Impact of initial-state parametrizations on isobar collisions

Andreas Kirchner

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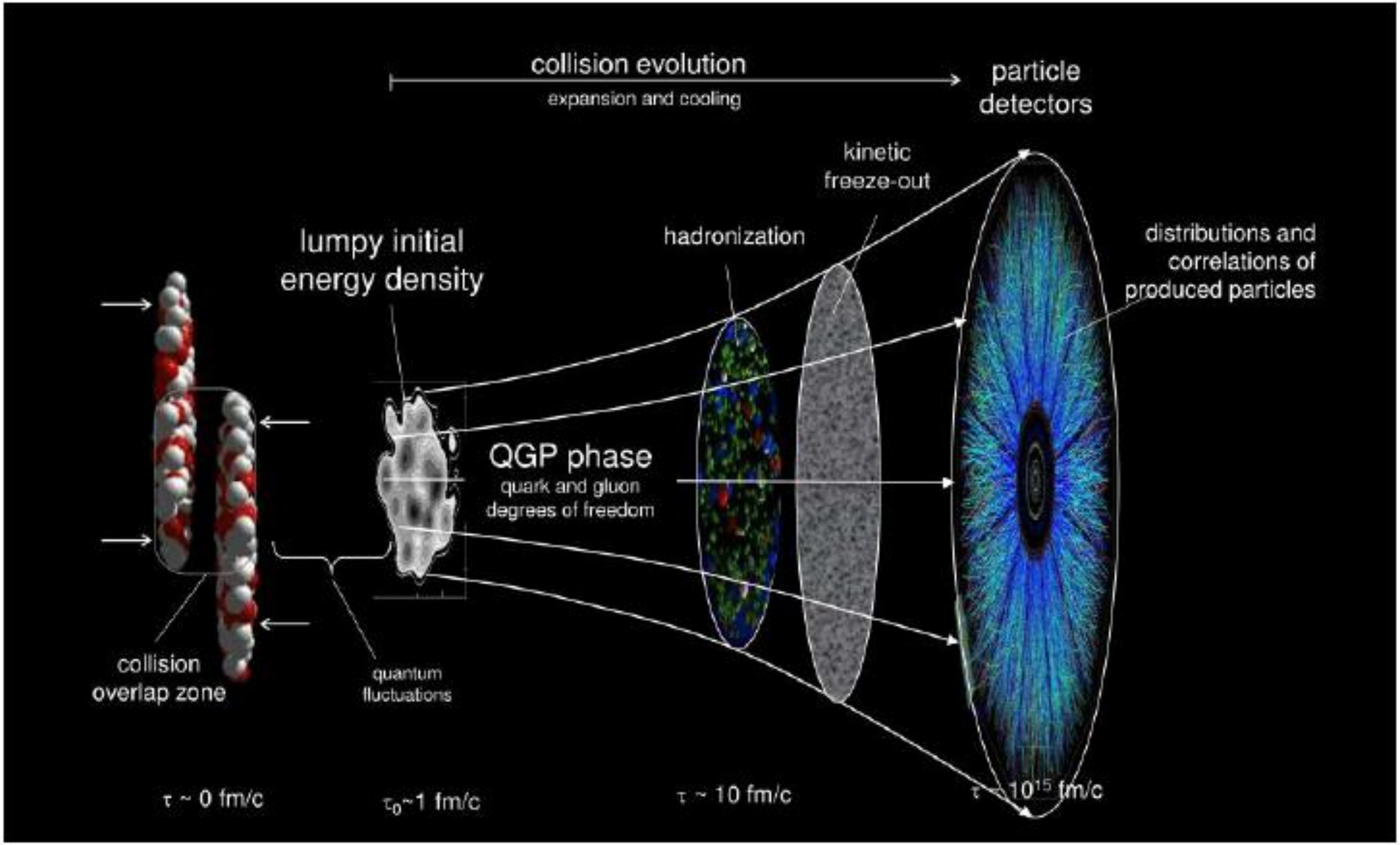
Intersection of nuclear structure and high-energy nuclear collisions

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

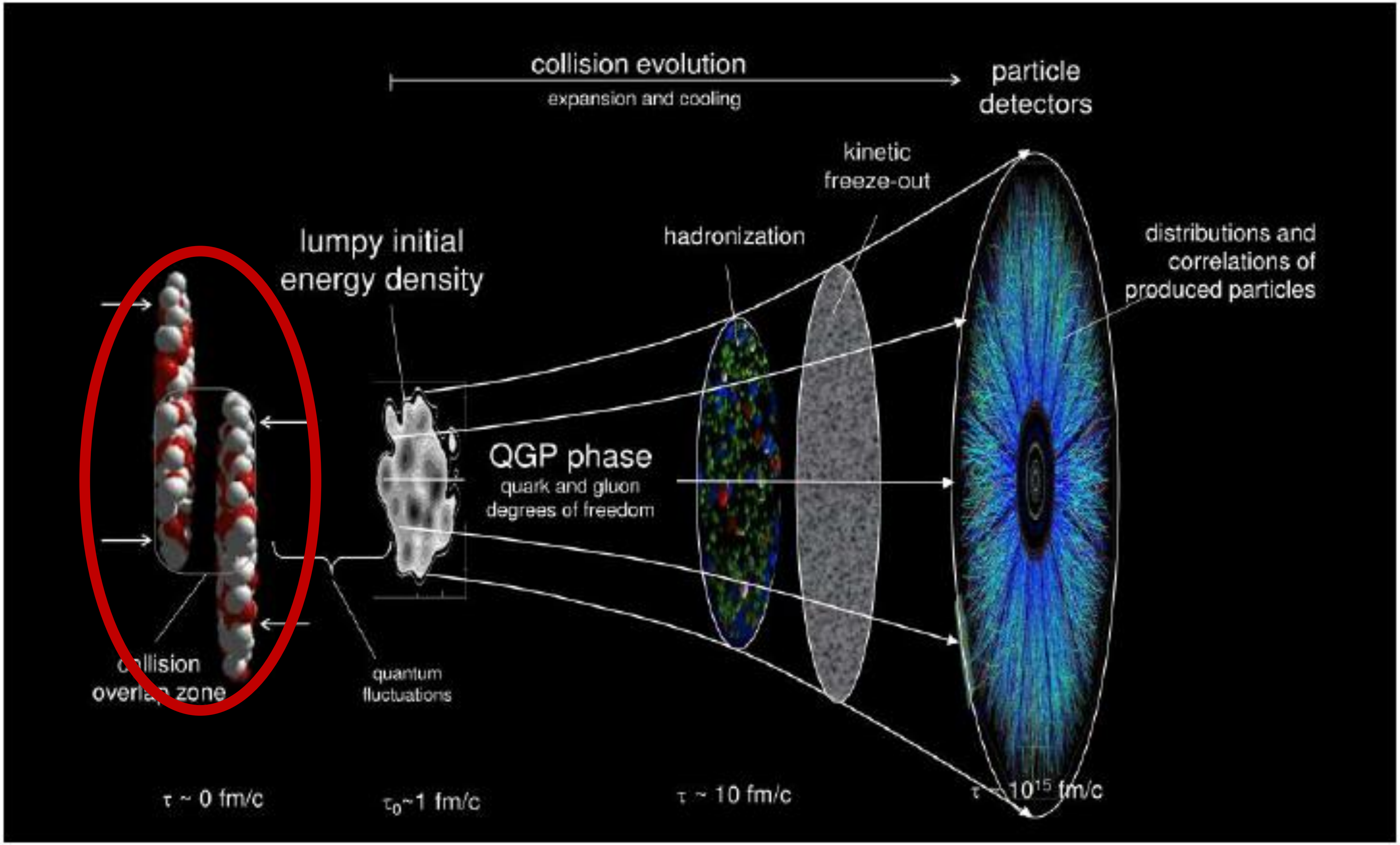
IsoQuant SFB1225

Overview

- Short introduction to heavy ion collisions
- Overview of observables & initial state predictors
- Initial state results
- Mode-by-mode hydrodynamics (FluiduM)
- Final state results



collision evolution
expansion and cooling
particle detectors
kinetic freeze-out
hadronization
lumpy initial energy density
distributions and correlations of produced particles
QGP phase
quark and gluon degrees of freedom
collision overlap zone
quantum fluctuations
τ ~ 0 fm/c
τ_0~1 fm/c
τ ~ 10 fm/c
τ ~ 10^{15} fm/c



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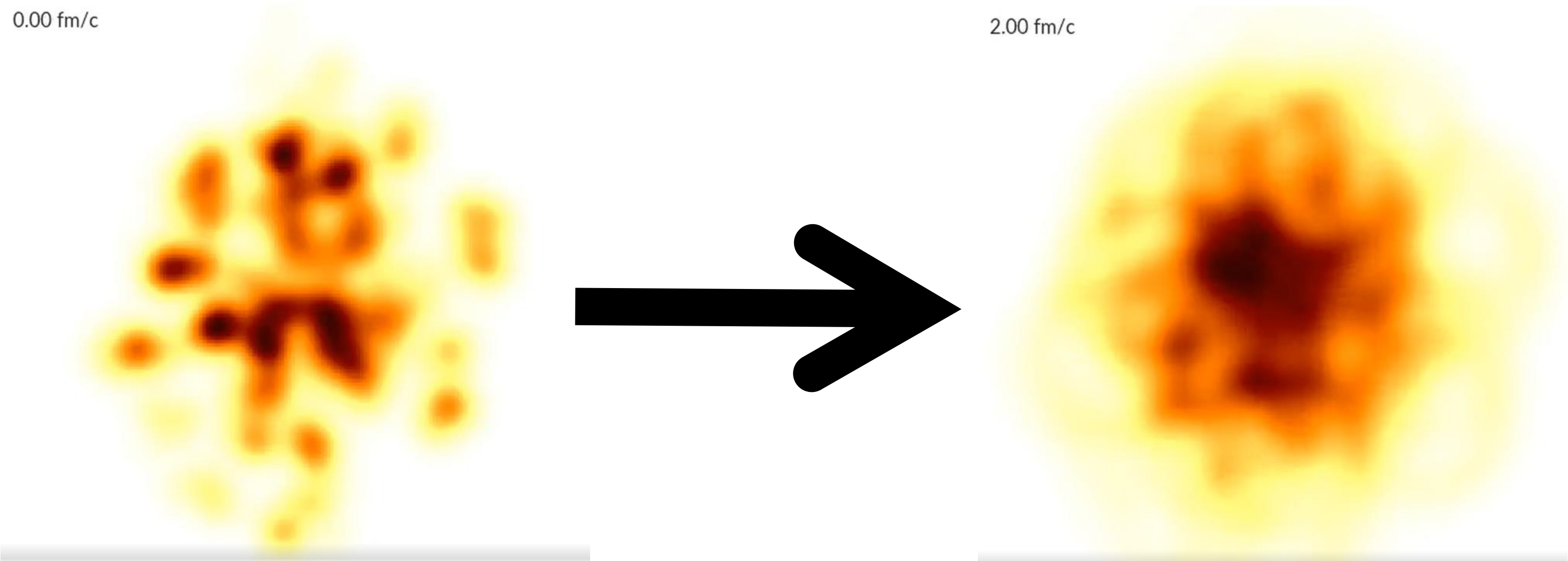
Initial state

- Collision modelled by different frameworks, e.g.:
  - Glauber
  - IP-GLASMA
  - TrenTo
  - CGC
- Pre-hydro modelling possible via free streaming



(1504.02160, 0812.3393)

How does TrenTo work?

- Sample nucleons according to Wood-Saxon
- Put gaussian on each x-y position with width w and norm k
- Check for collisions in each nucleus

  -> Get reduced thickness functions T_A and T_B
- Combine them according to

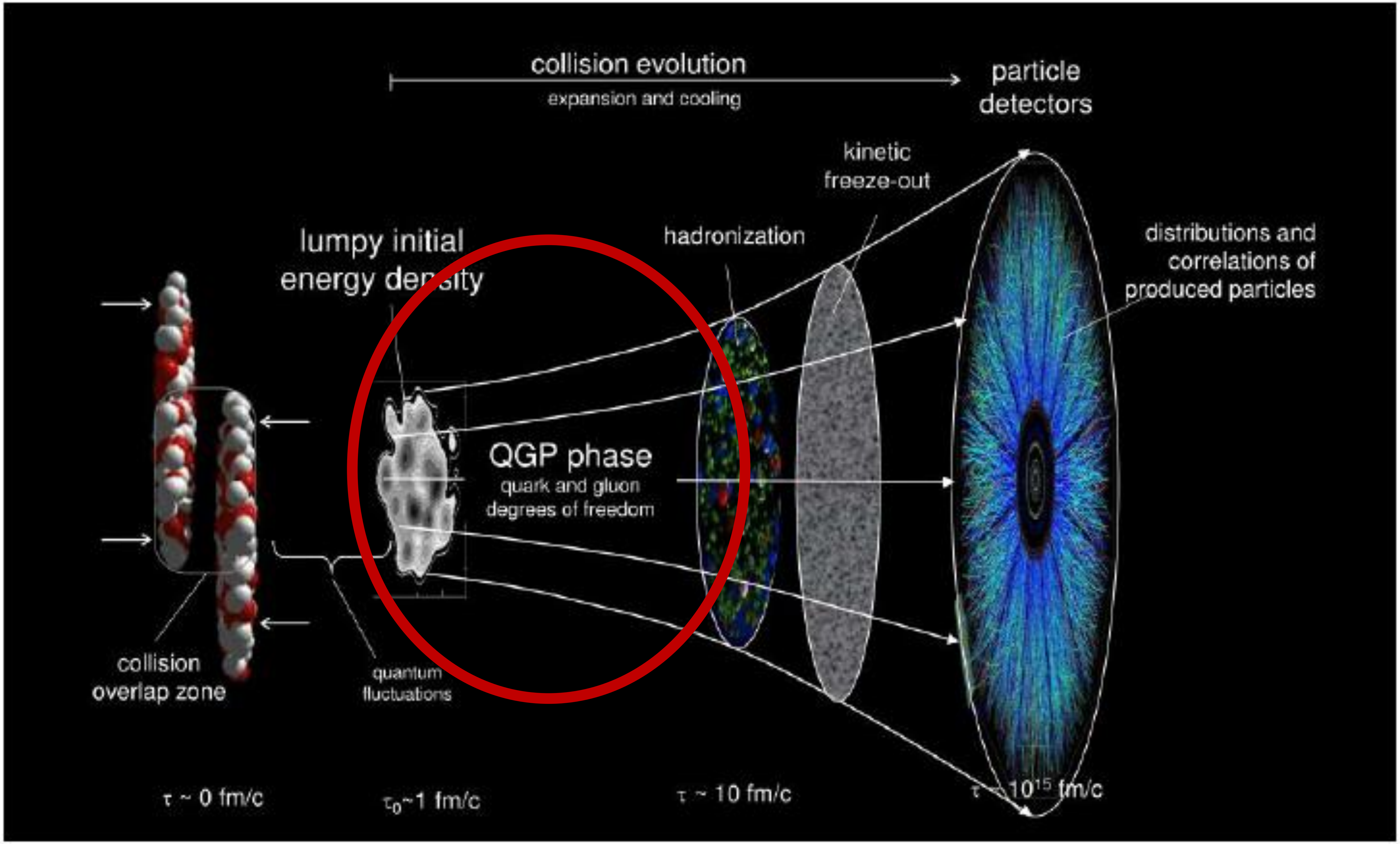
$$T_R(p; T_A, T_B) = \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p}$$

(1412.4708)

$$T_R = \begin{cases} \max(T_A, T_B) & p \to +\infty, \\ (T_A + T_B)/2 & p = +1, \quad \text{(arithmetic)} \\ \sqrt{T_A T_B} & p = 0, \quad \text{(geometric)} \\ 2\,T_A T_B/(T_A + T_B) & p = -1, \quad \text{(harmonic)} \\ \min(T_A, T_B) & p \to -\infty. \end{cases}$$

Trento parameters

- reduced thickness: p
- nuclear fluctuations: k
- nucleon width: w
- minimum nucleon-nucleon distance: d
- number of nucleon constituents: m
- nucleon constituent width: v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Small primer in hydrodynamics

- Hydrodynamic equations derived from energy-momentum conservations (+other conservation laws, e.g. baryon number current)

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\Downarrow$$

$$u^\mu \partial_\mu \epsilon + (\epsilon + p + \pi_{\mathrm{Bulk}}) \nabla_\mu u^\mu + \pi^{\mu\nu} \nabla_\mu u_\nu = 0$$

$$(\epsilon + p + \pi_{\mathrm{Bulk}}) u^\mu \nabla_\mu u^\nu + \Delta^{\mu\nu} \partial_\mu (p + \pi_{\mathrm{Bulk}}) + \Delta^\nu_\alpha \nabla_\mu \pi^{\mu\alpha} = 0$$

- Form of energy-momentum tensor based on general tensor decomposition

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + (p + \pi_{\mathrm{Bulk}}) \Delta^{\mu\nu} + \pi^{\mu\nu}$$

Viscous hydrodynamics

- Supplemental equations for viscous corrections: Second order Israel-Stewart equations

$$P^{\mu\nu\rho}_{\sigma}\left[\tau_S(u^\lambda \nabla_\lambda \pi^\sigma_\rho - 2\pi^{\sigma\lambda}\omega_{\rho\lambda}) + 2\eta\nabla_\rho u^\sigma\right] + \pi^{\mu\nu} = 0$$

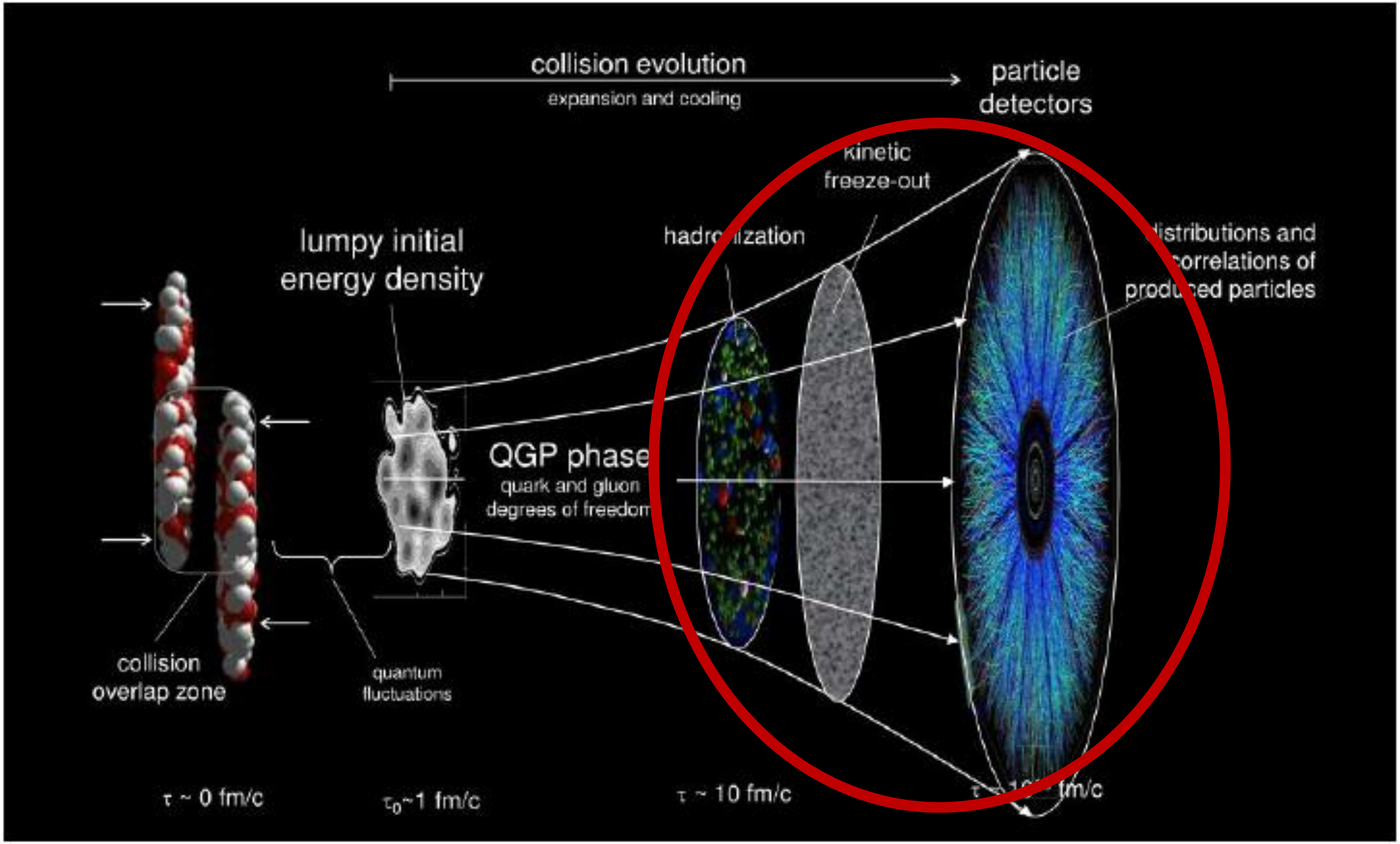
$$\boxed{\tau_{\mathrm{Bulk}} u^\mu \partial_\mu \pi_{\mathrm{Bulk}}} + \boxed{\pi_{\mathrm{Bulk}}} + \boxed{\zeta \nabla_\mu u^\mu} = 0$$

