Dileptons as probes of the pre-equilibrium stage in heavy and light-ion collisions

Maurice Coquet, Heavy-ion seminar, Saclay, 11/05/2026

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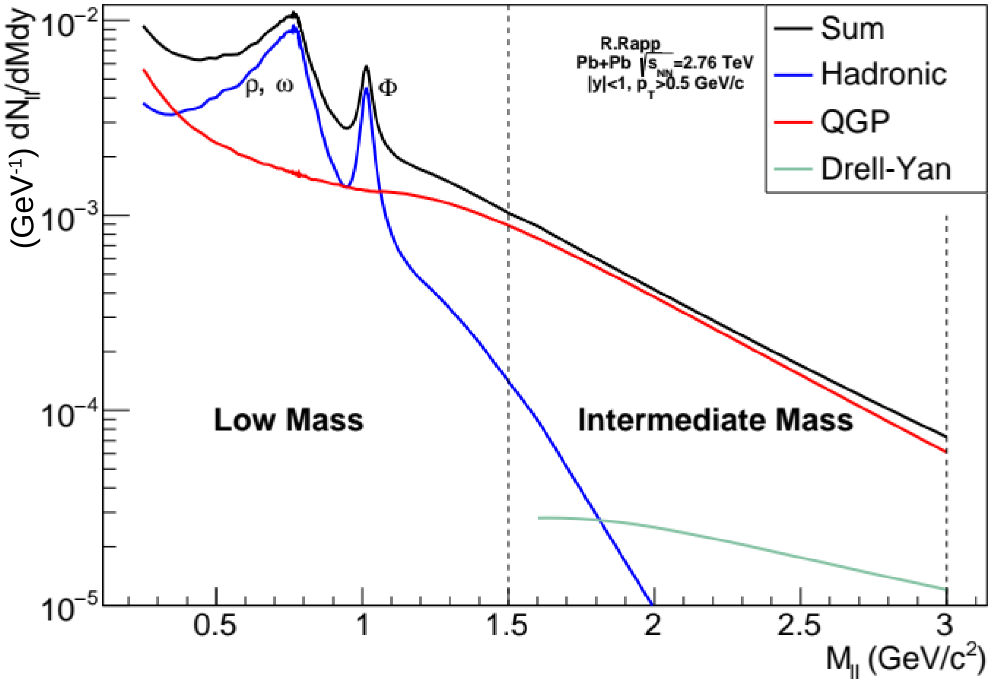
Dilepton production as a probe

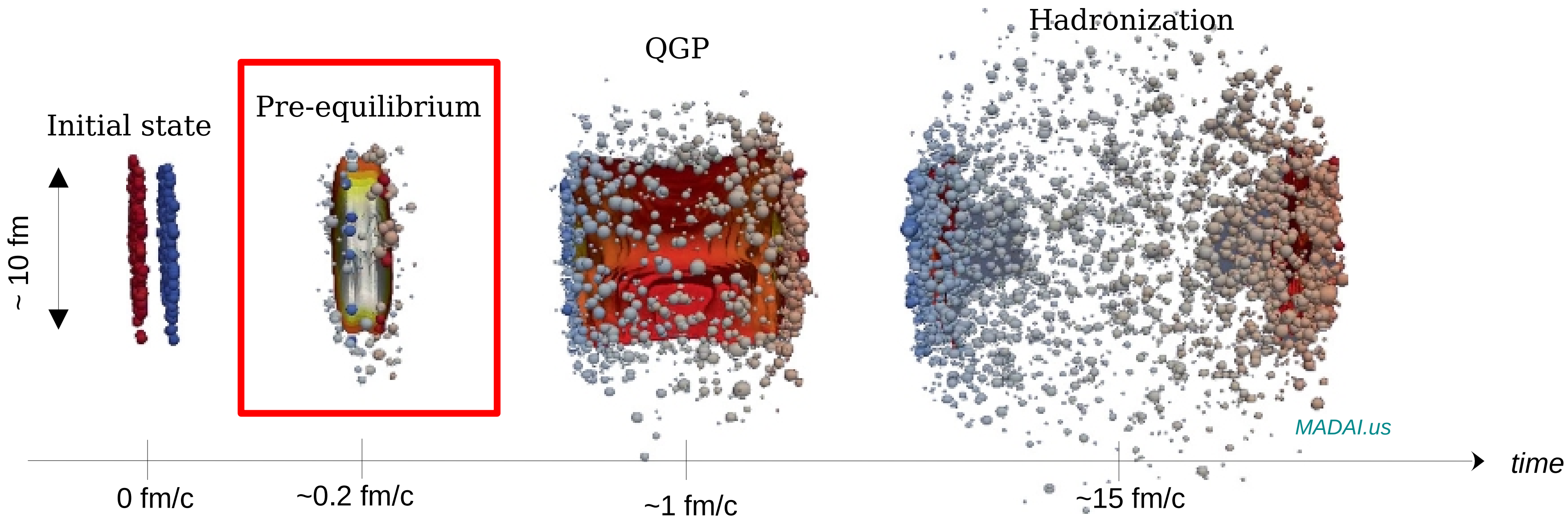
- Produced throughout the history of the collision → probe entire space-time dynamics
- Dilepton carry extra information: invariant mass → not affected by blue-shift

➔ **High mass ↔ High T ↔ early times**



➔ **Sensitive to early-times/pre-equilibrium emission**

Pre-equilibrium



- Stage between far-from-equilibrium initial state and near-equilibrium QGP

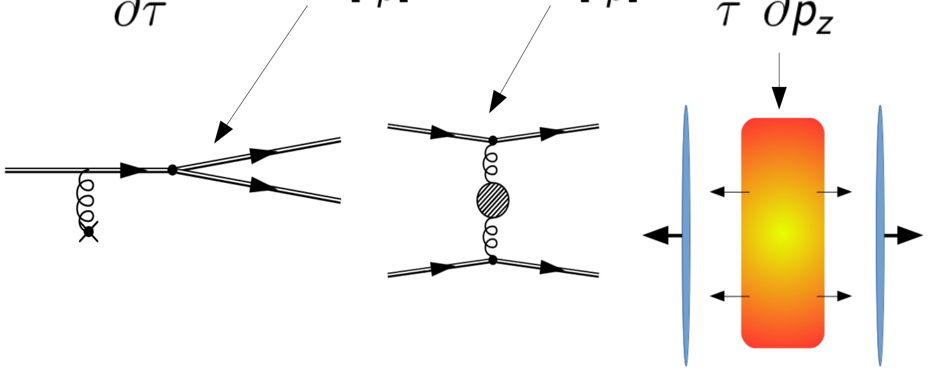
  → Stage during which **most of the entropy of the collision** is produced

Modeling the early stages: QCD kinetics

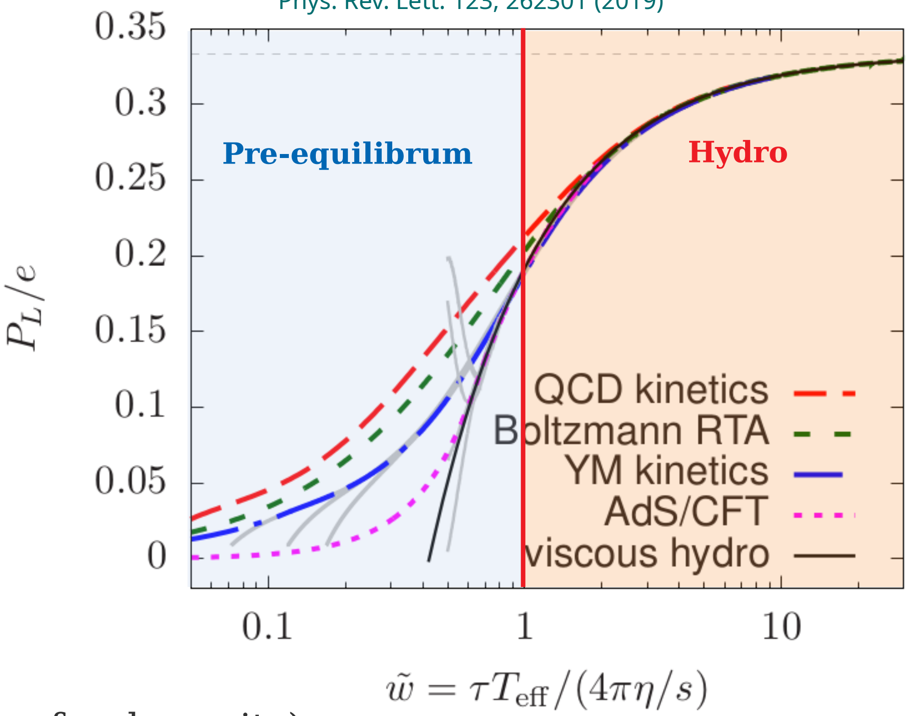
- Kinetic theory **[Phys. Rev. D 99, 054018 (2019)]** → **based on weak coupling assumption**

