Bayesian constraints on the initial stage using *Trajectum*

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Based on:

- GN, van der Schee, to appear

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Trajectum

- New heavy ion code developed in Utrecht (now MIT/CERN).
- Contains initial stage, hydrodynamics and freeze-out, as well as an analysis suite.
- Easy to use, example parameter files distributed alongside the source code.
- Fast, fully parallelized.
- Publicly available at `sites.google.com/view/govertnijs/trajectum`.

[GN, van der Schee, Gürsoy, Snellings, 2010.15130; 2010.15134]

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Bayesian analysis workflow

- Generate 1000 sets of parameters (varying 22 parameters), run the model for them. Here, we use:
  - Initial conditions: modified TRENTo + free streaming.
  - Hydrodynamics: second order, with temperature dependent shear and bulk viscosities.
  - Freeze-out: Cooper-Frye with PTB viscous corrections.
  - Afterburner: SMASH.
- Train a gaussian process emulator on the resulting theory predictions.
- Generate posterior distributions using ptemcee.

[Bernhard, 1804.06469]

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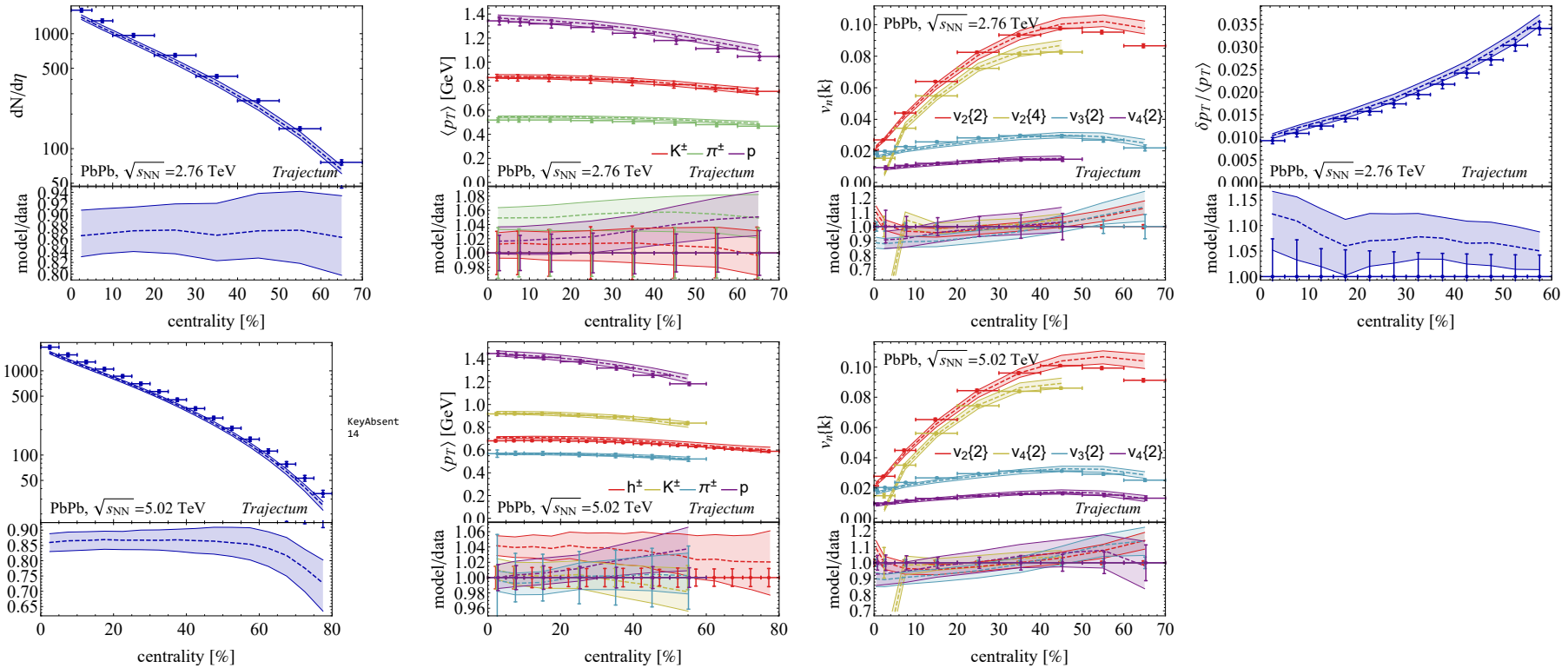
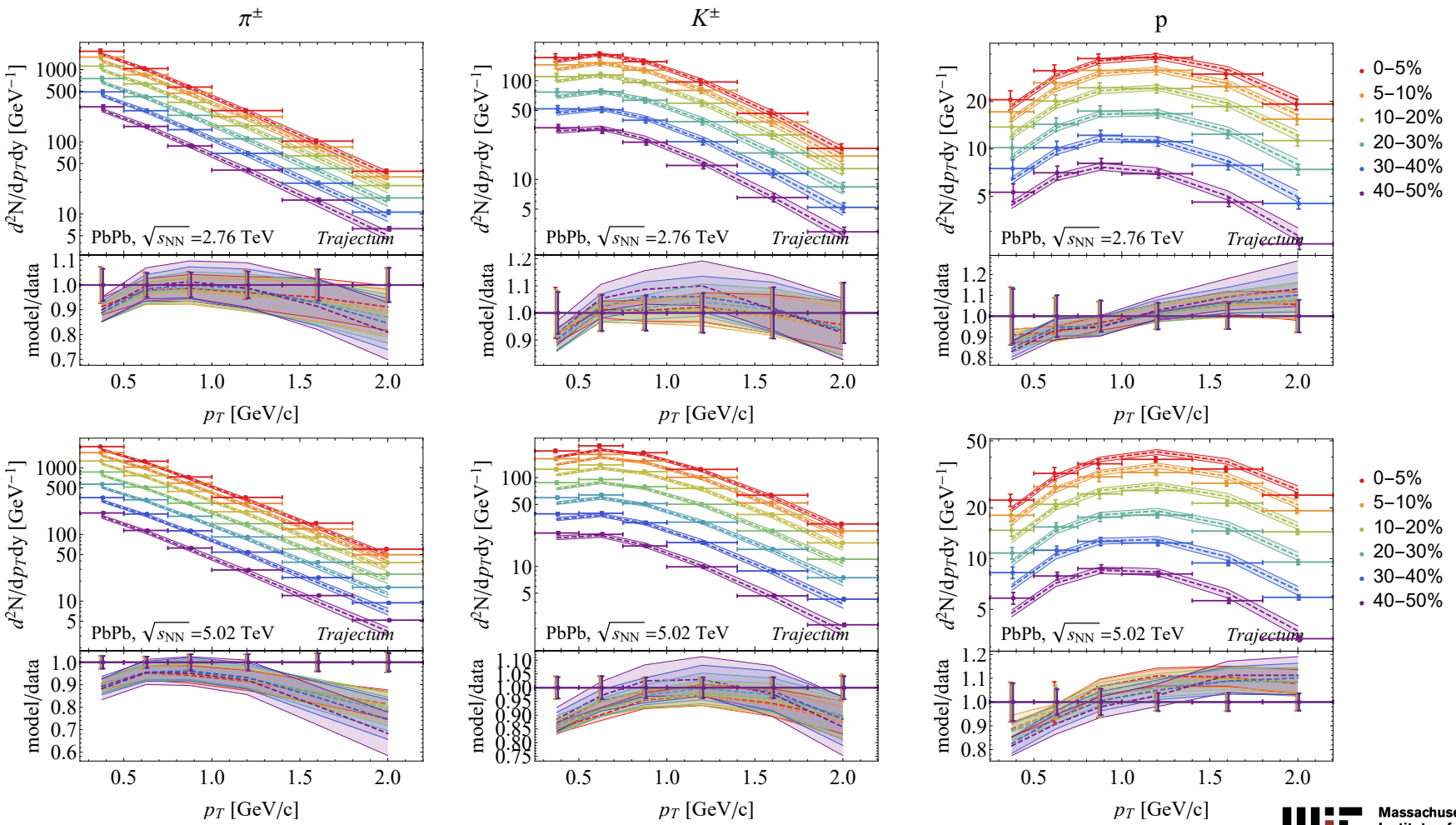
Data used in our most recent fit: integrated observables



