



Particle production and collectivity across system size

Jan Fiete Grosse-Oetringhaus, CERN
on behalf of WG5

HL/HE-LHC Physics Workshop: Final Jamboree, CERN
01.03.19

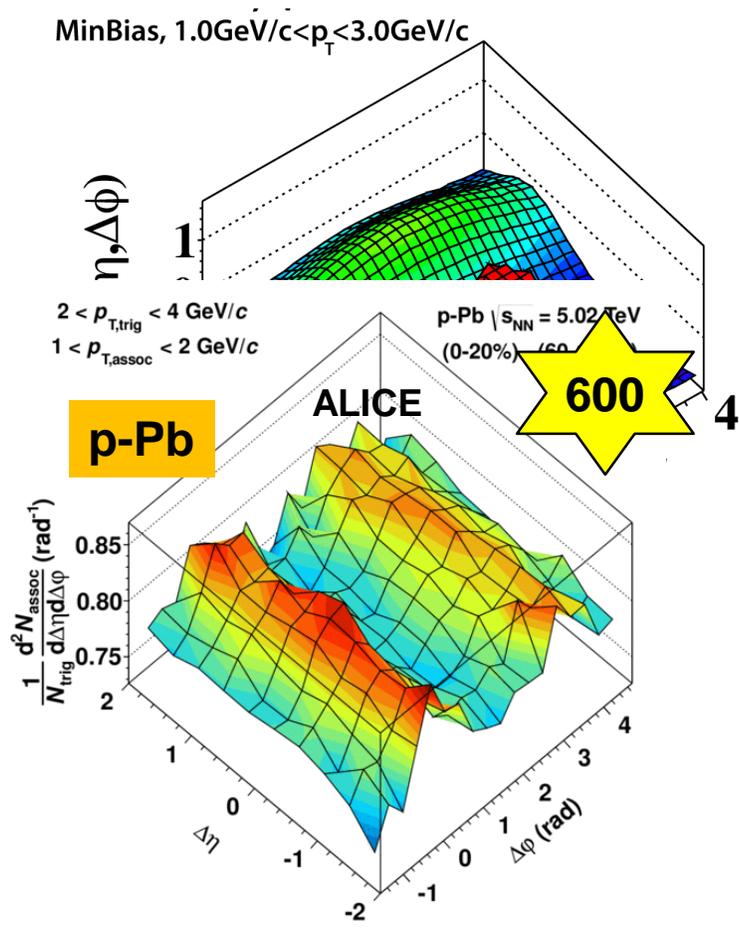
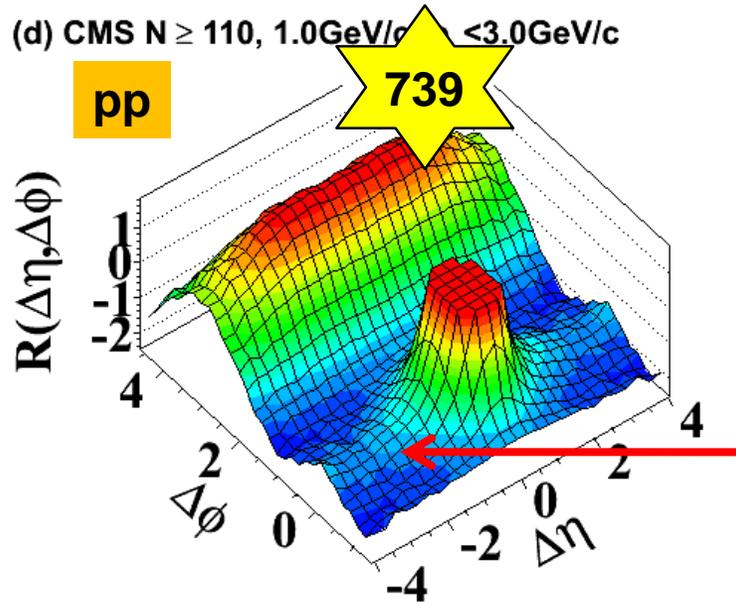


Preamble

None of the content of this talk was known when LHC was proposed, and when LHC started

First Discovery: The Ridge

Run 1+2



Collectivity in small systems: I

Urs Wiedem...

Sala Mosaici-1, 3rd Floor, Palazzo del Casinò

Correlations and fluctuations: I

Jacquelyn No...

Sala Perla, 1st Floor, Palazzo del Casinò

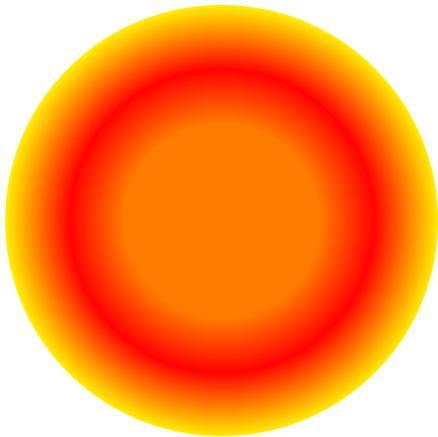
Quark Matter 2018

CMS. JHEP09(2010)091

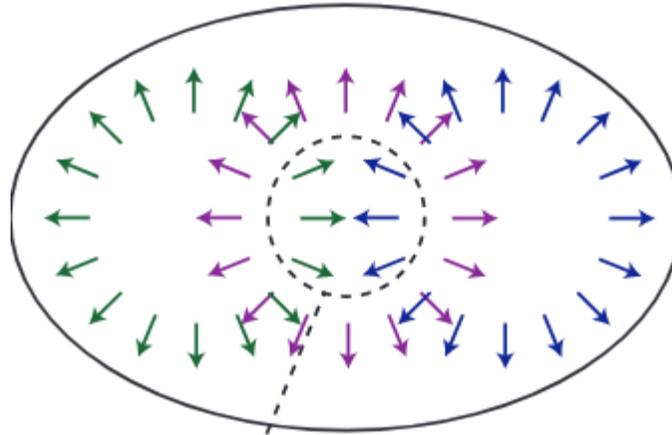
ALICE, PLB719 (2013) 29
 and also ATLAS, PRL110(2013)18,182302

Explanations

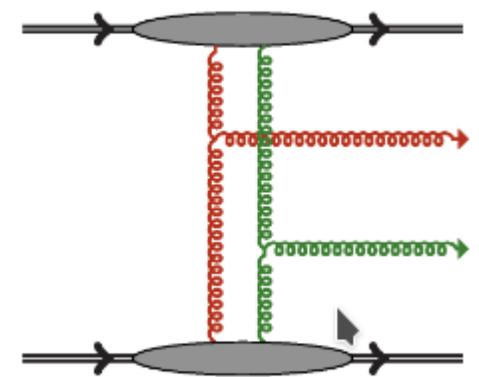
Hydrodynamic evolution



Escape mechanism



Initial-momentum correlations



PRD87(2013) 9,094034

PLB783(2018) 274

Many scatterings



Few scatterings

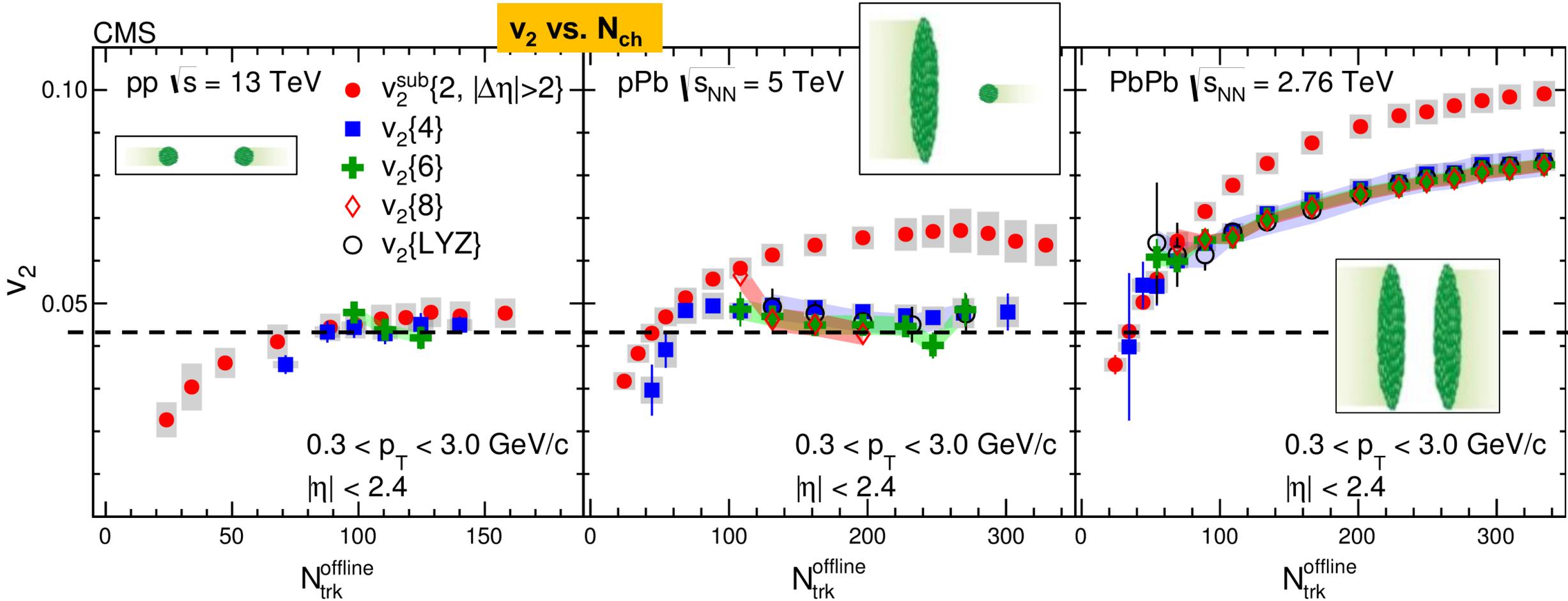


Initial conditions

(Perfect) fluid dynamics ↔ free streaming limit

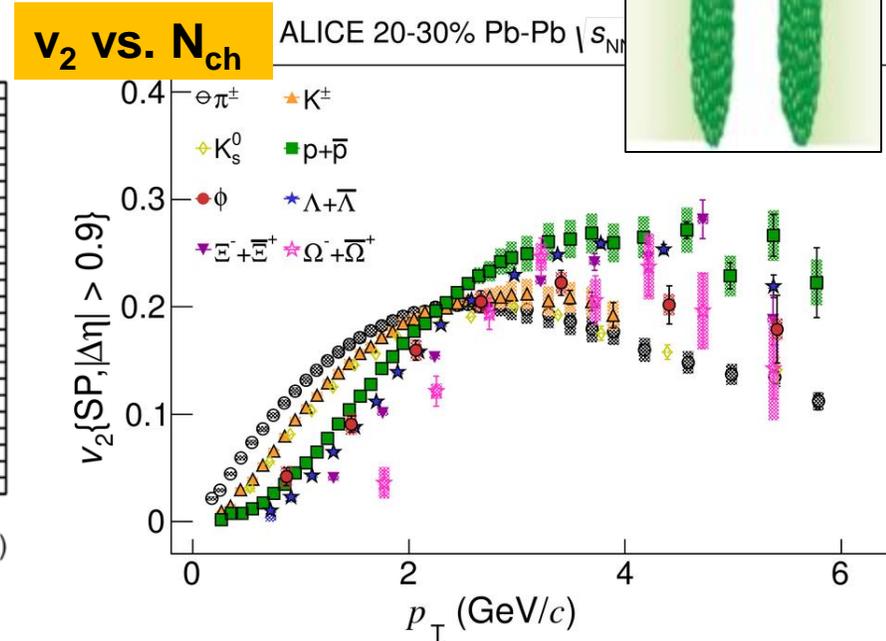
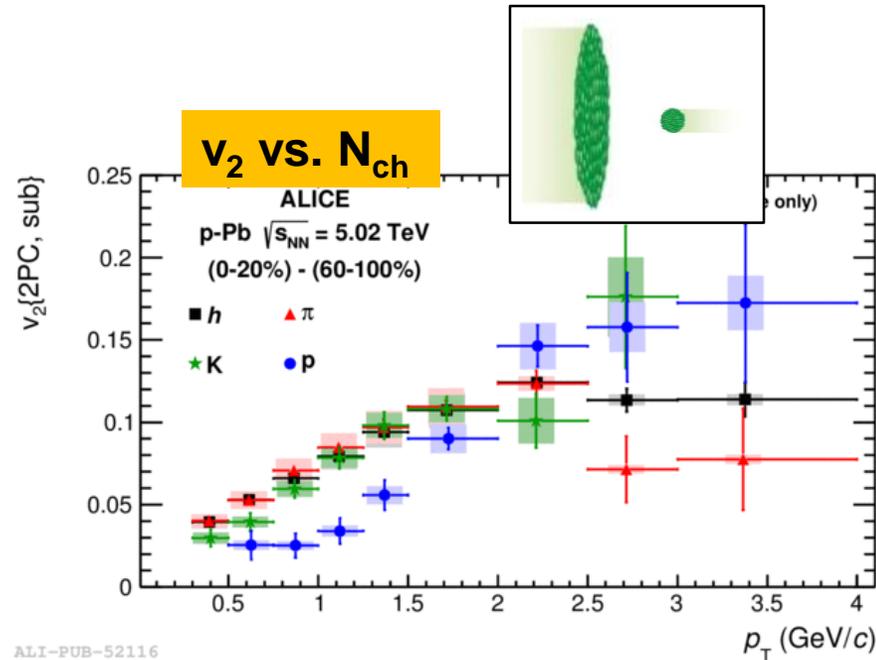
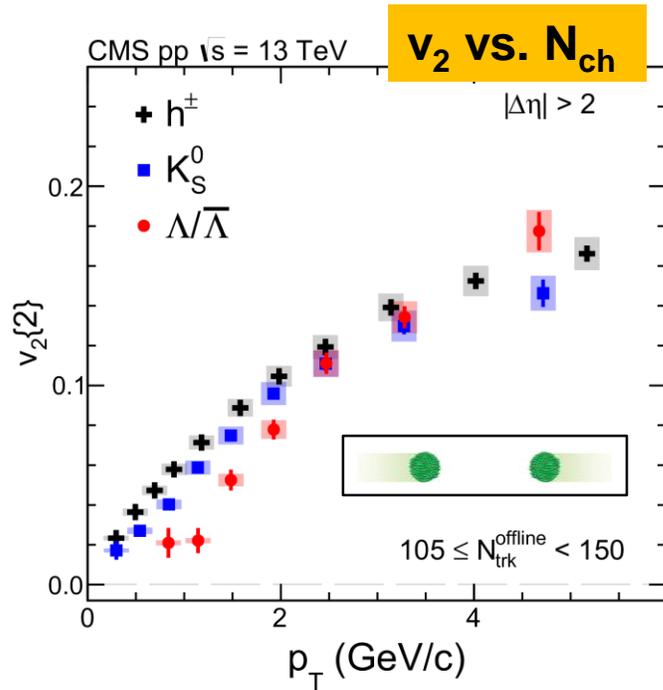
Theory spans still today a wide field

