Small system workshop

Future opportunities of collectivity in small systems at LHC

Maxime Guilbaud[(1)]

(1) CERN

16/03/19

New opportunities at LHC

Near and far future

- Run-3 + Run-4: Precision era
  - High lumi. LHC
  - Major upgrades on all experiments
    - ALICE: triggerless experiment, ITS+MFT…
    - ATLAS+CMS: timing layer (PID!!!), …
  - … in addition of some bonus (maybe?) from LHC: O-O run

- Run-5: Proposal for lighter ions

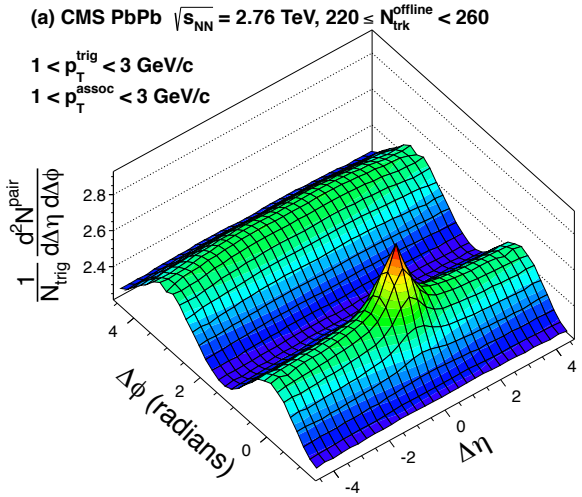
Proposed run scheduled

	Year	Systems, time, L_{int}	Total per Run (3 and 4)
RUN 3	2021 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.2/nb ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE O-O: 500/μb p-O: 200/μb
	2022 (6 weeks)	p-O + O-O 7 TeV, 1 week Pb-Pb 5.5 TeV, 5 weeks	
	2023 (4 weeks)	pp 8.8 TeV, few days p-Pb 8.8 TeV, 3.x weeks	
	LS3	ATLAS/CMS upgrades, ALICE: ITS3? FoCal?	
RUN 4	2027 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.8/nb, ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE
	2028 (6 weeks)	Pb-Pb 5.5 TeV, 2 weeks p-Pb 8.8 TeV, 3.x weeks pp 8.8 TeV, few days	
	2029 (4 weeks)	Pb-Pb 5.5 TeV, 4 weeks	
	LS4		
RUN 5		Intermediate AA, 11 weeks pp reference, 1 week	E.g. Ar-Ar 3-9/pb (optimal species to be defined)

This is only a proposal from a working group – none of this numbers are granted

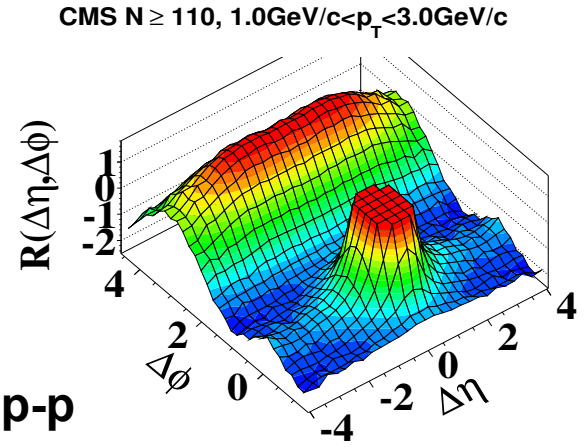
Why do we need this?

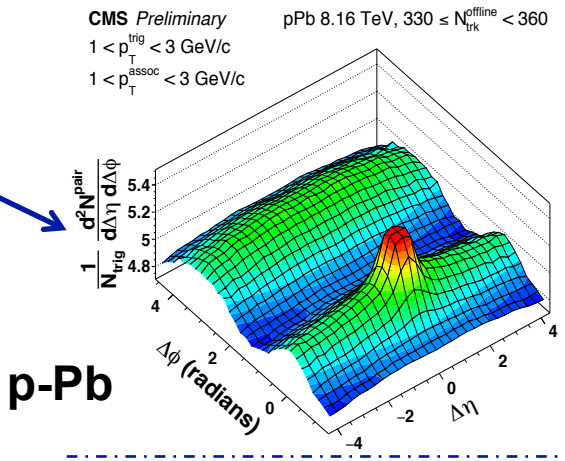
- Discovery of the ridge
  - Long range correlation
  - Similar to Pb-Pb collision



PLB (2013) 06, 028

Ridge observed in small systems

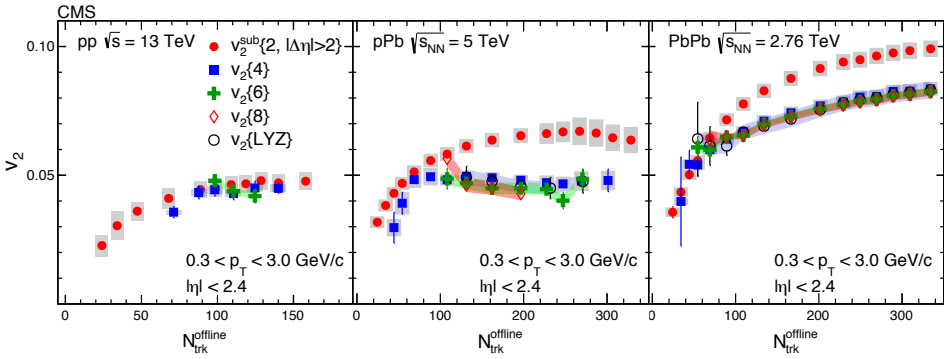




PRL (2018)120, 092301

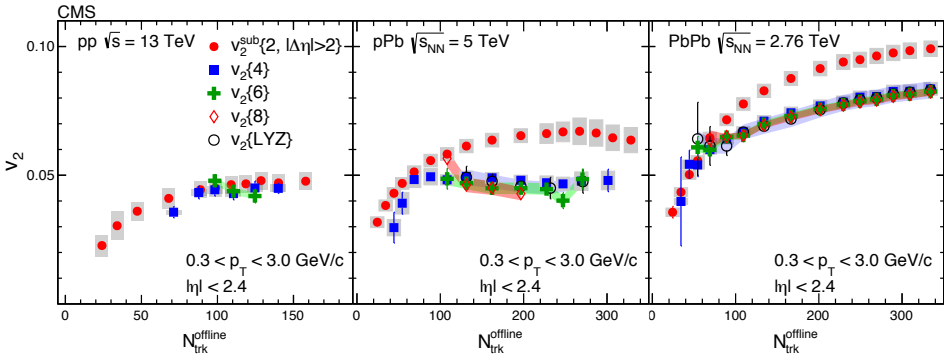
Question raised

- What is the nature of the ridge?
  - Collectivity
  - Multi-particle correlation



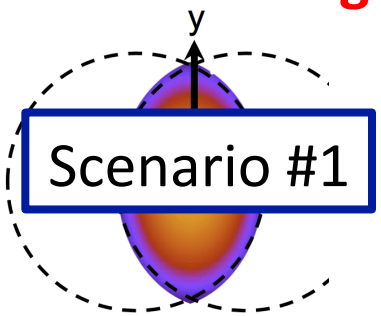
Question raised

- What is the nature of the ridge?
  - Collectivity
  - Multi-particle correlation



- How do we interpret that?

Observed long-range correlations in η ⇨ Rooted in **intial/early** stage

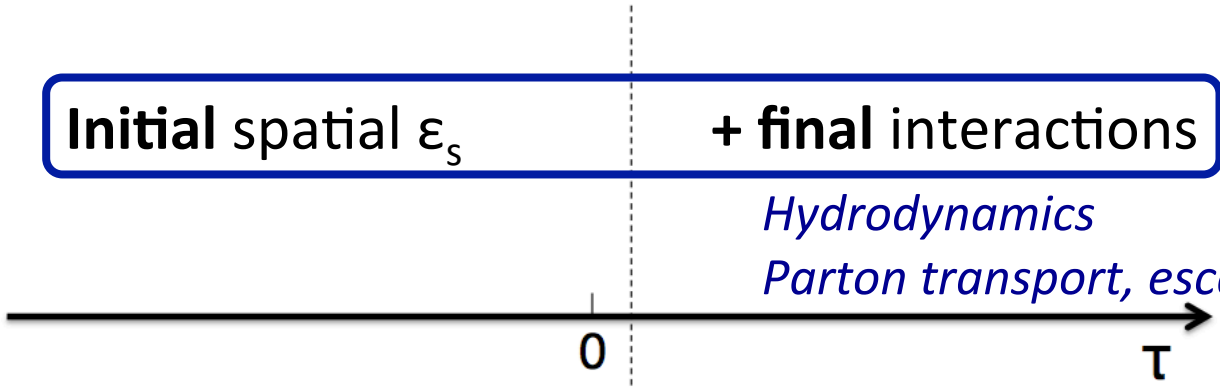


Scenario #1

Initial spatial ε_s **+ final** interactions

Hydrodynamics

Parton transport, escape



Scenario #2

Initial spatial ε_p
by initial interactions

CGC Glasma

Color-field domains, etc.

