

# Determining QGP initial conditions and medium properties via Bayesian model-to-data analysis

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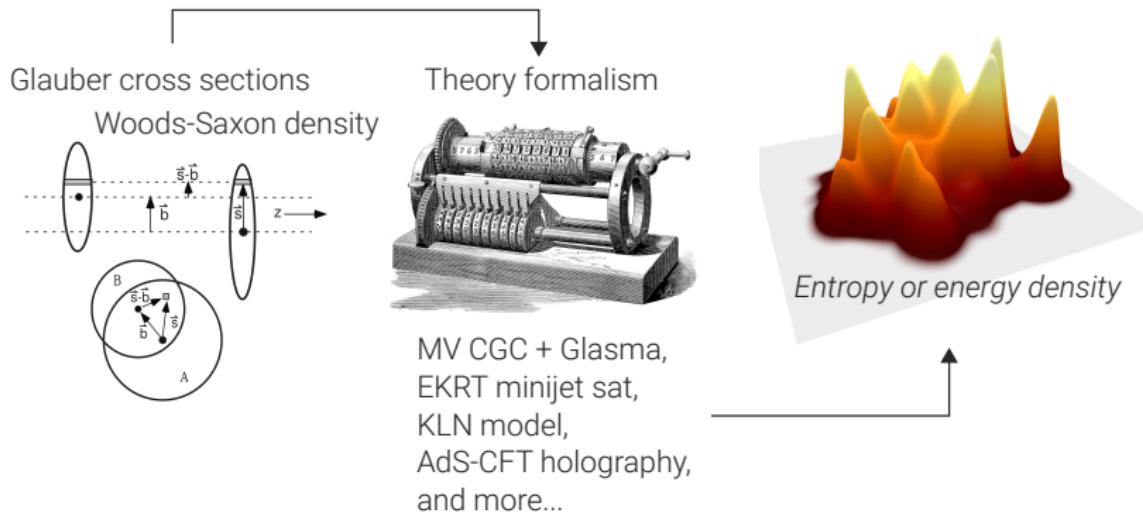
arXiv:1605.03954

Initial Stages | May 25, 2016



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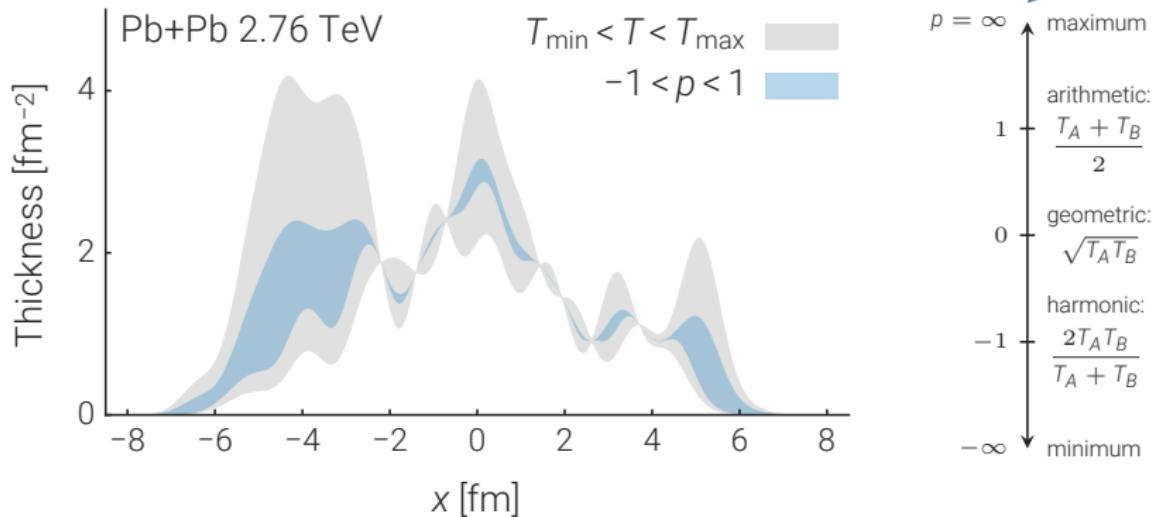
# Deconstructing initial condition models



- Woods-Saxon, Glauber modeling aspects generally well accepted
- Useful to separate cross sections and entropy deposition map, i.e.  $dS/dy \sim f(T_A, T_B)$  where  $T$  is the nuclear thickness. *The mapping  $f$  is a 2D surface.*

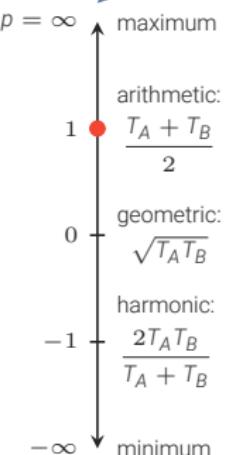
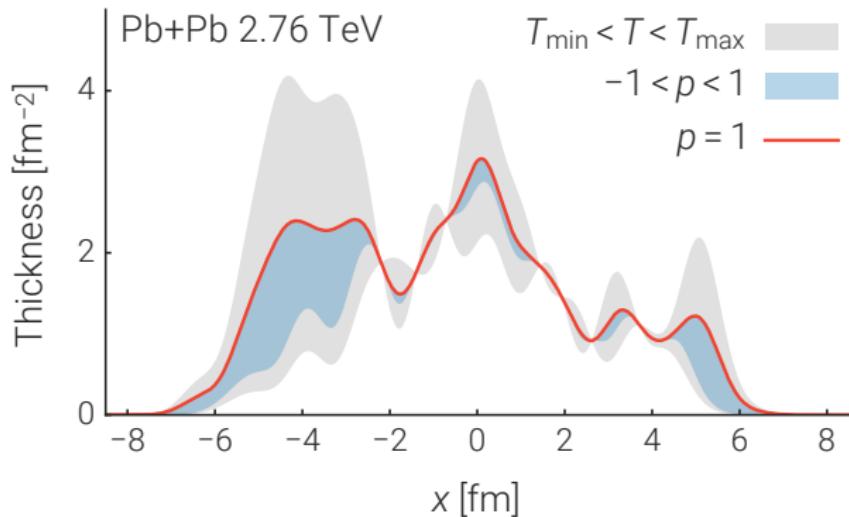
# Parametrizing the initial conditions

Generalized mean ansatz:  $\frac{ds}{d^2r dy} \propto \left( \frac{T_A^p + T_B^p}{2} \right)^{1/p}$



