Duke
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Hydrodynamic simulations of relativistic nuclear collisions with nucleon substructure:

- combined analysis of p+Pb and Pb+Pb collision systems at 5.02 TeV

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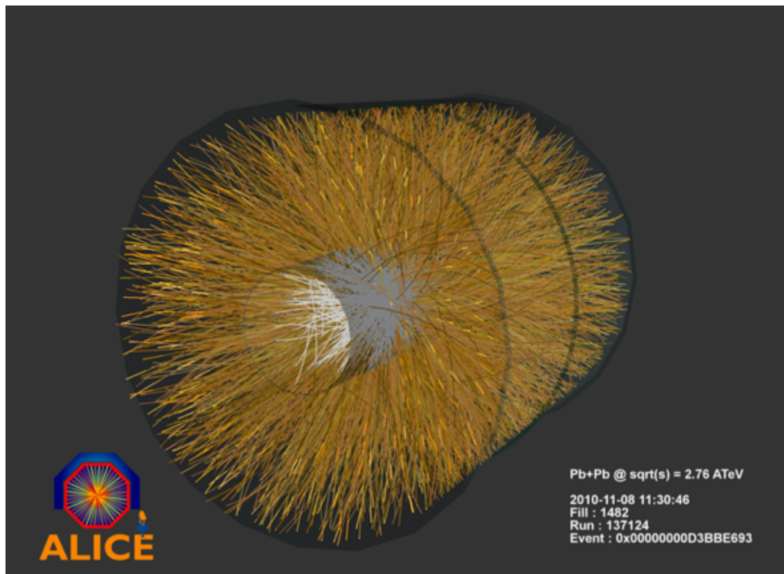
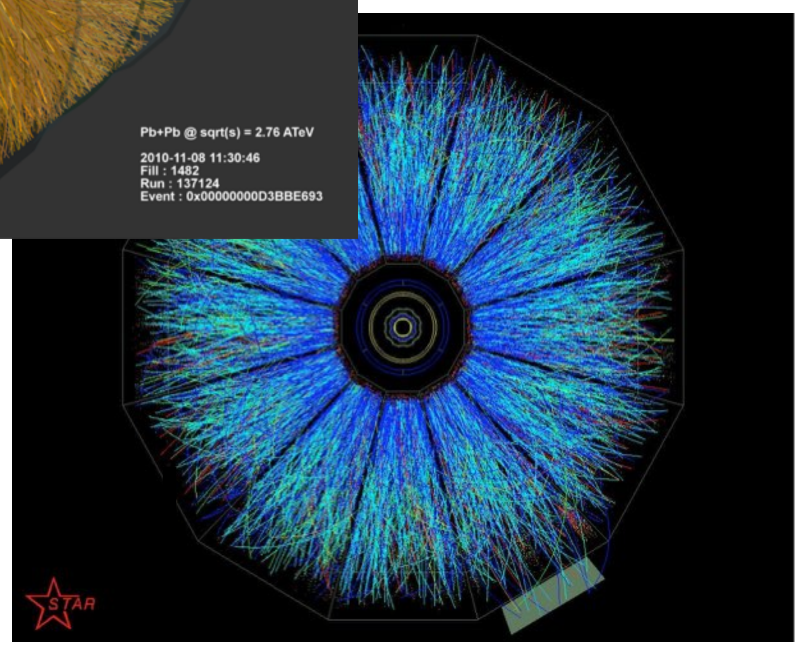
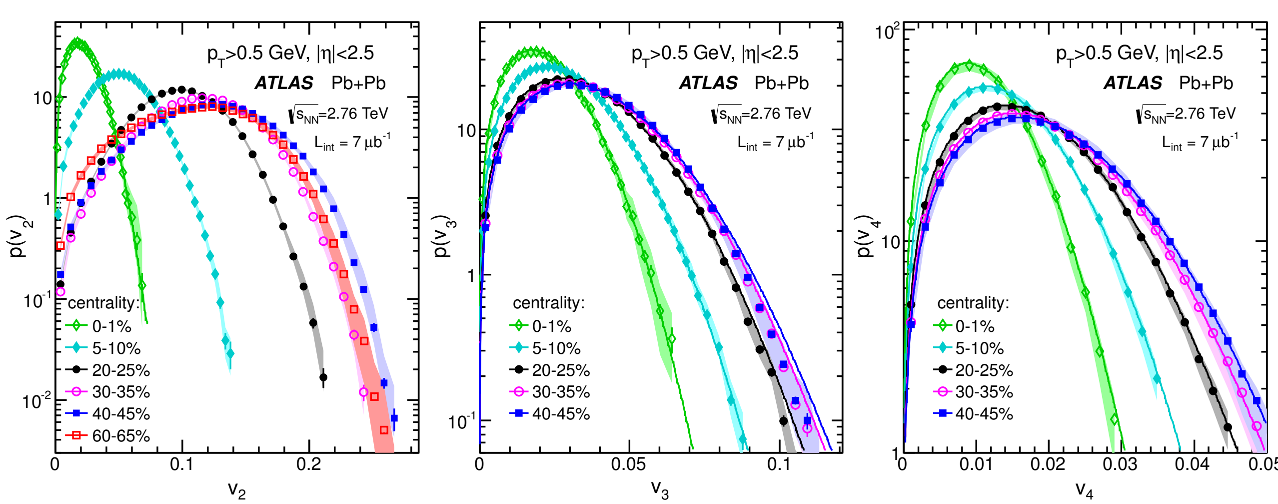
Probing QCD in Heavy-Ion Collisions

Data:

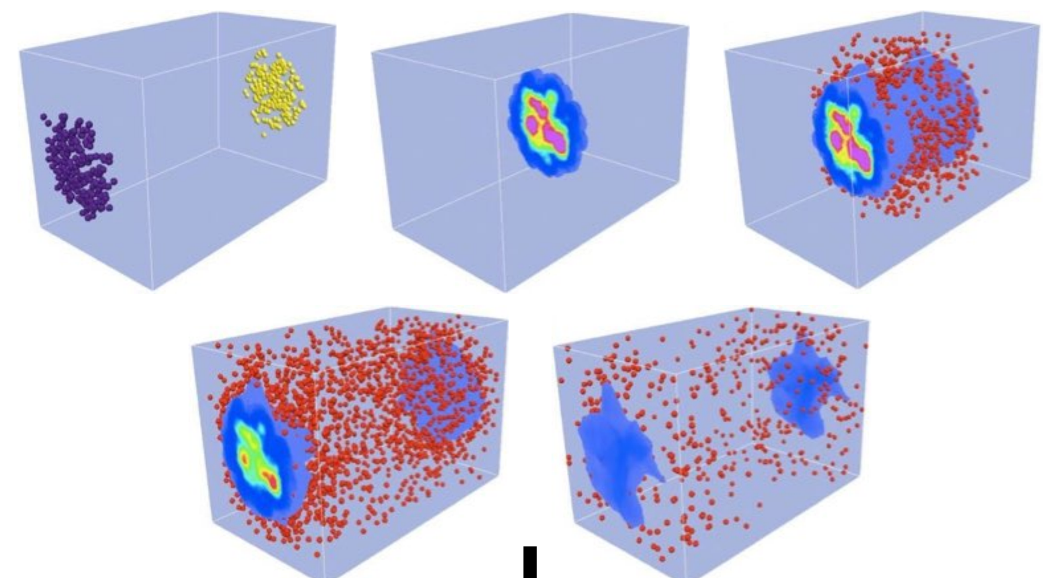


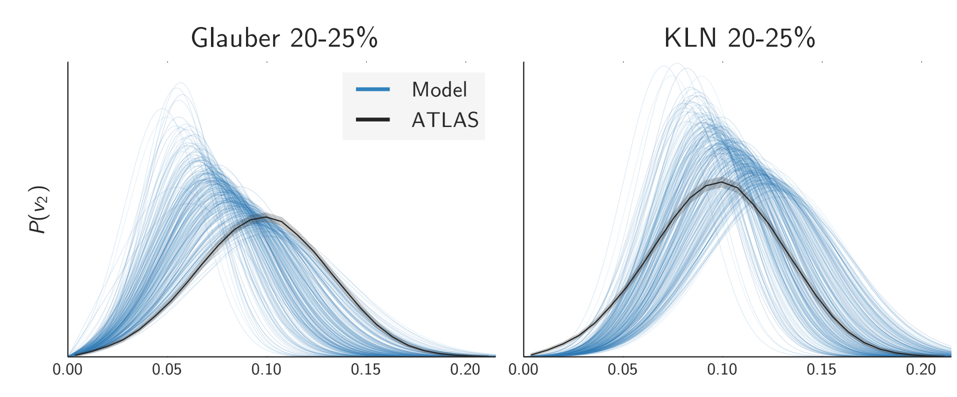




Model:

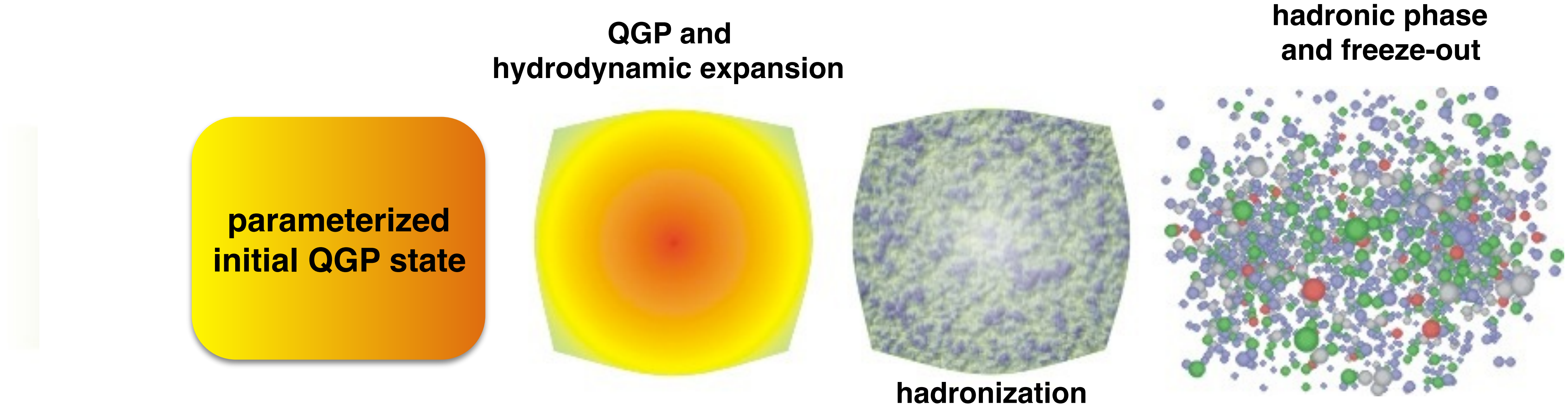
initial conditions, τ_0, η/s, ζ/s, ….





