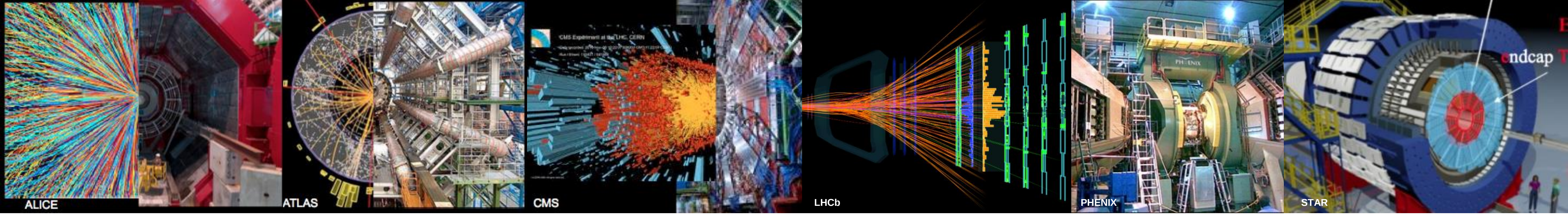


Emergence of Quark-Gluon Plasma Phenomena

Jan Fiete Grosse-Oetringhaus, CERN

EPS-HEP Conference 2019

Ghent, Belgium

Emerging Phenomena

Strokkur Geyser, Iceland

The emergence of Quark-Gluon Plasma phenomena in small systems has shaken the basic paradigms of the heavy-ion field

This talk discusses where we stand and what we can learn from it about fundamental quantum chromodynamics

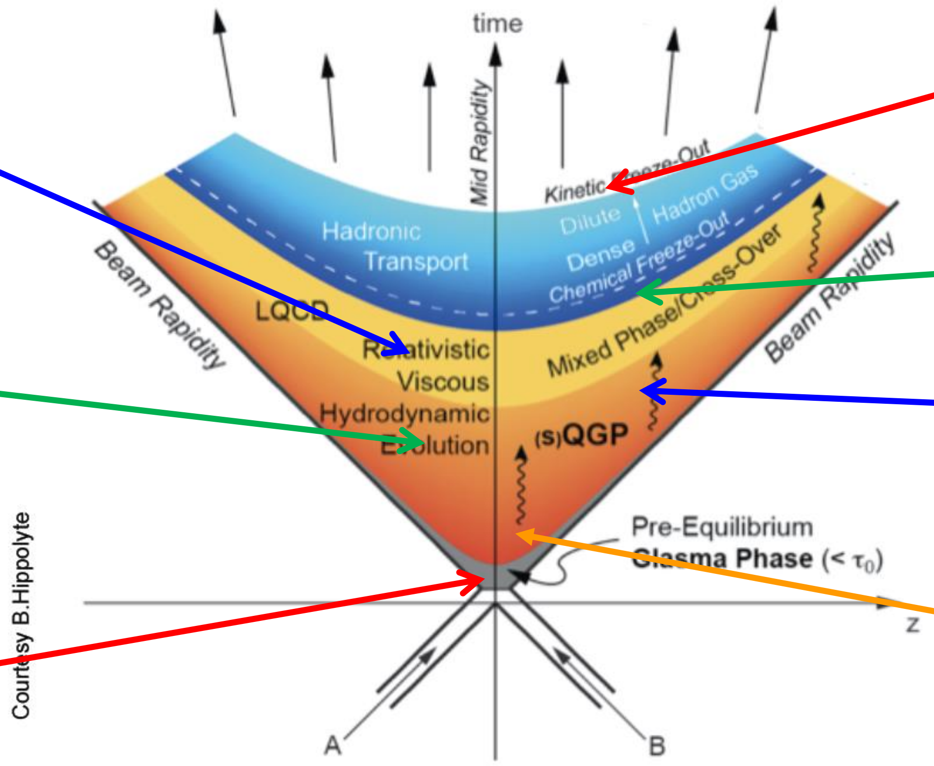
Heavy-Ion Collision

$dN_{ch}/d\eta \sim 2000$ particles

Large pressure
↓
collective flow

Dense medium
↓
Energy loss,
Quarkonia melting

Density fluctuations
↓
spatial anisotropies



Kinetical freeze-out
~ 90 MeV

Chemical freeze-out
~ 155 MeV

Viscous hydrodynamics
$\eta/s \sim 0.08 – 0.16$

Initial temperature
~ 300 MeV

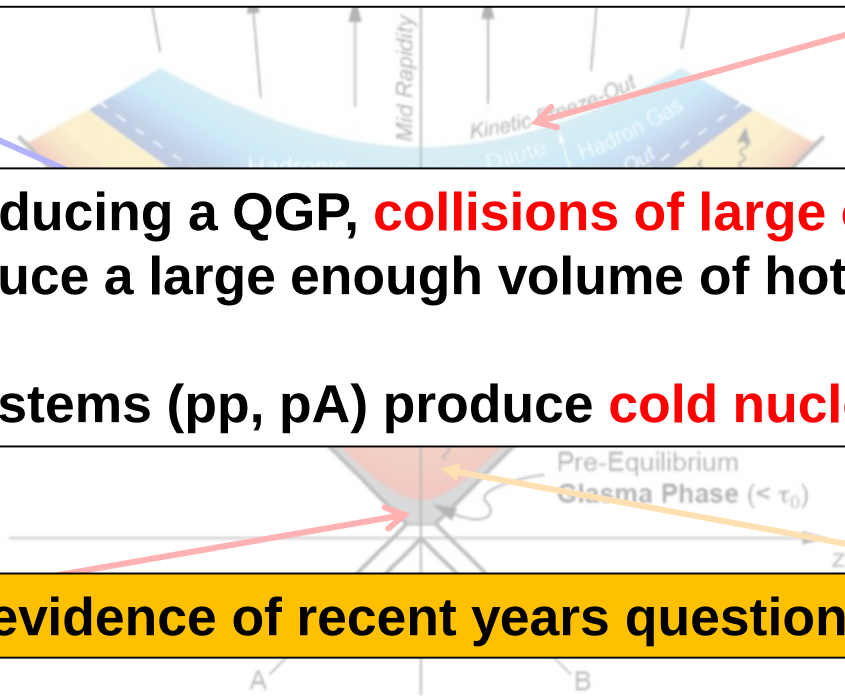
Values for LHC

Paradigms

Theoretical description (= HI SM) of the phenomena observed in heavy-ion collisions involves the formation of a deconfined state of matter: the Quark-Gluon Plasma (QGP)

Large pr...
↓
collective flow

Chemical



Basic paradigm: for producing a QGP, collisions of large objects (ions) are needed. Only these produce a large enough volume of hot and dense matter

Corollary: Small systems (pp, pA) produce cold nuclear matter → no QGP

Density fluctuations
↓
spatial anisotropies

Initial temperature
...eV

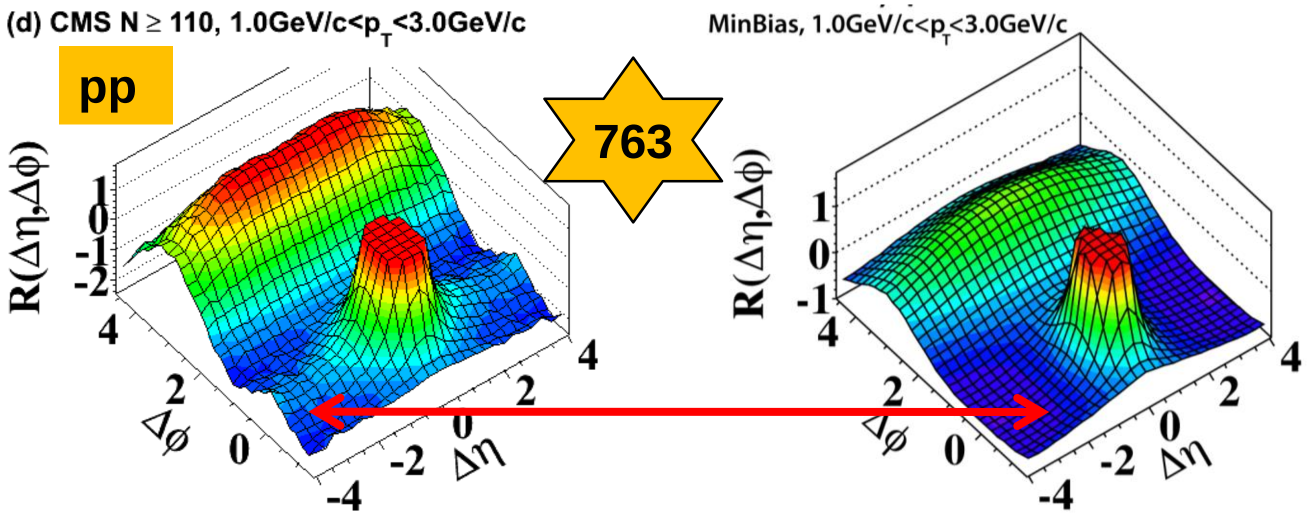
Experimental evidence of recent years questions this paradigm

Paradigms

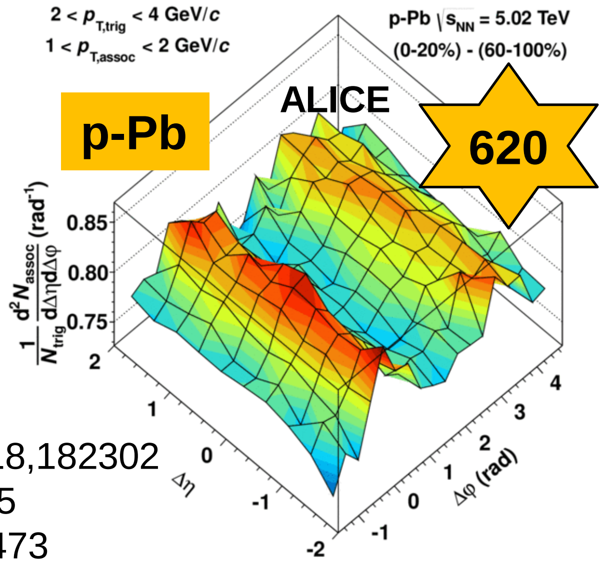
None of the content of this talk was known
when LHC was proposed, and
when LHC started

Quark Matter 2018

First Discovery: The Ridge



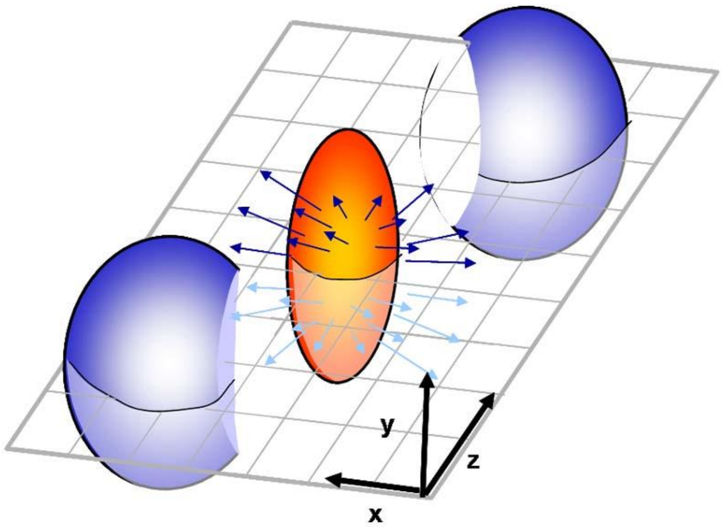
CMS, JHEP1009(2010)091



ALICE, PLB719 (2013) 29
and ATLAS, PRL110(2013)18,182302
and CMS, PLB718(2013)795
and LHCb, PLB762 (2016) 473

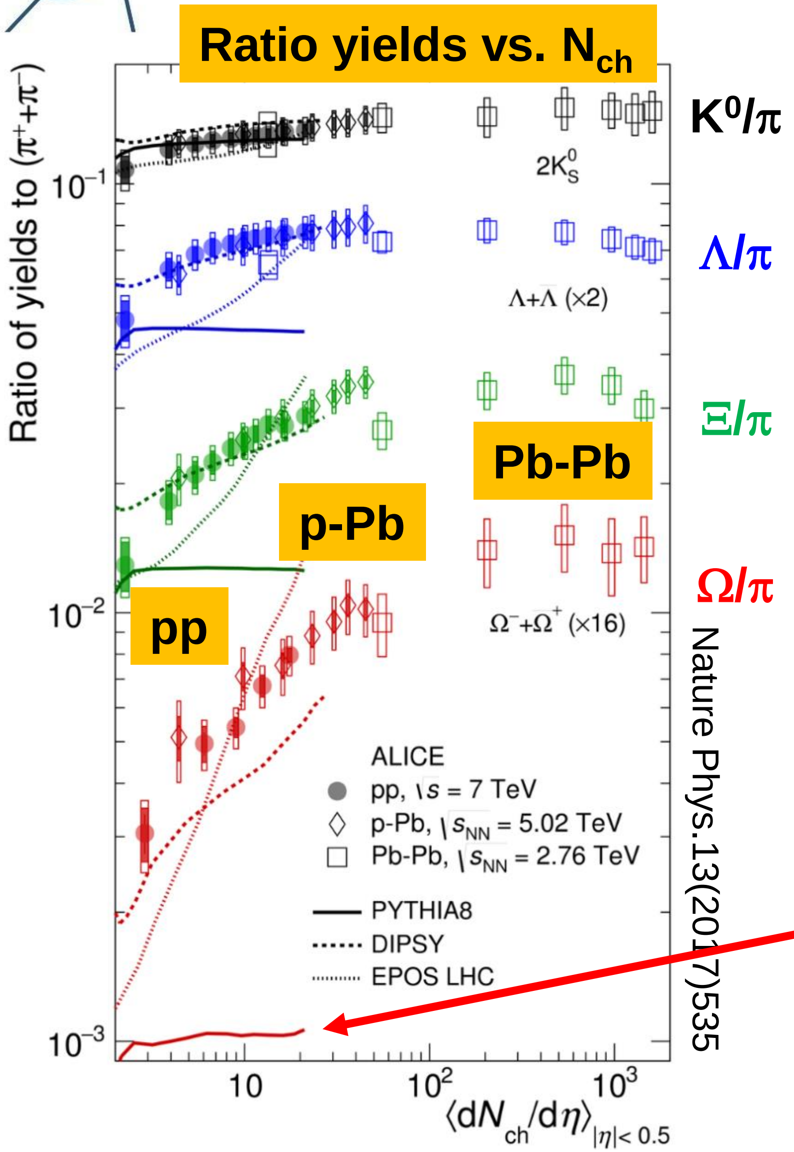
Unexpected in pp and p-Pb collisions

Well known from A-A collisions



Ridges are a direct consequence in hydrodynamic expansion description (called flow in heavy-ion collisions)