Data used in our most recent fit: spectra



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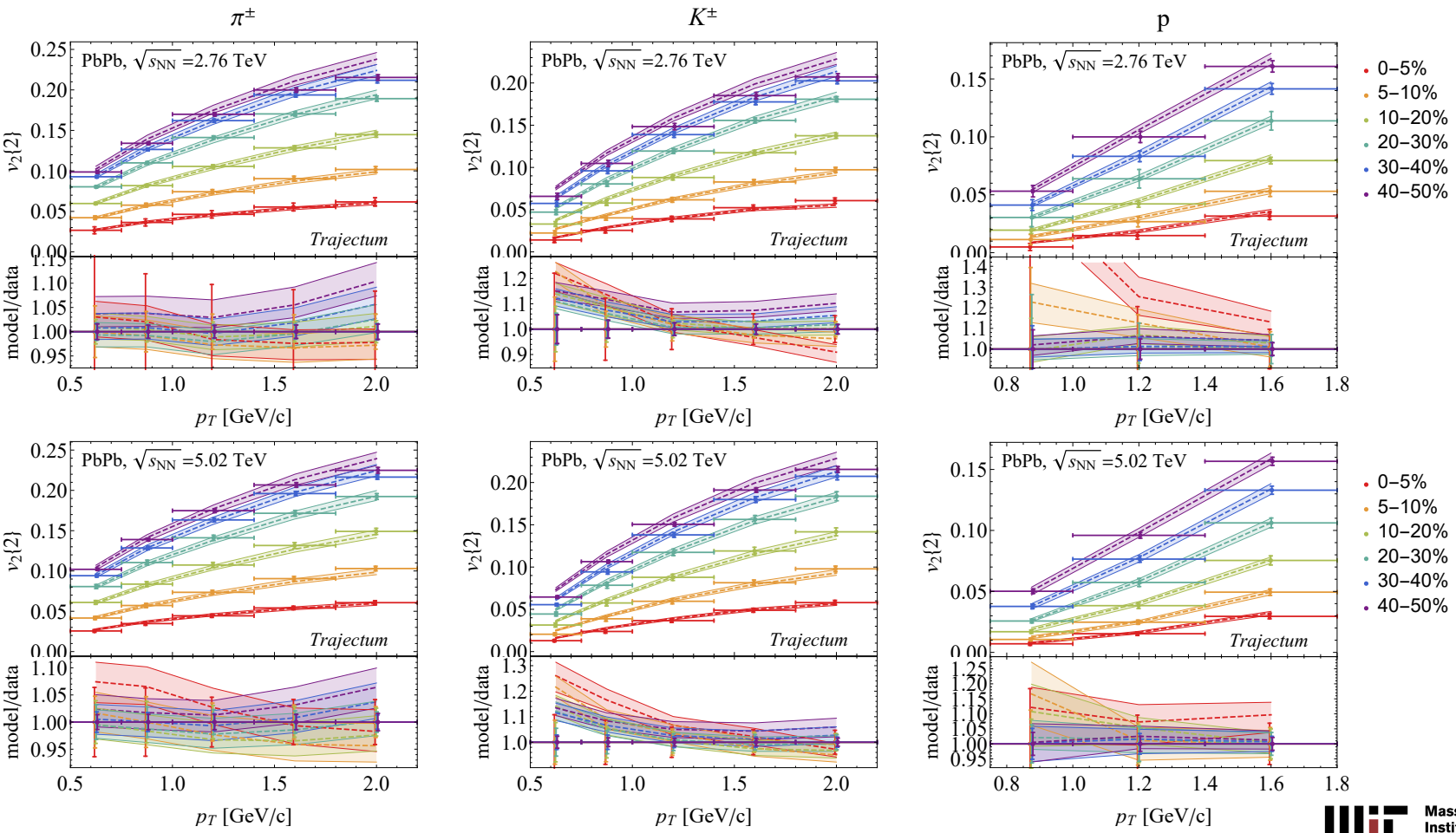
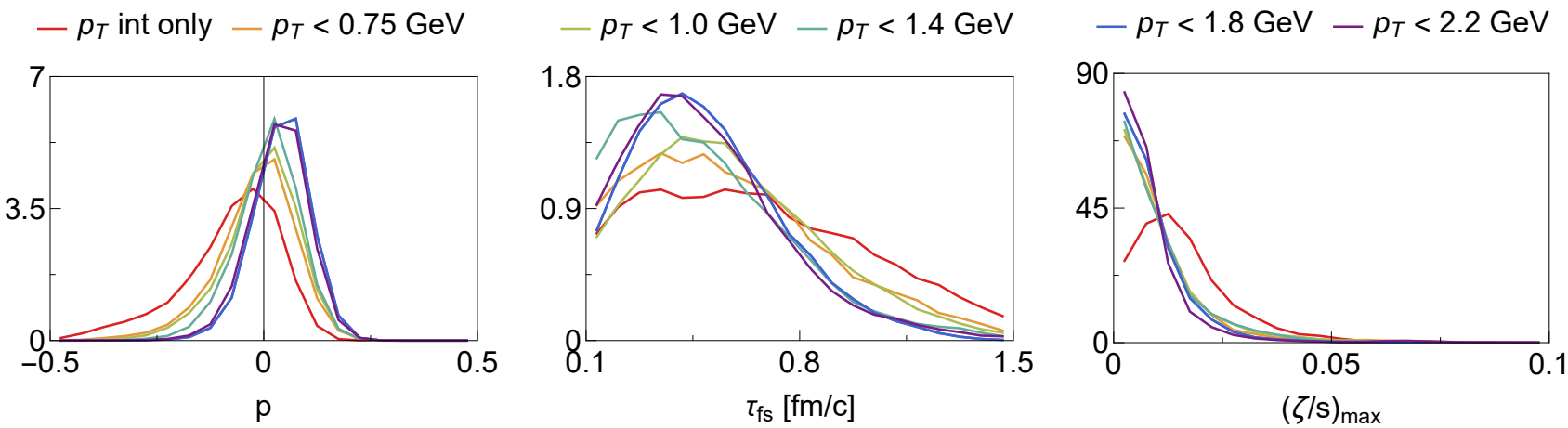
Data used in our most recent fit: p_T-differential v_2