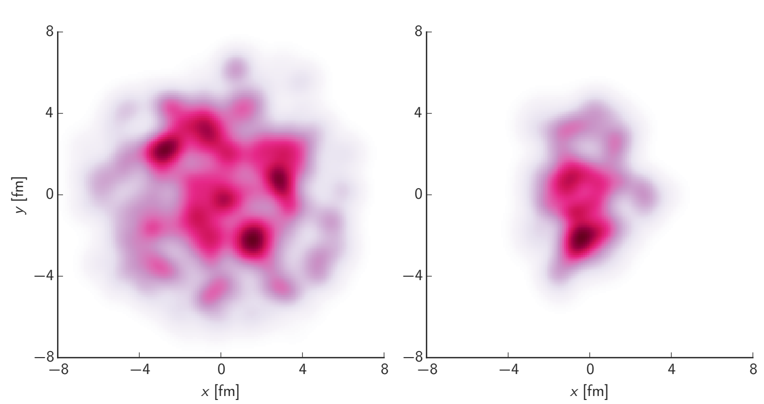
extracted QGP properties: η/s, …

Physics Model: Trento + iEbE-VISHNU



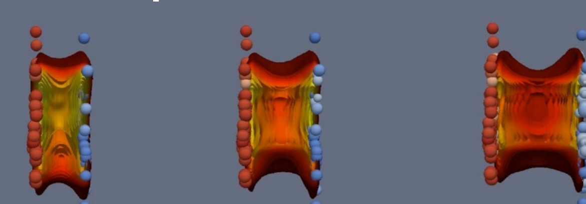
Trento:

- parameterized initial condition model based on phenomenological concepts for entropy deposition to a QGP



iEbE-VISHnew:

- EbE 2+1D viscous RFD
- describes QGP dynamics & hadronization
- EoS from Lattice QCD
- temperature-dependent shear and bulk viscosity as input



UrQMD:

- non-equilibrium evolution of an interacting hadron gas
- hadron gas shear & bulk viscosities are implicitly contained in calculation

Initial Condition Model: Trento

- effective, parametric, description of entropy production prior to thermalization
- based on **reduced thickness* T$_R$** as ansatz for *dS/dy*:

$$dS/dy\,|_{\tau=\tau_0} \propto T_R(p; T_A, T_B) \equiv \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$

- determine participant nucleons in A, B by sampling for each nucleon pair:

$$P_{\text{coll}} = 1 - \exp\left[-\sigma_{gg}\int dx\,dy \int dz\,\rho_A \int dz\,\rho_B\right]$$

Nuclear Thickness*:

$$T_A = \sum_i \gamma_i \int dz\,\rho_{\text{nucleon}}(x - x_i, y - y_i, z - z_i)$$

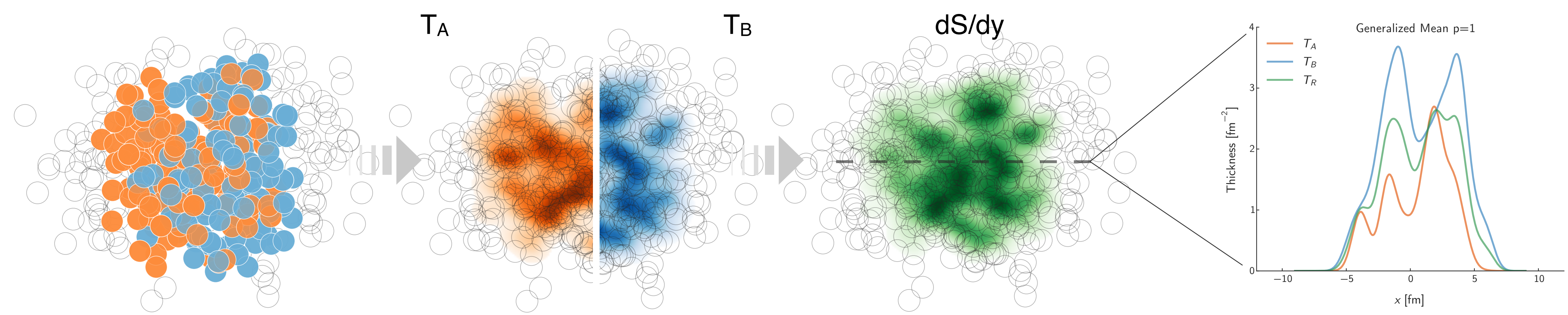
- sum is over participant nucleons with positions sampled from an uncorrelated Woods-Saxon distribution or correlated nuclear configurations when available
- introduce fluctuations via γ_i, sampled from a gamma distribution with unit mean:

$$P_k(\gamma) = \frac{k^k}{\Gamma(k)}\gamma^{k-1}e^{-k\gamma}$$

- nucleon density ρ_{nucleon} modeled as Gaussian in transverse plane

$$\int dz\,\rho_{\text{proton}} = \frac{1}{2\pi w^2}\exp\left(-\frac{x^2+y^2}{2w^2}\right)$$

(1) determine participants: **(2) construct thickness functions:** **(3) calculate entropy deposition:**



Bayesian Analysis

Each computational model relies on a set of physics parameters to describe the dynamics and properties of the system. These physics parameters act as a representation of the information we wish to extract from RHIC & LHC.

Model Parameters - System Properties

- initial state
- temperature-dependent viscosities
- hydro to micro switching temperature

estimate or calculate parameters

Physics Model:

- Trento
- iEbE-VISHNU

calculate observables & compare to data

Experimental Data

- ALICE flow & spectra

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Model Parameters - System Properties
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Bayesian analysis

Physics Model:
- Trento
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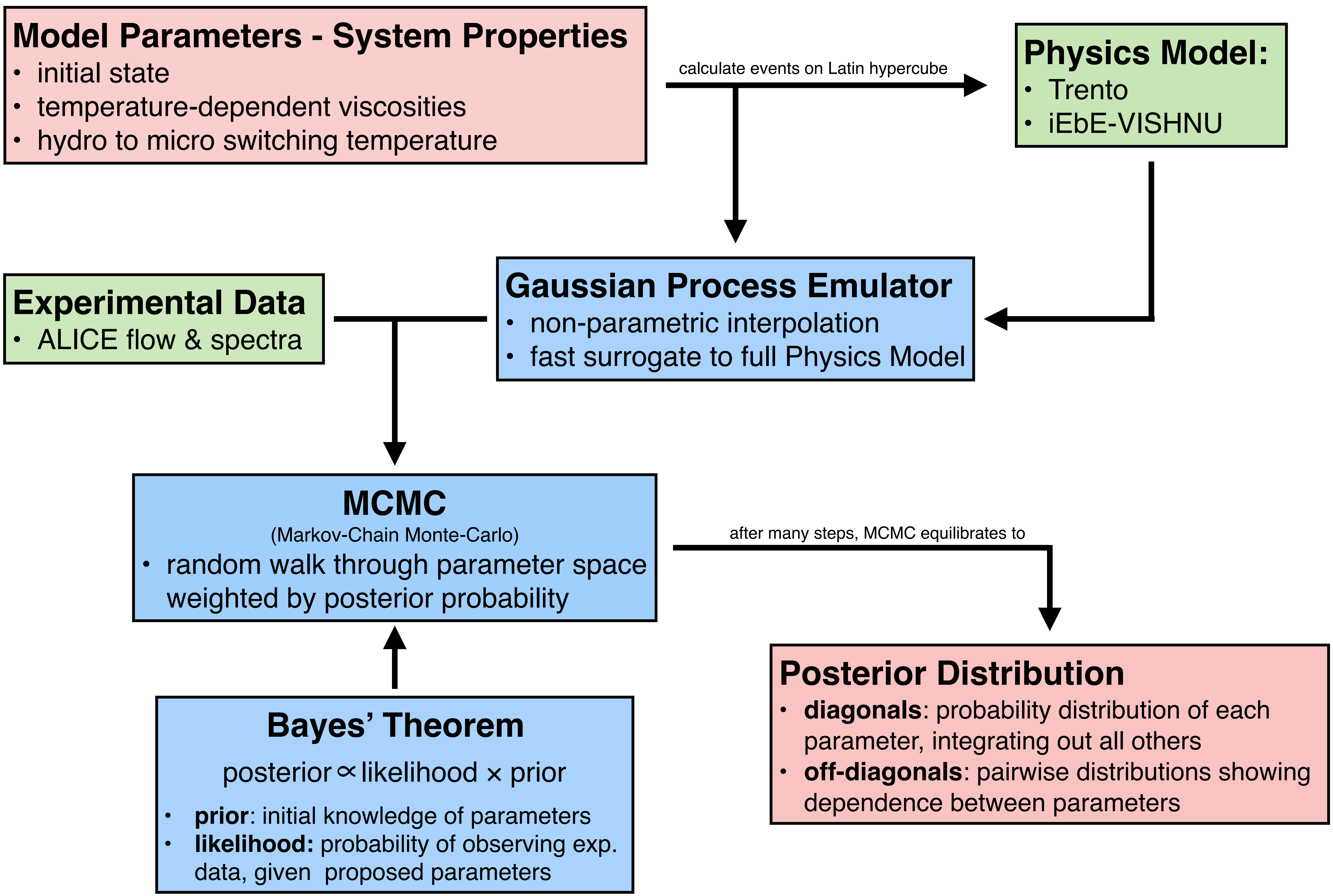
Experimental Data
- ALICE flow & spectra

