Freeze-out of charge fluctuations in the QGP: D-measure at the LHC

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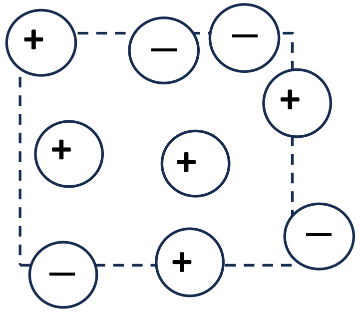
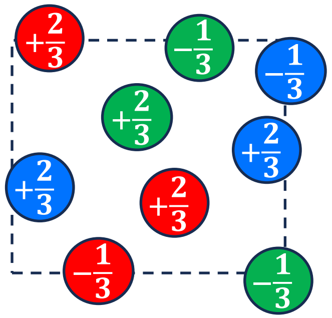
The Main Idea

While hadrons carry ***integer*** electric charges, quarks carry ***fractional*** electric charges.



Hadrons

vs



Quarks

$D_{QGP} < D_{HG}$ → Distinct signal for QGP in heavy-ion collisions

Quantified by D-measure:

$$D = 4\frac{\kappa_2[Q]}{\langle N_{\rm ch}\rangle}$$

Here $\kappa_2[Q] = \langle Q^2\rangle - \langle Q\rangle^2$

$$N_{\rm ch} = N_+ + N_-$$

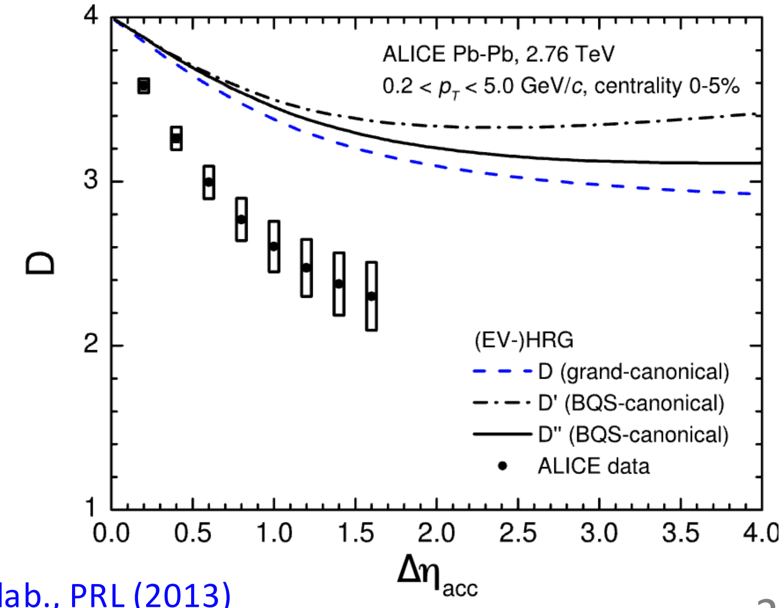
Koch, Jeon, PRL (2000);

Asakawa, Muller, Heinz, PRL (2000);

Previous estimates using grand canonical ensemble (GCE) limit:

- $D_{HG} \approx 3$
- $D_{QGP} \approx 1$

No quantitative calculations have been done for QGP w/o GCE limit



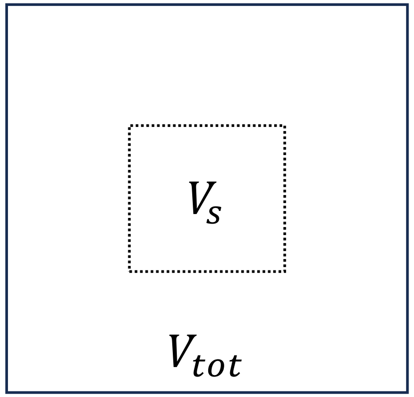
ALICE Collab., PRL (2013)

Vovchenko, Koch, PRC (2021)

GCE vs Heavy-Ion Collisions

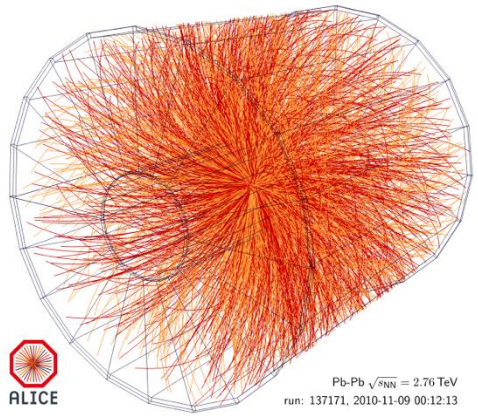
In Grand Canonical Ensemble (GCE):

- Coordinate space measurements
- Subvolume much smaller than total volume, $V_s \ll V_{tot}$
  - Charge conservation effects are neglected
  - Charges are free to fluctuate

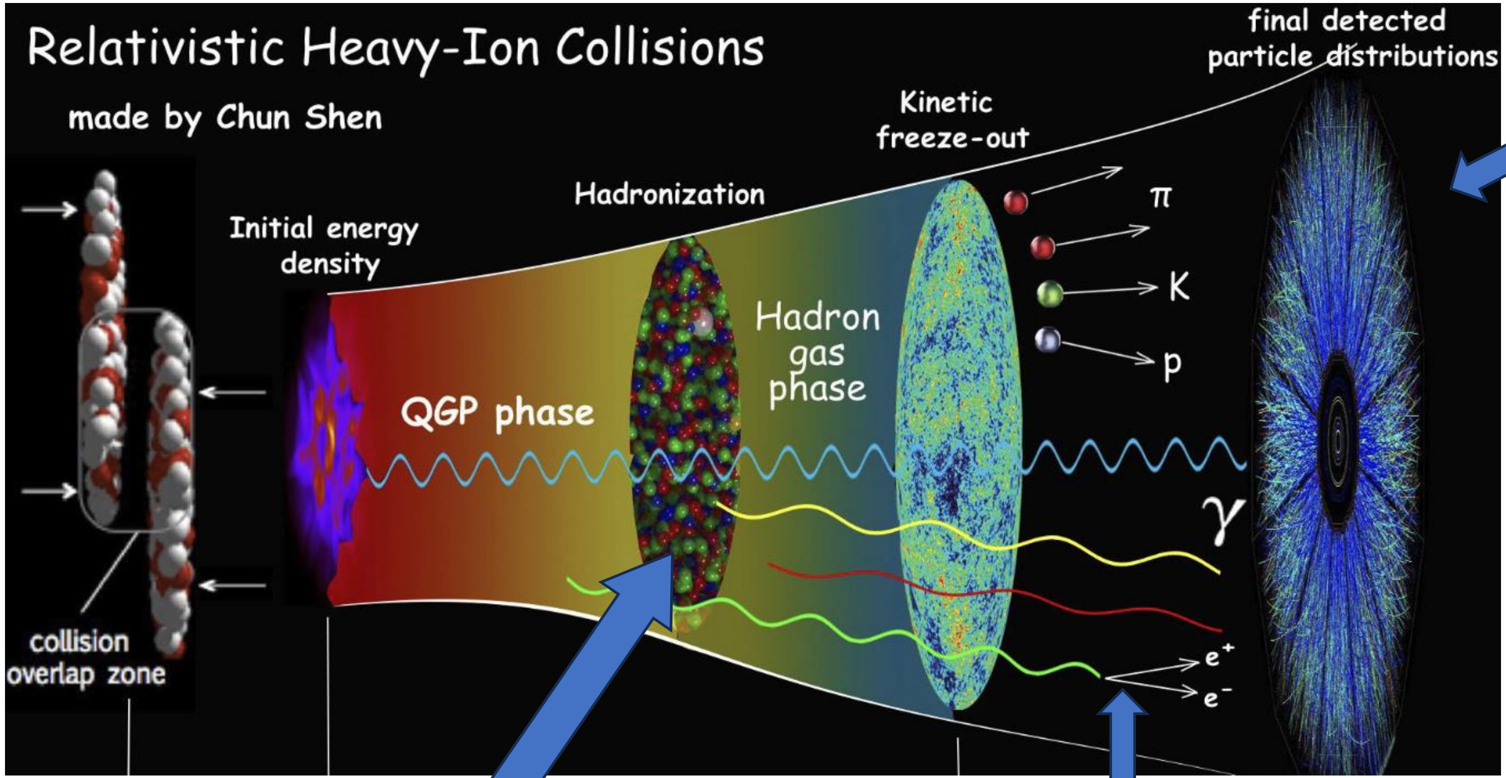


In heavy-ion collisions:

- Momentum acceptance cuts
- V_s is comparable to V_{tot}
  - Global charge conservation effects present
  - Local conservation effects come into play

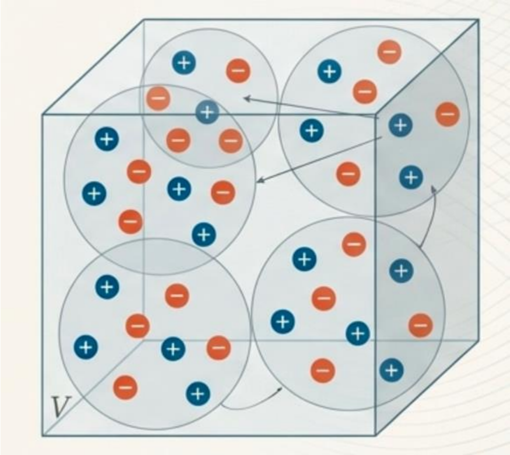


Overview

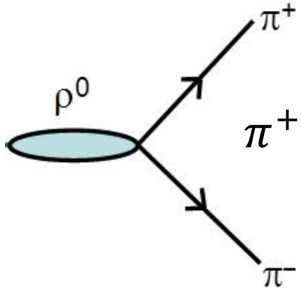


4. Momentum acceptance coordinates

3. Local charge conservation



2. Resonance decays



$\pi^+\pi^-$ are correlated!