In other words…

Emergence of hot QCD phenomena in small colliding systems

- Standard descriptions of p-p, p-A, and AA physics may lack ingredients
- Common paradigm? Universality?

Where is the onset of collectivity if any?

- What are the least ingredients to observe collectivity in terms of mulitiplicity? Energy? Density? …
- No observation in electron-positron collisions so far

In other words…

Emergence of hot QCD phenomena in small colliding systems

- Standard descriptions of p-p, p-A, and AA physics may lack ingredients
- Common paradigm? Universality?

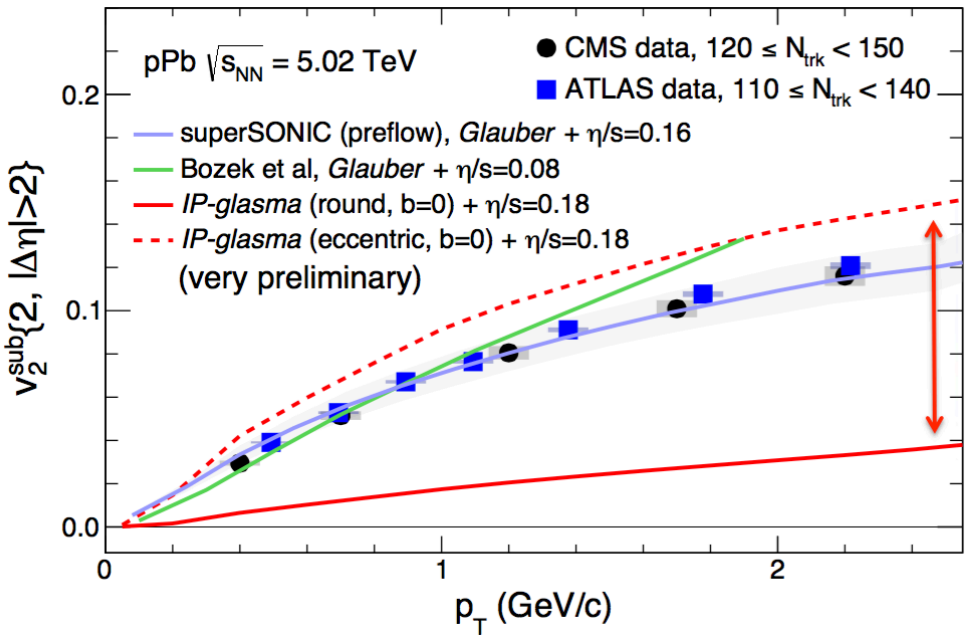
Where is the onset of collectivity if any?

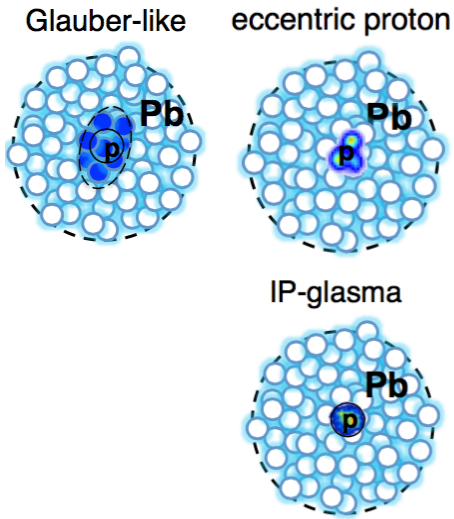
- What are the least ingredients to observe collectivity in terms of mulitiplicity? Energy? Density? …
- No observation in electron-positron collisions so far

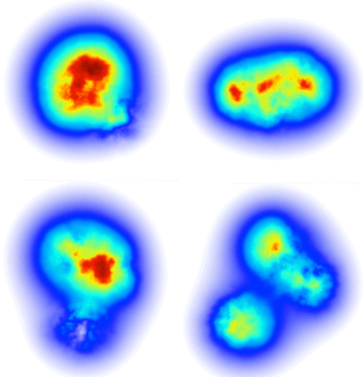
Disclamer: I am not intending to answer all these questions here.
Today I will focus and what LHC has to offer and what can be done

What are the driving factors?

- Initial geometry and its fluctuations







Mantysaari, Schenke, PRL 117, 052301 (2016)

- Medium response/transport coefficient (if any?)
- "background" – so-called non-flow also matters!

A lot of studies/measurements have already been carried out to understand all this aspects

State of the art

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)
Low p_{T} spectra ("radial flow")	yes	yes	yes
Intermediate p_{T} ("recombination")	yes	yes	yes
Particle ratios Statistical model	GC level $\gamma_s^{\mathrm{GC}} = 1$, 10–30%	GC level except Ω $\gamma_s^{\mathrm{GC}} \approx 1$, 20–40%	GC level except Ω MB: $\gamma_s^{\mathrm{C}} < 1$, 20–40%
HBT radii ($R(k_{\mathrm{T}})$, $R(\sqrt[3]{N_{\mathrm{ch}}})$)	$R_{\mathrm{out}}/R_{\mathrm{side}} \approx 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$
Azimuthal anisotropy (v_{n}) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Charge-dependent correlations	yes	yes	yes
Higher-order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)
Non-linear flow modes	up to v_6	not measured	not measured
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_{n} distributions	$n = 2$–4	not measured	not measured
Direct photons at low p_{T}	yes	not measured	not observed
Jet quenching through dijet asymmetry	yes	not observed	not observed
Jet quenching through R_{AA}	yes	not observed	not observed
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed†	suppressed	not measured

† J/ψ ↑, Υ(↓) w.r.t. RHIC energies.

State of the art

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)
Low p_{T} spectra ("radial flow")	yes	yes	yes
Intermediate p_{T} ("recombination")	yes	yes	yes
Particle ratios Statistical model	GC level $\gamma_s^{\mathrm{GC}} = 1$, 10–30%	GC level except Ω $\gamma_s^{\mathrm{GC}} \approx 1$, 20–40%	GC level except Ω MB: $\gamma_s^{\mathrm{C}} < 1$, 20–40%
HBT radii ($R(k_{\mathrm{T}})$, $R(\sqrt[3]{N_{\mathrm{ch}}})$)	$R_{\mathrm{out}}/R_{\mathrm{side}} \approx 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$
Azimuthal anisotropy (v_{n}) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Charge-dependent correlations	yes	yes	yes
Higher-order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)
Non-linear flow modes	up to v_6	not measured	not measured
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_{n} distributions	$n = 2$–4	not measured	not measured
Direct photons at low p_{T}	yes	not measured	not observed
Jet quenching through dijet asymmetry	yes	not observed	not observed
Jet quenching through R_{AA}	yes	not observed	not observed
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed†	suppressed	not measured

† J/ψ ↑, Υ(↓) w.r.t. RHIC energies.