- Bayesian analysis allows us to simultaneously calibrate all model parameters via a model-to-data comparison
- determine parameter values such that the model best describes experimental observables
- extract the probability distributions of all parameters

Setup of a Bayesian Statistical Analysis

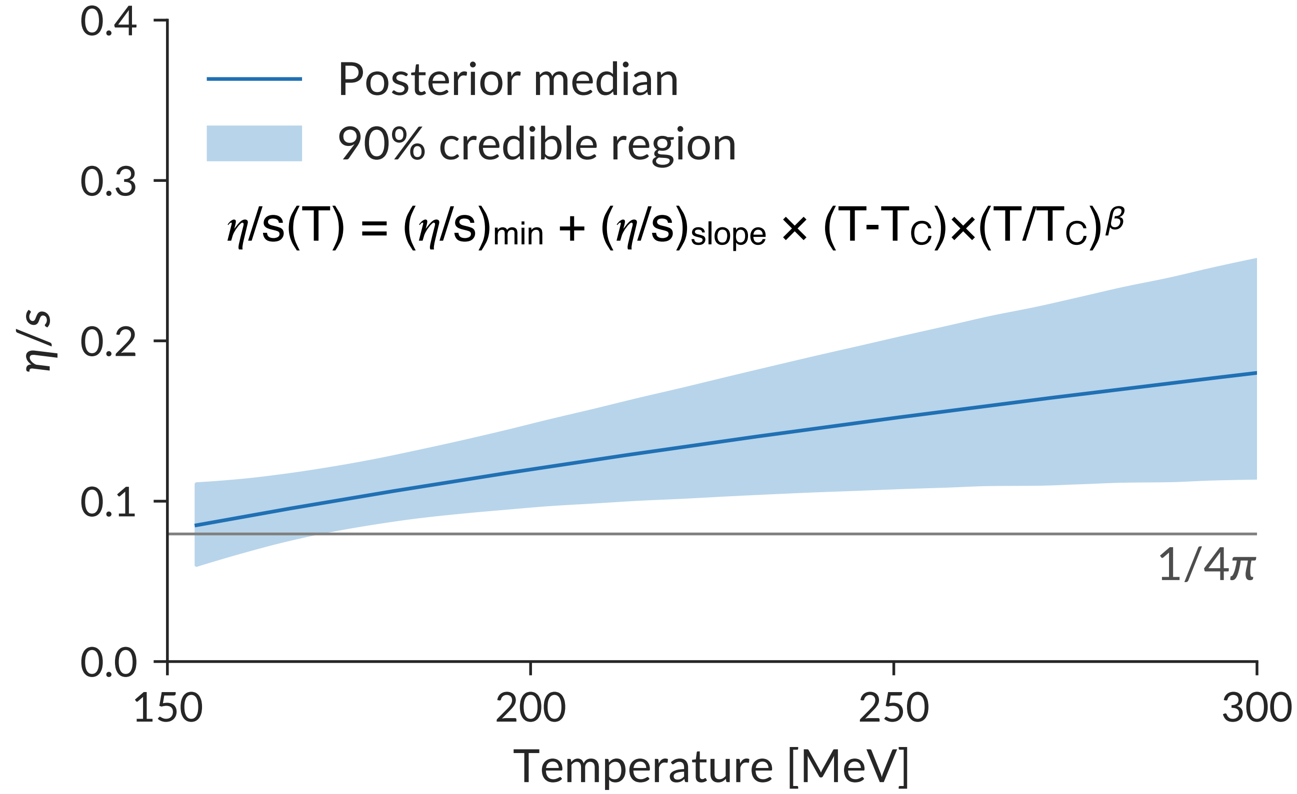


Previous Results: Temperature Dependence of Viscosities

temperature dependent shear viscosity:

- analysis favors small value and shallow rise
- results do not fully constrain temperature dependence:
  - inverse correlation between $(\eta/s)_{slope}$ slope and intercept $(\eta/s)_{min}$
  - insufficient data to obtain sharply peaked likelihood distributions for $(\eta/s)_{slope}$ and curvature β independently
- current analysis most sensitive to T< 0.23 GeV

▸ **RHIC data may disambiguate further**

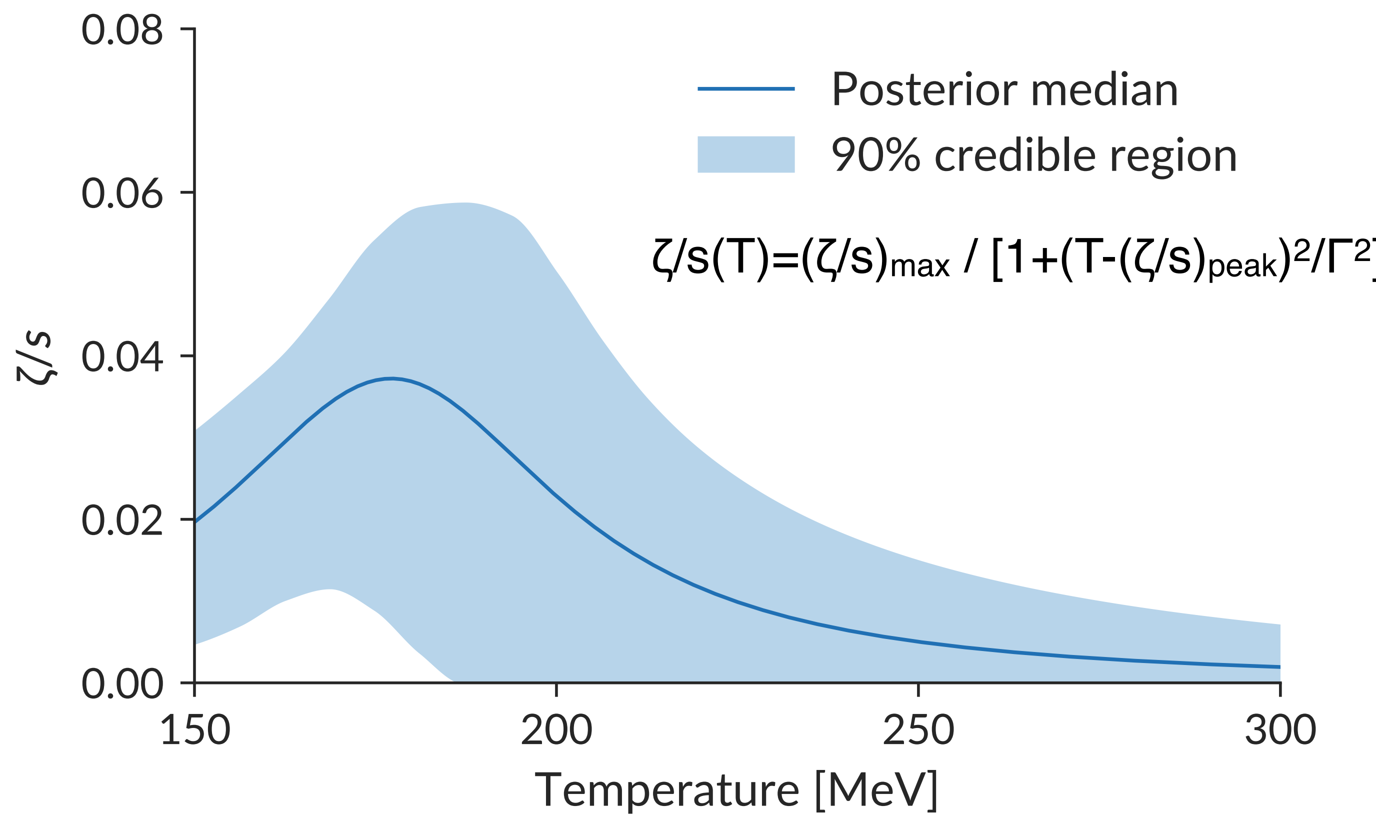


temperature dependent bulk viscosity:

- setup of analysis allows for vanishing value of bulk viscosity
- significant non-zero value near T_C favored, confirming the presence / need for bulk viscosity

caveat of current analysis:

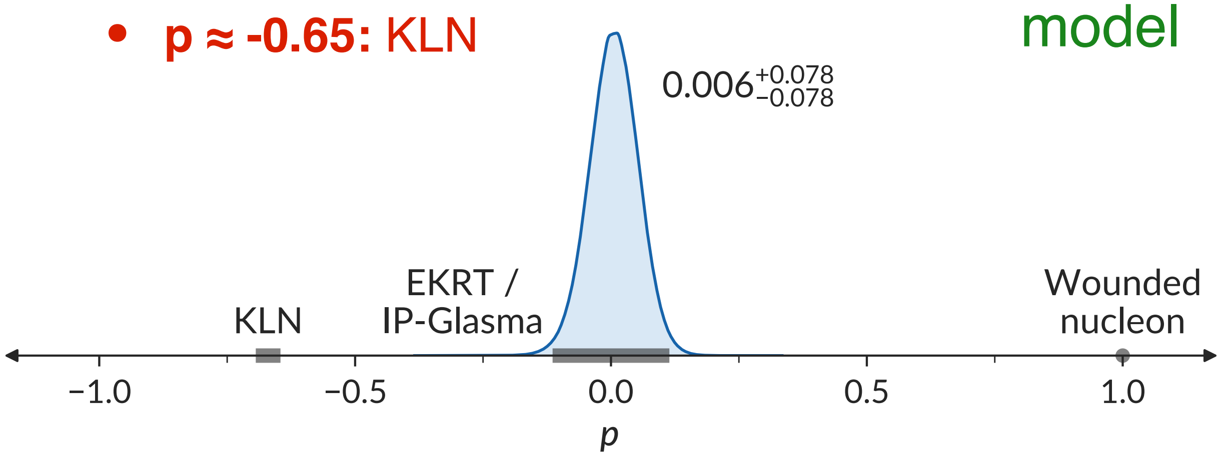
- bulk-viscous corrections are implemented using relaxation-time approximation & regulated to prevent negative particle densities