System Comparison



Ridge component characterized with multi-particle correlations: pp ~ p-Pb < Pb-Pb
→ True collective effect above $N_{ch} \approx 100$

System Comparison – Identified Particles



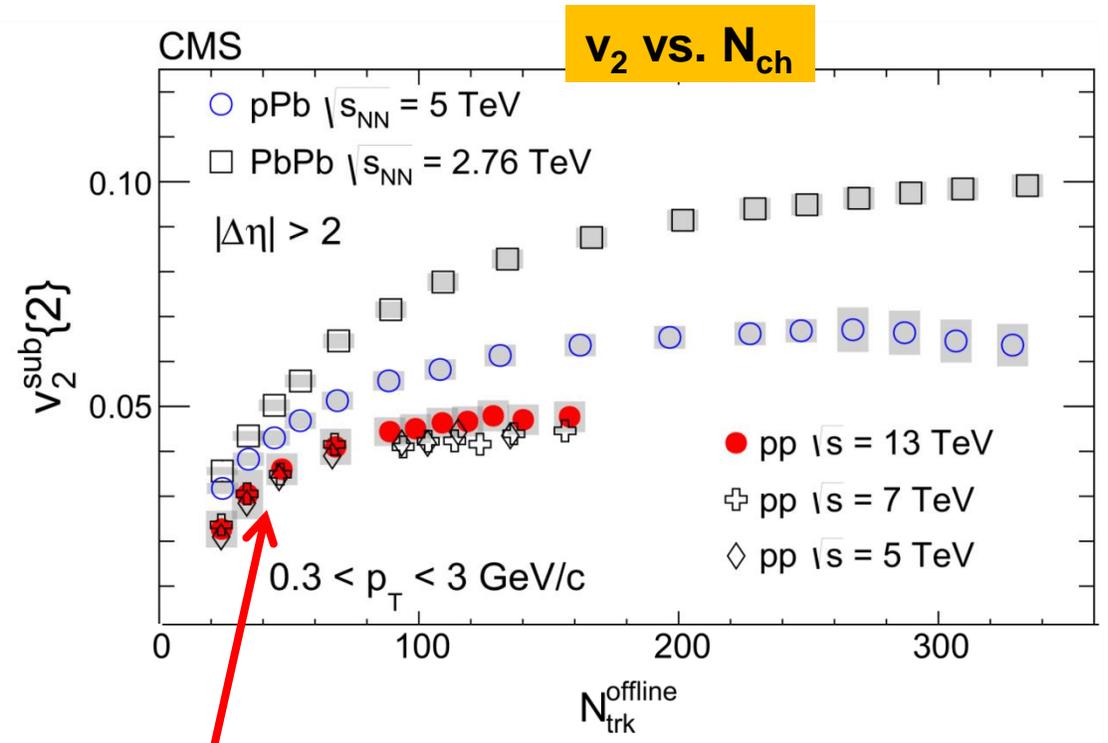
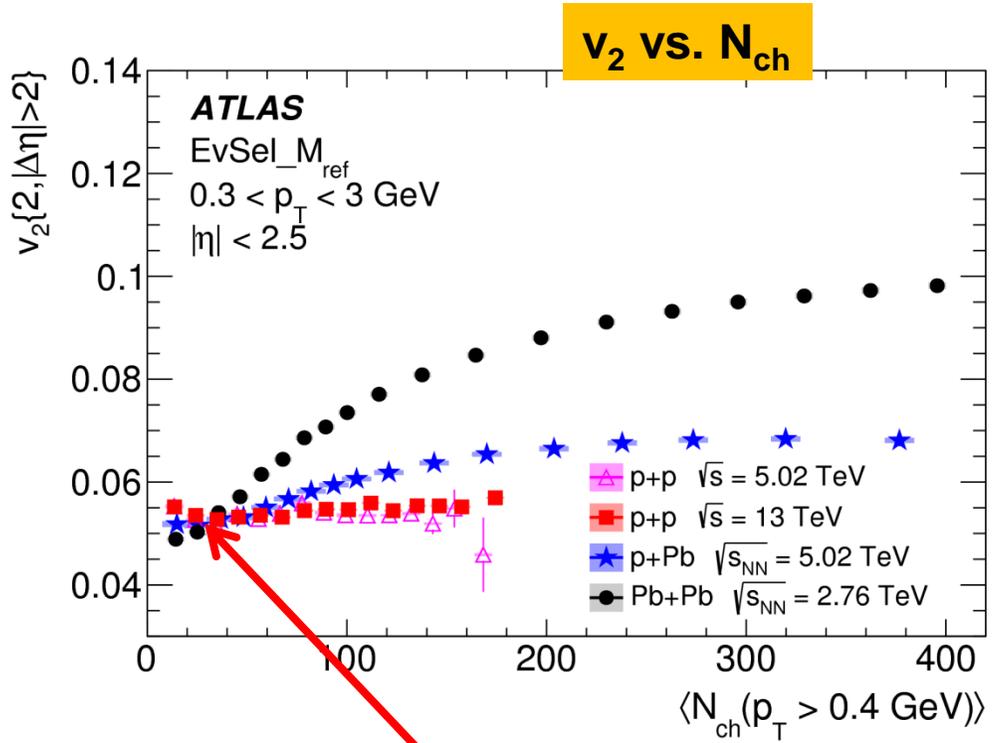
Mass splitting and crossing observed in small and large systems

PLB765 (2017) 193

PLB726 (2013) 164

JHEP06 (2015) 190

v_2 Coefficients in pp



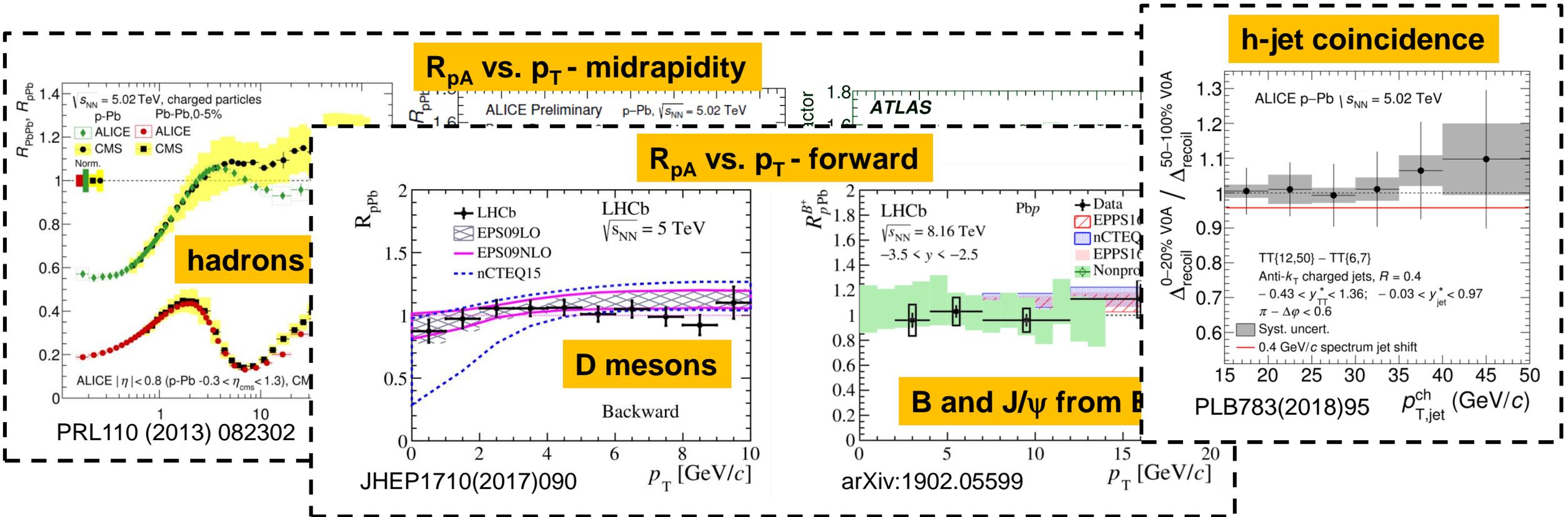
Few particle correlations dominated by jets, resonance decays
Experimental result : procedure dependent