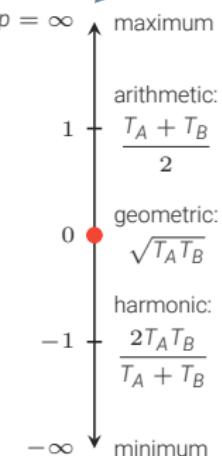
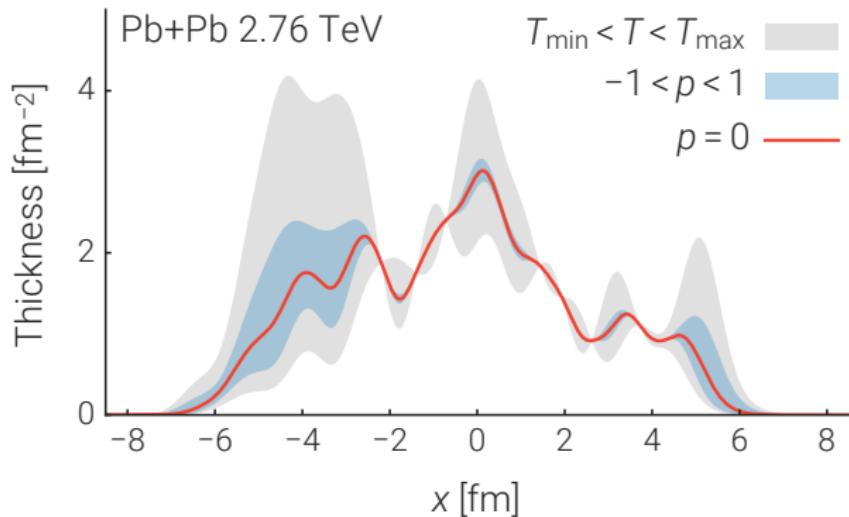
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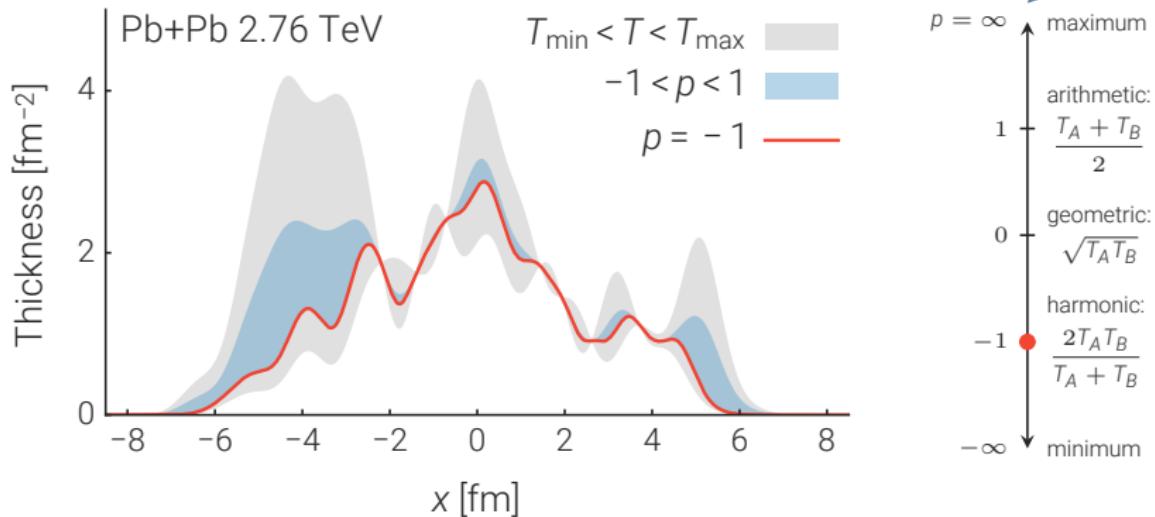
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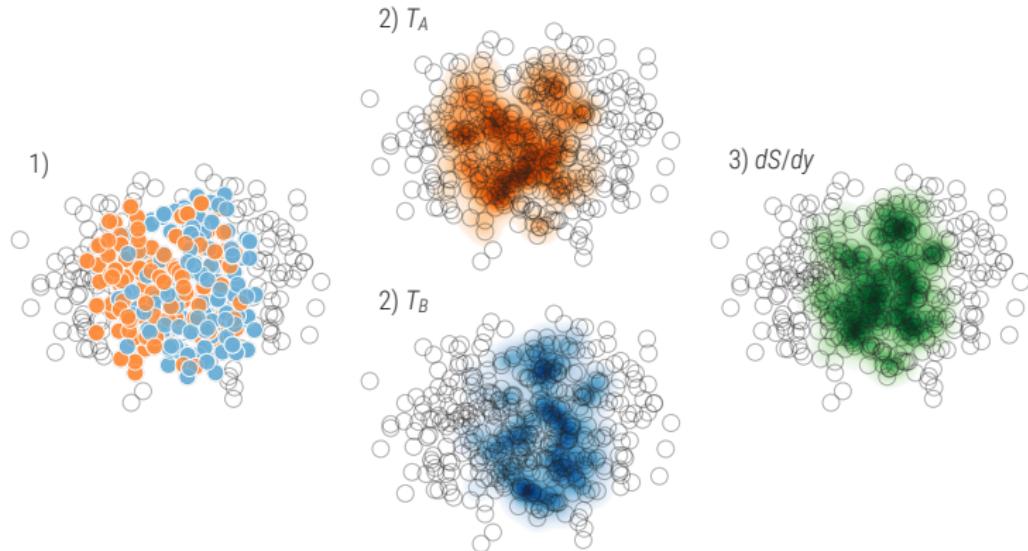
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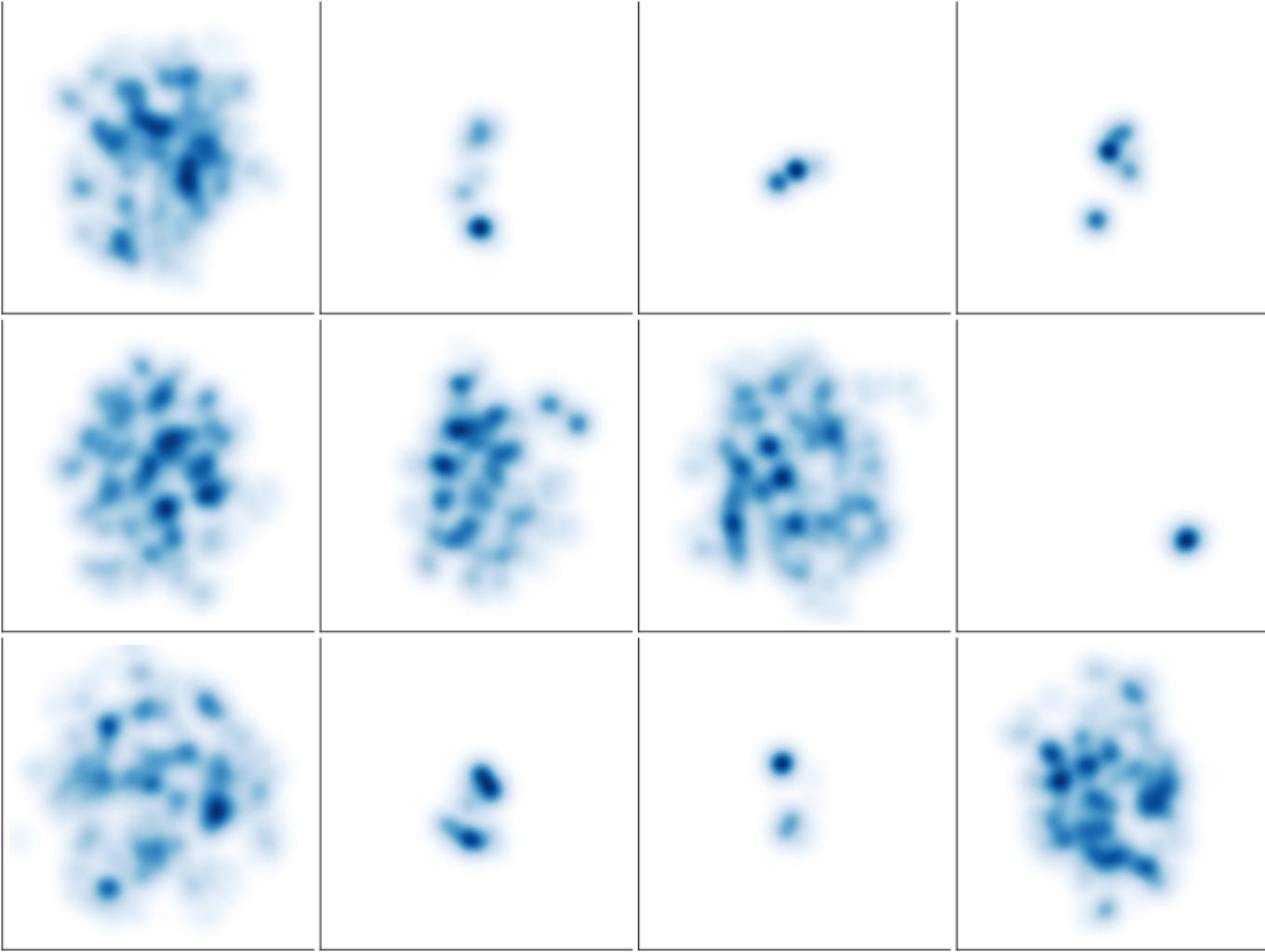




