Probing QGP using local charge fluctuations in heavy-ion collisions

Jonathan Parra

Collaborators: **Roman Poberezhniuk**, Volker Koch, Claudia Ratti, Volodymyr Vovchenko

JP, R. Poberezhniuk, et al., arXiv:2504.02085 (2025)

UNIVERSITY of HOUSTON
DEPARTMENT OF PHYSICS

QM25

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NuSTEAM
Nuclear Science in Texas to Enhance and Advance Mentees

Phase Diagram of Nuclear (QCD) Matter

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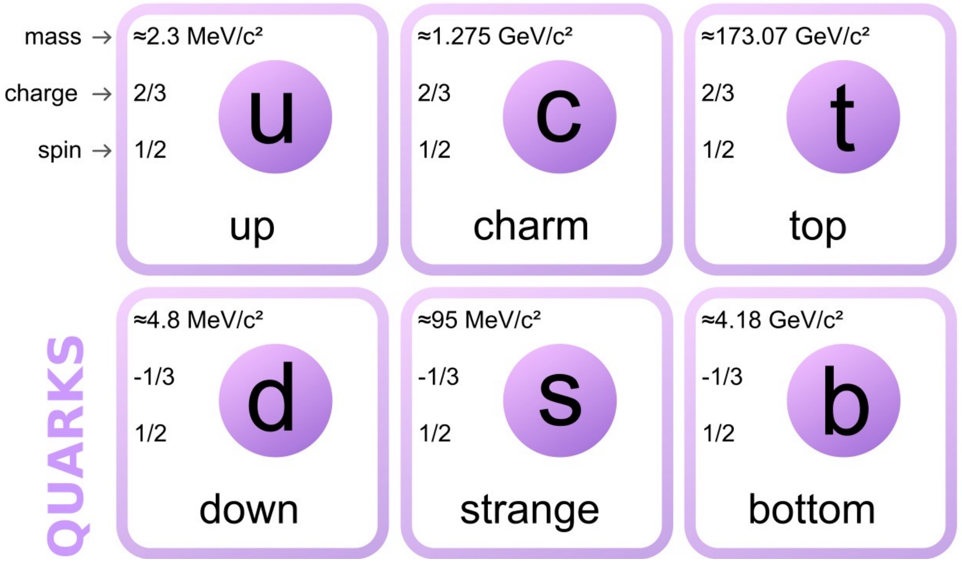
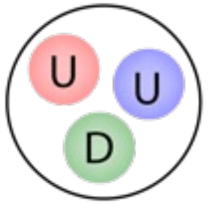
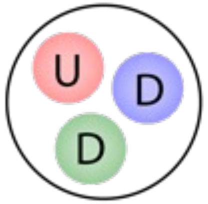




Proton

U = "up" quark $+\frac{2}{3}$ e

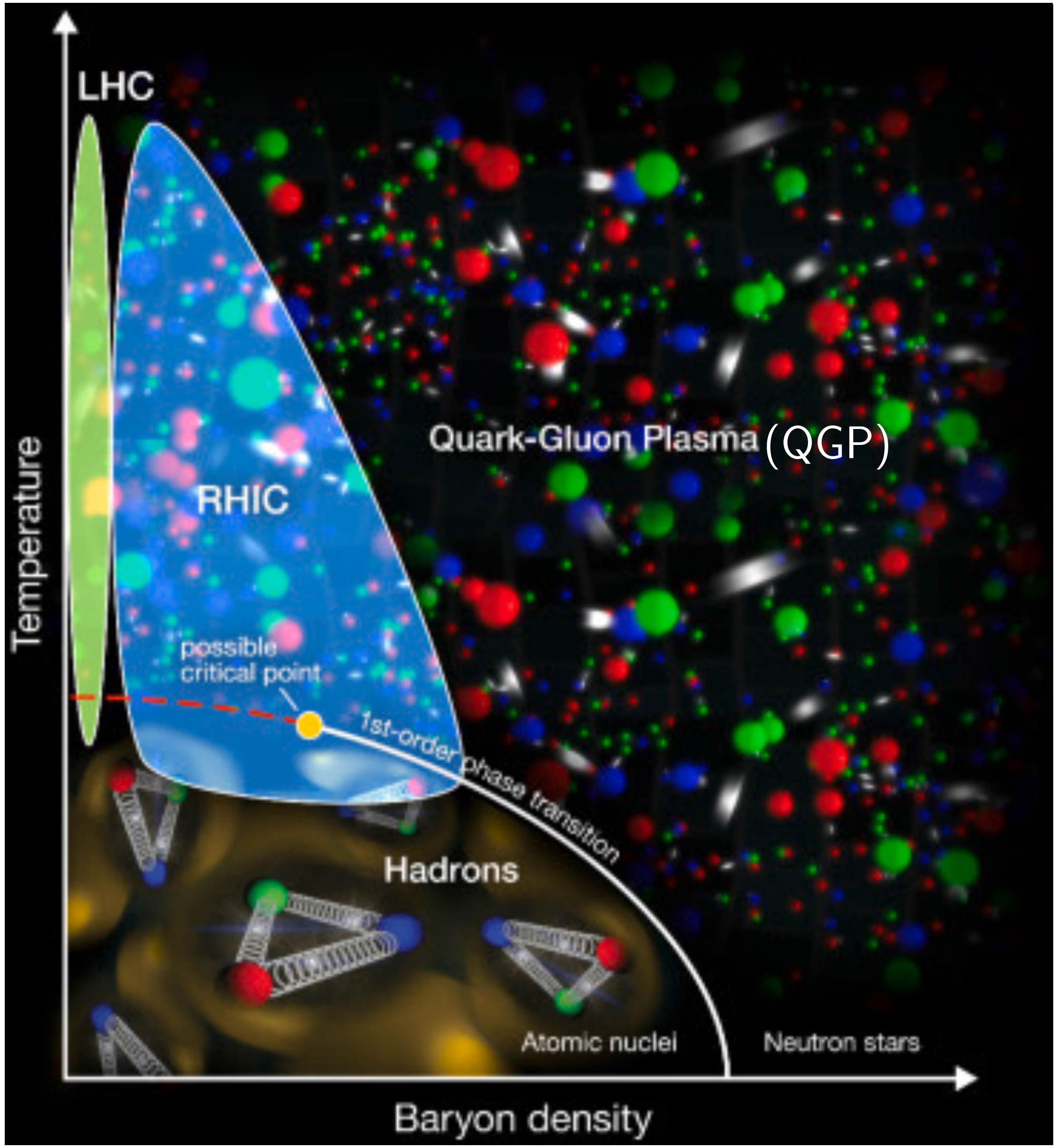
D = "down" quark $-\frac{1}{3}$ e



Neutron

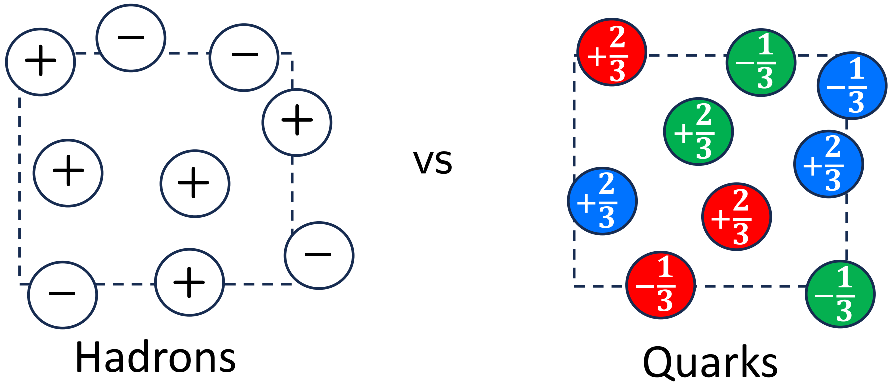
Quarks make up hadrons!

BNL



The Main Idea

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



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

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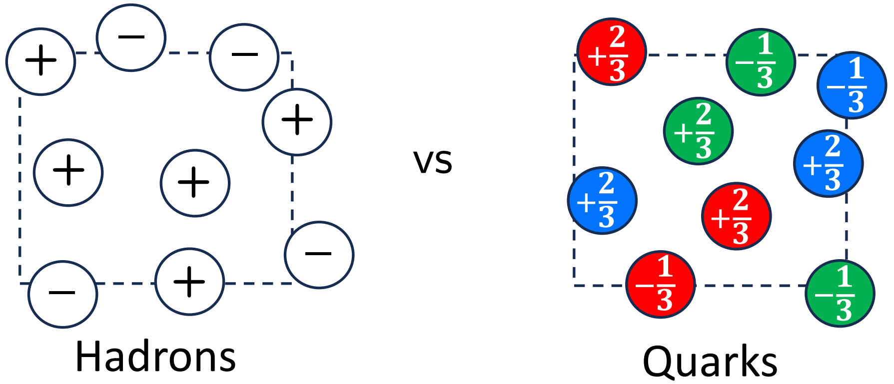

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Quantified by D-measure:

$$D = 4\frac{\kappa_2[N_+ - N_-]}{\langle N_{\mathrm{ch}} \rangle} = 4\frac{\kappa_2[Q]}{\langle Q^+ + Q^- \rangle}$$

Koch, Jeon, Phys. Rev. Lett 85, 2076 (2000)
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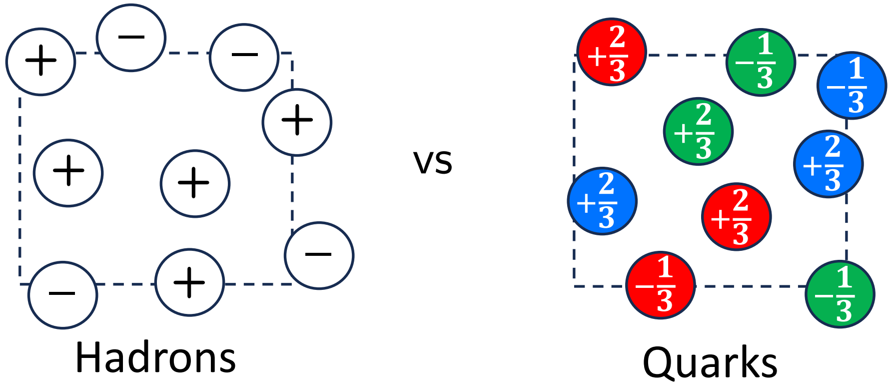

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- $D_{HG} \approx 2.8 - 4$
- $D_{QGP} \approx 1 - 1.5$

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

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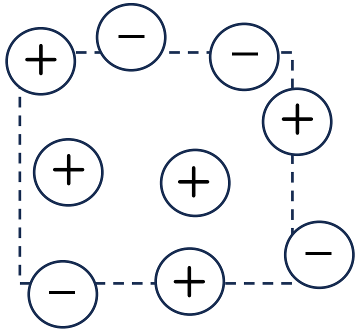
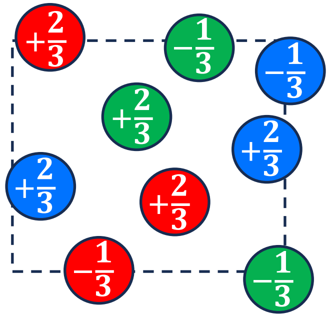


