Strangeness production in Heavy Ion Collisions

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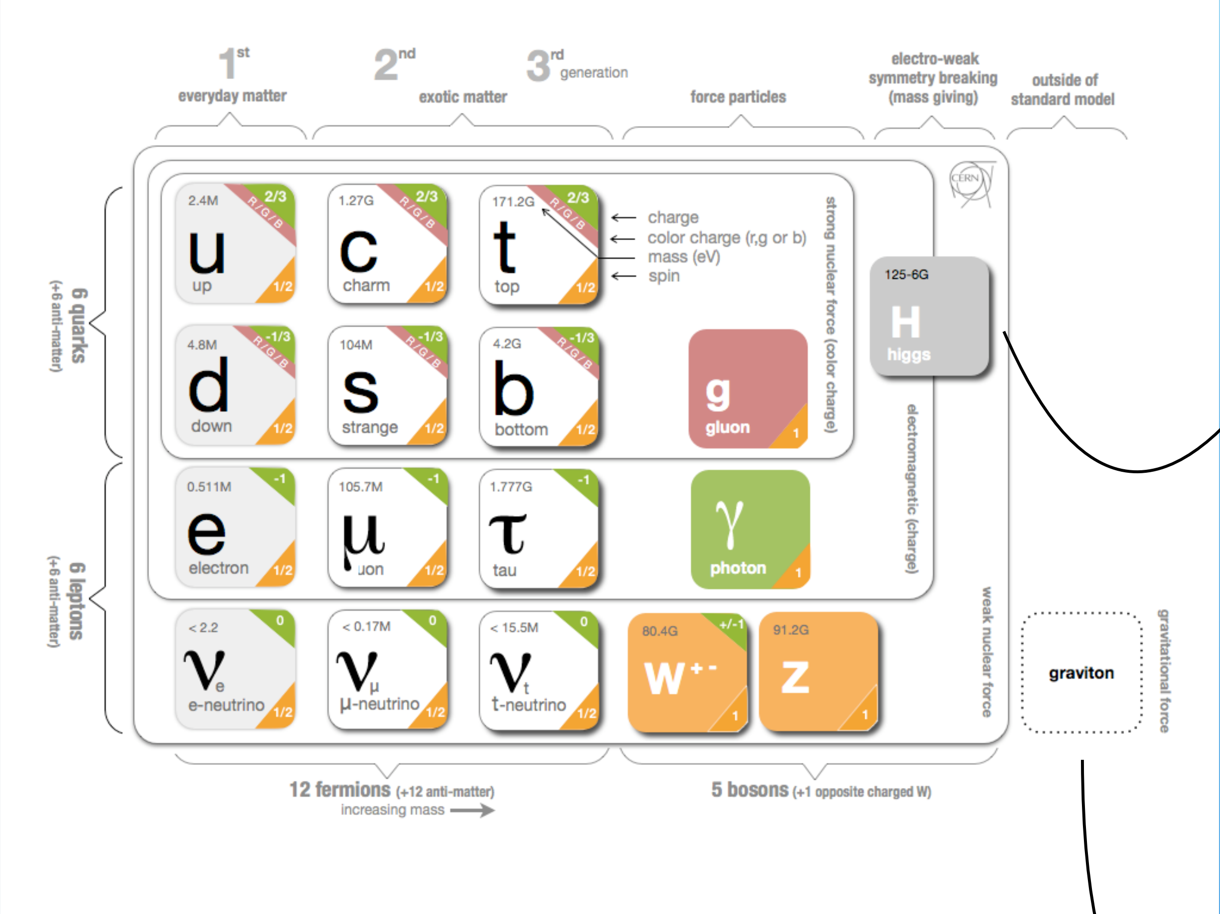
Volga River

Outline

1. Strangeness in the Standard Model
2. Relativistic Heavy Ion Physics and the Quark Gluon Plasma (QGP)
   - QGP Signatures
3. Strangeness Enhancement as QGP signature
4. Observation of Strangeness Enhancement
5. What else can we learn from strangeness ?
6. Strangeness in exotic systems (strangelets, antihypernuclei etc)
7. Summary and outlook

I Introduction

Strangeness within the Standard Model of Particle Physics



2012: Discovery of the Brout Englert Higgs boson or Higgs boson.
The Higgs field pervades the vacuum and generates particle mass

2016: Discovery of gravitational waves by VIRGO/LIGO

Discovery of strange particles, 1947, Rochester and Butler (UK)

"Evidence for the existence of new unstable elementary particles"
G. D. Rochester & C. C. Butler, Nature 160 (1947) 855–857

Evidence for the existence of new unstable elementary particles

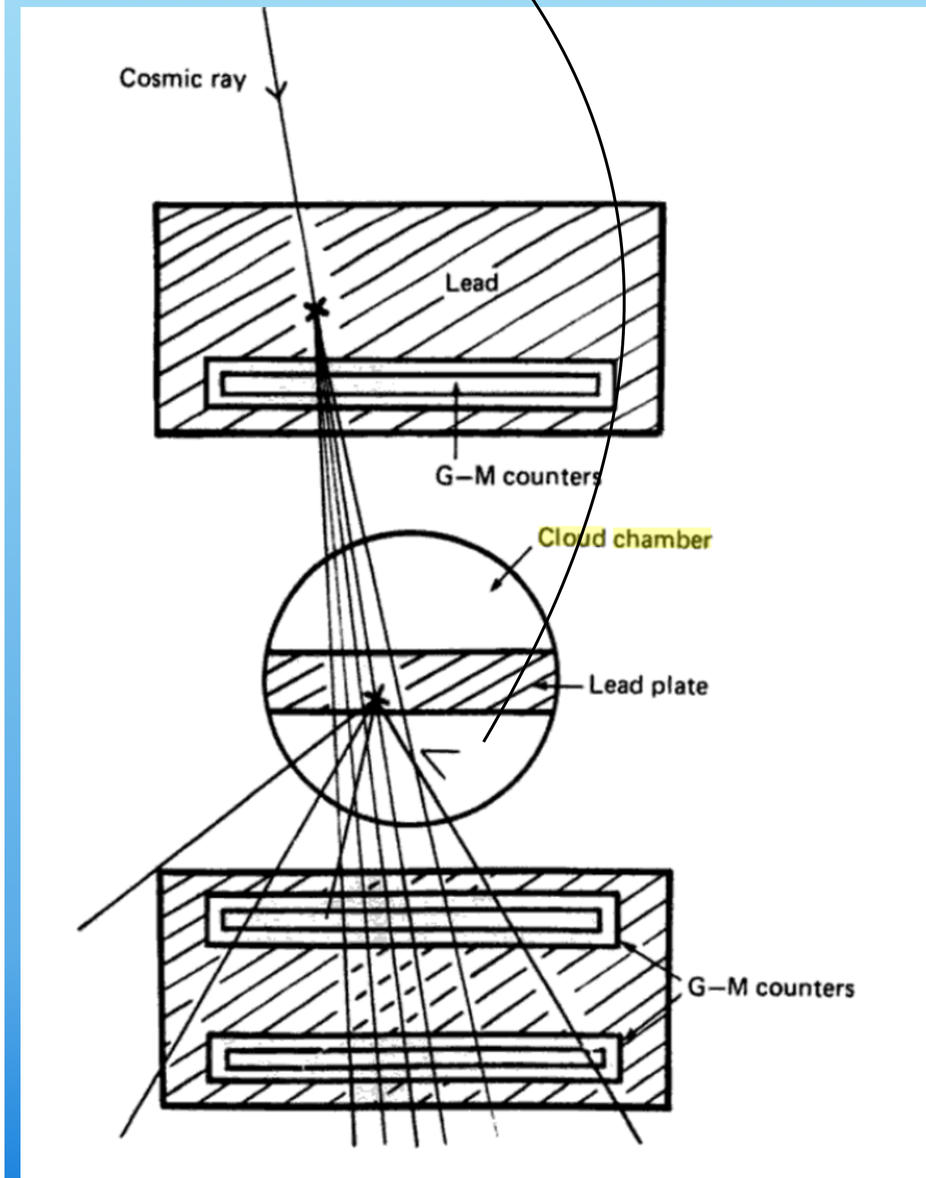
By Dr. G. D. Rochester & Dr. C. C. Butler

Physical Laboratories, University, Manchester

Among some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe

Experiment of Rochester and Butler, UK

The "V0" decay topology



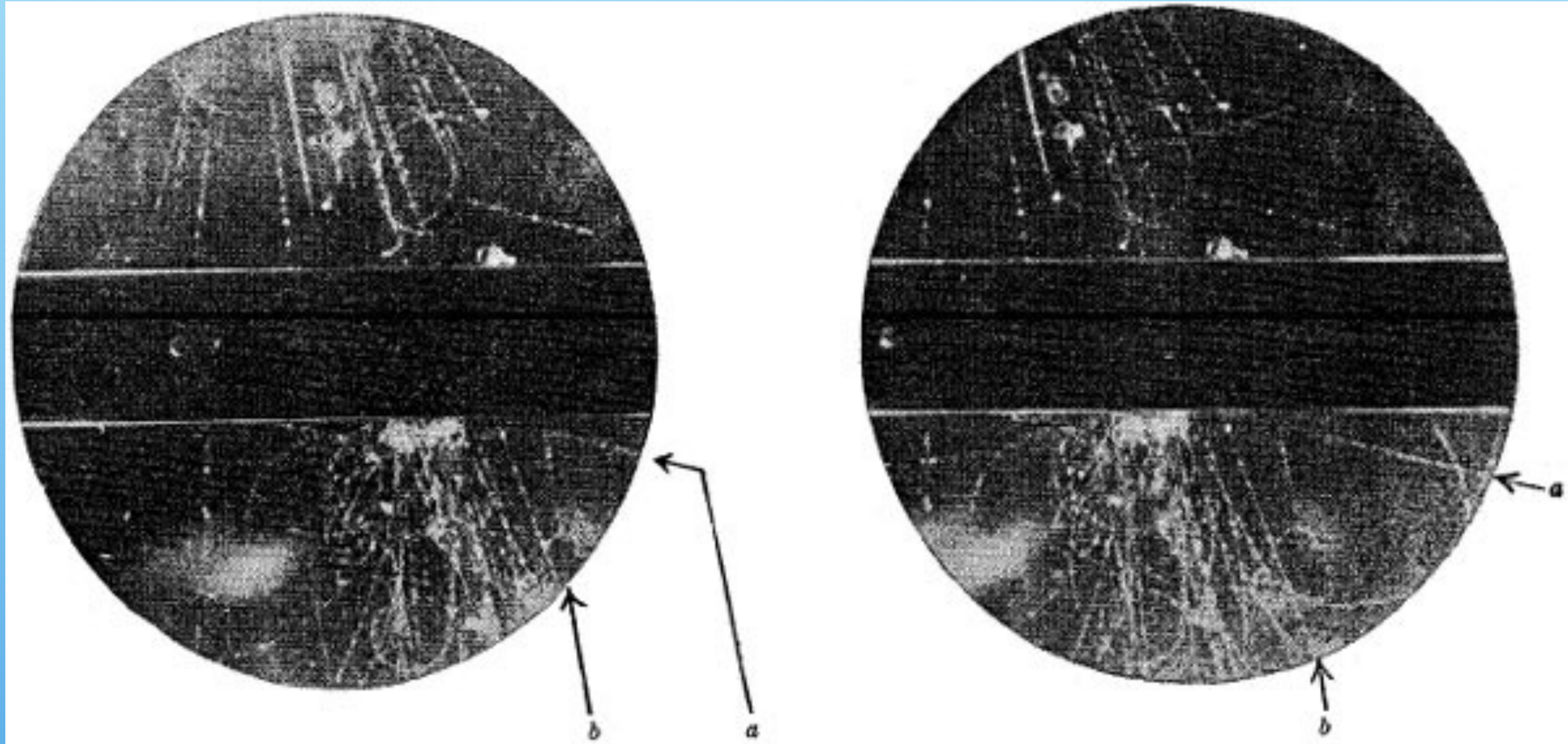
They used a Cloud chamber within a magnetic field of 3500 Gauss triggered by Geiger Mueller counters positioned in the 3 banks above and below the cloud chamber. Lead shielding was making sure the trigger would fire only for an energetic cosmic ray event.

Signal : 2 events out of 5000 photogaphs taken during 1500 hours of operation.

The Experiment was at sea level (no mountains in England !)

Experiment of Rochester and Butler

The "V0" decay topology

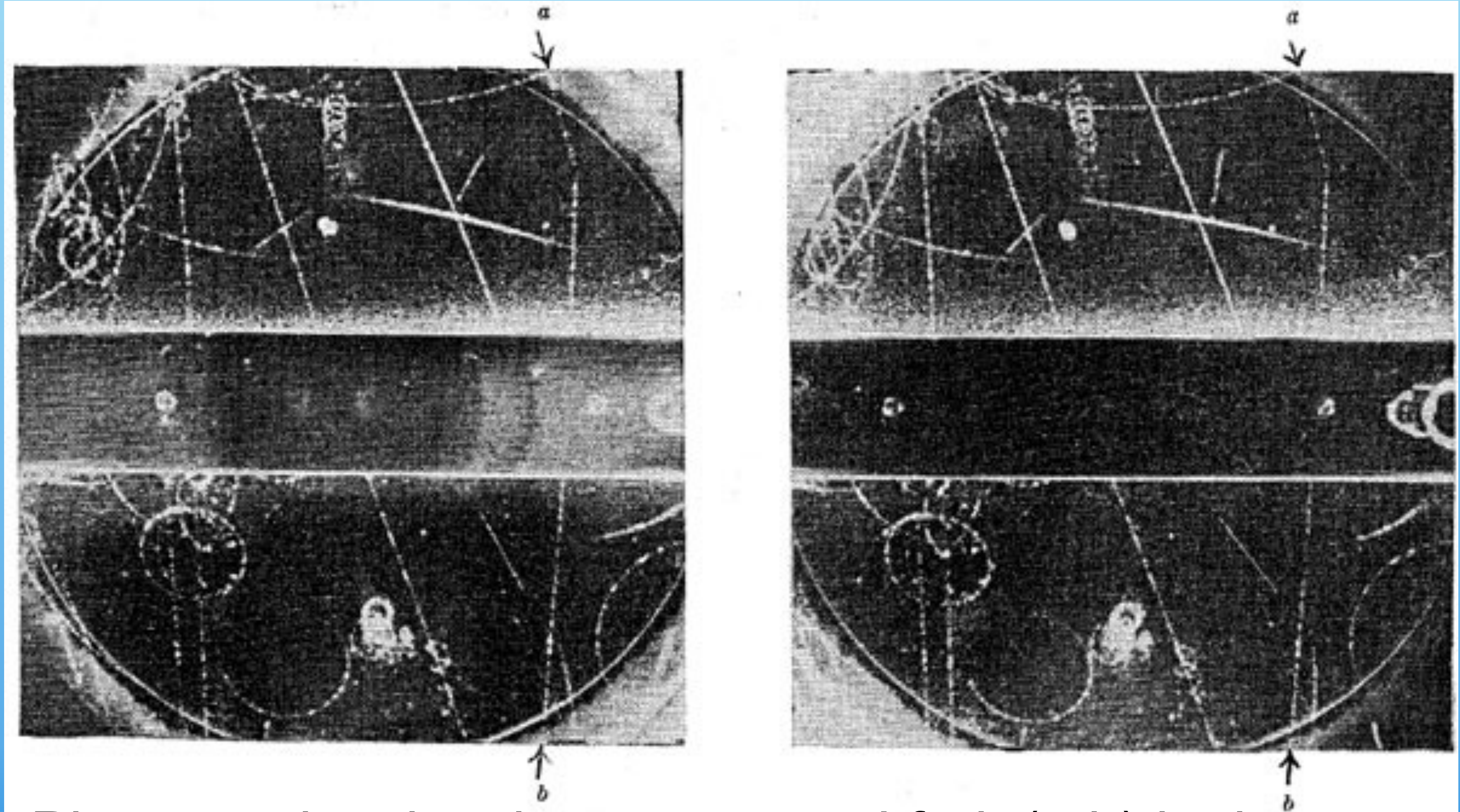


Photographs showing an unusual fork (a,b) in the gas.

K0s -> pi+ pi- with BR= 69%

Lambda -> proton pi- with BR=63.9%

The "Kink"decay topology



Photographs showing an unusual fork (a,b) in the gas.
K+ -> mu+ nu_mu BR=63.56%

Discovery of strange particles

"Evidence for the existence of new unstable elementary particles"
G. D. Rochester & C. C. Butler, Nature 160 (1947) 855–857

We conclude from all the evidence that Photograph 1 represents the decay of a neutral particle, the mass of which is unlikely to be less than 770*m* or greater than 1,600*m*, into the two observed charged particles. Similarly, Photograph 2 represents the disintegration of a charged particle of mass greater than 980*m* and less than that of a proton into an observed penetrating particle and a neutral particle. It may be noted that no neutral particle of mass 1,000*m* has yet been observed; a charged particle of mass 990*m* ± 12 per cent has, however, been observed by Leprince-Ringuet and L'héritier[2].

m here is =mass of electron
So Rochester and Butler give limits for the mass of the parent particle for the observed decay of 375-800 MeV

Compare to PDG (2016) value for mass of K+-=493.67 MeV
K+->mu+ nu_m with BR 63%
mass of K0= 497.61 Me

Relativistic Heavy Ion Collisions and Quark Gluon Plasma

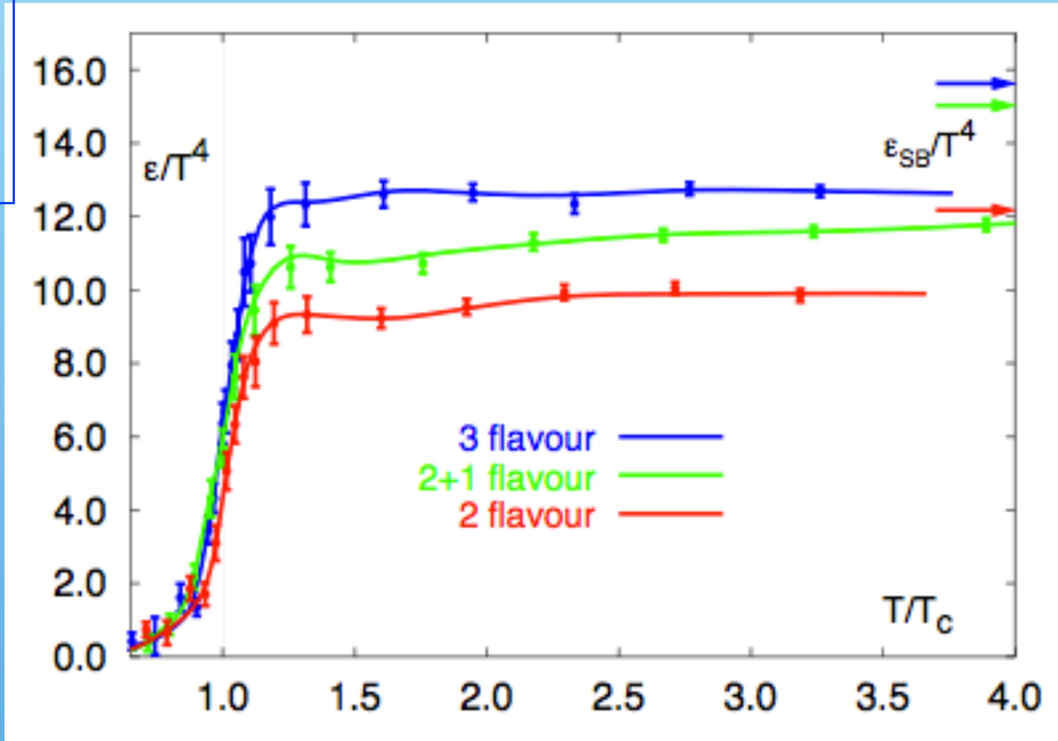
The QCD phase transition between hadronic and partonic phase

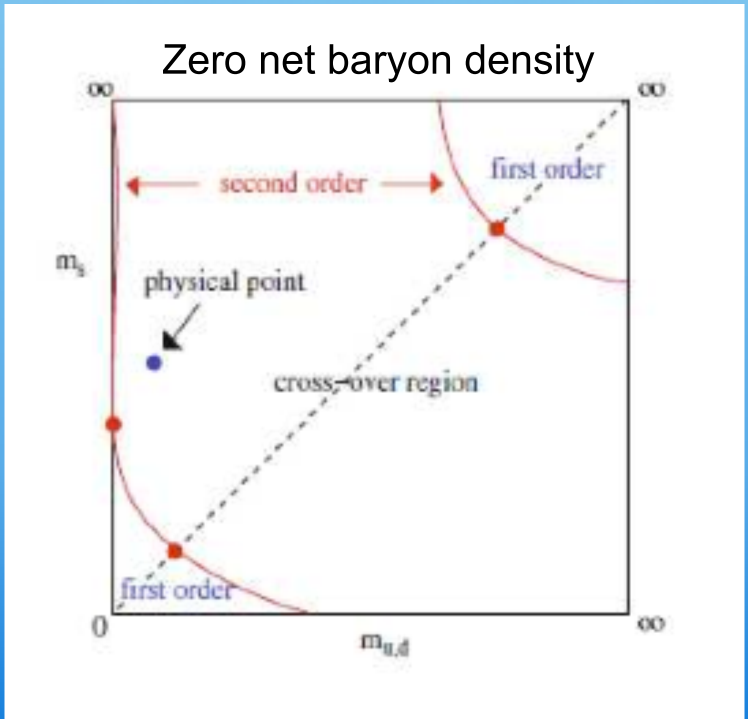
QCD on the lattice predicts a cross over at zero net baryon density with critical temperature Tc~154+-9 MeV (2014), critical energy density ~0.6 GeV/fm^3

(Nuclear Density: rho=0.15 GeV/fm^3
Density inside Nucleon: rho=0.5 GeV/fm^3)

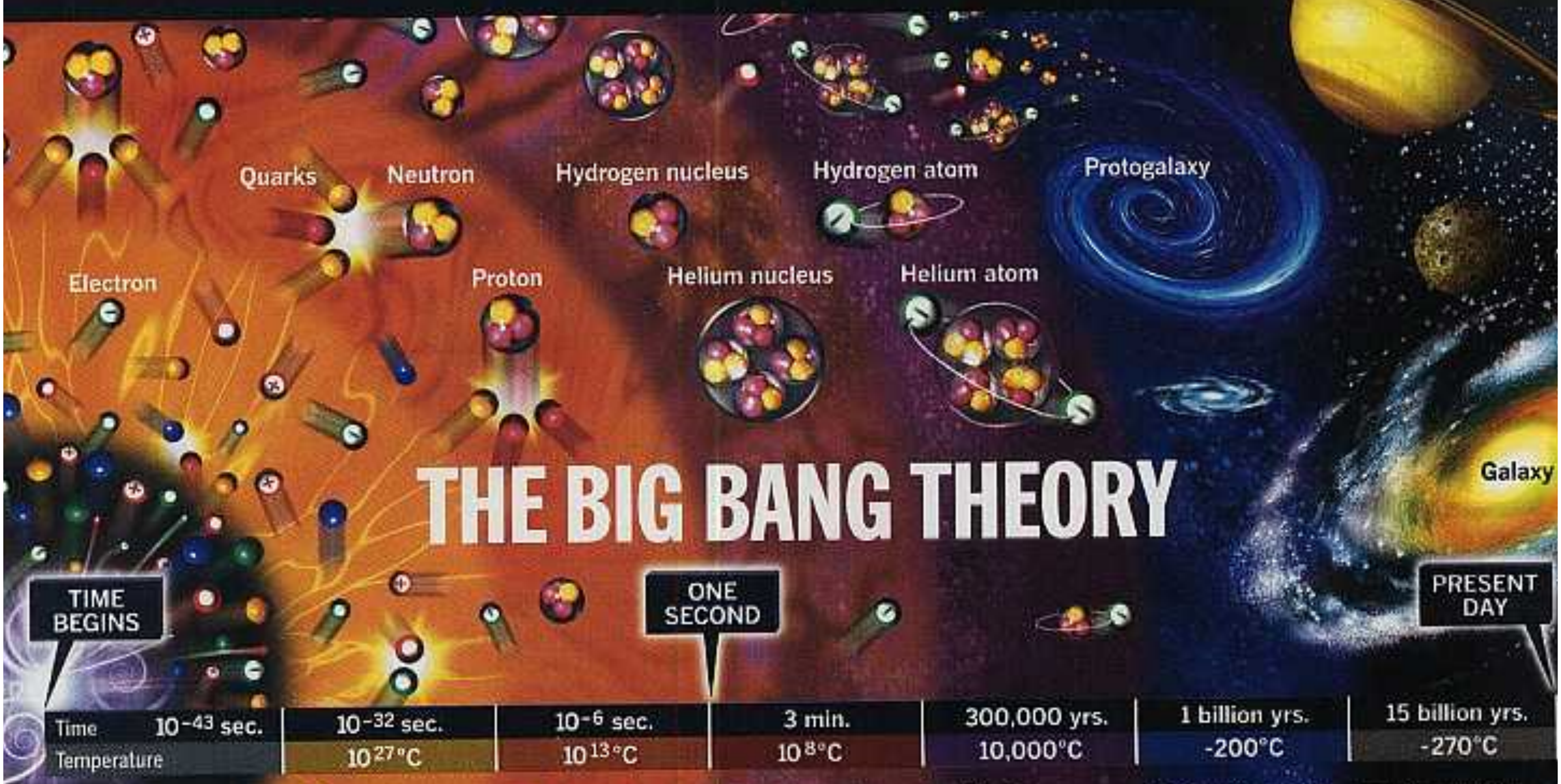
Zero net baryon density

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





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).

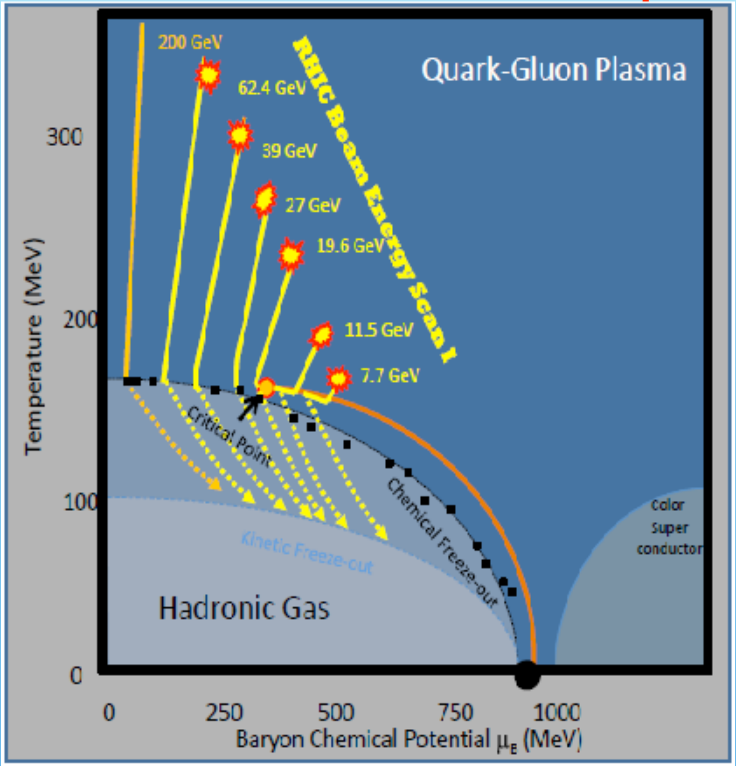


The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang.

The QCD phase transition is the only phase transition of the early universe that can be reproduced in the Lab today.

Why is this possible ? Because T(critical) is expected to be ˜200 MeV, and this is in principle reachable with todays accelerators

The expected QCD phase diagram



Phases of QCD Matter

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

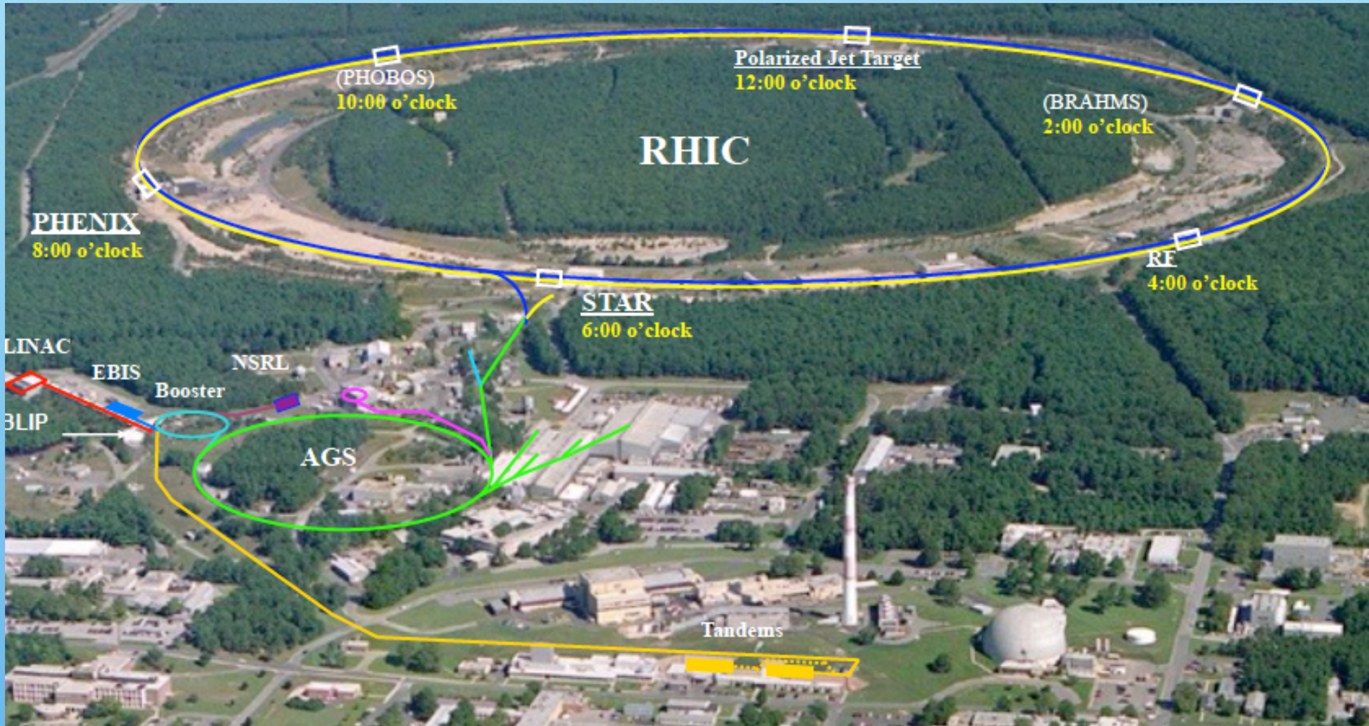
The order of the transition is expected to change with the net baryon density.

Goal: explore experimentally the QCD phase diagram (order of transition, critical point, properties of the QGP).