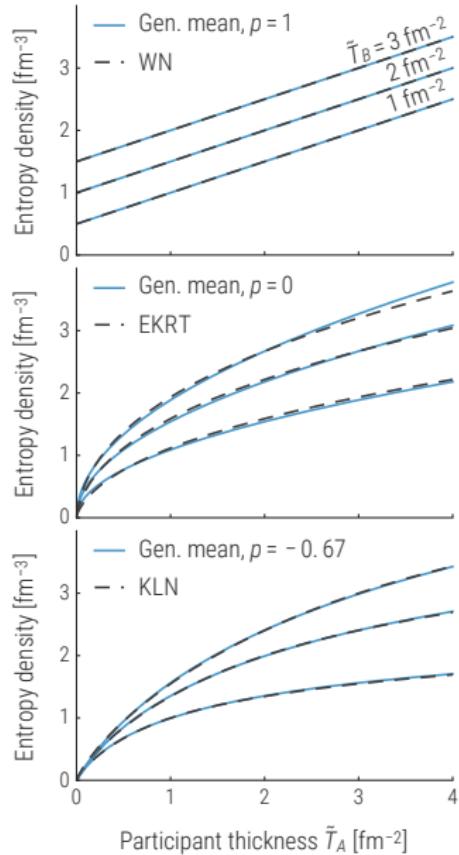
1 Calc participants:  $P_{\text{coll}}(b) = 1 - \exp[-\sigma_{gg} T_{pp}(b)], \quad \int 2\pi b db P_{\text{coll}}(b) = \sigma_{\text{NN}}^{\text{inel}}$

2 Build participant density:  $T_A(x, y) = \sum_{i=1}^{N_{\text{part}, A}} \gamma_i T_p(x - x_i, y - y_i), \quad \gamma \sim \Gamma(k, 1/k)$

3 Parametrize entropy deposition:  $dS/dy \propto \left( \frac{T_A^p + T_B^p}{2} \right)^{1/p}$



# Compare parametrization to existing IC models



- Wounded nucleon model

$$\frac{dS}{dy d^2r_\perp} \propto \tilde{T}_A + \tilde{T}_B$$

- EKRT model PRC 93, 024907 (2016)  
after brief free streaming phase

$$\frac{dE_T}{dy d^2r_\perp} \sim \frac{K_{\text{sat}}}{\pi} p_{\text{sat}}^3(K_{\text{sat}}, \beta; T_A, T_B)$$

- KLN model PRC 75, 034905 (2007)

$$\frac{dN_g}{dy d^2r_\perp} \sim Q_{s,\min}^2 \left[ 2 + \log \left( \frac{Q_{s,\max}^2}{Q_{s,\min}^2} \right) \right]$$

# Modern event-by-event hybrid model

- TRENTo initial conditions

Moreland, Bernhard, Bass, PRC 92, no. 1, 011901 (2015)

norm    entropy normalization

$p$     entropy deposition parameter

$k$     proton-proton multiplicity fluctuations

$w$     Gaussian nucleon width

- HotQCD equation of state

Bazavov, et. al. PRD 90, 094503 (2014)

- iEBE-VISHNU hydrodynamics

Shen, Qiu, Song, Bernhard, Bass, Heinz, Comp. Phys. Comm. 199, 61 (2016)

$\eta/s$  min    shear viscosity minimum

$\eta/s$  slope    shear viscosity slope

$\zeta/s$  norm    bulk viscosity normalization

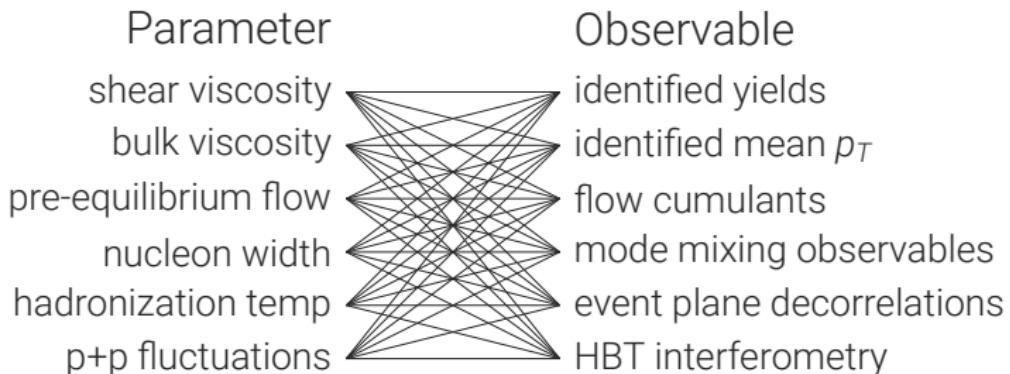
$T_{sw}$     hydro-to-urqmd switching temp