Constraining the Initial State

p quantifies the attenuation of entropy production in the off-diagonal regions of dS/dy ∝ $T_R(p;T_A,T_B)$:

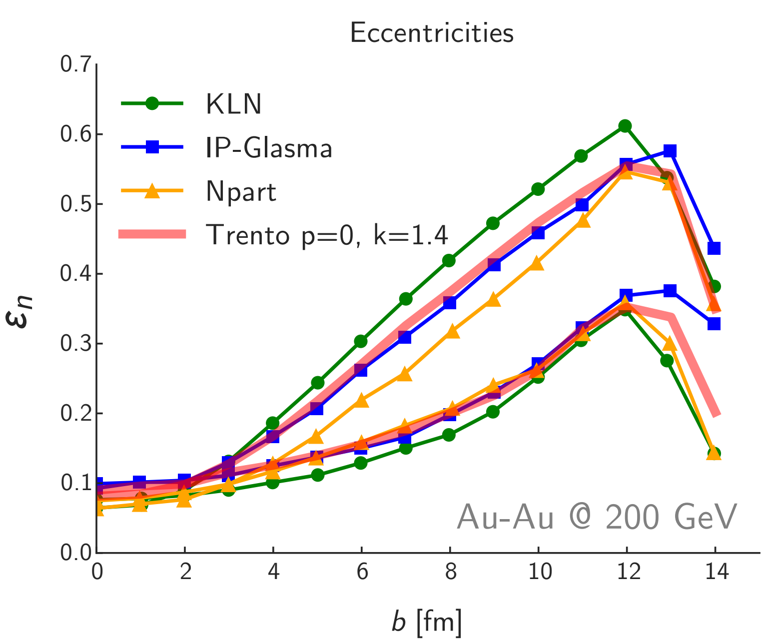
- **-1 < p < 0**: features seen in saturation models:
  - **p = 0:** IP-Glasma & EKRT
  - **p ≈ -0.65:** KLN
- **p=1**: wounded nucleon model

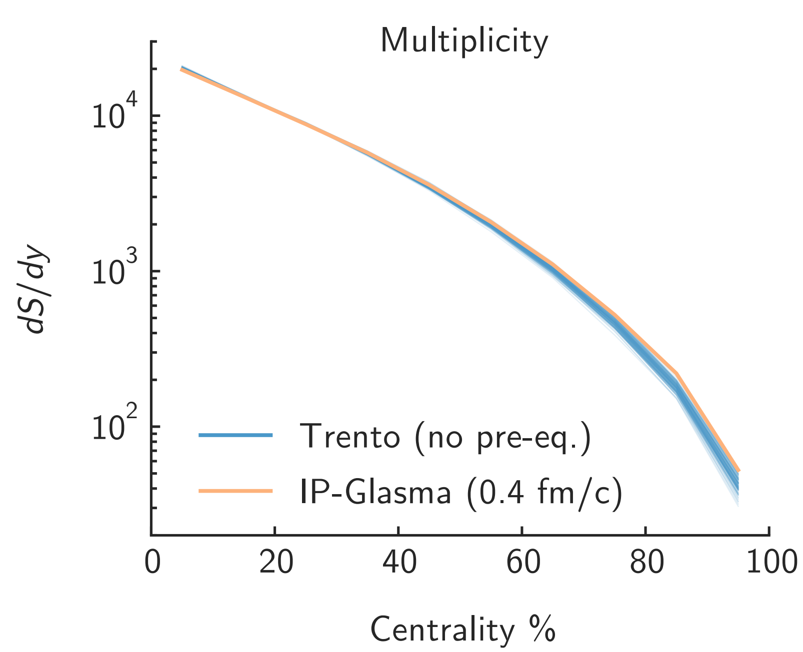


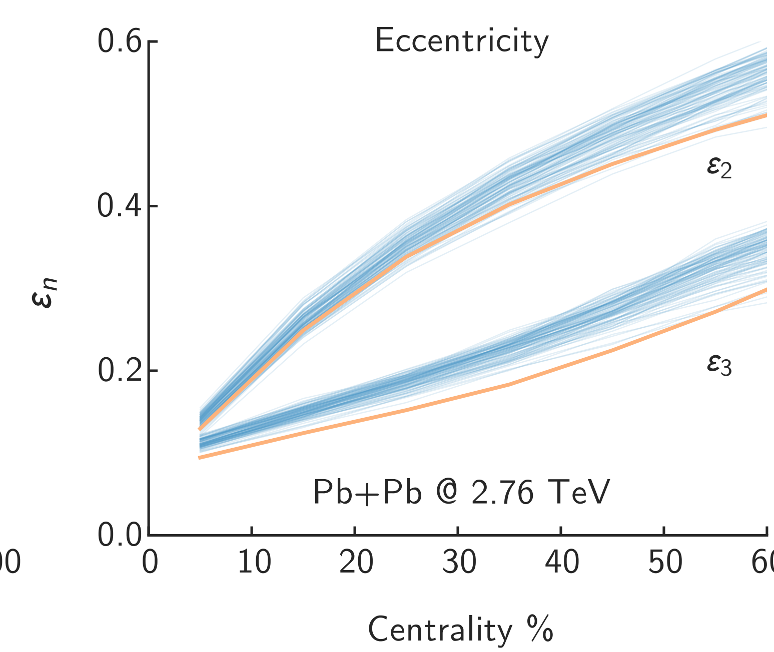
- ▸ **analysis strongly favors eccentricity scaling and entropy deposition seen in the EKRT & IP-Glasma models**
- ▸ **wounded nucleon and KLN models disfavored**
- ▸ **no conclusion yet on 2 component WN+BC model**
- **still need to corroborate scale of fluctuations being probed**

Trento vs. IP-Glasma:

note: no pre-equilibrium flow in the current Trento analysis, may account for larger ε_n



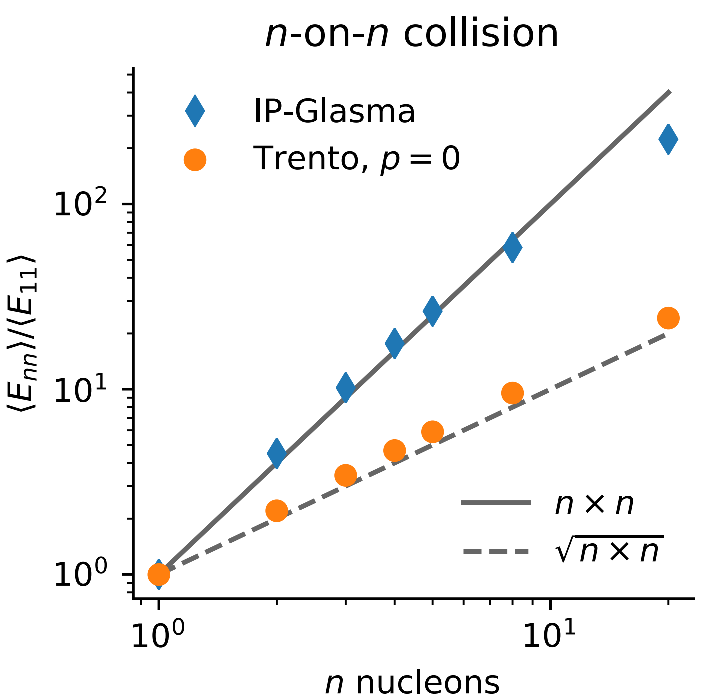


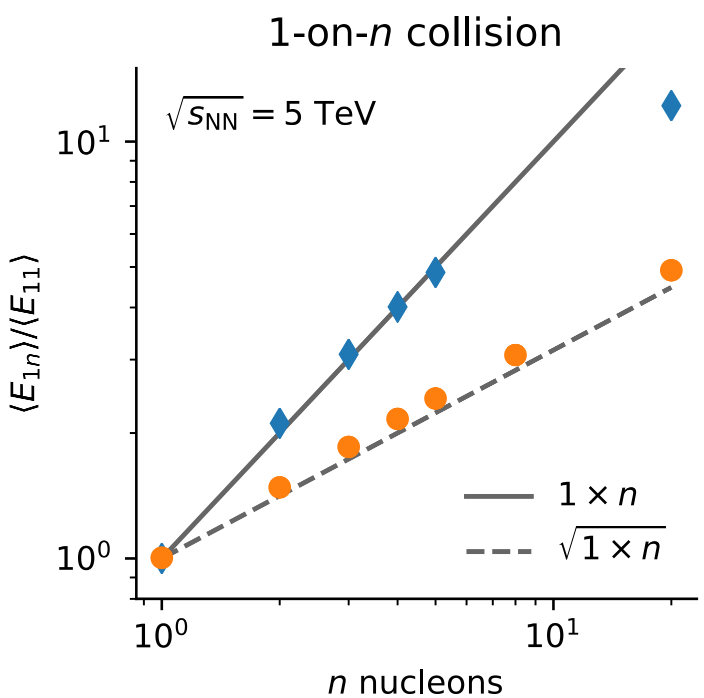


Beware: Trento ≠ IP-Glasma

Rail car test:

- nucleons are lined up in a 1D configuration, e.g. m projectile and n target nucleons (c.f. rail cars)
- choose a standard width for nucleons
- all nucleons will collide inelastically
- assume CM energy of 5.02 TeV
- let E_{mn} be the average total energy deposited within $|\eta|<0.5$ for m nucleons colliding with n nucleons
- evaluate E_{nn}/E_{11} and E_{1n}/E_{11}:





▸ test shows the following scaling for energy deposition:

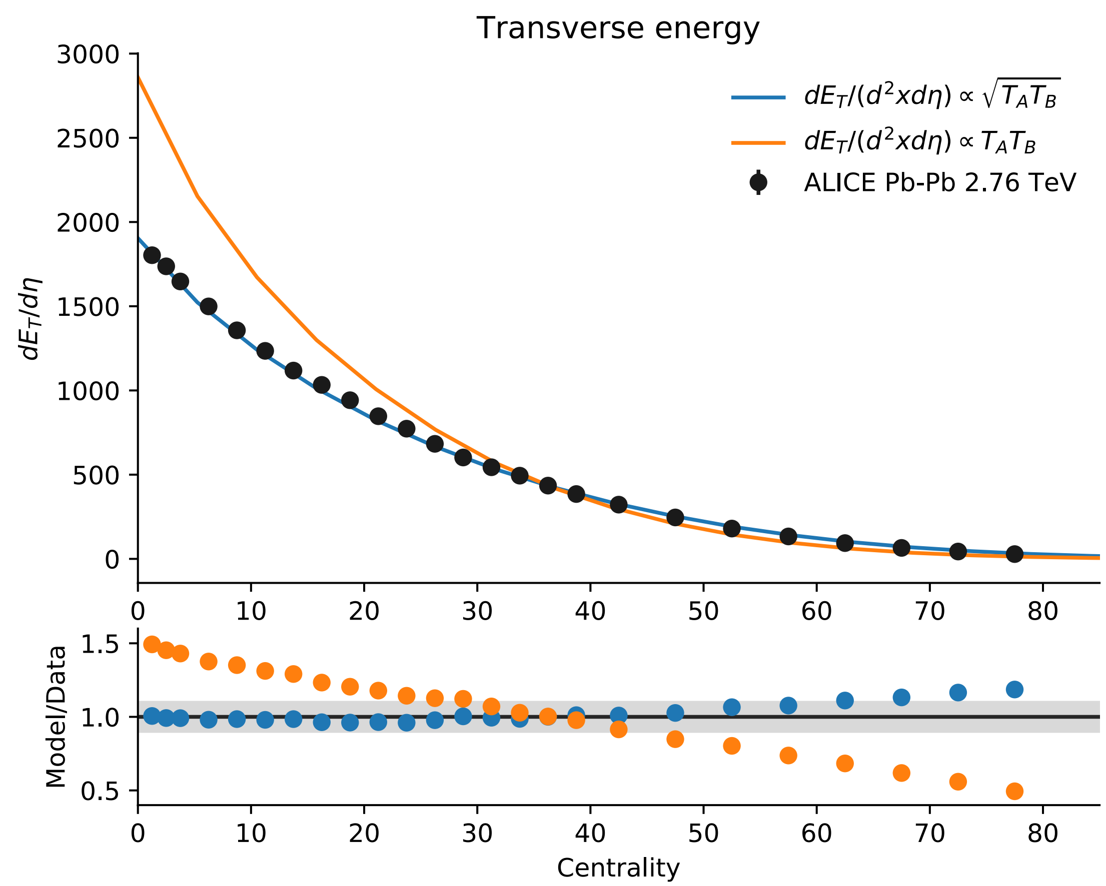
IP-Glasma: $T_A T_B$

Trento: $\sqrt{T_A T_B}$

(for n>10, IP-Glasma saturates, so scaling may not apply for ultra-central collisions)

E_T scaling as differentiator

- Trento analysis shows a significant sensitivity of the centrality dependence of E_T on the type of T_A-T_B scaling:



Note that the above analysis uses Trento's method for centrality determination (Glauber cross sections). Other IC models (e.g. IP-Glasma) calculate centrality differently, which may affect the E_T scaling.
A consistent centrality determination among all IC models would resolve this ambiguity

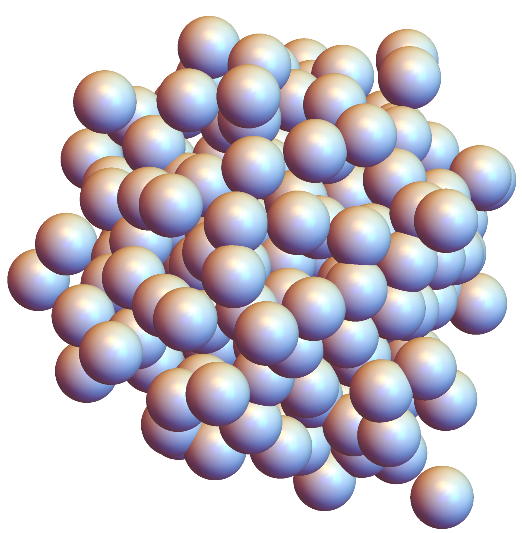
Nucleon Substructure

Nucleon Substructure

Original Trento model:

- sample nucleon positions from spherical or deformed Woods-Saxon distributions
- solid angles resampled to preserve minimum distance d_{min}
- Gaussian nucleons of width w
- works very well for large nuclei

^{208}Pb nucleus

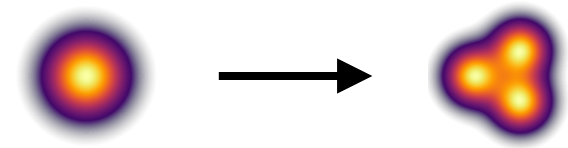


Caveat:

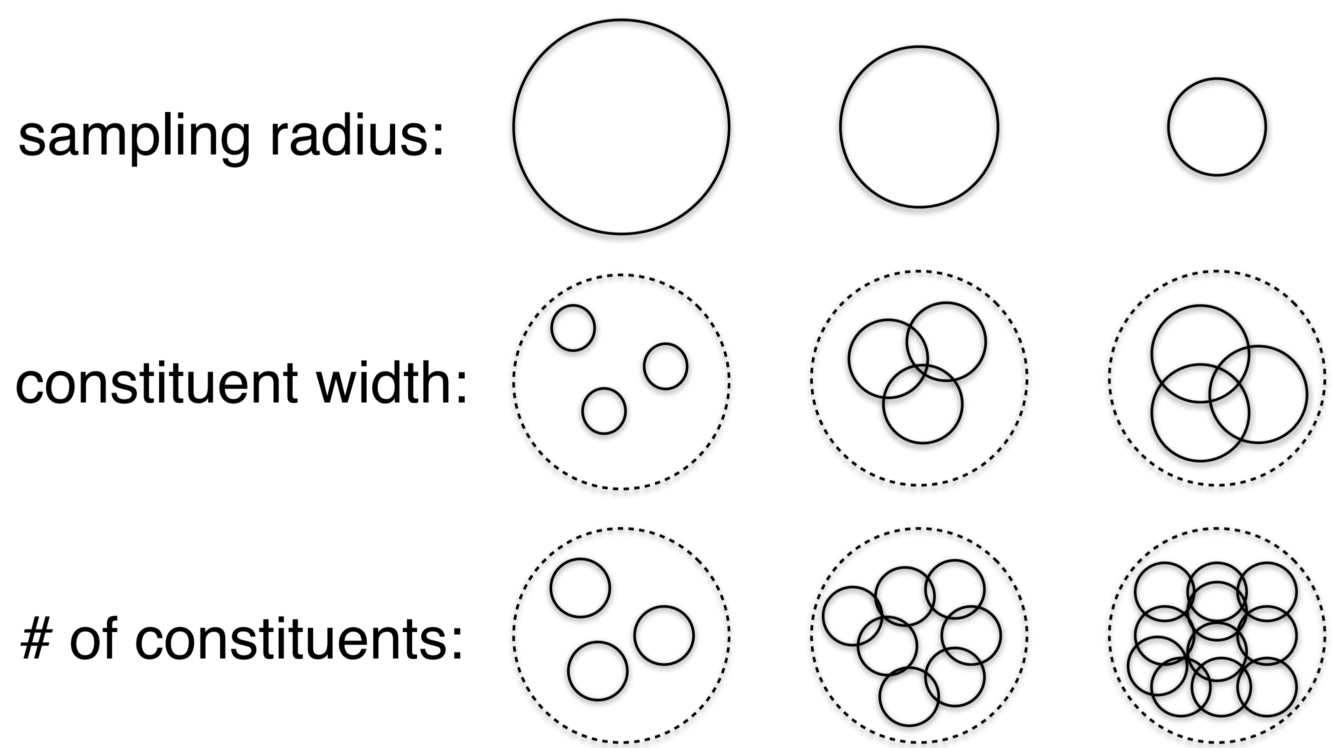
- spherical protons do not allow for proper eccentricities in p+A or small/ asymmetric collision systems

Trento with nucleon substructure:

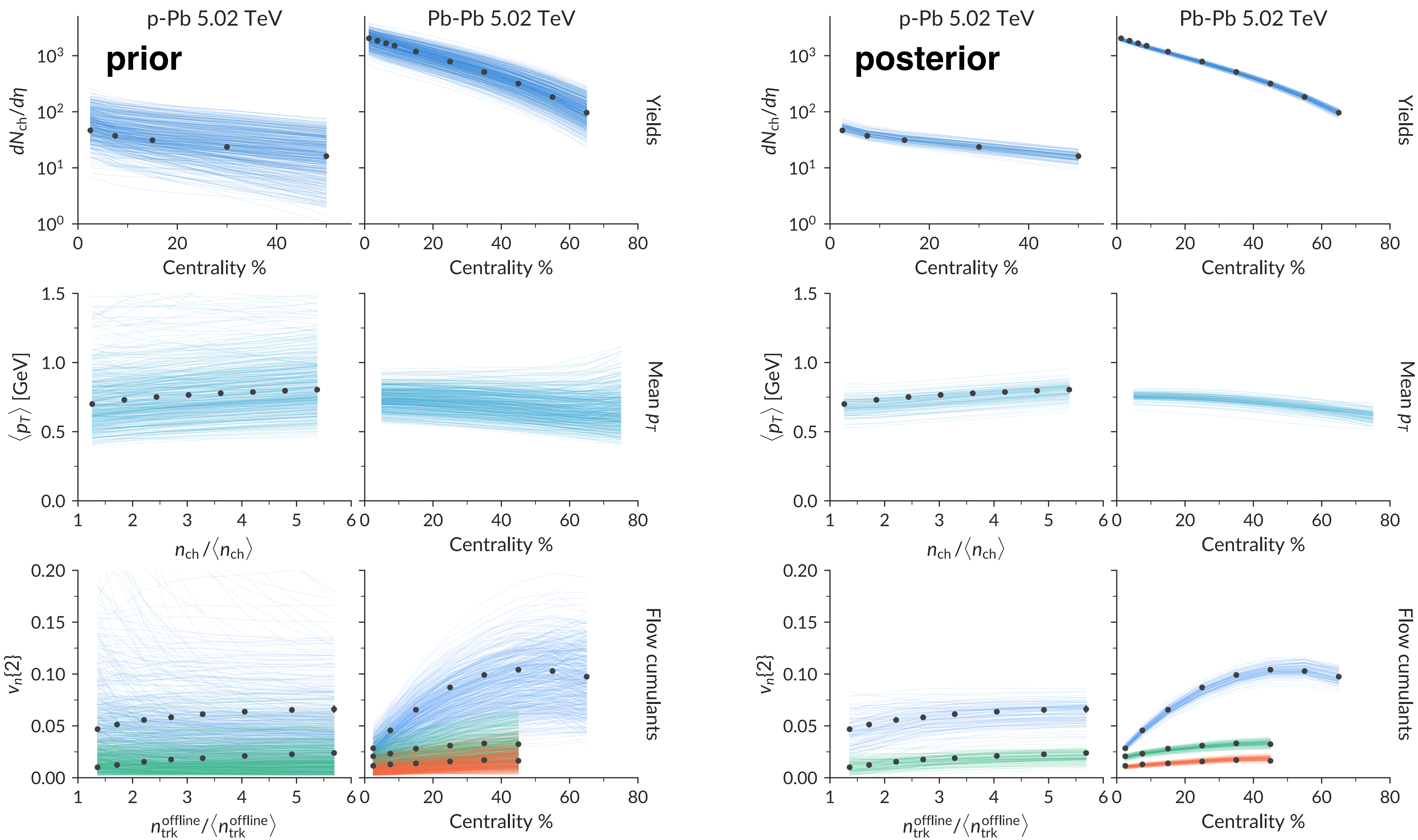
- trade Gaussian nucleons for lumpy nucleons



- additional parameters:
  - sampling radius of constituent positions
  - constituent Gaussian width
  - number of constituents in each nucleon

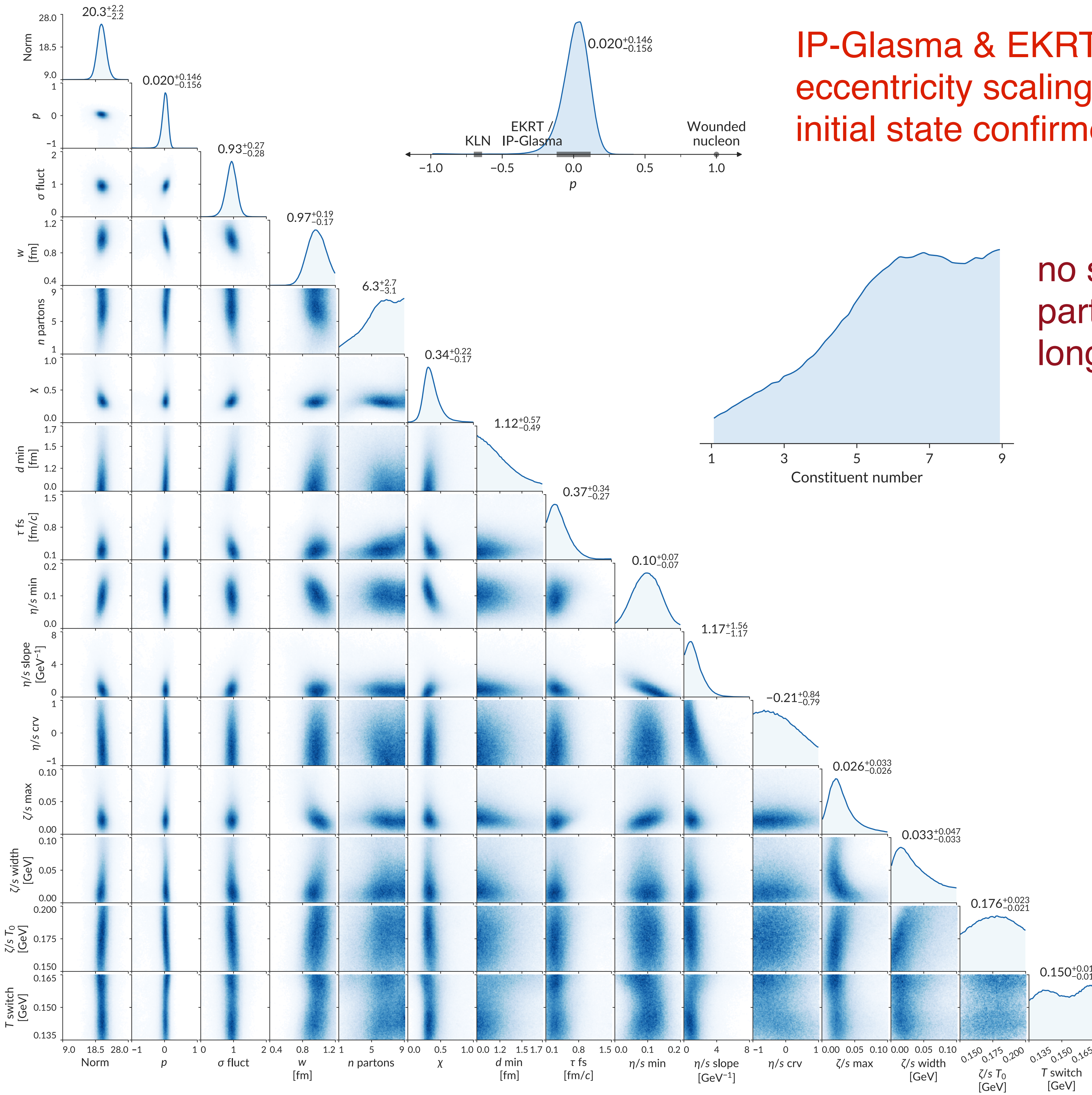


Simultaneous Calibration on AA and pA



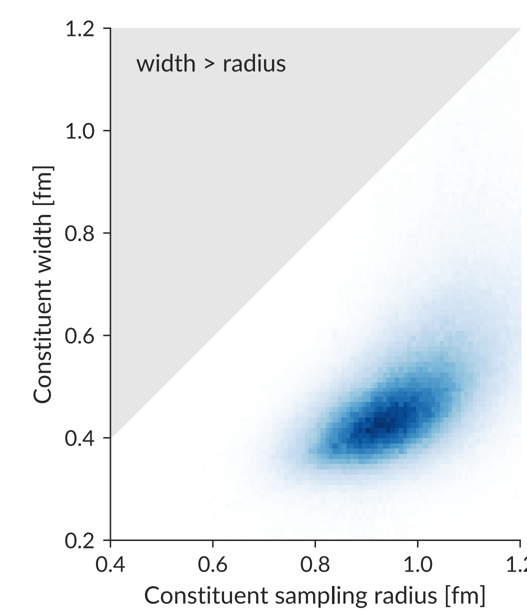
- ALICE & CMS data for AA & pA at 5.02 TeV
- calibration on 15 parameters, for initial state, shear and bulk viscosities
- restriction on 1 energy to keep computational effort reasonable
- generally larger uncertainties in posterior, due to less data than in the AA calibrations for 2 energies…