A lot of work still need to be done

State of the art

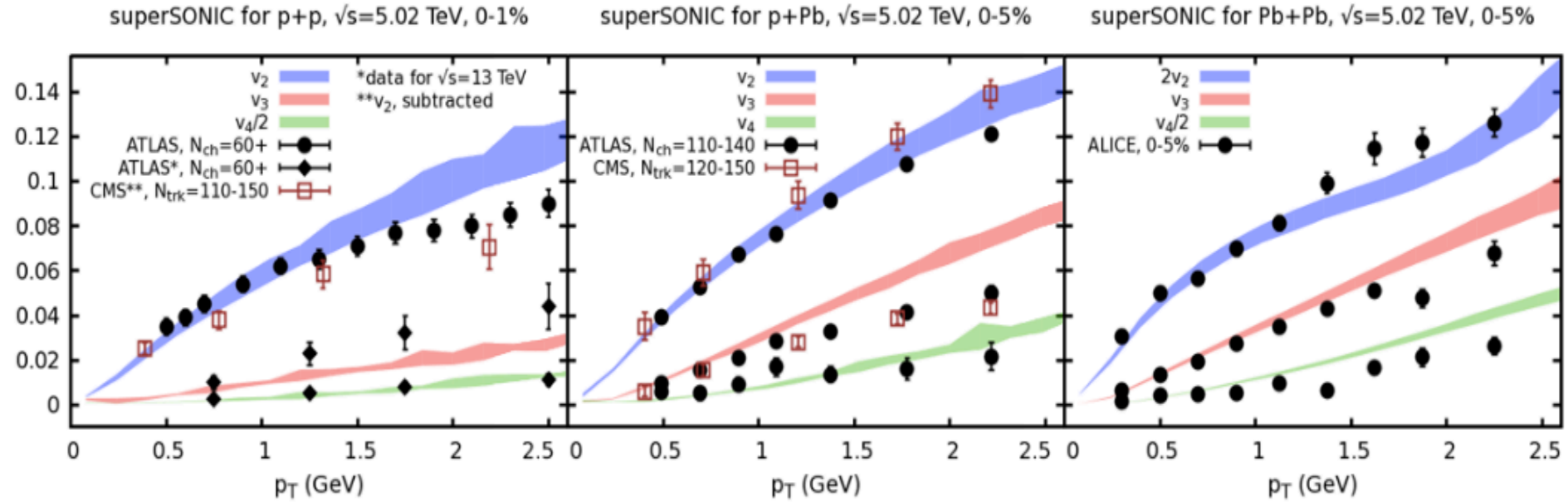
Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)
Low p_{T} spectra ("radial flow")	yes	yes	yes
Intermediate p_{T} ("recombination")	yes	yes	yes
Particle ratios Statistical model	GC level $\gamma_s^{\mathrm{GC}} = 1$, 10–30%	GC level except Ω $\gamma_s^{\mathrm{GC}} \approx 1$, 20–40%	GC level except Ω MB: $\gamma_s^{\mathrm{C}} < 1$, 20–40%
HBT radii ($R(k_{\mathrm{T}})$, $R(\sqrt[3]{N_{\mathrm{ch}}})$)	$R_{\mathrm{out}}/R_{\mathrm{side}} \approx 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$
Azimuthal anisotropy (v_{n}) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Charge-dependent correlations	yes	yes	yes
Higher-order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)
Non-linear flow modes	up to v_6	not measured	not measured
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_{n} distributions	$n = 2$–4	not measured	not measured
Direct photons at low p_{T}	yes	not measured	not observed
Jet quenching through dijet asymmetry	yes	not observed	not observed
Jet quenching through R_{AA}	yes	not observed	not observed
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed†	suppressed	not measured

A lot of work still need to be done

Still a significant fraction of these observables are lacking of (robust) pre/post-diction

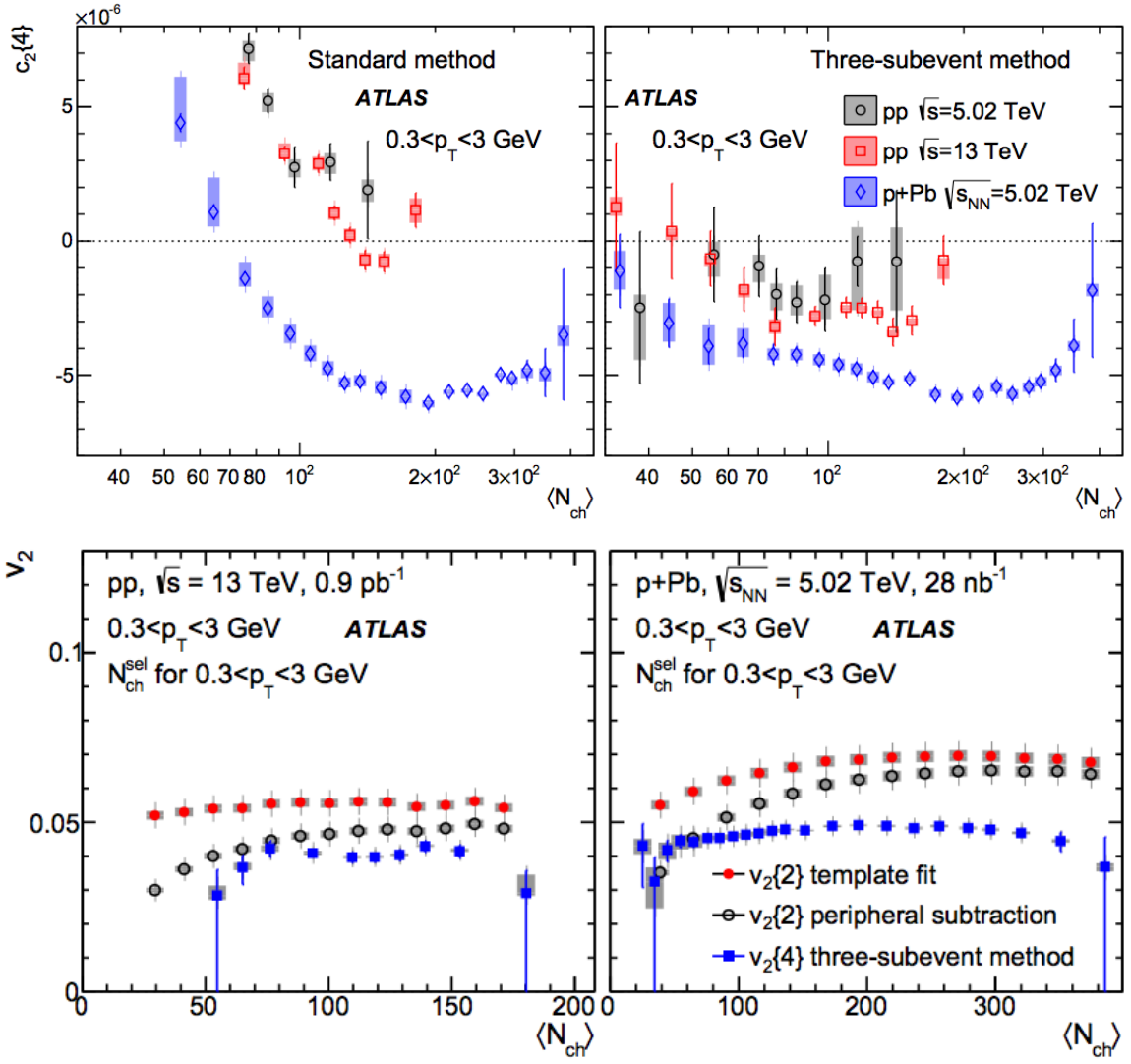
A word on $v_2\{2\}$

- Extensively measured in data at LHC
- Theoretical prediction available for most of the "competitors"
  - One example bellow
- More data won't bring much for this observable only
  - Not forgetting about known experimental ambiguity
  - Systematic and much more precise PID studies still can be performed



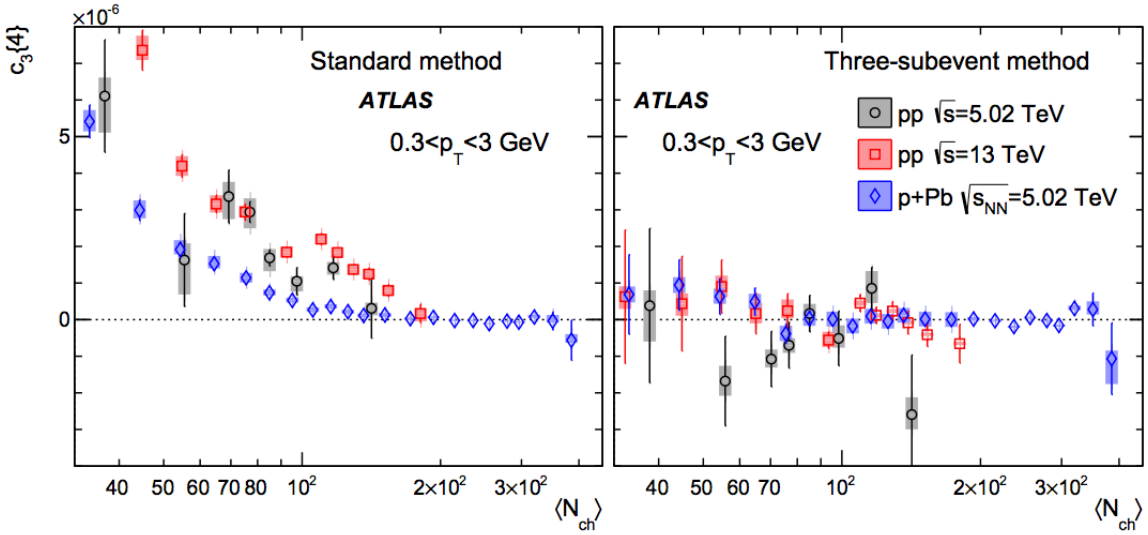
Multi-particle cumulant c_2 (v_2) Run 1 + 2 results