Accelerators

Relativistic Heavy Ion Collider

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



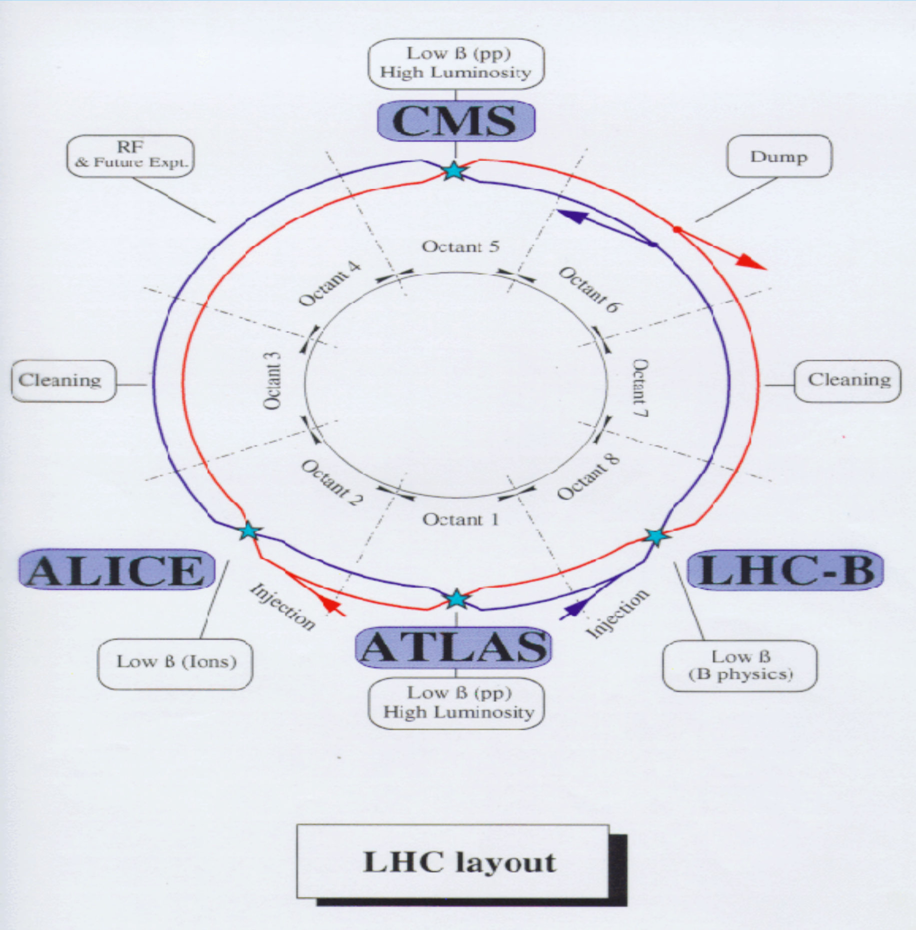
RHIC has been exploring nuclear matter at extreme conditions over the last 15 years 2000-2015

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR and PHENIX

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



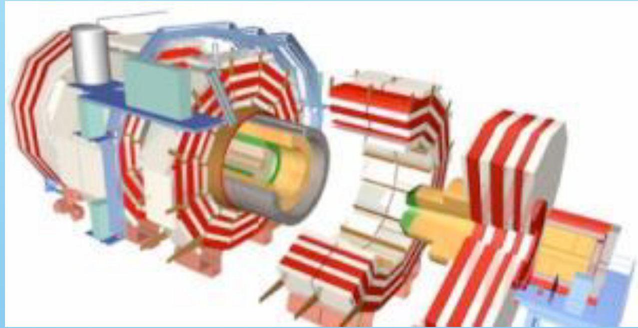
run-1: p+p $\sqrt{s_{NN}}$ =0.9, 2.76, 7, 8 TeV, p+Pb $\sqrt{s_{NN}}$ =5.02 TeV, Pb+Pb at $\sqrt{s_{NN}}$ =2.76 TeV
run-2; p+p $\sqrt{s_{NN}}$ = 13 TeV Dec 2015: Pb+Pb at $\sqrt{s_{NN}}$ =5.1 TeV, 2016: p+Pb 5 and 8 TeV
+ fixed target (LHCb)

And the CERN SPS with 1 experiment

Current Experiments with Heavy Ion program

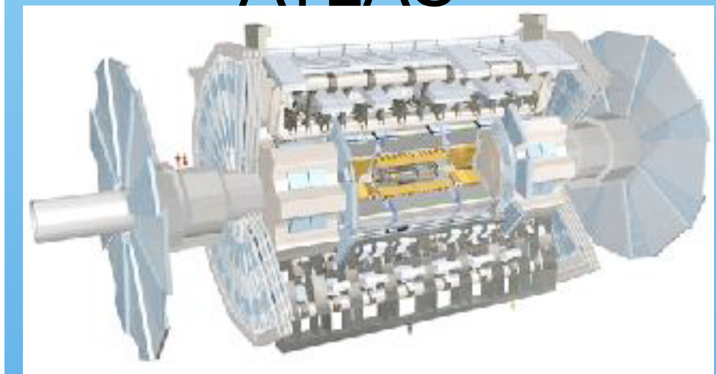
LHC

CMS



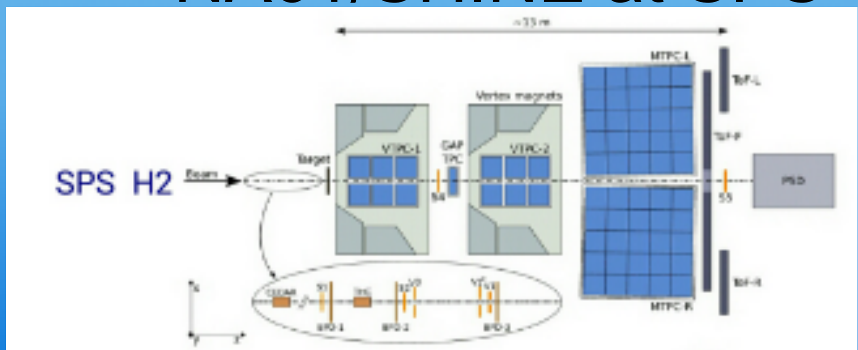
LHCb

ATLAS

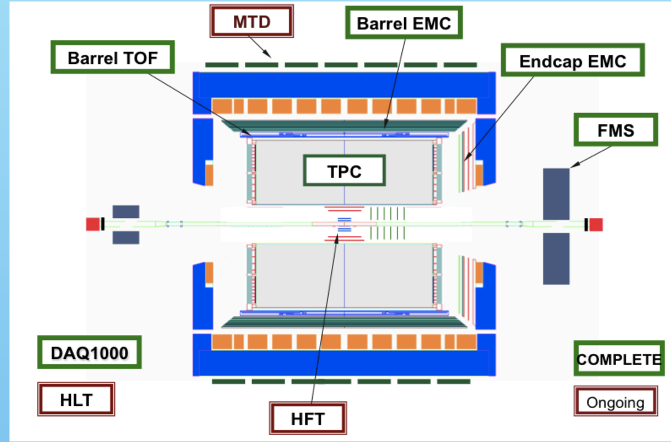


ALICE

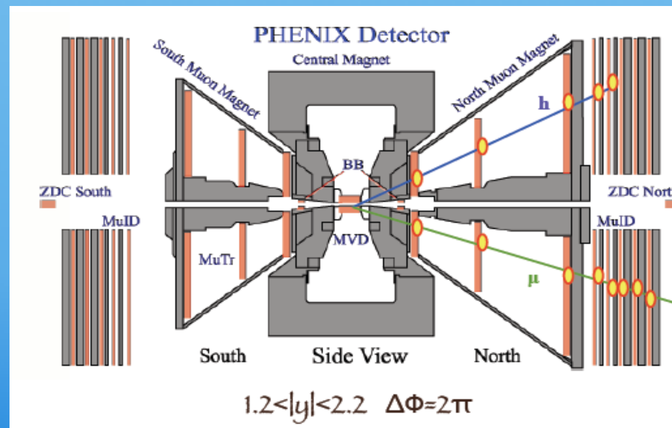
NA61/SHINE at SPS



STAR at RHIC



PHENIX at RHIC
(data analysis only)



Stopped data taking but data analysis is in progress

Previous and present experiments

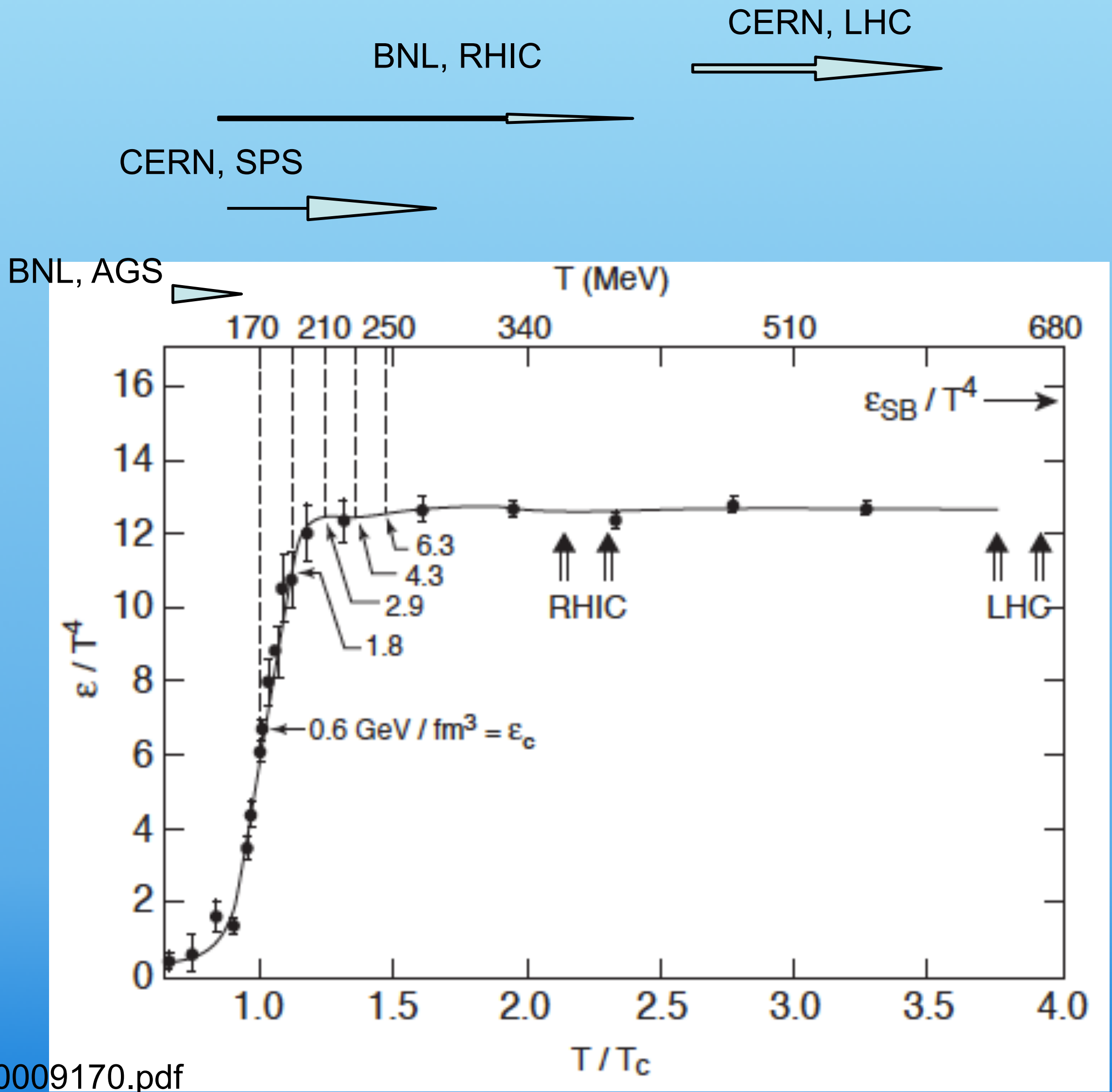
BNL AGS (E866, E917 …)

CERN SPS (NA35, NA36, NA49, NA44,
WA80, WA93, WA98
WA85, WA94, WA97, NA57,
NA50, NA52. NA61/SHINE…)

BNL RHIC (STAR PHENIX PHOBOS BRAHMS)

CERN LHC (ALICE, CMS. ATLAS,, LHCb)

Reach of accelerators in terms of initial Temperature



U. Heinz, 0009170.pdf

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

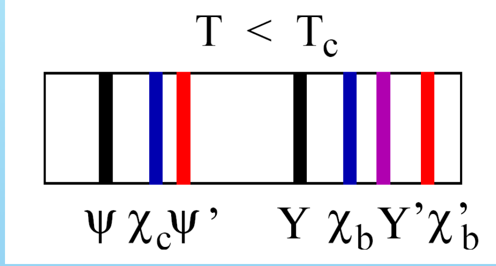
Hadronic mass/width changes (Pisarski 1982) → rho etc

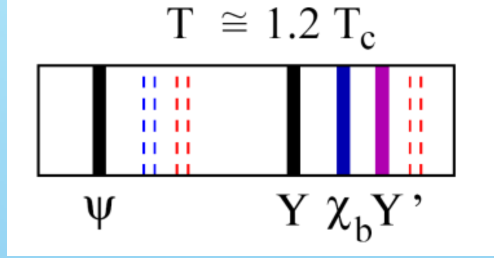
Charmonia suppression (Satz, Matsui 1987) → T(dissociation) of ccbar, bbbar

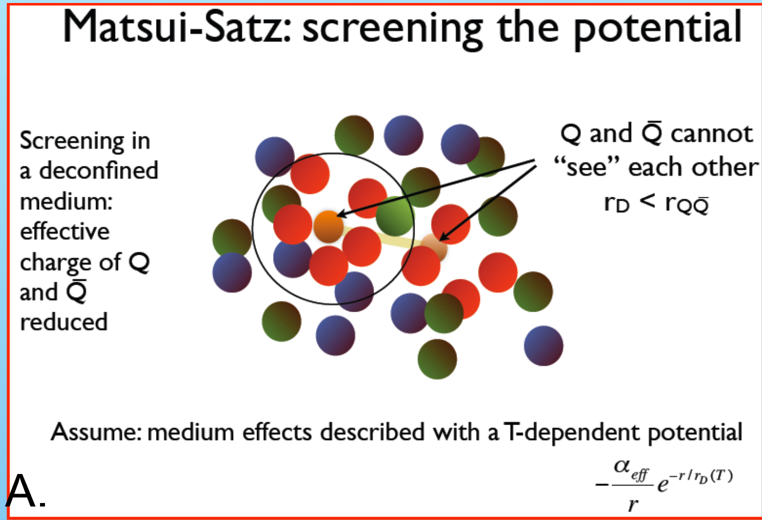
Jet quenching (J D Bjorken 1982) → medium density

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

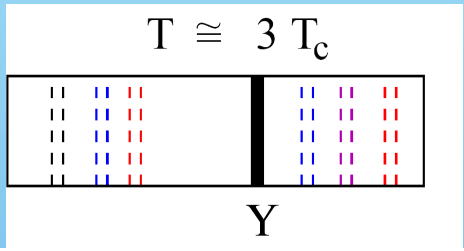
Quarkonia suppression as QGP signature



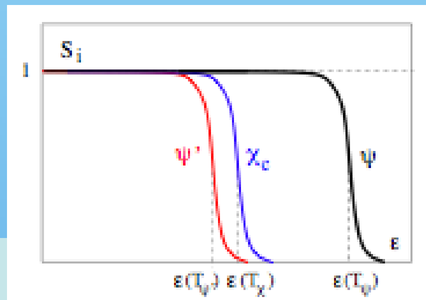


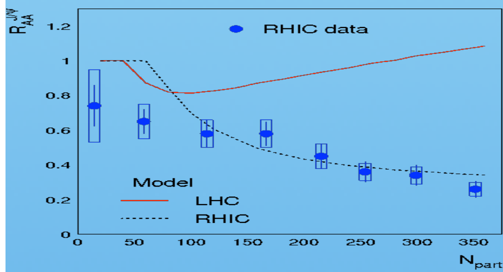


H. Satz, Nucl. Phys. A (783): 249-260(2007)



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

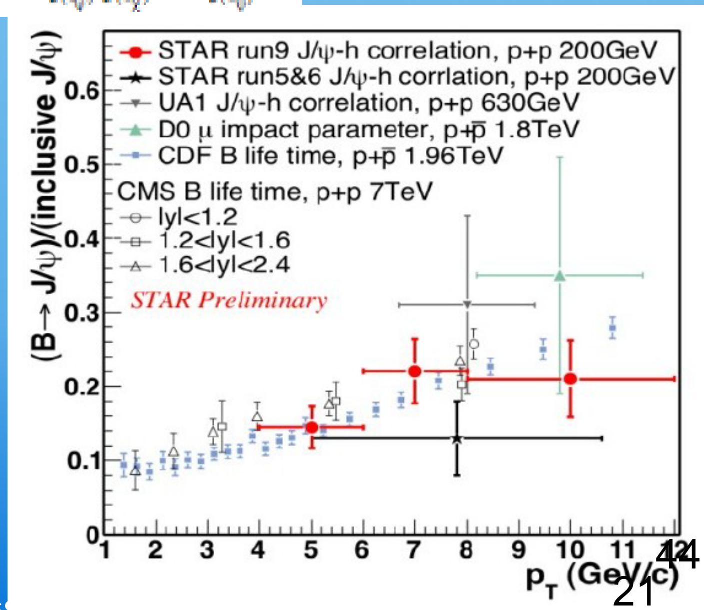




Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

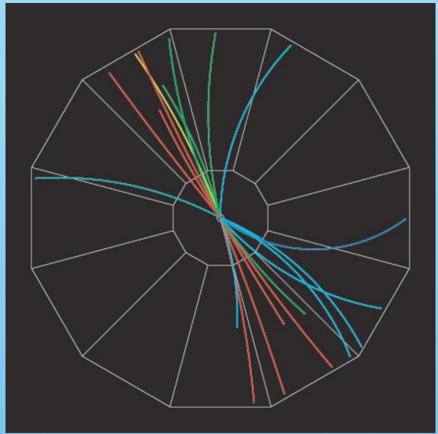
Many effects play a role like dissociation in QGP, cold matter absorption, recombination/ coalescence from c, cbar, feeding, eg B mesons carry 10-25% of charmonia yields (B->J/Psi from J/Psi-h correlation STAR measurement)

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

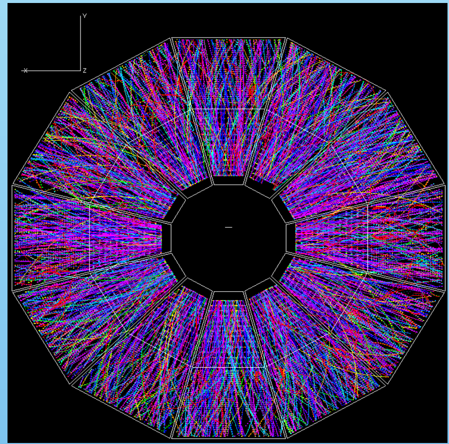


Jet quenching as QGP signature

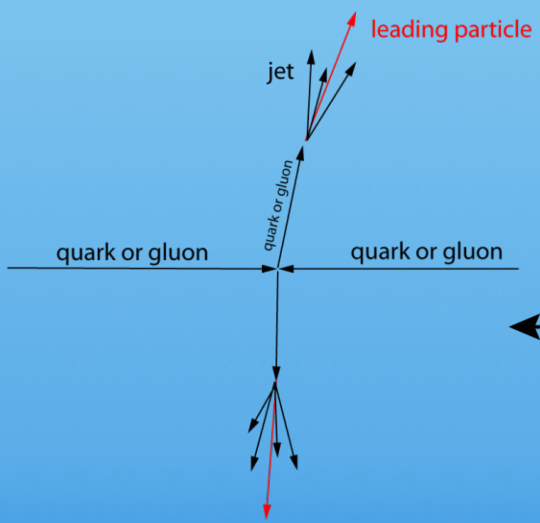
p+p Collision

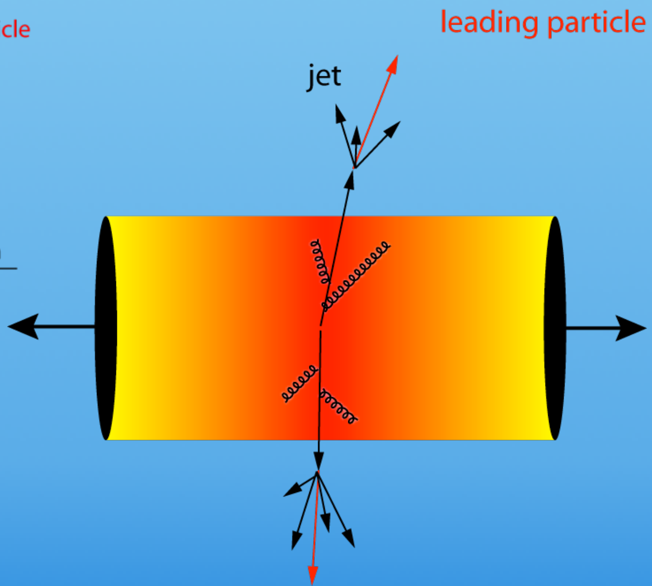


Au+Au Collision

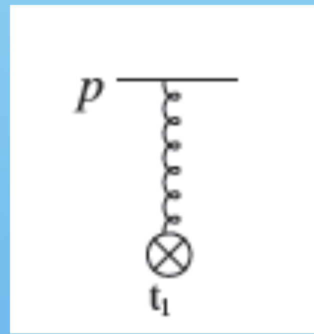


Partons interact with the medium and loose energy through eg gluon radiation

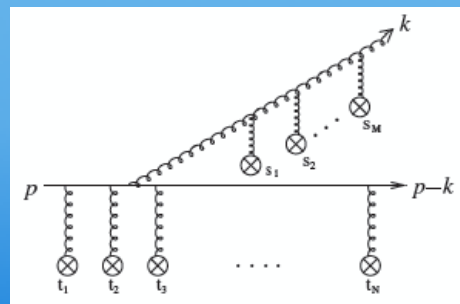




Collisional "elastic" energy loss: elastic interaction with the medium



Radiative energy loss: parton radiation due to interaction with the medium



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

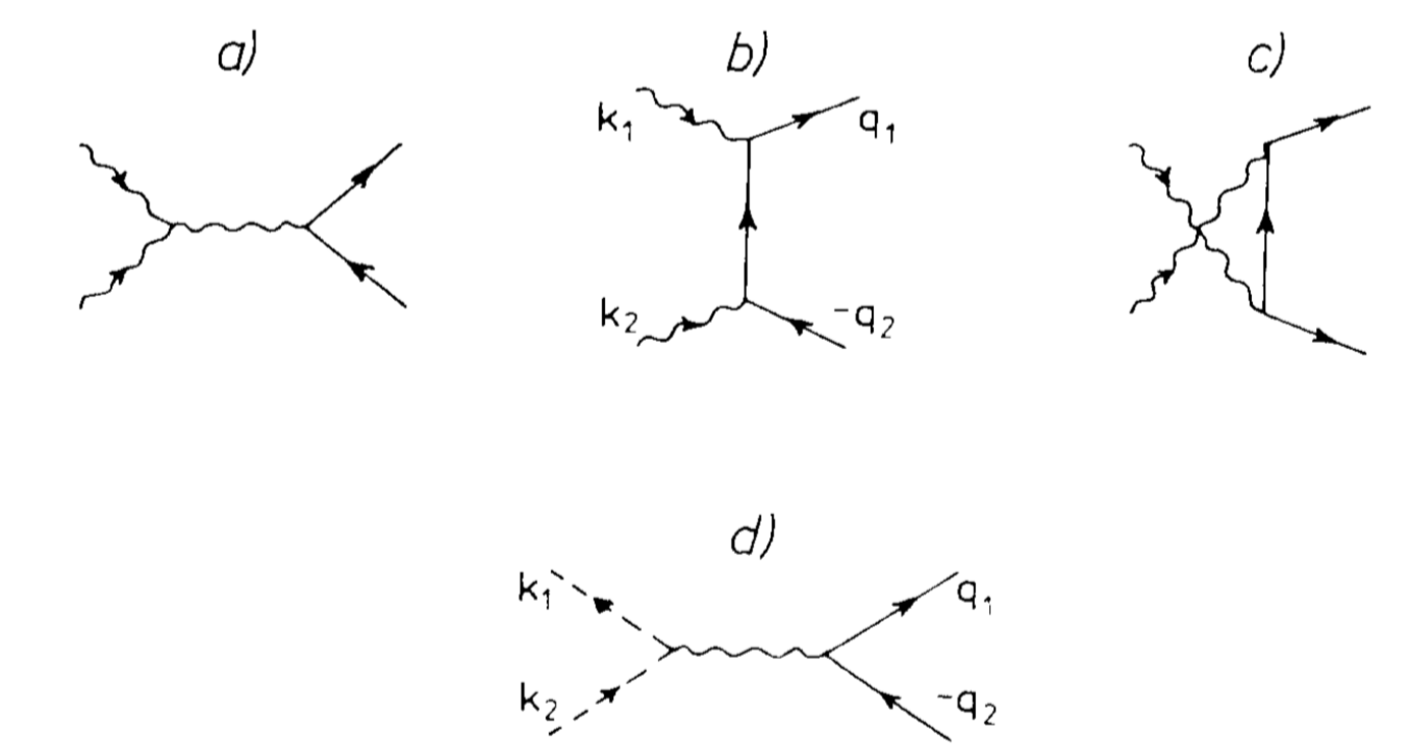
J. Rafelski, "Extreme States of Nuclear Matter - 1980, " Republished in: Eur. Phys. J. A 51 (2015) 115.

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.

Strangeness Enhancement as QGP signature

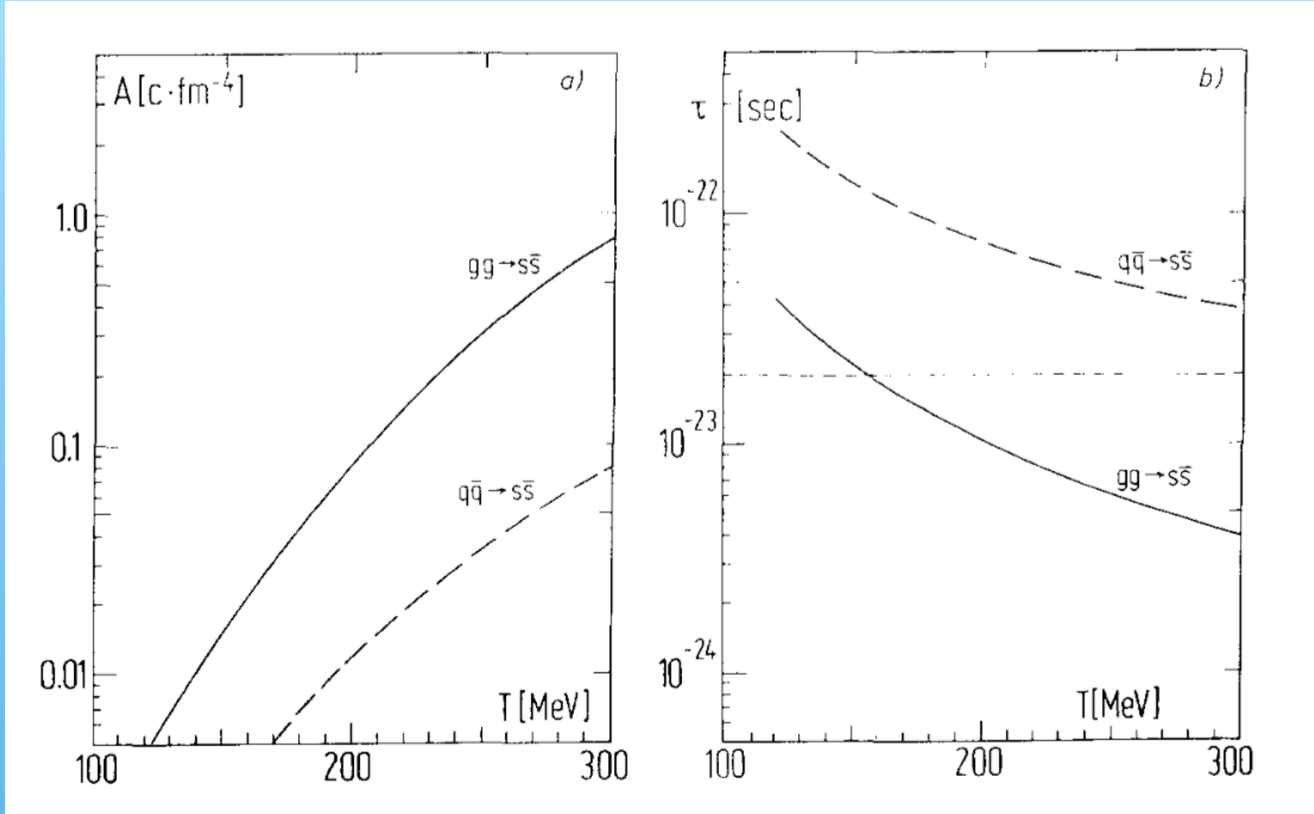
In the QGP strangeness production proceeds mainly via gluons, allowing strangeness to reach equilibrium within the timescale of the high density state of a heavy ion collision



Lowest order QCD diagrams for ss production: (a)–(c) $gg \to s\bar{s}$; (d) $q\bar{q} \to s\bar{s}$.

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

Comparison of production modes of ssbar in the QGP



Left: A=Rates, Right: time constant tau, both shown as a function of temperature T.

Full lines: gg -> ssbar and qqbar -> ssbar.
Dashed line: only qqbar->ssbar

Left: The gluon contribution dominates the strangeness creation rate *A*.

Right: characteristic relaxation times towards chemical equilibrium. Again it is seen that the gluonic strangeness production is the dominant process since tau(gluon) is substantially smaller than tau(quark) (dashed lines).

