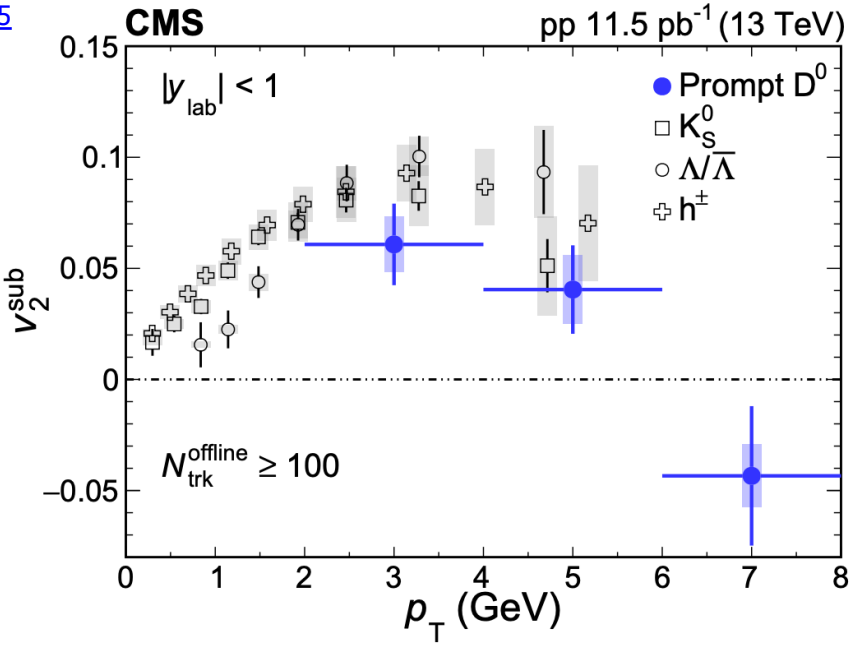
⬇

Z boson
PbPb

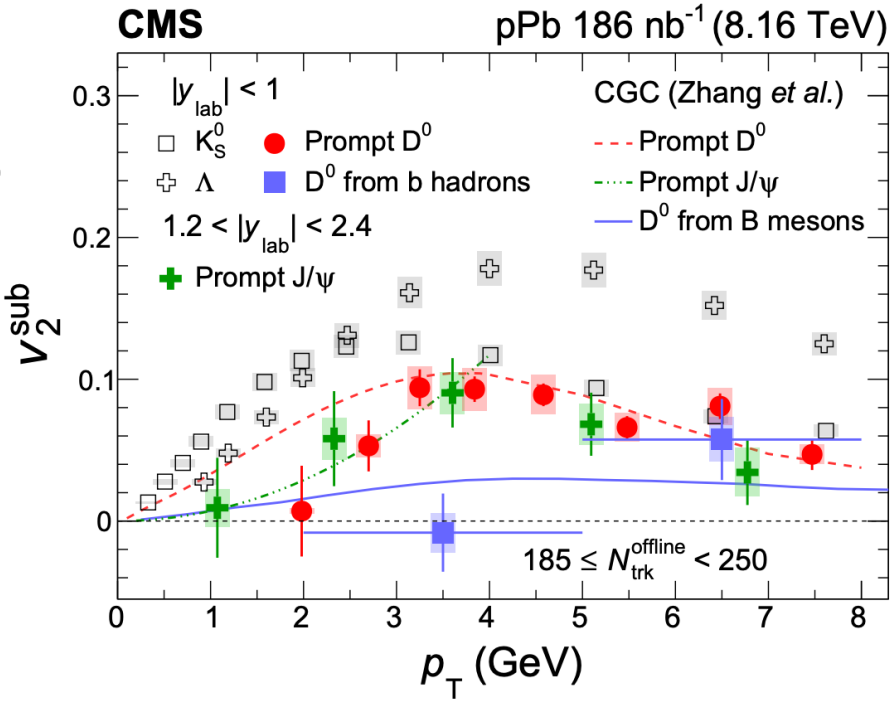
D^0 FLOW IN PP AND PPB

arXiv:2009.07065

pp



pPb



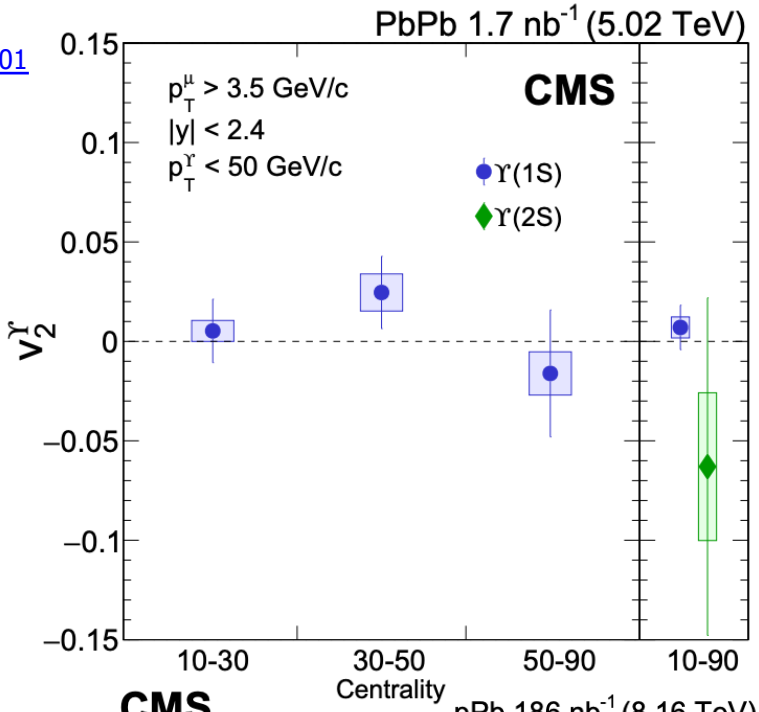
- Indications of positive D^0 v_2 in pp
- ($b \rightarrow D^0$) has much smaller v_2 compared to prompt D^0 in pPb
  - mass dependent v_2

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Y(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