1. Fluctuations at hadronization (primordial charges)

$\boldsymbol{\omega}$ – Distinguishes HG from QGP

Parametrization of the Grand-Canonical Charge Susceptibility

In GCE, $\kappa_2[Q] = V\chi_2^Q$

$$\chi_2^Q = \langle n_{\rm ch}^{\rm prim}\rangle + \varphi_2^{Q,\rm prim}$$

Skellam baseline (Self correlations)

Correction (2-particle correlations)

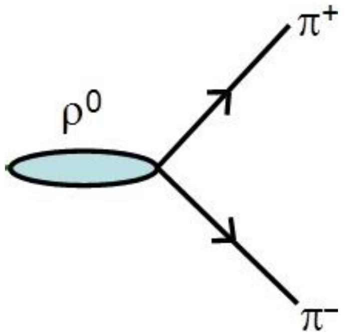
Before decays, strength of interactions is parametrized by ω:

$$\chi_2^Q = \omega\langle n_{\rm ch}^{\rm prim}\rangle \qquad \omega = \frac{\kappa_2[Q]}{\langle N_{\rm ch}^{\rm prim}\rangle} \qquad \varphi_2^{Q,\rm prim} = (\omega - 1)\langle n_{\rm ch}^{\rm prim}\rangle$$

After resonance decays, net charge remains conserved but multiplicities of + and – charges increase:

$$\langle n_{\rm ch}\rangle = \gamma_Q\langle n_{\rm ch}^{\rm prim}\rangle$$

$\gamma_Q \approx 1.67$ Thermal FIST



Correlated!

$$\boxed{\chi_2^Q = \langle n_{\rm ch}\rangle + \left(\frac{\omega}{\gamma_Q} - 1\right)\langle n_{\rm ch}\rangle}$$

Grand-Canonical Fluctuations in Hadron Gas

Electric charge fluctuations can freeze-out in the hadron gas phase or as early as in the QGP phase. Particles detected in experiment may contain the memory of where this occurs.

This distinguishes whether a signal is obtained for HG or QGP.

$$\omega = \frac{\kappa_2[Q]}{\langle N_{\mathrm{ch}}^{\mathrm{prim}} \rangle}$$

variance

charged hadron multiplicity

For hadron gas scenario, ω can be estimated by Poisson statistics, with

$$\kappa_2[Q] \approx \langle N_{\mathrm{ch}}^{\mathrm{prim}} \rangle \rightarrow \omega_{HG} = 1$$

But ω is enhanced by Bose-Einstein statistics for pions and the presence of multi-charged hadrons. An HRG model calculation (Thermal-FIST) gives

$$\boxed{\omega_{HG} = 1.1 \text{ at 155-160 MeV}}$$

Thermal FIST

Grand-Canonical Fluctuations in QGP

But for QGP (quarks), we must take a closer look:

In GCE, $\kappa_2[Q] = V\chi_2^Q$

$$\omega = \frac{\kappa_2[Q]}{\langle N_{\rm ch}^{\rm prim}\rangle} = \frac{VT^3\chi_2^Q}{S}\frac{S}{\langle N_{\rm ch}^{\rm prim}\rangle}$$

$$= \frac{\chi_2^Q}{s/T^3}\frac{S}{\langle N_{\rm ch}\rangle}\frac{\langle N_{\rm ch}\rangle}{\langle N_{\rm ch}^{\rm prim}\rangle}$$

Given by free QGP limit:

$(\chi_2^Q)_{\rm QGP} = 2/3$ $\quad (s/T^3)_{\rm QGP} = \frac{19\pi^2}{9}$

(Stefan-Boltzmann limit)

$\gamma_Q \approx 1.67$ calculated using a thermal model estimate at T = 155 MeV (Thermal-FIST)

$S/N_{\rm ch} = 6.7 \pm 0.8$ at LHC energies

P. Hanus, A. Mazeliauskas, K. Reygers, PRC (2019)

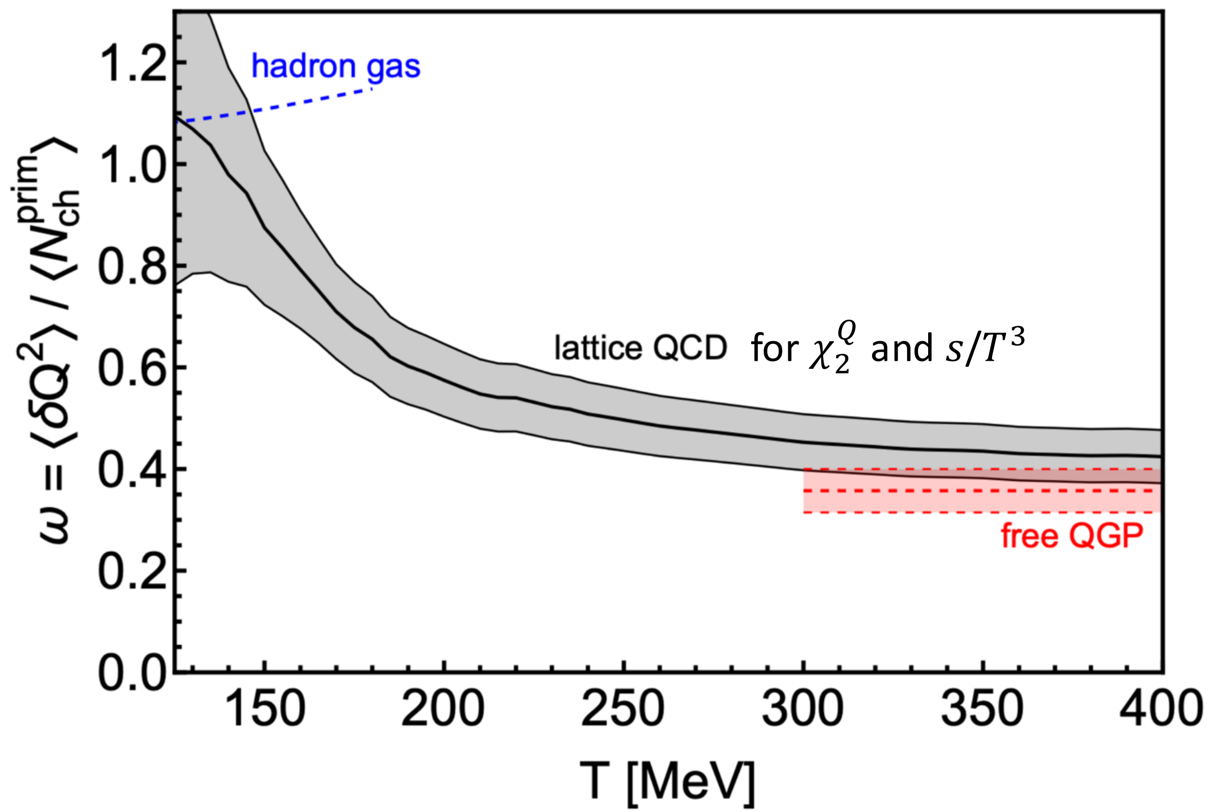
$$\boxed{\omega_{QGP} = 0.36 \pm 0.04}$$

Compared to $\omega_{HG} = 1.1$

Grand-Canonical Fluctuations (General Case)

Using Lattice QCD data (first principles calculations), we can justify our estimates for ω

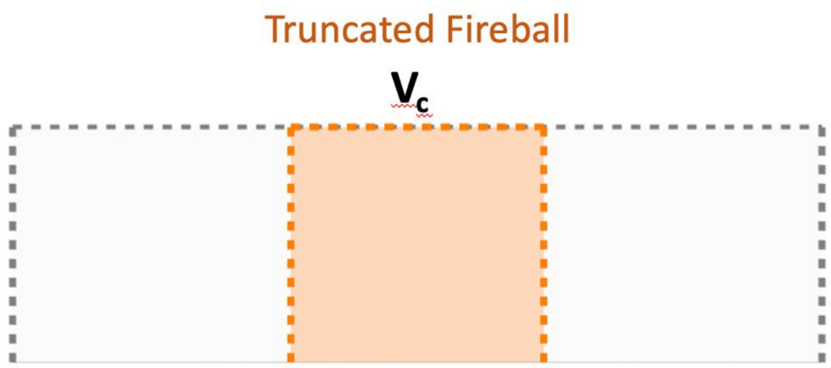
Temperature dependence of ω



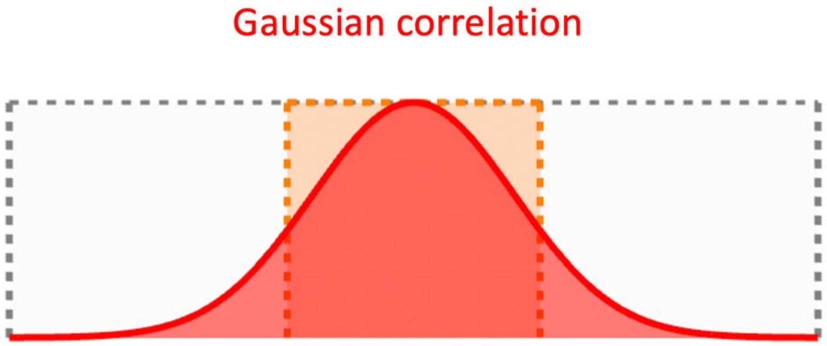
$\omega_{HG} \approx 1.1$ around T < 160 MeV (hadron gas regime)

ω_{QGP} approaches the Stefan-Boltzmann limit ($\omega_{QGP} \approx 0.36$), justifying our value for ω_{QGP}.