-> Gluonic channel dominates ssbar production in the QGP

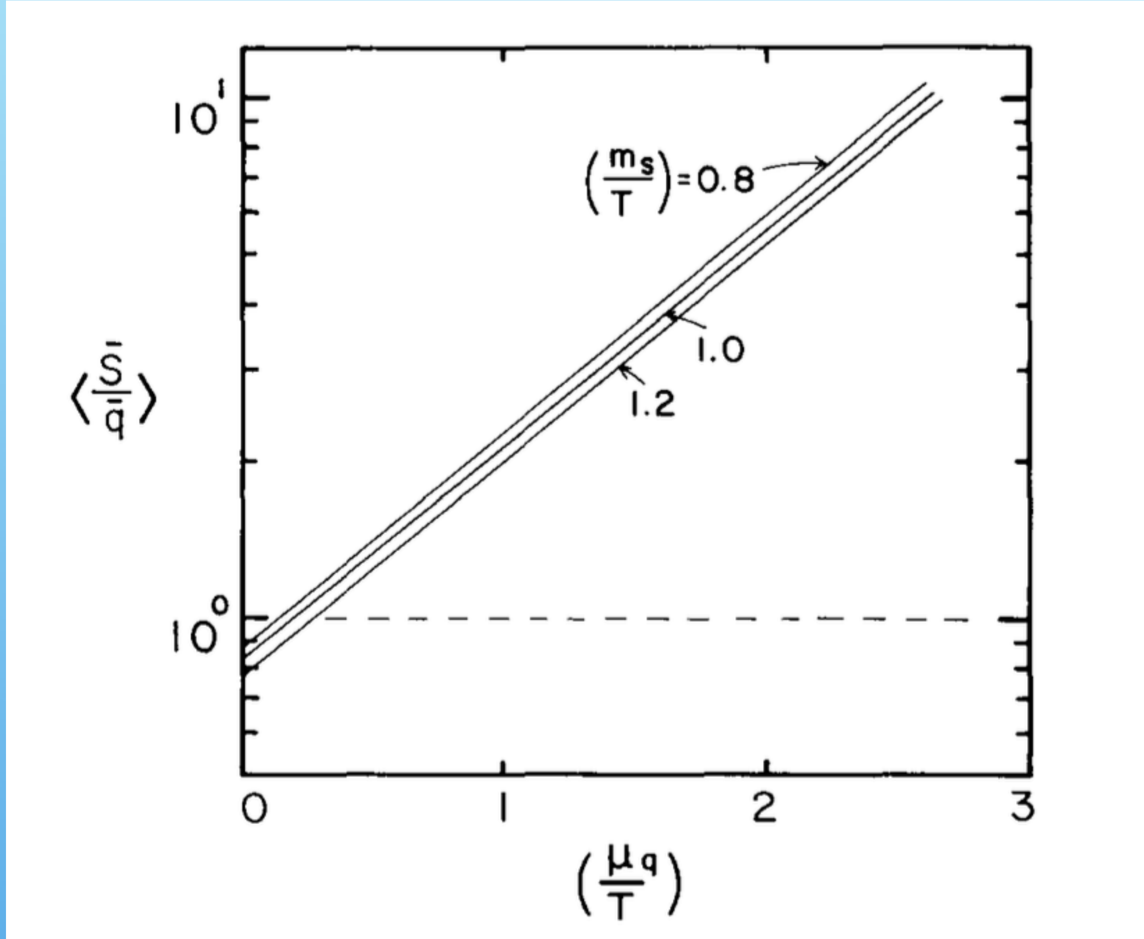
Strangeness production in the QGP

Strangeness enhancement is expected due to

* The dominance of the gluonic production channel for strangeness in the QGP
* High gluon density in the QGP
* To the mass of the s quark being similar to the critical temperature T for the QCD phase transition

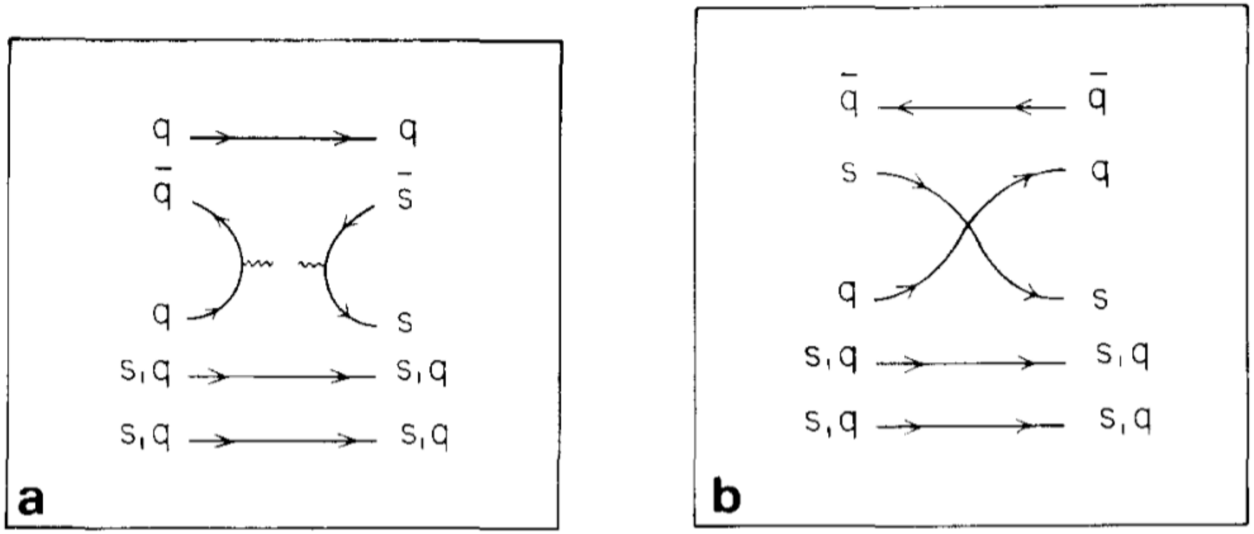
In particular Koch-Mueller-Rafelski find that for mass(s) = 0.5-1 xTcritical (Tc assumed =200 MeV), that is for mass(s)=100-200 MeV, the strangeness formation time is similar to the expected lifetime of the QGP -> strangeness chemical equilibration in QGP is possible, leading to abundant strange quark density in QGP

Strangeness enhancement and mu_B



Strange to nonstrange antiquark ratio increases with mu_B

Strangeness hadronic reactions



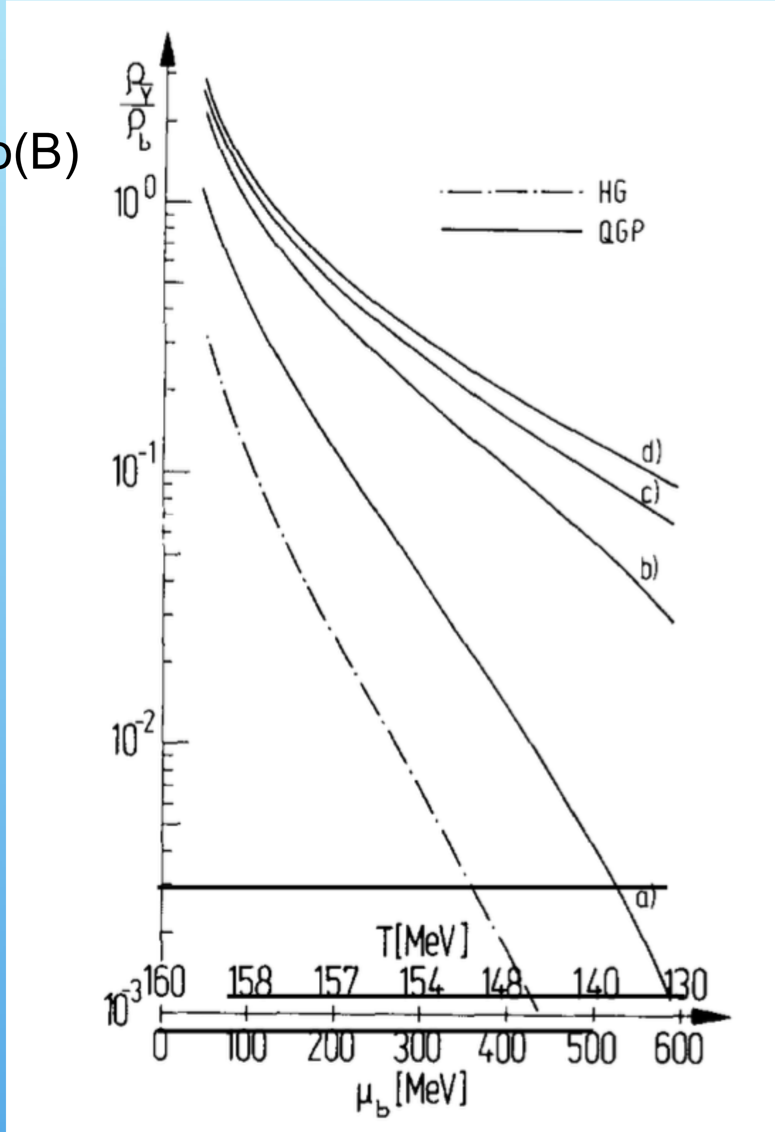
Strangeness production: annihilation of qqbar and production of ssbar pair

Strangeness exchange reaction

Fig. 5.1. (a) Typical quark flow diagram for strangeness production reaction: annihilation of a $q\bar{q}$ pair and production of a $s\bar{s}$ pair. Several quark spectator lines are also indicated. (b) Typical quark flow diagram for strangeness exchange reaction: exchange of the s-quark from the initial K-meson to the final baryon. Several quark spectator lines are also indicated.

Strangeness as QGP Signature

Antihyperons
per baryon
rho(Anti-Y)/rho(B)

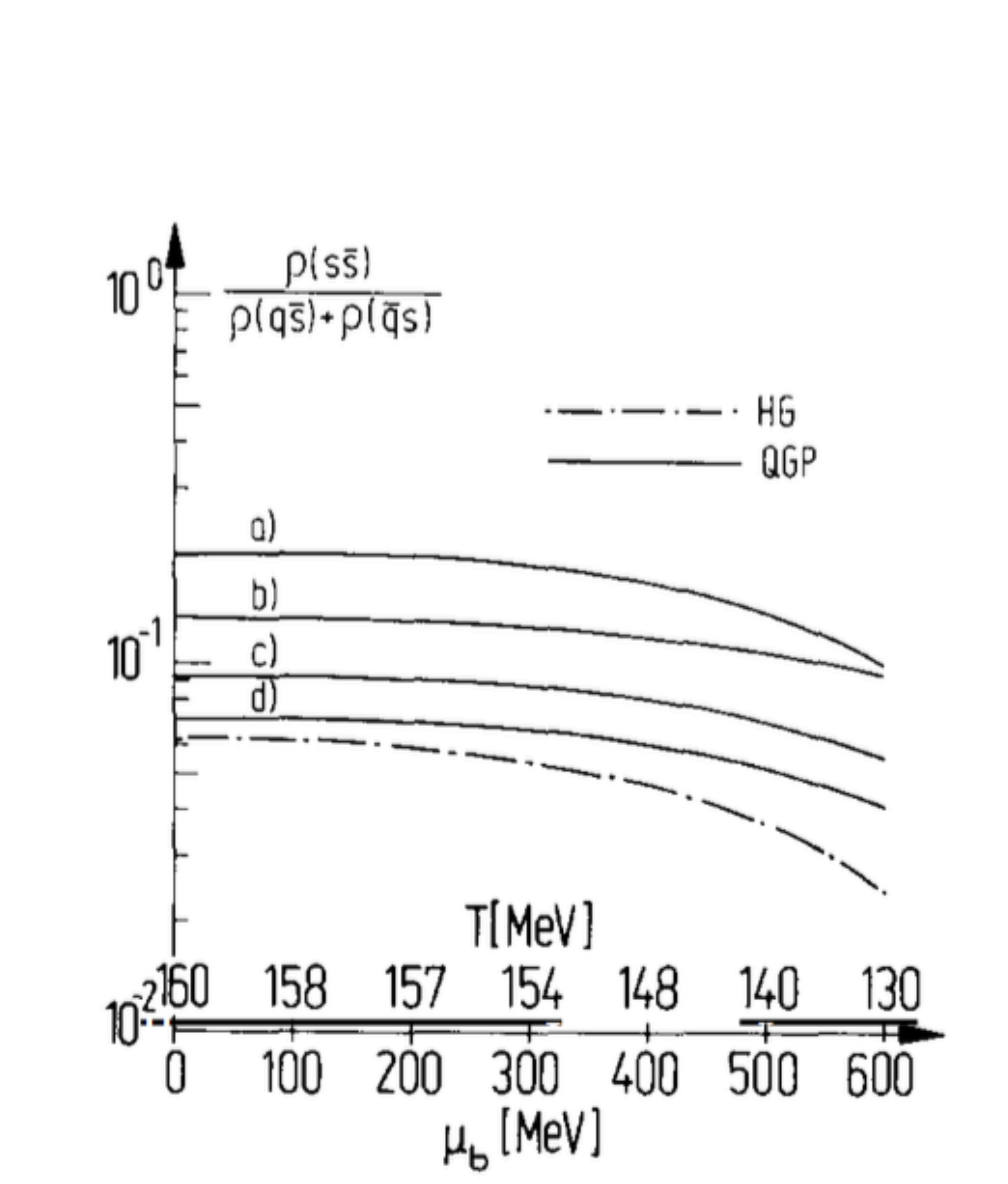


Antihyperons per baryon along the assumed critical curve is higher in QGP (full lines) as compared to Hadronic Gas in equlibrium.
(a) recombination from QGP without fragmentation
(b)-(d): including fragmentation (different parameters used)

The strong antihyperon enhancement persists for all hadronization scenarios (b)-(d)

All strange particles are expected to be enhanced out of QGP as compared to Hadron Gas, however antihyperons show the largest enhancement

Phi enhancement

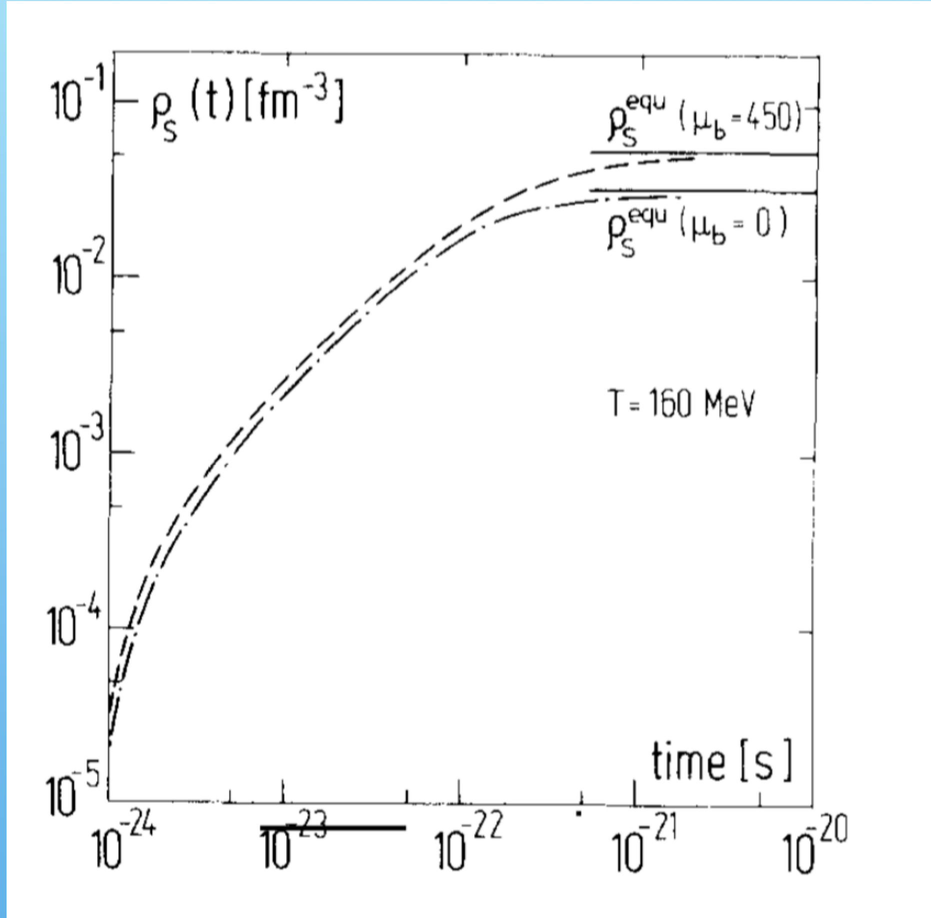


Phi is less enhanced than other strange particles along the assumed critical curve when comparing QGP (full lines) to Hadronic Gas (dashed line) in equlibrium.

(a) recombination from QGP
(b)-(d): including fragmentation

Koch, Mueller, Rafelski,

Approach to equilibrium of total ssbar density in Hadron Gas



Hadronic reaction rates are much too small to allow for equilibration of strange particle densities during a nuclear reaction unless plasma is formed. After a reaction time of 3X 10^-23 s the gross density of strange particles would still remain an order of magnitude off its equilibrium value

Strangeness does not reach equilibrium in Hadron Gas within the time scale of a heavy ion collision

Mu_b=0 | Mu_b=450 MeV

Particles | Antiparticles | Particles

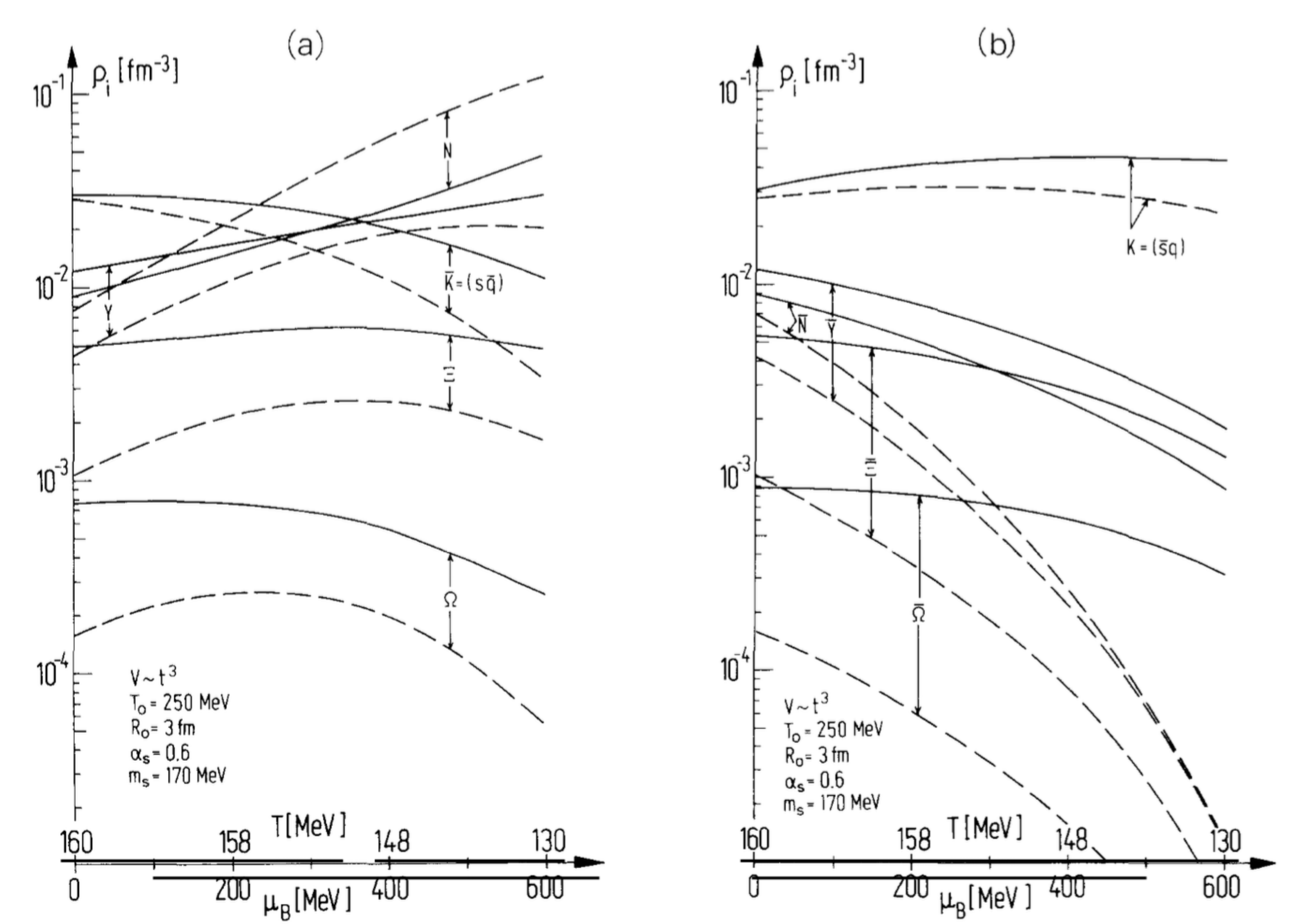
Fig. 5.5. Approach to equilibrium of various strange particle densities in hot hadronic matter at fixed temperature $T = 160$ and $\mu_b = 0$ (a) and $\mu_b = 450$ MeV (b) and (c). In (a) at $\mu_b = 0$. Strange and antistrange particles have the same abundance. At finite baryon density ($\mu_b = 450$ MeV) $\bar{s}$-hadrons are shown in (b) while s-hadrons are shown in (c).

For strange antibaryons the underpopulation is even more pronounced, with two to three orders of magnitude missing to equilibrium.

This means that even the observation of saturated hadronic equilibrium for these particles would be pointing to the temporary presence of a quark-gluon plasma seed, at least.

* **The predicted antihyperon enhancement resulting from the quark-gluon plasma region, can — if actually observed —only be explained by invoking the deconfined plasma state. (Koch, Mueller, Rafelski)**

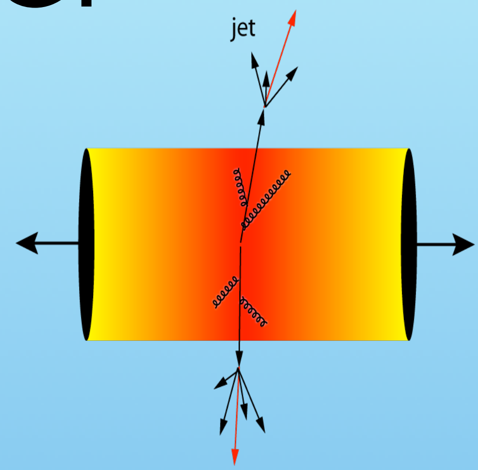
Comparison of s,sbar in QGP and Hadron Gas



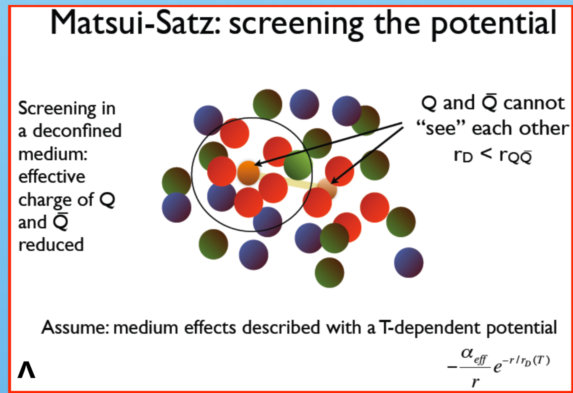
In this calulcation a quark-gluon plasma was assumed to be formed in the collision, cooling to the critical temperature at about 8 fm/c after the start of the reaction, and completing the break-up into hadrons within an additional time interval of 7fm/c.

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.

Strangeness is part of the QGP

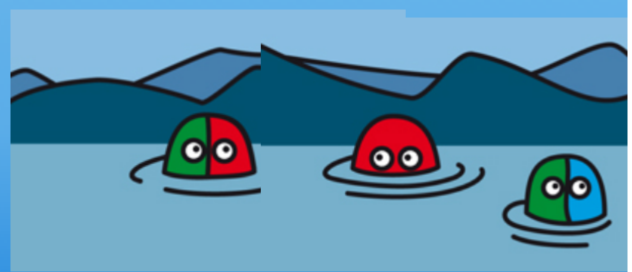


Hard probes like jets and single hadrons at high pT are like "external" to the QGP. They are traversing the QGP and are affected by the QGP, creating phenomena like jet quenching.



Quarkonia suppression is another example of an "external" probe, namely c cbar pairs are affected by QGP via color screening, without that c and cbar quarks need to get equilibrated.

Strangeness : due to the mass of strange quark of ~150 MeV being similar to the critical Temperature of the QCD phase transition, strangeness is expected to reach equlibrium and therefore we expect to have a Quark Gluon Plasma made of u,d,s quarks and gluons.
-> Strangeness is a part of the QGP



Picture taken from QM2011

Special about Strangeness

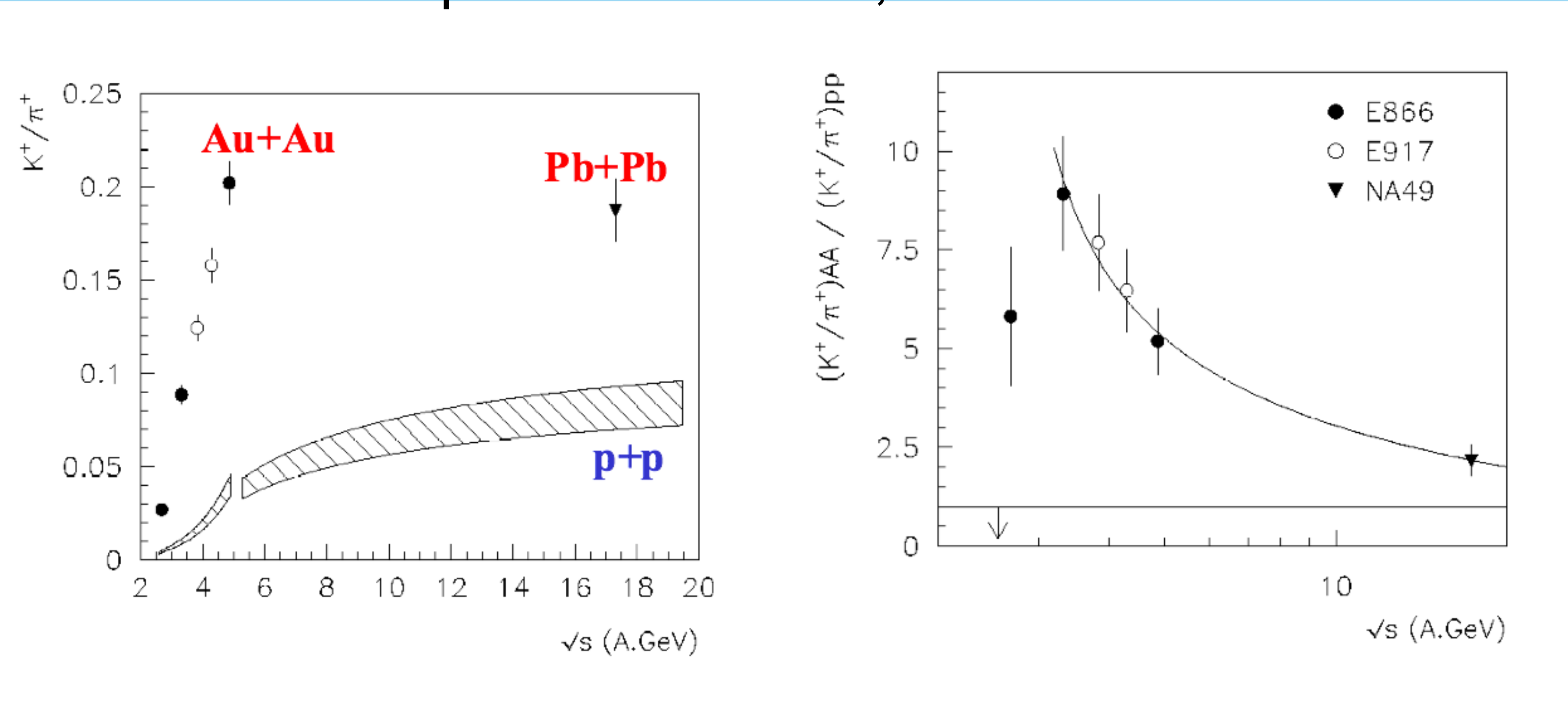
While hard probes serve as signatures to prove existence of QGP and to measure its characteristics like eg dN/dy(gluon) from jet quenching or the temperature of the QGP which is reached at a particular collision energy via Quarkonia suppression and direct photons

-> Strangeness as a part of the QGP itself, can give crucial information for the QCD phase boundary and the measurement of the critical values, like the critical Temperature.

Observation of Strangeness Enhancement

Strangeness enhancement has been observed in AGS at BNL

Experiments E866, E917

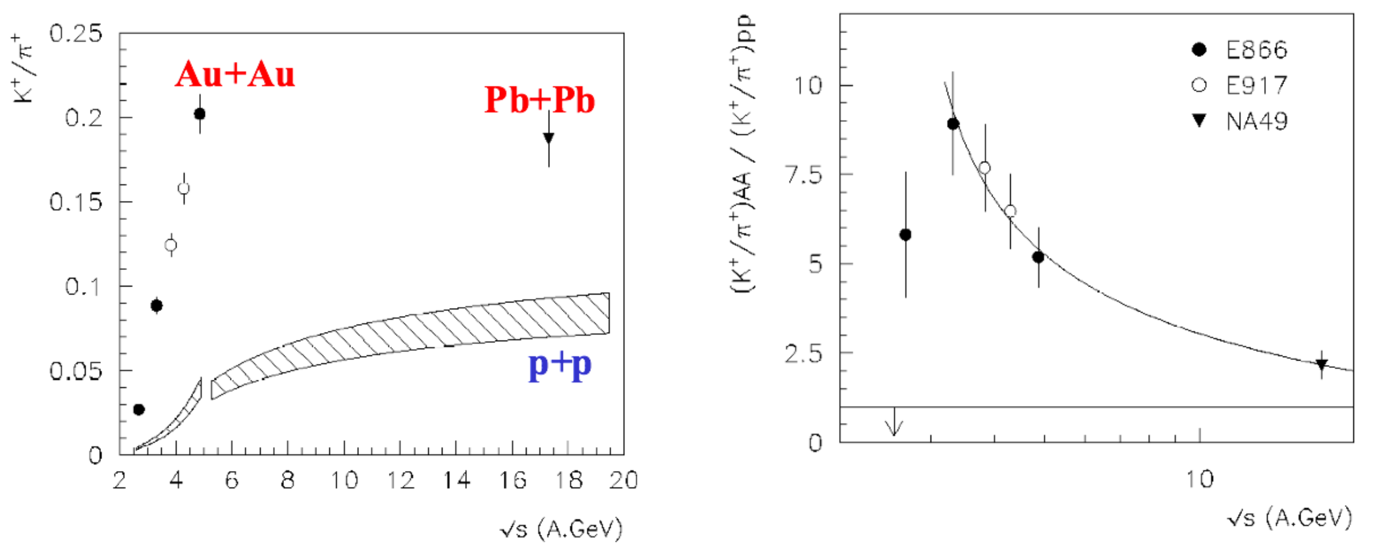


J.C. Dunlop and C.A. Ogilvie, Phys. Rev. C61:031901 (2000)

Enhancement grows larger with smaller energy?!

Strangeness enhancement has been observed in AGS at BNL

Experiments E866, E917



J.C. Dunlop and C.A. Ogilvie, Phys. Rev. C61:031901 (2000)

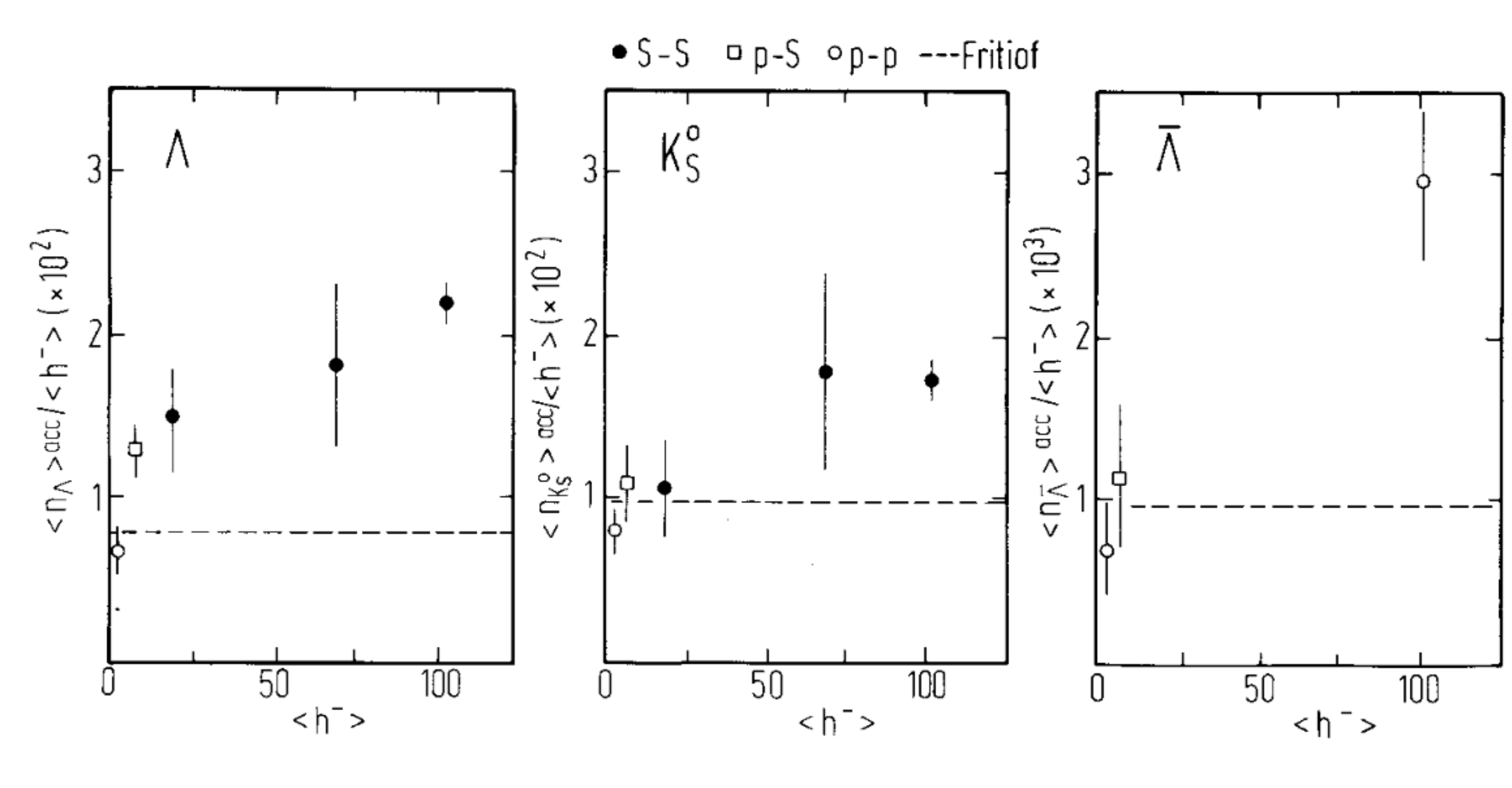
Enhancement grows larger with smaller energy !?