- UrQMD hadronic afterburner

Bass et. al, Prog. Part. Nucl. Phys. 41, 255 (1998)

Bleicher et. al, J. Phys. G 25, 1859 (1999)

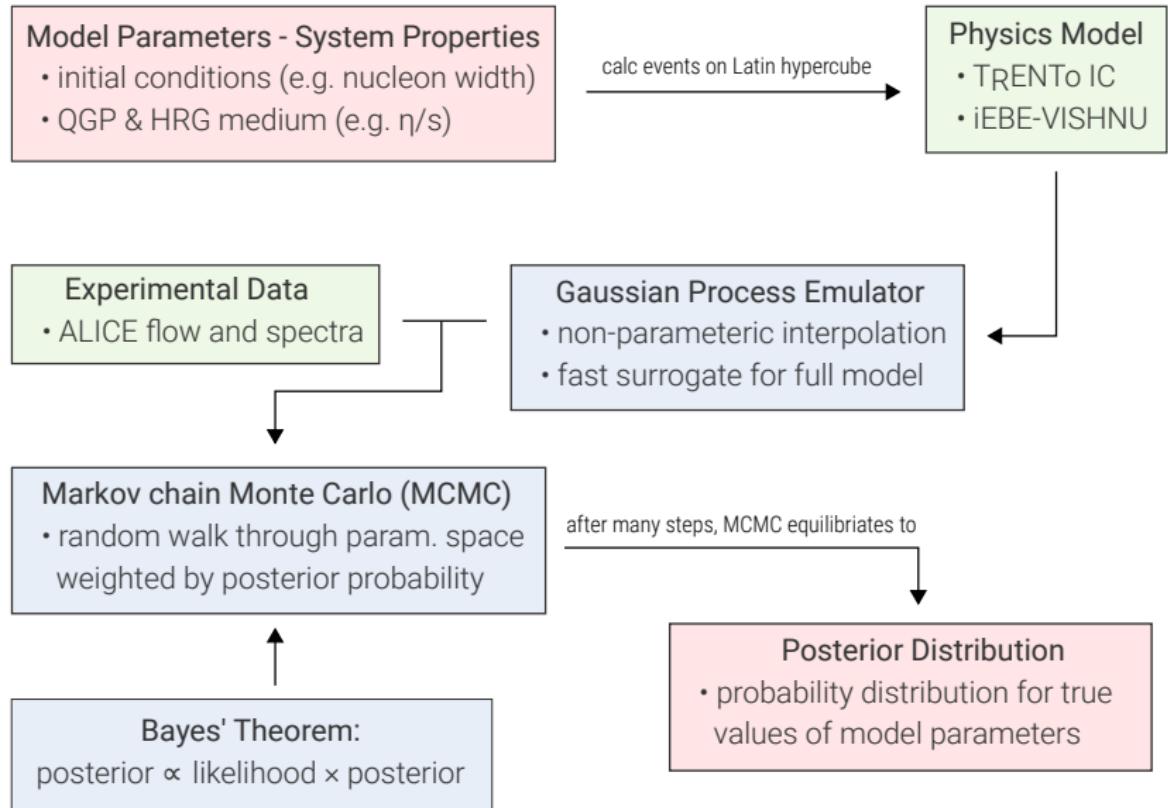
# The challenge of rigorous model-to-data comparison



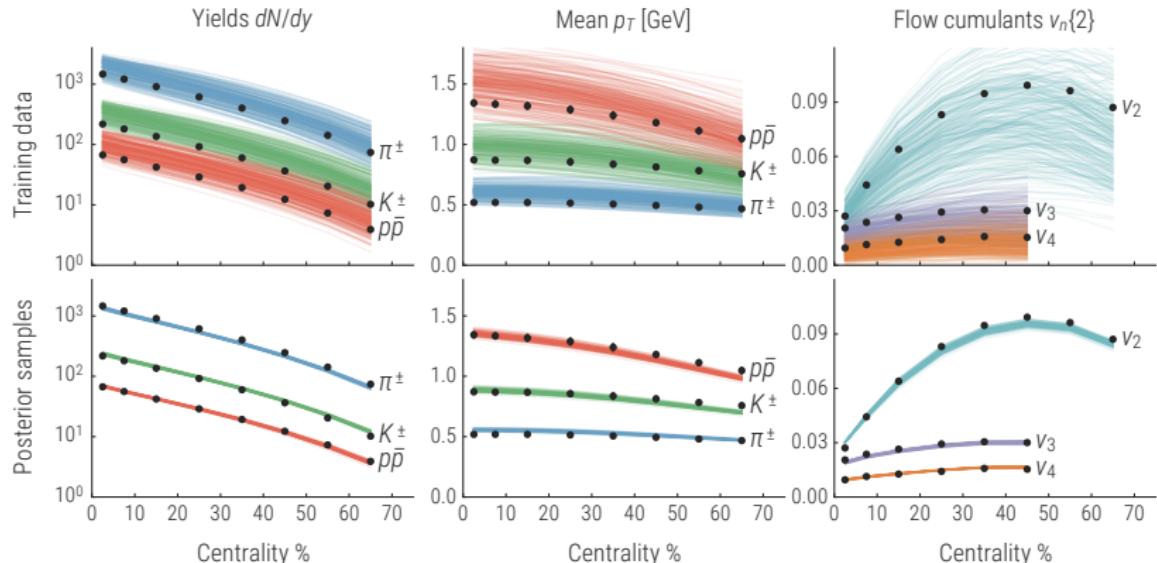
Testing a single set of parameters requires  $\mathcal{O}(10^4)$  hydro events  
...and evaluating eight different parameters five times each  
requires  $5^8 \times 10^4 \approx 10^9$  hydro events.

That's roughly  $10^5$  computer years!