- Described by relativistic Boltzmann equation

$$-\frac{\partial f_{\vec{p}}}{\partial \tau} = \mathcal{C}^{1\leftrightarrow 2}[f_{\vec{p}}] + \mathcal{C}^{2\leftrightarrow 2}[f_{\vec{p}}] - \frac{p_z}{\tau}\frac{\partial f_{\vec{p}}}{\partial p_z}$$



Phys. Rev. Lett. 123, 262301 (2019)



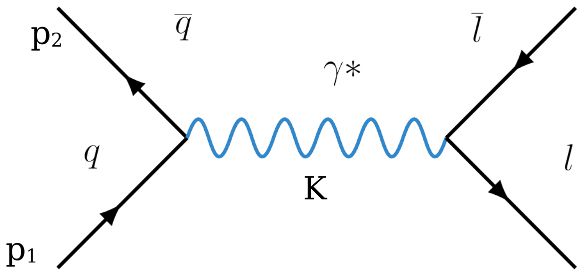
- Thermalization controlled by a relaxation rate

$$\tau_R(\tau) = 4\pi(\eta/s)/T_{eff}(\tau) \qquad \tilde{w} = \tau/\tau_R(\tau)$$

- Hydrodynamics applicable for w~1 (Reynolds number of order unity)

Dilepton production

- At leading order (LO), production by quark-antiquark annihilation:



$$\frac{dN^{l^+l^-}}{d^4x d^4K} = \int \frac{d^3p_1}{(2\pi)^3 2p_1} \frac{d^3p_2}{(2\pi)^3 2p_2} f_q(x, \mathbf{p}_1) f_{\bar{q}}(x, \mathbf{p}_2) |\mathcal{A}|^2 (2\pi)^4 \delta^{(4)}(P_1 + P_2 - K),$$

$f_{q/q}$: quark/anti-quark phase space distributions
A: matrix element of the diagram

Main assumptions :
→ Boost invariance along the longitudinal direction
→ Transverse flow neglected (high T ↔ early times)

Dilepton production

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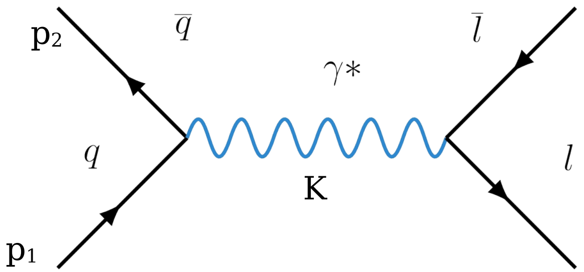


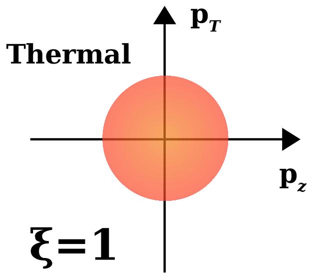
$$\frac{dN^{l^+l^-}}{d^4x d^4K} = \int \frac{d^3p_1}{(2\pi)^3 2p_1} \frac{d^3p_2}{(2\pi)^3 2p_2} f_q(x,\mathbf{p}_1) f_{\bar{q}}(x,\mathbf{p}_2) |\mathcal{A}|^2 (2\pi)^4 \delta^{(4)}(P_1 + P_2 - K),$$

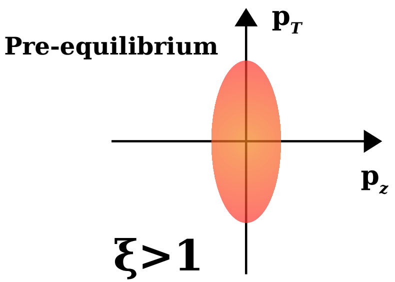
→ encode effects in quark/anti-quark distribution

→ How pre-equilibrium effects manifest themselves in the spectra of dileptons ?

Parametrizing the pre-equilibrium

- Pressure anisotropy→ **momentum anisotropy**





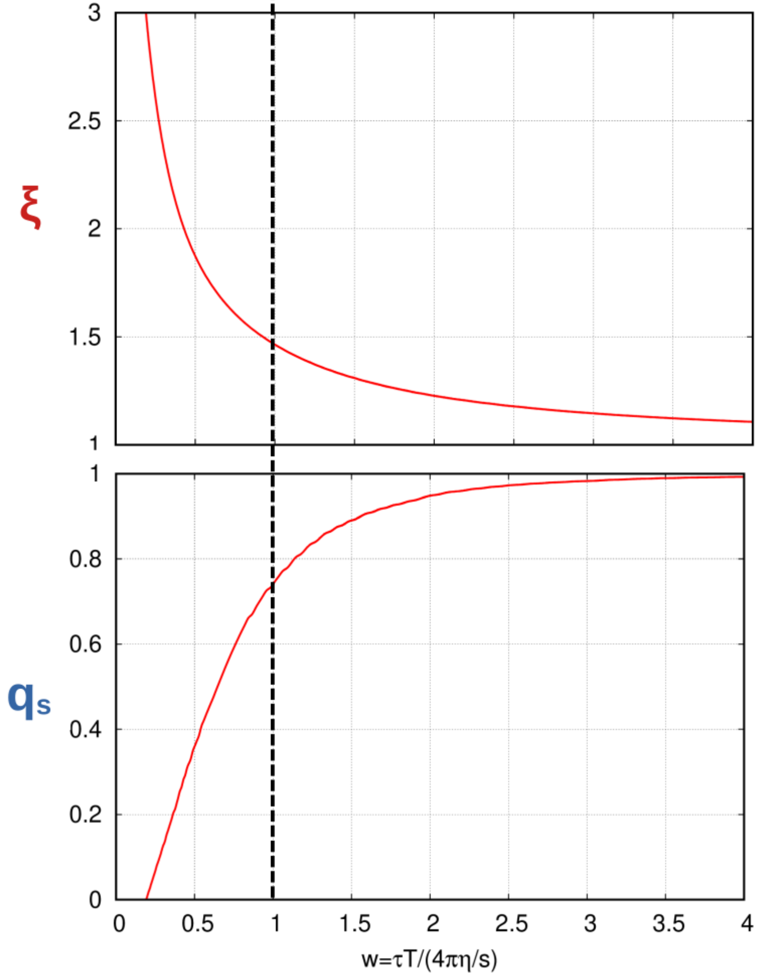
→ parametrize quark distribution with anisotropy variable **ξ**

$$f_q(\tau, p_T, p_L) = q_s(\tau) f_{FD}\left(-\sqrt{p_T^2 + \xi^2(\tau) p_L^2} / \Lambda(\tau) \right)$$

- Initial state models predict a **gluon-dominated medium at early times**, very few quarks

  → quark suppression factor $\mathbf{q_s}$

Both parameters computed using QCD kinetics



Computing the yield

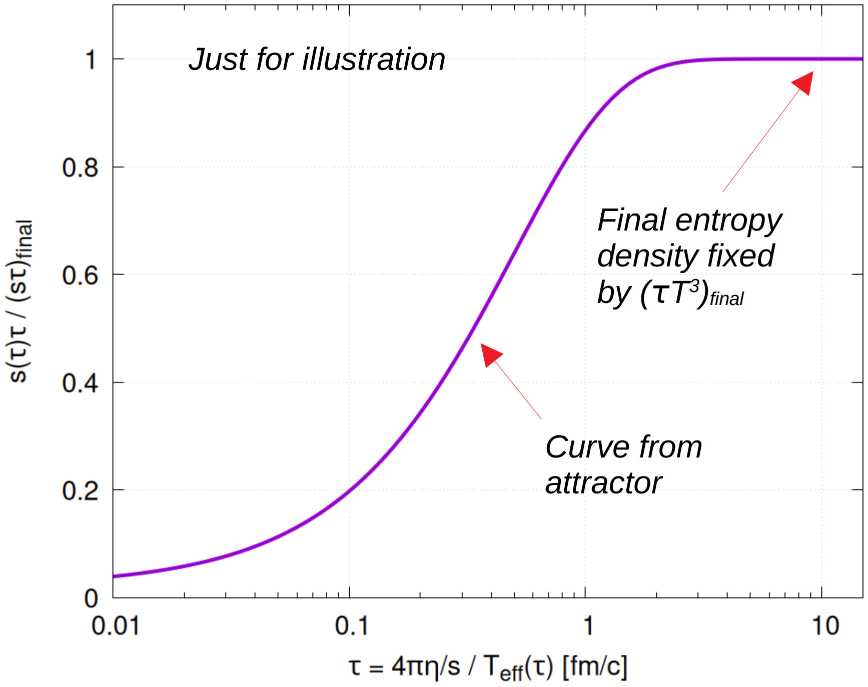
- The production rate is integrated over the space-time history of the medium
- Time evolution is fixed by : attractor curve + produced entropy density must match the one computed from final state charged particle multiplicity

$$(\tau T^3)_{final} = \frac{(s\tau)_{final}}{C_{EOS}} = \frac{dN_{ch}/d\eta (S/N_{ch})}{C_{EOS} A_T}$$

$$T_{\rm eq}\tau_{\rm eq} \sim 4\pi\eta/s$$
$$T^3_{\rm eq}\tau_{\rm eq} \sim (T^3\tau)_{\rm final}$$

