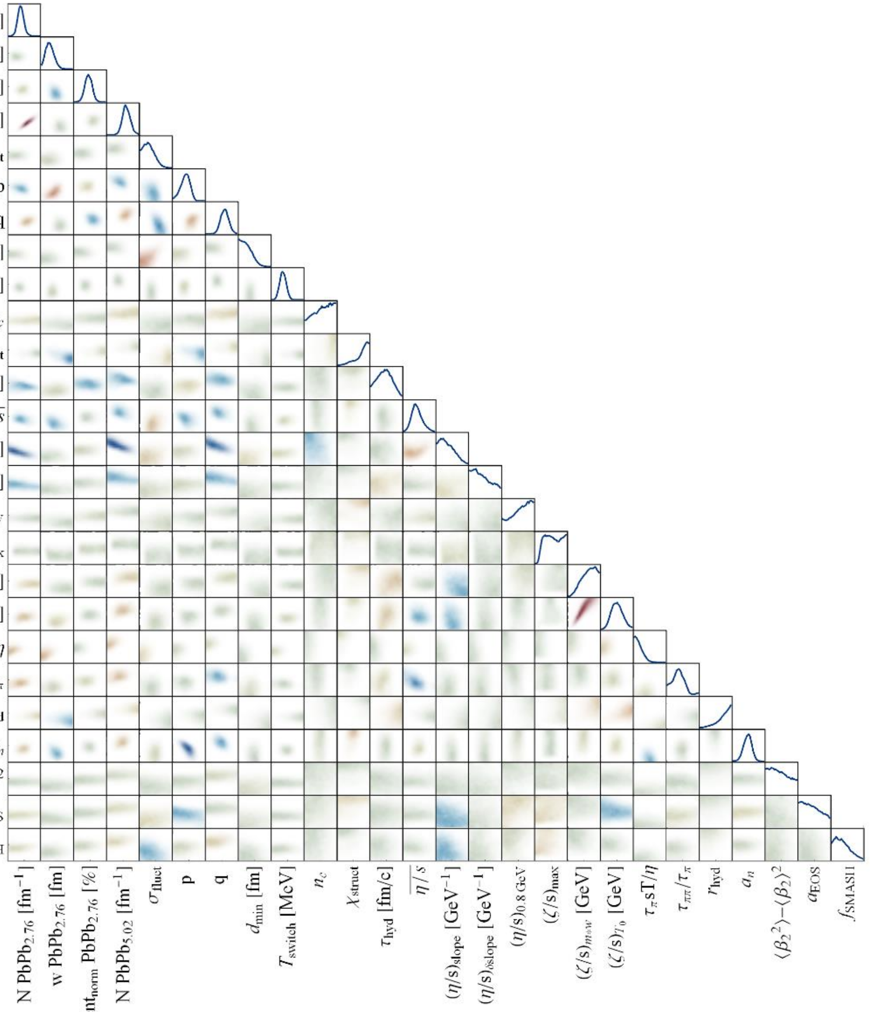
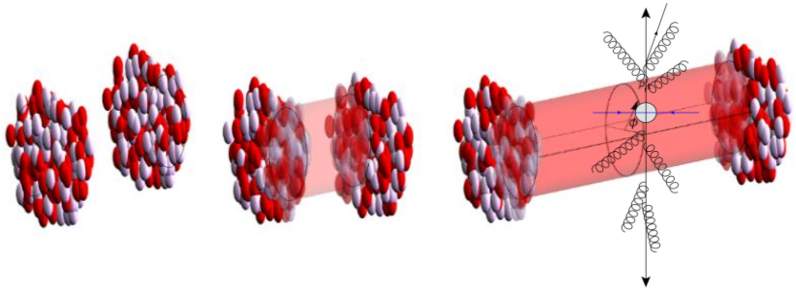
Universiteit Utrecht



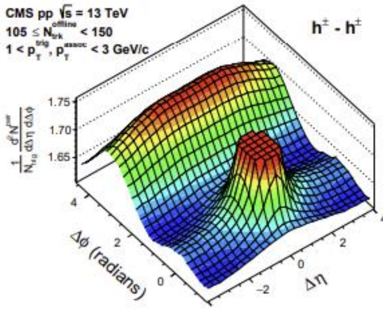
Anisotropic flow in small systems

Hydrodynamics at its limits

Together with Govert Nijs



Wilke van der Schee
Initial Stages, Copenhagen
21 June 2023



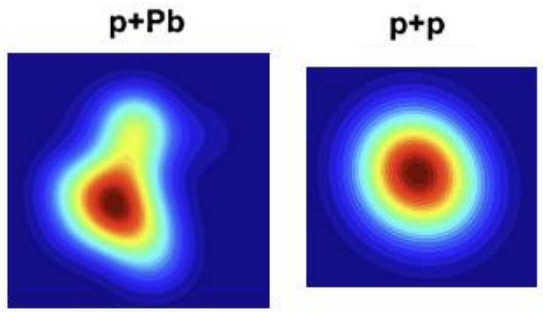
One fluid to rule them all --- Panta Rei

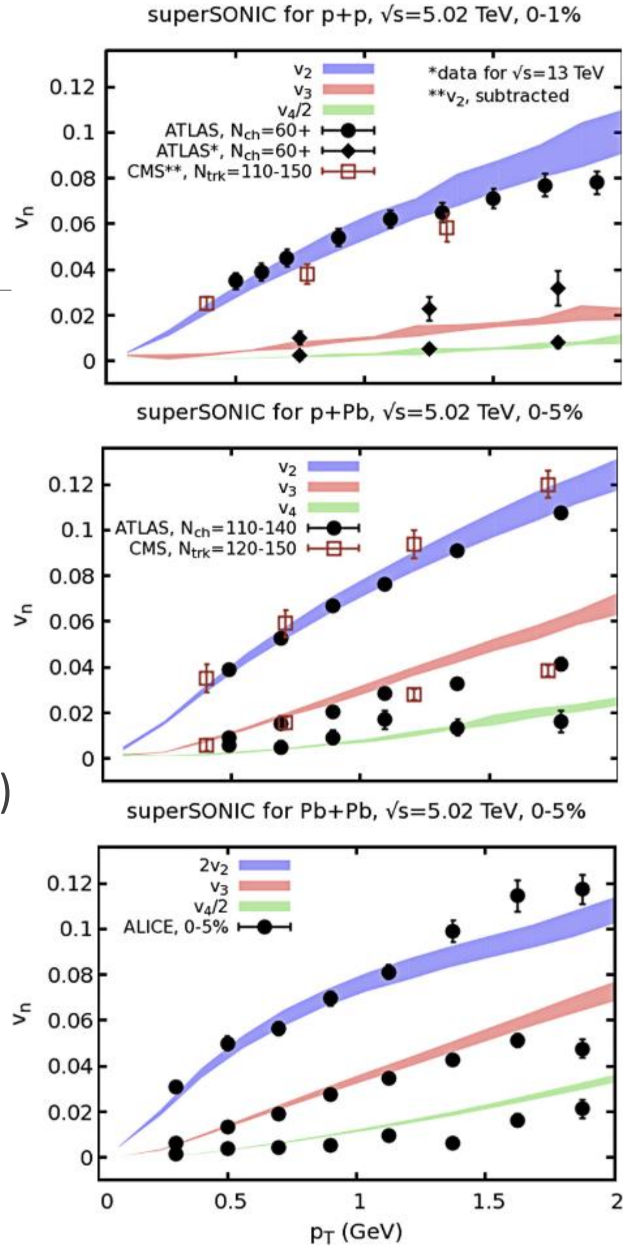
Long range rapidity correlations seen in near-side ridge

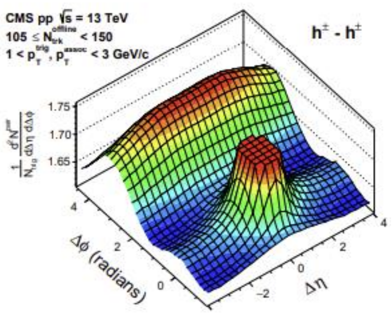
- Most natural explanation in terms of a geometric effect --- hydro?
- Low multiplicity: correlations dominated by `non-flow' effects:
  - Momentum conservation (away side ridge)
  - Fragmentation (also: *resonance decays*)

Hydrodynamic models describe the data well (?)