Israel-Stewart Ideal Navier-Stokes

- Navier-Stokes: Introduce viscosity

  -> Allows non-zero viscous corrections
- Israel-Stewart: Introduce relaxation time

  -> Equations remain valid out of equilibrium



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Particle Production

- Cooper-Frye freeze-out: $\frac{dN}{d^3p d^3x} = f(p^\mu, T(x), u^\mu(x), \pi^{\mu\nu}(x), \pi_{\text{bulk}})$

$$E\frac{dN}{d^3p} = -\frac{1}{(2\pi)^3} p_\mu \int_{\Sigma_f} d\sigma^\mu f(p^\mu, T(x), u^\mu(x), \pi^{\mu\nu}(x), \pi_{\text{bulk}})$$

- Distribution function f: Bose/Fermi + corrections, e.g. $f = f_{\text{eq}} + \delta f_{\text{shear}} + \delta f_{\text{bulk}}$
- Additional steps:
  - Chemical/kinetic F.O.
  - Hadronic afterburner/rescattering

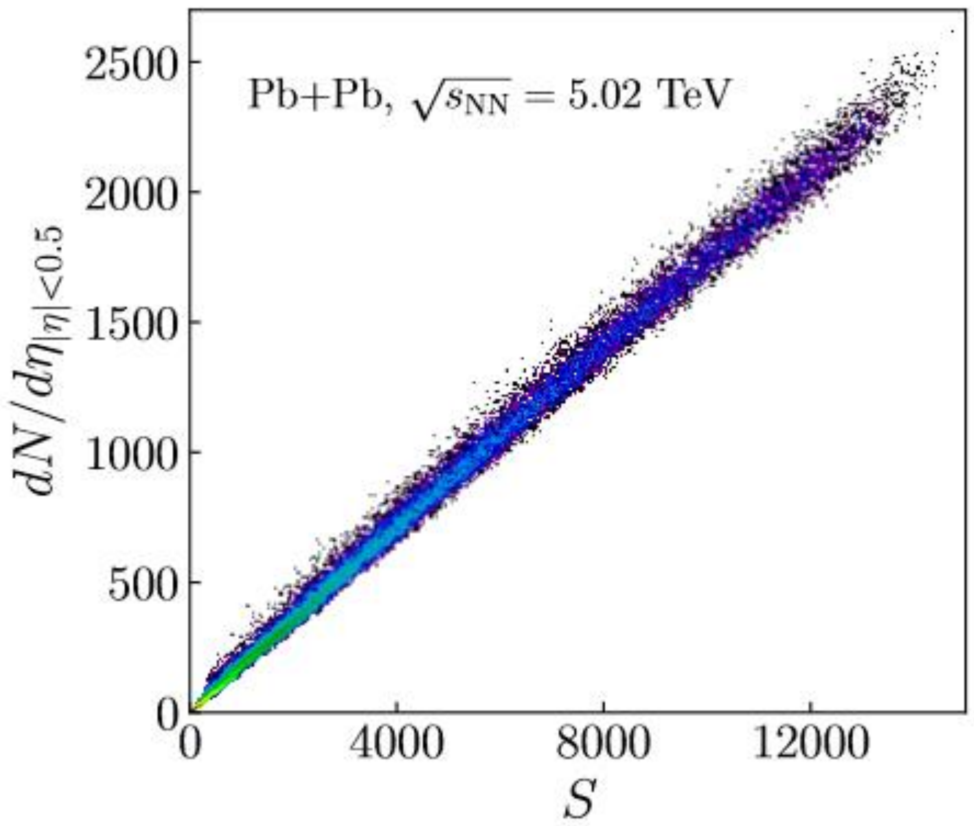
f_{eq} Bose/Fermi distribution

$$\delta f_{\text{shear}} = f_{\text{eq}}(1 \pm f_{\text{eq}}) \frac{p_\mu p_\nu \pi^{\mu\nu}}{2(e+p)T^2}$$

$$\delta f_{\text{bulk}} = f_{\text{eq}}(1 \pm f_{\text{eq}}) \left[\frac{E_p}{T}\left(\frac{1}{3} - c_s^2\right) - \frac{1}{3}\frac{m^2}{TE_p}\right] \frac{\tau_\Pi \pi_{\text{bulk}}}{\zeta}$$

Observable overview – N_ch

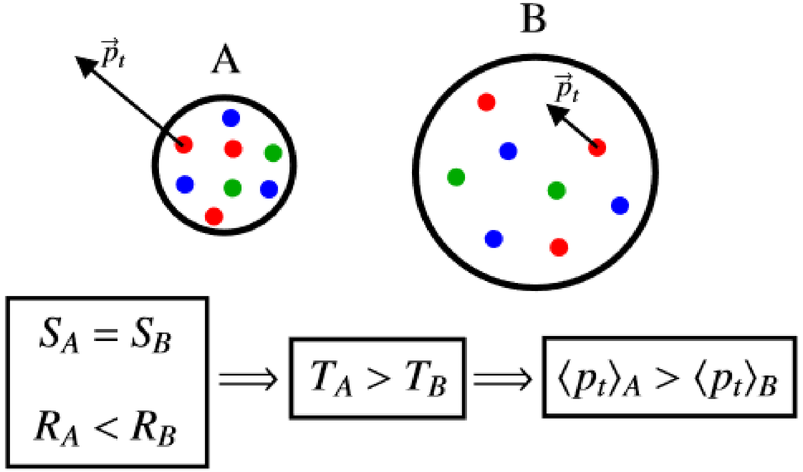
- Measure/count number of produced particles
- Initial state predictor: entropy
- Ideal gas: entropy proportional to produced particles

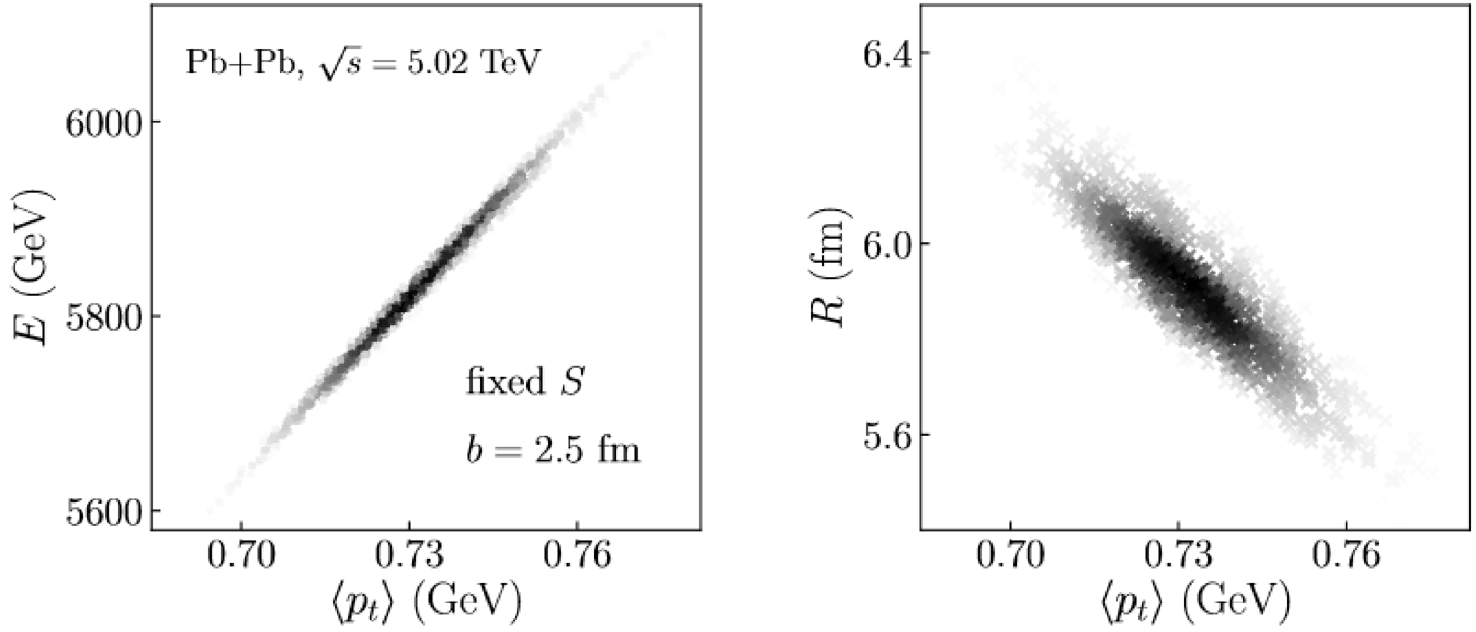


From G. Giacalone

Obeservable overview – mean pT

- Average momentum of measured particles -> $\langle p_t \rangle$
- Intial state predictor: energy/system size



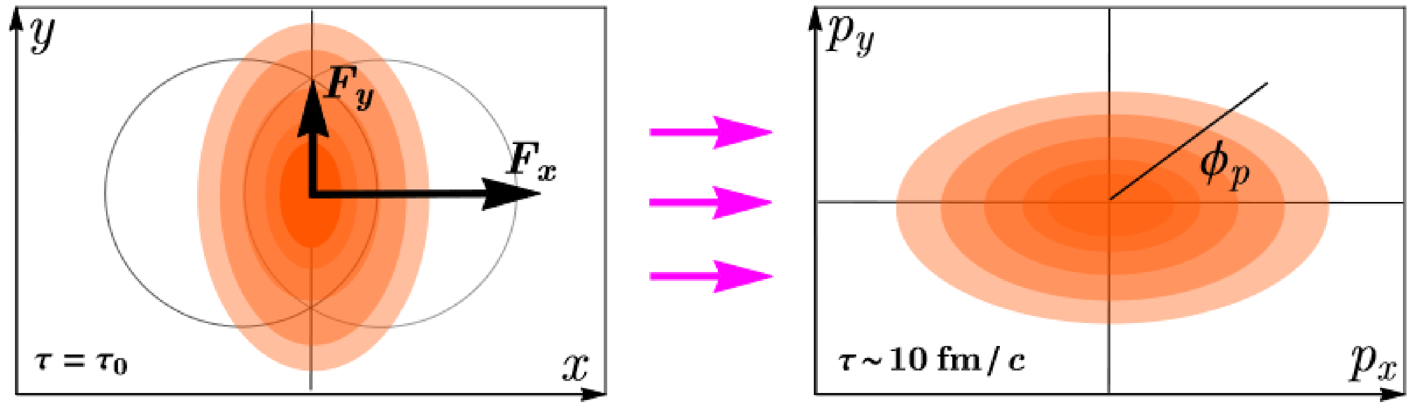


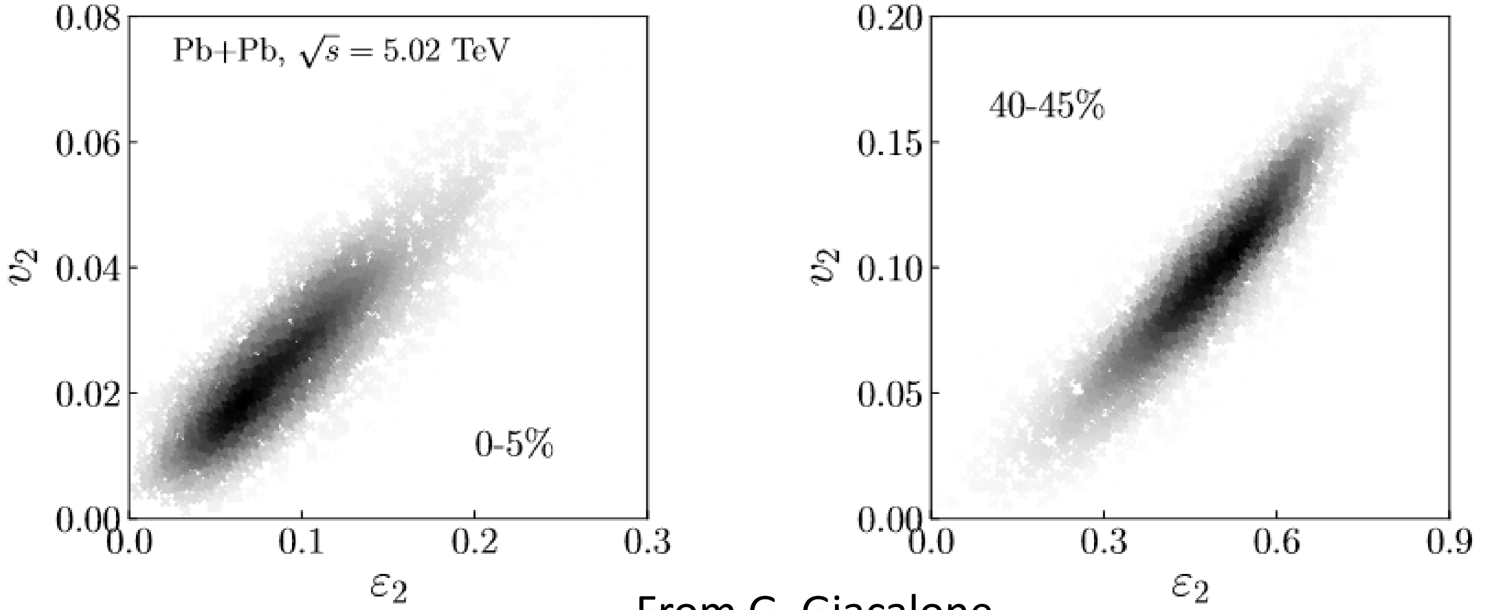
(2004.01765)

Observable overview - flow

- Fourier transformation of spectra -> flow harmonics
- Initial state predictor: eccentricities

$$\varepsilon_2 = \frac{\left|\int_{\mathbf{x}} \mathbf{x}^2 s(\mathbf{x}, \tau_0)\right|}{\int_{\mathbf{x}} |\mathbf{x}|^2 s(\mathbf{x}, \tau_0)},$$





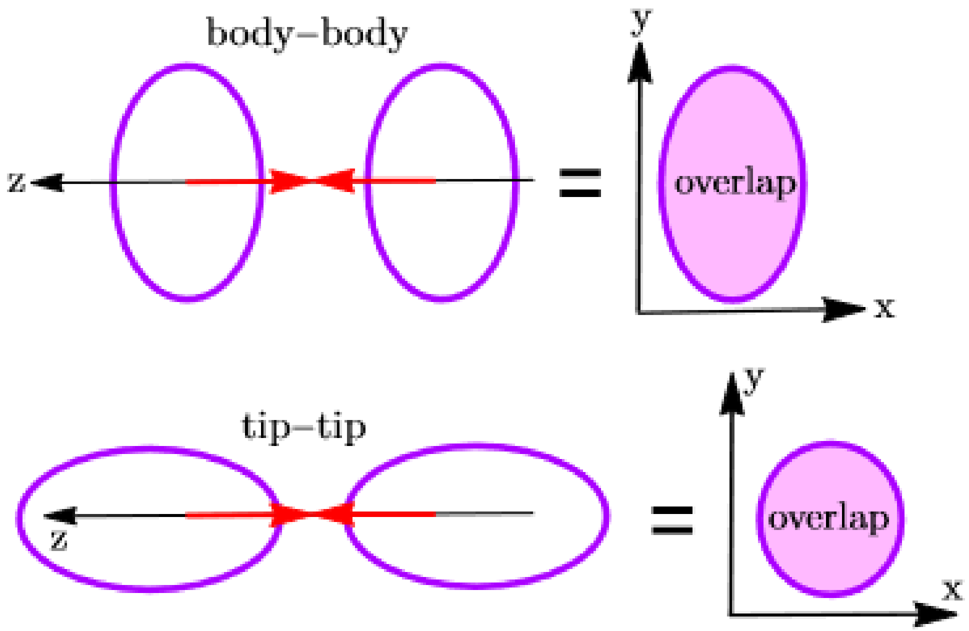
From G. Giacalone

Observable overview – Pearson correlator

- Correlation between flow and mean pT

  -> Measure of axial deformations

$$\rho(v_2^2, \langle p_t \rangle) = \frac{\langle \delta v_2^2 \delta \langle p_t \rangle \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta \langle p_t \rangle)^2 \rangle}},$$



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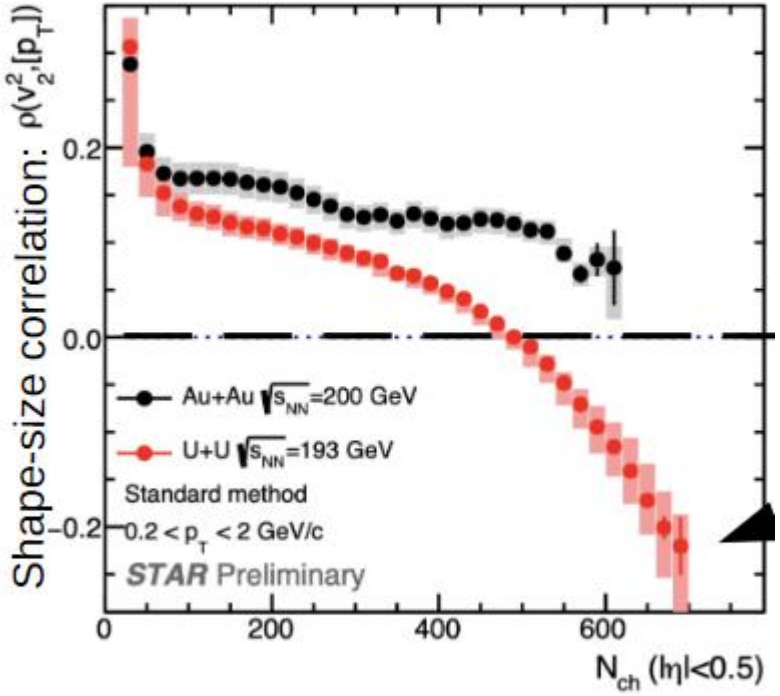


v2 is anticorrelated with <pT>

From G. Giacalone

Setup - TrenTo

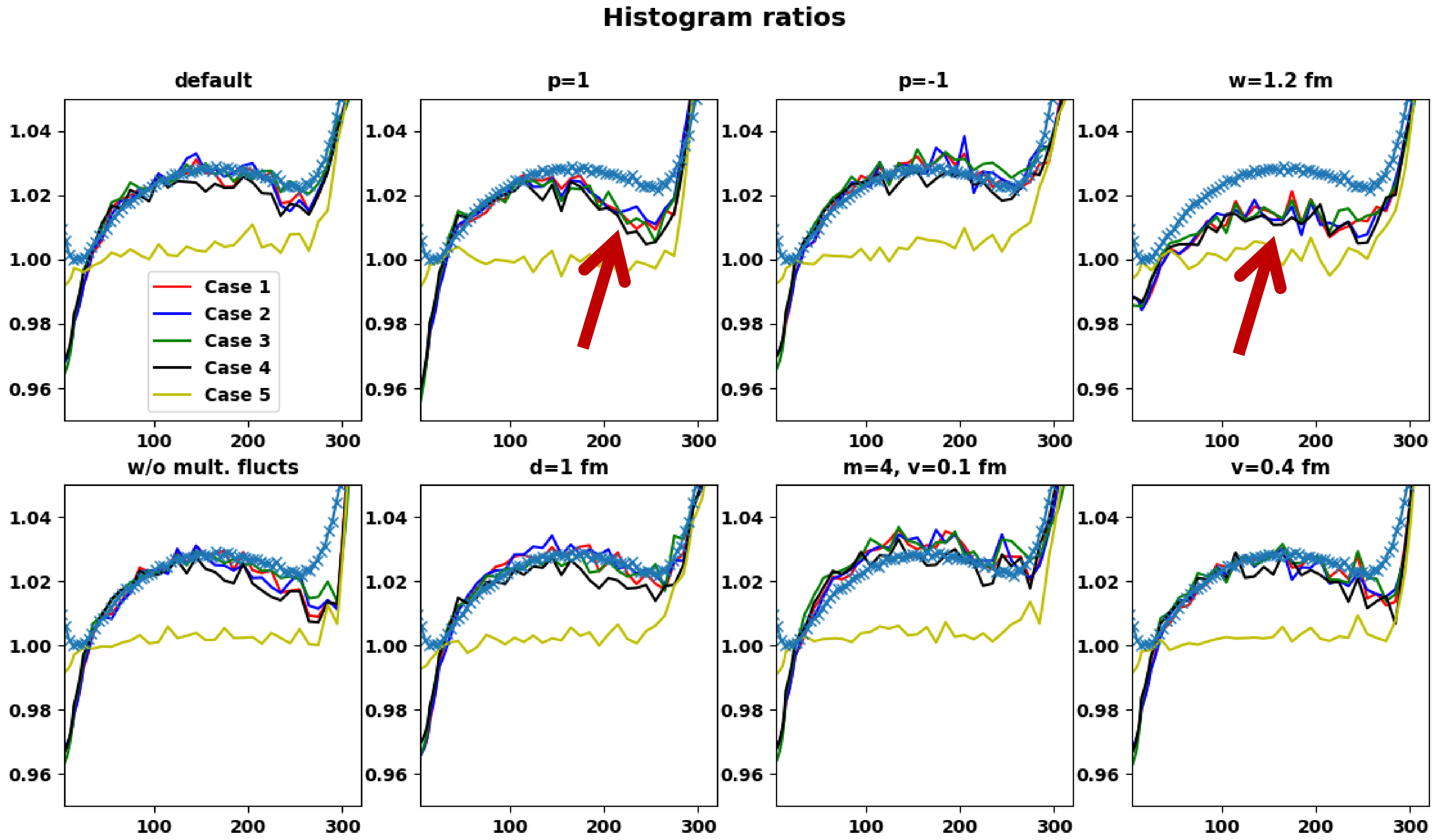
- Take every possible combination of TrenTo and nuclear parameters
- Use 20M minimum bias events per combination

batch number/val.	x	p	w	k	d	m	v
1	4.2	0.0	0.5	1			
2	4.2	1.0	0.5	1			
3	4.2	-1.0	0.5	1			
4	4.2	0.0	1.2	1			
5	4.2	0.0	0.5	16			
6	4.2	0.0	0.5	1	1.0		
7	4.2	0.0	0.5	1		4	0.1
8	4.2	0.0	0.5	1		4	0.4

system to run	R_0 (fm)	a_0 (fm)	β_2	β_3	γ (°)
Case1 (^{96}Ru+^{96}Ru) [full ^{96}Ru]	5.09	0.46	0.16	0	30
Case2 (^{96}Ru+^{96}Ru)	5.09	0.46	0.16	0	0
Case3 (^{96}Ru+^{96}Ru)	5.09	0.46	0.16	0.20	0
Case4 (^{96}Ru+^{96}Ru)	5.09	0.46	0.06	0.20	0
Case5 (^{96}Ru+^{96}Ru)	5.09	0.52	0.06	0.20	0
Case6 (^{96}Zr+^{96}Zr) [full ^{96}Zr]	5.02	0.52	0.06	0.20	0