Bulk viscosity over entropy density ζ/s



- Lower bulk viscosity than other groups.
- This is mostly due to the inclusion of p_T-differential observables.

[GN, van der Schee, Gürsoy, Snellings, 2010.15130]

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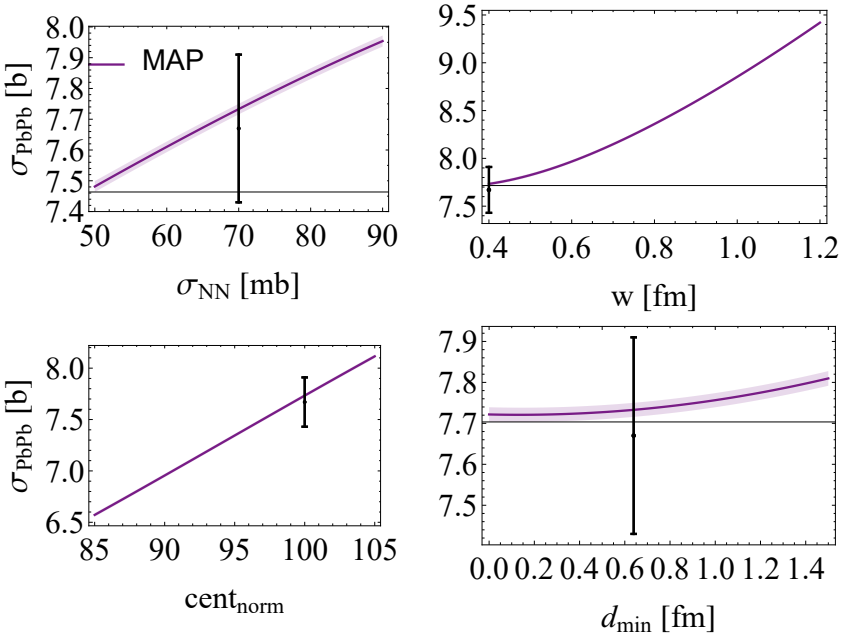
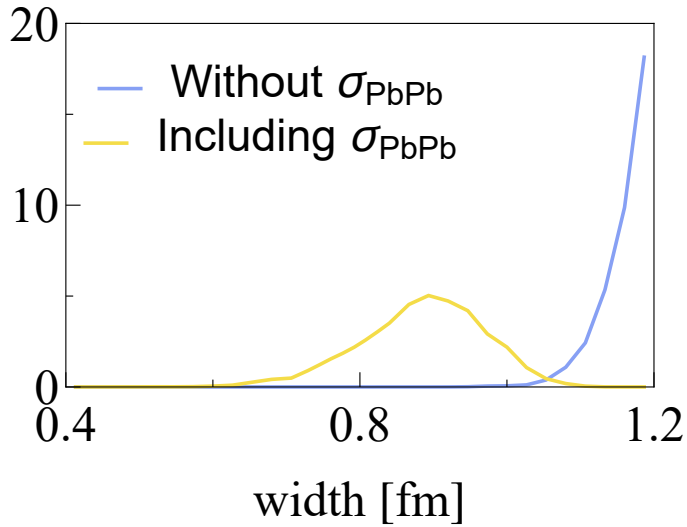
The cross-section σ_{AA} for different nucleon widths