- In the case of superSONIC a relatively simple initial Glauber model (3 constituents)







See also talk by Parker Gardner (Wed 16:10)

See also talk by Huichao Song (Wed 15:20)

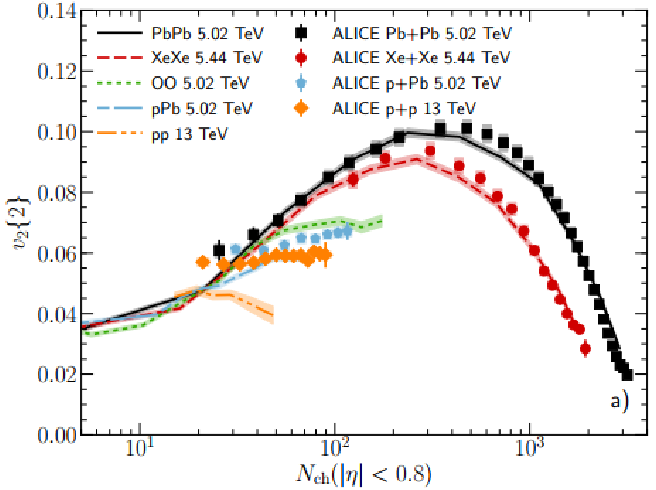
One fluid to rule them all --- Panta Rei

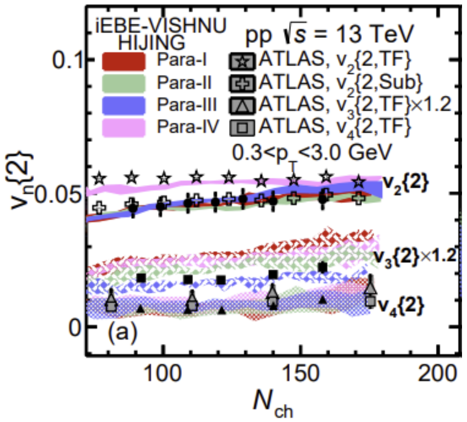
Similar results from IP-Glasma + MUSIC + UrQMD

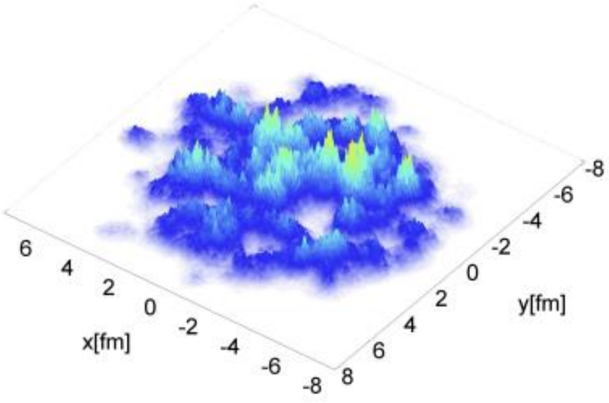
- Initial state in this case very `bumpy’
- PbPb/XeXe elliptic flow larger than small systems at same small multiplicity

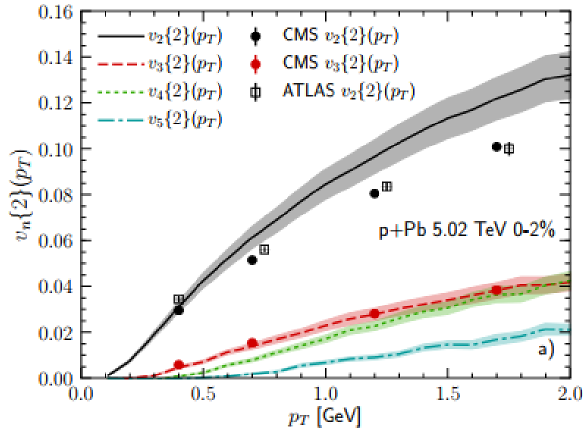
Similar results from HIJING/Trento + iEBE-VISHNU for pp collisions

- Initial state is varied from HIJING to Trento
- Describes data well

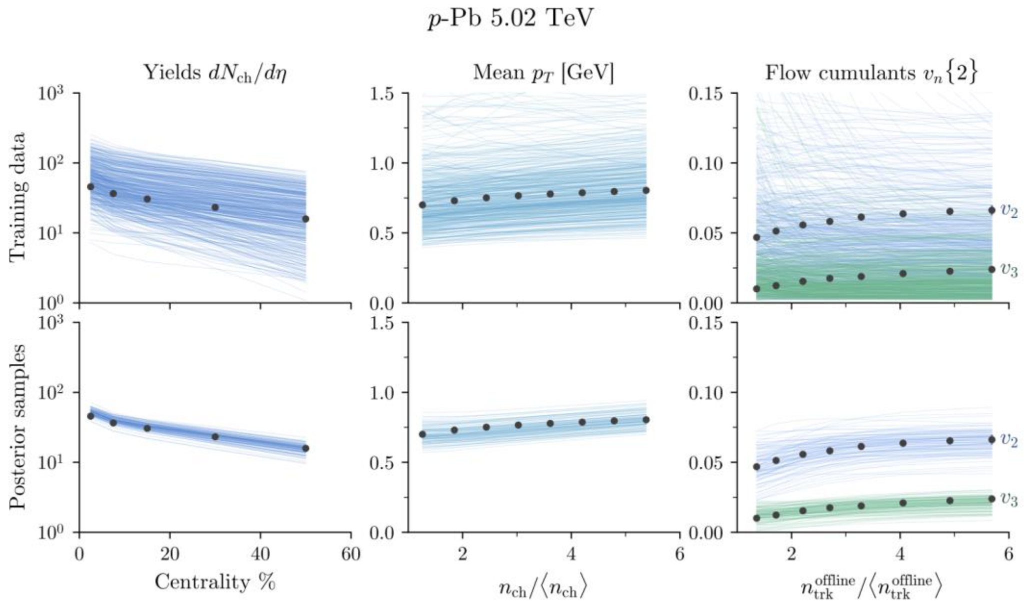








Bayesian analysis of p-Pb

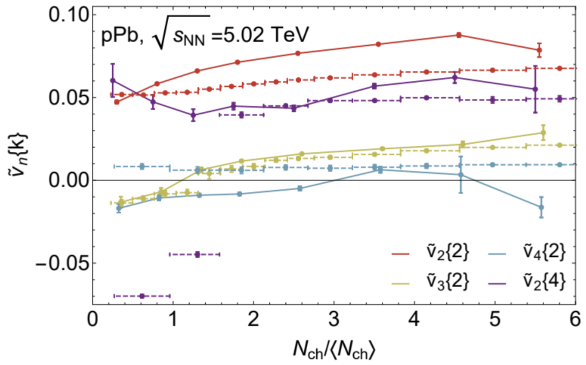


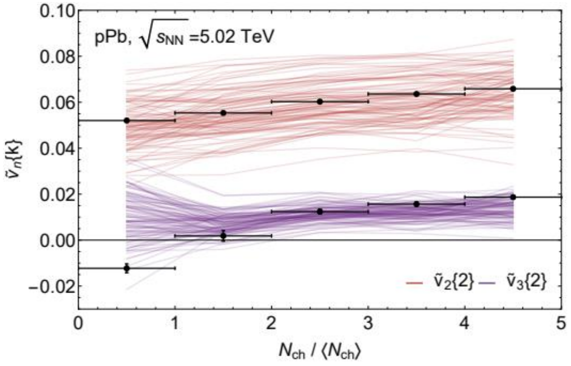
Bayesian analysis including p-Pb collisions

- Requires nucleon `substructure’: n constituents of width v
- More challenging to emulate/compute than PbPb

MAP comparison of Trajectum in 2020

- Reasonable agreement
  - Curious imaginary values both in theory and data of $v_3\{2\}$





Scott Moreland, Jonah Bernhard and Steffen Bass, Estimating initial state and quark-gluon plasma medium properties using a hybrid model with nucleon substructure calibrated to p-Pb and Pb-Pb collisions (2018)
Govert Nijs, WS, Umut Gürsoy and Raimond Snellings, Bayesian analysis of heavy ion collisions with the heavy ion computational framework Trajectum (2020)

Anisotropic flow in small systems

The success of hydro or anything goes?

- Requires a systematic study: vary parameters consistent with PbPb data
  - Including changes in initial state and changes in viscosities
- Do we do an apples-to-apples comparison?
  - Small multiplicity: need to understand `non-flow subtraction'
  - Resonance decays lead to non-trivial correlations

This talk: use *Trajectum* to study this in detail

Future aim: what are the limits of hydro?

The limits of hydrodynamics is a great motivation in theory and experiment: upcoming OO and pO runs in 2024 ☺. Possibility of Neon run in 2025?