Key results: initial state



IP-Glasma & EKRT eccentricity scaling for initial state confirmed

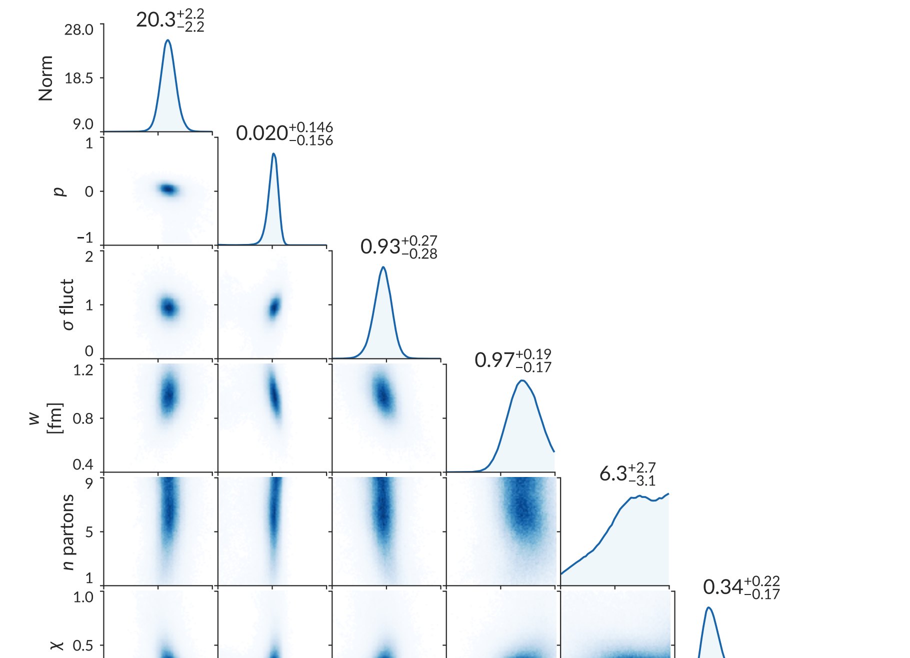
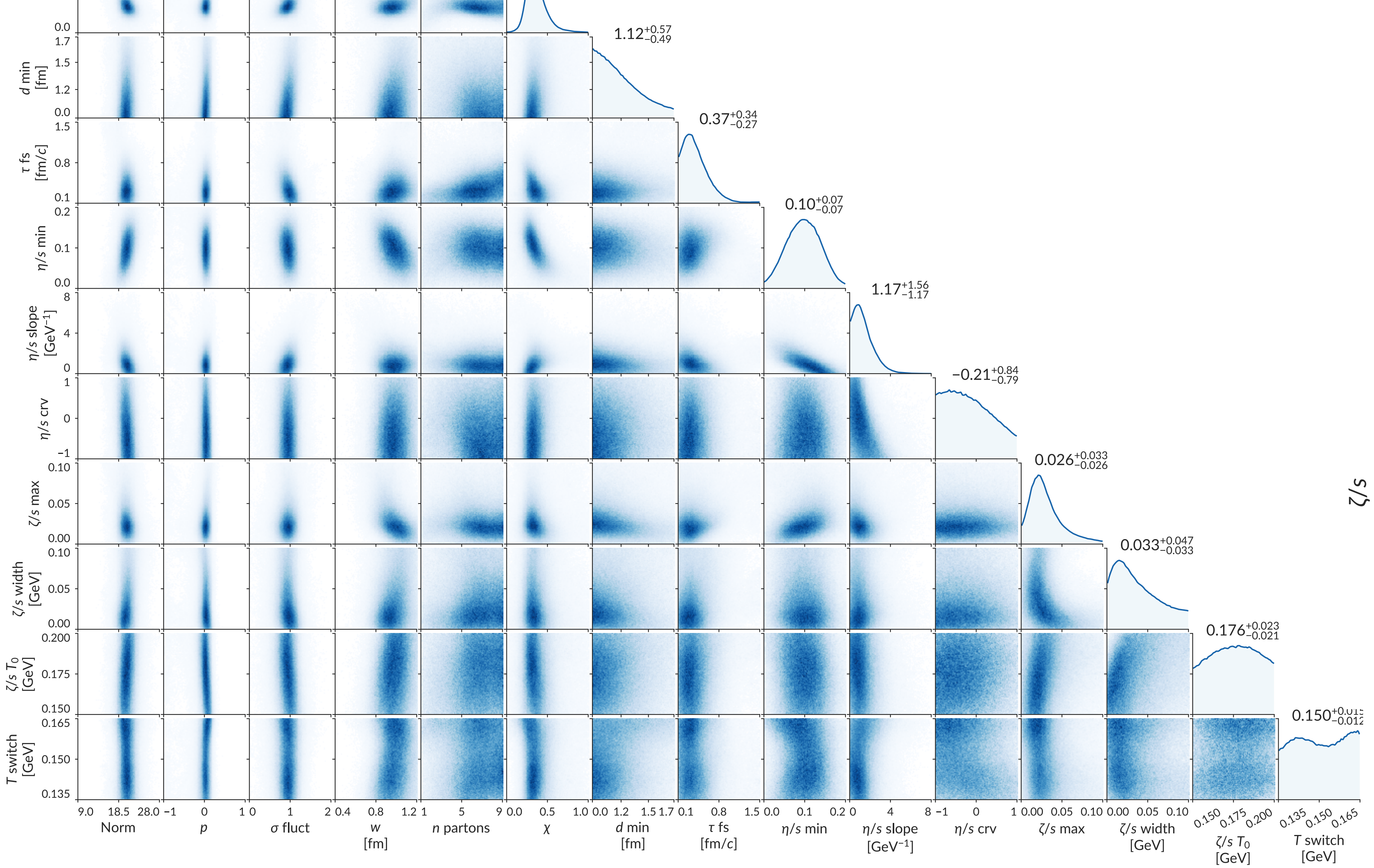
no strong preference for a particular constituent # as long as n>3

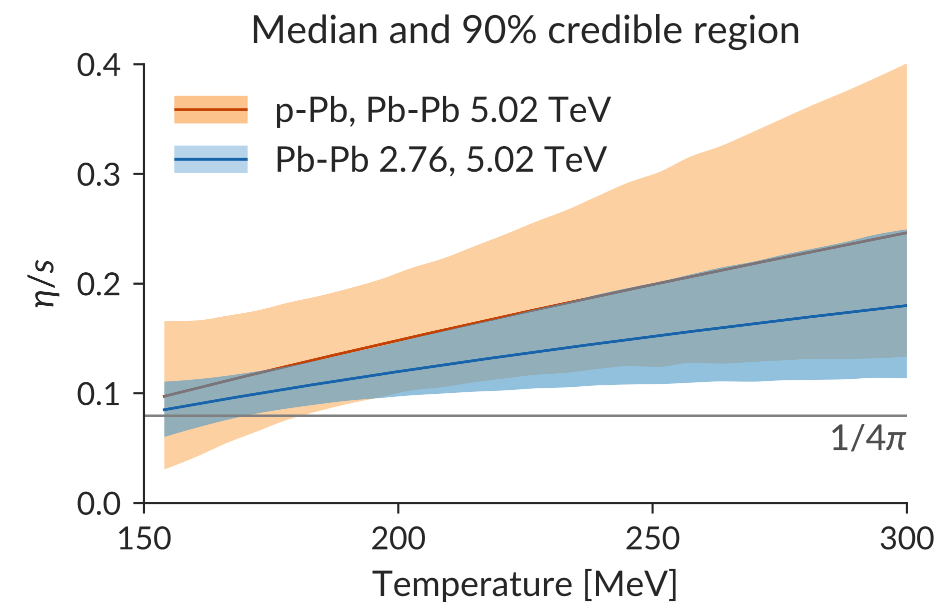


constituent width & sampling radius are well constrained to

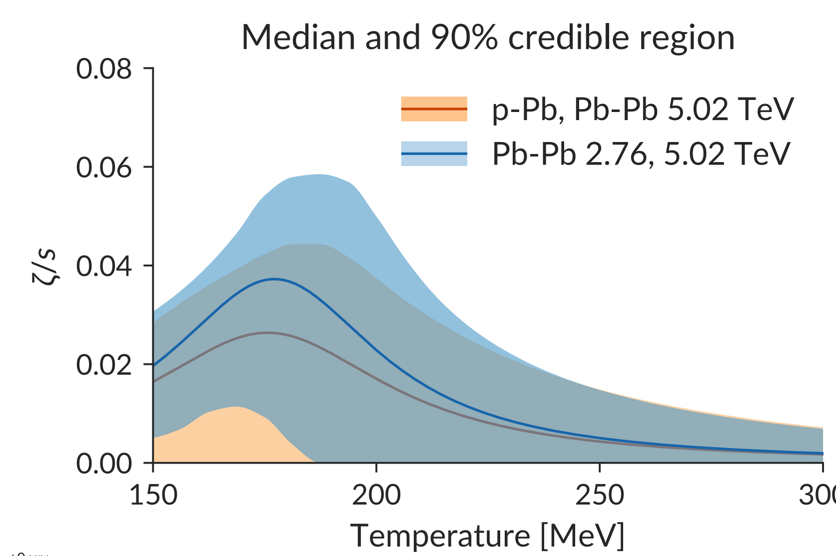
- r = 0.99 ± 0.16
- w = 0.47 ± 0.18

Key results: viscosities



- shear and bulk viscosities are fully compatible with previous calibration on Pb+Pb @ 2.76 TeV & 5.02 TeV
- uncertainty bands are larger in AA + pA analysis due to focus on single beam energy
- for bulk properties, multiple beam energies are more important than inclusion of small systems



Summary & Future Directions

- **Nucleon substructure:**
  - necessary for the description of pA
  - Bayesian analysis favors n>3 constituents
- **Temperature dependence for shear & bulk viscosities**
  - Multiple beam energies for AA have larger constraining power than pA & AA at one energy
- **Scaling of energy deposition:**
  - Trento ≠ IP-Glasma ($\sqrt{(T_A T_B}$) vs. $T_A T_B$
  - centrality-dependence of E_T as differentiator (requires consistent centrality determination for all IC models)
- **Future directions:**
  - calibration of pA, dA and AA for RHIC and LHC simultaneously
  - inclusion of hard probes into calibration

this work has been made possible through support by

Open Science Grid

NERSC National Energy Research Scientific Computing Center

SSGF STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

Resources

Trento:

- J. Scott Moreland, Jonah E. Bernhard & Steffen A. Bass: Phys. Rev. C 92, 011901(R)
- https://github.com/Duke-QCD/trento

iEbE-VISHNU:

- Chun Shen, Zhi Qiu, Huichao Song, Jonah Bernhard, Steffen A. Bass & Ulrich Heinz: Computer Physics Communications in print, arXiv:1409.8164
- http://u.osu.edu/vishnu/

UrQMD:

- Steffen A. Bass et al. Prog. Part. Nucl. Phys. 41 (1998) 225-370 , arXiv:nucl-th/9803035
- Marcus Bleicher et al. J.Phys. G25 (1999) 1859-1896 , arXiv:hep-ph/9909407
- http://urqmd.org

MADAI Collaboration:

- Visualization and Bayesian Analysis packages
- https://madai-public.cs.unc.edu

Duke Bayesian Analysis Package:

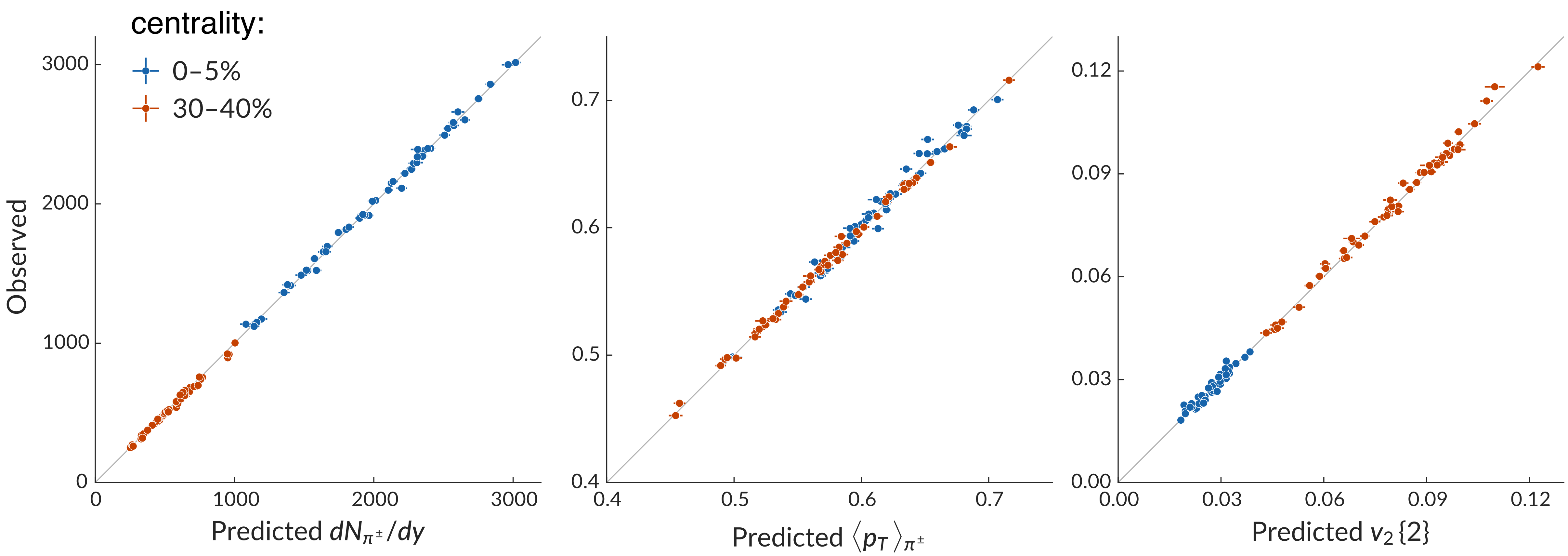
- https://github.com/jbernhard/mtd

The End

Precision Science
or
“Smoke & Mirrors”?

