Cold nuclear matter in heavy ion collisions

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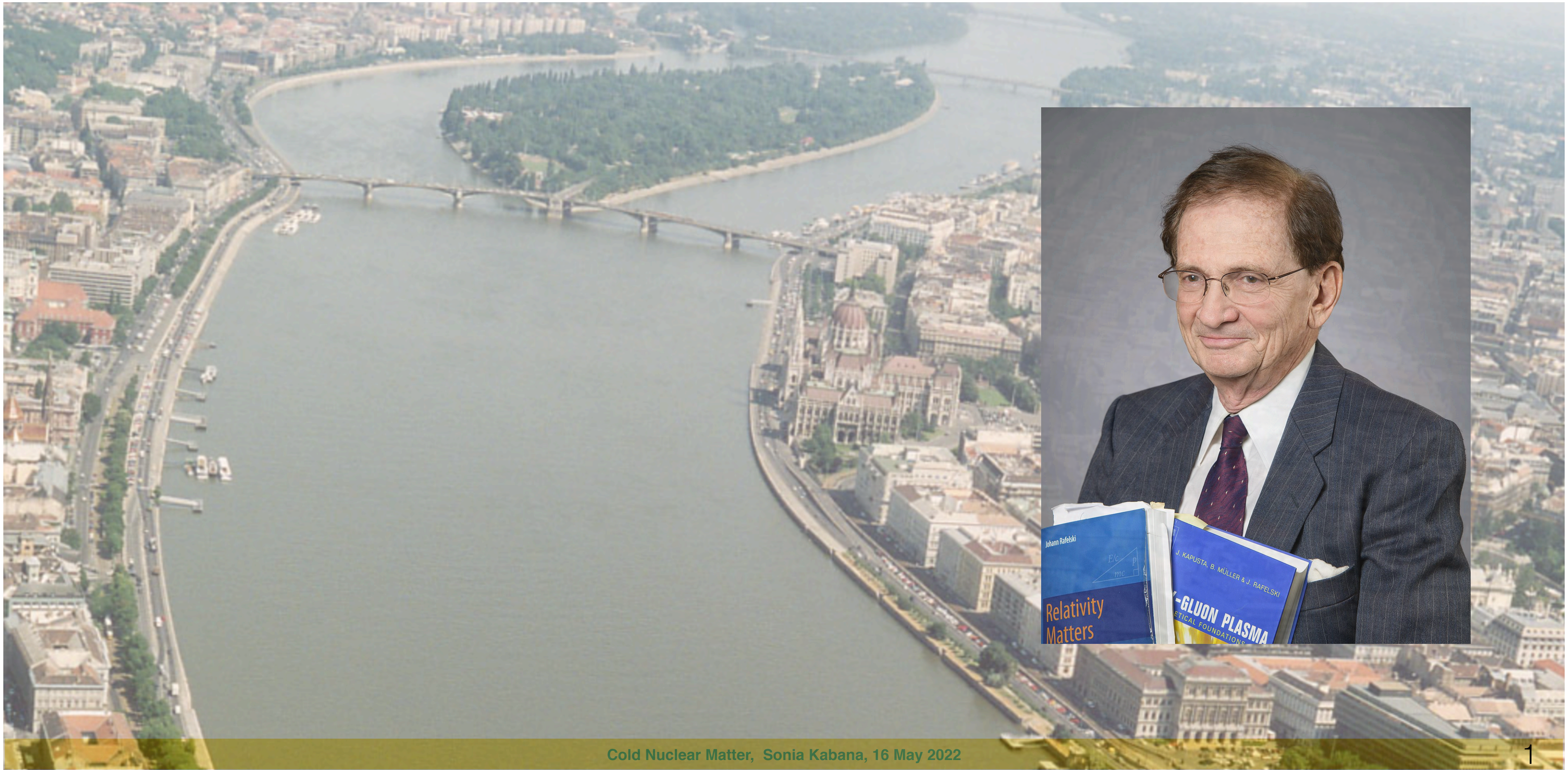
SAPHIR

Margaret Island Symposium 2022 on Vacuum Structure, Particles, and Plasmas
15 - 18 May 2022, Budapest, Hungary



Outline

Introduction

Collectivity

jet quanching

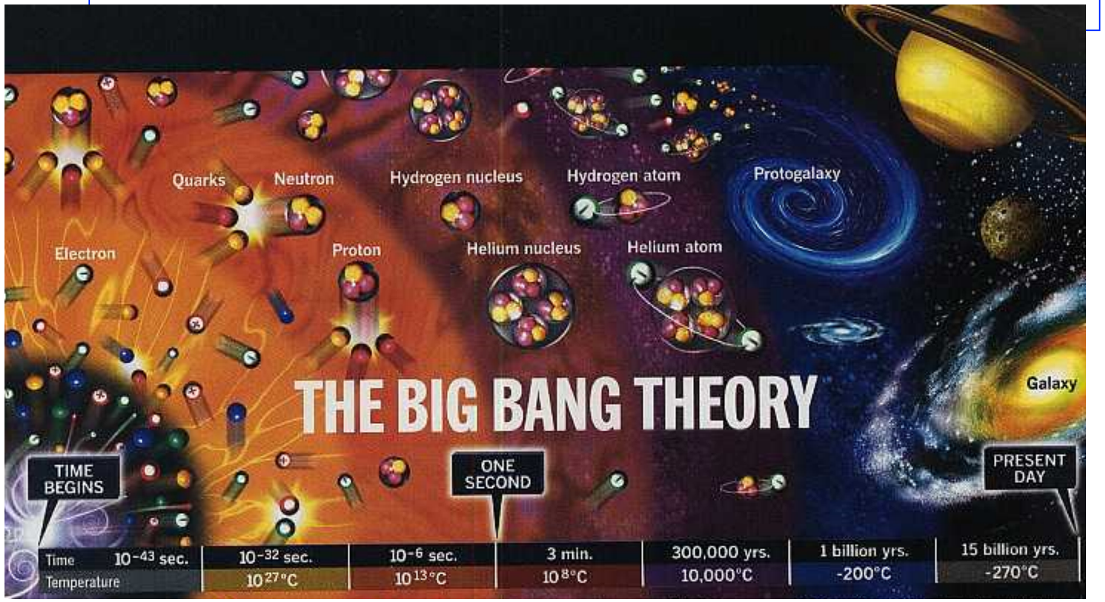
Quarkonia

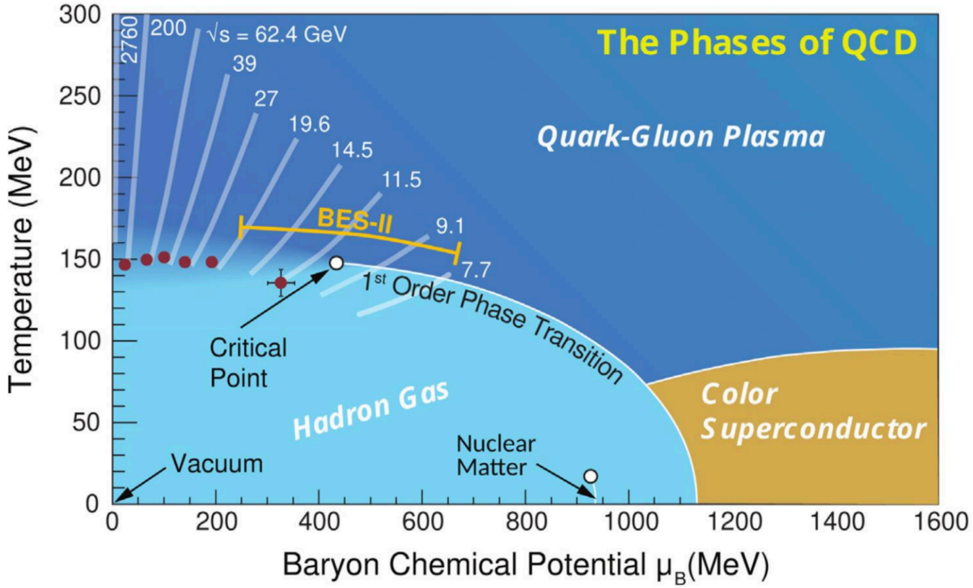
Strangeness

Conclusions and outlook

Introduction - The Quark Gluon Plasma

QCD on the lattice predicts a cross over at zero net baryon density with critical temperature Tc~154+-9 MeV (2014), critical energy density ~0.6 GeV/fm^3



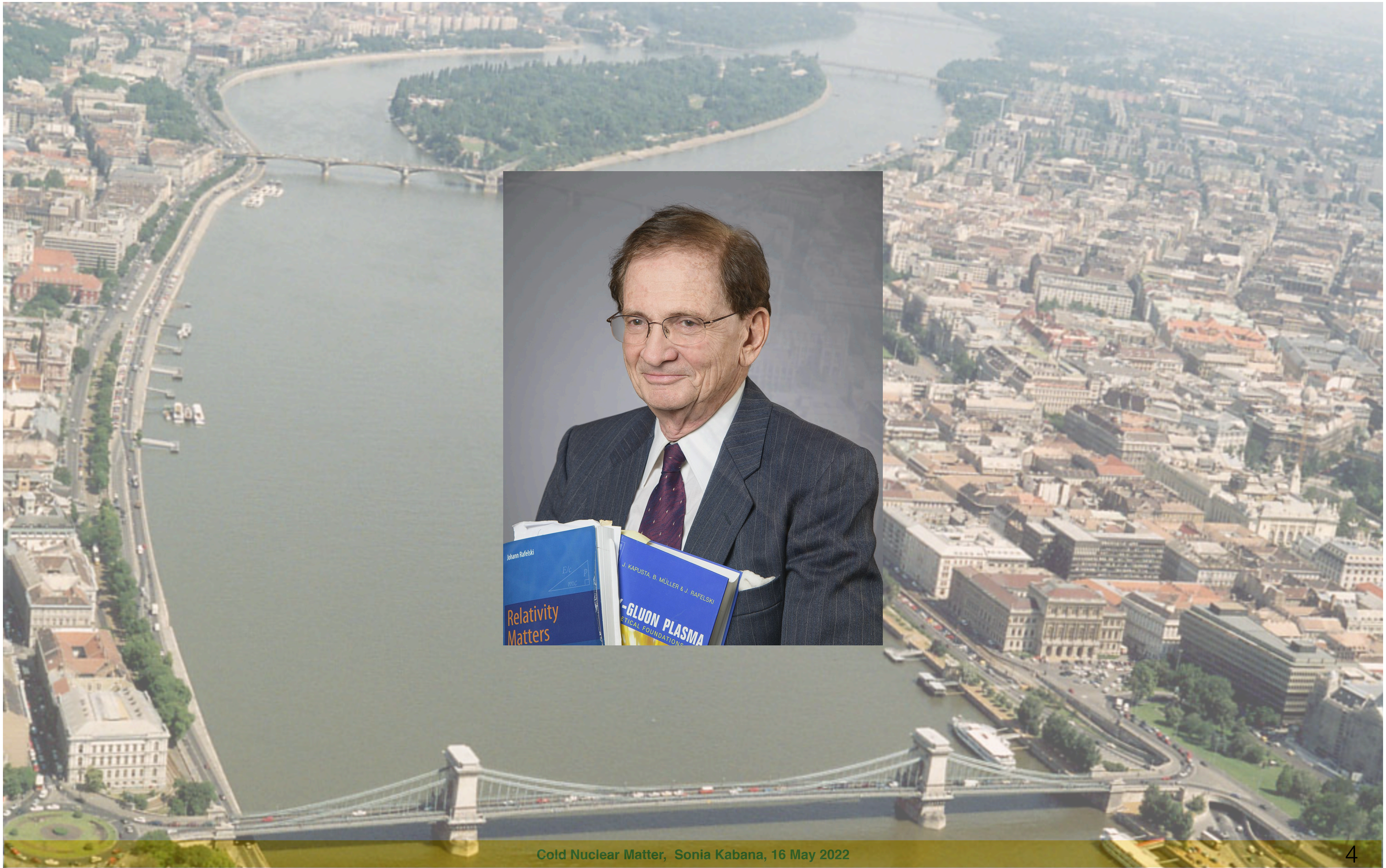


From Phys. Rept. 853 (2020) Adam Bzdak et al

In the last few decades the experimental program with ultrarelativistic heavy ion collisions searched for the Quark Gluon Plasma state by eg

* searching for predicted QGP signatures in A+A
* use p+p and p+A to estimate the non-QGP background" and tune the non-QGP parts in models

Jan Rafelski has been a pioneer of the QGP field from the very begin in the 80' s !



Introduction - Cold Nuclear Matter

Cold Nuclear Matter (CNM) effects: effects other than a hot and dense medium produced in the collision, that cause modification to particle production

Examples of CNM effects:

Modifications to the gluon-nuclear-parton distribution functions (nPDFs) in the nucleus [1, 2],

Nuclear absorption (nuclear break up) [3, 4]

Parton energy loss [5]

The Cronin effect [6]

Other initial state effects: Color Glass Condensate (CGC) effective theory [7,8,9]

Comover interaction [10]

[1] K. J. Eskola, P. Paakkinen, H. Paukkunen, and C. A. Salgado, EPPS16: Nuclear parton distributions with LHC data, Eur. Phys. J. C 77, 163 (2017).
[2] K. Kovarik et al., nCTEQ15- Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework, Phys. Rev. D 93, 085037 (2016).

[3] D. C. McGlinchey, A. D. Frawley, and R. Vogt, Impact parameter dependence of the nuclear modification of J/ψ production in d+Au collisions at √ sNN = 200 GeV, Phys. Rev. C 87, 054910 (2013).
[4] F. Arleo, P. B. Gossiaux, T. Gousset, and J. Aichelin, Charmonium suppression in pA collisions, Phys. Rev. C 61, 054906 (2000).

[5] I. Vitev, Non-Abelian energy loss in cold nuclear matter, Phys. Rev. C 75, 064906 (2007).
[6] J. W. Cronin, H. J. Frisch, M. J. Shochet, J. P. Boymond, R. Mermod, P. A. Piroue, and R. L. Sumner, Production of hadrons with large transverse momentum at 200, 300, and 400 GeV, Phys. Rev. D 11, 3105 (1975).
B. Kopeliovich et al, Cronin effect in hadron production off nuclei, *Phys.Rev.Lett*. 88 (2002) 232303 • e-Print: hep-ph/0201010 [hep-ph]

[7] T. Altinoluk and N. Armesto, Eur. Phys. J. A 56, no.8, 215 (2020) [arXiv:2004.08185 [hep-ph]].
[8] F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, Ann. Rev. Nucl. Part. Sci. 60 (2010), 463-489 [arXiv:1002.0333 [hep-ph]]
[9] Y. V. Kovchegov and E. Levin, Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. 33 (2012), 1-350
[10] E. G. Ferreiro, Excited charmonium suppression in proton–nucleus collisions as a consequence of comovers, Phys. Lett. B749 (2015) 98–103. arXiv:1411.0549, doi:10.1016/j.physletb.2015.07.066.

Introduction - Cold Nuclear Matter

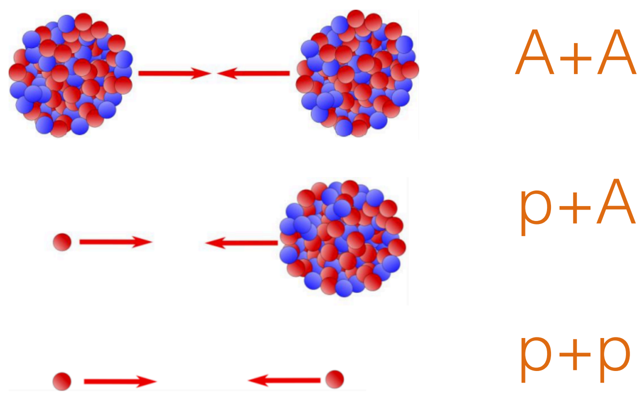
Cold Nuclear Matter (CNM) effects are quantified by comparing measurements of p+p and p+A collisions as well as d+A and collisions of light nuclei like 3He+A and to models tuned to describe world data.
Also comparisons to other collision systems like gamma+A are important to constraint the models.