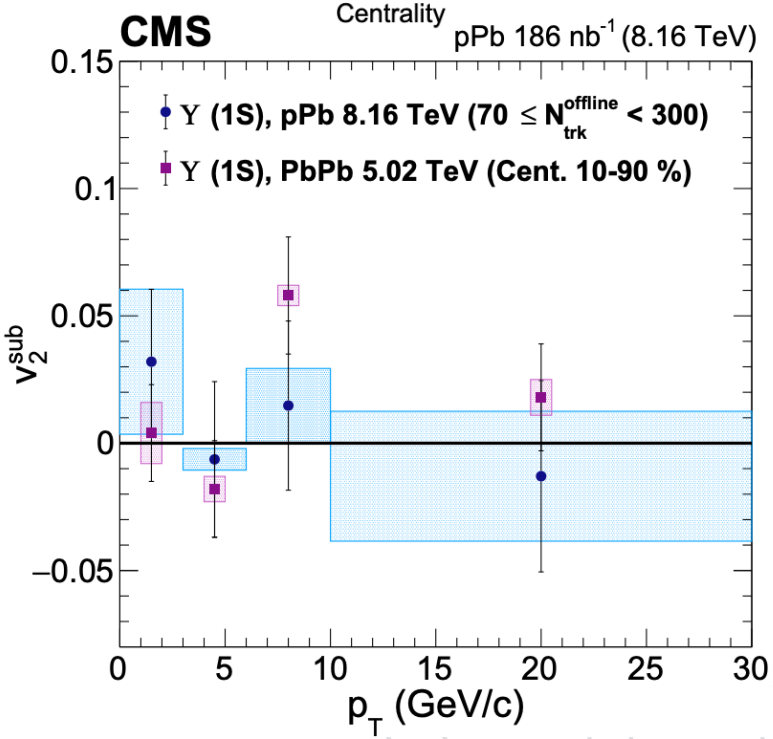
Y(1S) AND Y(2S) FLOW

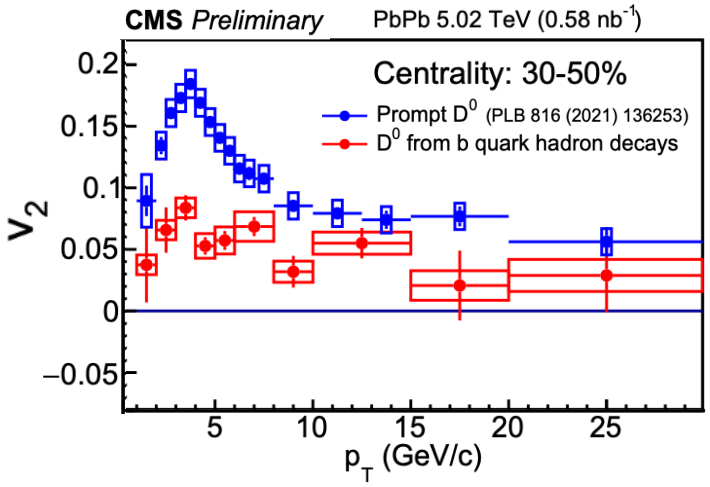
arXiv:2006.07707
CMS-PAS-HIN-21-001

PbPb



pPb





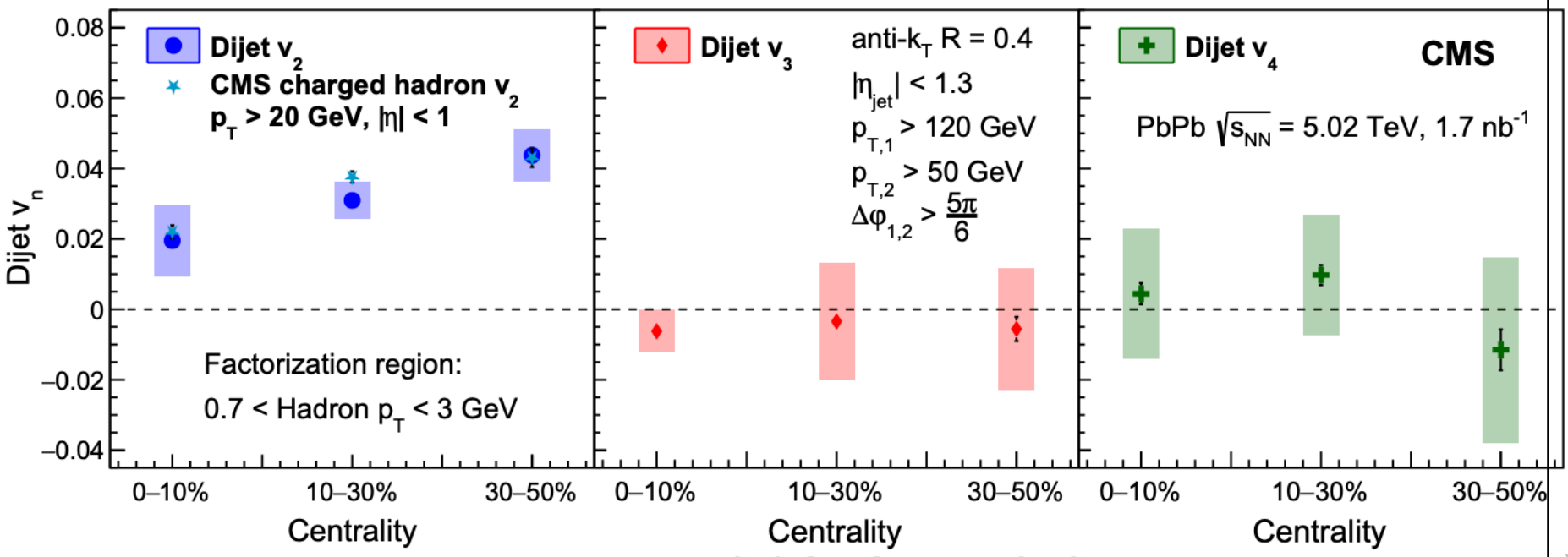
- v_2 of Y(1S) and Y(2S) are both consistent with 0 in PbPb
  - But non-zero (b→D^0) v_2 in PbPb
- Y(1S) v_2 consistent with 0 in pPb

Details in Florian's talk:
Saturday 9:15

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Y(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

DIJET FLOW IN PBPB

CMS-PAS-HIN-21-002



- Significant v_2 for dijet -> path length dependence of energy loss
- Dijet v_3 and v_4 are consistent with 0 -> need better precision to constraint initial state effect