→

$$\tau_{\rm eq} \sim \sqrt{\frac{(4\pi\eta/s)^3}{(T^3\tau)_{\rm final}}}$$



E.g. for 0-5 % Pb-Pb :
→ $\eta/s = 0.16$ → $\tau_{eq} = 1$ fm/c
→ $\eta/s = 0.32$ → $\tau_{eq} = 3$ fm/c

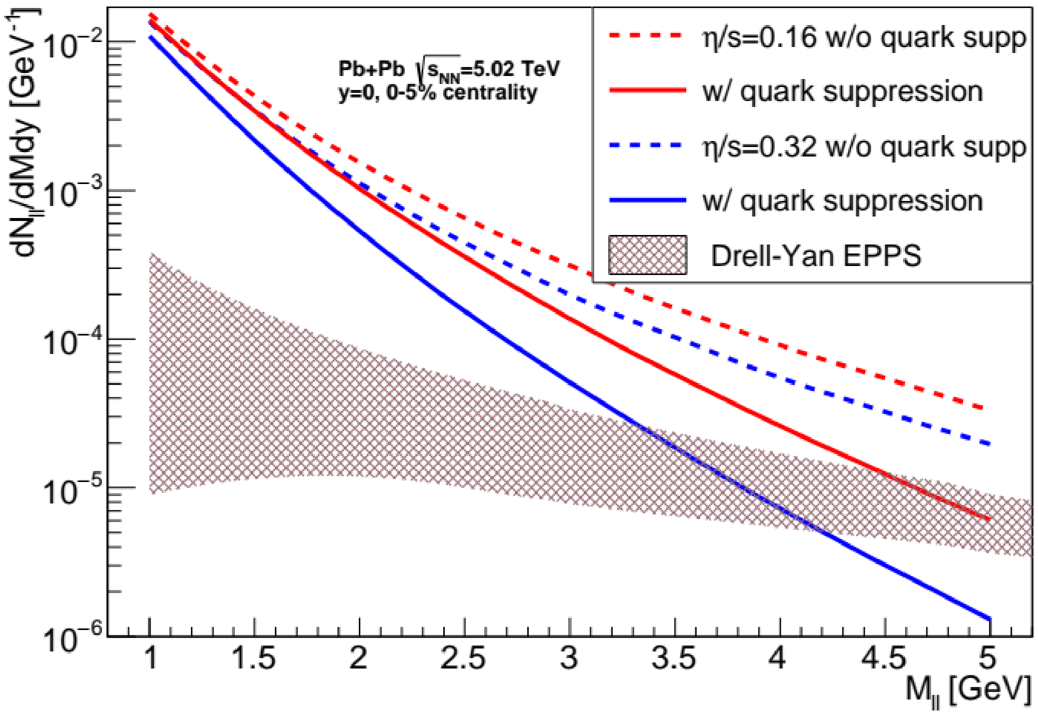
Invariant mass spectrum

Phys.Lett.B 821 (2021) 136626

- Invariant mass spectrum of dileptons from QGP including pre-equilibrium stage

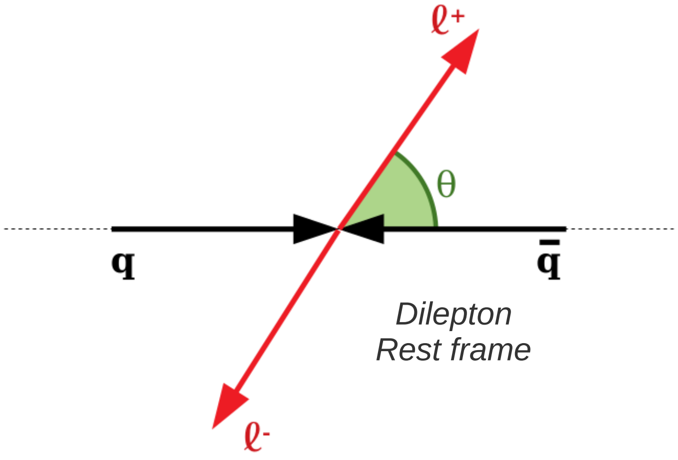
  → access to early-stage chemistry
  → access to equilibration time
  ($\propto (\eta/s)^{3/2}$)

- **Drell-Yan process calculated at NLO dominates dilepton production at high mass**



Angular distribution of leptons

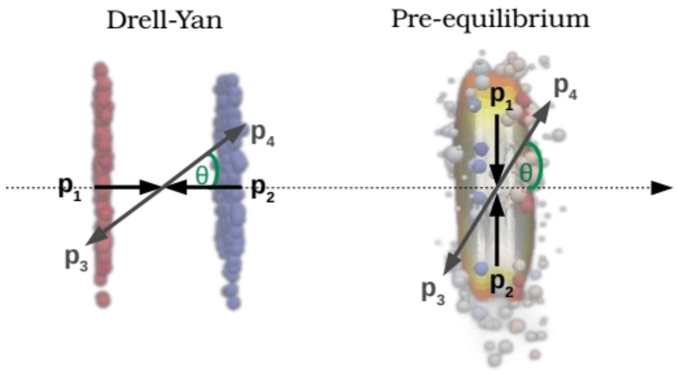
- Angle θ of positive lepton with respect to incoming quarks in dilepton rest frame



$$\frac{dN}{d\cos\theta} \propto 1+\cos^2\theta$$

- Leptons emitted in similar direction as the incoming quarks

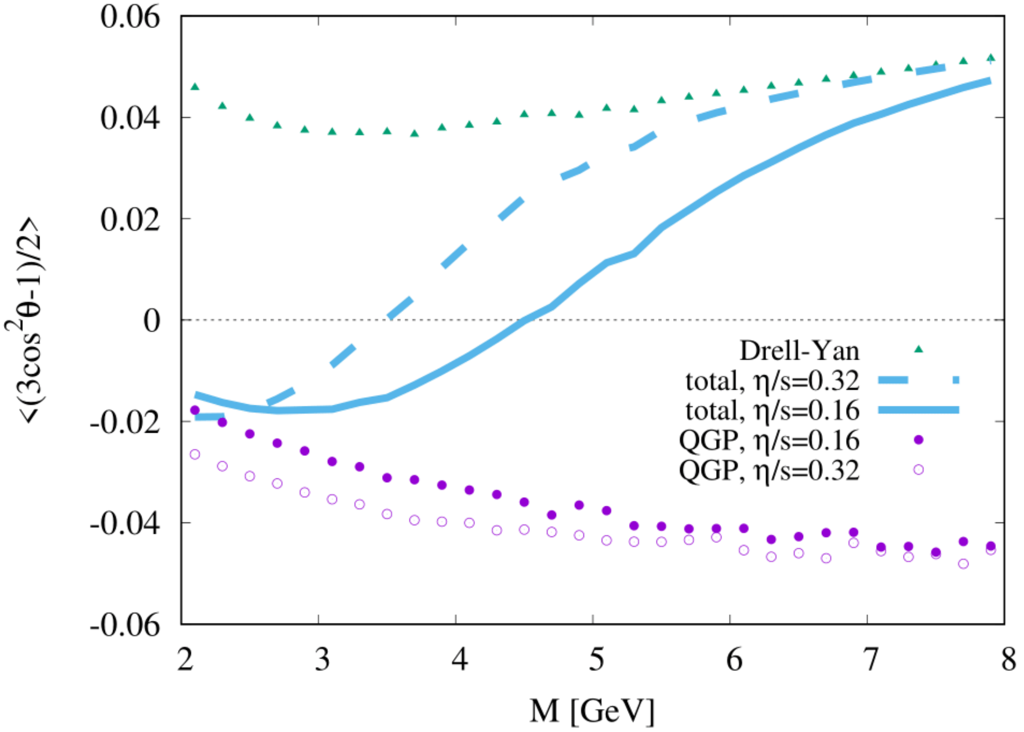
- If θ measured w.r.t. beam axis in the dilepton rest frame (Collins-Soper frame)



- **Drell-Yan: longitudinal quarks** → positive anisotropy w.r.t beam axis
- **Pre-equilibrium: transverse quarks** → negative anisotropy w.r.t beam axis