TrenTo - Results

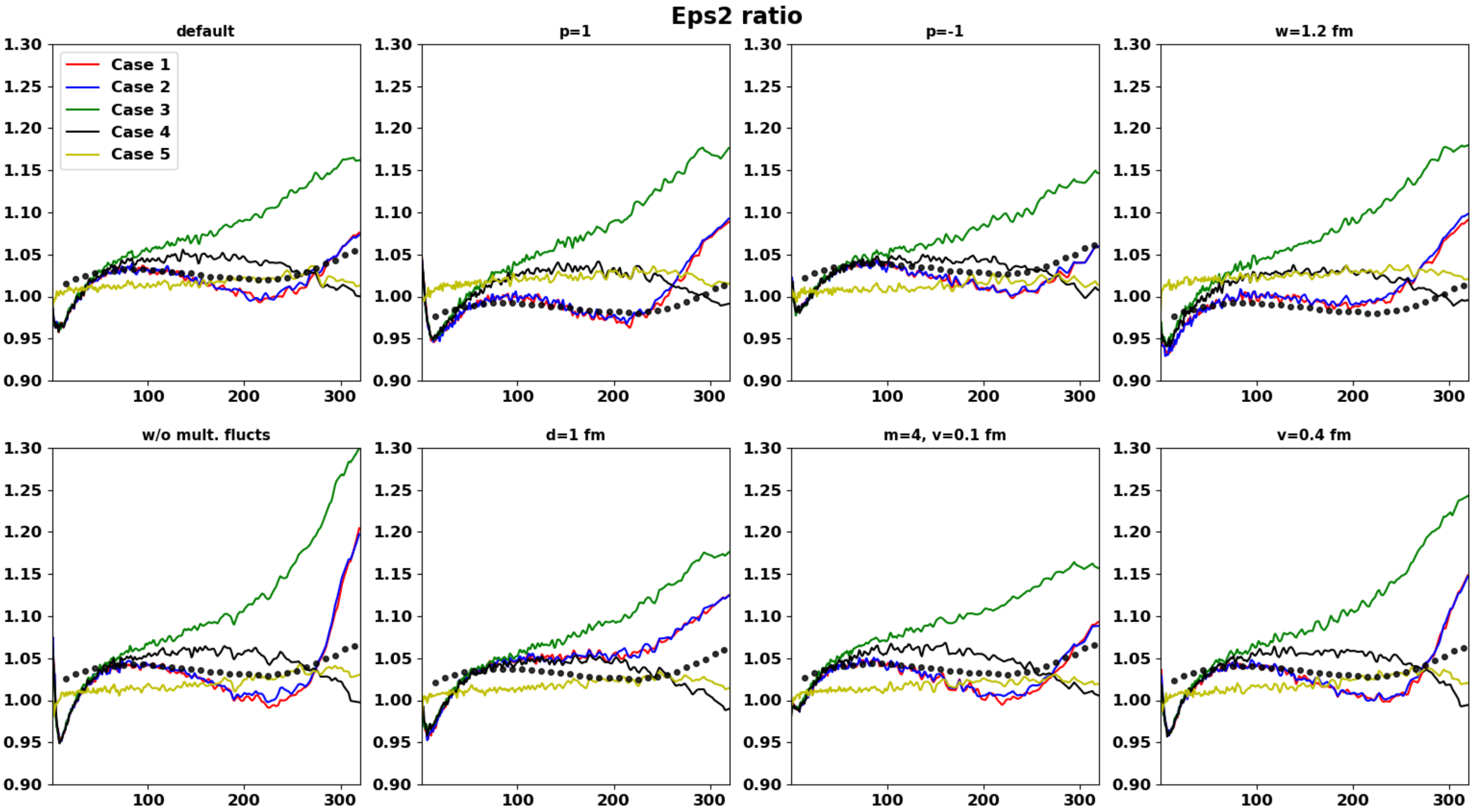
Case4 (^{96}Ru+^{96}Ru)	5.09	0.46	0.06	0.20	0
Case5 (^{96}Ru+^{96}Ru)	5.09	0.52	0.06	0.20	0
Case6 (^{96}Zr+^{96}Zr) [full ^{96}Zr]	5.02	0.52	0.06	0.20	0



Nuclear skin thickness dominates histogram ratio

TrenTo - Results

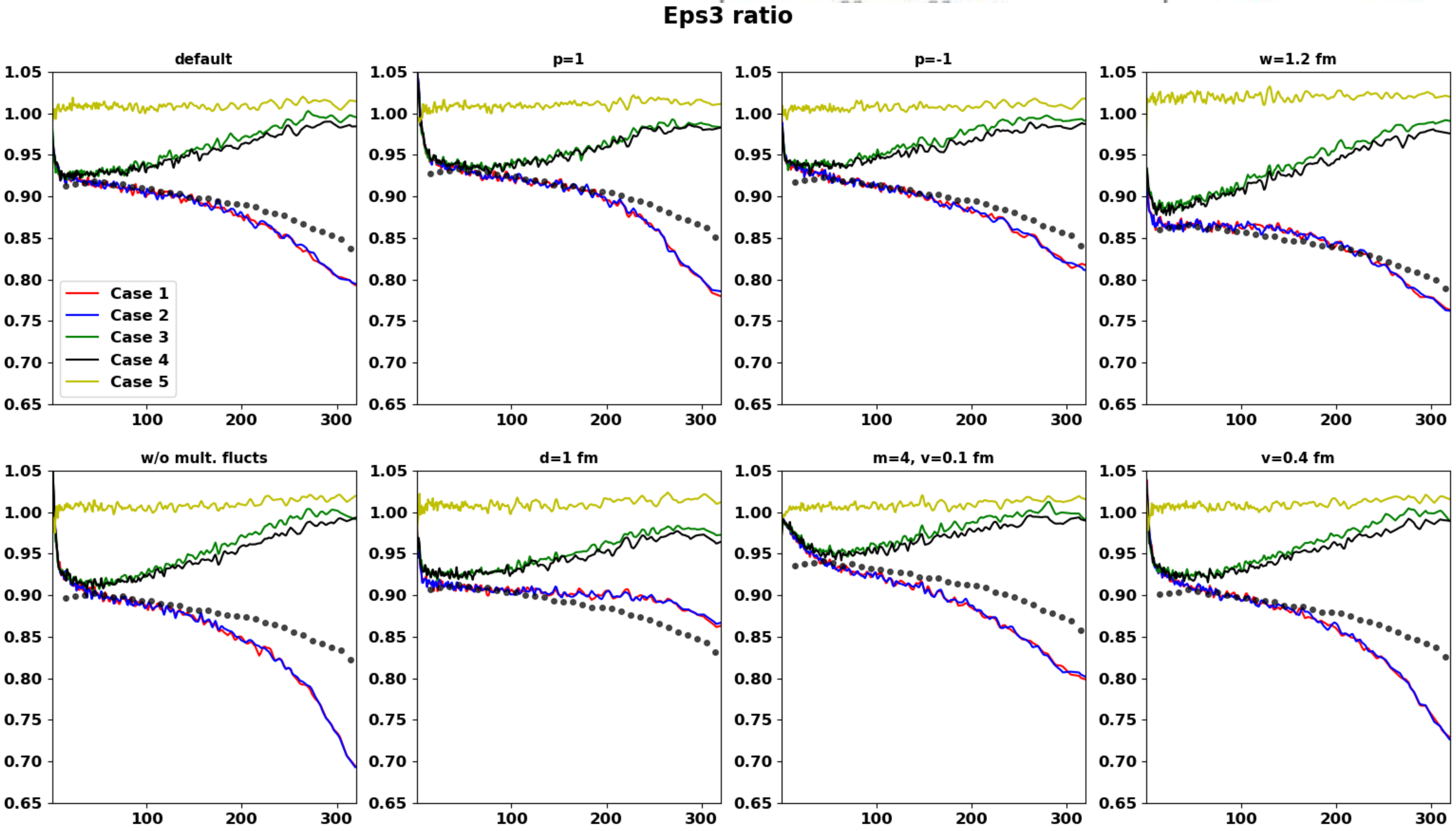
Case2 (^{96}Ru+^{96}Ru)	5.09	0.46	0.16	0	0
Case3 (^{96}Ru+^{96}Ru)	5.09	0.46	0.16	0.20	0
Case4 (^{96}Ru+^{96}Ru)	5.09	0.46	0.06	0.20	0



β dominates ratio of eccentricities

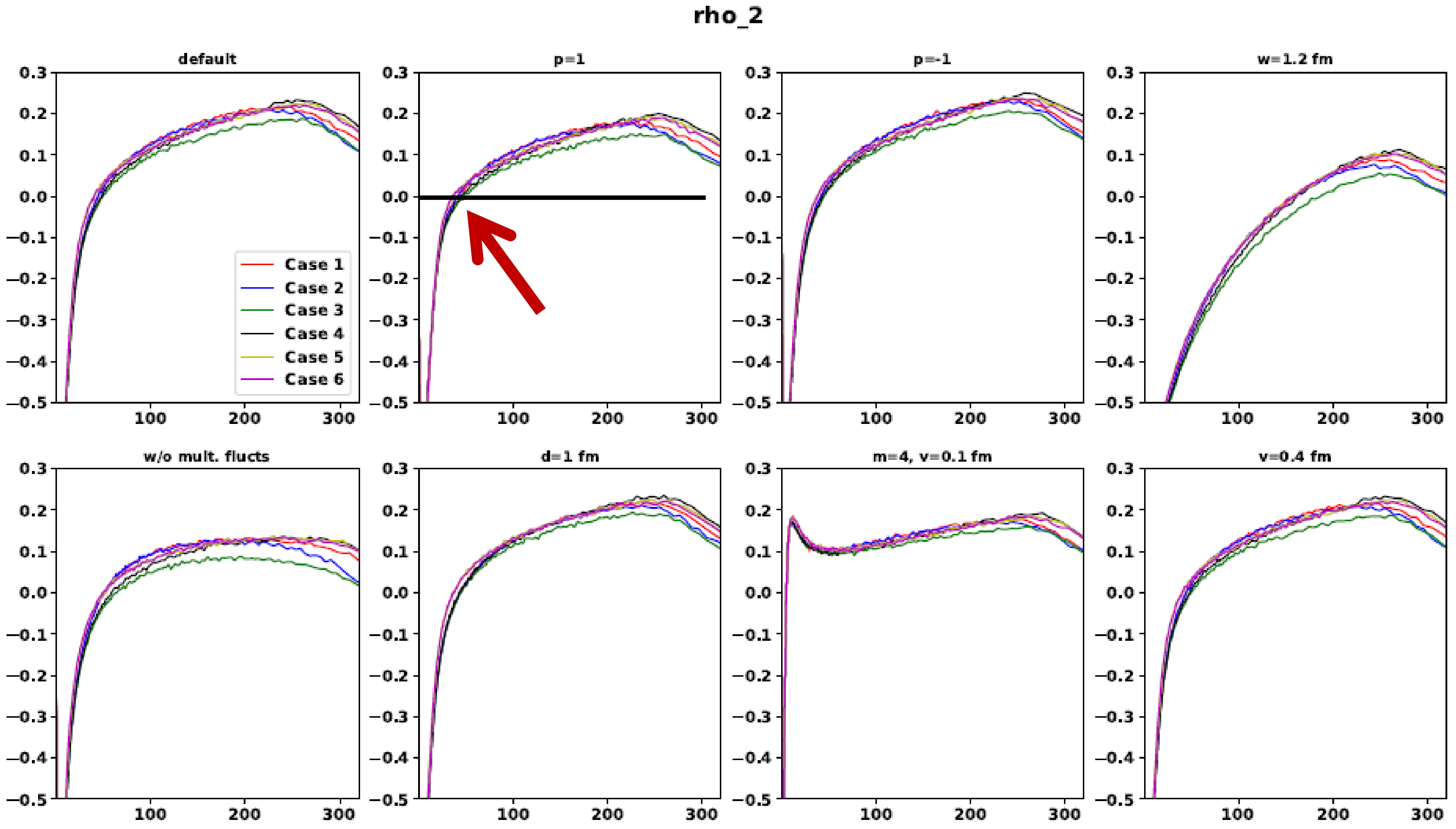
TrenTo - Results

Case2 (^{96}Ru+^{96}Ru)	5.09	0.46	0.16	0	0
Case3 (^{96}Ru+^{96}Ru)	5.09	0.46	0.16	0.20	0
Case4 (^{96}Ru+^{96}Ru)	5.09	0.46	0.06	0.20	0



β3 dominates ratio of e3

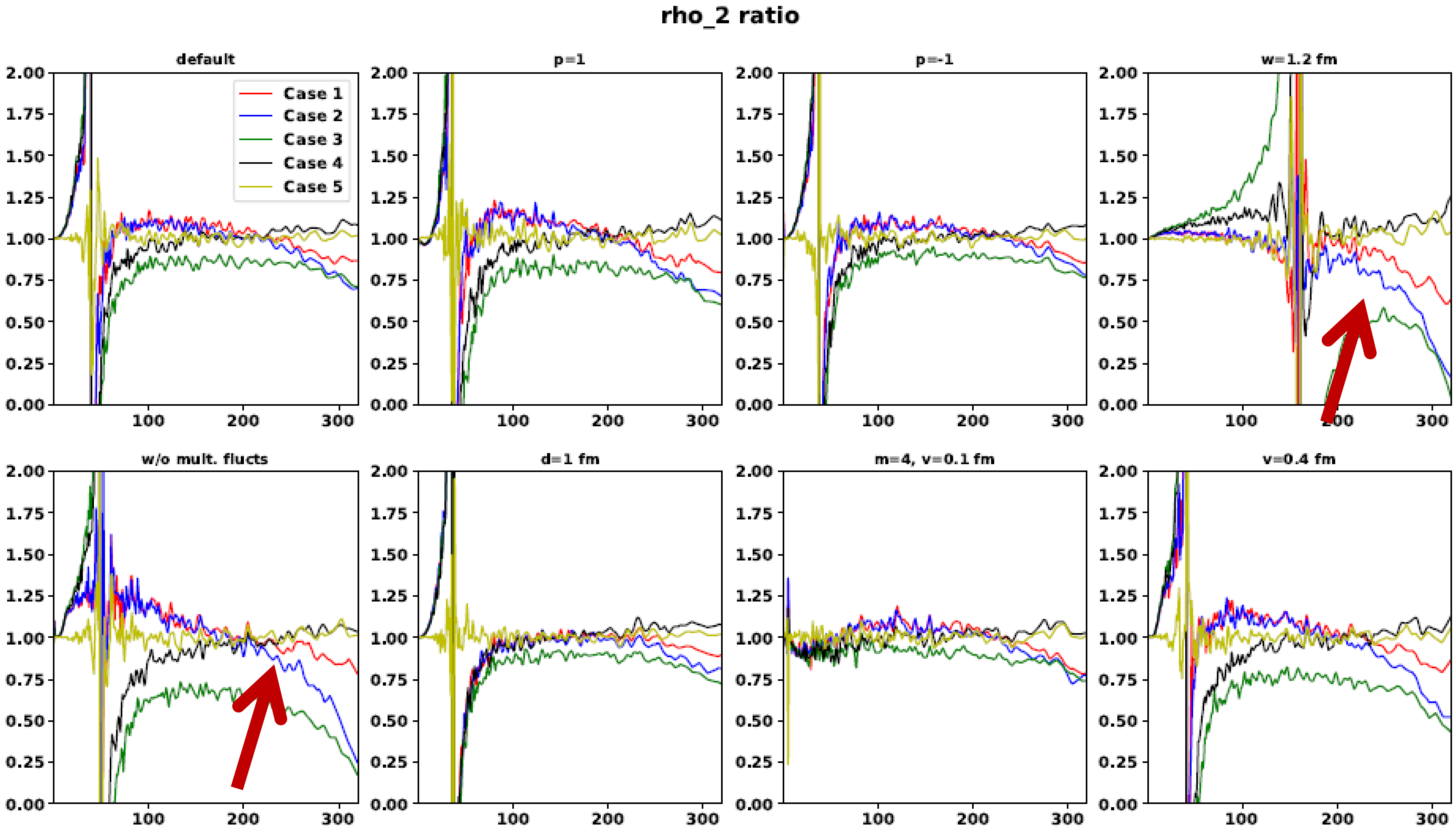
TrenTo - Results



Sign change -> ``Divergent ratios“

TrenTo - Results

Case1 (^{96}Ru+^{96}Ru) [full ^{96}Ru]	5.09	0.46	0.16	0	30
Case2 (^{96}Ru+^{96}Ru)	5.09	0.46	0.16	0	0



Pearson correlator sensitive to triaxiality

TrenTo - Results

- There are certain observables more sensitive to one nuclear structure parameter than others:
  - Histogramm ratio -> a0
  - V2,v3 ratio-> betas
  - Rho-> gamma
- Ratios only affected by „degree of sharpness of QGP“ when considering TrenTo parameters
  - Nucleon width w
  - Thickness p
  - Constituent size v

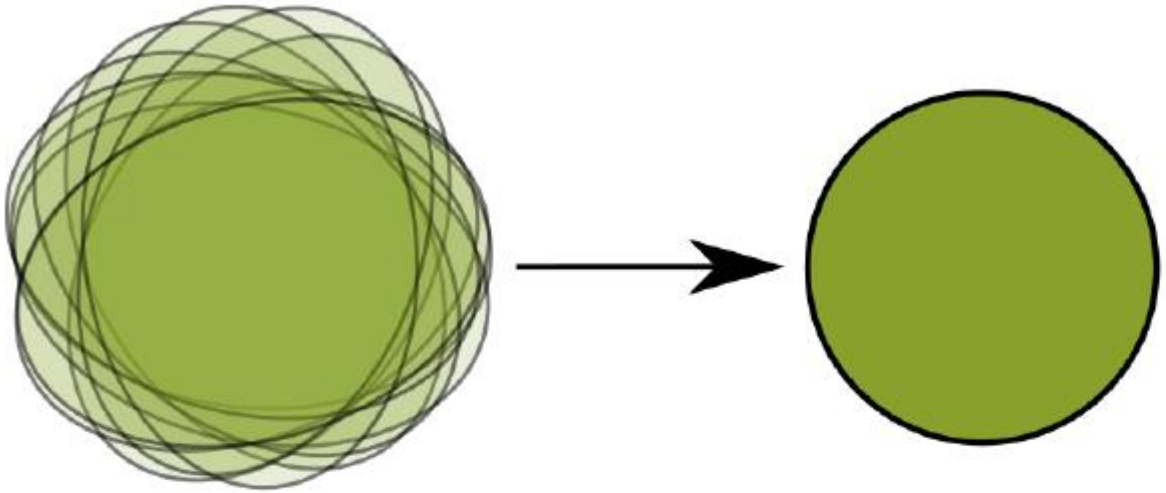
⇨ Which is smallest set obsevables most sensitive to nuclear structure, but least sensitive to collision parameters?

