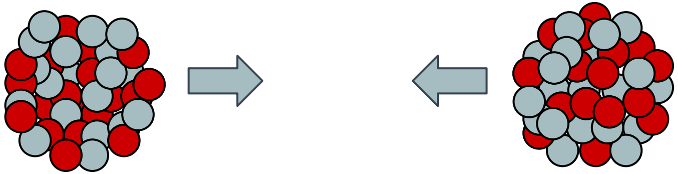
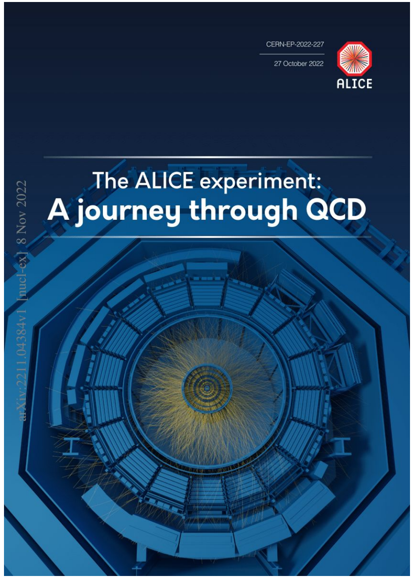
Heavy-ion collisions basics

Dariusz Miśkowiec
GSI Darmstadt



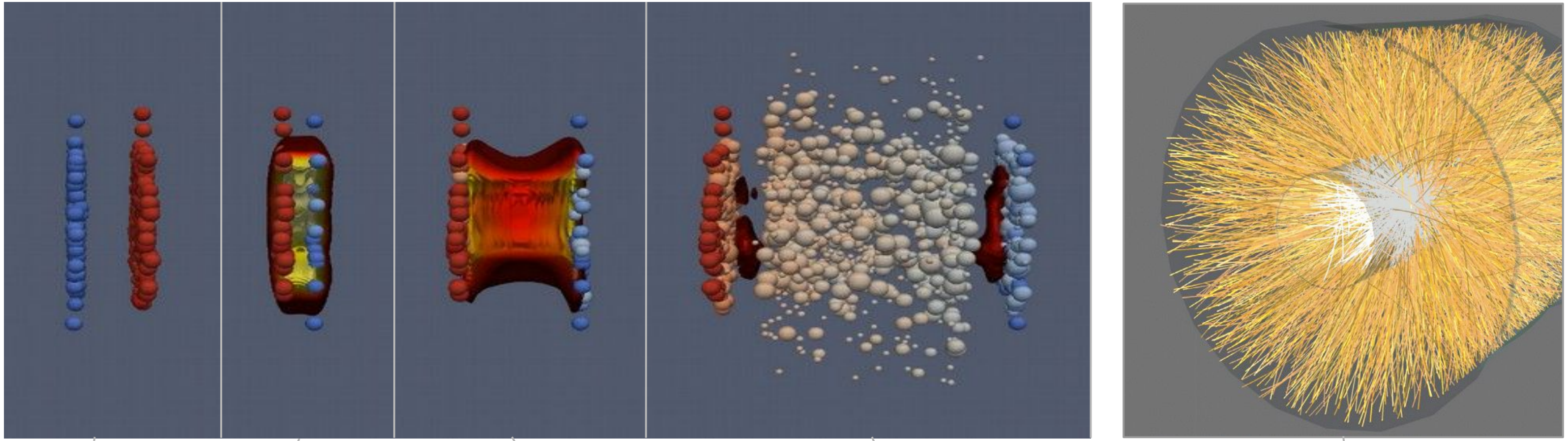
this talk

- introduce concepts
- plots only for illustration
- …mostly taken from ALICE white paper arxiv:2211.04384



phases of a relativistic nucleus-nucleus collision

Figure: Hannah Petersen and Jonah Bernhard, MADAI collaboration



initial conditions	parton scattering	quark-gluon plasma	hadron scattering	particles interact with detectors

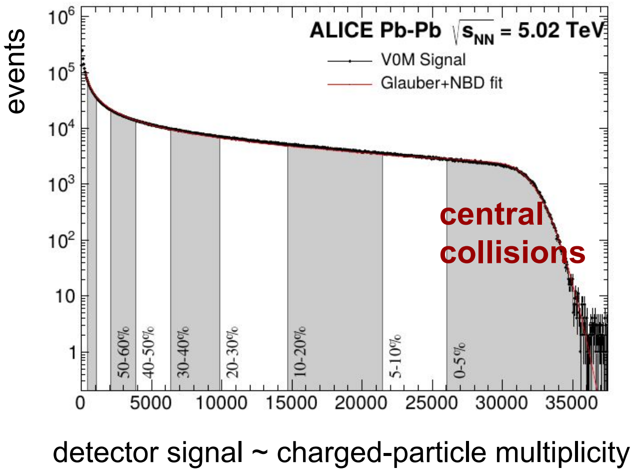
food transformation

initial conditions	parton scattering	quark-gluon plasma	hadron scattering	particles interact with detectors

initial conditions

initial conditions

ALICE, arxiv:2211.04384



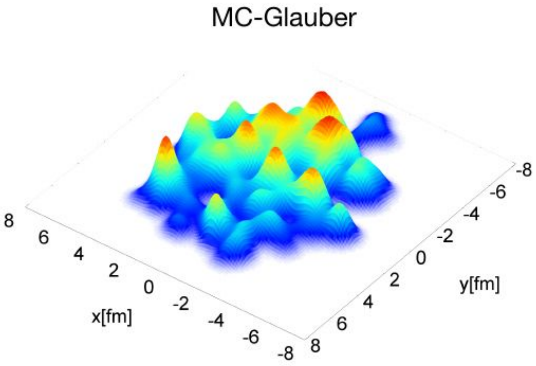
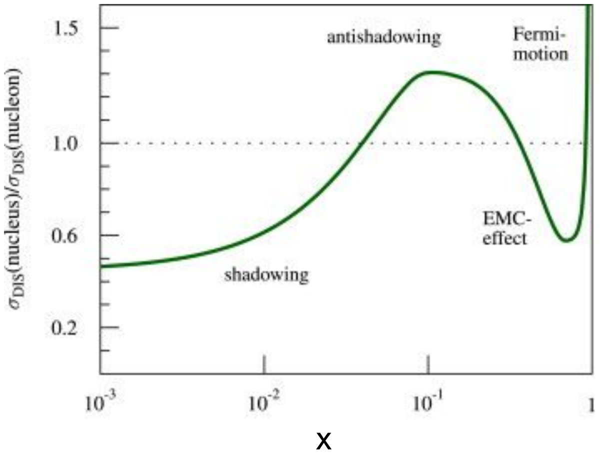


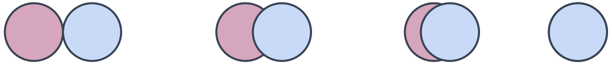
figure from H. Paukkunen, Nucl. Phys. A926 (2014) 24