-> Mu_b dependence of strangeness enhancement (S.K. P Minkowski and others)

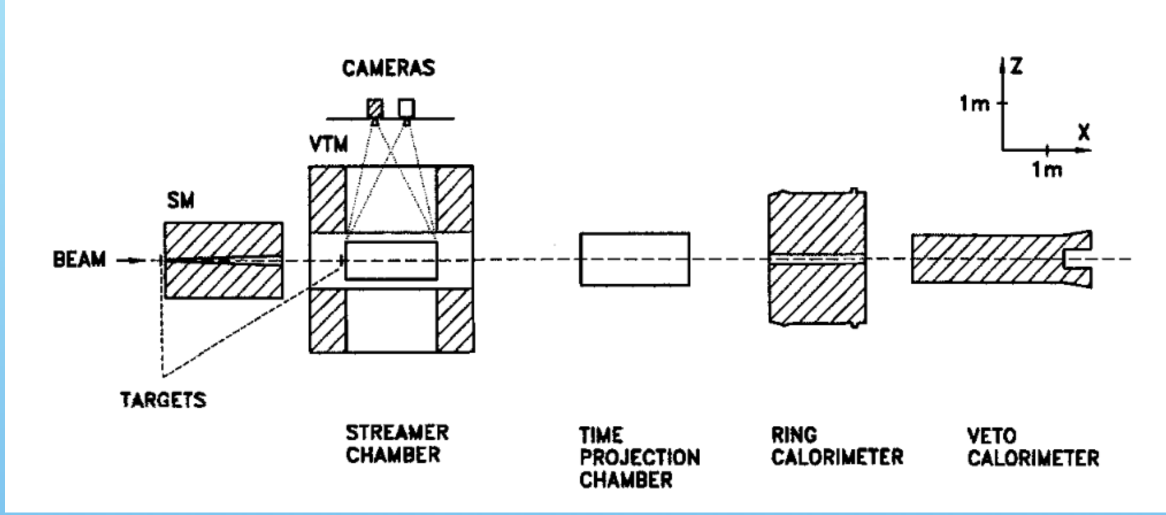
-> Canonical suppression due to small number of produced strange particles (M. Gorenstein et al and others)

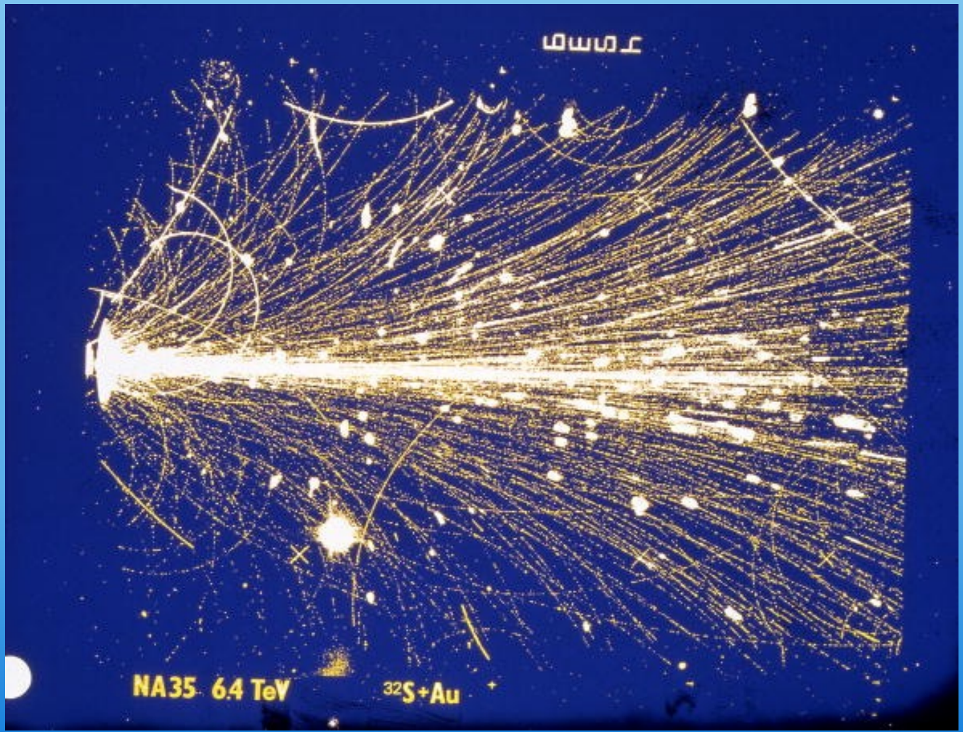
First observation of ssbar enhancement in SPS at CERN by NA35

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



NA35

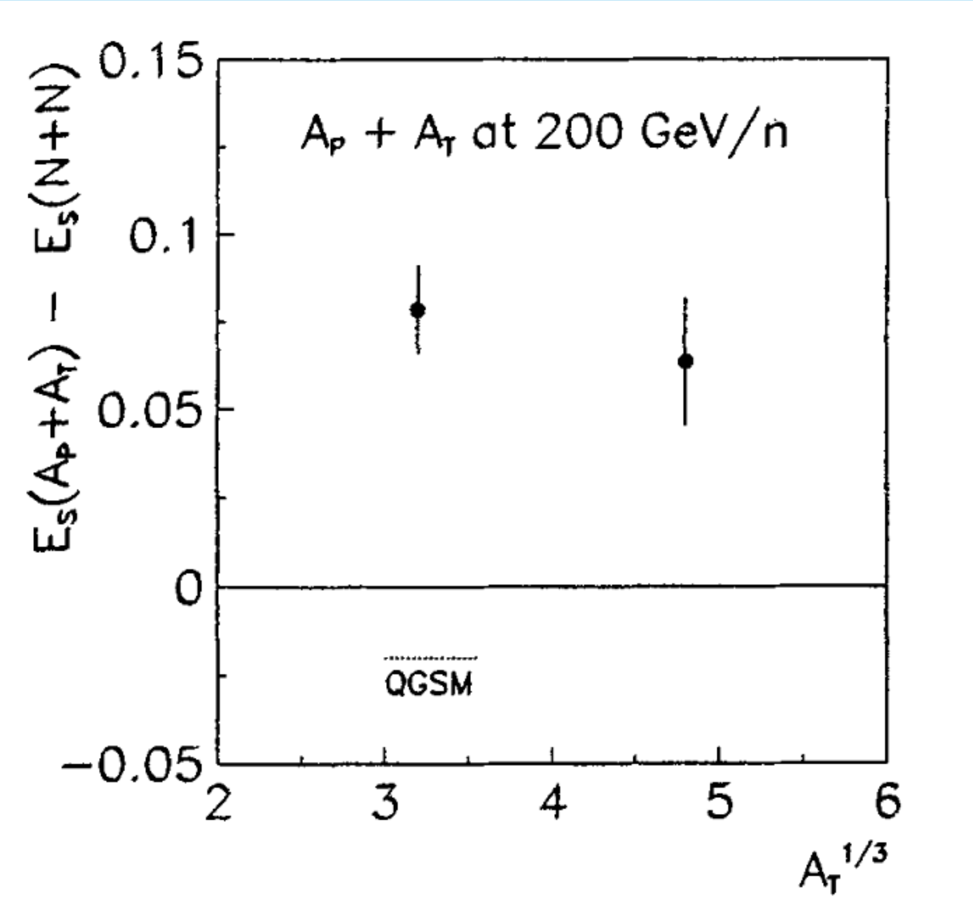




Streamer chamber picture, NA35 exp. CERN

Target dependence : S+Ag and S+S

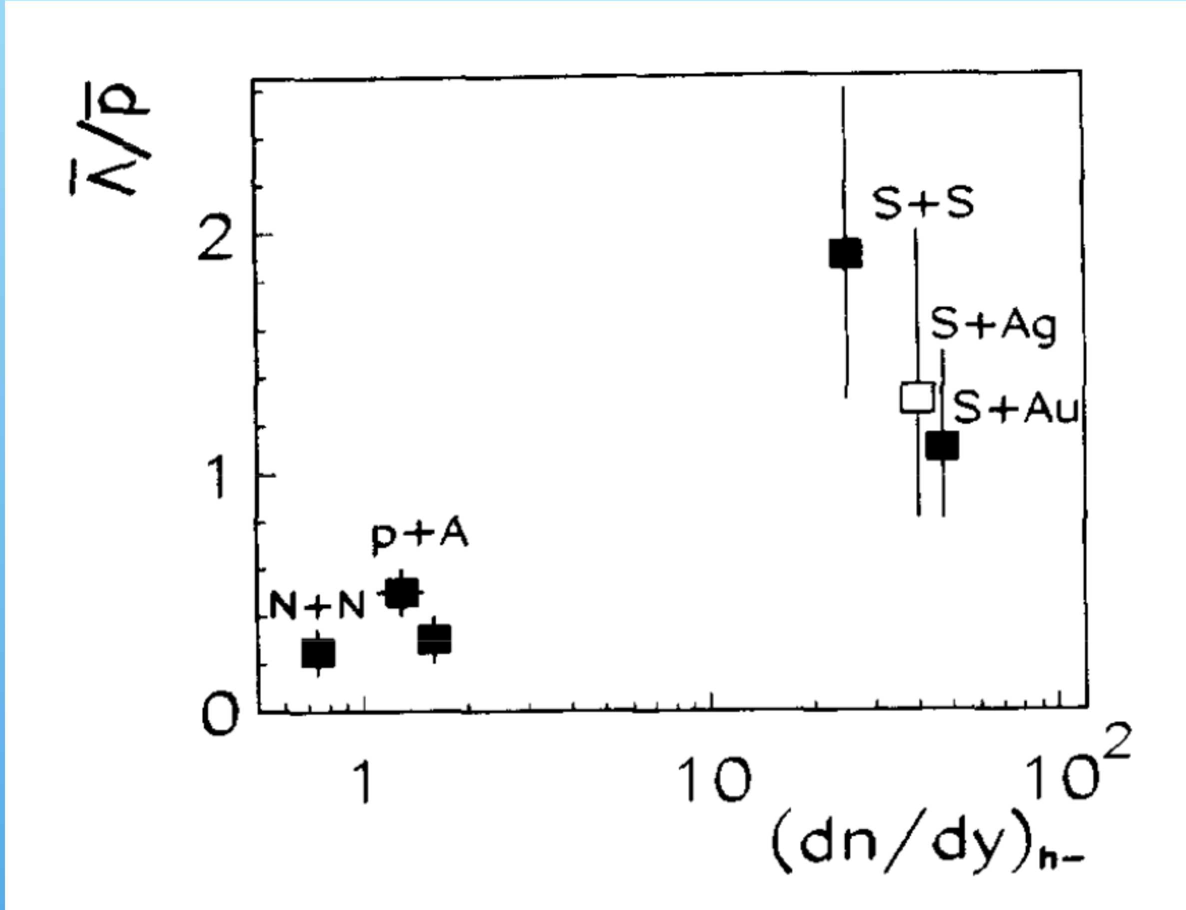
NA35, z. Phys. C 64, 195 207 (1994)



No target dependence of ssbar enhancement over pions between S+S and S+Ag

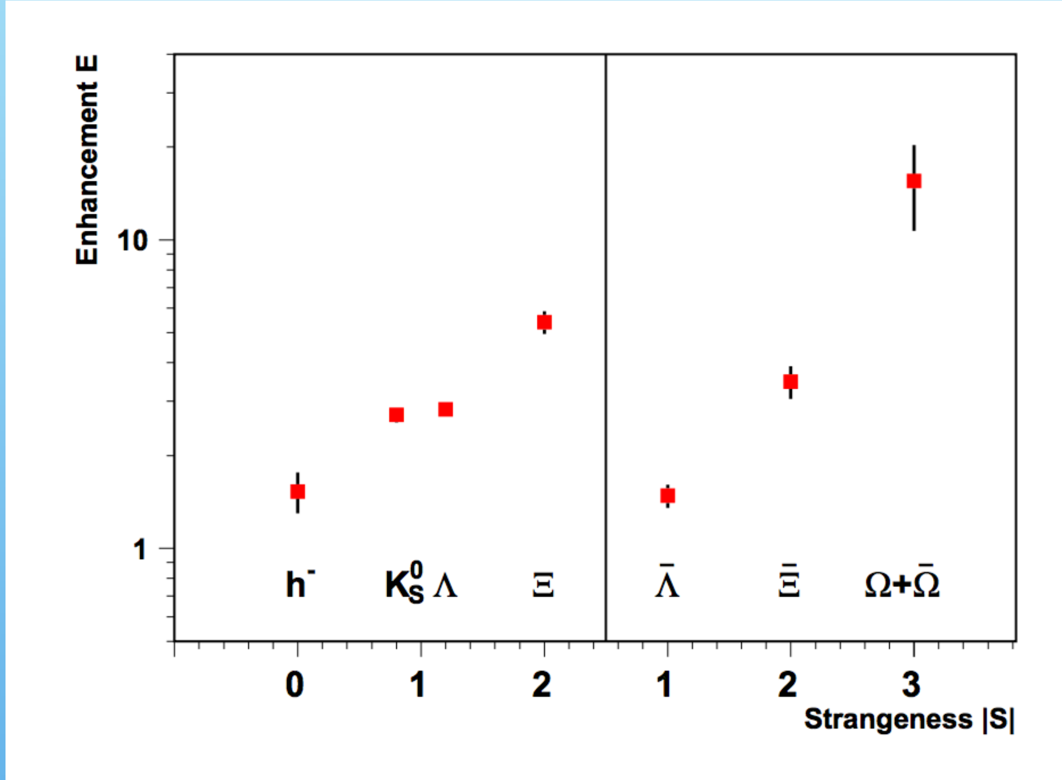
$$E_S = \frac{\langle \Lambda \rangle + 4 \cdot \langle K_S^0 \rangle}{3 \cdot \langle \pi^- \rangle},$$

Antibaryon enhancement in NA35



NA35 Coll,
Physics Letters B 366 (1996) 56-62

First measurement of strange (anti)baryons Xi, Omega by WA97

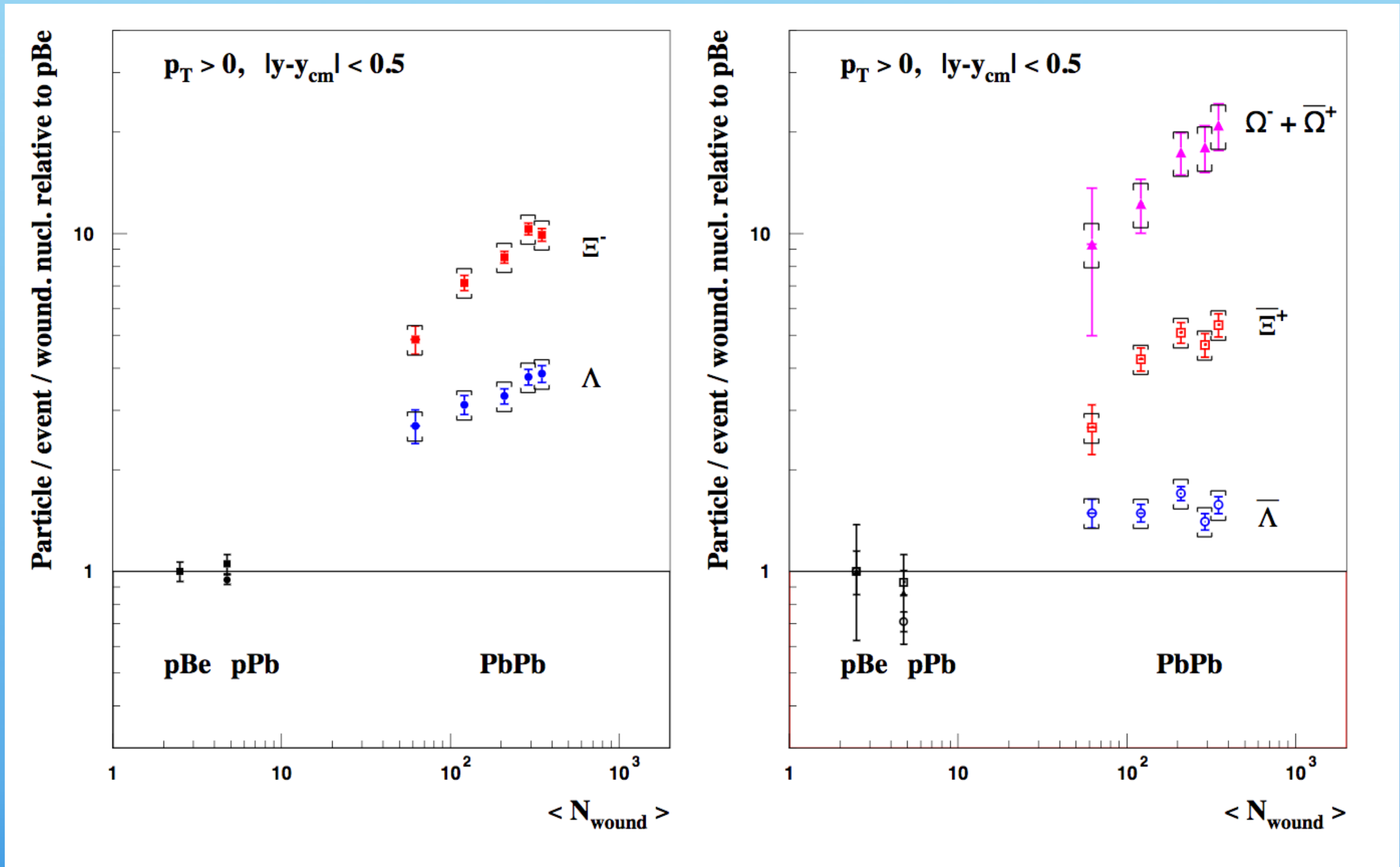


WA97 exp, Phys. Lett. B 449 , 3-4 (1999) 401-6

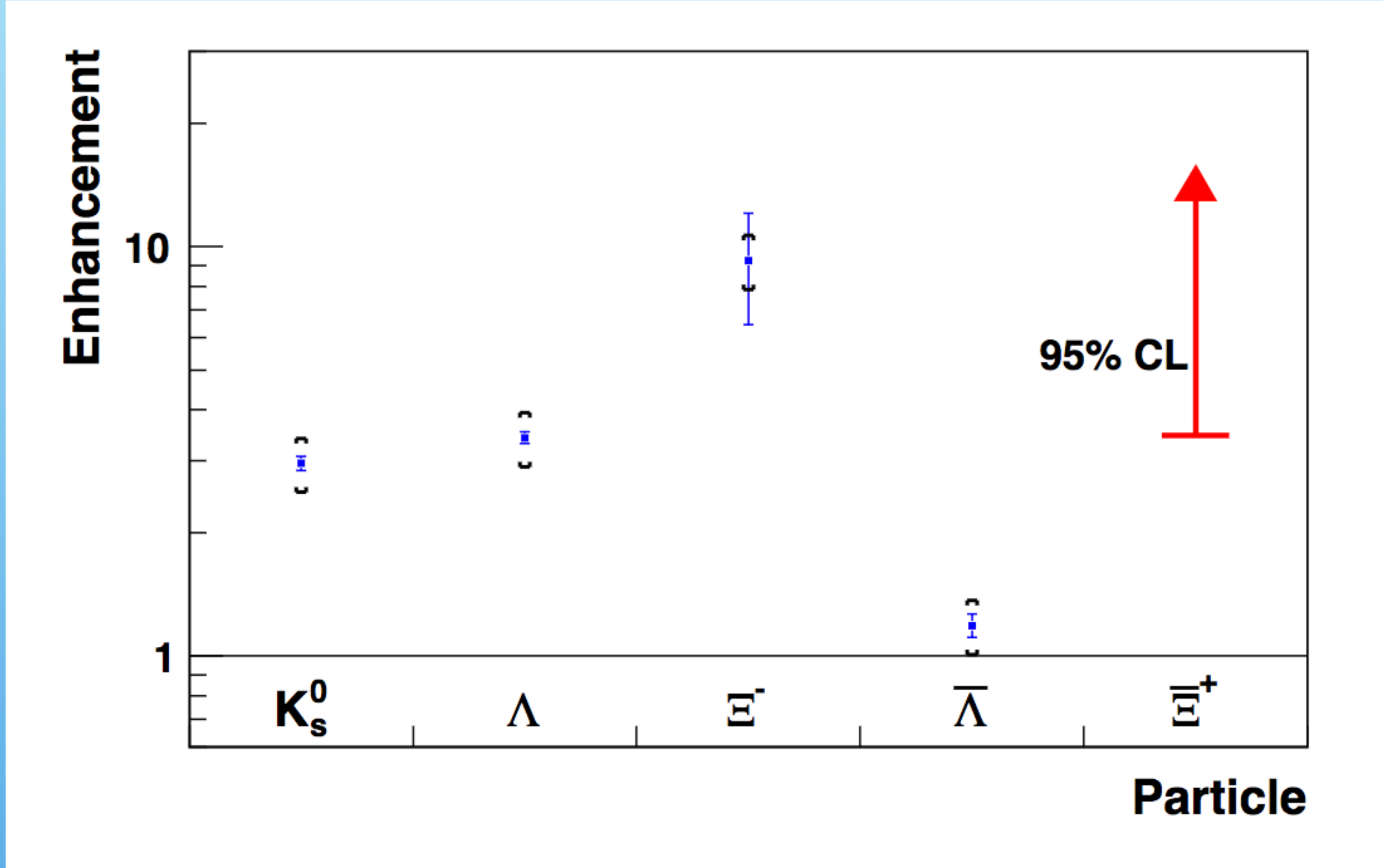
Enhancement increases with strangeness content

NA57 PbPb sqrt(s)=17 GeV

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



NA57 Pb+Pb at 40 GeV beam

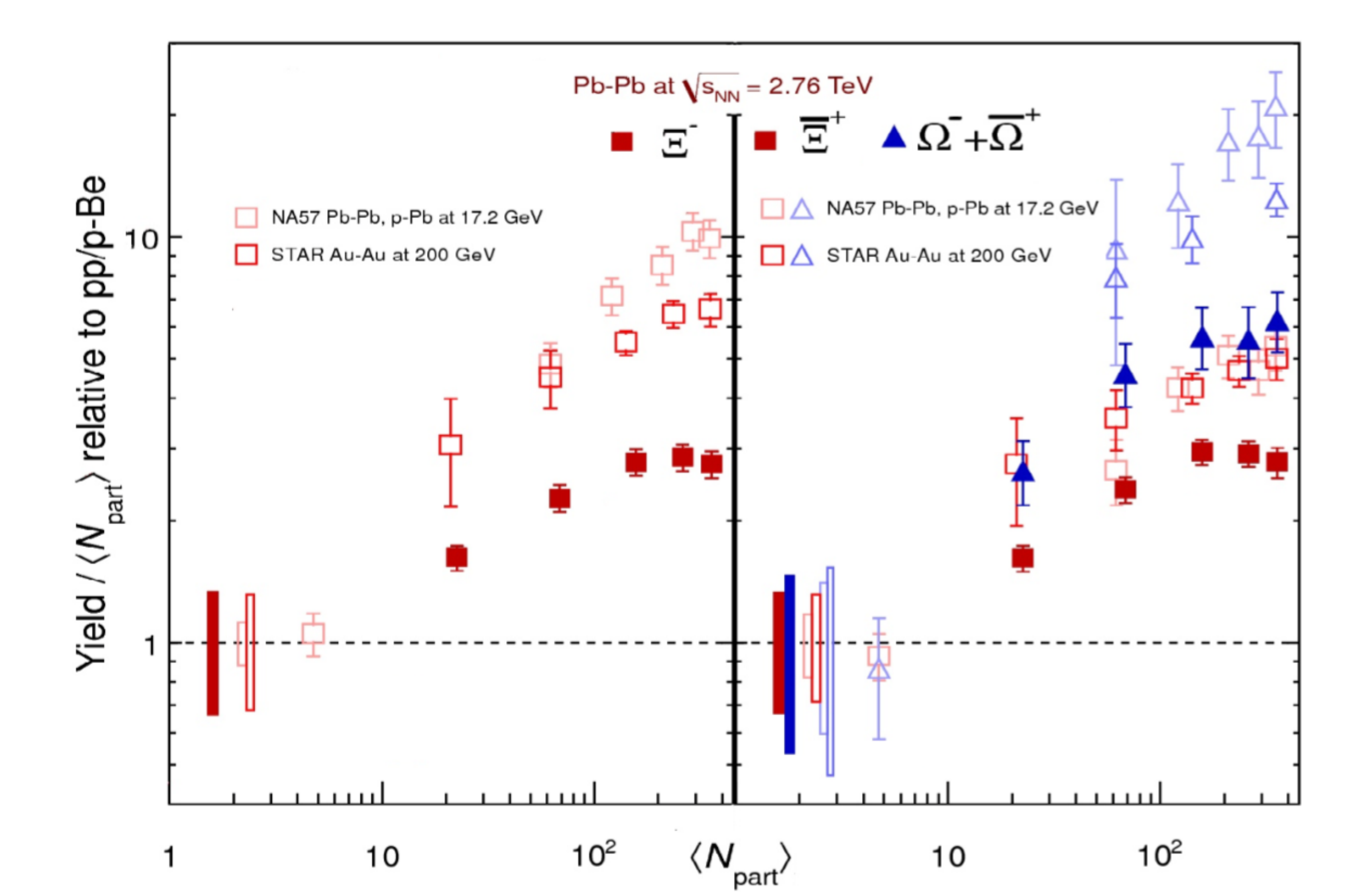


https://arxiv.org/pdf/1001.1884.pdf

Similar enhancement for Lambdas and Xis in 40 GeV and at 158 GeV

LHC, RHIC, SPS

ALICE, Phys. Lett. B 728 (2014) 216,



Strangeness enhancement gets smaller as collision energy increases here from SPS 17 GeV -> RHIC 200 GeV -> LHC 2.76 TeV

Some selected results from Statistical Models

Extracting (Temperature, muB,…) at chemical freeze out from thermal models

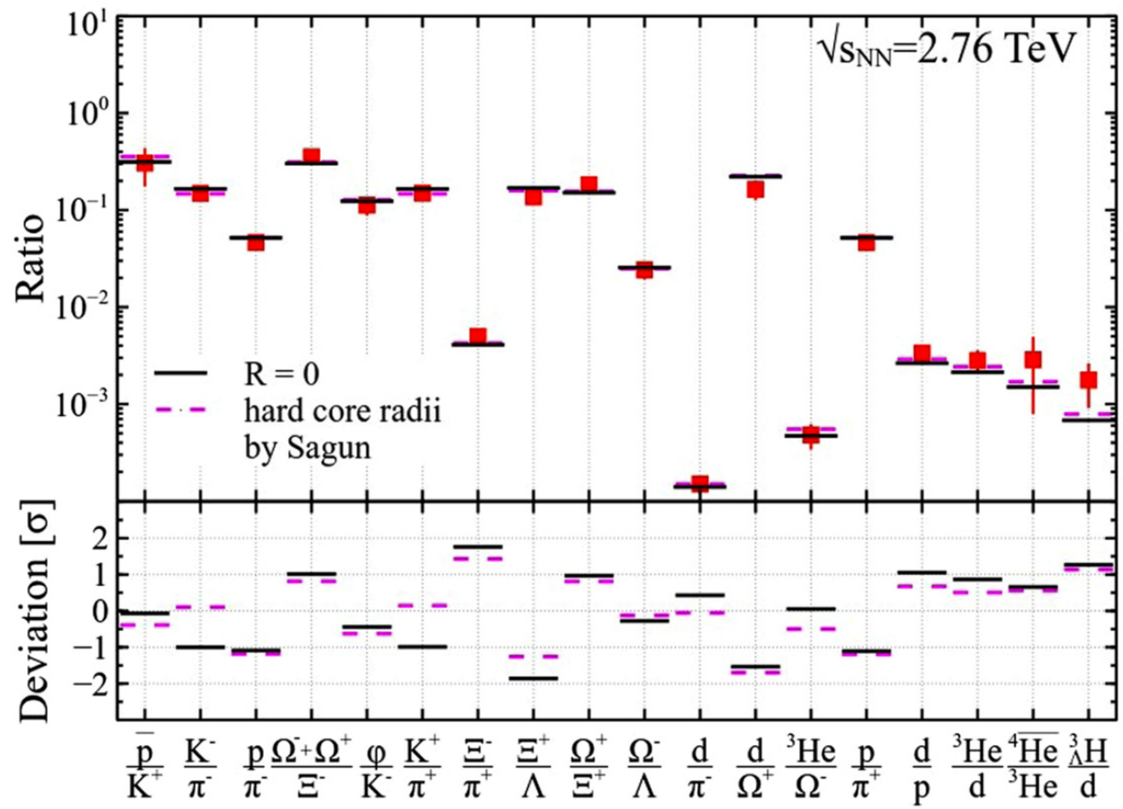
P. B Munzinger, J Stachel, A Andronic
J Cleymans, H Oeschler, K Redlich et al
K. Bugaev et al
M. Gazdzicki, Marc Gorenstein et al
F Becattini et al
J Rafelski et al
S.K, P. Minkowski
H. Satz et al
and others

Using eg ratios of hadrons with u,d,s quarks leads to temperature at chemical freeze out near Tc

Hadron Resonance Gas Model (HRGM) with multi-component hard-core repulsion (MHRGM)

K.A. Bugaev et al. / Nuclear Physics A 970 (2018) 133–155

Pb+Pb sqrt(s)= 2.76 TeV



With hard-core radii

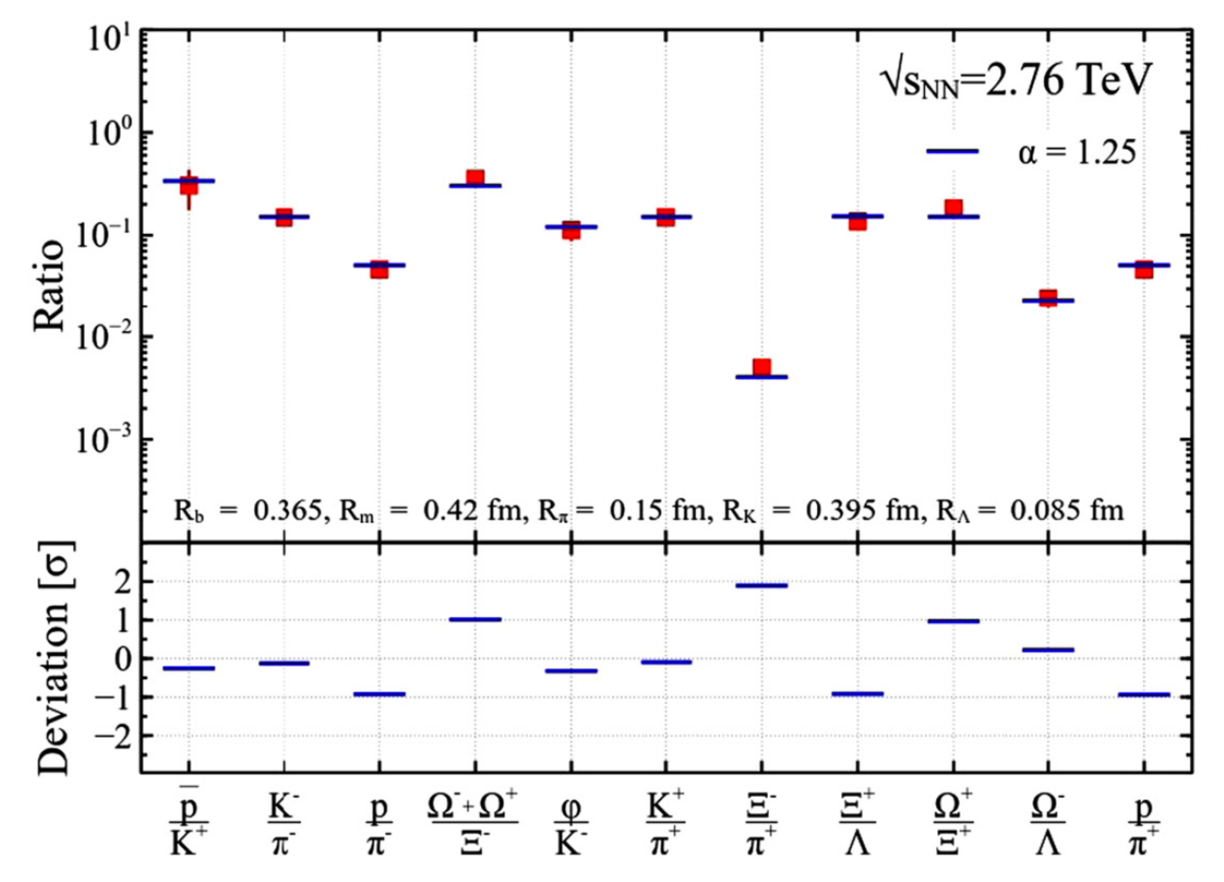
Fig. 3. The full set of ALICE data (see Table 2) was fitted by the MHRGM with the hard-core radii taken from Ref. [5] with the CFO temperature $T_{CFO} \simeq 151 \pm 7$ *MeV and* $\chi^2/ndf \simeq 13.827/17 \simeq 0.8$. *For a comparison the ideal gas fit results are also shown which correspond to* $T_{CFO} \simeq 148 \pm 7$ *MeV and* $\chi^2/ndf \simeq 19.63/17 \simeq 1.15$. The upper panel shows the fit of the ratios, while the lower panel shows the deviation between data and theory in units of estimated error.