# Solution: Bayesian methodology

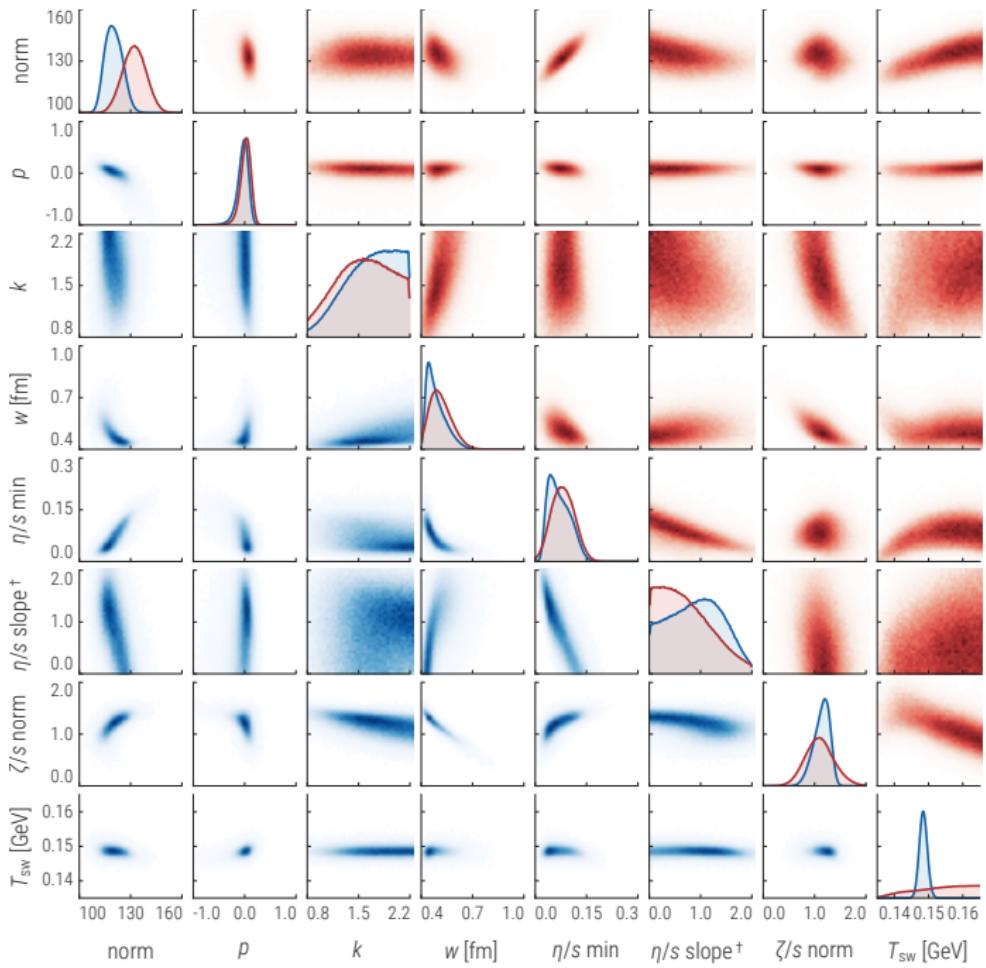


# Calibrating the model: before and after



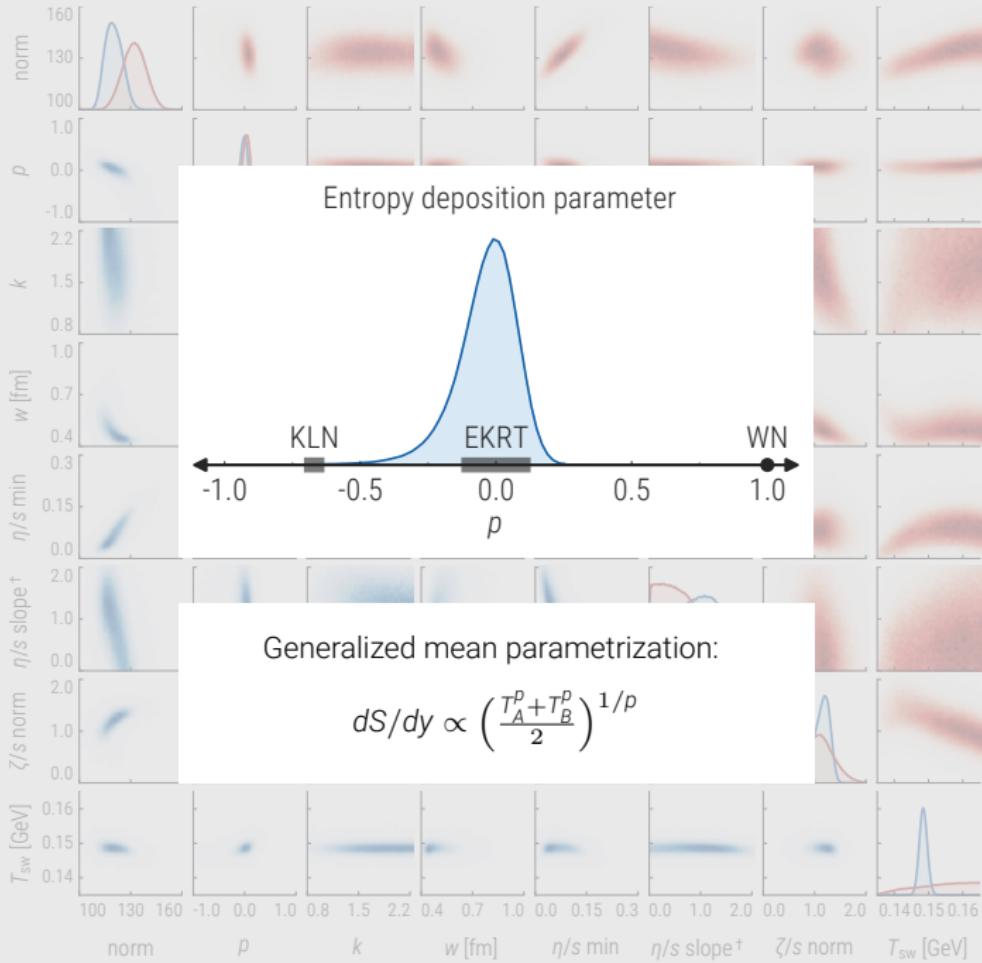
- Top: run model ( $\times 10^4$  events) at each design point ( $\times 300$  evals)
- Bottom: emulator predictions for 100 samples from the posterior