See also talks by Govert Nijs (Thu 16:00)

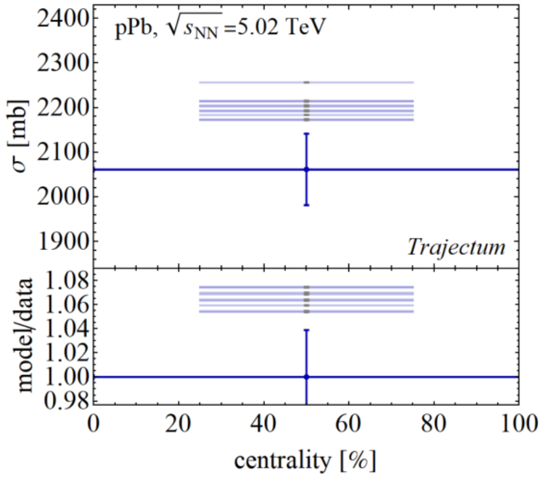
Back to basics: the total hadronic cross section

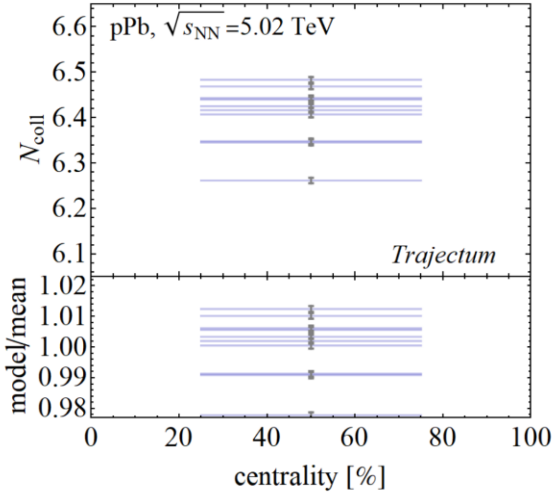
Total cross section on the high side

- Based on 10 `likely' parameter settings
- Even with a nucleon width of ~0.6 fm

$$\sigma_{AB} = A\,B\,\sigma_{NN}/\langle N_{\rm col}\rangle$$

- Average N_{coll} hence a bit low



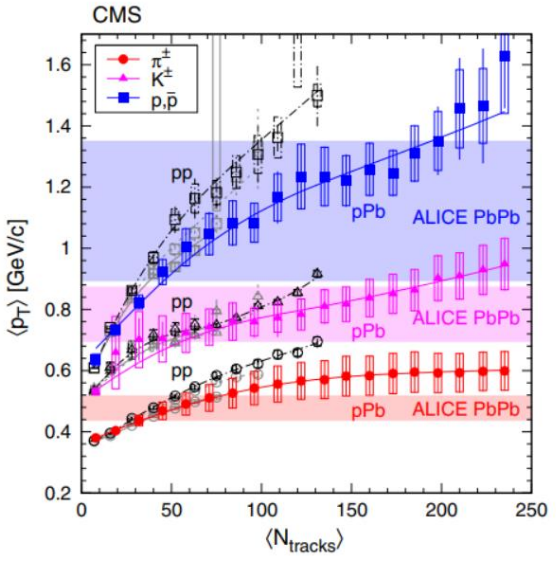


Implies reduce nuclear thickness of about 7% higher than CMS value

- Could have serious implications for pPb R_{AA}

	T_{AA} [mb^{-1}]
Trajectum	0.0947±0.0010
CMS	0.0983±0.0044

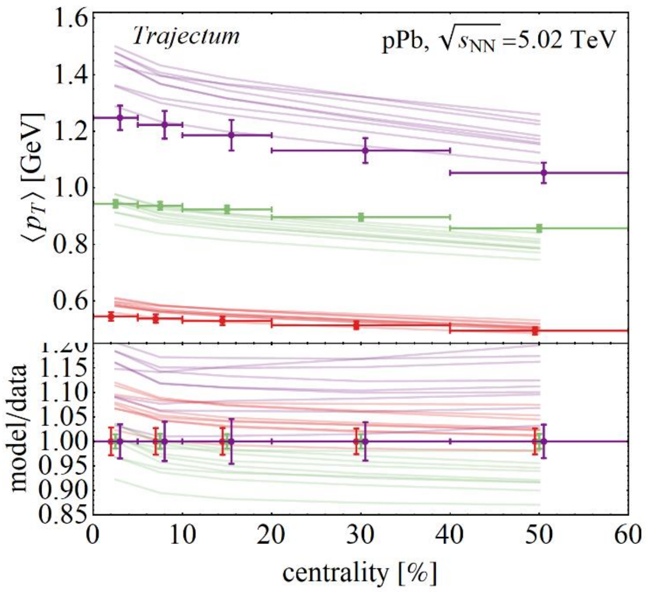
$$\langle T_{AB}\rangle = \langle N_{\rm col}\rangle/\sigma_{NN}$$

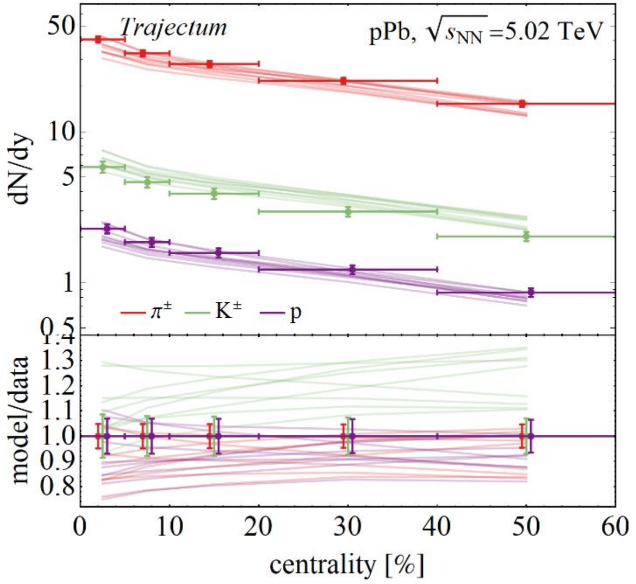


Yields and mean transverse momentum pPb

Same 10 likely settings that compare well with pPb

- No new fitting parameters (uses norm of PbPb)
- Proton mean p_T overestimated compared to ALICE (see however CMS)
- Significant systematic uncertainty: constrain by Bayesian global analysis?

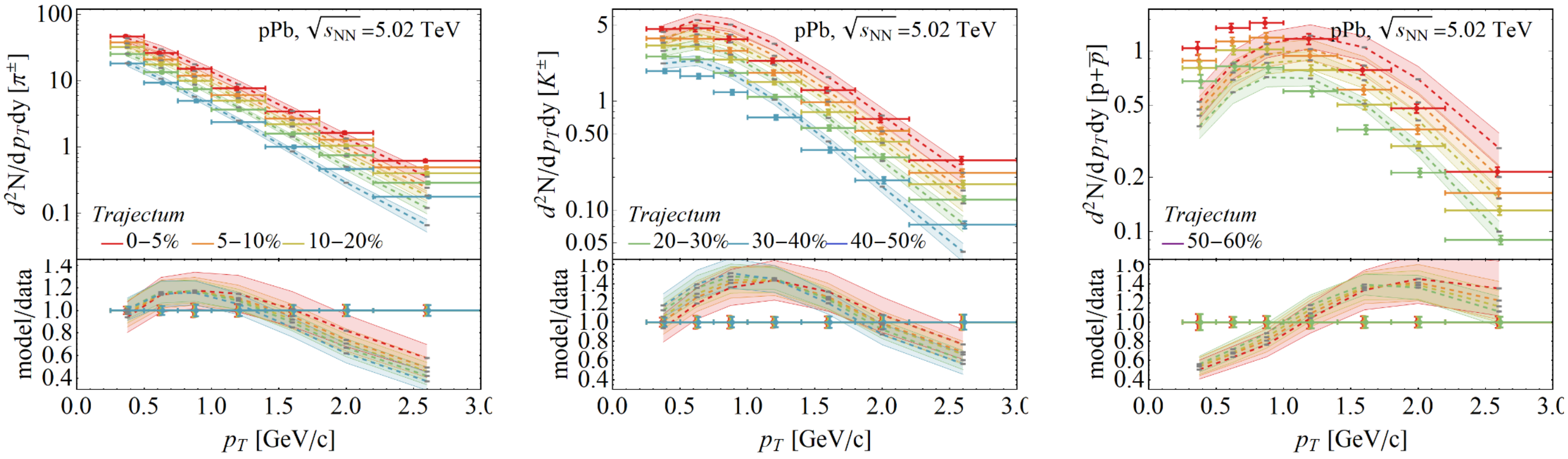




Spectra

More differential: identified spectra

- Significant distortions in shape
- Hadronisation is difficult, also uncertainty due to afterburner