Angular distribution of leptons

Phys.Rev.Lett. 132 (2024) 23, 232301

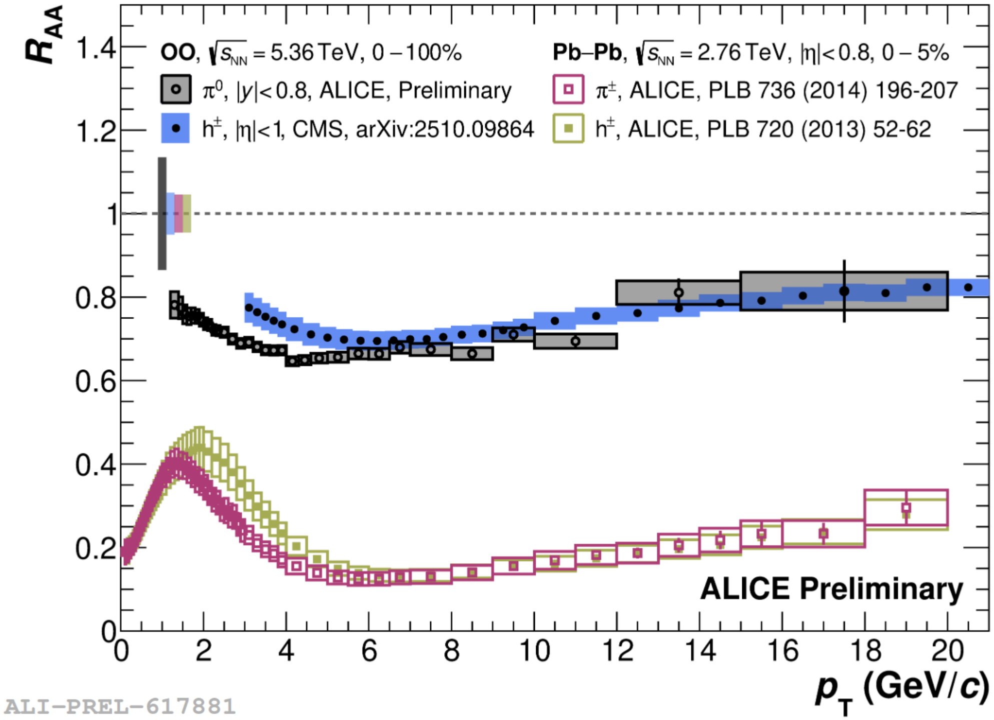


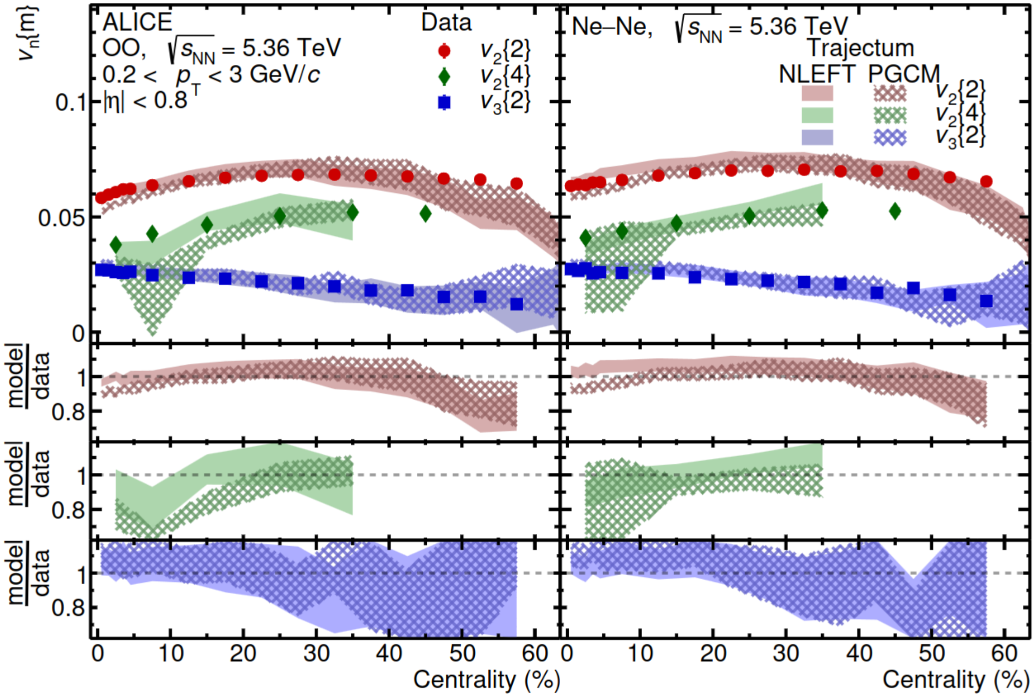
- Dilepton quadrupole moment as a function of mass
- Negative for thermal dileptons, positive for Drell-Yan
- Sum of the two contributions is negative for 2 < M < 4 GeV/c^2, i.e. carries signature of anisotropy in the early times
  → direct measurement of anisotropy

→ Direct measurement of anisotropy as a function of time

What about light ions ?

ALICE, arXiv:2509.06428

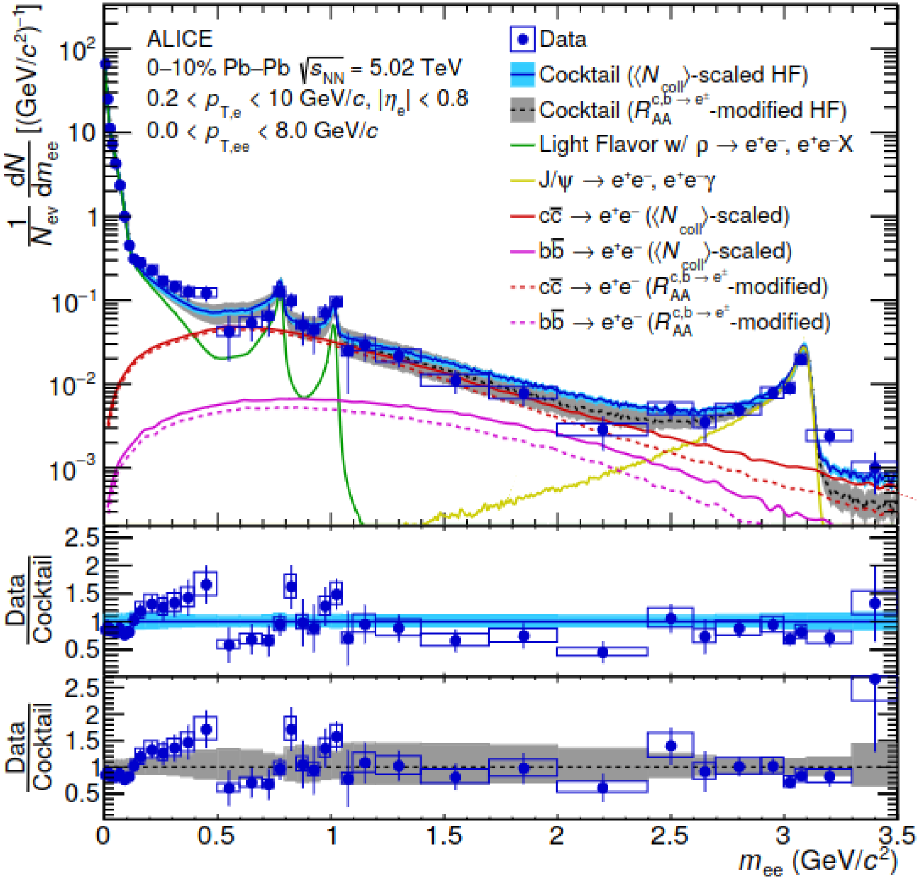




Experimental signatures of hot medium produced in OO collision (e.g. hadron quenching and flow)

What about light ions ?