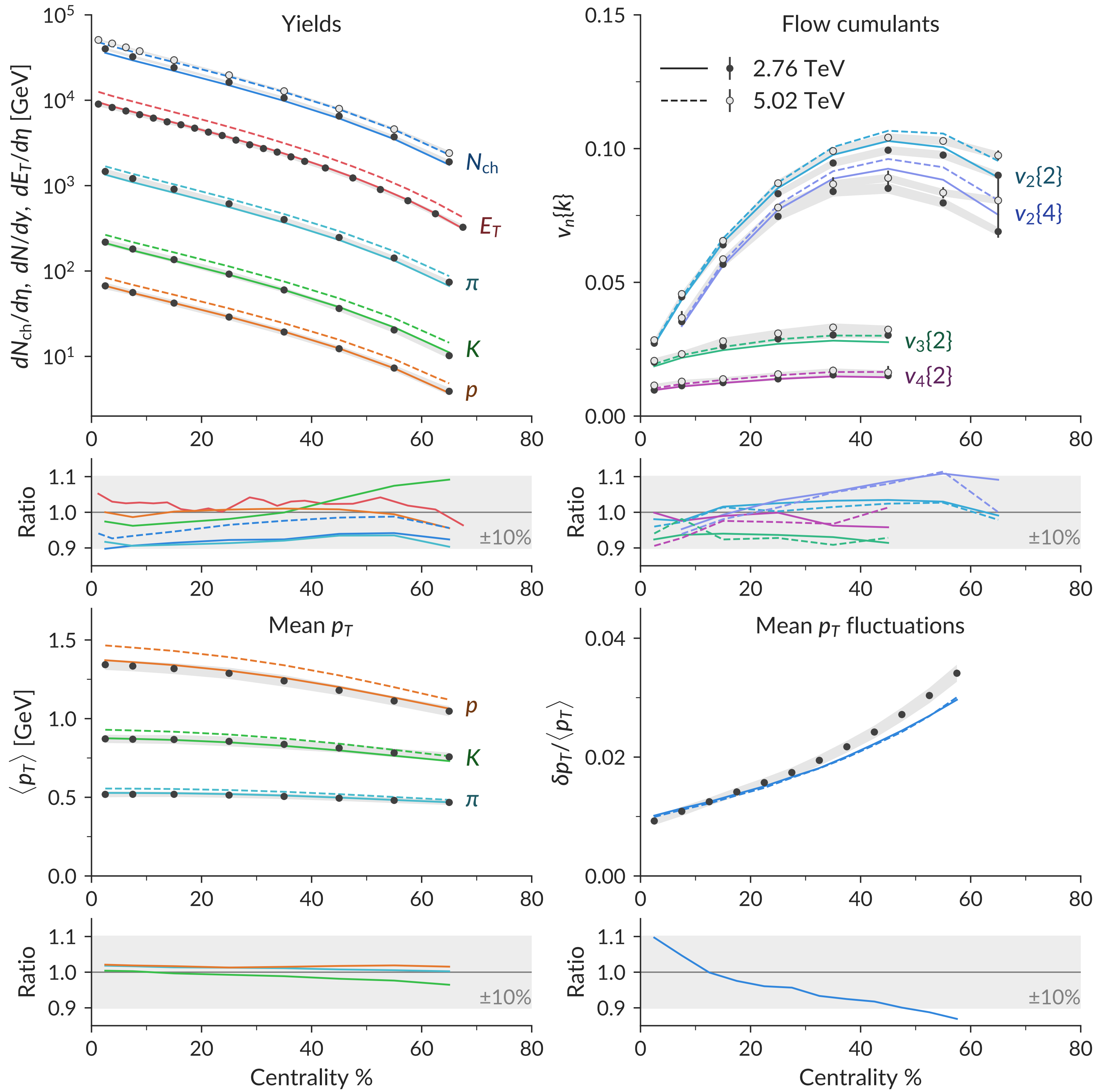
Validation

- generate a separate Latin hypercube validation design with 50 points
- evaluate the full physics model at each validation point
- compare physics model output to that of the previously conditioned GP emulators:



- note that since GPEs are stochastic functions, only ~68% of predictions need to fall within 1 standard deviation

Verification: Explicit Model Calculation



- explicit physics model calculations (no emulator) with parameter values set to the maximum of the posterior probability distributions yield excellent agreement with data!

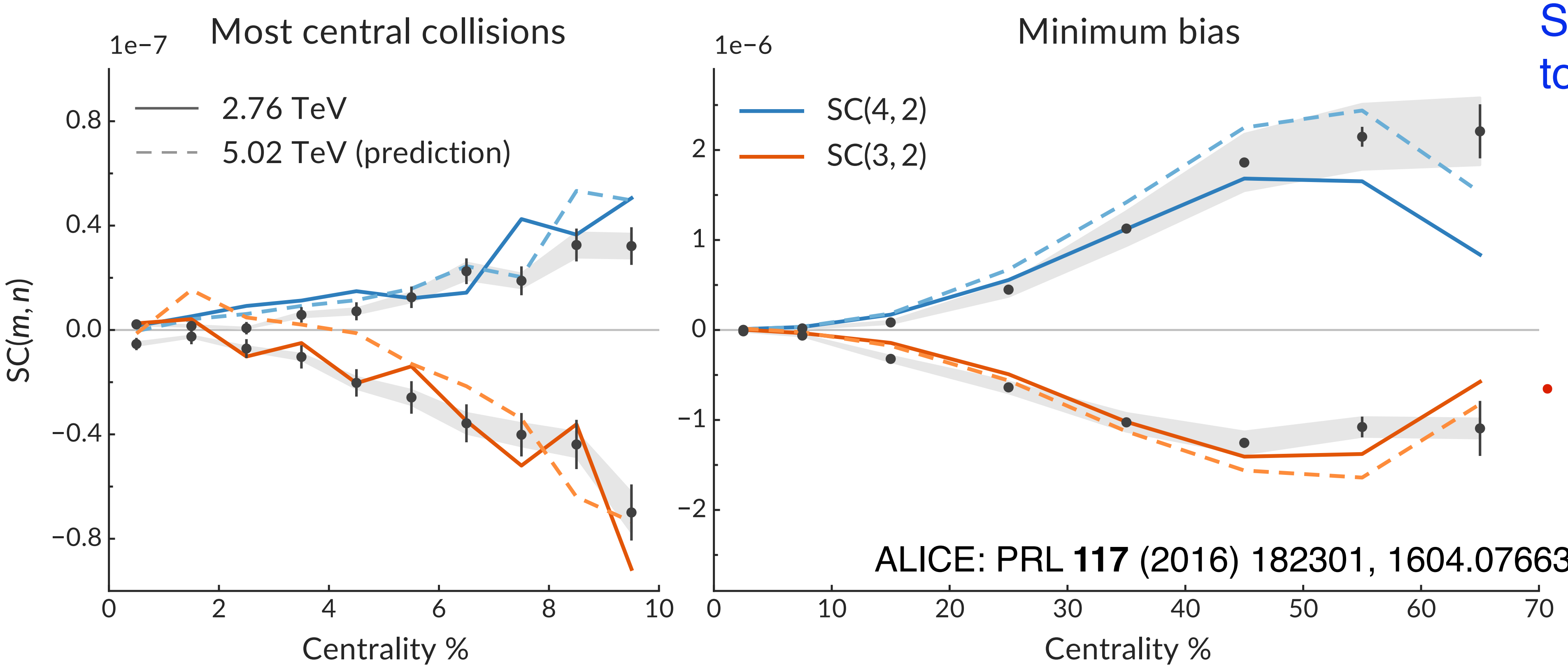
- description of data to within ±10% accuracy

Non-Calibrated Observables

The robustness and quality of the Physics Model can be tested by making predictions on observables not used during calibration using highest likelihood parameter values.

Example: correlations between event-by-event fluctuations of flow harmonics

$SC(m,n) = \langle v^2_m v^2_n \rangle - \langle v^2_m \rangle \langle v^2_n \rangle$



SC(m,n) are sensitive to:

- initial conditions
- evolution model
- QGP transport coefficients

- excellent agreement of model prediction to data!

Closure Test

Need to verify that analysis can recover “true” values for the parameters: run physics model with chosen set of parameters, generate “fake data” from model output and then conduct analysis on that fake data to test if the input parameters can be recovered!

- both, smooth functions as well as peaked functions, can be reproduced well within the 90% CR
- note: due to reduction of information when going from model output to observables & model/GP uncertainties one should not expect a one-to-one reconstruction
- bulk analysis is mostly sensitive to area under bulk peak, not peak position, height & width independently