Small collision systems and the Electron Ion Collider

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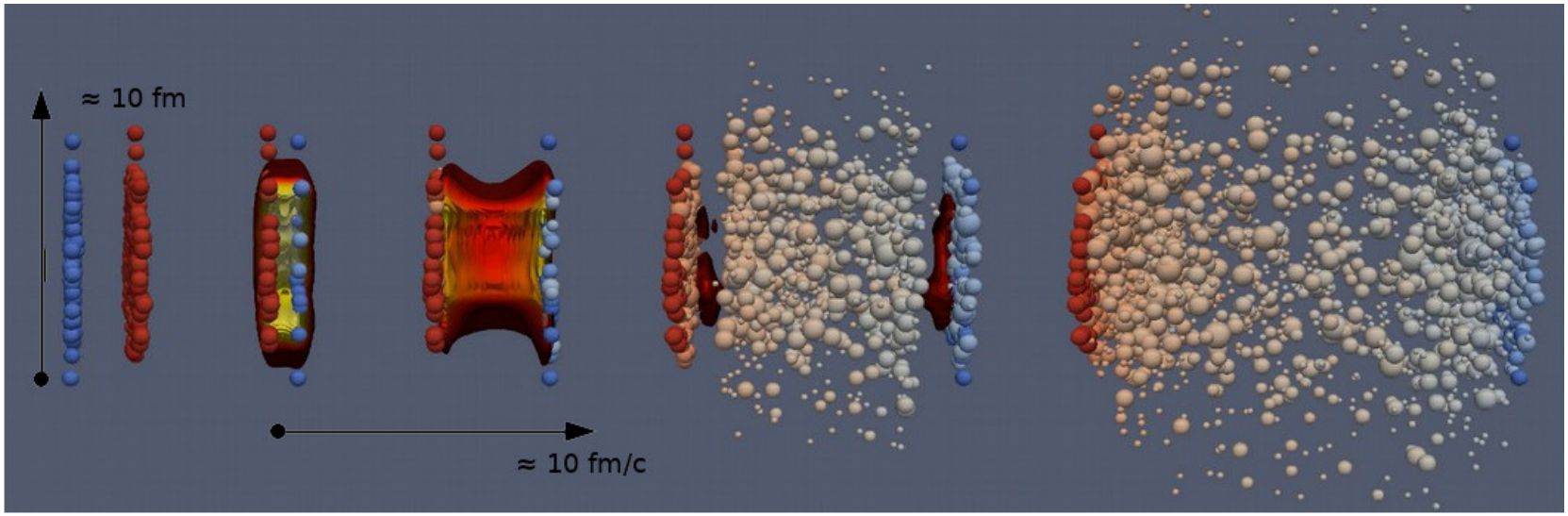
Light-Cone Conference, Palaiseau, 17th of September 2019

Heavy-ion collisions: scrutinizing QCD matter

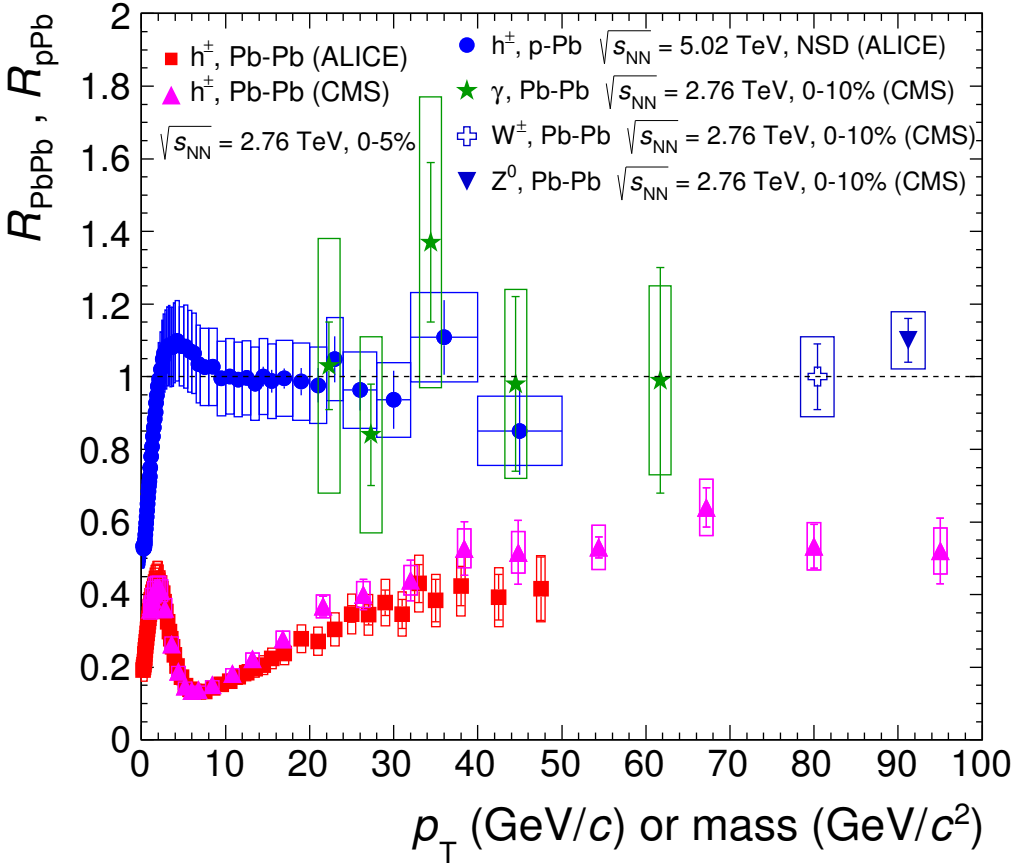


Madai visualisation of MUSIC hydrodynamics.

- "macroscopic" system:
  study QCD matter in & out-of equilibrium properties
- different perspective with respect to hadron structure:

  information about thermodynamics systems for energy densities where matter is **chirally restored & deconfined**