Mode-by-mode hydrodynamics

- Idea: Describe event ensemble instead of single event

  -> Statistical symmetry

  -> BG-fluctuation splitting

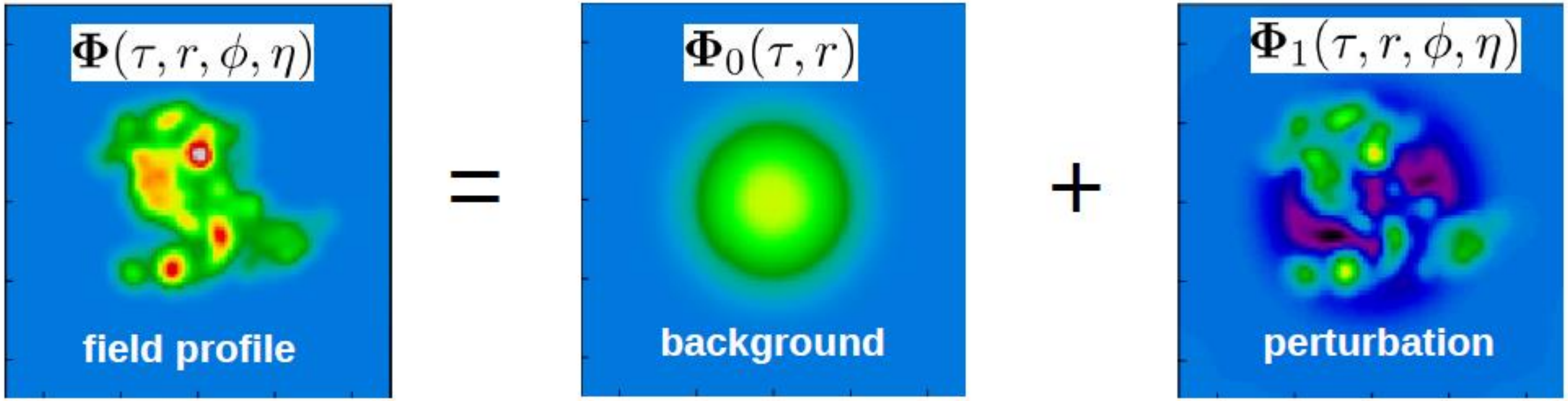


$$\Phi(\tau, r, \varphi, \eta) = \Phi_0(\tau, r) + \epsilon\Phi_1(\tau, r, \varphi, \eta)$$

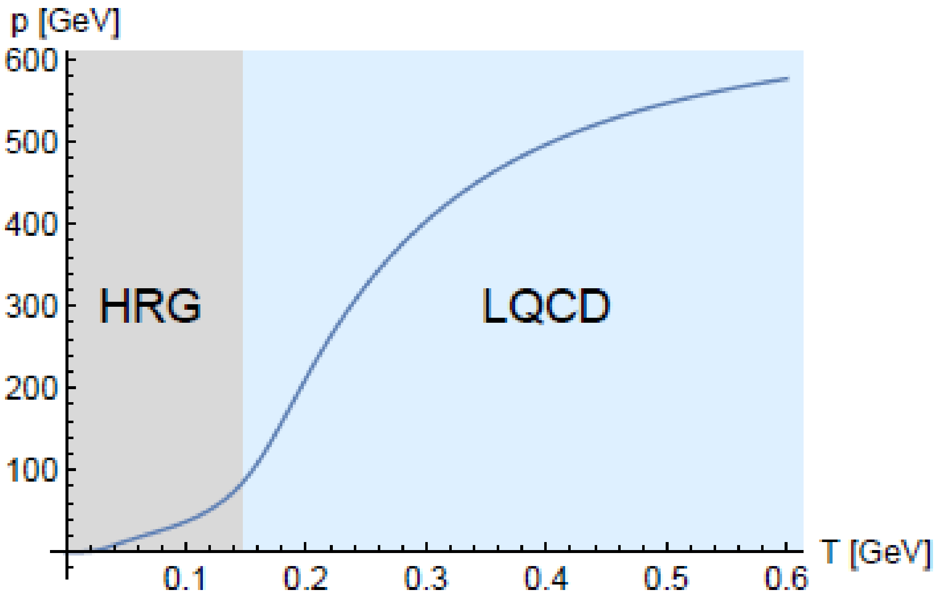
- BG has Bjorken boost invariance + statistical symmetry -> 1+1D EoM
- 1+1D linearised EoM for perturbations coupled with BG
- BG gives averaged quantities (yields, <pT>), while fluctuations encoded in perturbations

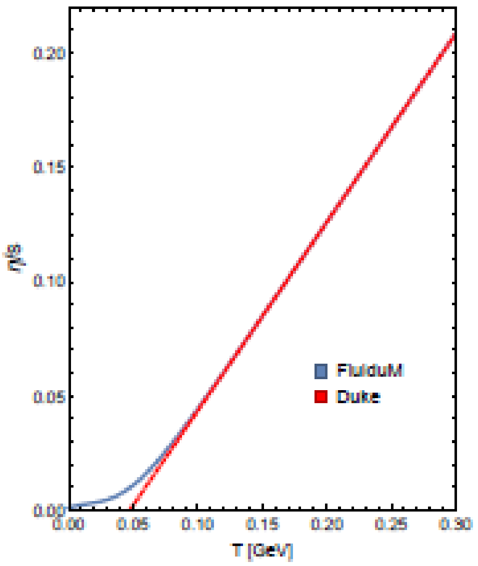
Implementation: FLuiduM

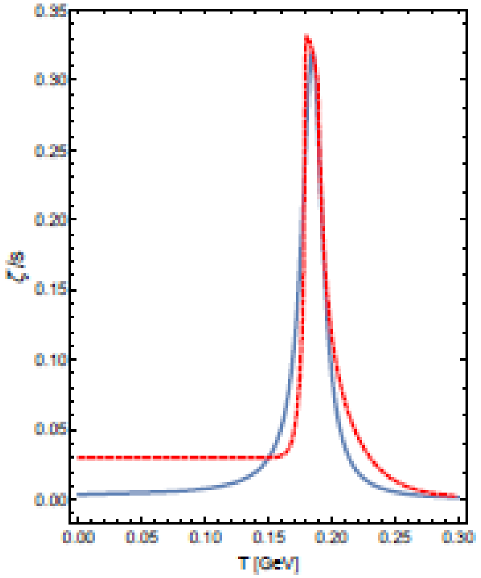
- FluiduM is Mathematica/julia code package to solve 1+1D hydro equations
- EoM: Energy-momentum conservation + 2nd order Israel-Stewart
- Evolution does not violate causality
- Validated against Gubser-Flow
- Particlization+Resonance decays: Cooper-Frye+FastReso



Validation: Setup





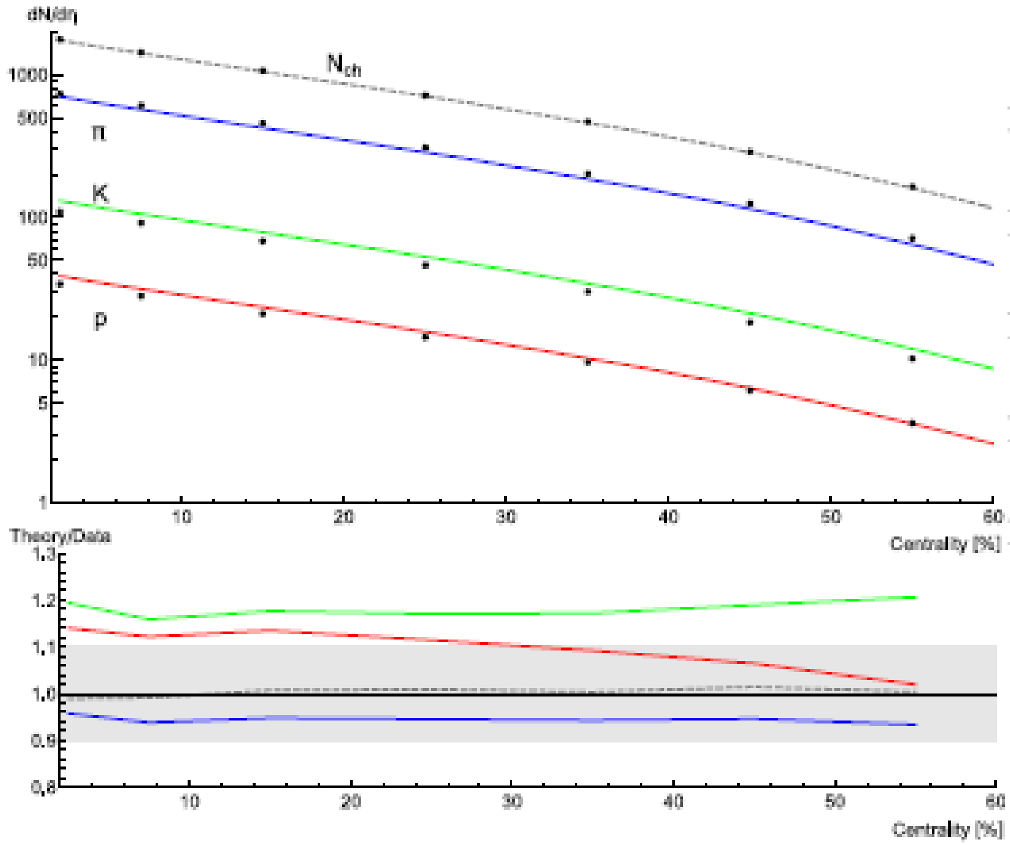


- EoS: HRG ($T < T_c = 154\,\text{MeV}$) and LQCD ($T > T_c$)
- Viscosities $\frac{\eta}{s}(T)$ and $\frac{\zeta}{s}(T)$
- $T_{fo} = 148\,\text{MeV}$

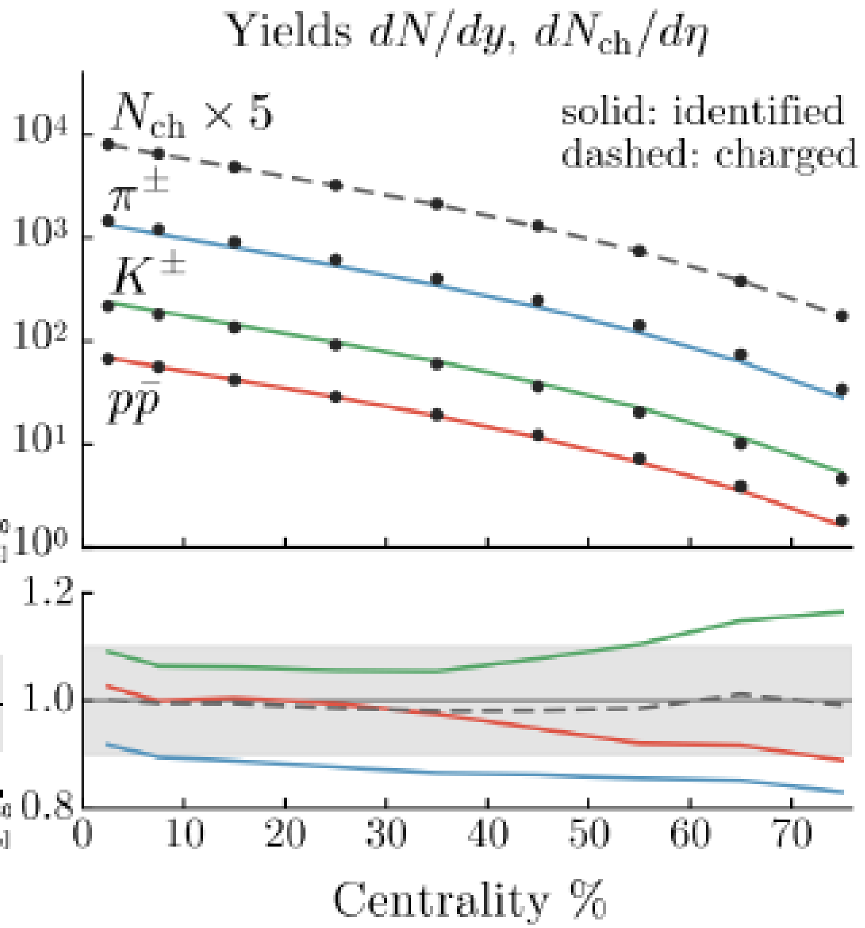
- δf_{shear}, but no δf_{bulk}
- Setup nearly identical to model of first bayesian analysis of Duke group (arxiv:1605.03954)

Validation: Results

FluiduM

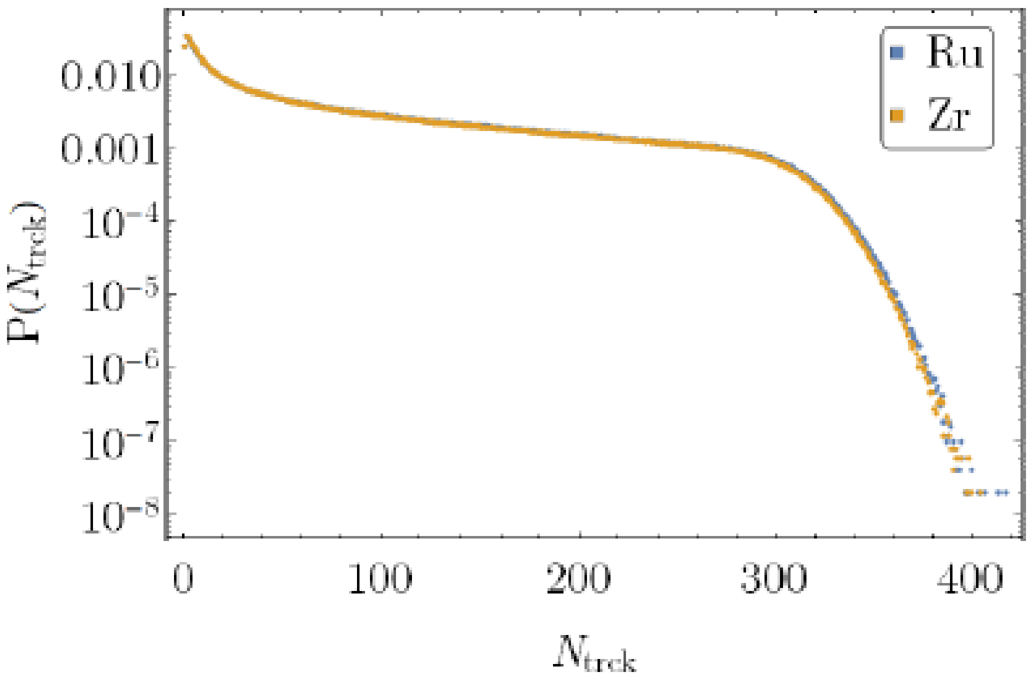


Duke



Setup – full hydro

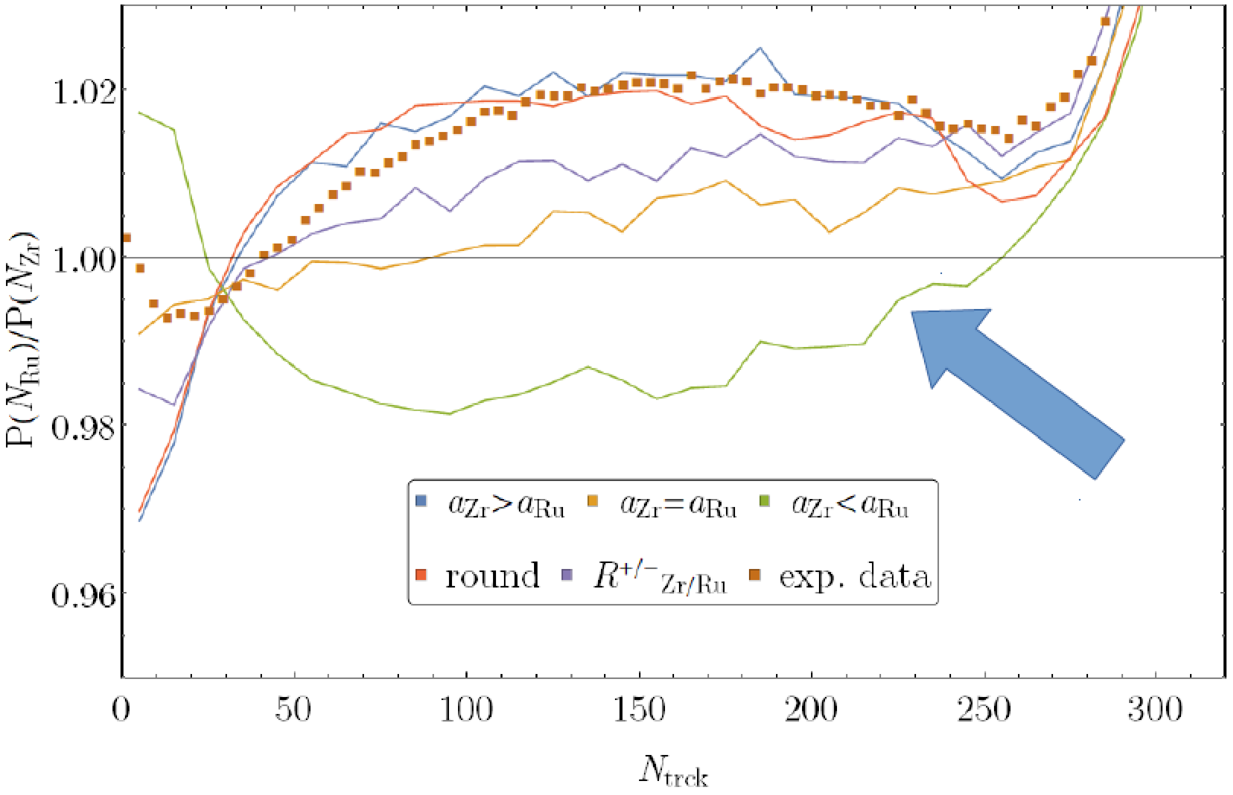
- Run TrenTo for initial state
- Define 0.5% centrality bins using 50M minimum bias events
- Run 400k events in select bins (→ effectively 80M events)
- Scan large range of nuclear (R, a, β_2, β_3), collision (k → multiplicity fluctuation, p → energy depostition, w → nucleon size, d → nucleon repulsive core, m → number of partons, v → parton size) and QGP (η/s, ζ/s, T_{fo}, τ_0) parameters

