UNIVERSIDAD DE TARAPACA

CENTRO CIENTÍFICO
TECNOLÓGICO
DE VALPARAÍSO

QCD in dense Media

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Workshop on "half a century of QCD"
at the International Conference on New Frontiers in Physics ICNFP 2024

26 August - 4 September, 2024
Orthodox Academy of Crete, Kolymbari, Greece

Outline

Review of selected topics on QCD in dense media created in heavy ion collisions from the experimental point of view

I Introduction

II Accelerator facilities and experiments

III Some historic milestones

IV Selected physics results:

1. Direct photons
2. Collectivity, flow, strangeness
3. Jet quenching
4. Quarkonia suppression
5. Various

IV Conclusions and outlook

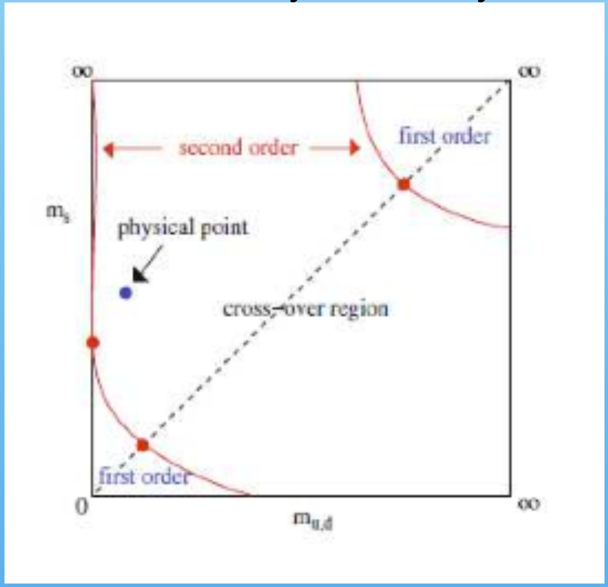
I Introduction

The QCD phase transition
between hadronic and partonic phase

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

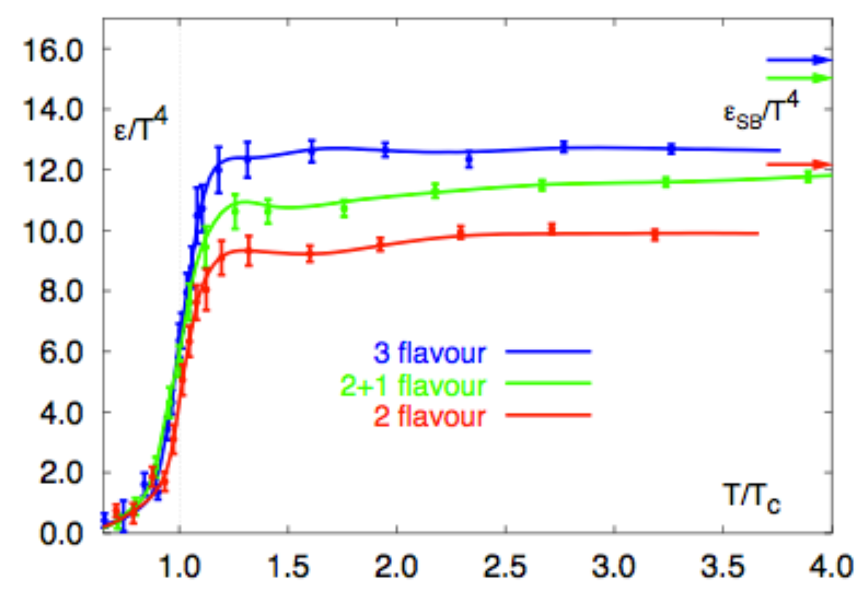
F. Karsch, Lect. Notes Phys. 583 (2002) 209, hep-lat/0106019

Zero net baryon density



The order of the transition depends on the parton masses.
A cross over is expected by Lattice QCD for the physical point (for the physical u,d,s masses).

Zero net baryon density



TD Cohen, L. Glozman,
arXiv:2311.07333 **[hep-ph]**

T(chiral phase transition)=130 MeV
T(deconfinement phase transition)=300 MeV

The physics of heavy ion collisions

Quantum chromodynamics (QCD) predicts that at high temperatures and/or densities the hadronic matter undergoes a phase transition or cross over into a state of deconfined quarks and gluons, the so called Quark Gluon Plasma (QGP).

Motivated by this expectation, an experimental program started about 3 decades ago aiming to create and study dense and hot nuclear matter by colliding heavy ions at ultrarelativistic energies in accelerators.

Bevalac, LBNL, (1975-) BNL, AGS (1986-) CERN, SPS (1988-) BNL, RHIC (2000-) CERN, LHC (2009-)

fixed target

collider mode and fixed target

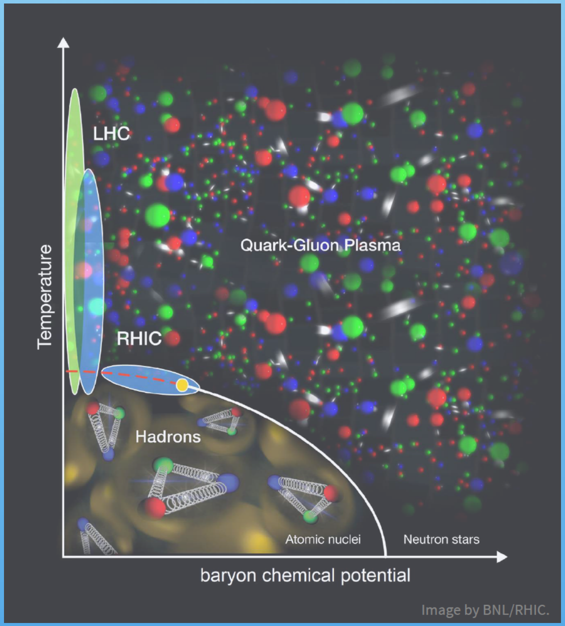
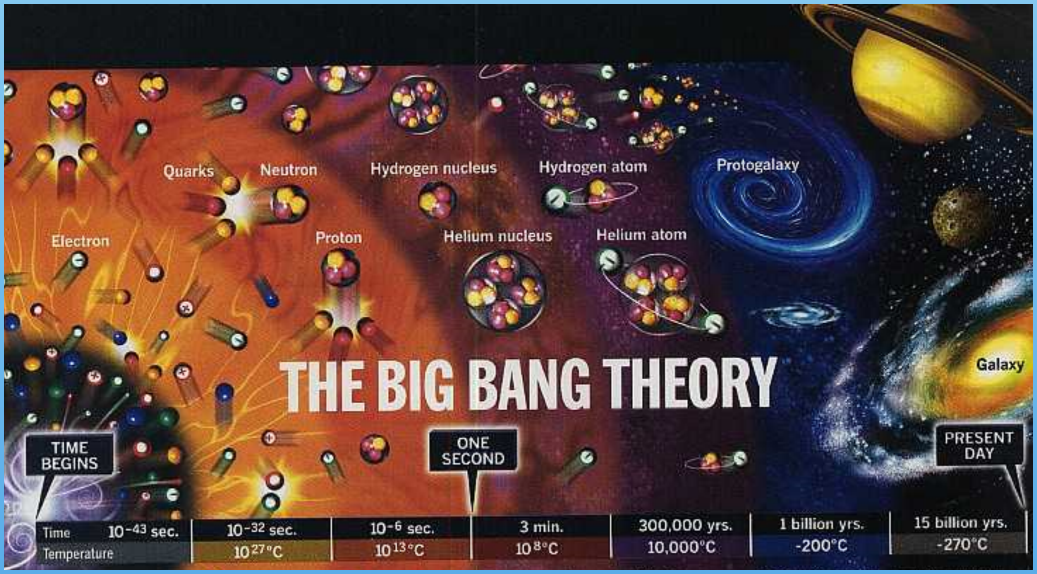
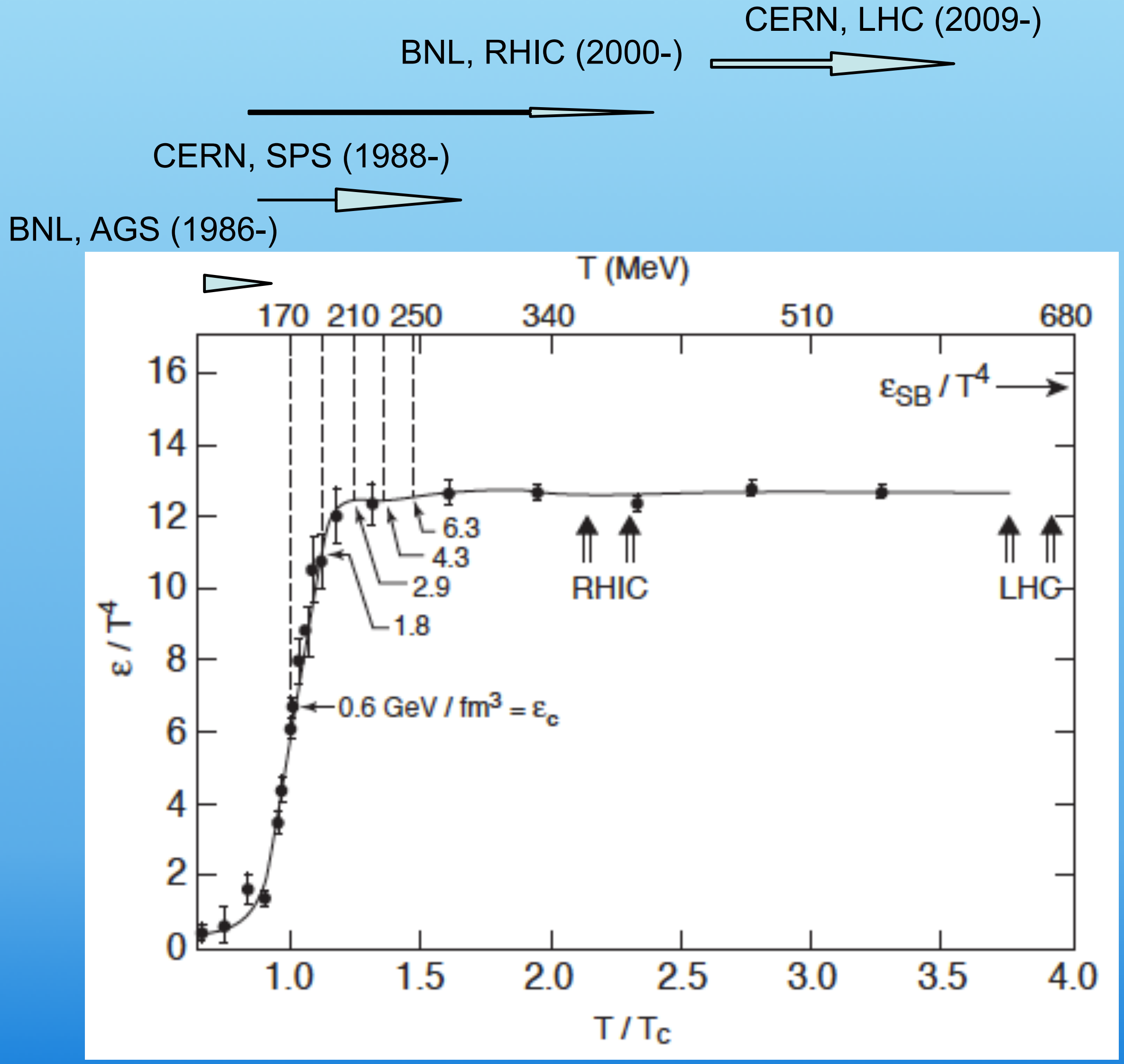


Image by BNL/RHIC.



The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang.
The QCD phase transition is the only phase transition of the early universe that can be reproduced in the Lab today.

Reach of accelerators in terms of initial Temperature



CERN, LHC (2009-)

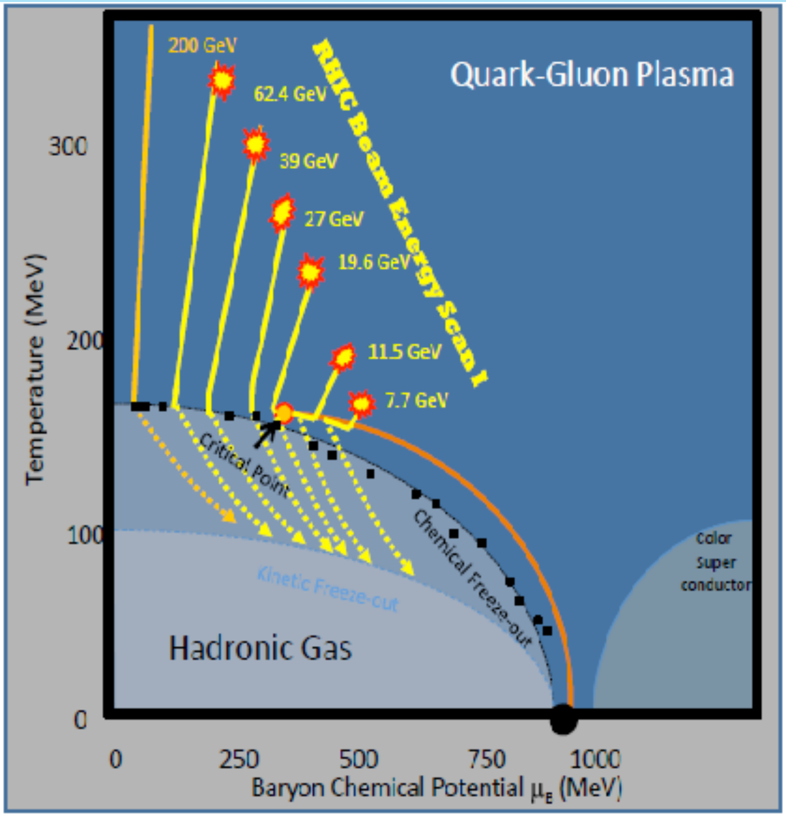
BNL, RHIC (2000-)

CERN, SPS (1988-)

BNL, AGS (1986-)

U. Heinz et al, 0009170.pdf

The QCD phase diagram



Phases of QCD Matter

Areas of different net baryon densities and temperatures can be probed using different collision energies and nuclei.

The order of the transition is expected to change with the net baryon density.

Goal: explore experimentally the QCD phase diagram with various particles and nuclei collisions and various collision energies (to study order of transition, critical point, properties of the QGP).

Signatures of the Quark Gluon Plasma

Direct photons from QGP → T(QGP)

Strangeness enhancement (Mueller, Rafelski 1981) → K/pi

U,d,s yields for T(freeze out) or pT slopes (Van Hove, H Stoecker et al) → plateau vs energy at Tc → e_init(crit), sqrt(s)(“crit”)

Multiquark states from QGP (Greiner et al) → ‘small QGP-lumps’

Critical fluctuations near the critical point, Tc → K/pi, <pT>, etc

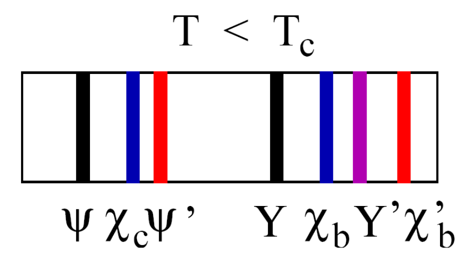
Hadronic mass/width changes (Pisarski 1982) → rho etc

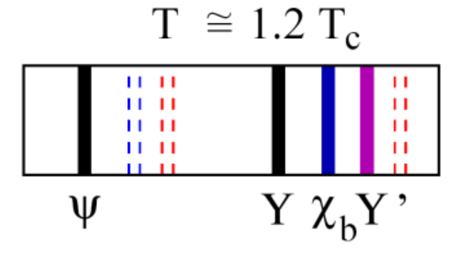
Charmonia suppression (Satz, Matsui 1987) → T(dissociation) of ccbar, bbbar

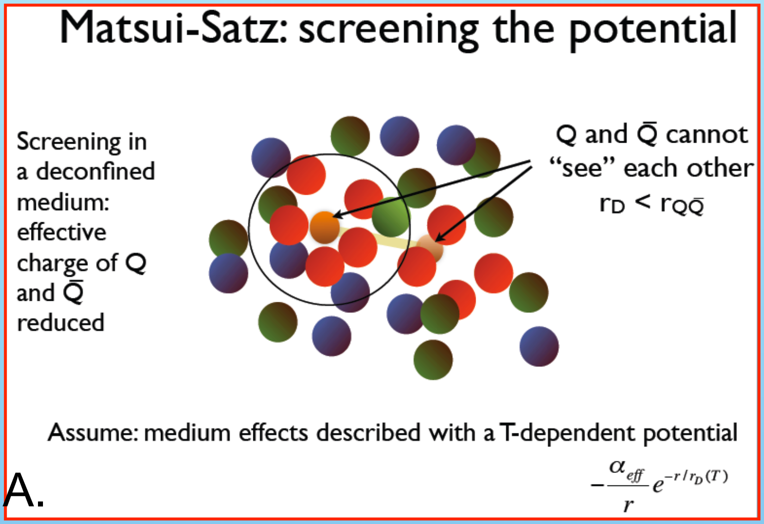
Jet quenching (J D Bjorken 1982) → medium density

--> Goal is to achieve a combination of many signatures

Quarkonia suppression as QGP signature






Matsui-Satz: screening the potential

Screening in a deconfined medium: effective charge of Q and $\bar{Q}$ reduced

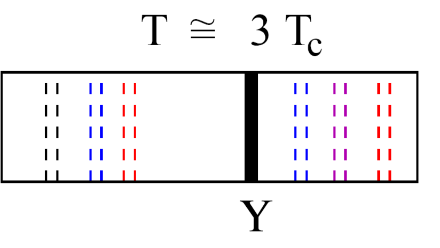
Q and $\bar{Q}$ cannot "see" each other

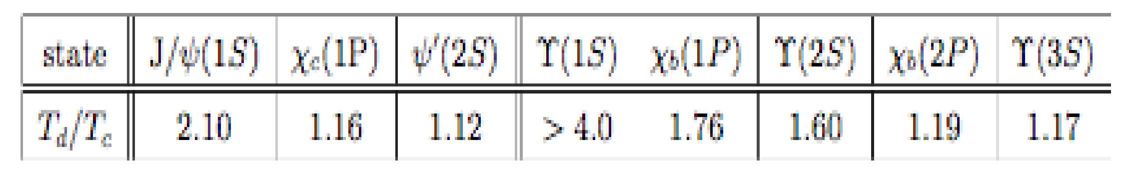
$r_D < r_{Q\bar{Q}}$

Assume: medium effects described with a T-dependent potential

$-\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$

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



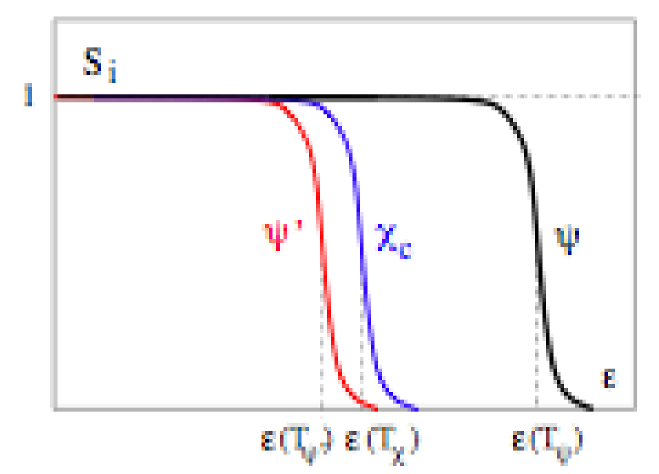


state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

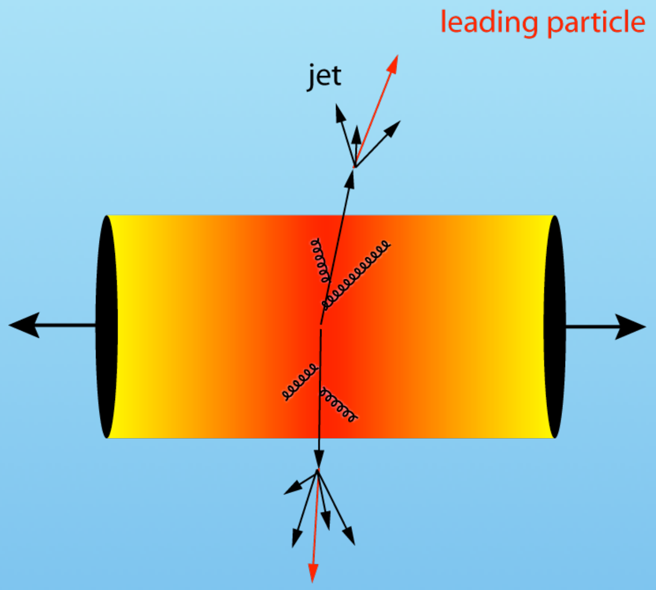
Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

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



Jet quenching

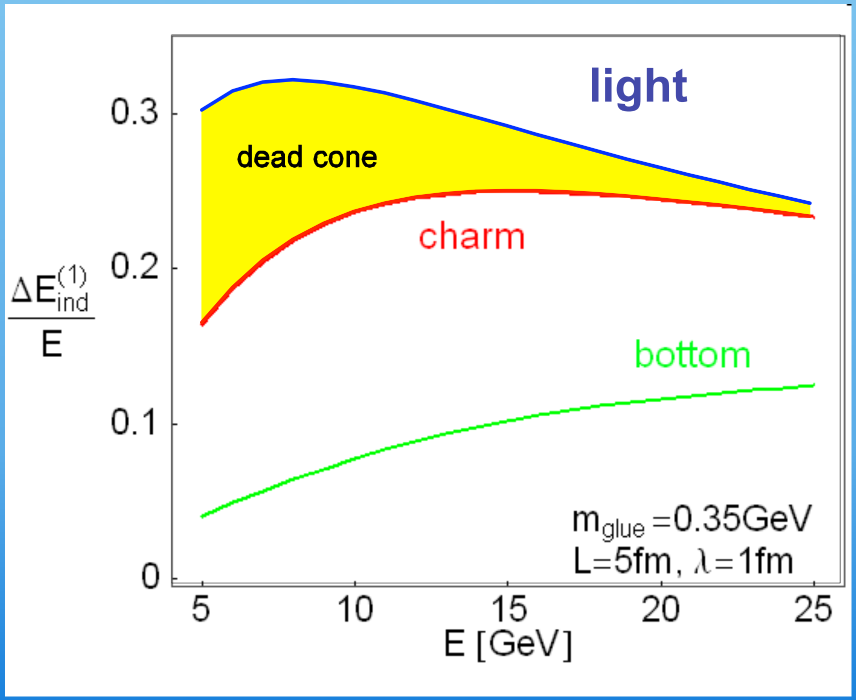


"The nuclear modification factor" R_{AA}

compares A+A to expectations from p+p :

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

N coll : Average number of NN collisions in AA collision

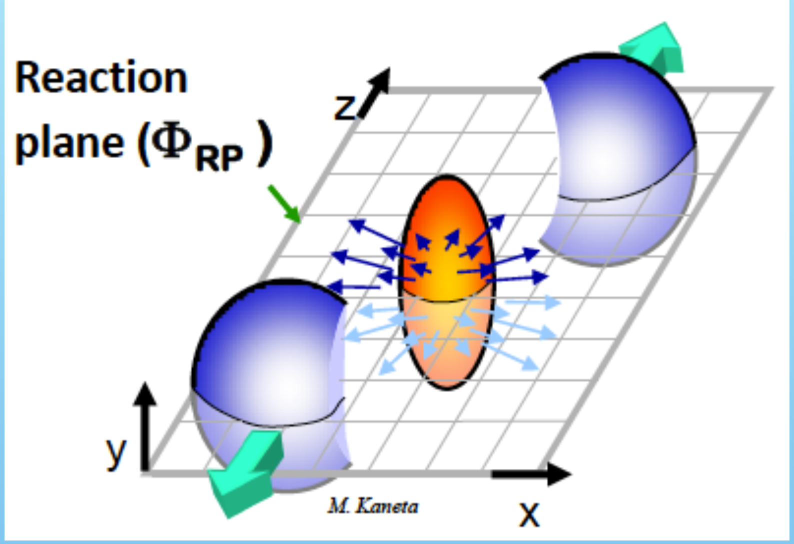


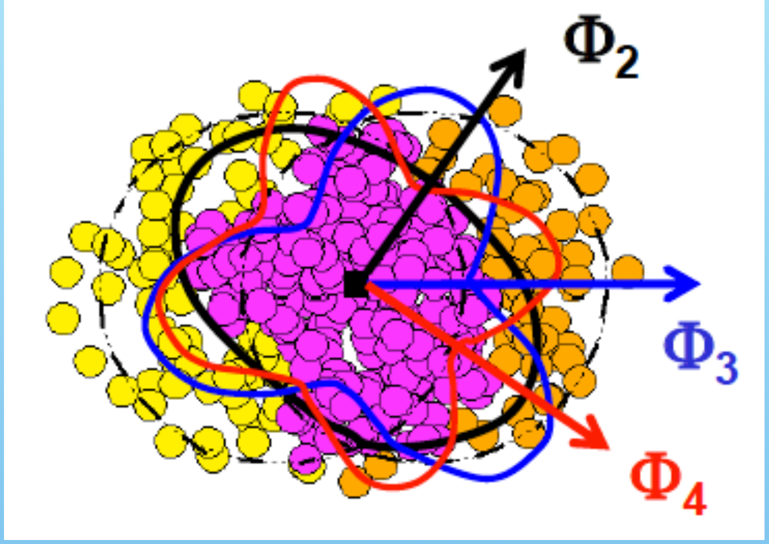
Suppression of jets in AuAu: $R_{AA} < 1$

Quarks are expected to exhibit different radiative energy loss depending on their mass (**D.Kharzeev et al. Phys Letter B. 519:1999**)

M.Djordjevic PRL 94 (2004)

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





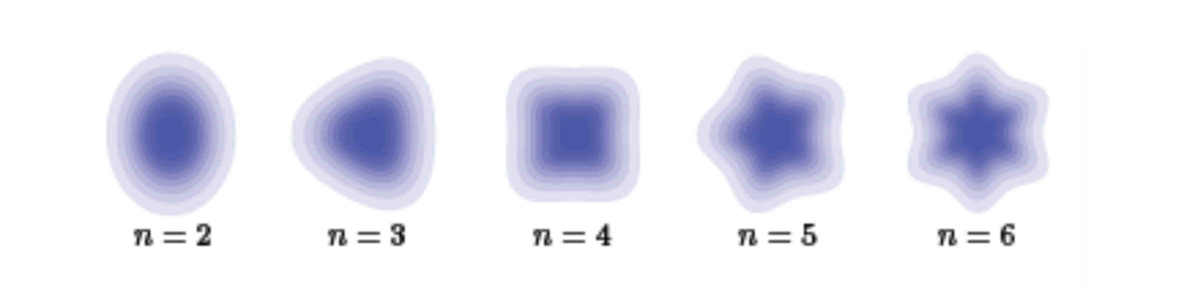
Matter in the overlapp area of two colliding nuclei gets compressed and heated

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, ...)



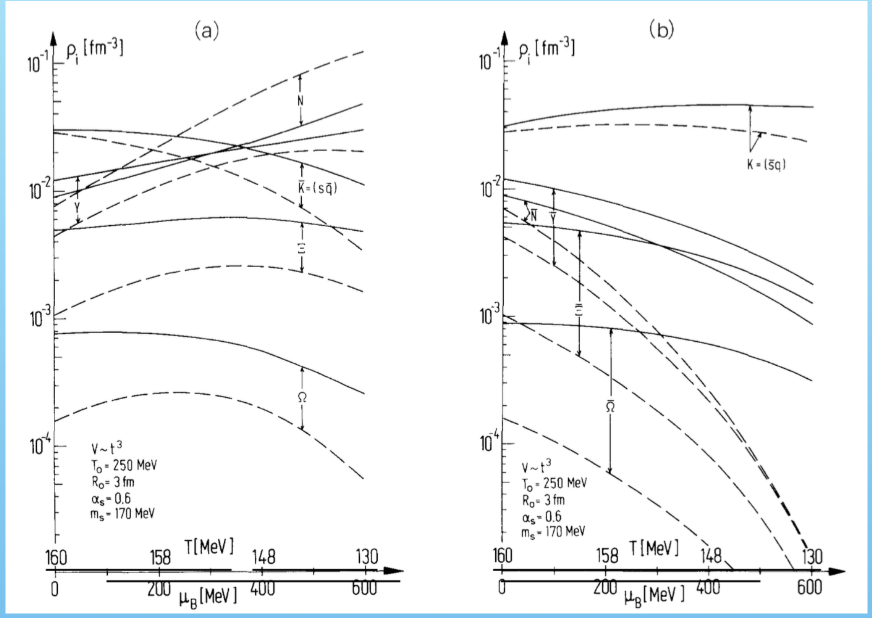
Higher harmonics

Strangeness Enhancement as QGP signature

Initial idea introduced by J Rafelski:

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

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



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.

The densities of strange particles are enhanced in the QGP and especially the densities of strange antibaryons are predicted to exceed substantially the hadronic equilibrium values.

Mueller and Rafelski found that ssbar production in QGP is dominated by gg to ssbar channel, leading to equlibration times comparable to the QGP lifetime

II Accelerator facilities and experiments

Some of the experiments

SPS, CERN
NA35, NA36, NA44, NA45/CERES, NA49, NA50,
NA52/NEWMASS, WA97/NA57, WA98.
NA61/SHINE

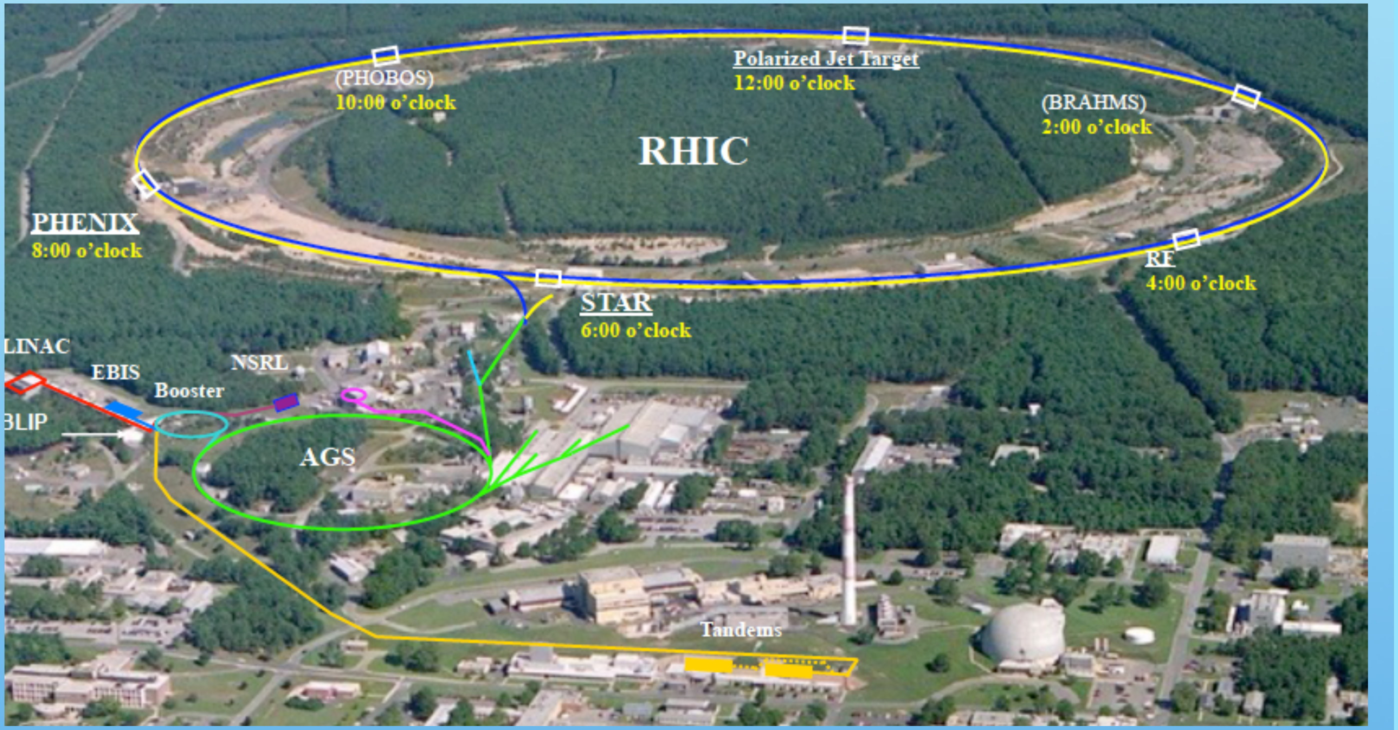
RHIC, BNL
BRAHMS, PHOBOS, STAR, PHENIX (data analysis), sPHENIX

LHC, CERN
ALICE,ATLAS,CMS,LHCb

FAIR, NICA

Relativistic Heavy Ion Collider

at the Brookhaven Lab, Long Island, New York, USA



RHIC has been exploring nuclear matter at extreme conditions over the last 15 years 2000-2015

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

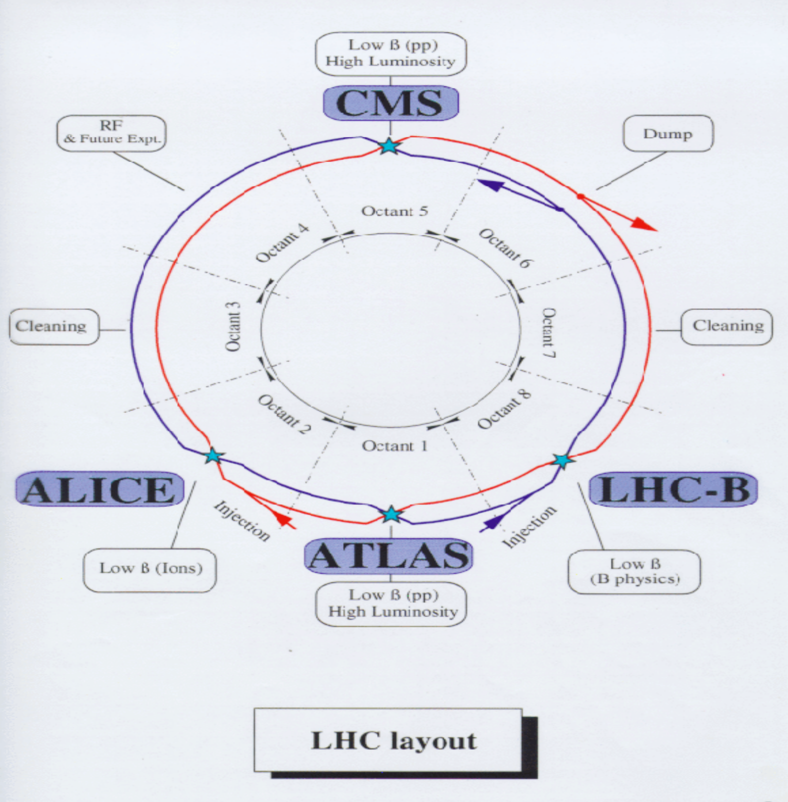
Still runing: STAR

Still analysing data:
PHENIX
New: sPHENIX

Colliding systems:
p+p, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U, Zr+Zr, Ru+Ru

Some of the energies A+A :
$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39 GeV
+ Fixed target

Large Hadron Collider (LHC) at CERN



run-1 (2009-13) : p+p $\sqrt{s_{NN}}$ =0.9, 2.76, 7, 8 TeV, p+Pb $\sqrt{s_{NN}}$ =5.02 TeV, Pb+Pb at $\sqrt{s_{NN}}$ =2.76 TeV

run-2 (2015-18) : p+p $\sqrt{s_{NN}}$ = 5.02, 13 TeV p+Pb 5.02, 8.16 TeV Pb+Pb at $\sqrt{s_{NN}}$ =5.02 TeV

+ other (Xe+Xe, fixed target (LHCb))

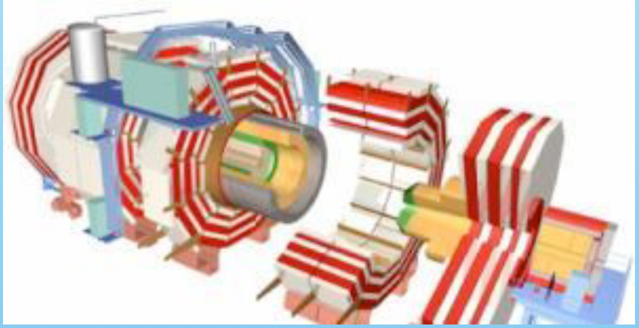
Current Experiments with Heavy Ion program

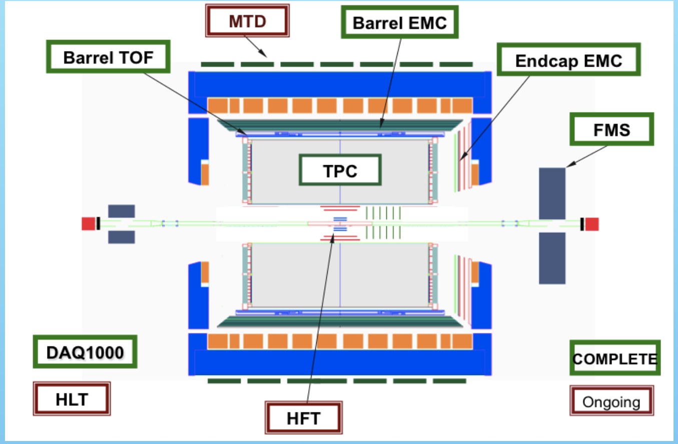
CMS

LHC

LHCb

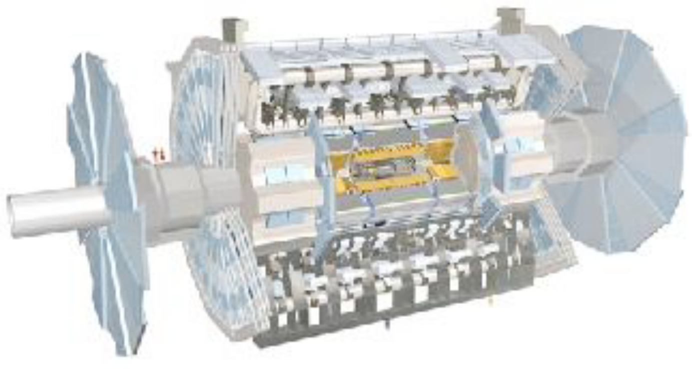
STAR at RHIC



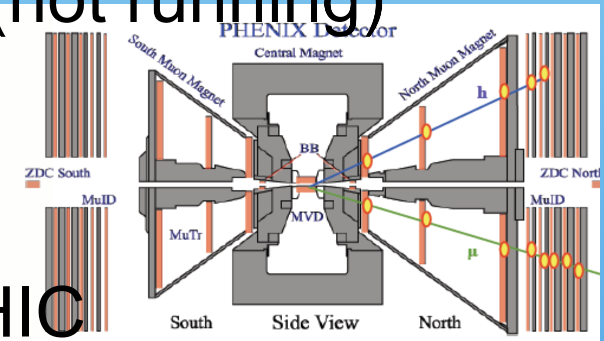


ATLAS

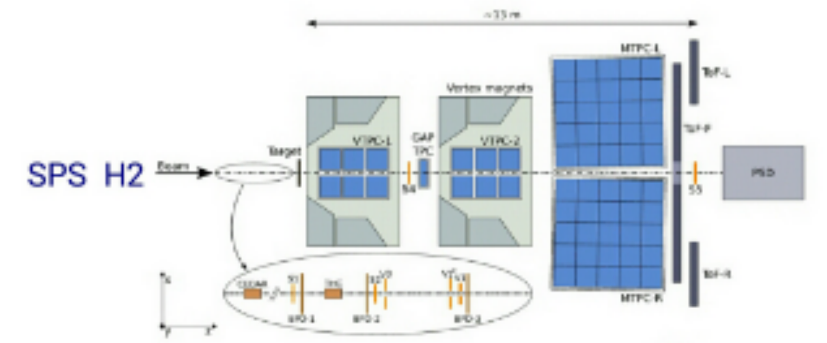
ALICE



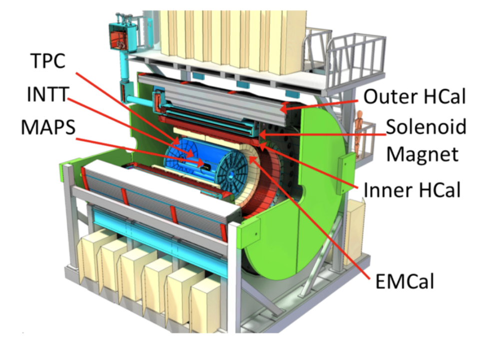

PHENIX at RHIC (not running)