QGP community: traditional view on pp & pPb collisions



taken from arXiv:1405.2737, Z^0 from arXiv:1410.4825

$$R_{PbPb} = \frac{\sigma_X^{PbPb}}{A^2 \cdot \sigma_X^{pp}}$$

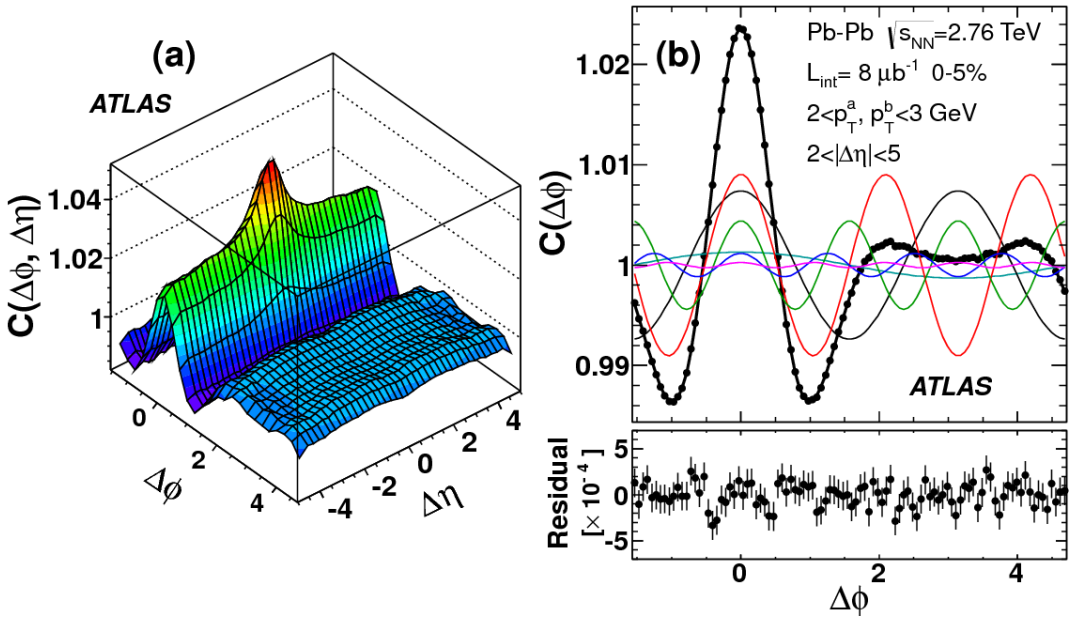
$$R_{pPb} = \frac{\sigma_X^{pPb}}{A \cdot \sigma_X^{pp}}$$

centrality integrated formulae,

A=208: nuclear mass number of lead.

- pp/pPb $\approx$ references, e.g. high-p_T-R_{PbPb} definition for energy loss
- interpretation rediscussed after the first round of LHC results
- goal of this talk:
  point out connections to nucleon structure field, EIC in particular

Heavy-ion collisions: azimuthal particle correlations

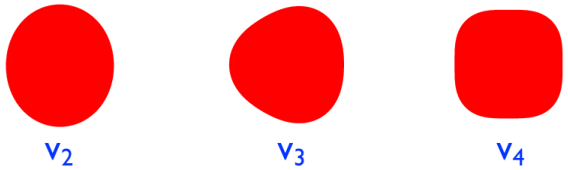


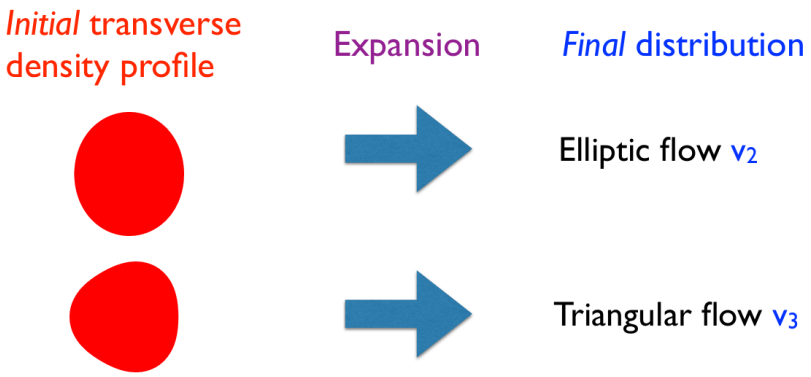
example from ATLAS arXiv:1203.3087

- 2-(and more)-particle correlations typically azimuth and pseudorapidity differences from particle momentum vectors
- (long-range) azimuthal correlations observed in heavy-ion collisions
- large 'elliptic'-flow, positive 2nd Fourier coeff.: main discovery at RHIC
  with energy loss alias 'jet quenching'
- at the LHC: higher fourier-decomposition and event-by-event analysis
  e.g. by ATLAS arXiv:1305.2942
- How do we understand this in heavy-ion collisions?

Heavy-ion collisions: hallmark observable collective flow

- The single-particle distribution is essentially independent of rapidity η but depends on azimuthal angle, φ in each event
- Fourier decomposition : $f(\varphi)=\sum_n V_n e^{-in\varphi}$
- $v_n \equiv |V_n|$=anisotropic flow fluctuates event to event



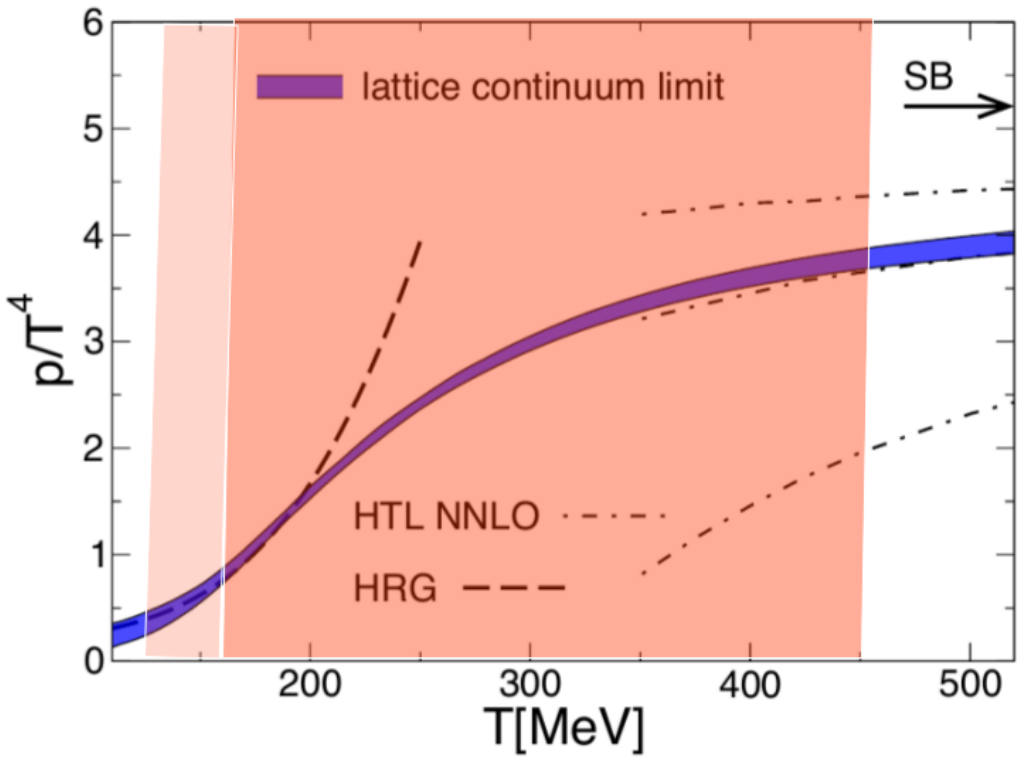


In hydrodynamics, anisotropic flow is a response to the anisotropy of the initial density profile.