From the very begin of the search for the QGP by colliding ultrarelativistic A+A, the p+p, p+A systems have been used as a reference in the search for deviations due to QGP in A+A collisions

In last years, evidence has been found that some observables in small systems like p+A, d+A and other, are consistent with models assuming formation of QGP droplets when the most central collisions are considered: for example strangeness, collectivity, Psi(2S) suppression

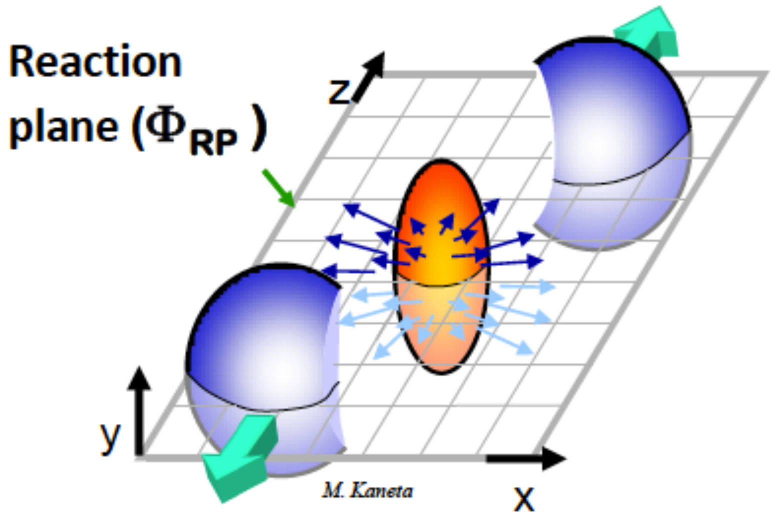
Other observables do not show deviations from CNM effects in p+A like eg: Jet quenching, J/Psi suppression

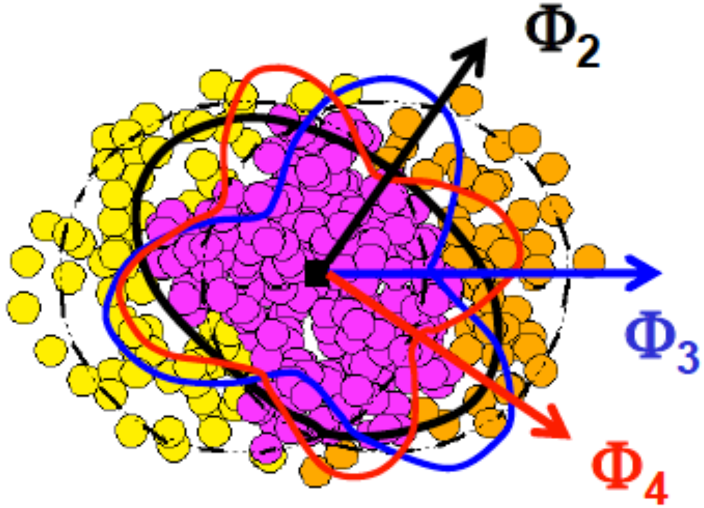
We will review some of this evidence.



RHIC energies

Flow coefficients v_n, n=1,2,3..





Matter in the overlapp area of two colliding nuclei gets compressed and heated

Initial anisotropy gets transfered into the momentum space via pressure gradients

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

$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

v : flow coefficients
(v1: directed flow,
v2: elliptic flow, ...)

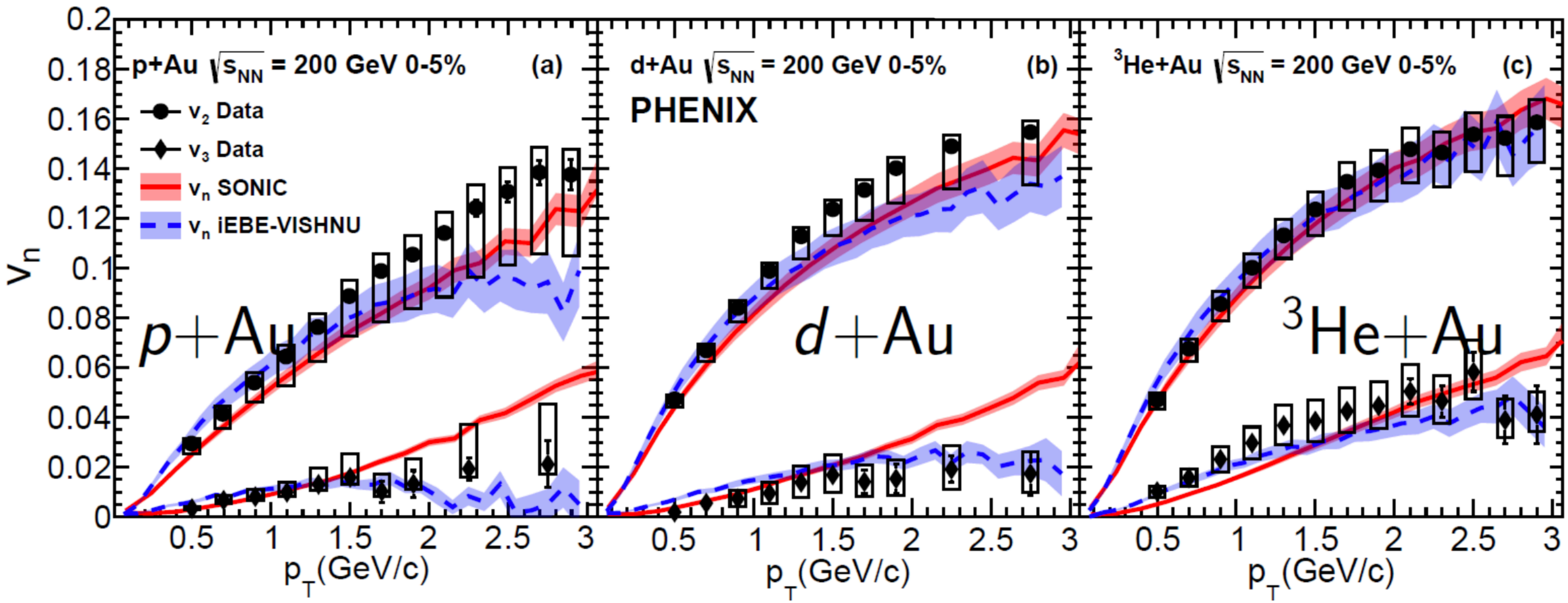
Higher harmonics

Collectivity, PHENIX small systems

Creating small circular, elliptical, and triangular droplets of quark-gluon plasma, PHENIX Coll., Nature Phys. 15, 214 (2019) https://arxiv.org/pdf/1805.02973.pdf

Reconfirmed in (PHENIX Coll.), PRC 105 024901 (2022)

Observation of elliptic and triangular flow patterns of charged particles produced in p+Au, d+Au, and 3He+Au collisions at √s(NN) = 200 GeV



Data are well reproduced with iEBE-VISHNU and SONIC, which both used shear viscosity to entropy ratio of: η/s = 0.08 ≈1/4π

Hydrodynamical models, which include the formation of a short-lived QGP droplet, provide a simultaneous description of these measurements.

Collectivity, PHENIX small systems

Creating small circular, elliptical, and triangular droplets of quark-gluon plasma, PHENIX Coll., Nature Phys. 15, 214 (2019) https://arxiv.org/pdf/1805.02973.pdf
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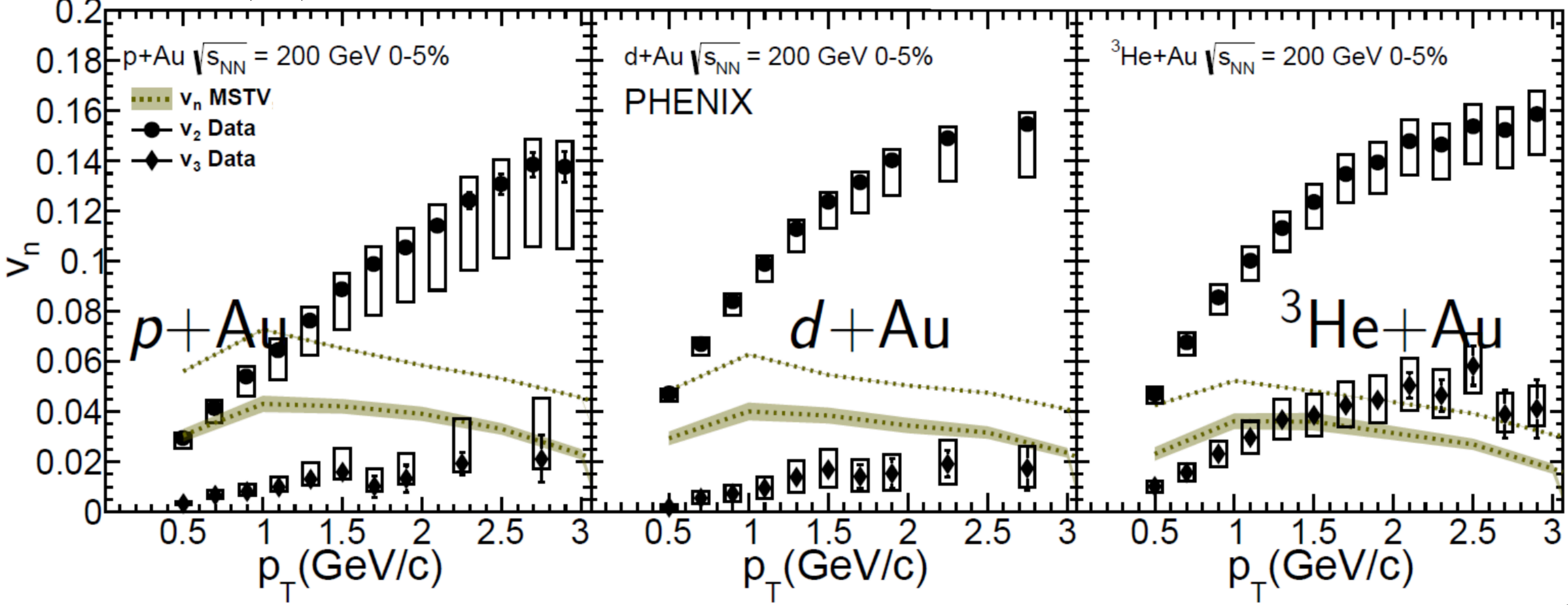
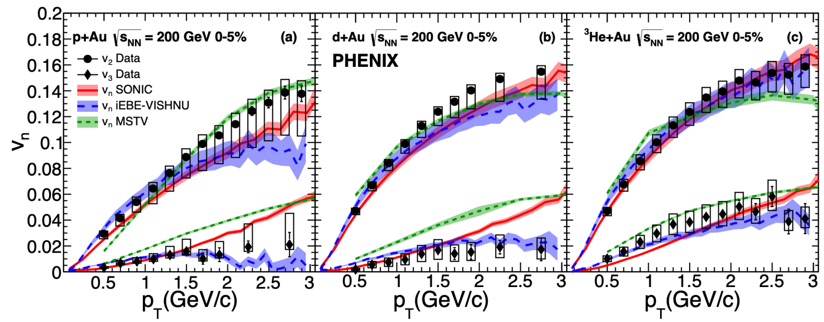


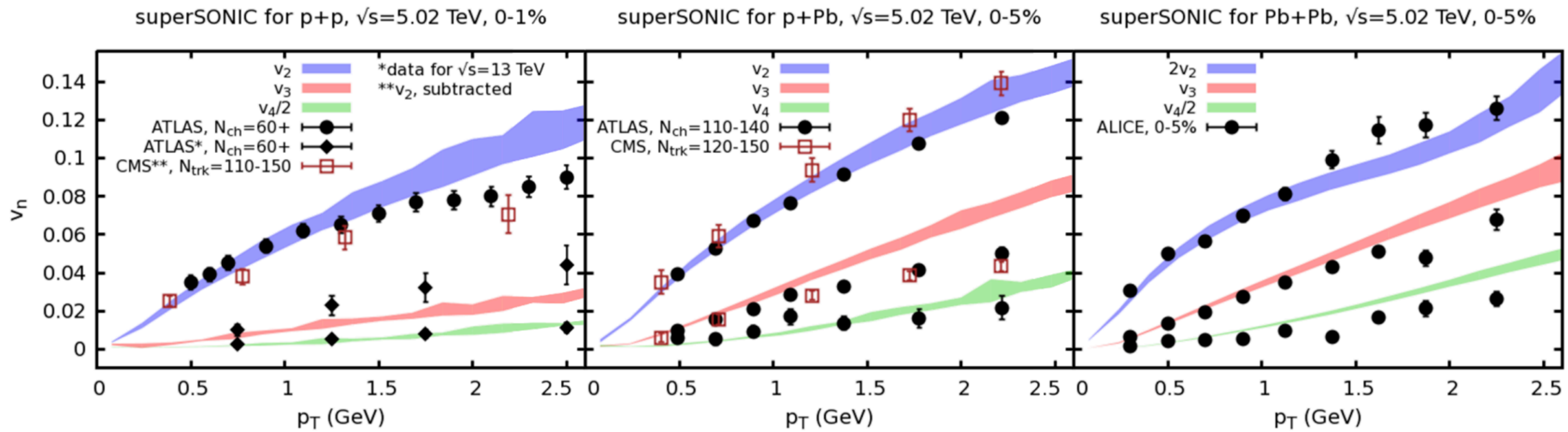
Data are not reproduced by initial state effects only

(erratum for the model MSTV (M. Mace, V. Skokok, P. Tribedy, R. Venugopalan): PRL 123, 039901 for data in (PHENIX Coll.), Nat. Phys. 15, 214-220 (2019) ->)



LHC energies

One fluid to rule them all: viscous hydrodynamic description

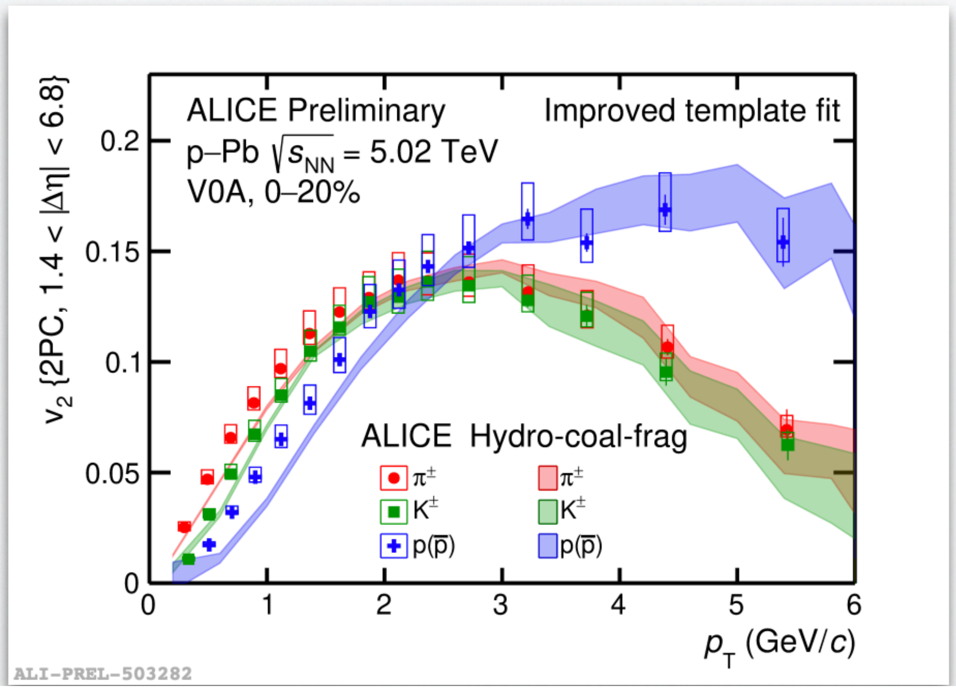


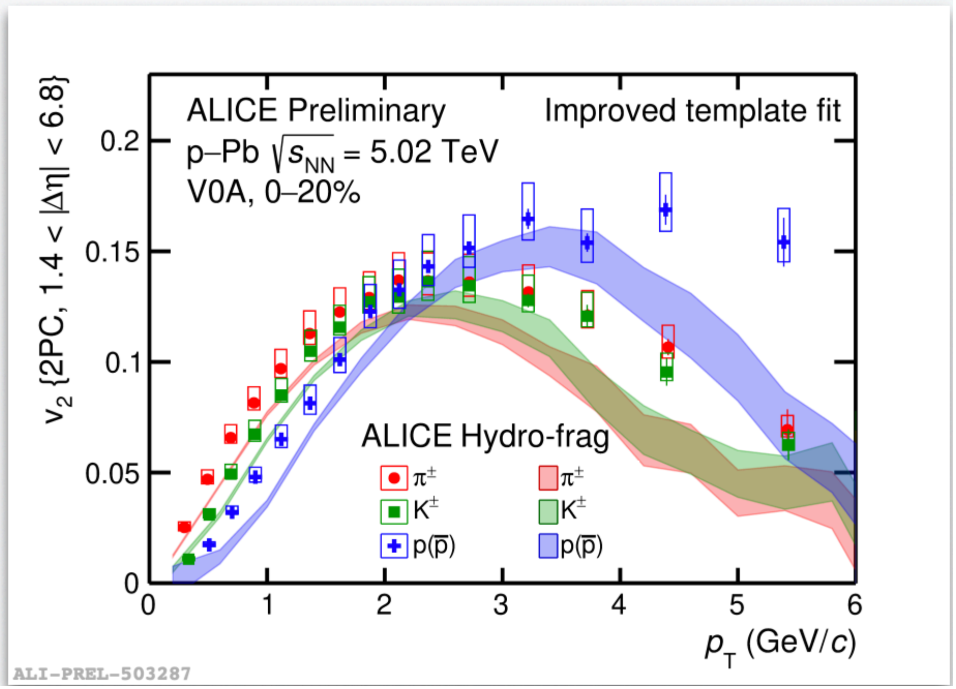
Weller RD, Romatschke P. Phys. Lett. B 774:351 (2017)