Second Discovery: Strangeness



Strange baryon production increases faster than multiplicity

Smooth across collision system from pp to Pb-Pb

Direct consequence of energetically cheaper production of s-sbar in a QGP (compared to K-Kbar in vacuum)

s $\bar{s}$ vs. K $\bar{K}$

Traditional MC codes completely fail to reproduce trend

Torbjorn Sjostrand [1808.03117]: "we lack some fundamental insight on baryon production"

Intriguing proof that high-multiplicity pp and p-Pb are
more than an incoherent superposition of vacuum processes

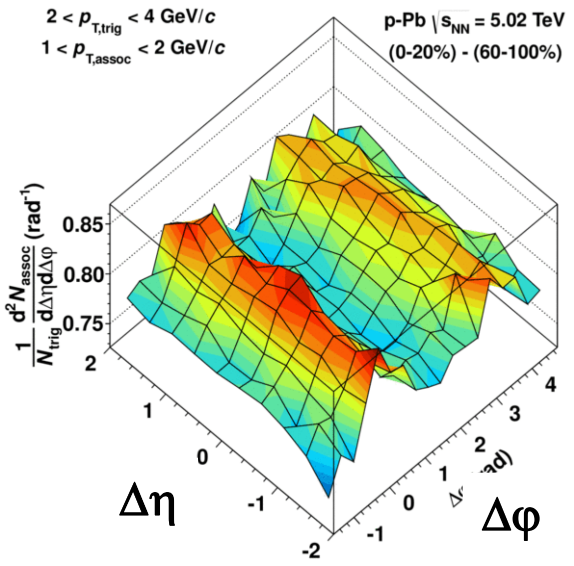
How quickly flow can build up in a small system?

What is the role of final-state interactions?

What is the microscopic mechanism for strangeness enhancement?

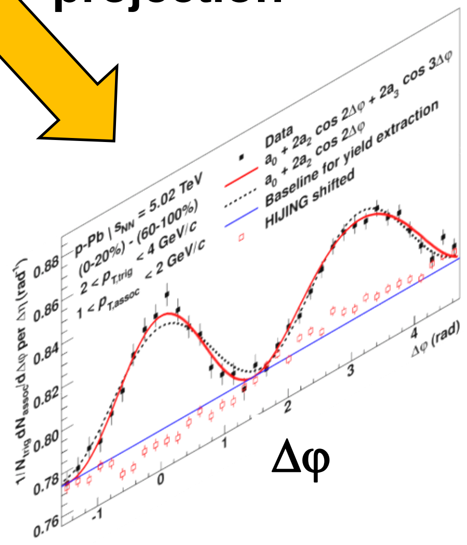
Significant experimental effort and theory development has followed and is ongoing.
I will try to give you a flavour…

What is v_2?



"the second Fourier harmonic of the ridge"

projection



Fourier decomposition

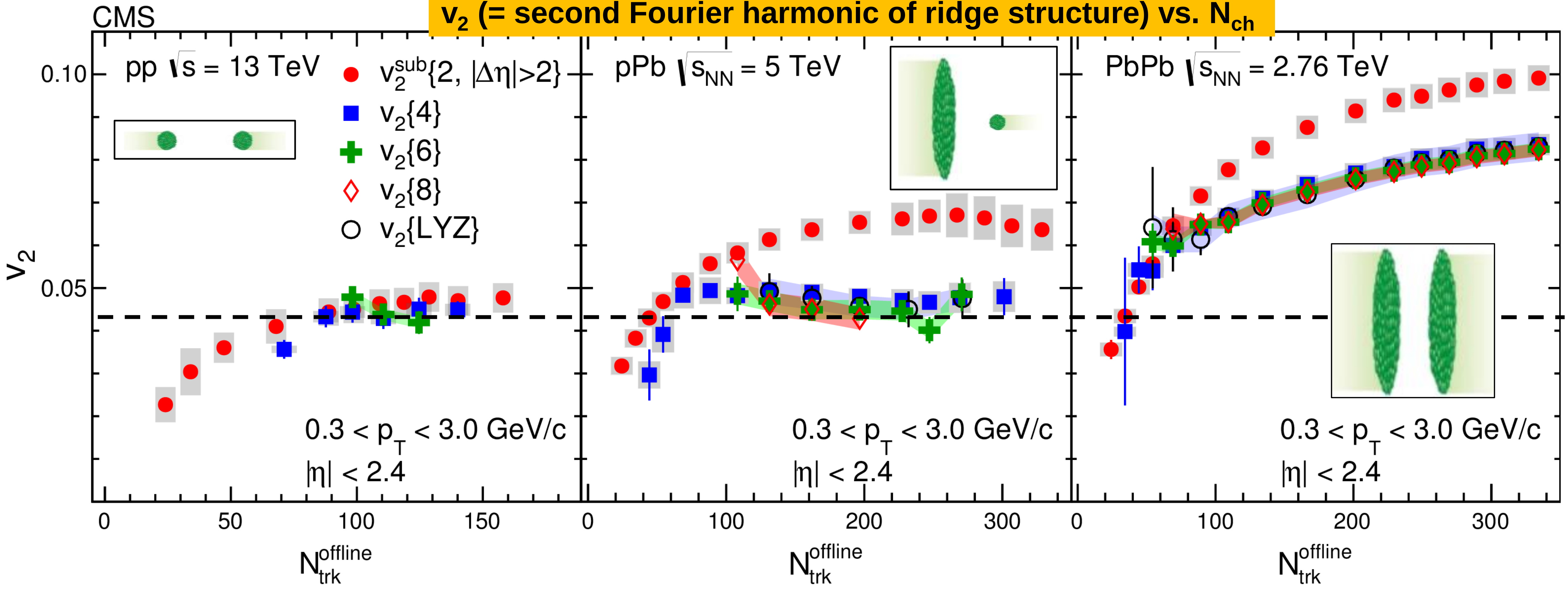
$$\frac{dN}{d\varphi} = A\left(1 + 2\sum_n v_n \cos n(\varphi - \Psi_n)\right)$$

Simplified view

True Collectivity

How many particles contribute to the phenomena?

v_2 (= second Fourier harmonic of ridge structure) vs. N_{ch}

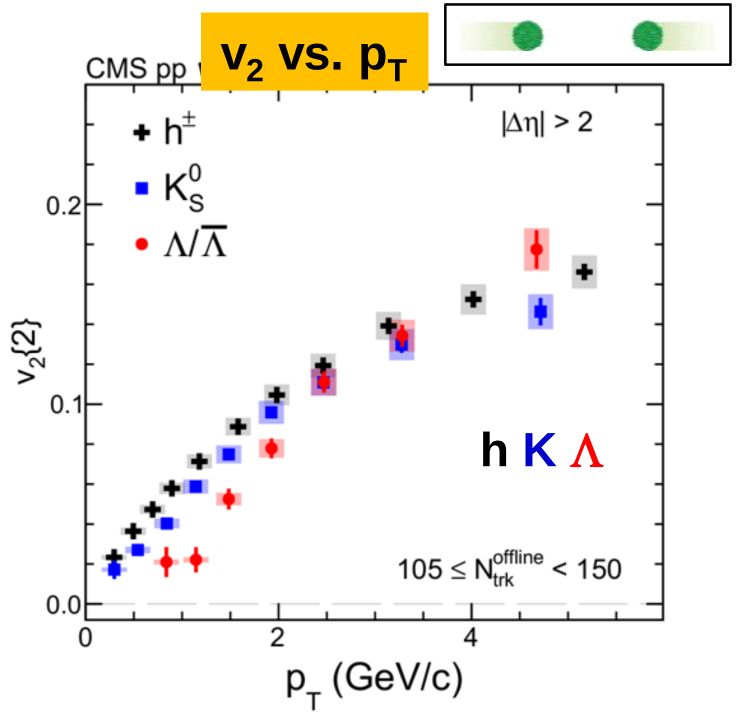


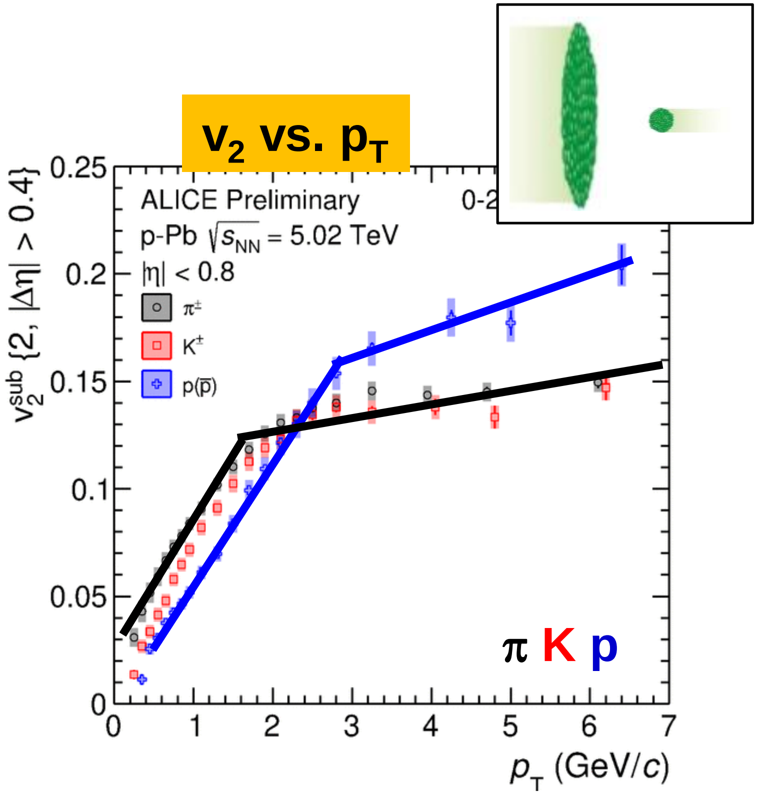
Ridge component characterized with multi-particle correlations: pp ~ p-Pb < Pb-Pb
→ At least 6 particles involved above $N_{ch} \approx 90$

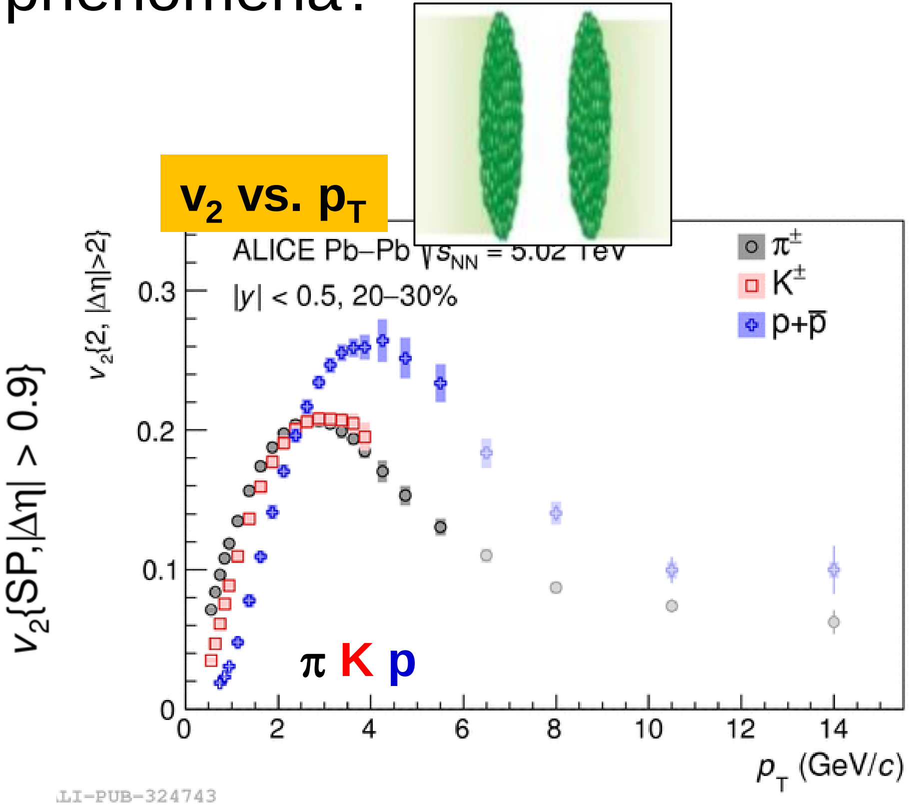
PLB 765 (2017) 193

Species Dependence

Which particles participate in the phenomena?