Collective nature of dilute systems not understood, yet

Energy Loss

Run 1+2

- If v_n are caused by final-state interactions, partons should lose energy

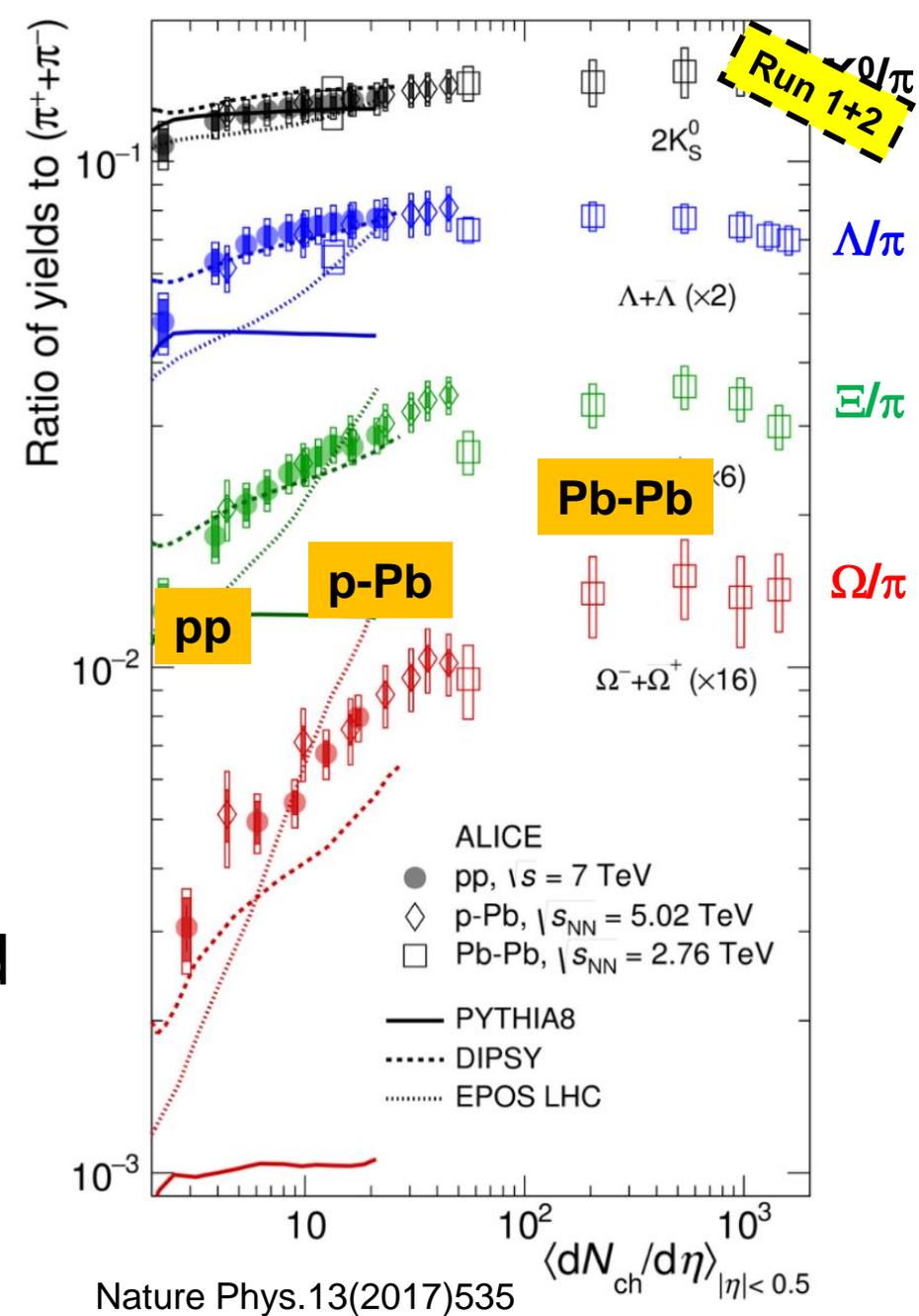


No significant signal observed for hadrons, D and B



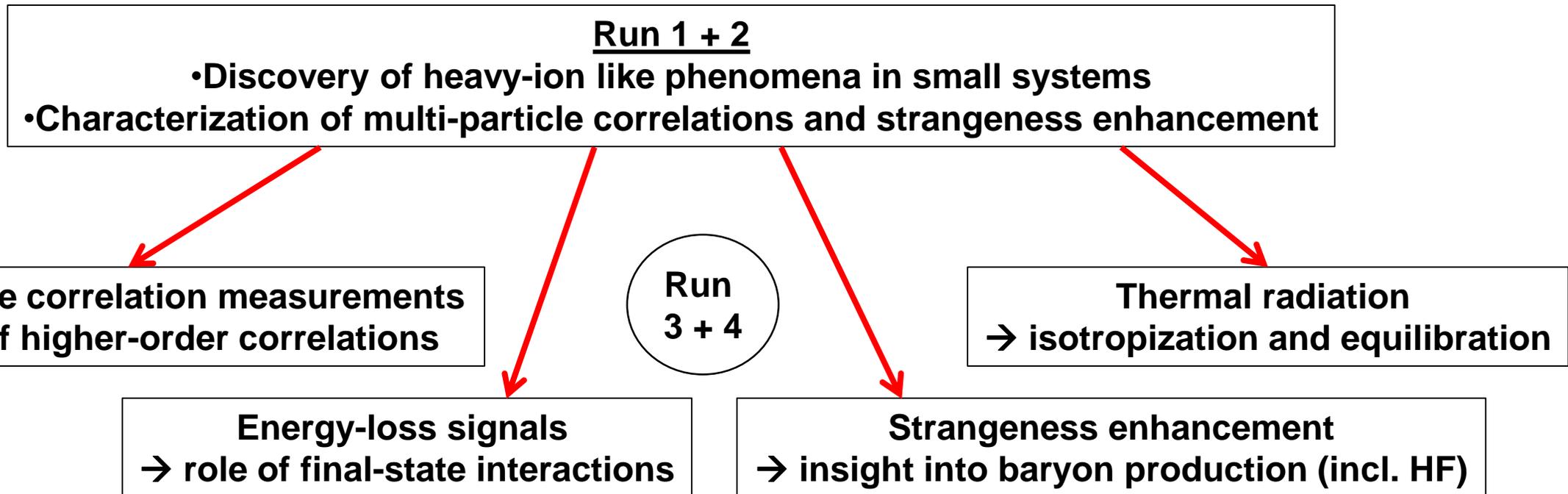
Second Discovery: Strangeness

- Strange baryon production increases with increasing multiplicity
 - Λ , Ξ , Ω
 - **Smooth** across system (pp, p-Pb, Pb-Pb)
 - Multiplicity only relevant variable here?
 - Need more overlap for final answer
- Traditional MC codes fail to reproduce trend
 - Torbjorn Sjostrand [1808.03117]
“we lack some **fundamental** insight on baryon production”



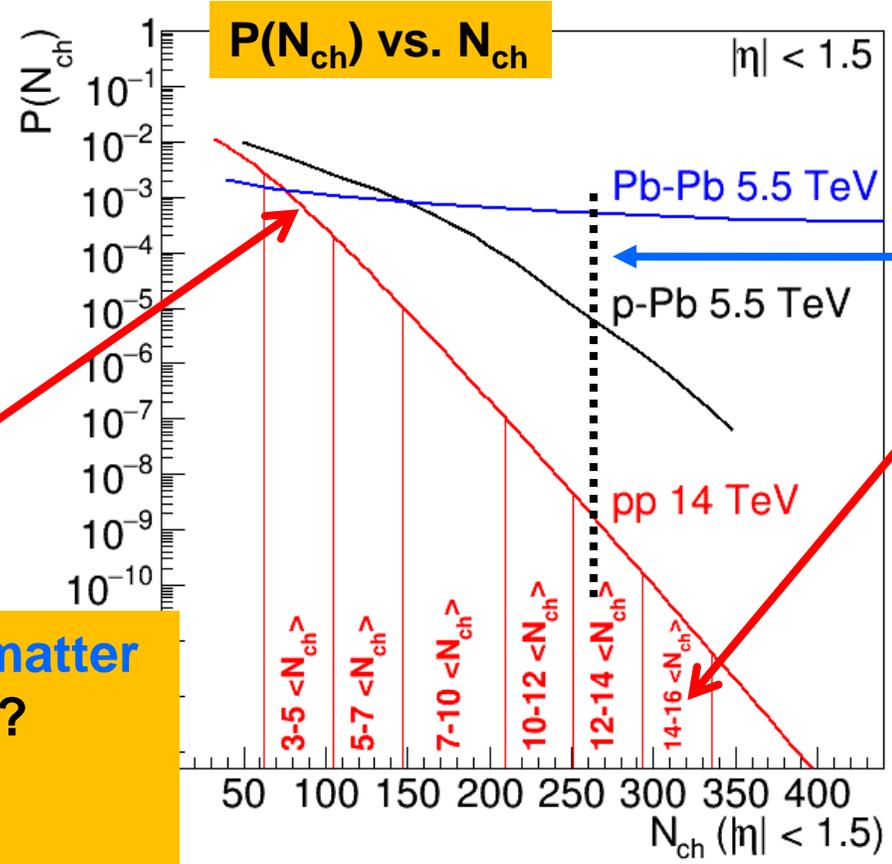
Résumé

- Observations challenge **two paradigms** at once
 - What is smallest system for which heavy ion “standard model” remains valid?
 - Can the standard tools for pp physics remain standard?



Multiplicity Distribution

- Run 3: 200 pb⁻¹ 14 TeV high-multiplicity pp program → extremely rare events



65% central in Pb-Pb

>25k events @ 14-16 $\langle N_{ch} \rangle$
 ~ 300 particles in $|\eta| < 1.5$

What is **smallest droplet of matter** showing collective behavior?
 Origin of collectivity in few particle system?

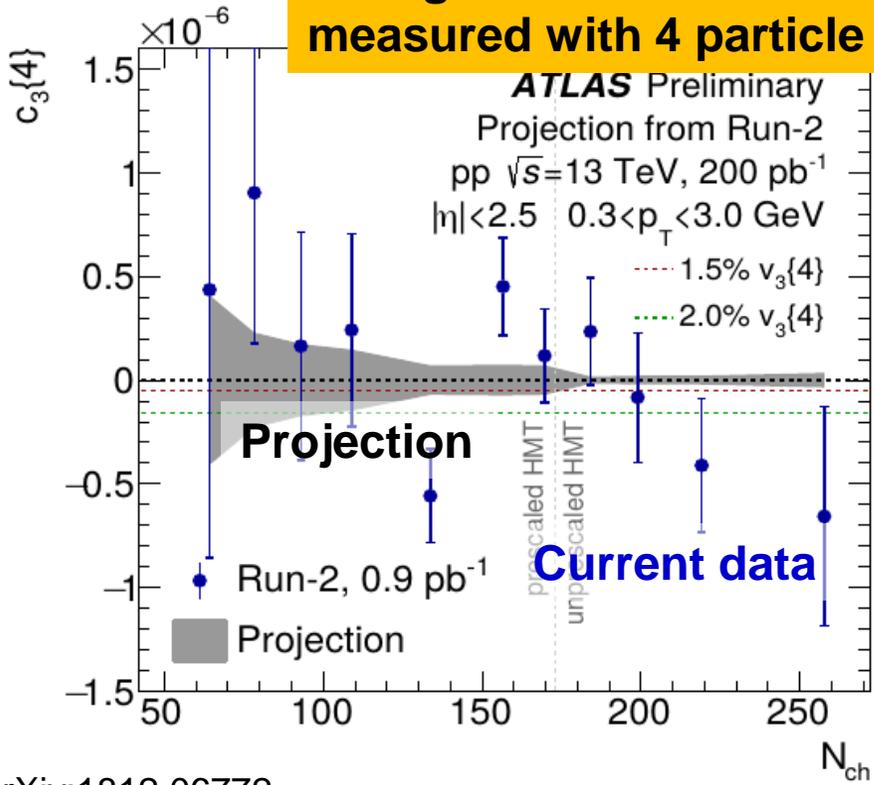
Significant overlap between pp and PbPb
 If pp behaves as PbPb, we can look for “standard” PbPb physics

arXiv:1812.06772

Higher-Order Correlations in pp

- True collectivity (all particles involved?)
 - Need to suppress jet contribution

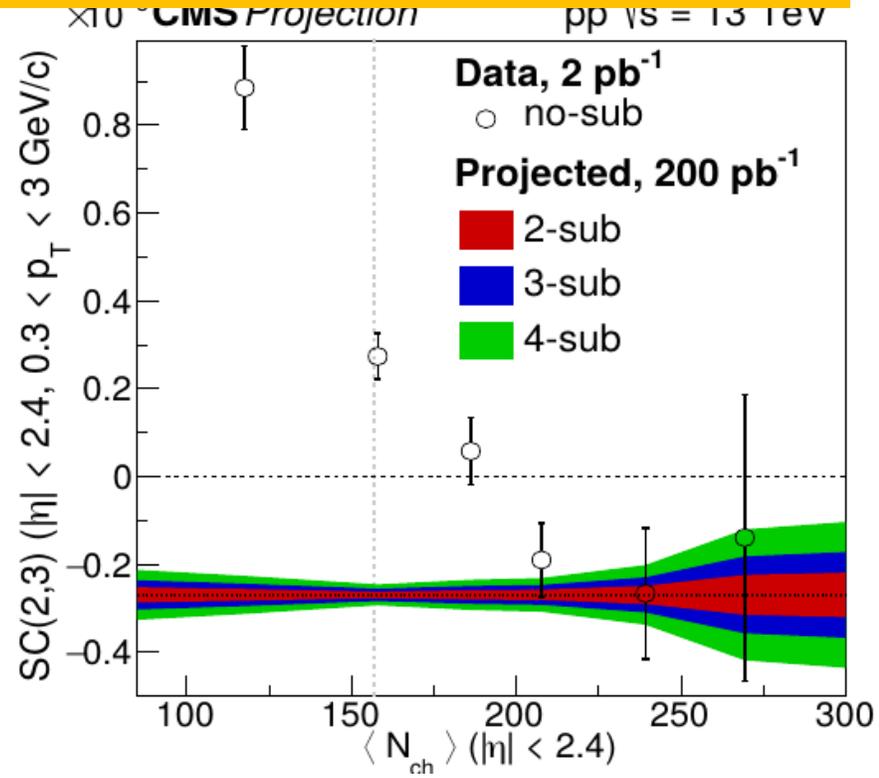
Triangular flow: 3rd harmonic measured with 4 particle correlations