NA61/SHINE at SPS



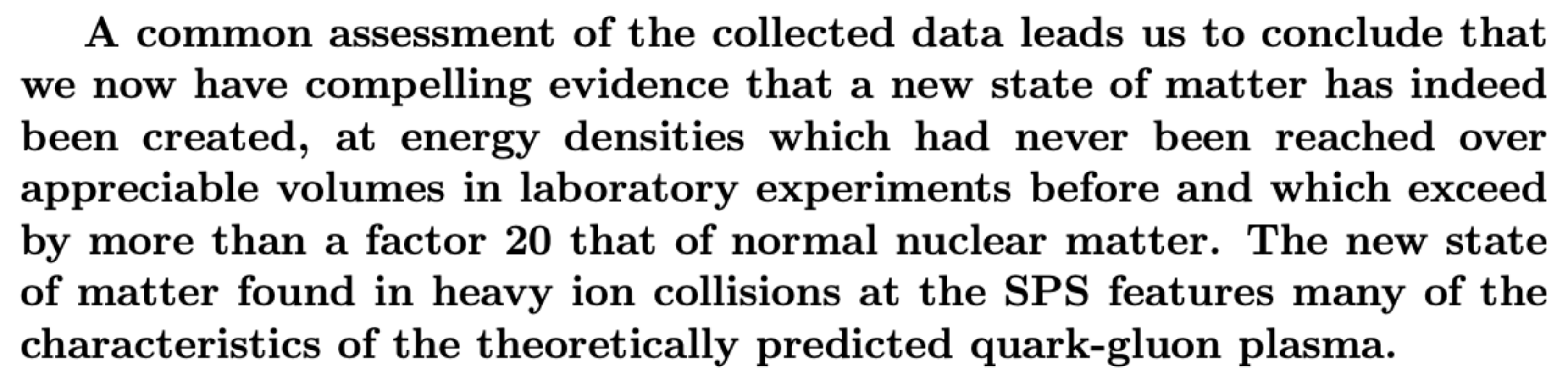
sPHENIX at RHIC

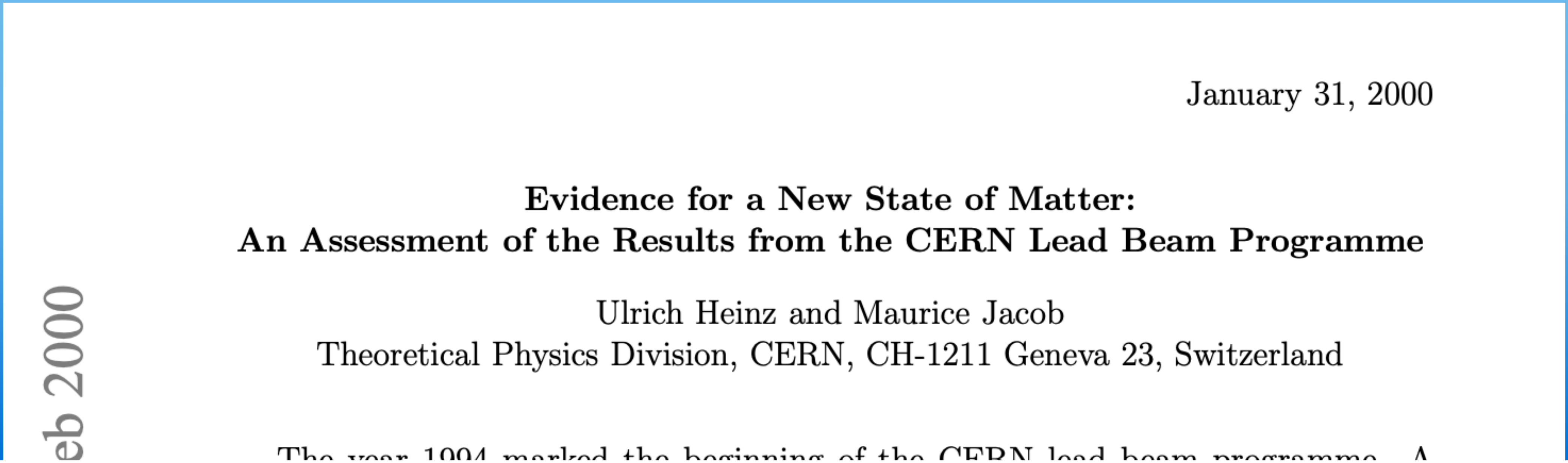


III Some historic milestones

Some historic milestones:

The discovery of a new state of matter (QGP) at CERN (2000)


A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.


eb 2000

January 31, 2000

Evidence for a New State of Matter:
An Assessment of the Results from the CERN Lead Beam Programme

Ulrich Heinz and Maurice Jacob
Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland

The year 1994 marked the beginning of the CERN lead beam programme. A

Some historic milestones:

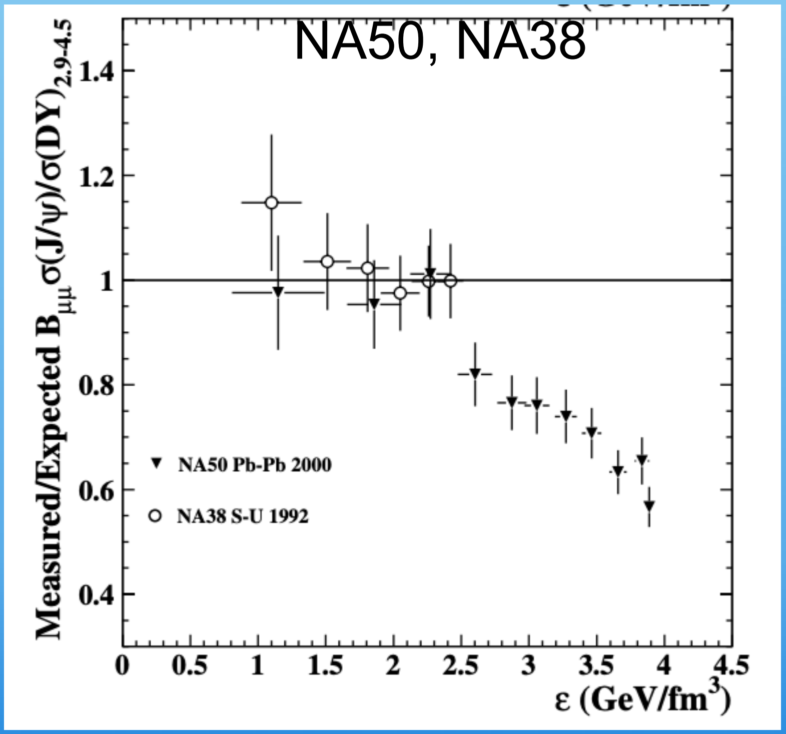
The discovery of a new state of matter (QGP) at CERN (2000)

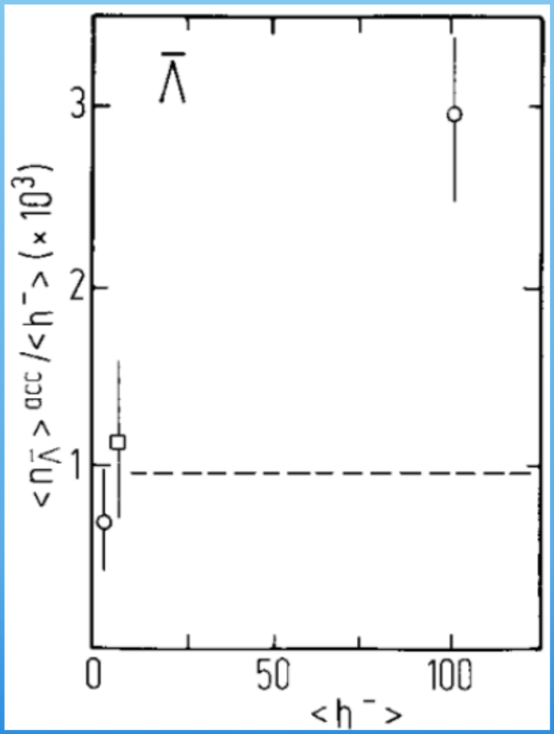
Discovery of suppression of J/Psi in central Pb+Pb at sqrt(s)=17 GeV
Discovery of strangeness enhancement (and of strange antibaryons) in fixed target S+A and Pb+Pb collisions at SPS.
and other.

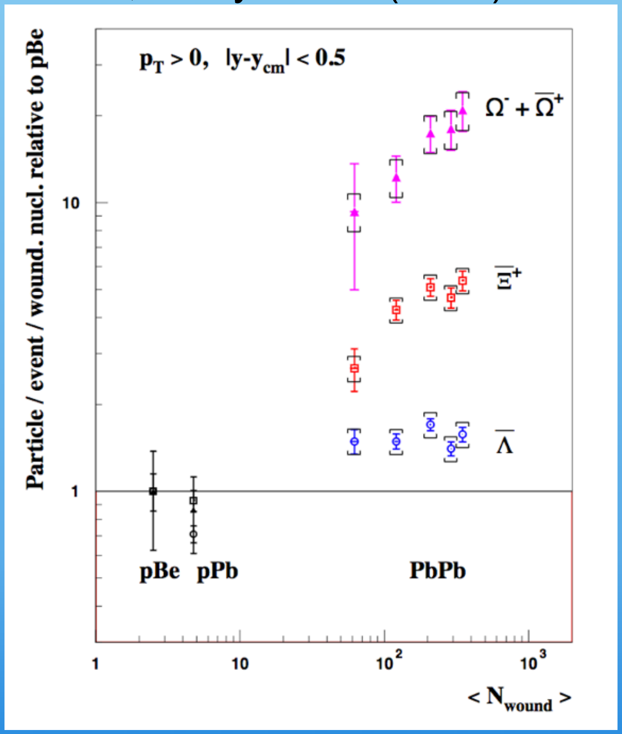
L. Kluberg, Eur. Phys. J. C (2005)

NA35, Zeitschrift für Physik C Particles and Fields, June 1990, Volume 48, Issue 2, pp 191–200

NA57, J.Phys. G32 (2006) 427-442


NA50, NA38

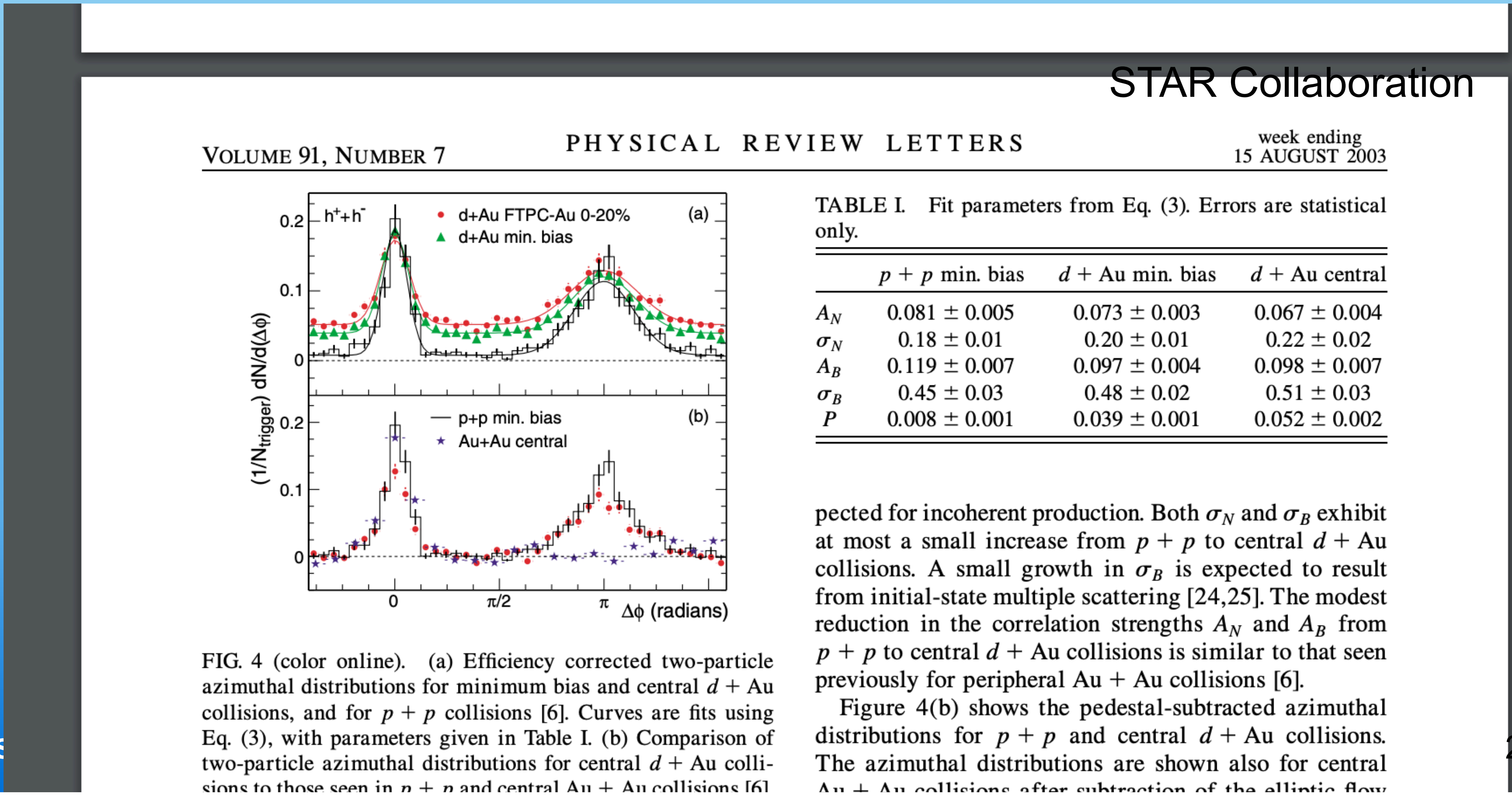




Some historic milestones:

The discovery of suppression of high pT hadrons in Au+Au collisions at sqrt(s)=200 GeV by experiments at RHIC (2003)

PHENIX Collaboration, “Suppression of hadrons with large transverse momentum in central Au+Au collisions at √ s NN = 130 GeV”, Phys. Rev. Lett. 88 (2002) 022301, doi:10.1103/PhysRevLett.88.022301, arXiv:nucl-ex/0109003.
STAR Collaboration, “Centrality dependence of high pT hadron suppression in Au+Au collisions at √ s NN = 130 GeV”, Phys. Rev. Lett. 89 (2002) 202301, doi:10.1103/PhysRevLett.89.202301, arXiv:nucl-ex/0206011.



STAR Collaboration

VOLUME 91, NUMBER 7 — PHYSICAL REVIEW LETTERS — week ending 15 AUGUST 2003

FIG. 4 (color online). (a) Efficiency corrected two-particle azimuthal distributions for minimum bias and central d + Au collisions, and for $p+p$ collisions [6]. Curves are fits using Eq. (3), with parameters given in Table I. (b) Comparison of two-particle azimuthal distributions for central d + Au collisions to those seen in $p+p$ and central Au + Au collisions [6].

TABLE I. Fit parameters from Eq. (3). Errors are statistical only.

	$p+p$ min. bias	d + Au min. bias	d + Au central
A_N	0.081 ± 0.005	0.073 ± 0.003	0.067 ± 0.004
σ_N	0.18 ± 0.01	0.20 ± 0.01	0.22 ± 0.02
A_B	0.119 ± 0.007	0.097 ± 0.004	0.098 ± 0.007
σ_B	0.45 ± 0.03	0.48 ± 0.02	0.51 ± 0.03
P	0.008 ± 0.001	0.039 ± 0.001	0.052 ± 0.002

pected for incoherent production. Both σ_N and σ_B exhibit at most a small increase from $p+p$ to central d + Au collisions. A small growth in σ_B is expected to result from initial-state multiple scattering [24,25]. The modest reduction in the correlation strengths A_N and A_B from $p+p$ to central d + Au collisions is similar to that seen previously for peripheral Au + Au collisions [6].

Figure 4(b) shows the pedestal-subtracted azimuthal distributions for $p+p$ and central d + Au collisions. The azimuthal distributions are shown also for central Au + Au collisions after subtraction of the elliptic flow

Some historic milestones:

The discovery of the strongly interacting QGP at RHIC (RHIC white papers 2005)

Expected a weakly interacting QGP, found a strongly coupled liquid QGP:

QGP behaves almost like a perfect liquid (has extremely low shear viscosity, extracted based on measurements of flow coefficients vs pT, compared to hydrodynamic models).

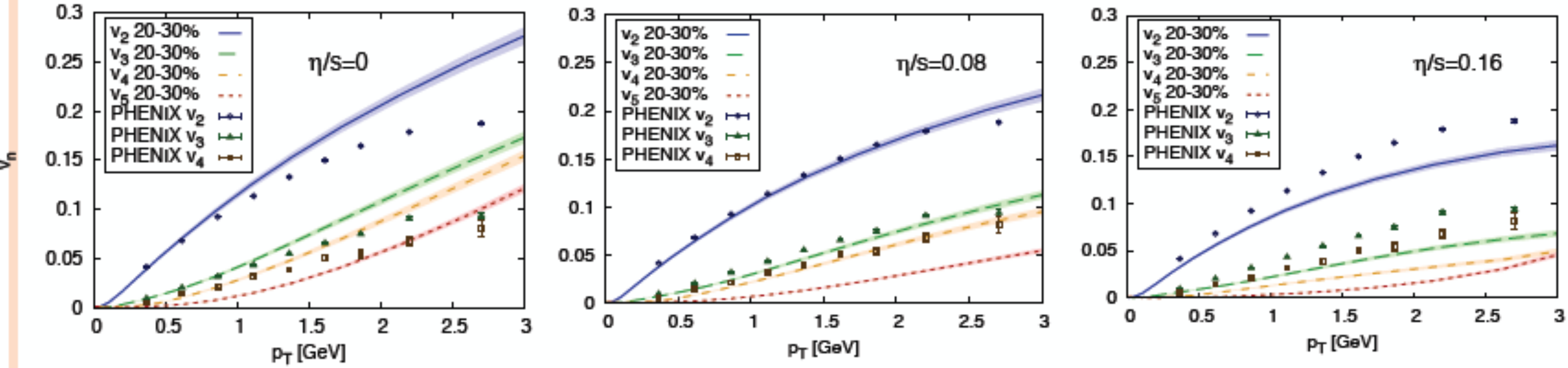
Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment,
Nucl.Phys. **A757** (2005) 1-27, nucl-ex/0410020

Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration,
Nucl.Phys. **A757** (2005) 184-283, nucl-ex/0410003

The PHOBOS perspective on discoveries at RHIC,
Nucl.Phys. **A757** (2005) 28-101, nucl-ex/0410022

Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions,
Nucl.Phys. **A757** (2005) 102-183, nucl-ex/0501009

Schenke, Jeon, and Gale, PRC (2012)



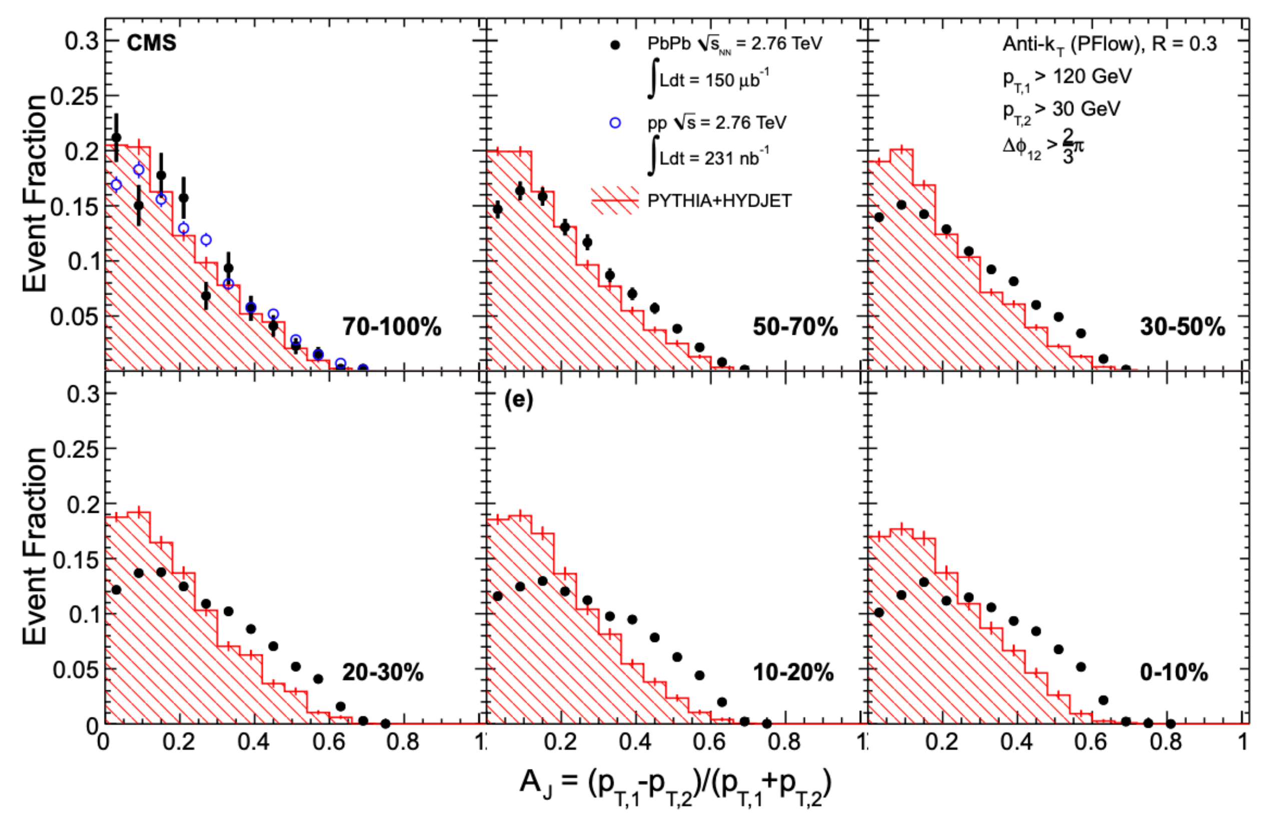
Some historic milestones:

Discovery of jet quenching at LHC

Dijet Assymetry AJ

$$A_{\mathrm{J}} = \frac{p_{\mathrm{T},1} - p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}},$$

leading jet pT>120 GeV,
subleading jet pT>30 GeV



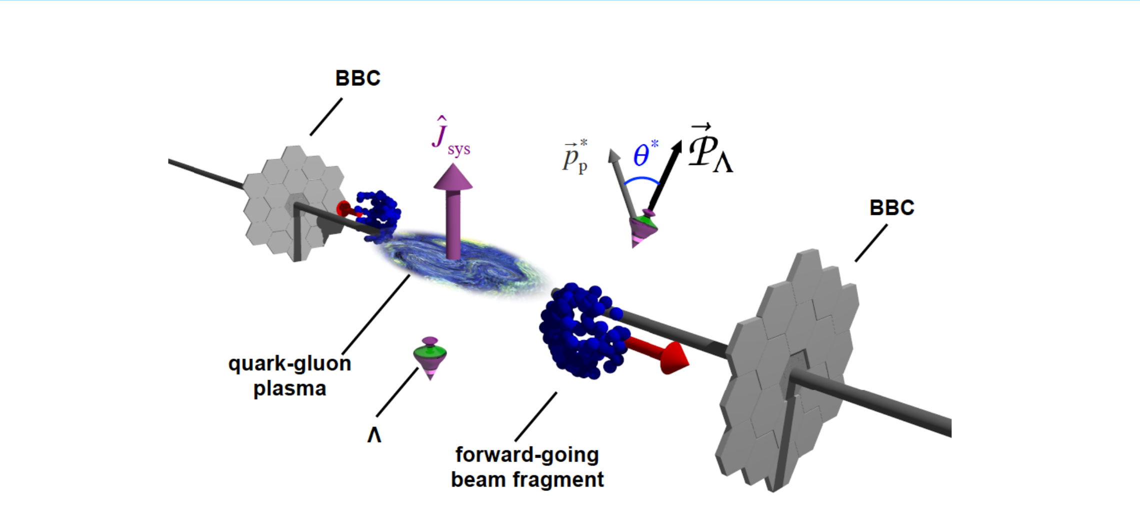
Dijet assymetry AJ in central PbPb collisions increases beyond the expected changes from energy resolution effects modeled in PYTHIA+HYDJET.

The leading jet has lost less energy to parton-medium interactions than the subleading jet.

Some historic milestones:

First Vorticity measurement in AuAu 200 GeV 20-50% centrality

STAR, Nature, 2017, 1701.06657



Average vorticity points towards the direction of the angular momentum J(sys) of the collision.

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1+\alpha_{\mathrm{H}}|\vec{\mathcal{P}}_{\mathrm{H}}|\cos\theta^*\right).$$

H: Lambda/Anti-Lambda

P_{H} : Lambda/AntiL polarizatin vector in the hyperon rest frame

decay parameter $\alpha_\Lambda = -\alpha_{\overline{\Lambda}} = 0.642 \pm 0.013$

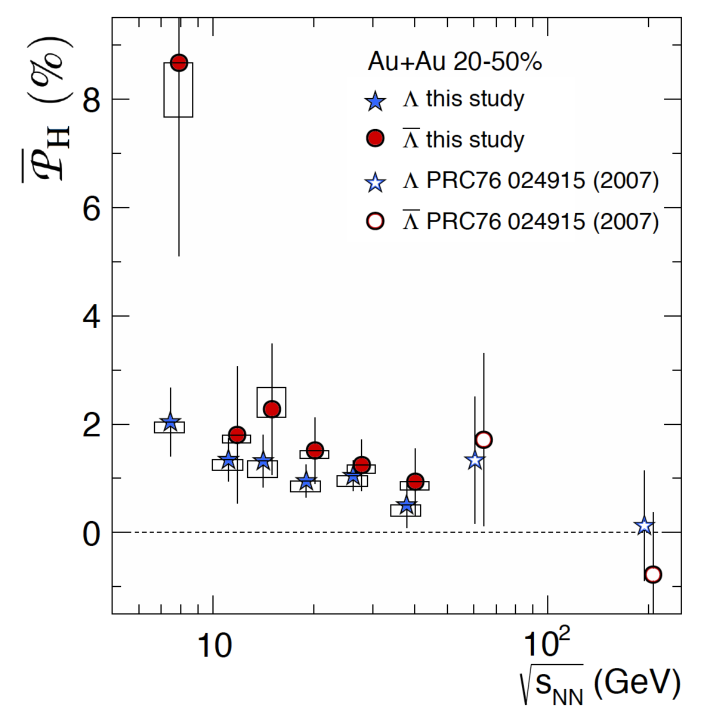
Average projection of the Polarization on J(sys) is extracted:

noted here as "global polarization"

$$\overline{\mathcal{P}}_{\mathrm{H}} \equiv \langle \vec{\mathcal{P}}_{\mathrm{H}} \cdot \hat{J}_{\mathrm{sys}} \rangle = \frac{8}{\pi\alpha_{\mathrm{H}}} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{\mathrm{sys}}}\right)\right\rangle}{R_{\mathrm{EP}}^{(1)}},$$

Some historic milestones:

sQGP vorticity



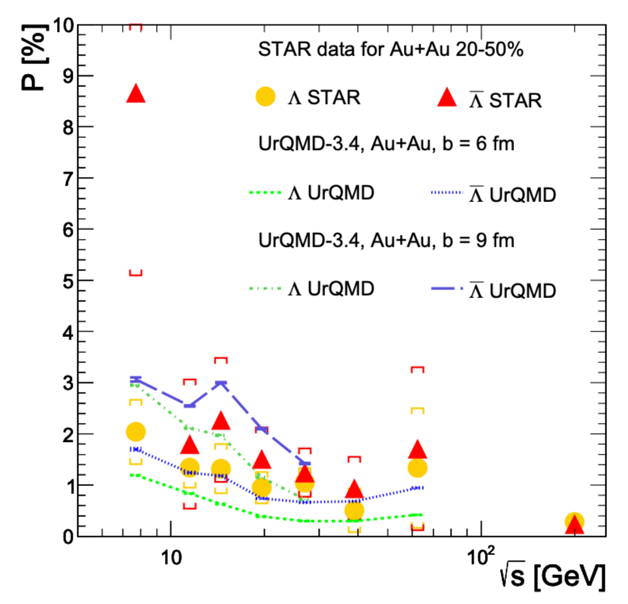
STAR, Nature, 2017, 1701.06657

Measurement of vorticity in Au+Au collisions with 20-50% centrality via the average polarization of Lambda and Antilambda.
Fluid vorticity can be calculated using the hydrodynamic relation (Becatini et al 1610.02506.)

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\bar{\Lambda}'}\right)/\hbar,$$

P_H: average polarization with
H: Lambda or Antilambda

With T the temperature. The vorticity found is
omega = (9+-1) 10ˆ21 s-1
with an additional systematic error of a factor of 2 which by far surpasses the vorticity of all known fluids
For example solar subsurface flow has omega= 10-7 s-1, and superfluid nanodroplets omega=10ˆ7 s-1



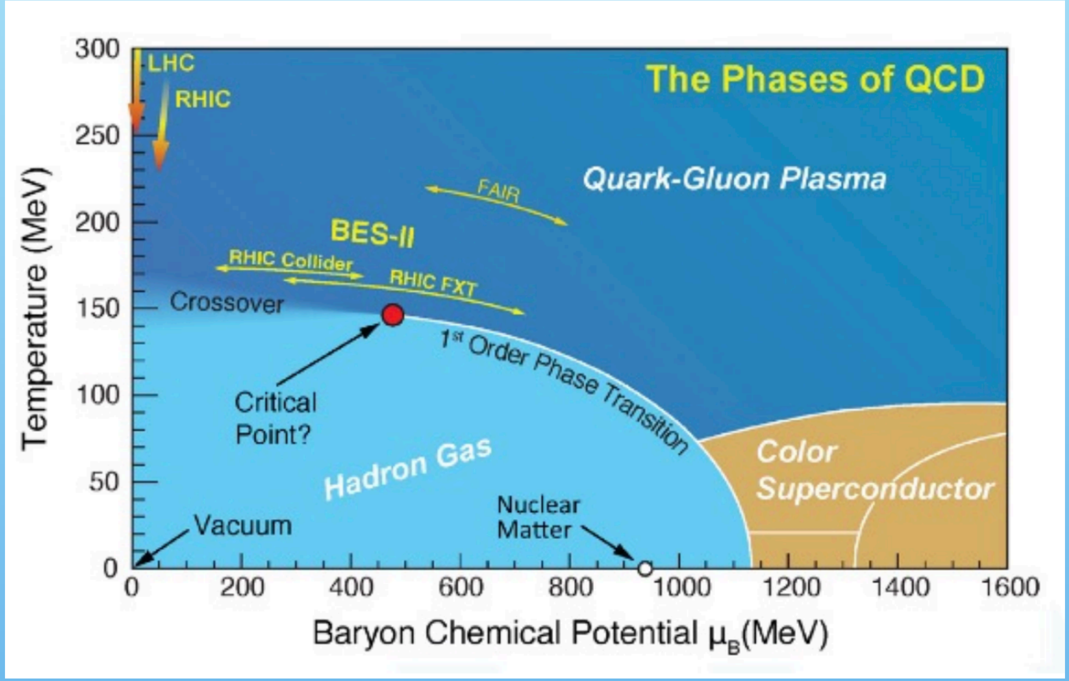
O.Vitiuk, L.Bravina, E.Zabrodin, PLB803 (2020) 135298

Difference between Lambda and Antilambda can be understood with the URQMD model eg as due to different freeze-out with respect to the thermsl vorticity field

Some historic milestones:

Beam energy scans

STAR Beam Energy Scan I and II, NA61/SHINE

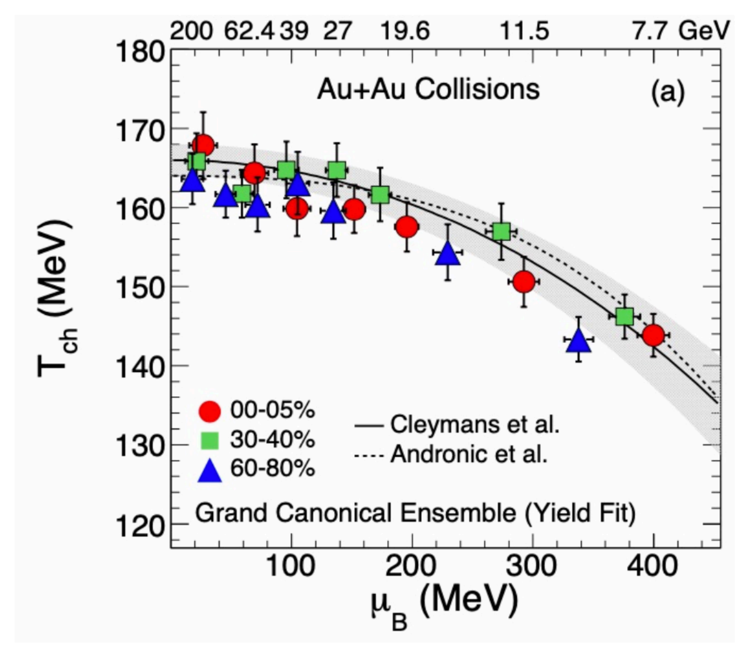


STAR BES-I (2010-2011):
7.7, 11.5, 19.6, 27, 39, 62,4, 200 GeV

STAR BES-II (2019-2021):
7.7, **9.2**, 11.5, **14.6**, **17.3**, 19.6 GeV
and fixed target (Ebeam 3.85 to 100 GeV)

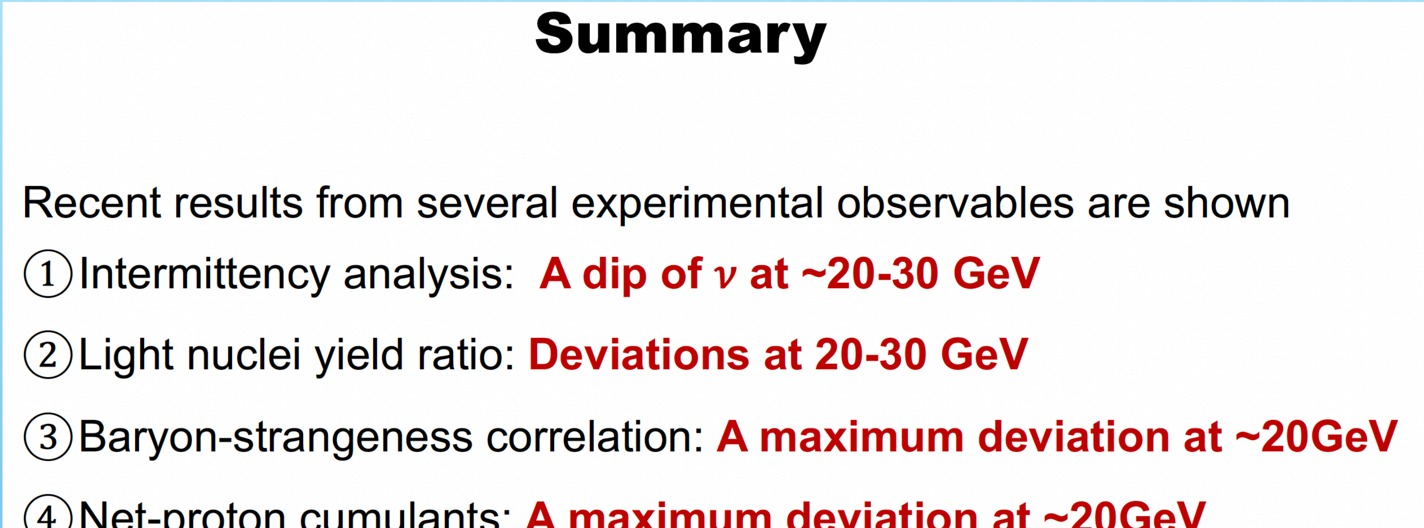
NA61/SHINE: fixed target eg 13A,19A,30A
40A, 75 A GeV.

Goals of Beam energy scans:
Search for the critical point
Search for the first-order phase transition
Search for the onset of QGP formation



PRC96 (2017) 44904

Search for critical point



Summary

Recent results from several experimental observables are shown

①Intermittency analysis: **A dip of ν at ~20-30 GeV**

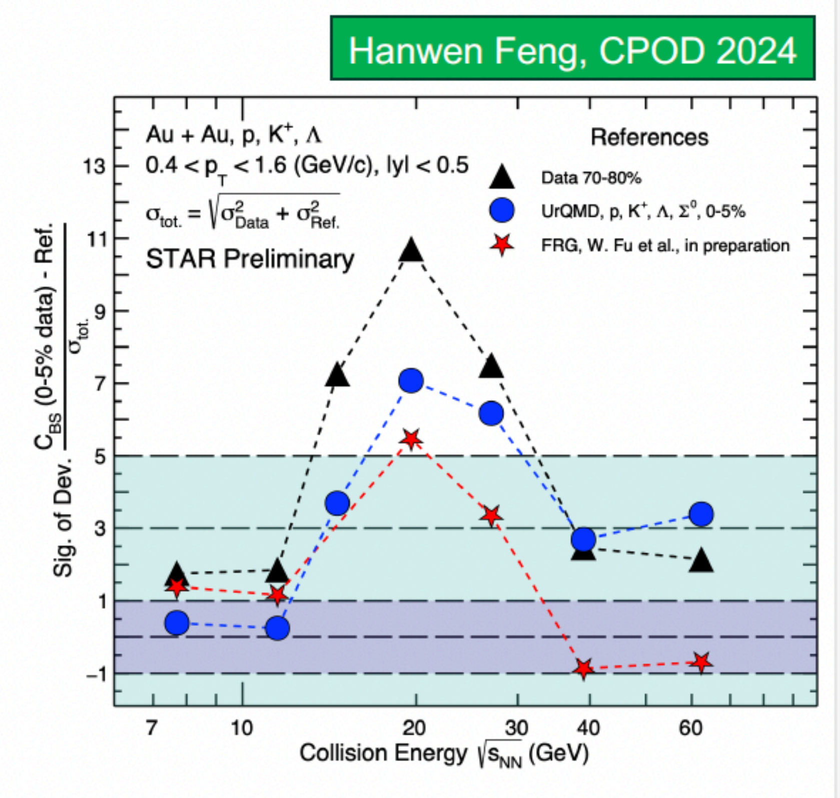
②Light nuclei yield ratio: **Deviations at 20-30 GeV**

③Baryon-strangeness correlation: **A maximum deviation at ~20GeV**

④Net-proton cumulants: **A maximum deviation at ~20GeV**

Zhang, SQM 2024, Strasbourg, France

Hanwen Feng, CPOD 2024

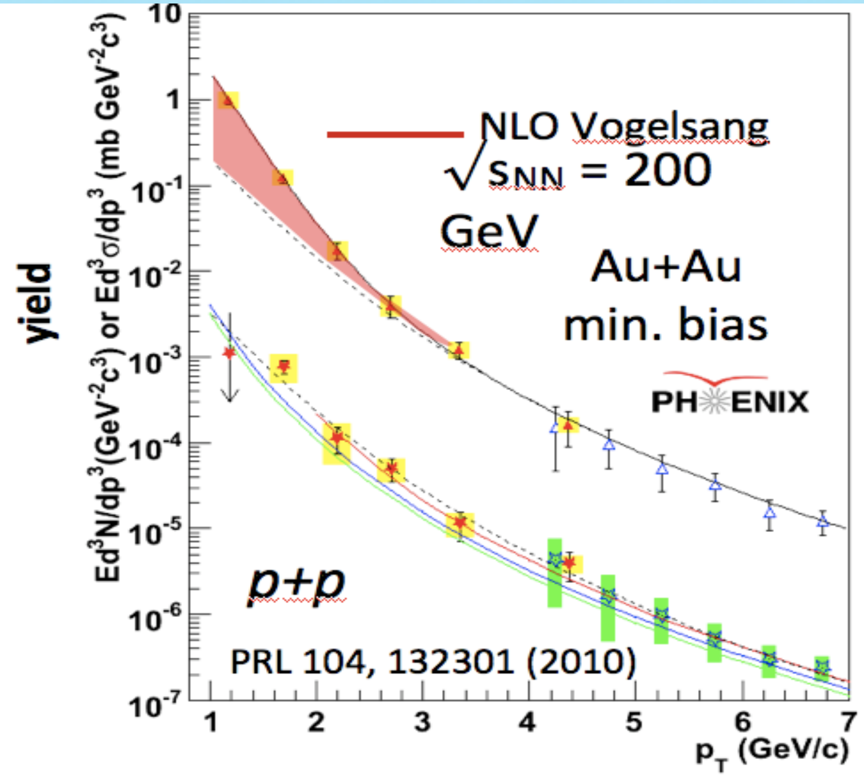


One example: Baryon-Strangeness correlation is not monotonic around 20 GeV

IV Selected physics results:

1. Direct photons

RHIC PHENIX: Direct photon excess in min bias Au+Au at



Confirmed also with other measurement method : PHENIX 1405.3940, published in PRC 91 (2015) 064904

Direct photons in p+p described by NLO

Direct photon excess in min. bias Au+Au at 200 GeV over p+p at 200 GeV below pT ~2.5 GeV

Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope 220 ± 20 MeV --> T(init) from hydrodynamic models : 300-600 MeV, depending on thermalization time

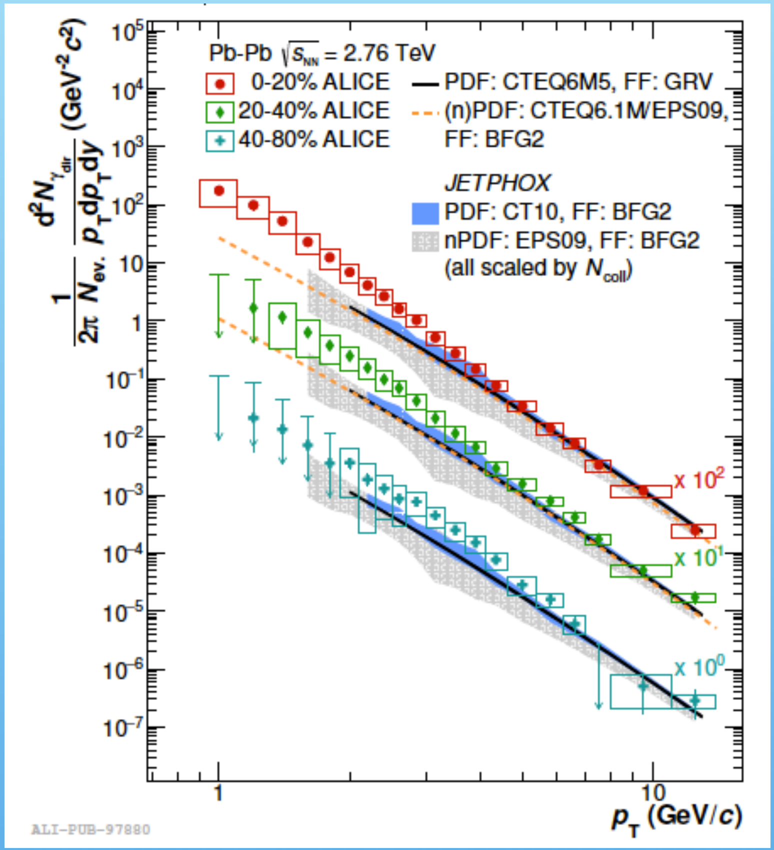
Critical d+Au check : No exponential excess in d+Au