Local Charge Conservation



vs



To account for exact charge conservation, we use the 2-point density correlator,

$$\mathcal{C}_2^Q(\mathbf{r}_1, \mathbf{r}_2) \equiv \langle \delta\rho_Q(\mathbf{r}_1)\delta\rho_Q(\mathbf{r}_2)\rangle \quad \text{where} \quad \delta\rho_Q(\mathbf{r}_i) = \rho_Q(\mathbf{r}_i) - \langle \rho_Q(\mathbf{r}_i)\rangle$$

Vovchenko, PRC (2024)

$$\mathcal{C}_2^Q(\mathbf{r}_1, \mathbf{r}_2) = \chi_2^Q \left[\underbrace{\delta(\mathbf{r}_1 - \mathbf{r}_2)}_{\text{local correlation}} - \underbrace{\frac{\varkappa(\mathbf{r}_1, \mathbf{r}_2)}{V_{\text{tot}}}}_{\text{balancing contribution}} \right] \qquad \mathbf{r} = \eta$$

Gaussian local charge conservation:

$$\varkappa(\eta_1, \eta_2) \propto \exp\left[-\frac{(\eta_1 - \eta_2)^2}{2\sigma_\eta^2} \right]$$

Width of local conservation is related to:

$$\frac{V_c}{V_{\text{tot}}} = \sqrt{\frac{\pi}{2}} \frac{\sigma_y}{\eta_{\max}} \text{erf}\left(\frac{\eta_{\max}}{\sqrt{2}\sigma_y} \right)$$

Blast-Wave Model

To calculate acceptance probabilities, we use the blast-wave model:

$$\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV} \qquad p(\eta) \approx 0.84 p_\pi(\eta) + 0.12 p_K(\eta) + 0.04 p_p(\eta)$$

Single-particle species momentum distribution:

$$\boxed{\frac{d^3 N_i}{dp_T d\tilde{\eta}}(\eta) = \frac{E(\tilde{\eta},\eta) p_T^2 \cosh\tilde{\eta}}{\sqrt{(p_T \cosh\tilde{\eta})^2 + m^2}} \int_0^1 \zeta d\zeta\ \exp\left[-\frac{E(\tilde{\eta},\eta)\ \cosh\rho}{T}\right] I_0\left(\frac{p_T \sinh\rho}{T}\right)}$$

$$E(\tilde{\eta},\eta) \equiv m_T\ \cosh(y-\eta) = m_T\ \cosh\left(\operatorname{arcsinh}\left[\frac{p_T\ \sinh\tilde{\eta}}{m_T}\right] - \eta\right) \qquad \begin{aligned} \rho &= \tanh^{-1}(\beta_s \zeta^{n_{\mathrm{BW}}}) \\ m_T &= \sqrt{p_T^2 + m_i^2} \end{aligned}$$

Acceptance probability:

$$p_i(\eta) = \frac{\displaystyle\int_{p_T^{\min}}^{p_T^{\max}} dp_T \int_{-\tilde{\eta}_{\mathrm{cut}}}^{\tilde{\eta}_{\mathrm{cut}}} d\tilde{\eta} \frac{d^3 N}{dp_T d\tilde{\eta}}(\eta)}{\displaystyle\int_0^\infty dp_T \int_{-\infty}^{\infty} d\tilde{\eta} \frac{d^3 N}{dp_T d\tilde{\eta}}(\eta)}$$

Momentum Acceptance

Combining the previous equations,

$$\kappa_2[Q^{\rm acc}] = \int_{-\eta_{\rm max}}^{\eta_{\rm max}} d\eta_1 \int_{-\eta_{\rm max}}^{\eta_{\rm max}} d\eta_2\, C_2^{Q,\rm acc}(\eta_1,\eta_2)$$

$$C_2^{Q,\rm acc}(\eta_1,\eta_2) = \rho_V \left[p(\eta_1)\langle n_{\rm ch}\rangle + p^2(\eta_1)\,\varphi_2^Q\right]\delta(\eta_1-\eta_2) \;-\; \rho_V^2\, p(\eta_1)p(\eta_2)\,\frac{\omega}{\gamma_Q}\langle n_{\rm ch}\rangle\frac{\varkappa(\eta_1,\eta_2)}{V_{\rm tot}}$$

Binomial acceptance model: each particle at spatial rapidity η is detected with probability p(η).
Self-corr. (1-body) → ×p(η); pair corr. (2-body) → ×$p(\eta_1)p(\eta_2)$. The D-measure reads:

$$D = 4\frac{\kappa_2[Q]}{\langle Q^+ + Q^-\rangle} = 4\left\{\underbrace{1}_{\text{Skellam baseline}} - \underbrace{\left(1-\frac{\omega}{\gamma_Q}\right)\frac{\langle p^2(\eta)\rangle}{\langle p(\eta)\rangle}}_{\text{local 2-particle correlations}} - \underbrace{\frac{\omega}{\gamma_Q}\frac{\langle p(\eta_1)p(\eta_2)\rangle_\varkappa}{\langle p(\eta)\rangle}}_{\text{long-range 2-particle correlations}}\right\}$$

where,

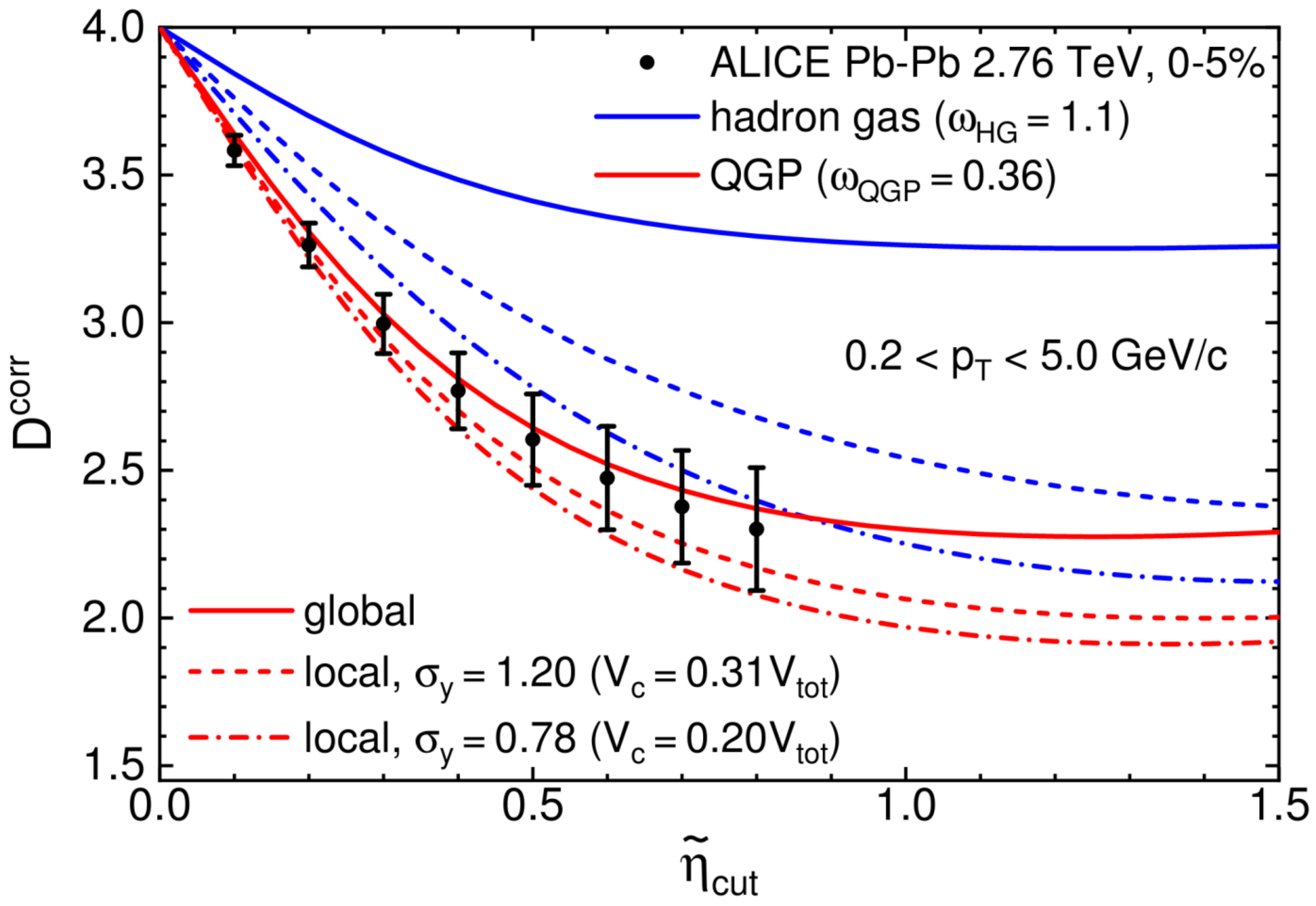
$$\langle p^n(\eta)\rangle = \frac{1}{2\eta_{\rm max}}\int d\eta p^n(\eta)$$ and p(η) is found using BW model calculations

$$\langle p(\eta_1)p(\eta_2)\rangle_\varkappa = \frac{1}{4\eta_{\rm max}^2}\iint d\eta_1 d\eta_2 p(\eta_1)p(\eta_2)\varkappa(\eta_1,\eta_2)$$

Parra, RP, Koch, Ratti, Vovchenko, 2504.02085 (2025)

Comparison to ALICE Run 1 Data

$$D = 4\left\{1 - \left(1 - \frac{\omega}{\gamma_Q}\right)\frac{\langle p^2(\eta)\rangle}{\langle p(\eta)\rangle} - \frac{\omega}{\gamma_Q}\frac{\langle p(\eta_1)p(\eta_2)\rangle_{\varkappa}}{\langle p(\eta)\rangle}\right\}$$



Parameters used:

$\omega_{HG} = 1.1$ $\omega_{QGP} = 0.36$

γ_Q = 1.67

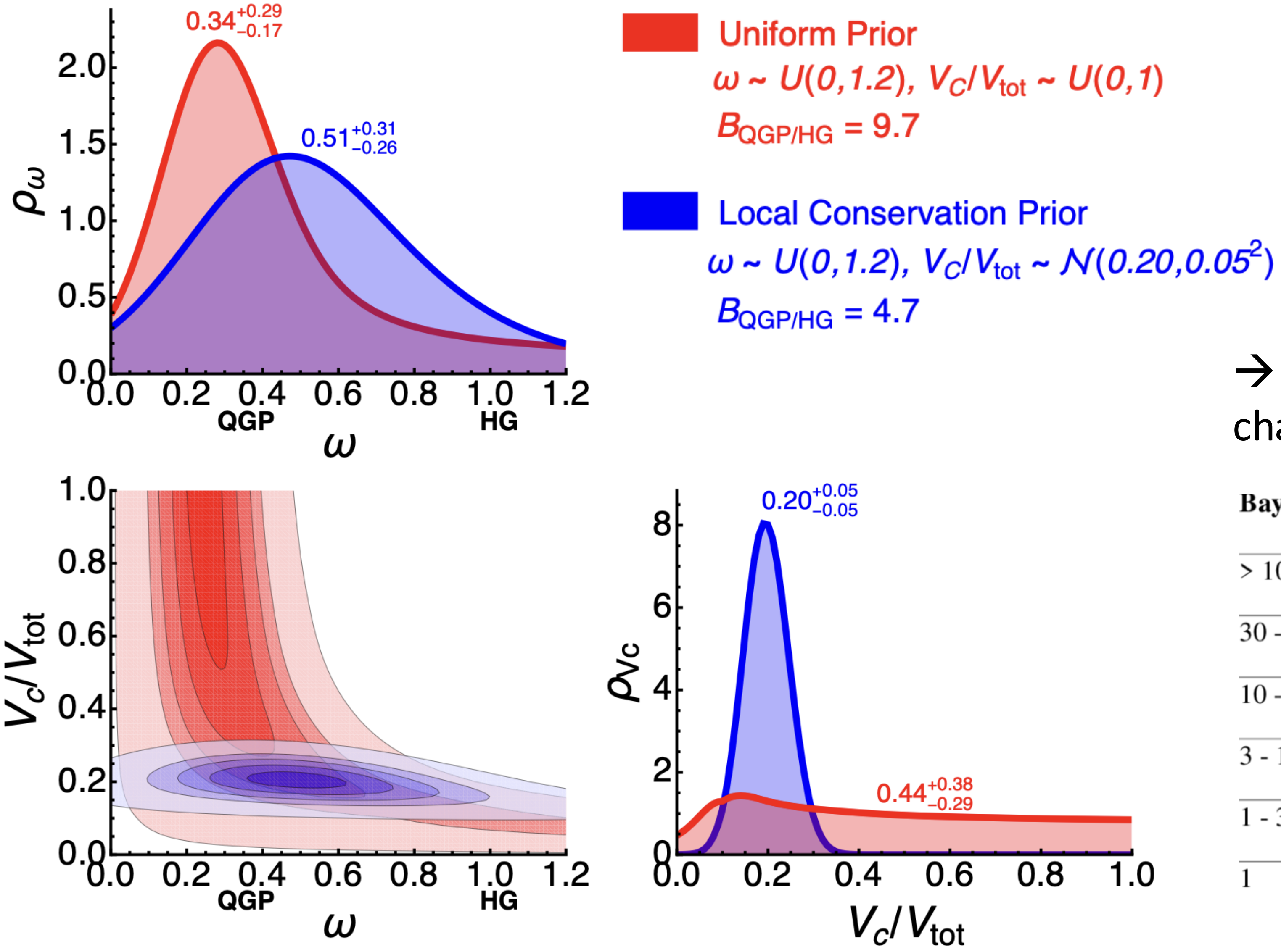
- Vary σ_y for global and local charge conservation

$$D^{\mathrm{corr}} = \frac{D' + D''}{2}$$

$$D' = D + 4\langle p(\eta)\rangle, \qquad D'' = \frac{D}{1 - \langle p(\eta)\rangle}$$

Parra, RP, Koch, Ratti, Vovchenko, 2504.02085 (2025)

Bayesian analysis of ω and σ parameters in D-measure

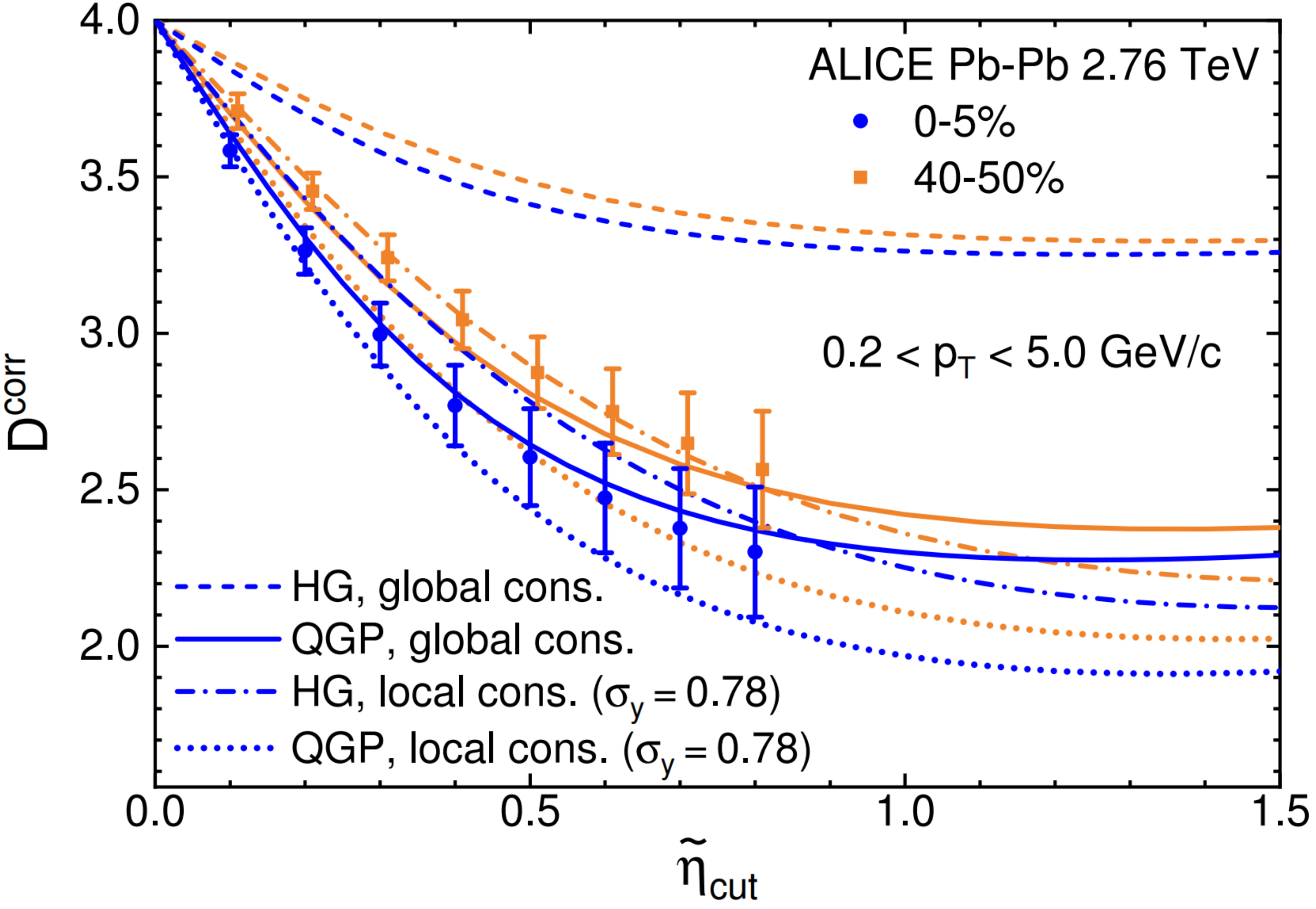


→ **Moderate** evidence for freeze-out of charge fluctuations in QGP phase (ω).

Bayes factor BF_{12} for H_1 over H_2	Evidence category
> 100	Extreme evidence for H_1 over H_2
30 - 100	Very strong evidence for H_1 over H_2
10 - 30	Strong evidence for H_1 over H_2
3 - 10	Moderate evidence for H_1 over H_2
1 - 3	Anecdotal evidence for H_1 over H_2
1	No evidence over H_2

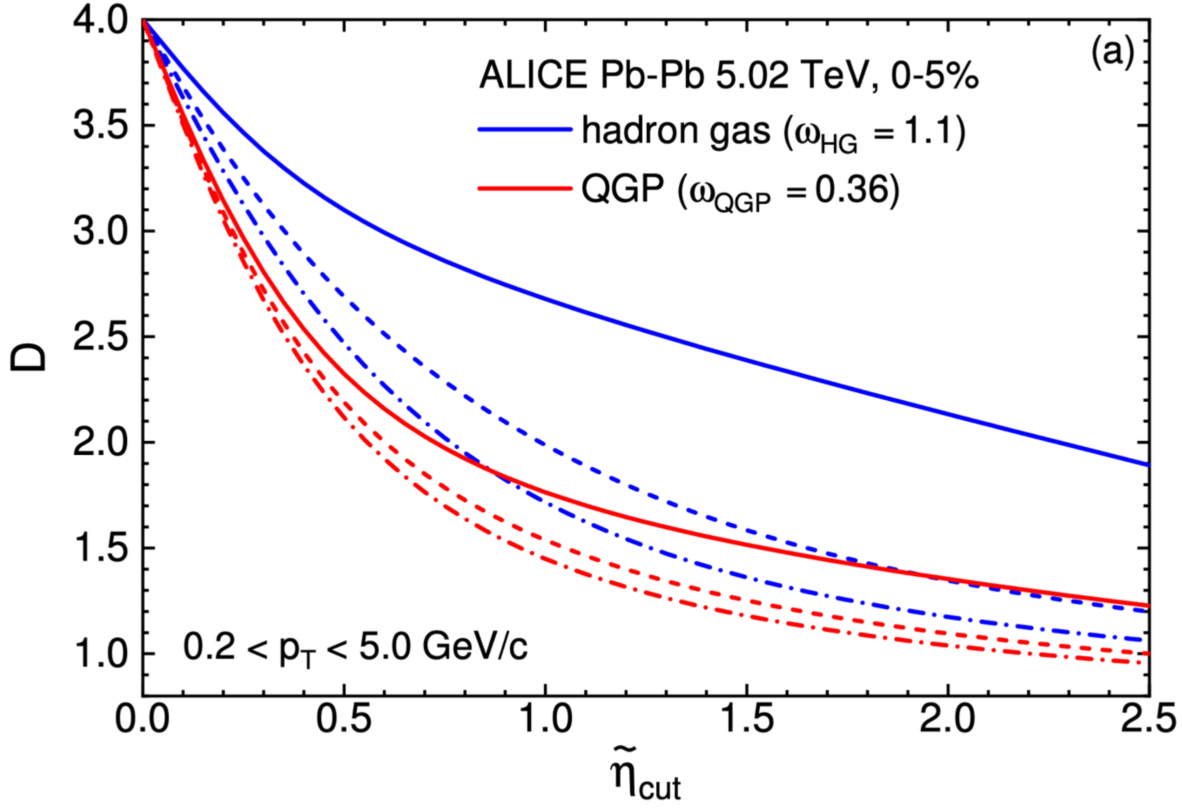
Parra, RP, Koch, Ratti, Vovchenko, 2504.02085 (2025)