- Fit gives T~ 151+-7 MeV and chi^2/DOF=0,8

- Ideal gas fit gives chi^2/DOF=1.15

IST EOS

K.A. Bugaev et al. / Nuclear Physics A 970 (2018) 133–155

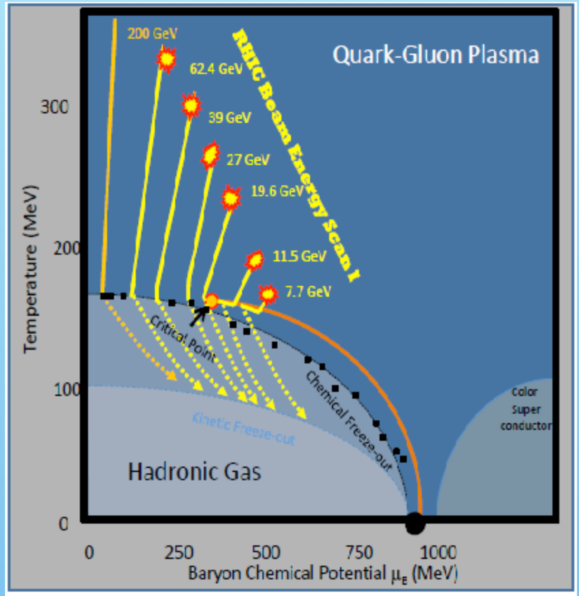


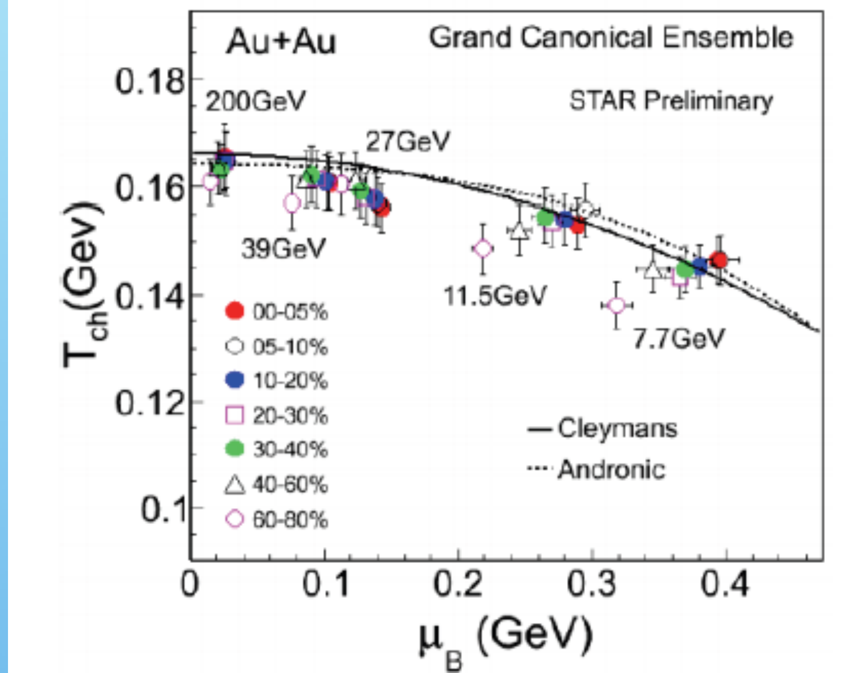
Van der Waals EOS with induced surface tension (abbreviated IST EOS)

Fig. 4. Same as in Fig. 3, but the fit was obtained by the IST EOS with the new hard-core radii found in Ref. [29]. The obtained CFO temperature is $T_{CFO} \simeq 148 \pm 7$ *MeV. The (anti)nuclei ratios are not included in the fit and its quality is* $\chi^2/ndf \simeq 8.92/10 \simeq 0.89$. The upper panel shows the fit of the ratios, while the lower panel shows the deviation between data and theory in units of estimated error.

- (Anti)nuclei are not included in the fit
- Fit gives T= 148+-7 MeV and chi^2/DOF=0,9

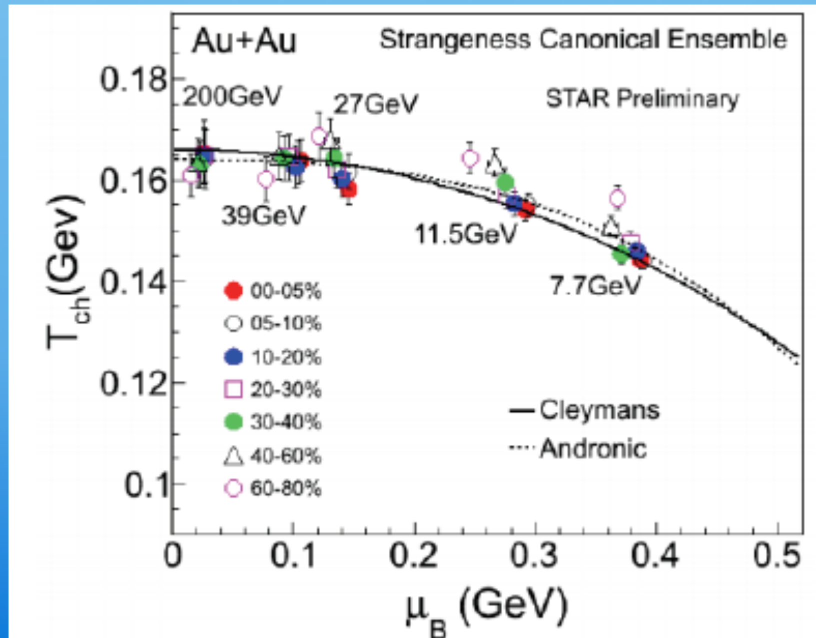
Chemical freeze out temperature vs baryochemical potential





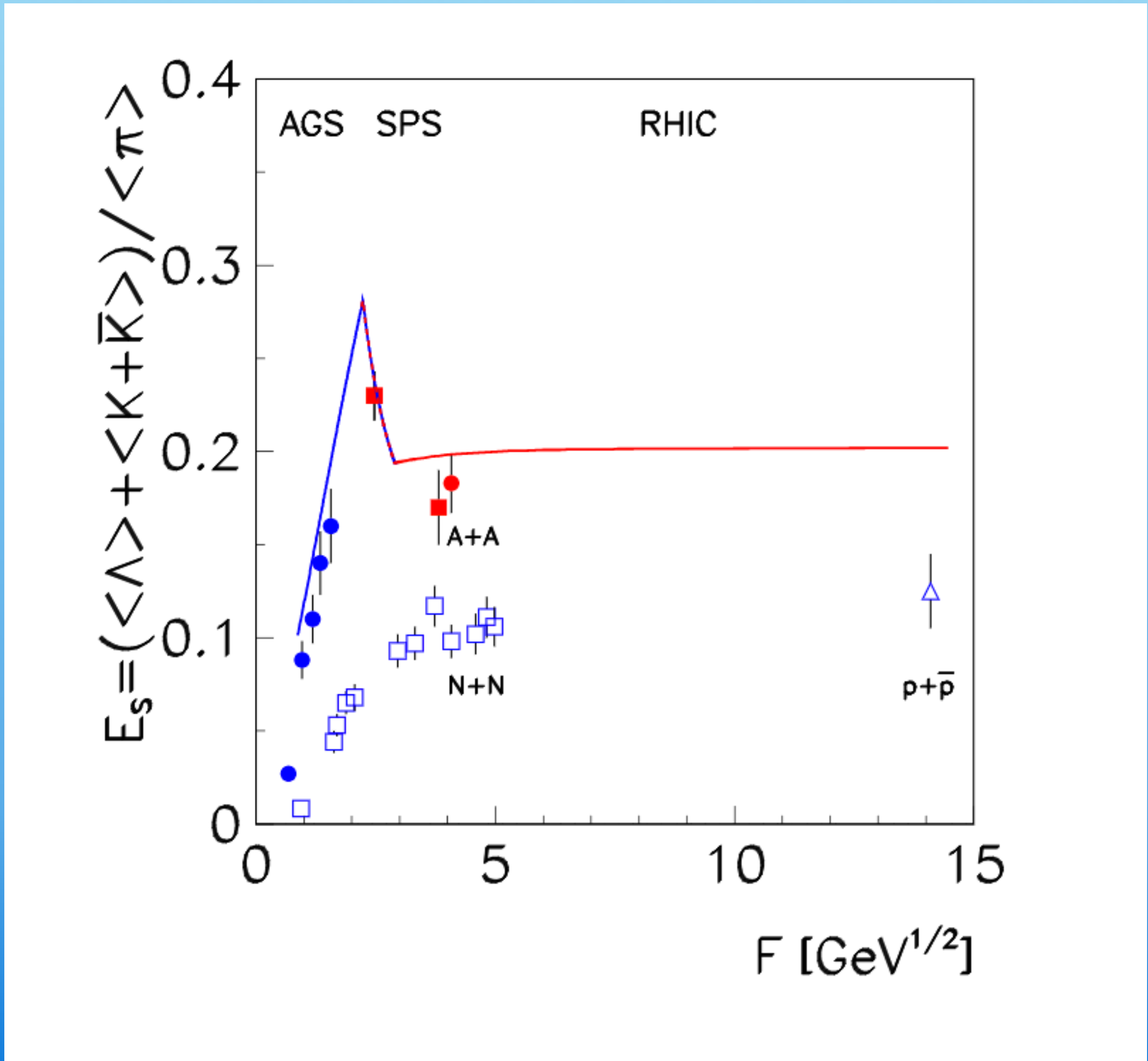
Model used for particle ratio fits: THERMUS by J Cleymans et al

Grand canonical ensemble and strangeness canonical ensemble fits to particle ratios give consistent results for mid-central and central Au+Au collisions and disagree for peripheral collisions



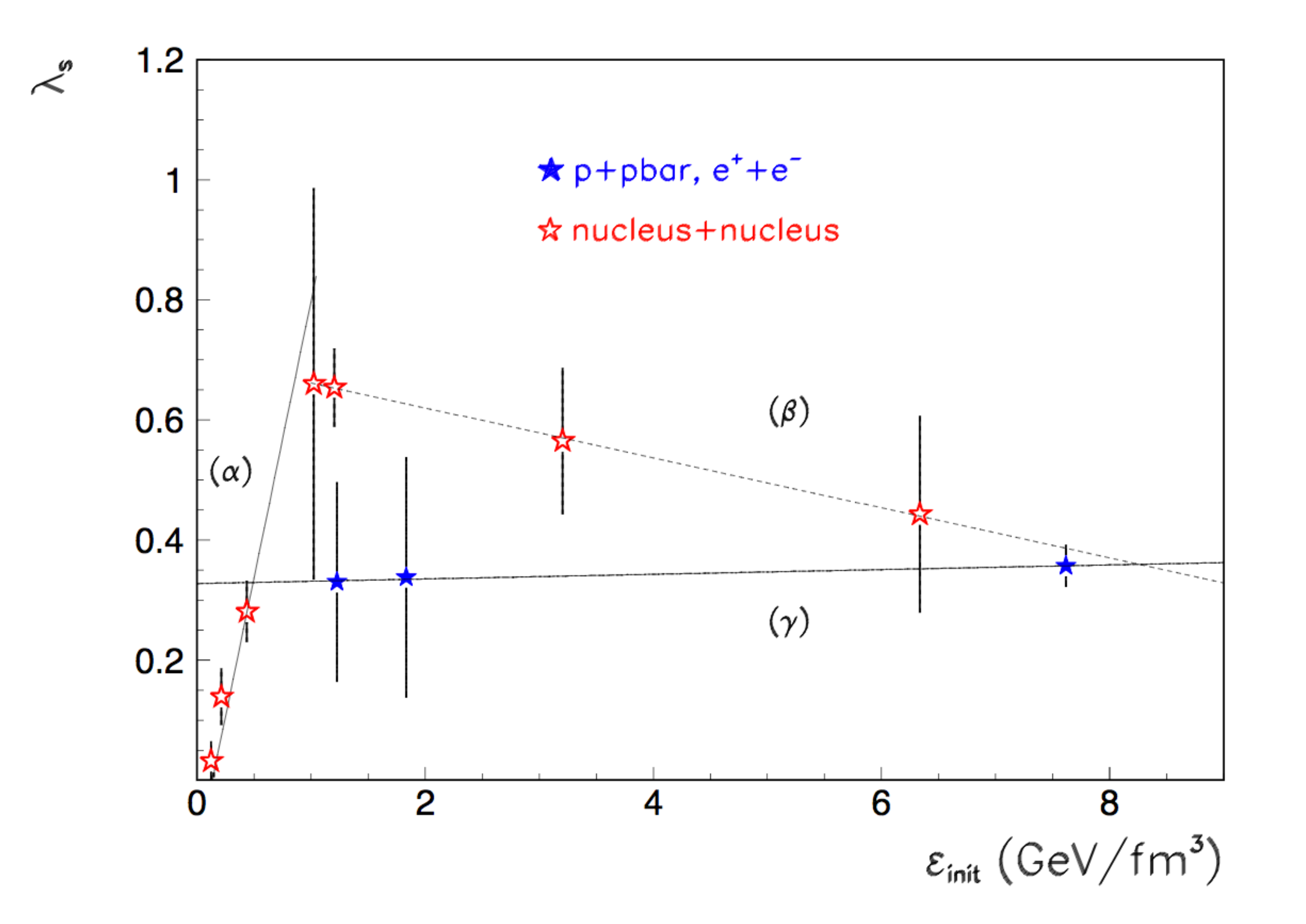
Energy dependence of s/q
The "Horn"

M. Gorenstein, M. Gazdzicki, Acta Phys. Pol. B 30, (1999) 2705.



"Horn" proposed as signature for the QCD phase transition occuring nearby

Maximum of strangeness suppression factor

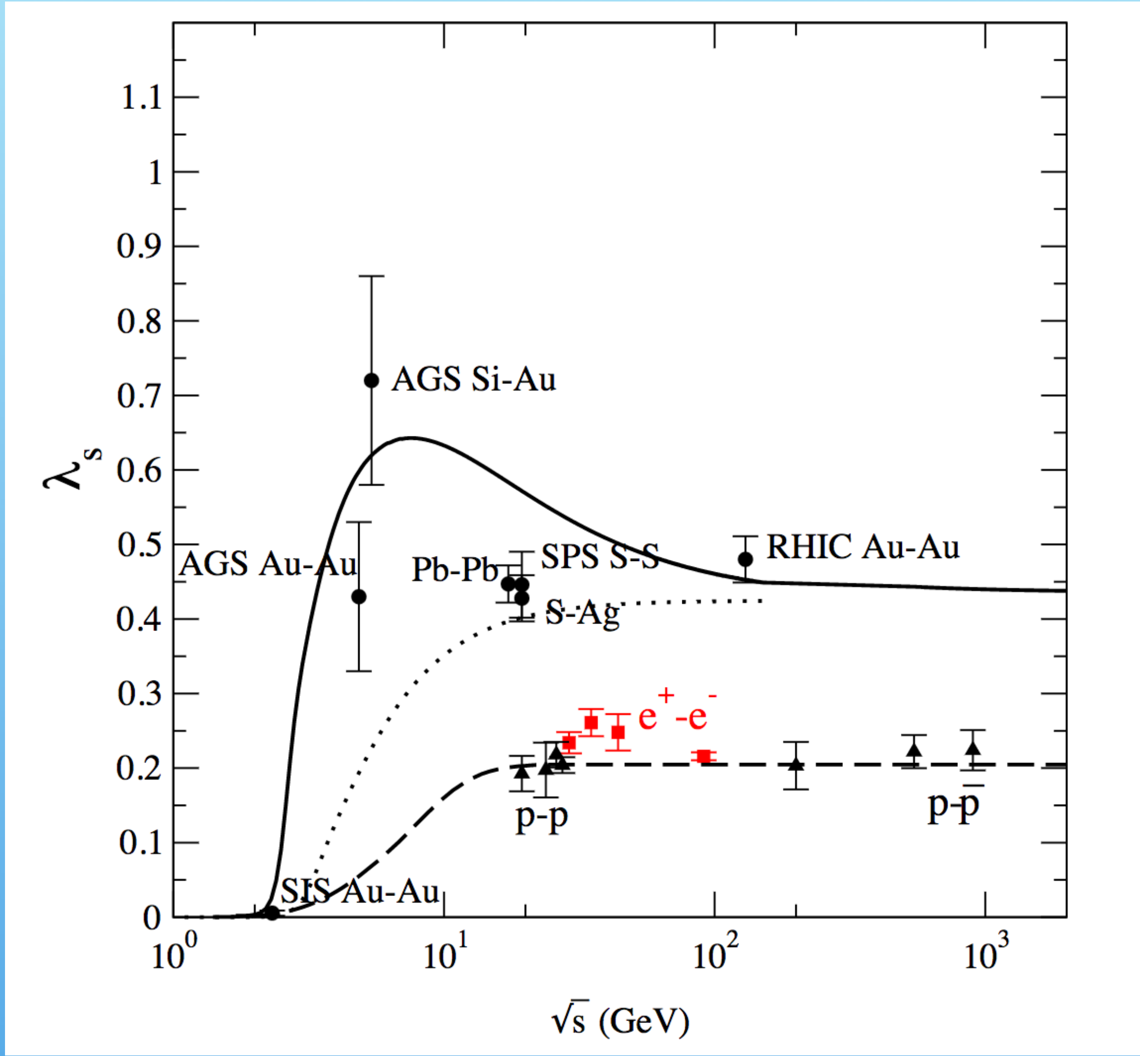


Maximum of λs occurs at or below initial energy density of 1 GeV/ fm^3 (red points)

The maximum is not seen in p +pbar and e+e- collisions

S.K., Eur.Phys.J. C21 (2001) 545-555

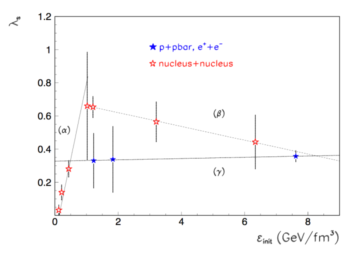
Again the maximum of λs

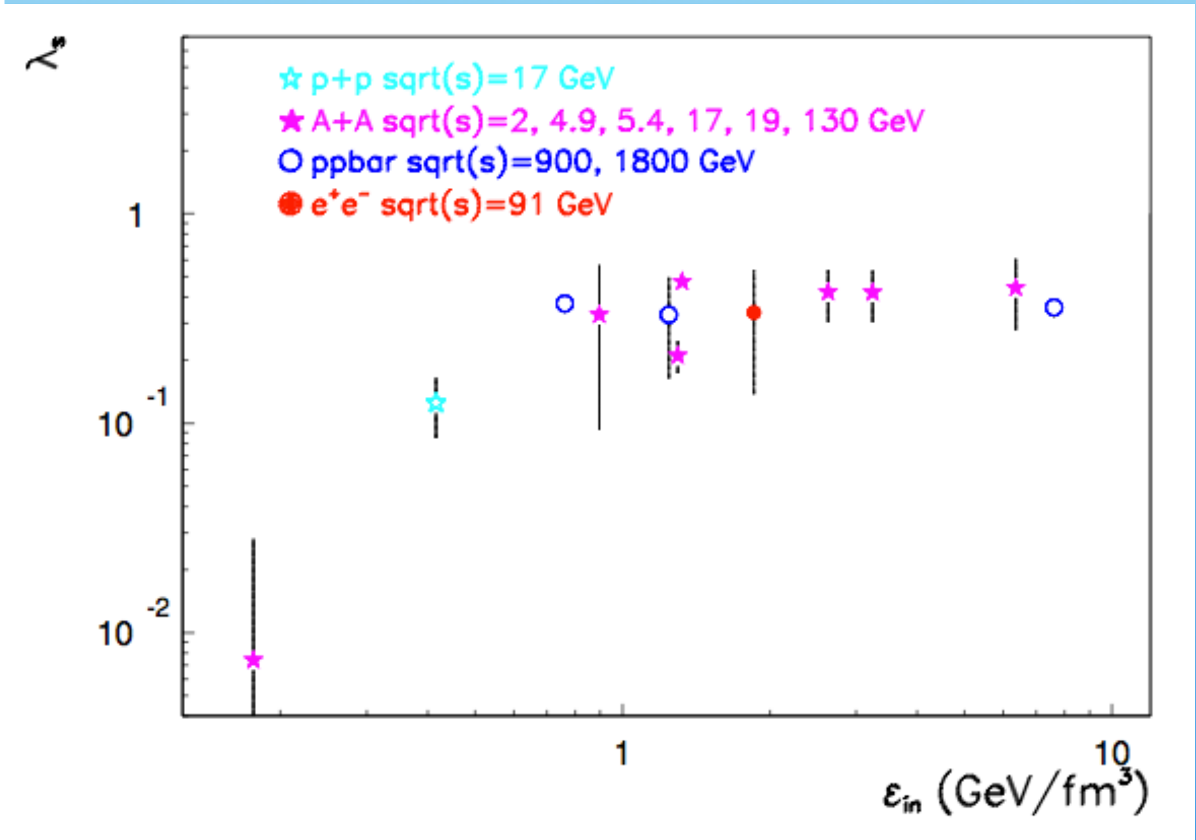


A later study revealing again the maximum of strangeness suppression factor by P Braun Munzinger, J Cleymans, K Redlich, H Oeschler, Nucl.Phys. A697 (2002) 902-912

Figure 2: The Wroblewski ratio λ_s (for definition see text) as a function of $\sqrt{s}$. The thick solid line has been calculated using the freeze-out values of the temperature and the baryon chemical potential. The dotted line has been calculated using $\mu_B = 0$ and only varying T. The dashed line has been calculated using a radius of 1.2 fm, keeping μ_B=0 and taking the energy

The maximum dissappears at muB=0





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

After extrapolating all points to muB=0 the maximum of λs dissappear
This suggest that the maximum is entirely due to the finite values of mu_B

After eliminating the effect of having different mu_B for each point, small and large systems universally agree and depend only on initial Bjorken energy density reached in the collision

The onset of saturation reveals the onset of the QCD phase transition
(Van Hove's signature)

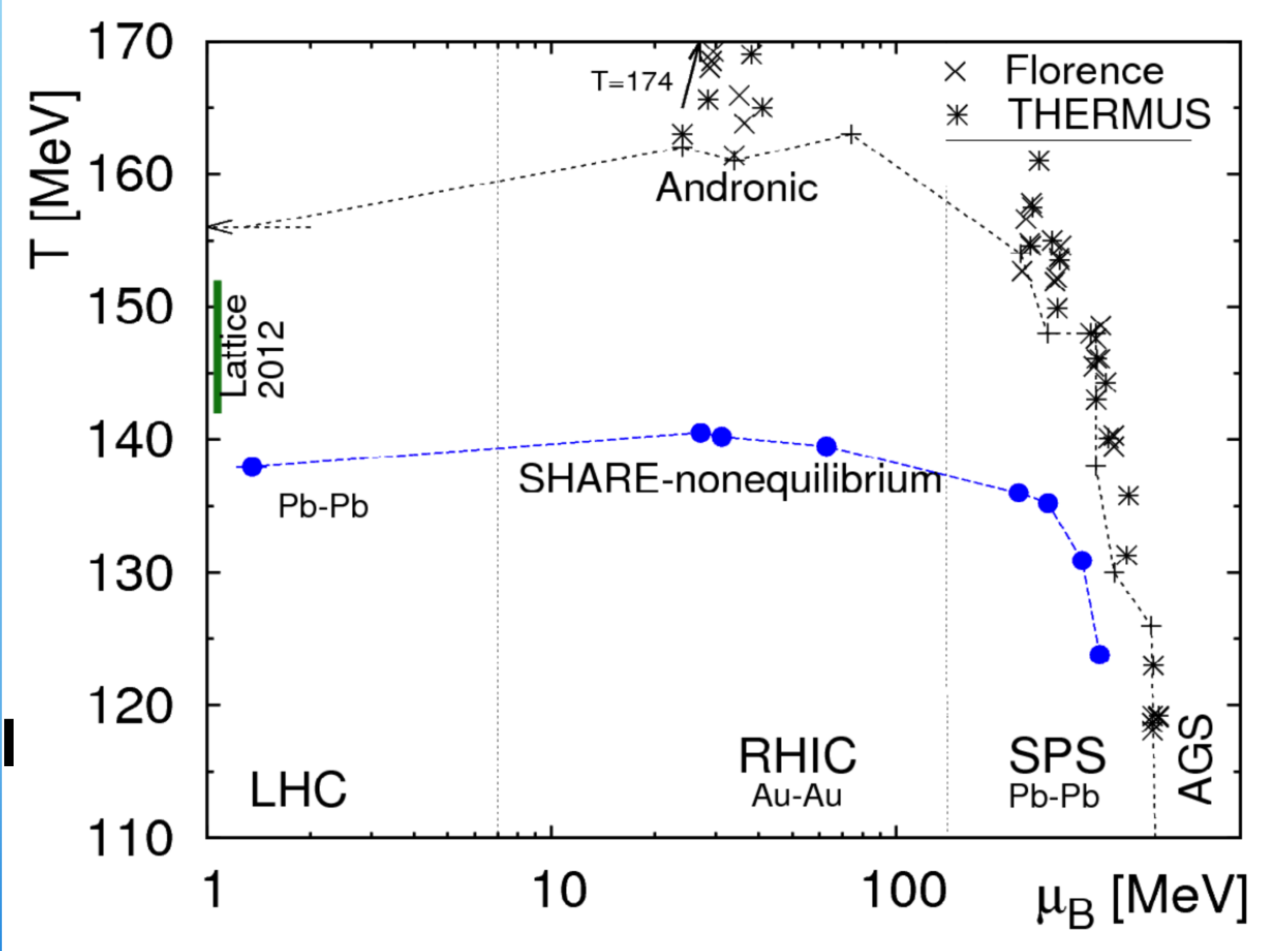
Statistical Model by J. Rafelski - SHARE

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

Finds that strange and light quarks deviate from equilibrium yield

T about ~ 140 MeV at high energy

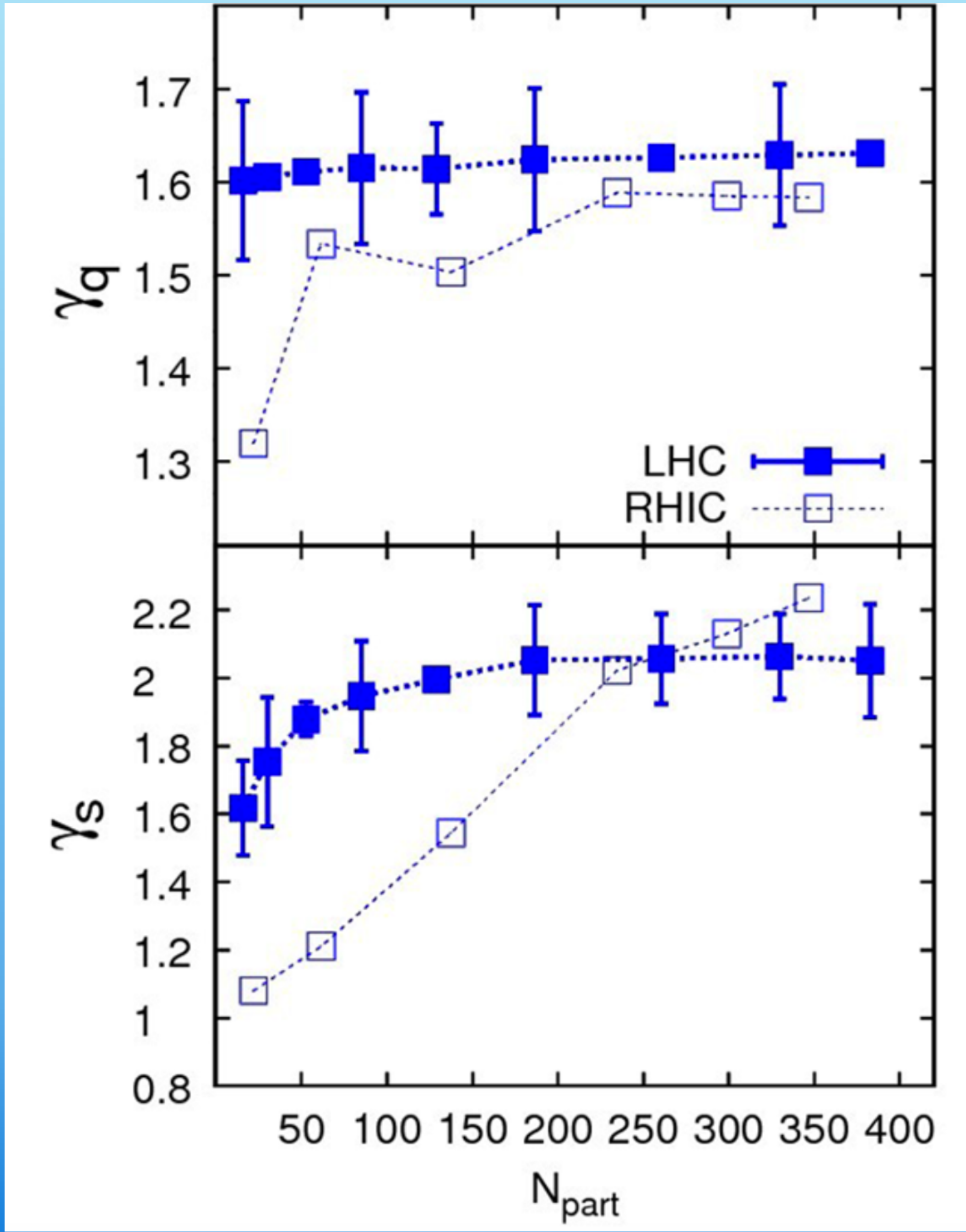
Comparison of results of SHINE with A Andronic et al and Lattice QCD calculations



J. Rafelski SHARE

J. Rafelski, Eur. Phys. J. A 51, 114 (2015).

Strange quark gamma_s and light quark gamma_q fugacities for LHC Pb+Pb 2.76 TeV (full points) and RHIC (open points) as a function of N_part



Resolution of the proton anomaly

The "proton anomaly": Protons and antiprotons from the statistical model ere found to deviate by 2.7 sigma from data

J. Stachel,et al, J. Phys. Conf. Ser. 509, 012019 (2014). The Statist. hadronization model prodicts 25% more protons than in the data.

The resolution of the proton anomaly: In A. Andronic et al, hep-ph 1808.03102 the authors estimate the piN interaction contributions to the proton yield , employing the S-matric formulation of statistical mechanics to integrate in their statistical model the effect of broad resonances and of non resonant contributions.

(See lecture of Dr Po Man LO this week in HISS-2018)

Resolution of the proton anomaly

A. Andronic et al, hep-ph 1808.03102

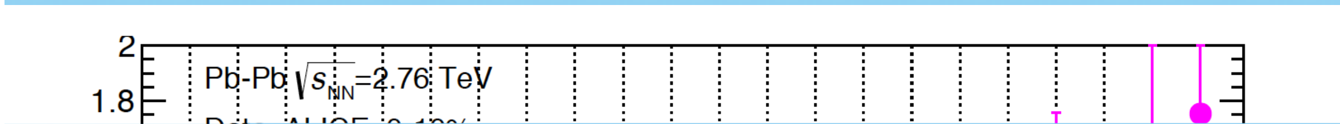


FIG. 3. The ratio of data on the multiplicity per unit rapidity, dN/dy, for hadrons measured at midrapidity to the statistical hadronization results, including the S-matrix corrections to the proton and antiproton production yields. The lower panel shows the difference between data and model results, normalized by the standard deviation σ of the data for a given species.