collision centrality

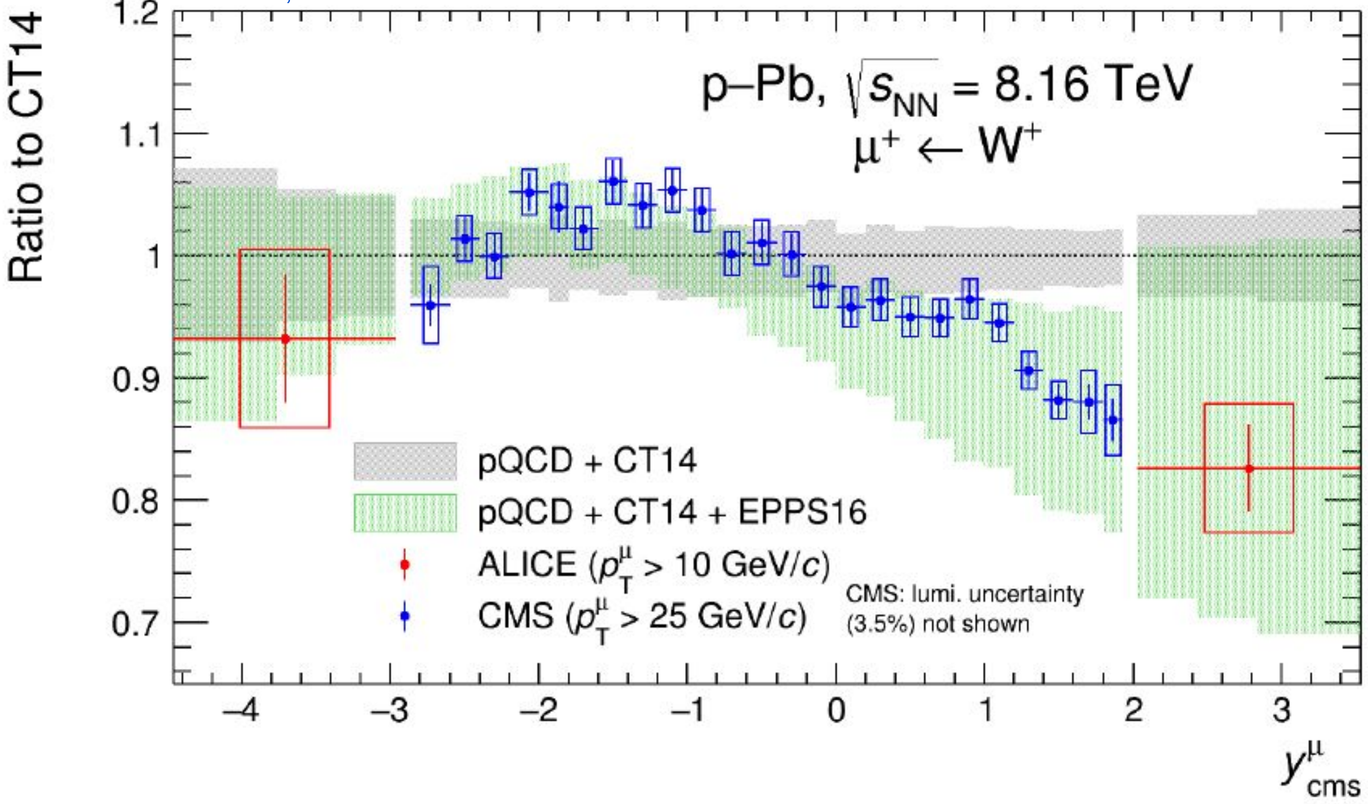
energy distribution

nuclear PDF



initial conditions: typical measurement

ALICE, arxiv:2211.04384



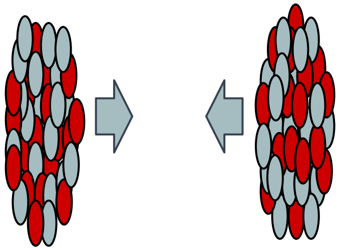
nPDF from p-Pb collisions

initial conditions	parton scattering	quark-gluon plasma	hadron scattering	particles interact with detectors

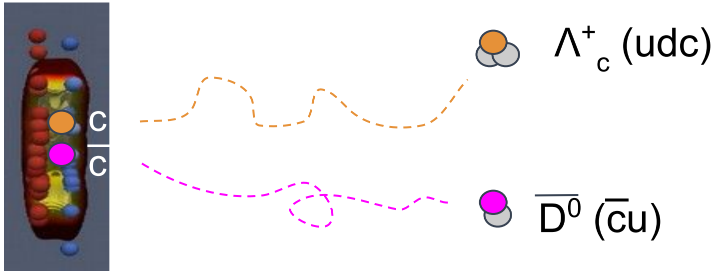
parton scattering

initial scatterings

soft and hard



heavy flavor production

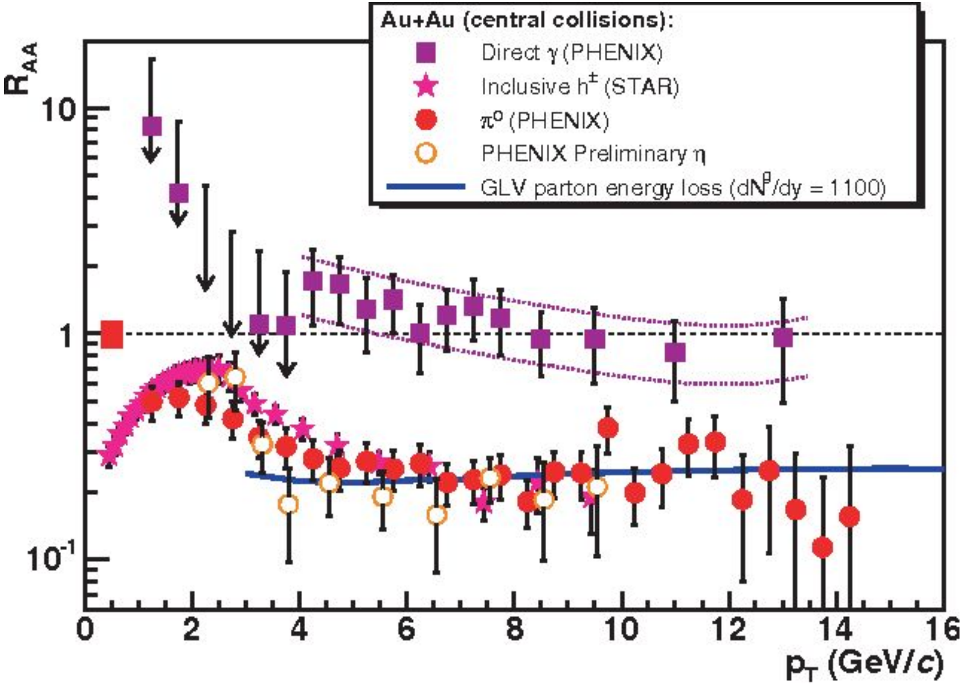


hard interactions ~ N_{coll}
soft interactions ~ N_{part}

c, b quarks produced in initial scatterings
fragmentation fractions defined at the end

typical observable: nuclear modification factor R_{AA}

K. Reygers (PHENIX), arXiv:hep-ex/0512015



$$R_{\rm AA}(p_{\rm T}) = \frac{1}{\langle N_{\rm coll}\rangle} \frac{{\rm d}N_{\rm AA}/{\rm d}p_{\rm T}}{{\rm d}N_{\rm pp}/{\rm d}p_{\rm T}}$$

number of NN collisions within Au-Au collision, averaged over centrality

photons, Z^0, W have R_{AA}~1
unlike hadrons, which interact with QGP

initial conditions	parton scattering	quark-gluon plasma	hadron scattering	particles interact with detectors

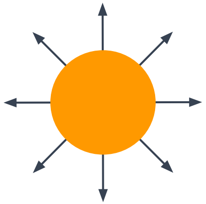
quark-gluon plasma

collective flow

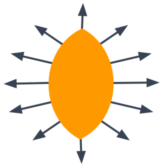
average velocity of particles is position dependent

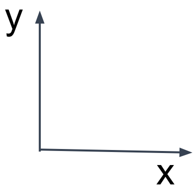
longitudinal flow

radial flow



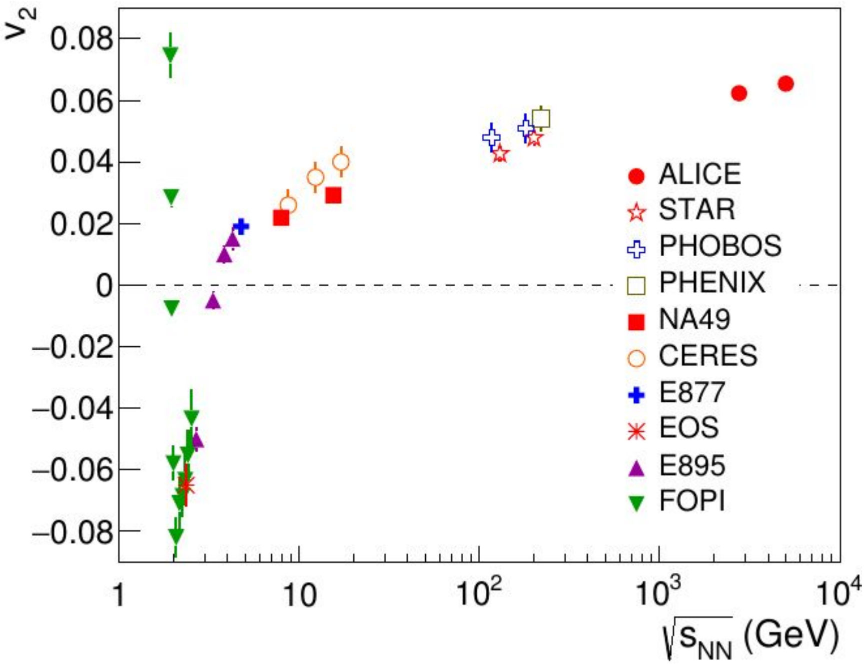
anisotropic flow





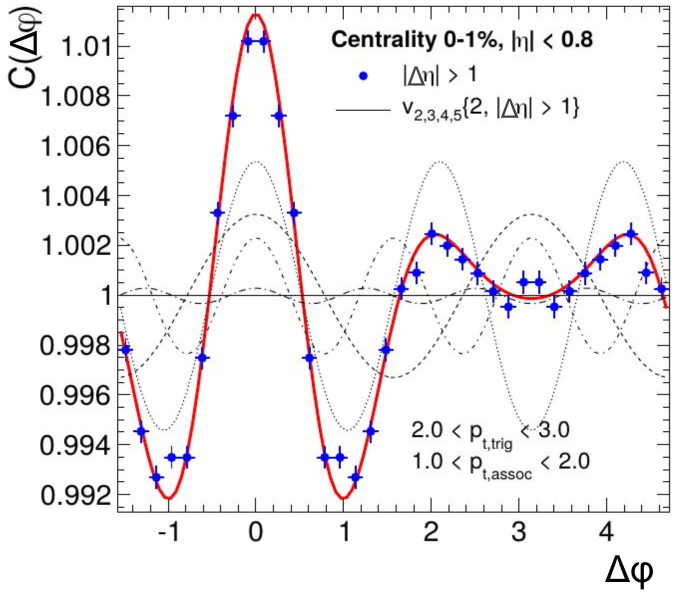
collective flow

ALICE, arxiv:2211.04384



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

ALICE, arxiv:2211.04384

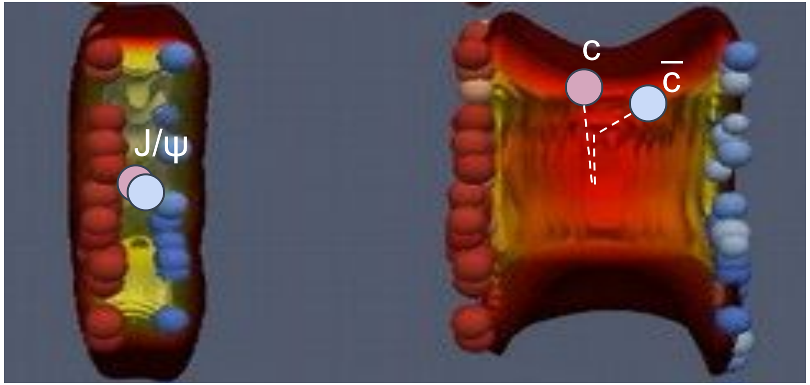


perfect liquid at RHIC and LHC

research frontiers:

- **higher harmonics**
- **more and more particle species**
- **flow fluctuations**

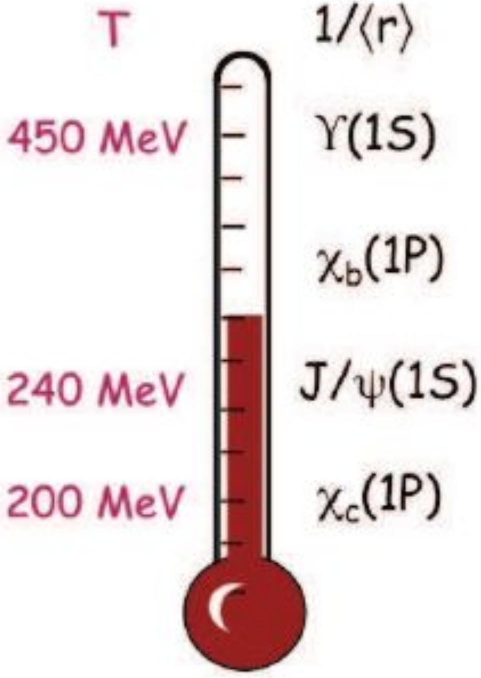
melting of quarkonia



- quarkonia produced in initial parton scattering
- dissociated while going through quark-gluon plasma
- especially the excited states

suppression of quarkonia is a signature of QGP

Matsui and H. Satz, Phys. Lett. B178(1986)416

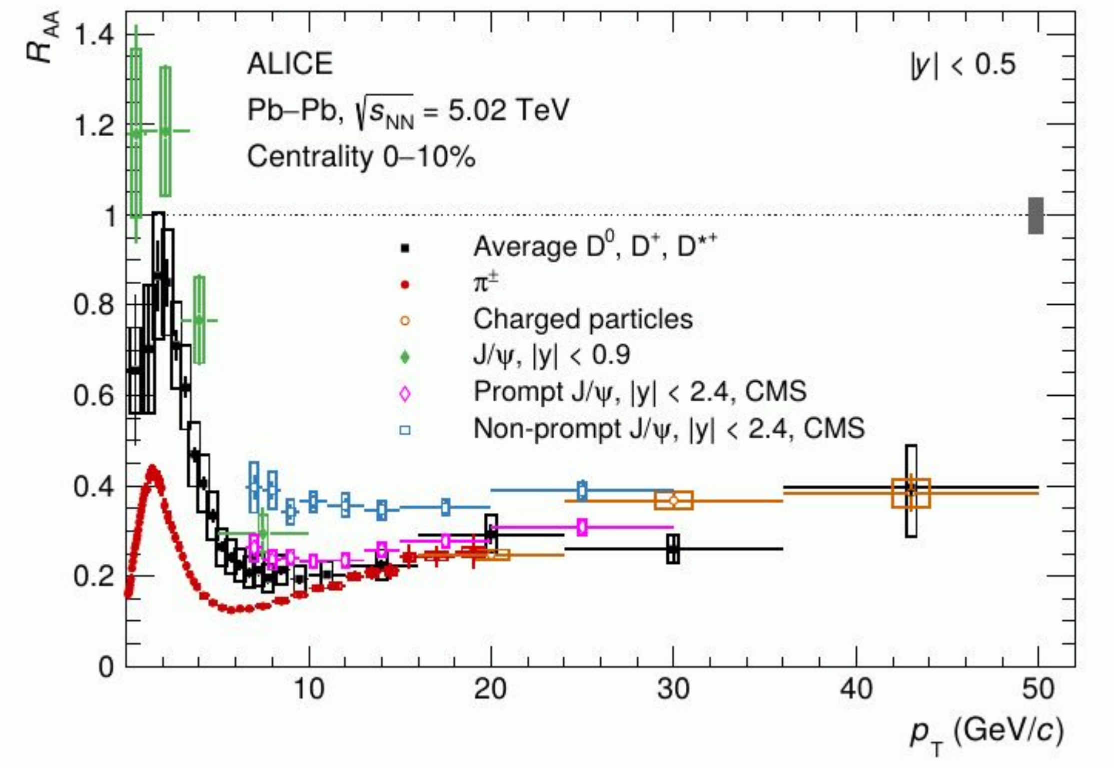


QGP thermometer

Fig. from Á. Mócsy, Eur.Phys.J.C61:705-710,2009

energy loss of quarks in QGP

ALICE, arxiv:2211.04384



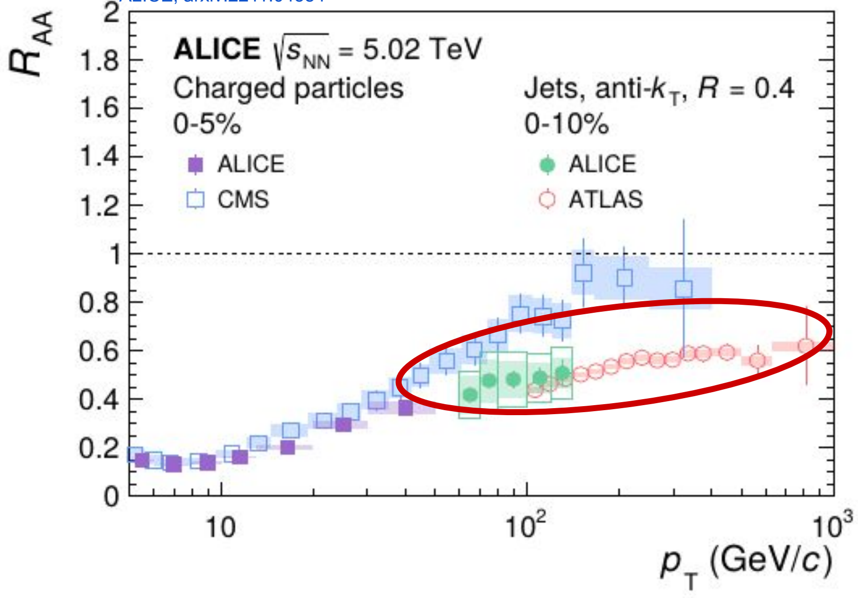
$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

$R_{AA} < 1$ = signature of energy loss

mass ordering:
pions < charm < beauty

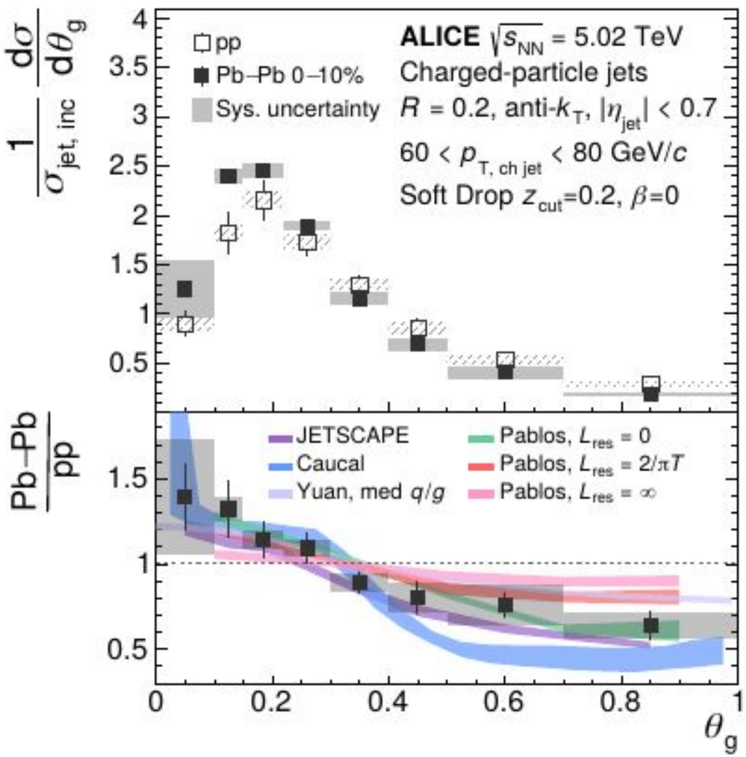
jet modification by QGP

ALICE, arxiv:2211.04384



- **jets lose energy in QGP**
- **especially the large R**

ALICE, arxiv:2211.04384



suppression of wide jets by QGP

elliptic flow of hadron species

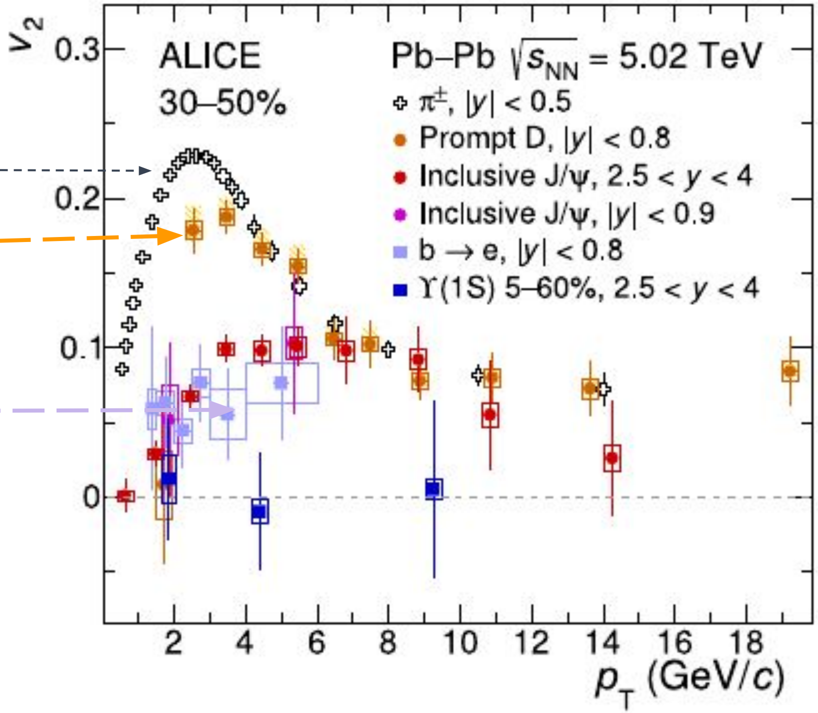
elliptic flow:

pions

open charm

open beauty

ALICE, arxiv:2211.04384

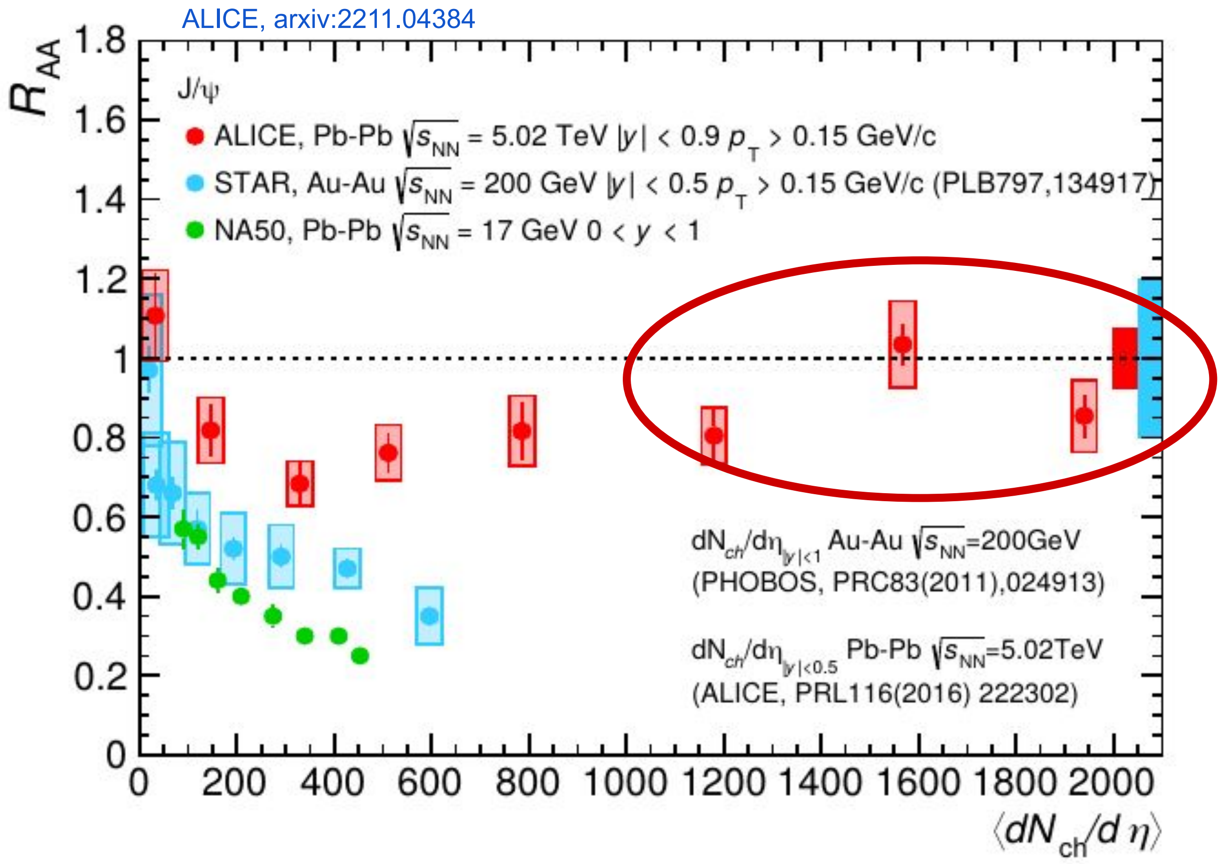


παντα ρει except Upsilon

initial conditions	parton scattering	quark-gluon plasma	hadron scattering	particles interact with detectors

hadronization

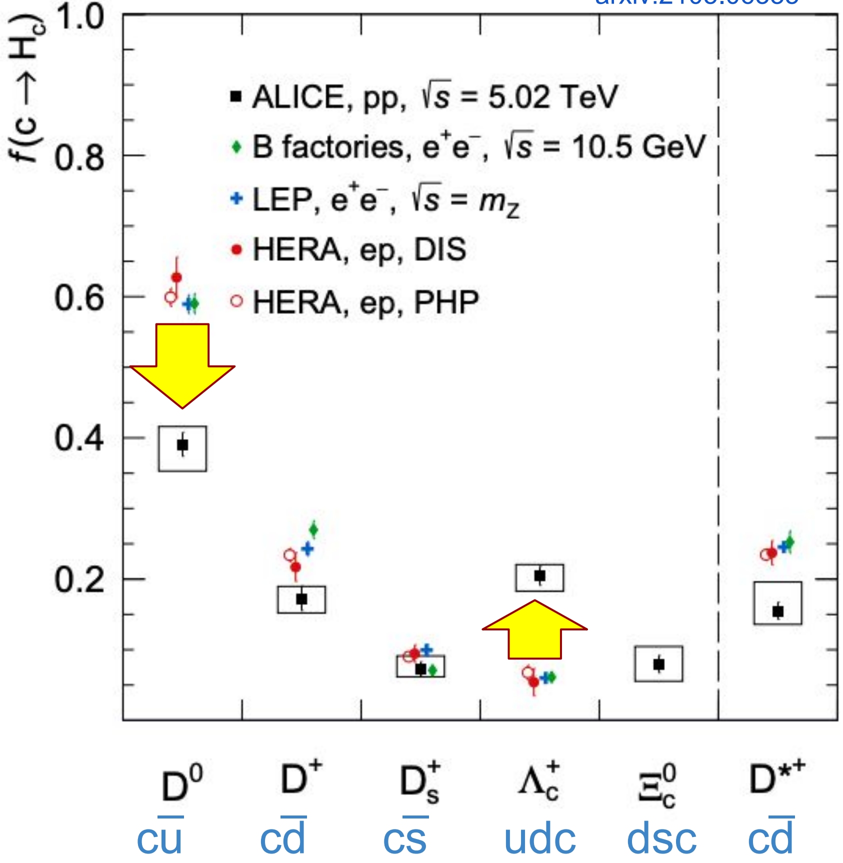
J/ψ production by quark coalescence



c $\bar{c}$ recombination → J/ψ yield enhanced in central collisions

hadronization of heavy quarks into meson and baryons

arxiv:2105.06335

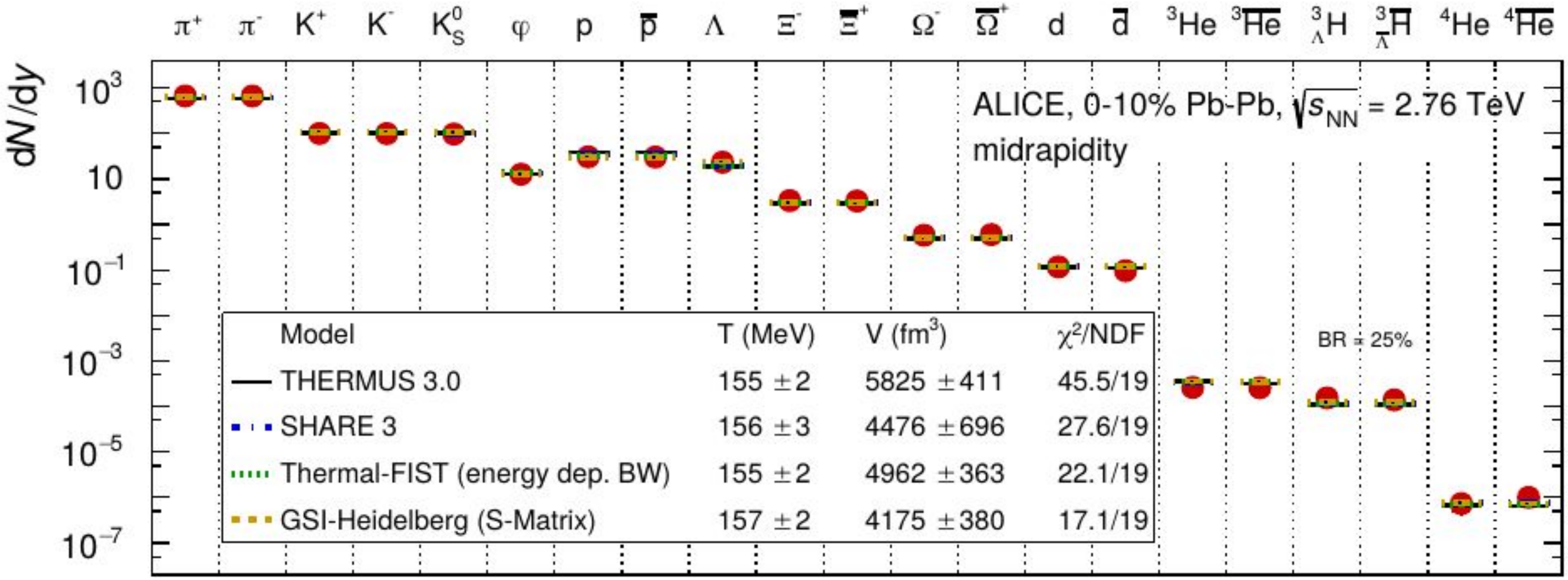


quark coalescence → hadronization of c into baryons enhanced in pp compared to ee and ep