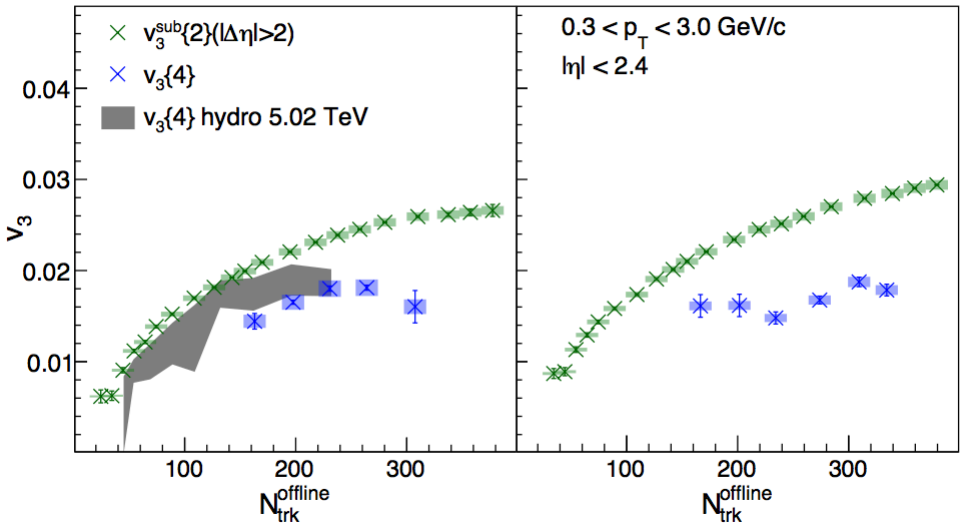
- Probe collectivity
  - Golden observable so far
- Sensitive to:
  - **IS geometry and fluctuations**
  - **Flow fluctuations** $P(v_n)$
  - … but also non flow
    - *Subevent needed to study the onset*
- Sub-event technique mitigate the issue but require larger sample



Multi-particle cumulant c_3 (v_3) Run 1 + 2 results

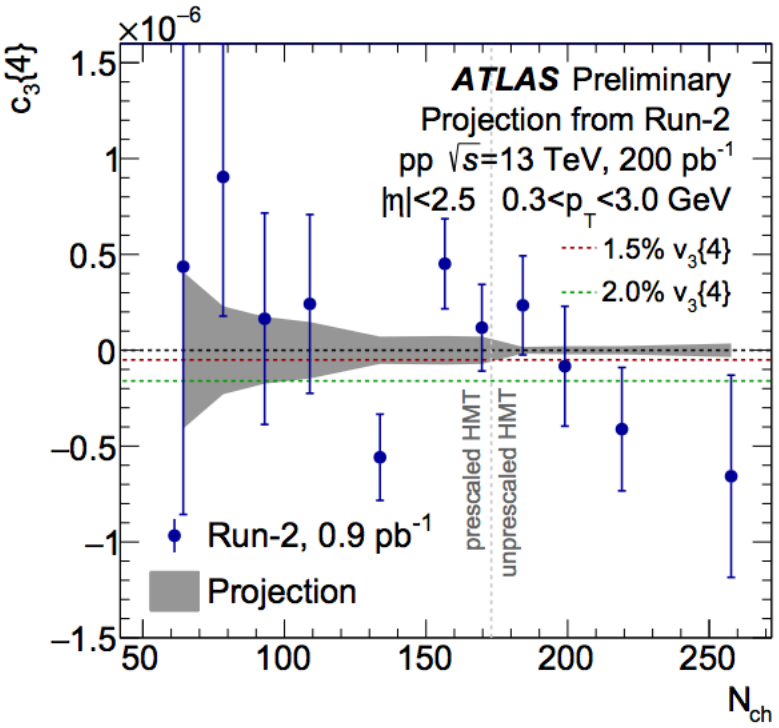
- v_3 is a better handle to study IS fluctuations
  - Easier to understand things when you try to break the problem in pieces
- Caveats:
  - Harder to get
  - Need more statistic and precise measurement
  - Need to go down in multiplicity

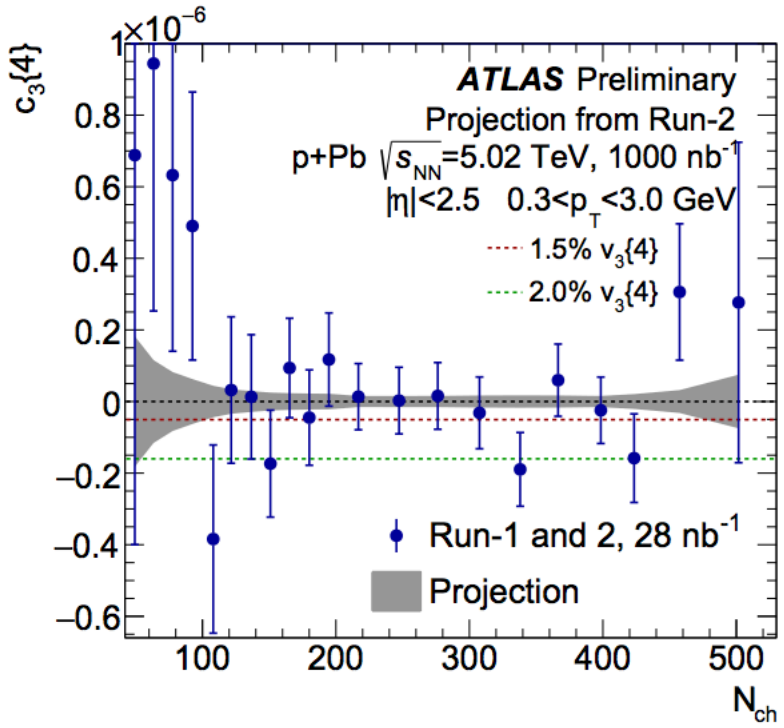




Prediction for HL-LHC

- Large sample available at HL-LHC will drastically reduce the statistical precision for all harmonic order (2, 3 and beyond)
  - At low multiplicities: onset of collective signal
  - At high multiplicities

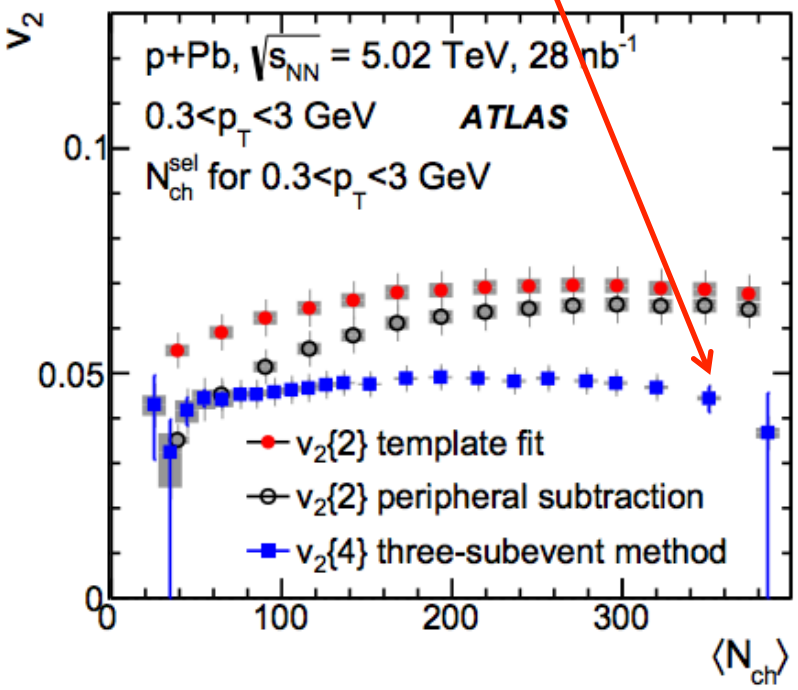


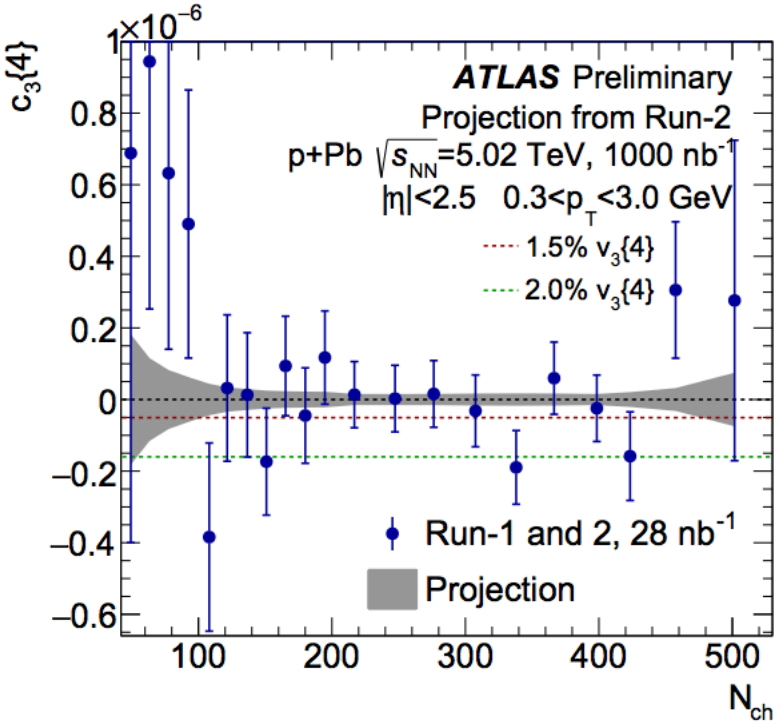


Prediction for HL-LHC

- Large sample available at HL-LHC will drastically reduce the statistical precision for all harmonic order (2, 3 and beyond)
  - At low multiplicities: onset of collective signal
  - At high multiplicities