Direct thermal photons were firmly established for the first time at RHIC

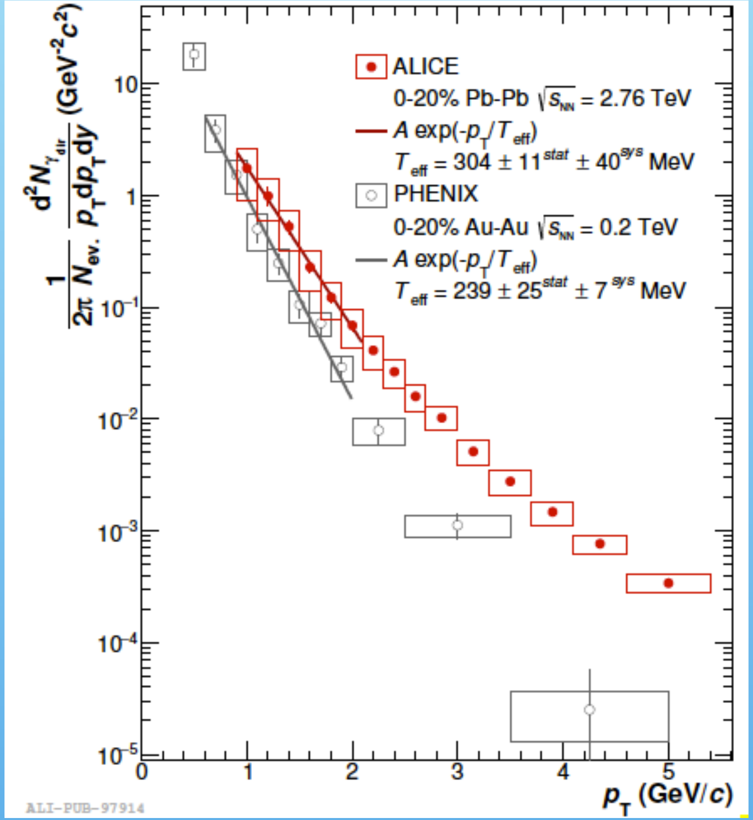
ALICE direct photons

ALICE Phys. Lett. B 754 (2016) 235-248
1509.07324

ALICE: different centralities



ALICE vs PHENIX



- 2.6σ excess in low p_T in 0–20% central
- T_{eff} = 304±11±40 MeV (30% larger than at RHIC)

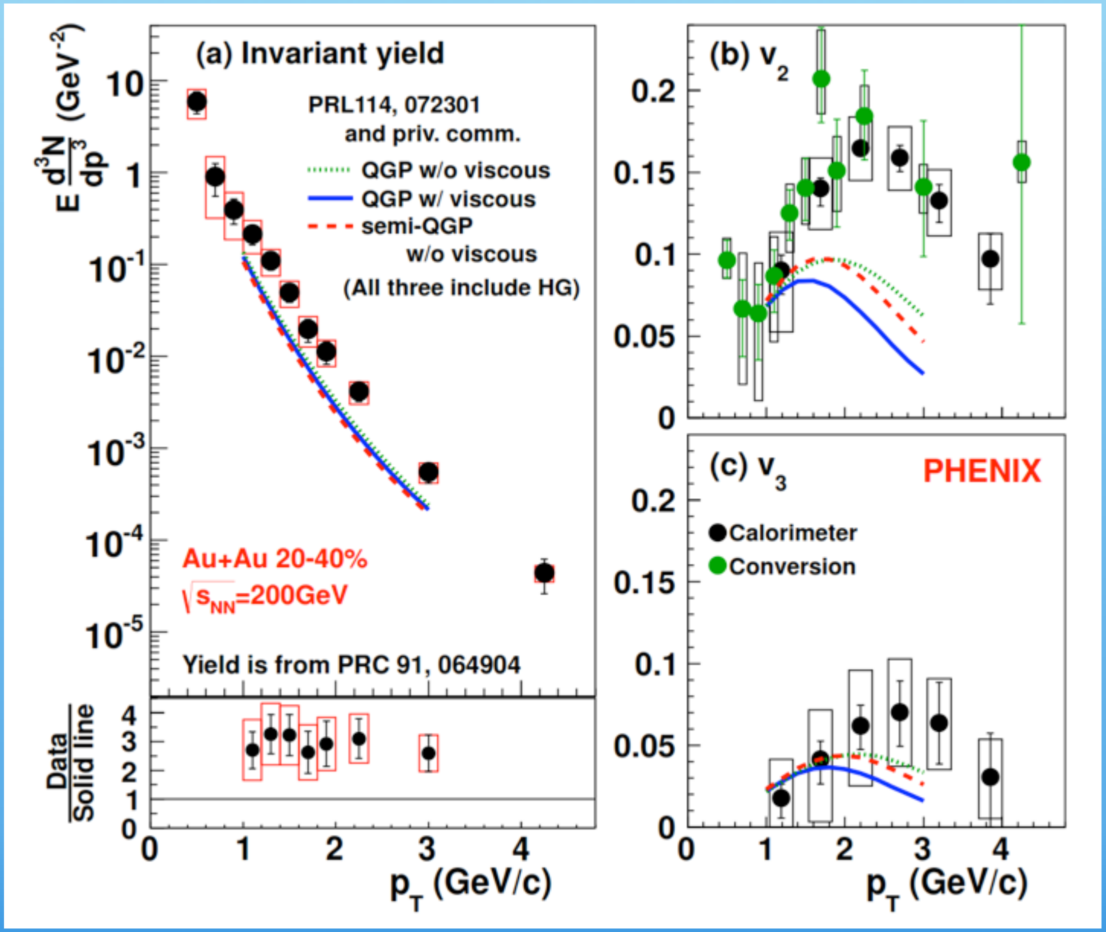
T(dir. phot.) at RHIC and LHC is > than critical Tcrit~154 MeV
The real initial T of the source is higher than the measured T

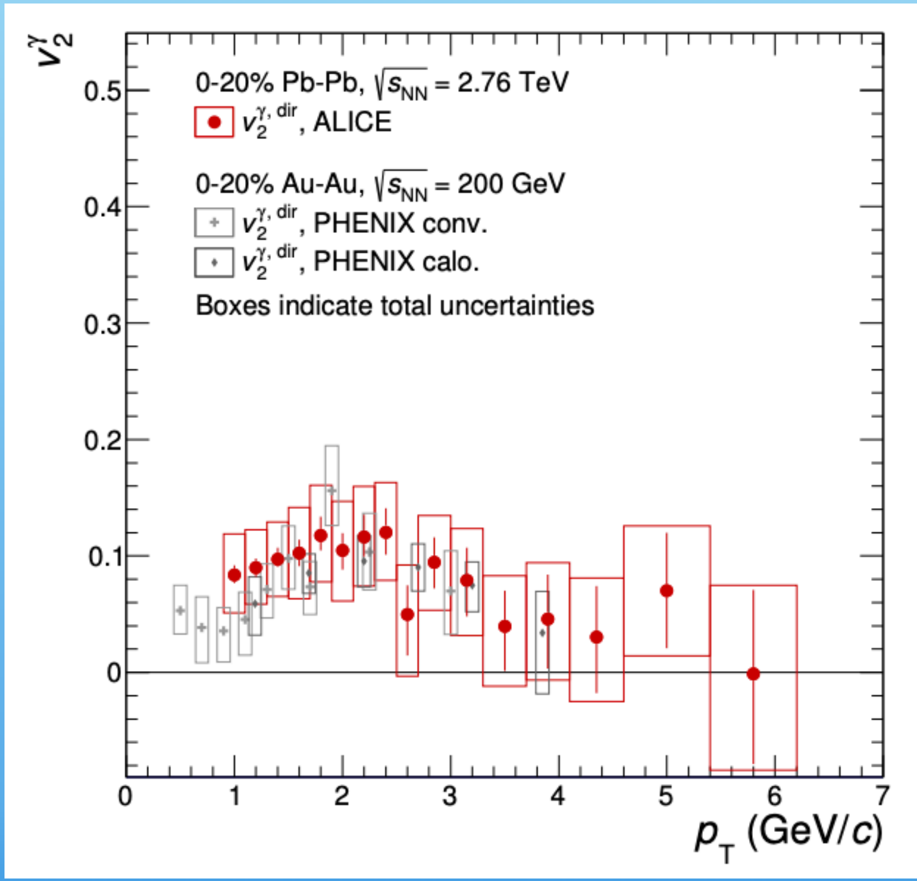
Direct photons also flow

Example: viscous hydro + thermal emission

PHENIX: Phys. Rev. C 91 064904 (2015) and 1405.3940

ALICE Coll., 1805.04403





Thermal direct photons with large flow v2, v3: challenge for models

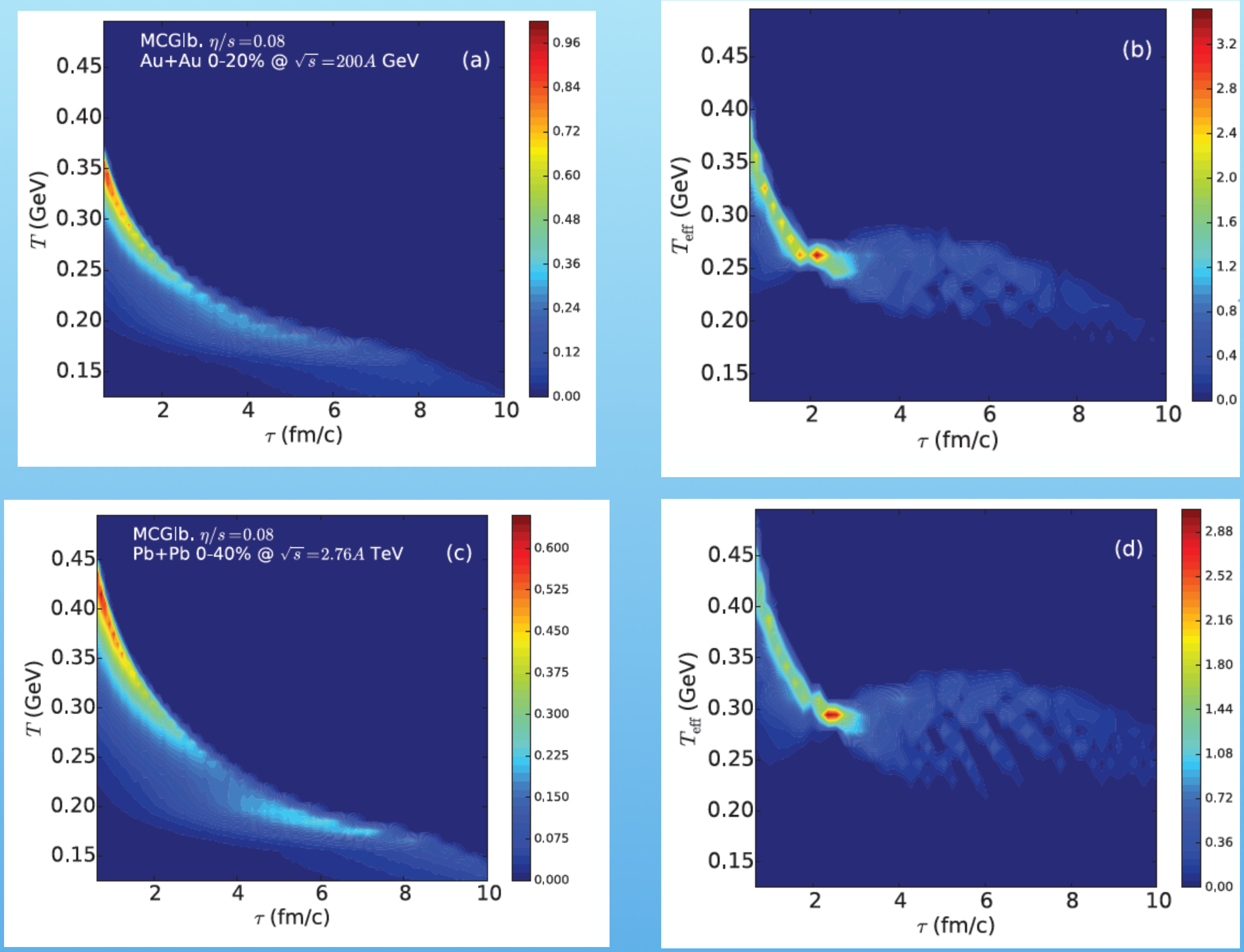
v2 of direct photons in 0-20% Pb+Pb is similar to data from PHENIX 0-20% Au+Au

Time evolution of direct photon production

C. Gale et al, 1308.2440

RHIC

LHC



The 3rd dimension in these plots is cross section of photons

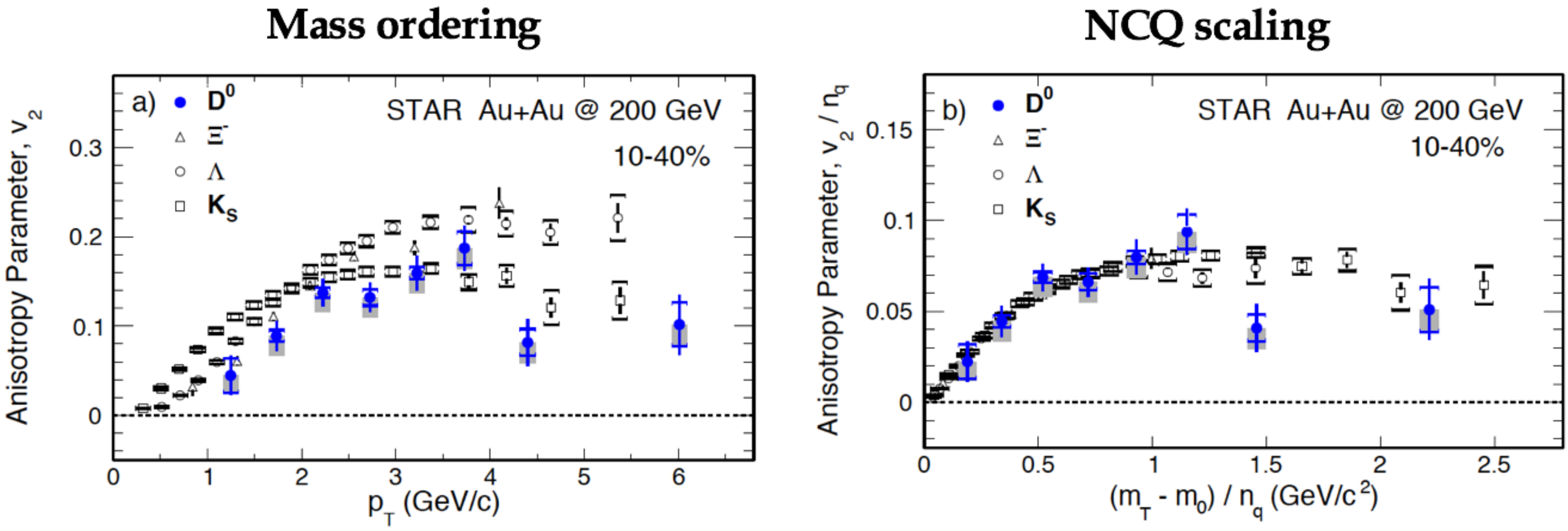
*** Most direct photons at RHIC and LHC are emitted from time near Tc**

3. Collectivity, Flow, Strangeness

Strangeness and charm v2

STAR D0 v2 from STAR Heavy Flavor Tracker

1701.06060, STAR



Mass ordering

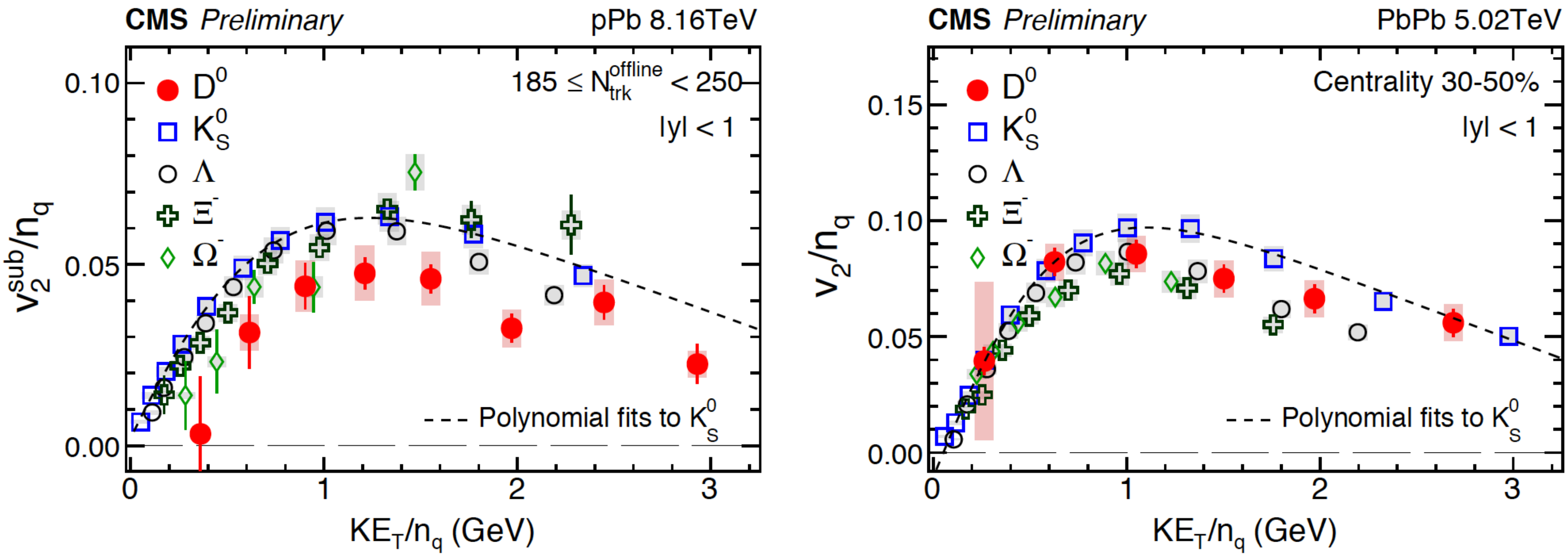
NCQ scaling

v2 of D0 in Au+Au follows Number-of-Constituent-Quarks scaling of other hadrons

-> Evidence for thermalization of u,d,s,c mesons

CMS D0 and strange particles in pPb, PbPb

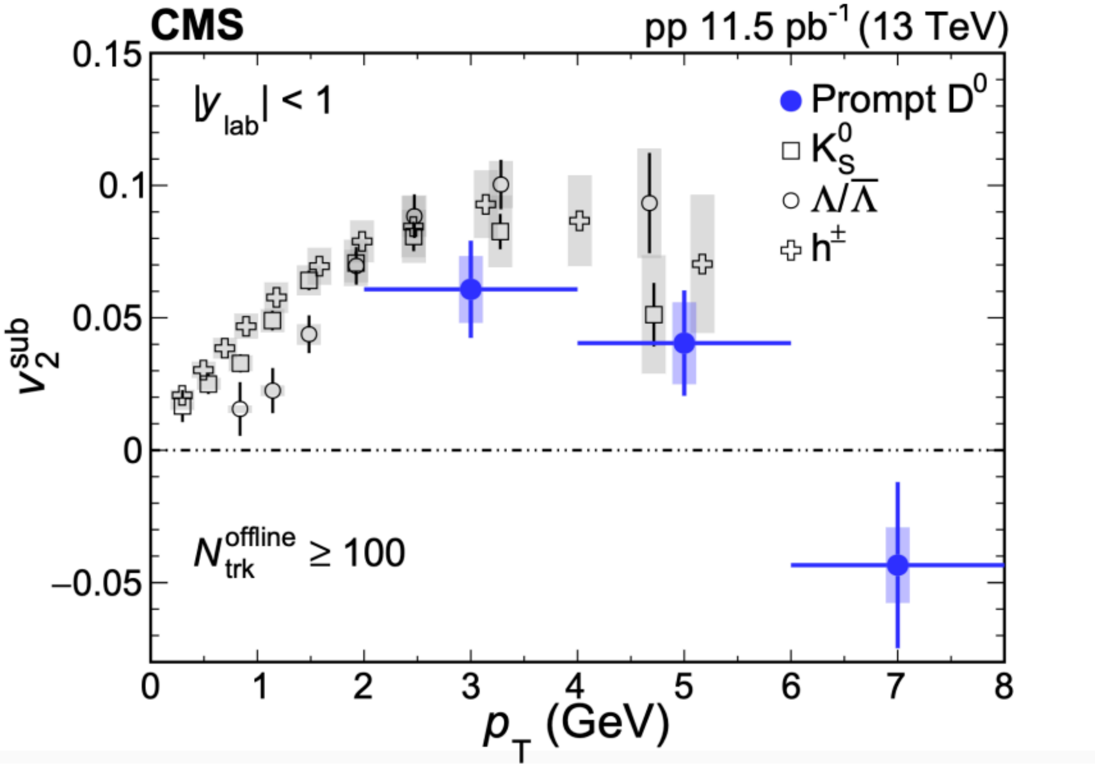
pPb 8.16 TeV PbPb 5.02 TeV CMS 1705.01974

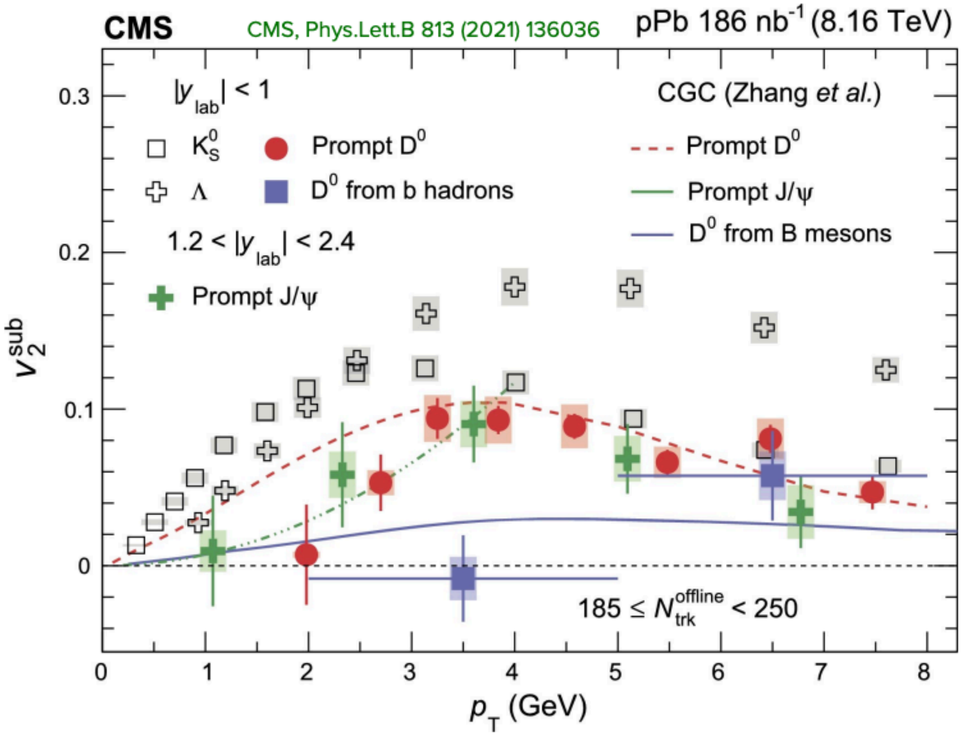


Left, pPb at high mult: v2/nq of strange particles tend to lie on a universal curve below 1.5 GeV, while D0 fall below indicating weaker collective behaviour for charm quarks

Right, PbPb semiperipheral: v2/nq of strange particles and D0 tend to lie on a universal curve below 1.0 GeV, indicating strong collective behaviour of D0 similar to the bulk of QGP medium

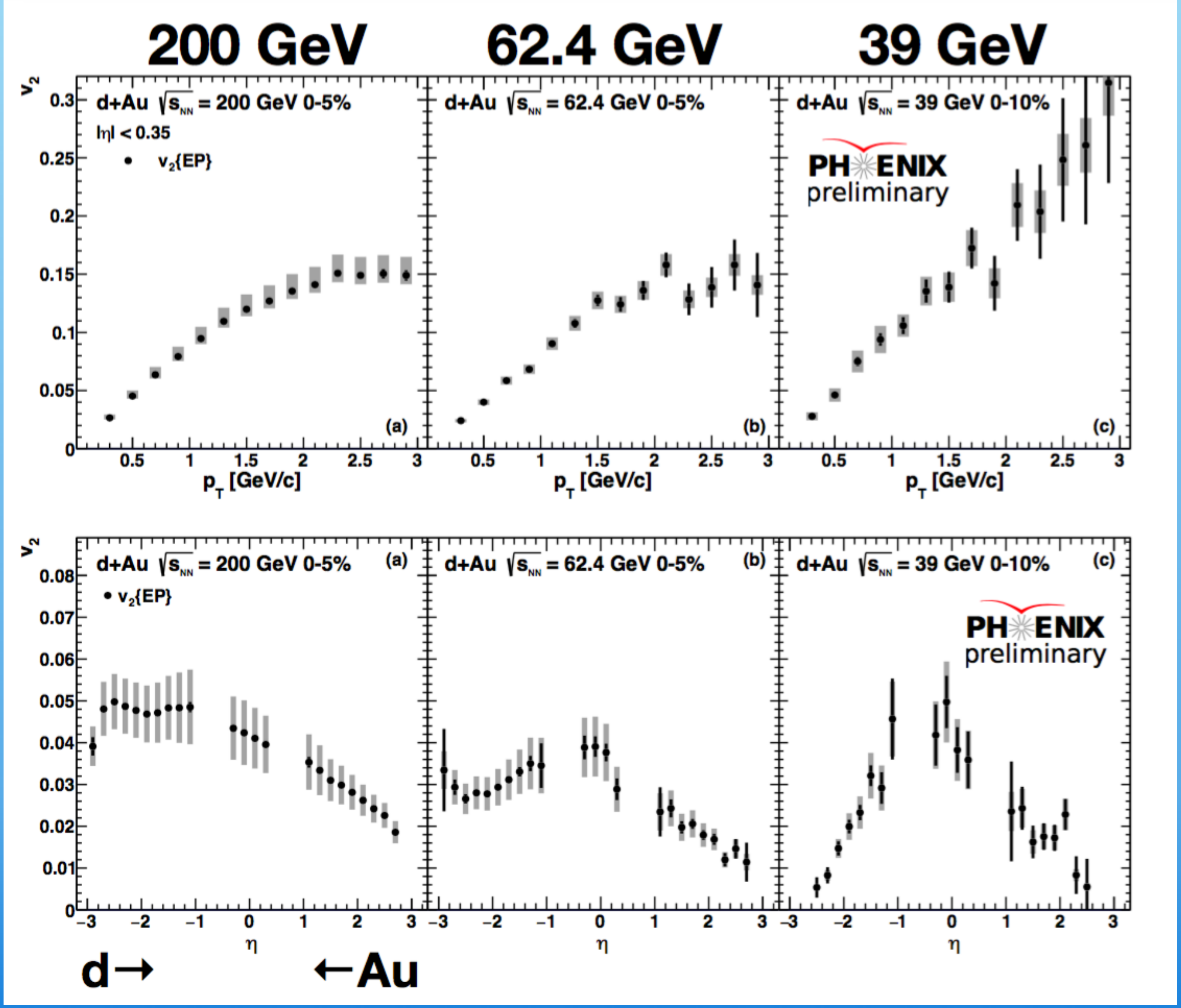
V2 charm and beauty LHC





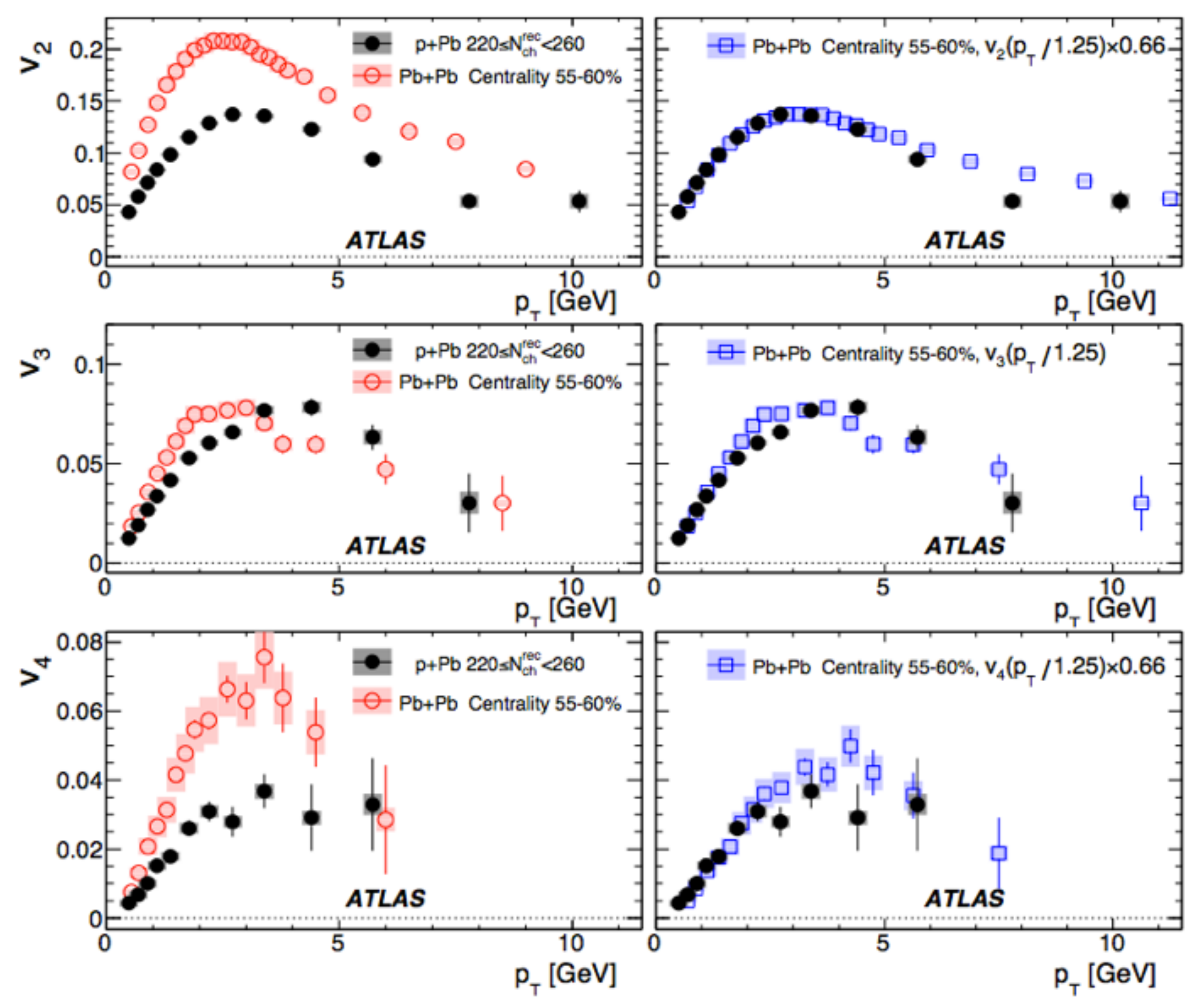
Finite v2 for charm in pp pPb
No flow for beauty in pPb

v2, v3 observed also in small systems: PHENIX, d+Au



PHENIX,
J.Velkovska,
QM2017

Large flow observed in p+Pb collisions at sqrt(s)=5.02 TeV



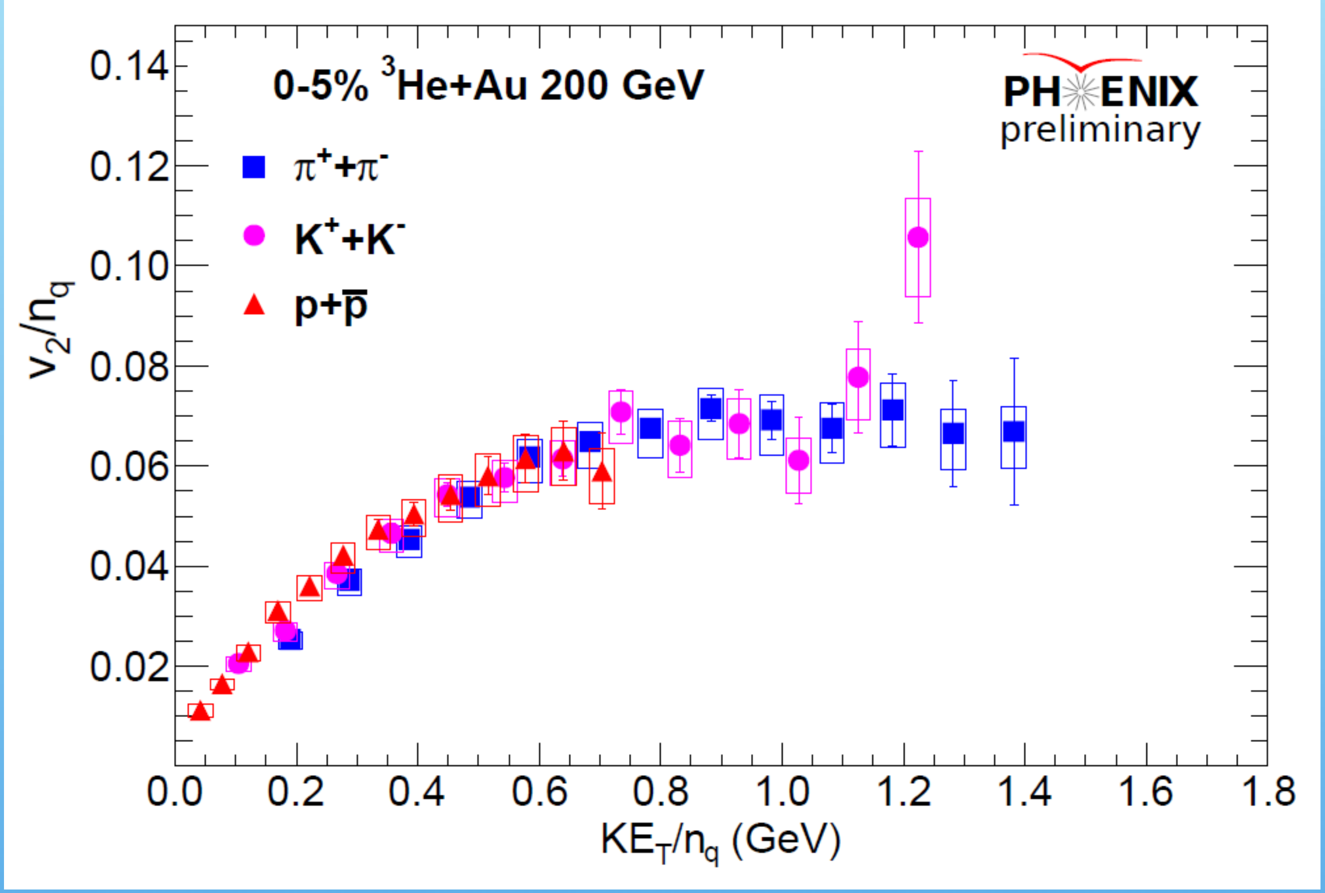
Results from ATLAS 1409.1792

After applying scale factor of 1.25 accounting for the difference in mean pT of pPb and PbPb as proposed by Basar and Teaney :

The shape of the v_n distributions in pPb and PbPb are found to be similar

Evidence for collectivity in p+Pb ?