- The cross-section depends strongly on the nucleon width w and the centrality normalization $\text{cent}_{\text{norm}}$.
- ALICE finds: 7.67 ± 0.24 b. [ALICE PRELIMINARY, ALICE-PUBLIC-2022-004]



Fitting the cross-section implies $w \approx 0.4\,\mathrm{fm}$

	σ_{PbPb}[b]	$\sigma_{p\mathrm{Pb}}$[b]
unconstrained	8.74 ± 0.11	2.429 ± 0.032
$w = 0.4$ fm	7.887 ± 0.013	2.151 ± 0.004
$w = 0.8$ fm	8.532 ± 0.006	2.360 ± 0.002
$w = 1.2$ fm	9.569 ± 0.021	2.673 ± 0.003
ALICE	7.670 ± 0.24	2.061 ± 0.08



- Without σ_{PbPb}, all Bayesian analyses favor large nucleon width.
- Taking σ_{PbPb} into account, w decreases, but for compatibility with experiment, we need $w \approx 0.4\,\mathrm{fm}$.

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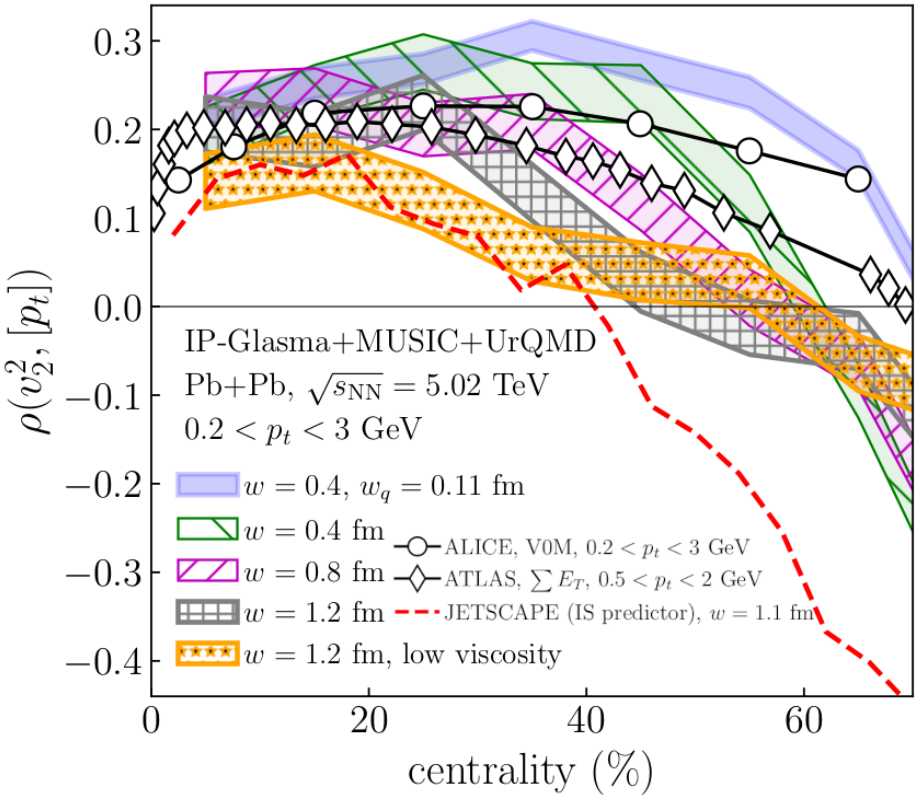
$\rho(v_2^2, \langle p_T \rangle)$ for different nucleon widths

- The correlation between v_2^2 and $\langle p_T \rangle$ is sensitive to the nucleon width w.
- Smaller w is preferred.
- This is a statistically challenging observable.