Coefficients v2,v3,v4 for p+p, p+Pb, Pb+Pb data with hydrodynamic model (superSONIC) with constituent quark Monte Carlo Glauber initial conditions, pre-equilibrium dynamics, viscous hydrodynamics with eta/s=1/4pi and hadronic scattering
(Note: p+p model is for 5 TeV and data are for 13 TeV)

The experimentally observed flow signals in proton+proton, proton+nucleus and nucleus+nucleus collisions seem to have a common hydrodynamic origin

Z. Moravcova, ALICE Col. QM2022





Models from W. Zhao et al, PRL 125, 072301 (2020)
combine hydrodynamics, quark coalescence, and jet fragmentation

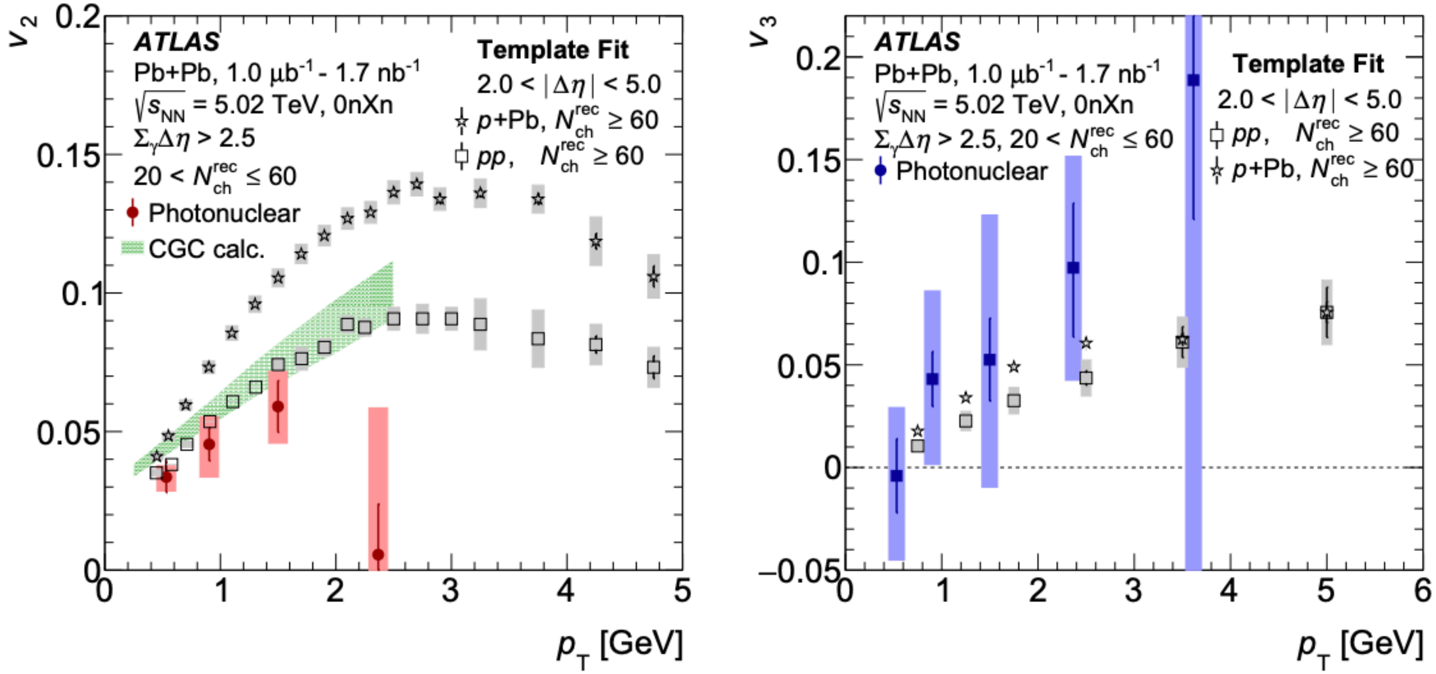
Model with quark coalescence describes the data better
-> **suggests partonic collectivity in p+Pb**

Model without quark coalescence cannot describe the data

Collectivity ATLAS gamma+Pb

(ATLAS Coll.), PRC 104 014903 (2021)

Charge particle flow coefficients in gamma+Pb

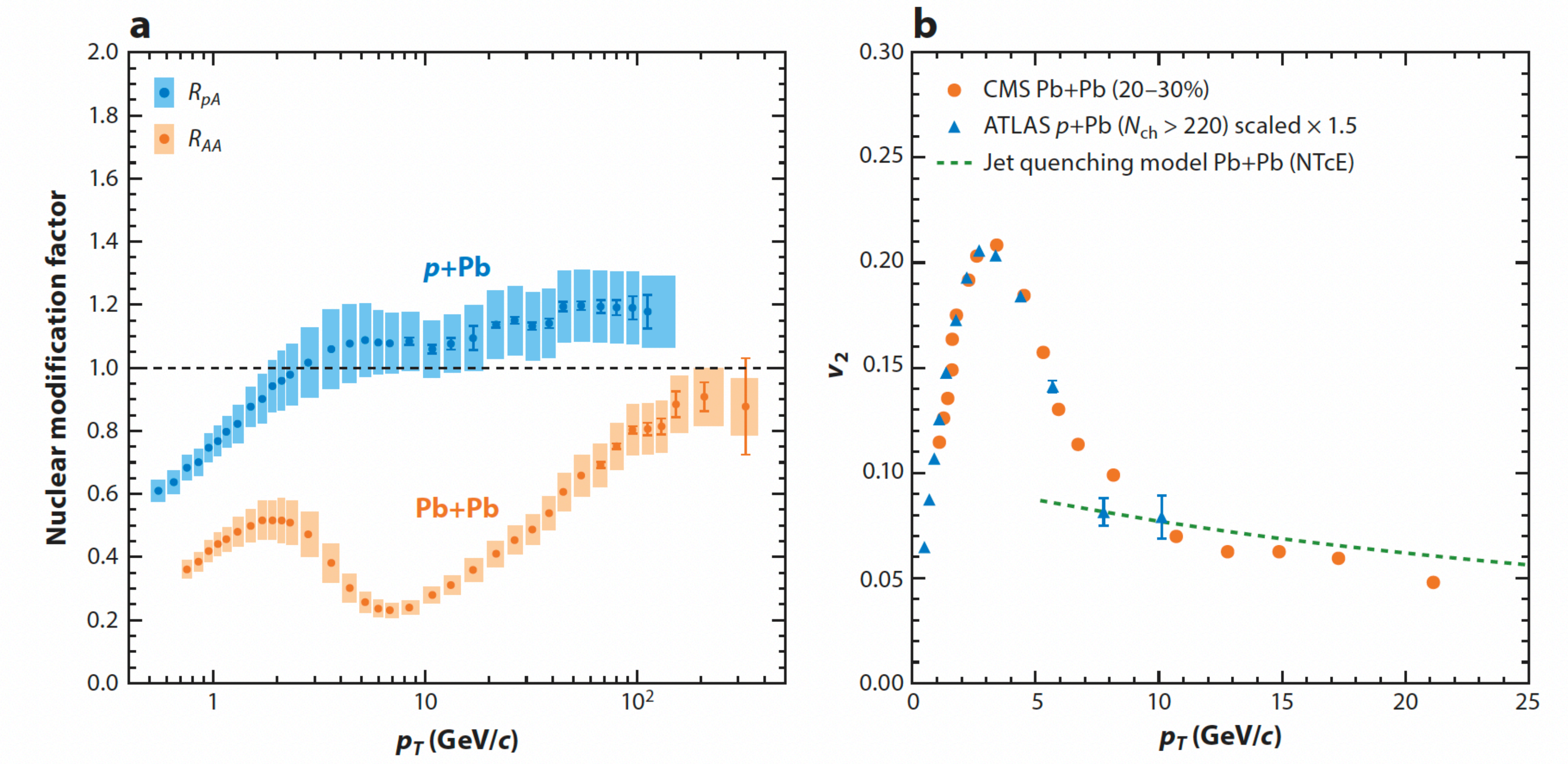


Charge particle flow coefficient v2 in gamma+Pb is similar to p+p in the pT region below 2 GeV

It can be reproduced by CGC calculations only (Shu et al, PRD 103, 054017 (2021)).

Jet quenching

Jet quenching, CMS



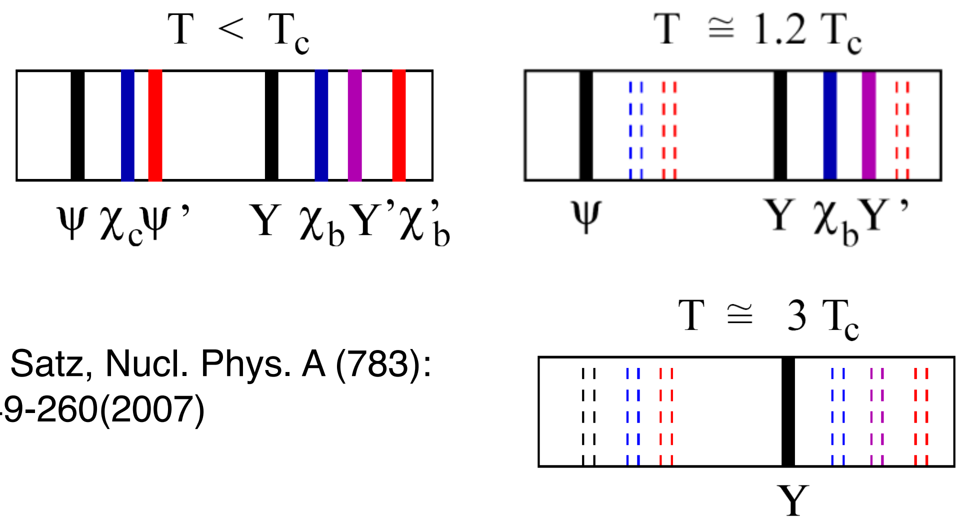
Annu. Rev. Nucl. Sci. 2018, 68:211-35, J. Nagle, W. Zajc
Khachatryan V, et al. (CMS) J. High Energy Phys. 04:039 (2017)

Unidentified hadrons RAA

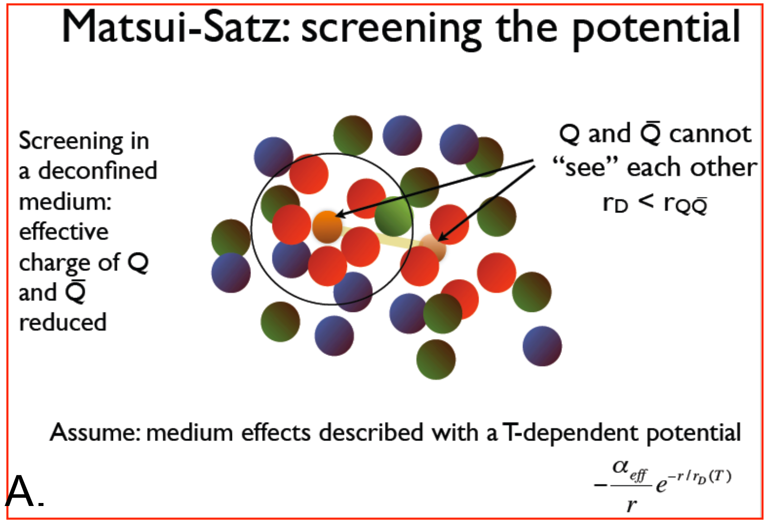
- in p+Pb is unsuppressed at pT>2 GeV
- in Pb+Pb it is strongly suppressed below pT about 110 GeV

Flow v2 vs pT, is the same in p+Pb and Pb+Pb

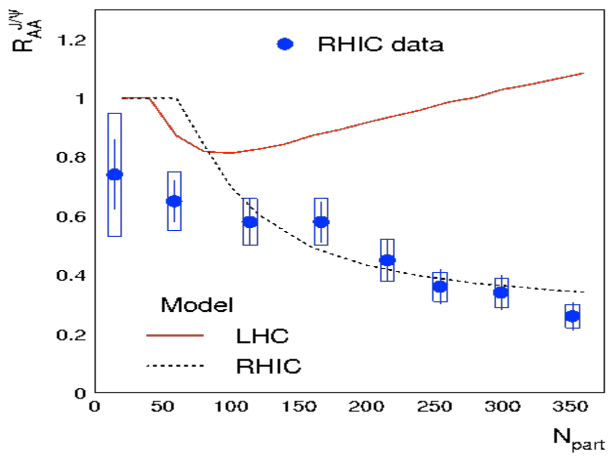
Quarkonia



H. Satz, Nucl. Phys. A (783): 249-260(2007)



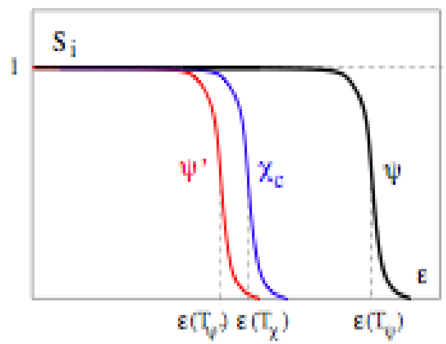
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17



Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

Many effects play a role like dissociation in QGP, cold matter absorption, recombination/ coalescence from c, cbar, feeding, eg B mesons carry 10-25% of charmonia yields (B->J/Psi from J/ Psi-h correlation STAR measurement)

Other theoretical models: B. Kopeliovich et al, D. Kharzeev, E. Ferreiro, A. Capella, A. Kaidalov, P. B. Munzinger et al, et al etc.