taken from from J.-Y. Olltrault's talk at Epiphany conference '19

- transverse collision-zone **geometry in coordinate space** inducing azimuthal particle **correlations in final state in momentum space**
- today: trying to confront ab-initio calculations for or extract viscous corrections as shear and initial state geometry fluctuations

Heavy-ion collisions: thermodynamics via hadronisation



T-range probed at the LHC according to hydrodynamic models

p/T^4: pressure over temperature^4

HRG: Hadron Resonance Gas

HTL: Hard thermal loop

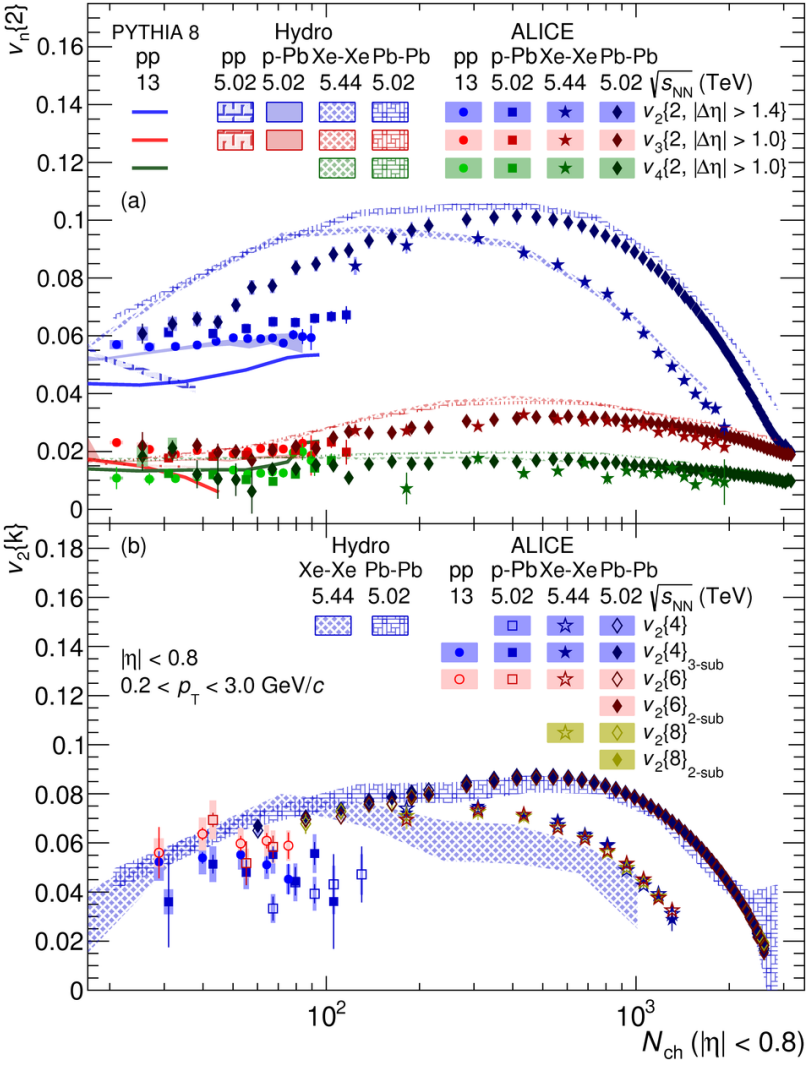
SB: Stefan-Boltzmann limit of non-interacting quarks and gluons

hadron species particle density in ideal HRG: $n_i = \frac{g_i}{2\pi} \int_0^\infty \frac{dp p^2}{e^{(E-\mu)/T} \pm 1}$

Figure taken from PLB 370 (2014), T-range from PRC 89, 044910 (2014)

- HRG: QCD statistical operator below $T \approx 155$ MeV/cross-over
- common hadronisation temperature of QGP close to freeze-out: particle production via HRG
  $\rightarrow$ temperature T & μ_B snap-shot from particle abundances
- heavy-ion collisions in thermodynamic limit $V \rightarrow \infty$:
  grand-canonical ensemble used for fits to experimental data
- thermal fit works, non-trivial fluctuations checks as well

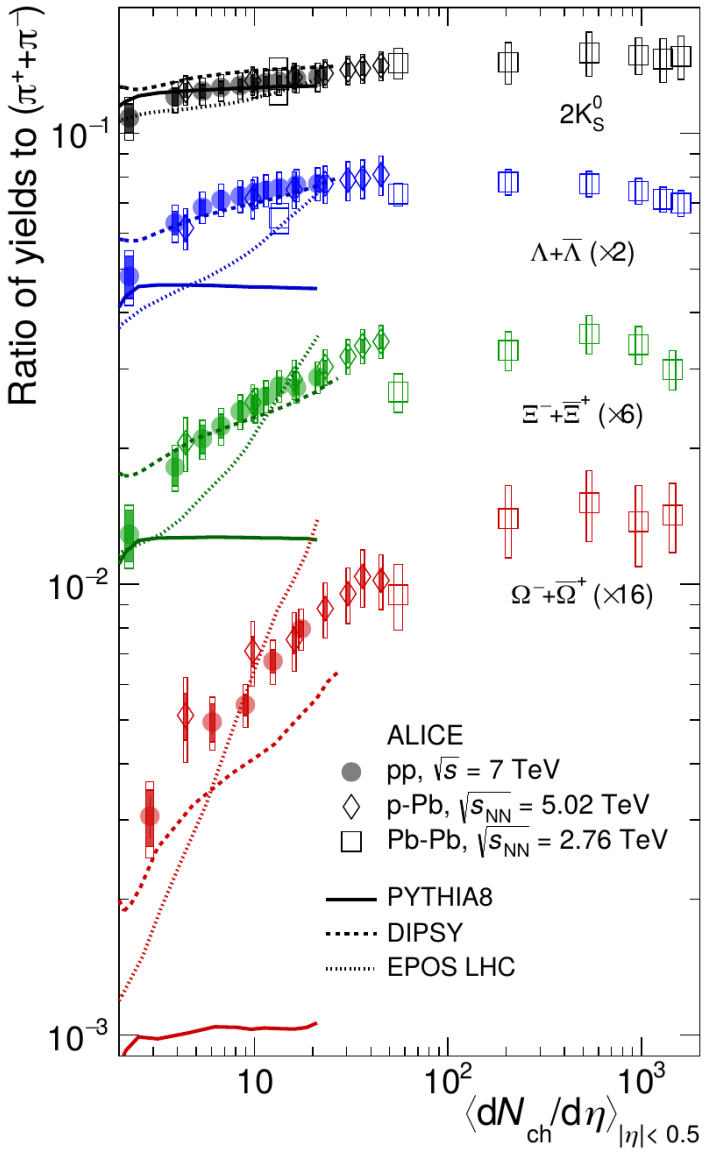
Observations in pp & pPb collisions: azimuthal correlations



arXiv:1903.01790

- continuum between different collision systems apart from "average"-geometry in PbPb non-central for 2nd harmonic
- number of particles: control parameter to first approximation