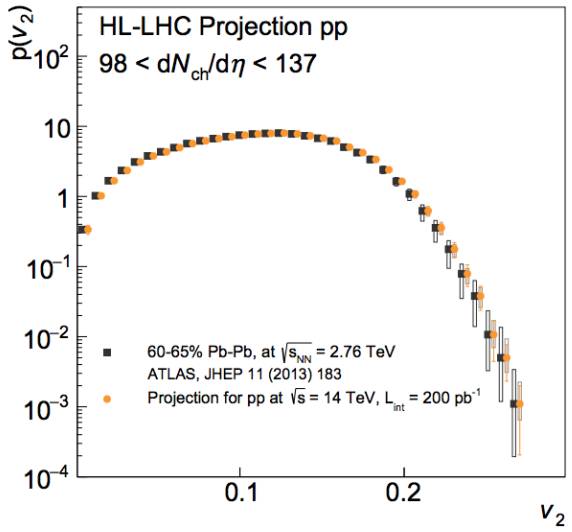
Is it really constant at high N_{ch}?

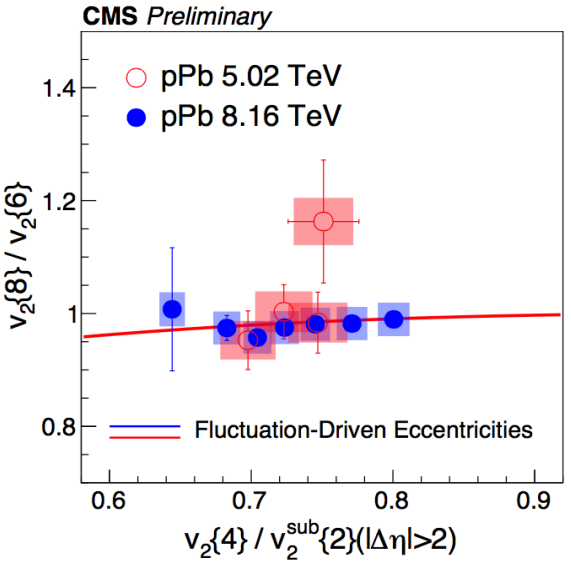




Is the v_n driven by ε_n in small system?

- $P(v_n)$ has never been measured in small systems
  - Measurement enable at HL-LHC
  - Details of IS conditions and FS dynamics
  - Better handle on flow fluctuations
- Cumulant ratio
  - Shape of the distribution linked to universality
  - Same in p-A and A-A? What about p-p
- Complementary informations
  - Most straight forward way to understand if eccentricity plays a major role
  - Needs high precision cumulant measurement together with $P(v_n)$ distribution

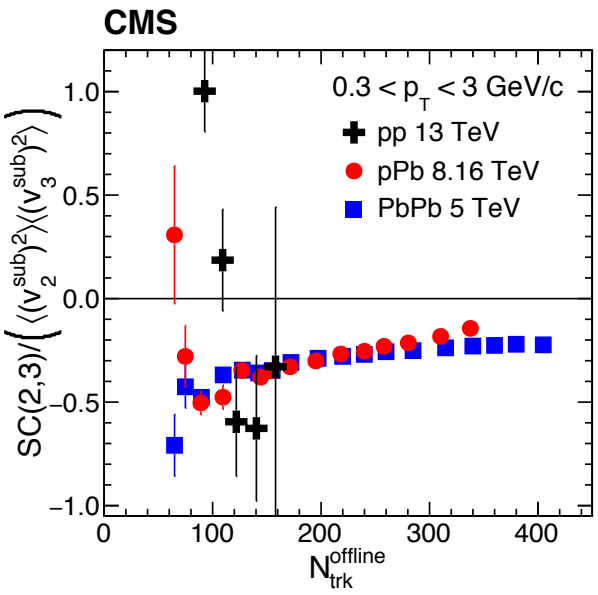


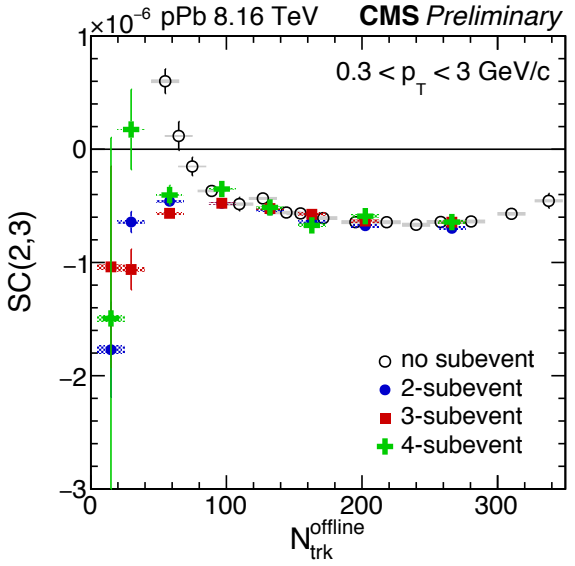


Deeper into the details: SCs

- Symmetric cumulant $SC(n,m) = \left\langle v_n^2 v_m^2 \right\rangle - \left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle$
  - Correlation between harmonics
  - Sensitive to both medium response and IS fluctuation (depending on *n* and *m*)
  - Cumulant based technique: same advantages/same caveats

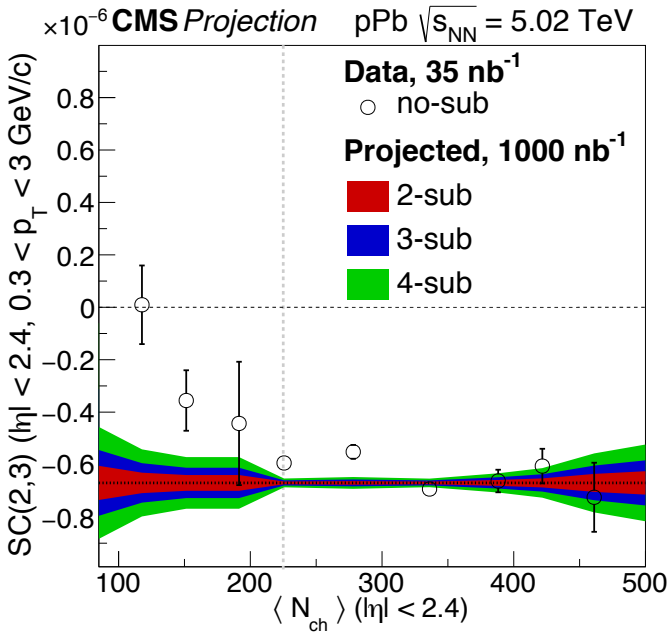
- Within current precision: p-A and A-A are very similar at high multiplicity
  - w/ or w/o subevents





HL-LHC prediction for SCs

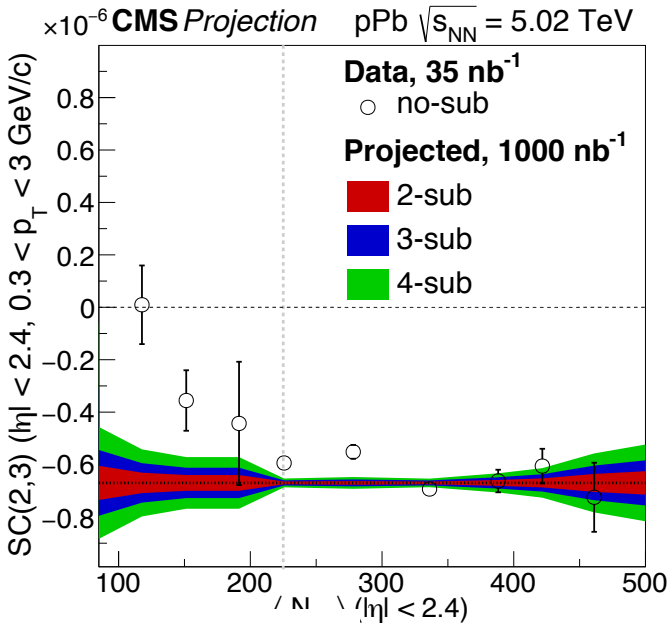
- Great improvement of the experimental precision there in pp and pA
- Will lead to tighter constrains on IS here **EVEN IF** so far not a lot of theoretical calculation are available



HL-LHC prediction for SCs

- Great improvement of the experimental precision there in pp and pA
- Will lead to tighter constrains on IS here **EVEN IF** so far not a lot of theoretical calculation are available