[Giacalone, Schenke, Shen, 2111.02908]



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The TRENTo phenomenological ansatz

- The standard TRENTo formula combines thickness functions of the two nuclei T_A and T_B into an energy density:

$$T^{00} \propto \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p},$$

with p a parameter.

- Some useful limits:

p	-1	0	1
T	$\frac{2}{\frac{1}{T_A}+\frac{1}{T_B}}$	$\sqrt{T_A T_B}$	$\frac{T_A+T_B}{2}$

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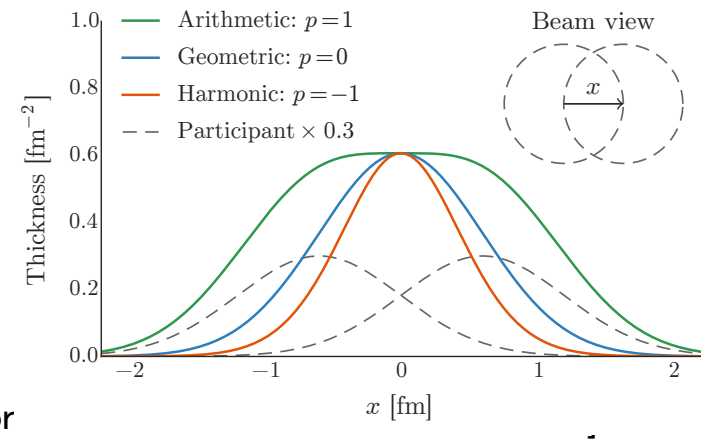

- Binary scaling $T = T_A T_B$ is not available.

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The q parameter

- We make the following modification to the TRENTo formula:

$$T^{00} \propto \left(\frac{T_A^p + T_B^p}{2} \right)^{q/p},$$

  introducing the parameter q.
- We now include *binary scaling* as a limit when $p = 0$, $q = 2$.
- Assuming approximate conformality of the equation of state, we can also interpret the right hand side as an *entropy density* by setting $q = 4/3$.

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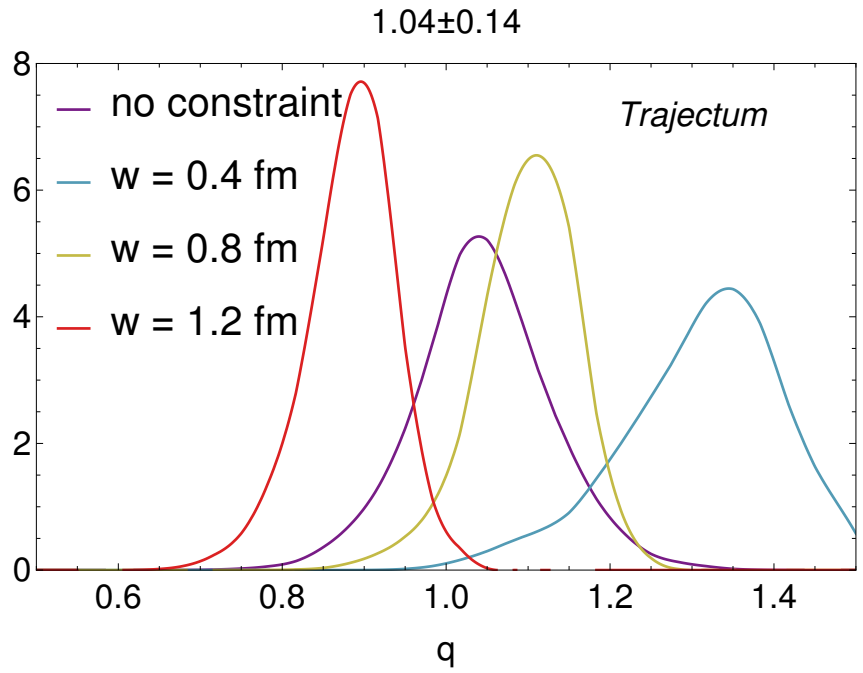
Posterior distribution for q

- Full Bayesian analysis favors values around $q = 1$.
- Binary scaling ($q = 2$) is strongly disfavored.
- Fixing the nucleon width w at different values has a large effect on the fitted value for q.
- Fixing $w = 0.4\,\text{fm}$ favors $q \approx 4/3$.