Hadrons

vs



Quarks

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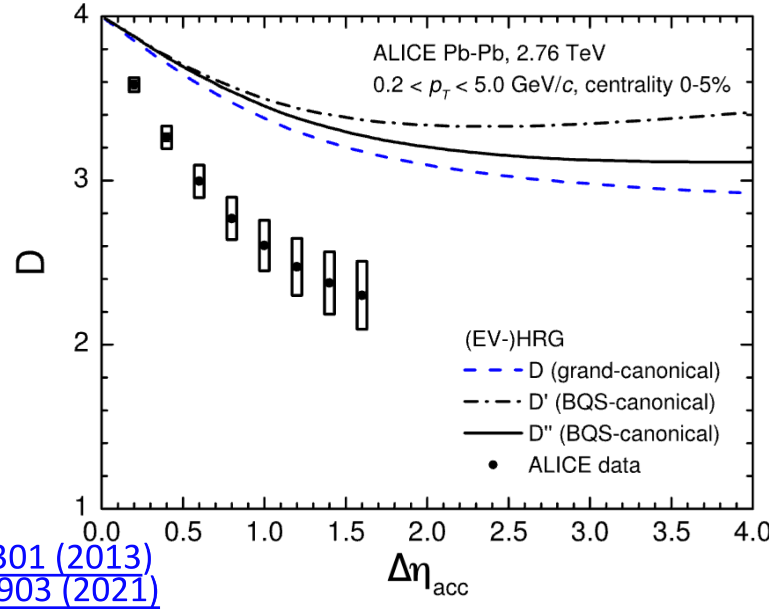

ALICE Collab., Phys. Rev. Lett. 110, 152301 (2013)
Vovchenko, Koch, Phys. Rev. C 103, 044903 (2021)

GCE vs Heavy-Ion Collisions

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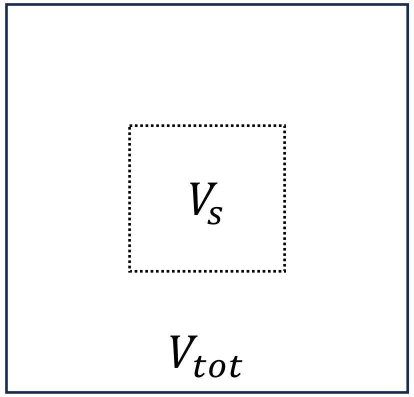
In Grand Canonical Ensemble (GCE):

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



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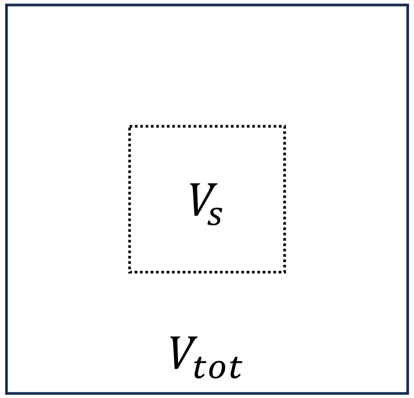
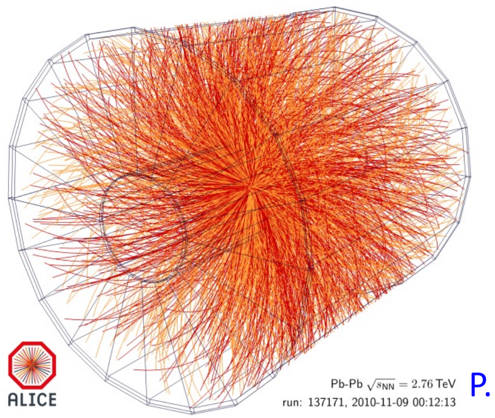
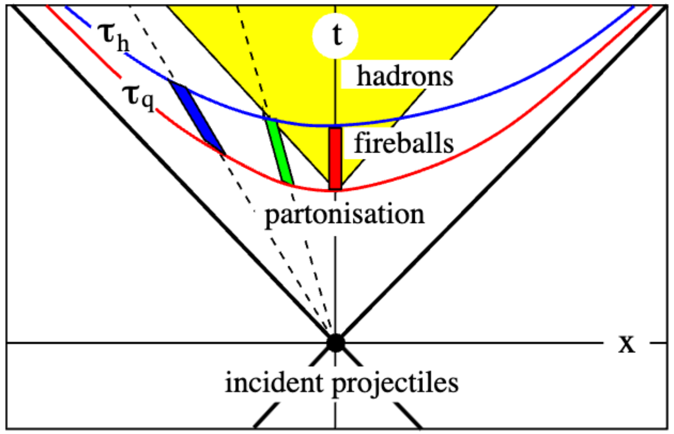


In heavy-ion collisions:

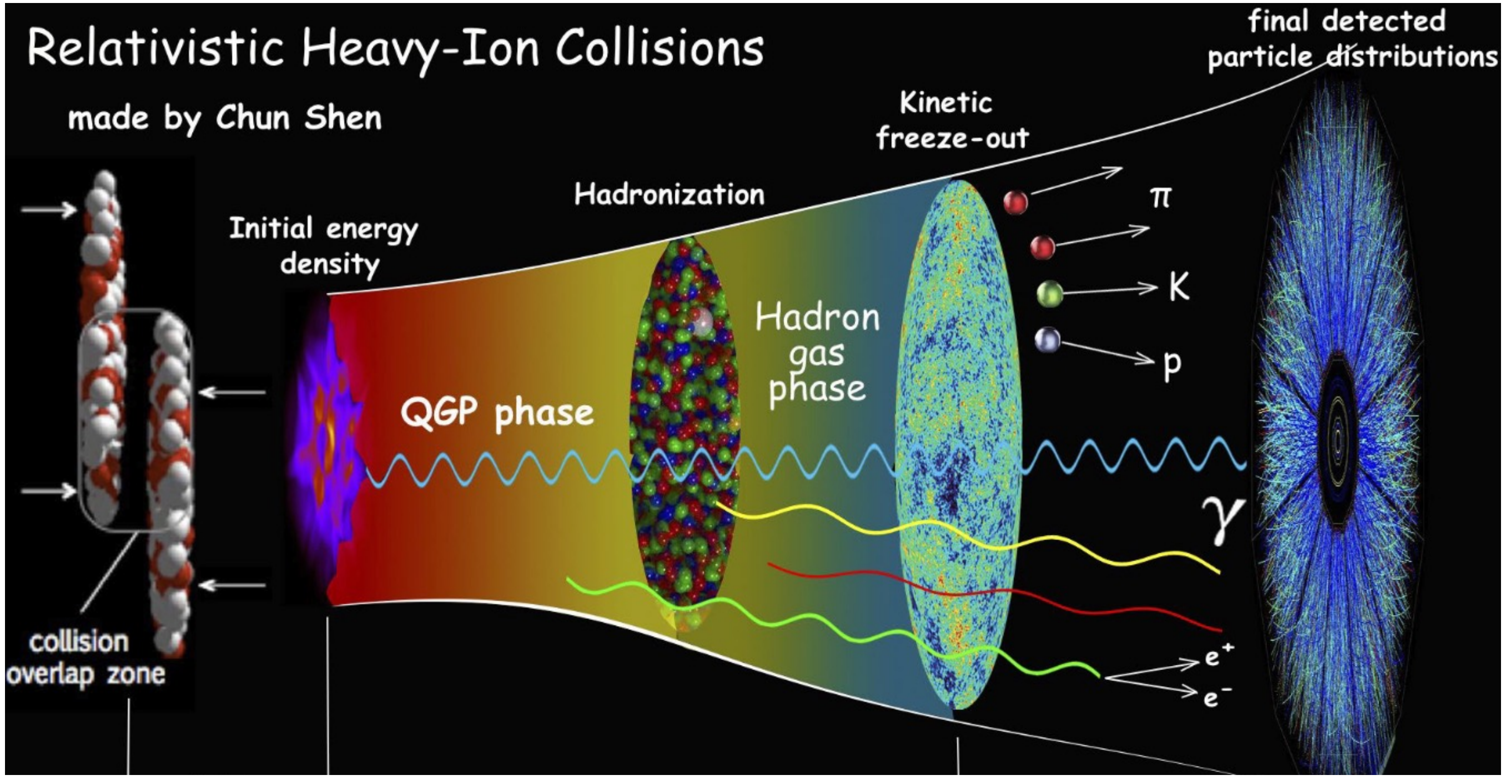
- Kinematical cuts
- V_s is comparable to V_{tot}
  - Global charge conservation effects present
- Presence of causally disconnected regions of fireball
  - Local conservation effects come into play





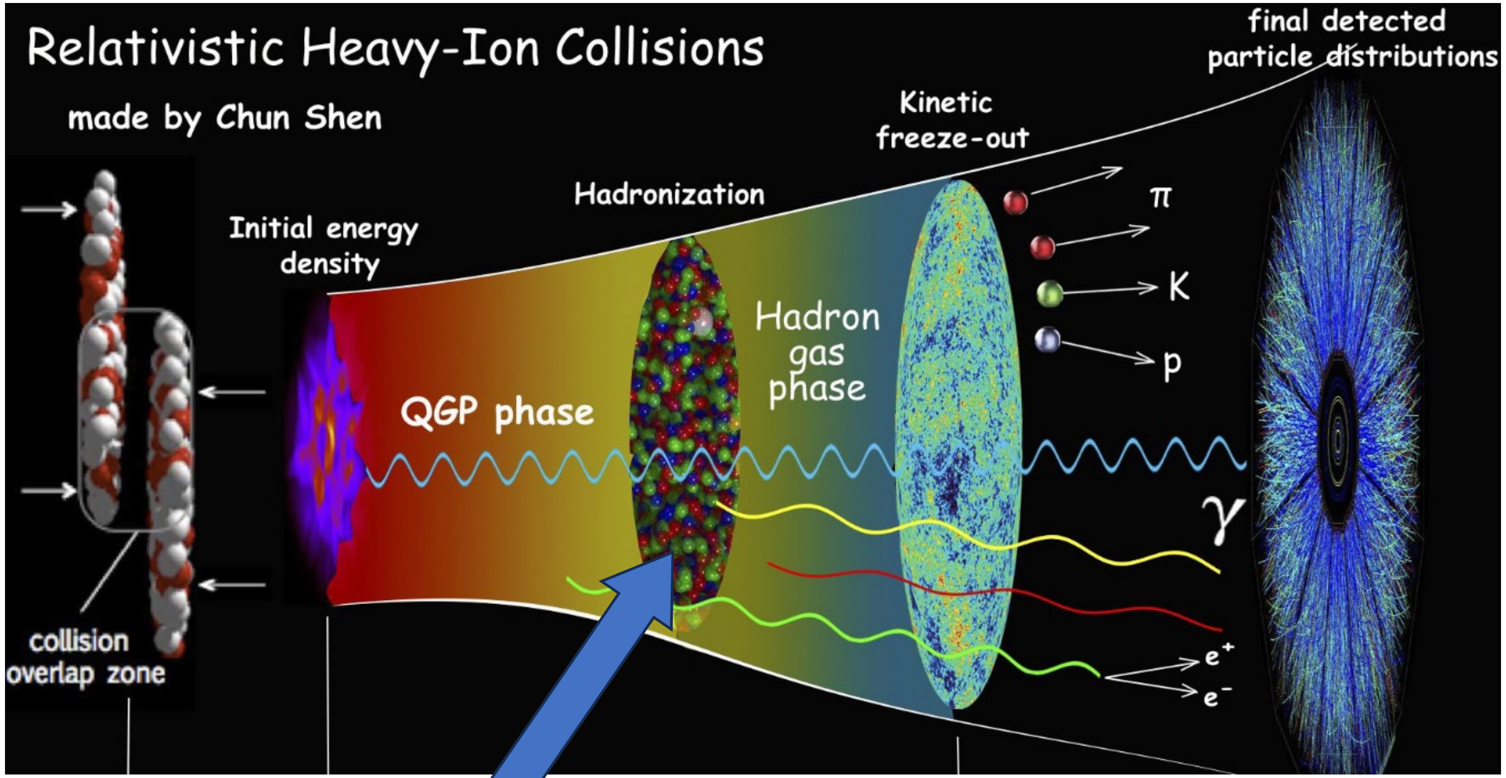
P. Castorina, H. Satz, IJMPE Vol. 23 No. 4 (2014)
S. Pratt, C. Plumberg , Phys. Rev. C 104, 014906(2014)