Species dependence behaviour observed in small and large systems

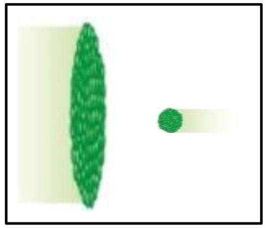
- **Mass dependent splitting**
- **Crossing at p_T ~ 2-3 GeV/c**

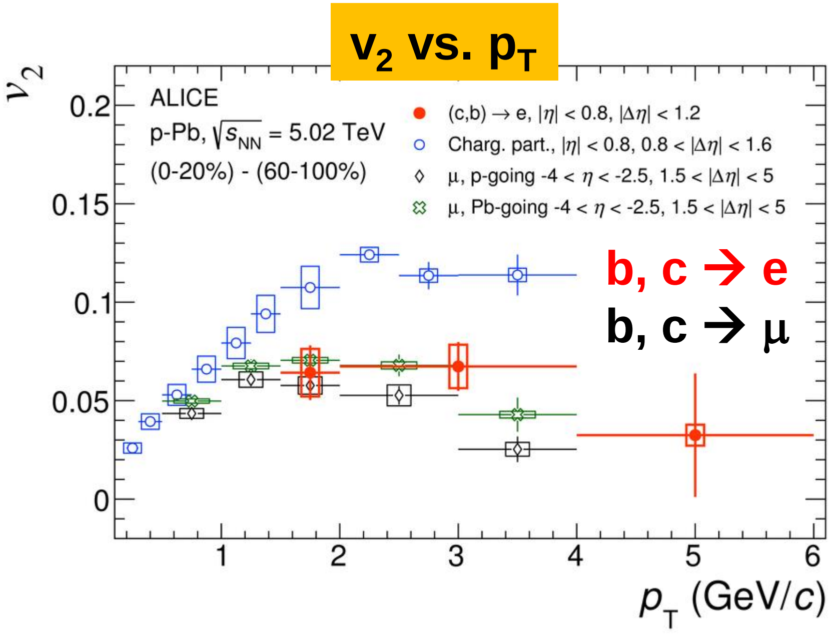
→ **Common velocity field**

PLB765 (2017) 193

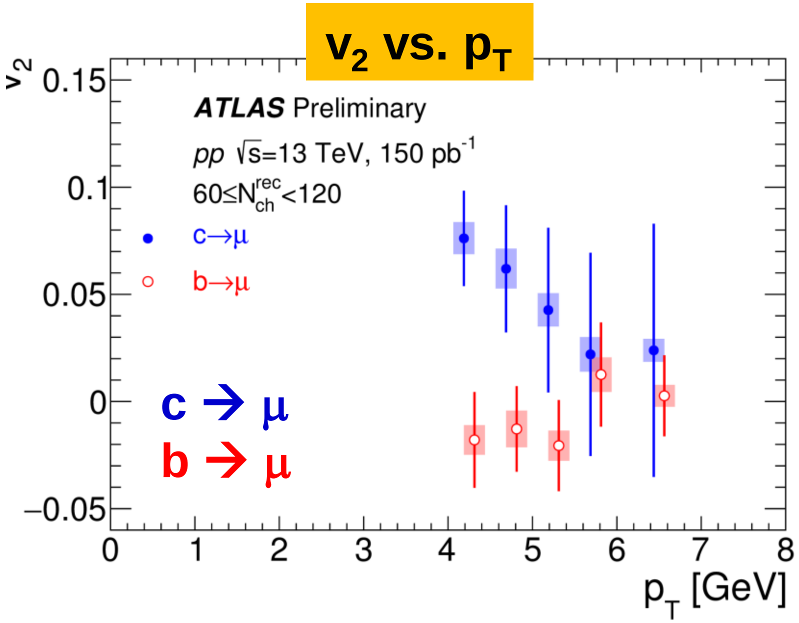
JHEP09(2018)006

What about Heavier Quarks?

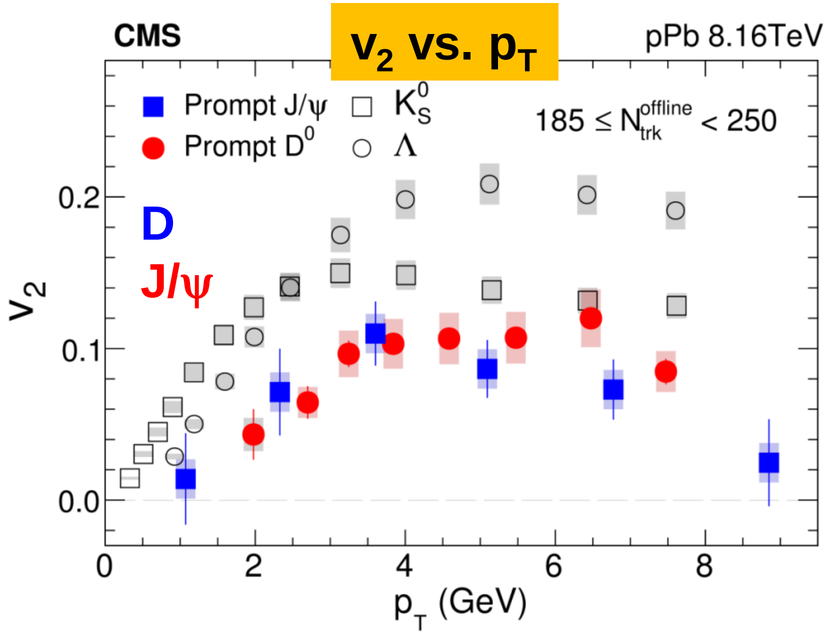




PRL122 (2019) 072301



ATLAS-CONF-2019-023



PLB791(2019)172

- Ridge structures for HF decay leptons, D and J/ψ
- Clear signal for open and closed charm
- No or small ridge for high p_T b → μ. Too heavy to participate in system evolution?

Low-Multiplicity Puzzle

- Low mult. dominated by jets, resonance decays (~negligible in high-multiplicity pp or p-Pb)
  - Extracting v_2 coefficient requires subtraction procedure
  - Experimental result is procedure dependent

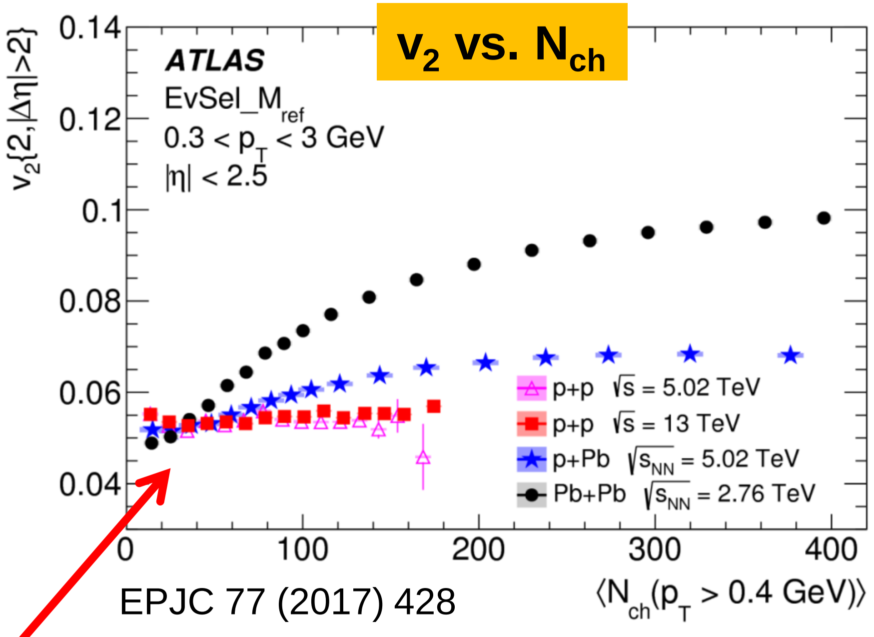
    Template fit: $Y(\Delta\phi) = \mathrm{F}Y_{LM}(\Delta\phi) + \mathrm{G}(1 + 2\sum_n V_{n\Delta}^{fit}\cos(n\Delta\phi))$
    (ATLAS)

    Peripheral subtraction: $V_{n\Delta}^{sub} = V_{n\Delta}^{HM} - \alpha \frac{N^{LM}}{N^{HM}} V_{n\Delta}^{LM}$
    (ALICE, CMS)
  - Large effect at low multiplicity (toy study here)

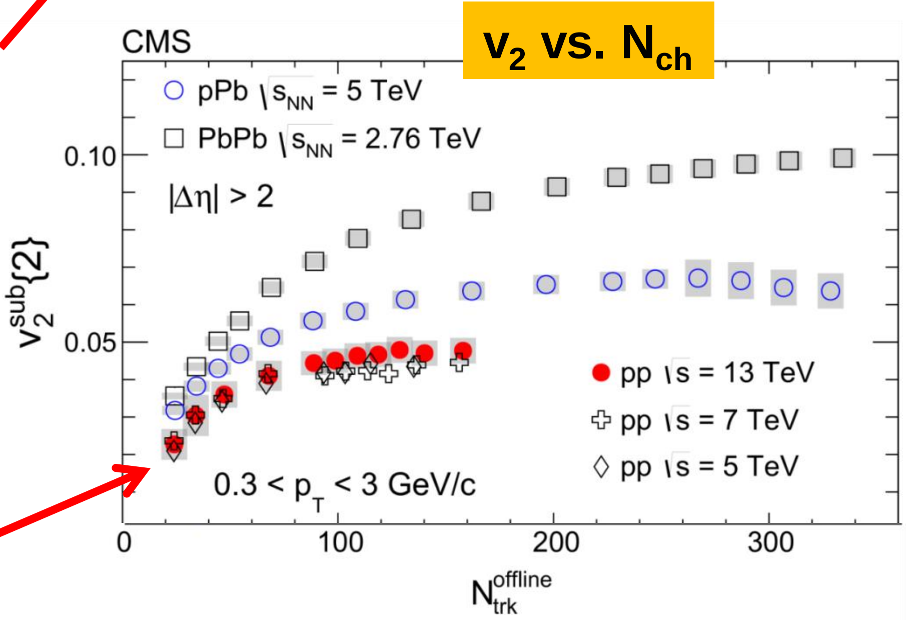
- Key problem: Ridge “too small to stick out”

NB to experts: v_2 at low multiplicity not well defined. Focusing on near side may be a solution.

Collective nature of dilute systems not understood, yet



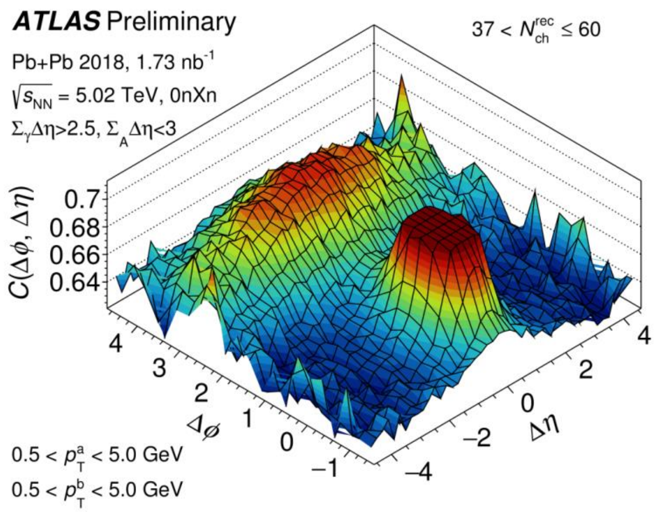
EPJC 77 (2017) 428

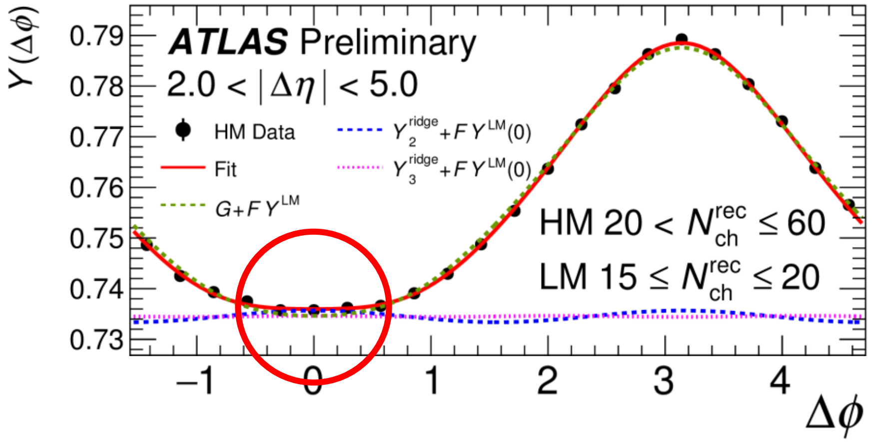


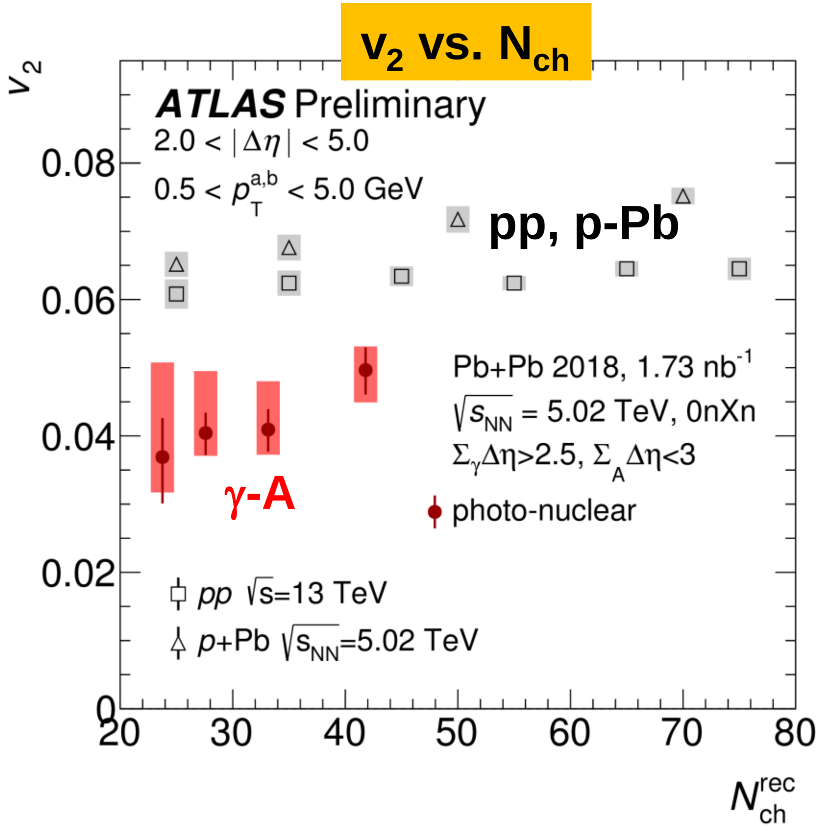
PLB 765 (2017) 193

Ridge in γ-A Collisions

- γ-A collisions (in ultra peripheral Pb-Pb collisions)
  - Probe of initial state
- Template fit method. Extremely small signal!
- v_2 finite (~50% compared to pp and p-Pb)
  - Can be interpreted as due to initial-state momentum correlations