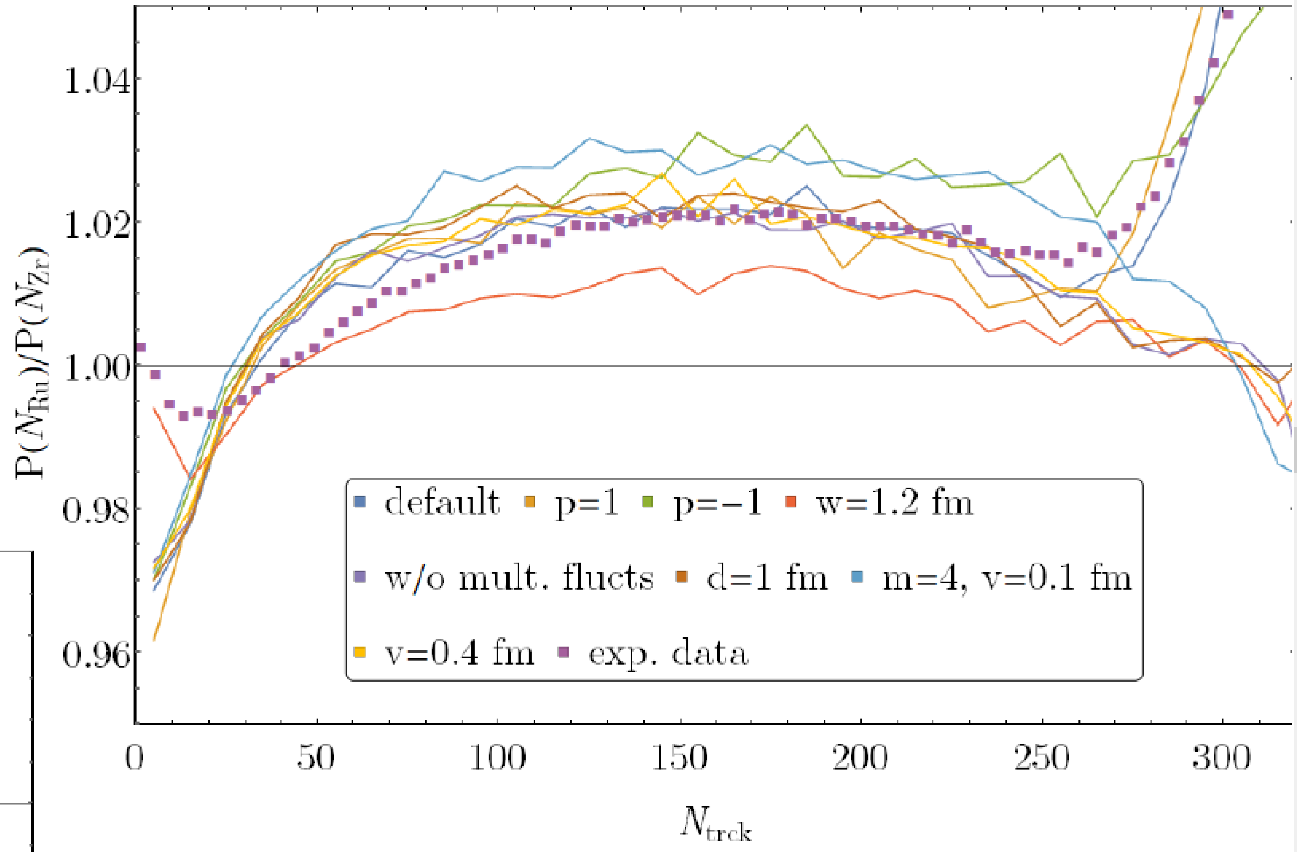


Histogram multiplicity through linear rescaling of TrenTo entropy

Initial state results

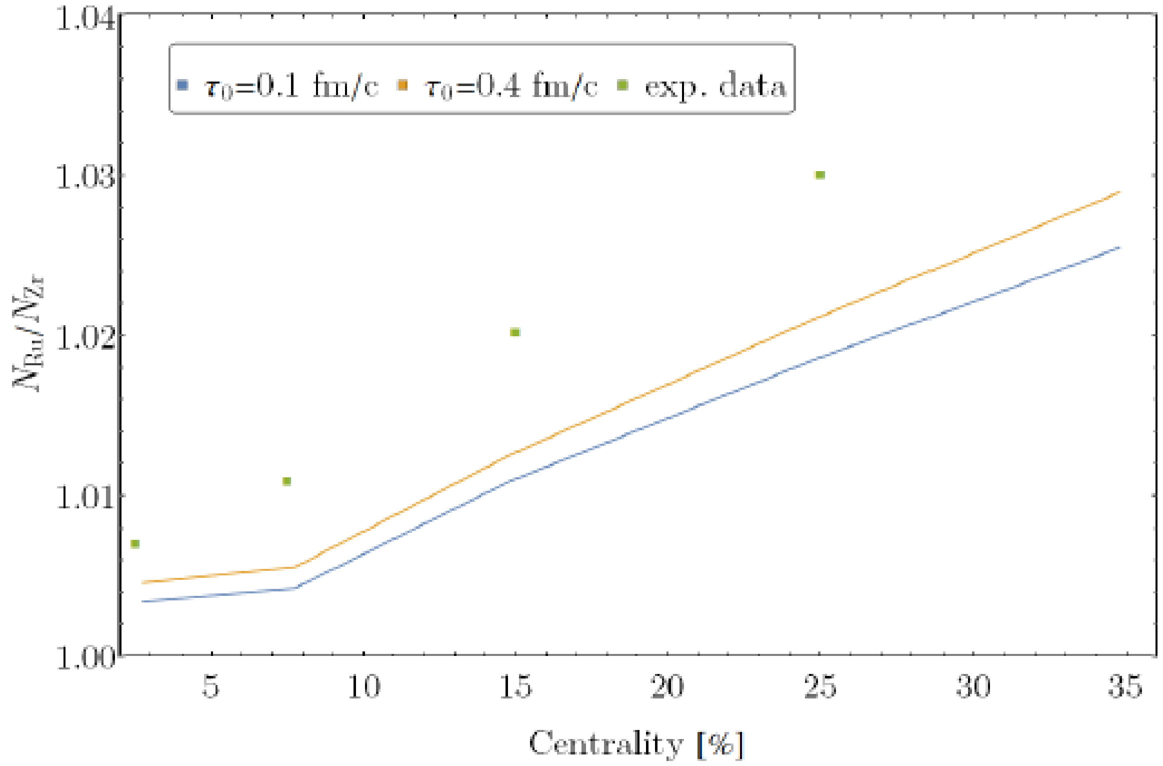
Histogram multiplicity ratio dominated by diffusivity

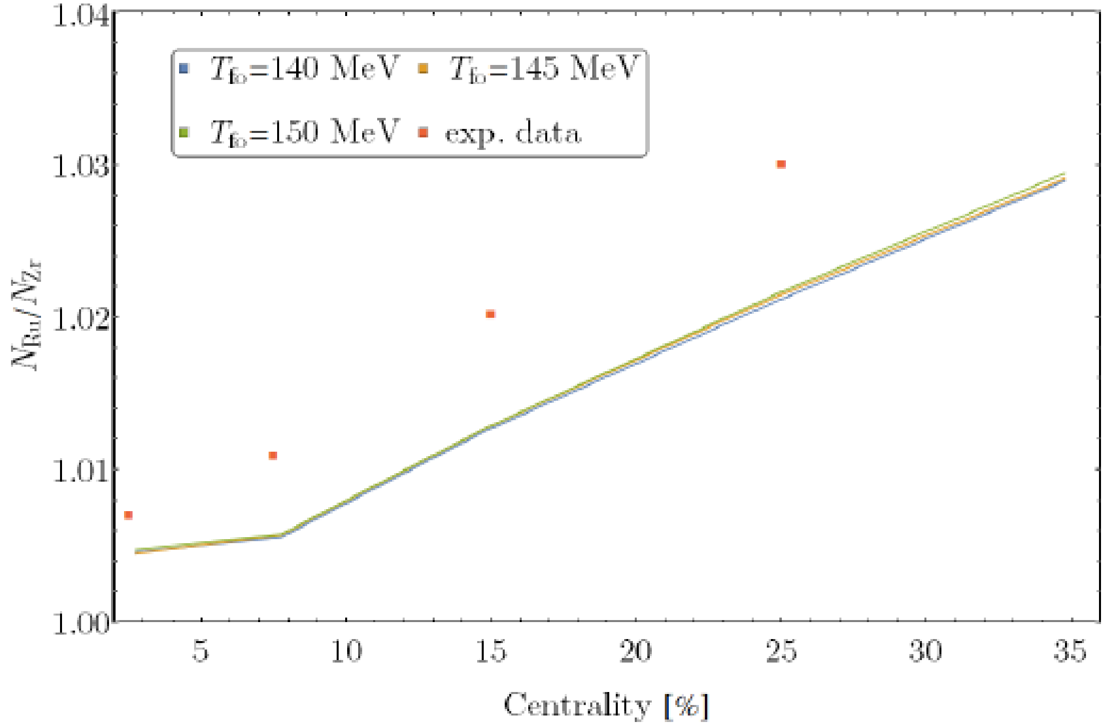




Default: p=0, w=0.5 fm, k=1

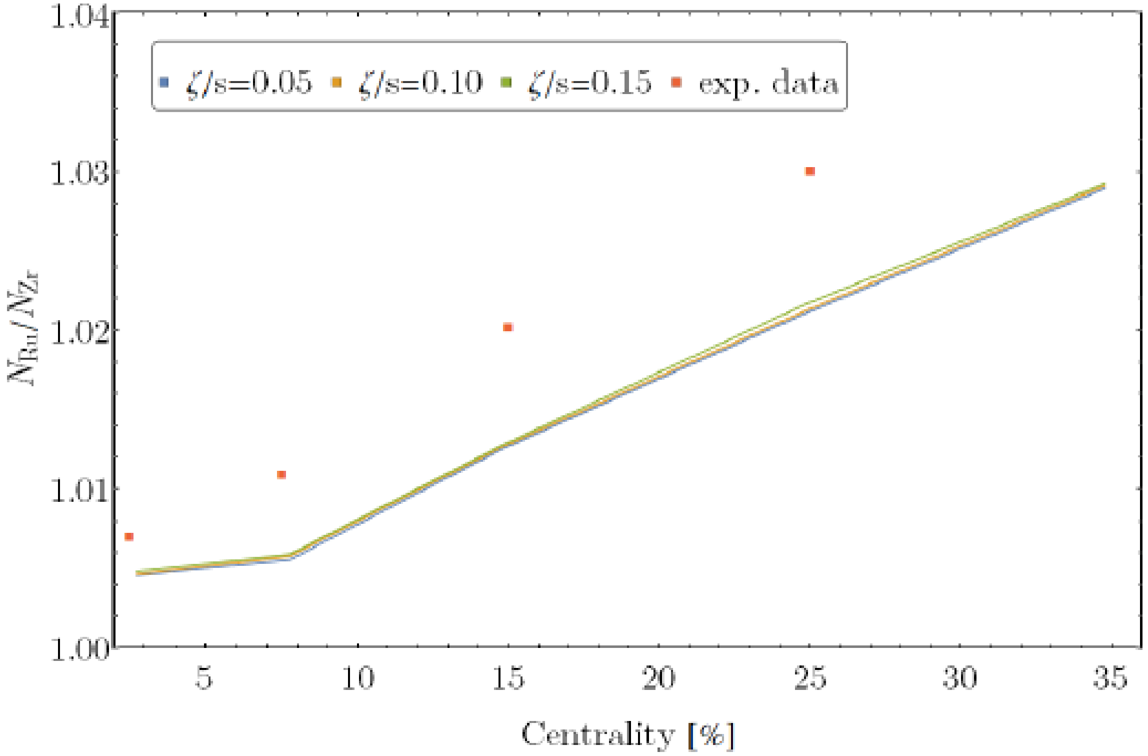
QGP parameters

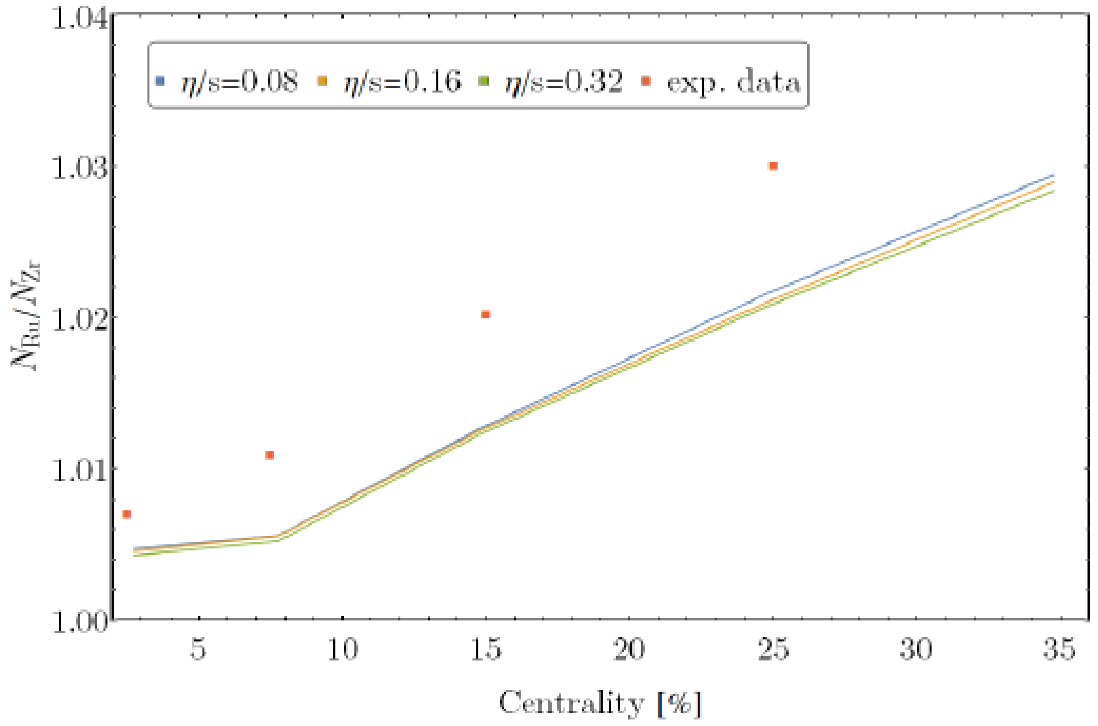




Multiplicity ratio not dependent on initialization time and freeze-out temperature