Sensitivity to n-m correlations

Sensitivity to 1.5% $v_3\{4\}$

**Symmetric cumulants:
Correlation of nth and mth order flow**

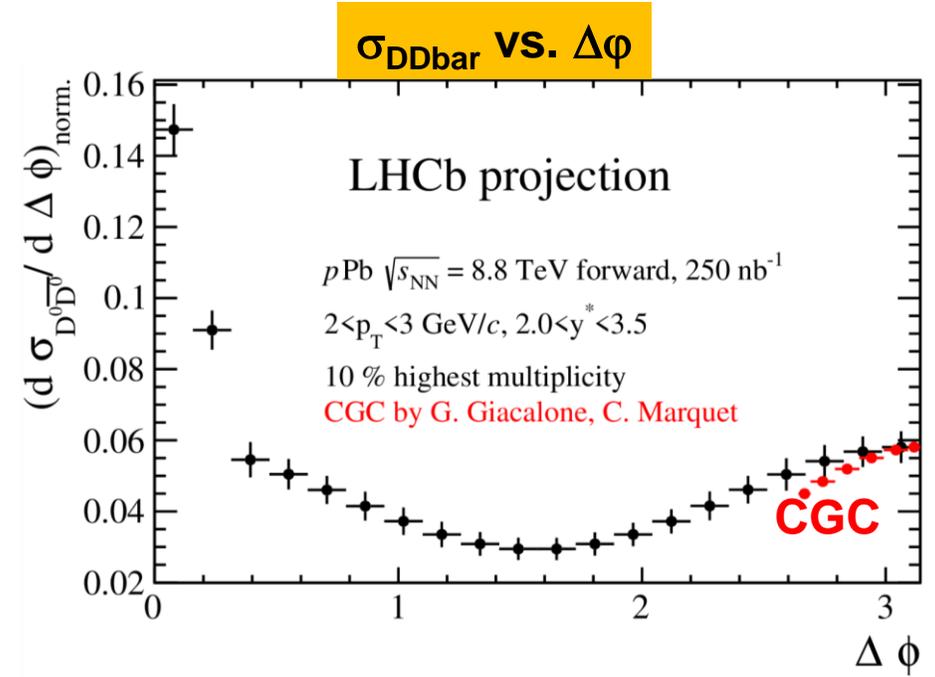
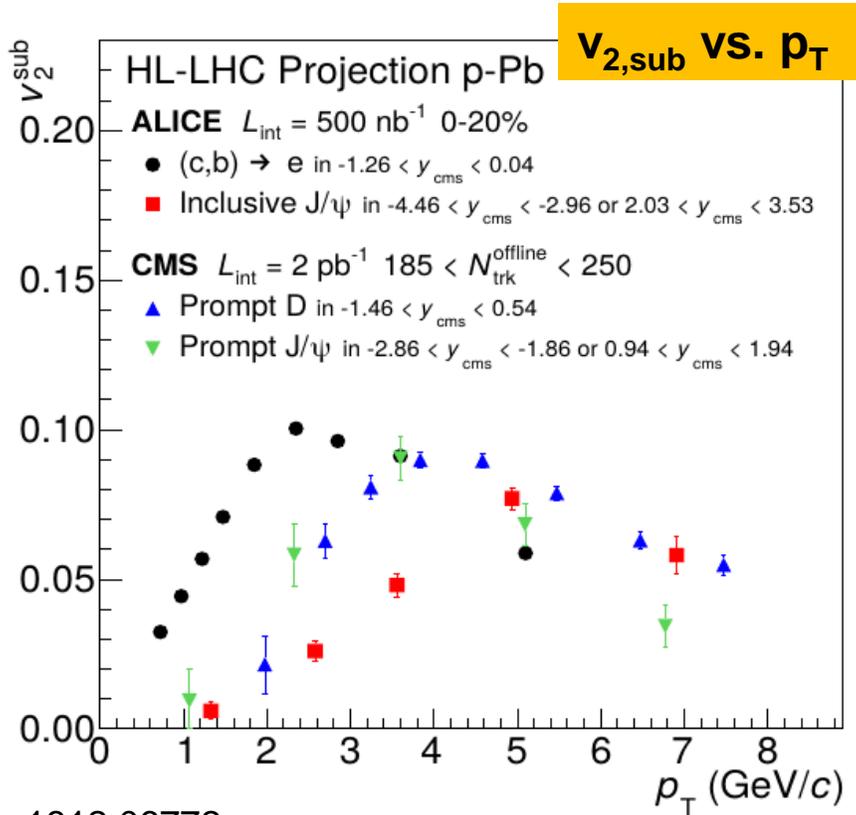


**Constrain models describing collective effects
Nature of collectivity of few-particle systems**

Charm & Beauty

Run 3+4

- c & b produced in initial hard scattering
 → clean probe of medium evolution



D-Dbar correlations → a window to the CGC

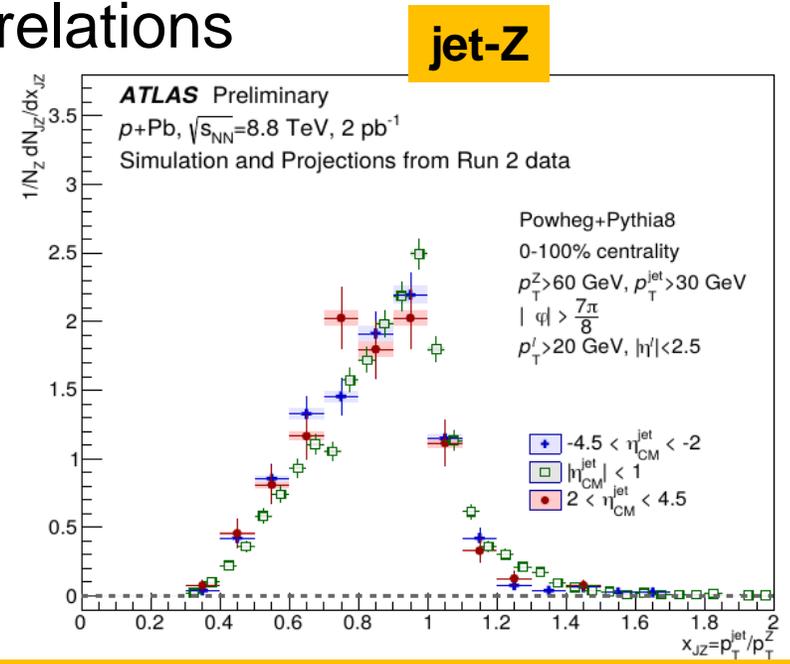
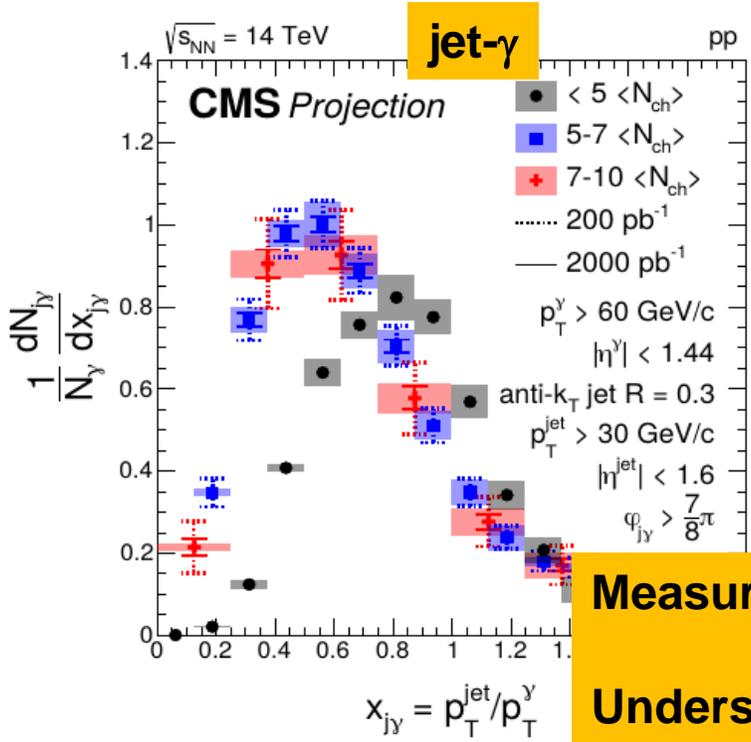
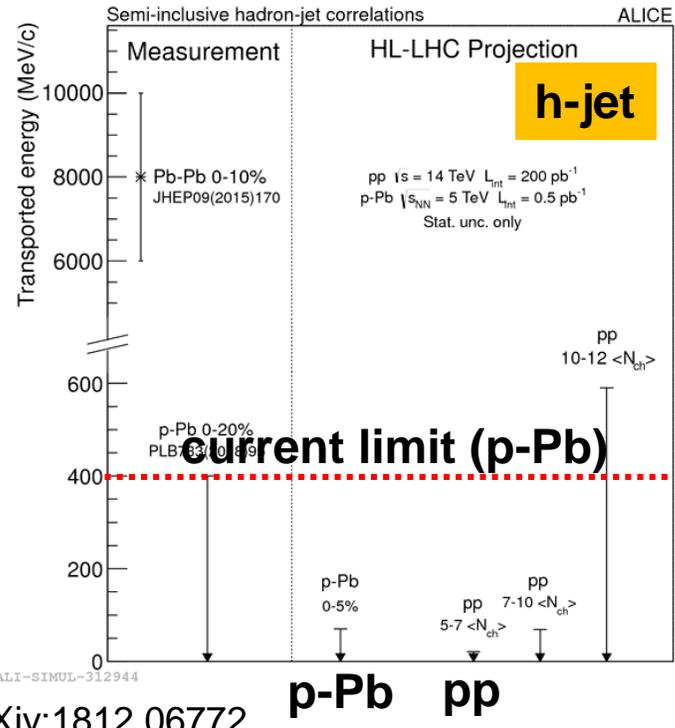
**Participation of heavy quarks in small-system evolution
 → role of final-state interactions**

Constrain models by additional “handle” quark mass

arXiv:1812.06772

Energy Loss

- If v_n caused by final-state interactions, partons should lose energy
- Single-particle observables (“ R_{pA} ”) not sensitive
- Coincidence measurements \rightarrow h-jet, jet- γ , jet-Z correlations



Measure energy loss signal, or put stringent limit

Understand role of final-state interactions

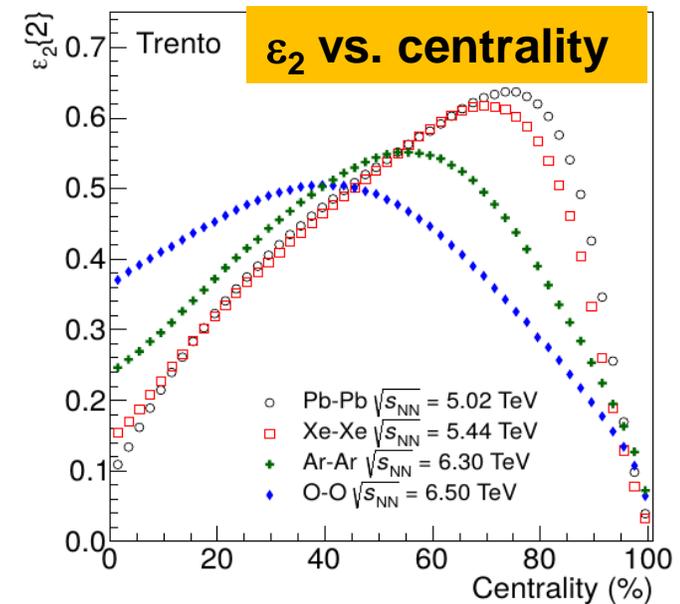
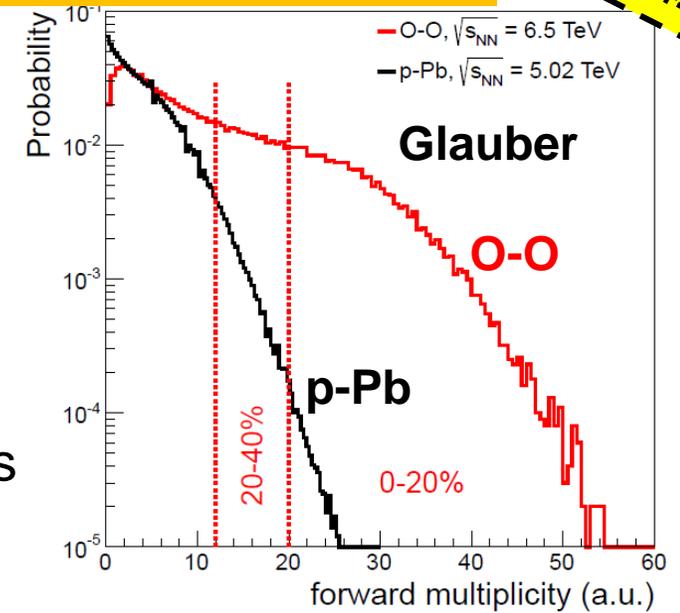


Oxygen-Oxygen Collisions

- AA geometry but N_{ch} , N_{part} , N_{coll} as p-Pb
 - Centrality shoulder allows **geometry selection** (N_{coll} , ϵ_2)
- System large enough to exhibit jet quenching
 - Critical test of understanding of energy loss for short path lengths
 - If no quenching in O-O
 - also p-Pb has insufficient energy density for quenching
- Connection of initial-state geometry and flow
 - Different eccentricity profiles of Pb-Pb/Xe-Xe and O-O
- Oxygen in LHC
 - Relatively easy setup and commissioning (for low L_{inst})
 - **Few $100 \mu b^{-1}$ sufficient** for key measurements like R_{AA} , v_n , ... (demonstrated by Xe-Xe)