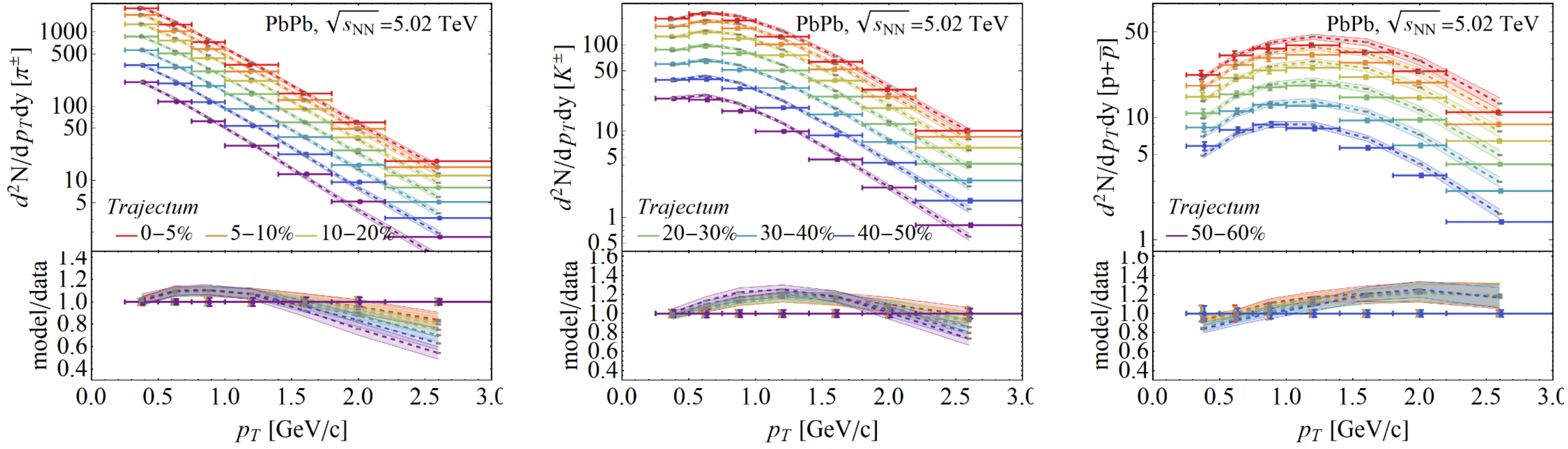


ALICE, Multiplicity dependence of charged pion, kaon, and (anti)proton production at large transverse momentum in p-Pb collisionsat $\sqrt{s_{NN}}$ = 5.02 TeV (2016)

Spectra

More differential: identified spectra

- Significant distortions in shape
- Hadronisation is difficult, also uncertainty due to afterburner
- Smaller but similar tensions with data for PbPb



The elephant in the room: `non-flow' subtraction

Theory: usually ignored in hydro (hydro does not have `non-flow'?)

- Exceptions: Zhao, Ko, Liu, Qin and Song (pp, 2001.06742) and Zhao, Ryu, Shen and Schenke (dAu, γ-Pb 2211.16376, 2203.06094)

Experiment: almost always subtracted as much as possible (?) by imposing largest Δη gap

- Δη gap depends on experiment and is rarely varied

Method 1: cumulants

$$v_n\{2\}^2 = \langle\langle e^{in(\phi_i - \phi_j)}\rangle\rangle$$

First average: within acceptance all particle pairs i, j in a single event
Second average*: average over ensemble of events

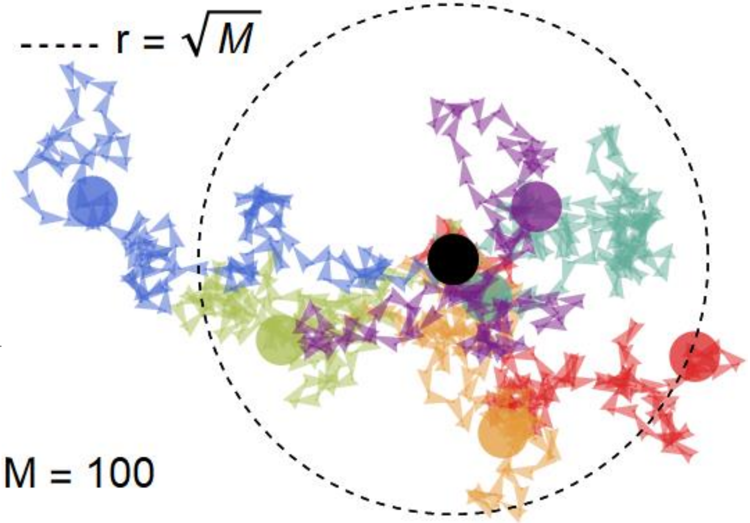
Method 2: subevents

$$v_n\{2, |\Delta\eta| > \gamma\}^2 = \langle\langle e^{in(\phi_i - \phi_j)}\rangle\rangle$$

First average: within acceptance all particle pairs i (with $\eta < \gamma/2$) and j (with $\eta > \gamma/2$)
Second average*: average over ensemble of events
Note: not equivalent even for $\gamma = 0$ (!)

* In practice one first averages over small centrality classes and then averages over those results to obtain a larger bin. For some observables this is extremely important (SC, $\rho(v_2\{2\}, p_T)$), but for $v_n\{2\}$ it makes only a small difference. Often it is not explicitly mentioned how the third averaging is done.

Cumulants



Method 1: cumulants

$$v_n\{2\}^2 = \langle\langle e^{in(\phi_i - \phi_j)} \rangle\rangle$$

Efficient computation:

$$Q_n = \sum_{a=i}^{M} e^{in\phi_i}$$

$$v_n\{2\}^2 = \langle \frac{|Q_n|^2 - M}{M(M-1)} \rangle$$

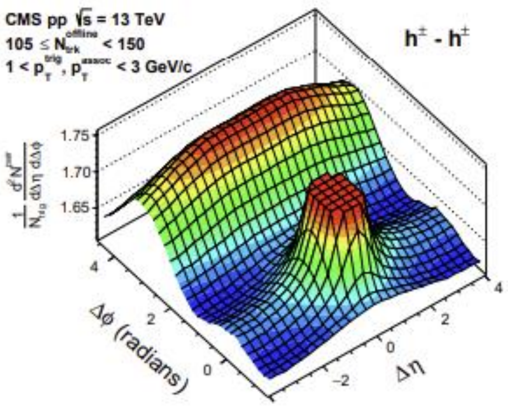
Requires M computations instead of M^2.
The $-M$ subtracts $i = j$ in double sum

Important theorem:
If ϕ_i are randomly drawn from $f(\phi)$ then $v_n\{2\}$ will converge to the true Fourier coefficients of $f(\phi)$

Easy to understand for $f(\phi)$ = constant:
Q_n is a random walk, so for many events:

$$|Q_n| = \sqrt{M} \to v_n\{2\} = 0 \text{ (for } n > 0)$$

Important caveat:
ϕ_i are not drawn randomly
In this talk we focus on correlations due to resonance decays



Subevent

Method 2: subevents

$$v_n\{2, |\Delta\eta| > \gamma\}^2 = \langle\langle e^{in(\phi_i - \phi_j)}\rangle\rangle$$

Efficient computation:

$$Q_{n,a} = \sum_{i\in\{\eta<\gamma/2\}}^{M_a} e^{in\phi_i}$$

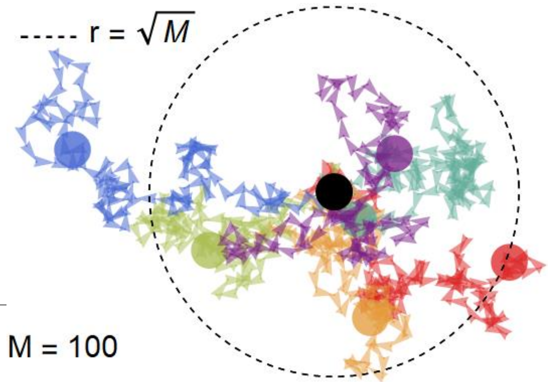
$$Q_{n,b} = \sum_{i\in\{\eta>\gamma/2\}}^{M_a} e^{in\phi_i}$$

$$v_n\{2\}^2 = \langle\frac{\Re(Q_{n,a}Q^*_{n,b})}{M_a M_b}\rangle$$

(for infinite # events the imaginary part vanishes anyway)

Three comments

- Particles from different regions: less effect from resonances
- Smaller phase space: fewer particles, harder statistically
- For large γ event-plane decorrelation is important



Intuition: random walk with resonances

Method 1: cumulants

$$v_n\{2\}^2 = \langle\langle e^{in(\phi_i-\phi_j)}\rangle\rangle$$

Efficient computation:

$$Q_n = \sum_{a=i}^{M} e^{in\phi_i}$$

$$v_n\{2\}^2 = \langle \frac{|Q_n|^2 - M}{M(M-1)} \rangle$$

Requires M computations instead of M^2.
The $-M$ subtracts $i = j$ in double sum

Oversimplified ansatz:
Zero intrinsic flow and every particle decays into two particles with the same transverse direction.

New `flow' due to resonances:

$$M \to 2M$$
$$Q_n \to 2Q_n$$
$$v_n\{2\}^2: \quad 0 \to \langle \frac{M}{M(M-1)} \rangle \approx 1/M$$

When is can this be ignored?