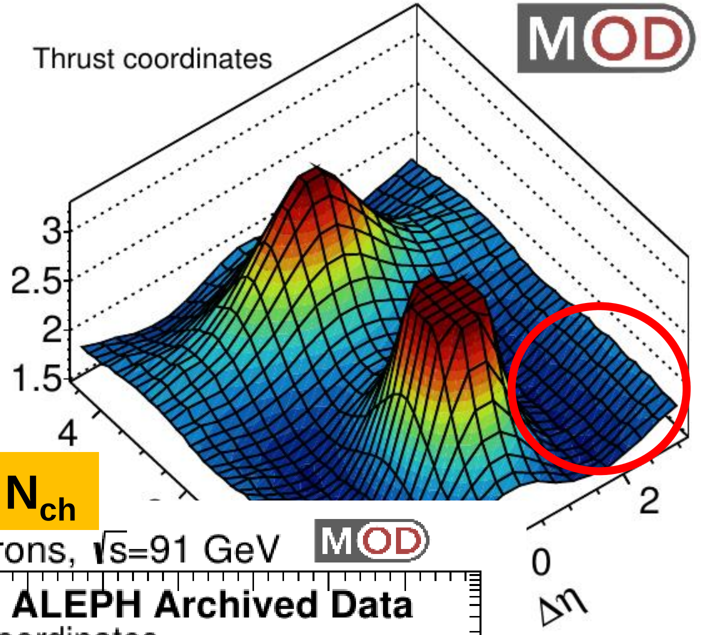




ATLAS-CONF-2019-022

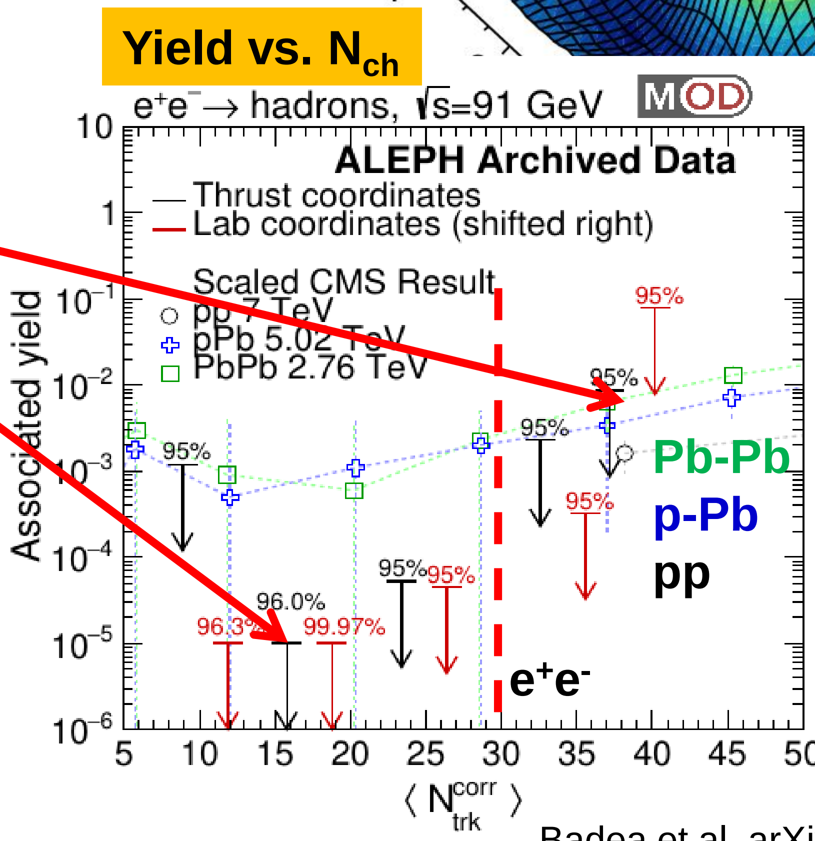
And e^+e^- ?

- Could ridge be related to fundamental process?
- Re-analysis of archived ALEPH data
  - No ridge structure → limit
- Also no signal in ep (ZEUS), see link



Small uncertainties in pPb, PbPb
Large uncertainties in ee

Large uncertainties in pPb, PbPb
Small uncertainties in ee

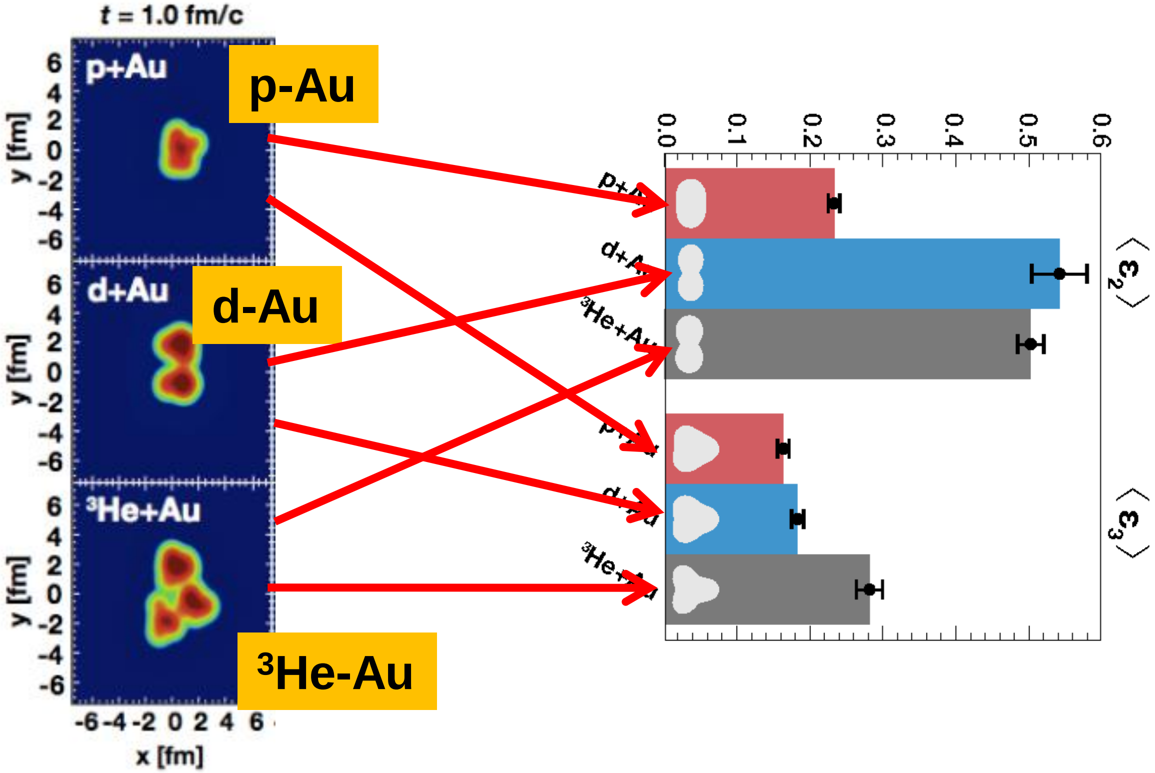


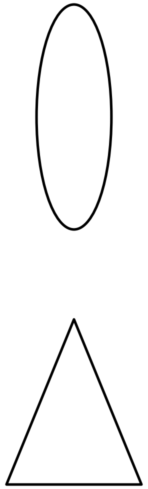
- However, compatible with pp and p-Pb
  - Call is still out!
- What is the smallest droplet of matter showing these phenomena?

Badea et al, arXiv:1906.00489

Quark-Gluon droplets engineered

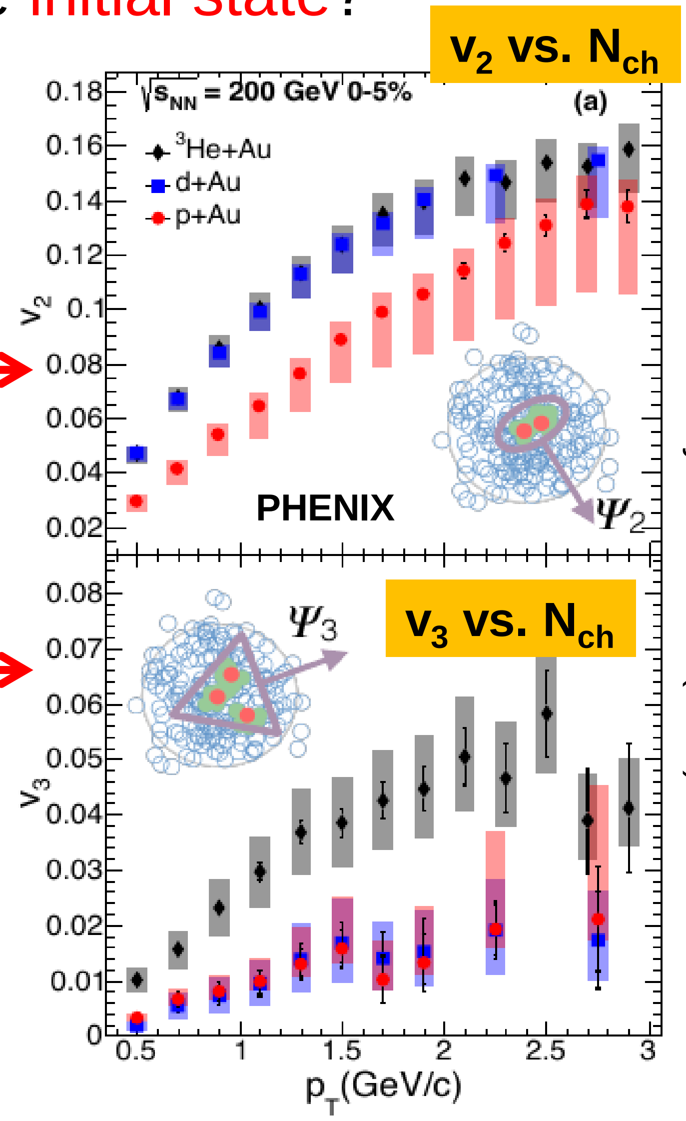
What is the relation to the overlap shape of the initial state?