P(#signal) vs. #signal

Run 3+4

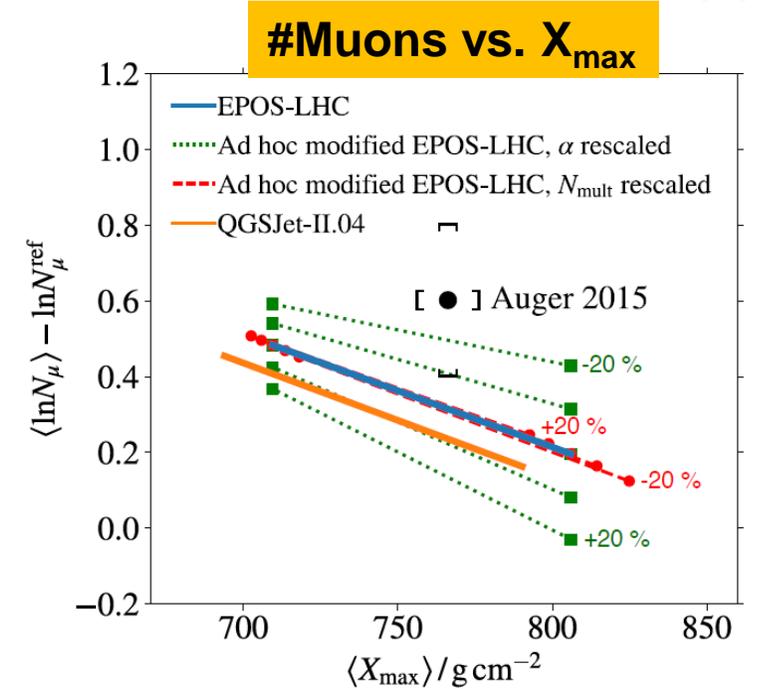
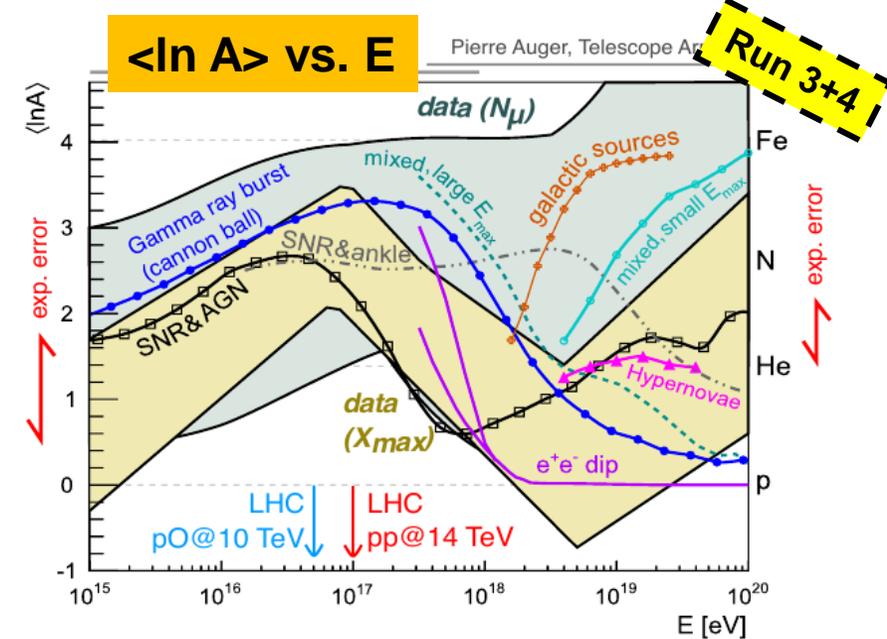


arXiv:1812.06772



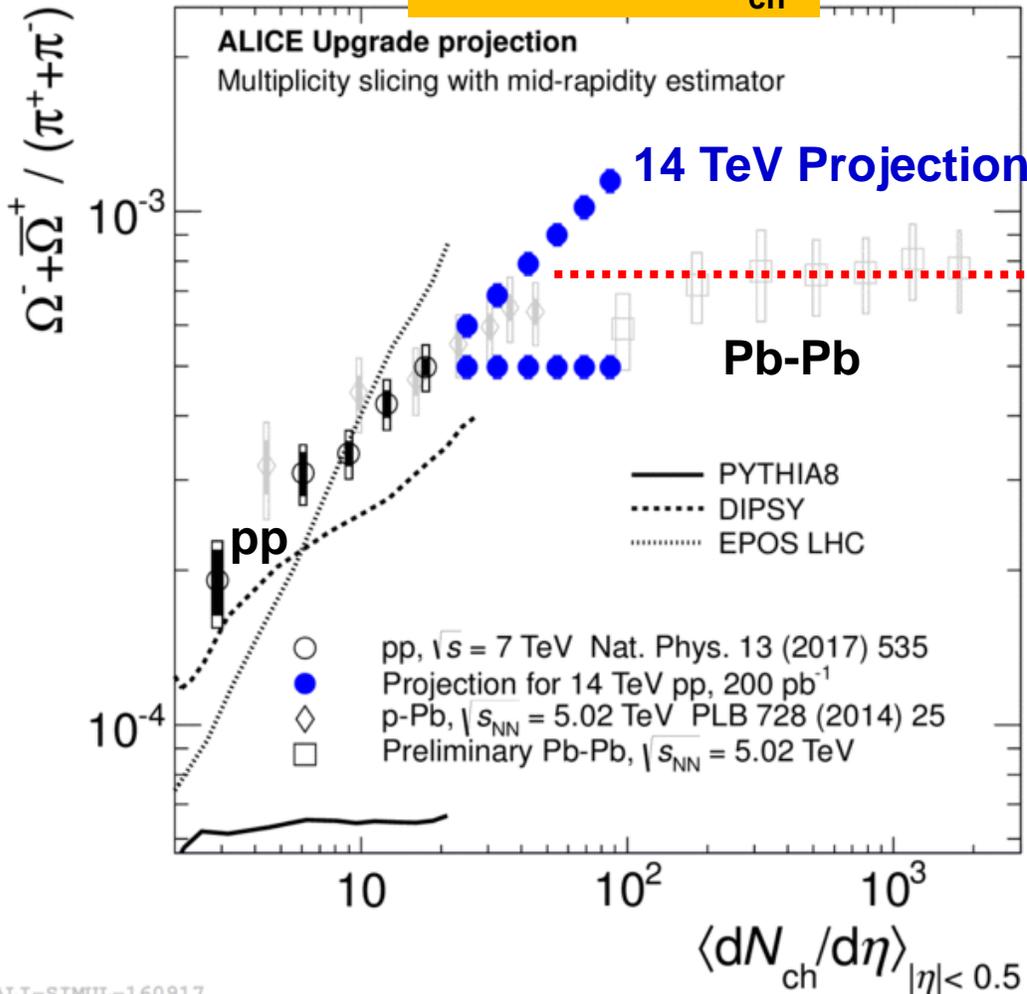
Proton-Oxygen Collisions

- Cosmic-ray community has expressed strong interest in short p-O run to constrain models describing **cosmic-ray showers**
 - Could be easily appended to a O-O run
- Muon deficit in models may be related to an excess of neutral pions (see e.g. arXiv:1902.08124)
 - Models mitigate this by adding collective effects or additional strangeness
- Measurement wish list
 - Production of π , K, p (ALICE, LHCb)
 - Production of π^0 and n (LHCf)
 - Energy flow for hadrons and γ (CMS+CASTOR, ATLAS)



Strangeness Enhancement in pp

Ω/π ratio vs. N_{ch}



Thermal limit in grand canonical ensemble (= many body system in equilibrium)

Does strangeness enhancement continue with same trend?

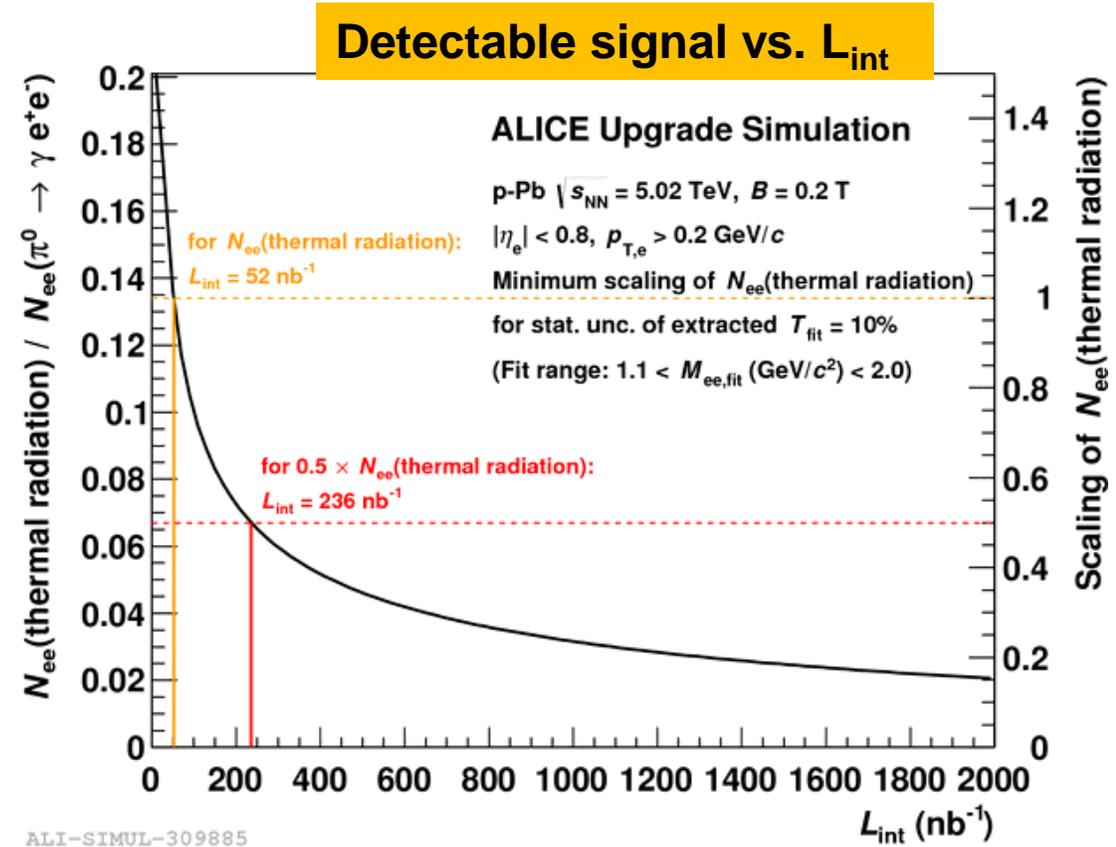
Is there a smooth connection to Pb-Pb?

Thermal limit reached or exceeded in pp?

Thermal Radiation in p-Pb

Run 3+4

- Direct access to temperature of a potential emitting medium
- Strength of signal unclear
 - Run 3 and 4 sensitive to 25% of signal predicted by R. Rapp
[Acta Phys. Polon. B42 (2011) 2823]





Proposed Run Schedule for Run 3 and 4



Schedule Considerations

Run 3 and 4

- **Pb-Pb 5.5 TeV (confirmed):** 13/nb ALICE/ATLAS/CMS, 2/nb LHCb
- **pp 5.5 TeV (confirmed):** 600/pb ATLAS/CMS, 50/pb LHCb, 6/pb ALICE

Small systems program

- **pp 14 TeV (updated):** 200/pb in Run-3 at low(er) m [w/o perturbation to HL]
- **p-Pb 8.8 TeV (updated):** 1.2/pb ATLAS/CMS, 0.6/pb ALICE/LHCb
- **pp 8.8 TeV (new):** 200/pb ATLAS/CMS/LHCb, 3/pb ALICE
- **O-O 7 TeV (new):** 500/ μ b – pilot-like 3-4 days
- **p-O 9.9 TeV (new):** 200/ μ b – pilot-like 1-2 days



Proposed Run Schedule for Run 3 and 4

	Year	Systems, time, L_{int}	Total per Run (3 and 4)
R U N 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/ μ b p-O: 200/ μ b
	2022 (6 weeks)	p-O + O-O 7 TeV, 1 week (after EYETS?) 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?	
R U N 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	

Run 5 will be discussed in the next talk

This is a proposal agreed in WG5 and reflects the physics discussed in the YR. The final run schedule is decided by the LHCC upon discussion with the experiments.



Summary

- Small-systems discoveries opened a field not known to exist when LHC started
- Observations challenge **two paradigms** at once
 - What is smallest system for which heavy ion “standard model” remains valid?
 - Can the standard tools for pp physics remain standard?
- Rich physics program in Run 3 and 4
 - Chapter 9 in WG5 Yellow Report – arXiv:1812.06772
- Aim: Demonstrate that **unified description** from pp to Pb-Pb collisions is feasible **or** show that **different mechanisms** are justified