Calibrated to identified particles



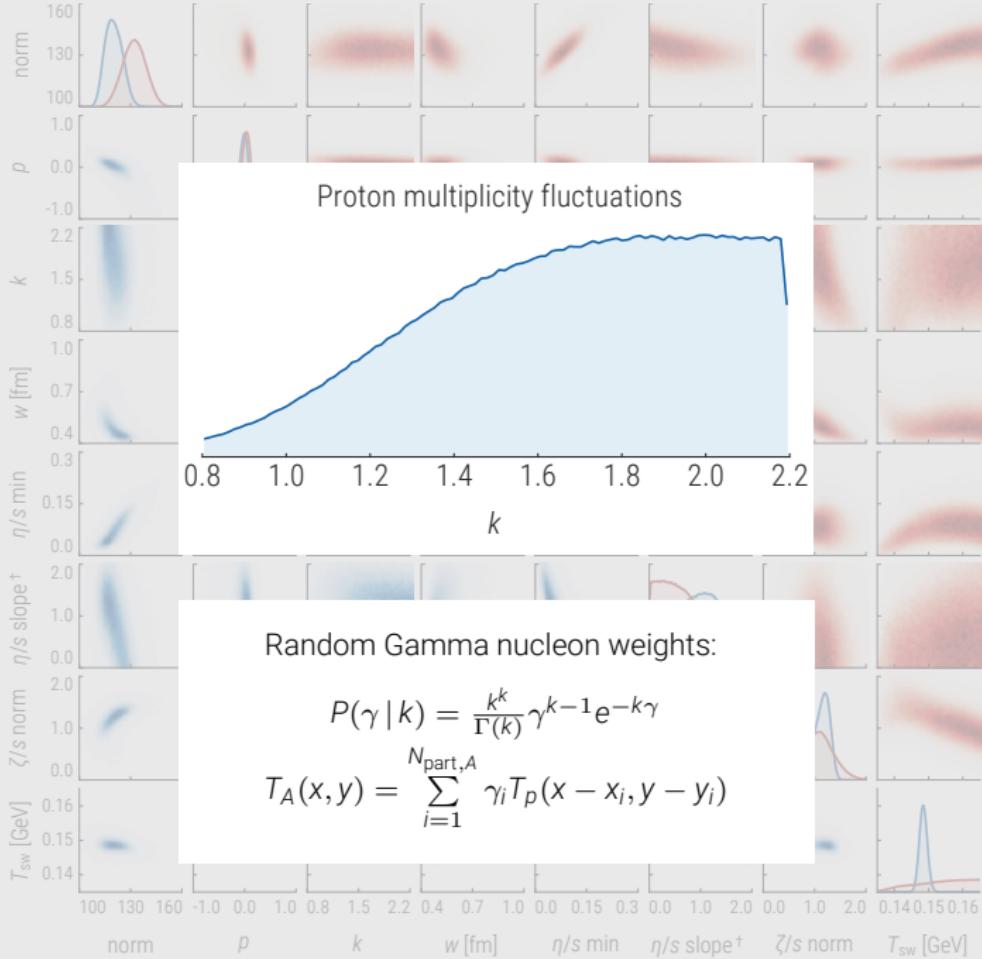
Calibrated to charged particles

Calibrated to identified particles



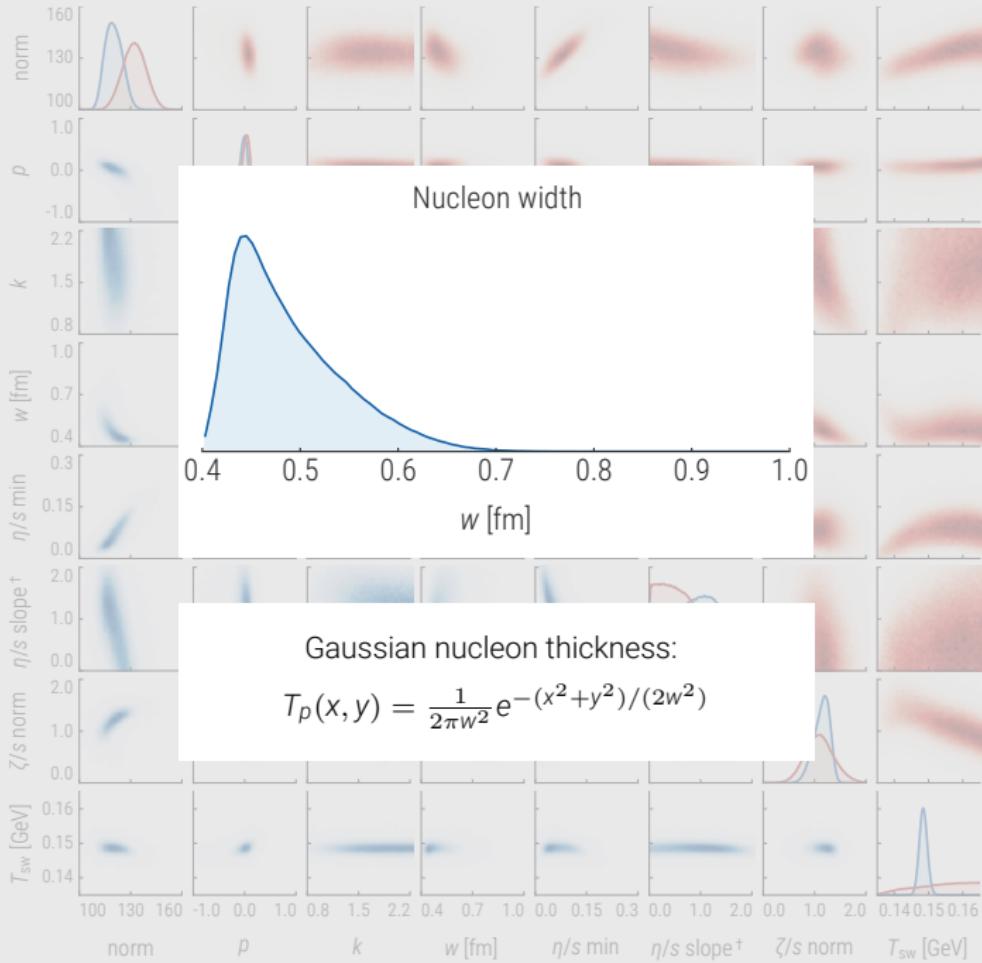
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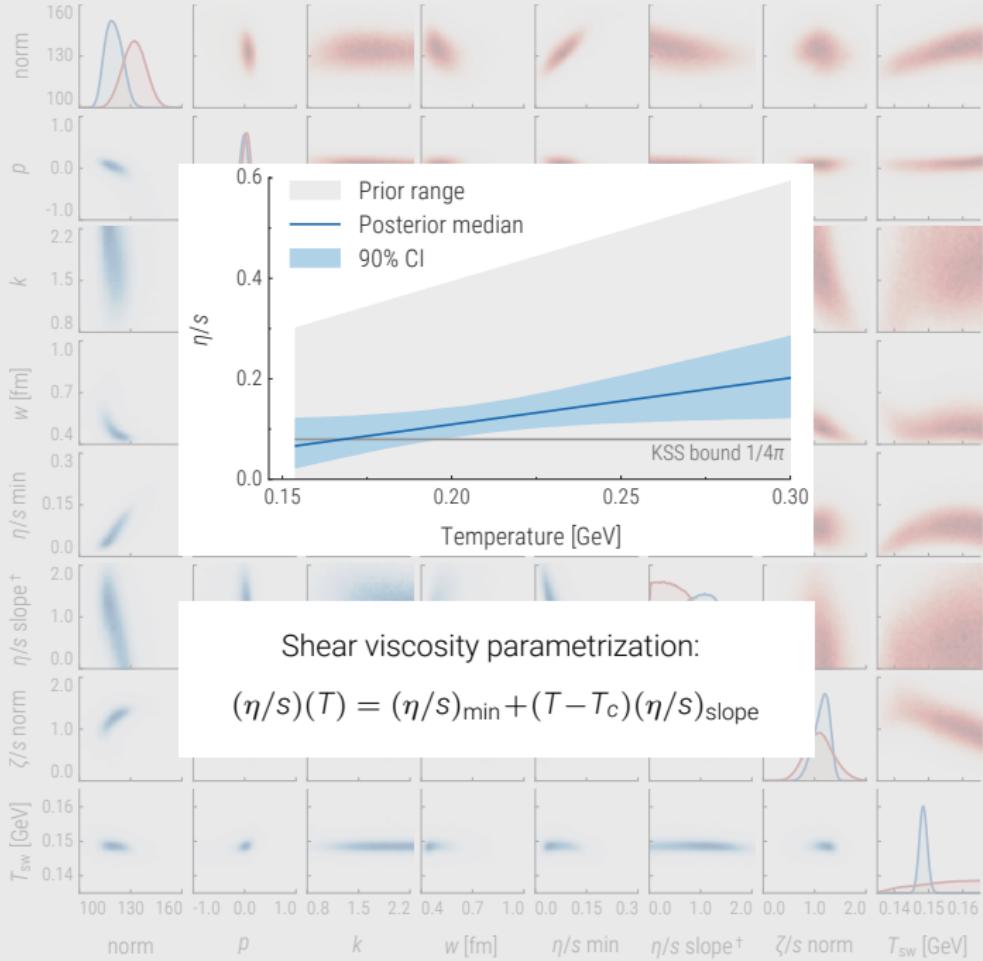
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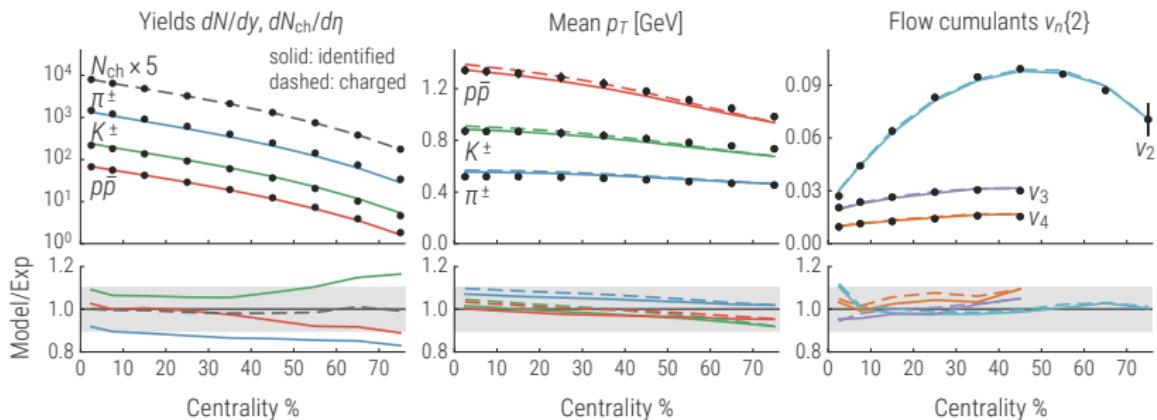