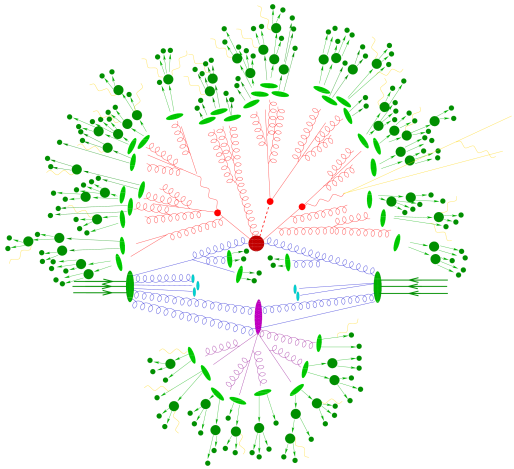
Obervations in pp & pPb collisions: hadronisation

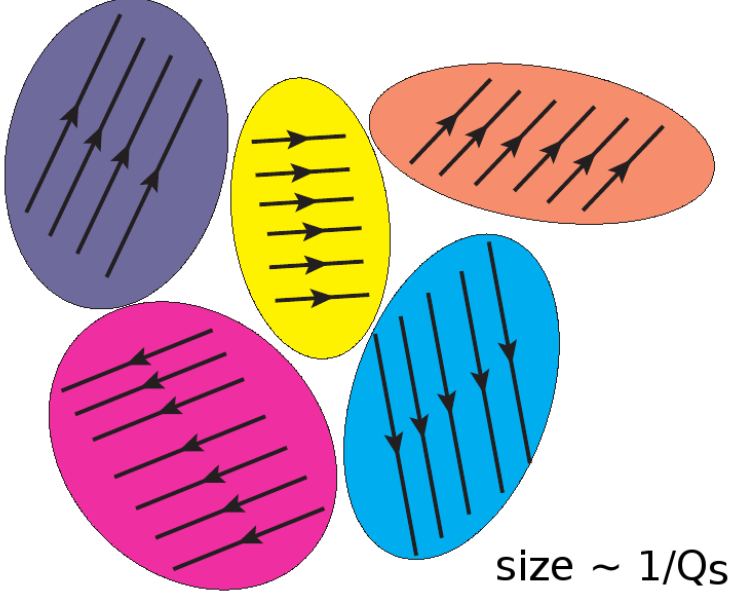


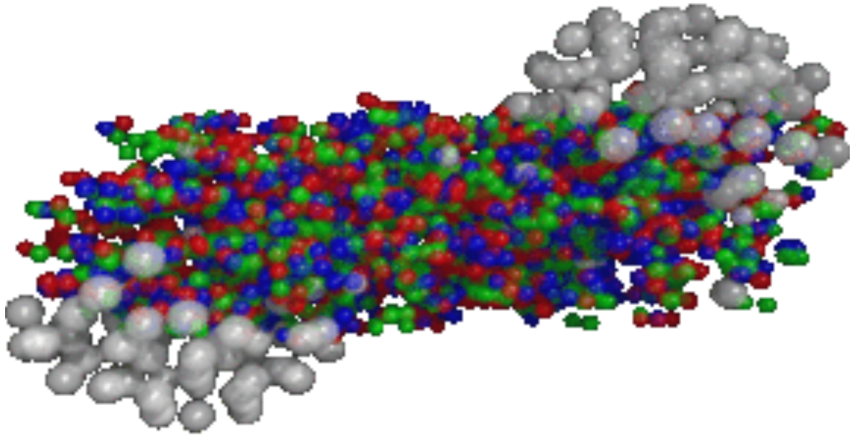
arXiv:1606.07424

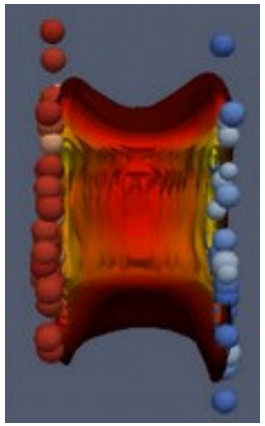
- pp/pPb collisions smoothly approaching thermodynamic limit
- charged particle multiplicity - i.e. entropy - the only relevant control parameter
- also modifications observed for heavy-flavour hadronisation

The question(s)





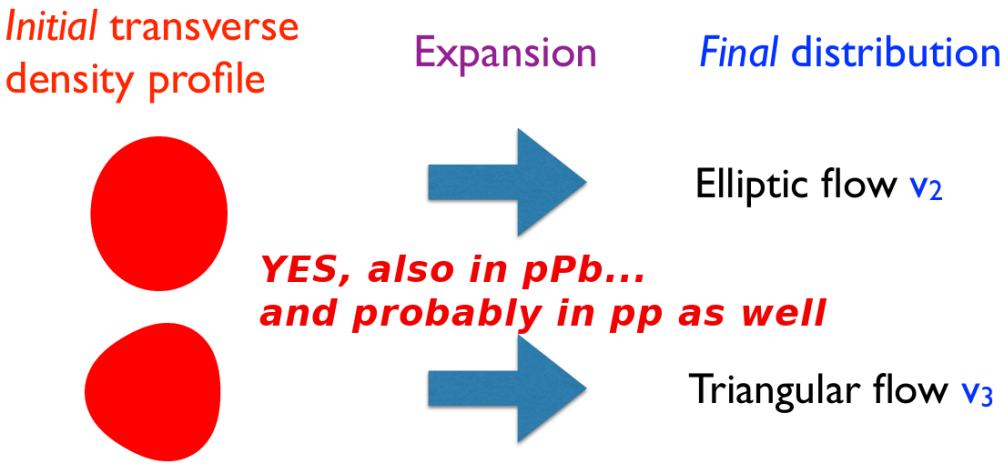


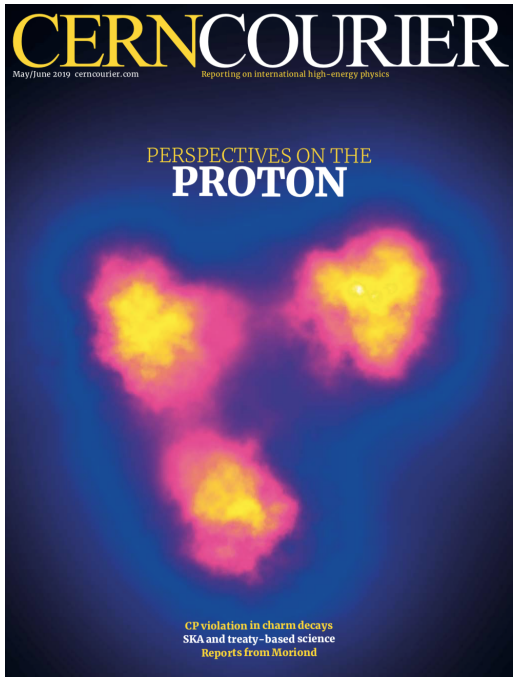


different pictures: 'collinear' MPI, CGC colour domains, few-touch transport, fluid.