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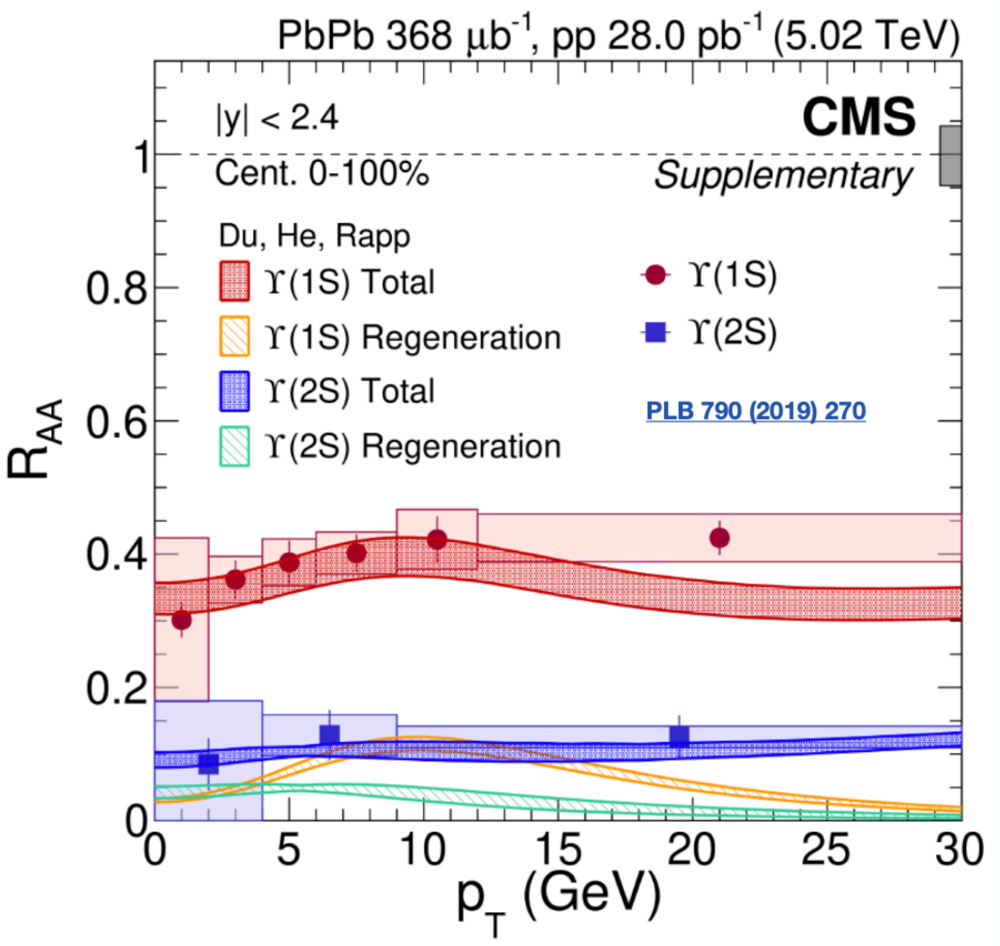
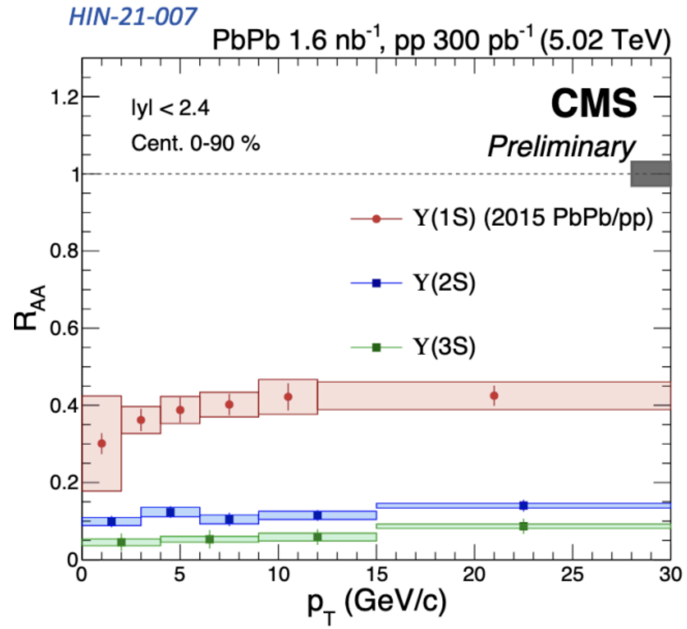
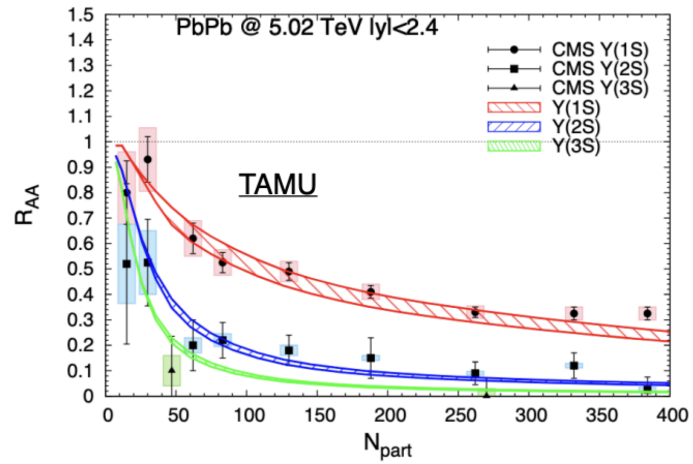
Quarkonia, CMS Y in Pb+Pb



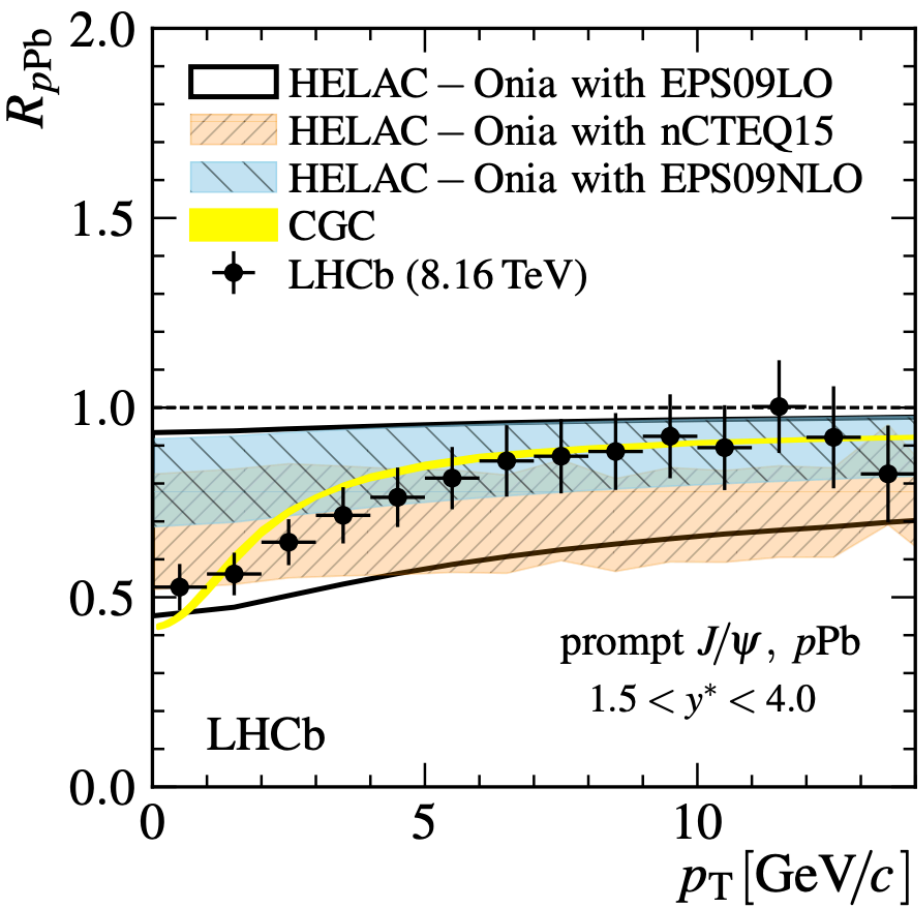
S. Lee, (CMS Coll.), QM2022

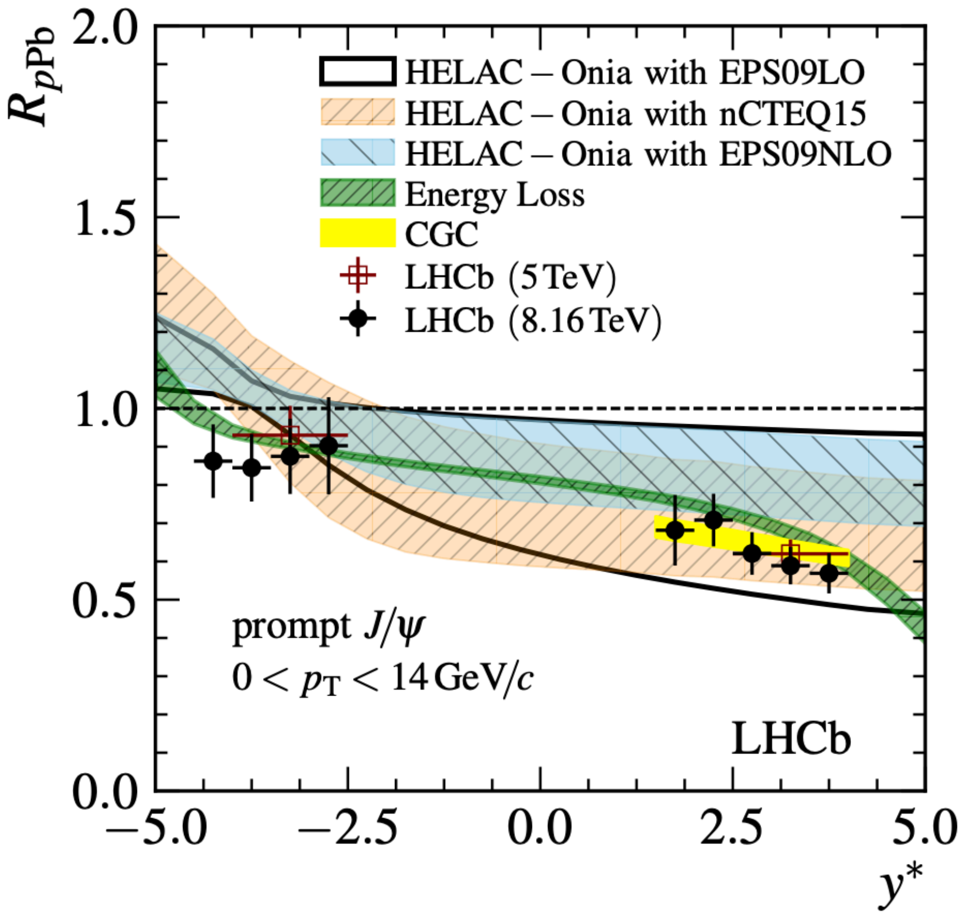




Ordering of suppression of Y(1S), Y(2S), Y(3S) states clearly agrees with the sequential melting scenario

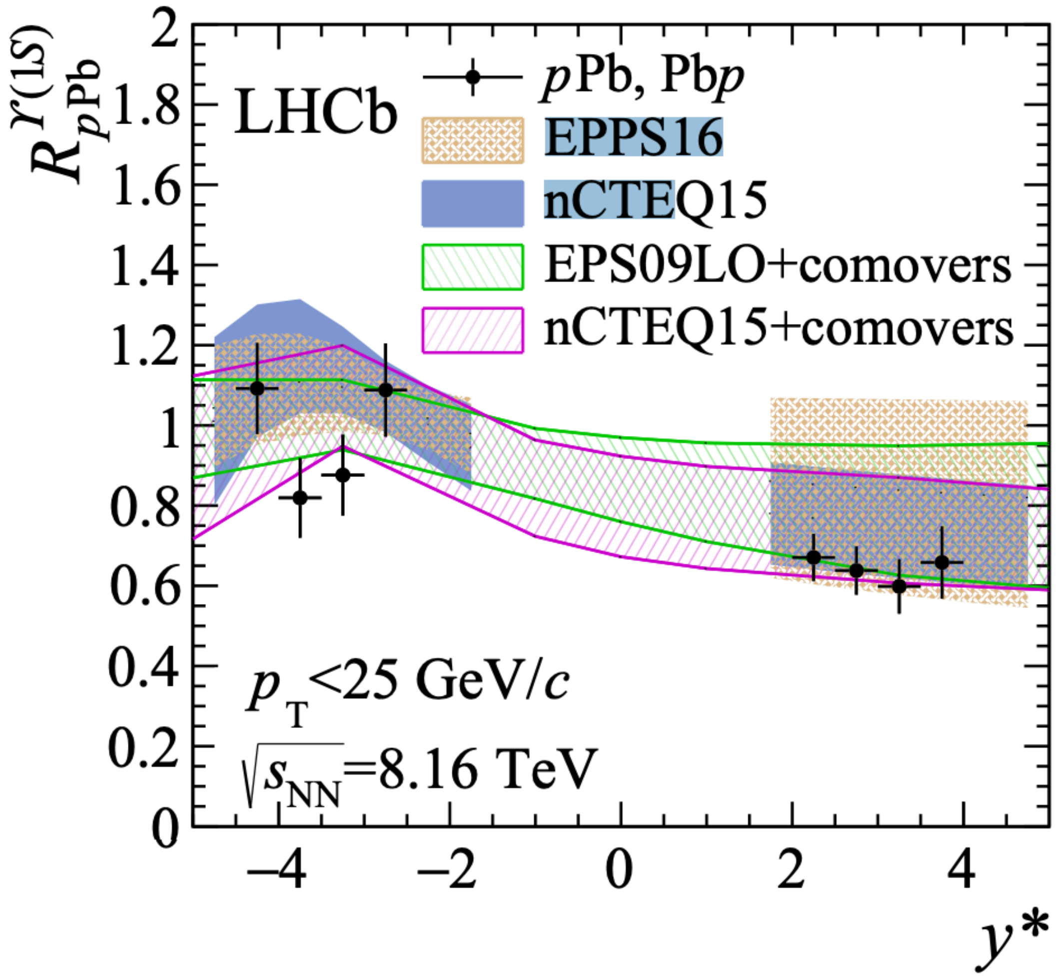
Quarkonia, J/Psi p+Pb LHCb





J/Psi in p+Pb is consistent with models with CGC, Energy loss, CNM effects

Quarkonia, Upsilon p+Pb LHCb

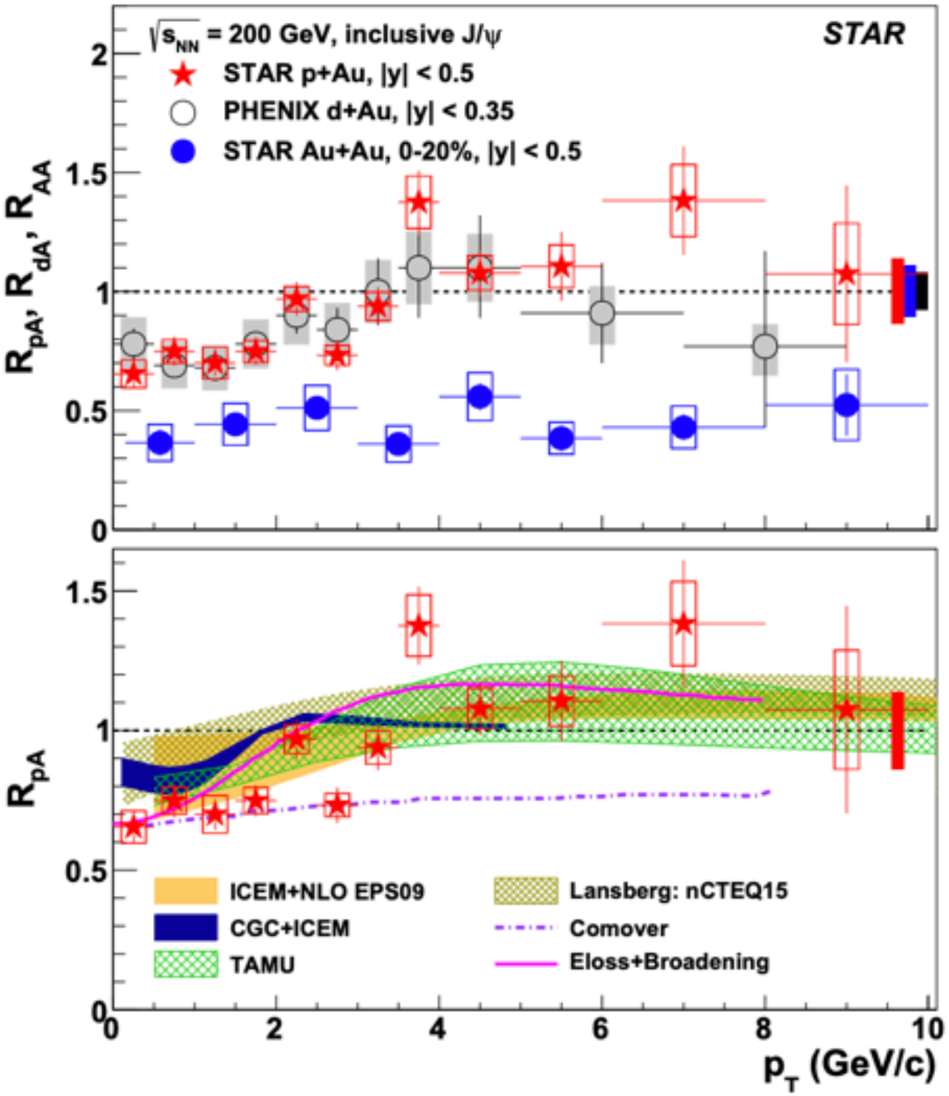


G. Manca, LHCb Coll., *PoS* HardProbes2018 (2019) 141 • Contribution to: HP2018, 141

Y(1S) in p+Pb is consistent with CNM effects

STAR 2022

https://arxiv.org/pdf/2110.09666.pdf



J/Psi -> mumu
- p+Au similar to d+Au : similar CNM effects

- CNM in p+Au, d+Au contributes to J/Psi suppression in pT<2 GeV

- J/Psi from AuAu (0-20% centrality) suppressed in all pTs

- The models are consistent with data in most of the points apart form the comover model which underestimates data above pT 3.5 GeV by 2.3 sigma

- ICEM and Lansberg calculations include only nPDF effects based on EPS09 [1] and nCTEQ15 [2] parameterizations, respectively.