Ellipticity
ε_2 and v_2

Triangularity
ε_3 and v_3



Nature Physics 15, 214 (2019)

Initial-state anisotropy imprinted on final-state observable
Requires hydrodynamic expansion (spatial → momentum)

Initial-state momentum correlation models cannot reproduce the effect, see backup

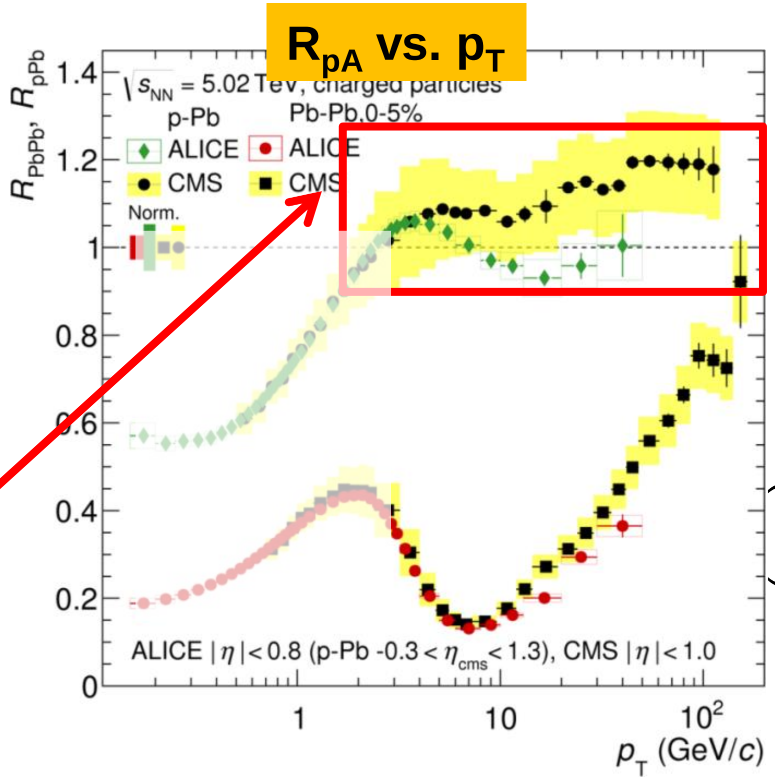
Energy Loss

- If observed phenomena are due to final-state interactions, partons should lose energy
  - Traditional heavy-ion observable R_{AA}

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

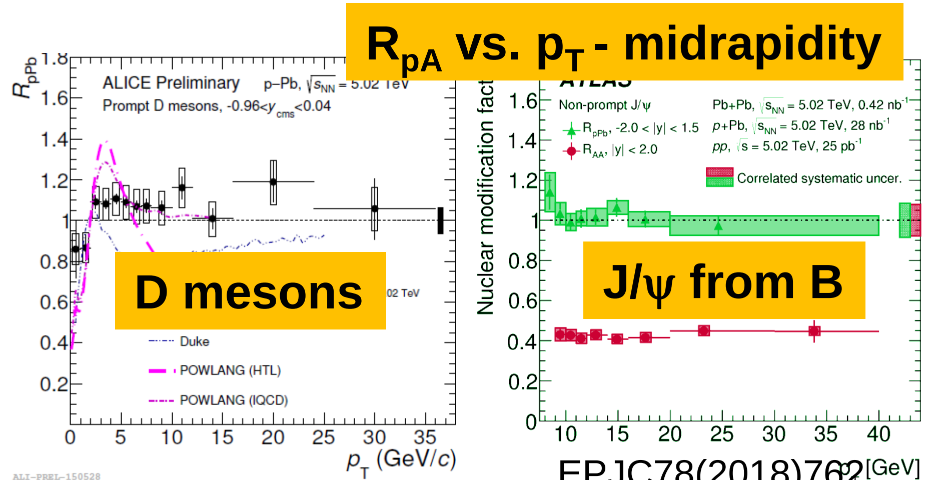
R_{AA} = 1 → no modification

R_{AA} != 1 → medium effects

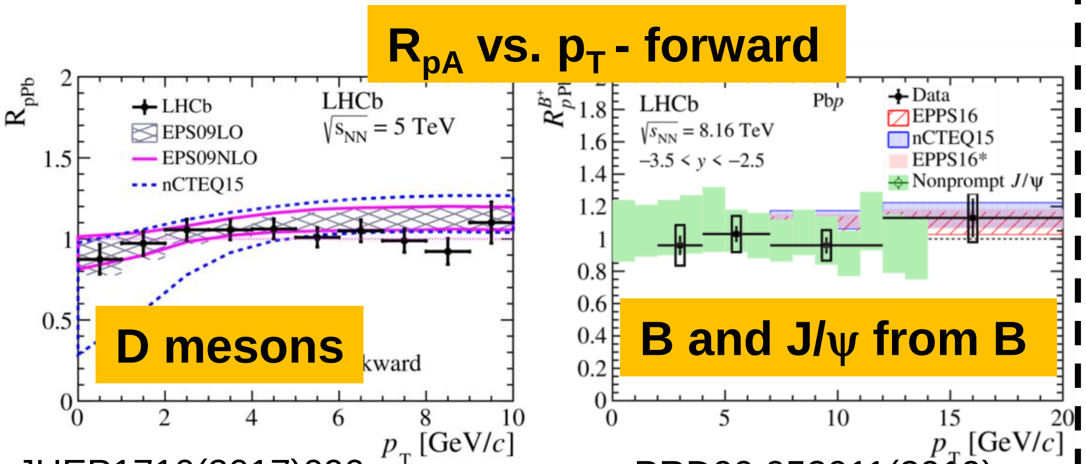


JHEP 1811 (2018) 013

- No sign of suppression for hadrons, D and B

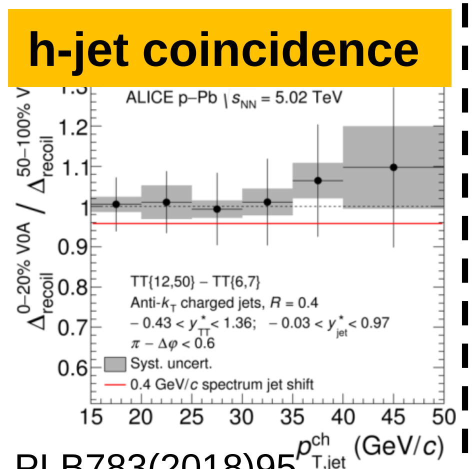


EPJC78(2018)762



JHEP1710(2017)090

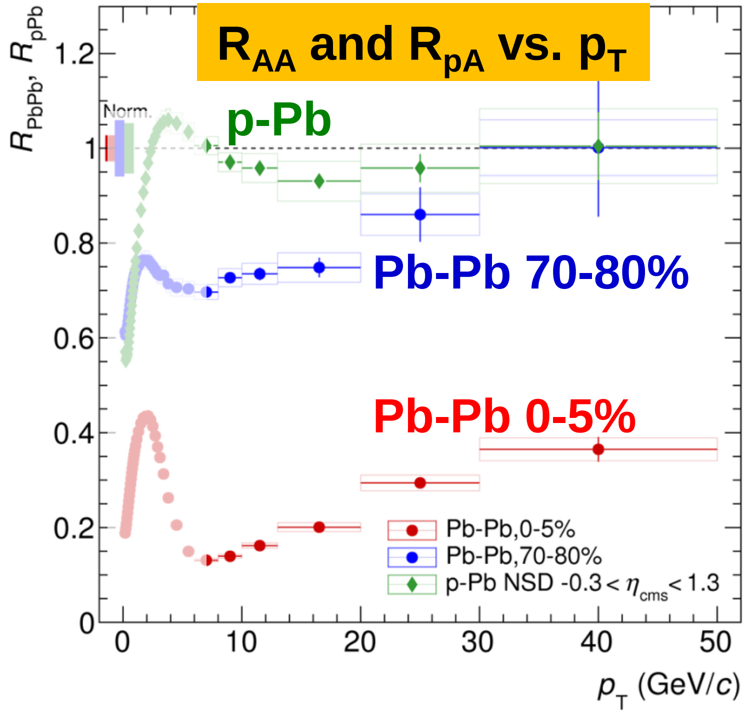
PRD99,052011(2019)



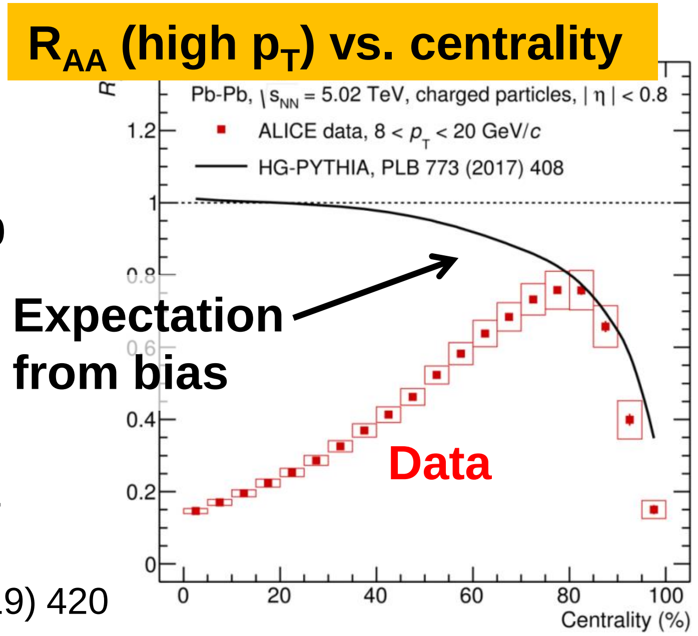
PLB783(2018)95

Absence of Energy Loss

- No evidence of parton energy loss in p-Pb
  - However, present in all Pb-Pb collisions
- When does energy loss turn on?
- Peripheral Pb-Pb has same size as average p-Pb
  - R_{AA} ~ 0.8 (peripheral Pb-Pb) vs. R_{pA} ~ 1 (p-Pb)
- Measurement in 80-100% clarified inconsistency
  - Reproduced by simple superposition model HG-PYTHIA (Loizides, Morsch, PLB773 (2017) 408)
  - Peripheral Pb-Pb: average NN impact parameter larger than in pp
- No energy loss in peripheral collisions
- Stresses relation of (soft) yields and (high p_T) spectra
  - Positive correlation between hard scattering and underlying event



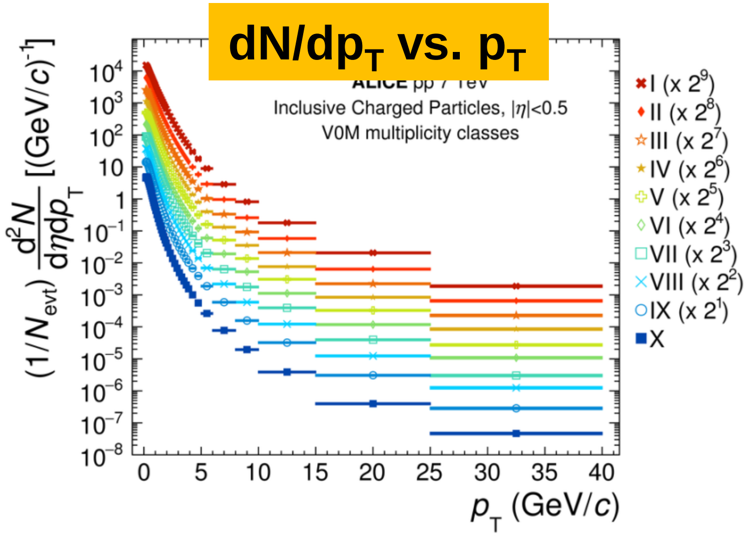
JHEP 04 (2017) 039, JHEP 1811 (2018) 013

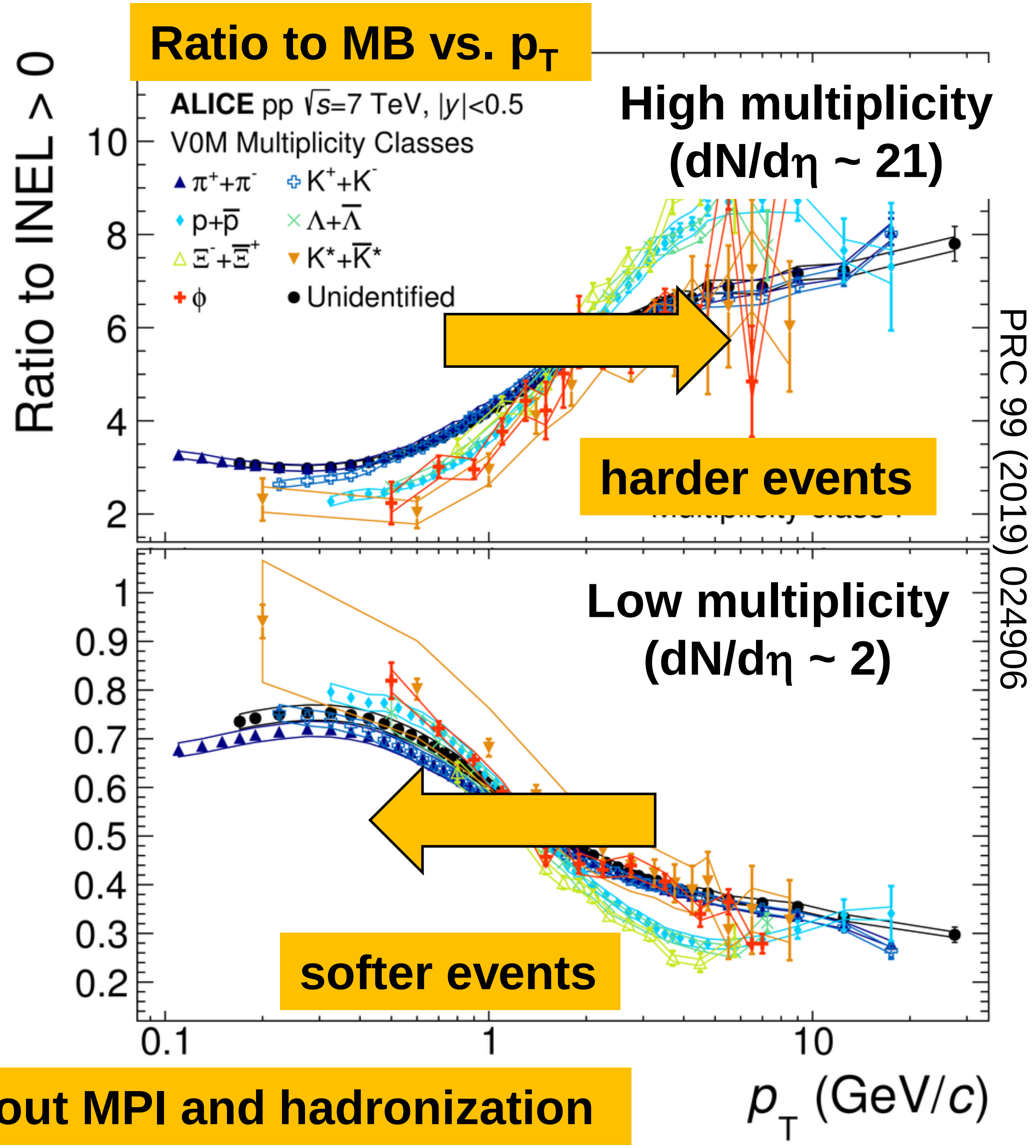


PLB793 (2019) 420

Spectra "vs." Yields

- Mentioned biases already present in pp
- Detailed characterization of particle production as function of forward multiplicity

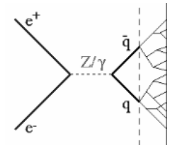


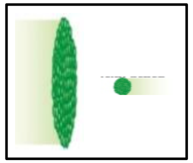


- Hardening of spectra with multiplicity
  - More pronounced for particles with larger mass

Rich and complex dynamics with multiplicity – teaches about MPI and hadronization

Interim Summary

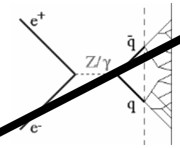



	ee	pp	pA	AA
Long-range correlations (ridges)	✗ Limit	✓	✓	✓
Strangeness enhancement	?	✓	✓	✓
Energy loss	?	?	✗ Limit	✓

Interim Summary

	ee	pp	pA	AA



Long-range correlations (ridges) — Limit

Strangeness enhancement — ?