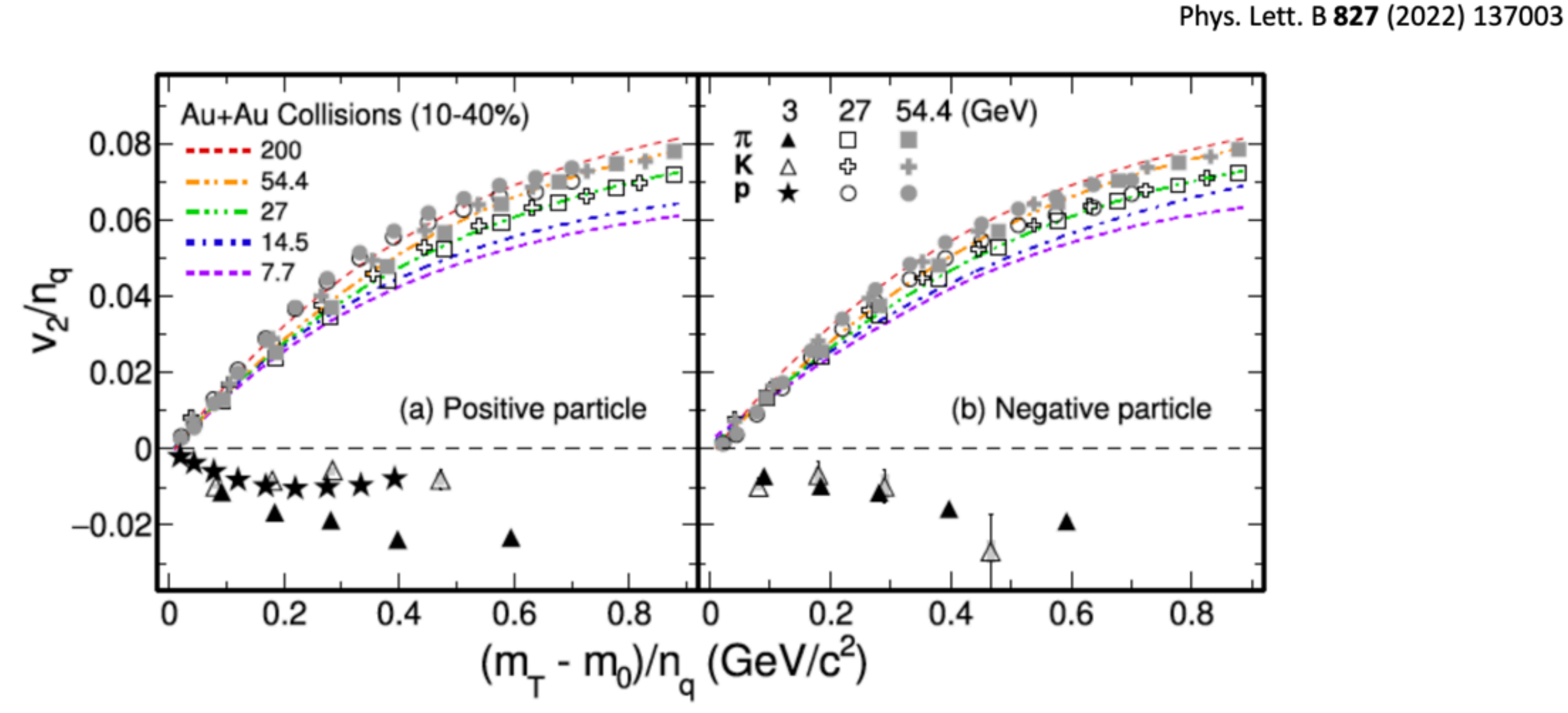
Number of quark scaling in 3He+Au



S Huang,
STAR, QM15

The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small ^{3}He+Au system

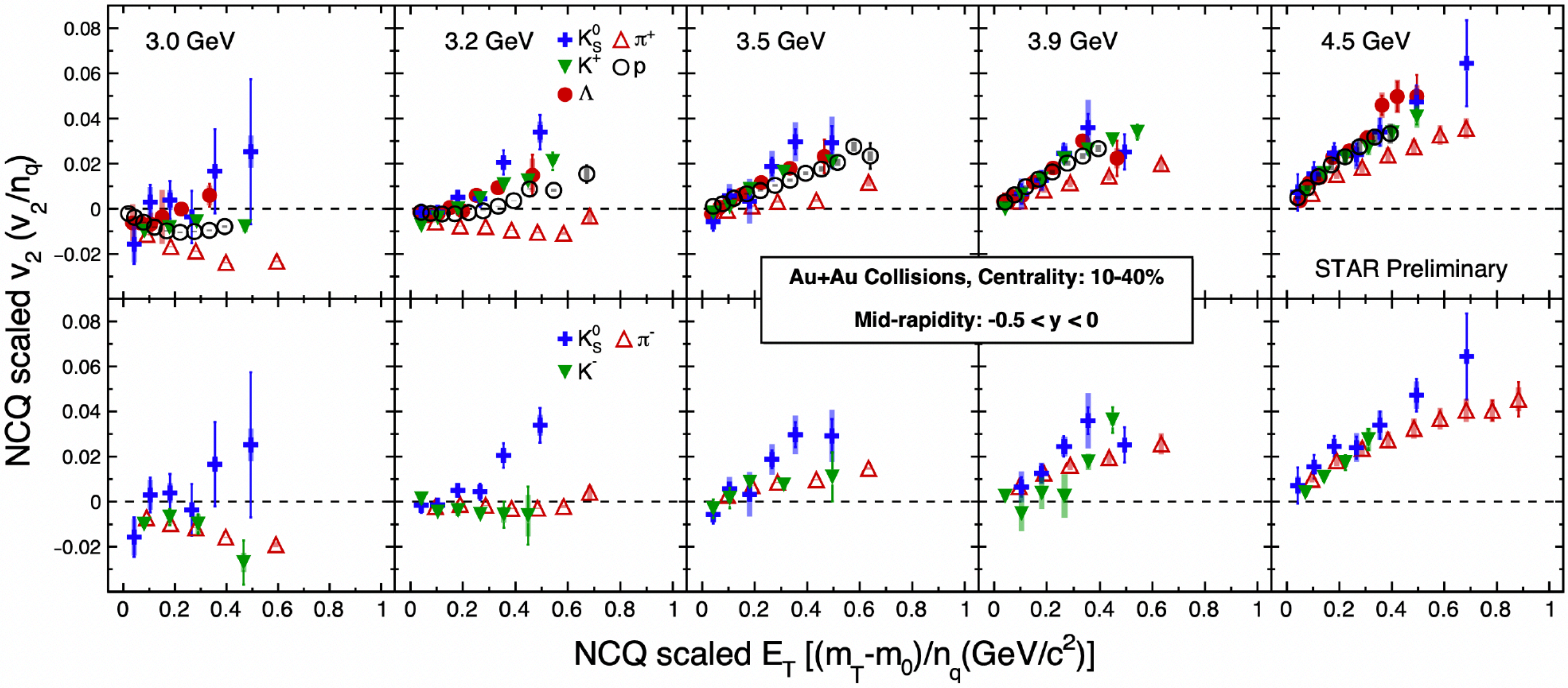
Partonic collectivity dissappears at 3 GeV AuAu



The Number of Constituent Quarks scaling (NCQ) holds from 14.5 GeV on, and breaks in 3 GeV AuAu

NCQ scaling from 3 to 4.5 GeV AuAu

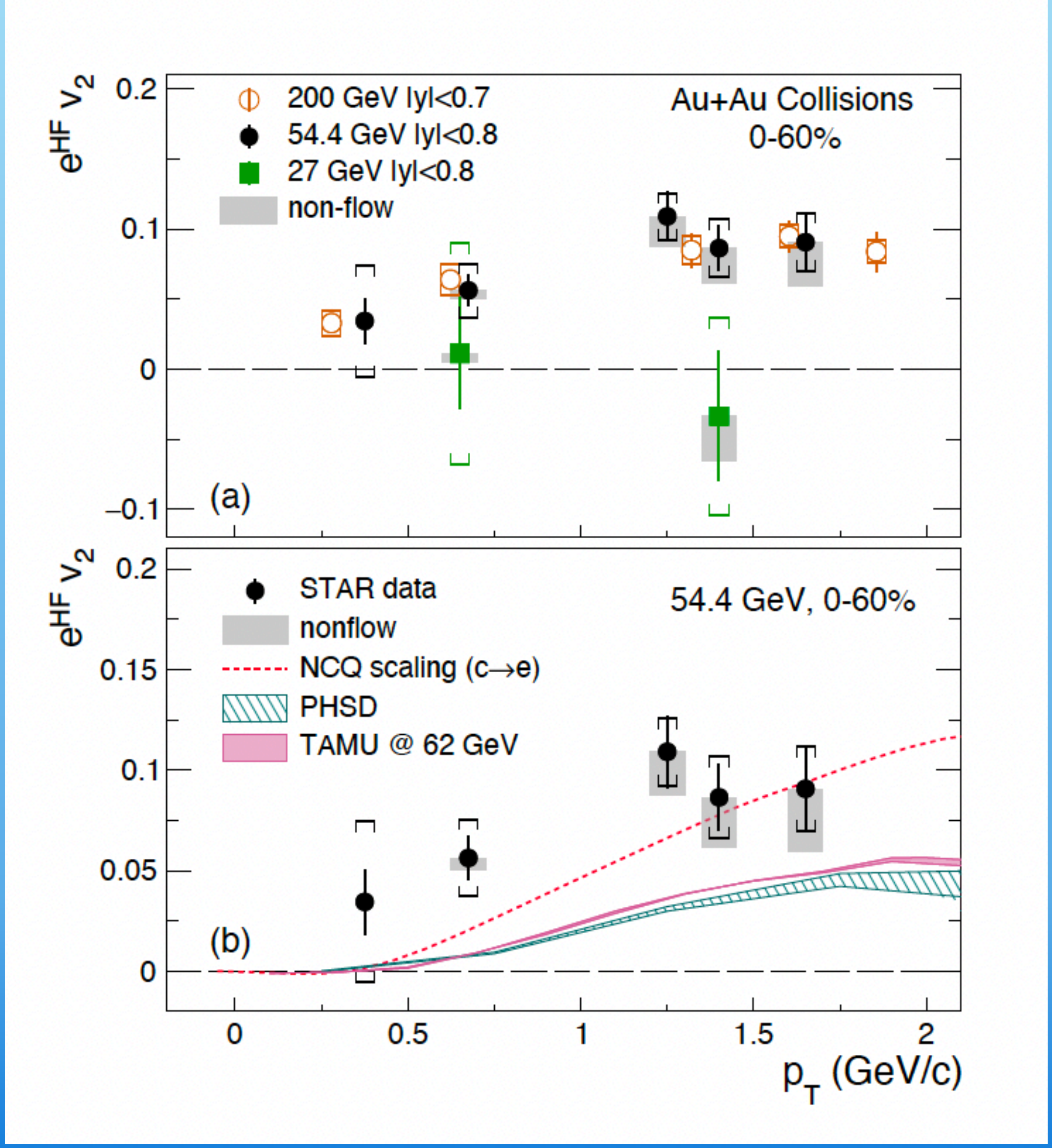
STAR Coll. Shusu Shi et al, SQM2024



The Number of Constituent Quarks (NCQ) scaling becomes gradually better from 3.2 to 4.5 GeV AuAu

STAR heavy flavor decay electron elliptic flow (v2) in Au+Au collisions at 27, 54 (0-60%) compared to 200 GeV

STAR Collaboration, ArXivL 2303.03546, accepted by PLB



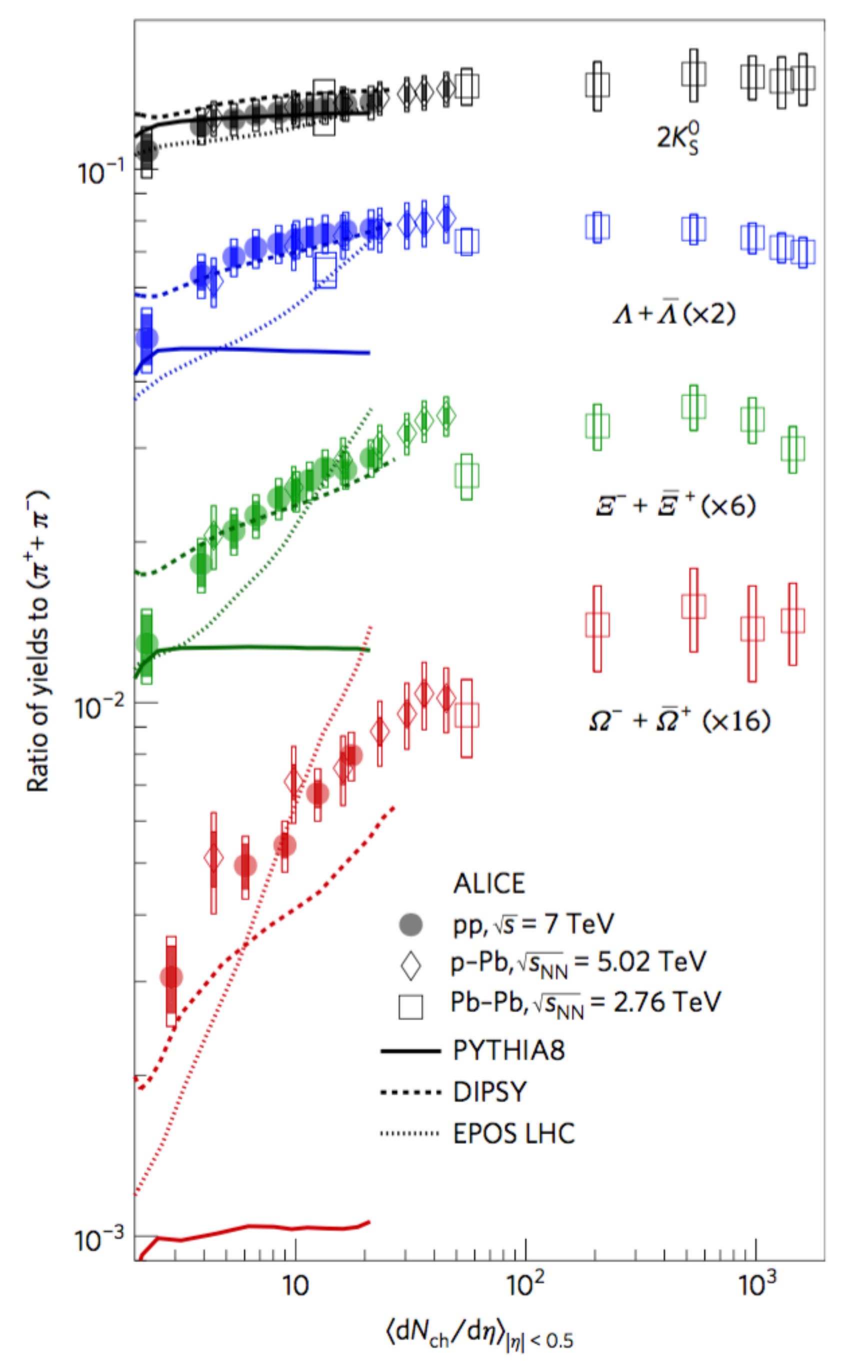
* The elliptic flow of heavy flavor electrons in Au+Au collisions at 54.4 GeV is comparable to 200 GeV, and non-zero above pT 0.5 GeV/c, indicating strong charm quark interactions with the medium

* The elliptic flow of heavy flavor electrons in Au+Au collisions at 27 GeV is consistent with zero at all pT within large uncertainties

* The elliptic flow of heavy flavor electrons in Au+Au collisions at 54.4 GeV at hight pT is consistent with the expected v2 assuming that the c quark follows the Number of constituent Quark scaling

Strangeness

ALICE, PRL 2017
p+p sqrt(s)=7 TeV, pPb= 5 TeV, PbPb= 2.76 TeV

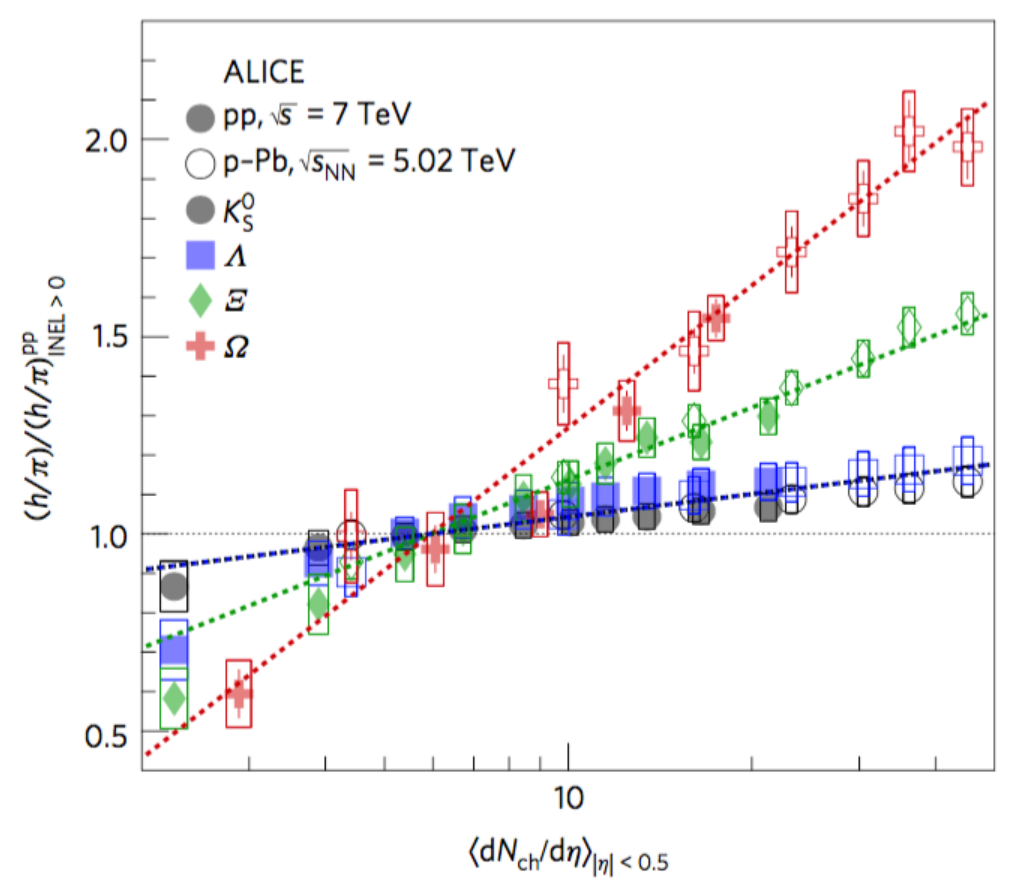


These data show for the first time in pp collisions, that the yields of strange particles relative to pions increase significantly with multiplicity

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

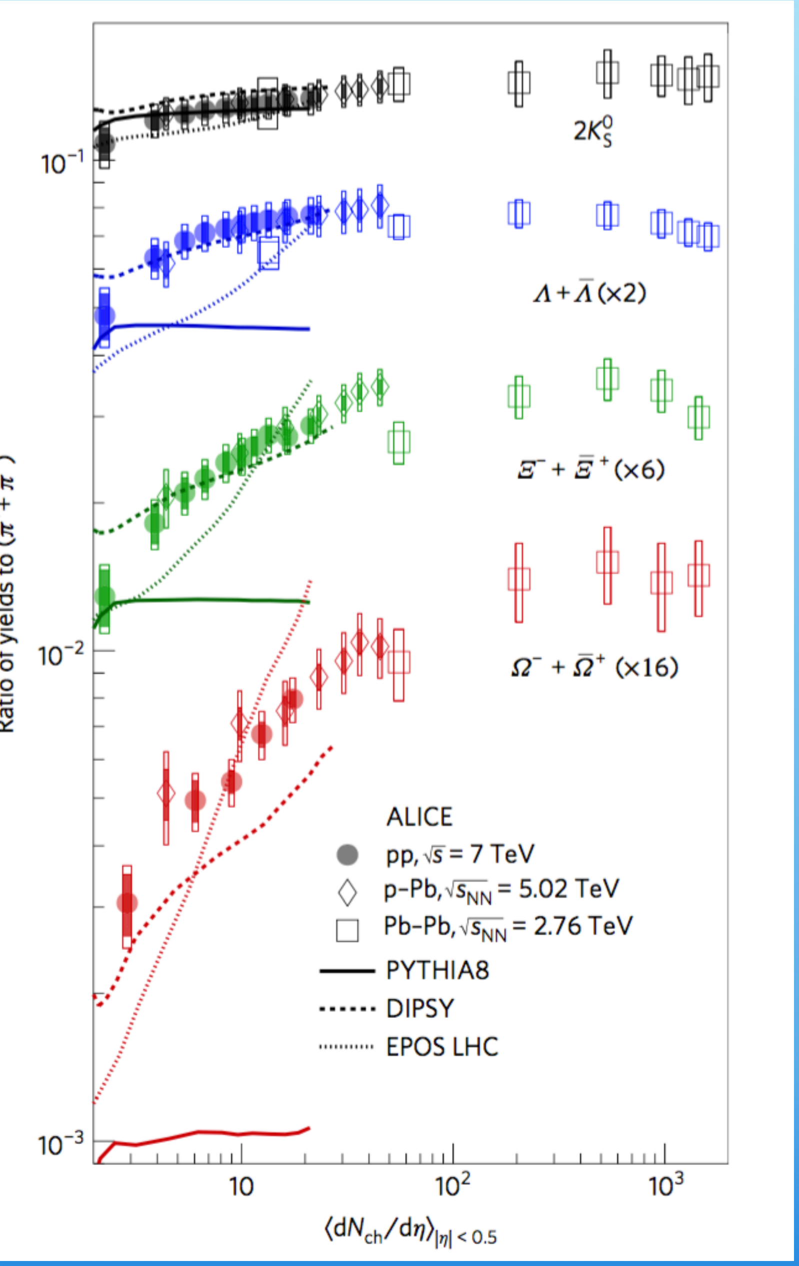
Novel phenomenon in pp at the LHC:
strangeness enhancement in p+p and p+Pb increases with charged multiplicity and reaches values observed in Pb+Pb collisions

ALICE



The observed enhancement of strange/pi ratio with event charged multiplicity shows a hierarchy determined by the strangeness content (lines are fits to determine the dependence on dNch/deta)

ALICE



The measurement of ALICE shows consistent strangeness enhancement in pp, pPb and PbPb collisions which depends on strangeness content and cannot be reproduced by models at same time as p/pi ratio

These new measurements at LHC point towards possible formation of QGP matter at high Temperature and density also in small collisions systems.

Comment from ALICE paper:

> **"The remarkable similarity of strange particle production in pp, p–Pb and Pb–Pb collisions adds to previous measurements in pp, whch also exhibit characteristic features**
>
> **known from high-energy heavy-ion collisions and are understood to be connected to the formation of a deconfined QCD phase at high temperature and energy density.**

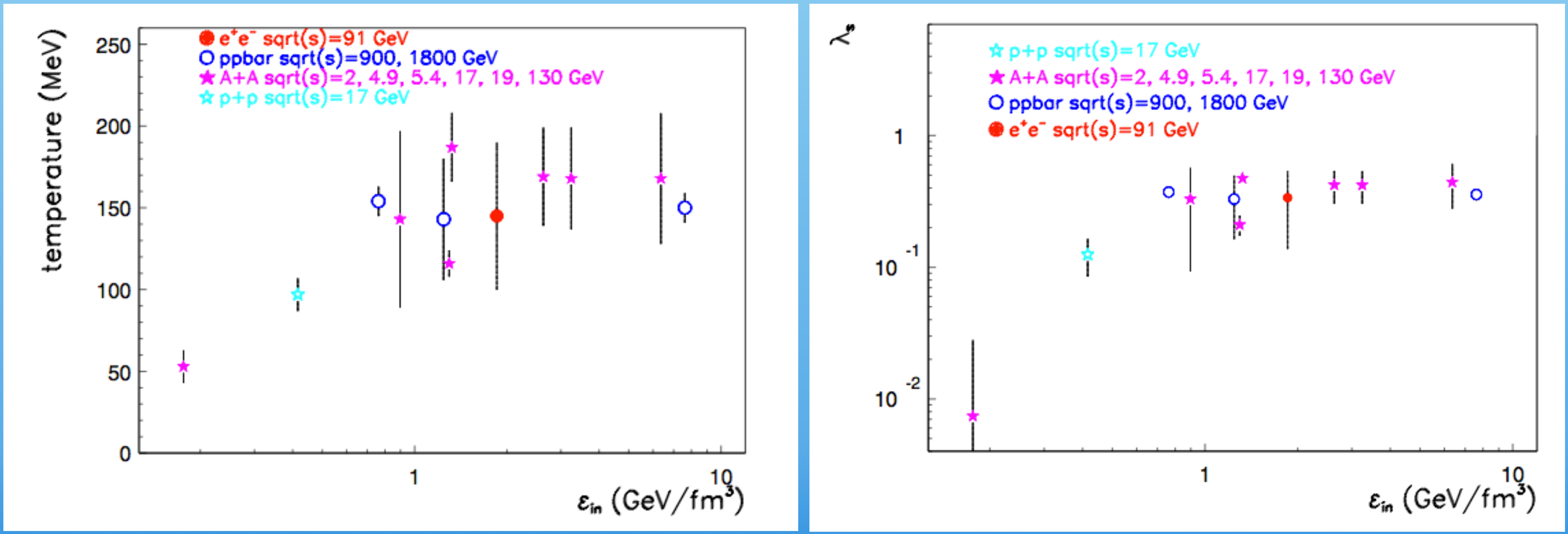
QGP formation also in small systems?

Do small QGP droplet form in p+p, p+A?

New data on collectivity seen in p+A, p+p prompt the idea that QGP may form in p+p, p+A (with centrality selection)

S.K. P. Minkowski, 2001 New J. Phys. 3, 4:
First demonstration of evidence for the universality of the QGP phase transition in p+p, p+A, A+A appearing above a critical energy density.

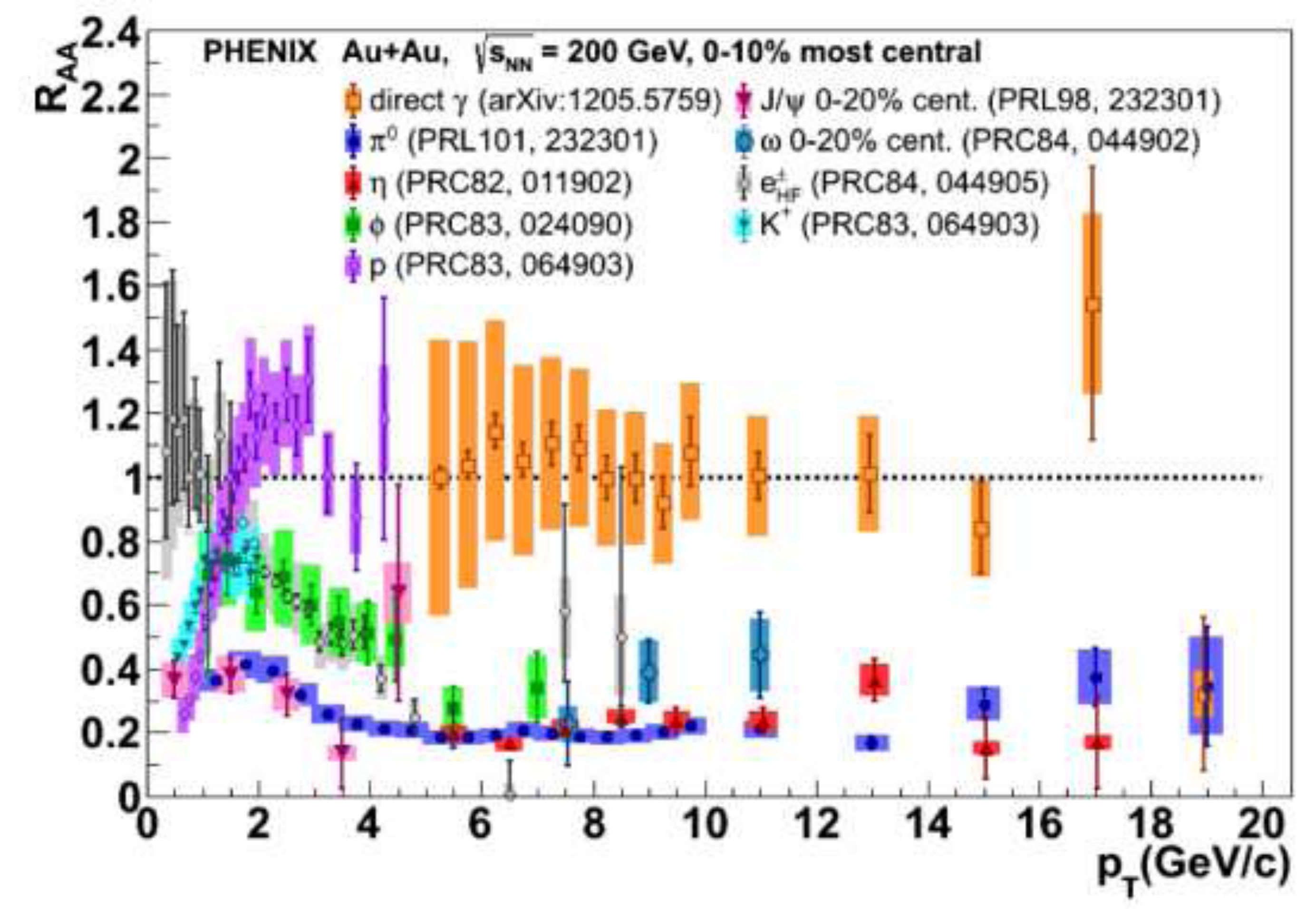
S.K., P. Minkowski, 2001 New J. Phys. 3 4



Differences of AA, pp, pA vs initial energy density dissappear at same muB

4. Jet quenching

Jet quenching of light hadrons at RHIC

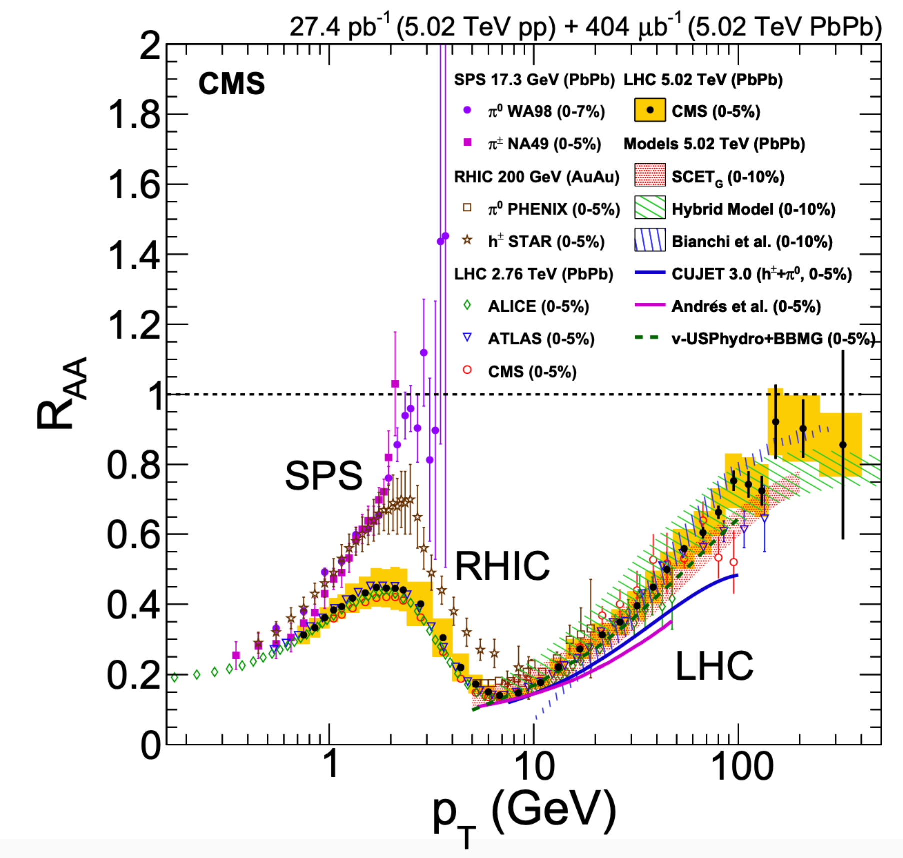


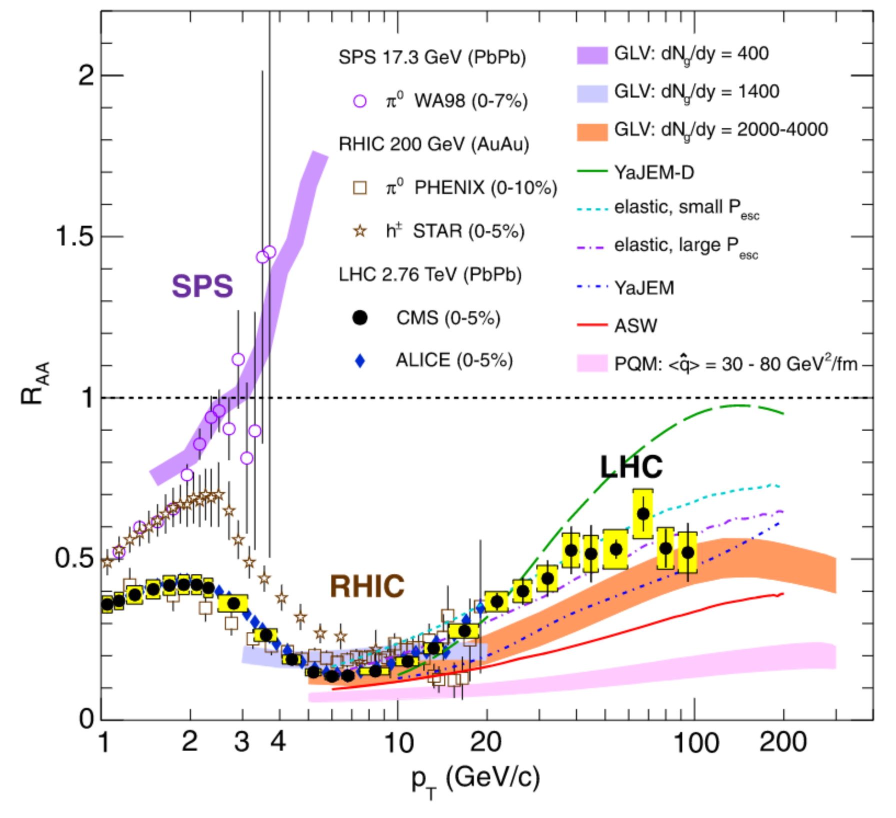
*** Light hadrons are quenched**
*** Photons are not quenched**

Jet quenching hadrons vs PT at various energies

CMS, EPJC
(2012) 72:1945

CMS, 2405.10785





(Right): RAA compared to models for energy loss allows for an estimate of gluon density dN/dy(gluon)
Here as an example we get (GLV model):

- **dN/dy(g)=400 for SPS**
- **dN/dy(g)=1400 for RHIC**
- **dN/dy(g)=2000-4000 for LHC**

To estimate with confidence dN/dy(g), we should understand the mechanism of jet quenching via studies of its dependence from pT, energy, event plane, path length, centrality, quark mass etc

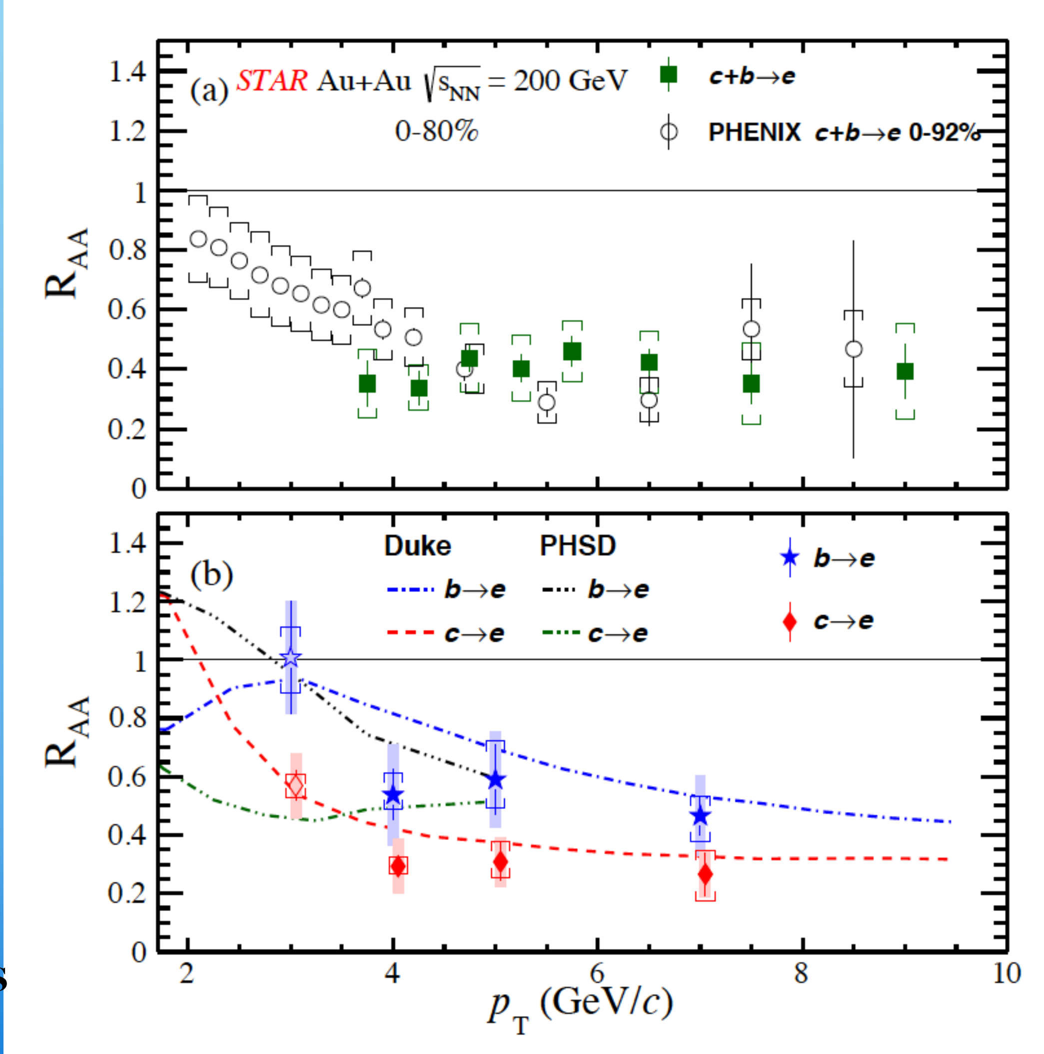
STAR (2022) Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

STAR Collaboration, EPJC **82** (2022) 1150, arXiv:2111.14615

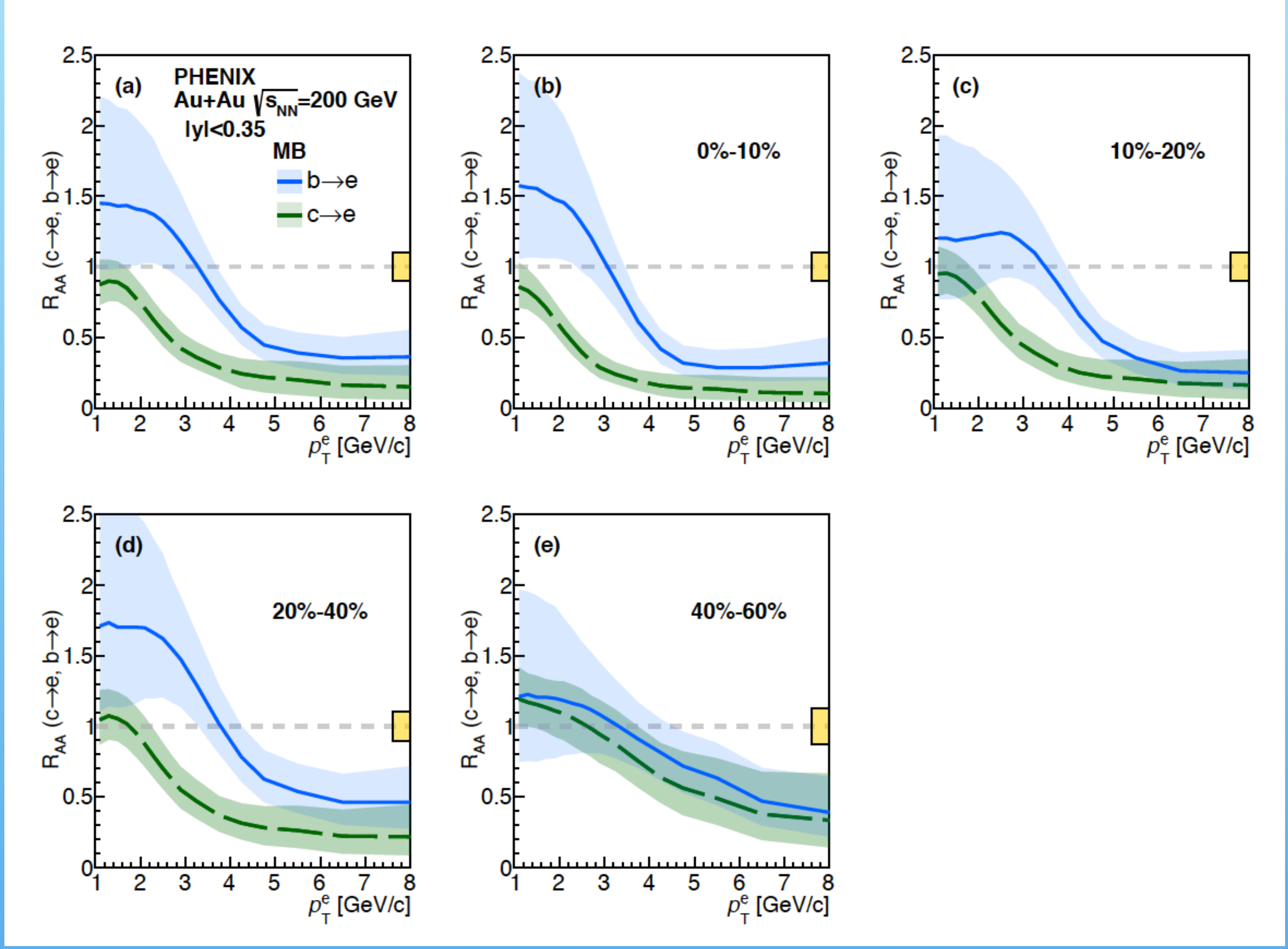
PHENIX Collaboration, PRC93, 034904 (2016), 1509.04662

- PHSD: Parton-Hadron-String-Dynamics model
- Duke: modified Langevin transport model
- Both models include heavy quark (HQ) diffusion in the QGP medium, HQ hadronization through coalescence and fragmentation and mass-dependent energy loss mechanisms
- Data consistent with model predictions

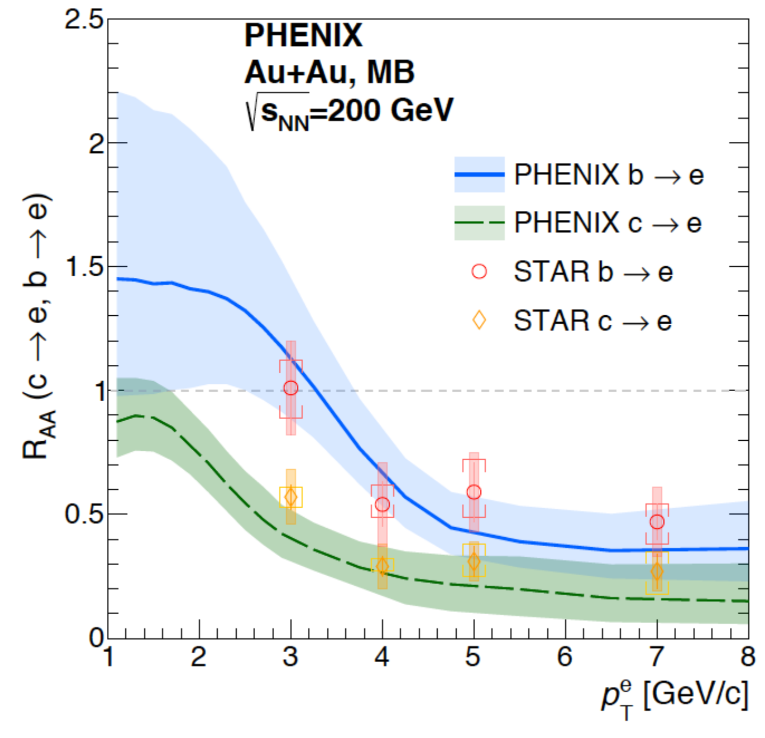
- **R(AA) vs pT of c+b —> e: STAR and PHENIX are consistent**
- **Evidence of mass ordering of R_{AA} of electrons from bottom and charm in Au+Au collisions at 200 GeV is observed**
- **Results are consistent with models including mass-dependent energy loss mechanisms**



PHENIX hierarchy of suppression of b—>e and c —>e in Au+Au collisions at 200 GeV



PHENIX, 2203.17058

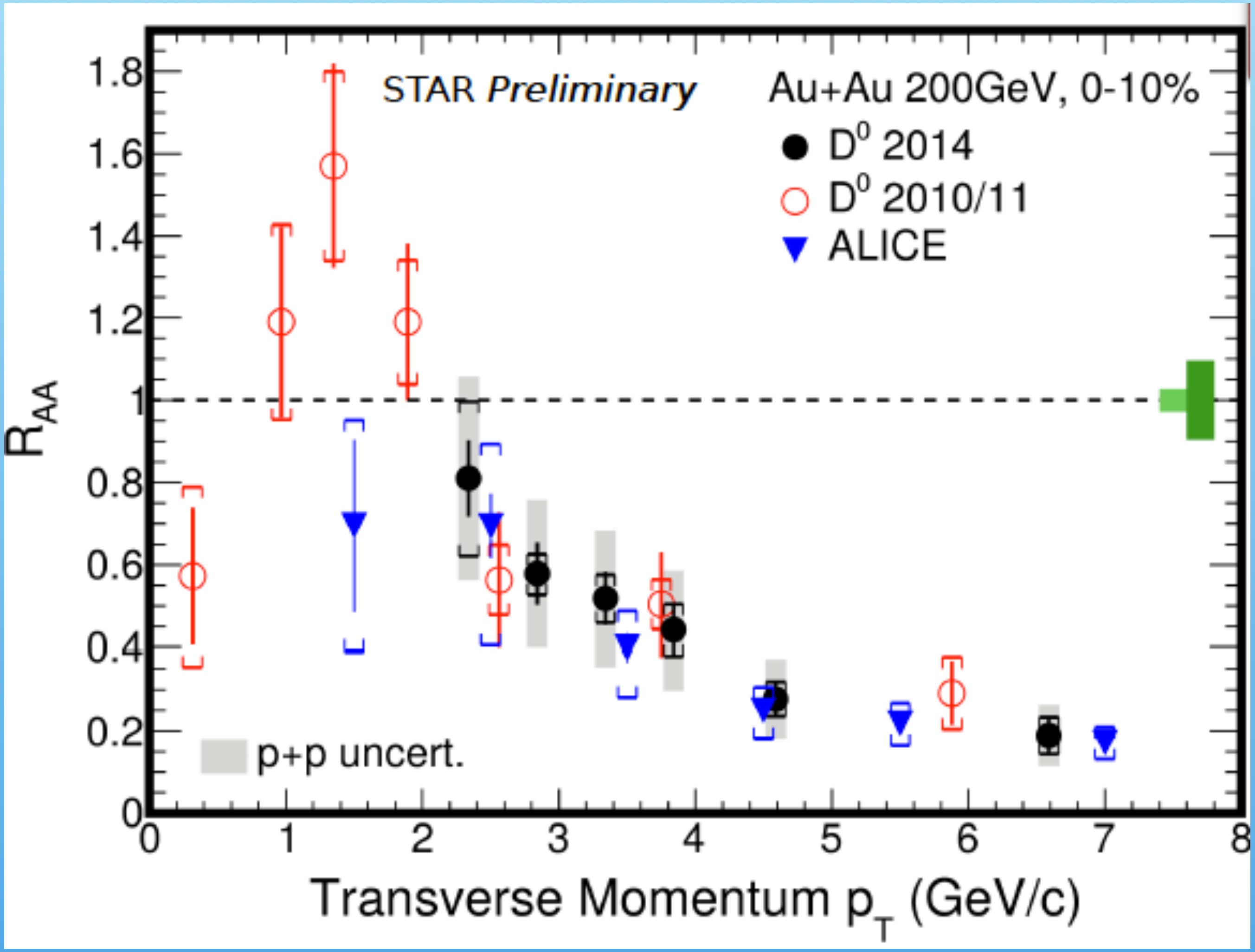


STAR Coll, arXiv:2111.14615.