- In the mass region $1 < M < 5$ GeV/c^2, dilepton spectrum is dominated by combinatorial background from semi-leptonic decays of heavy flavors
- Ideal dilepton spectrum scales with system size like $(dN_{ch}/d\eta)^{4/3}$ → scales like space-time volume → QGP dilepton signal in OO is expected to be only a few % of the signal in PbPb
- dN/dη ~ 10x smaller in central OO than PbPb : Ncoll ~ 30x smaller in OO
- Combinatorial background : scales like $Ncoll^2$ → OO should be much cleaner than PbPb



ALICE, Phys.Rev.C 112 (2025) 5, 054906

Scalings

- Including pre-equilibrium, scaling laws can be deduced from parametric form :

$$\frac{dN_{ll}}{dMdy} = A_\perp \tau_{\rm eq}^2 T_{\rm eq}^3 \mathcal{N}\left(\frac{M}{T_{\rm eq}}\right) \quad \text{where} \quad \tau_{\rm eq} \sim \sqrt{\frac{(4\pi\eta/s)^3}{(T^3\tau)_{\rm final}}} \quad T_{\rm eq} \sim \sqrt{\frac{(T^3\tau)_{\rm final}}{4\pi\eta/s}}$$

Garcia-Montero, Plaschke, Schlichting, arXiv:2403.04846

→ Assuming fixed η/s and the following scalings : $dN/d\eta \propto A, \quad A_\perp \propto A^{2/3}$

One gets : $T_{eq} \propto A^{1/6}$, $\tau_{eq} \propto A^{-1/6}$ → $\frac{dN_{ll}}{dMdy} \propto A^{5/6}\mathcal{N}\left(\frac{M}{A^{1/6}}\right)$

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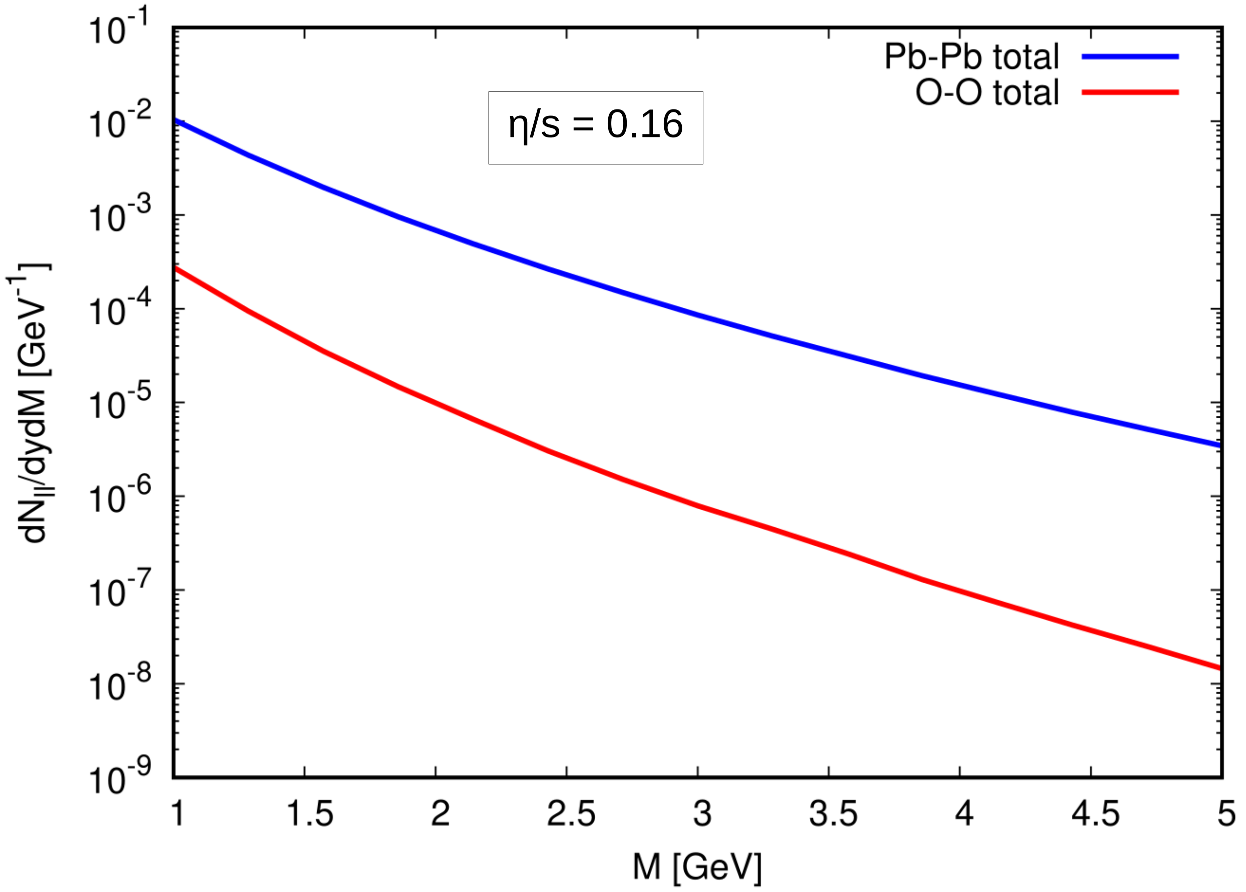
PbPb :	OO :
τ_{eq} ~ 1 fm/c	τ_{eq} ~ 1.5 fm/c
T_{eq} ~ 400 MeV	T_{eq} ~ 260 MeV

η/s = 0.16

OO spectrum

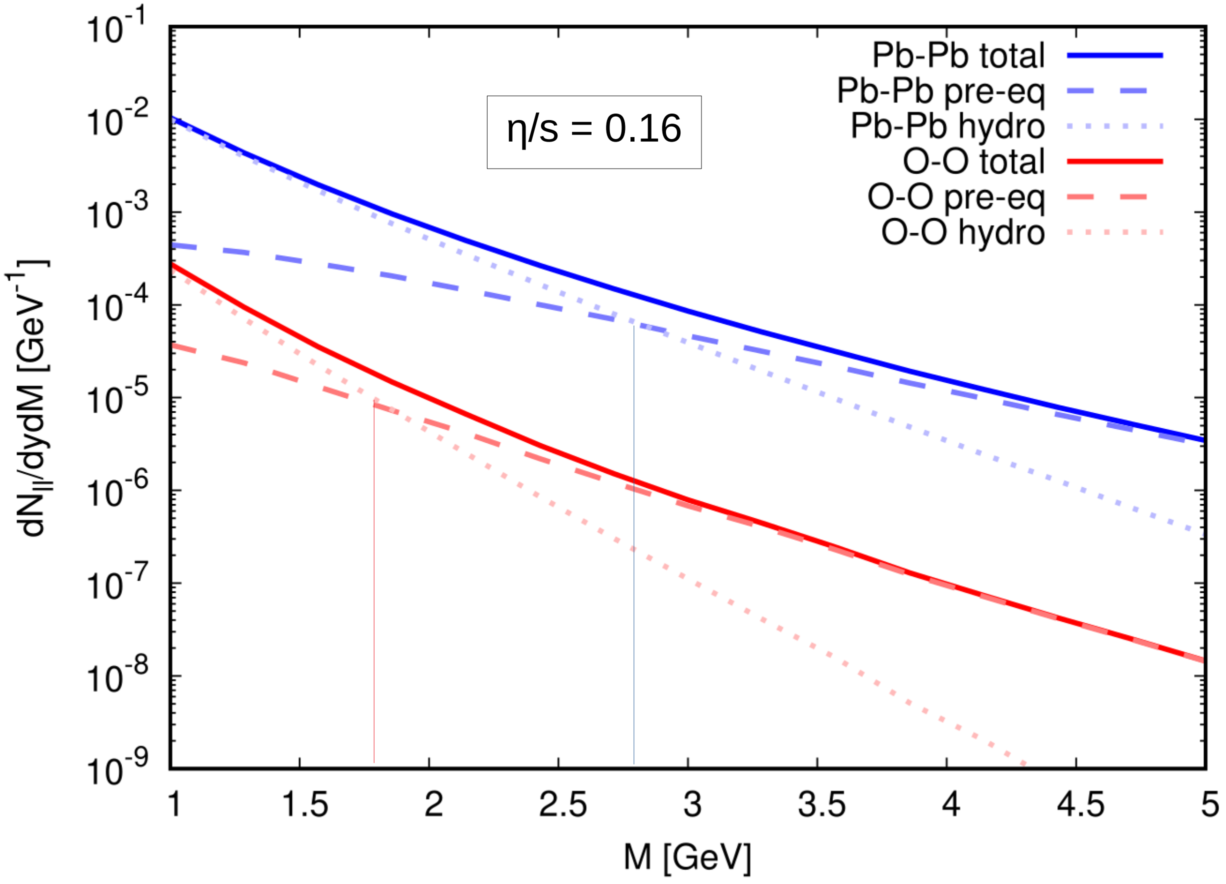
- Using these approximate laws, the PbPb spectrum can be rescaled to reproduce the expected spectrum in OO