QGP parameters

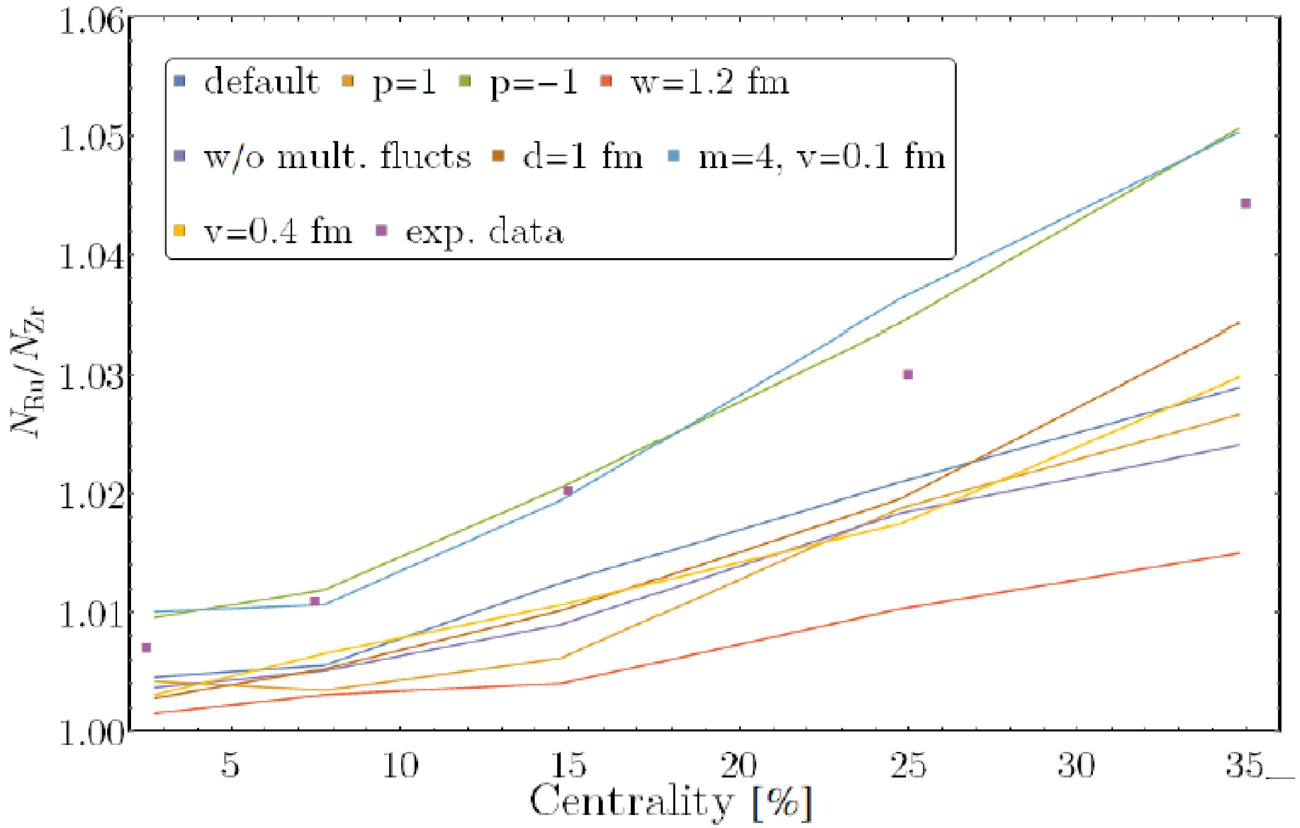


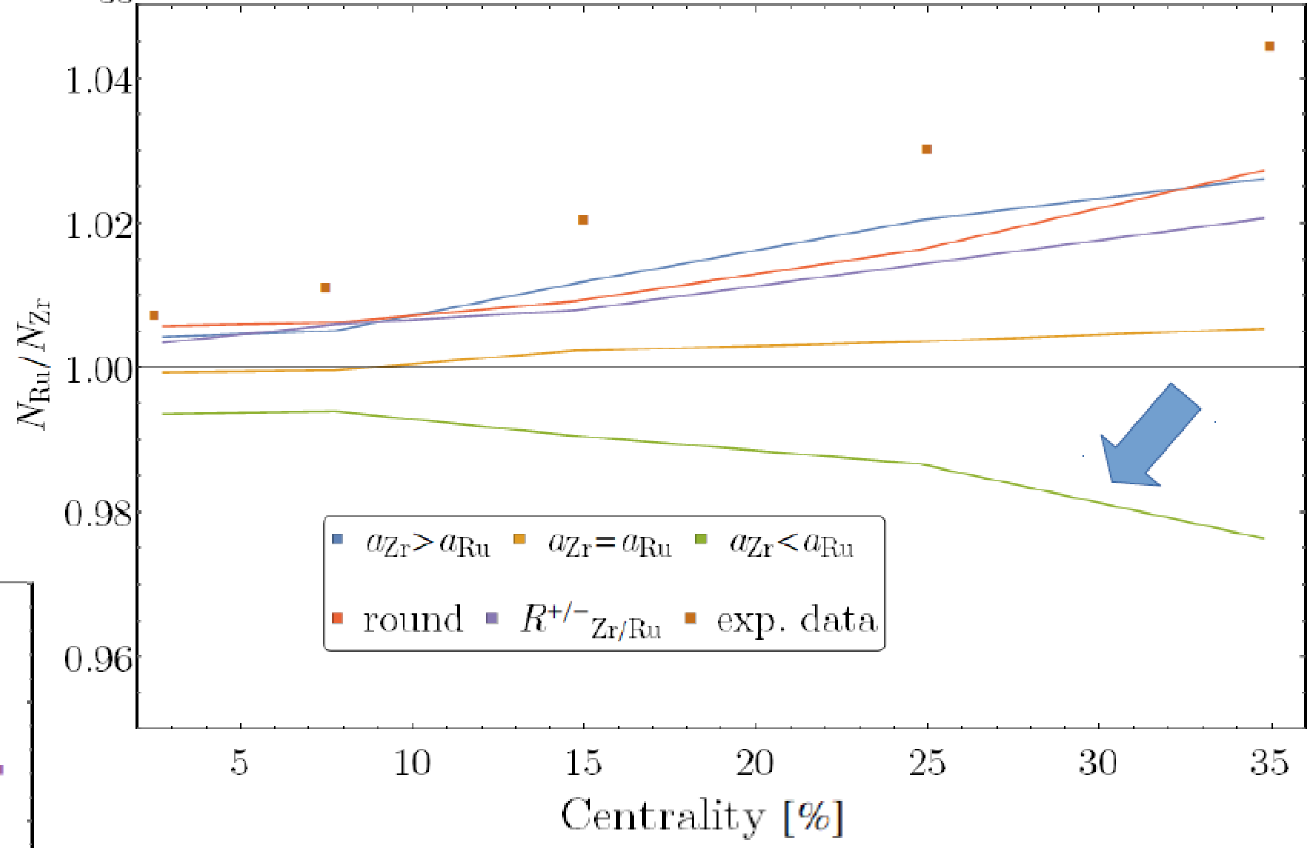


Multiplicity ratio not sensitve to medium viscosities

Final state results

Multiplicity ratio dependent on
``degree of sharpness´´ of QGP





Multiplicity ratio dominated by
diffusivity

Default: p=0, w=0.5 fm, k=1

Conclusion

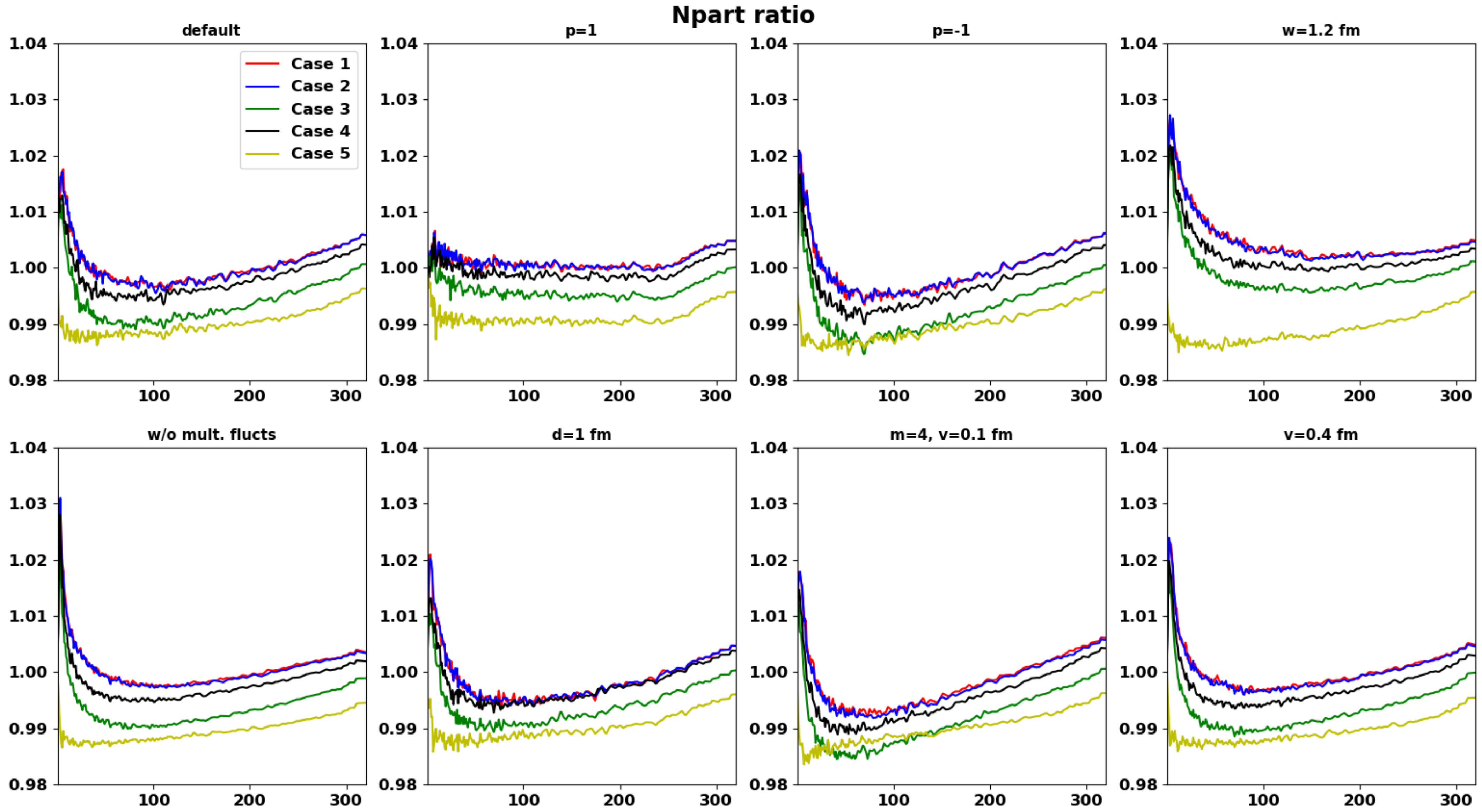
- Different intitial state predictors have varying dendence on nuclear structure parameters (histograms-> a0, …)
- TrenTo parameters have limited influence (``sharpness of QGP‘‘)
- Dependence on TrenTo and nuclear structure parameters carry over to final state multipliciy ratios

-> Which is best set of observables?

Outlook

- Extend parameter scan to more observables/initial state predictors
- Confirm parameter (in)dependence of initial state predictors with hydro simulations for corresponding final state observables

Backup - additional observables



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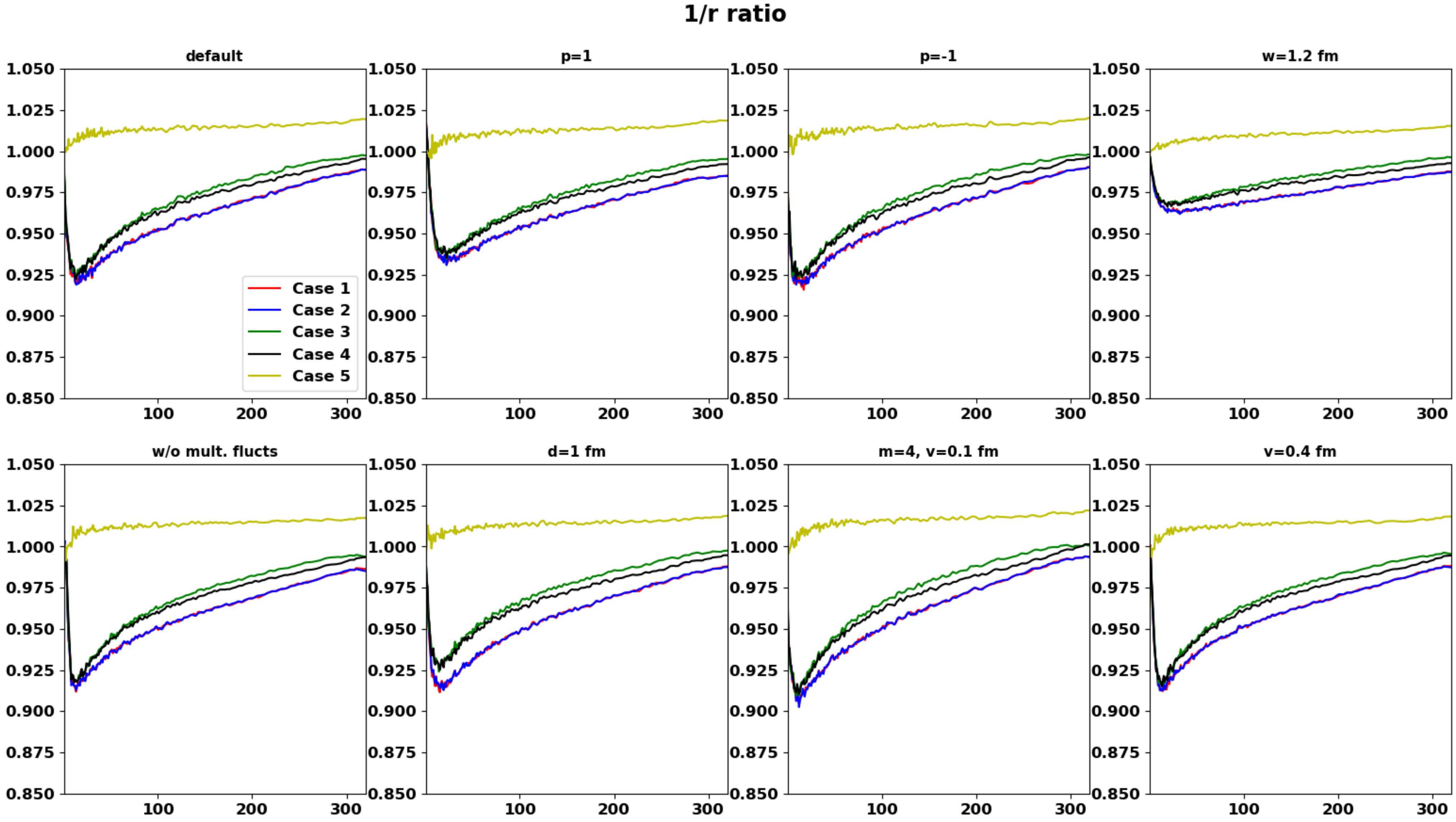

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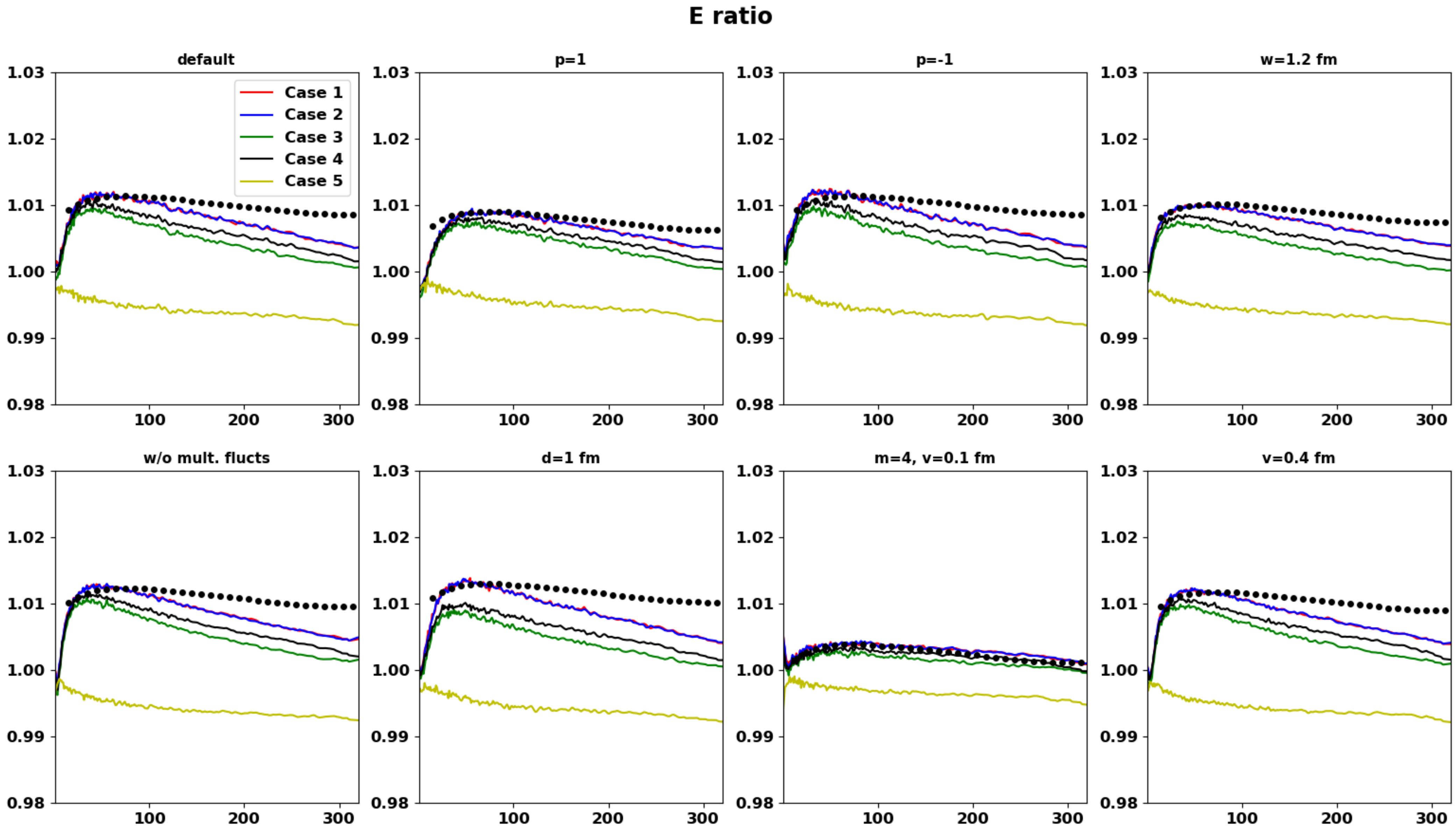

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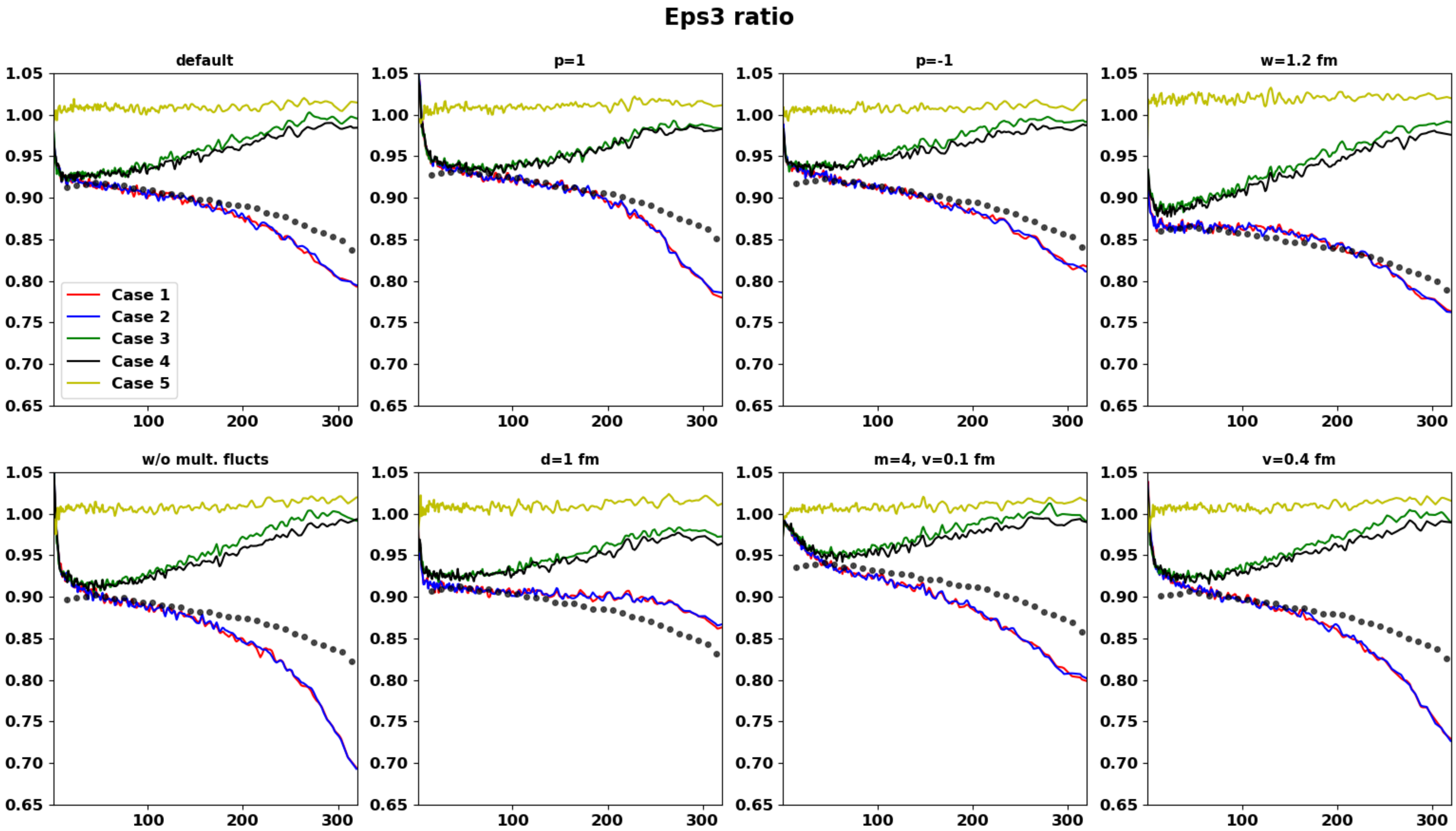

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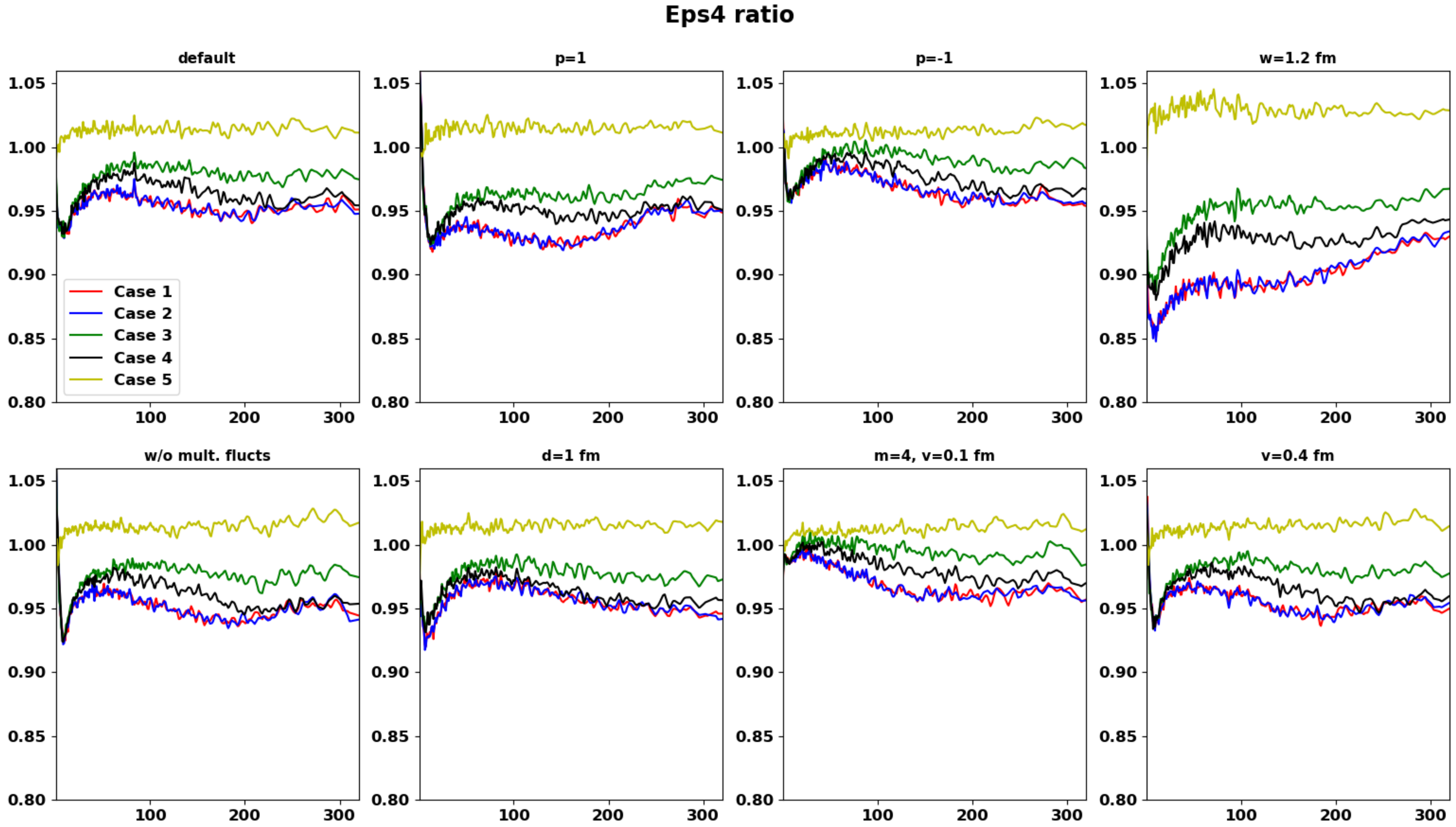