K^0_S/Λ
pPb/PbPb

⬇

J/ψ
PbPb
pPb

⬇

D^0
PbPb
pp/pPb

⬇

Υ(1S/2S)
pPb/PbPb

⬇

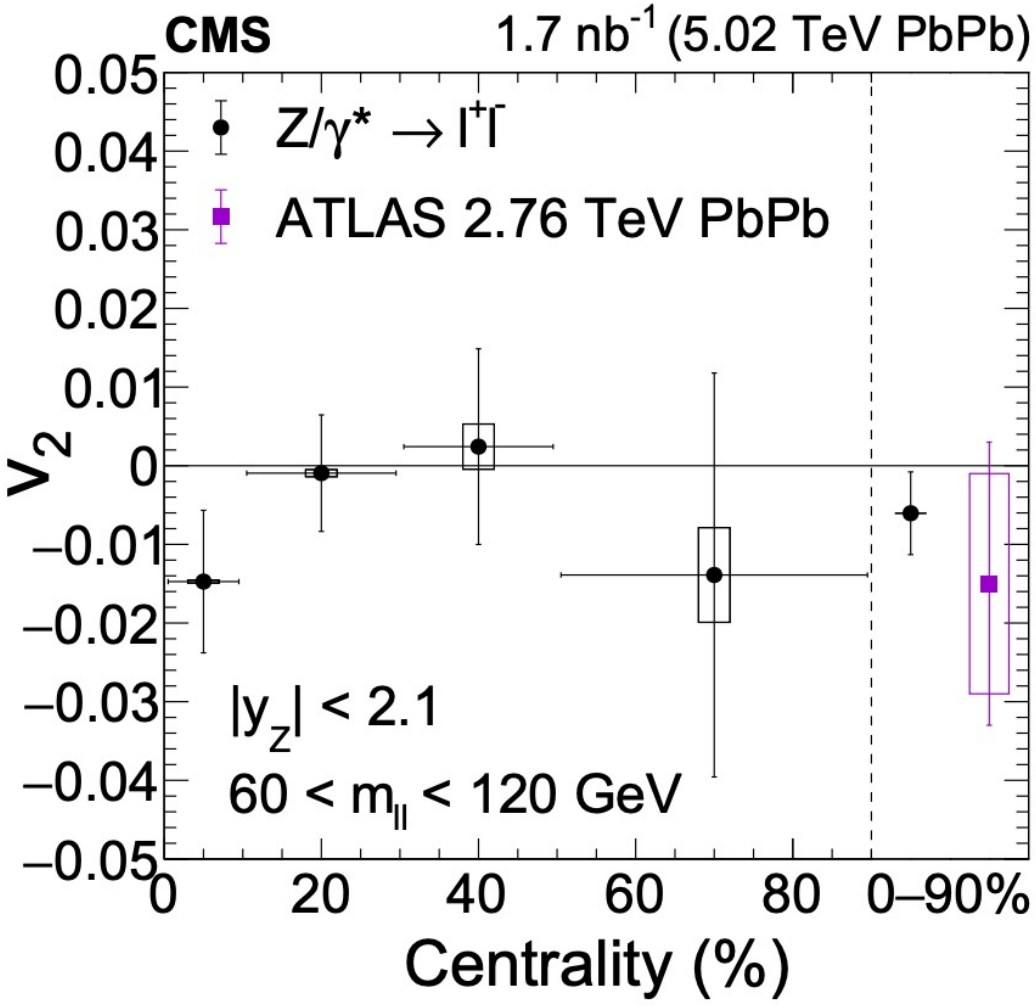
Dijet
PbPb

⬇

Z boson
PbPb

Z BOSON FLOW IN PBPB

arXiv:2103.14089



- v_2 is consistent with 0 for Z bosons in PbPb
  - Z bosons do not experience significant final-state interactions in the medium