Semi-peripheral collisions

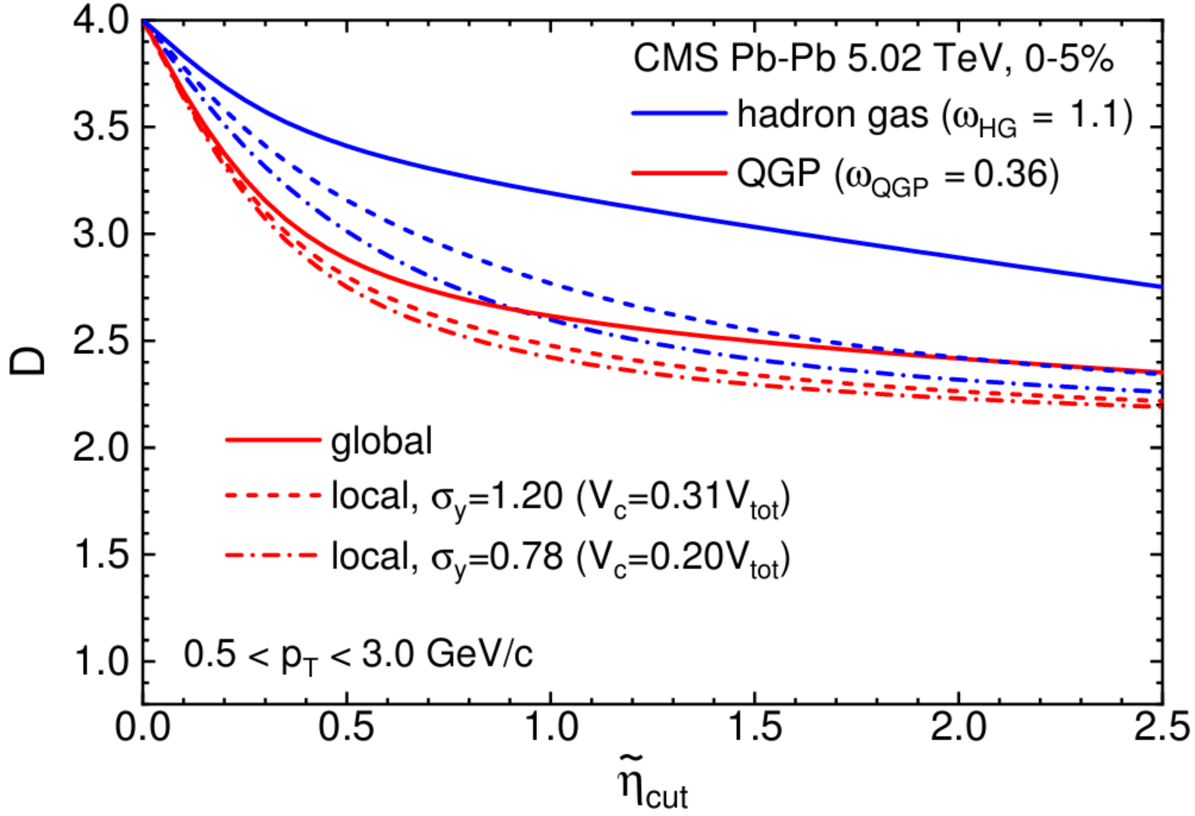


LHC Run 2 predictions

ALICE



CMS



Conclusion and Outlook

- We performed quantitative calculations for charge fluctuations for QGP and hadronic scenario.
  - To do this, we incorporated global/local charge conservation effects, resonance decays, and momentum acceptance.
- We obtained moderate evidence for freeze-out of charge fluctuations in QGP phase.
- We presented predictions for ALICE Run 2 using our formalism.
- Looking forward to ALICE Run 2 data to refine the result.
- This formalism can be extended to RHIC energies.

Conclusion and Outlook

- We performed quantitative calculations for charge fluctuations for QGP and hadronic scenario.
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- Looking forward to ALICE Run 2 data to refine the result.
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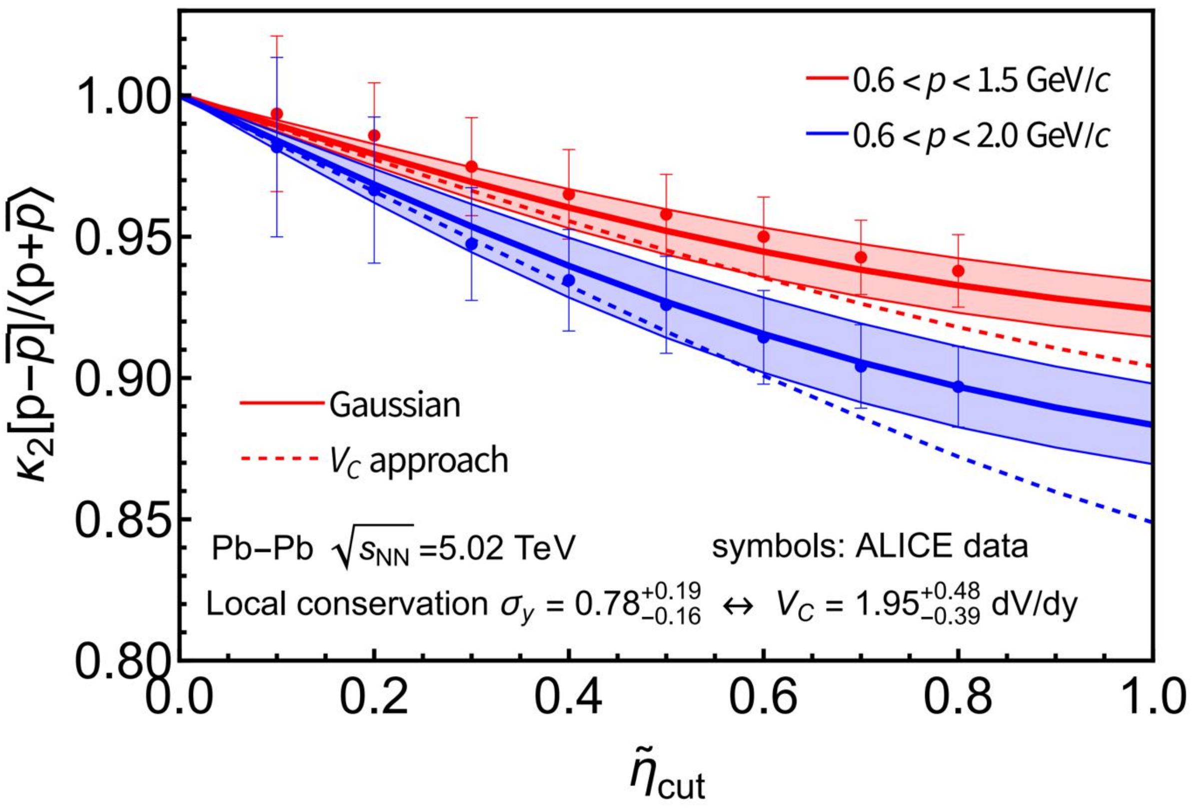
Thank you for your attention!

Backup Slides

Local Charge Conservation



V. Vovchenko, PRC (2024)

Global:

$$\sigma_\eta \to \infty : \varkappa(\eta_1, \eta_2) \to 1$$

$$\mathcal{C}_2^Q(\eta_1, \eta_2) = \chi_2^Q \left[\delta(\eta_1 - \eta_2) - \frac{1}{V}\right]$$

Integrating C_2^Q yields the net-charge variance

$$\kappa_2[Q]|_{|\eta|<\eta_{\rm cut}} = \int_{-\eta_{\rm cut}/2}^{\eta_{\rm cut}/2} d\eta_1 \int_{-\eta_{\rm cut}/2}^{\eta_{\rm cut}/2} d\eta_2 \mathcal{C}_2^Q(\eta_1, \eta_2)$$

$$\kappa_1[Q] = V\alpha\chi_1^Q$$

$$\kappa_2[Q] = V\alpha\,(1-\alpha)\,\chi_2^Q \qquad \beta = 1 - \alpha$$

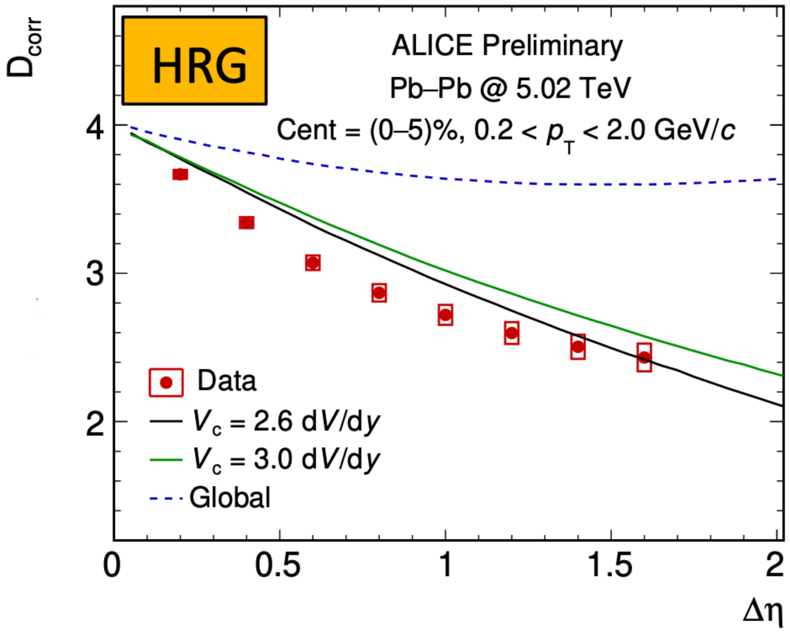
$$\kappa_3[Q] = V\alpha\beta\,(1-2\alpha)\,\chi_3^Q$$

$$\kappa_4[Q] = V\alpha\beta\,\left[\chi_4^Q - 3\alpha\beta\frac{(\chi_3^Q)^2 + \chi_2^Q\chi_4^Q}{\chi_2^Q}\right]$$