Comparison of the model to experimental data from Pb+Pb collisions at sqrt(s)= 2.76 TeV (ALICE)

The new model yields an improved chisquare = 19.7 per 19 DOF compared to previous model giving chisquare = 29.2

Strange particles

Apart from looking after strangeness enhancement, strange particles are used for a number of studies like

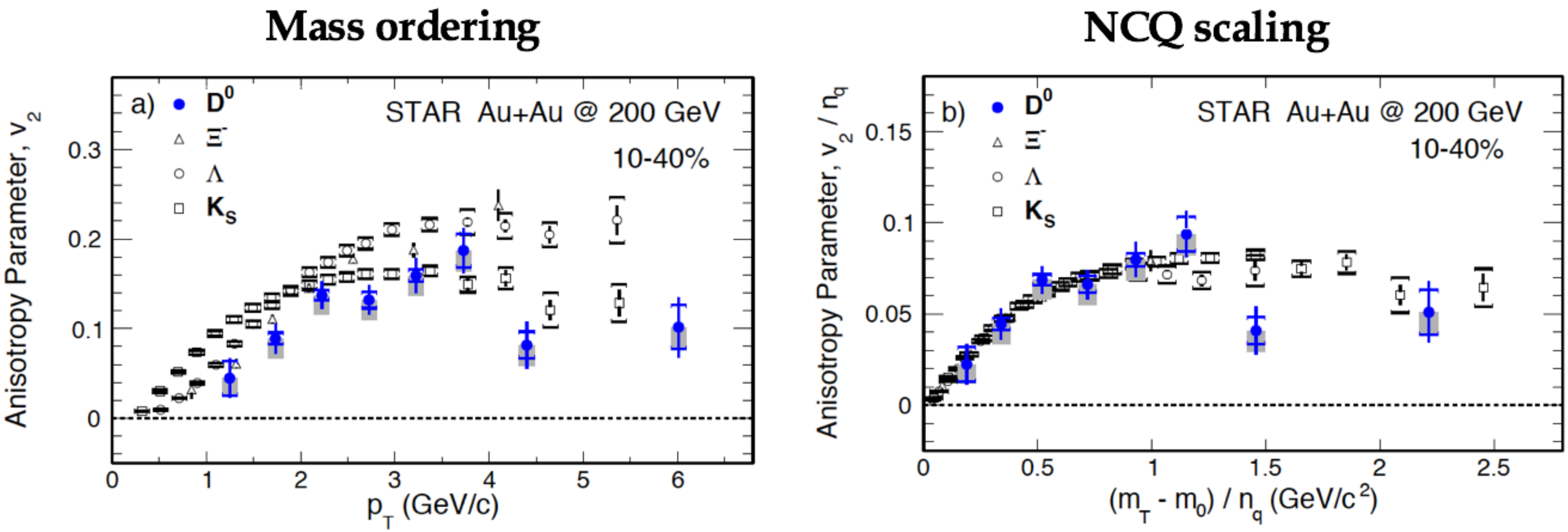
- RAA study vs pT,
- flow,
- correlations,
- polarization of Lambda,
- transverse momenta and extraction of transverse flow and thermal freeze out Temperature,
- test of number of constituent quark scaling,
- to extract T and chemical potentials at chemical freeze out, - and other.

Number of Constituent Quark scaling

Number-of-Constituent-Quarks scaling

Au+Au at sqrt(s)=200 GeV

1701.06060, STAR



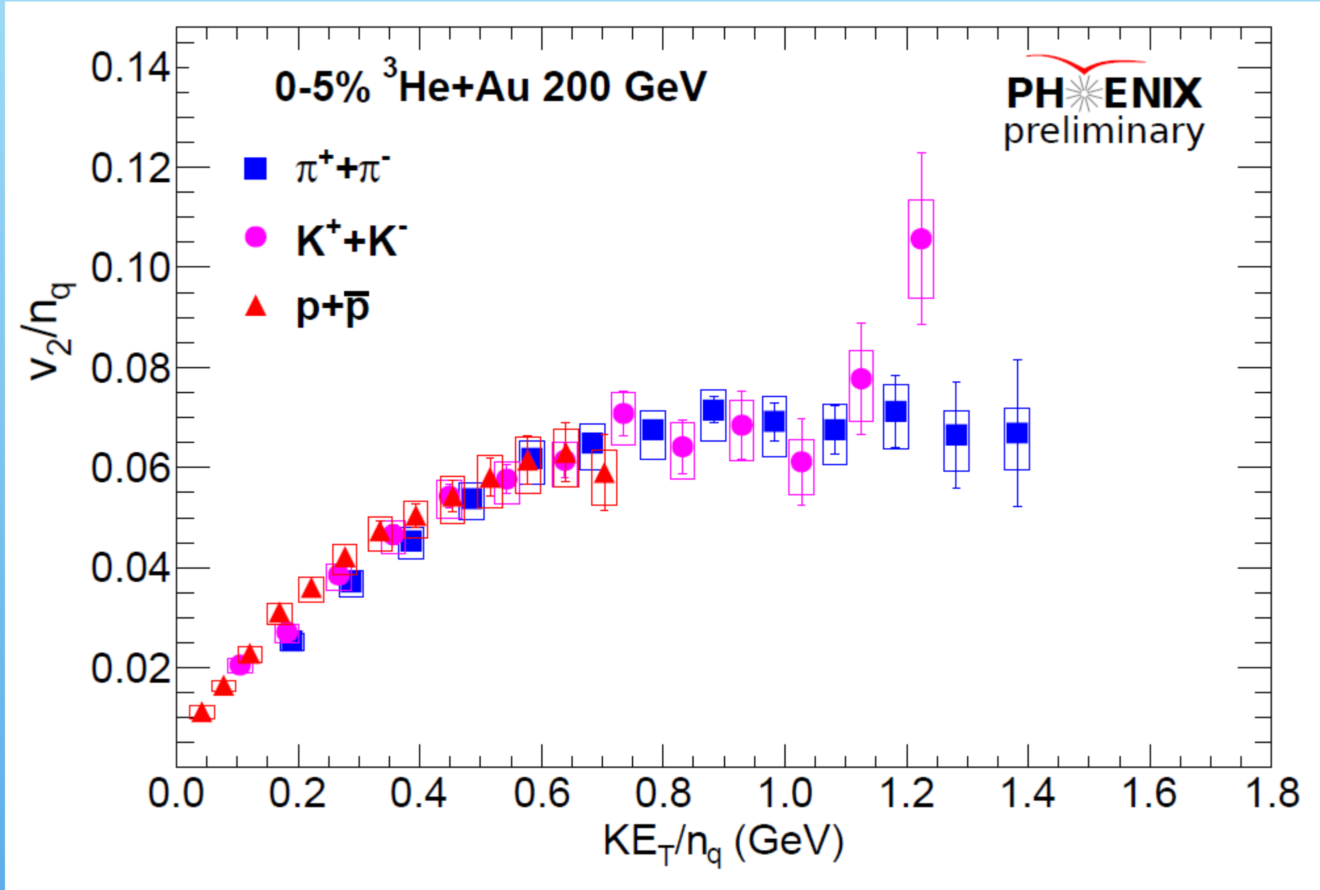
Strange hadrons as well as D0 follow the Number-of-Constituent-Quarks scaling

-> suggest hadronization out of partonic matter

-> Thermalization of charmed mesons?

-> Production of hadrons mainly via recombination of partons?

Number of constituent quark scaling seen also in small systems: 3He+Au

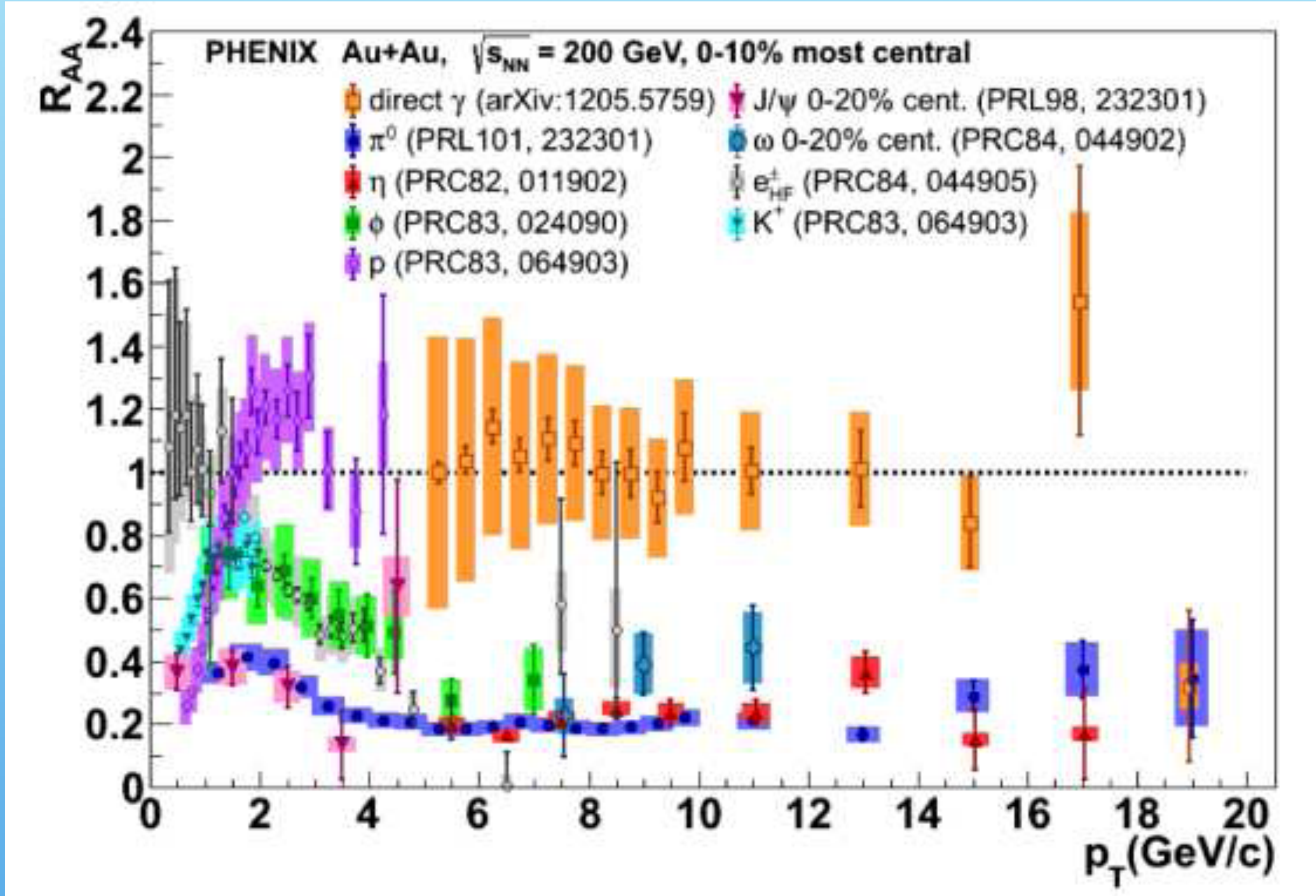


S Huang, STAR, QM15

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

RAA of strange particles

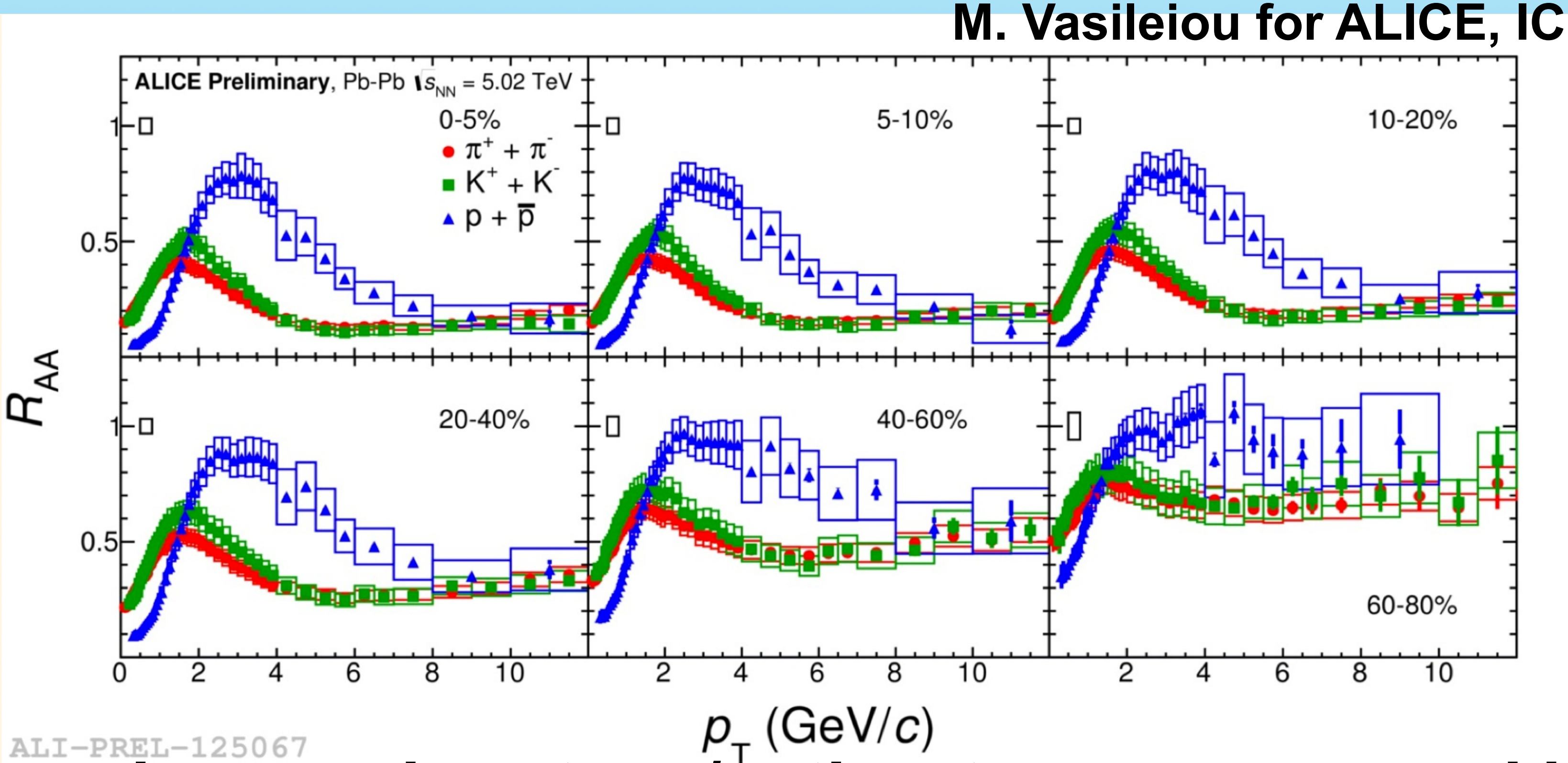
Jet quenching of light hadrons at RHIC



*** Light hadrons with u,d,s quarks are quenched**
*** Photons are not quenched**

ALICE RAA Pb+Pb 5.02 TeV

M. Vasileiou for ALICE, ICNFP2017

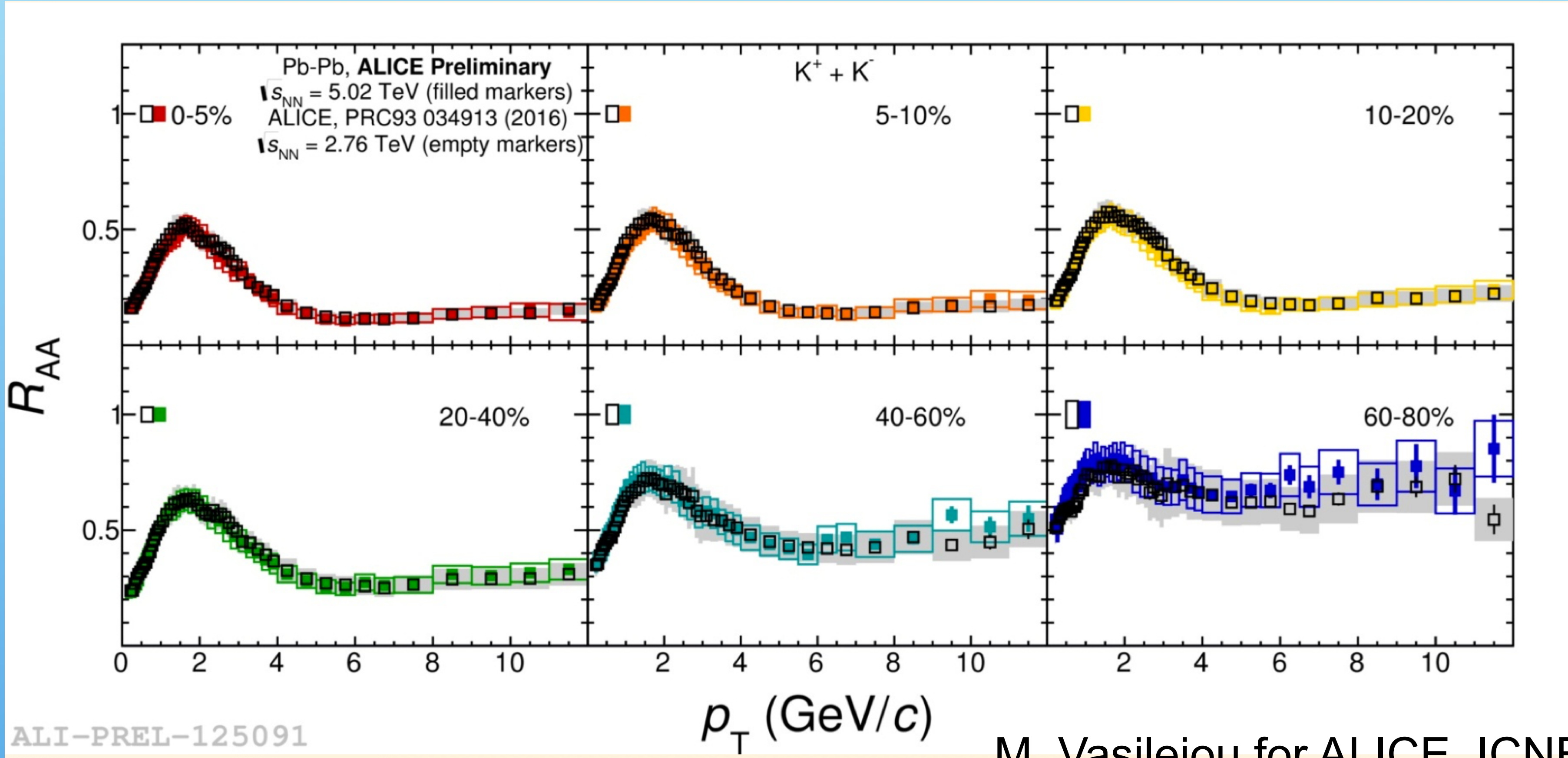


- Kaons, pions and protons/antiprotons suppressed in Pb +Pb below expectation from p+p superposition (RAA=1).

- Suppression maximal at most central collisions and high pT

- Suppression similar for all species and at all centralities at high pT

RAA of Kaons in Pb+Pb at 2.76 and 5.02 TeV



M. Vasileiou for ALICE, ICNFP2017

-> RAA of Kaons in Pb+Pb is energy independent between 2.76 and 5.02 TeV

Latest Highlights about Strangeness yields over pions

Recently published results from ALICE in Nature

nature physics

LETTERS

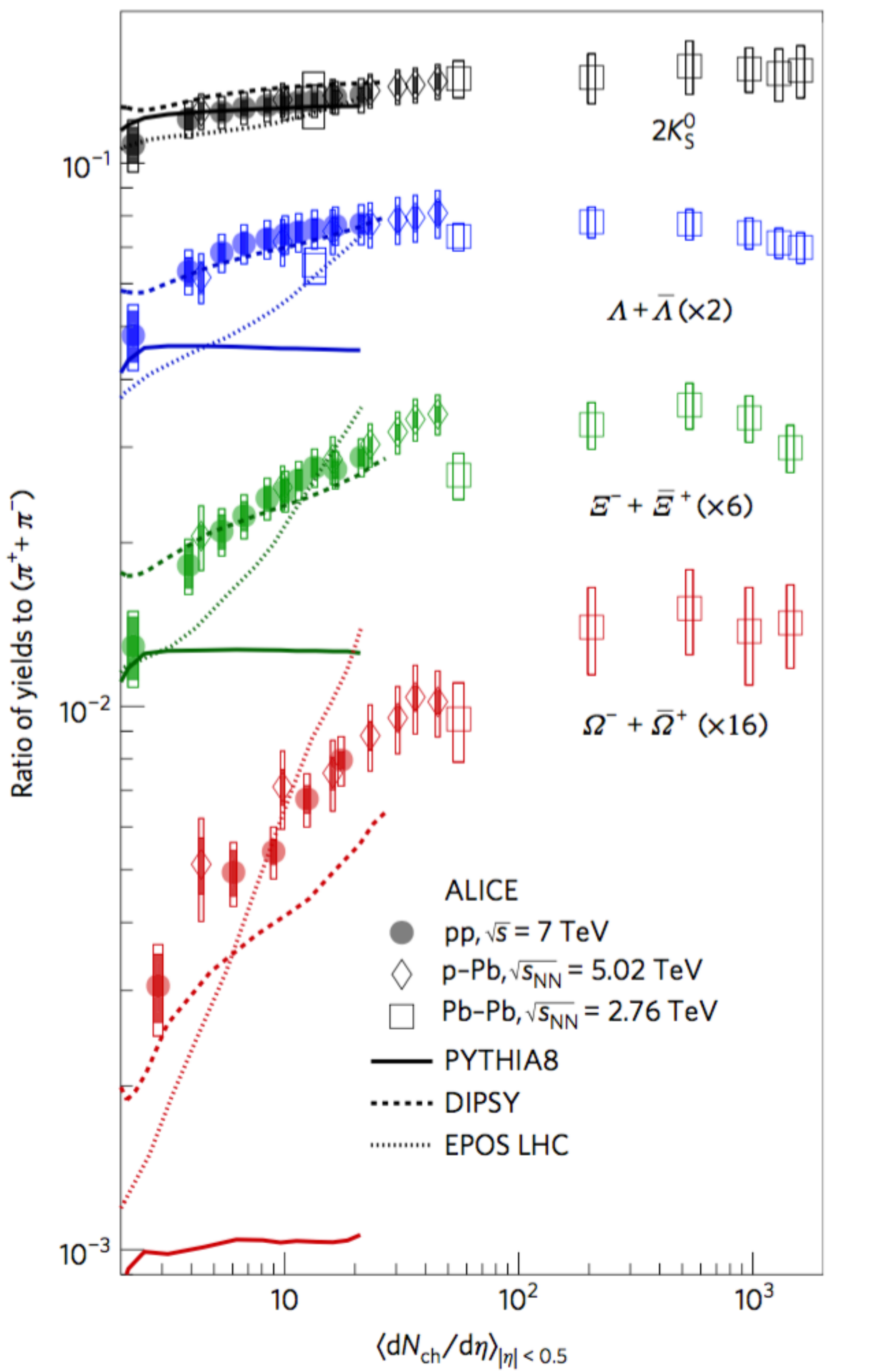
PUBLISHED ONLINE: 24 APRIL 2017 | DOI: 10.1038/NPHYS4111

OPEN

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

ALICE Collaboration†

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



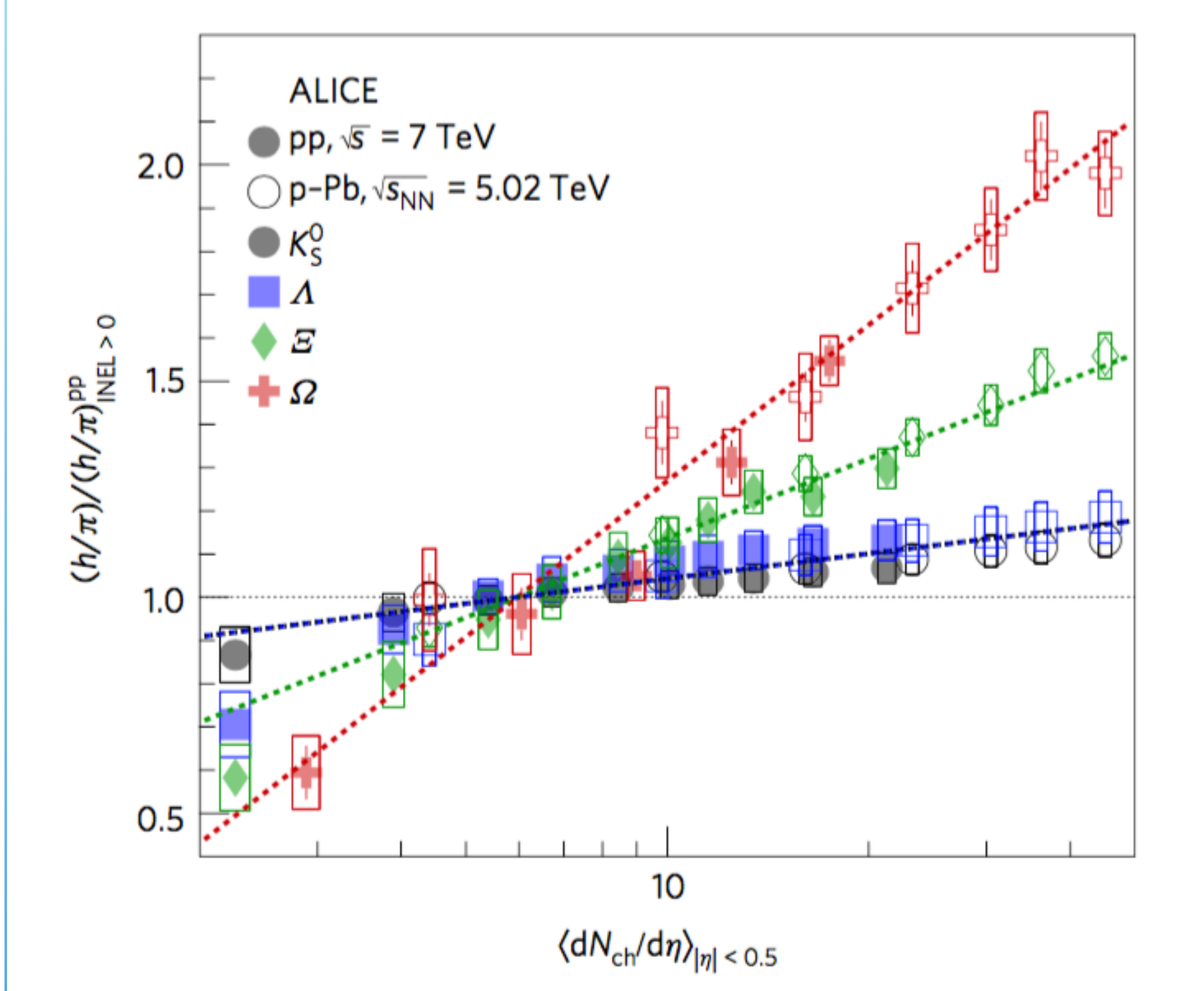
ALICE

The new data released by ALICE 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

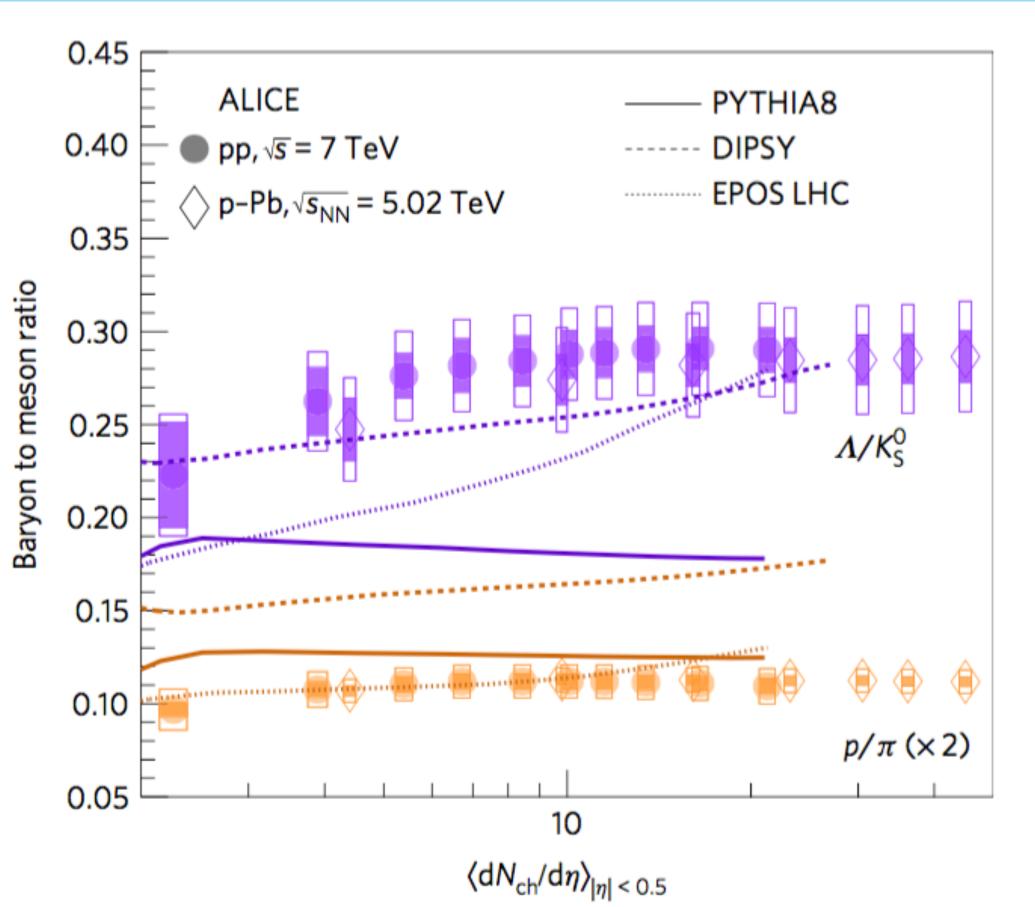
ALICE



The observed enhancement of strange/pi ratio in A+A over p+p (double ratio strange/pi AA/pp) with event charged multiplicity shows a hierarchy determined by the strangeness content

(lines are fits to determine the dependence on dNch/deta)

ALICE

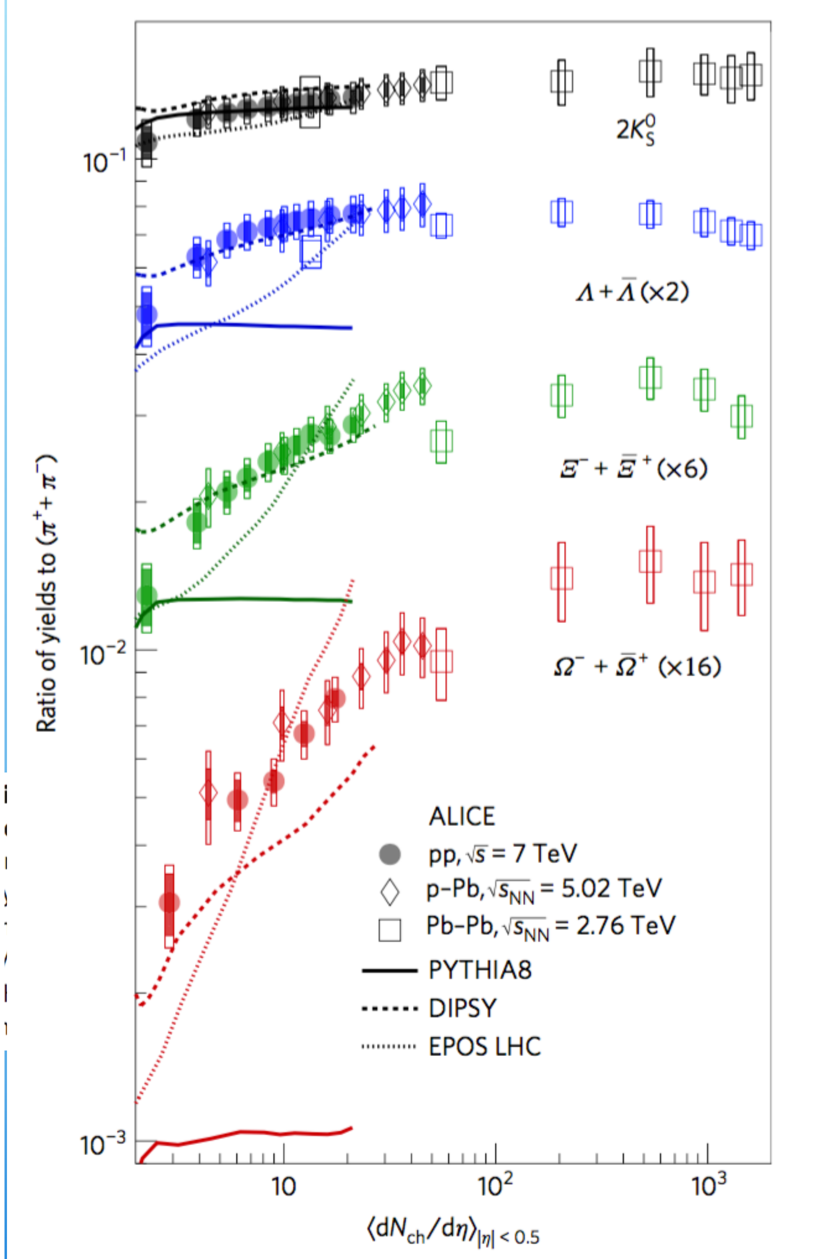


The ratios L/K0s (mave points) and p/pi (yellow points) do not change significanctly with the charged multiplicity demonstrating that the observed enhancement of strange hadrons over pions is not due to the different hadron masses

The models cannot reproduce simoultaneously the observation of strangeness enhancement over pions as a function of multiplicity and the constant p/pi ratio ve multiplicity.