Overview



Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected
particle distributions
Kinetic
freeze-out
Hadronization
Initial energy
density
π
K
p
Hadron
gas
phase
QGP phase
γ
collision
overlap zone
e+
e−

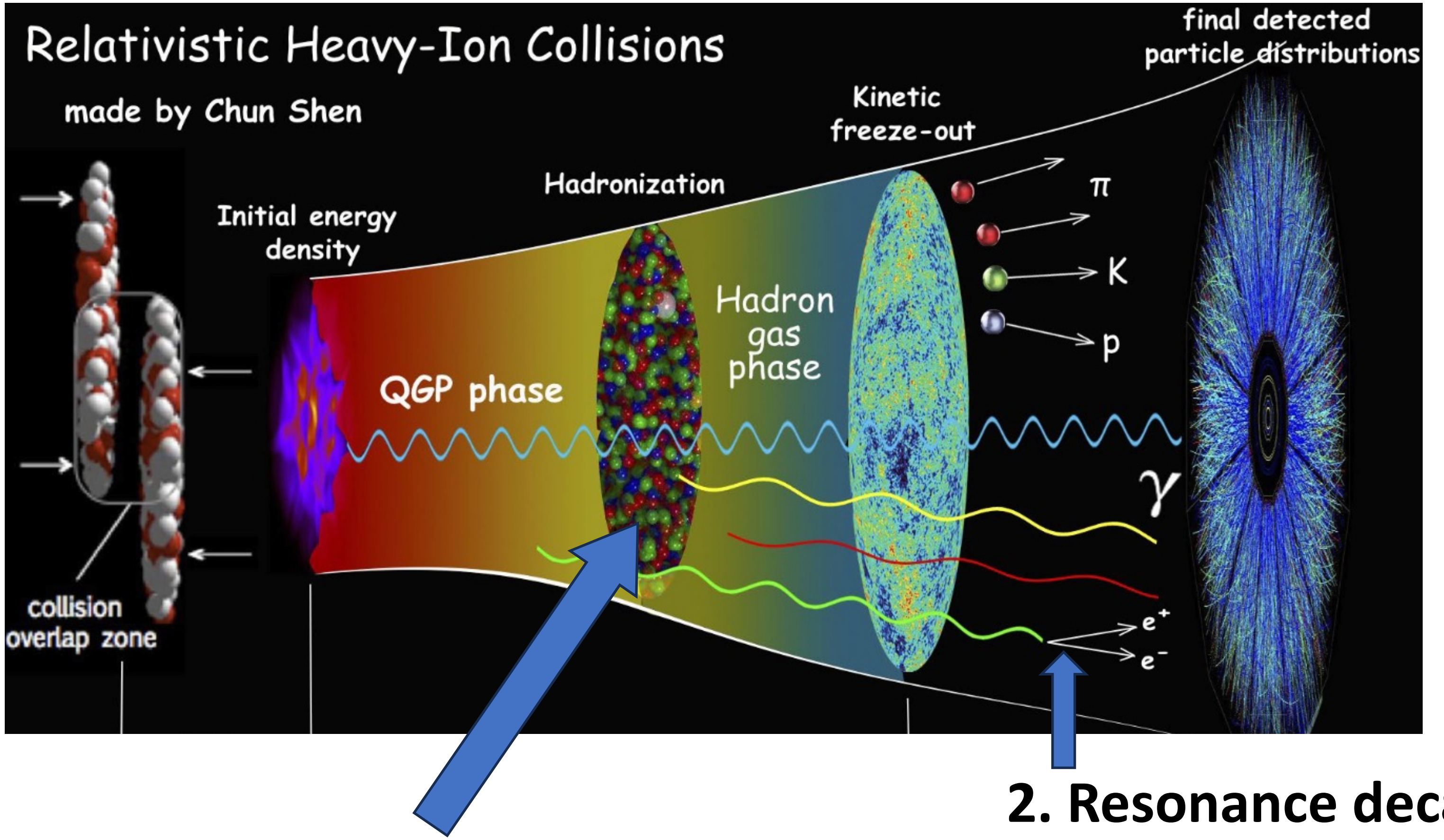
Overview



1. Fluctuations at hadronization (primordial charges)

ω – Distinguishes HG from QGP

Overview



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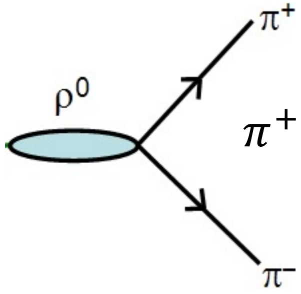
2. Resonance decays



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

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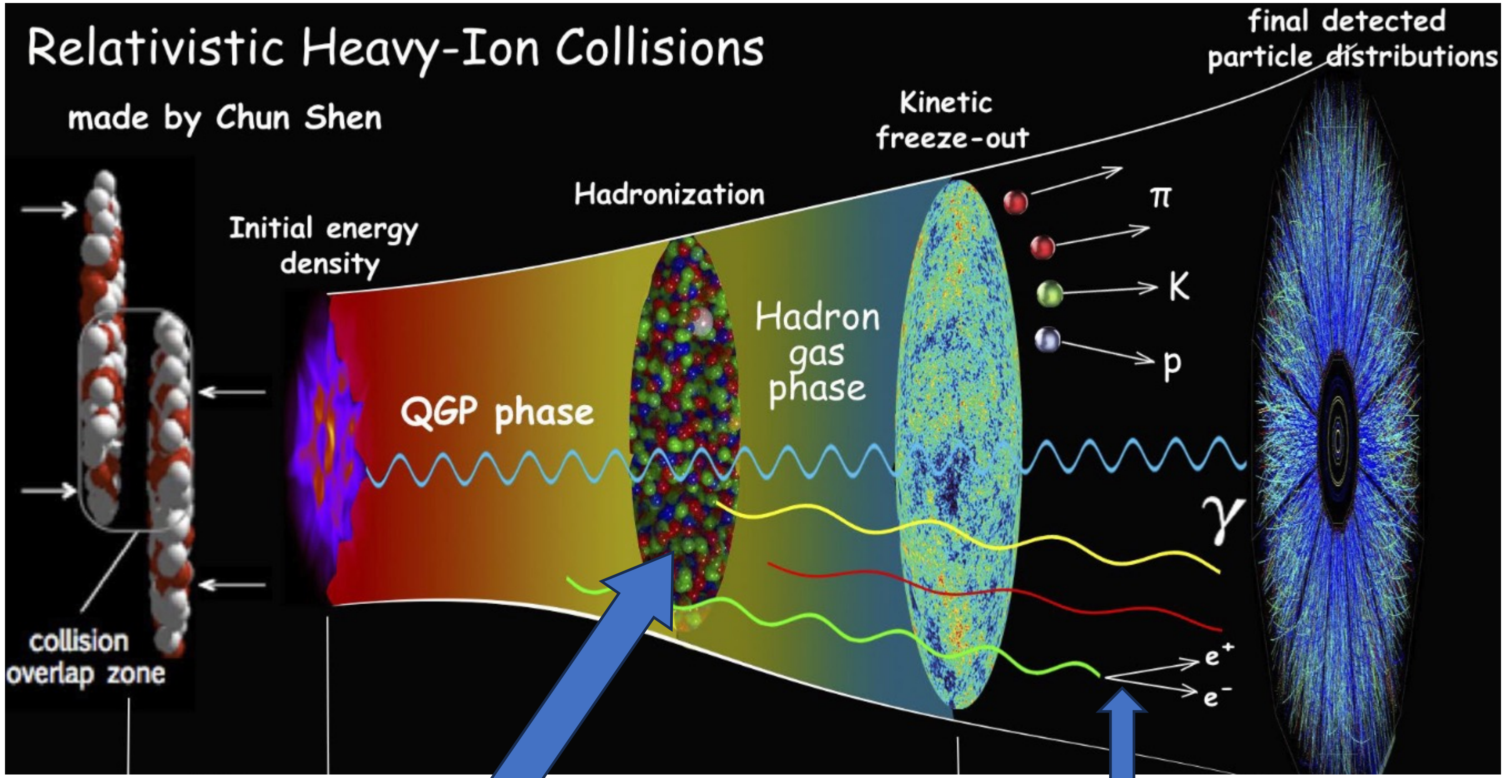

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$\boldsymbol{\omega}$ – Distinguishes HG from QGP

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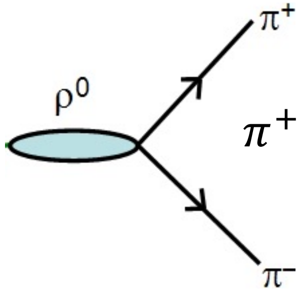

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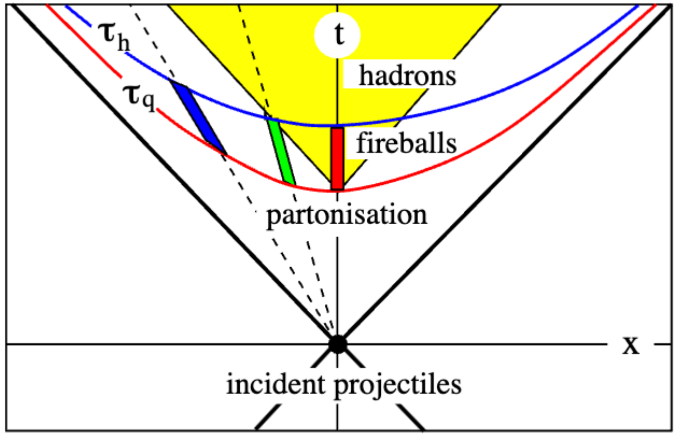
3. Locality of charge conservation