Backup



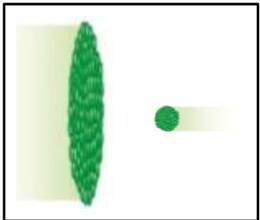
Collision Systems

pp



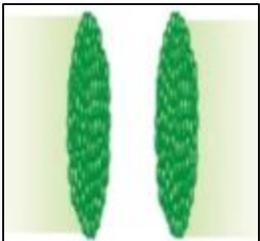
- Smallest system where collective effects have been observed
- “Closest” to e^+e^-

p-Pb

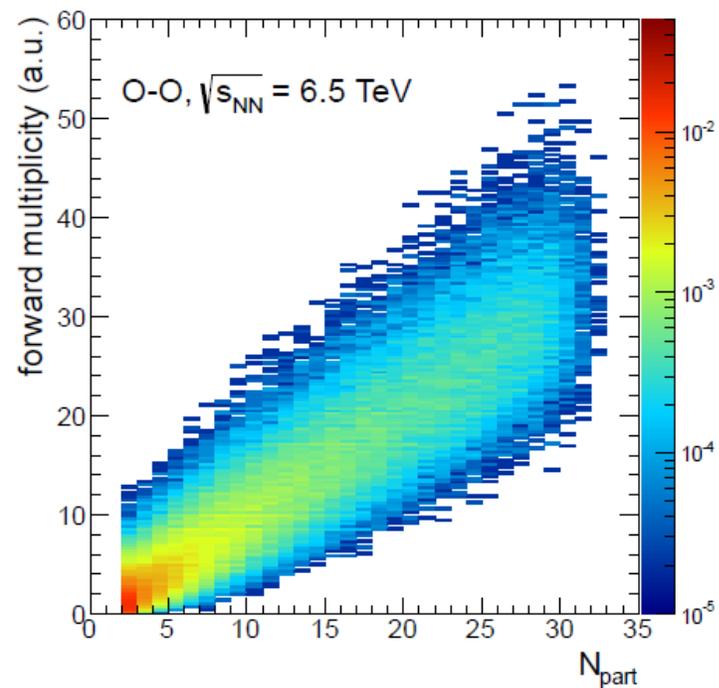
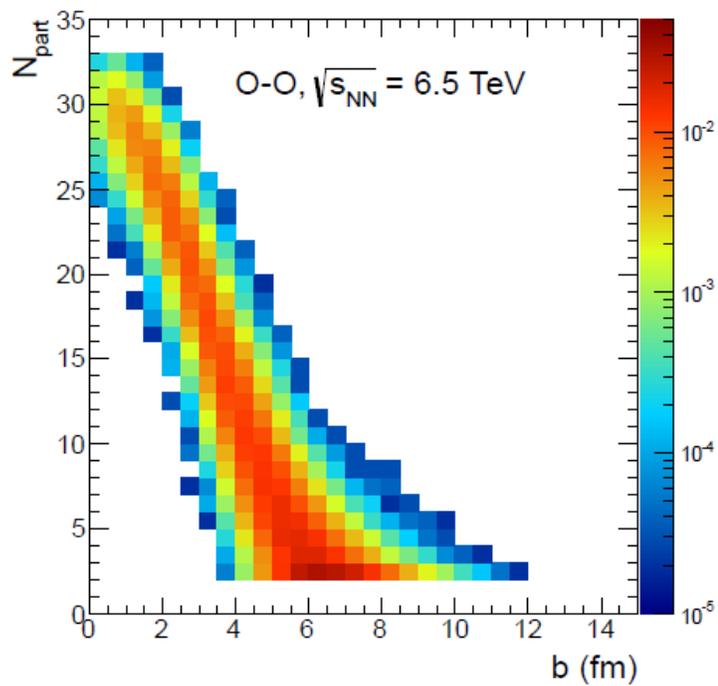
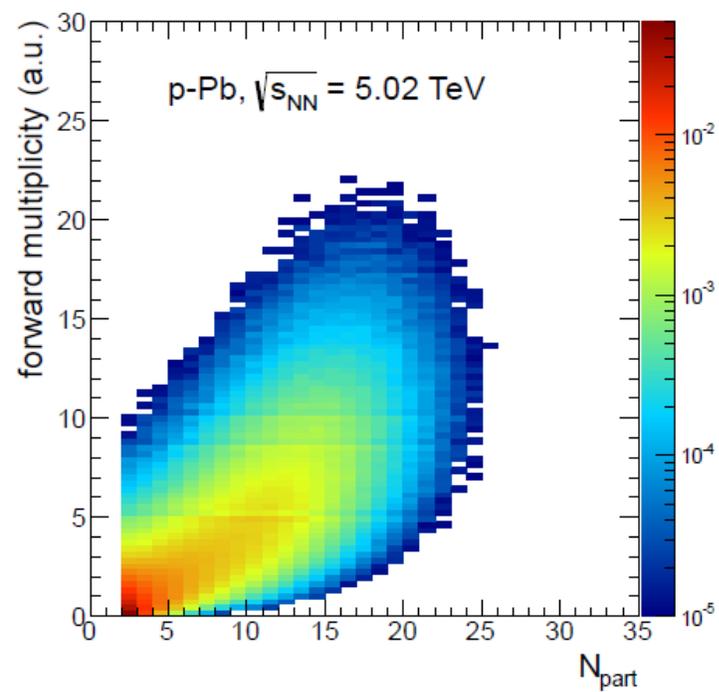
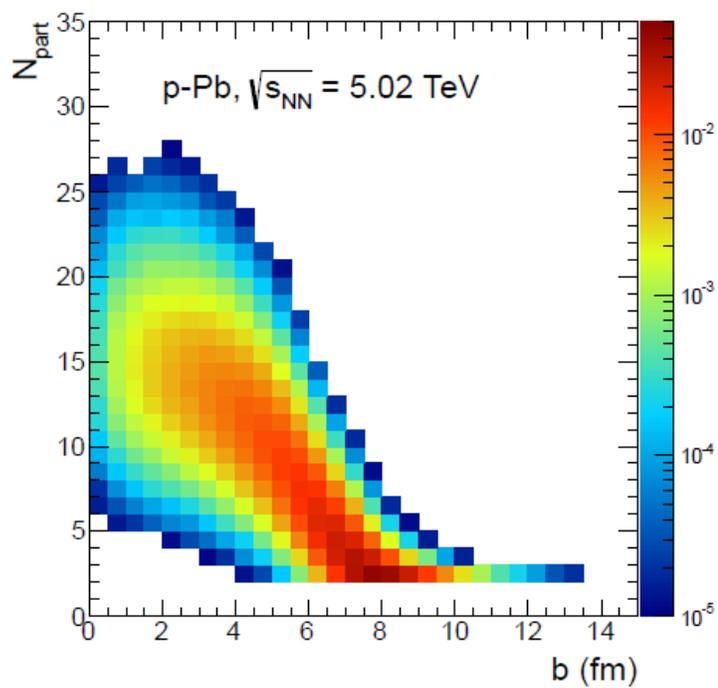


- Saturation-dominated regime
- Well known geometry
- Pb-going and p-going direction in the same event

Pb-Pb

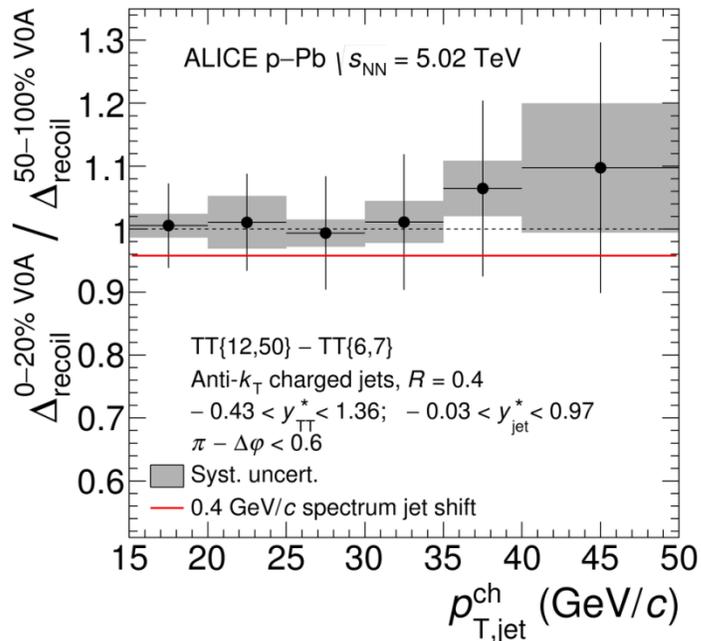


- True collective reference

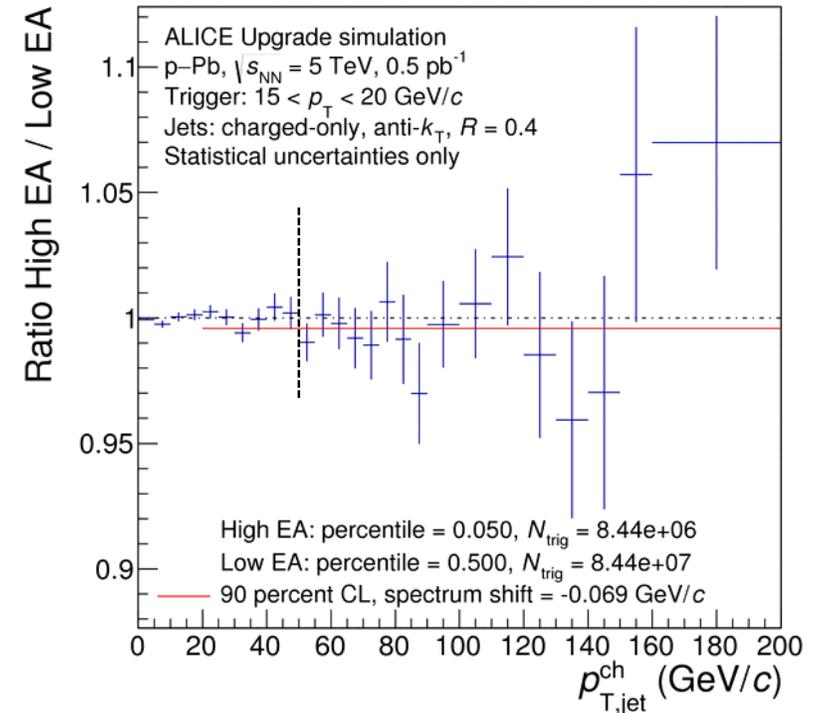


Energy Loss in p-Pb

- Hadron-jet correlations assess energy loss w/o need of reference
 - Currently set limit of 400 MeV in p-Pb (>10x smaller than in Pb-Pb)
- 500 nb⁻¹ sample can improve this to 70 MeV