- Is there "life" beyond/"between" partonic scattering and hadronisation?
- How do we reconcile these "pictures"? Can we find an overall frame?

The current understanding

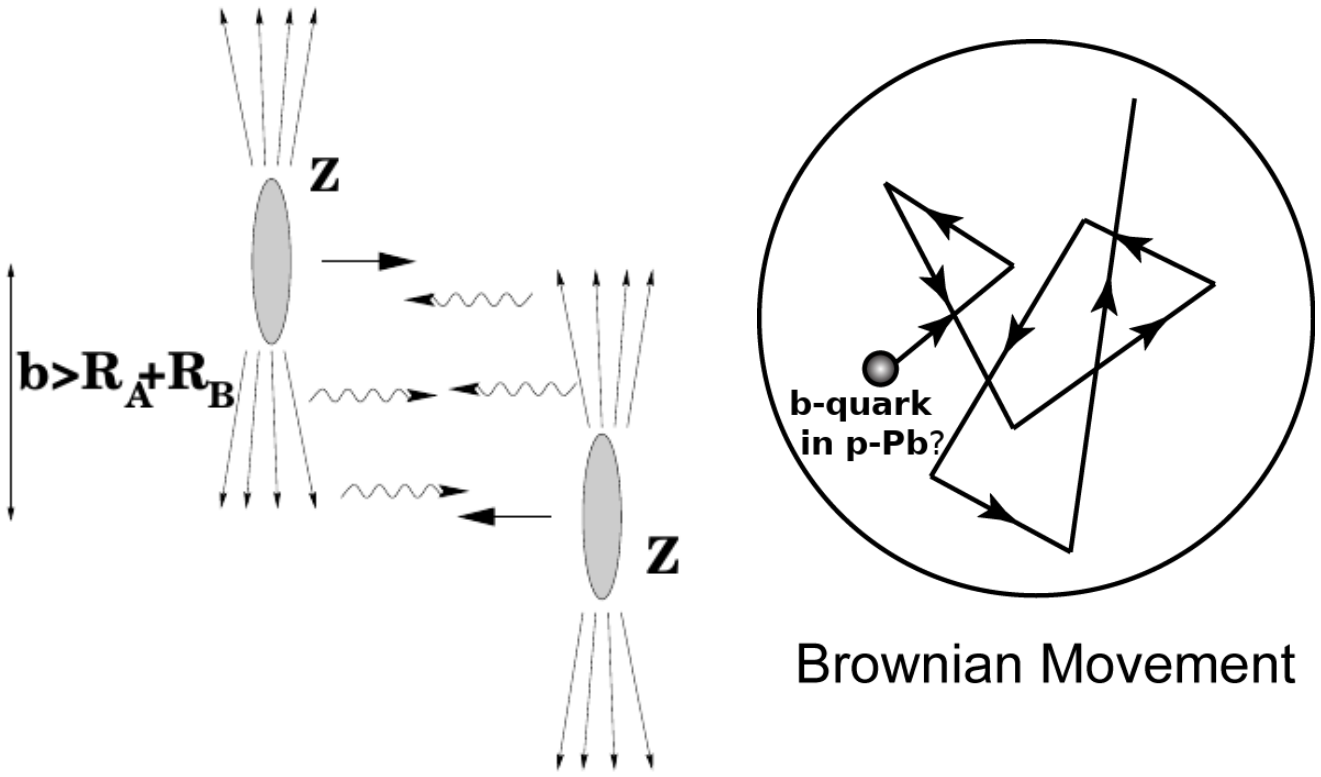




- coordinate space geometry as correlation source via hydro or transport
- require sub-nucleonic geometry fluctuations

  e.g. discussed in arXiv:1701.07145 arXiv:1705.03177
- Open: Do we need different concepts?
- Or simply: "One fluid to rule them all"? arXiv:1701.07145
- know that there are correlations at low-x...do we see them as well?

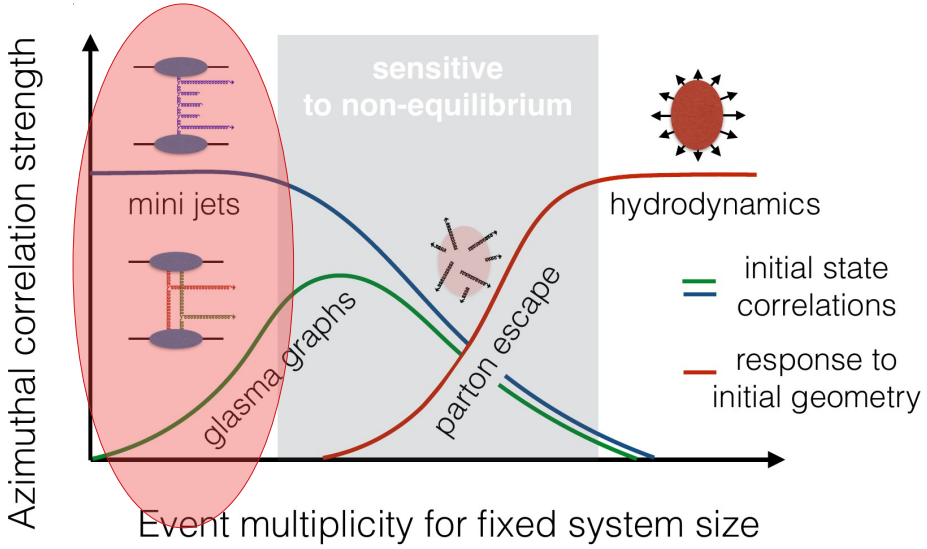
The immanent future at hadron colliders



Two future areas of interest, photon-induced reactions as well as *b*-quarks in inclusive reactions.

- looking into correlations in photo-production via ultra-peripheral collisions: a quasi-real, a vector-meson dominated, photon as probe
- heavy quarks: heavy-flavour still dragged?
- search for partonic energy loss, vary geometry for this among other cases
- detailed correlation observables as in PbPb
  $\rightarrow$ see excellent talk by Maxime