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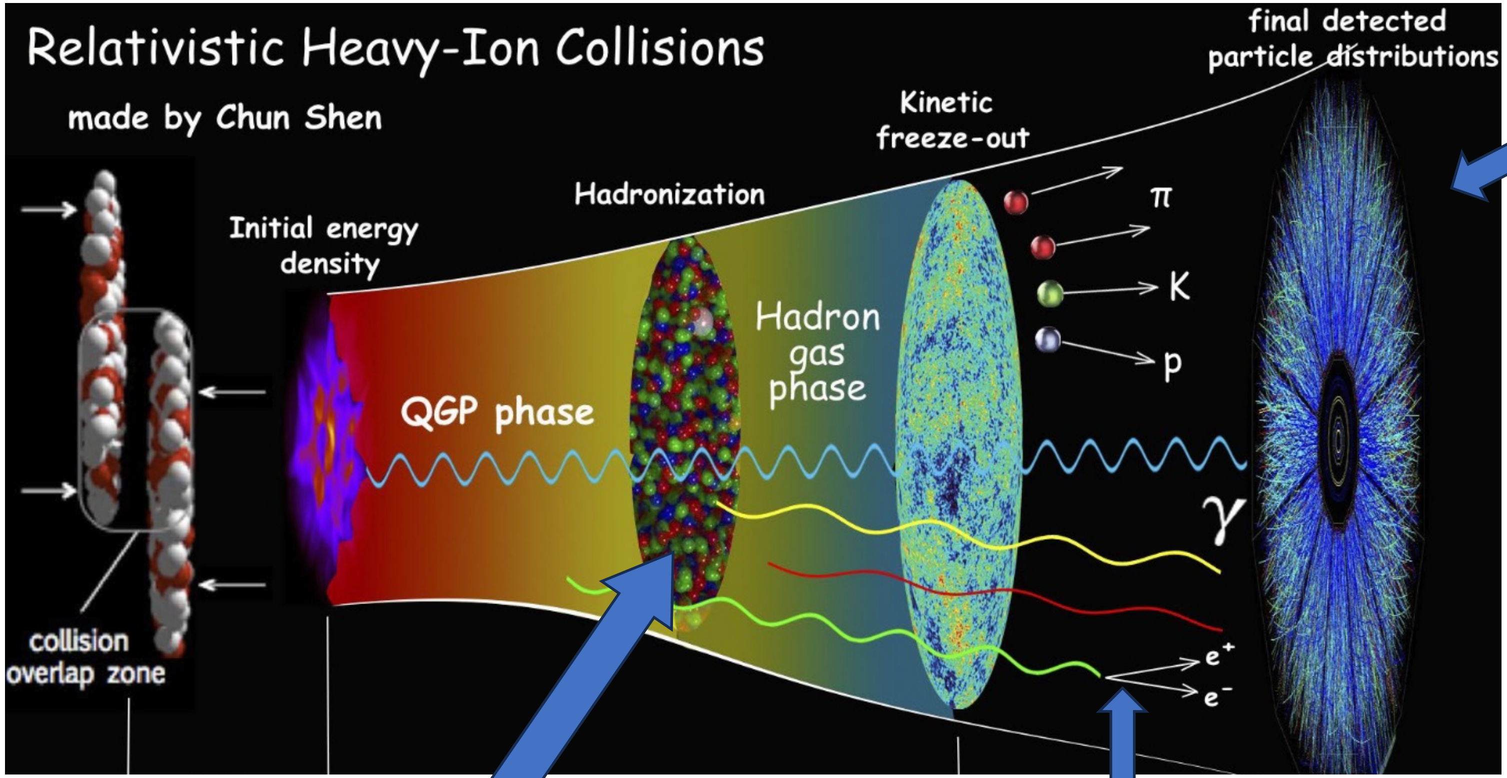

4. Momentum acceptance coordinates

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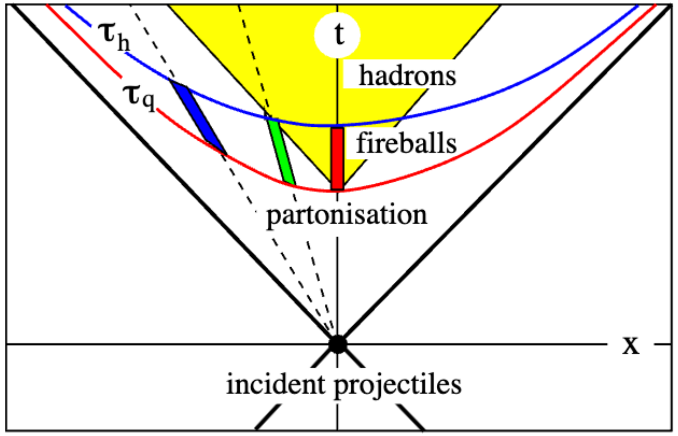

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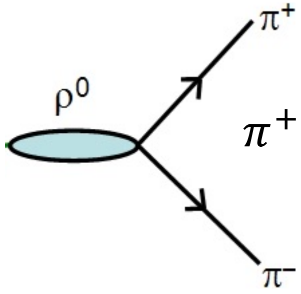

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1. Fluctuations at hadronization (primordial charges)

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

1. Freeze-out of Fluctuations at Hadronization, ω

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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

$$\boxed{\omega_{HG} = 1.1}$$

Vovchenko, Stoecker, Comput. Phys. Commun. 244, 295 (2019)

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Given by free QGP limit:

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

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P. Hanus, A. Mazeliauskas, K. Reygers, Phys. Rev. C (2019)

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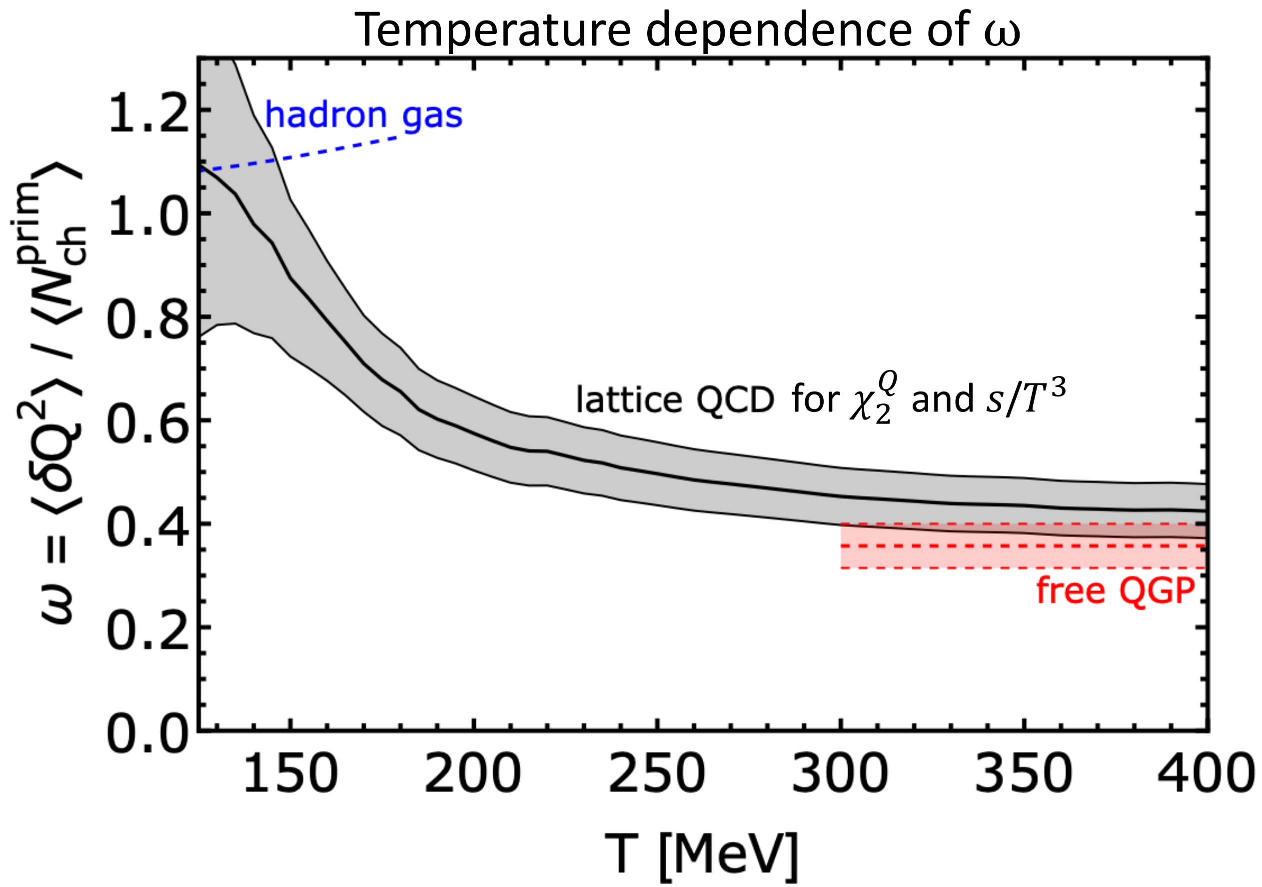
$$\boxed{\omega_{QGP} = 0.36 \pm 0.04}$$

Compared to $\omega_{HG} = 1.1$

1. Freeze-out of Fluctuations at Hadronization, ω

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



$\omega_{HG} \approx 1.1$ around T < 160 MeV (hadron gas regime) and $\omega_{QGP} \approx 0.4$ at T > 300 MeV (QGP regime). ω_{QGP} approaches the Stefan-Boltzmann limit ($\omega_{QGP} \approx 0.36$), justifying our value for ω_{QGP}.

2. Charge Susceptibility, χ_2^Q with ω and Resonance Decays, γ_Q

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

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

Self correlations 2-particle correlations

Before decays, strength of interactions is parametrized by ω:

$$\chi_2^Q = \omega \langle n_{\mathrm{ch}}^{\mathrm{prim}} \rangle \qquad \varphi_2^{Q,\mathrm{prim}} = (\omega - 1)\langle n_{\mathrm{ch}}^{\mathrm{prim}} \rangle$$

When $\omega = 1$, there are no correlations

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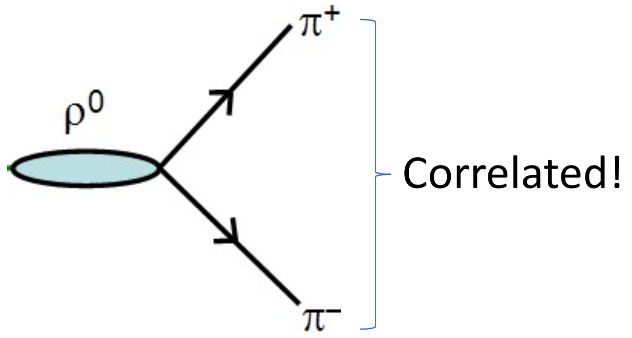
After resonance decays, net charge remains conserved but multiplicities of charges increase by a factor γ_Q → additional correlations introduced, rebalancing of self and 2-particle correlations

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

$\gamma_Q \approx 1.67$ at T = 155 MeV

$$\rightarrow \varphi_2^Q = \left(\frac{\omega}{\gamma_Q} - 1 \right) \langle n_{\mathrm{ch}} \rangle$$



Final charge susceptibility:

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

3. Correlations and Charge Conservation Implementation, C_2^Q

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

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

V. Vovchenko, PRC 110, L061902 (2024)

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

Gaussian local charge conservation:

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

Global:

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

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

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V. Vovchenko, PRC 110, L061902 (2024)

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local correlation balancing contribution

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Width of local conservation is related to:

$$\frac{V_c}{V_{\text{tot}}} = \sqrt{\frac{\pi}{2}}\frac{\sigma_y}{\eta_{\max}}\text{erf}\left(\frac{\eta_{\max}}{\sqrt{2}\sigma_y}\right) \qquad \sigma_\eta \to \infty : V_c \to V_{\text{tot}}$$

4. Momentum Acceptance Coordinates

Combining the previous equations and integrating C_2^Q yields the net-charge variance:

$$\kappa_2[Q]|_{|\eta|<\eta_{\rm cut}} = \int_{-\eta_{\rm cut}/2}^{\eta_{\rm cut}/2} d\eta_1 \int_{-\eta_{\rm cut}/2}^{\eta_{\rm cut}/2} d\eta_2 C_2^Q(\eta_1,\eta_2)$$

$$C_2^Q(\mathbf{r}_1,\mathbf{r}_2) = \chi_2^Q\left[\delta(\mathbf{r}_1-\mathbf{r}_2) - \frac{\varkappa(\mathbf{r}_1,\mathbf{r}_2)}{V_{\rm tot}}\right] \quad \mathbf{r} = \eta$$