initial conditions	parton scattering	quark-gluon plasma	hadron scattering	particles interact with detectors

hadron scattering

chemical freezout

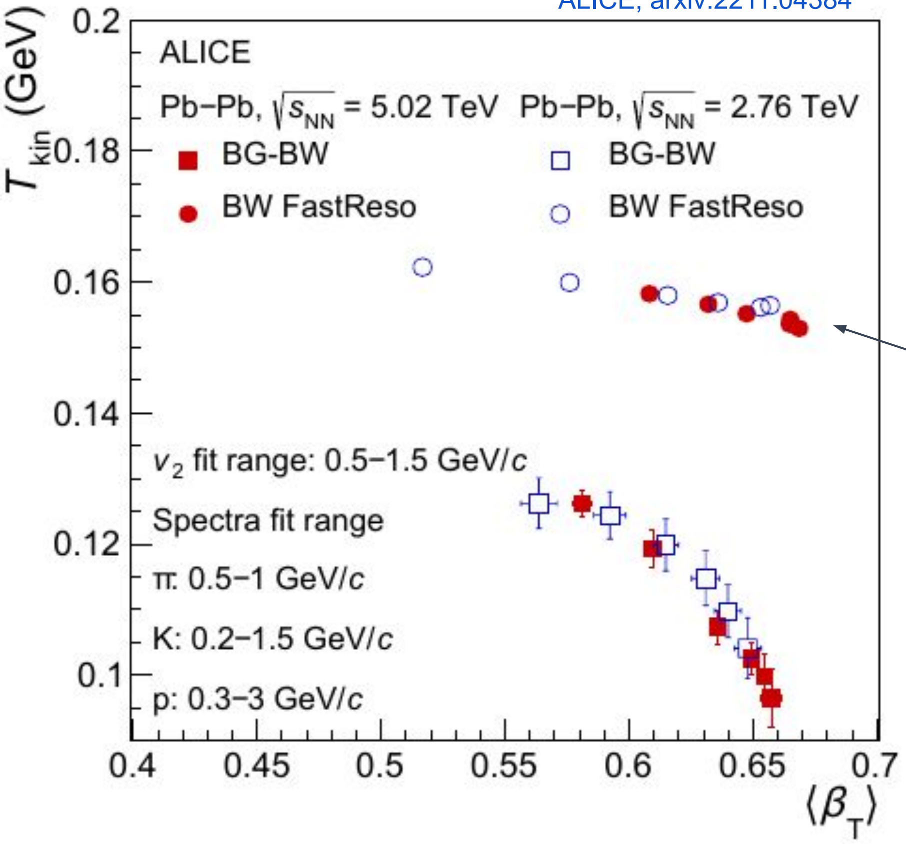


ALICE, arxiv:2211.04384

T_{chem} = 155 MeV ≈ T_c

kinetic freezeout - temperature

ALICE, arxiv:2211.04384



temperature and transverse flow from pion, kaon, proton spectra

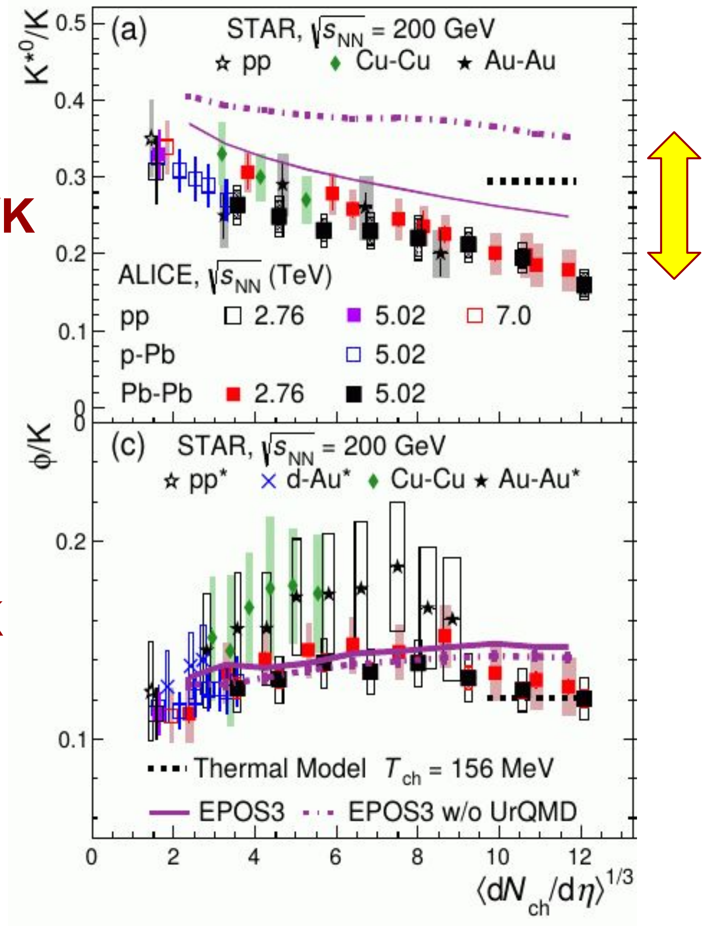
new analysis: $T_{kin} \approx T_{chem}$