Energy loss — ?

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	GC level	GC level except Ω	GC level except Ω
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	MB: $\gamma_s^{C} < 1$, 20–40%
(from two particle correlations)			
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			
Jet que			
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

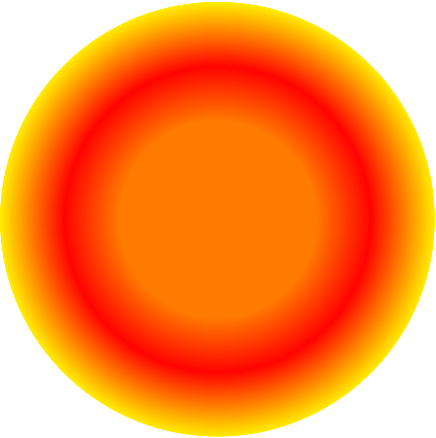
Wealth of measurements a legacy for QCD modeling

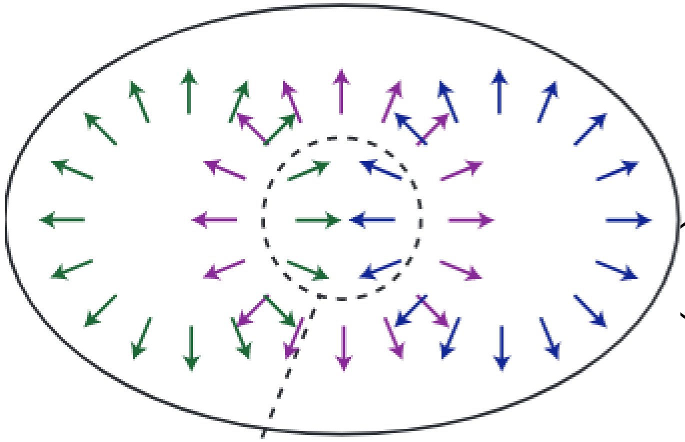
Small systems is a complete program in itself

arXiv:1812.06772

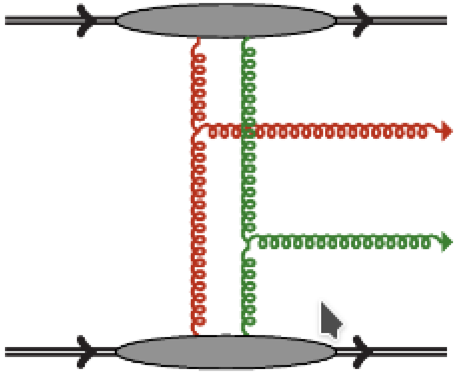
Explanations

Hydrodynamic evolution	Escape mechanism	Initial-momentum correlations





PLB783(2018) 274
PLB753(2016)506



PRD87(2013) 9,094034

Many scatterings ⟷ Few scatterings ⟷ Initial conditions

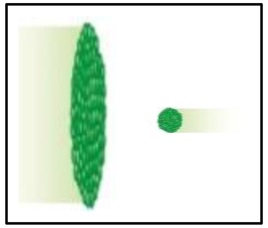
(Perfect) fluid dynamics ↔ free streaming limit

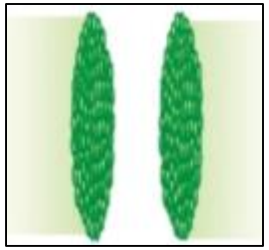
Theory spans still today a wide field

Modelling

“AA” models
Hydrodynamic models
Statistical models
…

pp 

p-Pb 

Pb-Pb 

“pp” models
Vacuum processes
amended by MPI, CR, ropes

Degree of complexity

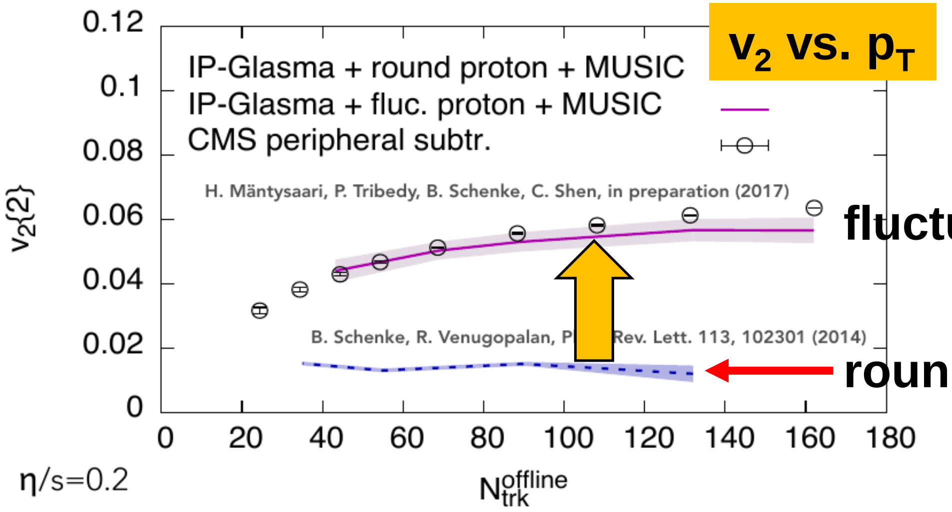
“single process limit”

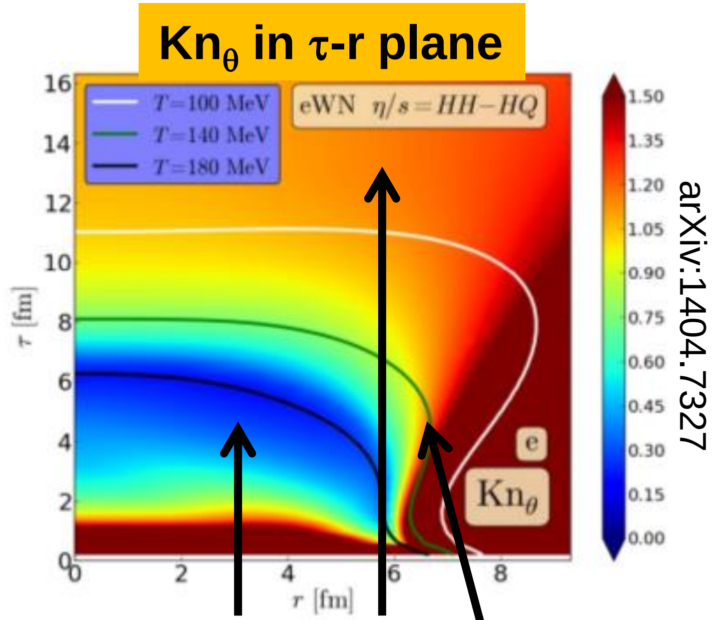
“thermal limit”

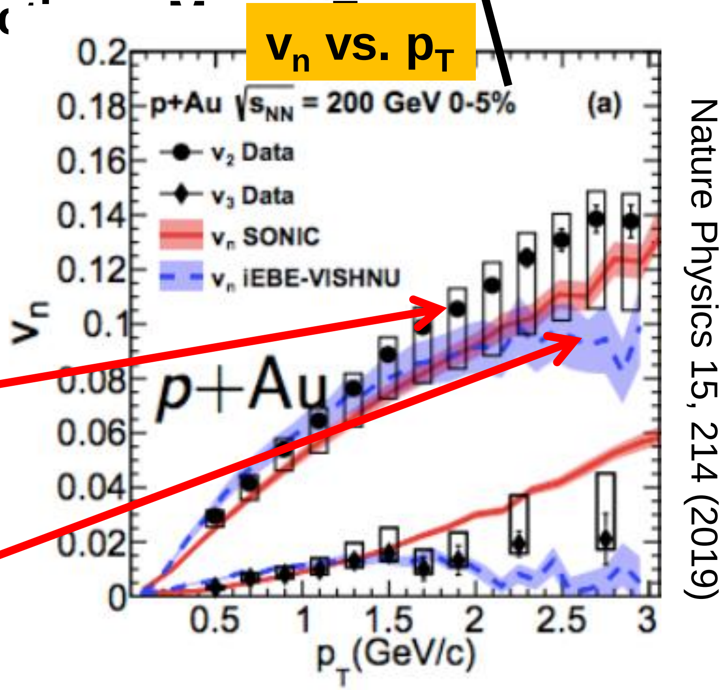
Underlying QCD is the same – tremendous opportunity for modelling

Hydrodynamics

- Hydrodynamics requires local thermal equilibrium
  - Needs sufficient interactions vs. short lifetime
  - Knudsen number ~ microscopic over macroscopic length scale
- However, calculations quantitatively successful
  - even far from equilibrium
  - for large pressure anisotropy in expansion (L vs. ⊥)
- Requires fluctuating (and not round) proton



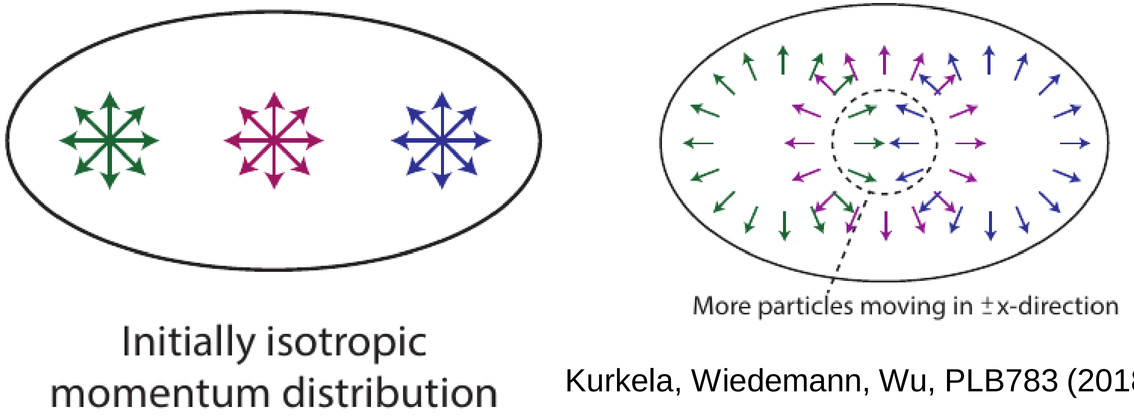




“Escape” Mechanism / Kinetic Theory

- Few interactions are sufficient for anisotropy
  - Partons more likely to escape in the short direction