  … despite interesting effort to understand this via a wounded hot-spot approach



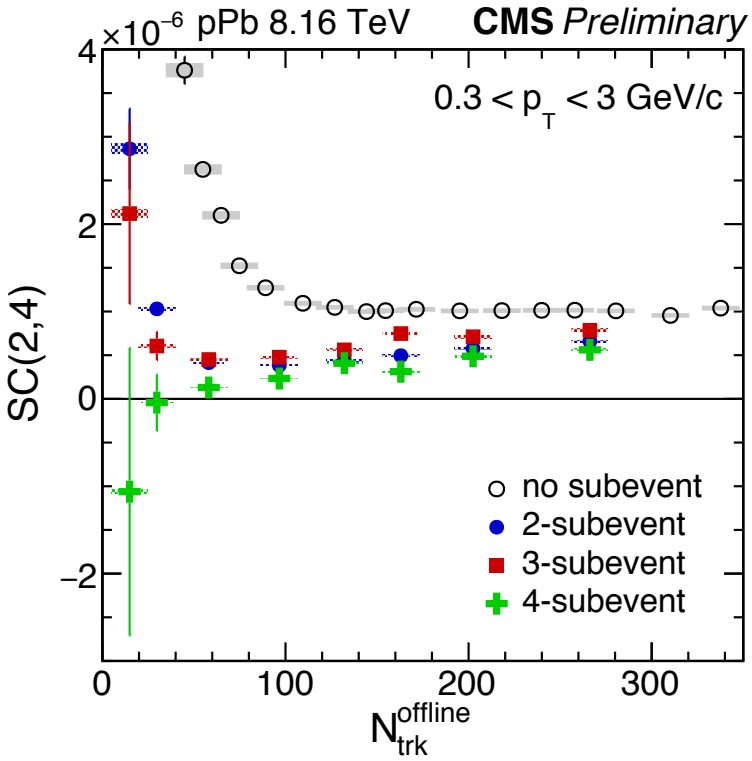
Symmetric cumulants as a probe of the proton substructure at LHC energies

Javier L. Albacete,[1,*] Hannah Petersen,[2,3,4,†] and Alba Soto-Ontoso[1,2,‡]

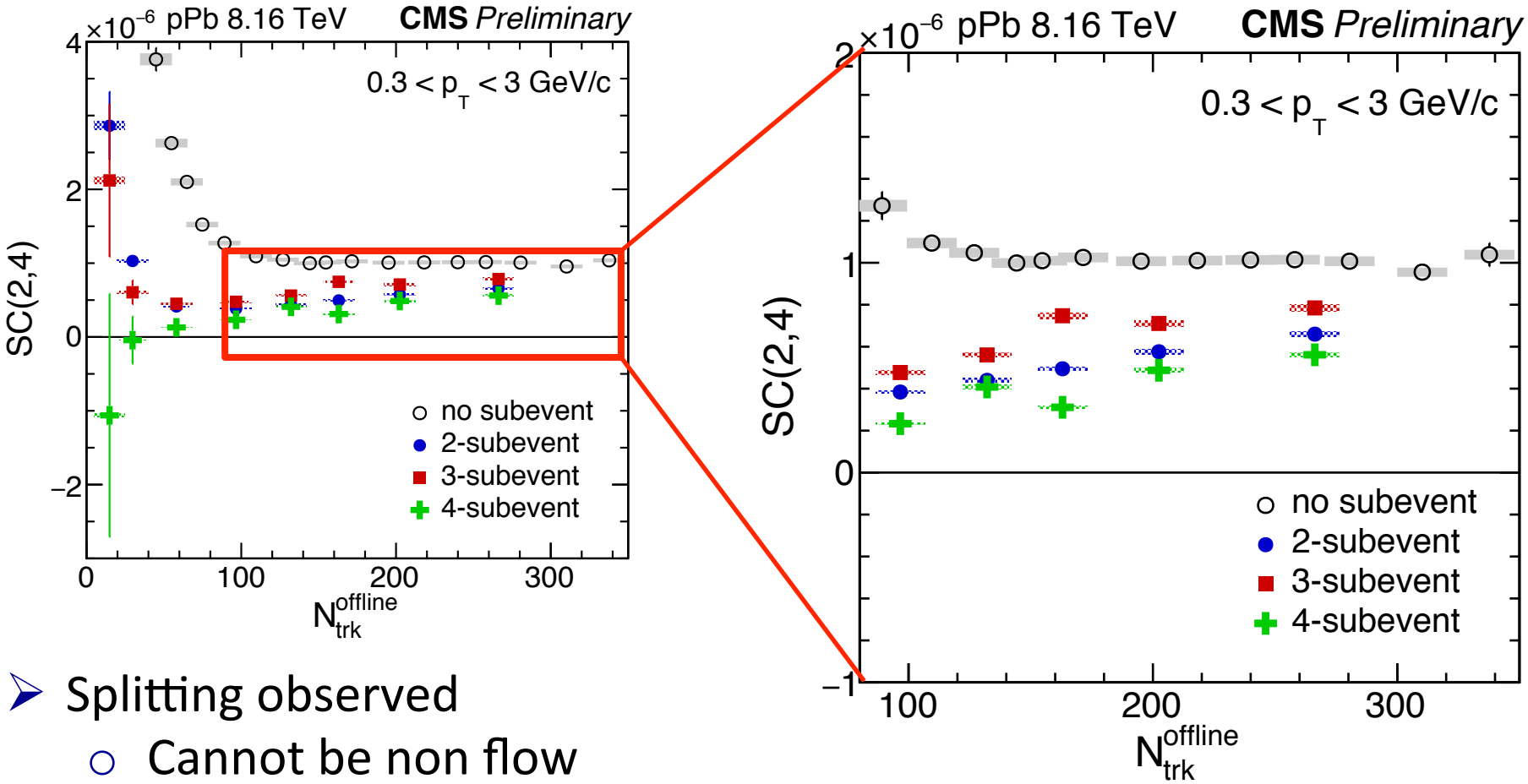
https://arxiv.org/pdf/1707.05592.pdf

Really need to understand how to discribe the IS condition -- is there any geometrical contribution at the sub-nucleonic scale?

SC(2,4) – a more complex case



SC(2,4) – a more complex case

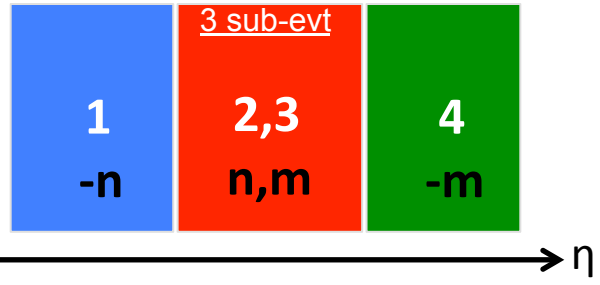


- Splitting observed
  - Cannot be non flow
  - Factorization breaking – also observed by ATLAS https://arxiv.org/pdf/1705.04176.pdf

Can we factorize out contributions?

Longitudinal dynamics

- Detailed studies of this in small system are still not fully covered
  - In particular the effect on sub-event cumulant
  - This is shown in the data but poorly quantified

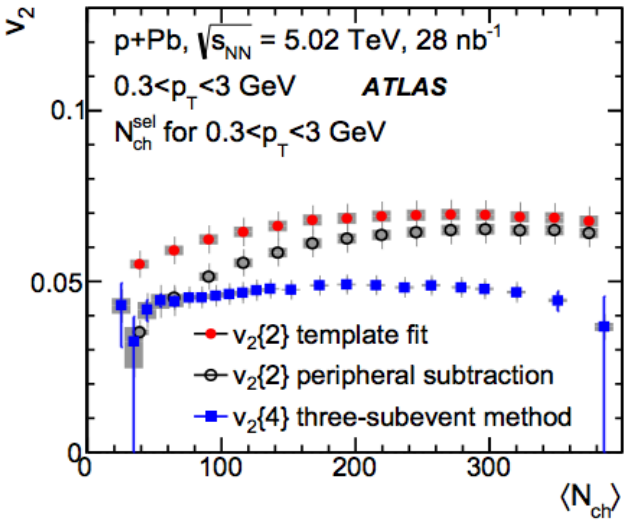


- Some ideas to study that
  - "Standard" way: look at cumulant with different number of sub-event and compare OR look at correlators directly <<4>>, <<2>>, …
  - "non-standard" way: Possible to combine (add, subtract, …) to isolate terms that are dominated by factorisation breaking
    - Is this possible?
    - Needs to make sure that anything measured is actually usable for our theory friends
  - Other ideas?

Can we factorize out contributions?