rescattering of K*^{0} daughters

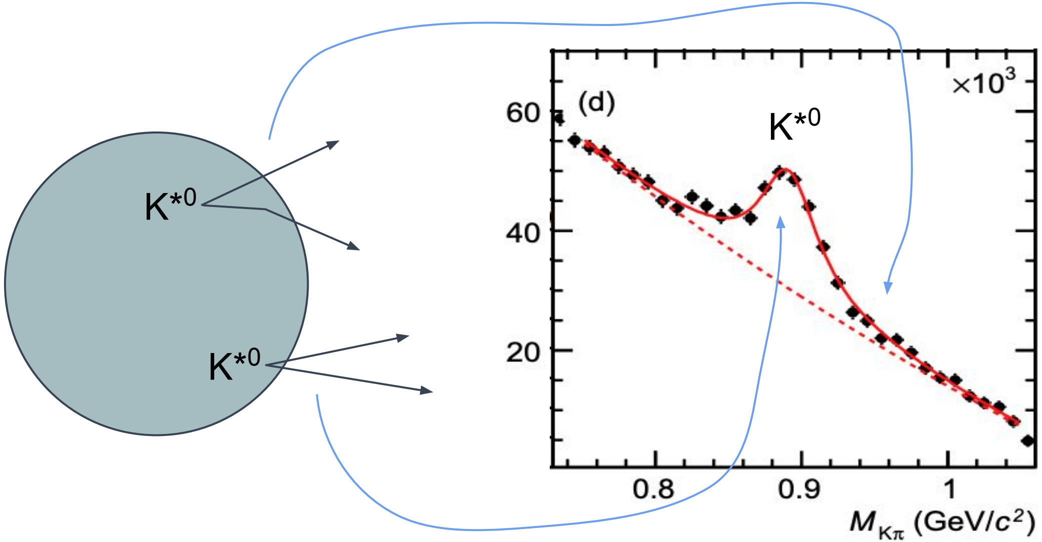
ALICE, arxiv:2106.13113

K*^{0}/K

Φ/K



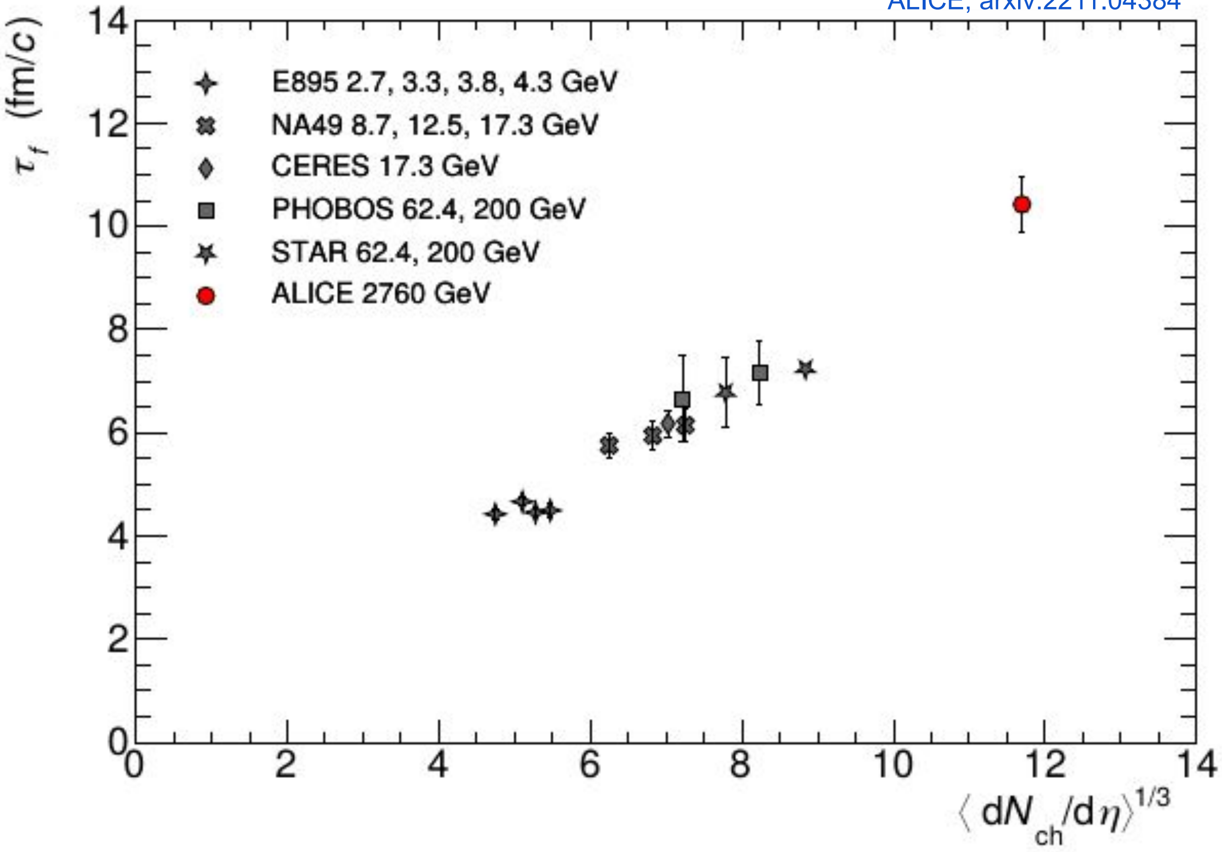
	cτ	decay
K*(892)^0	4.2 fm	→ $K^{\pm}\pi^{\mp}$
Φ(1020)	46 fm	→ $K^{+}K^{-}$



rescattering in hadronic phase

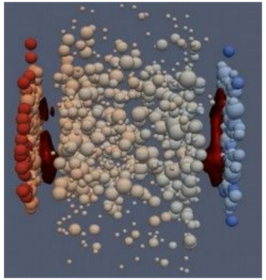
kinetic freezeout - size

ALICE, arxiv:2211.04384



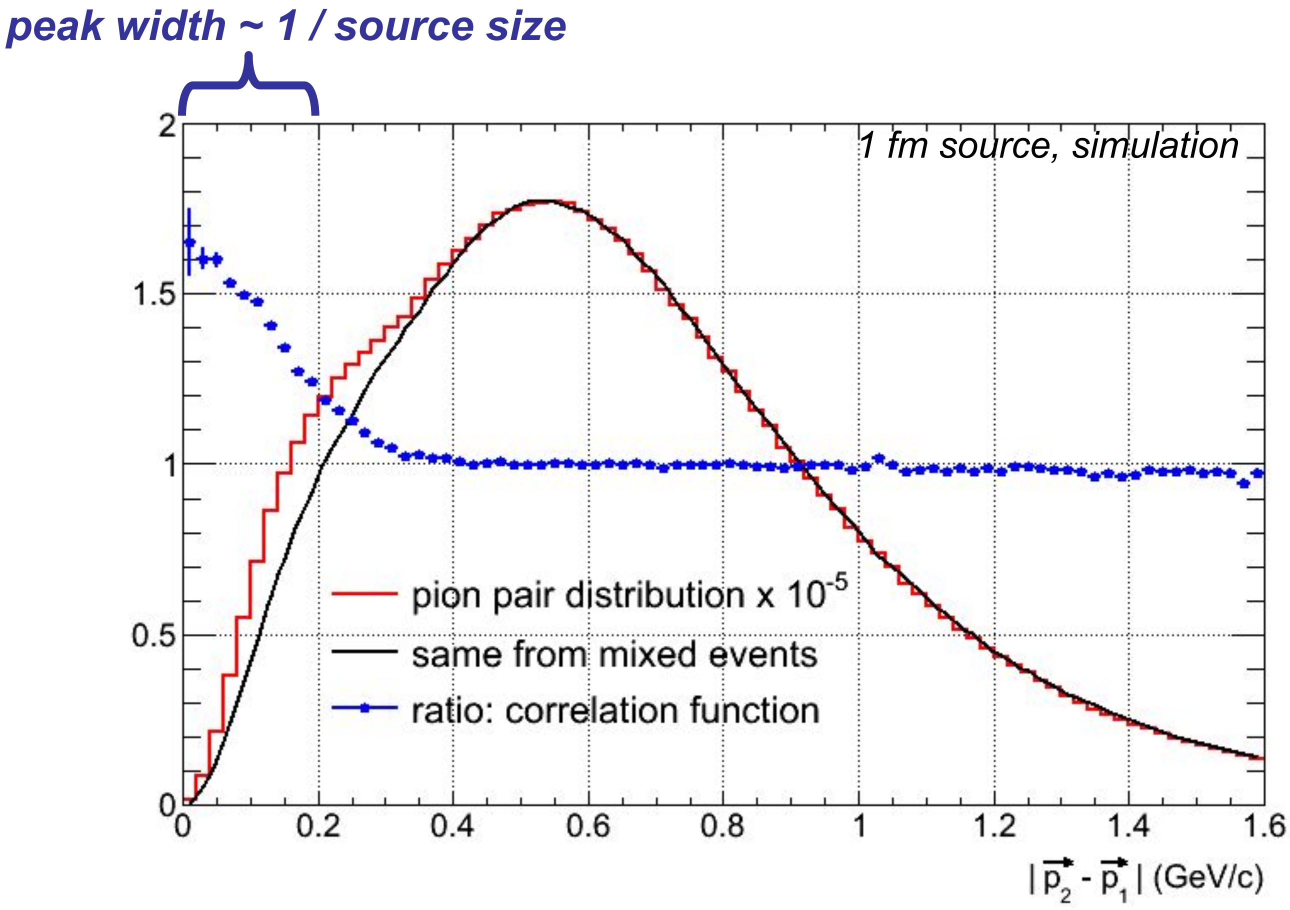
kinetic freezeout time
from pion femtoscopy

final size:



20-30 fm

femtoscopy: two-particle correlation analysis



$$C(\vec{k}^*) = \int S(\vec{r}^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^*$$

measured two-particle correlation function

particle source distribution

mutual interaction (BE or FD, Coulomb, strong)