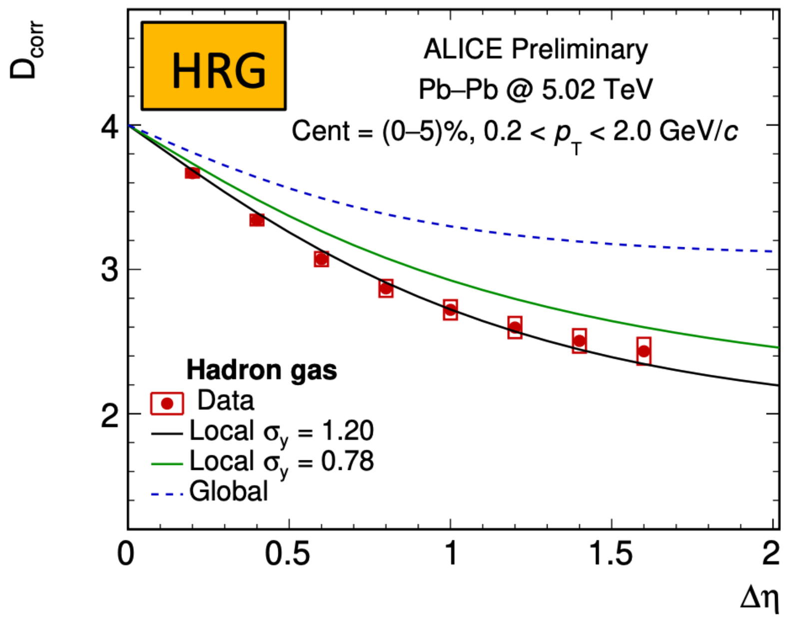
Subensemble Acceptance Method (SAM)

Preliminary Run 2 data

Subvolume approach



Gaussian correlation



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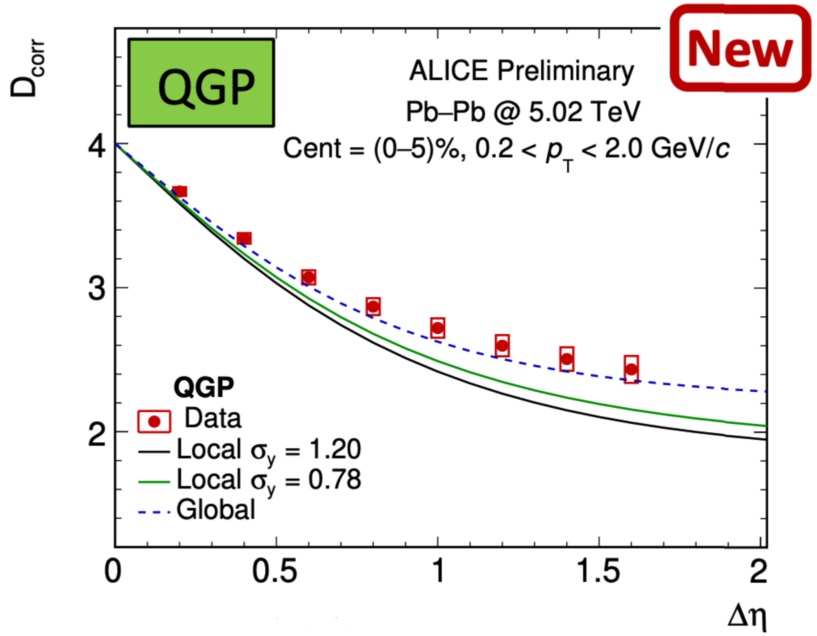
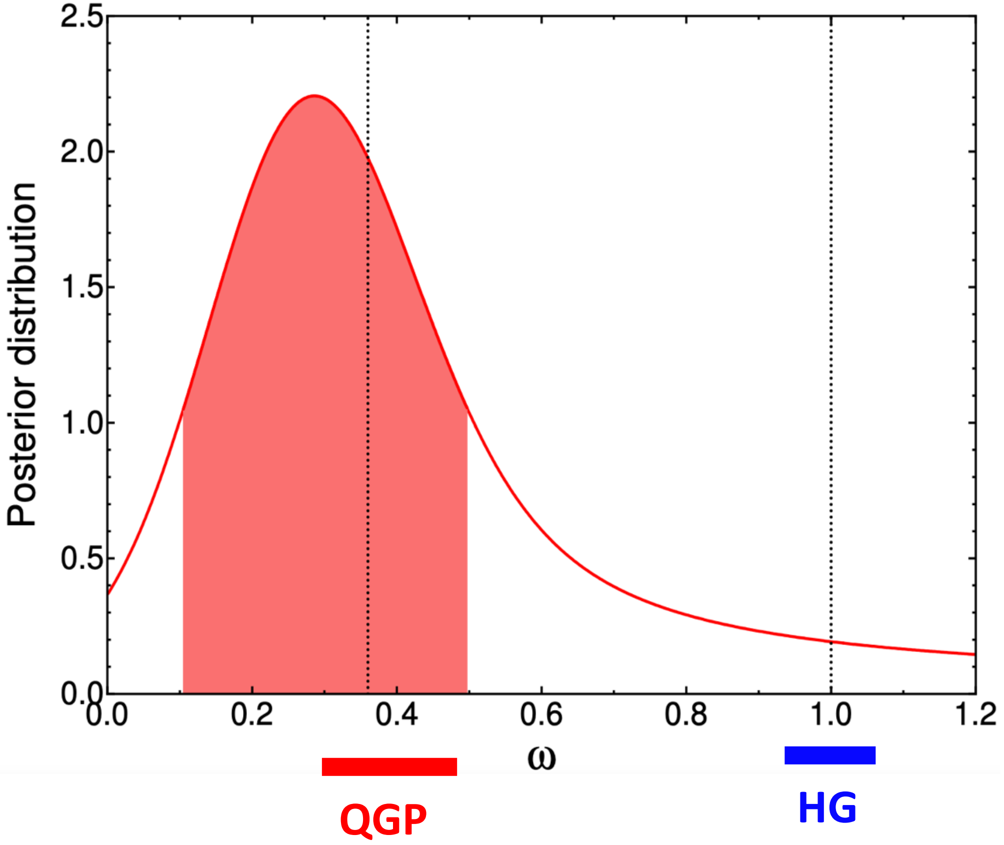
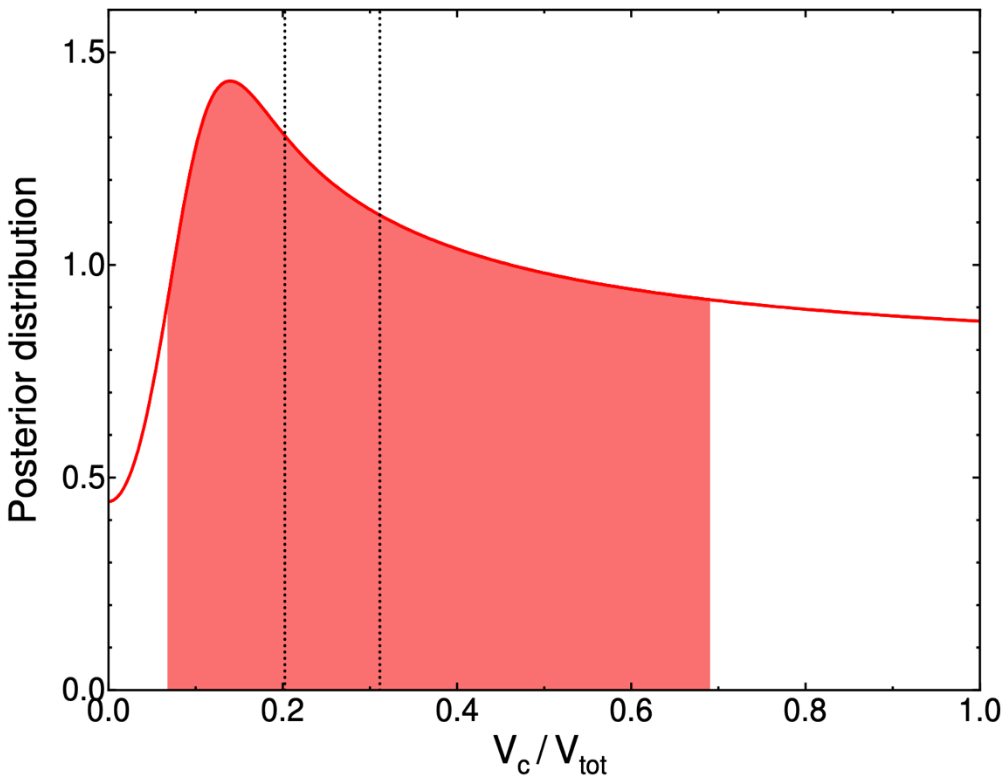


from the talk of Mesut Arslandok at QM2025

Bayesian analysis of ω and σ parameters in D-measure





Moderate evidence for freeze-out of charge fluctuations in QGP (ω).