Non flow

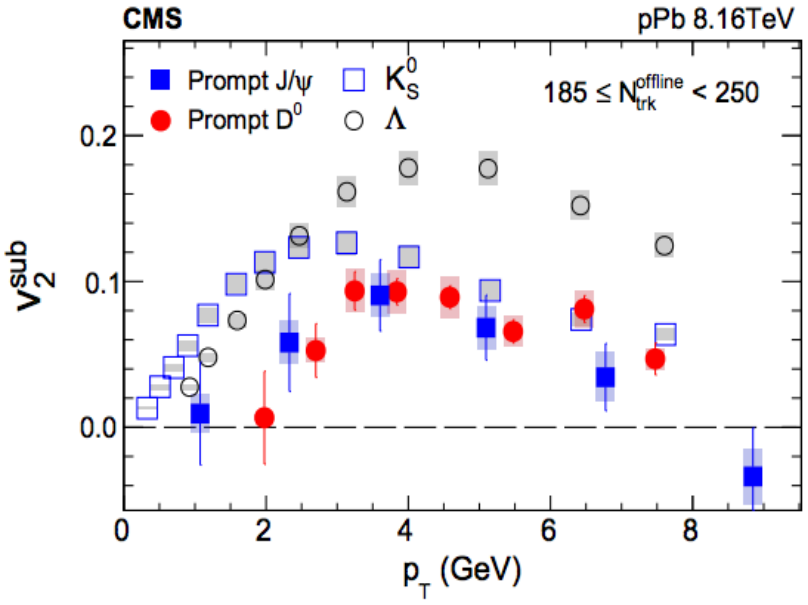
- A proper understanding of flow goes with a proper understanding of non-flow
  - Different method from 2-p give different answer based on assumption
  - Important to study the onset



- Cumulant with sub-event helps but can we do better?
  - Can we factorise out (partially) terms that depends on non-flow in subevent cumulant and actually measure it?
    - Comparison/combination of various definition of n-subevent cumulant
  - Not trivial most likely ☹

Hard sector: heavy flavor v_n

- Large v_2 observed for charmed quark
  - Similar magnitude for J/Ψ and D^0
  - Smaller than lighter flavor at low p_T
  - Uncertainties are still large
- The observed pattern is still very similar to A-A

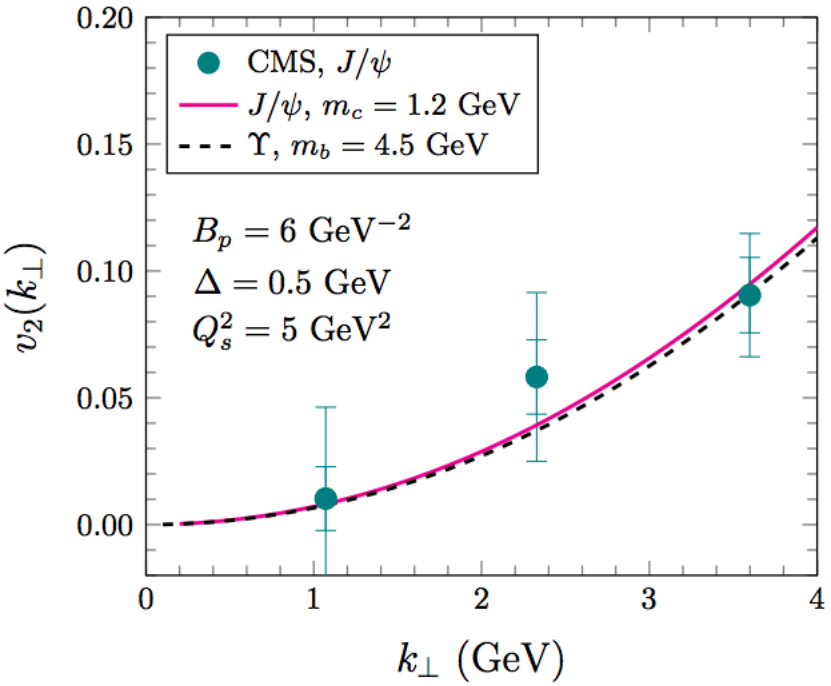


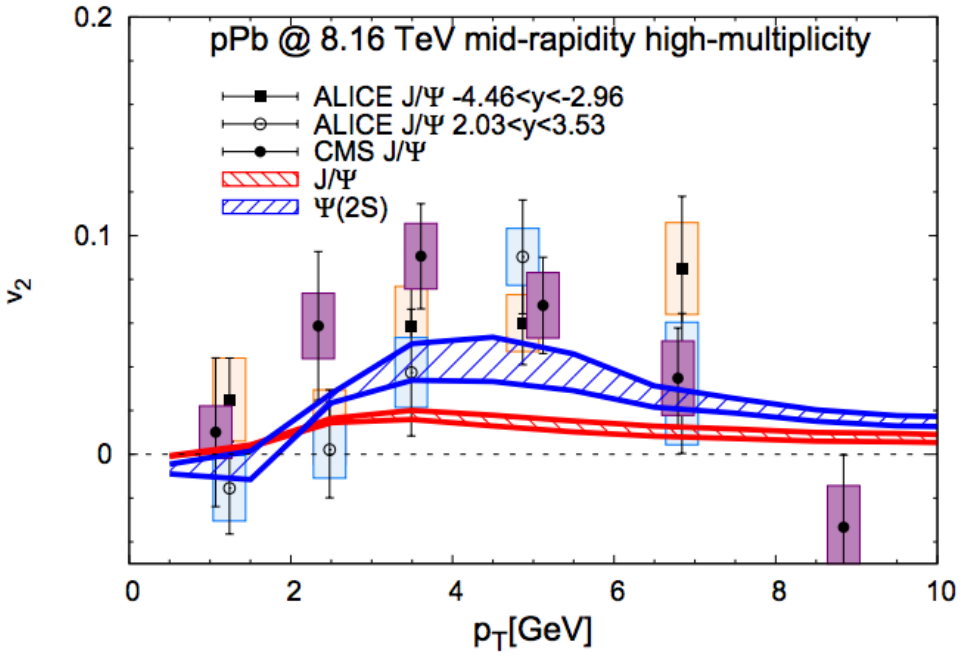
Magnitude surprisingly high!!!

The puzzle

- Data compared to Model
  - IS interaction like (CGC -- left)
  - Final state interaction like (Rapp -- right)

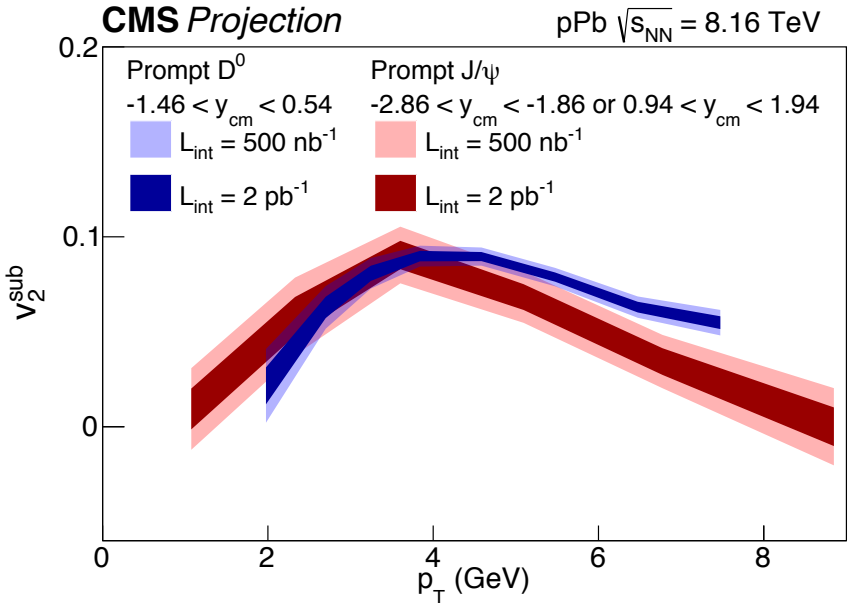
- Final state interaction alone cannot explain this

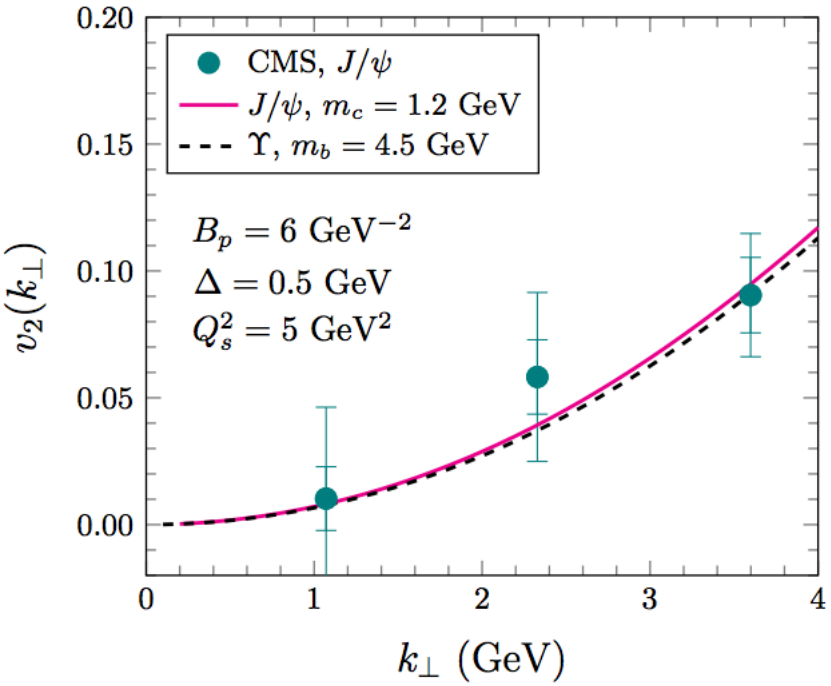




What can be improved?