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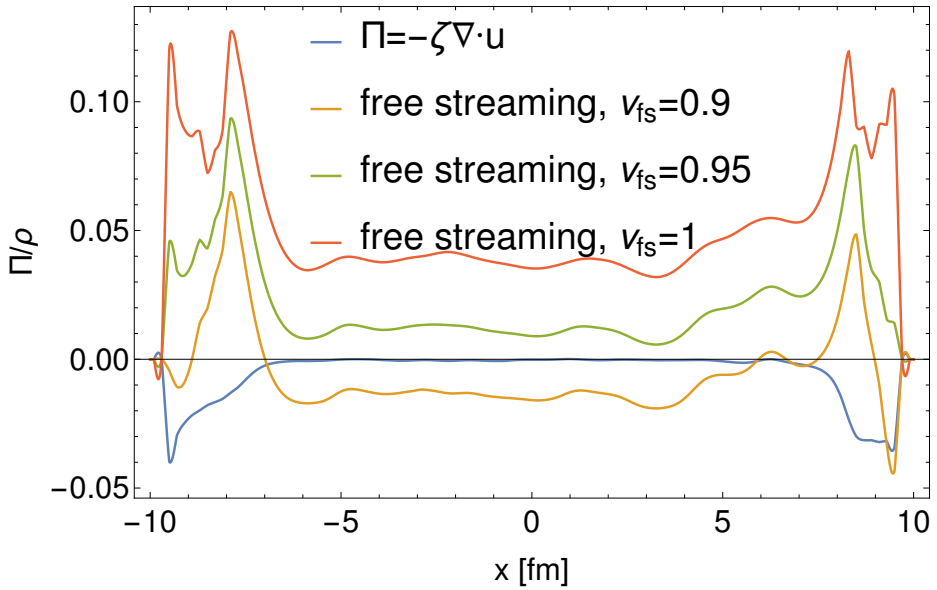
Weakly and strongly coupled initial stage

- In AdS/CFT simulations of the initial stage, the shear stress and bulk pressure quickly relax to their 'hydro' values:

$$\pi^{\mu\nu} = 2\eta\sigma^{\mu\nu}, \quad \Pi = -\zeta\nabla\cdot u.$$

- In free streaming however, the initialization of $\pi^{\mu\nu}$ and Π is qualitatively different.



[van der Schee, Romatschke, Pratt, 1307.2539; GN, van der Schee, Gürsoy, Snellings, 2010.15134]

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The r_{hydro} parameter

- We compute the hydrodynamic values for $\pi^{\mu\nu}$ and Π explicitly from the velocity u^μ, to second order:

$$\pi^{\mu\nu}_{\text{hydro}} = 2\eta\sigma^{\mu\nu} + \mathcal{O}(\partial^2), \qquad \Pi_{\text{hydro}} = -\zeta\nabla\cdot u + \mathcal{O}(\partial^2).$$

- We then mix the hydrodynamic values with the free streaming values and initialize hydrodynamics with

$$\pi^{\mu\nu} = r_{\text{hydro}}\pi^{\mu\nu}_{\text{hydro}} + (1 - r_{\text{hydro}})\pi^{\mu\nu}_{\text{fs}},$$
$$\Pi = r_{\text{hydro}}\Pi_{\text{hydro}} + (1 - r_{\text{hydro}})\Pi_{\text{fs}},$$

with $r_{\text{hydro}} \in [0, 1]$ interpolating between the two scenarios.