DIPSY: model describes data the best, and includes color ropes that cause enhanced production of strange particles and baryons

ALICE



The novel measurement of ALICE: 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

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

"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.

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

Till few years ago, p+p, p+A in the heavy ion community were assumed to be QGP-free systems by definition, and therefore systems to which people compared A+A to find the QGP

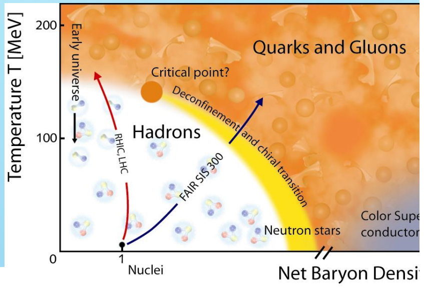
New data on collectivity seen in p+A, p+p prompt the idea that QGP may form in p+p, p+A if certain conditions are reached

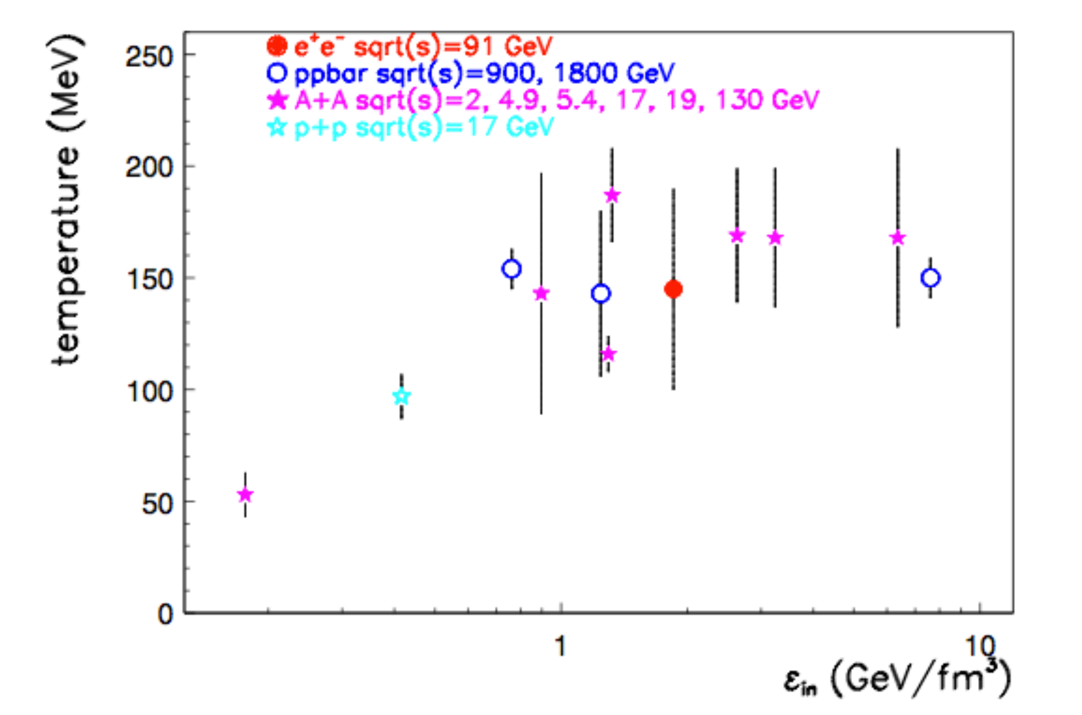
Do small QGP droplet form in p+p, p+A?

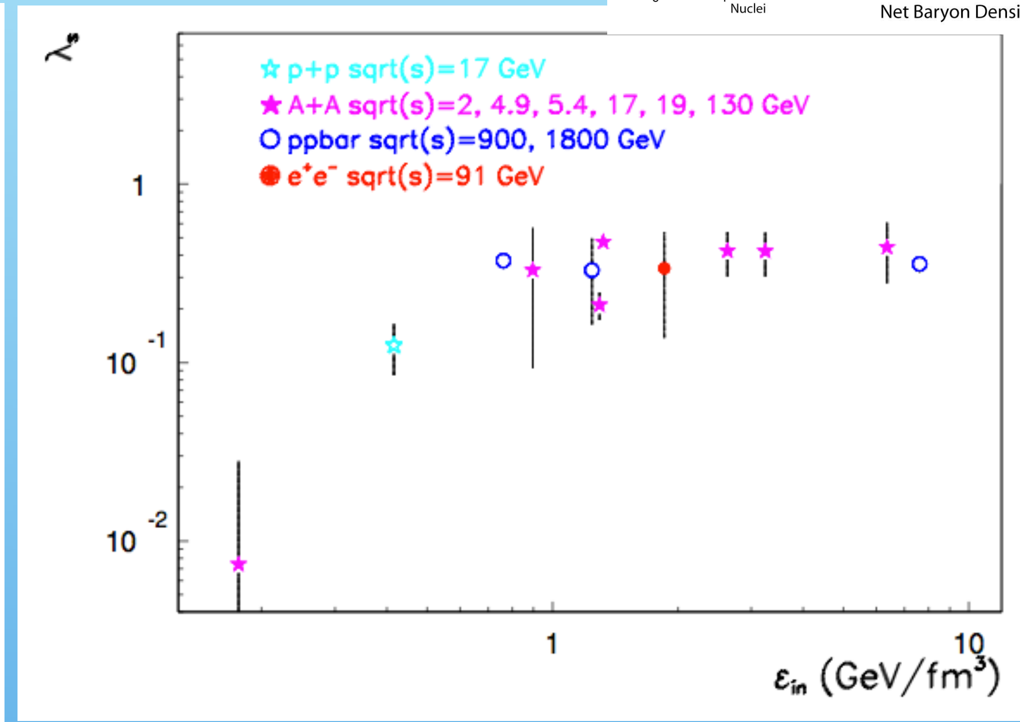
S.K. P. Minkowski, 2001 New J. Phys. 3, 4: proposed the universality of QGP phase transition in p+p, p+A, A+A appearing above a critical energy density.

-> what counts is the energy density reached in the collision not the size of colliding particles or nuclei

Universality of the QCD phase transition in p+p, p+A, A+A in both T





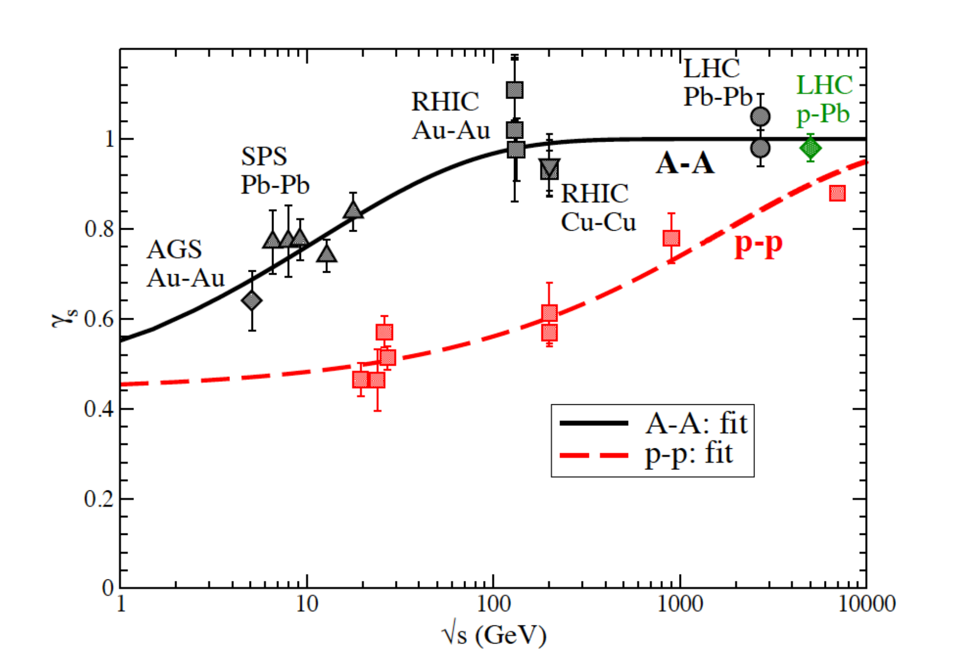


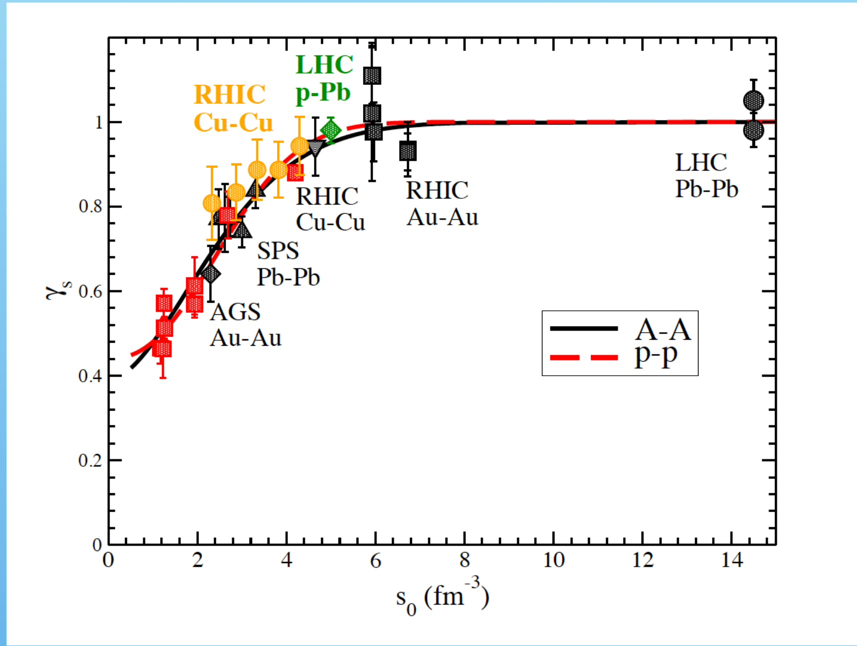
S.K., P. Minkowski, 2001 New J. Phys. 3 4

Key idea: extrapolate to muB=0 Consequences:
-> Universality of onset of phase transition near ~0.8 GeV/fm^3
-> Universality of onset of saturation of strangeness suppression factor
Differences of AA, pp, pA dissapear at high enough initial energy density and at same muB

Universal Strangeness Production

results from F Becattini et al   P. Castorina, S Plumari, H Satz, 1709.02706





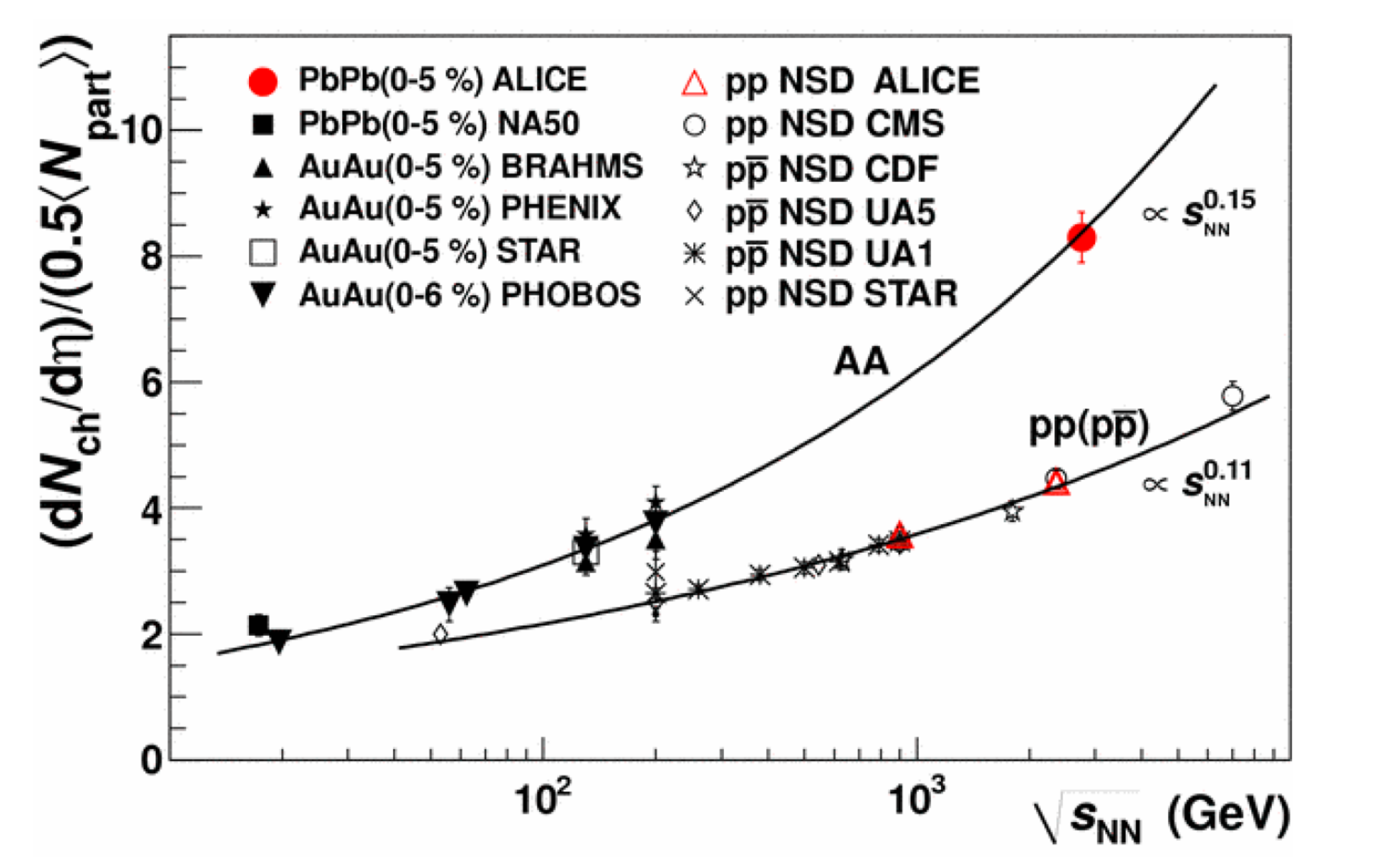
s_0 initial entropy density calculated using the Bjorken relation

$$s_0\,\tau_0 \simeq \frac{1.5 A^x}{\pi R_x^2}\left(\frac{dN}{dy}\right)^x_{y=0}, \quad \text{with } x \sim pp, pA, AA,$$

Gamma_s factor depends in universal way from s_0 for small and big systems

P Castorina - H Satz

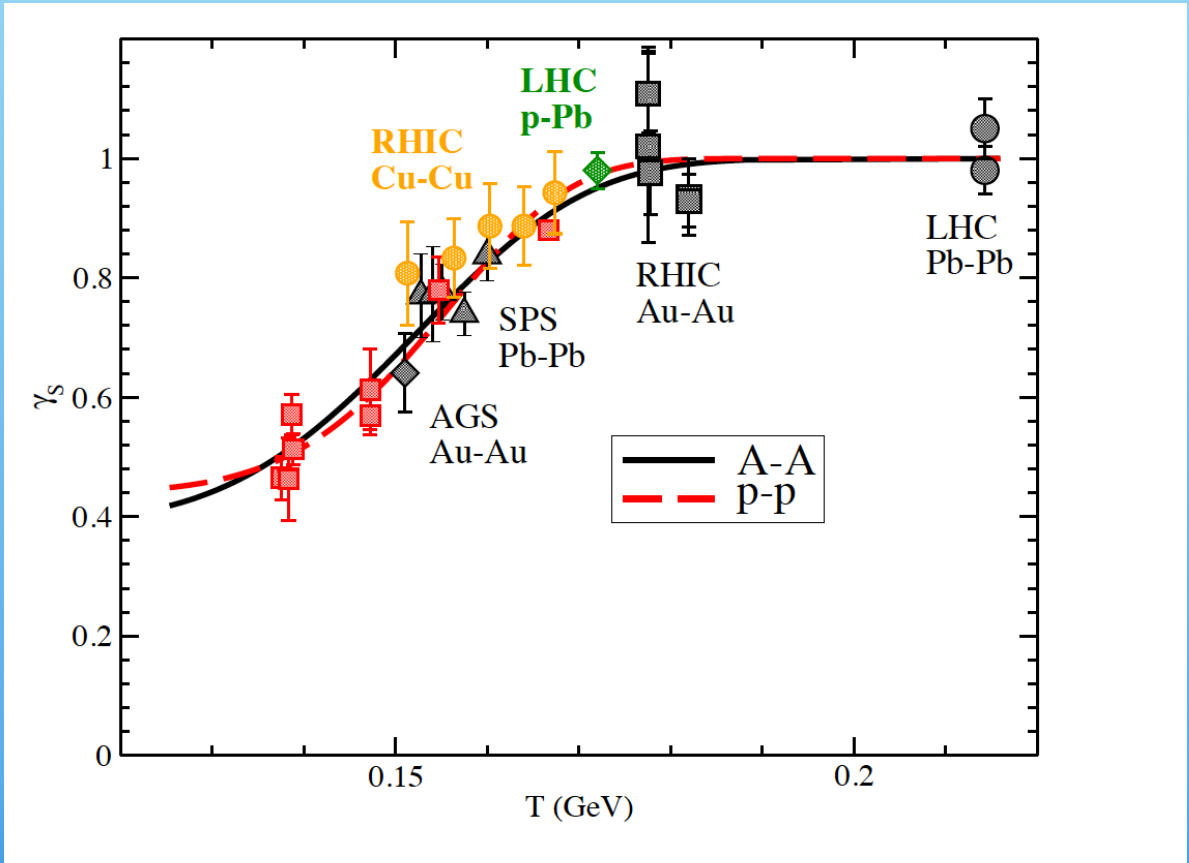
K. Aamodt et al. (ALICE Coll.), Phys. Rev. Lett. 105 (2010) 252301.



They calculate the initial entropy density using a parametrization of data from above figure and the Bjorken formula

Strangeness suppression is happening only below Tc

P. Castorina, S Plumari, H Satz, 1709.02706



Gamma_s becomes 1 near T_c

Strangeness in exotic states

Absolutely stable Strange Quark Matter … is possible

E Witten, 1984

For more than few hundreds u,d,s quarks, the energy per baryon (E/A) of quark matter can also be below the energy of the most stable atomic nucleus 56Fe, which has Energy per baryon number Mass(56Fe)cˆ2/56 = 930.4 MeV

With E/A(strange quark matter)= 4Bpiˆ2/muˆ3, the E/A of Strange Quark Matter can be
E/A = 829 MeV for bag constant B=57.5 MeV fm-3 (or Bˆ(1/4)=145 MeV) and
E/A = 915 MeV for bag constant B=85,3 MeV fm-3 (Bˆ(1/4)=160 MeV).

In this cases Strange Quark Matter from u,d,s quarks would be the ground state of matter.

Bodmer A R 1971 Phys. Rev. D 4 1601
Witten E 1984 Phys. Rev. D 30 272
Terazawa H 1979 INS Report 338 University of Tokyo, Terazawa H 1989 J. Phys. Soc. Japan 58 3555, Terazawa H 1989 J. Phys. Soc. Japan 58 4388, Terazawa H 1990 J. Phys. Soc. Japan 59 1199

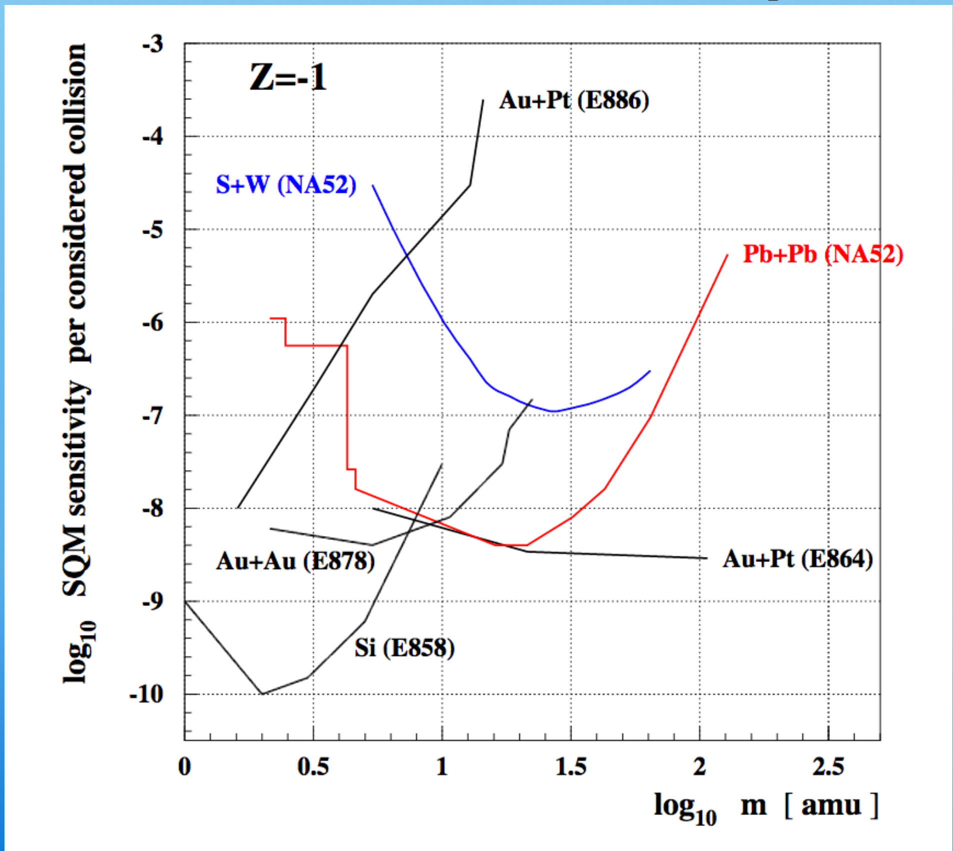
From Strangelets to Strange Stars

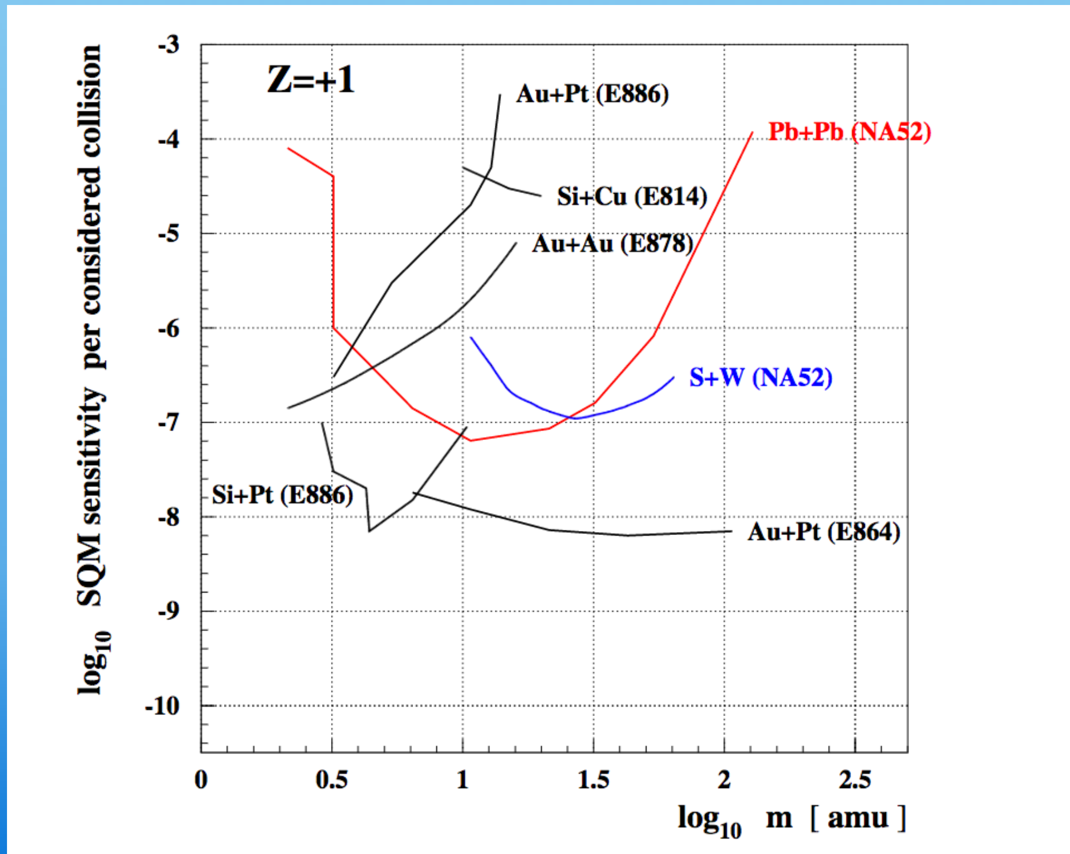
One may expect novel states to exist like strange nuggets or strangelets (for small A like A~10-100) to strange stars

Experimental searches for strangelets with small A

In accelerators (AGS BNL, NA52 at CERN SPS, etc)
In cosmic rays with detectors on earth (centauro events)
In Space (AMS)

Limits on strangelet production from AGS E864 and SPS Na52 experiment





A committee studied the probability that strangelets could destroy our planet ?

Will relativistic heavy-ion colliders destroy our planet?

Arnon Dar[*,†], A. De Rújula[*] and Ulrich Heinz[*]

[*] Theory Division, CERN, CH-1211 Geneva 23, Switzerland
[†] Department of Physics and Space Research Institute,
Technion, Israel Institute of Technology, Haifa 32000, Israel

Abstract

Experiments at the Brookhaven National Laboratory will study collisions between gold nuclei at unprecedented energies. The concern has been voiced that "strangelets"– hypothetical products of these collisions– may trigger the destruction of our planet.

A committee studied the probability that strangelets could destroy our planet ?

and concluded NO

Will relativistic heavy-ion colliders destroy our planet?

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[†] Department of Physics and Space Research Institute, Technion, Israel Institute of Technology, Haifa 32000, Israel

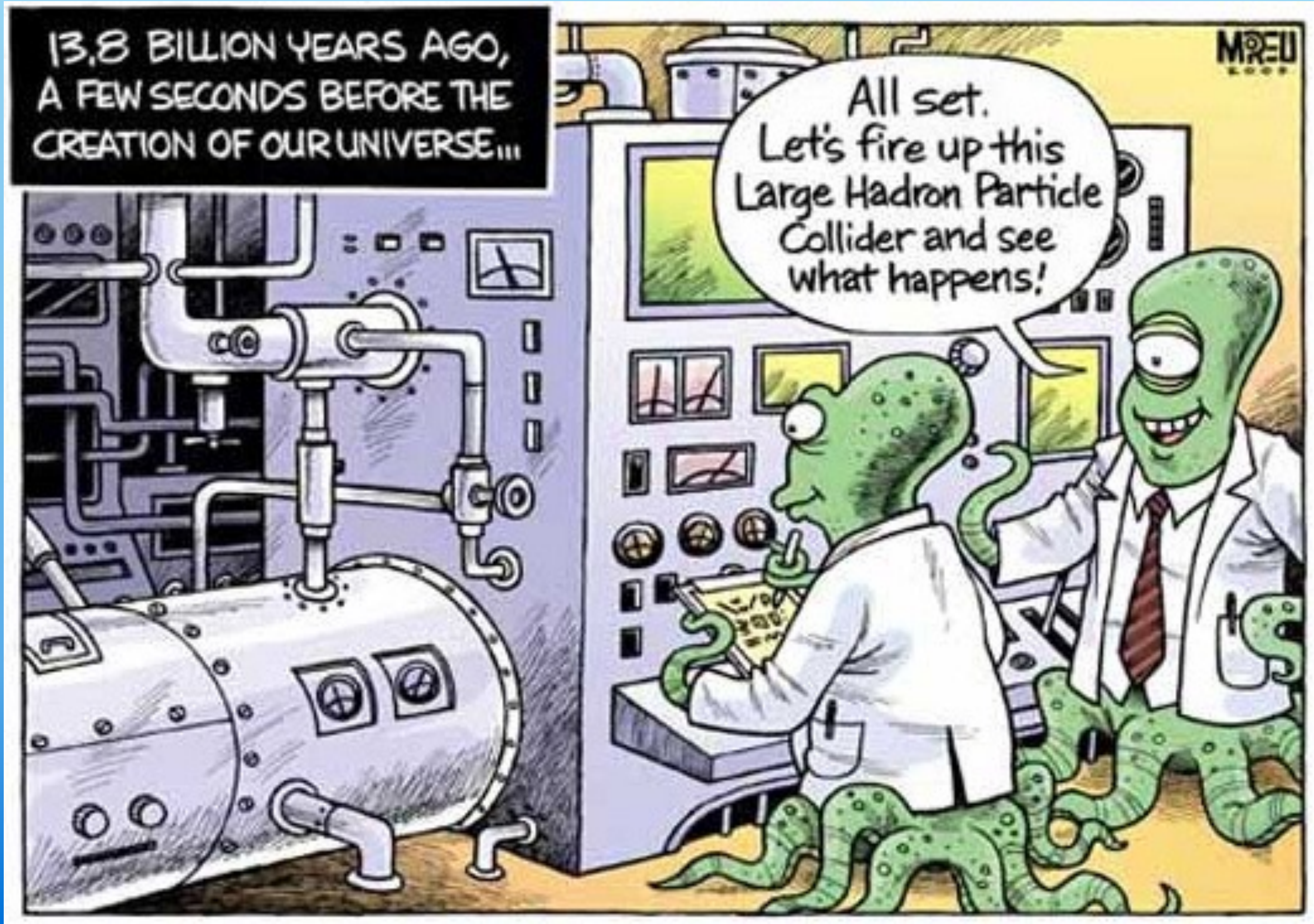
Abstract

Experiments at the Brookhaven National Laboratory will study collisions between gold nuclei at unprecedented energies. The concern has been voiced that "strangelets"– hypothetical products of these collisions– may trigger the destruction of our planet.

but

Maybe it happened already ?

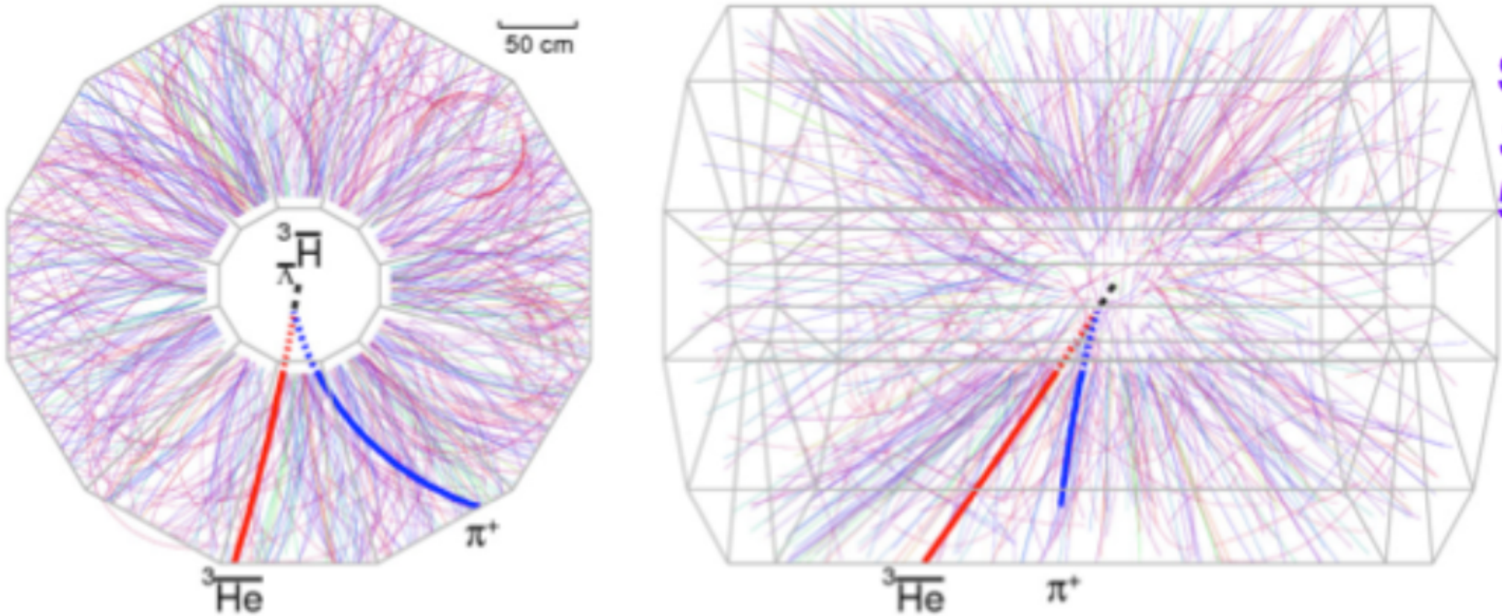
If you happen to pass from the CERN theory coffee room, there is an other "prediction" and/or "postdiction" haenging on the wall out there



Antihypernuclei

RHIC antihypertriton

Hypertriton: consists of a Lambda, a proton and a neutron, was discovered in 1952. However no antihypernuclei were observed, until STAR.