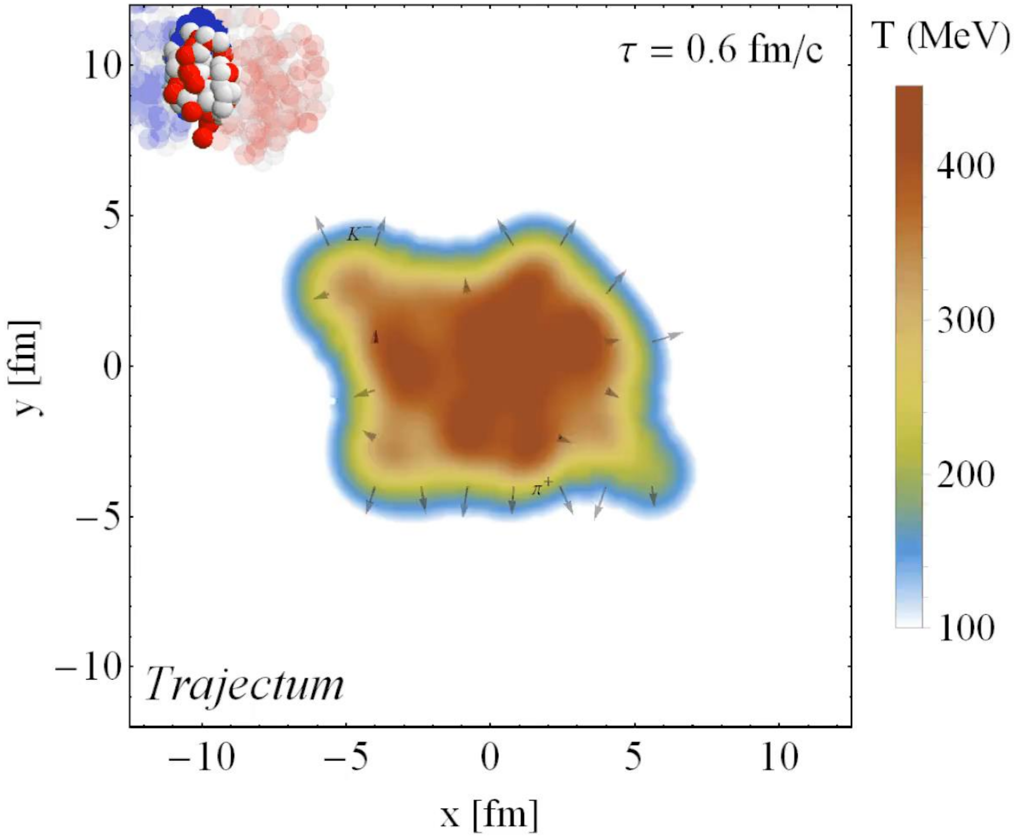
$$v_n \gtrsim 1/\sqrt{M}$$
$$\text{pPb: } v_n \sim 0.05,\ 1/\sqrt{M} \sim 0.1$$
$$\text{PbPb: } v_n \sim 0.1,\ 1/\sqrt{M} \sim 0.03$$

For pPb and cumulants this can be the dominant effect

Also present in all hydro codes that include resonance decays (!)

Now more serious: using *Trajectum*

1. Straightforward to use
2. Fast and publicly available
   - ~1 event/second on a laptop
3. Fully parallelized
   - Can run unlimited number of events
4. Resonance decays/interactions handled by SMASH

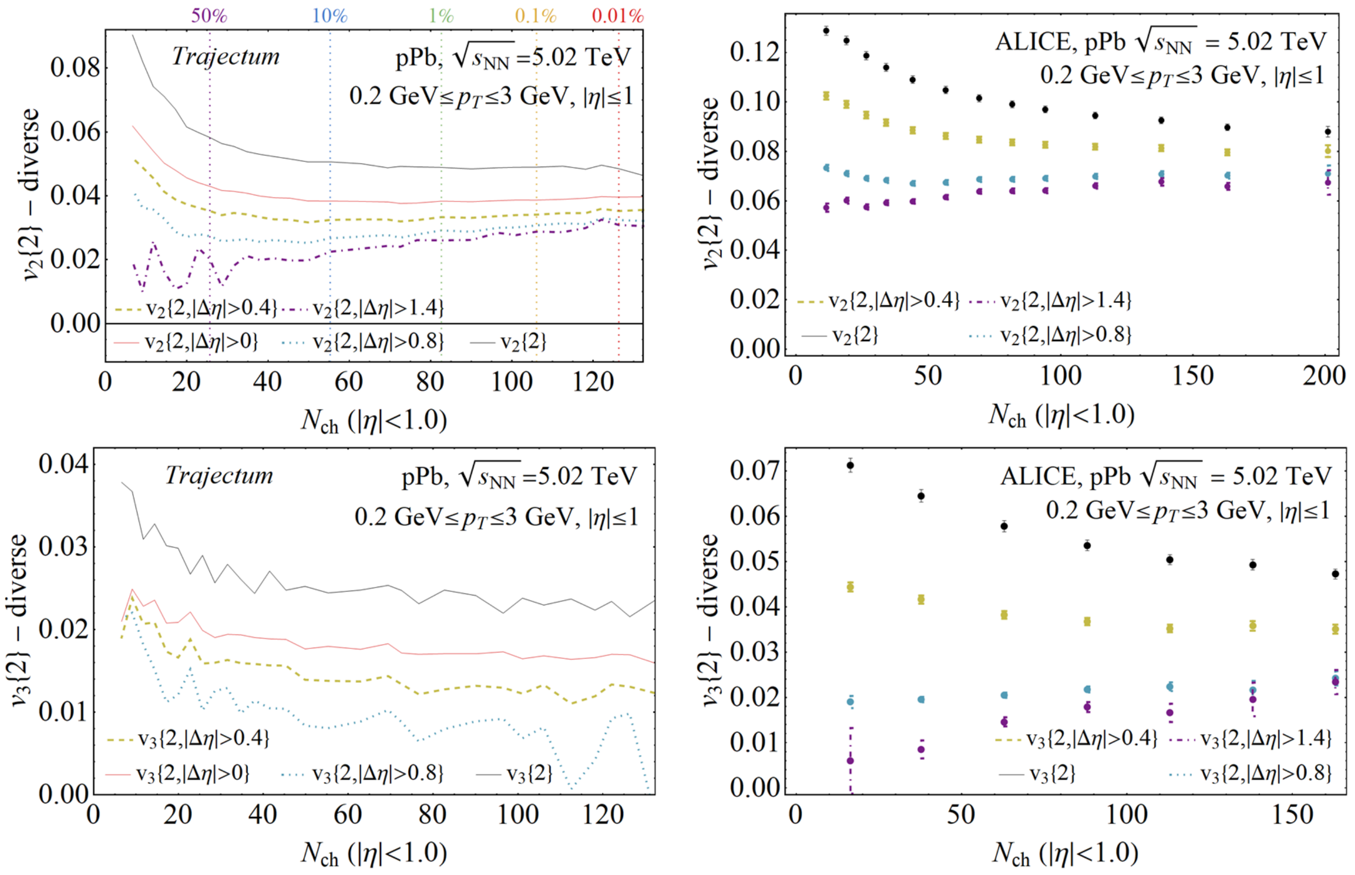



```
general{
    output=out
    format=smash
    f0500=false
    numevents=1
    seed=7398984.747399307
    debugoutput=true
    numthreads=2
}

entropyacceptanceprobability{
    0:0.0
    24:0.0
    24.5:0.05
    25.5:0.05
    26:0.0
    100:0.0
}

trentosubstructurePbPb{
    dmin=0.63933
    w=0.701919
    sigmann=70.0
    sigmafluct=0.73579
    p=0.14388
    q=1.0
    Eref=0.2
    norm=23.507
    freestreamingreferencetime=1.17085
    freestreamingvelocity=0.62672
    weaktostrong=0.0
    nref=20
    alpha=0
    nc=3.2747
    voverw=0.4892041602706295
}

secondorderhydro{
    numlatticesites=166.0
    latticesize=33.2
}

musclsolverktminmodfastmidpoint{
    cflconstant=0.08
}

LatticeEOStempdepDuke{
    shearhrg=0.0895066
    shearmin=0.0895066
    shearslope=0.43252
    shearcrv=0.231195
    shearrelaxationtime=6.318855
    bulkmax=0.0030138
    bulkT0=0.21471
    bulkwidth=0.10906
    bulkrelaxationtime=0.0687
    deltapipiovertaupi=1.333333333333
    phi7overpressure=0.128571
    taupipiovertaupi=1.61033
    lambdapiPiovertaupi=1.2
    deltaPiPiovertauPi=0.666666666666
    lambdaPipiovertauPi=1.6
    phi1overpressure=0
    phi3overpressure=0
    phi6overpressure=0
}

cooperfryehadronizer{
    freezeouttemp=153.456
    rapidityrange=0.1
}
```