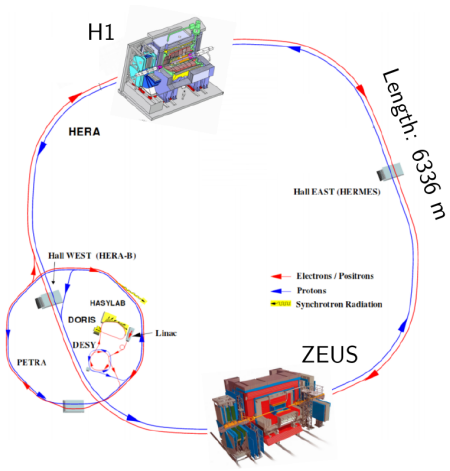
...and its limitations



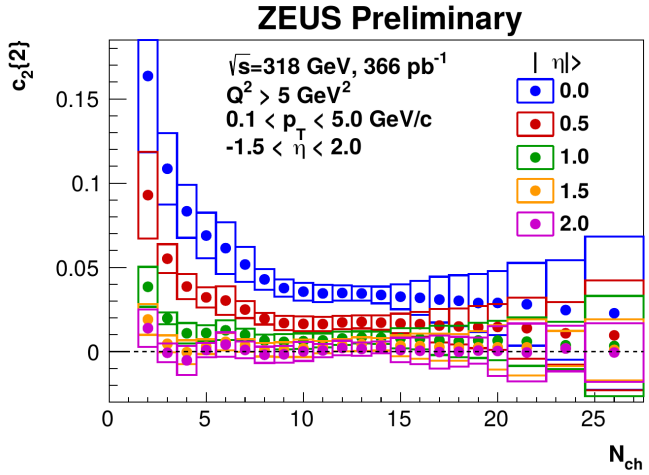
modified from: arXiv:1611.00329

- believing our theory friends: various initial state correlations exist $\rightarrow$ rich phenomenology!
- How isolate them? Do they matter in hh?
- In hh: MPI implicitly always in our heads for geometry and final state interactions: how to switch them off cleanly?
- Can we constrain independently from hh geometry & density?
- What drives 'thermal' particle production and factorisation breaking? Does it imply thermalisation or not?
- electron-hadron: an evident place to look for answers

ZEUS at HERA: a first look



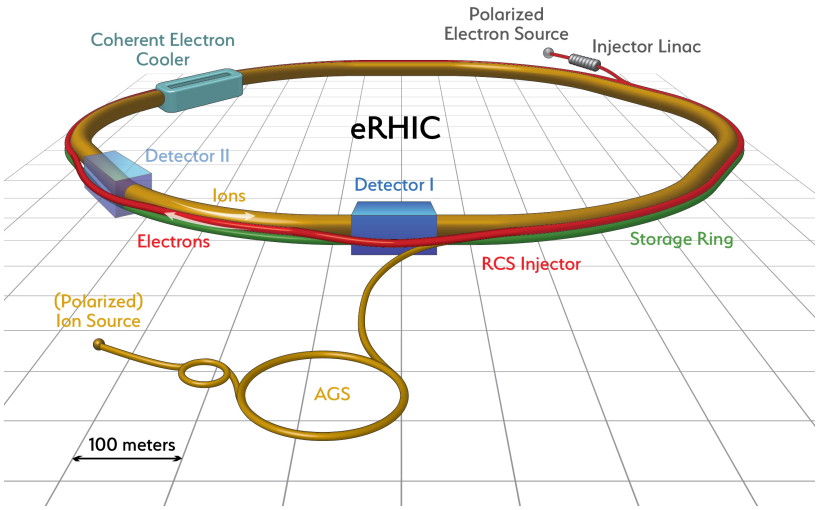
- Location: DESY, Hamburg, Germany
- Data taking: 1992 - 2007
- 27.6 GeV electrons/positrons
  920 GeV protons
  $\rightarrow \sqrt{s} = 318$ GeV
- H1 & ZEUS - 4π detectors
- HERA I+II:
  500 pb^{-1} per experiment

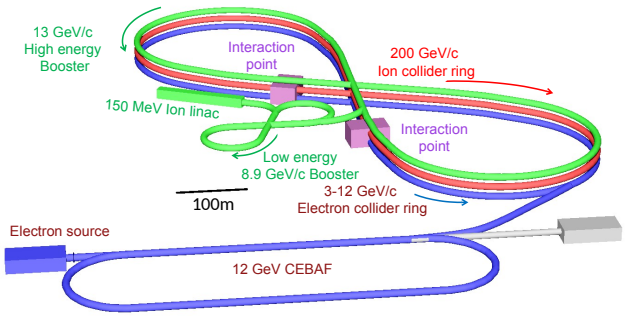


J. Onderwaater Quark Matter 18, ZEUS-prel-18-01. Result for $c_n\{2\} = \langle\langle 2 \rangle\rangle = \langle\langle e^{in(\phi_\alpha - \phi_\beta)} \rangle\rangle$

- nothing found for DIS $Q^2 > 5\text{GeV}^2$, multiplicities relatively small
  also in $e^+e^- \rightarrow Z \rightarrow h$ at LEP nothing found
- what can an Electron Ion Collider teach us?

The Electron Ion Collider

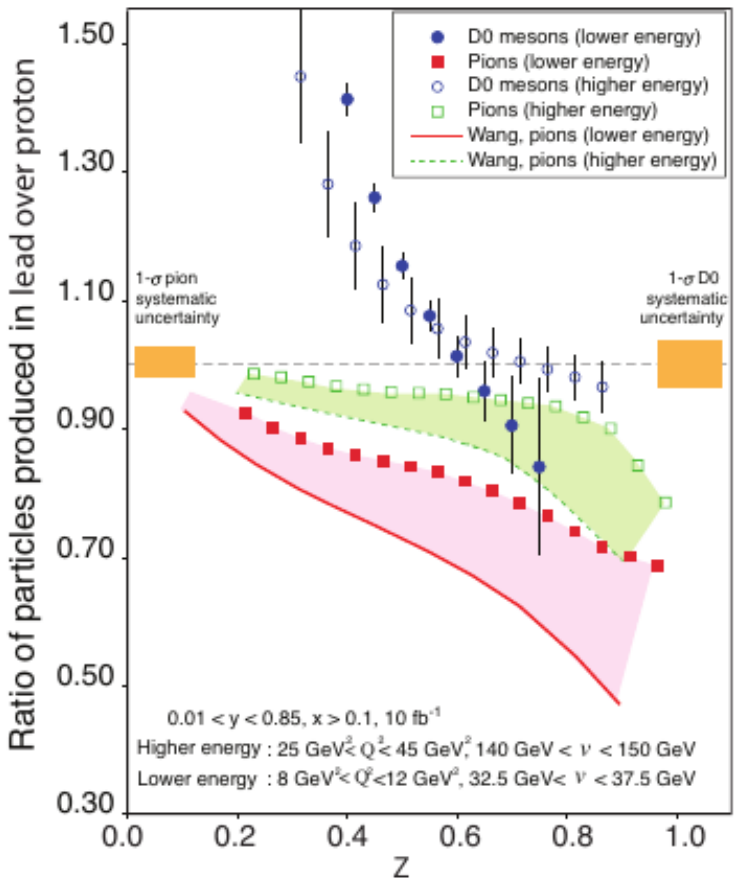




accelerator complex proposal BNL and JLAB.