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Y(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb

SUMMARY

Flow measurements in CMS with

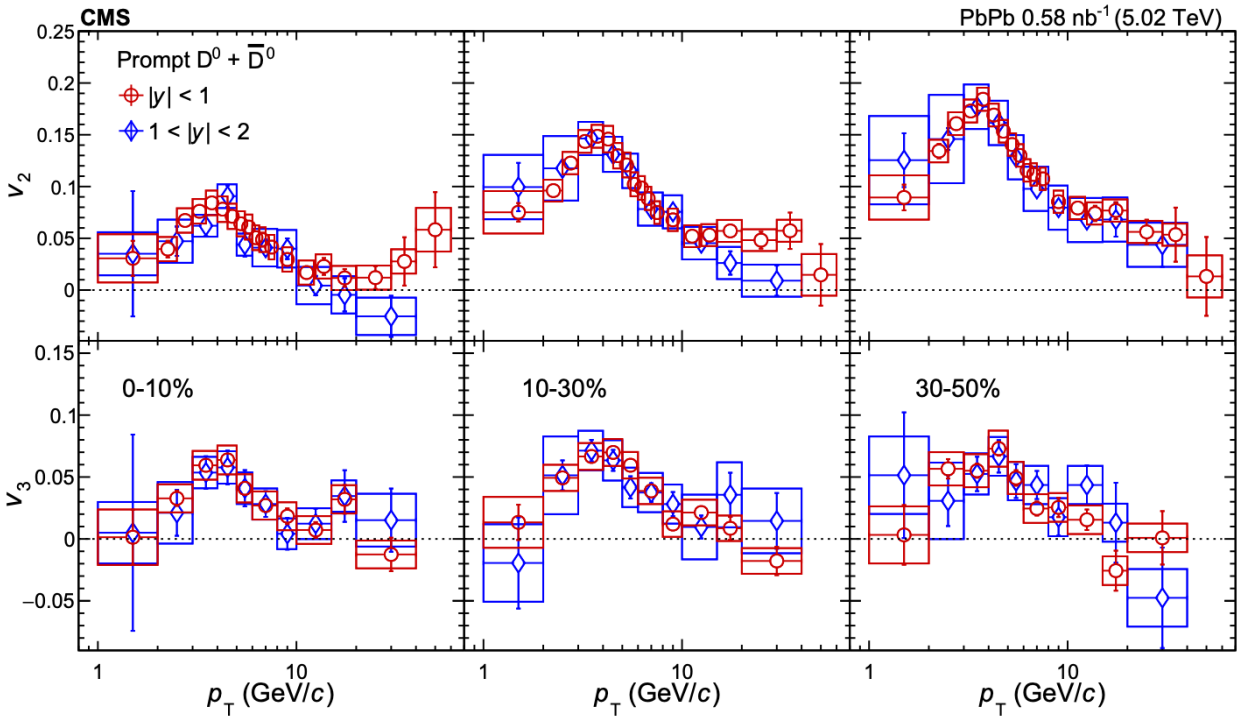
- Collision system size scan: PbPb, pPb, pp, γp collisions
- Particle species scan: Charged hadrons, strange/charm/bottom hadrons, Jets, Z boson