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

However, fluctuations in heavy-ion collisions are measured in momentum acceptance coordinates rather than spatial coordinates. Incorporating this,

$$\kappa_2[Q^{\rm acc}] = V_{\rm tot}\langle n_{\rm ch}\rangle\left[\underbrace{\langle p(\eta)\rangle}_{\text{Skellam baseline}} - \underbrace{\left(1-\frac{\omega}{\gamma_Q}\right)\langle p^2(\eta)\rangle}_{\text{2-particle correlations}} - \underbrace{\frac{\omega}{\gamma_Q}\langle p(\eta_1)p(\eta_2)\rangle_\varkappa}_{\text{long-range 2-particle correlations}}\right]$$

where,

$$\langle p^n(\eta)\rangle = \frac{1}{2\eta_{\rm max}}\int d\eta p^n(\eta)$$

and p(η) is found using Blast-Wave model calculations

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

D-Measure

We obtain the equation for D-measure inside momentum acceptance:

$$D = 4\frac{\kappa_2[Q]}{\langle Q^+ + Q^- \rangle} = 4\left\{1 - \left(1 - \frac{\omega}{\gamma_Q}\right)\frac{\langle p^2(\eta)\rangle}{\langle p(\eta)\rangle} - \frac{\omega}{\gamma_Q}\frac{\langle p(\eta_1)p(\eta_2)\rangle_{\varkappa}}{\langle p(\eta)\rangle}\right\}$$

Skellam baseline **2-particle correlations** **long-range 2-particle correlations**

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ω - Charge fluctuations at hadronization

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

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Skellam baseline

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$\langle p(\eta_1)p(\eta_2)\rangle_{\varkappa}$ - Local charge conservation

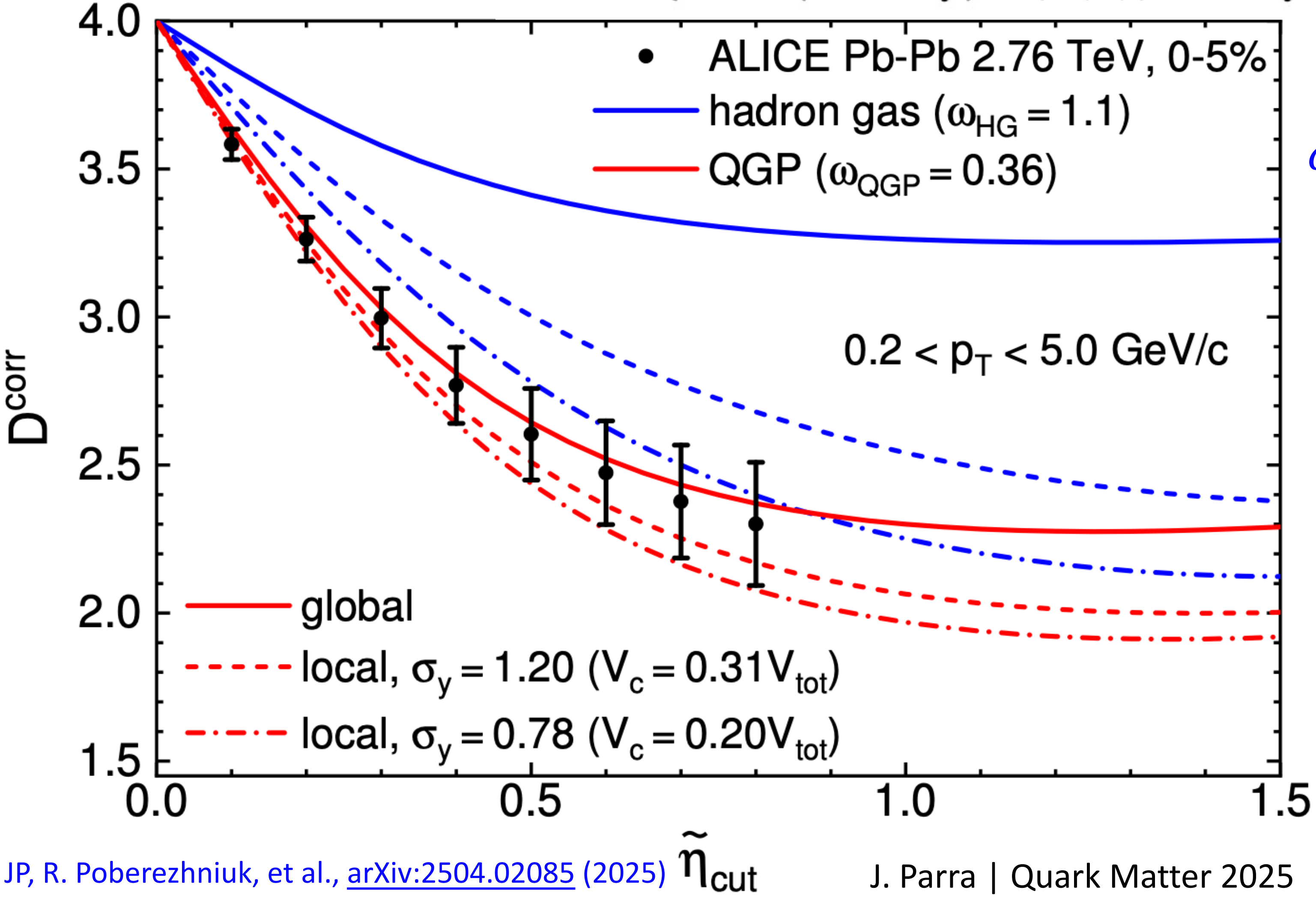
$\frac{\langle p^2(\eta)\rangle}{\langle p(\eta)\rangle}$ - Momentum Acceptance Cuts

$$p(\eta) = w_\pi p_\pi(\eta) + w_K p_K(\eta) + w_p p_p(\eta)$$

Let's compare to experimental data!

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:

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

$\gamma_Q = 1.67$

- Vary $\frac{V_c}{V_{tot}}$ for global and local charge conservation
- Values of which are based on local baryon conversation estimates

V. Vovchenko, PRC 110, L061902 (2024)

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

JP, R. Poberezhniuk, et al., arXiv:2504.02085 (2025)

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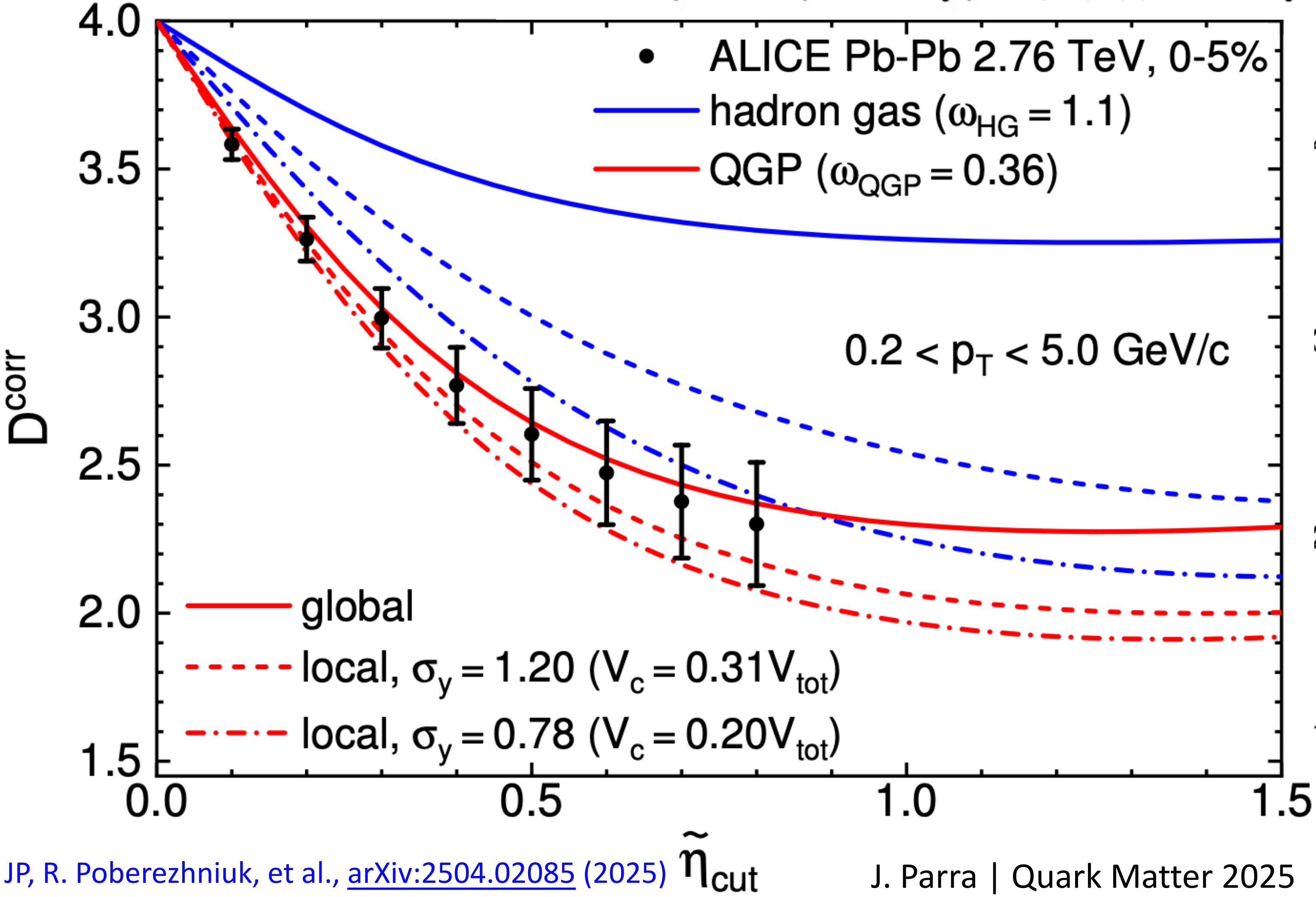
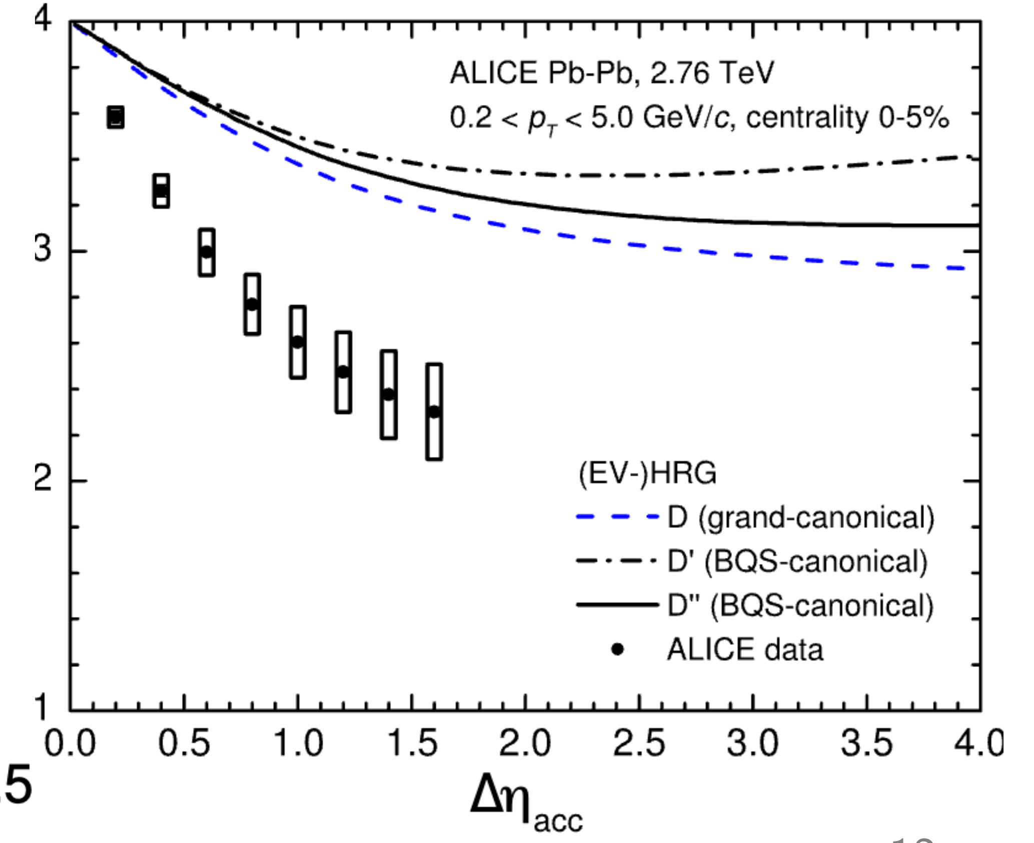