- Measurement precision
  - Projection already done for HL-LHC



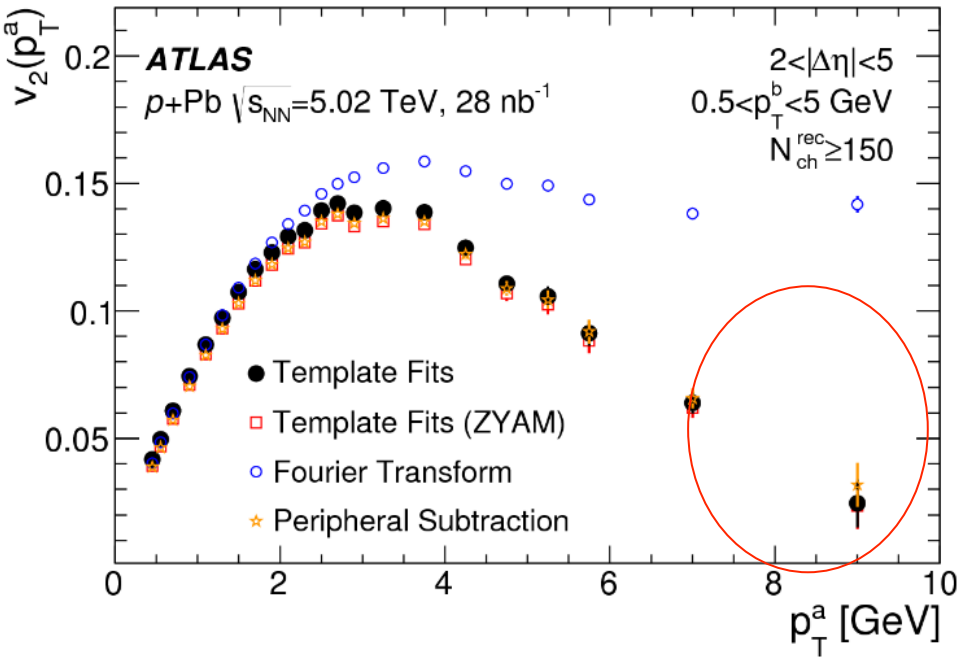


  - Upsilon v_n even more exciting in pPb

- What about small systems like p-p?
  - More data are needed to hope for equivalent signal significance respect to pPb

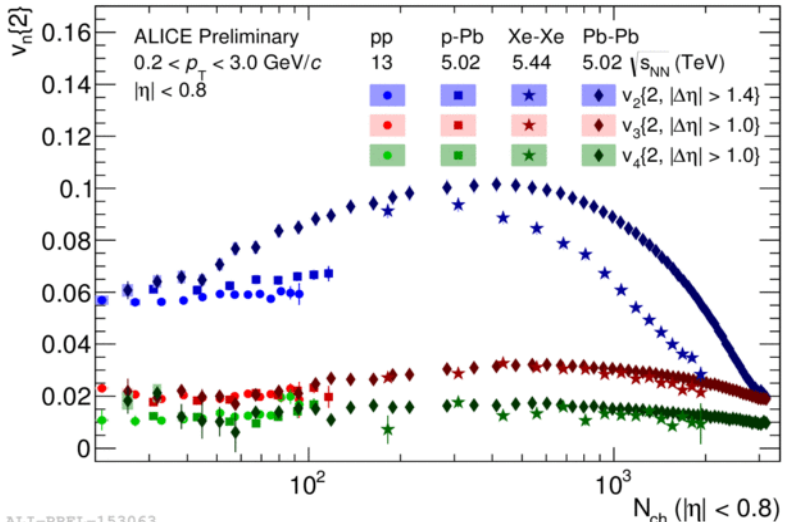
Hard sector: high-p_T v_n

- High-p_T v_2 related to parton energy loss
  - Unbiais observable compared to R_{AA}
  - No reference needed
- If jet-quenching exist in small systems such as pPb and pp, it very small
  - Can look at high-p_T v_n
  - Need to suppress non-flow their
    - 2PC + gap not sufficient probably
    - Need cumulant + sub-event



Light ions, Run3/4 and beyond

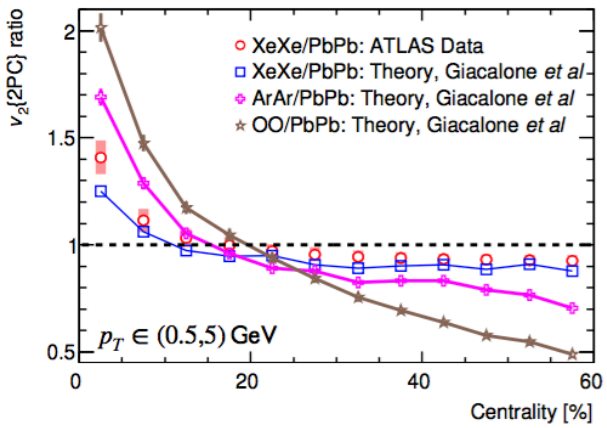
- From pp -> pA -> AA
  - Difficult to understand
    - Different geometry
    - Some signatures are there but some are not (jet-quenching)

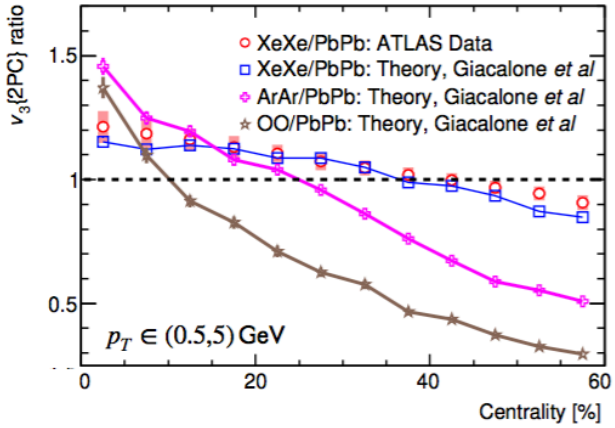


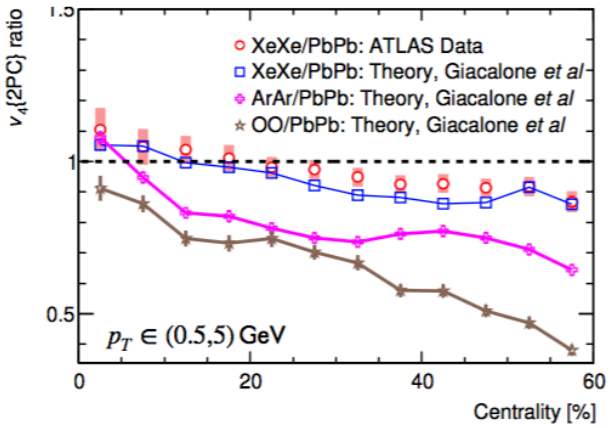
- System size dependence
  - What about smaller systems?
  - Opportunities to collect some O-O at LHC
    - A-A geometry but similar to p-Pb in terms of multiplicity, N_{part}…
    - Better understanding of the transition pA->AA
    - O-O system large enough to observe jet quenching

Light ions, Run3/4 and beyond

- Also some potential request for other species in Run 5
  - Going toward smaller ions Ar-Ar
    - Get more control on the geometry while studying the onset of collectivity







Wrap-up

- LHC will offer new opportunities
  - More precise/differential measurement from soft to hard sector
  - New colliding systems
  - Better detection systems: extended coverage, PID, large data acquisition capacities
- Need to find a coherent explanation for all the signature observed in small systems
  - Being able to chose between various scenario require close collaboration between theory and experiment
    - Find observable and event classification that are usable for all
  - Break the problem in pieces
    - Systematic studies of various observable
    - Factorization
- One way to go would be to combine cumulants with various “flavor” of subevents to isolates terms that strongly depends on non-flow or sensitive to factorization breaking for exemple