- At least 1 order of magnitued smaller



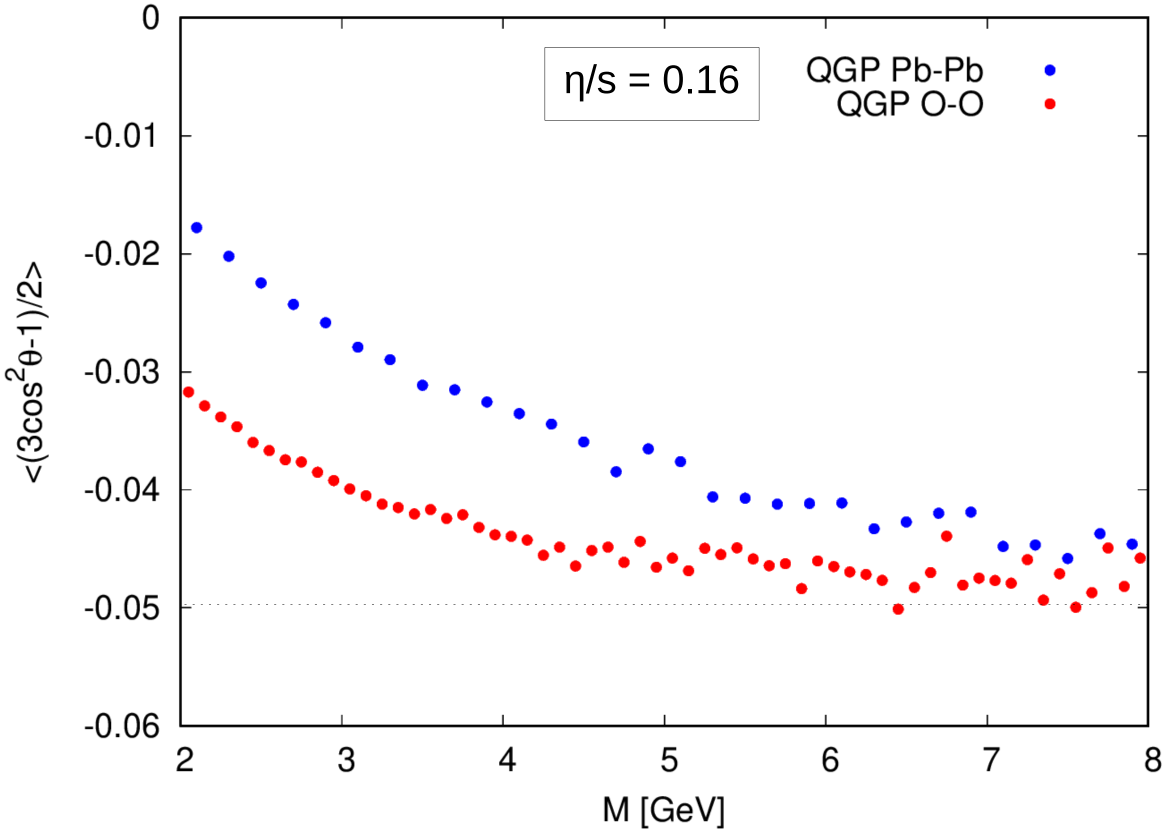
OO spectrum

- Using these approximate laws, the PbPb spectrum can be rescaled to reproduce the expected spectrum in OO
- At least 1 order of magnitued smaller
- Pre-equilibrium contribution starts to dominate the spectrum at lower mass in OO than PbPb



Polarization

- As pre-equilibrium contribution to the total QGP dilepton yield is more important in OO than in PbPb, quadrupole moment is more negative, closer to the lowest bound (-0.05), over the most of the mass range $2 < M < 8$ GeV/c^2

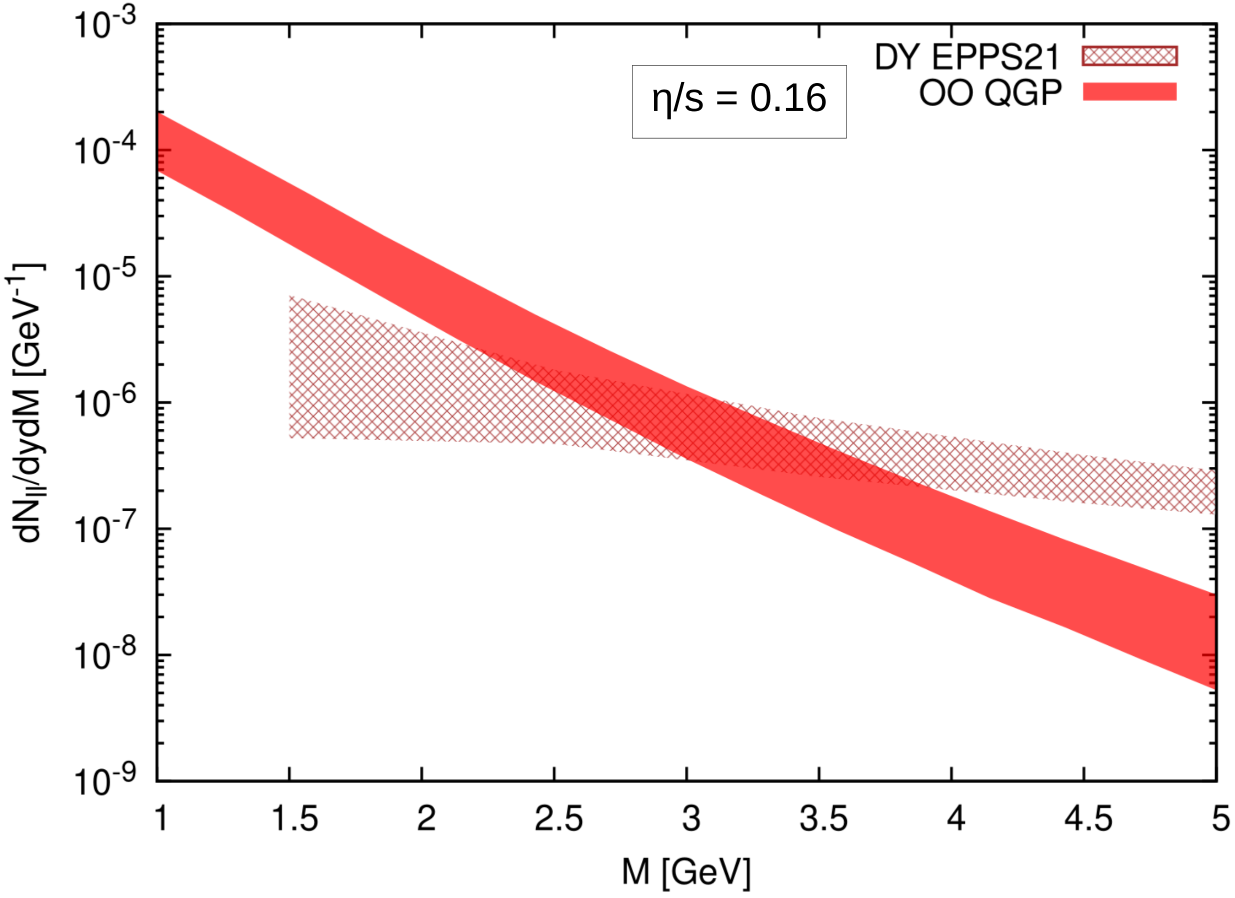


Comparison with Drell-Yan

- In addition to the scaled OO prediction, the yield is also computed using parameters from Glauber models

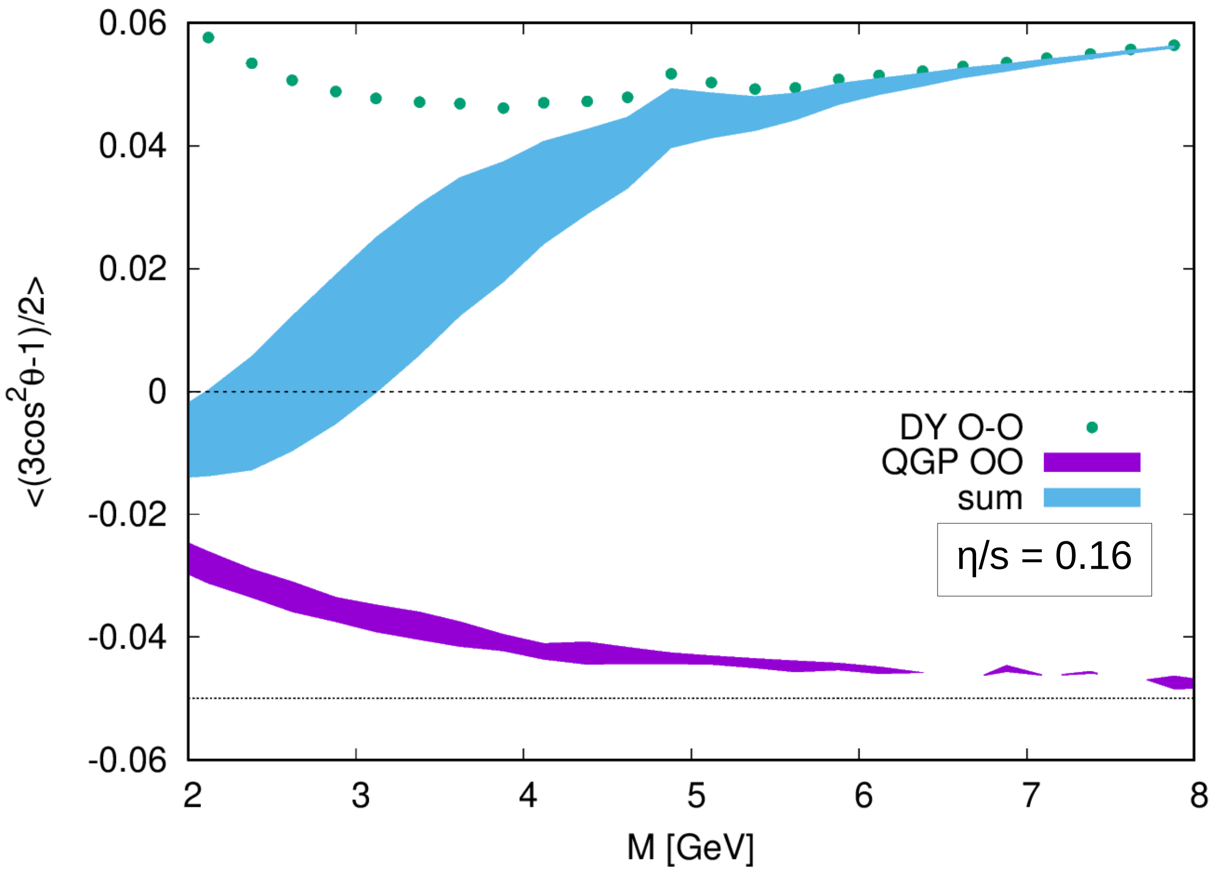
  → $A_\perp \sim 20 – 26\ fm^2$
  $dN/d\eta \sim 160 – 184$
  $\tau_{freezeout} \sim 3 - 5\ fm/c$