- two proposals for polarized intensity frontier electron-hadron colliders in the US with $\sqrt{s_{NN}} = 20- \approx 100\text{GeV}$
- decision process well advanced, see EIC User group meeting in Paris for details: Paris 19
- increase HERA luminosity by 2-3 orders of magnitude & operate with ions

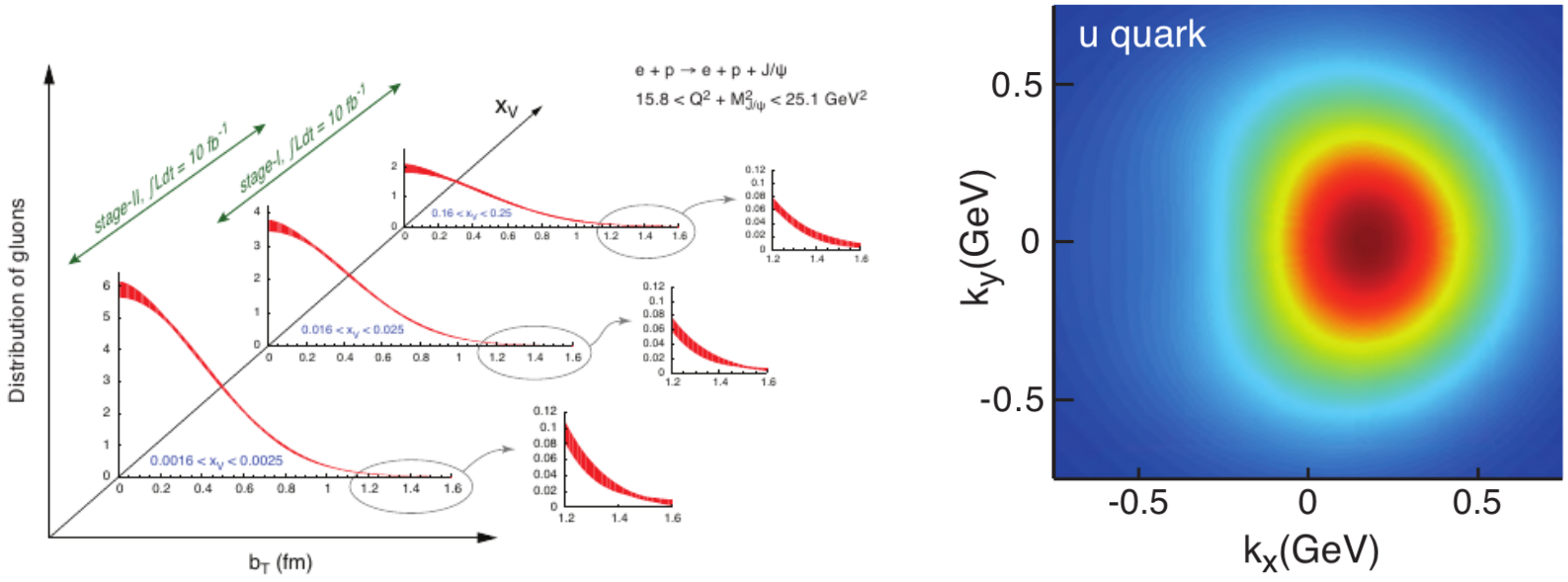
EIC: hadronisation



arXiv:1212.1701

- detailed investigation in light and heavy-flavour sector as function of kinematic variables and multiplicites
- probe jet universality and nuclear effects
- Where does a thermal description set in?
- What are the control parameters?

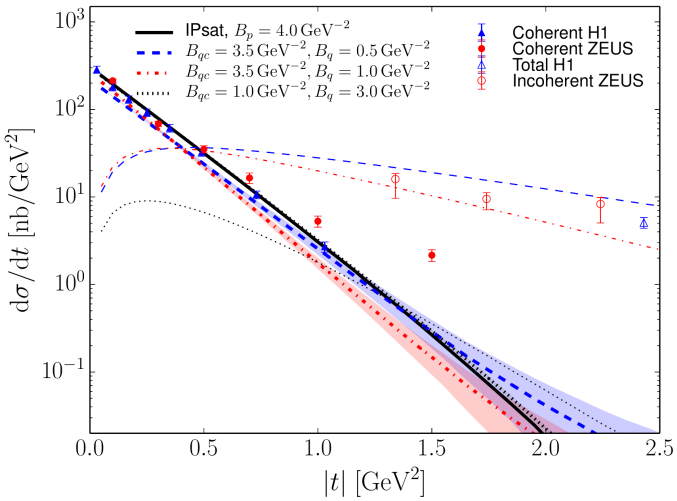
EIC: initial state geometry in momentum & coordinate space

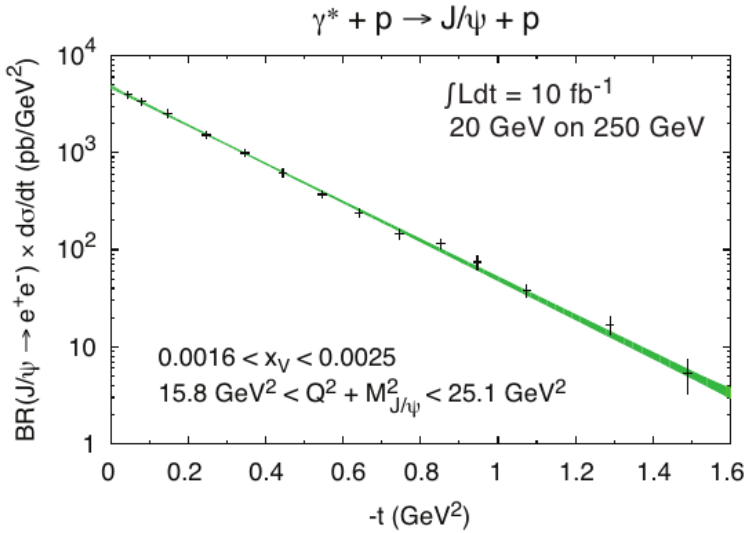


arXiv:1212.1701, right: unpolarized quark TMD for x=0.1 and polarized proton along y.

- geometrical picture of the initial state as input for hydrodynamic modelling
- caveat and advantage at once: close to no multi-parton interaction sensitivity
- clean environment to probe low-x correlation hypothesis via correlations
- direct connection to heavy-ion-like correlations at the moment very model-dependent