Δη in pPb collisions – MAP setting with varying cuts

Large and significant effects

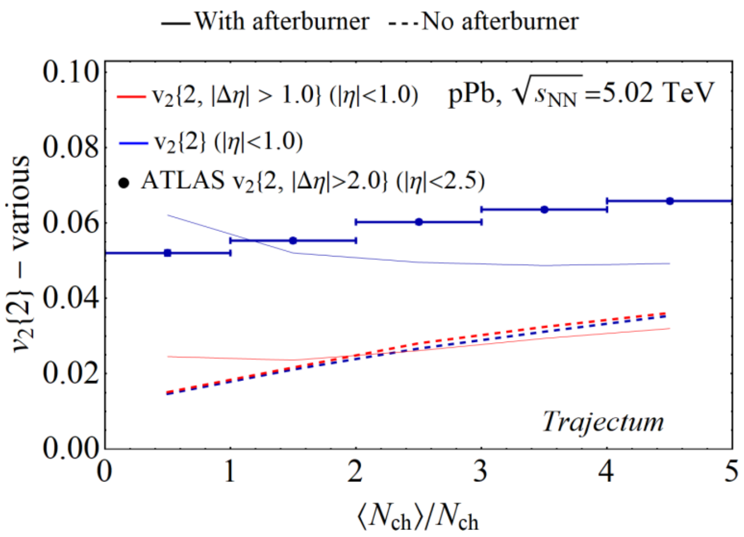
- Even Δη=0 decreases flow by ~20%
- For low multiplicity Δη is dominant effect
  - Even in 'hydro'
- Relatively unique measurement from ALICE
- Qualitative agreement
- Does not agree quantitatively
  - Not fitted in Bayesian analysis

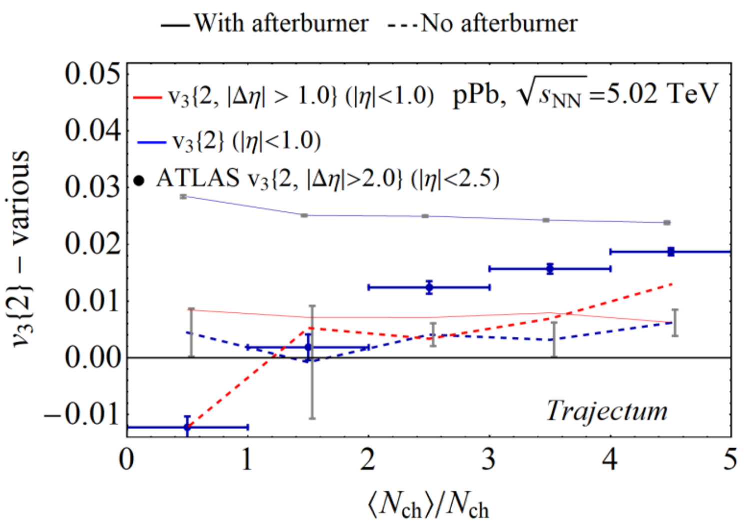


Δη in pPb collisions – Resonances and afterburner (SMASH)

Verification that effects are due to hadronic phase

- Cumulants (blue) and Subevent (red)
- Without afterburner the two methods agree (dashed)

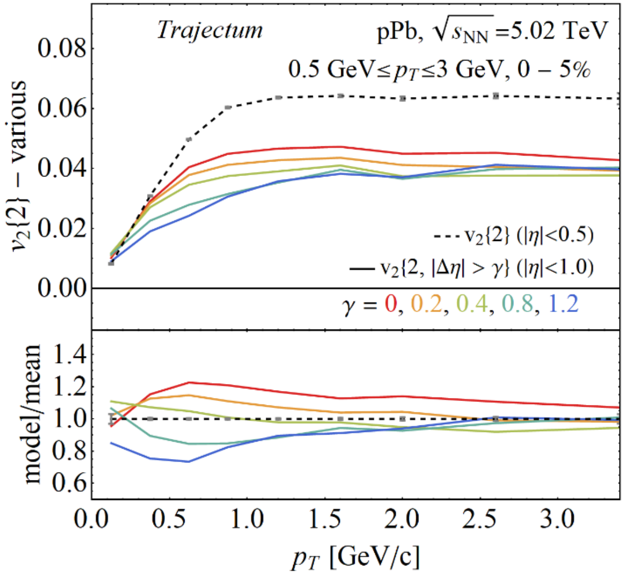


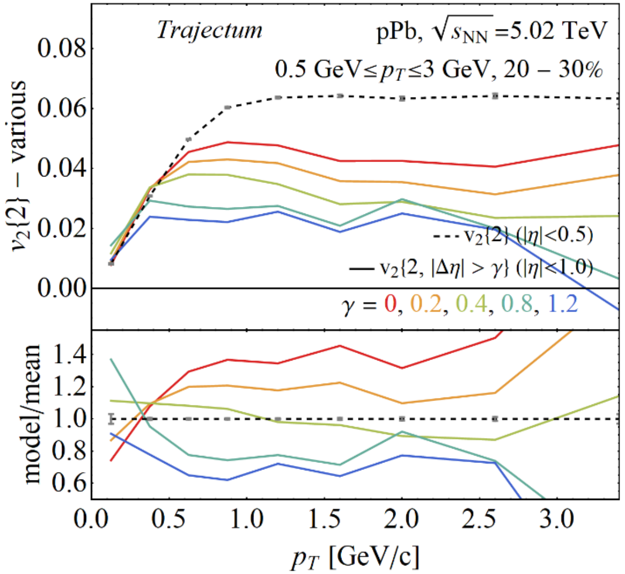


Δη in pPb collisions – p_T - differential

Similar effect when looking at p_T differential flow

- Stronger effect at lower multiplicity
- Converges at low p_T (attractor ;))

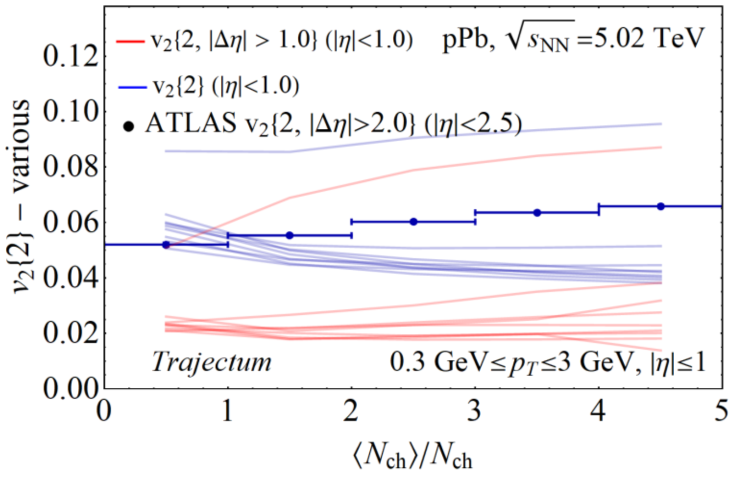


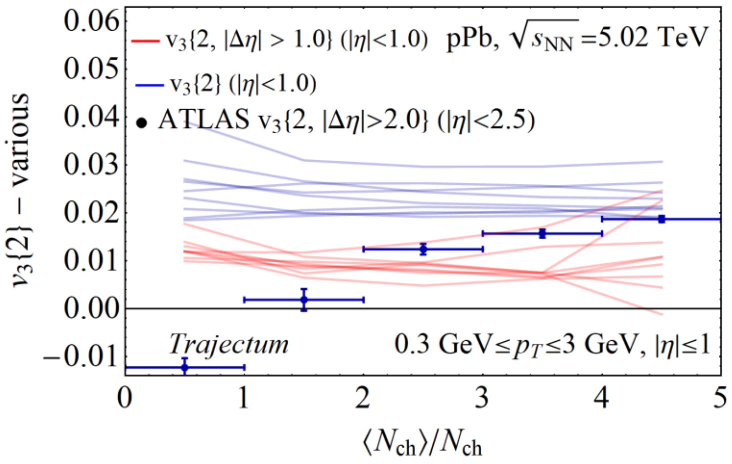


Elliptic flow in pPb collisions – a systematic analysis

Ten likely settings from posterior distribution

- Subevent method much smaller flow than cumulant method
- Realistically typically a factor two too low
  - Points to caveat to all previous pPb flow studies that include an afterburner/resonances
- One exception (next slide)

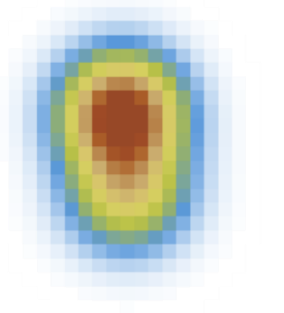


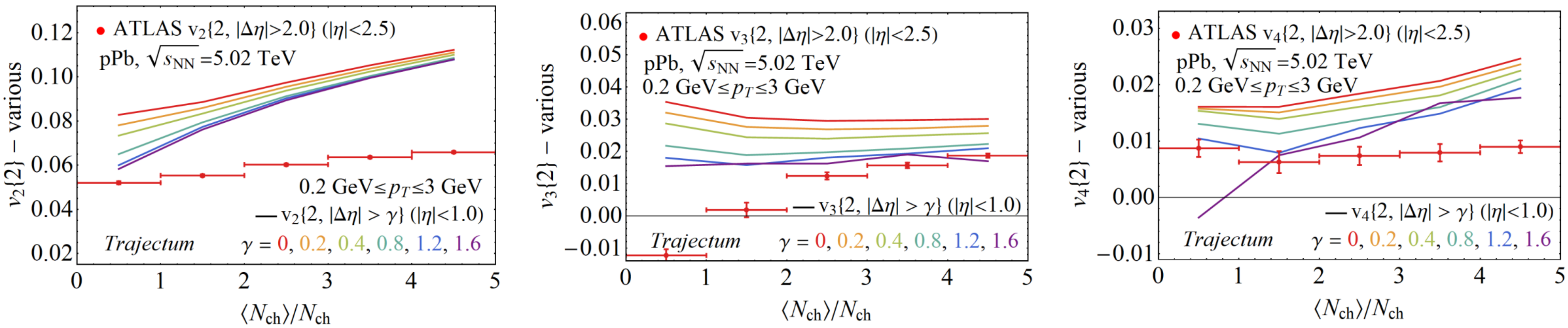


Elliptic flow in pPb collisions – two constituent model (?)