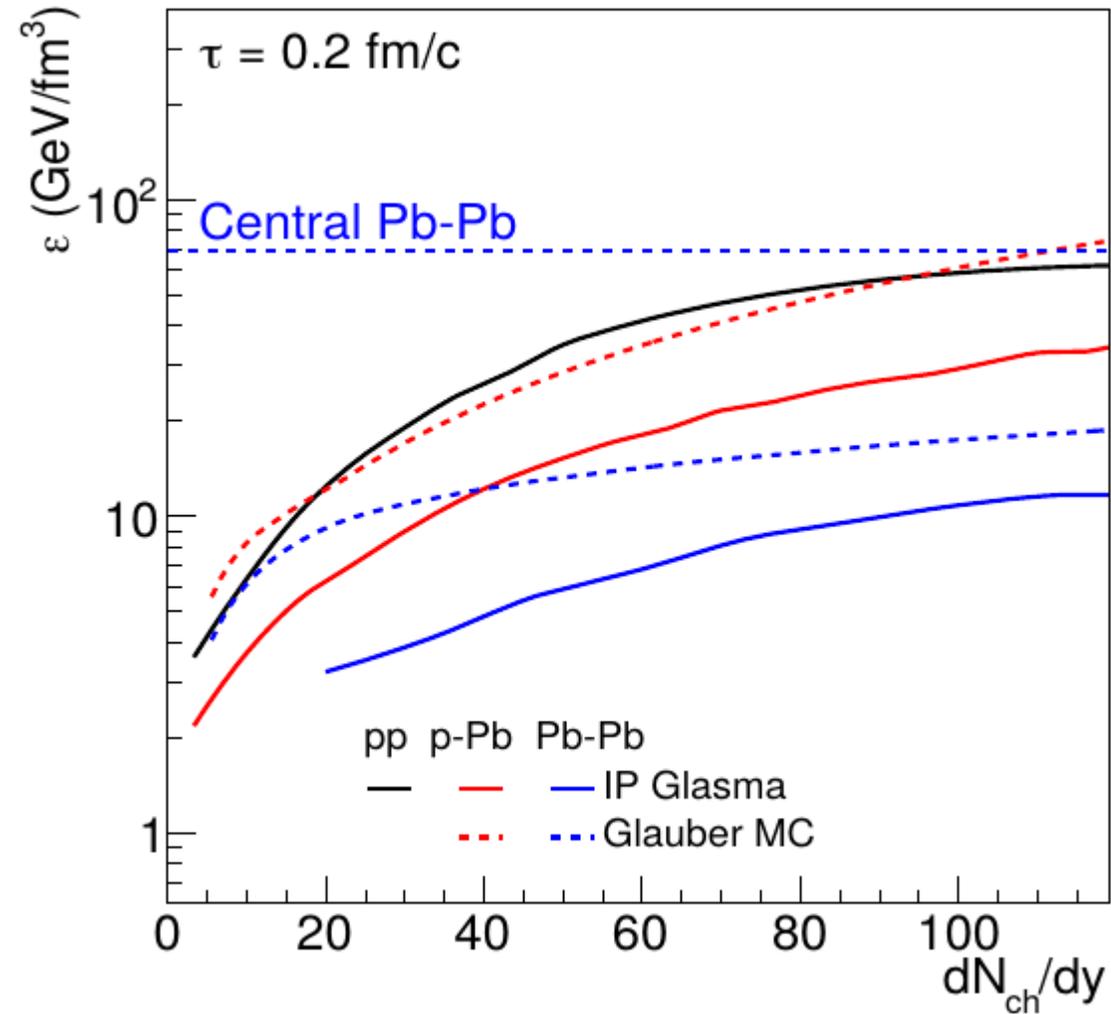


PLB783(2018)95

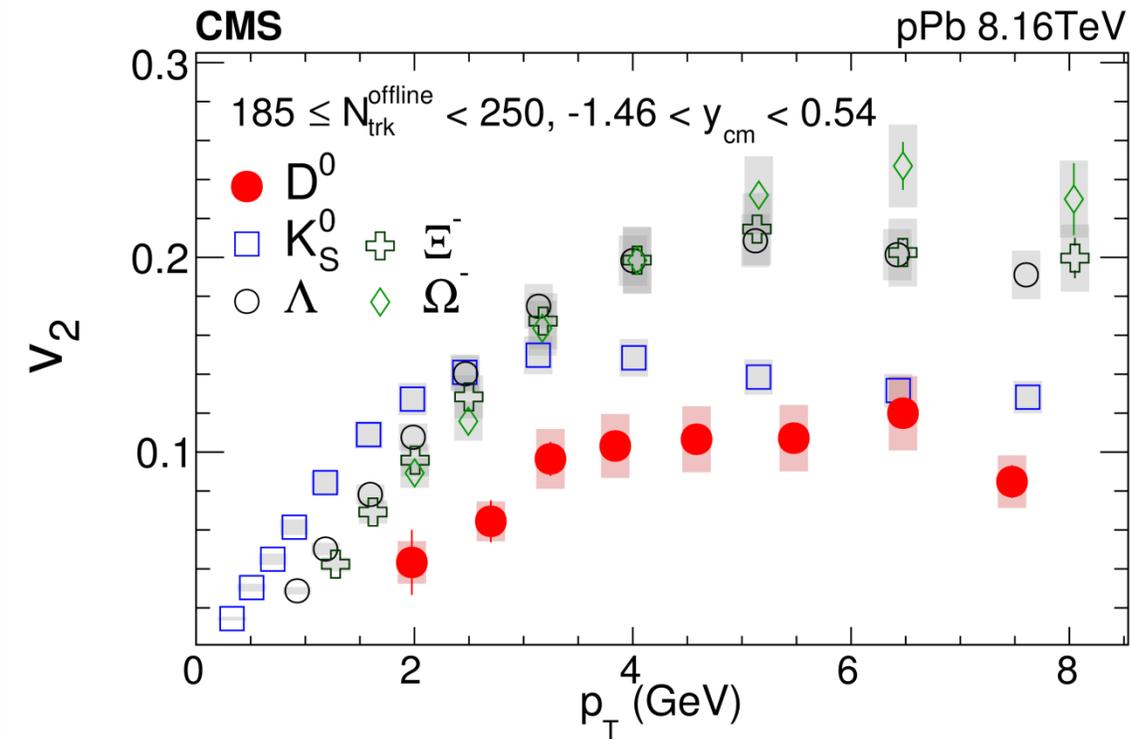


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Energy Densities



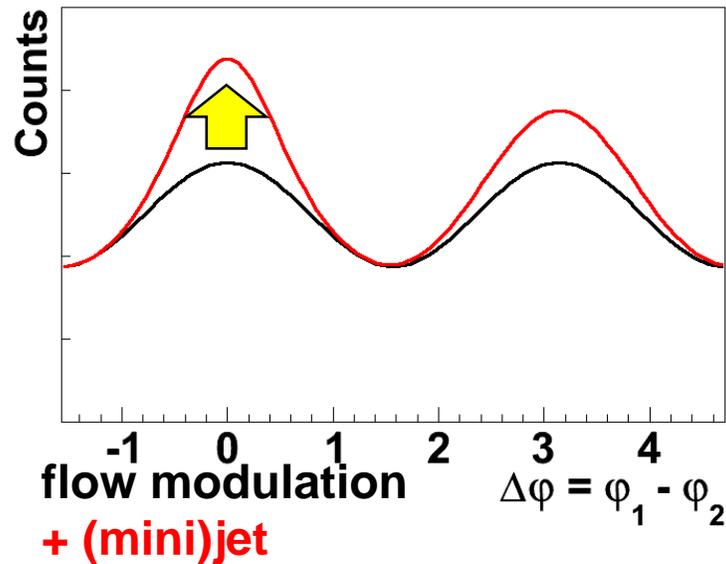
v_2 in p-Pb



Phys. Rev. Lett. 121 (2018) 082301

2D Two-Particle Correlations

- Flow component overlaid by (mini)jet contribution
- This can also be looked at in two dimensions
 - Azimuth $\Delta\phi$ and pseudorapidity $\Delta\eta$

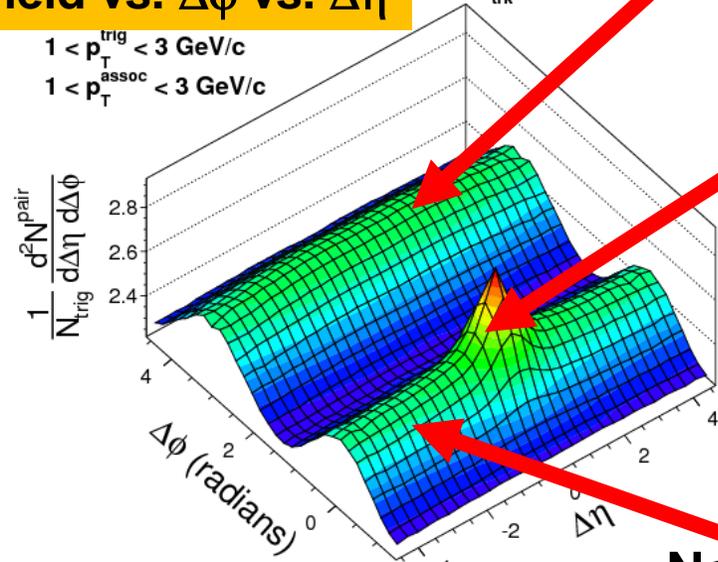


include $\Delta\eta$ axis

Yield vs. $\Delta\phi$ vs. $\Delta\eta$

$1 < p_T^{\text{trig}} < 3 \text{ GeV}/c$
 $1 < p_T^{\text{assoc}} < 3 \text{ GeV}/c$

$220 \leq N_{\text{trk}}^{\text{offline}} < 260$

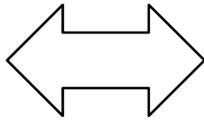
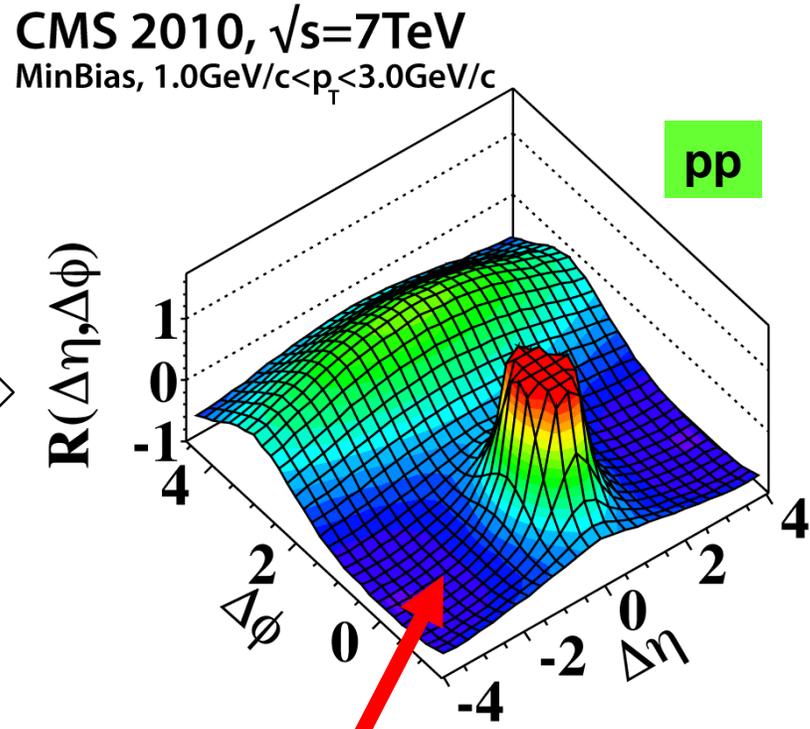
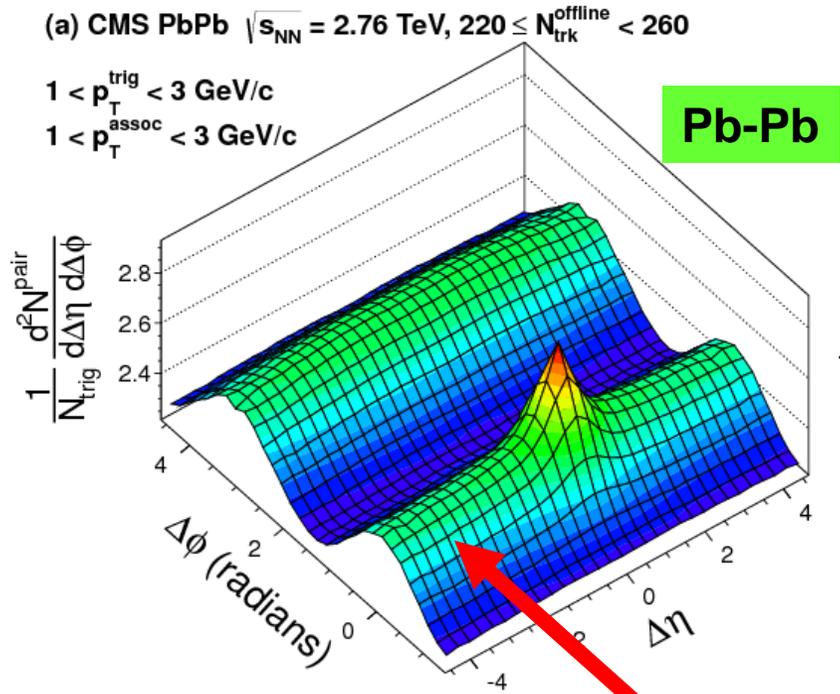


Away-side jet + flow
 ($\Delta\phi \sim \pi$, elongated in $\Delta\eta$)

Near-side jet
 + resonances, ...
 ($\Delta\phi \sim 0$, $\Delta\eta \sim 0$)

Near-side flow ridge
 ($\Delta\phi \sim 0$, elongated in $\Delta\eta$)

And in pp?



Near-side ridge (flow) only in Pb-Pb

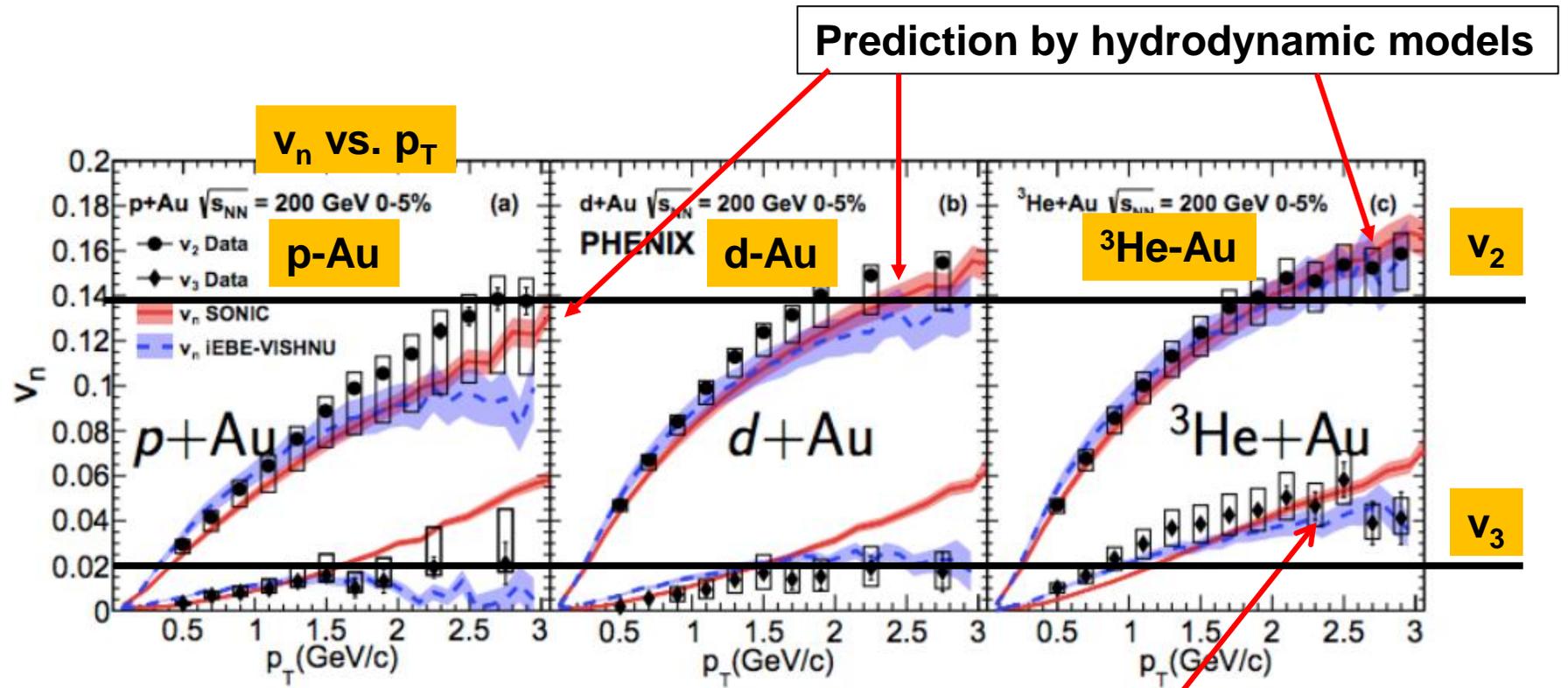
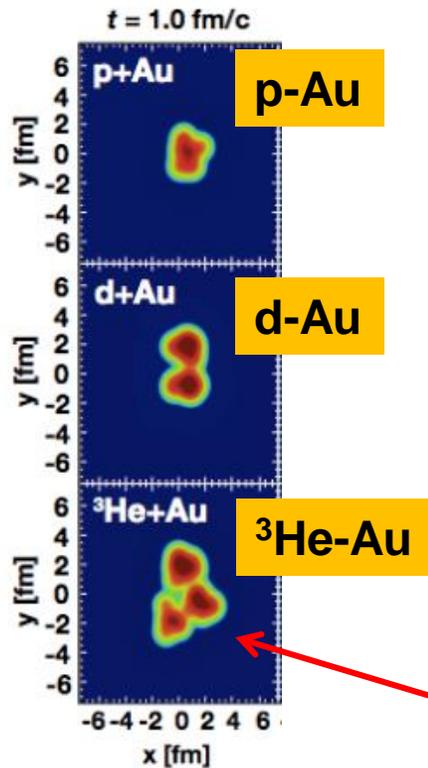
at least everyone thought so for a long time...