* b->e higher than c-> e in Au+Au 200 GeV Minimum Bias and various centralities exept the most peripheral collisions

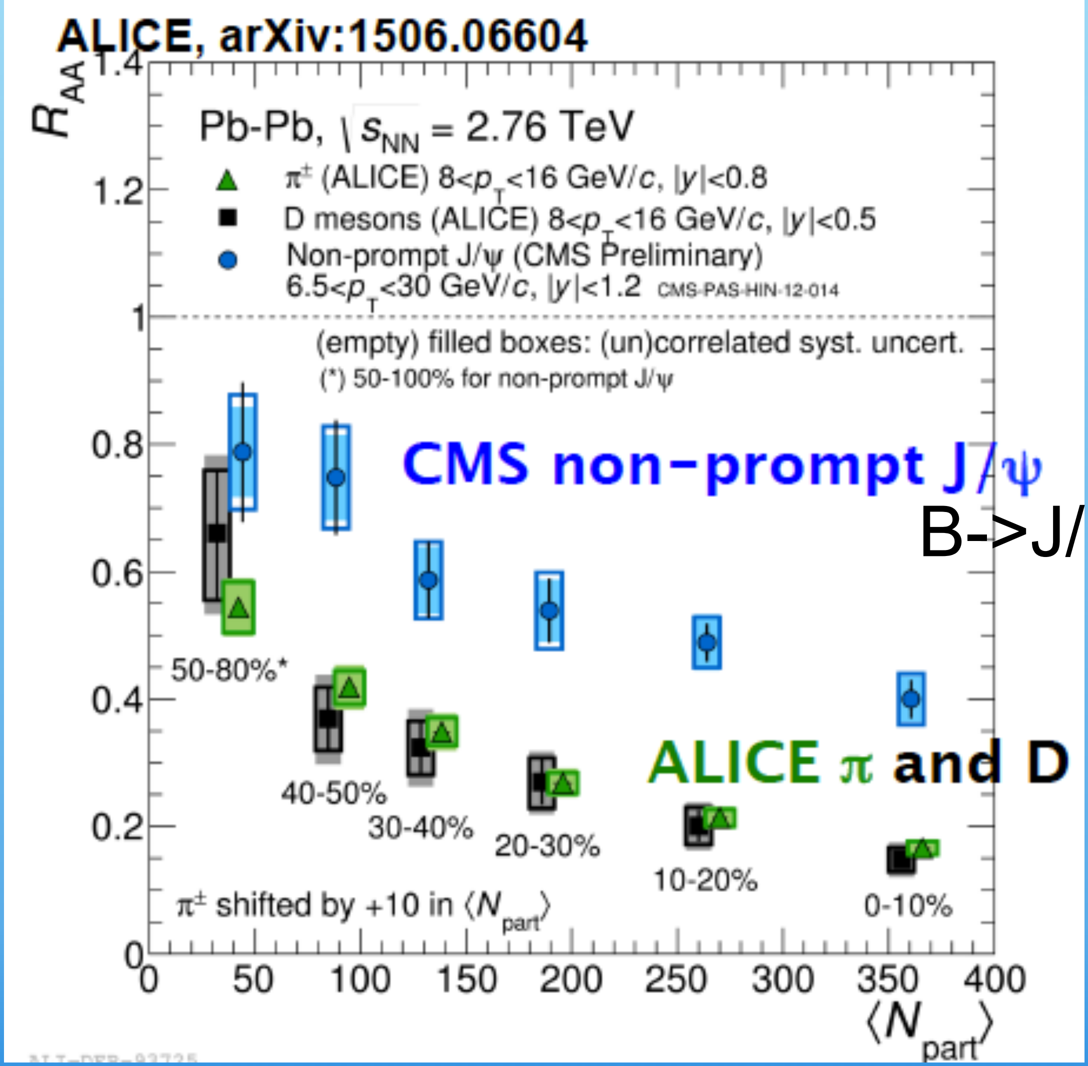
* STAR (points) and PHENIX (lines) b and c to electron measurements in Minimum Bias Au+Au 200 GeV are consistent

Comparison RHIC to LHC



RAA of D0 mesons is similar in RHIC and LHC at pT>2 GeV/c

RAA of open charm and beauty at the LHC



B->J/Psi

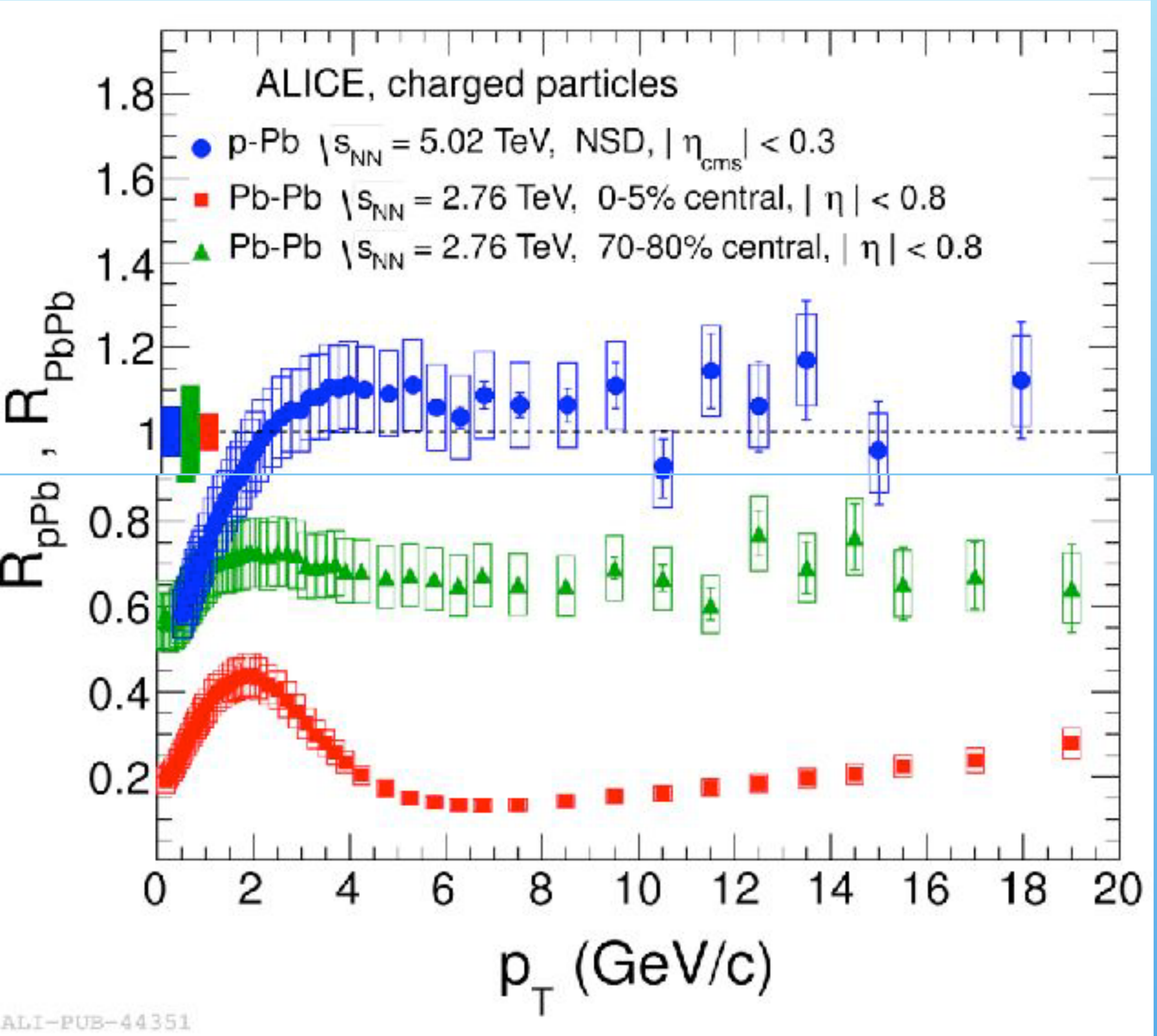
ALICE, QM2015

Pb+Pb ALICE, CMS:

RAA of D mesons is much smaller than RAA of non-prompt J/Psi representing open beauty (B->J/Psi X) (but pT range different)

RAA of pions and D mesons is consistent (pT range is the same)

ALICE p+Pb and Pb+Pb data at LHC



R(pPb) for charged particles is compatible with 1 at hight pT

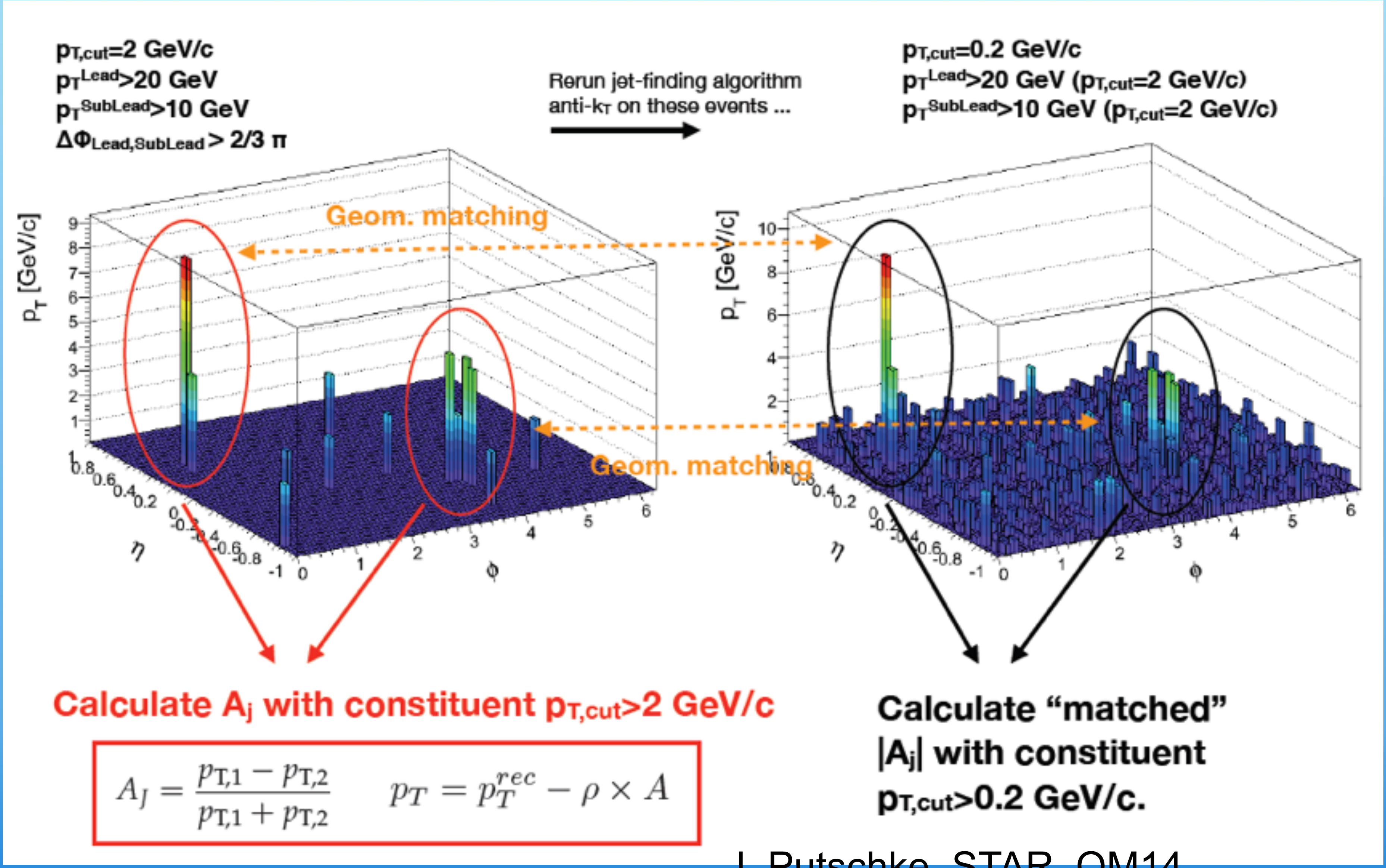
No jet quenching in p+Pb

The jet quenching seen in Pb+Pb is not due to cold nuclear matter effects

Dijets

Dijet imbalance in STAR: A_J

STAR, PRL 119, 062301 (2017)



$p_{T,cut}$=2 GeV/c
p_T^{Lead}>20 GeV
$p_T^{SubLead}$>10 GeV
$\Delta\Phi_{Lead,SubLead} > 2/3\,\pi$

Rerun jet-finding algorithm anti-k_T on these events ...

$p_{T,cut}$=0.2 GeV/c
p_T^{Lead}>20 GeV ($p_{T,cut}$=2 GeV/c)
$p_T^{SubLead}$>10 GeV ($p_{T,cut}$=2 GeV/c)

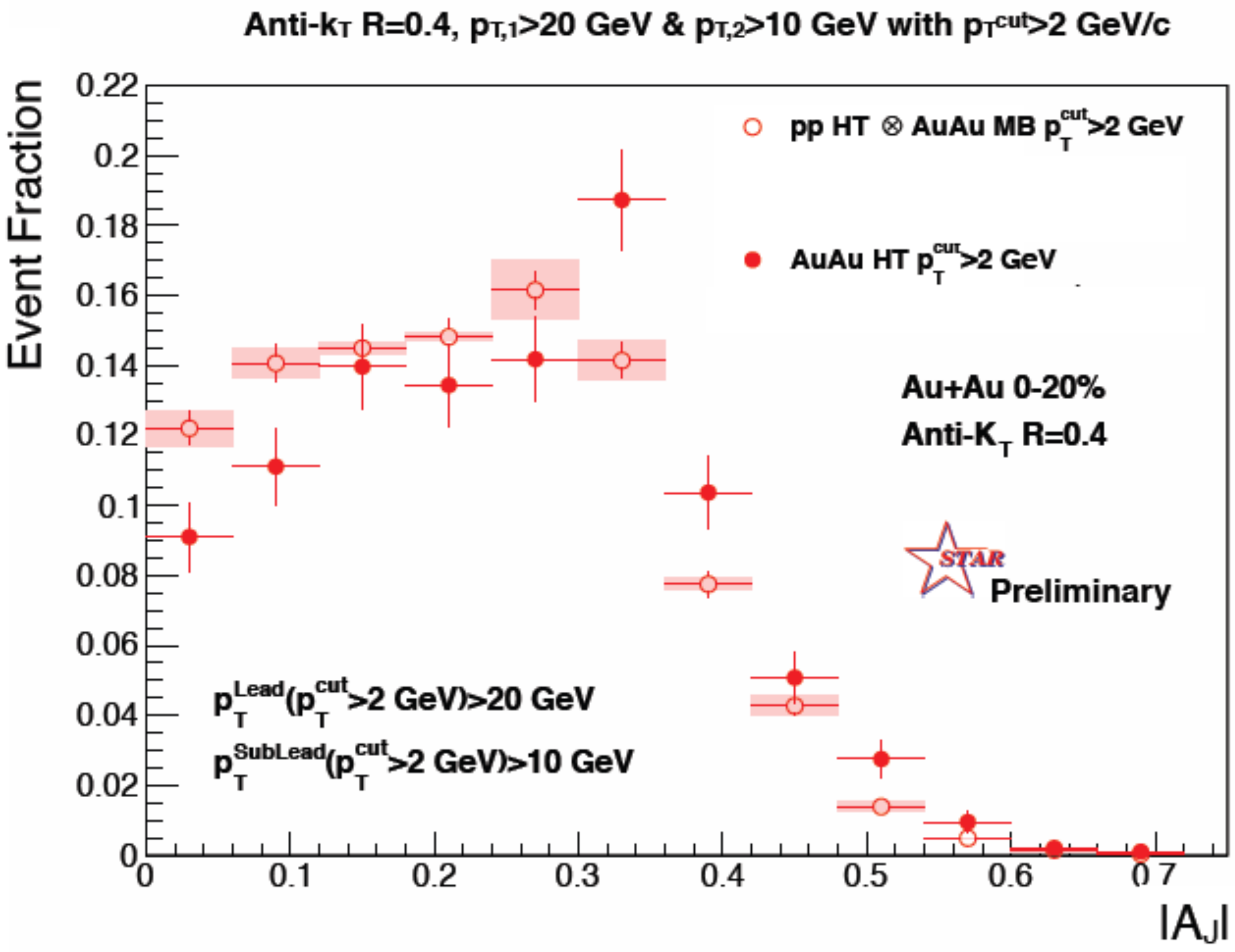
Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

Calculate "matched" $|A_j|$ with constituent $p_{T,cut}$>0.2 GeV/c.

J. Putschke, STAR, QM14

STAR, Dijet imbalance Au+Au 0-20% R=0.4



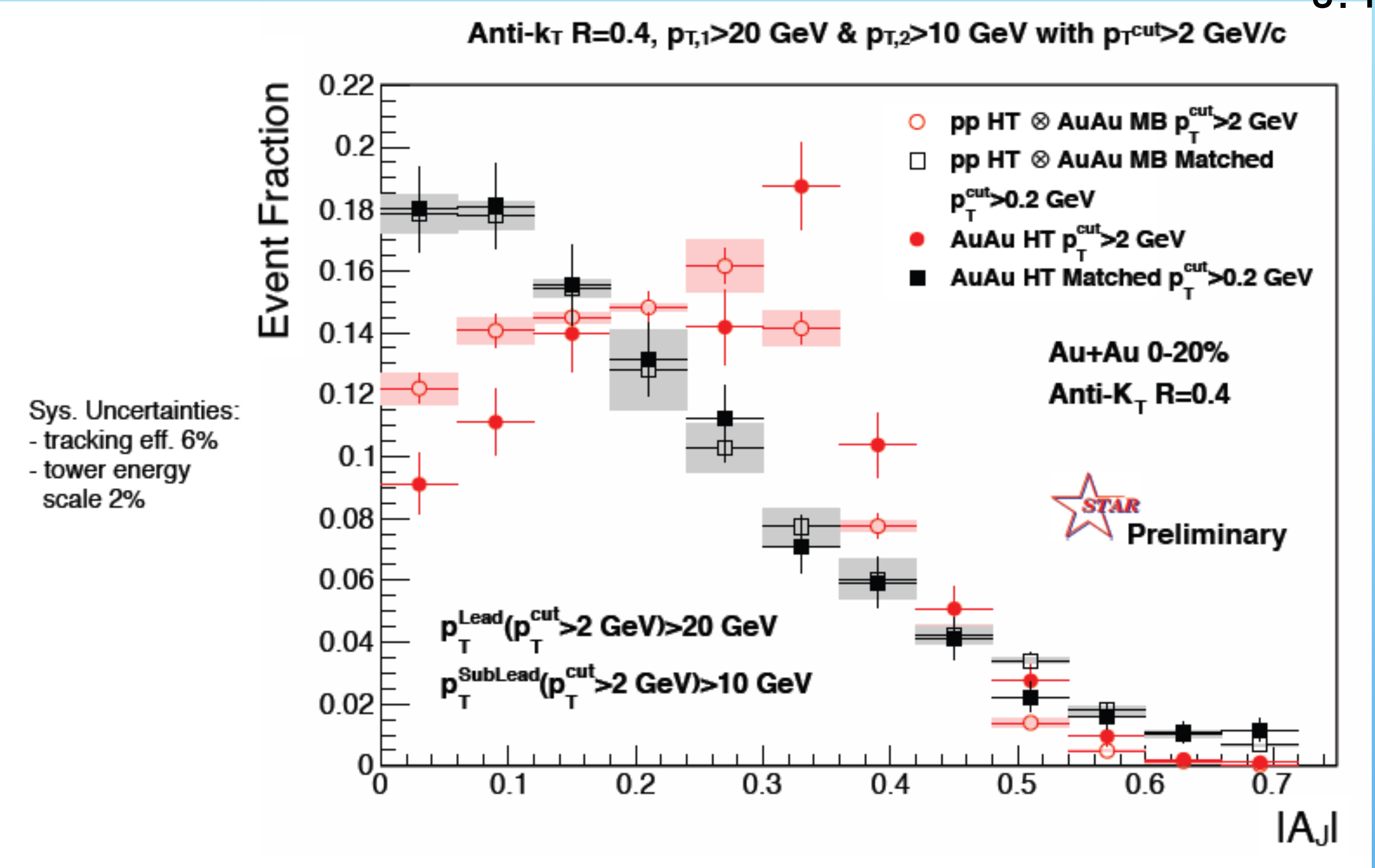
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

J. Putschke, STAR, QM14

STAR, Dijet imbalance Au+Au 0-20% R=0.4

J. Putschke, STAR, QM



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

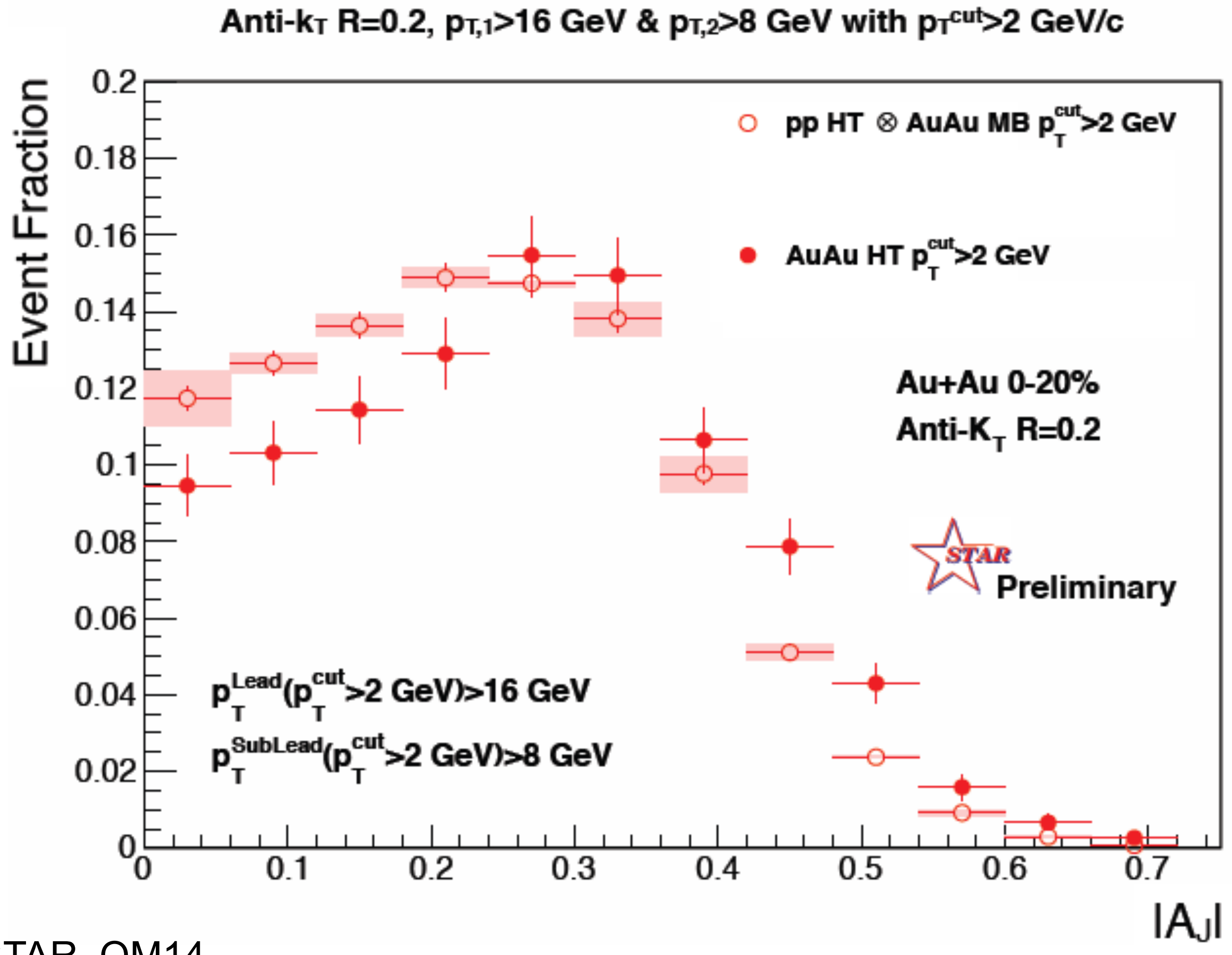
Red: ptcut>2 GeV
Grey: pTcut > 0.2 GeV (matched)

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

Quenched jet energy is recovered at low pT within a cone of R=0.4

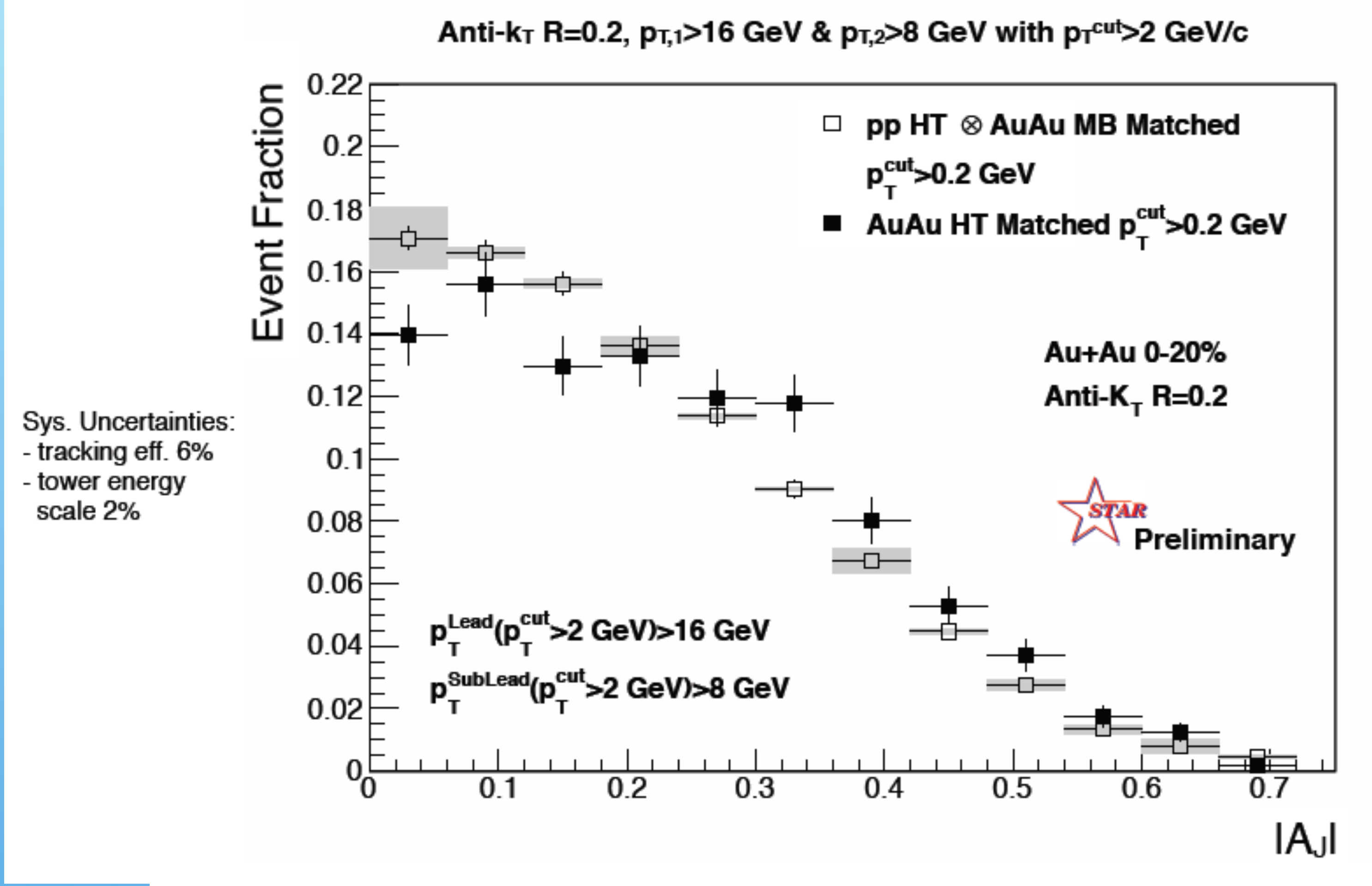
Dijet imbalance with R=0.2



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

J. Putschke, STAR, QM14

Dijet imbalance with R=0.2, matched

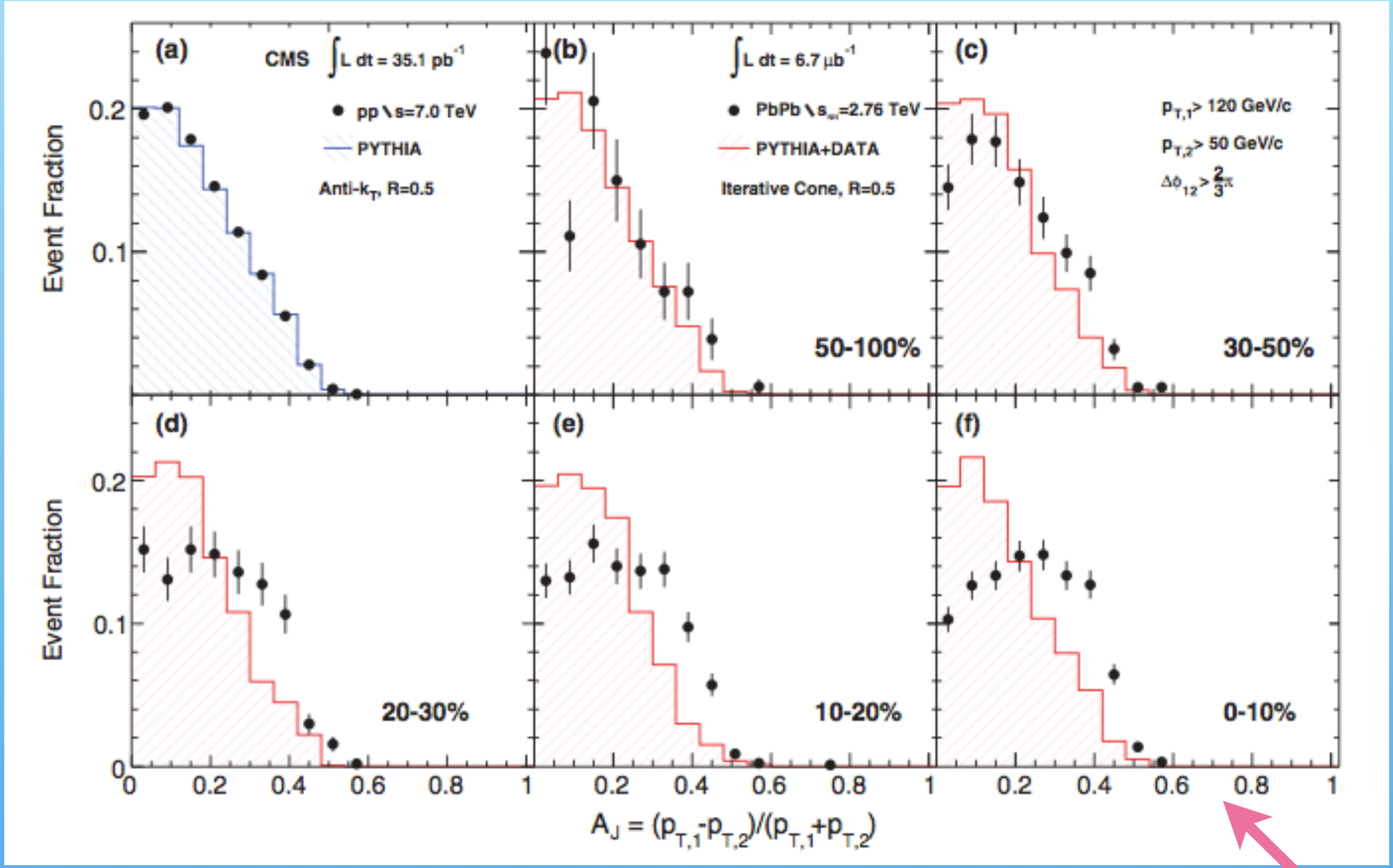


Matched Au+Au $A_J \neq$ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

J. Putschke, STAR, QM14

At RHIC the lost energy seem to reside inside a cone of R=0.4

Jet quenching via dijet imbalance at LHC



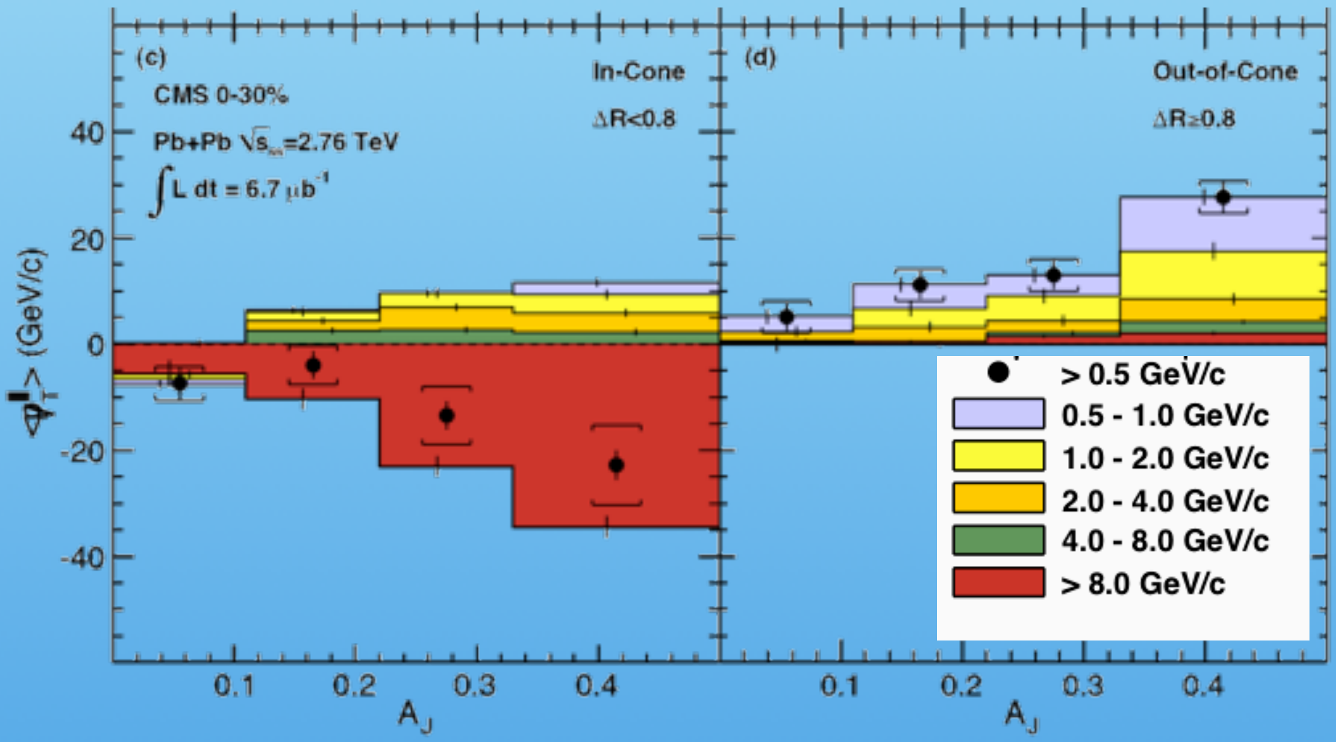
Observation of highly unbalanced dijet events in central PbPb collisions -> evidence for energy loss in medium or “jet quenching”

Where did the lost energy go?

CMS: Look at track-jet correlations

-> RHIC and LHC differ: **in LHC lost energy is moved from large to small PT and from small to large angles namely outside the leading and subleading jets cones.**

CMS, PRC 84 (2011) 024906



Color decoherence can lead to large angle emission

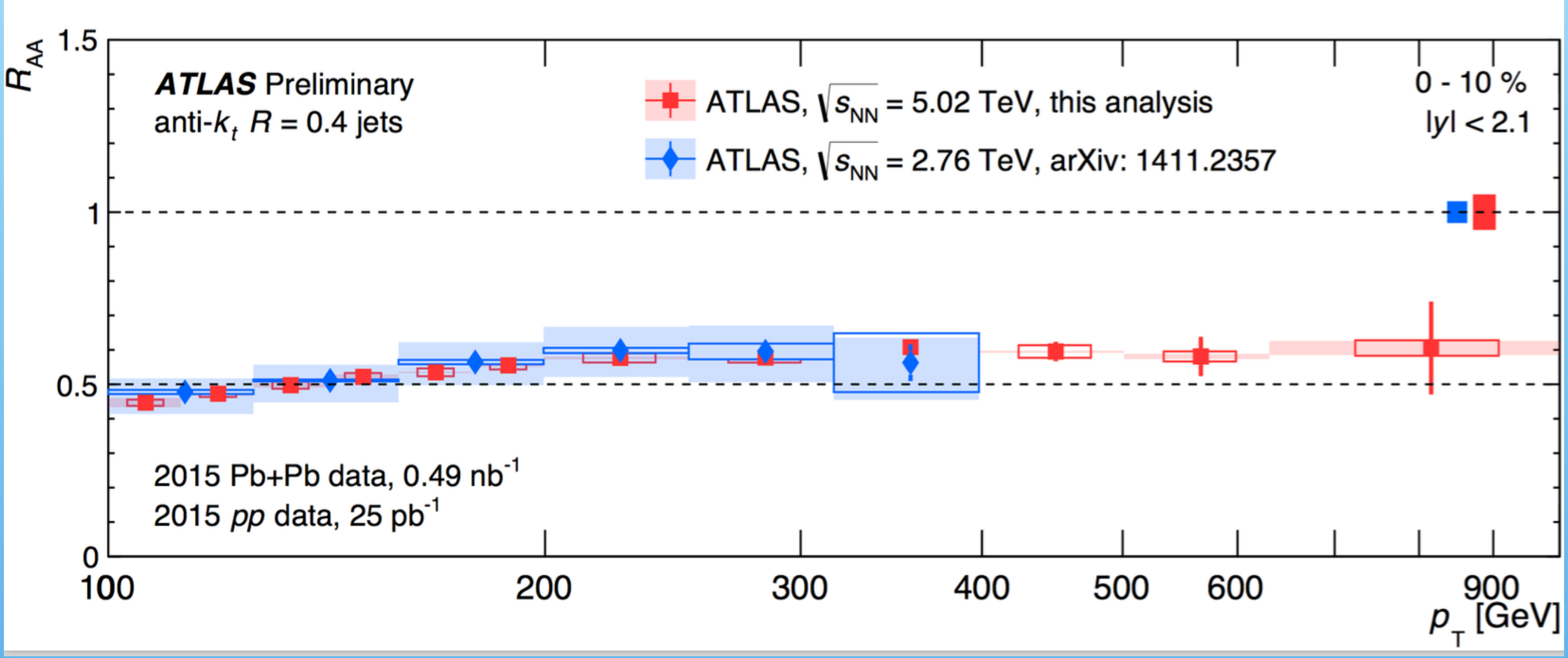
N. Armesto et al, 1207.0984
K. Tywokiuk et al 1401.8293

Colored bands show contribution to pT for five pT ranges

Dijet balance (or imbalance) characterization:

$$A = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$$

ATLAS Pb+Pb 5 TeV



Pb+Pb at 5 TeV is consistent with 2.76 TeV

Jet transport coefficient at RHIC and LHC

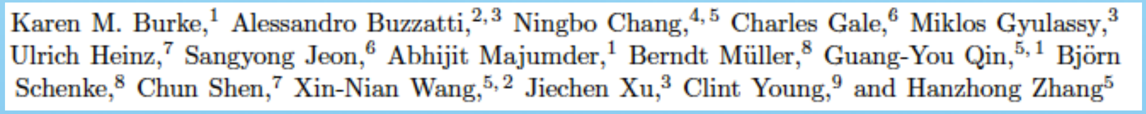
Extracting jet transport coefficient from data and models at RHIC and LHC

The JET collaboration of groups using different models has made an important step forward evaluating for the first time q-hut with a fit to both RHIC and LHC and reaching a good agreement of all models while fiting the experimental data at RHIC and LHC.

Models: GLV-CUJET, HT-M, HT-BW, MARTINI and McGill-AMY. GLV and its recent CUJET implementation.