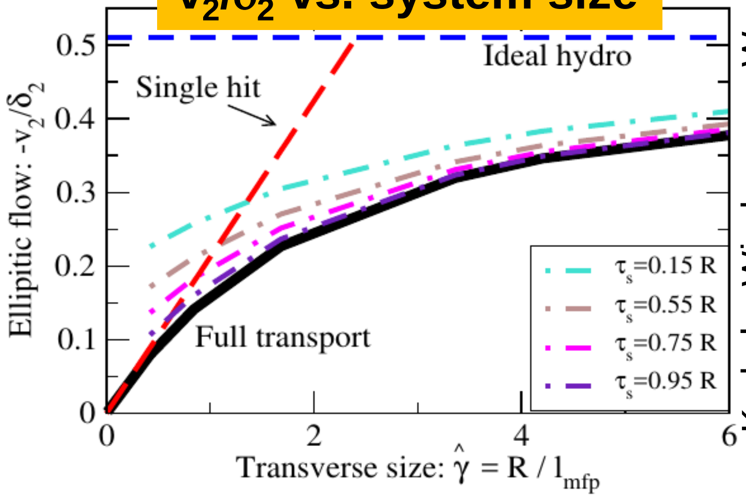
He et al, PLB753(2016)506



Kurkela, Wiedemann, Wu, PLB783 (2018) 274

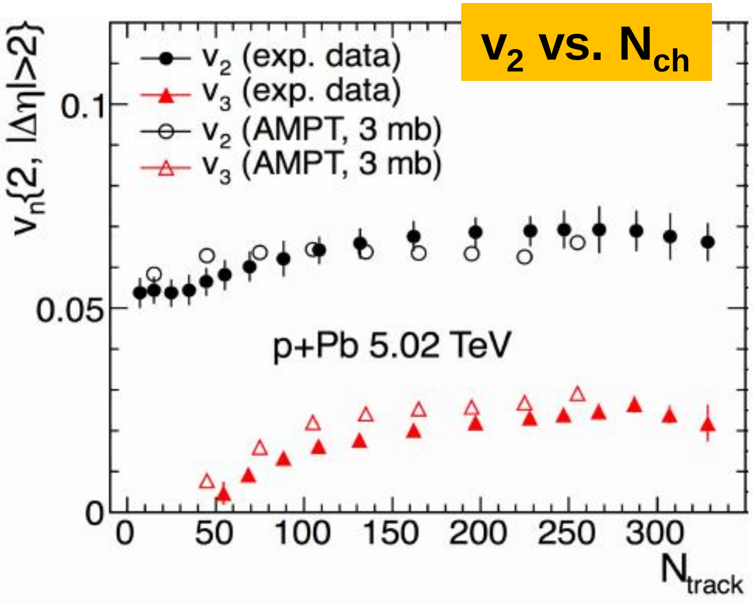
- In a small system, the single hit kinetic transport is equivalent to a full hydrodynamical transport
- MC implementation: AMPT
  - Reproduces v_n with small number of interactions

v_2/δ_2 vs. system size



Kurkela, Wiedemann, Wu, arXiv:1805.04081

v_2 vs. N_{ch}



Bzdak, Ma, PRL113, 252301

Thermo-Statistical Models

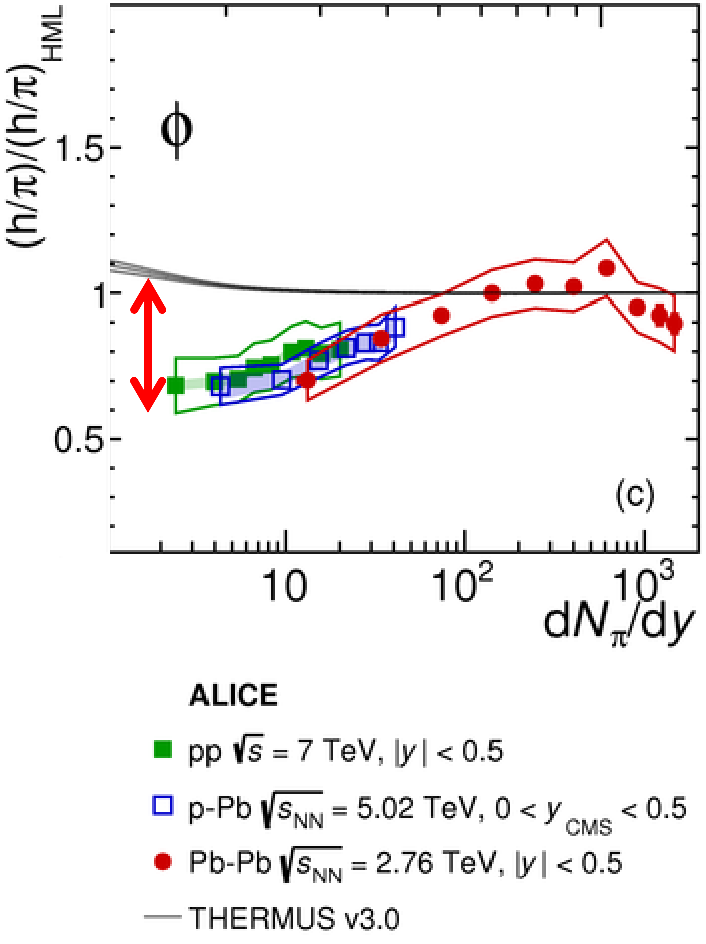
- Class of models which assumes equilibrated matter to predict particle yields
  - Few parameters: V, T, μ_B
  - Very successful in describing 12+ species in HI collisions
- Extension into small systems attempted
  - Needs “fudge” factor γ_S to correctly describe strangeness

$$z \rightarrow \gamma_S^s z$$

number of strange quarks

  - Effect of extension into non-equilibrated / partially equilibrated region

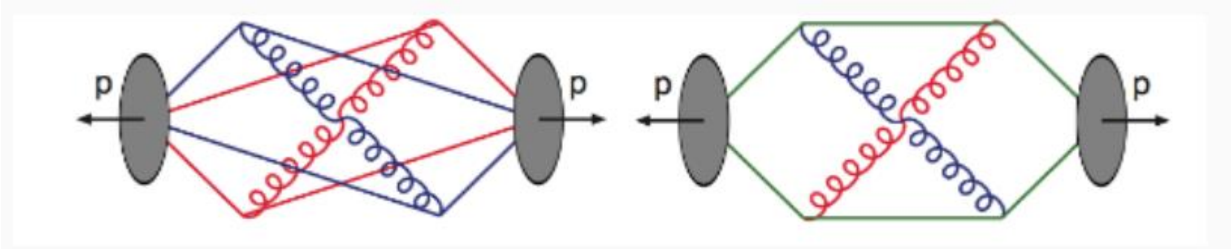
normalized ϕ/π ratio vs. N_{ch}

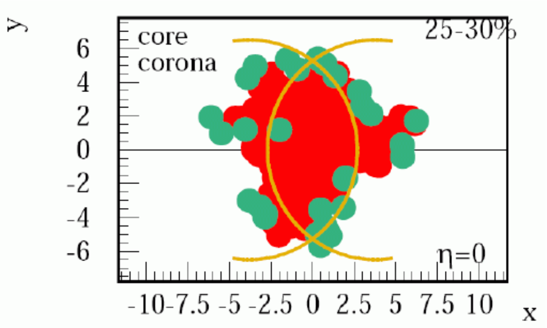


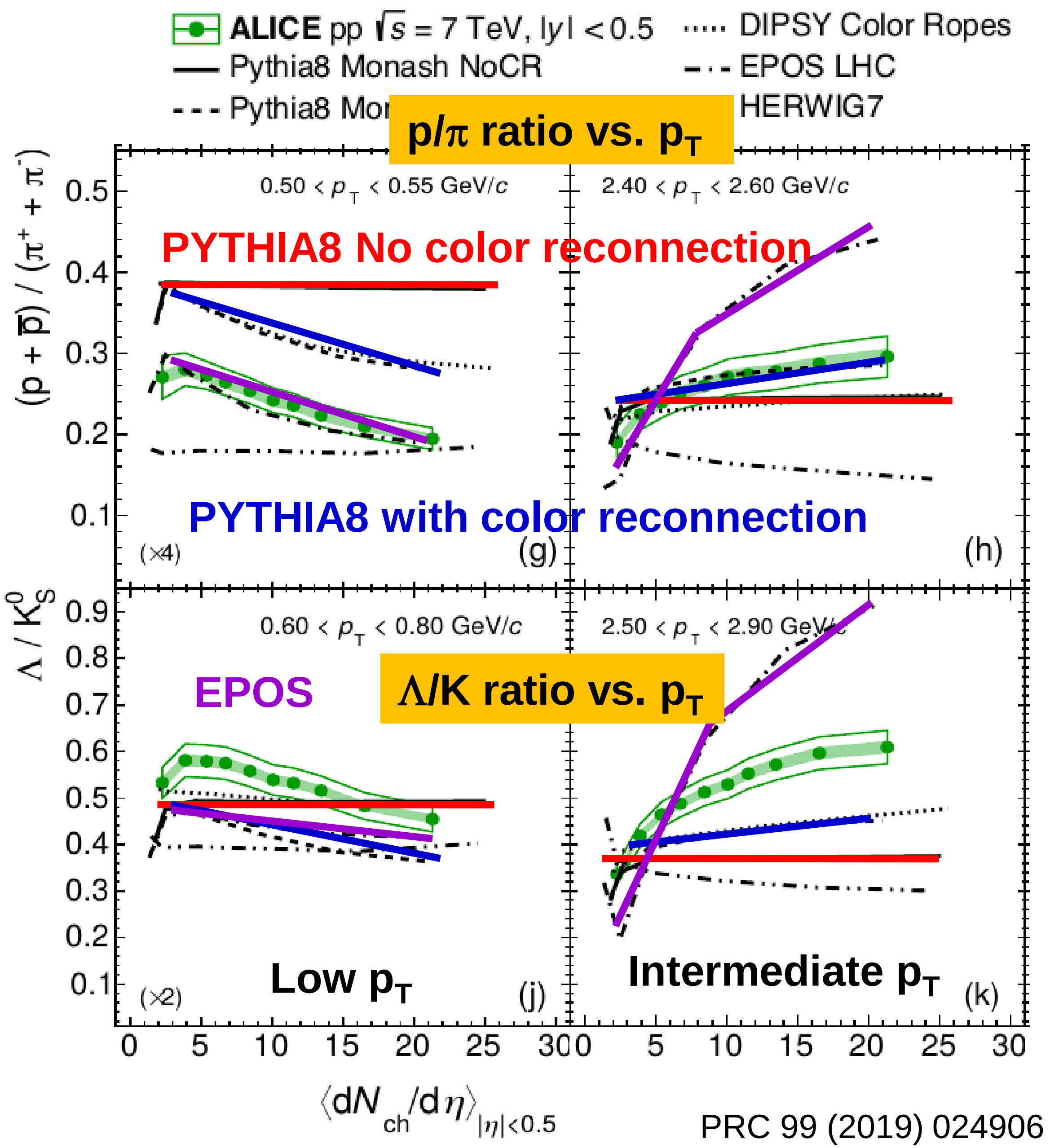
PRC 99, 024906

Baryon Production

- Models do not get baryon production right
  - Torbjorn Sjostrand [1808.03117]: “we lack some fundamental insight on baryon production”
- Incoherent superposition not successful
- Colour reconnection (PYTHIA, DIPSY), or collective expansion (EPOS) closer to data