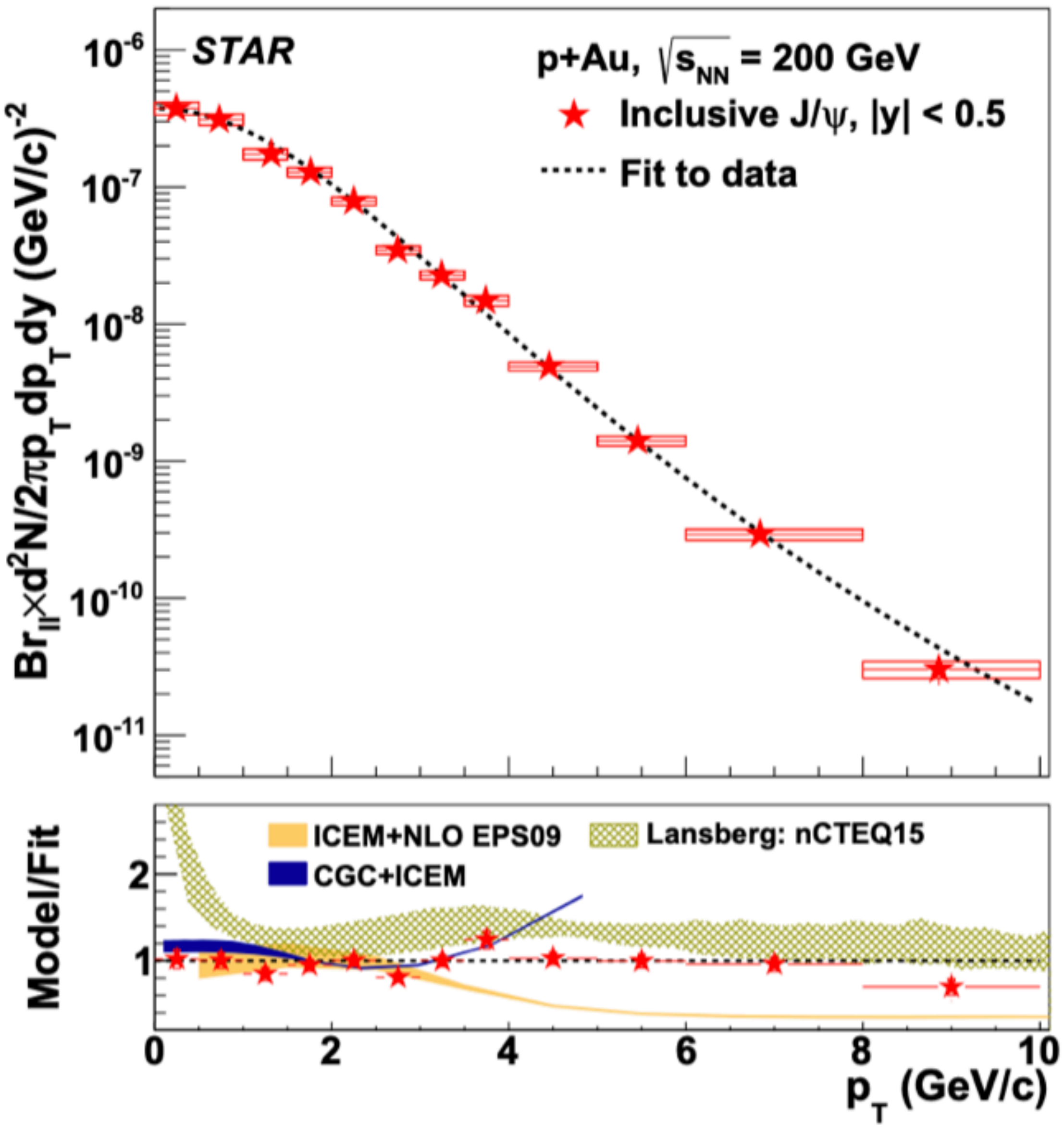
[1] K. J. Eskola, H. Paukkunen, C. A. Salgado, EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions, JHEP 04 (2009) 065. arXiv:0902.4154, doi: 10.1088/1126-6708/2009/04/065.

[2] K. Kovarik, et al., nCTEQ15 - Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework, Phys. Rev. D93 (2016) 085037. arXiv:1509.00792, doi:10.1103/PhysRevD. 93.085037.

- “Eloss+Broadening” model: interactions between charm and the cold nuclear medium induce both radiative energy loss and pT-broadening. The latter is responsible for the J/ψ enhancement above 2.5 GeV/c.

- TAMU: the NLO EPS09 nPDF is utilized, and the short-lived hot medium modifies the observed J/ψ yields in p+Au collisions through both dissociation and recombination.

STAR 2022

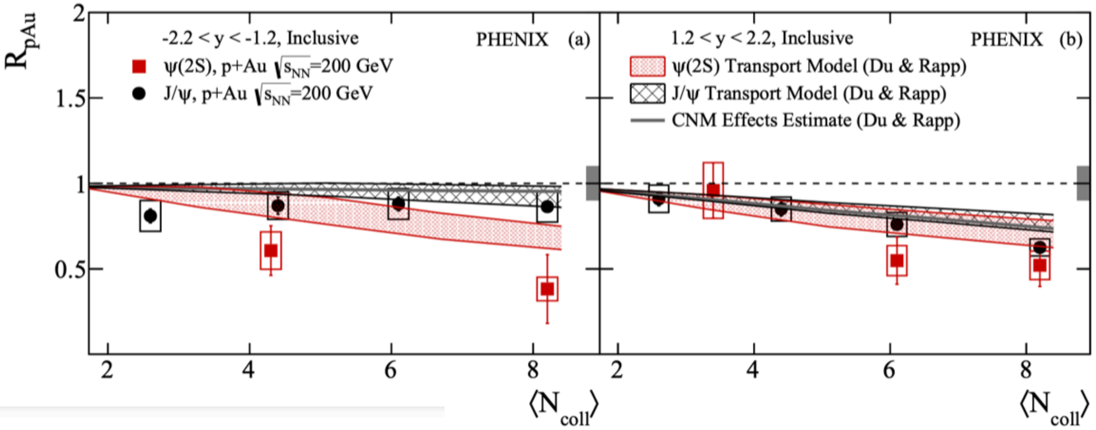


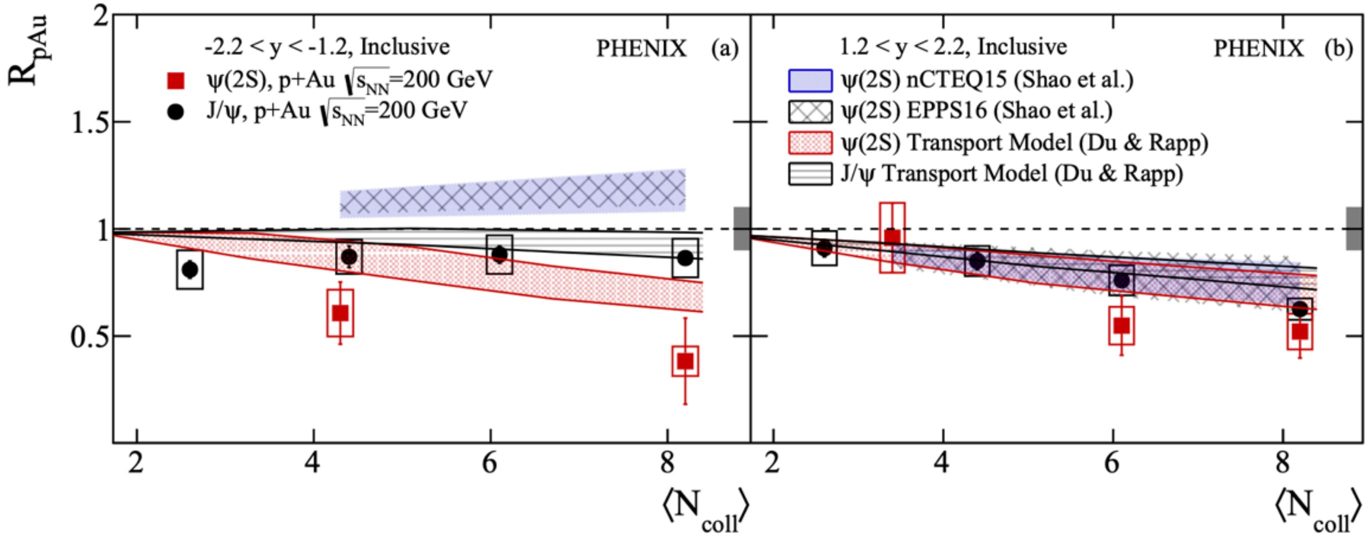
https://arxiv.org/pdf/2110.09666.pdf

Psi(2S) and J/Psi PHENIX

Psi(2S) and J/Psi PHENIX

https://arxiv.org/pdf/2202.03863.pdf





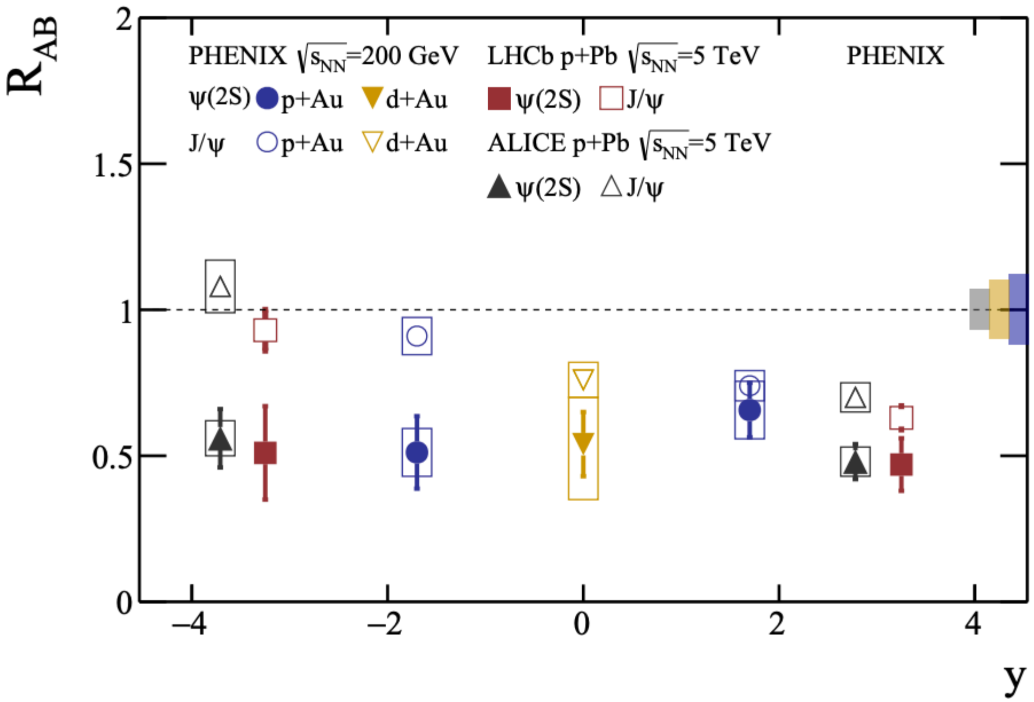
Backward rapidity Forward rapidity

-In forward rapidity Psi(2S) and J/Psi are similar and agree with expectation for CNM effects (line) nPDF and transport model

-In backward rapidity Psi(2S) is more suppressed than J/Psi (2.9 sigma effect) and falls below the expectation for CNM effects (line), nPDF does not describe data, transport model does better

p+Au PHENIX:
Jpsi agrees with CNM effects
Psi(2S) in backward y suppressed beyond CNM effects

Psi(2S) and J/Psi PHENIX



In comparing PHENIX J/ψ and ψ(2S) nuclear modification with LHCb and ALICE results, at forward rapidity the ψ(2S) nuclear modification is slightly more suppressed than the J/ψ nuclear modification at the most forward rapidity, suggesting that initial-state effects are the dominant contribution.

At backward rapidity, a clear trend is seen where the ψ(2S) is more suppressed than the J/ψ. This observed behavior reported by three different experiments is consistent with transport models that include hot-nuclear-matter effects in the A-going direction.

https://arxiv.org/pdf/2202.03863.pdf

p+A:

- J/ψ nuclear modification appears consistent with CNM effects

- The suppression observed in ψ(2S) nuclear modification is stronger than predicted by CNM effects.

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Strangeness

Strangeness Enhancement as QGP signature

Historical note

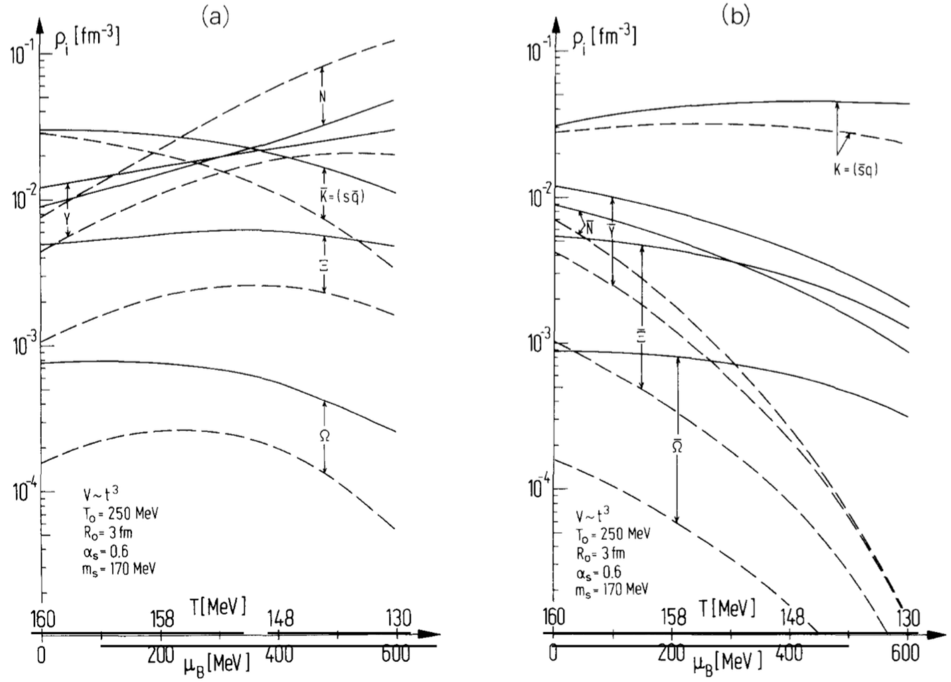
1980

Initial idea introduced by J Rafelski:

First mentioned in: J Rafelski and R Hagedorn, Ref TH.2969-CERN, 1980 :

J. Rafelski, "Extreme States of Nuclear Matter - 1980, " Republished in: Eur. Phys. J. A 51 (2015) 115.
P. Koch and J. Rafelski, "Time Evolution of Strange Particle Densities in Hot Hadronic Matter," Nucl. Phys. A 444 (1985) 678.
P. Koch, B. Muller and J. Rafelski, "Strangeness in Relativistic Heavy Ion Collisions," Phys. Rept. 142 (1986) 167.