Compare to previous estimates:



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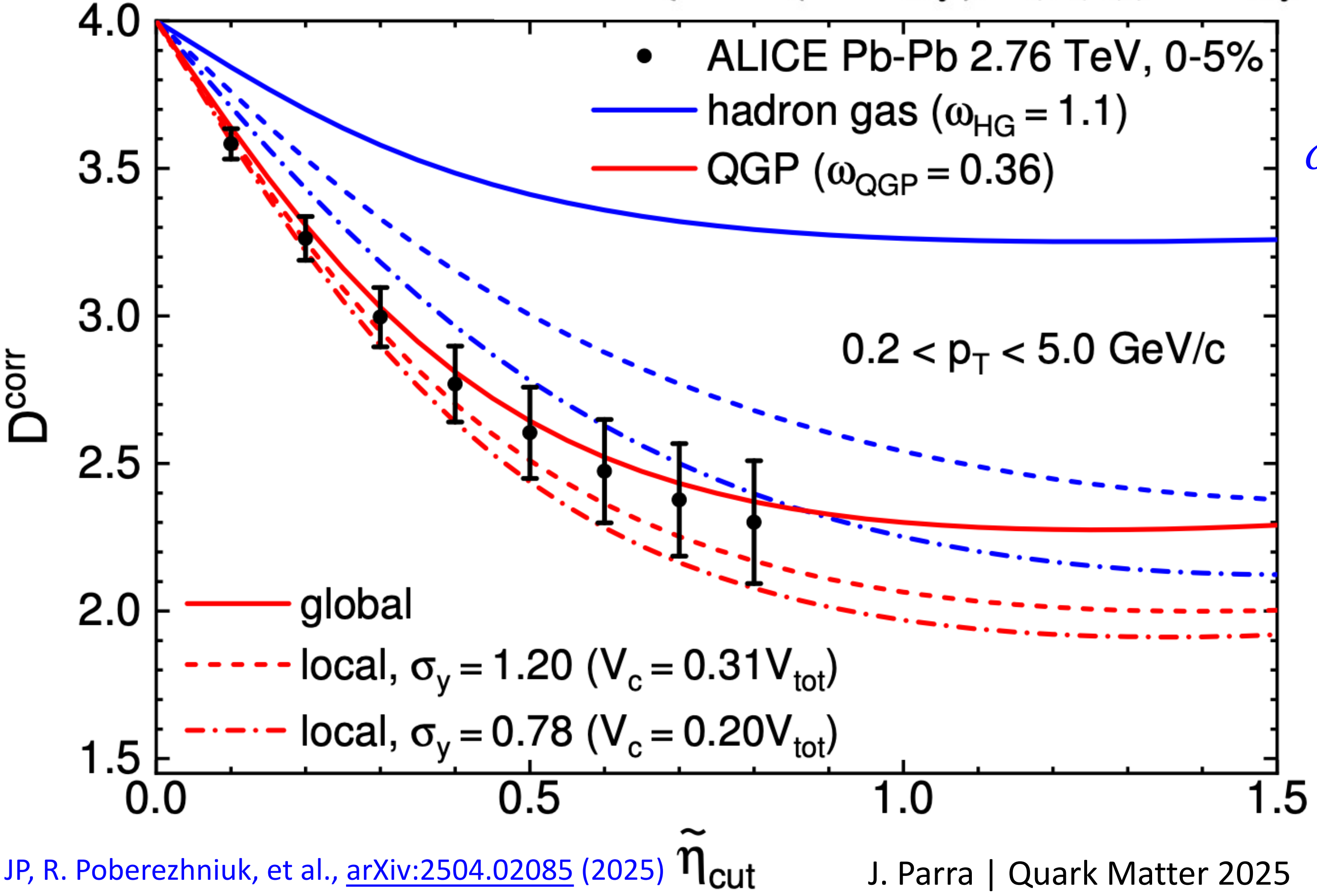

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JP, R. Poberezhniuk, et al., arXiv:2504.02085 (2025)

Bayesian analysis of ω and $V_c/\ V_{tot}$ parameters in D-measure

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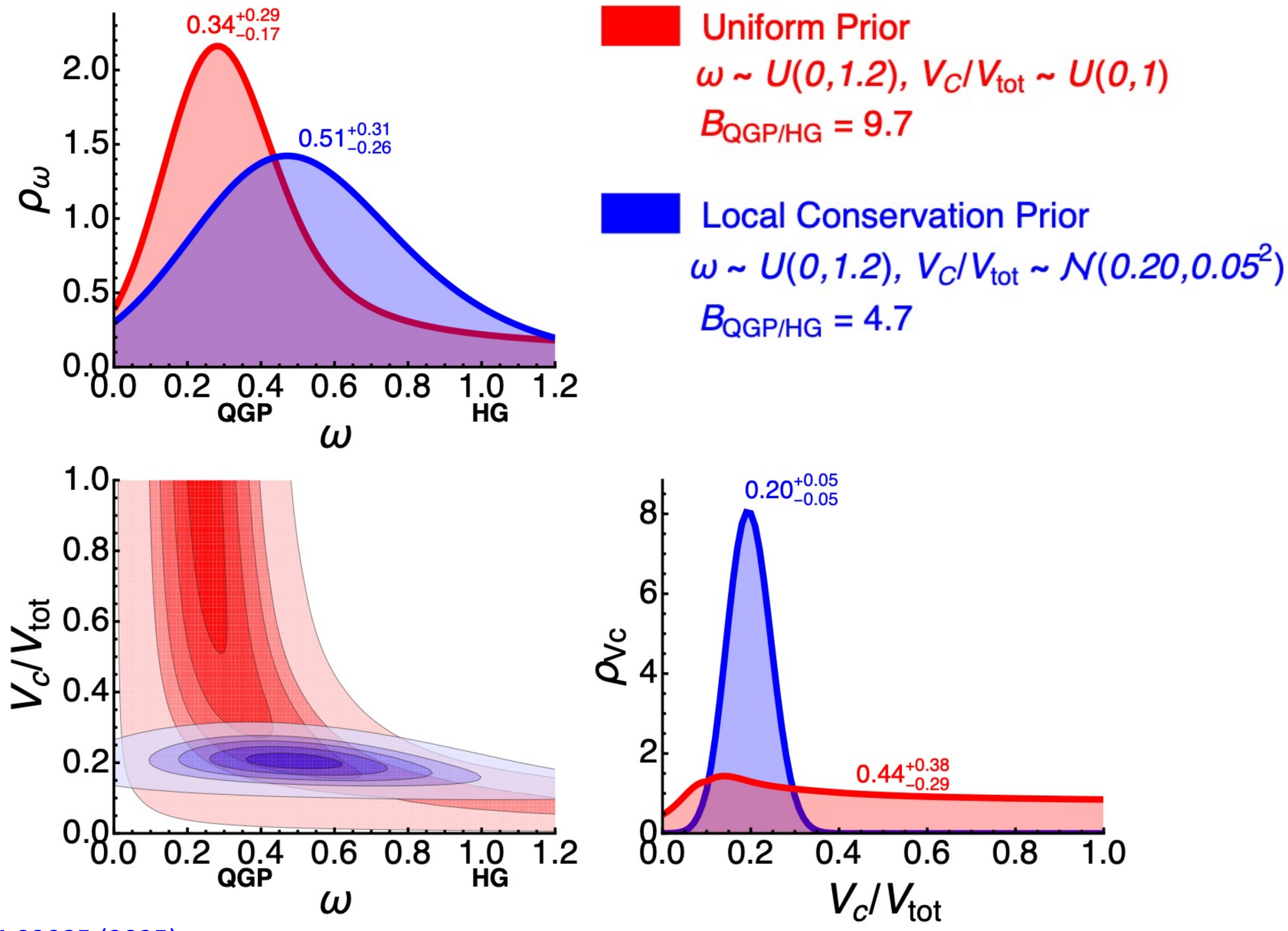
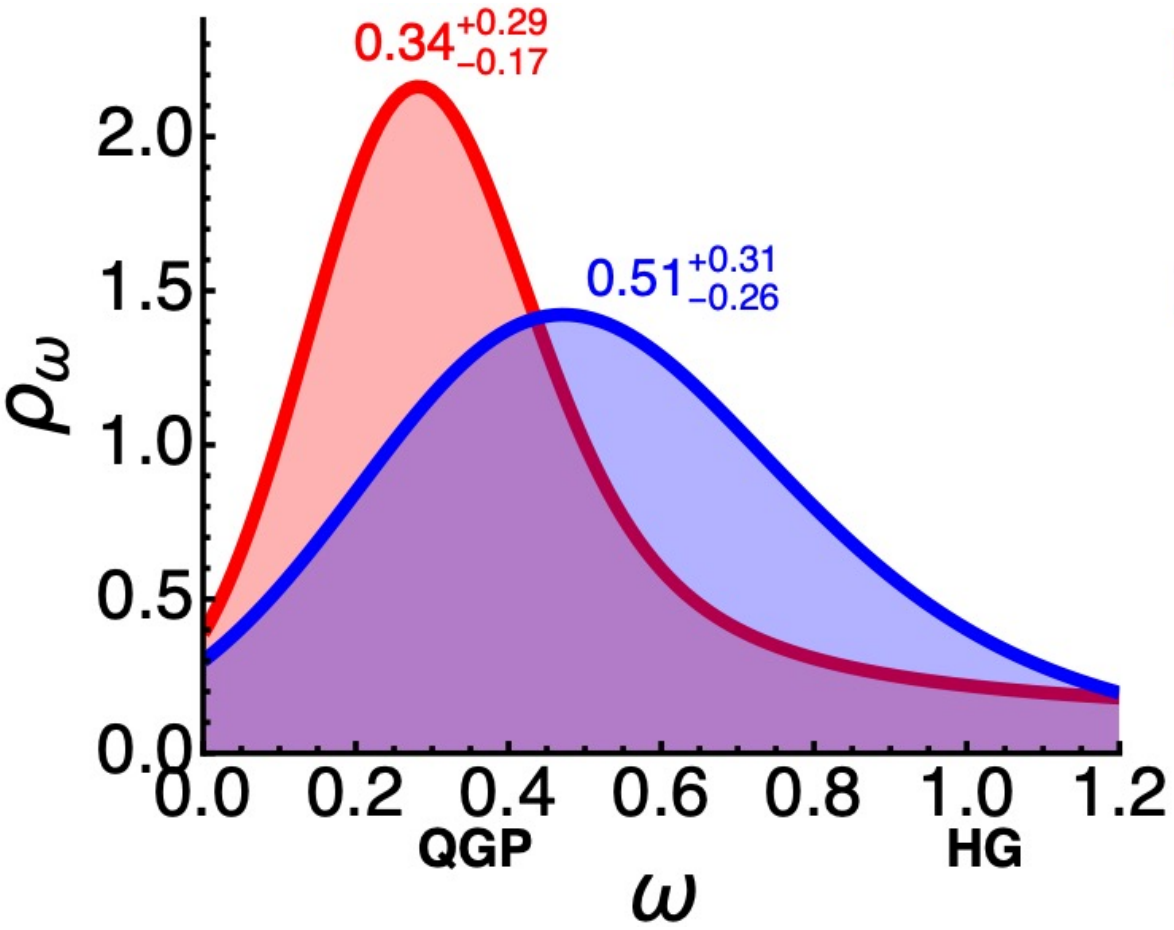