Initial or final state effect?

What is the relation to the shape of the initial state?

RHIC geometry scan



Triangular initial state \rightarrow large v_3



e^+e^- (archived ALEPH data)

Can we observe the same structures in e^+e^- collisions?

$10 < N < 20$

MOD PRELIMINARY

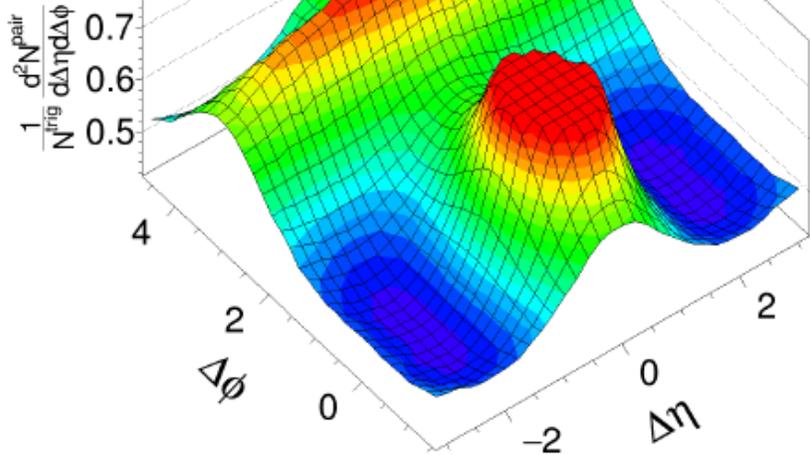
ALEPH e^+e^- , $\sqrt{s}=91\text{GeV}$

$10 \leq N_{\text{Trk}}^{\text{Offline}} < 20$

$|\eta| < 5.0$

$0.0 < p_T < 100.0 \text{ GeV}$

Thrust Axis



$N \geq 35$

MOD PRELIMINARY

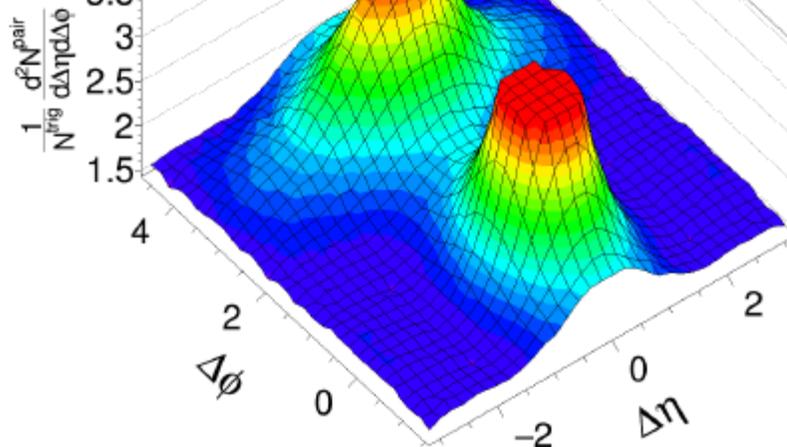
ALEPH e^+e^- , $\sqrt{s}=91\text{GeV}$

$35 \leq N_{\text{Trk}}^{\text{Offline}} < 999$

$|\eta| < 5.0$

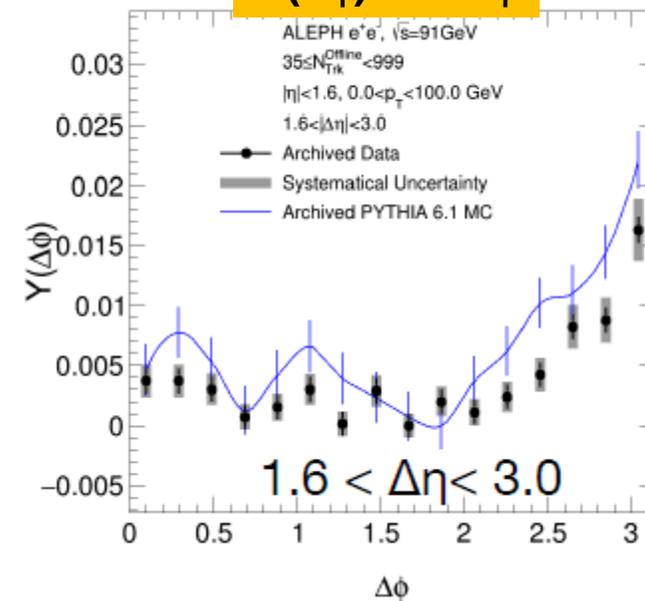
$0.0 < p_T < 100.0 \text{ GeV}$

Thrust Axis



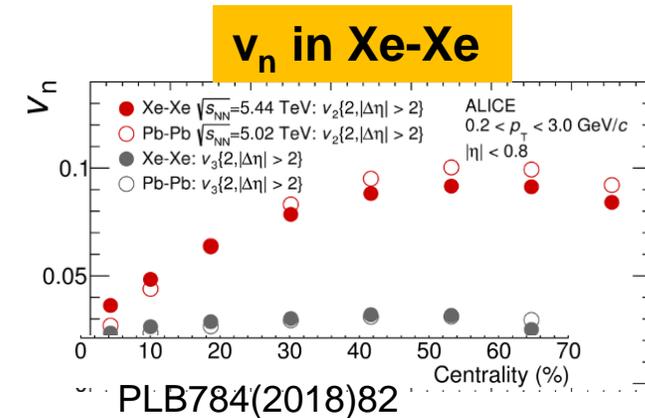
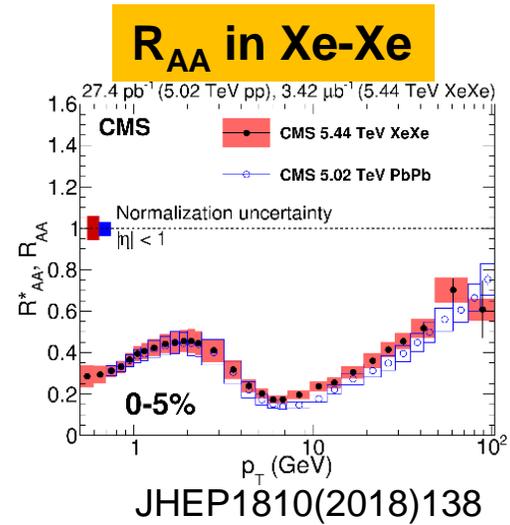
$Y(\Delta\phi)$ vs. $\Delta\phi$

MOD PRELIMINARY

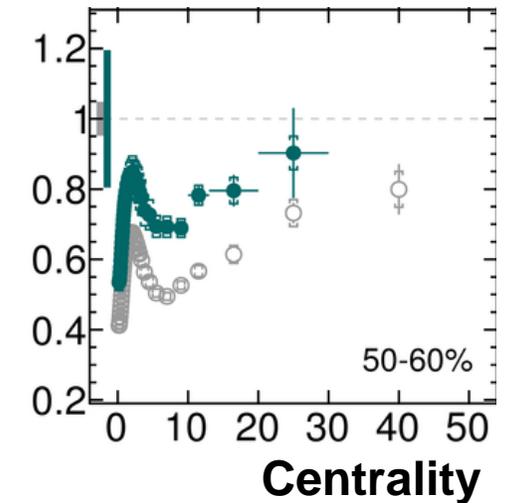
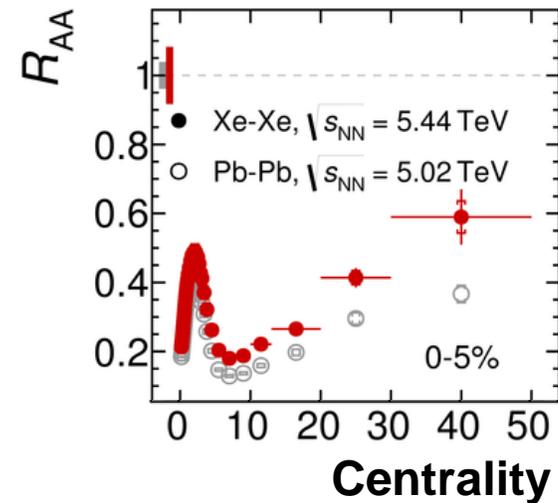
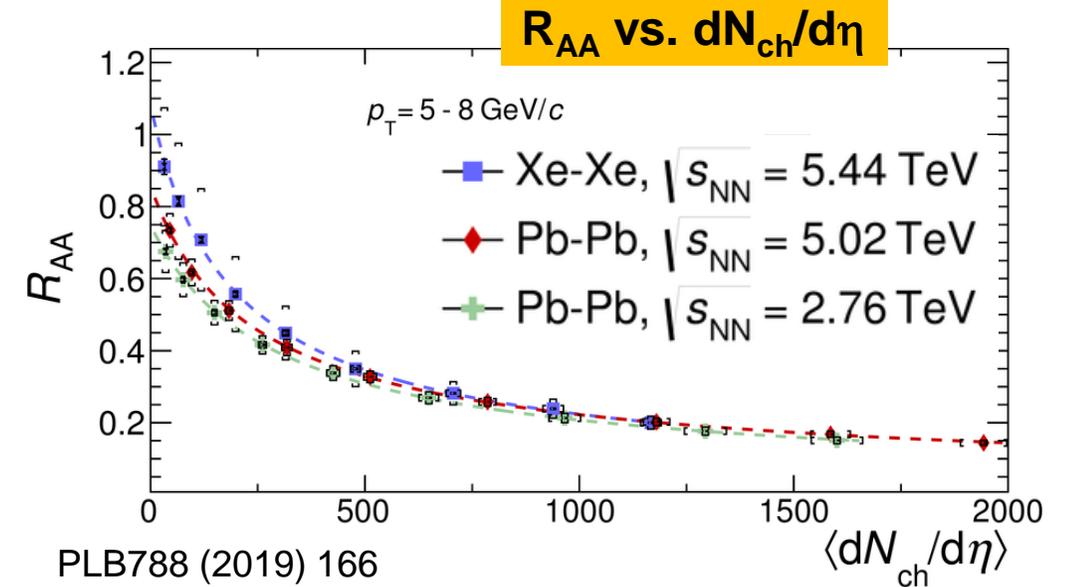
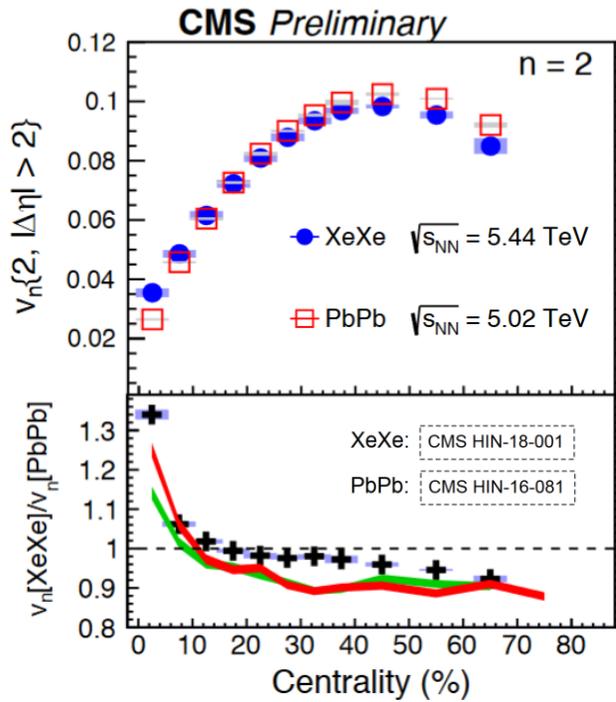


No collective effects found in ee collisions!

Xe-Xe Measurements



Changing A vs. changing centrality





Proposed Run Schedule

	Year	Systems, time, L_{int}	Total per Run (3 and 4)
R U N 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/ μ b p-O: 200/ μ b
	2022 (6 weeks)	p-O + O-O 7 TeV, 1 week (after EYETS?) 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?	
R U N 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		
R U N 5		Intermediate AA, 11 weeks pp reference, 1 week	E.g. Ar-Ar 3-9/pb (optimal species to be defined)

This is a proposal agreed in WG5 and reflects the physics discussed in the YR. The final run schedule is decided by the LHCC upon discussion with the experiments.



“I am more sure of the conclusions than of any single argument which suggested them to me.”

Richard P. Feynman

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