Calibrated to charged particles

# Running the model with high probability parameters

- Choose high probability model parameters from Bayesian posterior (right)
- Run full hybrid model using high probability parameters (bottom)

	Initial condition	QGP medium	
norm	120.	$\eta/s$ min	0.08
$p$	0.0	$\eta/s$ slope	$0.85 \text{ GeV}^{-1}$
$k$	1.5	$\zeta/s$ norm	1.25
$w$	0.43 fm	$T_{\text{sw}}$	0.148 GeV



# Conclusions

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## Initial condition properties

- Yields, mean  $p_T$  and flows impose strong constraints on IC.
- Entropy deposition mimicked by  $dS/dy \sim \sqrt{T_A T_B}$
- Data strongly prefers small nucleon width  $w \approx 0.4\text{--}0.6$  fm!
- A+A collisions weakly sensitive to p+p mult. fluctuations
- Preferred initial conditions similar to EKRT, IP-Glasma

## Hydrodynamic transport properties

- First quantitative credibility interval on  $(\eta/s)(T)$ !
- Data prefer non-zero bulk viscosity
- Hydro-to-micro  $T_{sw}$  determined by relative species yields

TRENTo is publicly available at [qcd.phy.duke.edu/trento](http://qcd.phy.duke.edu/trento)

More in the pre-print [arXiv:1605.03954](https://arxiv.org/abs/1605.03954)

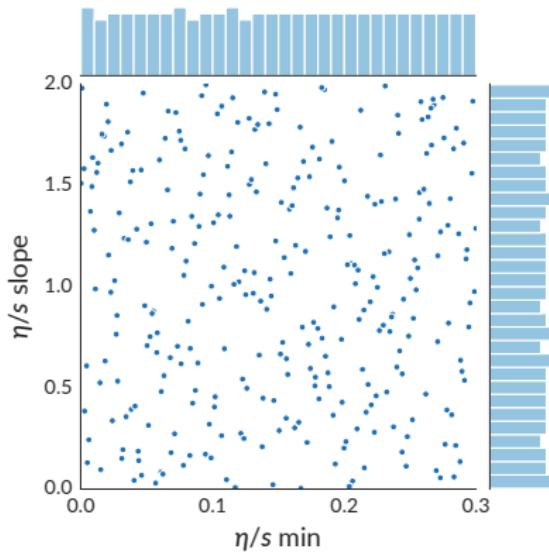
# Computer experiment design

## Maximin Latin hypercube

- Random, space-filling points
- Maximizes the *minimum* distance between points  
→ avoids gaps and clusters
- Uniform projections into lower dimensions

This work:

- 300 points across 8 dimensions
- 8 centrality bins
- $\mathcal{O}(10^7)$  events total



# TRENTo 3D, work in progress...

- Extend to forward/backward rapidities while maintaining mid-rapidity result:

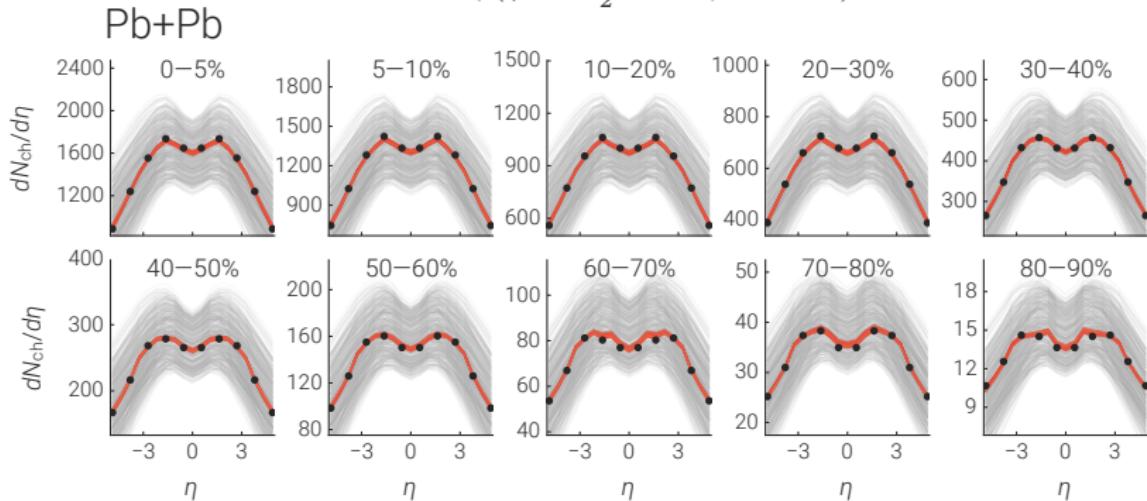
$$s(x_{\perp}, \eta) = s(x_{\perp}, \eta = 0) \cdot f(x_{\perp}, \eta)$$

- Parametrize  $f(x_{\perp}, \eta)$  by first few cumulants,

mean	std	skewness	kurtosis
$\mu(x_{\perp})$	$\sigma(x_{\perp})$	$\gamma(x_{\perp})$	$\kappa(x_{\perp})$

- Reconstruct  $f(\eta)$  by  $\mathcal{F}^{-1}$  cumulant generating function,

$$\mathcal{F}^{-1} \exp(i\mu k - \frac{\sigma^2}{2}k^2 + i\gamma k^3 - \kappa k^4)$$



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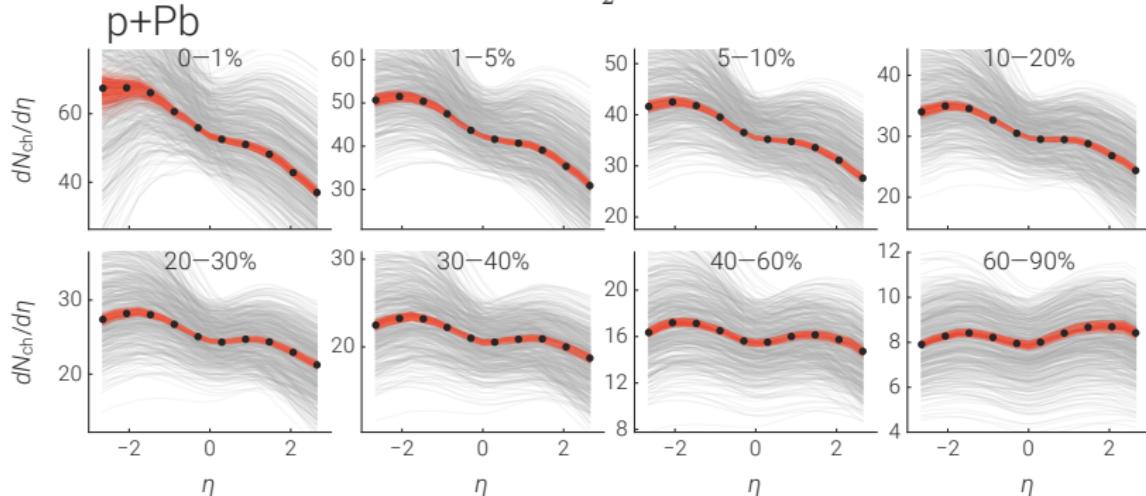
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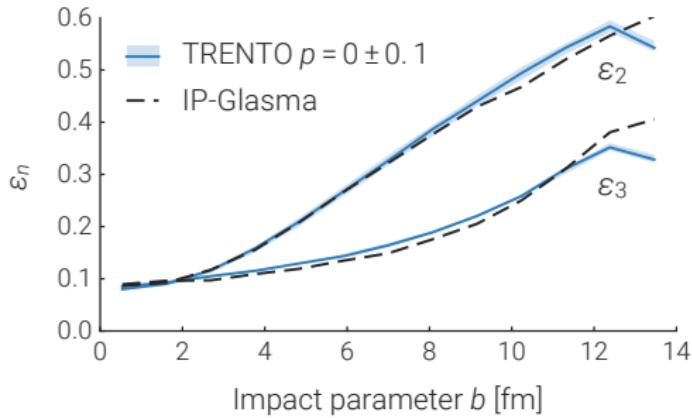
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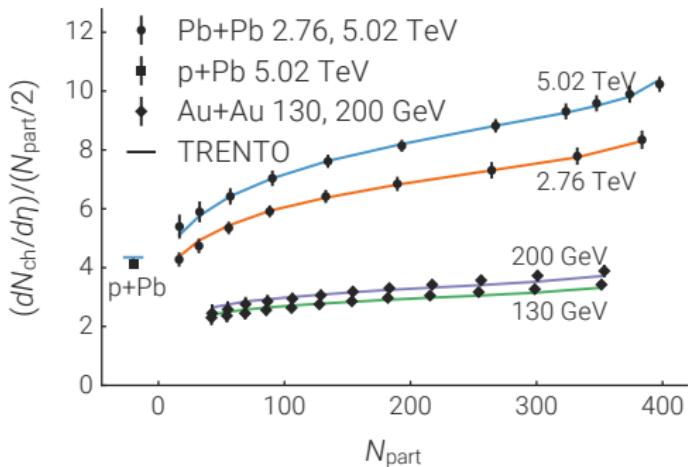
# Comparing to the IP-Glasma model



- IP-Glasma:  
multi-stage  
dynamical model,  
simple analytic  
mapping unknown.
- Analyze effective  
mapping via  
eccentricity  
harmonics  $\varepsilon_n$  (left).

Work ongoing: determine IP-Glasma effective mapping for direct comparison with TRENTo parametrization

# TRENTTo charged particle production



- Entropy deposition parameter  $p = 0$ , nucleon width  $w = 0.5 \text{ fm}$ , p+p fluctuation factor  $k = 1.6$ , normalization varied with energy but not collision system
- Good description of particle production at all energies, self consistent p+A and A+A multiplicities