Bayesian analysis of ω in D-measure



Uniform Prior
$\omega \sim U(0,1.2)$, $V_C/V_{tot} \sim U(0,1)$
$B_{QGP/HG} = 9.7$

Local Conservation Prior
$\omega \sim U(0,1.2)$, $V_C/V_{tot} \sim \mathcal{N}(0.20, 0.05^2)$
$B_{QGP/HG} = 4.7$

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

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

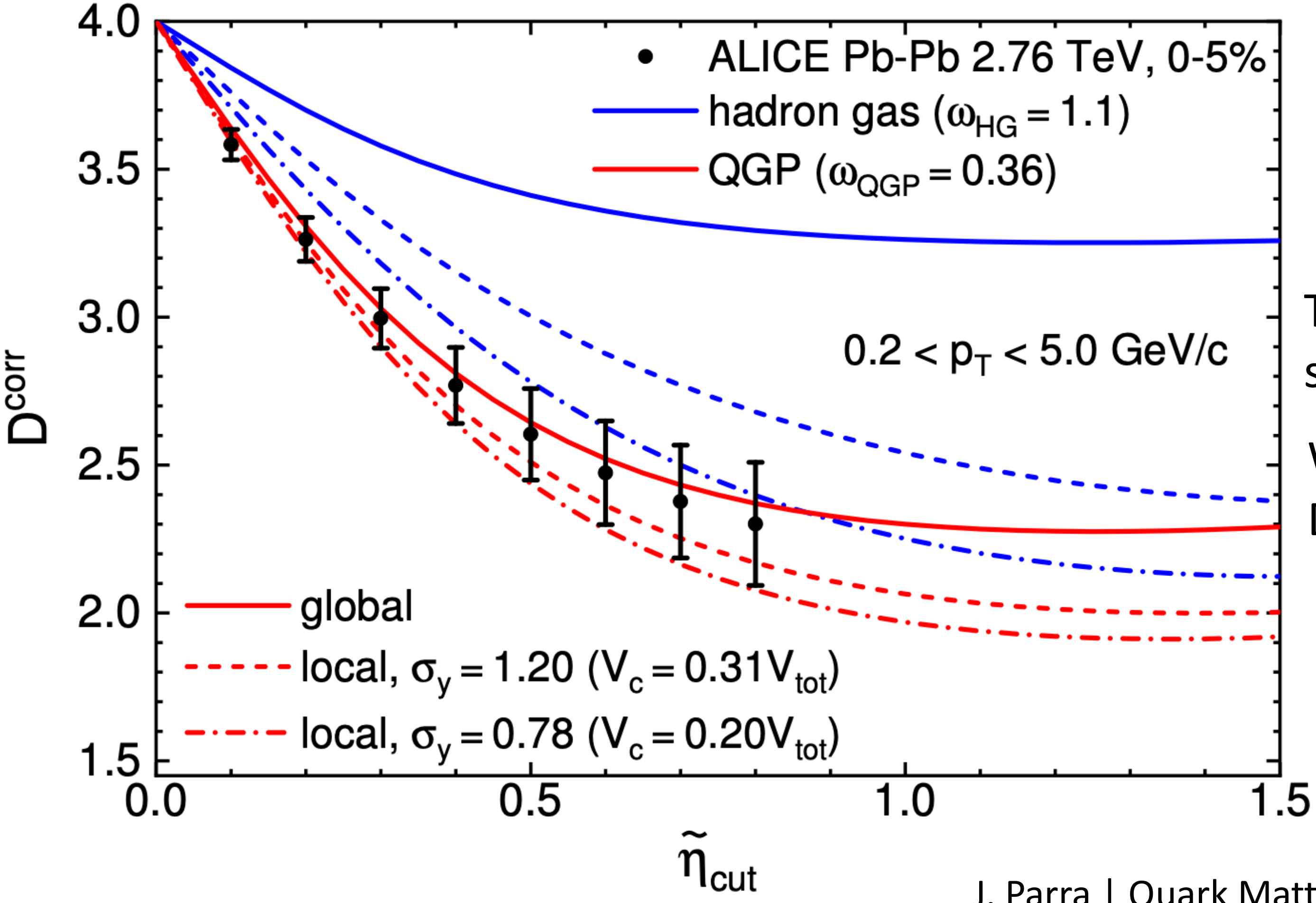
A comment on D' and D'' corrections

D-measure

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

Corrected D-measure

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



Where,

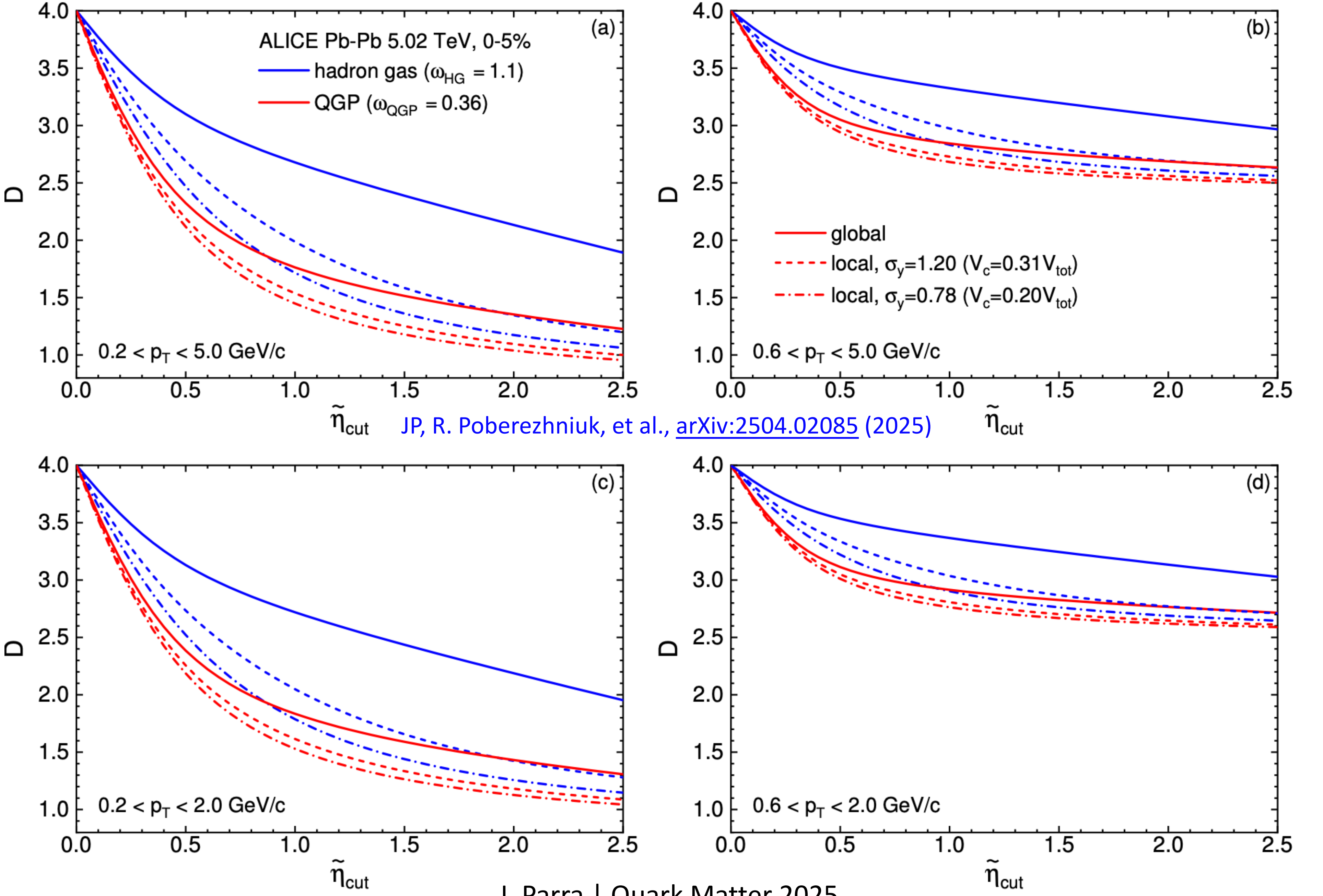
$$D_{\rm corr} = \frac{D' + D''}{2}$$

These additional corrections contribute to the sizable error bars.

We advocate for a direct analysis of uncorrected D-measure in LHC Run 2.

JP, R. Poberezhniuk, et al., arXiv:2504.02085 (2025)

ALICE Run 2 Predictions



JP, R. Poberezhniuk, et al., arXiv:2504.02085 (2025)

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Conclusion and Outlook

- We developed a new formalism to analyze net-charge fluctuations in heavy-ion collisions for HG and QGP scenarios.
  - We incorporated fluctuations at hadronization ($\omega_{HG} = 1.1$, $\omega_{QGP} = 0.36$), resonance decays, global/local charge conservation effects, and momentum acceptance.
- The HG scenario agrees with ALICE Run 1 D-measure when considering only a very local range of charge conservation, while QGP scenario is in fair agreement at any range.
- Bayesian analysis reveals moderate evidence for freeze-out of charge fluctuations in QGP phase.
- Looking forward to ALICE Run 2 data to test our predictions and obtain stronger conclusions.
- Outlook: different Bayesian priors, RHIC energies, high-order fluctuations, and more.

Thanks for your attention! ☺

Backup Slides

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:

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

Non-uniform volume distribution

We considered also non-uniform distribution of η (spatial) is characterized by volume rapidity density:

$$\rho_V(\eta) \;=\; dV/d\eta(\eta)$$

Thus,

$$\begin{aligned} C_2^Q(\eta_1,\eta_2) &= \rho_V(\eta_1)\chi_2^Q\left[\delta(\eta_1-\eta_2)-\rho_V(\eta_2)\frac{\varkappa(\eta_1,\eta_2)}{V_{\mathrm{tot}}}\right] \\ &= \rho_V(\eta_1)\langle n_{\mathrm{ch}}\rangle\delta(\eta_1-\eta_2)+\rho_V(\eta_1)\left(\frac{\omega}{\gamma_Q}-1\right)\langle n_{\mathrm{ch}}\rangle\delta(\eta_1-\eta_2) \\ &\quad -\rho_V(\eta_1)\rho_V(\eta_2)\frac{\omega}{\gamma_Q}\langle n_{\mathrm{ch}}\rangle\frac{\varkappa(\eta_1,\eta_2)}{V_{\mathrm{tot}}} \end{aligned}$$

Gaussian volume profile:

$$\rho_V(\eta) \;\propto\; \exp\left(-\frac{\eta^2}{2\sigma_V^2}\right)$$

Uniform (boost-invariant) profile:

$$\rho_V(\eta) \;\propto\; \frac{\theta(\eta_{\max}-|\eta|)}{2\eta_{\max}}$$

The effect was found to be virtually negligible at midrapidities.