- Drell-Yan dominates spectrum starting from $M \sim 2\text{-}3\ GeV/c^2$



Comparison with Drell-Yan

- Due to the crossing between QGP and Drell-Yan dileptons are lower masses in OO than in PbPb, the negative signature of the quadrupole moment of the total yield is present in a much more narrow mass range …

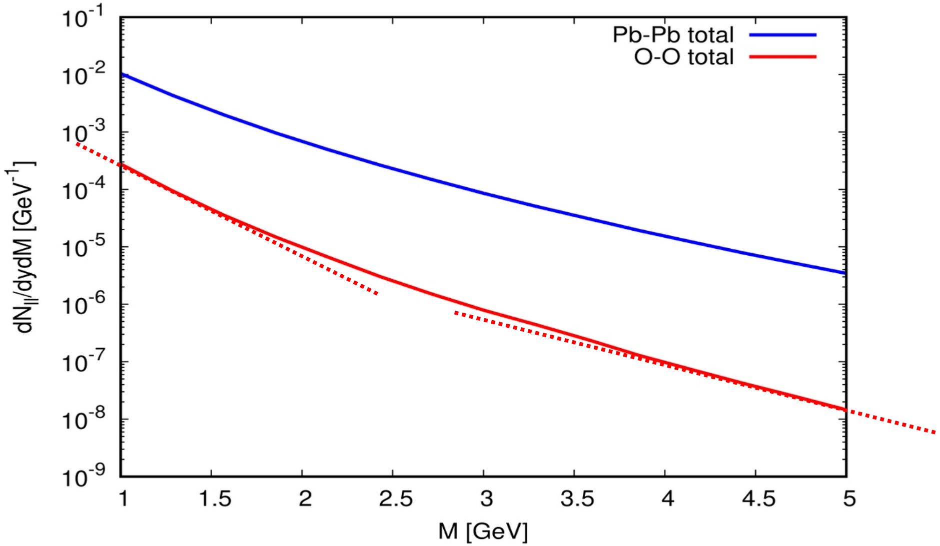


Do slopes measure temperature ?

It is often heard that the inverse slope of the dilepton spectrum gives access to the medium temperature

$$T_{slope} \equiv -\left(\frac{d}{dM}\ln\left(dN/dMdy\right)\right)^{-1} \qquad \rightarrow \text{If } \frac{dN}{dMdy} \sim \exp\left(\frac{-M}{T}\right) \text{ then } T_{slope} = T$$

But in general, dilepton yield has no reason to be exponential



Do slopes measure temperature ?

Going back to the scaling formula

$$\frac{dN}{dMdy} \sim A_\perp \tau_{eq}^2 T_{eq}^3 N\left(\frac{M}{T_{eq}}\right) \longrightarrow \boxed{T_{slope} = -T_{eq}\frac{N(M/T_{eq})}{N'(M/T_{eq})}}$$

If we measure T_{slope} as a function of mass for two different systems, e.g. PbPb and OO, then finding λ such that

$$T_{slope}^{OO}(M) = \lambda \cdot T_{slope}^{PbPb}\left(\frac{M}{\lambda}\right) \qquad \text{yields} \qquad \lambda = \frac{T_{eq}^{PbPb}}{T_{eq}^{OO}}$$

→ Comparing slopes of spectra from different systems could give access to ratios of equilibration properties

Conclusion

- Dilepton spectrum sensitive to early-time dynamics, **direct access to plasma anisotropy** through polarization
  - In O-O collisions, **pre-equilibrium dilepton production dominates** over thermal production in the intermediate mass range
- But Drell-Yan expected to overshine QGP dileptons quite quickly in OO

→ **Impact of hotspots in the initial energy density** profile could be important → to be checked using state-of-the-art initial state calculations

Thank you !

Backup

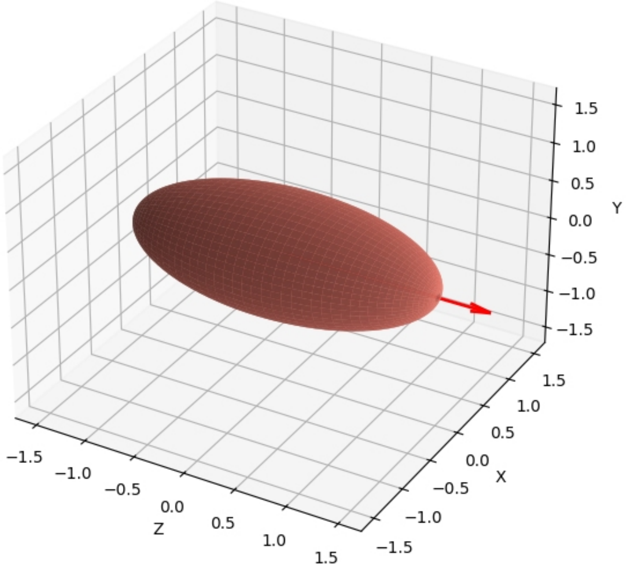
Angular distribution of leptons

- Quantified using the quadrupole moment of the angular lepton distribution:

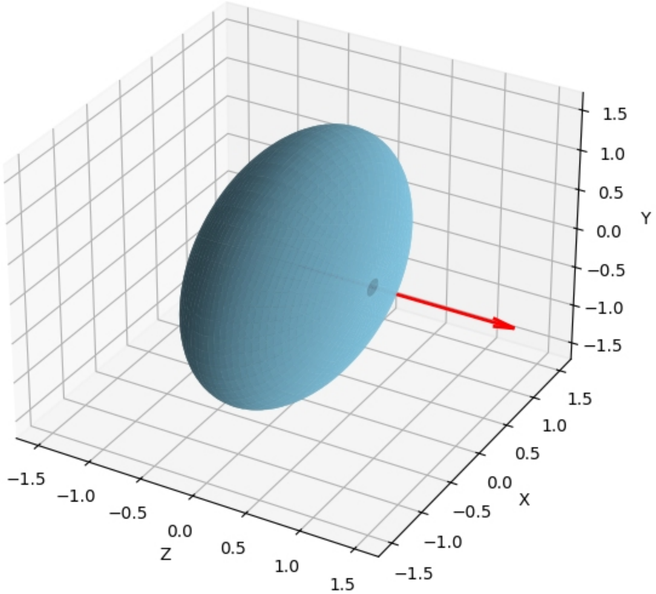
$$\lambda_\theta = \frac{3Q}{\frac{2}{5} - Q}$$

$$Q = \left\langle \frac{3\cos^2\theta - 1}{2} \right\rangle \equiv \frac{\int_{-1}^{1} d\cos\theta \; \frac{1}{2}(3\cos^2\theta - 1)\frac{dN}{d\cos\theta}}{\int_{-1}^{1} d\cos\theta \; \frac{dN}{d\cos\theta}}$$