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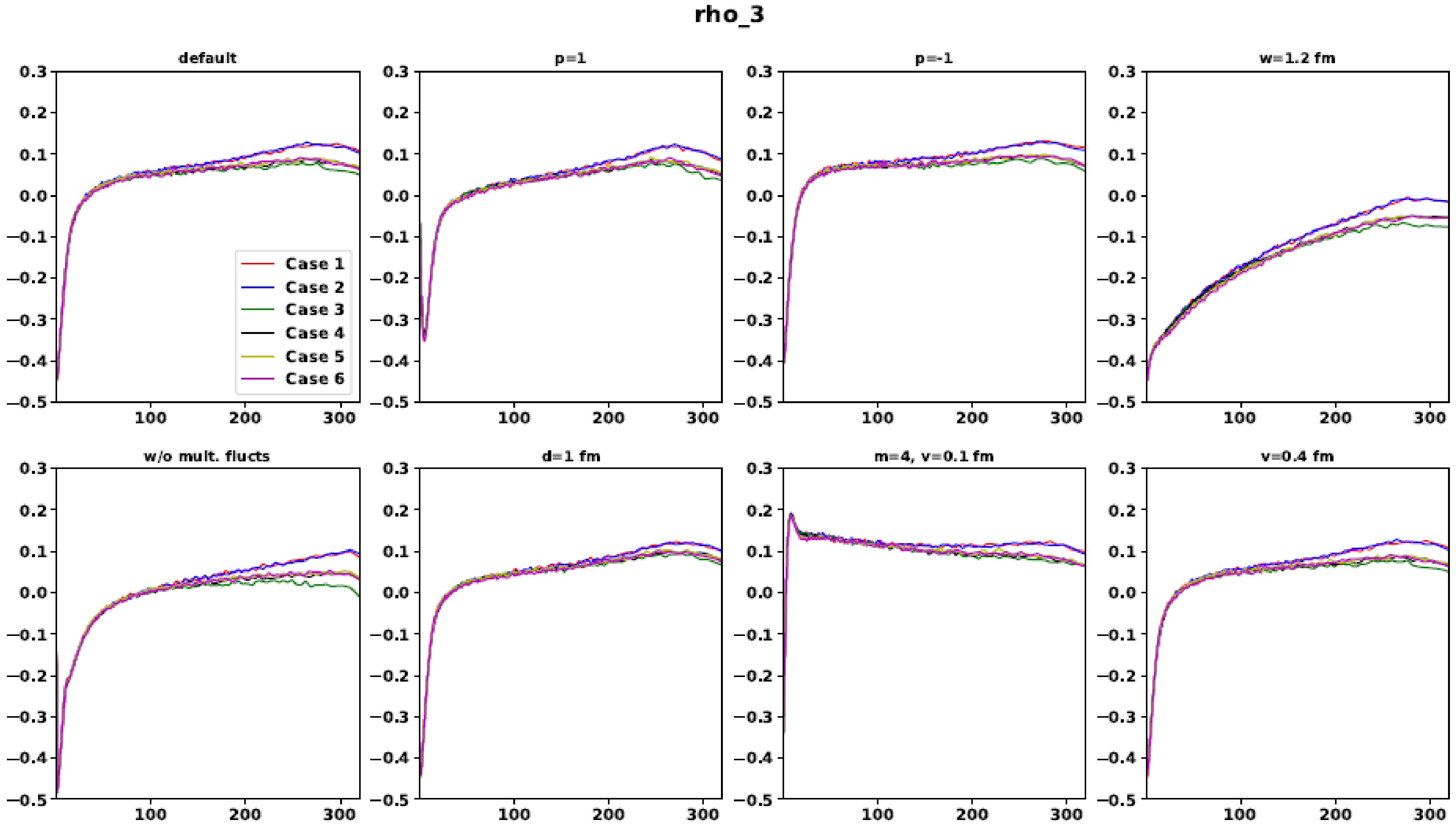

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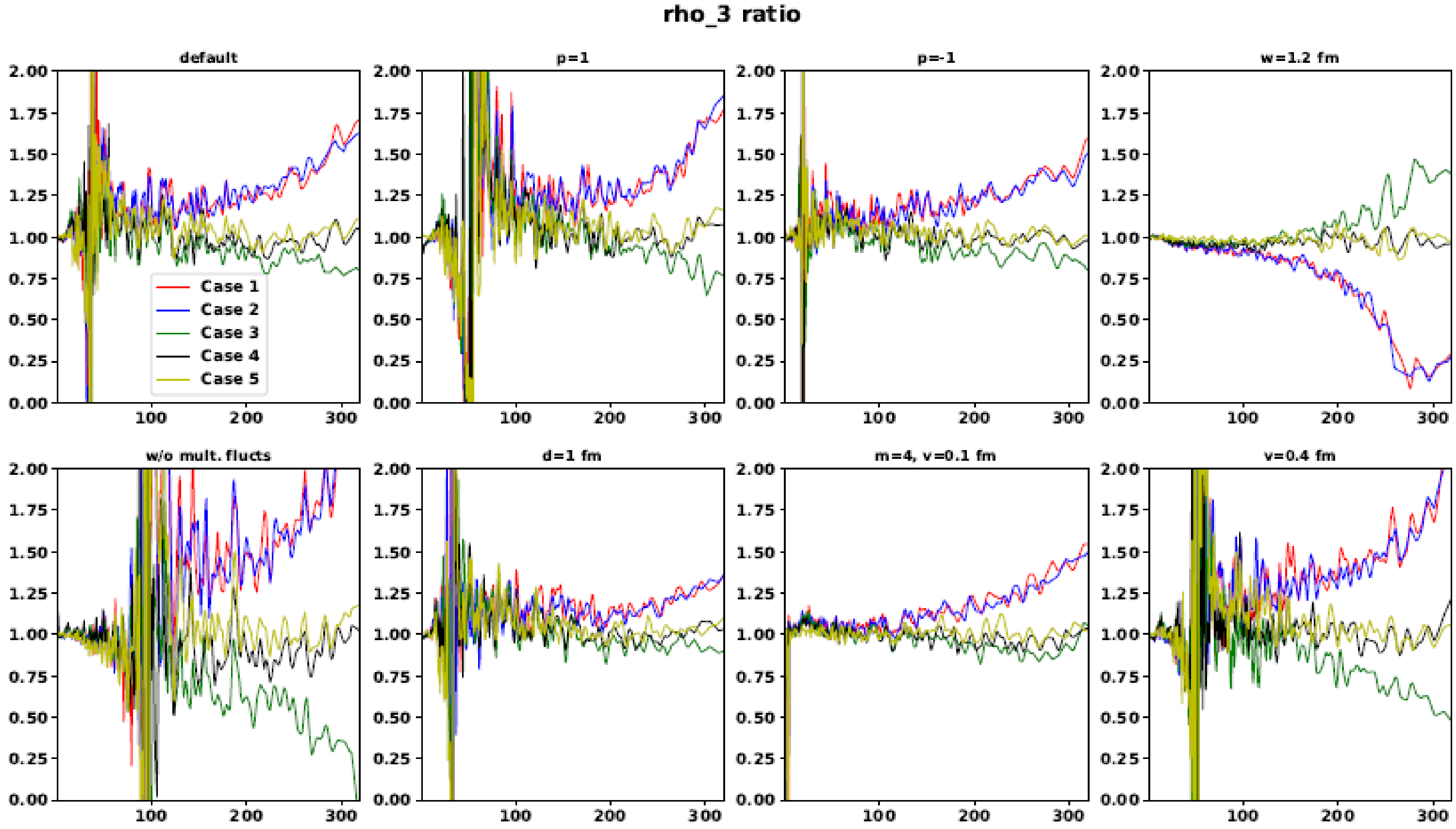

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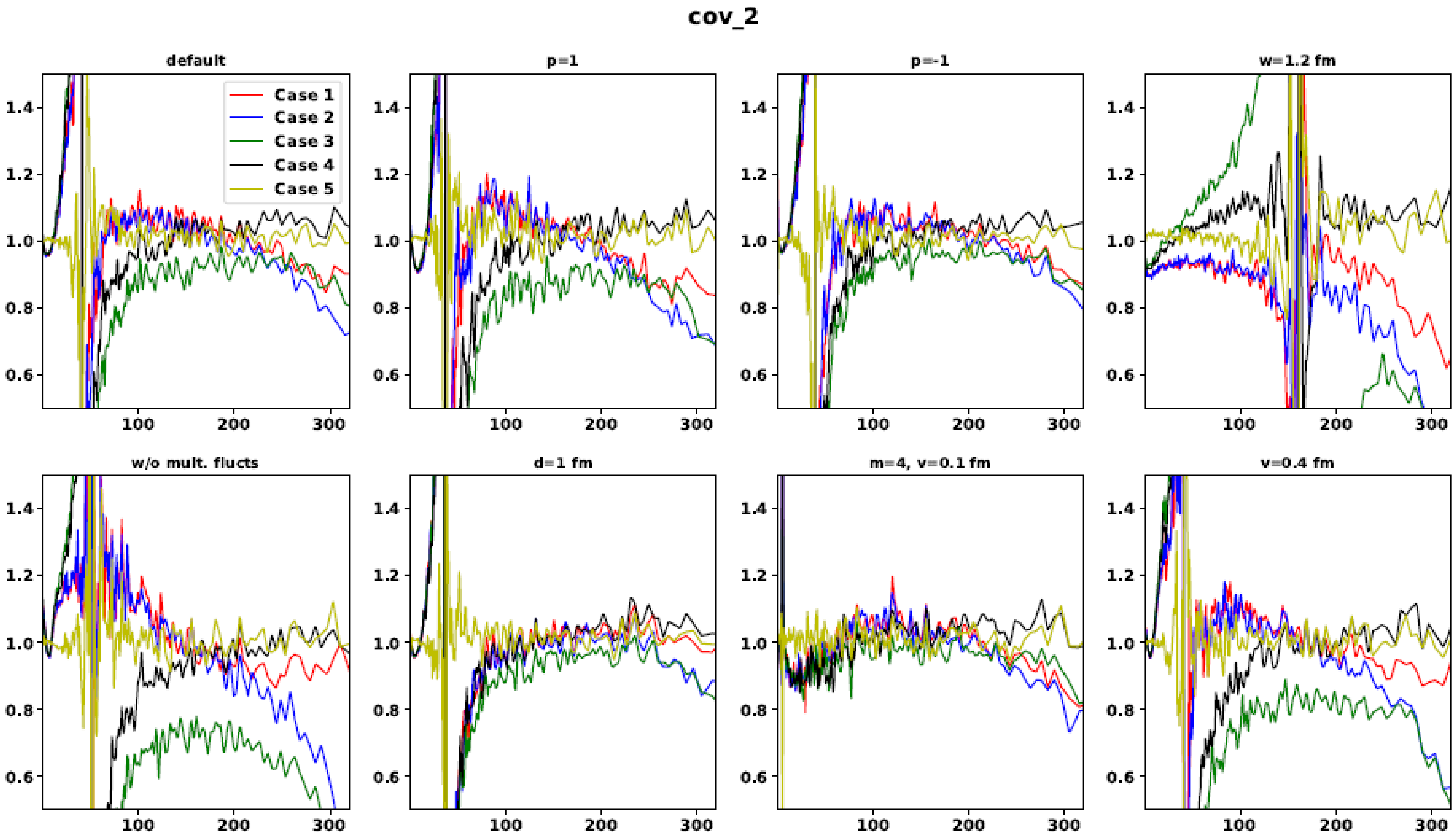
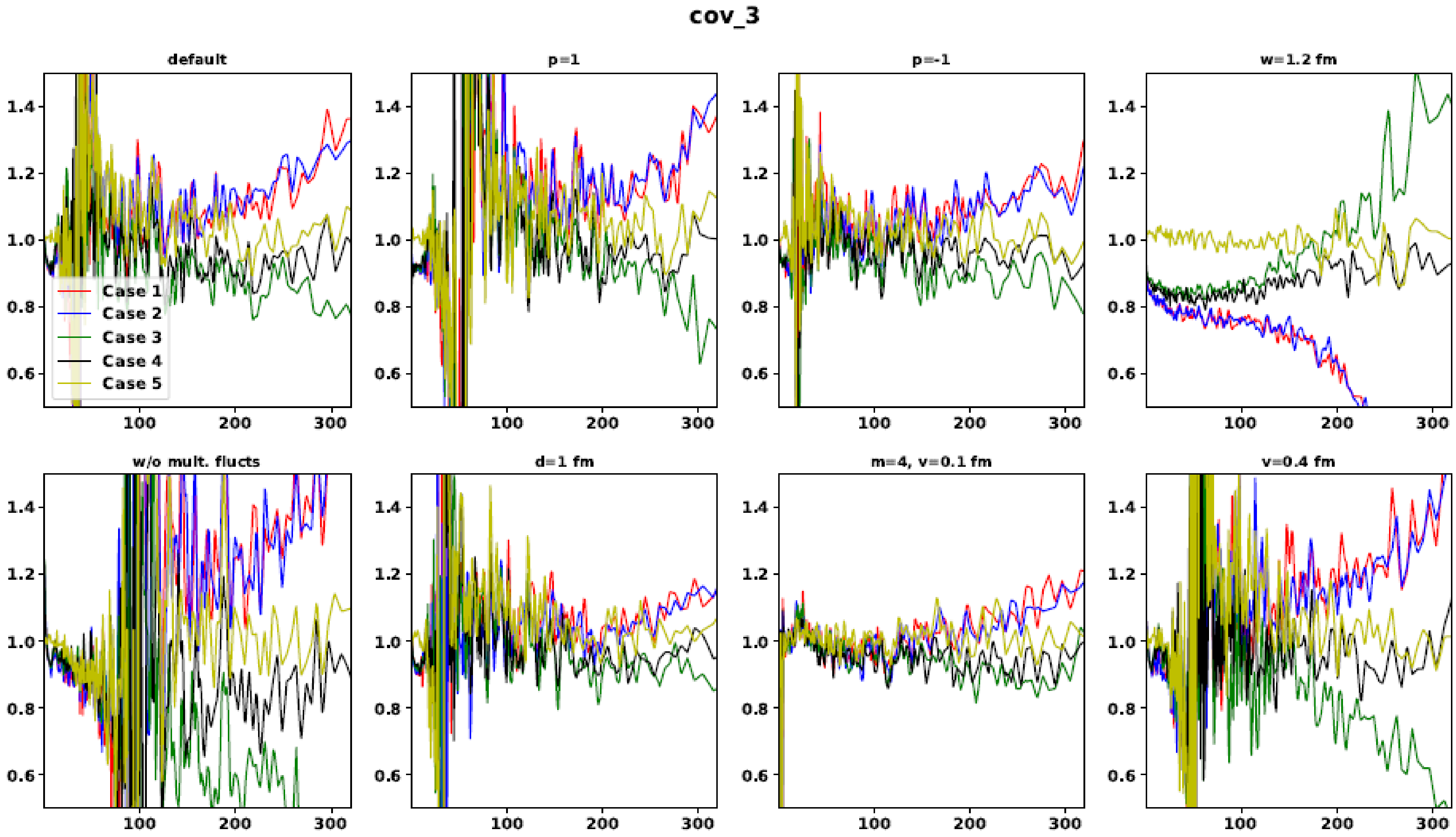
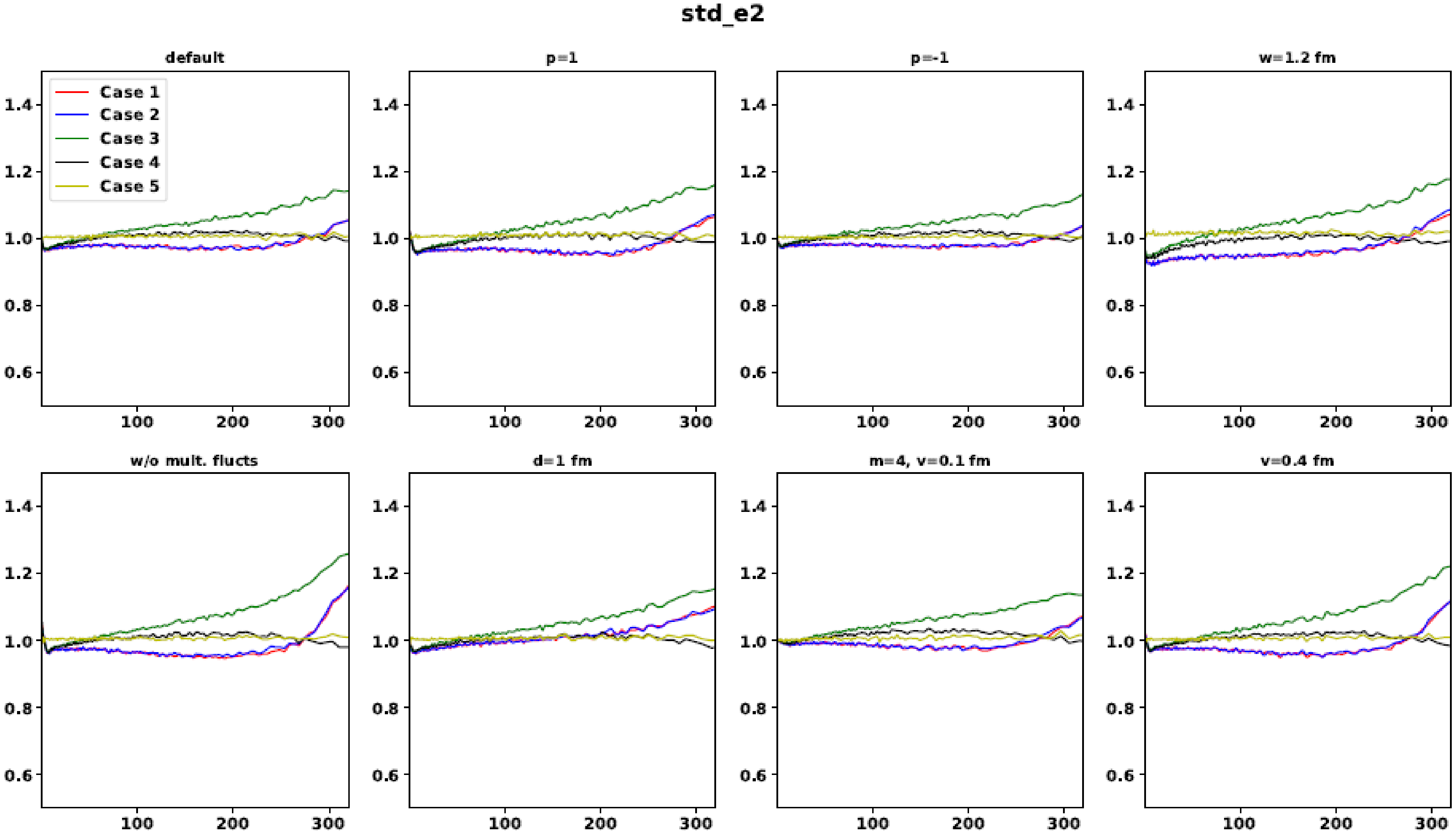