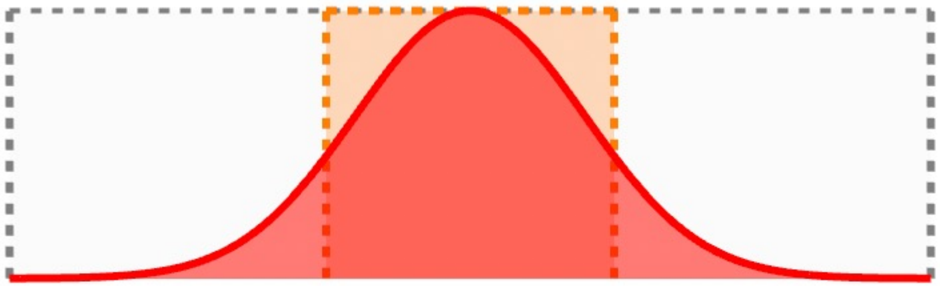
Truncated fireball vs Gaussian correlation

GCE Truncated Fireball

V_c

vs

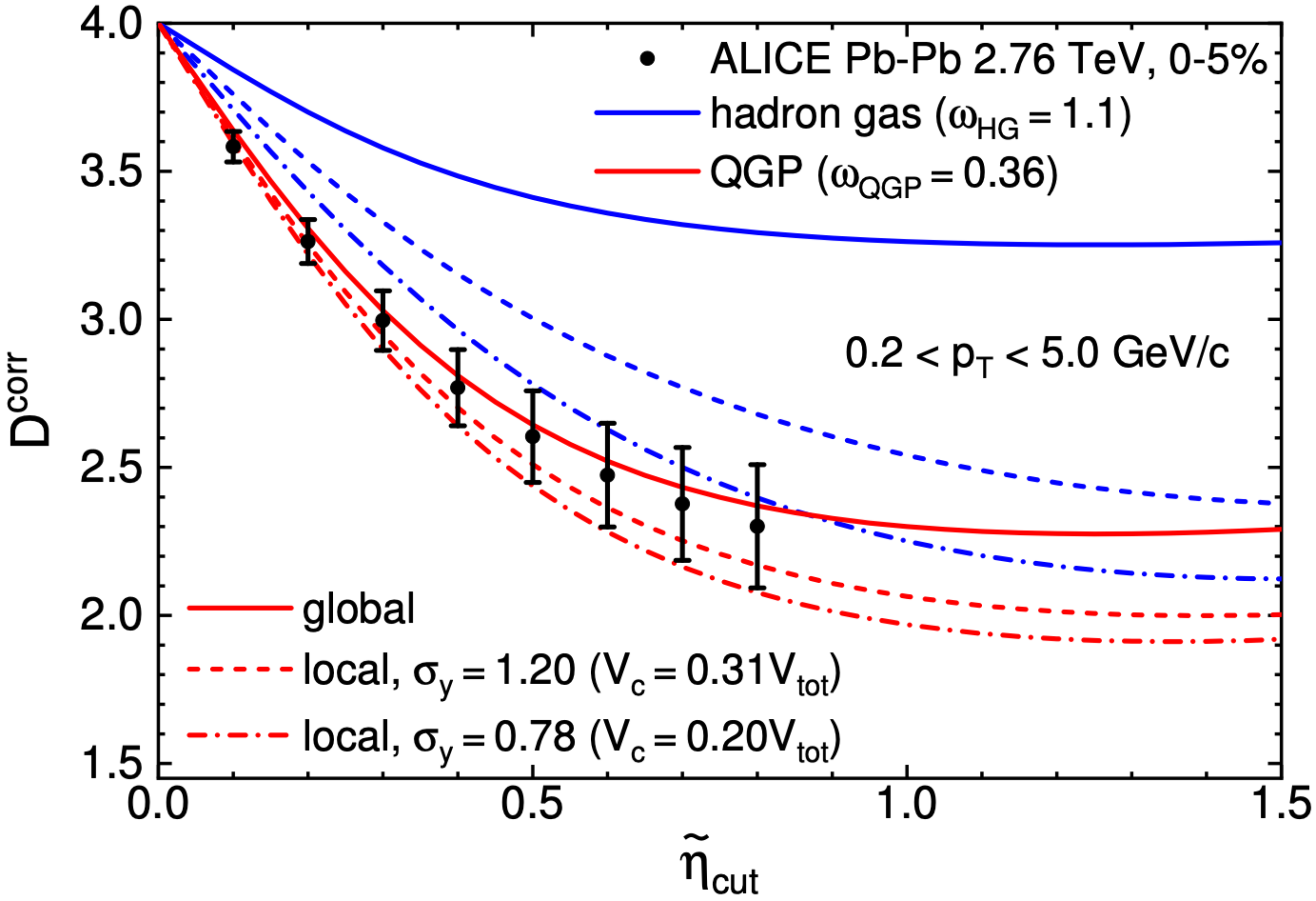
Gaussian correlation

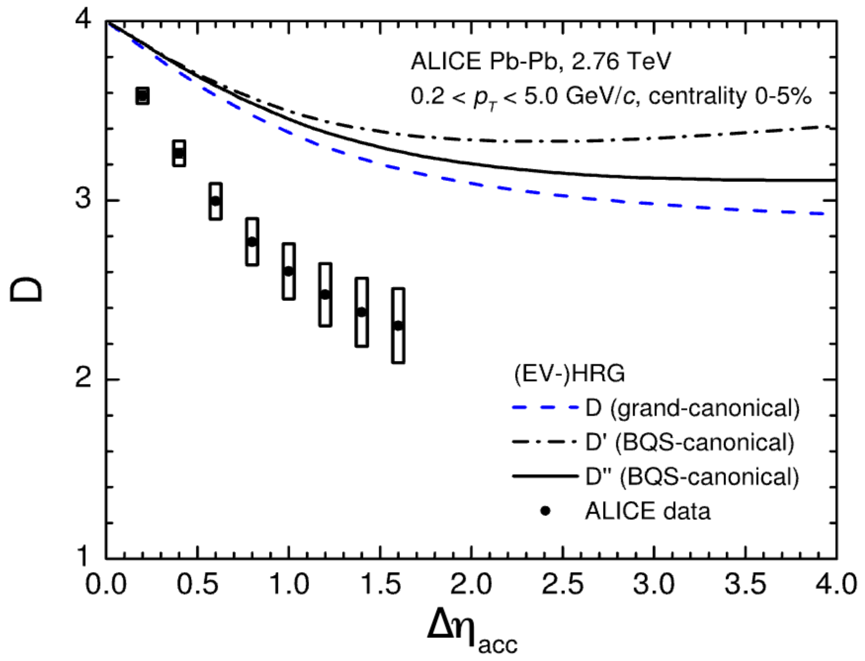


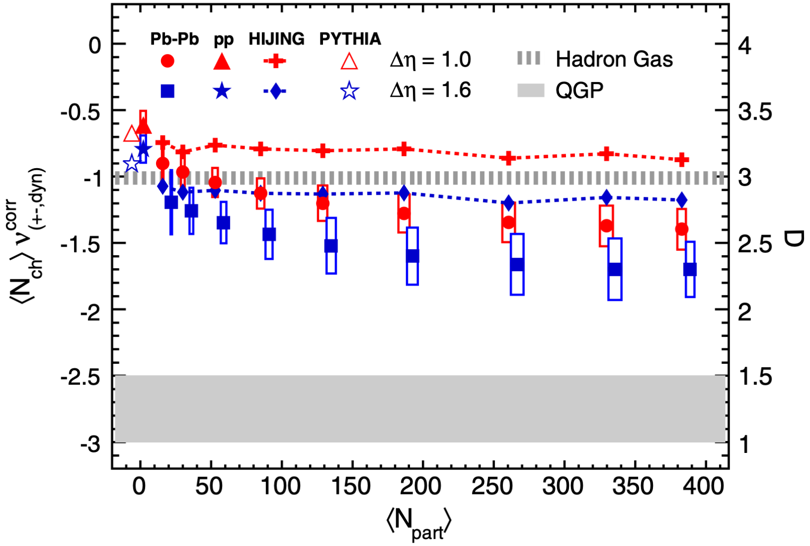
From V. Vovchenko PHENOmenal talk (2024)

With Gaussian correlation, hadrons at forward/backward rapidities also contribute to the system.

Comparison to previous estimates



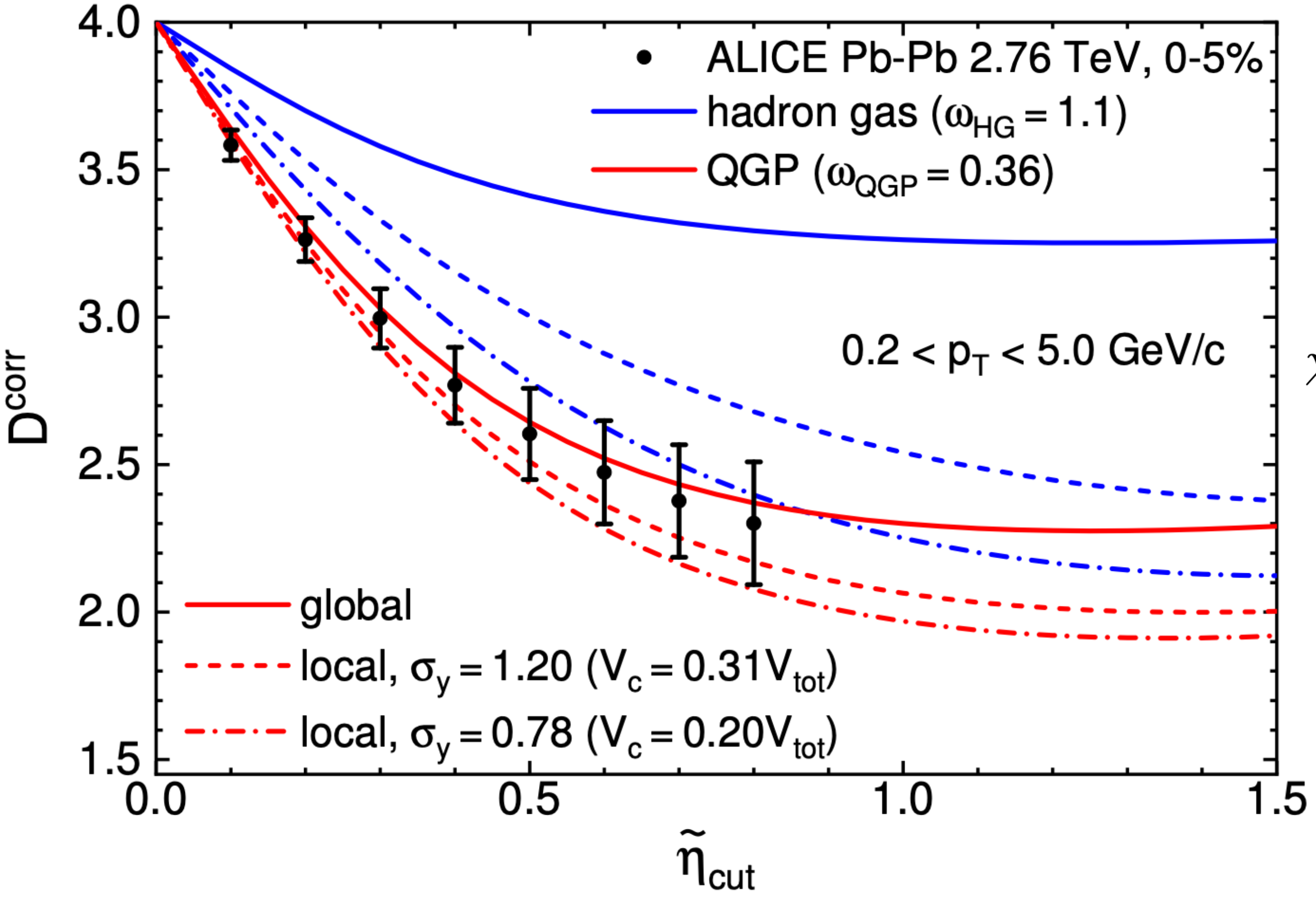




Bayesian analysis of ω and σ parameters in D-measure

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

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



Using first and last ALICE data points:

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