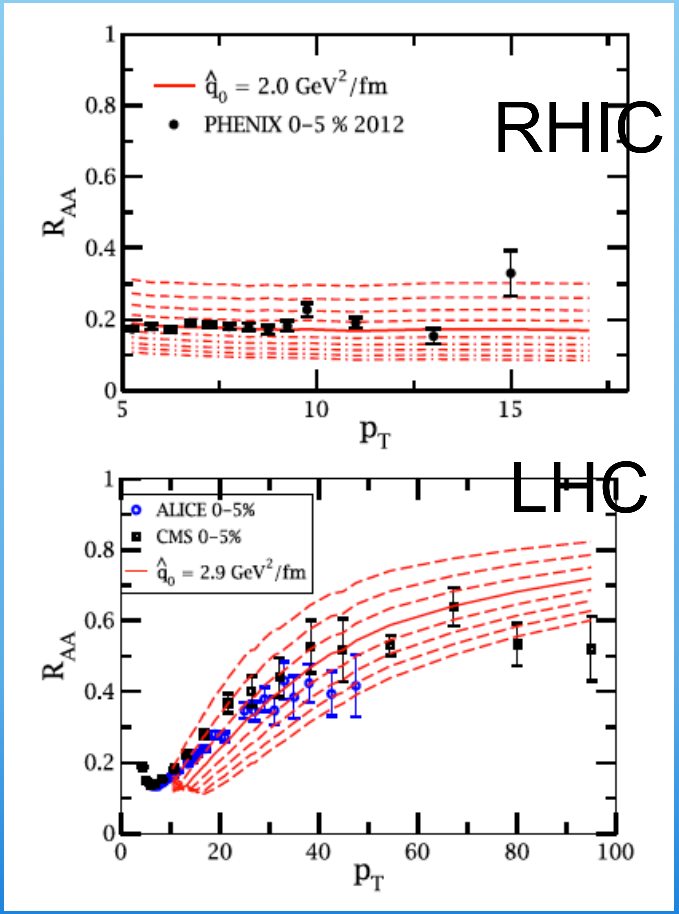
Jet transport coefficient for a jet initiated by a light quark considered (10 GeV jet assumed).

For the QGP medium viscous hydrodynamics (VISH2+1) is employed (Ohio State group).

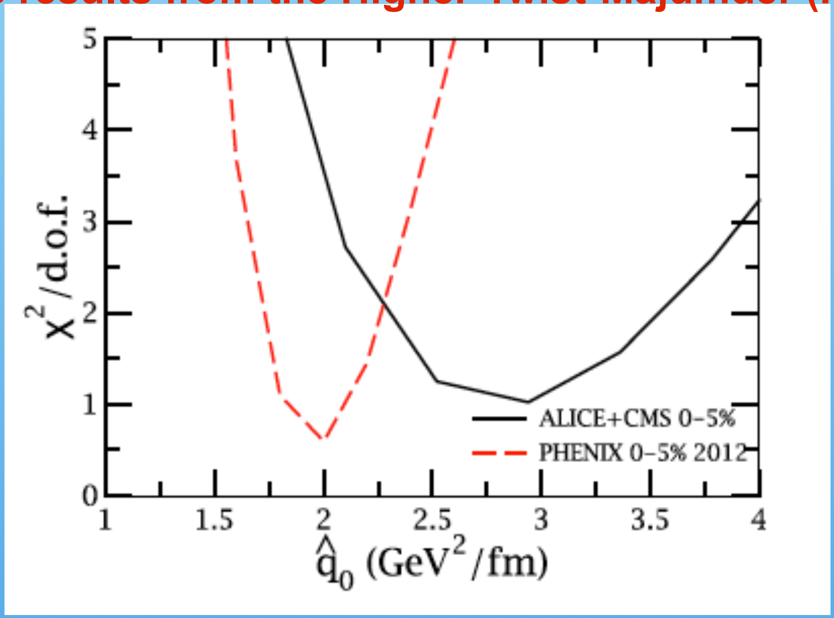


Karen M. Burke,[1] Alessandro Buzzatti,[2,3] Ningbo Chang,[4,5] Charles Gale,[6] Miklos Gyulassy,[3] Ulrich Heinz,[7] Sangyong Jeon,[6] Abhijit Majumder,[1] Berndt Müller,[8] Guang-You Qin,[5,1] Björn Schenke,[8] Chun Shen,[7] Xin-Nian Wang,[5,2] Jiechen Xu,[3] Clint Young,[9] and Hanzhong Zhang[5]

K. Burke et al, JET collaboration, 1312.5003



Example results from the Higher-Twist-Majumder (HT-M) model



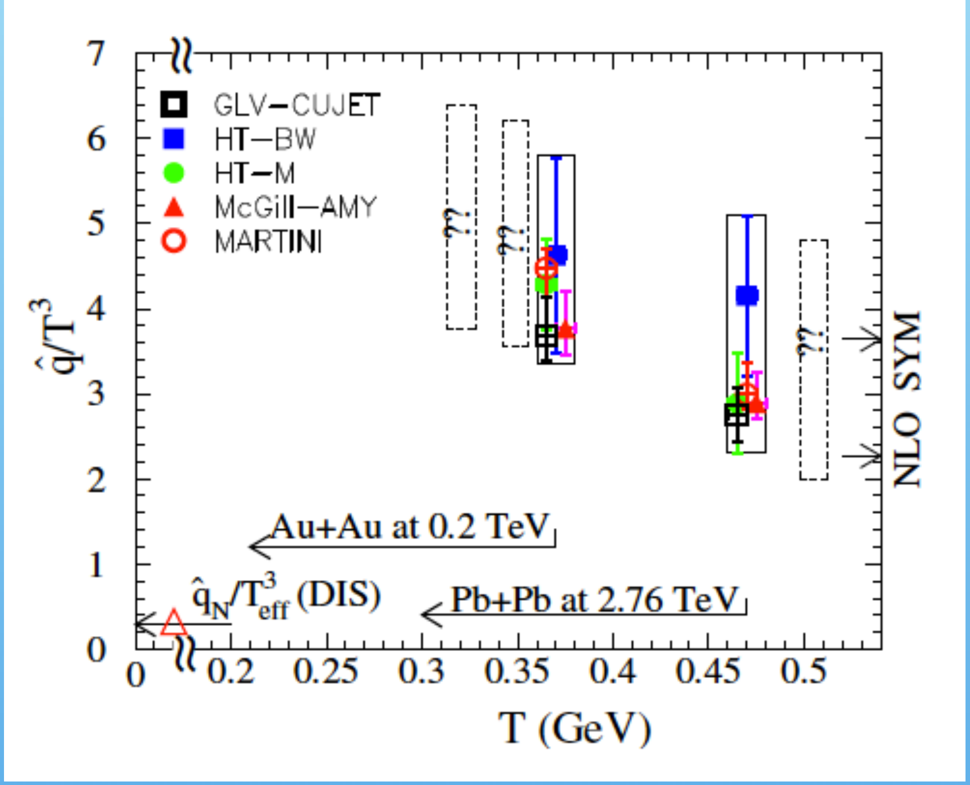
Dedx(radiative)~
q-hut

Example of fit to pi0 in central 0-5% Au+Au and Pb+Pb for the Higher-Twist-Majumder (HT-M) model.

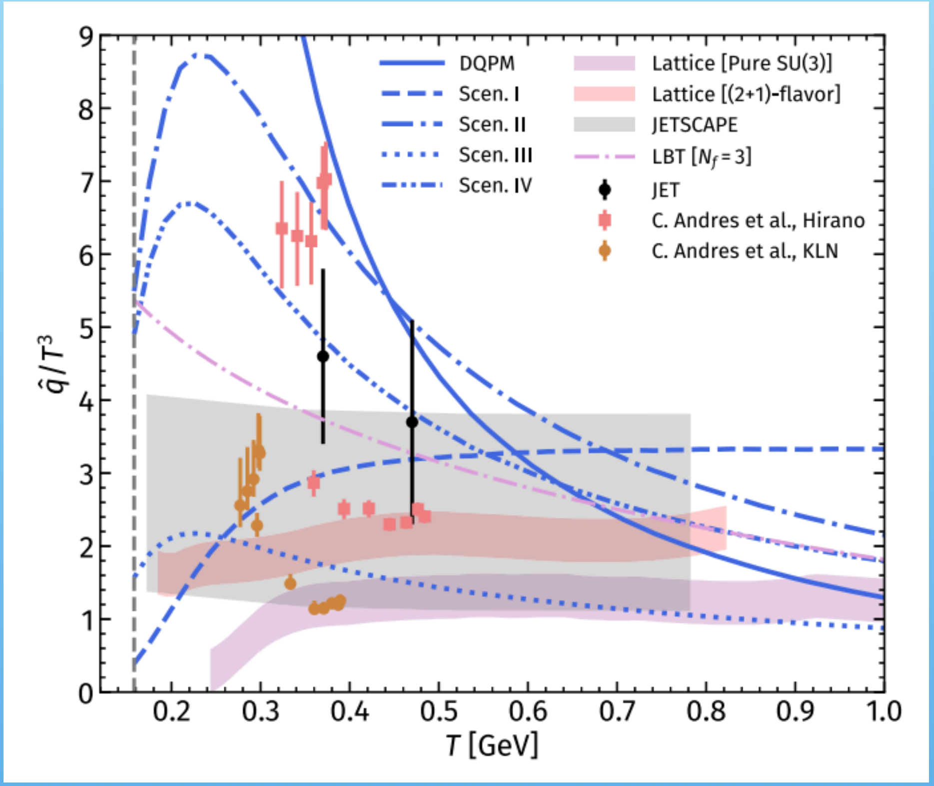
The model calculates the medium modified fragmentation function including multiple induced gluon emission.

Extracting jet transport coefficient from data and models at RHIC and LHC

Scaled jet transport parameter q-hut/T^3



Dashed boxes show expected values for sqrt(s)=0.063, 0.130 and 5.5 TeV

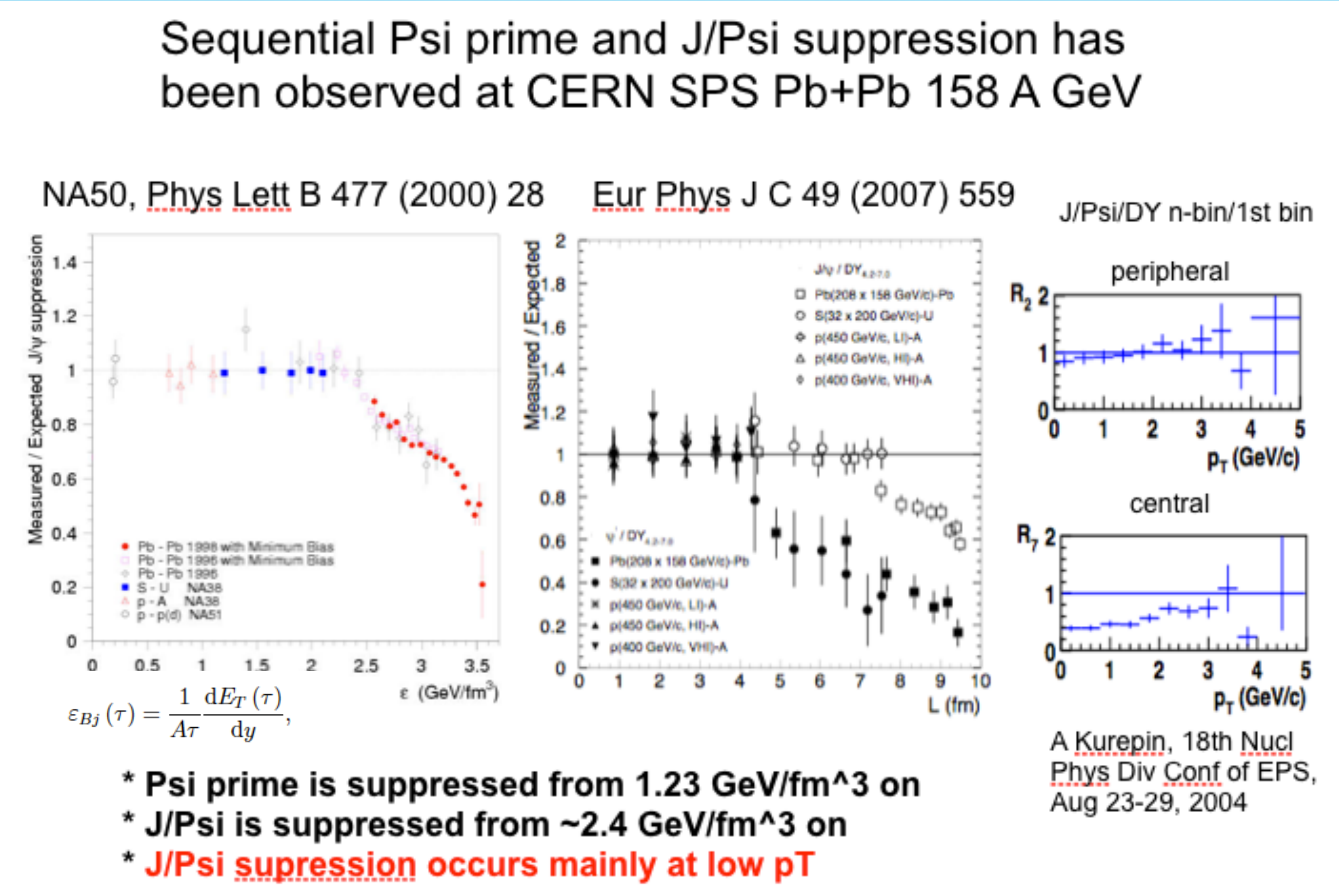


Ilia Grishmanovskii et al, PHYSICAL REVIEW C 110, 014908 (2024)

Results from JET collaboration agree with results from AdS/CFT correspondance shown here (left) with the arrows named NLO SYM

5. Quarkonia suppression

CERN press release 2000



Sequential Psi prime and J/Psi suppression has been observed at CERN SPS Pb+Pb 158 A GeV

NA50, Phys Lett B 477 (2000) 28

Eur Phys J C 49 (2007) 559

J/Psi/DY n-bin/1st bin

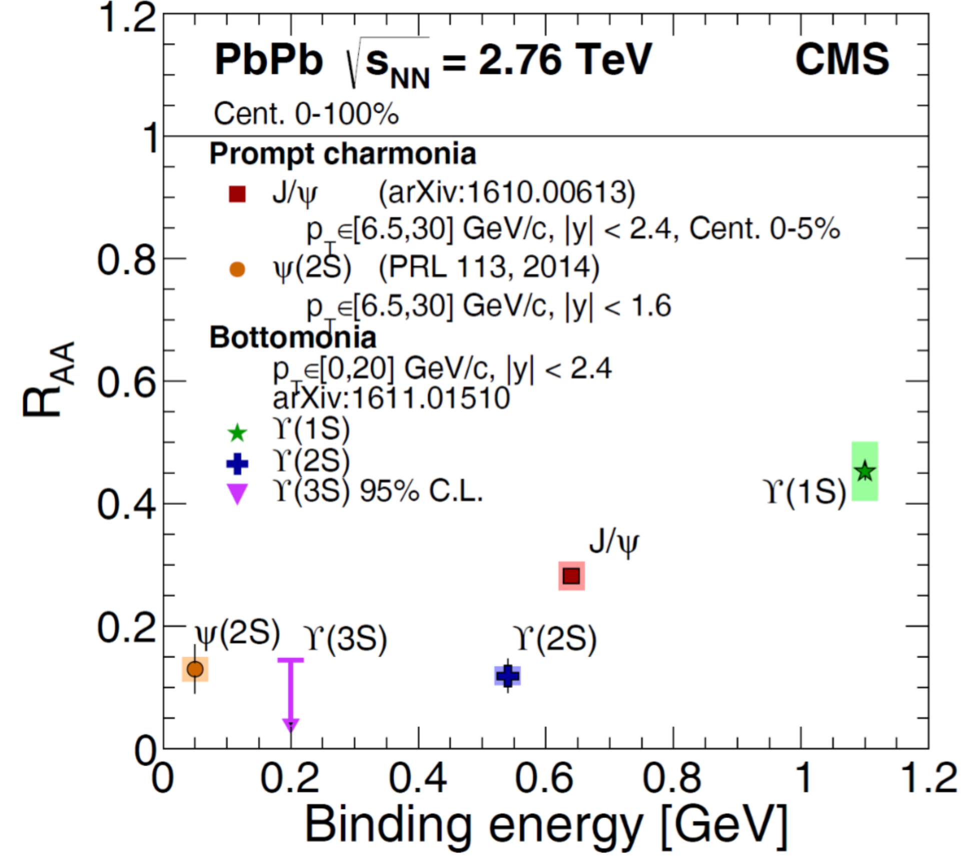
$$\varepsilon_{Bj}(\tau) = \frac{1}{A\tau}\frac{\mathrm{d}E_T(\tau)}{\mathrm{d}y},$$

A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

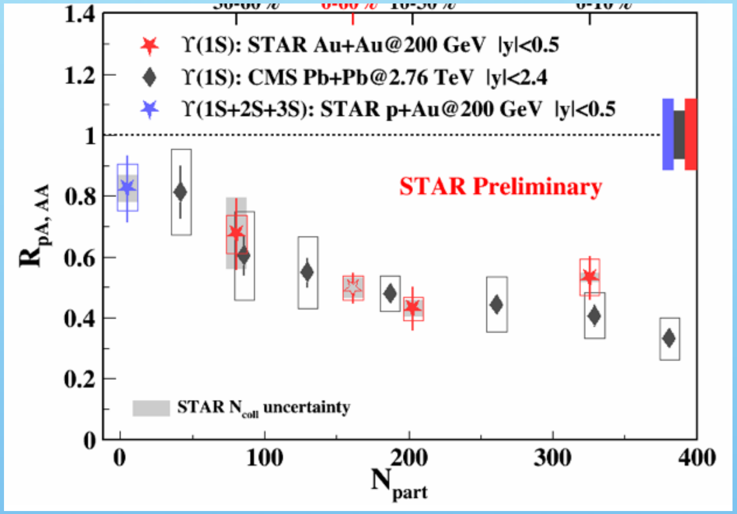
- **Psi prime is suppressed from 1.23 GeV/fm^3 on**
- **J/Psi is suppressed from ~2.4 GeV/fm^3 on**
- **J/Psi supression occurs mainly at low pT**

Hierarchy of quarkonia suppression has been observed at RHIC and LHC

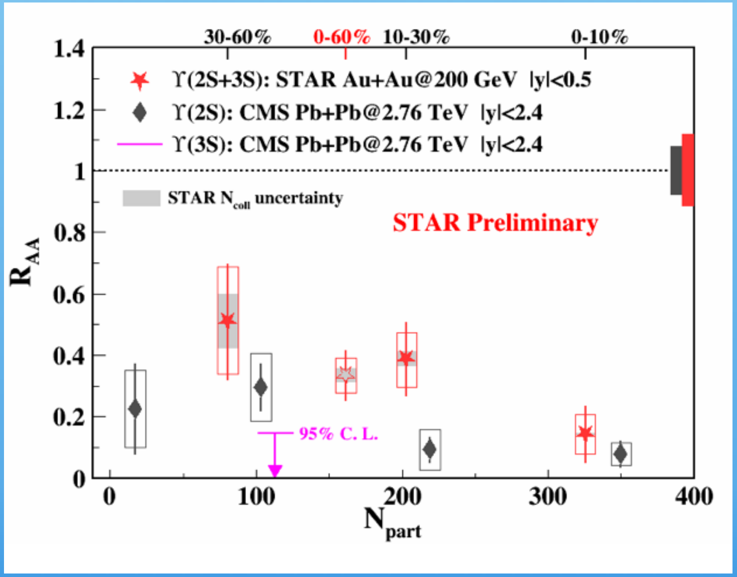
STAR, Z. Ye, QM2017



Y(1S)



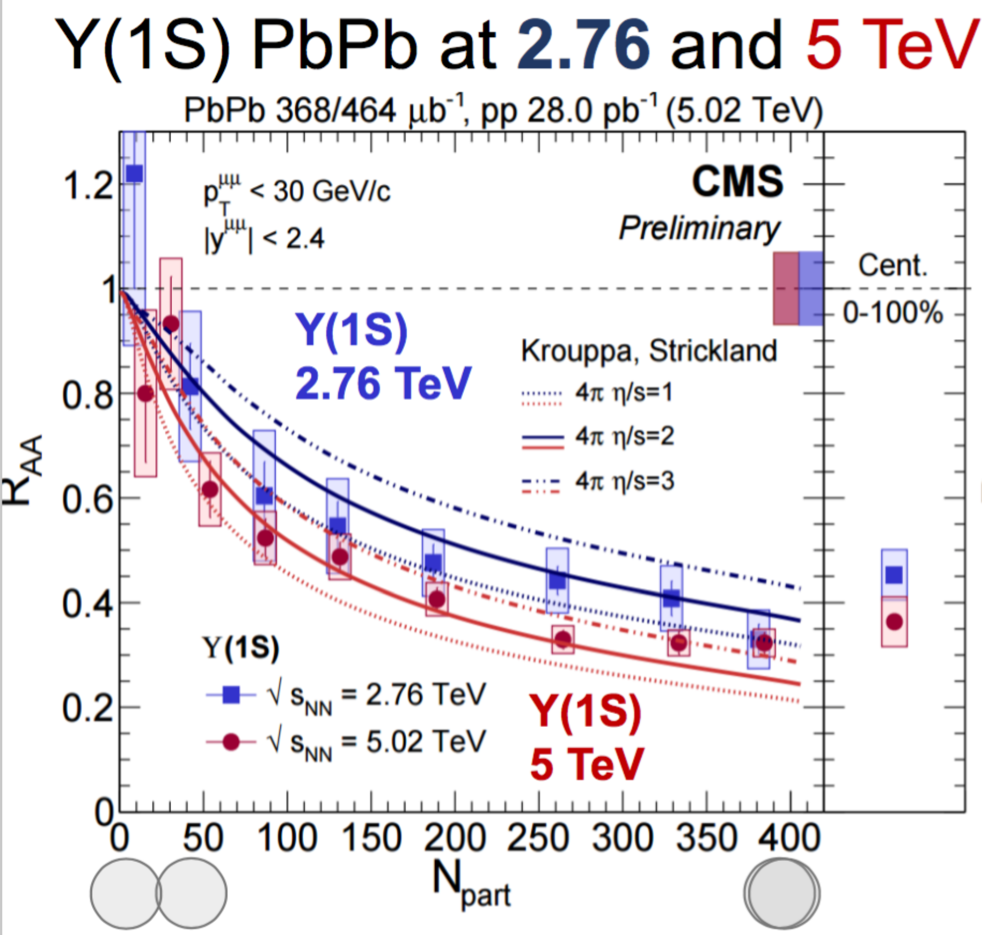
Y(2S+3S)

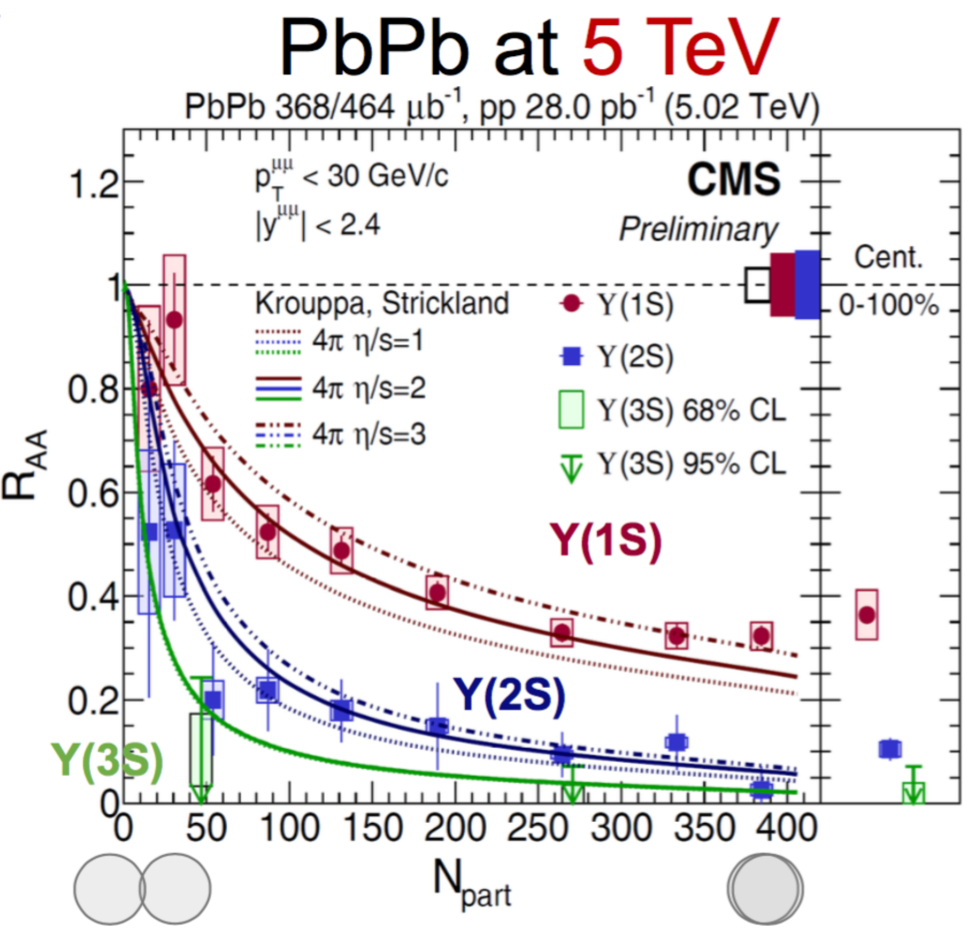


In central collisions Y(2S+3S) more suppressed than Y(1S)

Quarkonia at 5 TeV PbPb

CMS,J. J. Lee, QM2017 Y(1S) and Y(2S)


Y(1S) PbPb at **2.76** and **5 TeV**

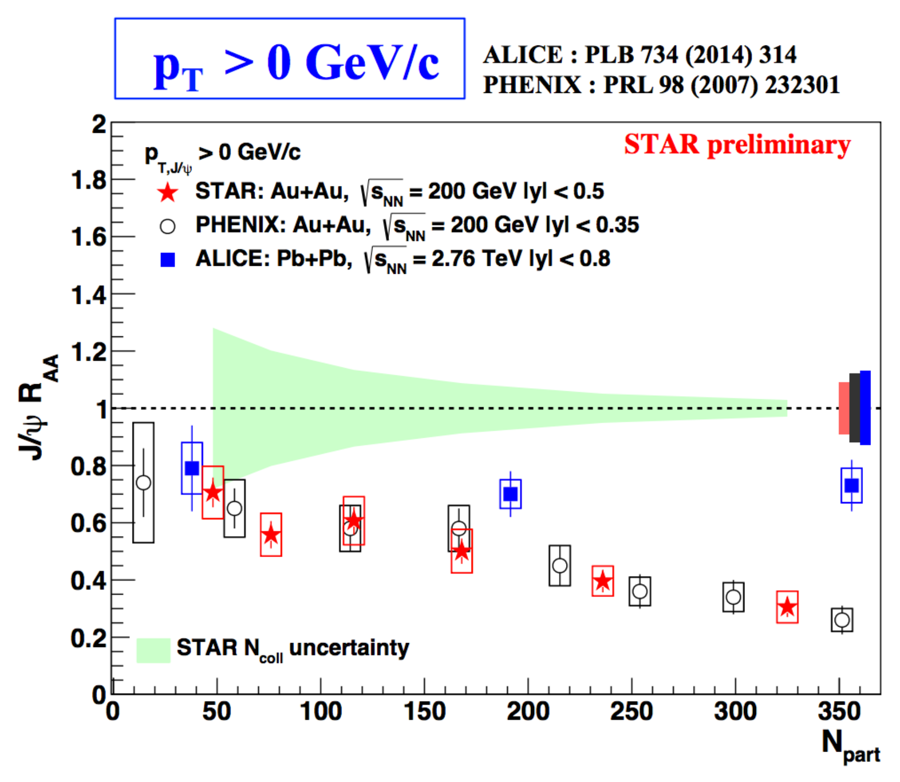

PbPb at **5 TeV**

- Indication of larger suppression at 5 TeV
- Consistent with predictions from a **hotter** and **denser** medium

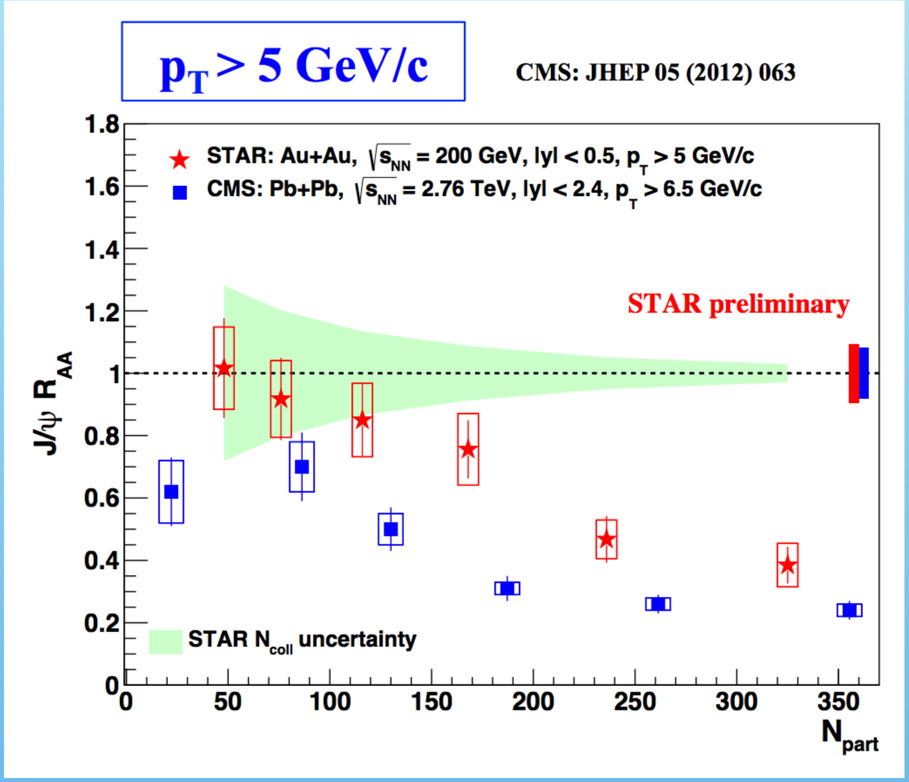
- Highest precision measurement
- Upsilon sequential suppression at 5 TeV
- Still no sign of Y(3S) with high statistics data

arXiv: 1611.01510
Submitted to PLB

J/Psi recombination at LHC



Low pT: RAA(ALICE) > RHIC



High pT : RAA at LHC more similar to RHIC

STAR, Z. Miller, WWND2017

RAA of J/Psi in Pb+Pb at LHC is below 1

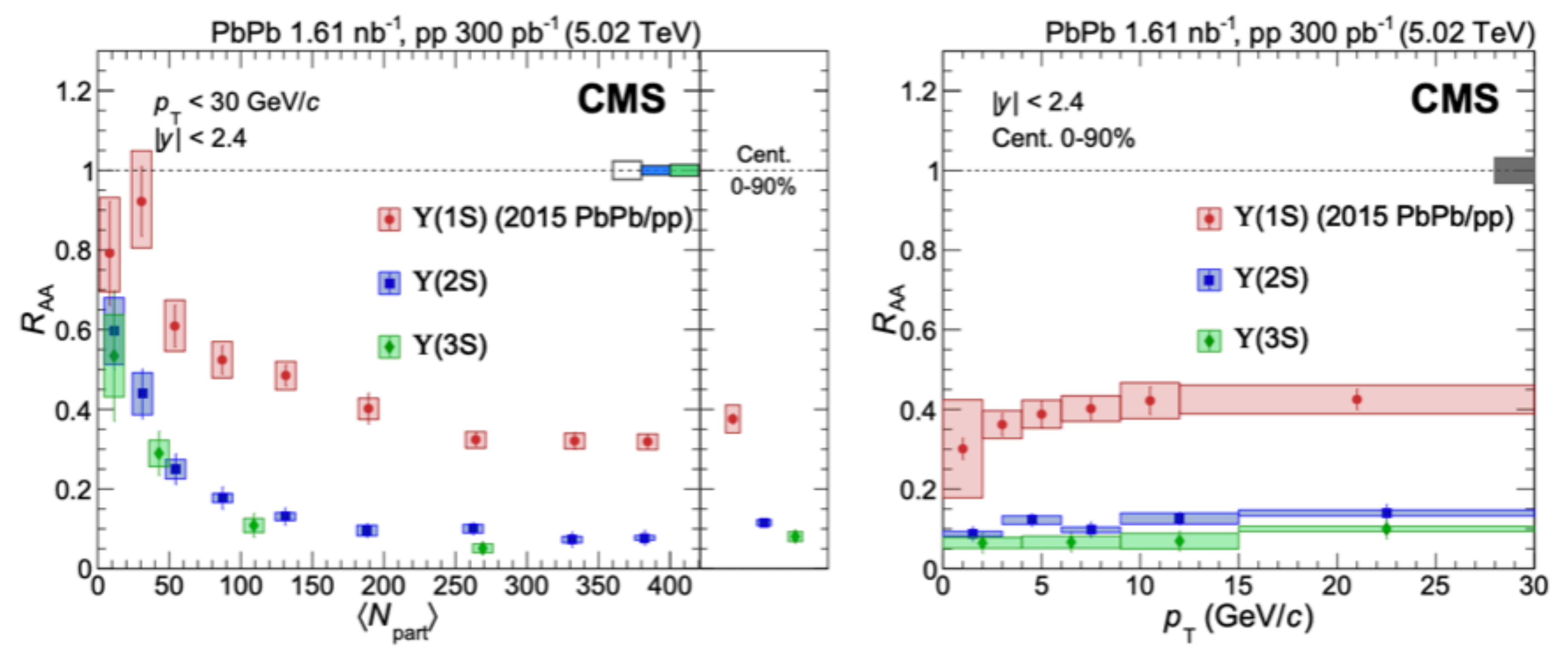
RAA of J/Psi is less suppressed at low pT, in central collisions ->

Indication of J/Psi regeneration at LHC at low pT

Upsilon suppression at LHC

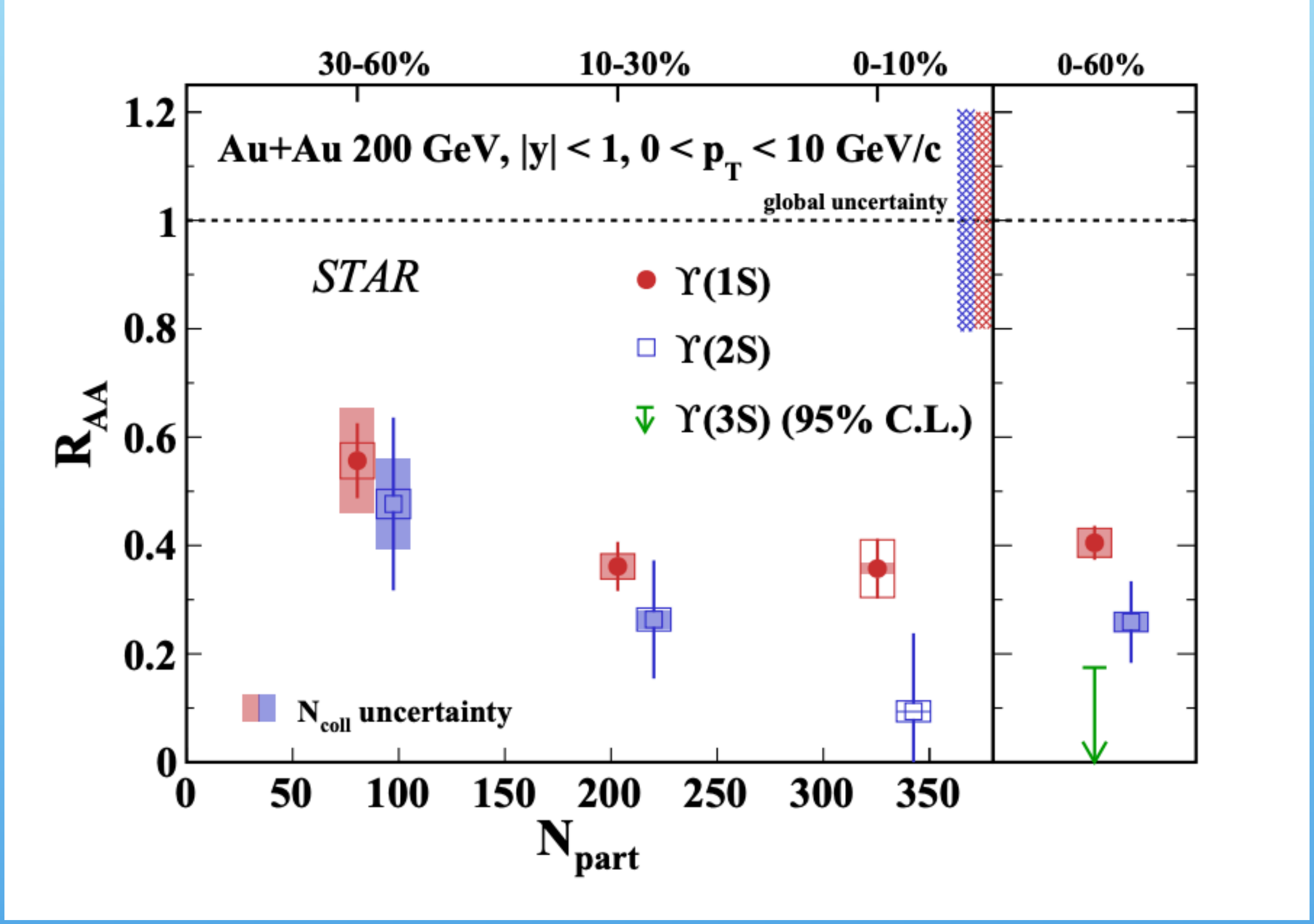
CMS

Phys. Rev. Lett. 133 (2024) 022302



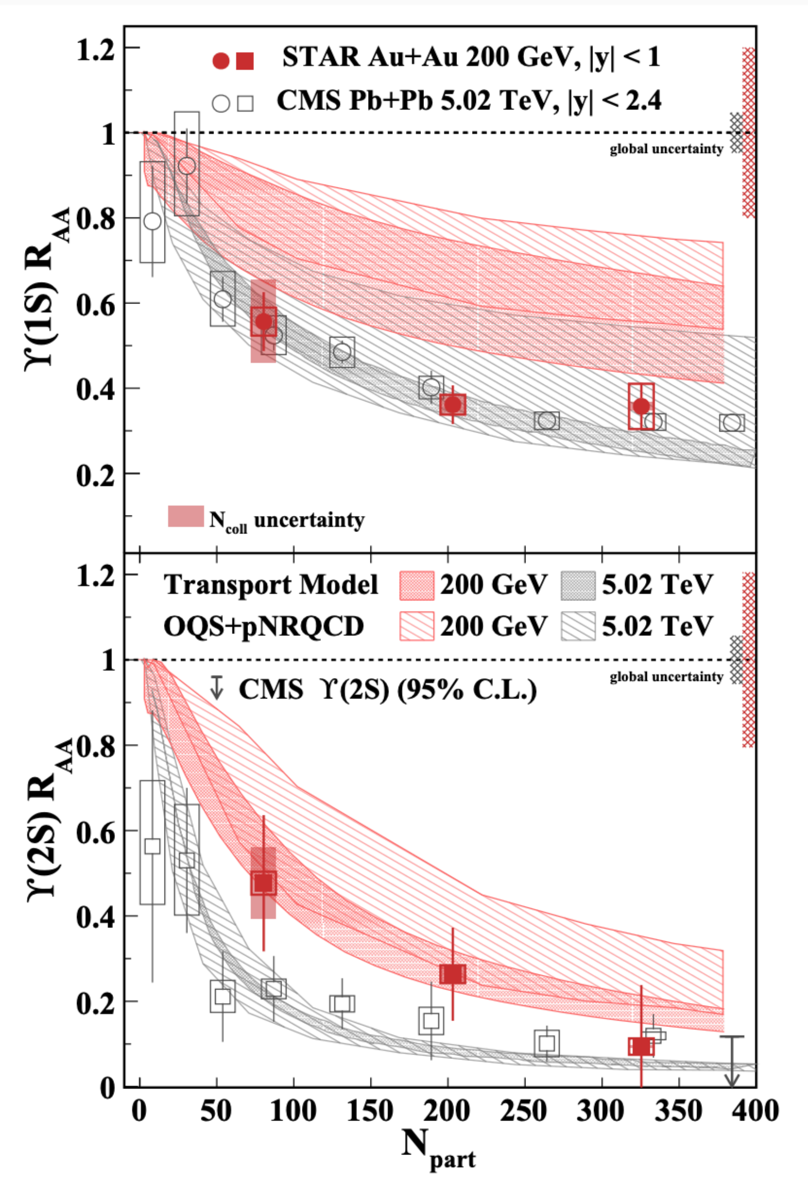
Observation of sequential suppression pattern at LHC

Upsilon suppression at RHIC



Observation of sequential suppression pattern at RHIC

Upsilon suppression at RHIC vs LHC



STAR Coll.