Strangeness enhancement and Strange Antibaryons are discussed as signature for Quark Gluon Plasma formation



First QGP signature observed

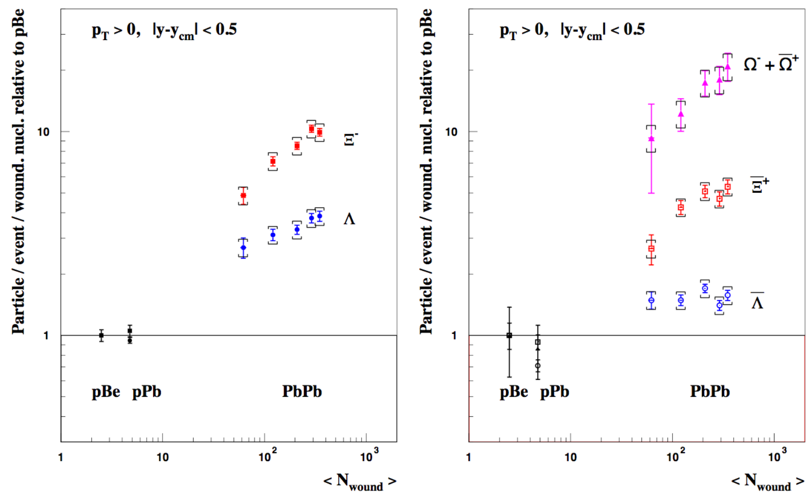
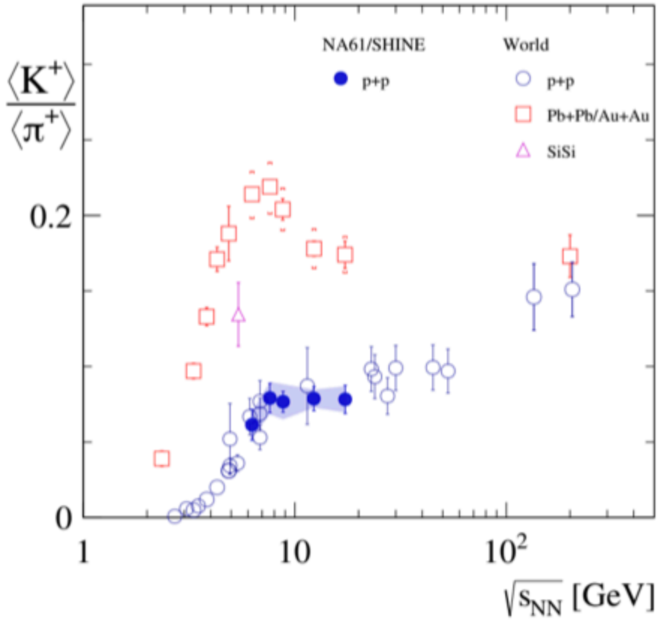
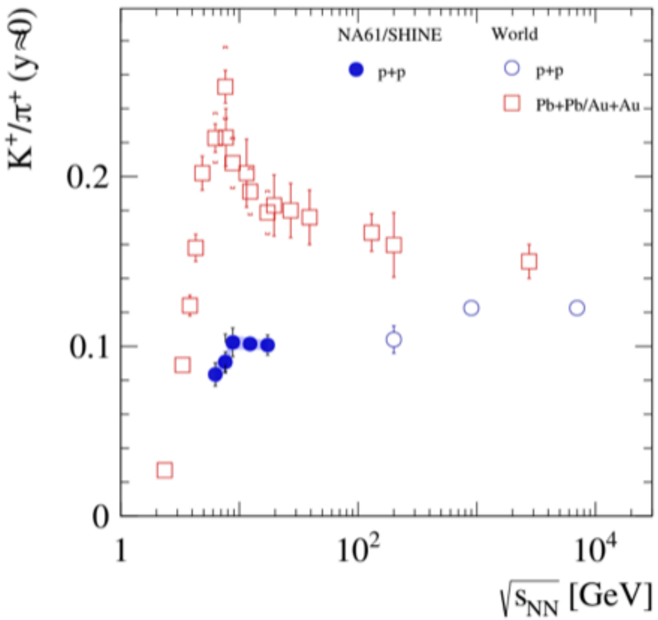


Figure 8. Hyperon enhancements E as a function of the number of wounded nucleons. The symbol ⎕ shows the systematic error.

Strangeness, NA61/SHINE

p+p

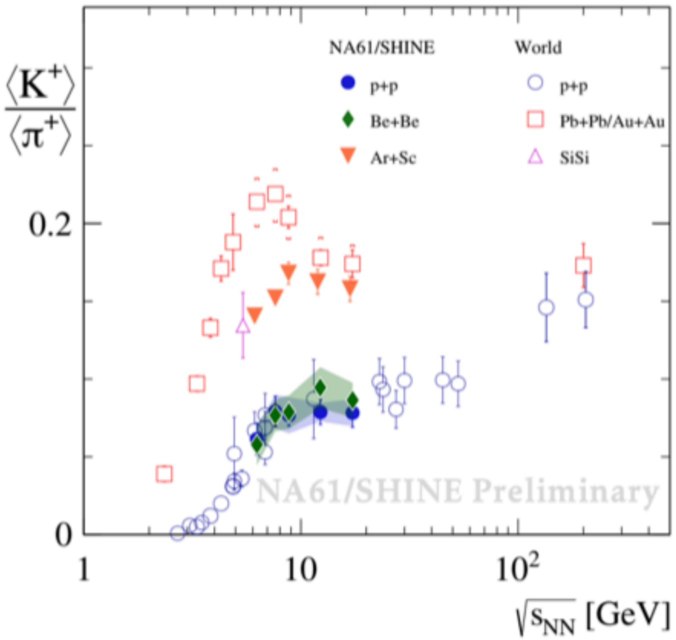


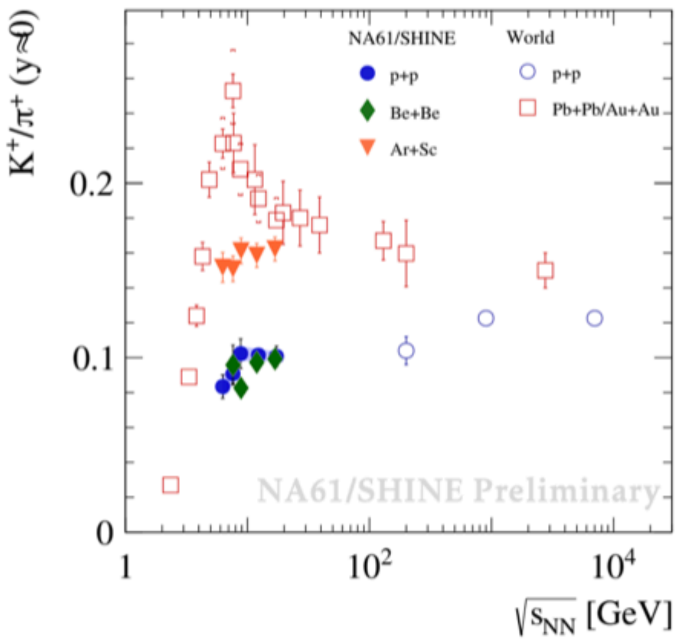


QM2022,
NA62/SHINE Coll.

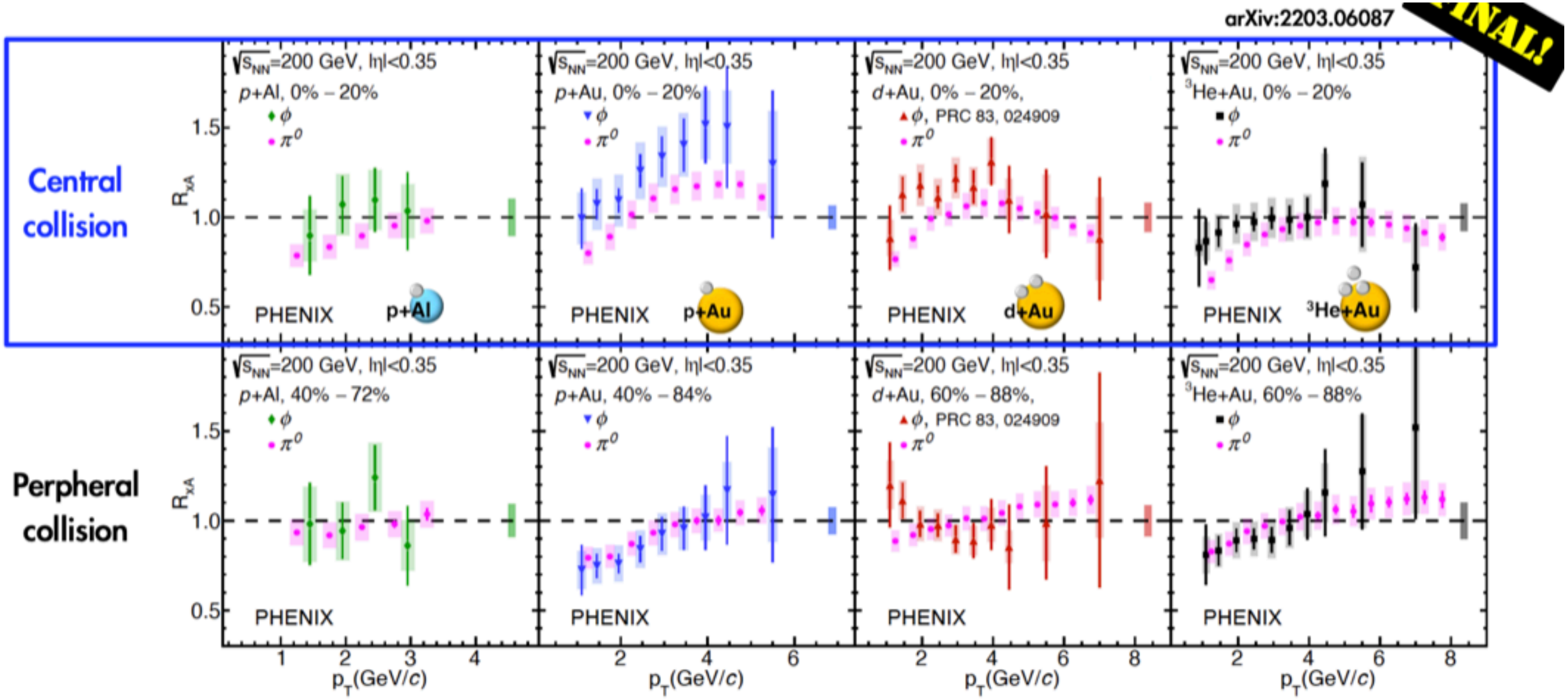
$p+p \approx$ Be+Be $\neq$ Ar+Sc $\ll$ Pb+Pb

Be+Be





PHENIX, arXiv: 2203.06087

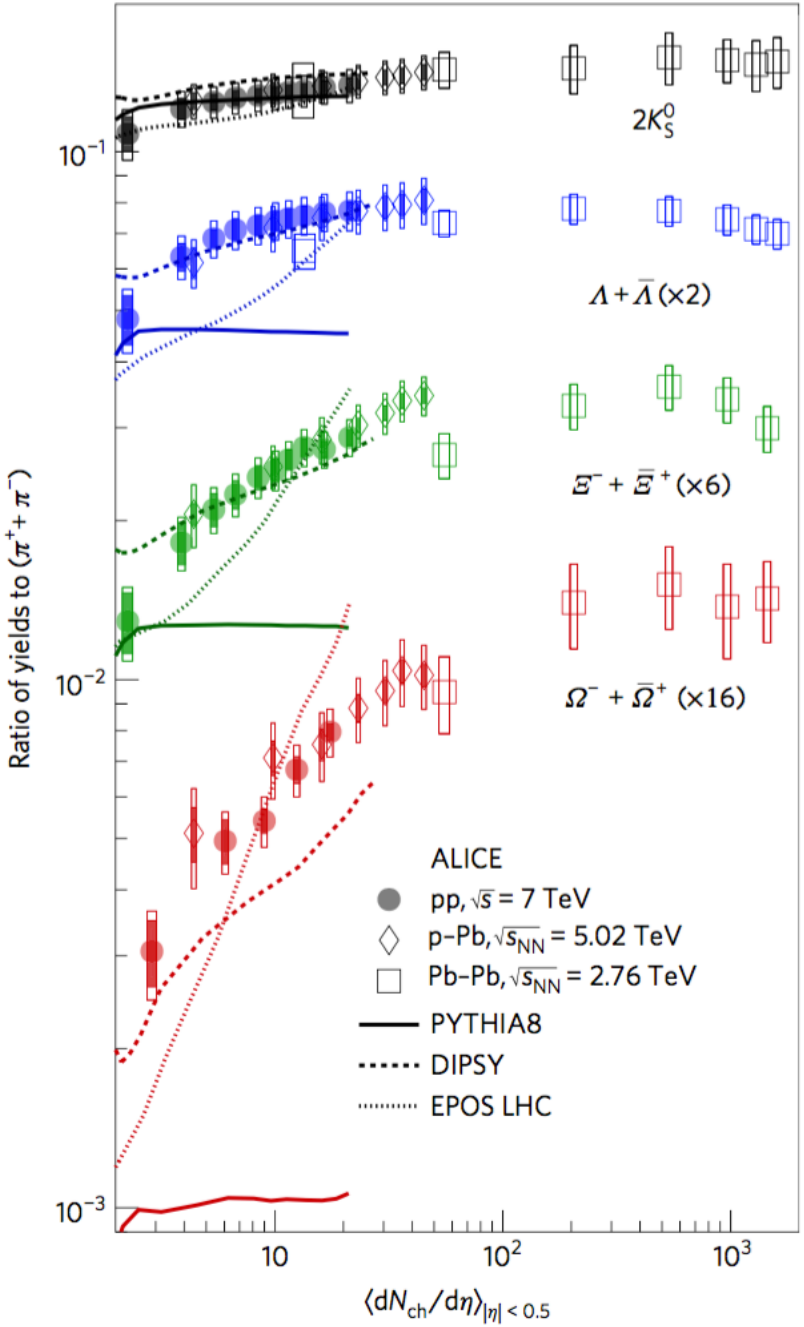


-Peripheral: similar modification of pi0 and phi

-Central: phi higher than pi0

Strangeness enhancement in small systems in most central collisions

Strangeness - ALICE



nature physics
LETTERS
PUBLISHED ONLINE: 24 APRIL 2017 | DOI: 10.1038/NPHYS4111
OPEN

Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions

ALICE Collaboration†

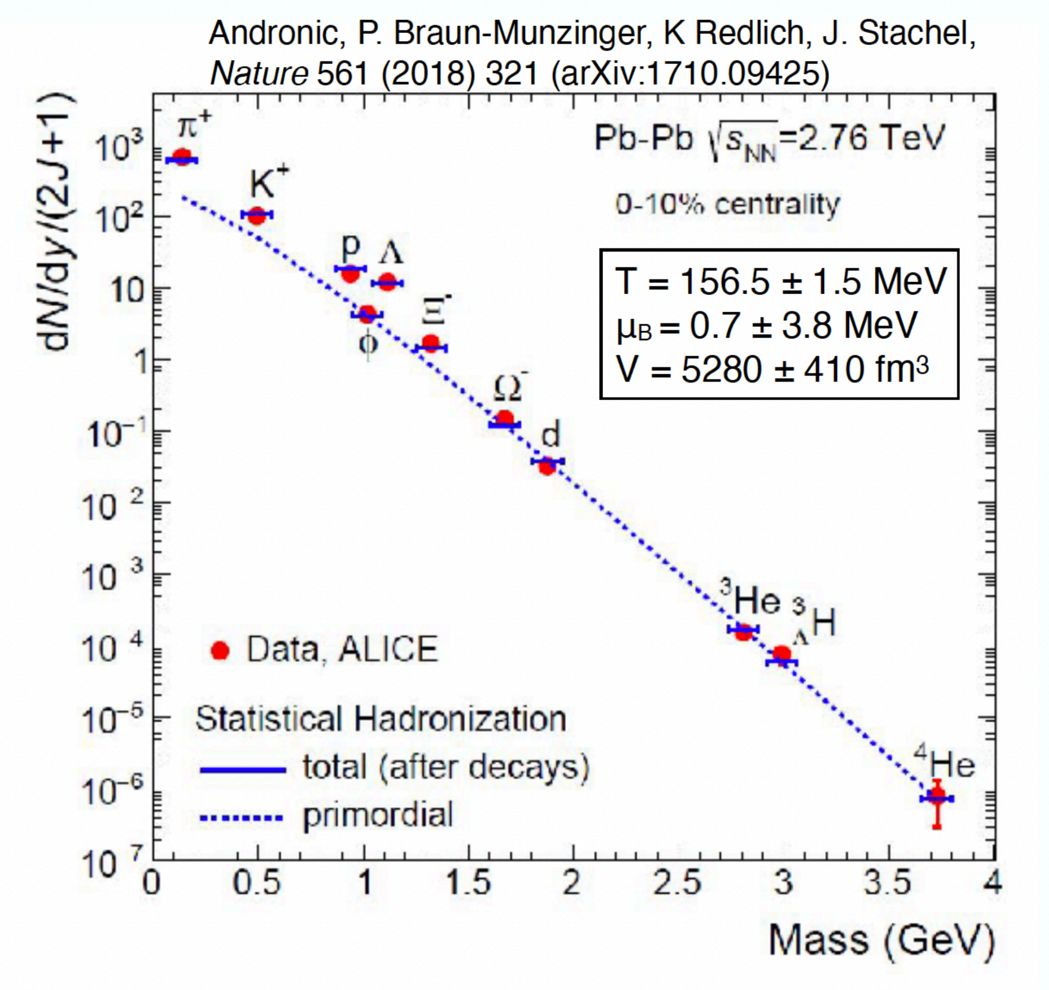
ALICE LHC: strangeness enhancement in p+p and p+Pb increases with charged multiplicity and reaches values observed in Pb+Pb collisions

The particle ratios in p+p are the same as those in p+Pb, Pb+Pb at same multiplicity densities

Strangeness in p+A at high multiplicity consistent with QGP (droplets)

p+p sqrt(s)=7 TeV, pPb= 5 TeV, PbPb= 2.76 TeV

Strangeness -> thermal model fits

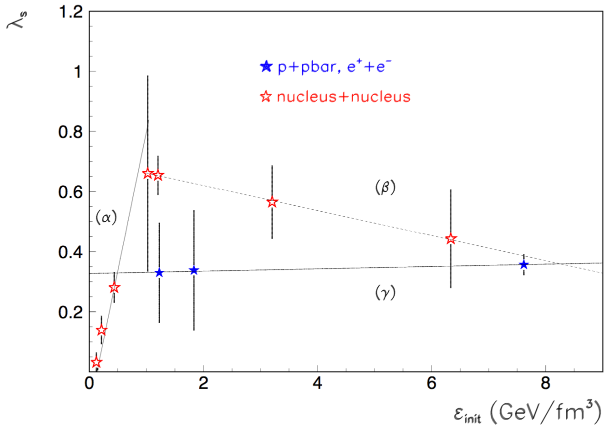


Thermal source hadronizing near T_c

Universality of the phase transition in p+p, p+A, A+A above ε(critical)

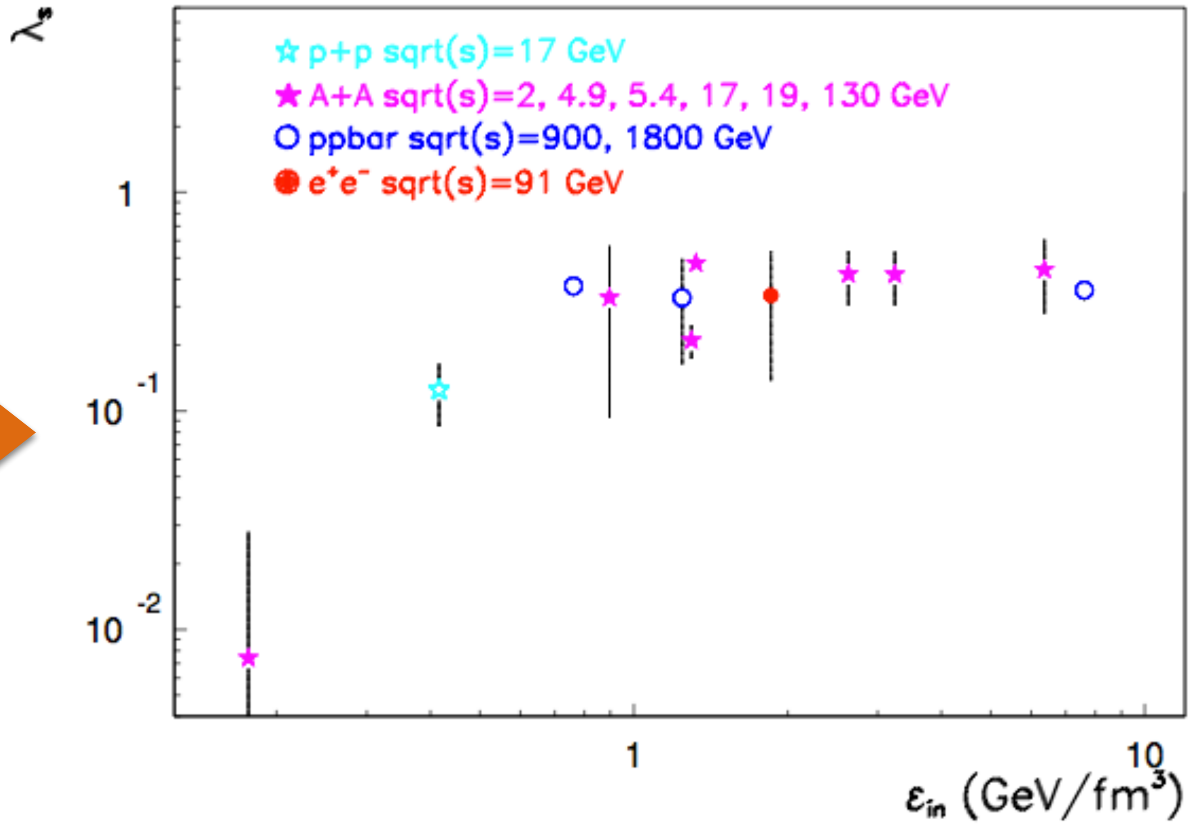
First discussion of evidence for universality (2001)

μ_b non-zero



S.K. Eur Phys J C 21 (2001) 545

μ_b zero



S.K. P. Minkowski, New J. of Phys (2001) 3 4

Universality of the strangeness supression factor in small and big systems after extrapolating to muB=0
Marek's horn dissappears.
Onset of saturation marks the phase transition above critical values
-> leads to identifying ε(critical)

Statistical Model by J. Rafelski et al - SHARE

Uses gamma(s) and gamma(q) factors to allow strange and light quarks to deviate from equilibrium

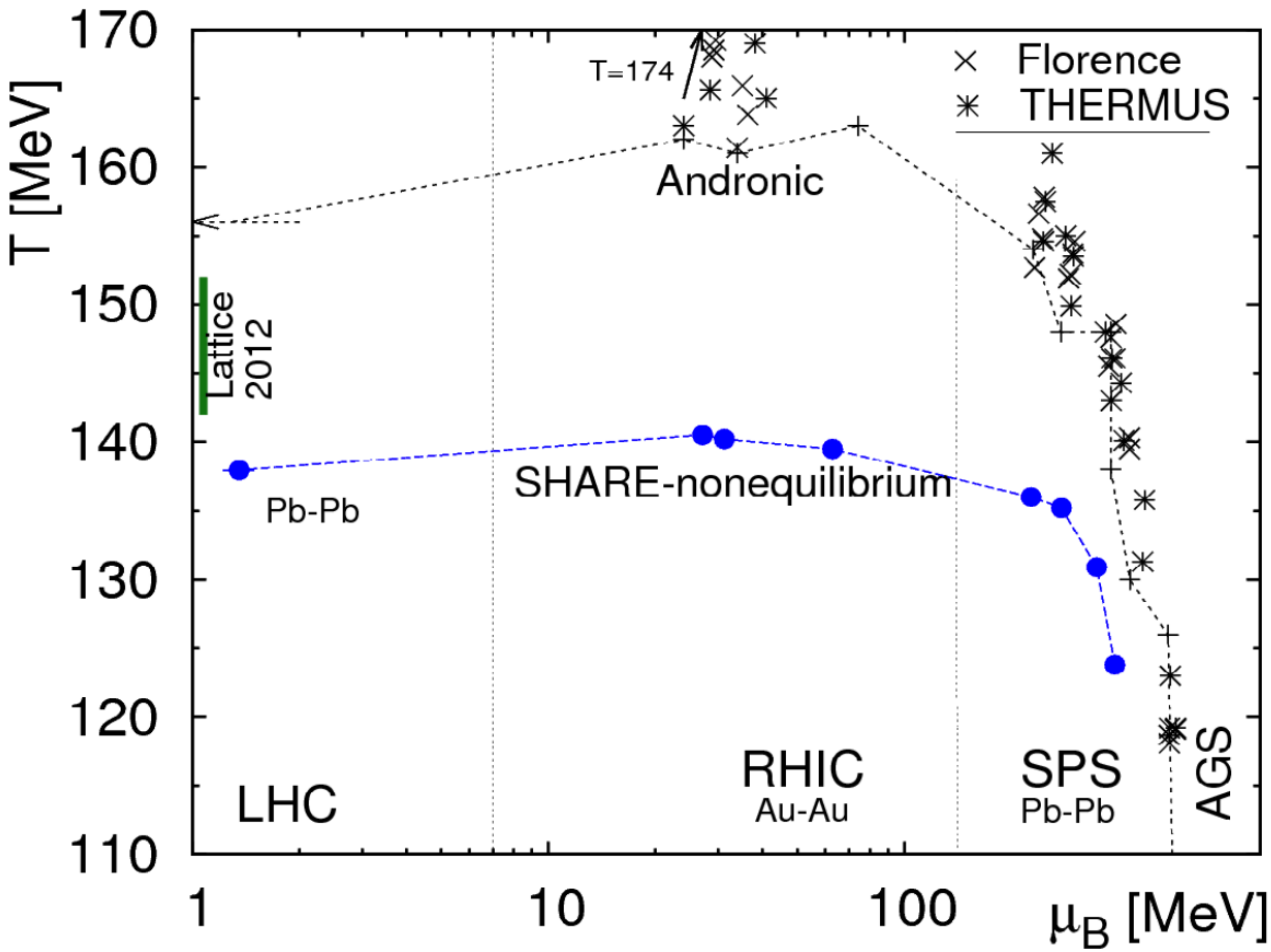
Finds that strange and light quarks deviate from equilibrium yield

T about ~ 140 MeV at high energy

Comparison of results of SHARE with A Andronic et al and Lattice QCD calculations

->

Temperatures extracted fall clearly below Tcrit(lattice) as it would be expected for hadrons at freeze out



Multiquarks and strangelets as " QGP droplets "

From Strangeness enhancement to Strange Quark Matter

Vol. 5 (2012) *Acta Physica Polonica B Proceedings Supplement* No 2

PLANETARY IMPACTS BY CLUSTERED QUARK MATTER STRANGELETS*

LANCE LABUN, JAN RAFELSKI

Department of Physics, The University of Arizona, Tucson, 85721, USA

(Received January 16, 2012)

We propose a model of clustered u-d-s quark matter that leads to stable bulk strange quark matter. We discuss qualitatively consequences of impacts by sub-planetary mass strangelets on rocky solar system bodies.

Multiquarks and strangelets as " QGP droplets "

L. Labun, J Rafelski

Planetary Impacts by Clustered Quark Matter Strangelets 383

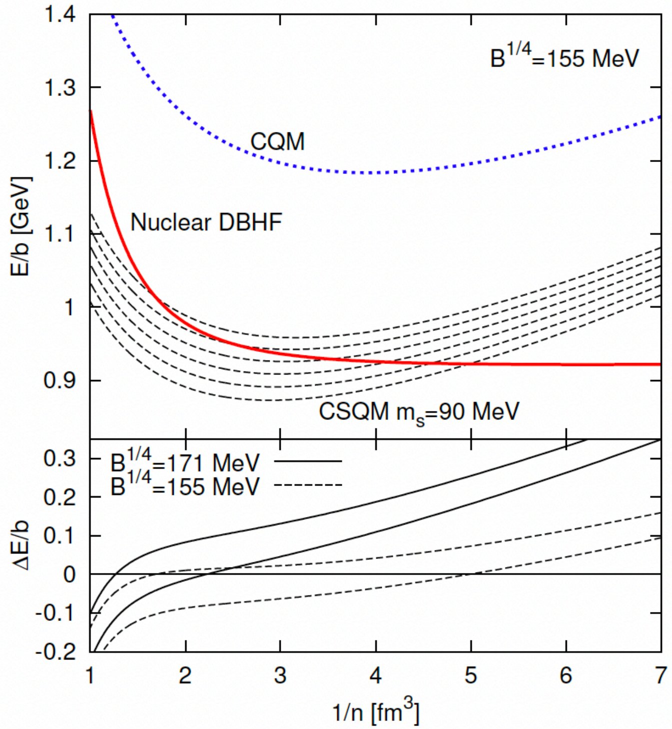
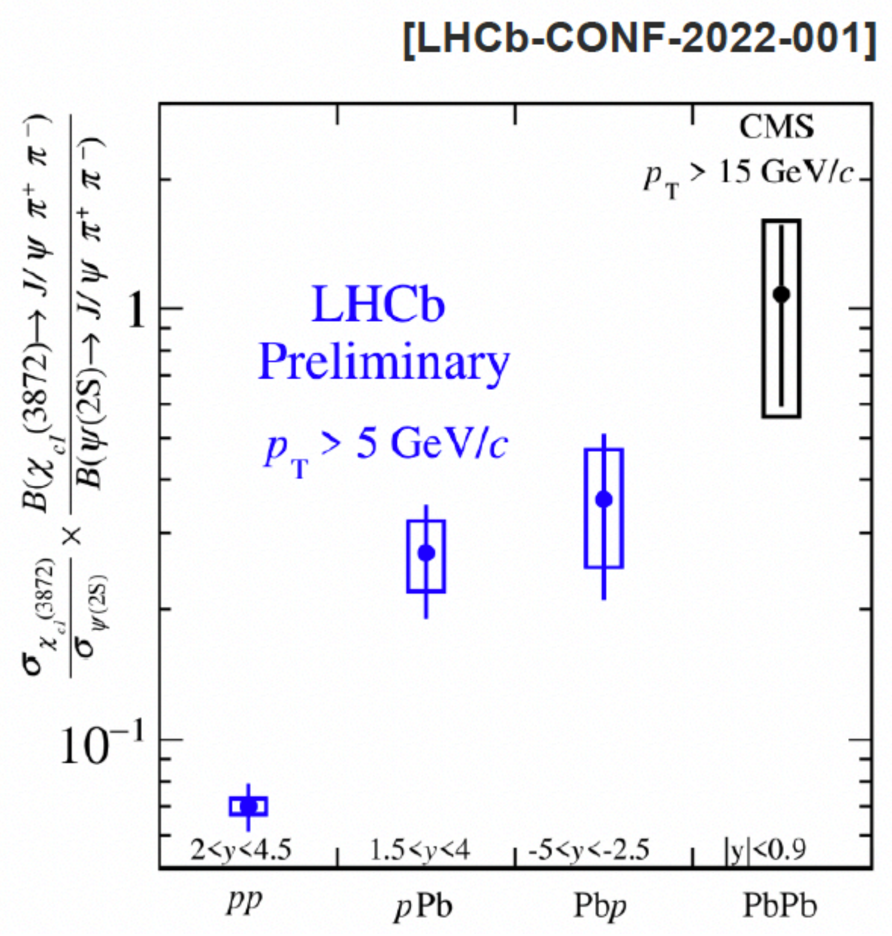