know interation and determine source size

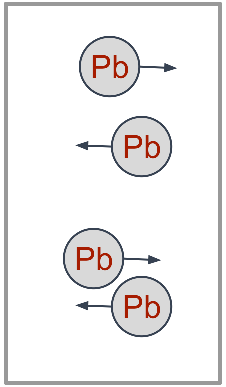
or

know source size and determine interation

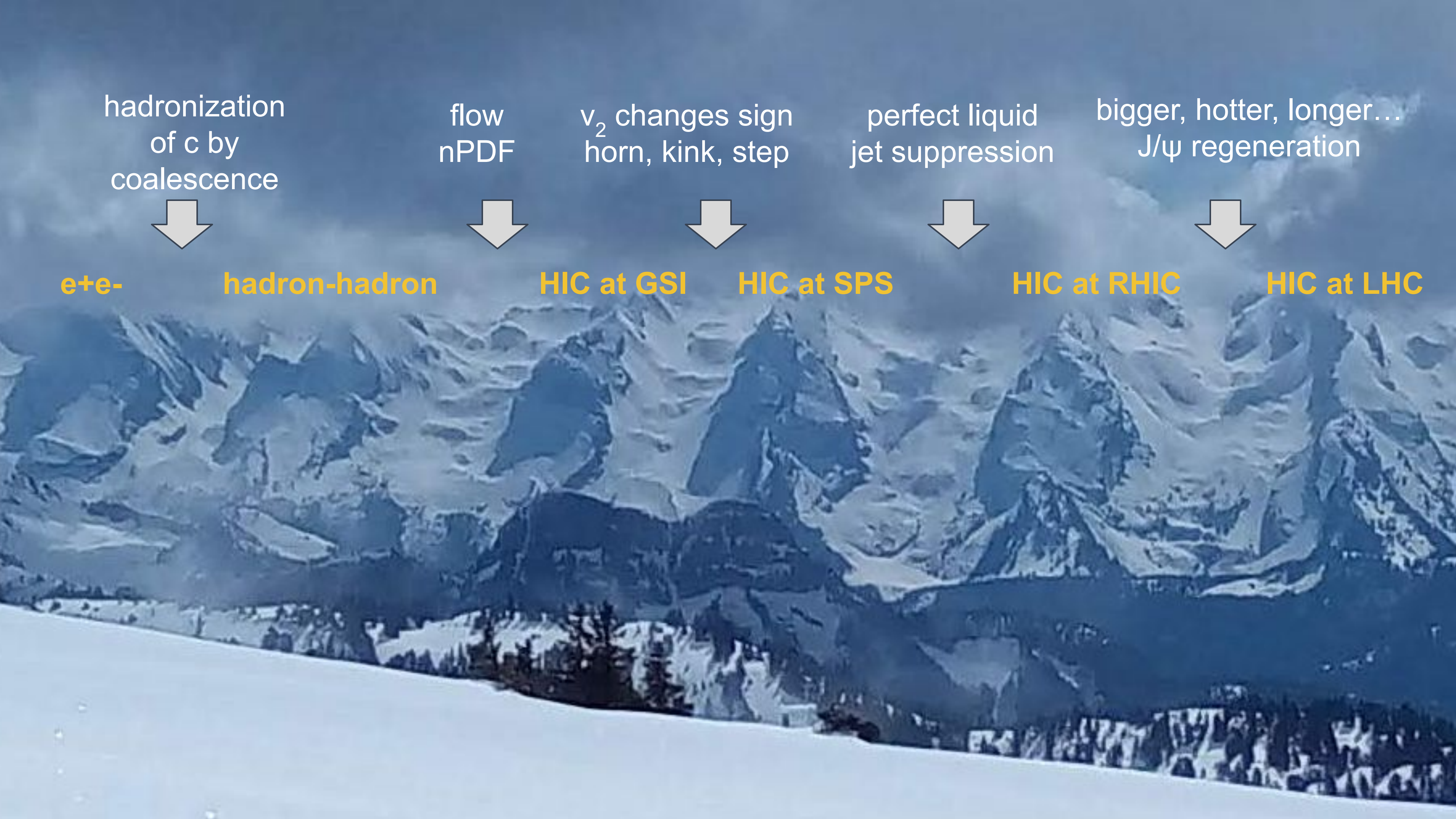
beyond central heavy-ion collisions

(ultra)peripheral Pb-Pb collisions

LHC = ~~Light~~ Hadron Collider

collision		interaction		vector meson		measurement
	→	γ-nucleus γ-nucleon γ-γ	→	ρ^0 J/ψ ψ' ϒ continuum	→	π π e e μ μ τ τ γ γ dijet

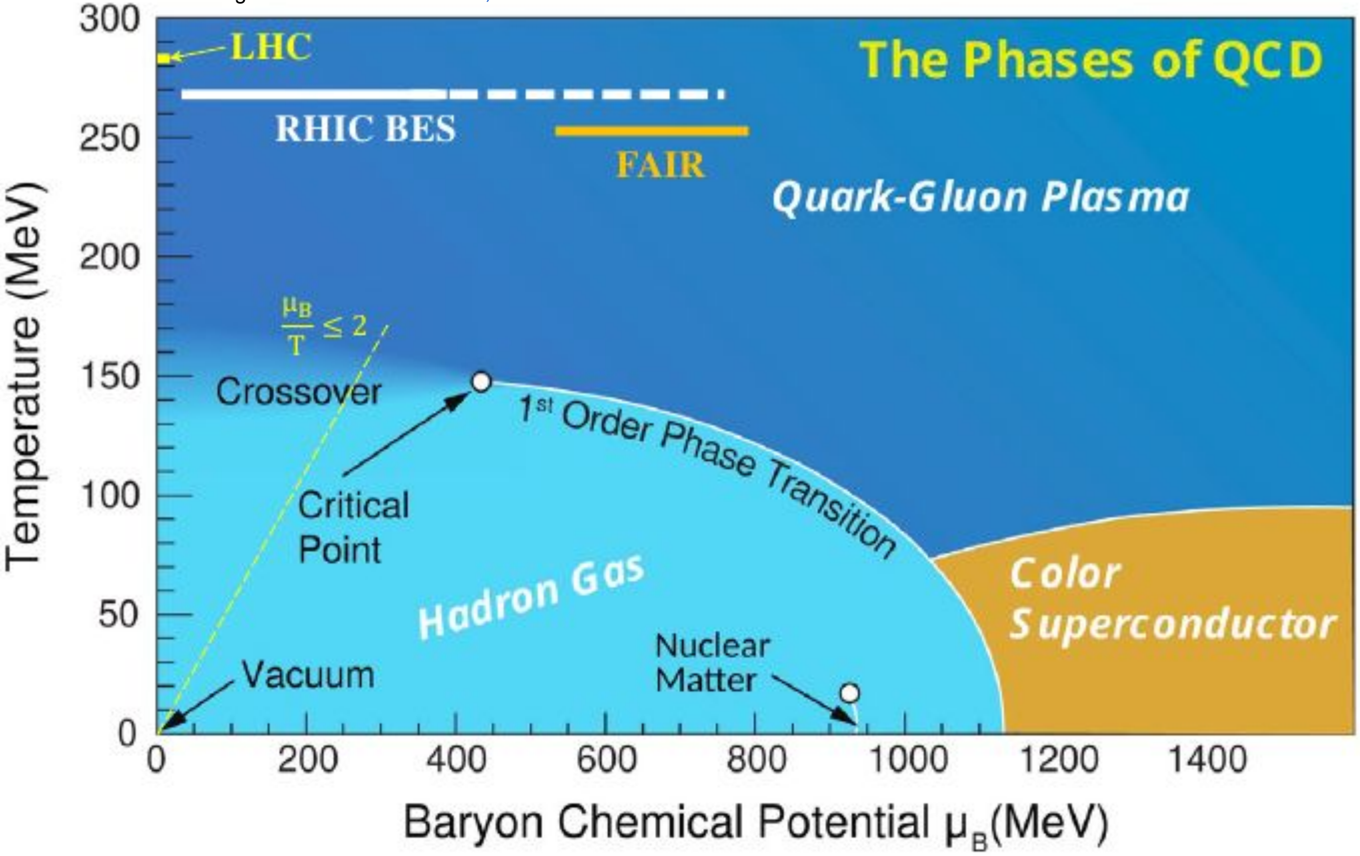
- **J/ψ: nuclear gluon distribution functions (shadowing)**
- **ρ^0: black-disk limit of hadronic interactions**
- **γ-γ: QED calculations yielding e.g. anomalous magnetic moment of τ**


hadronization of c by coalescence
flow
nPDF
v_2 changes sign
horn, kink, step
perfect liquid
jet suppression
bigger, hotter, longer…
J/ψ regeneration
e+e-
hadron-hadron
HIC at GSI
HIC at SPS
HIC at RHIC
HIC at LHC

THE END

phase diagram of QCD

figure from Achenbach et al, arxiv:2303.02579



quark-gluon plasma

flow as predicted by hydrodynamics,
not weakened by viscosity
→ low viscosity

system exhibits collective flow
→ liquid rather than gas,
expected by early papers

RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted

Monday, April 18, 2005

temperature

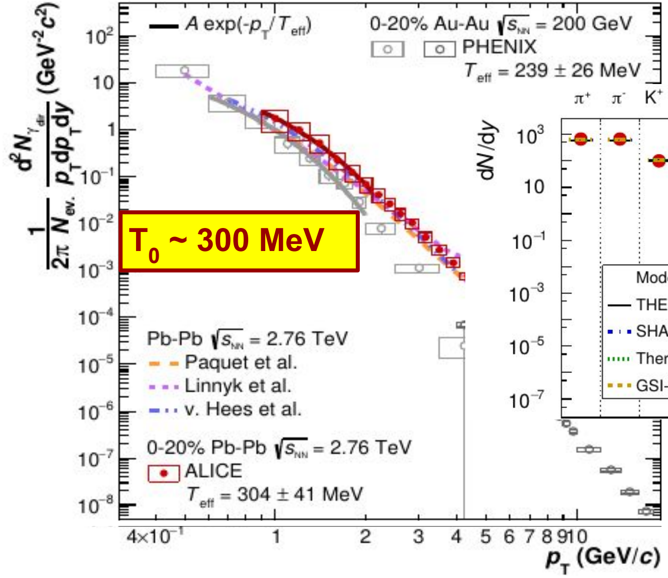
initial conditions	parton scattering	quark-gluon plasma	hadron scattering	particles interact with detectors

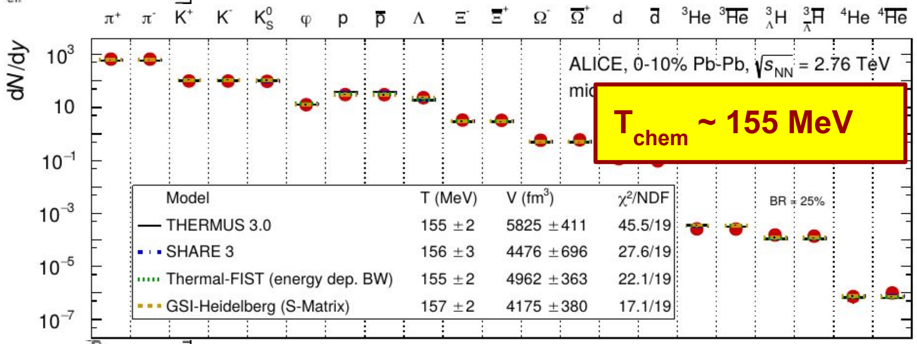
initial temperature
photons, dileptons

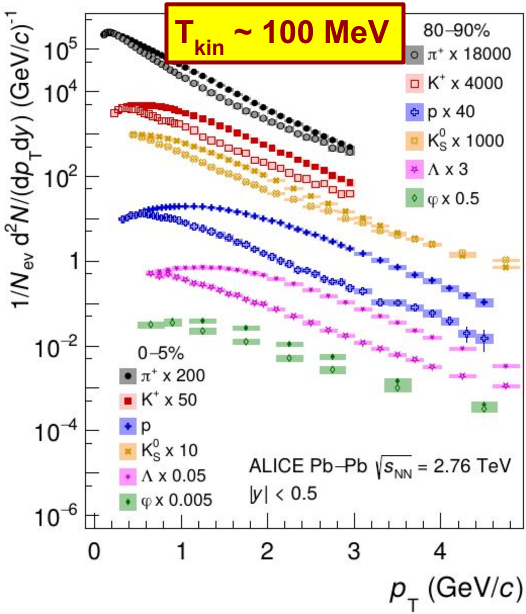
critical temperature
from latice calculation