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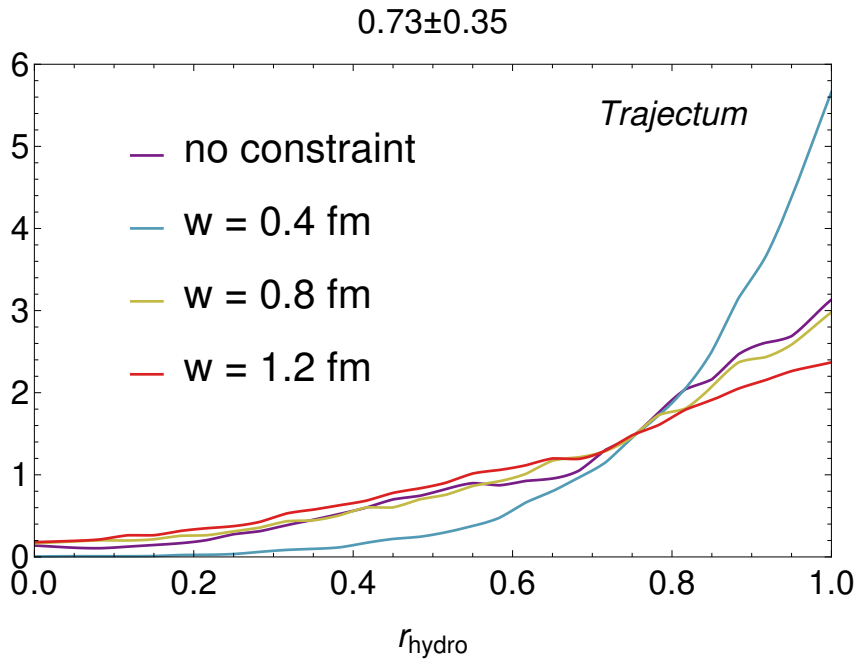
Posterior distribution for r_{hydro}

- $r_{\mathrm{hydro}} = 1$ is strongly favored over $r_{\mathrm{hydro}} = 0$, implying a preference for strongly coupled pre-hydrodynamic stage.
- The preference becomes even stronger for a nucleon width value compatible with experiment.



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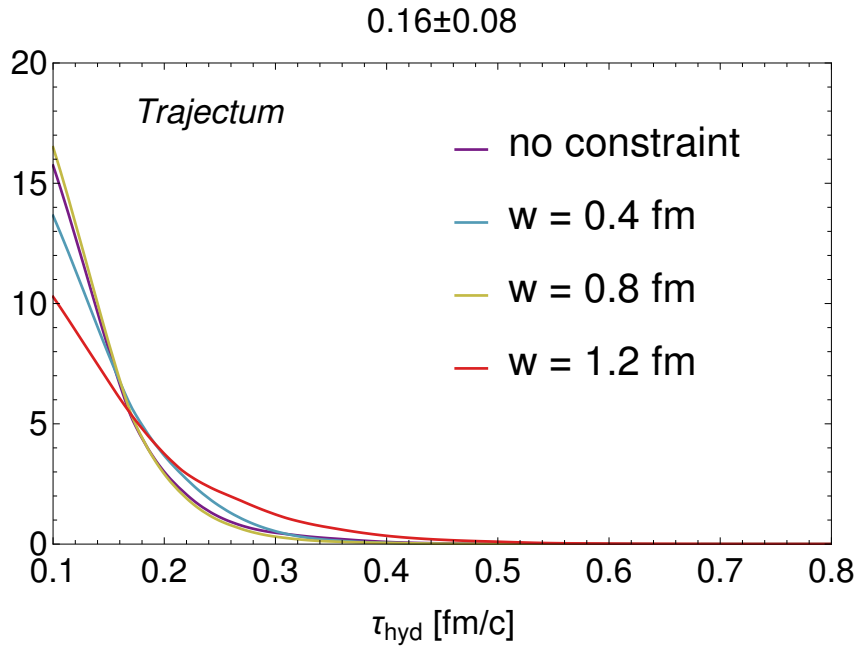
Free streaming time τ_{fs}

- Short pre-hydrodynamic stage is favored.
- This is consistent with fast hydrodynamization found in AdS/CFT.



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Conclusions & outlook

Conclusions:

- Describing the experimental cross-section requires smaller nucleon width.
- Binary scaling in TRENTo is strongly disfavored.
- Our fit favors a strongly coupled pre-hydrodynamic stage.

Outlook:

- Heavy quark diffusion.
- Adding flavor charges.
- Magnetic fields.

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