Upsilon Y(1S) shows similar suppression in RHIC and LHC

Y(2S) shows a hint of less suppression at RHIC

https://arxiv.org/pdf/2207.06568

6. Conclusions and outlook

Conclusions

- Over three decades of studies of heavy ion collisions at ultrarelativistic energies

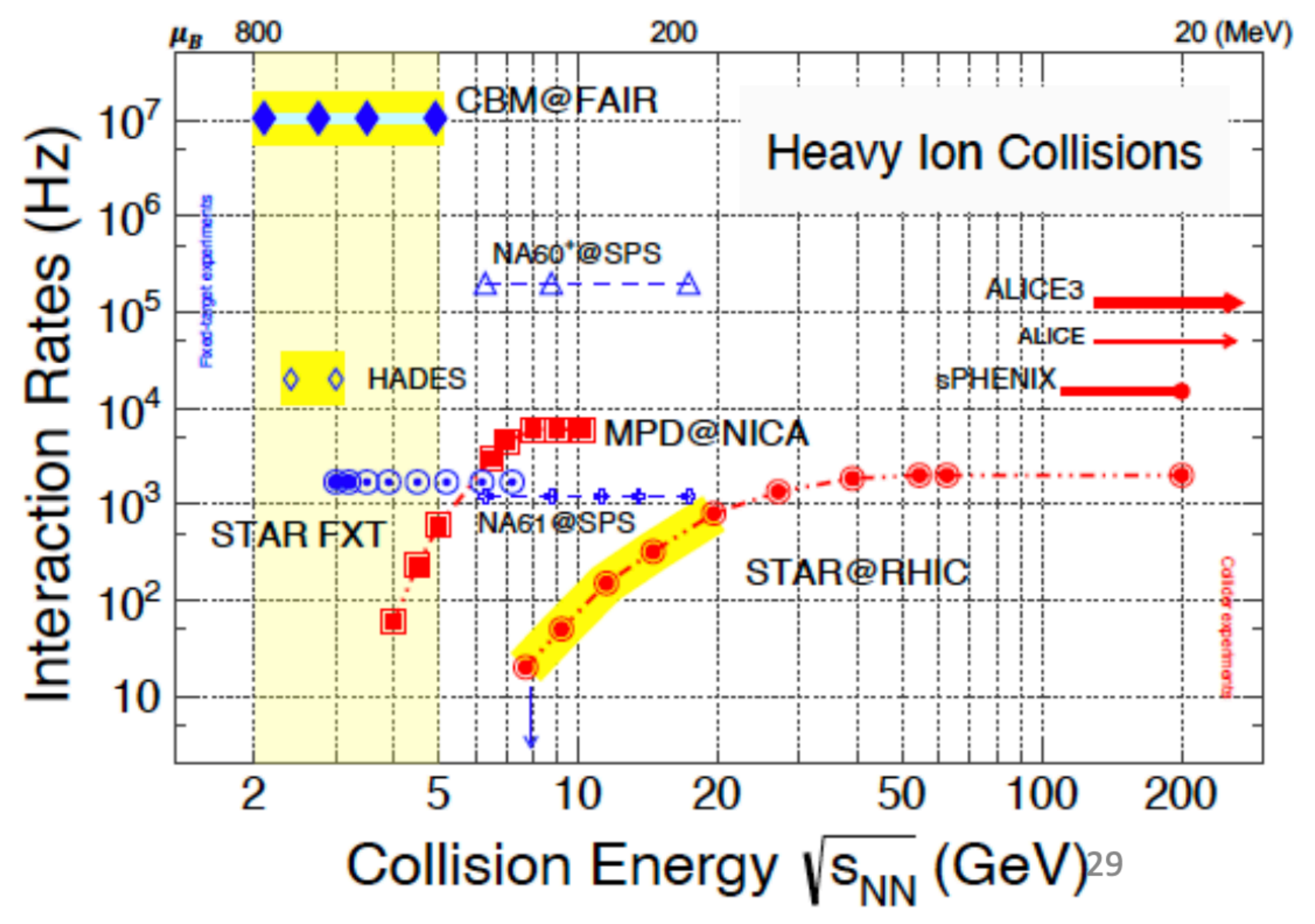
- Discovery of a new state of matter (CERN, SPS, RHIC, CERN, LHC) (Quark Gluon Plasma)

- We have obtained first quantitative estimates for characteristics of sQGP, like its shear viscosity, temperature, and vorticity. The sQGP has the smallest shear viscosity and the largest vorticity measured in fluids in the Lab.

Further studies are needed to study in detail and understand jet quenching, quarkonia suppression and other phenomena, search for a possible critical point and other new phenomena and map out the QCD phase diagram

Outlook

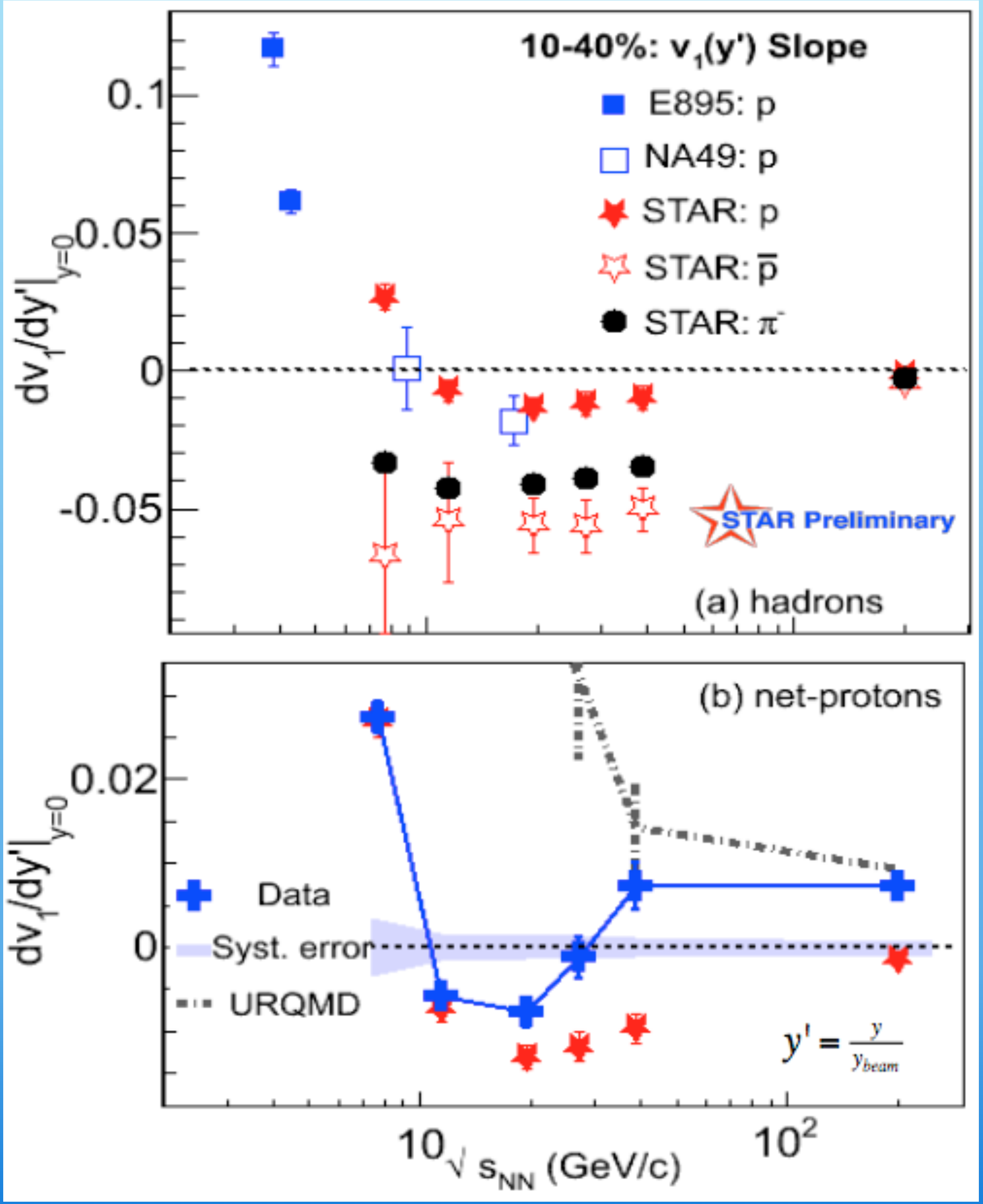
RHIC, BNL: sPHENIX, STAR, (PHENIX data analysis) (2024 pp AuAu), 2025 (AuAu)
SPS, CERN: NA61 (till 2027), NA60+ (2029)
LHC, CERN: ATLAS,CMS,ALICE, LHCb
New colliders: NICA at DUBNA (MPD), Russia and FAIR in Germany (CBM)



Thank you very much

Backup slides

Directed flow of protons BES 1



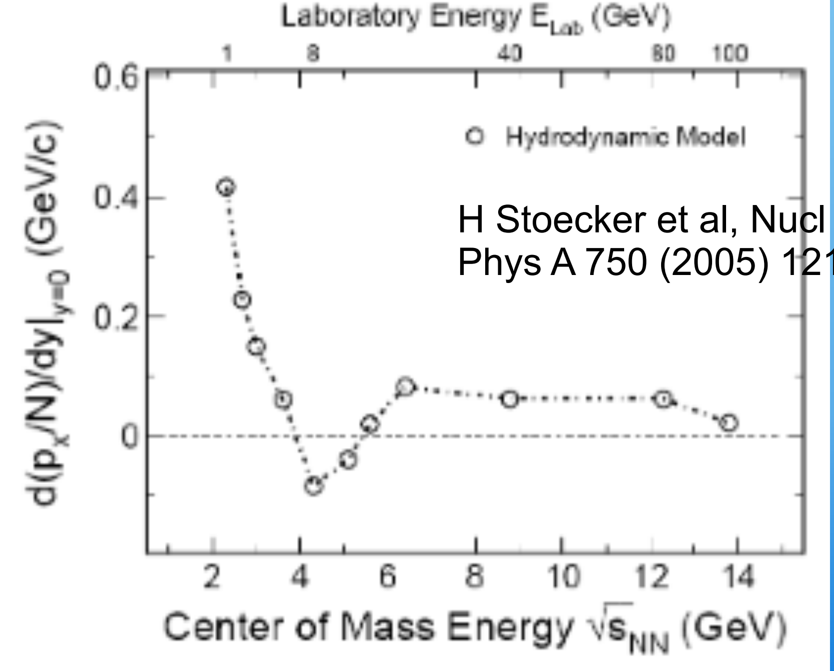
* Directed flow slope is sensitive to a 1st order transition

* STAR: v_1 slope changes sign from positive to negative between 7.7 and 11.5 GeV

Pions and antiprotons have always negative v1 slopes.

* Net-proton v_1 slope shows a minimum around 11.5-19.6 GeV

UrQMD model (model without phase transition) cannot explain the data

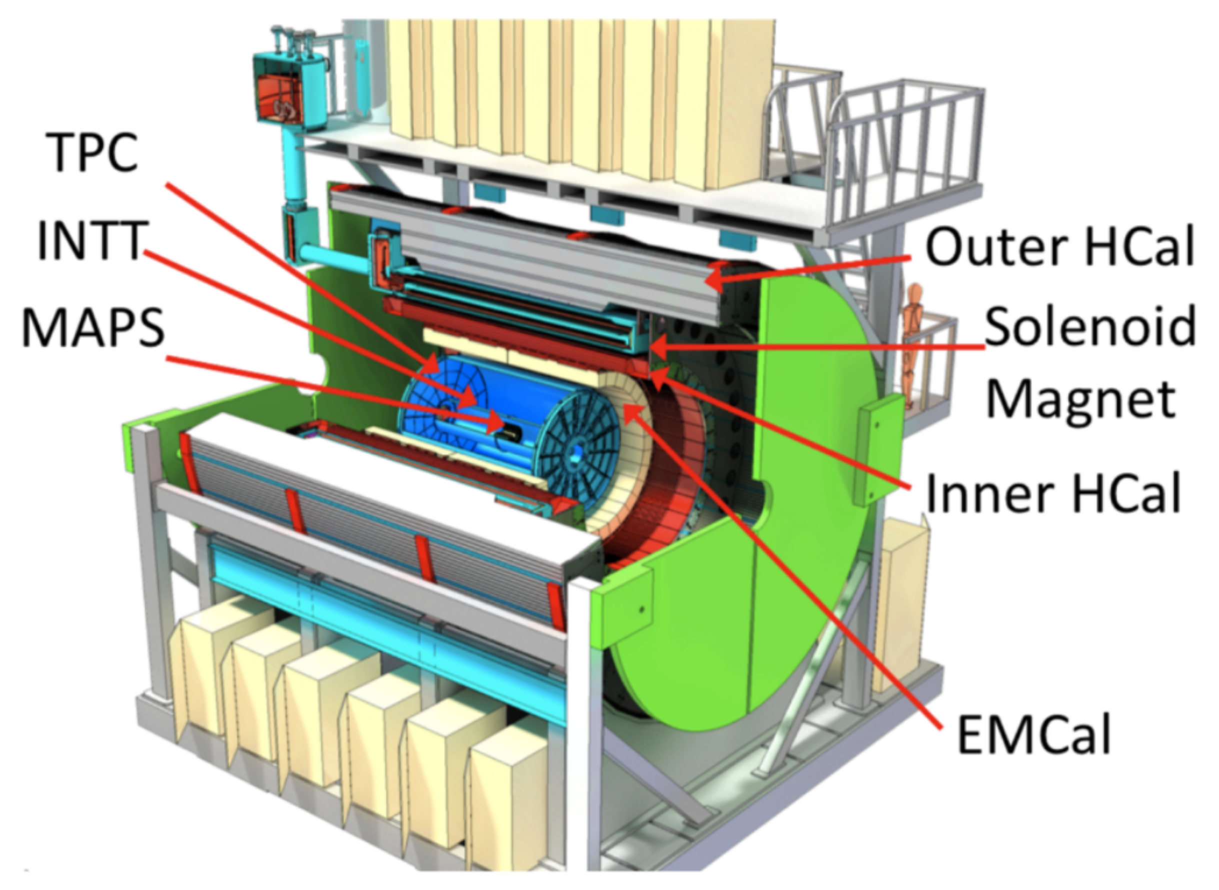


H Stoecker et al, Nucl Phys A 750 (2005) 121

- STAR upgrades for BES-II and 2020+
- New detector project at RHIC: sPHENIX

sPHENIX: start data taking 2022

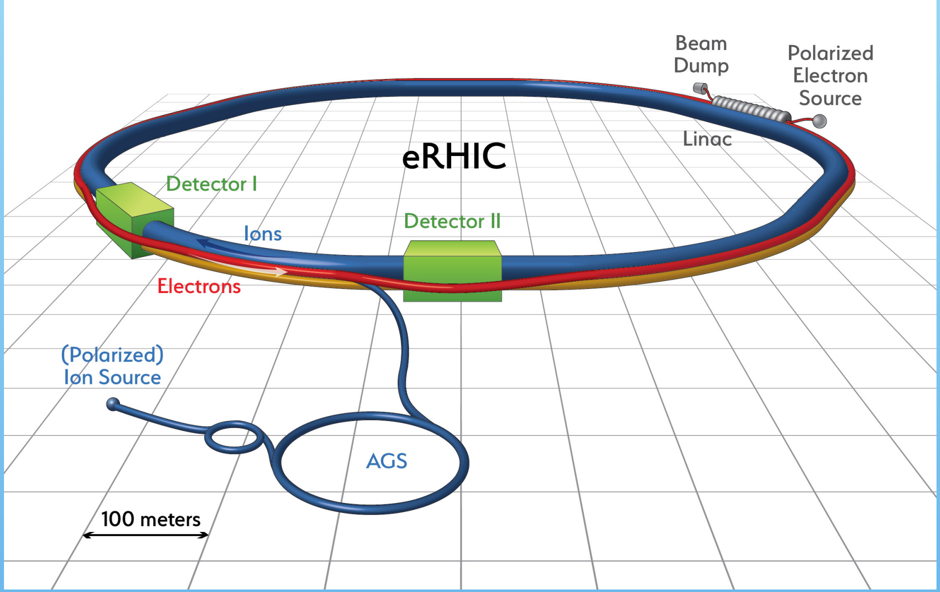
Extended Calorimetry precision vertexing and tracking for jet quenching, charm, beauty

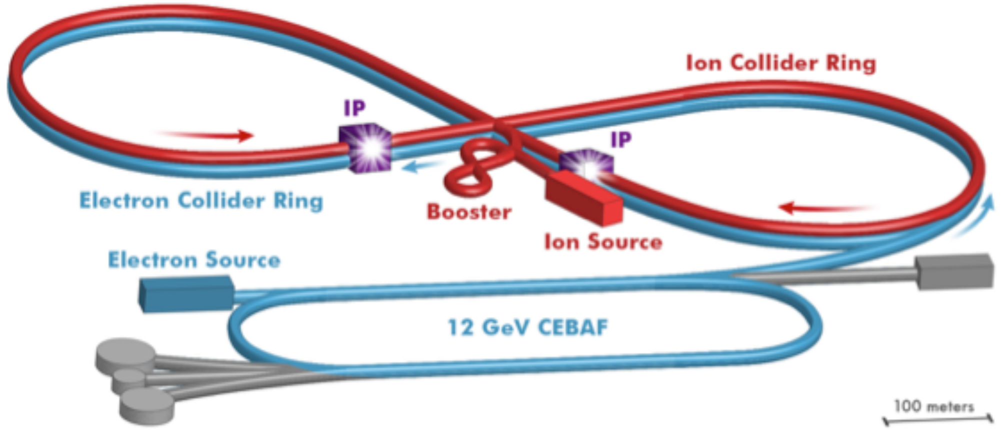


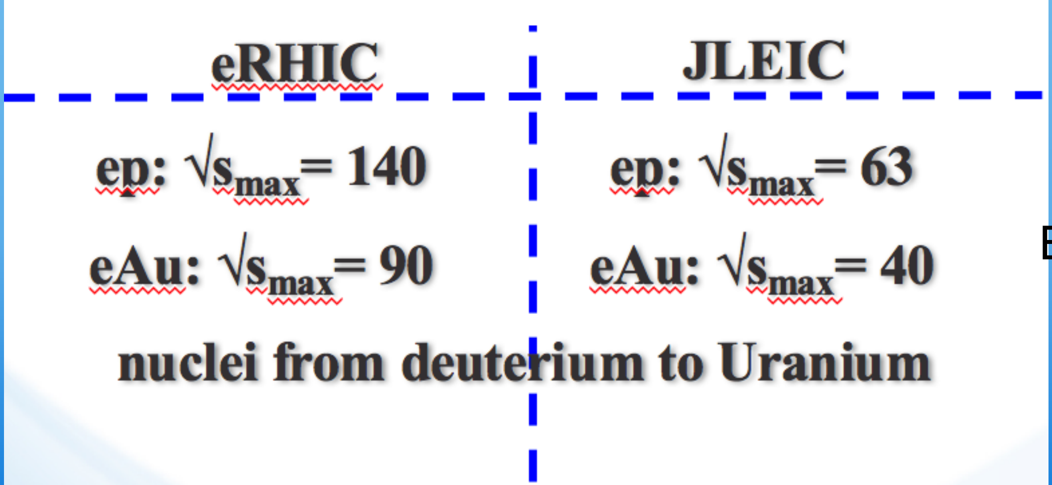
M. Connors,
Nucl.Phys. A967 (2017) 548-551

Electron Ion Collider EIC
eRHIC at BNL / JLEIC at JLAB

Start of construction estimated: 2022-2023

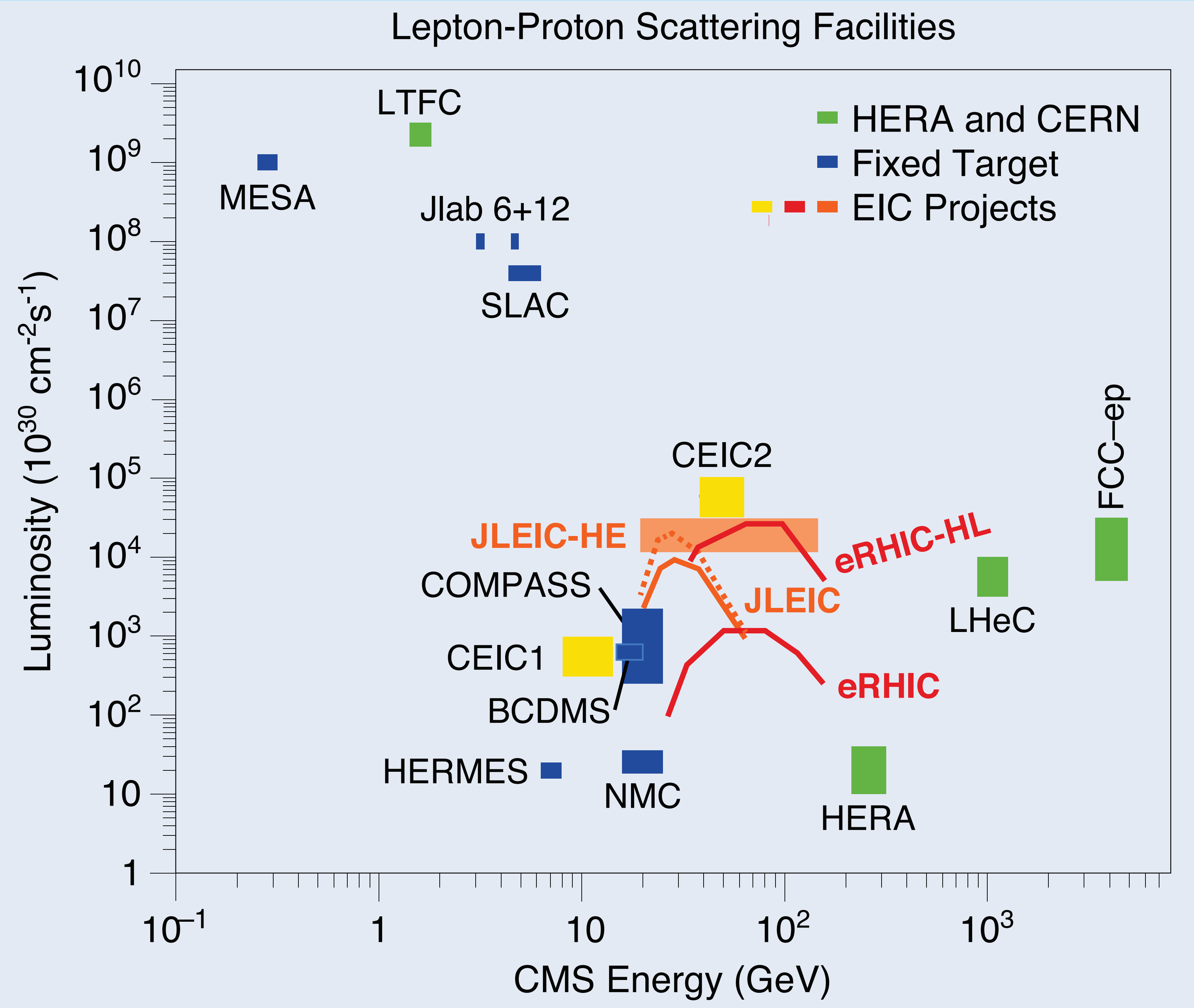






eRHIC	JLEIC
ep: $\sqrt{s}_{max} = 140$	ep: $\sqrt{s}_{max} = 63$
eAu: $\sqrt{s}_{max} = 90$	eAu: $\sqrt{s}_{max} = 40$
nuclei from deuterium to Uranium	

E. Aschenauer, ICNFP2017



E. Aschenauer, ICNF2017

Multi-parameter estimates from a variety of data

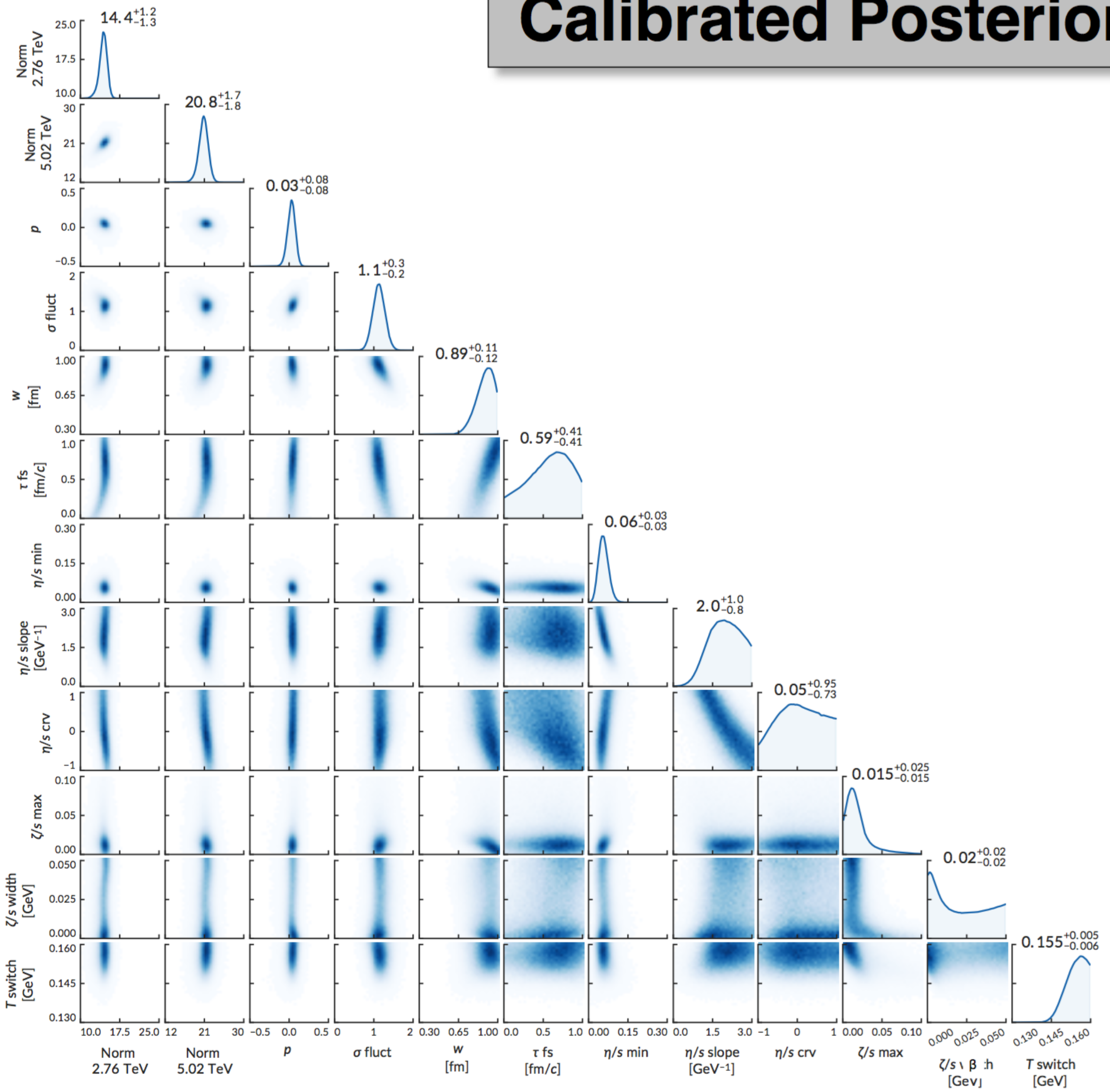
Multiple parameter estimation

Important progress in estimating properties of QGP using statistical analysis methods and a multi-parameter model-to-data comparison, with many different data (flow, spectra, etc)

S Bass et al Phys.Rev. C94 (2016) no.2, 024907, and others

Review: S. Bass, QM2017,

Calibrated Posterior Distribution



- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

Example of results I:

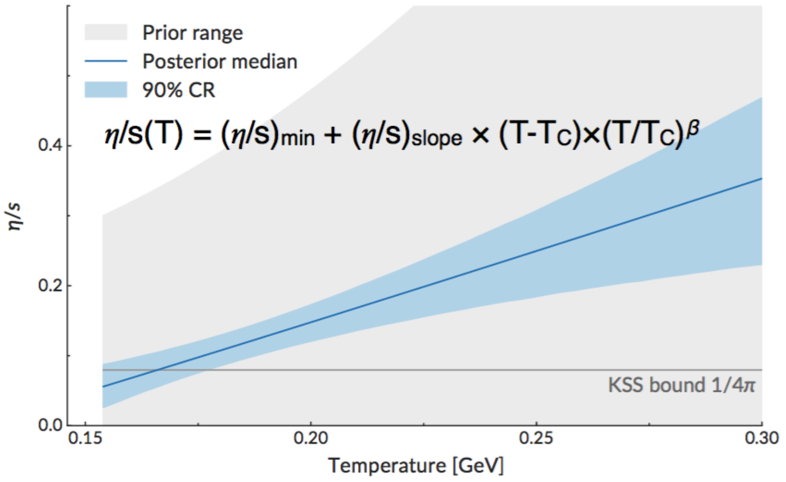
Review: S. Bass, QM2017,

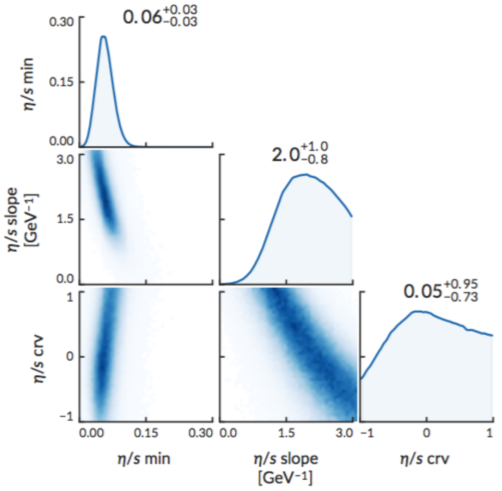
Temperature Dependence of Shear & Bulk Viscosities

temperature dependent shear viscosity:

- analysis favors small value and shallow rise
- results do not fully constrain temperature dependence:
  - inverse correlation between $(\eta/s)_{\mathrm{slope}}$ slope and intercept $(\eta/s)_{\mathrm{min}}$
  - insufficient data to obtain sharply peaked likelihood distributions for $(\eta/s)_{\mathrm{slope}}$ and curvature β independently
- current analysis most sensitive to T< 0.23 GeV

▸ **RHIC data may disambiguate further**



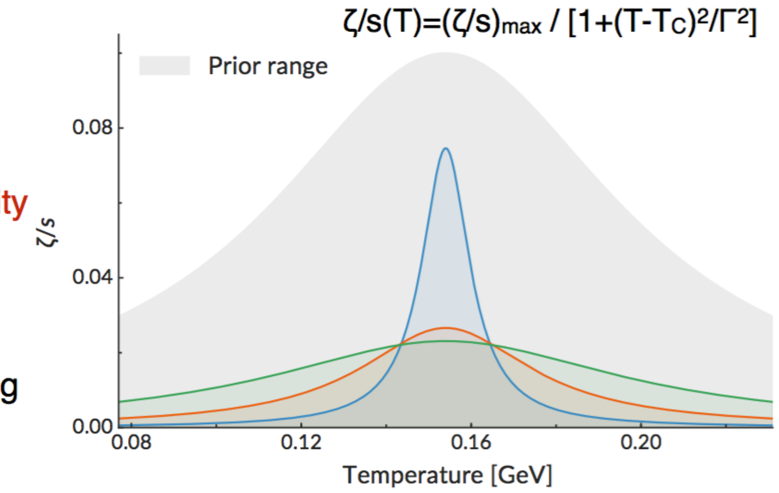


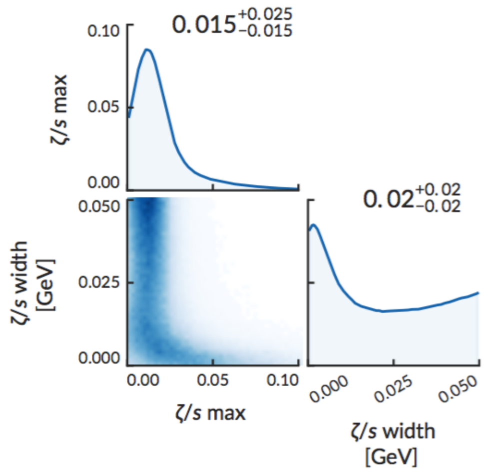
temperature dependent bulk viscosity:

- setup of analysis allows for vanishing value of bulk viscosity
- significant non-zero value at T_C favored, confirming the presence / need for bulk viscosity
- either high sharp peak or broad & shallow temperature dependence

caveat of current analysis:

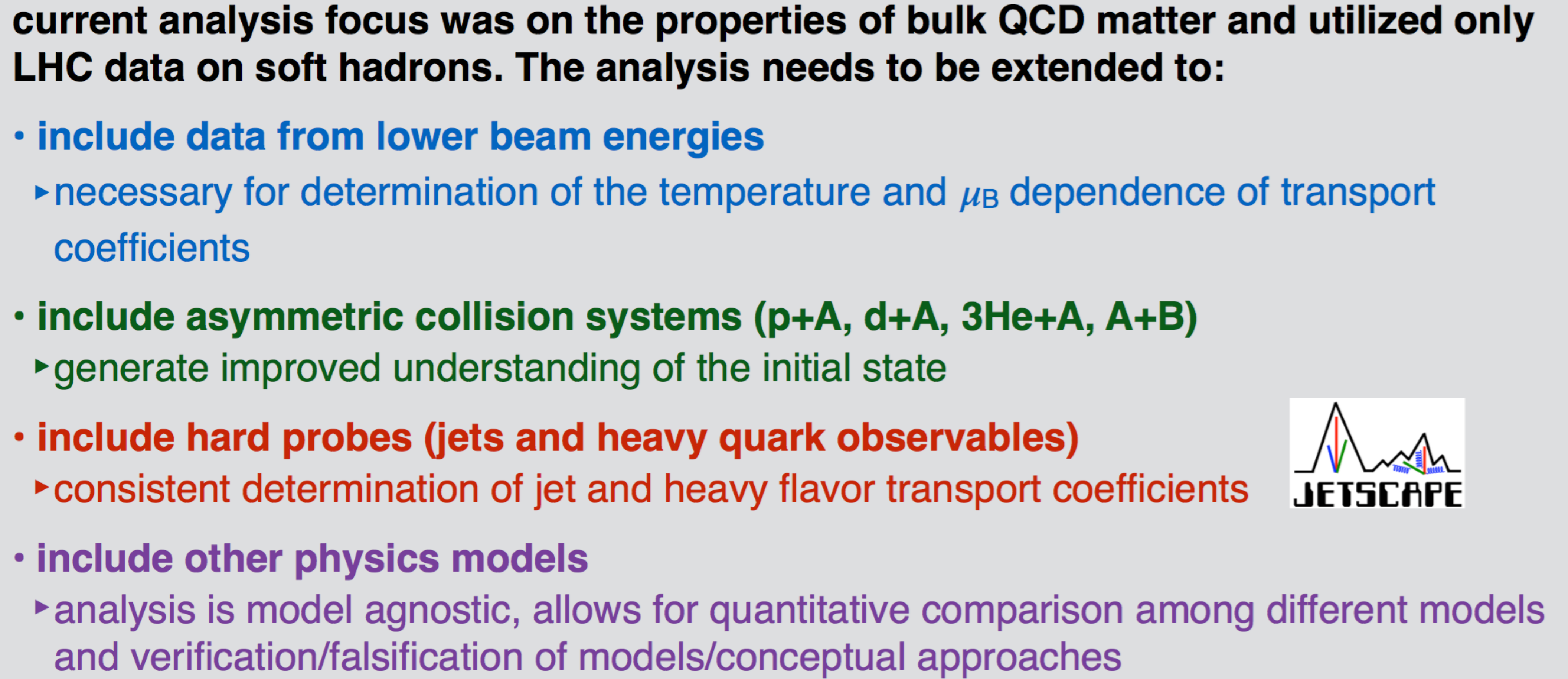
- bulk-viscous corrections are implemented using relaxation-time approximation & regulated to prevent negative particle densities





Needed developments

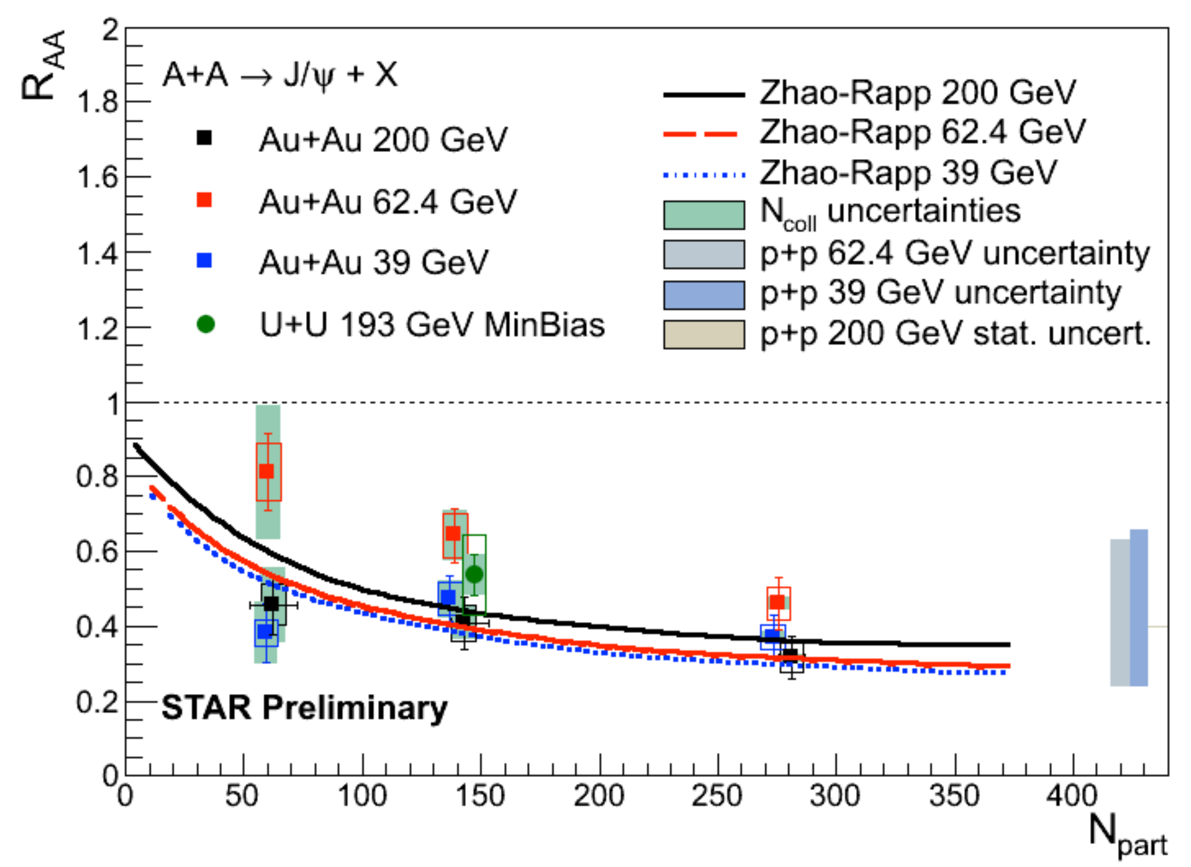
Review: S. Bass, QM2017,



current analysis focus was on the properties of bulk QCD matter and utilized only LHC data on soft hadrons. The analysis needs to be extended to:

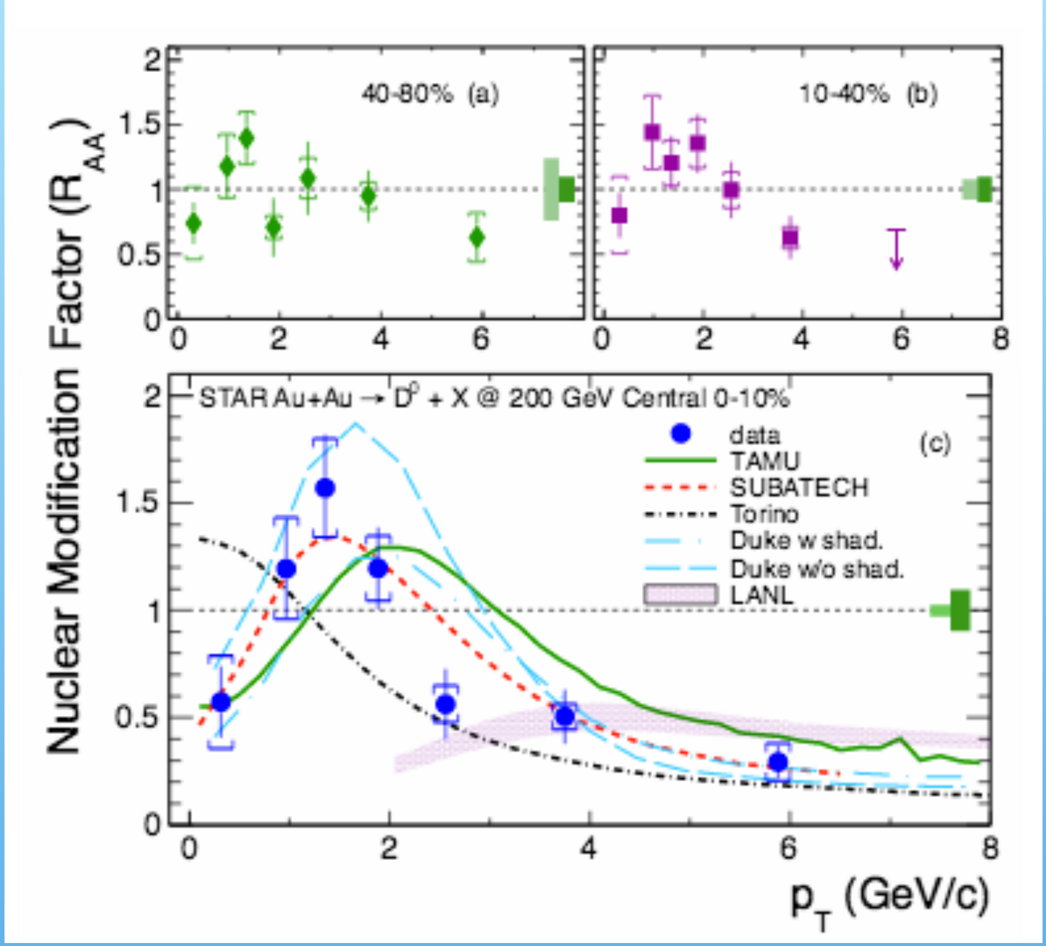
- **include data from lower beam energies**
  - necessary for determination of the temperature and μ_B dependence of transport coefficients
- **include asymmetric collision systems (p+A, d+A, 3He+A, A+B)**
  - generate improved understanding of the initial state
- **include hard probes (jets and heavy quark observables)**
  - consistent determination of jet and heavy flavor transport coefficients
- **include other physics models**
  - analysis is model agnostic, allows for quantitative comparison among different models and verification/falsification of models/conceptual approaches

RHIC Beam Energy Scan:
At which energy does J/Psi suppression turn off?