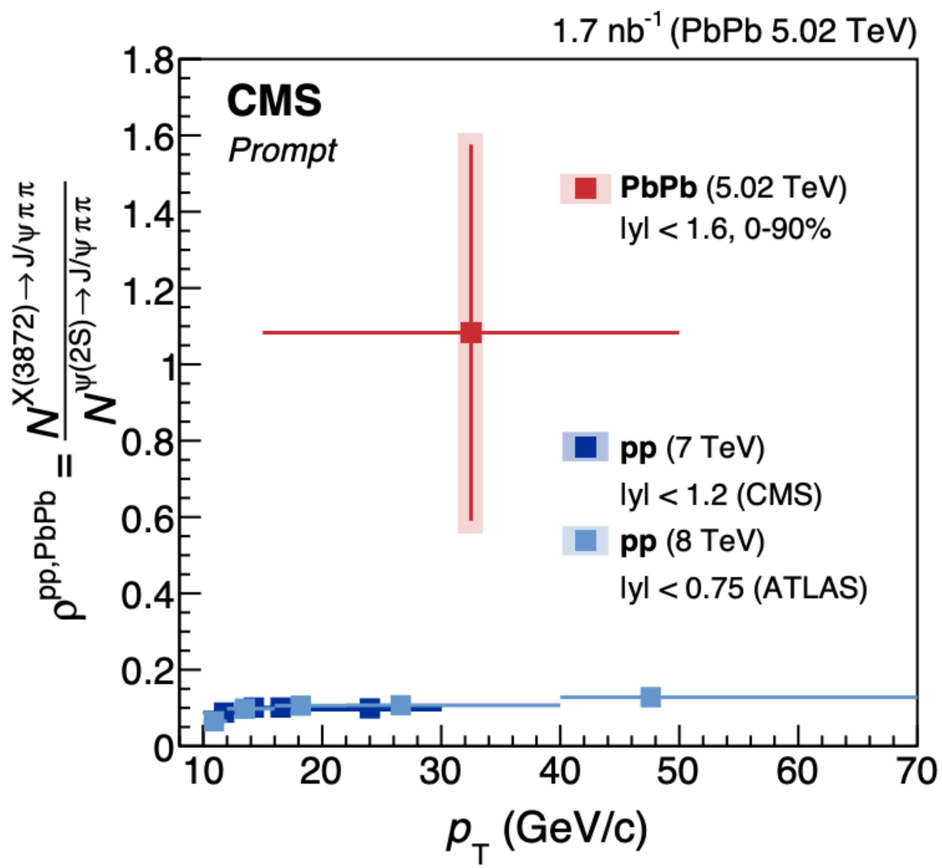
Fig. 1. Top frame: Energy per baryon E/b as a function of baryon density n. The lowest dashed curve is for clustered strange quark matter (CSQM) with $m_s =$ 90 MeV and each successive curve increases m_s by 10 MeV, ending with $m_s =$ 140 MeV for the uppermost dashed curve. Comparison curves for u, d-only clustered quark matter and Dirac–Brueckner–Hartree–Fock (DBHF) [12] are also shown. Bottom frame: the energy difference between CSQM and DBHF, with upper curve corresponding to $m_s = 140$ MeV and lower corresponding to $m_s = 90$ MeV. $B^{1/4} =$ 155 MeV for dashed lines and $= 171$ MeV for solid lines.

Ratio of tetraquark Xc1(3872) (uubar ccbar) to Psi(2S) in p+p, p+Pb, Pb+Pb



Emilie Maurice, LHCb Coll., QM2022

LHCb first pPb measurement



CMS first PbPb measurement
PRL 128, 032001 (2022)

Multiquarks: new QCD probes

Conclusions and outlook

Conclusions and outlook

-From the begin of times of QGP/Heavy Ion field p+p, p+A have been used as reference systems allowing to quantify the "No-QGP" case, especially the "cold nuclear matter "effects in p+A, and tune models which would be able to estimate a reliable " non-QGP " prediction for A+A

-p+A, d+A, (small A)+(big A) help to understand cold nuclear matter effects, (and also gamma+A) help to understand initial state effects (Color Glass Condensate) -> to tune models towards the understanding of A+A

-LHC/RHIC measurements of last years suggest QGP droplet formation in small systems (flow, strangeness)

-We dont see all QGP signatures in p+A (jet quenching, quarkonia suppression) but due to the small volume these "QGP signatures " may not be possible to be observed in small QGP droplets of p+A collisions at present energy.

-Also energy density reached in p+A will be less than in A+A at same energy, causing different quarkonia to dissociate (Psi(2S) dissociates at about 1.1 Tc, J/Psi at higher values).

-Smallest QGP droplets: strangelets (related: dibaryons, multiquark states) -> some multiquark states have been observed

Future
-Look R(pA) = AA/pA and not only R(AA)=AA/pp.
-Need systematic measurements with higher statistics of p+p, p+A, (light A+lightA), light A+heavy A) and ofcourse also A+A at various energies to better tune models

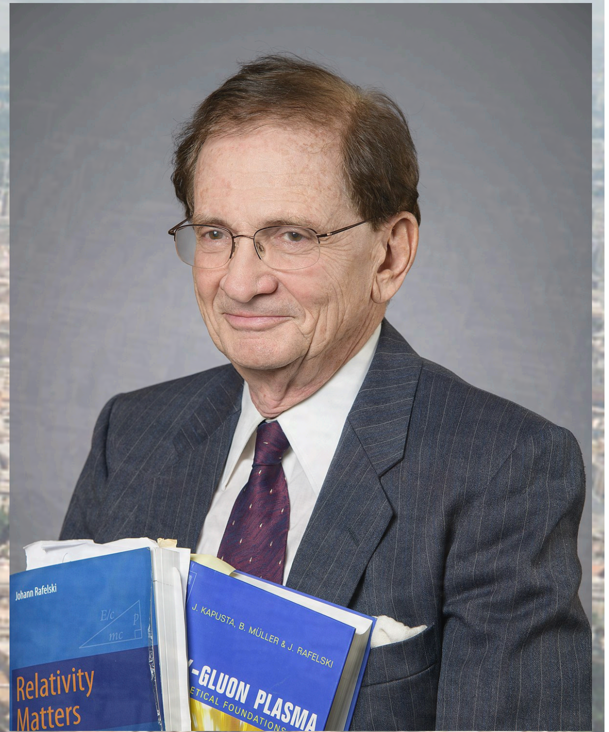
Happy Birthday !

Wszystkiego najlepszego !

Boldog Szueletesnapot !

יום הולדת שמח !

Yom Huledet Sameach !



Happy Birthday !

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Yom Huledet Sameach !

Memories from a QM conference far back !

(photo by L. McLerran)

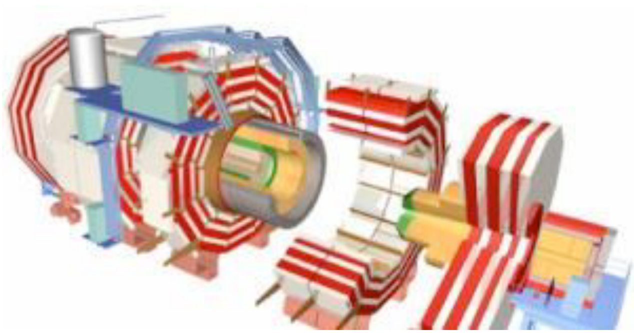
Happy Birthday !
Wszystkiego najlepszego !
Boldog Szueletesnapot !
יום הולדת שמח !
Yom Huledet Sameach !

Thank you very much

Backup Slides

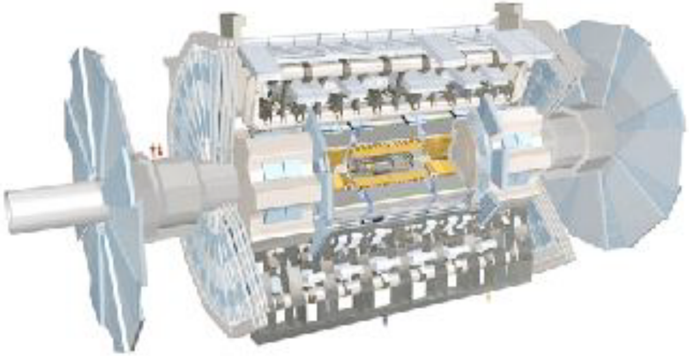
LHC

CMS

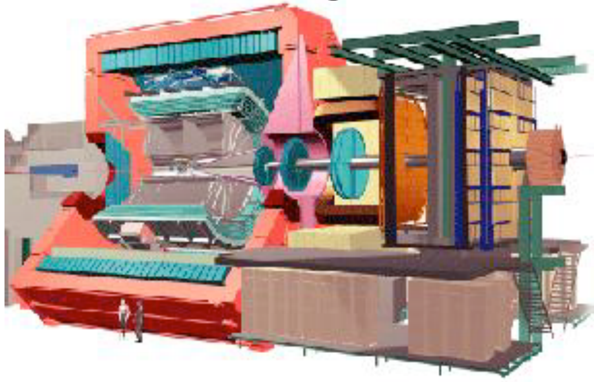


LHCb

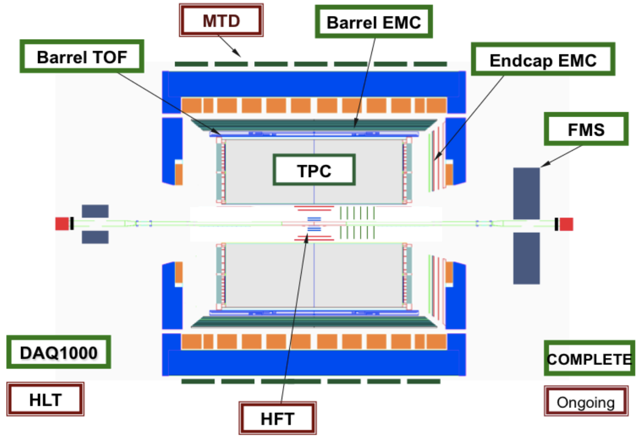
ATLAS



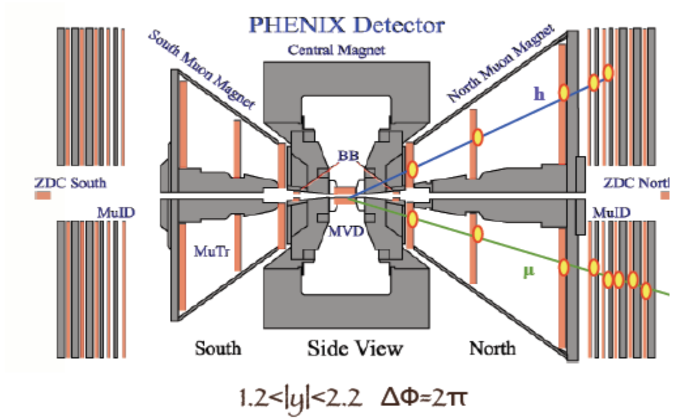
ALICE



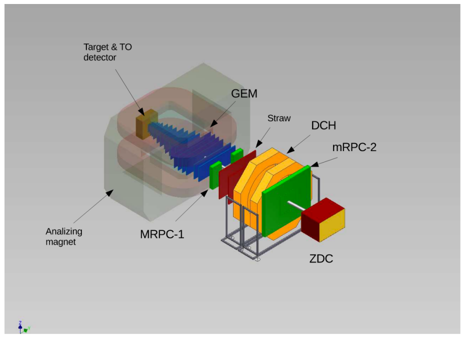
STAR at RHIC



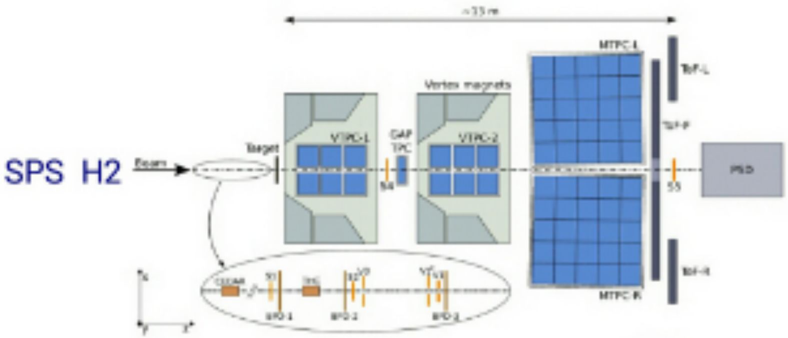
PHENIX at RHIC (data analysis only)



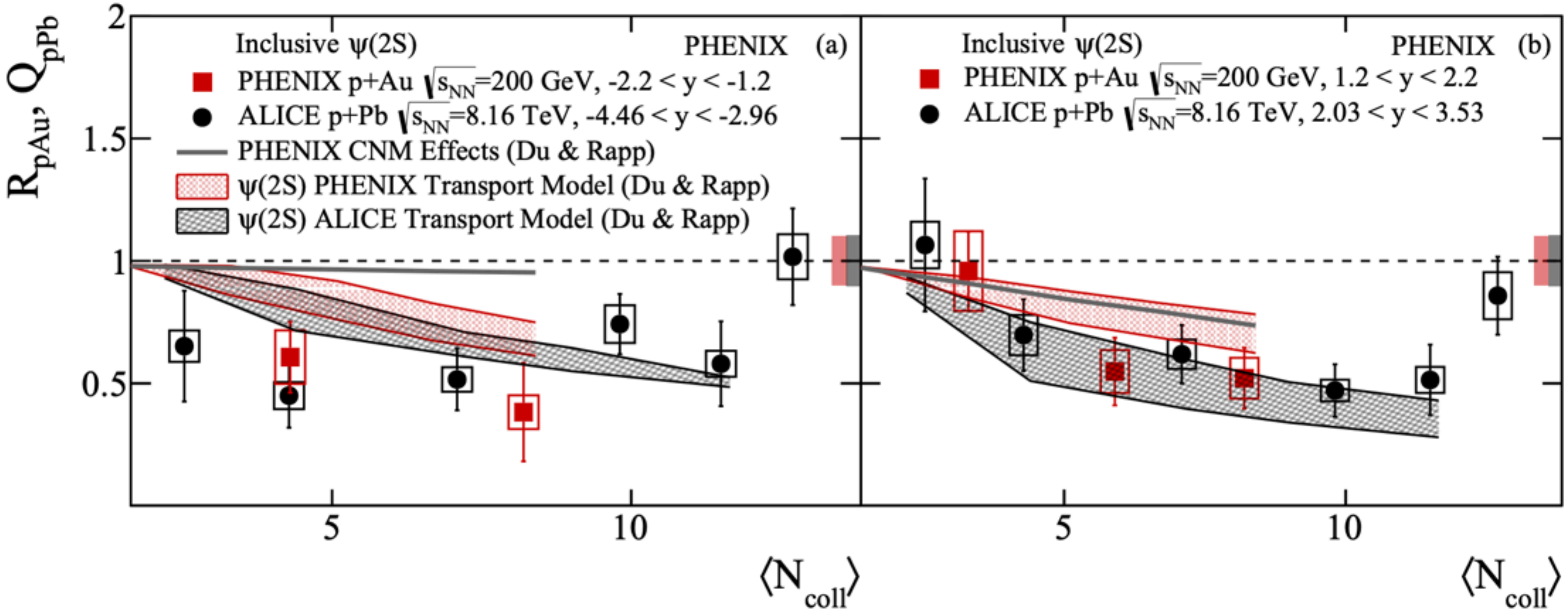
(BM@N NICA)



NA61/SHINE at SPS



Psi(2S) PHENIX, ALICE p+A



https://arxiv.org/pdf/2202.03863.pdf