Guess based on previous parameters: two constituents with subwidth 0.3 fm (rest is MAP)

- Clearly much more elliptic flow (even too much)
- Effects from Δη gap smaller at large multiplicity (also because of higher flow: $v_n \gtrsim 1/\sqrt{M}$)

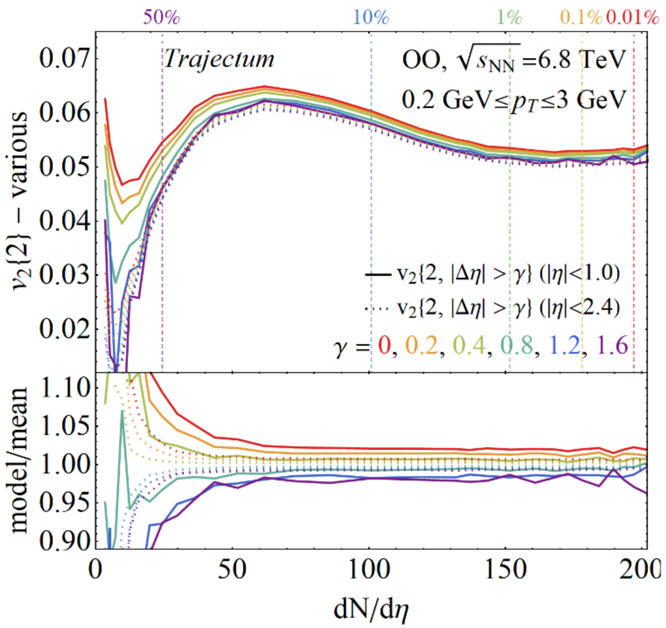


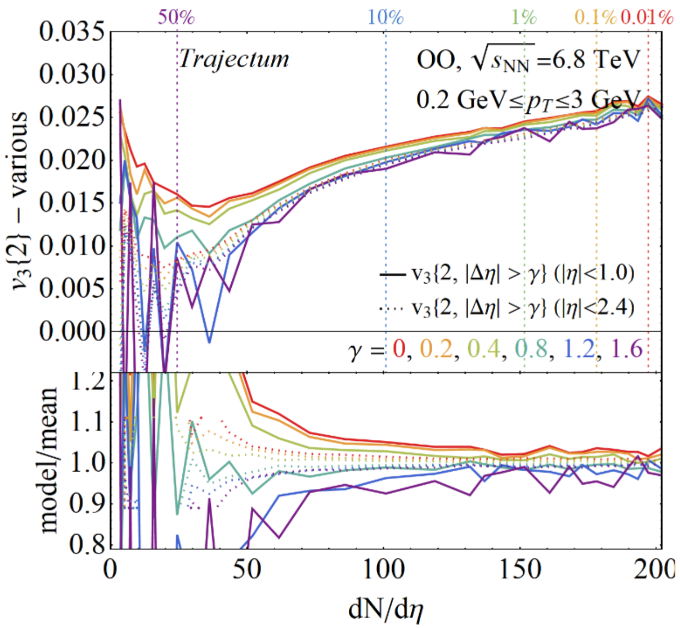


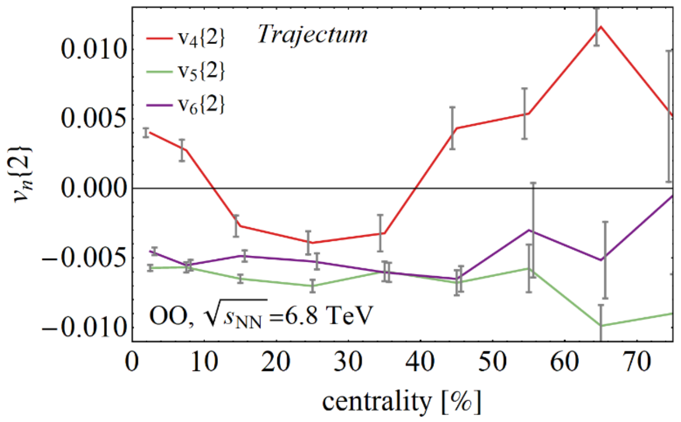
Exciting upcoming Oxygen run

Perfect system at moderate multiplicity: hydro at its limits

- $\Delta\eta$=0 important for ALICE coverage, but not dominant
- Important caveat: nuclear structure is not that well understood (fix this with Neon collisions?)
- Curious: resonance decays lead to negative $v_5\{2\}$ and $v_6\{2\}$