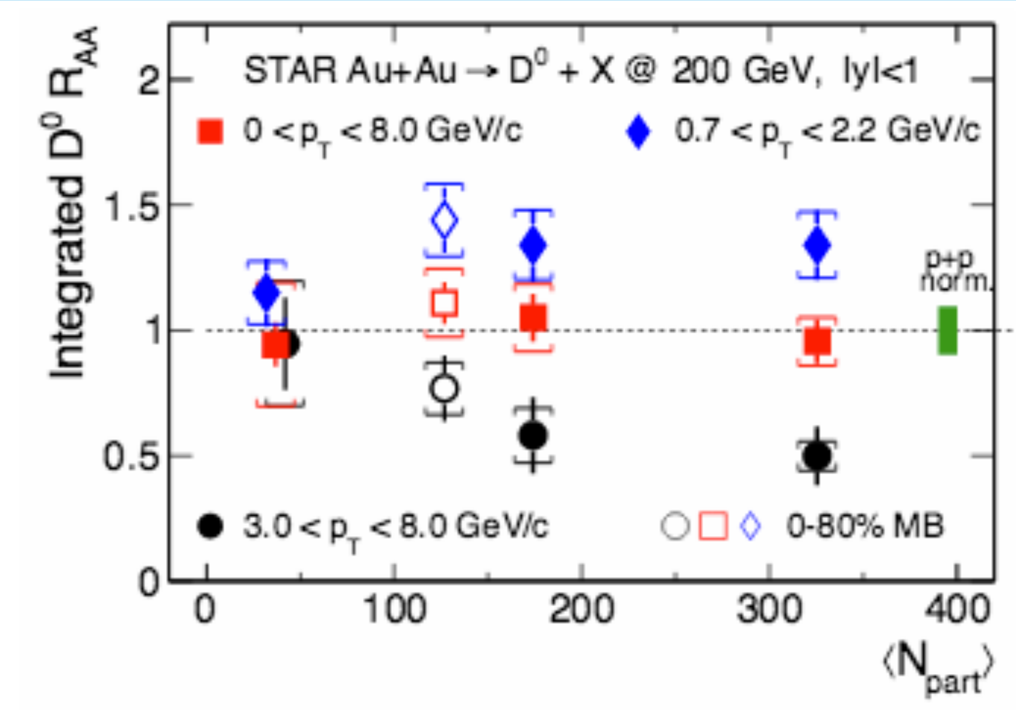


Color Evaporation Model (CEM) estimate for p+p reference used for 39, 62 GeV
R_{AA} in U+U 193 GeV is consistent within errors with Au+Au 200 GeV
R_{AA} of J/Psi is suppressed in similar way at 39, 62 and 200 GeV

STAR R_{AA} of D_0 in Au+Au 200 GeV



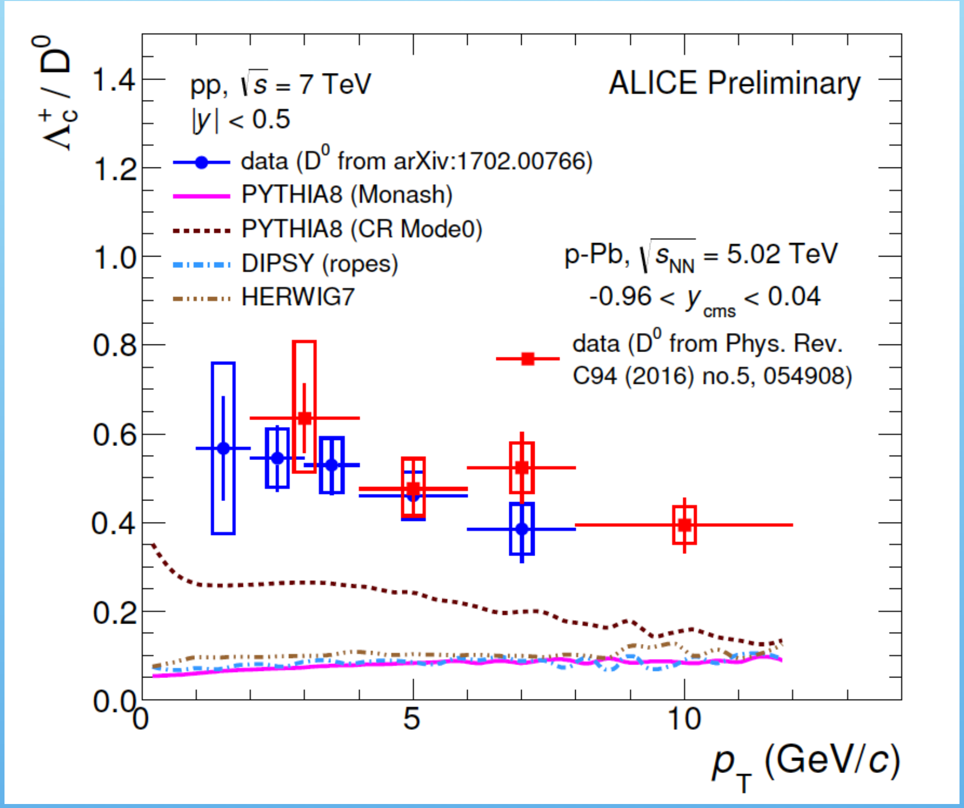
STAR: Phys. Rev. Lett. **113** (2014) 142301 and 1404.6185

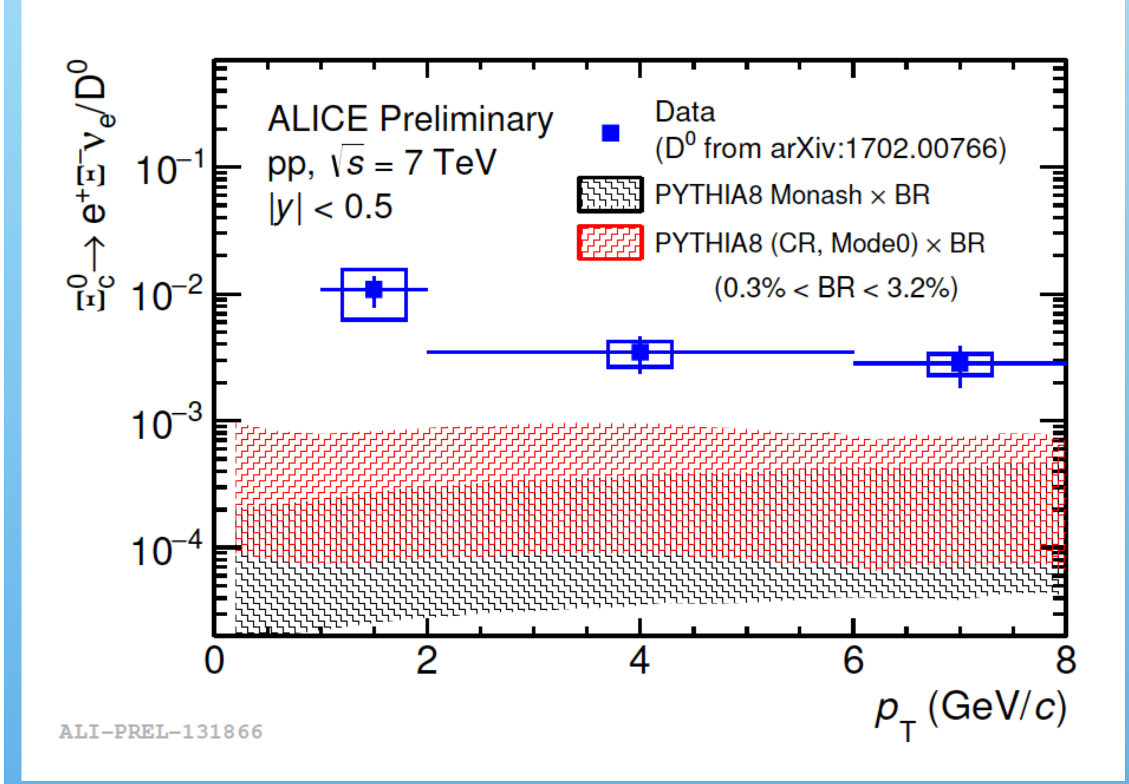


R_{AA} of D_0 at high p_T:

- RAA D0 suppression in central Au+Au 200 GeV
- suppression at high p_T similar to pions
- Enhancement at pT~0.7-2 GeV (described eg by models with charm quark coalescence with light quarks)

ALICE charmed baryons





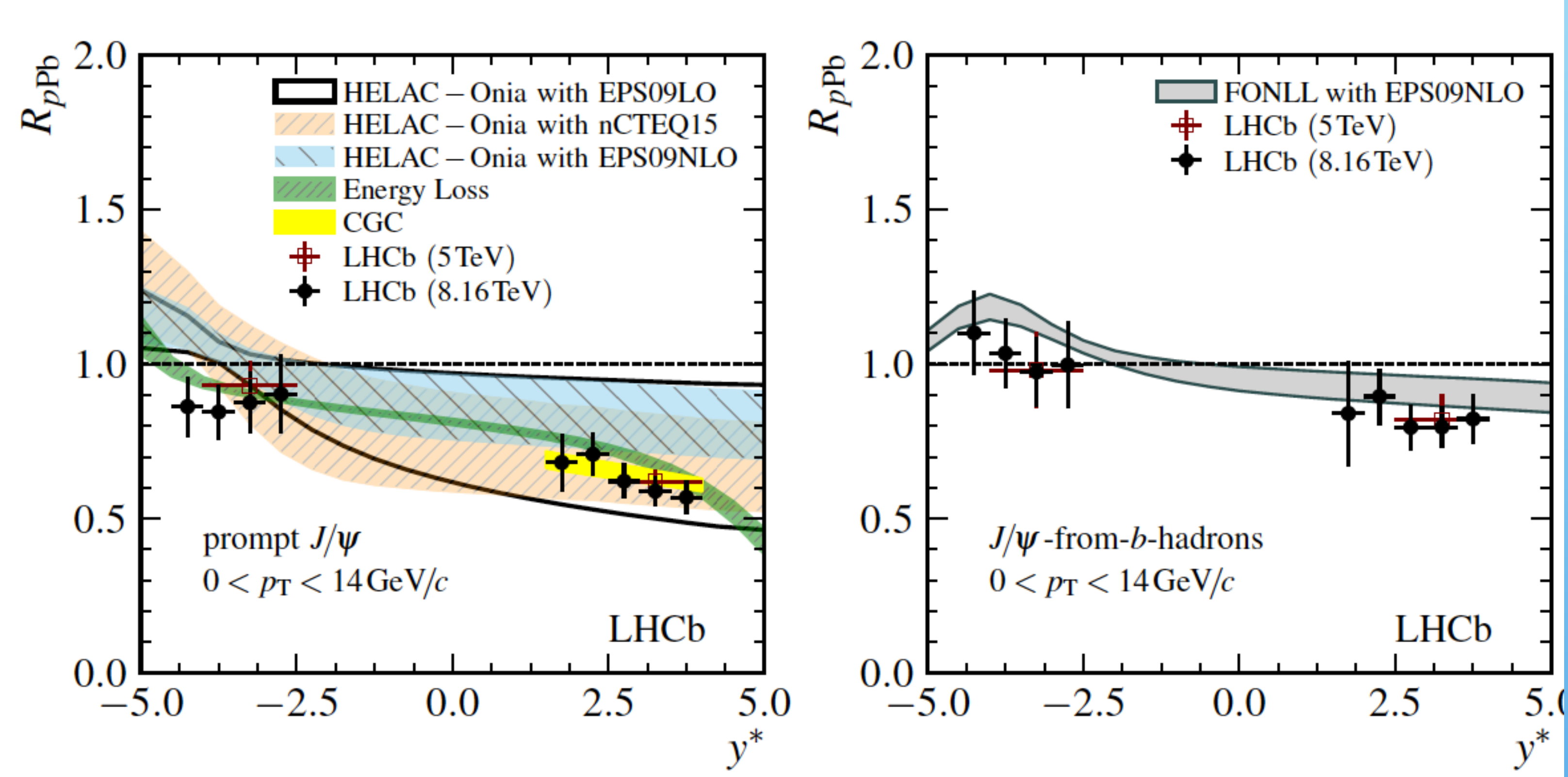
T Dahms, ICNFP

* New charmed baryon measurements from ALICE

* Charmed baryon to meson ratios are not well described by event generators

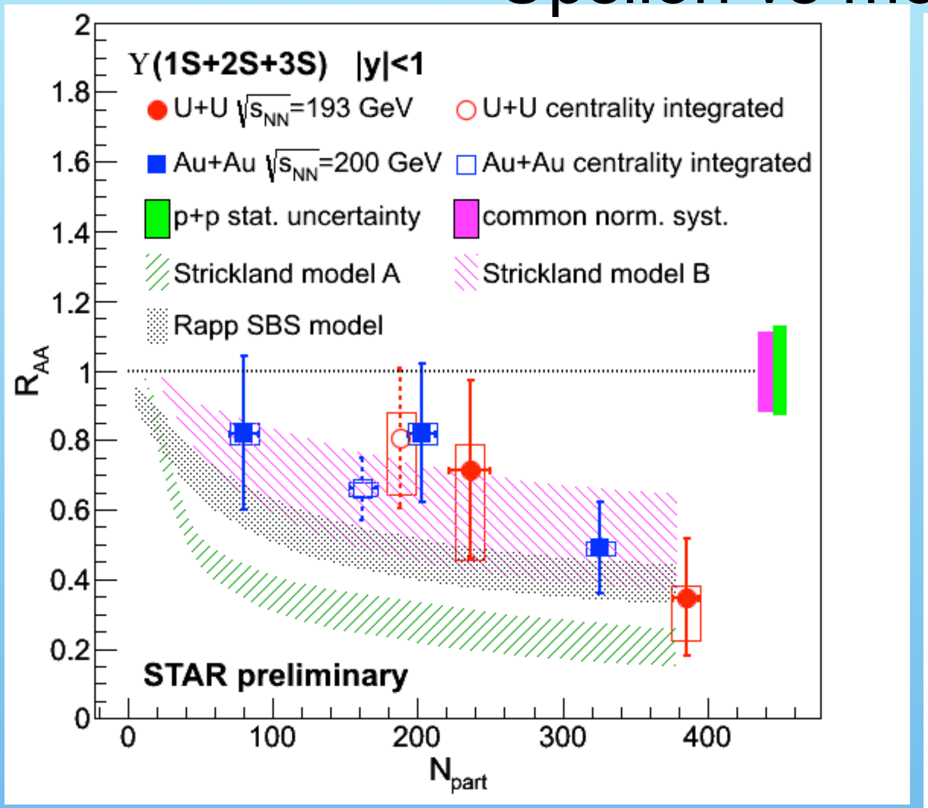
LHCb J/Psi and B->J/Psi in p+Pb

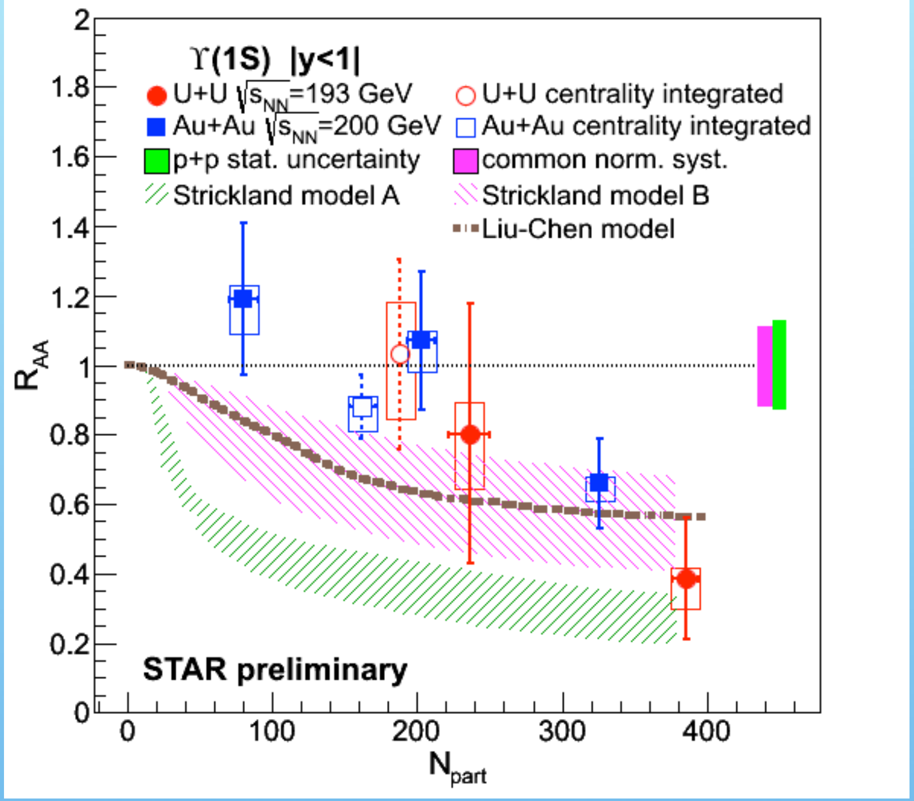
LHCb, 1706.07122



At backward rapidity prompt J/Psi not well described by models

Upsilon vs models at RHIC





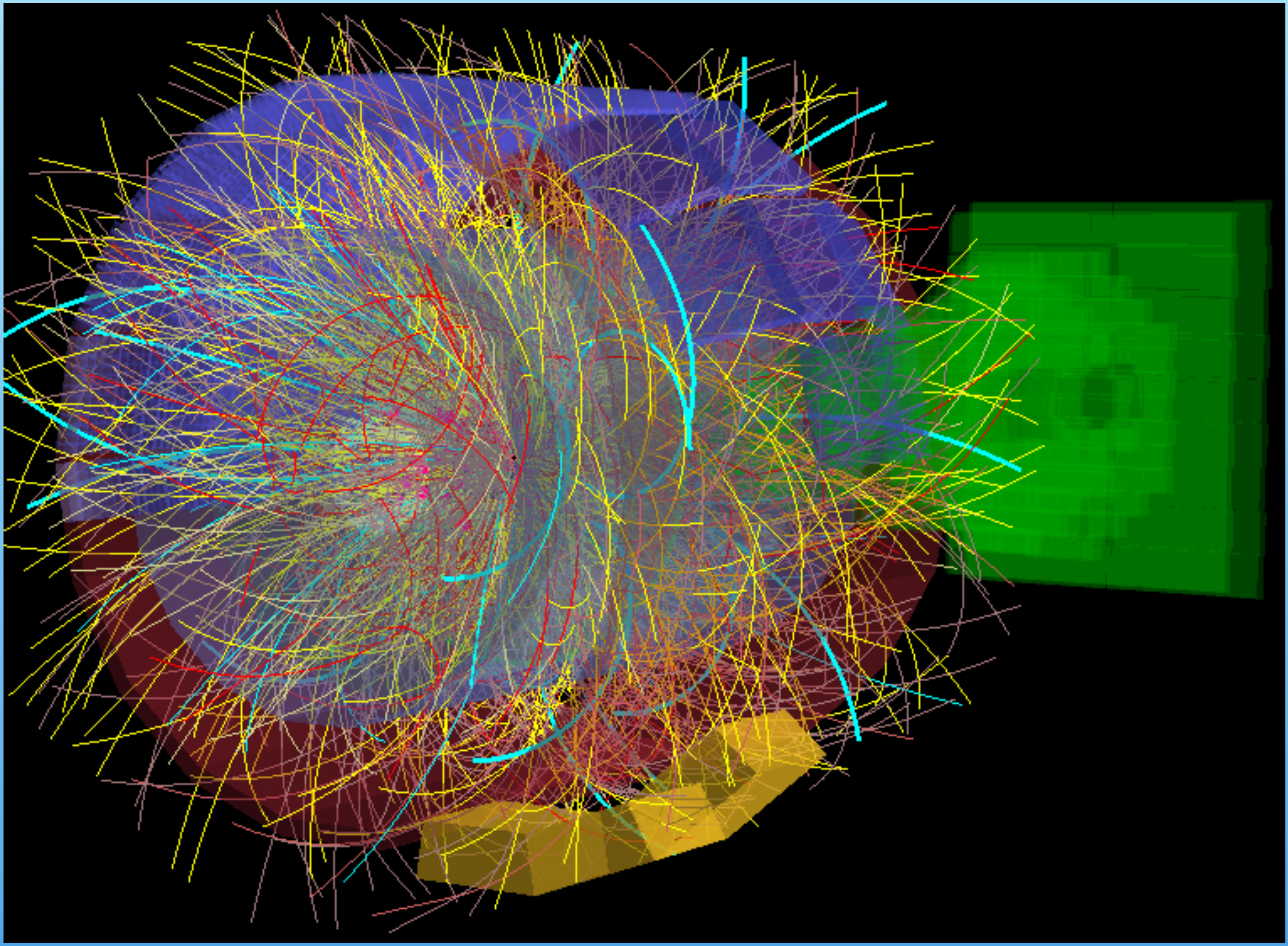
*** Model of Strickland, Bazov (Nucl. Phys. A 879, 25 (2012))**
No Cold Nuclear Matter effects
T(initial)=428-443 MeV
Potential model A is based on heavy quark free energy (disfavored)
Potential model B is based on heavy quark internal energy

*** Model of Liu, Chen, Xu, Zhuang (Phys Lett B 697, 32 (2011)**
Potential model, no Cold Nuclear Matter effects. T= 340 MeV

*** Model of Emerick, Zhaon, Rapp (Eur. Phys. J A48, 72 (2012))**
Cold Nuclear Matter effects included

Y data in agreement with Y melting scenario

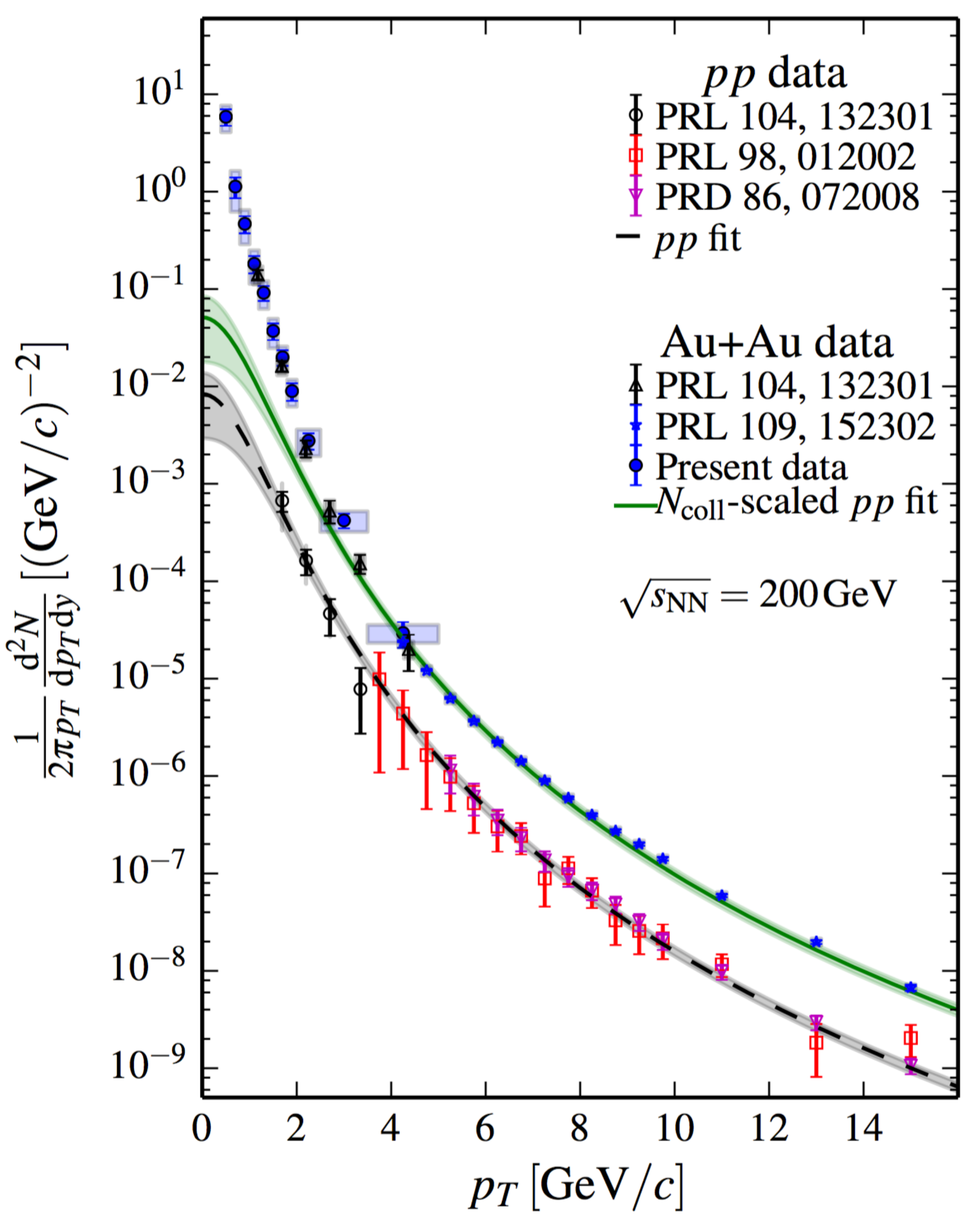
ALICE event Pb+Pb sqrt(s)=2.76 TeV



1800 charged particles per rapidity unit at midrapidity

PHENIX
AuAu 200 GeV

Wenqing Fan, ICNFP2017



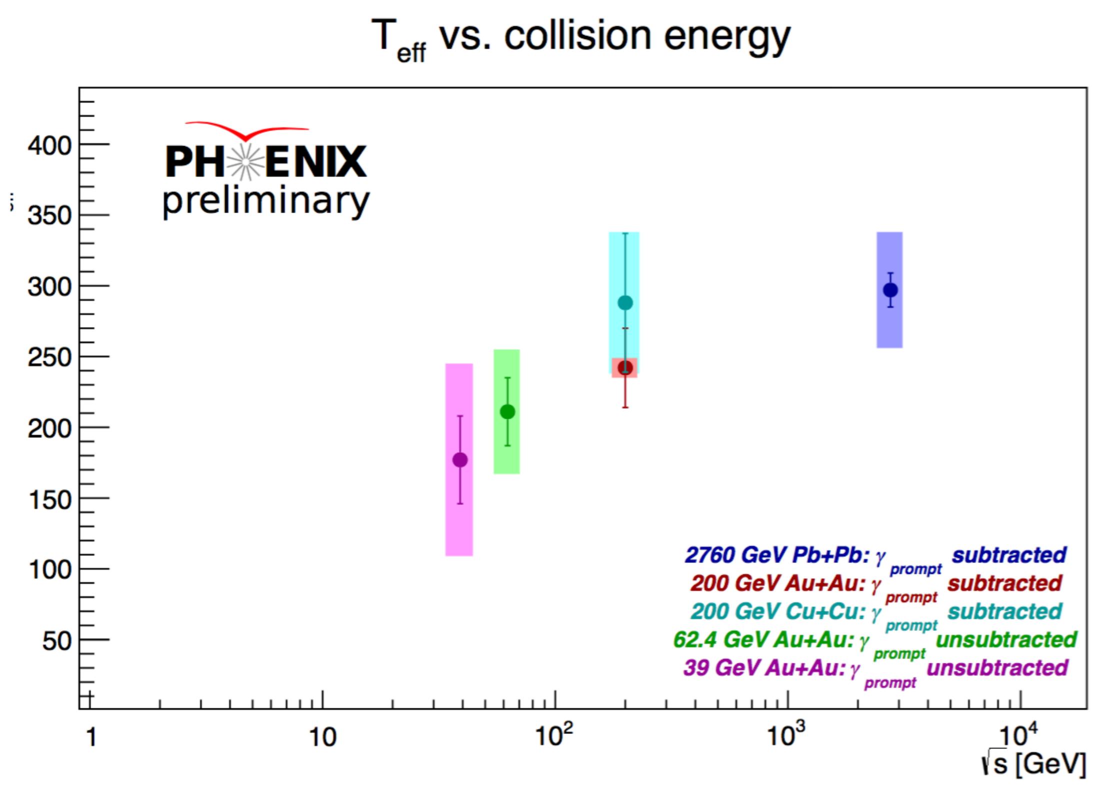
Different method:
Measuring gammas via external conversions in detector material

AuAu at low pT :
nearly exponential shape :
T(eff) 240 MeV > T_c

AuAu follows nr of collision scaling above pT 4 GeV like p+p

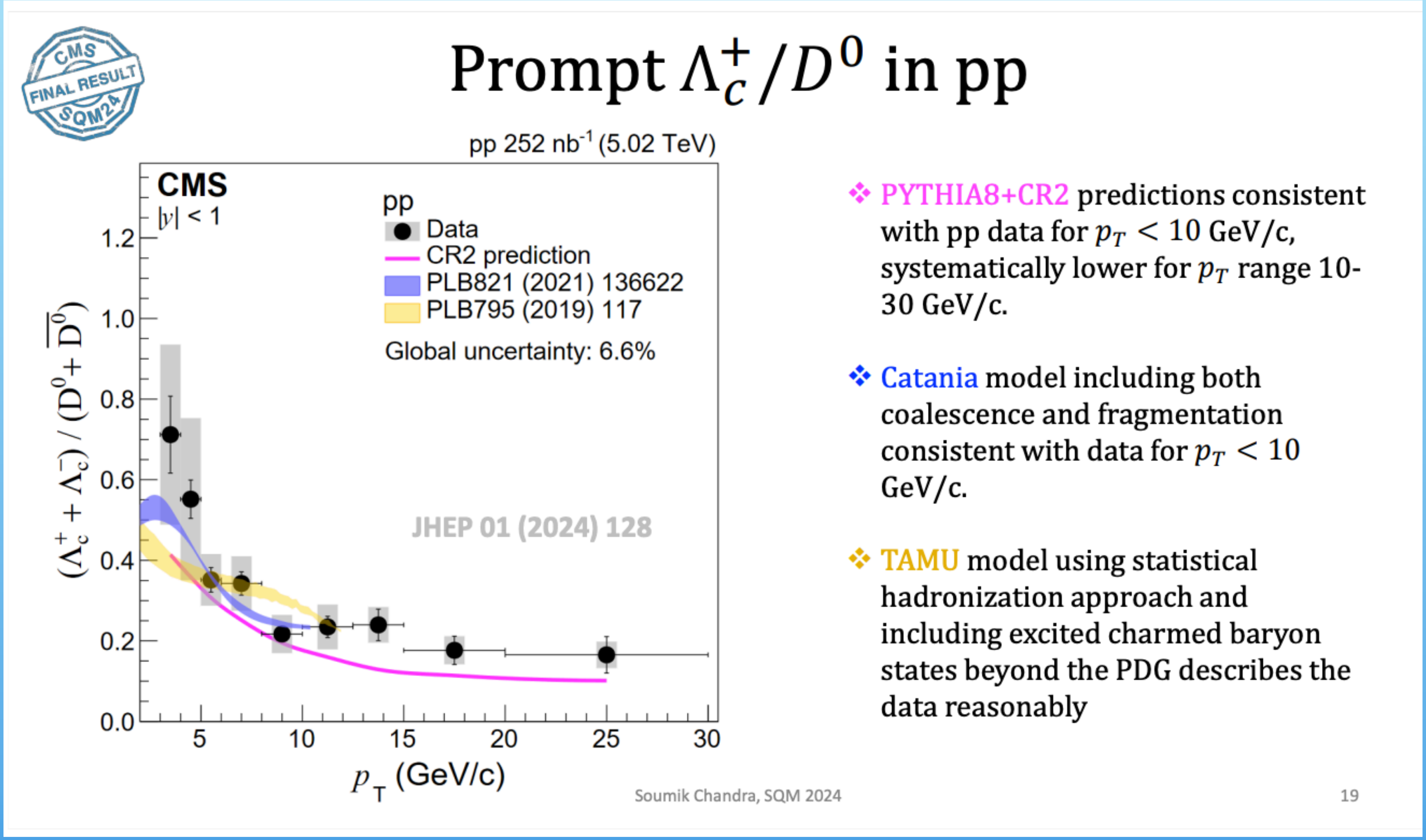
Results from RHIC Beam Energy Scan: direct photons

effective T(from direct photons)



PHENIX, Dheepali Sharma
QM2017

Strangeness in small systems



CMS FINAL RESULT SQM24

Prompt Λ_c^+/D^0 in pp

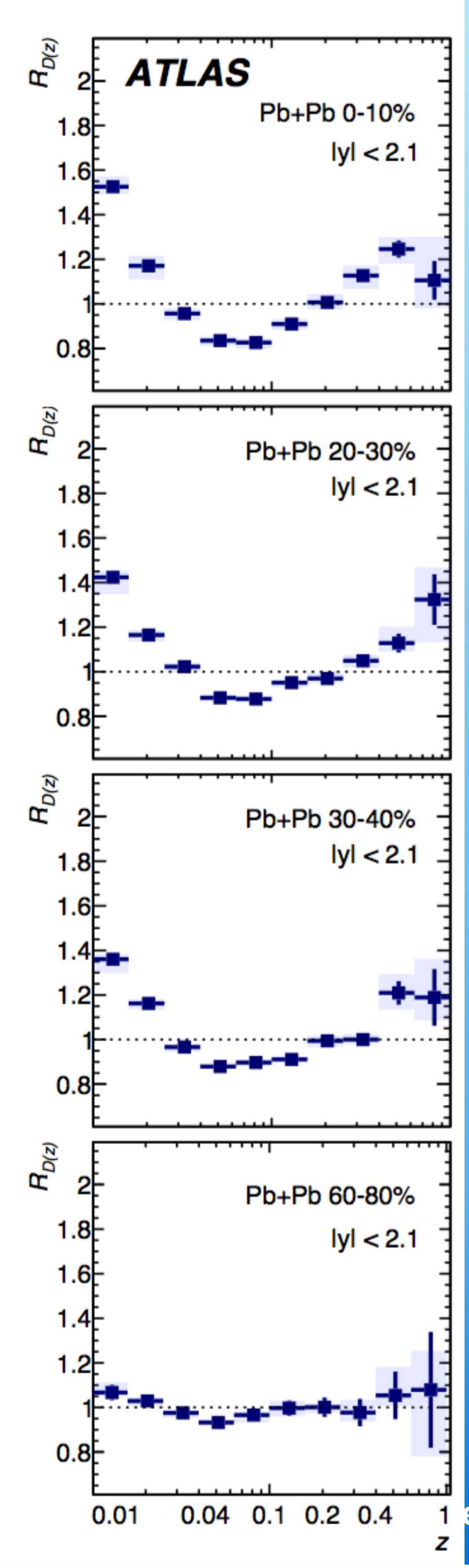
- PYTHIA8+CR2 predictions consistent with pp data for $p_T < 10$ GeV/c, systematically lower for p_T range 10-30 GeV/c.
- Catania model including both coalescence and fragmentation consistent with data for $p_T < 10$ GeV/c.
- TAMU model using statistical hadronization approach and including excited charmed baryon states beyond the PDG describes the data reasonably

Soumik Chandra, SQM 2024

19

Modification in Jet fragmentation

ATLAS arXiv:1702.00674



Jet fragmentation function D(z)

z: longitudinal momentum fraction of a particle with respect to jet

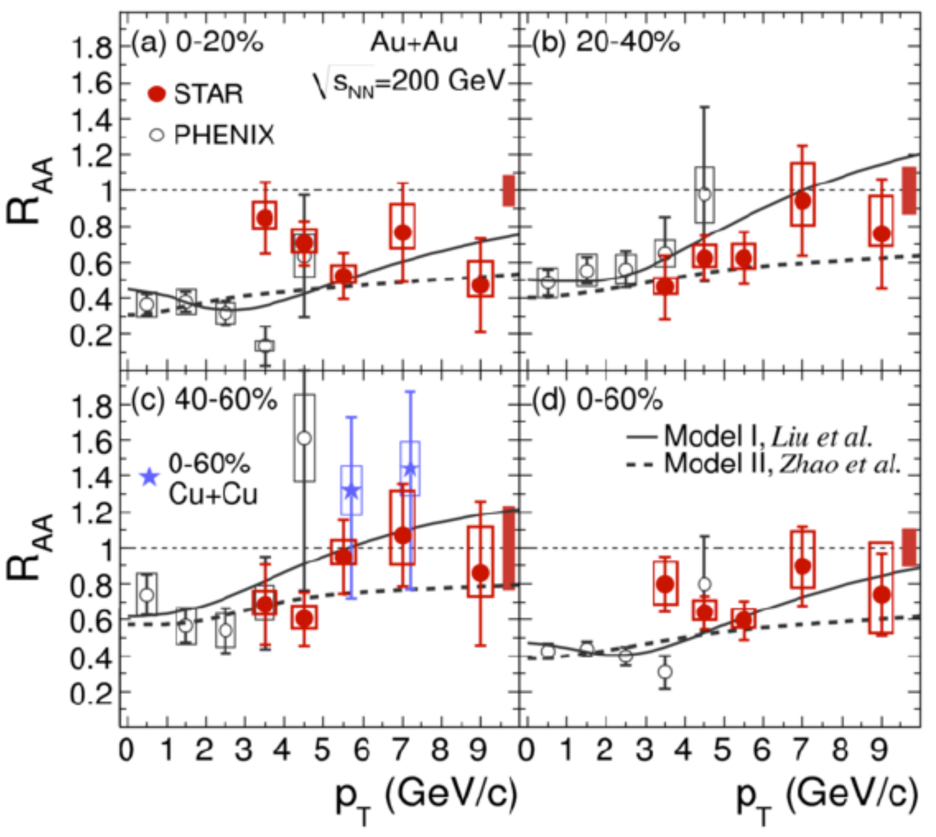
$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{\text{ch}}}{\mathrm{d}z},$$

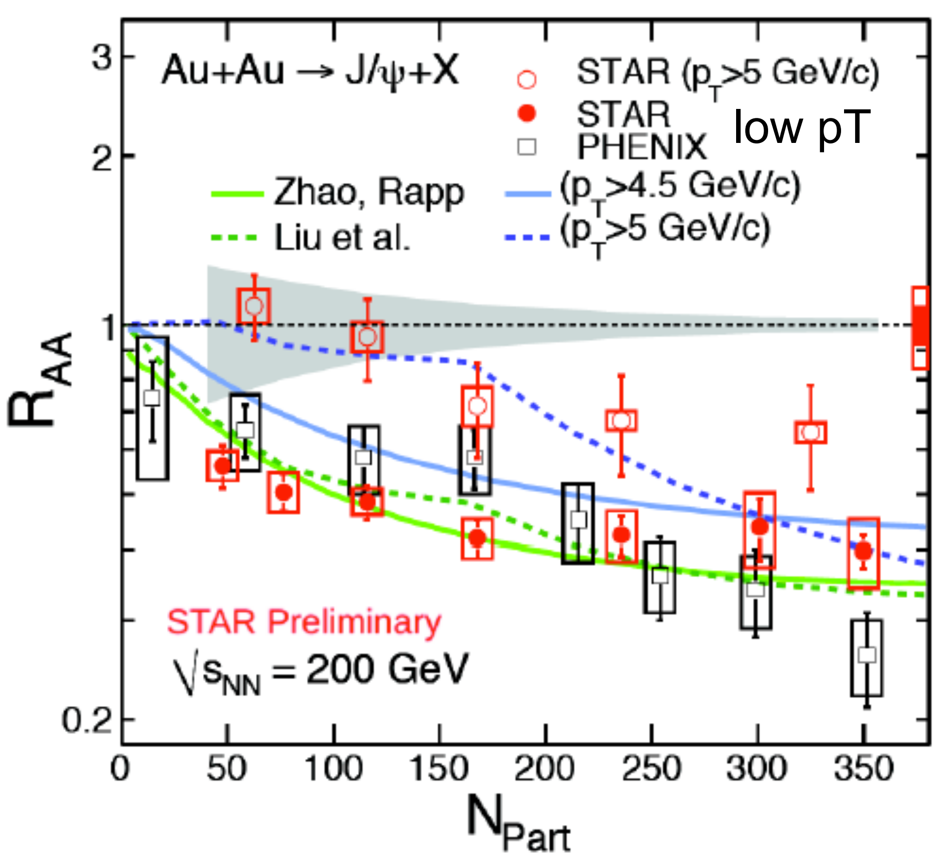
$$R_{D(z)} = D(z)|_{\text{cent}} / D(z)|_{pp}$$

In central Pb+Pb:
Enhancement at low z
Suppression at z around 0.1
Enhancement at high z

p_T dependence of J/Psi suppression in Au+Au, Cu+Cu 200 GeV

PLB 722 (2013) 55





Liu et al, PLB 678 (2009) 72
Zhao et al, PRC 82 (2010) 064905

- **J/Psi not suppressed at high p_T's in non-central collisions**

- **J/Psi suppressed at all p_T's for most central events**

- **R_{AA} of J/Psi is systematically larger for higher p_T. Low pT J/Psi is more suppressed**