chemical freezeout T
from particle yields

kinetic freezeout T
from particle spectra



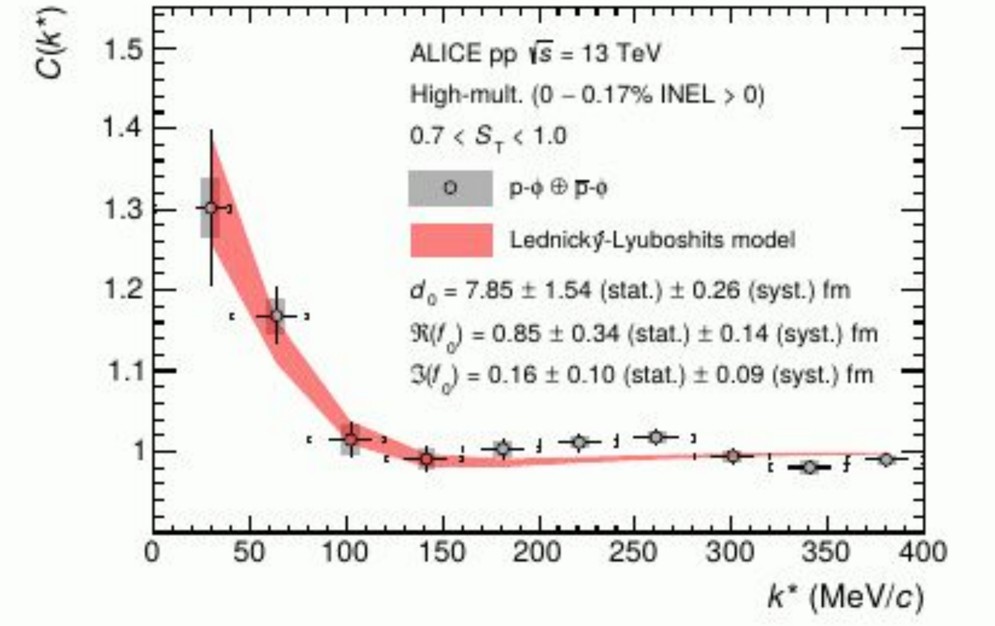




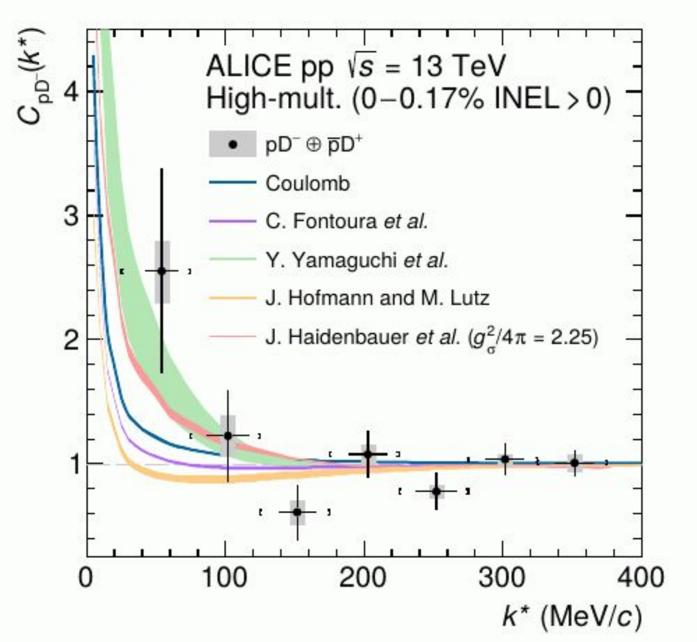
correlation measurement of two-particle interaction

p-ϕ

arxiv:2105.05578



p-D⁻



other recent combinations of species:

arxiv:2105.05190	p-p̄, p-Λ̄, Λ-Λ̄	arxiv:2201.05352	pD
arxiv:2104.04427	p-Λ	arxiv:2204.10258	ΛΞ
arxiv:2105.05683	p-K^-	arxiv:2205.15176	KN
arxiv:2111.06611	K^0_S-K^0_S, K^0_S-$K^\pm$	arxiv:2211.15194	K^+K^-

…as well as 10 earlier ALICE papers further covering p-p, p-K, p-Λ, Λ-Λ, p-Σ^0, p-Ξ^-, Λ-$K^\pm$, Λ-K^0_S, and p-Ω^- (Nature 588(2020)232)

signatures of collectivity in small collision systems

- spectra: transverse flow
- long-range two particles correlations: ridge (elliptic flow)
- HBT analysis: p dependence of HBT radii
- smooth evolution of strangeness production
- …

big surprise!

signatures of collectivity in small collision systems

- spectra: transverse flow
- long-range two particles correlations: ridge (elliptic flow)
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- …

big surprise!

…Really?

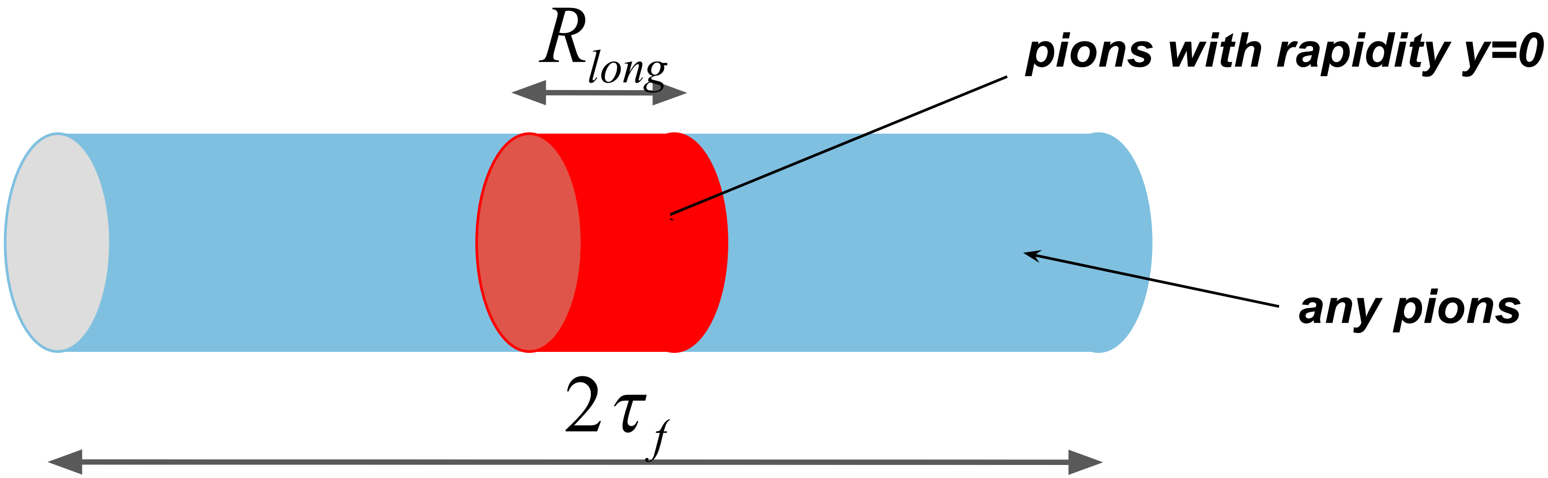
QM2008, panel discussion
Jurgen Schukraft said:

- even protons get obese these days
  - ⇨ p@LHC ~ small (but very dense) nucleus@SPS

	SPS	RHIC	LHC
# of partons in proton 3 + ∫g(x > 2GeV)	4	10	30

- 'QGP' physics with protons
  - ⇨ at least: onset of hadronic FS interactions
  - ⇨ maybe: collective hadronic/partonic dynamics
  - ⇨ why not: the QGP, mini serving

deducing expansion time from R_{long}



Makhlin-Sinyukov

$$R_{long} = \tau_f \sqrt{\frac{T}{m_t}}$$

Herrmann-Bertsch

$$R_{long} = \tau_f \sqrt{\frac{T}{m_t} \frac{K_2(m_t/T)}{K_1(m_t/T)}}$$

beauty decaying into J/ψ

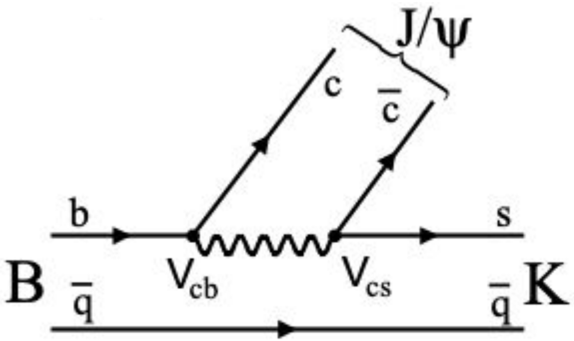


Fig. from Norbert Neumeister, DELPHI, Ph.D. thesis, 1996