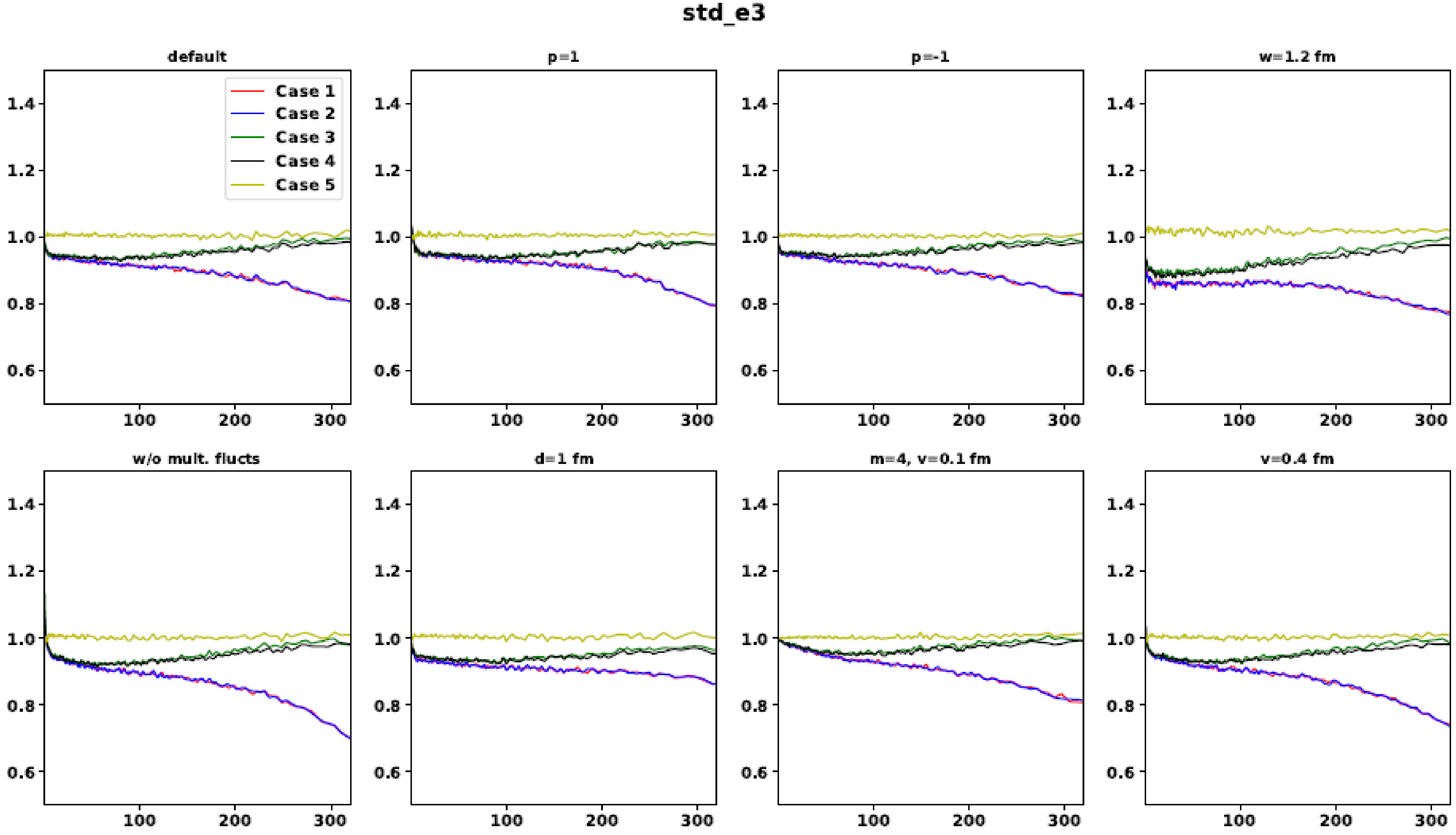
Backup - additional observables



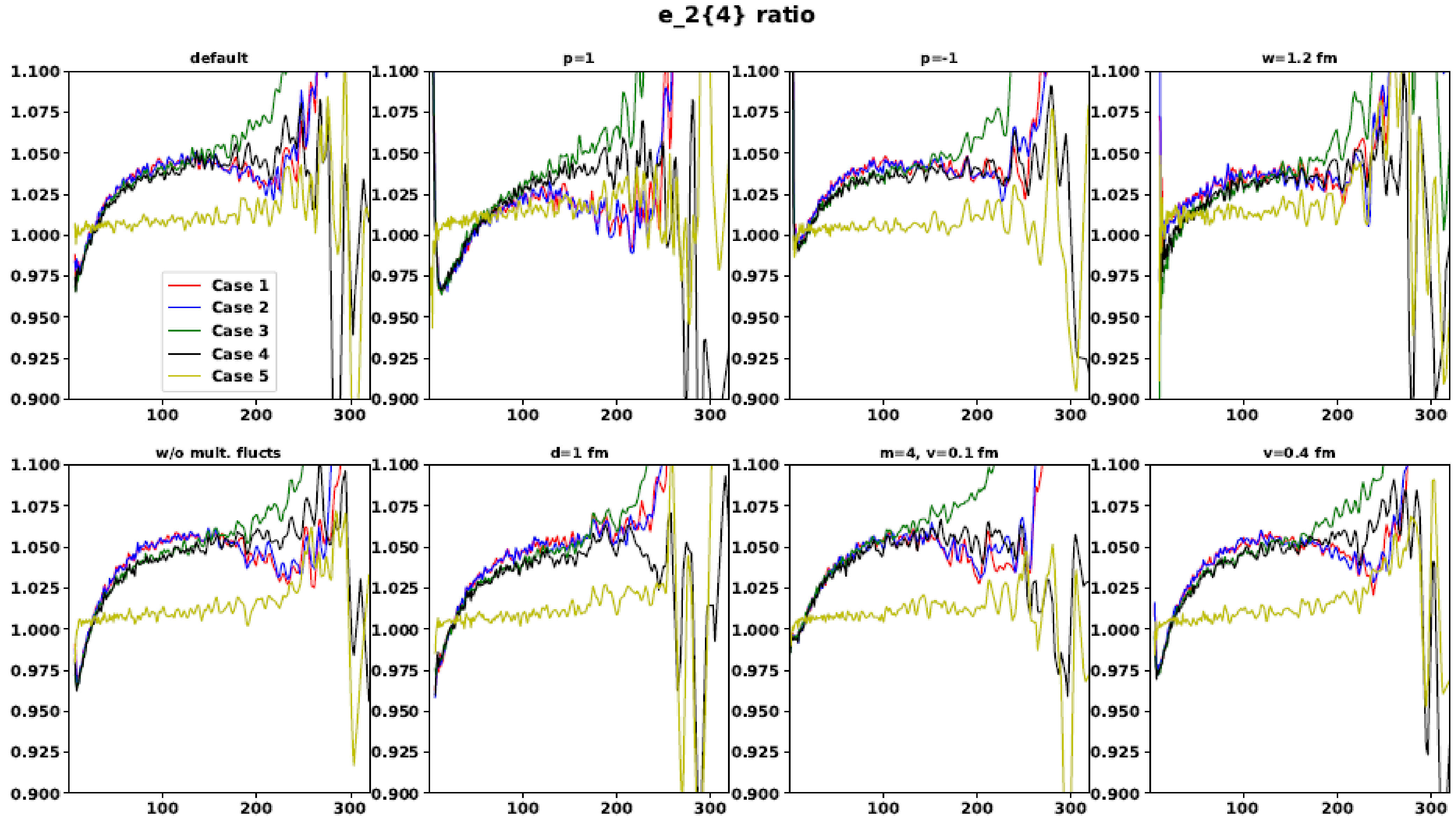
Backup - additional observables



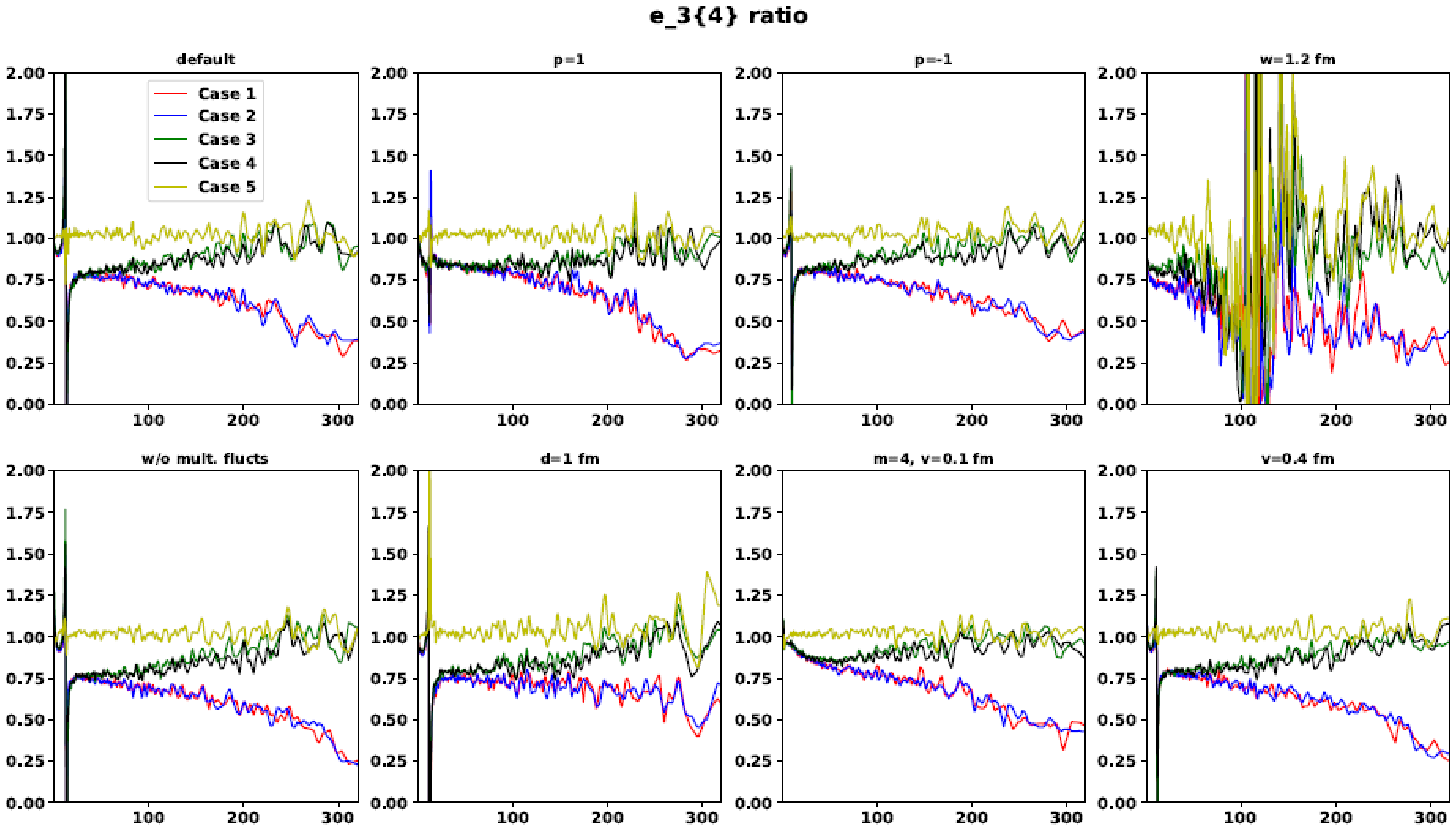
Backup - additional observables



Backup - additional observables

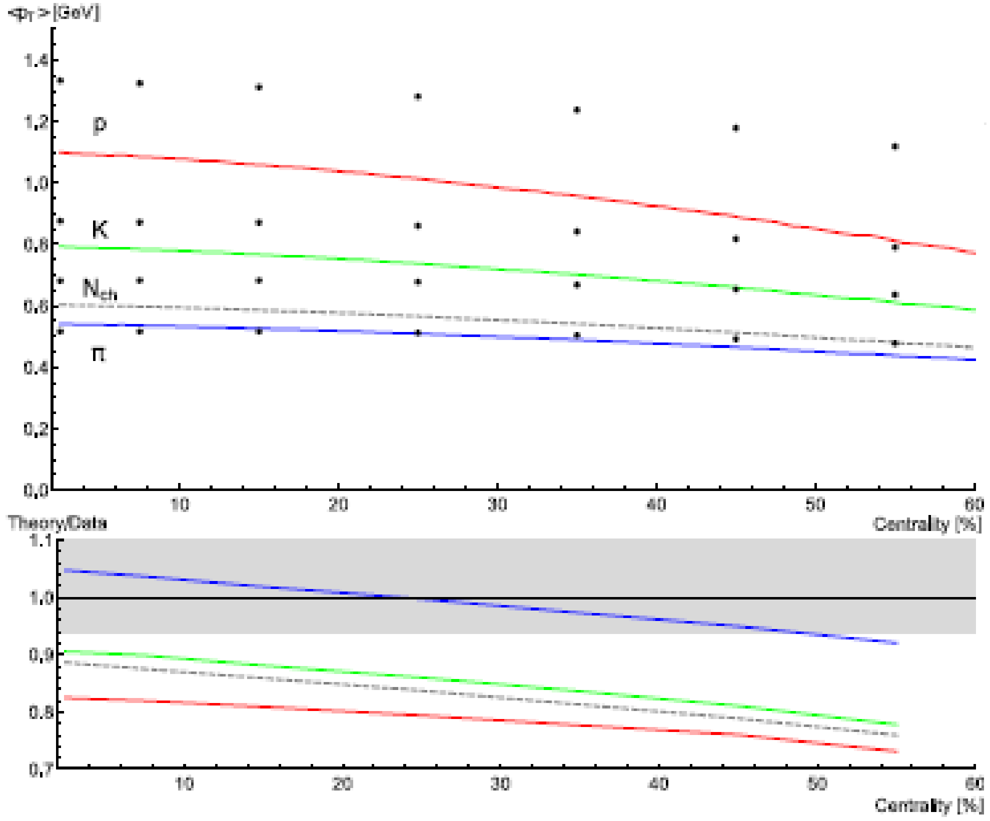


Backup - additional observables

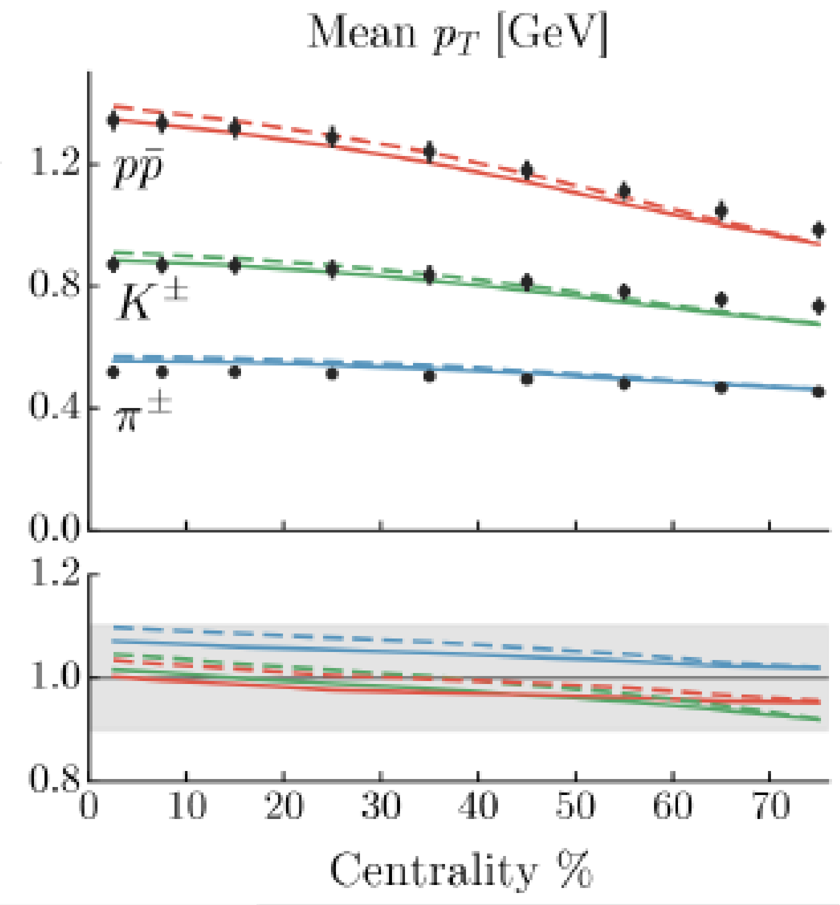


Backup - Validation: Results

FluiduM

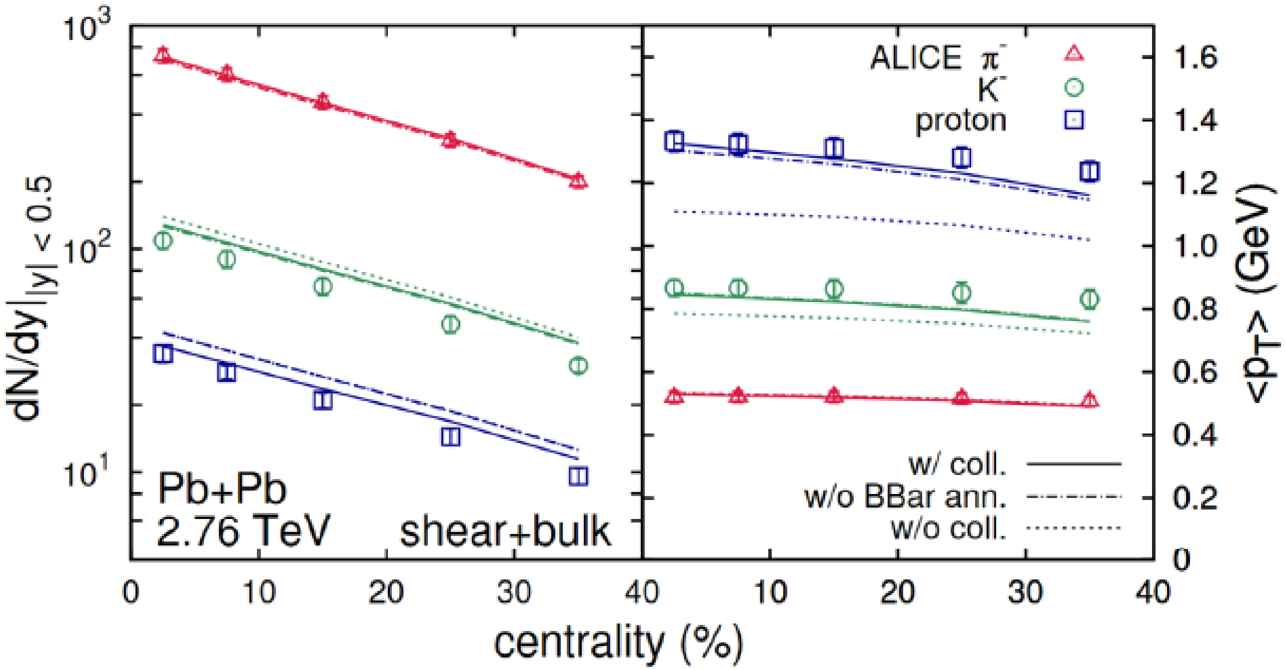


Duke



Backup - Validation: Interpretation

- Same tendencies for spectra as results from Duke group, but to many kaons and protons
- <pT> to small for heavier particles (kaons, protons)
- Both discrepancies ascribable to the UrQMD afterburner implemented in the Duke analysis (absent in FluiduM)



Arxiv: 1704.04216

Backup – Mode-by-mode fluctuations

- Expand event-by-event entropy profiles

$$s(r,\varphi) = \bar{s}(r)(1 + \delta s(r,\varphi))$$

$$a^{(m)}(r) = \sum_l a_l^{(m)} \psi_l^{(m)}(r)$$

$$a^{(m)}(r) = \sum_l a_l^{(m)} \psi_l^{(m)}(r)$$

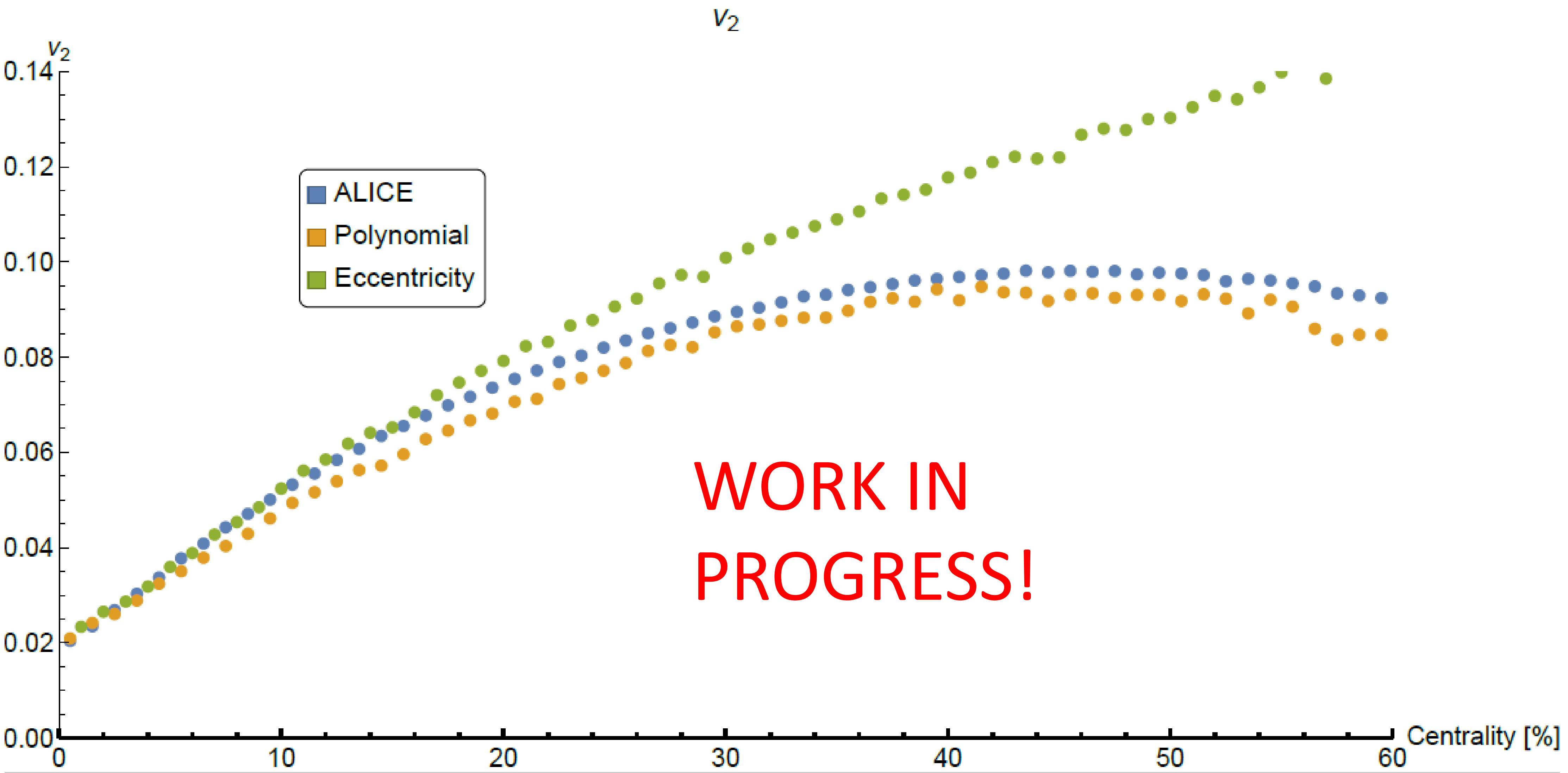
- Choose polynomials as radial basis

$$\psi_l^{(m)}(r) = \sum_{k \leq m} C_{l|k}^{(m)} r^k$$

- Fix first expansion coefficient to eccentricity
- Fluctuations encoded in two-point function
- Flow coefficient given by linear response of two-point function

$$v_n^2 = \tilde{S}^{l_1} < \epsilon_{l_1}^{(n)} \epsilon_{l_2}^{(-n)} > \tilde{S}^{l_2}$$

Backup - preliminary flow coefficients



WORK IN PROGRESS!