Initial state geometry: one example

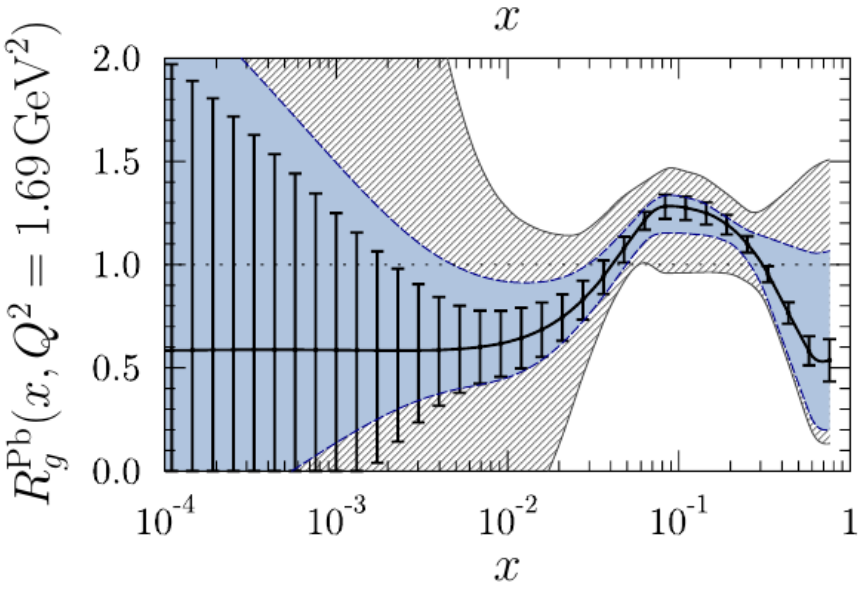


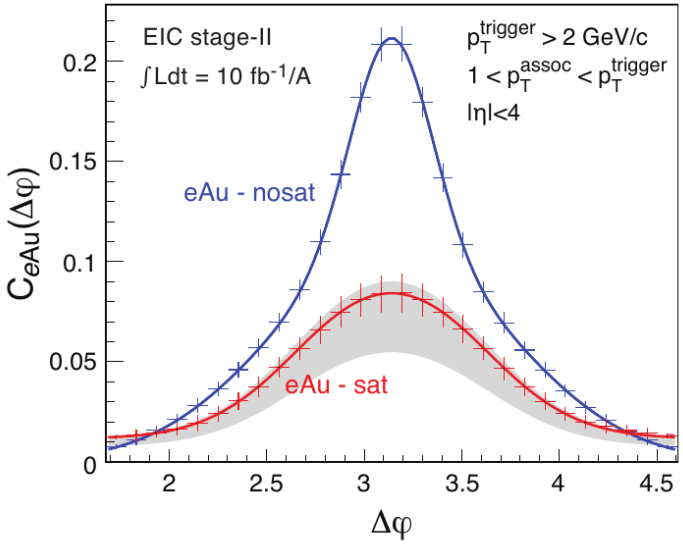


Left: fit to HERA data in arXiv:1603.04349, right: EIC projection from arXiv:1212.1701.

- in pA and pp collisions: proton geometry most unconstrained input information
- Ansatz for hydro: constrain coordinate shape & fluctuations by coherent and incoherent J/ψ-production
- connection model-dependent: independent MPIs sampled from single scattering model
- in low-x correlation scenario without MPI complication: require proton transverse-momentum structure, see e.g.arXiv:1901.10320
- EIC: precision for geometry relevant for RHIC collisions
- full opportunity exploitation will require theory work!

EIC: parton densities and saturation





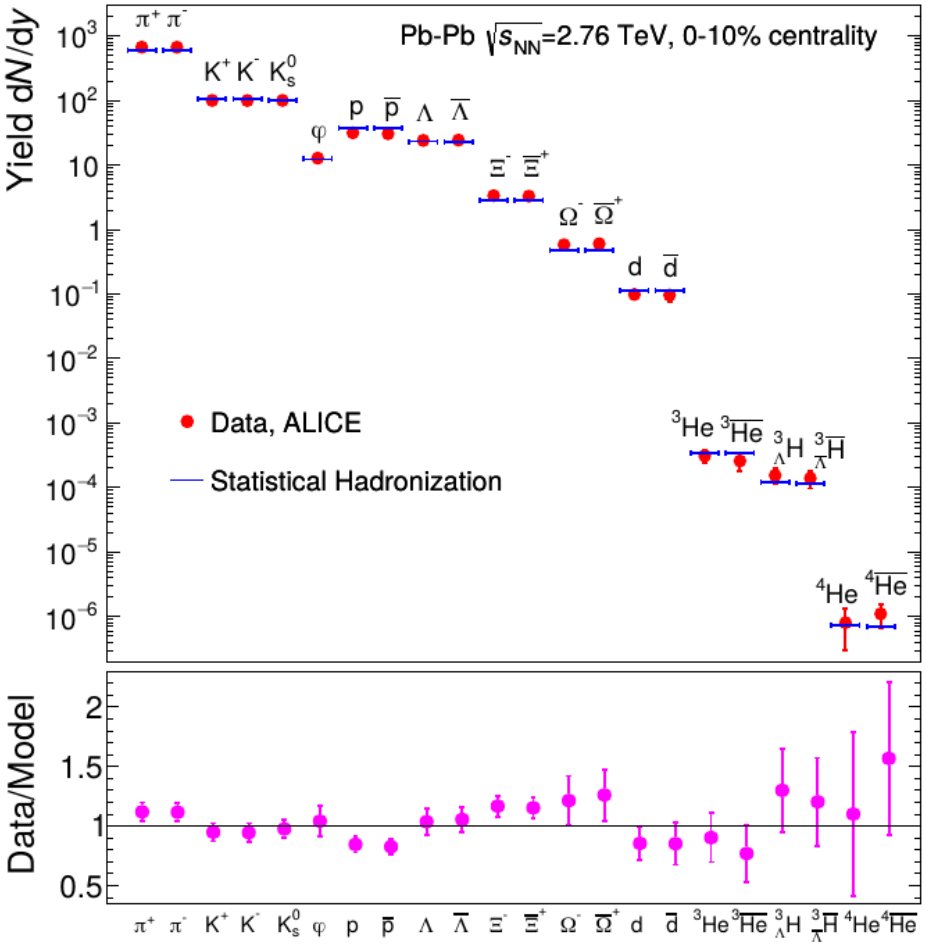
Left: blue only inclusive, black including $c\bar{c}$-constraint from arXiv:1708.05654, right: arXiv:1212.1701

- constraining directly partonic flux at intermediate x for RHIC and high-Q^2 LHC probes via parton densities
- constrain general initial state 'picture': do we see unambiguously low-x manifestations already at play in this x-regime with nuclei?
- reduce model-space for initial state in hadron-hadron collisions

Conclusions

- heavy-ion like observations in pp/pPb and UPC collisions: Hydrodynamics down to smallest length-scale, few-touch chaos or correlations at "impact"?
- community $\approx$ consensus: final state interactions main effect in pp/p-nucleus, correlations geometry-driven
- open: which degrees of freedom & scales, "transitions" & thermalisation, role of geometry in coordinate & momentum space, implications for High-Energy-Physics-modelling?
- precision input from the electron ion collider for "initial state" with "point-like" probe:
  important for hadronic collisions as constraint
- 'direct' connection based on assumptions & in the realm of modelling *today*
- Can we develop a solid universal picture by theory & experiment together at hh & eh for thermal system emergence and the initial state?
  $\rightarrow$ A lot of fun and head scratching ahead!

Back-up: hadronisation for thermodynamics



"Thermal" fit in Nature 561 (2018) 7723, 321

- thermal fits work, detailed corrections under discussion
- non-trivial cross checks with particle fluctuations working as well

  e.g. Braun-Munzinger et al. arXiv:1602.05811