Bayes factor with uniform priors: 9.8

$$k(\sigma_y) = \sqrt{2\pi}\sigma_y \mathrm{erf}\left(\frac{\eta_{\max}}{\sqrt{2}\sigma_y}\right) \approx \sqrt{2\pi}\sigma_y$$

$$V_c = k dV/dy$$

J. Parra, R. Poberezhniuk, et al., in preparation

Grand canonical net-charge susceptibility

Poisson baseline

correction (two-particle local correlations)

$$\chi_2^Q = \langle n_+ + n_- \rangle + \tilde{\chi}_2^Q$$

Parametrization: $$\chi_2^Q = \omega \langle n_+ + n_- \rangle$$

$$\tilde{\chi}_2^Q = (\omega - 1)\langle n_+ + n_- \rangle$$

Resonance decays: $$\chi_2^{Q,\mathrm{after}} = \gamma_+ \langle n_+ \rangle + \gamma_- \langle n_- \rangle + \tilde{\chi}_2^{Q,\mathrm{after}}$$

$$Q = \gamma_+ n_+ - \gamma_- n_- = n_+ - n_-$$

$$\chi_2^{Q,\mathrm{after}} = \chi_2^{Q,\mathrm{before}}$$

$$\chi_2^Q = \gamma_+ \langle n_+ \rangle + \gamma_- \langle n_- \rangle + (\omega - \gamma_+)\langle n_+ \rangle + (\omega - \gamma_-)\langle n_- \rangle$$

$$\gamma_Q = \frac{\gamma_+ \langle n_+ \rangle + \gamma_- \langle n_- \rangle}{\langle n_+ \rangle + \langle n_- \rangle}$$

$$\chi_2^Q = \gamma_Q \langle n_+ + n_- \rangle + (\omega - \gamma_Q)\langle n_+ + n_- \rangle$$

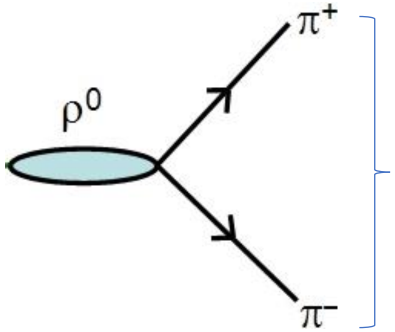
Charge Susceptibility, χ_2^Q and Resonance Decays, γ_Q

Next, we take resonance decays into account.

Decays like $\rho^0 \rightarrow \pi^+\pi^-$ introduce correlations between charged particles

Charge susceptibility after decays:

$$\begin{aligned}\chi_2^{Q,\mathrm{final}} &= \gamma_+\langle n_+\rangle + \gamma_-\langle n_-\rangle + \tilde{\chi}_2^{Q,\mathrm{final}} \\ &= \langle n_+ + n_-\rangle_{\mathrm{final}} + \tilde{\chi}_2^{Q,\mathrm{final}},\end{aligned}$$



But net electric charge density is conserved overall

$$n_Q = \gamma_+ n_+ - \gamma_- n_- = n_+ - n_-$$

$$\chi_2^{Q,\mathrm{final}} = \chi_2^{Q,\mathrm{prim}}$$

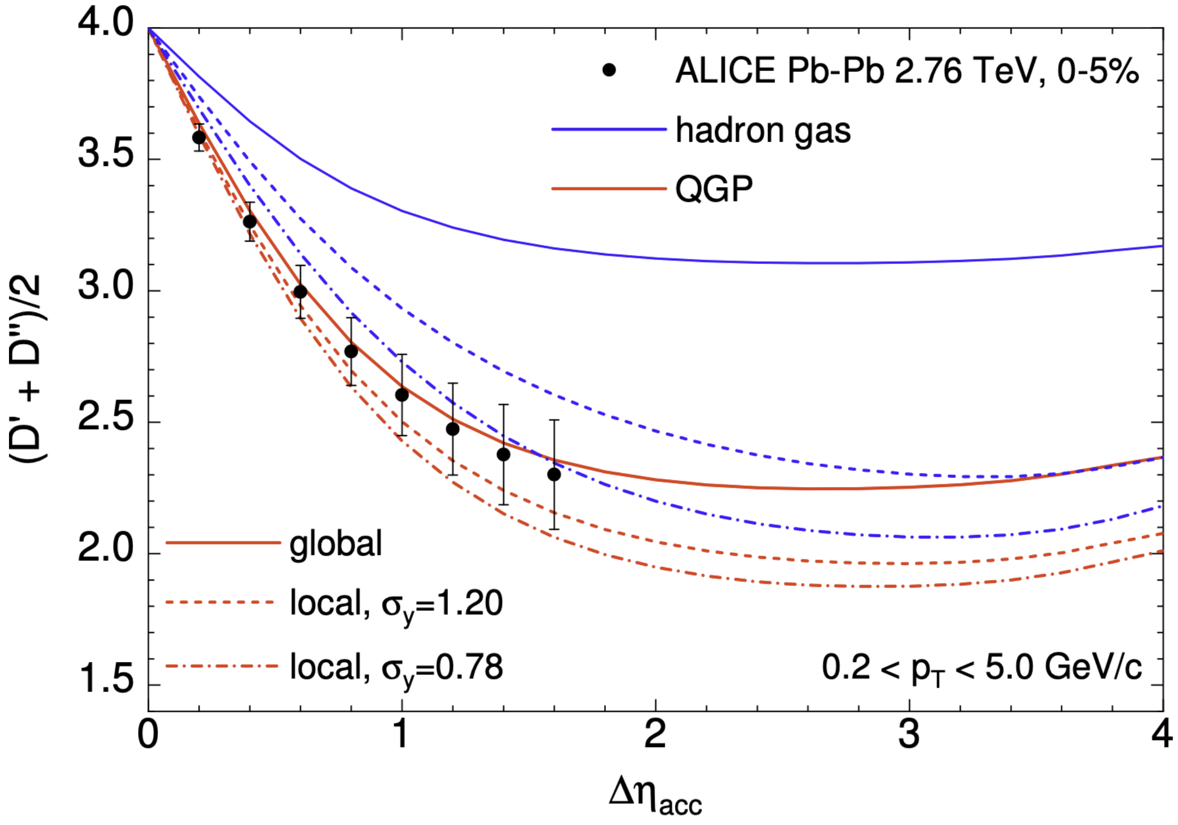
Implementing interaction parameter ω:

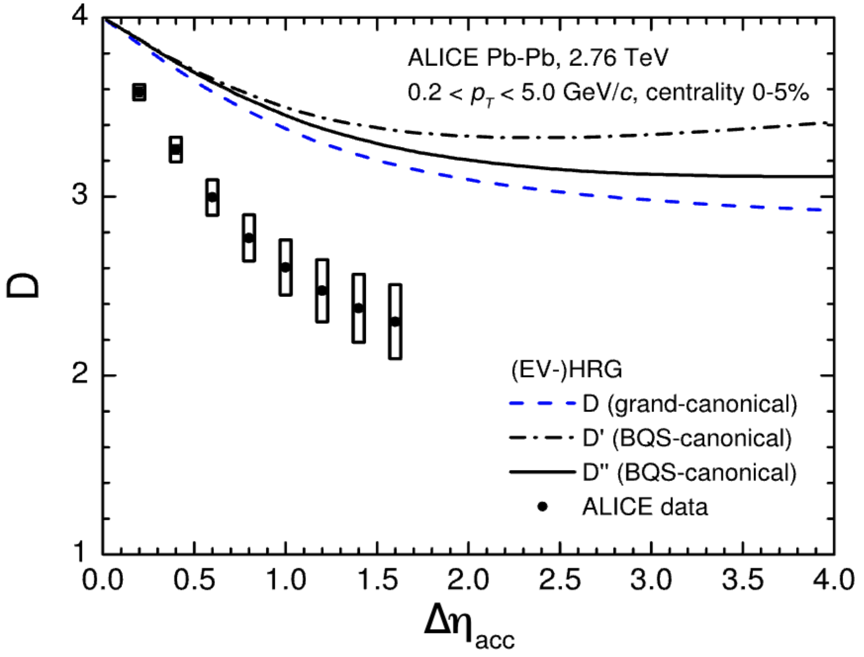
$$\chi_2^Q = \gamma_+\langle n_+\rangle + \gamma_-\langle n_-\rangle + (\omega - \gamma_+)\langle n_+\rangle + (\omega - \gamma_-)\langle n_-\rangle$$

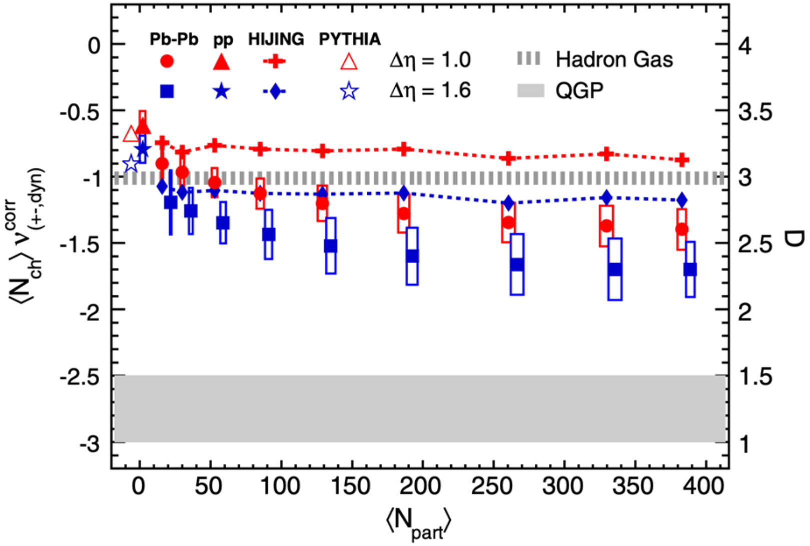
$\approx 5/3$

$$\boxed{\begin{aligned}\chi_2^Q &= \gamma_Q\langle n_+ + n_-\rangle + (\omega - \gamma_Q)\langle n_+ + n_-\rangle \\ &= \langle n_+ + n_-\rangle_{\mathrm{final}} + \left(\frac{\omega}{\gamma_Q} - 1\right)\langle n_+ + n_-\rangle_{\mathrm{final}}\end{aligned}}$$