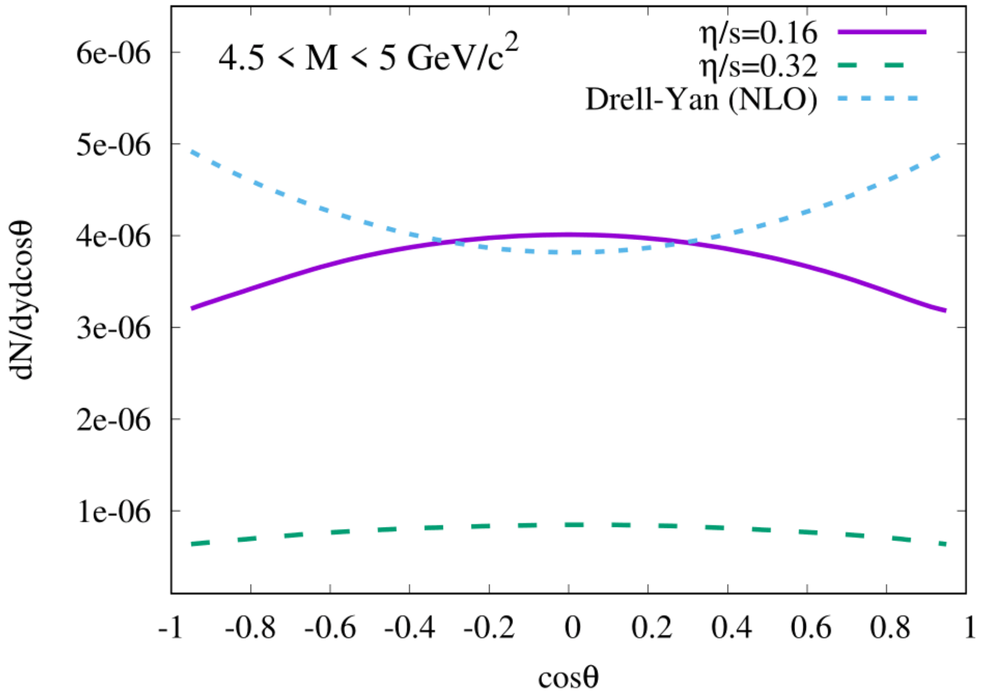
Prolate distribution : $Q > 0$



Oblate distribution : $Q < 0$

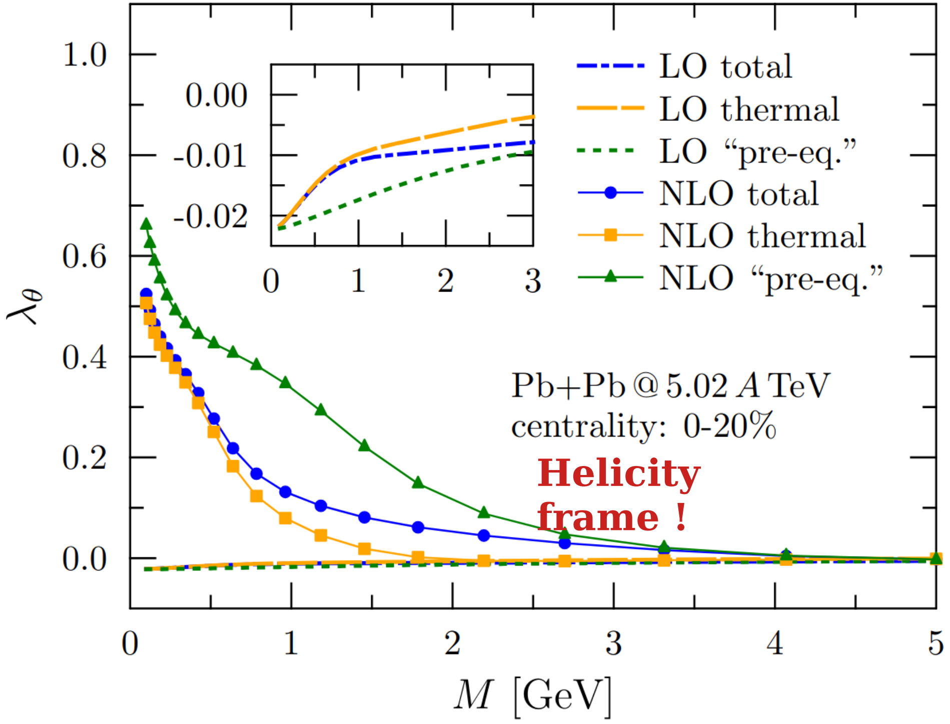


Angular distribution of leptons



- Angular distribution of dileptons for 0-5 % centrality Pb-Pb, $\sqrt{s_{NN}}$ = 5 TeV, |y| < 1
- Opposite behaviors for Drell-Yen and QGP+pre-equilibirum dileptons

Further considerations



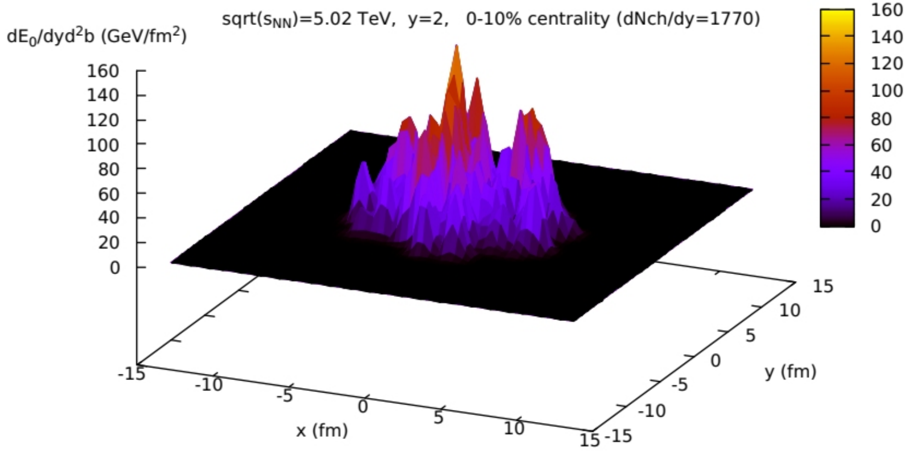
Wu et. al. arXiv:2412.15052

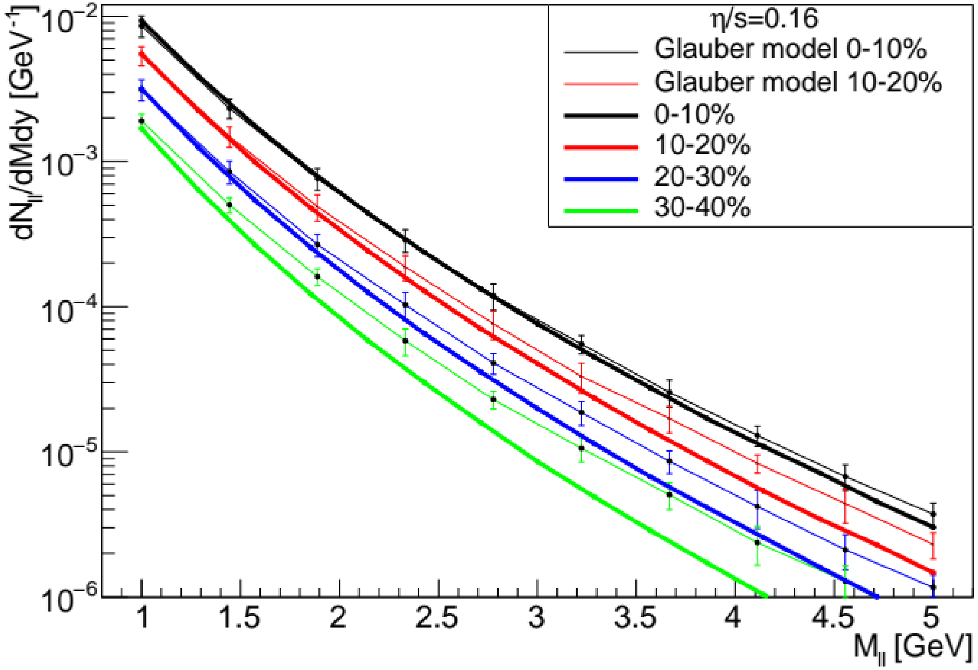
Estimating the transverse fluctuations

- Modelling of event-by-event fluctuations (hot spots) using a TMD-Glauber model : parametrization of gluon distributions in nucleons + Glauber→ parameters tuned to reproduce ALICE data for $dN_{ch}/d\eta$

$$\frac{dN_g}{d^2\mathbf{b}d^2\mathbf{P}dy} = \frac{\alpha_s N_c}{\pi^4\mathbf{P}^2(N_c^2-1)} \int \frac{d^2\mathbf{k}}{(2\pi)^2}\ \Phi_A(x,\mathbf{b}+\mathbf{b}_0/2,\mathbf{k})\ \Phi_B(x,\mathbf{b}-\mathbf{b}_0/2,\mathbf{P}-\mathbf{k})$$

- Important for large invariant mass region in more peripheral events





T. Lappi and S. Schlichting, Phys. Rev. D 97 (2018) no.3, 034034
S. Schlichting, X. Du, private communication