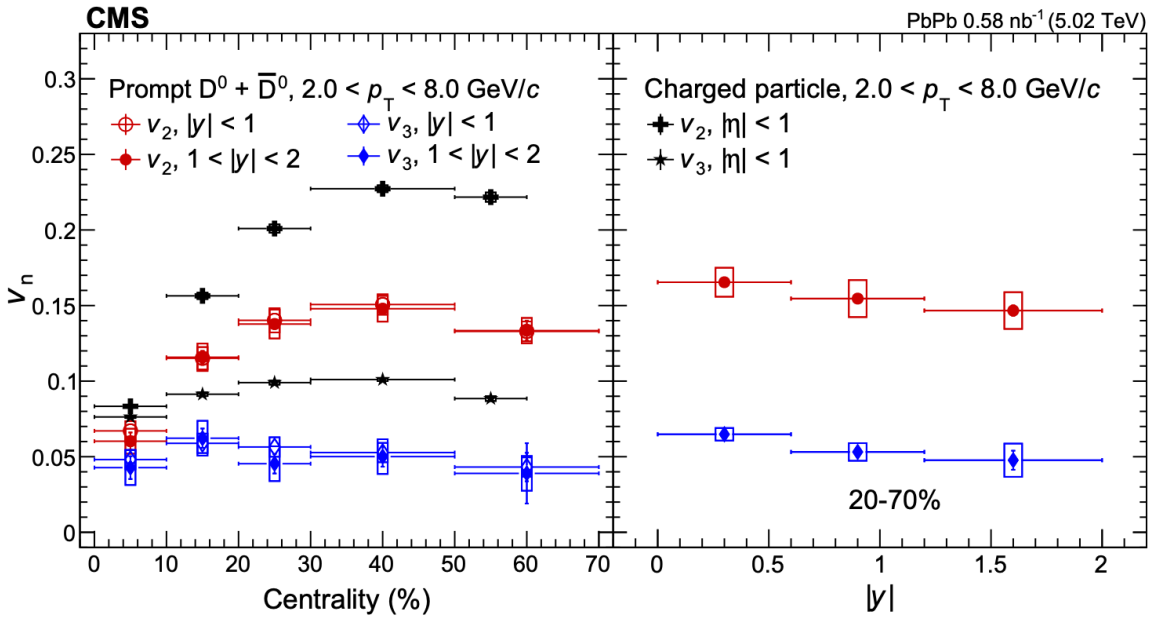
Do we see flow signals?

	Charged hadron	Strange	Prompt J/Ψ	b→ J/ψ	Prompt D^0	b→ D^0	Y(1S/2S)	Dijet	Z boson
PbPb	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**
pPb	**Yes**	**Yes**	**Yes**		**Yes**	**No**	**No**		
pp	**Yes**	**Yes**			**Yes**				

BACKUP - PROMPT D^0 IN PBPB

arXiv:2009.12628





- Significant prompt D^0 v_2 and v_3 in PbPb
- Less centrality dependence for v_3

K^0_S/Λ
pPb/PbPb
⬇
J/Ψ
PbPb
pPb
⬇
D^0
PbPb
pp/pPb
⬇
Y(1S/2S)
pPb/PbPb
⬇
Dijet
PbPb
⬇
Z boson
PbPb