Comparison to previous estimates



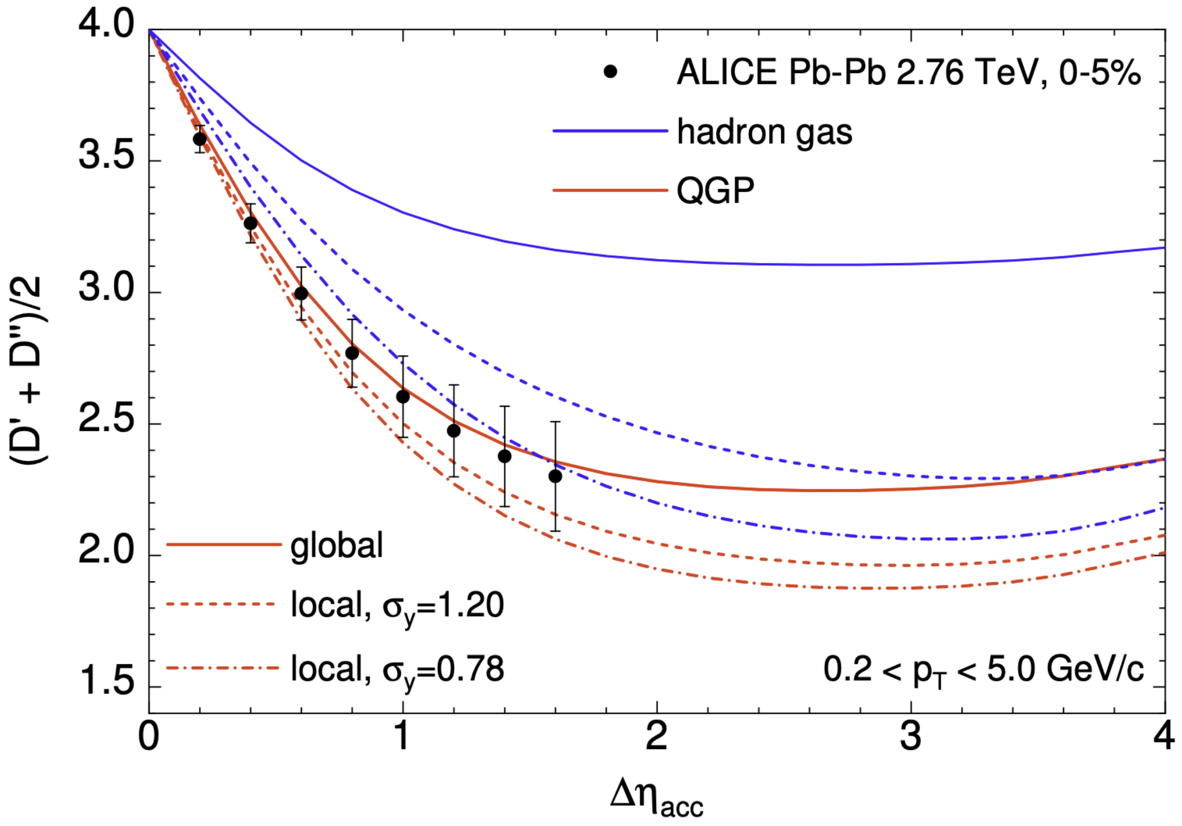




Bayesian analysis of ω and σ parameters in D-measure

Posterior probability = likelihood function → $p(\omega, \sigma_\eta|\vec{D}) = p(\vec{D}|\omega, \sigma_\eta)$

$$\rightarrow p(\omega, \sigma_\eta|\vec{D}) = p(\vec{D}|\omega, \sigma_\eta) = \frac{e^{-\chi^2/2}}{\sum_{\omega,\sigma_\eta} e^{-\chi^2/2}}$$



$$\chi^2 = \frac{(D_{0.1} - D_{0.1}(\omega, \sigma_\eta))^2}{\sigma_{0.1}^2} + \frac{(D_{0.8} - D_{0.8}(\omega, \sigma_\eta))^2}{\sigma_{0.8}^2}$$

Where, from the ALICE data points,
$D_{0.1}$ = 3.5833, $D_{0.8}$ =2.301, and
$\sigma_{0.1}$ = 0.051456, $\sigma_{0.8}$ = 0.208166

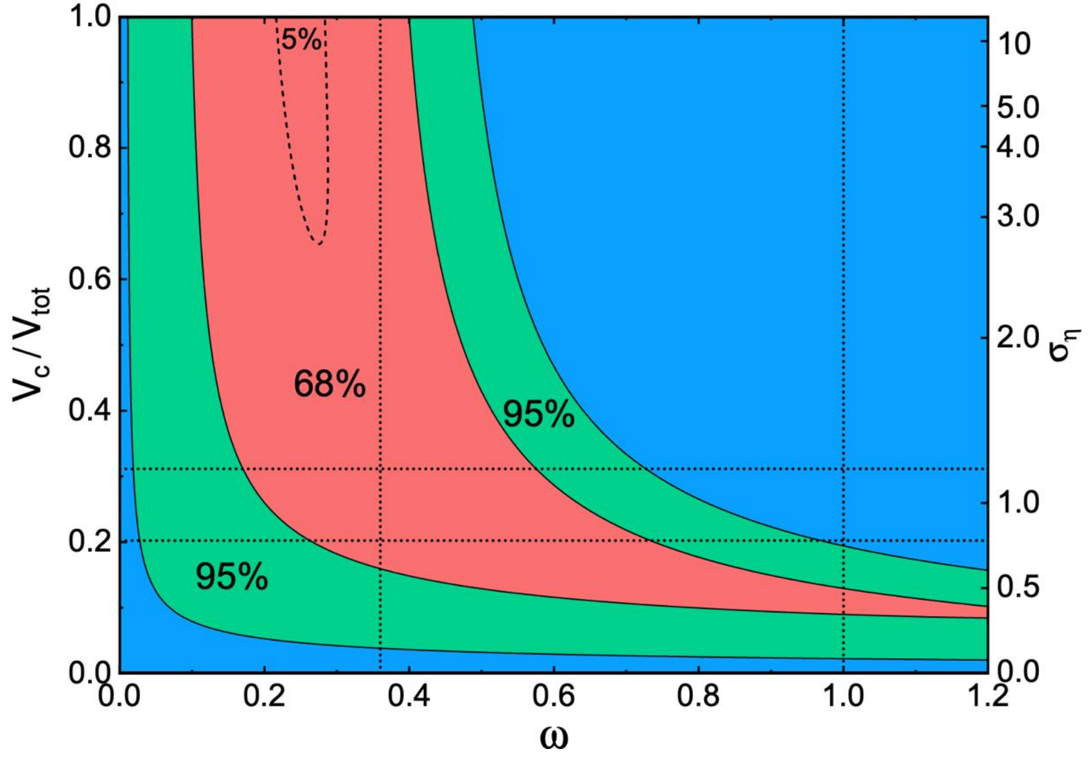
$$D_{0.1}(\omega, \sigma_\eta) = \frac{D'_{0.1}(\omega, \sigma_\eta) + D''_{0.1}(\omega, \sigma_\eta)}{2}$$

$$D_{0.8}(\omega, \sigma_\eta) = \frac{D'_{0.8}(\omega, \sigma_\eta) + D''_{0.8}(\omega, \sigma_\eta)}{2}$$

J. Parra, R. Poberezhniuk, et al., in preparation

Bayesian analysis of ω and σ parameters in D-measure

2-D Contour Plot of Posterior Probabilities



Regions where the sum,

$$\sum p(\omega, \sigma_\eta | \vec{D}) \Delta\omega \Delta\sigma_\eta$$

reach 0.68 and 0.95.

J. Parra, R. Poberezhniuk, et al., in preparation

Non-uniform volume distribution

$$\mathcal{C}_2^Q(\eta_1,\eta_2) = \frac{dV}{d\eta}(\eta_1)\chi_2^Q\left[\delta(\eta_1-\eta_2) - \frac{dV}{d\eta}(\eta_2)\frac{\varkappa(\eta_1,\eta_2)}{V_{\rm tot}}\right]$$
$$= \frac{dV}{d\eta}(\eta_1)\langle n_+ + n_-\rangle_{\rm final}\delta(\eta_1-\eta_2)$$
$$+ \frac{dV}{d\eta}(\eta_1)\left(\frac{\omega}{\gamma_Q}-1\right)\langle n_+ + n_-\rangle_{\rm final}\delta(\eta_1-\eta_2) - \frac{dV}{d\eta}(\eta_1)\frac{dV}{d\eta}(\eta_2)\frac{\omega}{\gamma_Q}\langle n_+ + n_-\rangle_{\rm final}\frac{\varkappa(\eta_1,\eta_2)}{V_{\rm tot}}$$

$$\langle p^n(\eta)\rangle = \frac{1}{V_{\rm tot}}\int d\eta\frac{dV}{d\eta}(\eta)p^n(\eta)$$

$$\langle p(\eta_1)p(\eta_2)\rangle_{\varkappa} = \frac{1}{V_{\rm tot}^2}\int d\eta_1\frac{dV}{d\eta}(\eta_1)\int d\eta_2\frac{dV}{d\eta}(\eta_2)p(\eta_1)p(\eta_2)\varkappa(\eta_1,\eta_2)$$

$$V_{\rm tot} = \frac{dV}{dy}\sqrt{2\pi}\sigma_V \qquad \frac{dV}{d\eta}(\eta) = \frac{dV}{dy}\exp\left(-\frac{\eta^2}{2\sigma_V^2}\right)$$

$$\sigma_V = 3.86$$