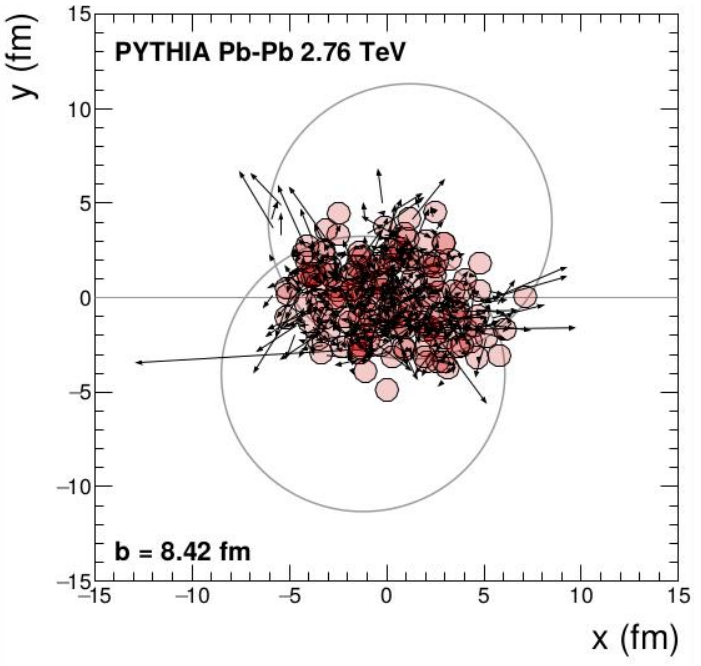


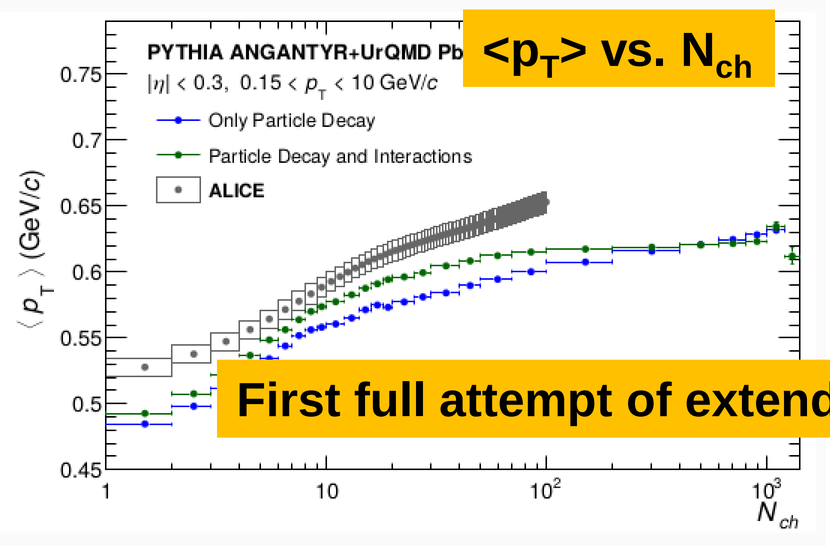


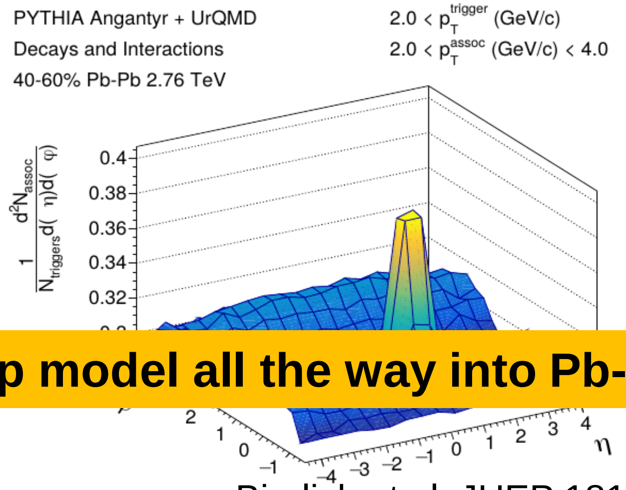
PRC 99 (2019) 024906

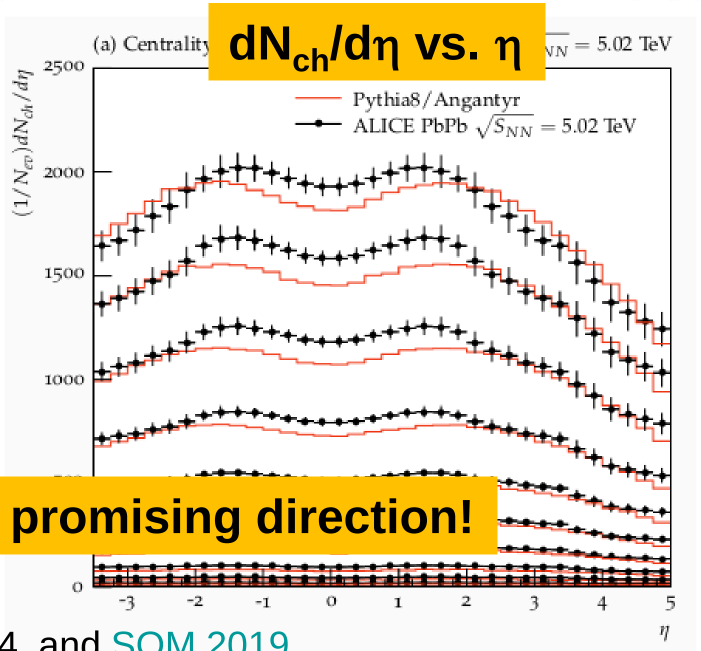
Angantyr

- Pythia MPI + CR model recently extended to heavy ions
  - Aim: produce a QGP-free final state
  - However: could microscopic dynamics make a mini-QGP?
  - AA through Glauber with Gribov colour fluctuations
  - Interfaced to UrQMD for multi-body hadronic phase
    [S. Bass el al.: Prog. Part. Nucl. Phys 41 (1998) 225]
- Good results for <p_T>, flow, charged particles









First full attempt of extending a pp model all the way into Pb-Pb. Very promising direction!

Bierlich et al, JHEP 1810 (2018) 134, and SQM 2019

Résumé

Tremendous experimental and theoretical progress in last years

<u>Run 1 + 2</u>

- **Discovery of heavy-ion like phenomena in small systems**
- **Characterization of multi-particle correlations and strangeness enhancement**
- **Absence of parton energy loss**

What's next?

Run 3 + 4

Non-flow-free correlation measurements
→ nature of higher-order correlations

Thermal radiation
→ isotropization and equilibration

Energy-loss signals
→ role of final-state interactions

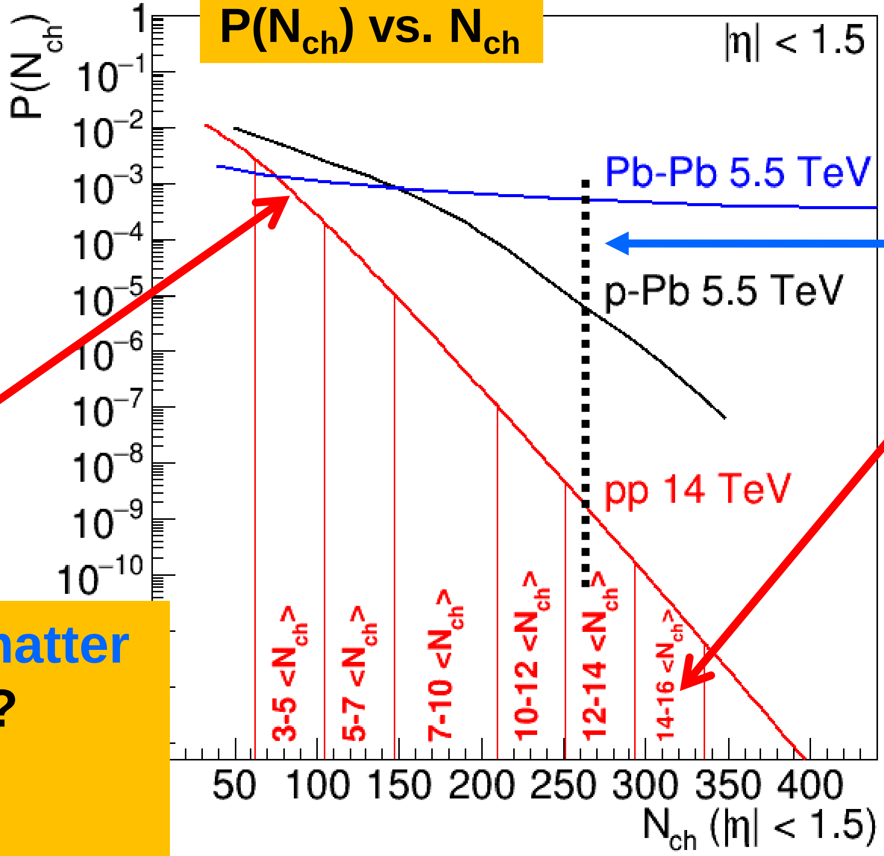
Strangeness enhancement
→ insight into baryon production (incl. HF)

Short excerpt in the following – for full details see HL-LHC Yellow Report: arXiv:1812.06772

Multiplicity Distribution

Run 3+4

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



arXiv:1812.06772

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?

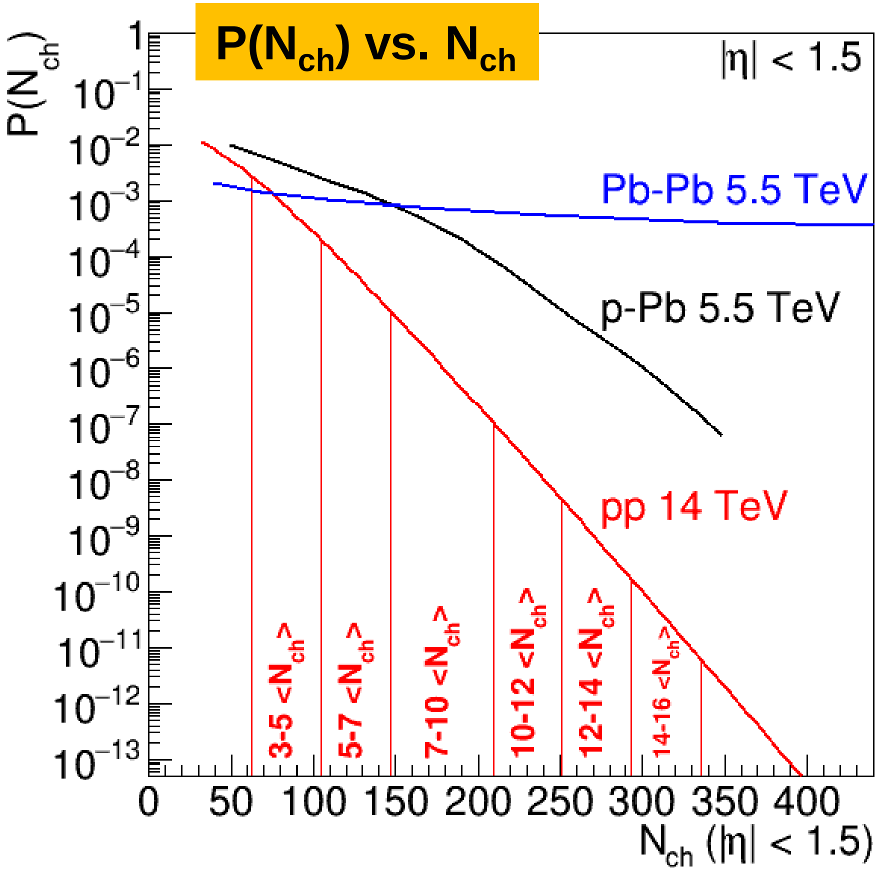
Significant overlap between pp and PbPb

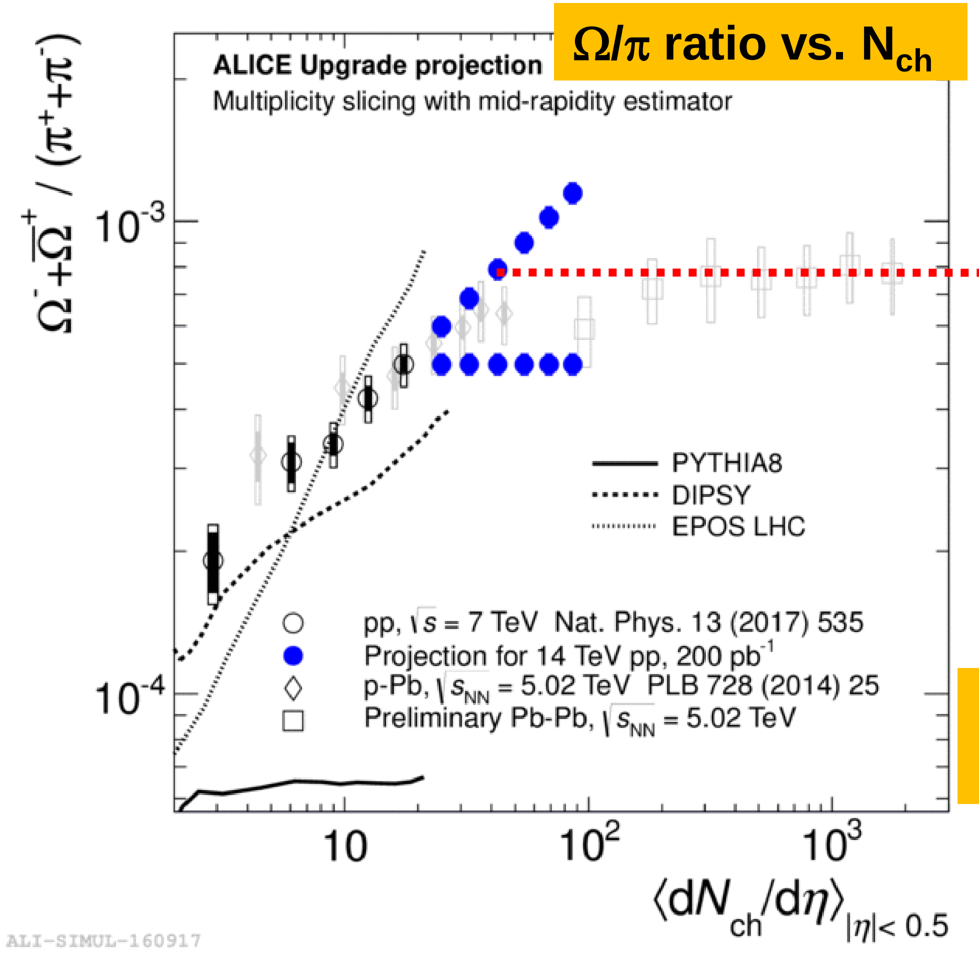
If pp behaves as PbPb, we can look for "standard" PbPb physics

Multiplicity Distribution

Run 3+4

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





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

Thermal limit reached or exceeded in pp?

arXiv:1812.06772

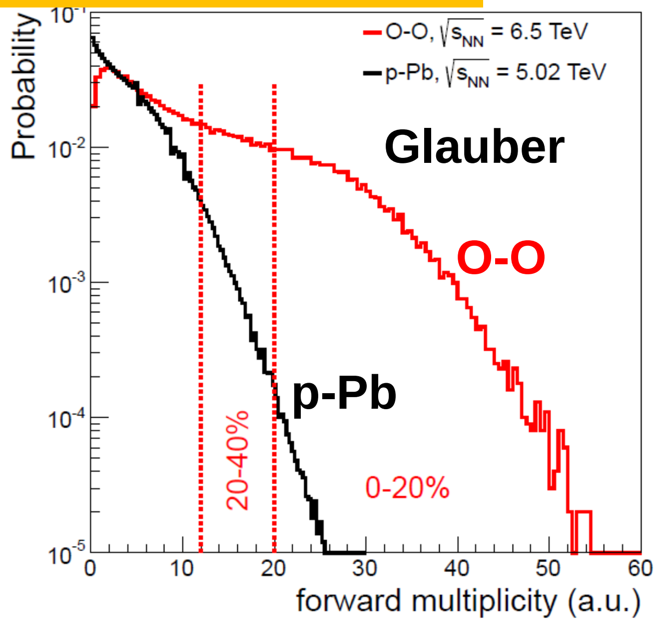
Puzzling Absence of Energy Loss

Run 3+4

- h-jet, γ-jet, Z-jet correlations (in p-Pb and pp collisions)
  - Stringent limit for energy transfer ~21 MeV/c (400 times smaller than measured in PbPb, and 20 times smaller than current limit)

- Recent idea: Oxygen-oxygen collisions
  - Symmetric but small collision system
    - 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
  - Under discussion at LHC ($\sqrt{s_{NN}}$ = 6.5 TeV) and RHIC (200 GeV)

P(#signal) vs. #signal



arXiv:1812.06772

Summary

- Small system observations challenge two paradigms at once
  - Smallest system in which heavy-ion “standard model” remains valid?
  - Can the standard tools for pp physics remain standard?
- Traditional HEP and traditional HI studies grow together
  - Tremendous experimental and theoretical progress in last 5+ years
  - The underlying QCD *is* the same theory
- Aim: Demonstrate that unified description from pp (ee) to Pb-Pb is feasible *or* show that different mechanisms are justified

Thank you for your attention!


Strokkur Geyser, Iceland