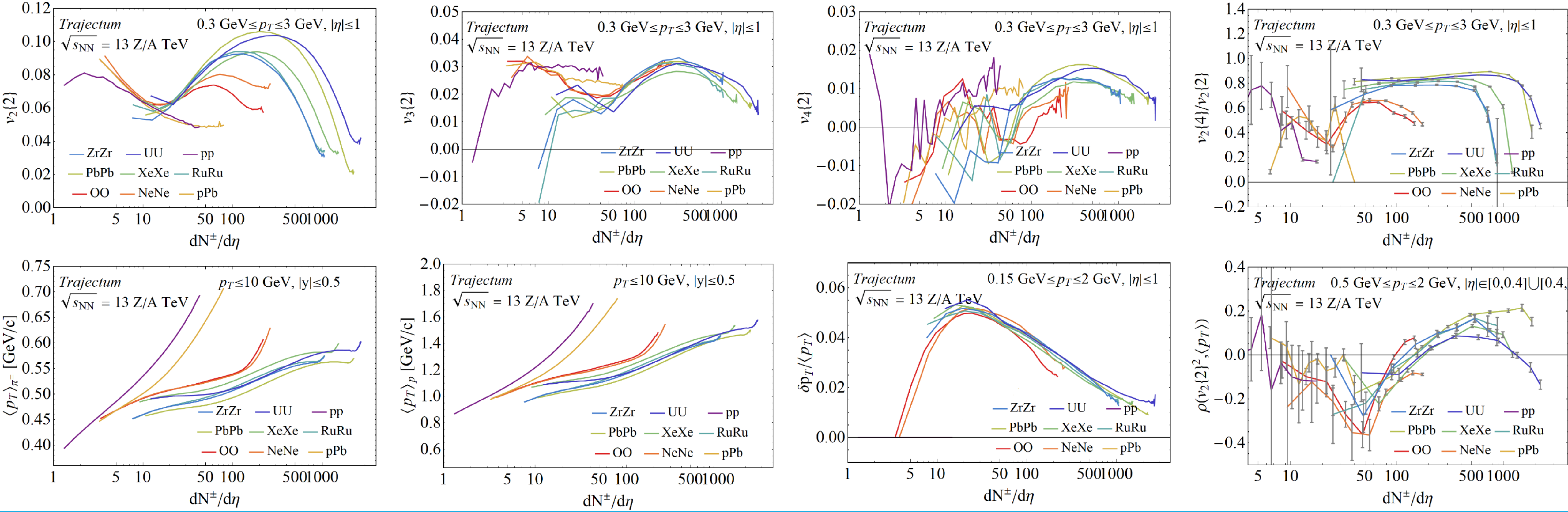




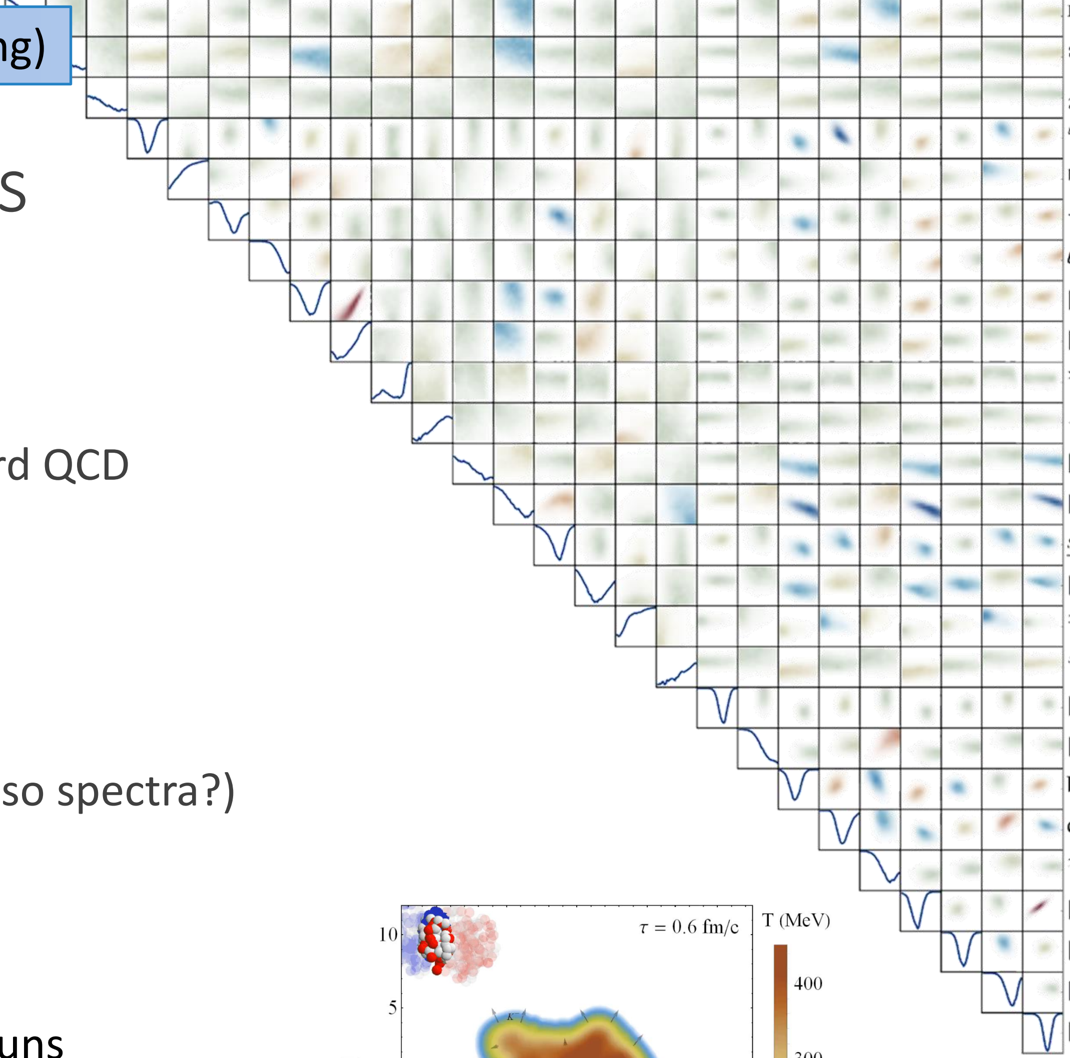


Bonus slide

Several systems with MAP settings (systematic analysis with ratios for some to appear)



See also talks by Debojit Sarkar, Yem-Jie Lee & Yuuka Kanakubo (Thu morning)



Important questions for small systems

Hydrodynamic signature is anisotropic flow

- Flow is small, signal $v_n \sim 1/\sqrt{M}$ and hence need to be careful
- Important: no discussion of `real non-flow', e.g. jets and hard QCD

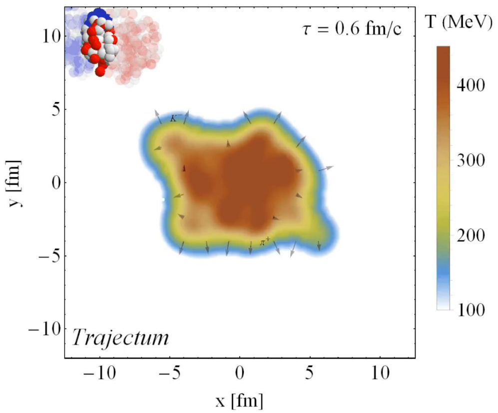
Collectivity is a broader concept than hydrodynamics

- pPb results depend sensitively on model parameters
  - Hard to conclude that `panta rei'; systematics is important
- At the moment unclear if any parameters fit consistently (also spectra?)

Useful to have a tool like *Trajectum*

- **Fast:** each curve for pPb takes only about 5k CPU hours,
  Runs ~400M Trento IC, ~1M hydro runs and ~30M SMASH runs
- Message both to theory + experiment: details and specifically cuts matter

Exciting time ahead with Oxygen and other small systems (Ne?);

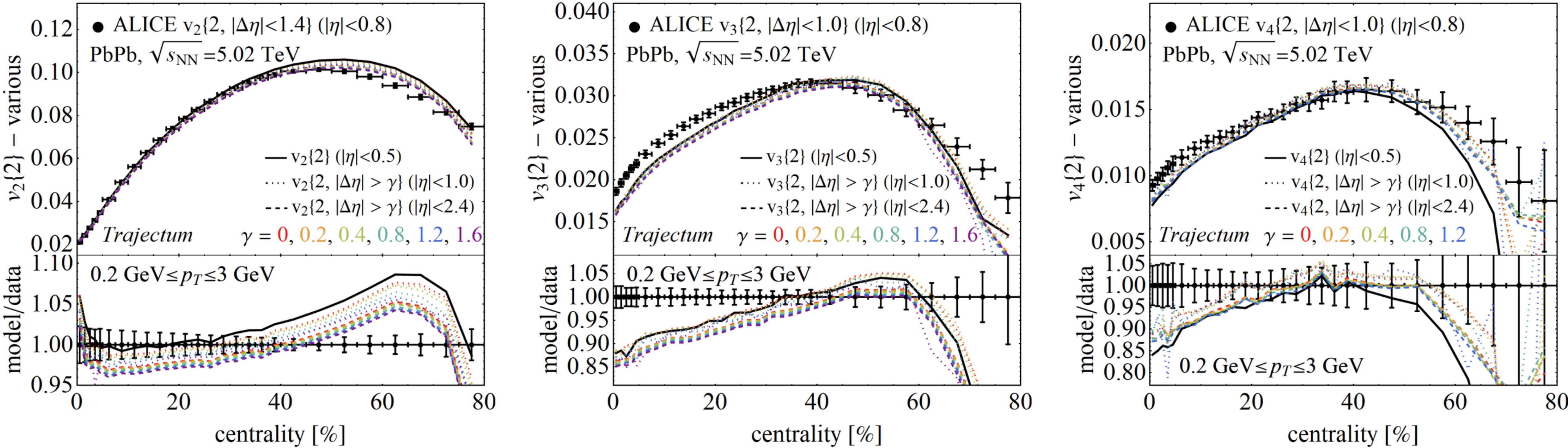


BACK-UP

$\Delta\eta$ in PbPb collisions – MAP setting with varying cuts

Small but significant effects

- Etagap always reduces v2, always increases v4 (even for $\Delta\eta = 0$)
- Settings fit to method 1 (black), but etacut potentially improves agreement (important within ALICE uncertainties)
- Larger effect for smaller detector acceptance (e.g. more important for ALICE than for ATLAS)
- In ratio with data effects are constant versus centrality (however small absolute effect: percent level * percent level)



MAP settings

For reference the settings used for most runs

- Except 10 settings drawn from posterior

	MAP
N $PbPb_{2.76}$ [fm^{-1}]	17.9188
σ_{NN} $PbPb_{2.76}$ TeV [mb]	61.8
w $PbPb_{2.76}$ [fm]	0.577622
$cent_{norm}$ $PbPb_{2.76}$ [%]	97.9491
N $PbPb_{5.02}$ [fm^{-1}]	22.3675
σ_{NN} PbPb 5.02 TeV [mb]	67.6
σ_{fluct}	0.510595
p	-0.0790886
q	1.2493
d_{min} [fm]	0.99714
T_{switch} [MeV]	149.742
n_c	2.30004
χ_{struct}	0.792271
τ_{hyd} [fm/c]	0.544193
$\overline{\eta / s}$	0.18022
$(\eta/s)_{slope}$ [GeV^{-1}]	0.132154
$(\eta/s)_{\delta slope}$ [GeV^{-1}]	0.371218
$(\eta/s)_{0.8\,GeV}$	0.324098
$(\zeta/s)_{max}$	0.0372411
$(\zeta/s)_{w}$ [GeV]	0.00517364
$(\zeta/s)_{T_0}$ [GeV]	0.35605
$\tau_\pi sT/\eta$	1.65841
$\tau_{\pi\pi}/\tau_\pi$	3.48342
r_{hyd}	0.829136
a_n	0.655107
$\langle \beta_2^2 \rangle - \langle \beta_2 \rangle^2$	0.0689689
a_{EOS}	-9.41155
f_{SMASH}	0.903164