STAR Collab., *Science* **328**, 58 (2010)

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$$

- ★ Anti-hypertriton: anti-proton, anti-neutron & anti-Λ – the first antinucleus with strangeness, and the heaviest antinucleus so far.
- ★ After searching >100 million AuAu collisions, found 70 anti-hypertritons.
- ★ Published in *Science* in March 2010; News stories in *Nature*, *Scientific American*, *National Geographic*, many news outlets worldwide.

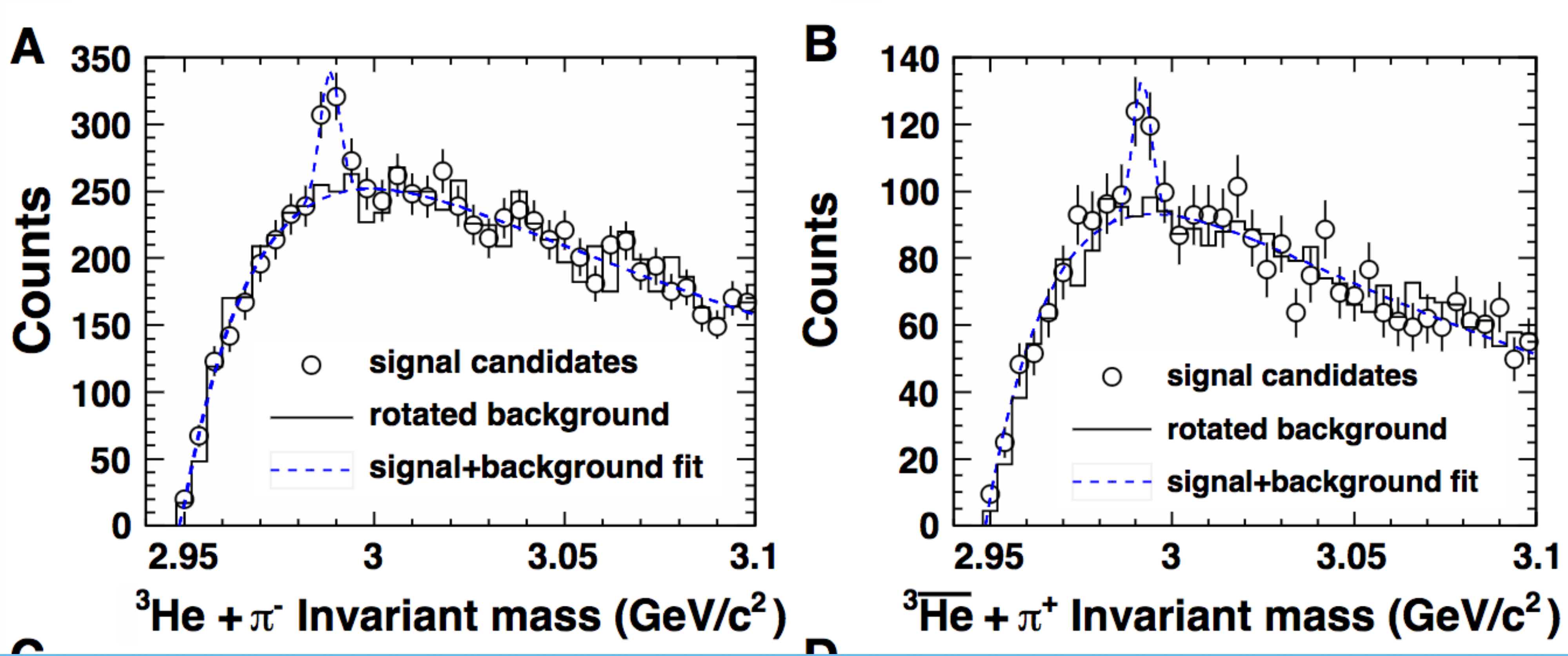
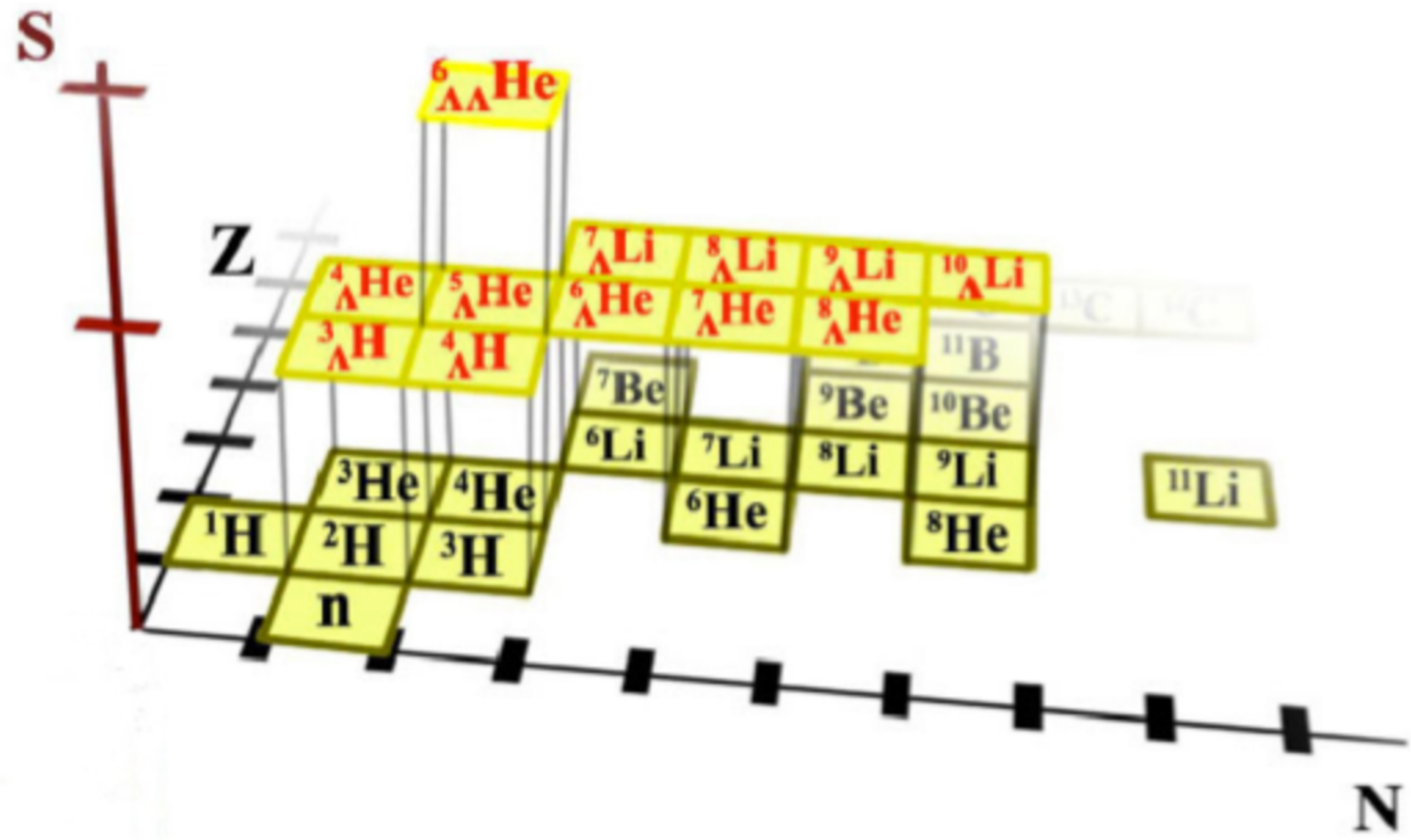
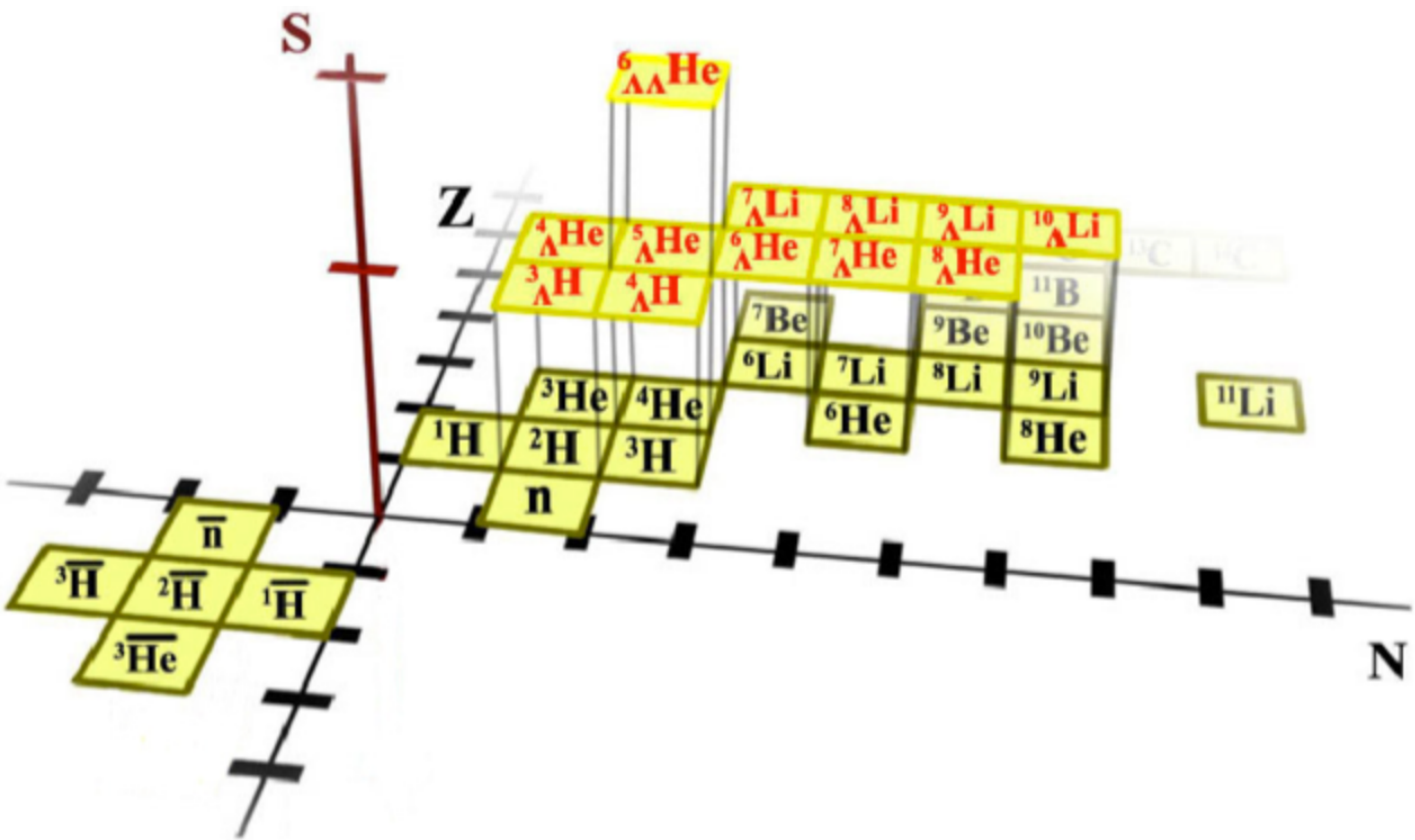


Figure 3: (A, B) show the invariant mass distribution of the daughter $^3\mathrm{He} + \pi$. The open circles represent the signal candidate distributions, while the solid black lines are background distributions. The blue dashed lines are signal (Gaussian) plus background (double exponential) combined fit (see the text for details). A (B) shows the $^3_\Lambda\mathrm{H}$ ($^3_{\bar{\Lambda}}\overline{\mathrm{H}}$) candidate distributions. (C) shows $\langle dE/dx \rangle$ versus rigidity (momentum/|nuclear charge units|) for negative tracks. Also plotted are the expected values for $^3\overline{\mathrm{He}}$ and π tracks. (D) and (C) demonstrate that the $^3\mathrm{He}$ and $^3\overline{\mathrm{He}}$ tracks ($|z(^3\mathrm{He})| < 0.2$) are identified essentially without background.

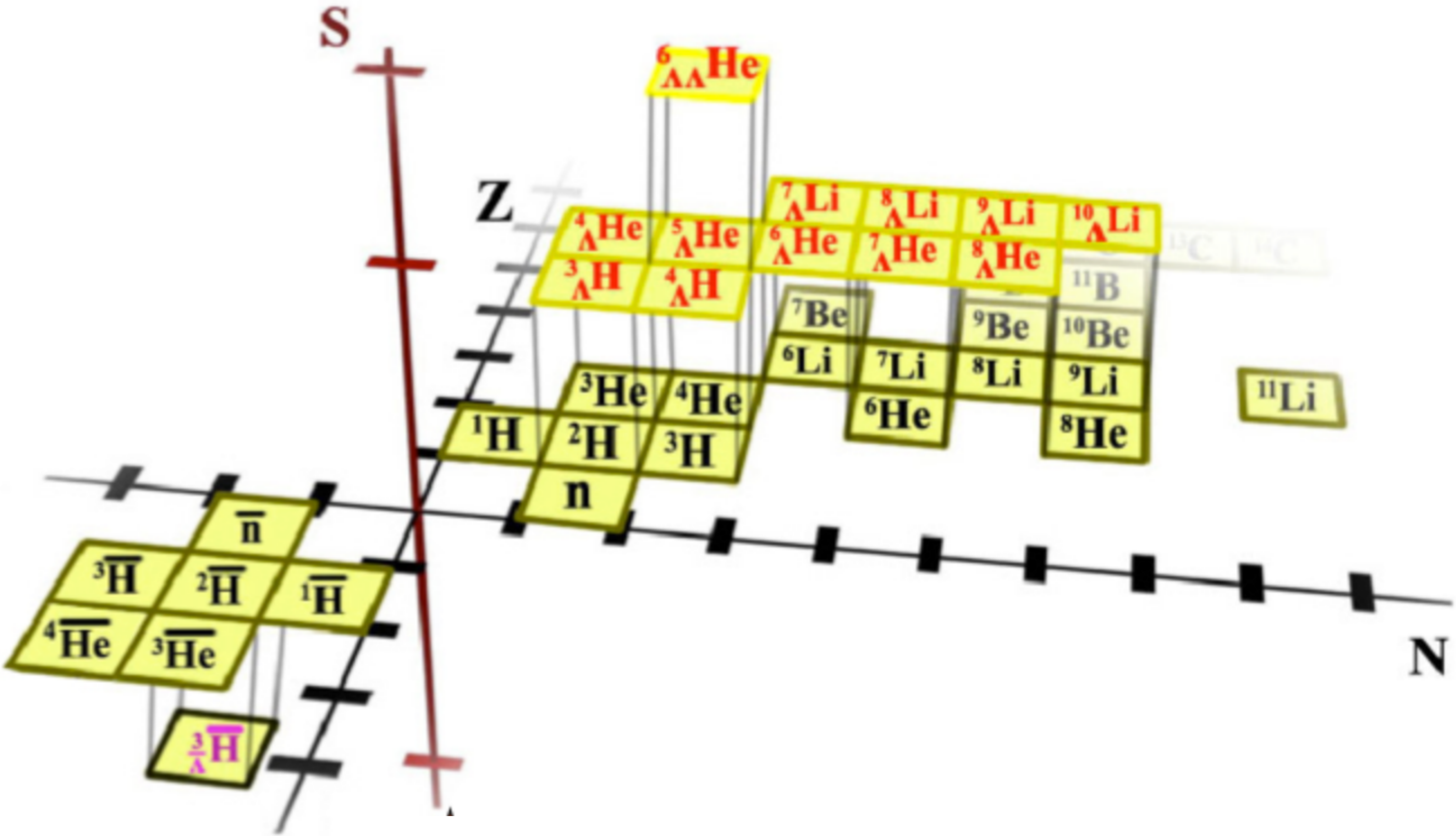
3-D chart of the Nuclides



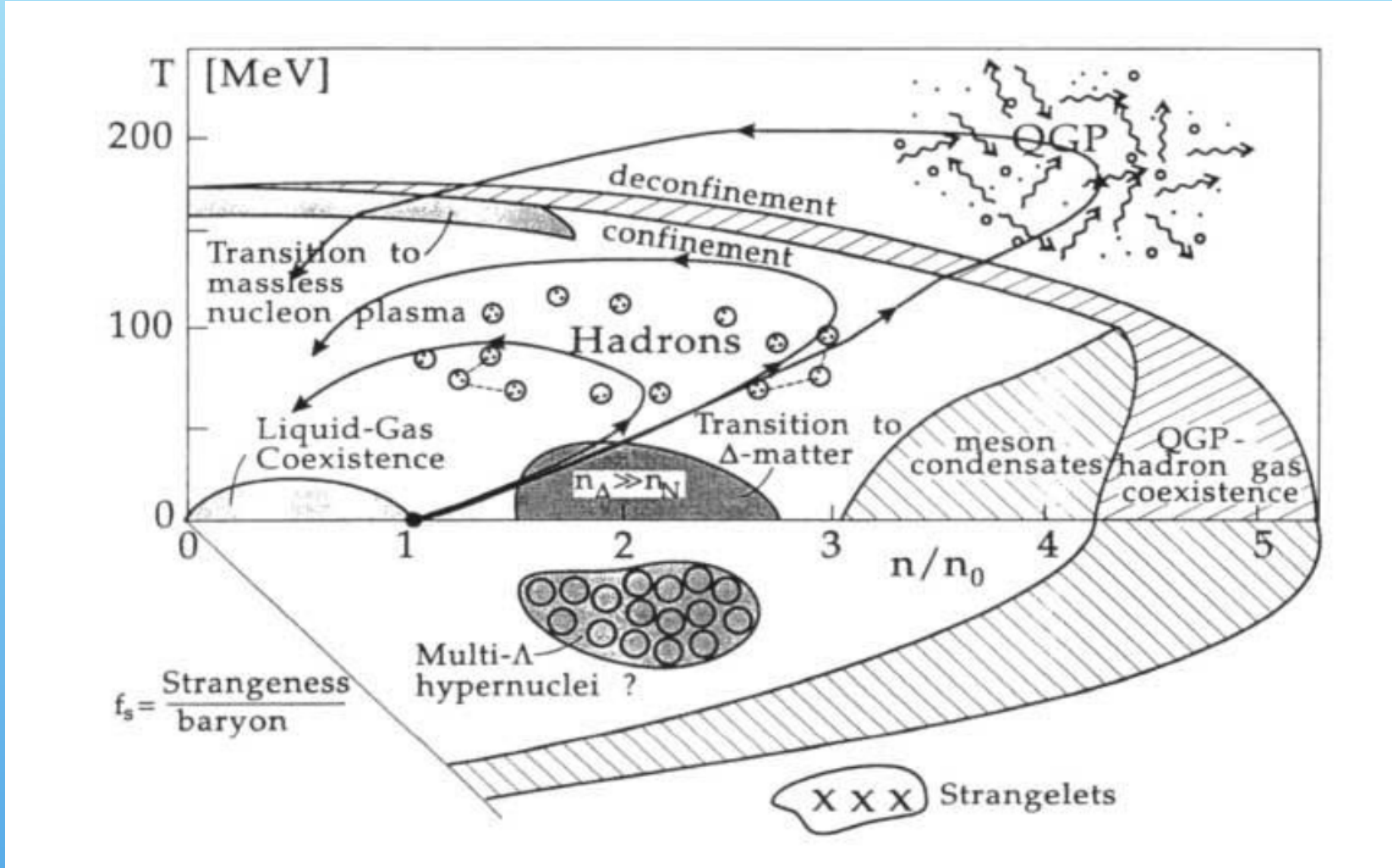
3-D chart of the Nuclides



3-D chart of the Nuclides



The Strange, the Multistrange and the Strangelet



Int J of Mod Phys 1996,W. Greiner

Conclusions and perspectives

- Strangeness Enhancement was the first QGP signature (predicted by J Rafelski) that has been observed in relativistic heavy ion collision experiments: in AGS at BNL and in SPS at CERN.

- In particular strangeness enhancement over light hadrons has been observed in central heavy ion reactions (S+Au, Au+Au, Pb+Pb and other) as compared to minimum bias p+p or p+A collisions at same energy

Experimental facilities: AGS at BNL, SPS at CERN, RHIC at BNL, LHC at CERN

Conclusions and perspectives

- Recently a number of observables in small systems (flow, particle correlations like the "ridge", number of constituent quark scaling) have prompted the question if QGP droplets can be formed also in small systems at sufficiently high energy.

- Latest highlight in strangeness measurements : Results from ALICE show that strangeness in p+p and p+Pb collisions at highest multiplicity reach same values as in Pb+Pb collisions and strangeness is more enhanced with higher strangeness content, namely strange (anti)baryons are enhanced.

Conclusions and perspectives

- The collision energy and corresponding initial energy density dependence of strange/non strange particle ratios (maximum of strangeness suppression factor λs, "Marek Gazdzicki's "horn", the extrapolation of λs to zero mu_B), reveal the onset of the QCD phase transition at a low collision energy, accessible to present and future beam energy scans in FAIR and NICA.

- In the case of mu_B=0 the onset occurs universally for small or big systems when plotted vs the initial Bjorken energy density (S.K. P. Minkowski) which is consistent with recent work of P Castorina and H Satz showing that strangeness gamma_s factor becomes 1 when plotted vs initial entropy density for all systems small or large.

- Recent work with S-Matrix formalism offered a resolution of the proton anomaly(A. Andronic et al).

Conclusions and perspectives

- Hadron resonance gas model with hard-core repulsion (MHRGM) and other developments as induced surface tension (K. Bugaev et al) achieved improved agreement with data (chiˆ2/DOF=0,8-0,9)

- - Strange particles are crucial probes for a number of studies beyond "strangeness enhancement", via their pT distributions, flow, 2-particle correlations to estimate the radius if their source, RAA and other characteristics. For example they exhibit the "Number of Constituent Quark Scaling" suggesting dominant hadron production via quark coalescence out of a hadronizing QGP.

- Absolutely stable Strange Quark Matter is possible (E Witten).
- Strange Quark Matter can exist in the core of neutron stars or quark stars
- Small droplets of Strange Quark Matter can be produced in particle collisions in accelerators and are searched by experiments as well as by space experiments like AMS.
- Exotic hadrons with strangeness like antihypernuclei have been observed

T. Sakaguchi, QM2017

Perspectives

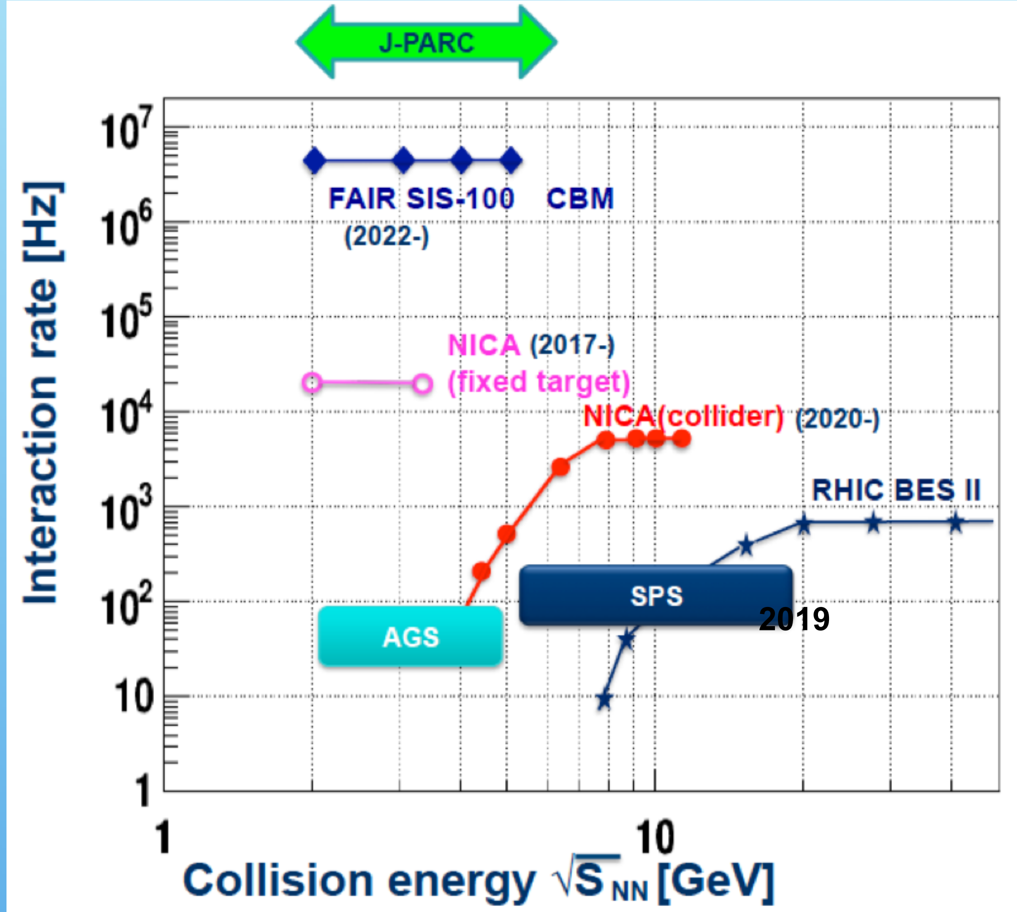
- LHC with future upgrades
- sPHENIX (2020+), eRHIC or JLEIC

- Further data taking and upgrades of existing experiments at RHIC, SPS and LHC

Low beam energy scans will be a strong focus of the field in next years:

- RHIC BESII (2019-2020) and fixed target
- New dedicated accelerator facilities and corresponding new experiments
- **NICA in Dubna, Russia**
- **FAIR in GSI, Germany**
- J-PARC in Japan,
- will allow to progress in significant way in the next decades.

Energy scans with Heavy Ions
Future: BESII, NICA, FAIR, J-PARC

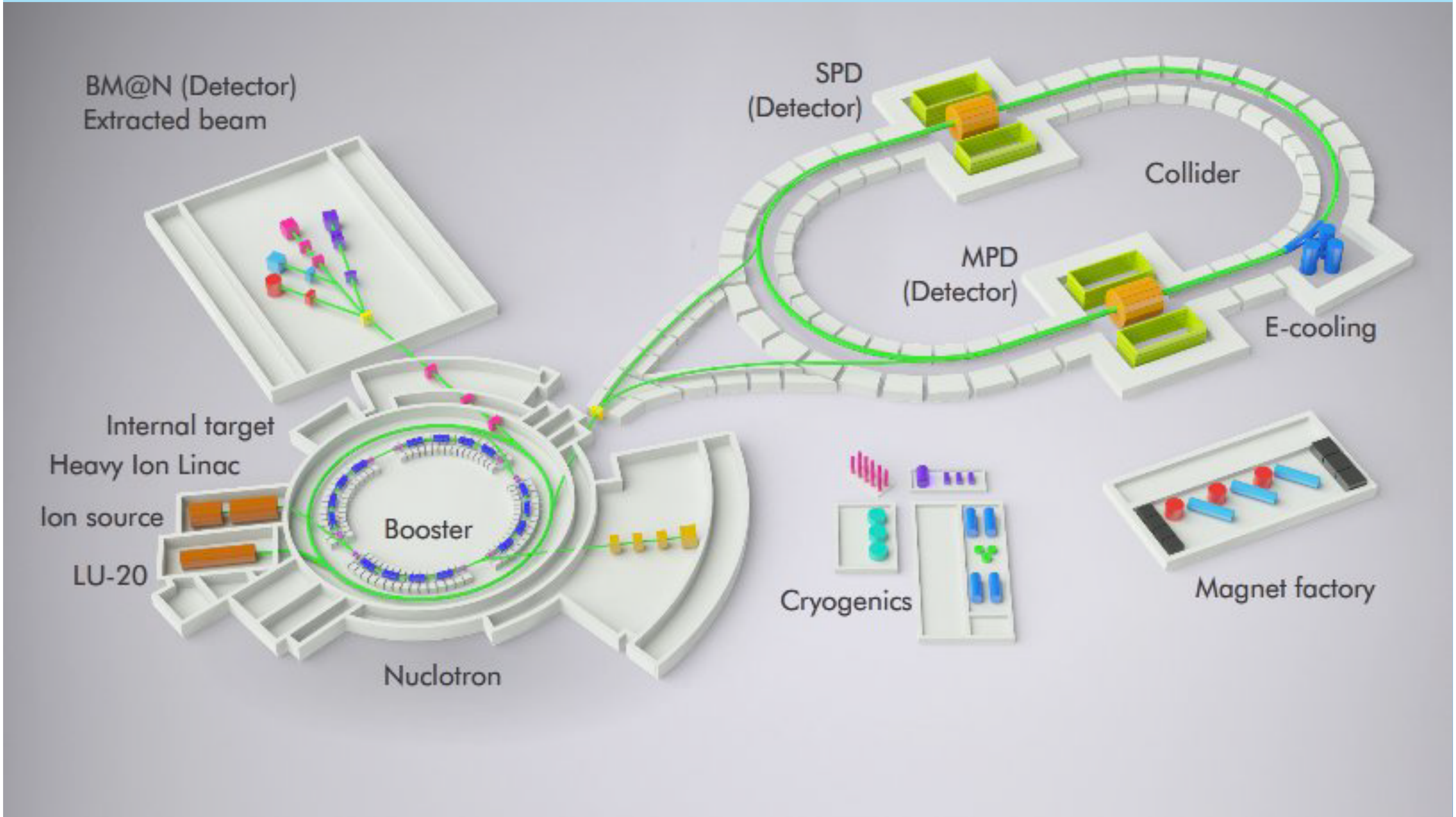


T. Sakaguchi, QM2017

Center of mass energy (sqrt(s)NN) of facilities for future heavy ion runs: FAIR: 2-6 (10) GeV, NICA: 4-11 GeV, RHIC: 7 (2.5) - 200 GeV LHC: 2.76, 5 TeV, J-PARC: 1-10 GeV
FCC (100 km circular ring, p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV)

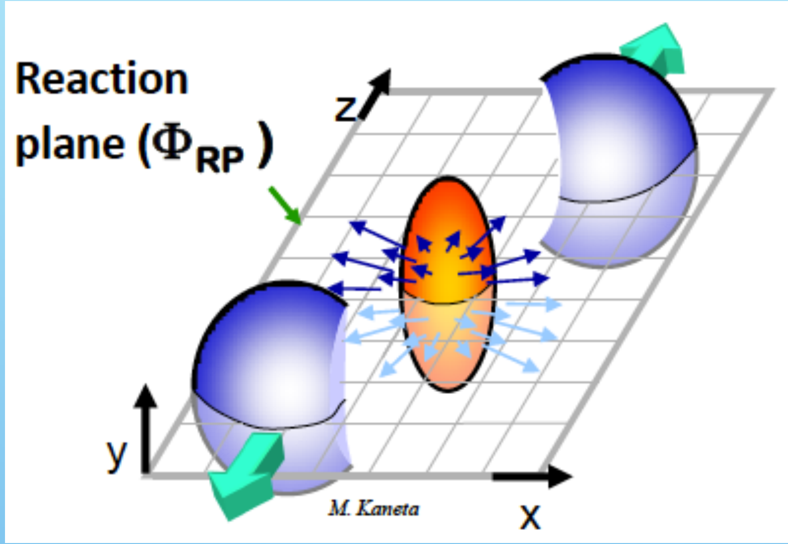
Strangeness is a crucial observable and will be a precious tool at all energies

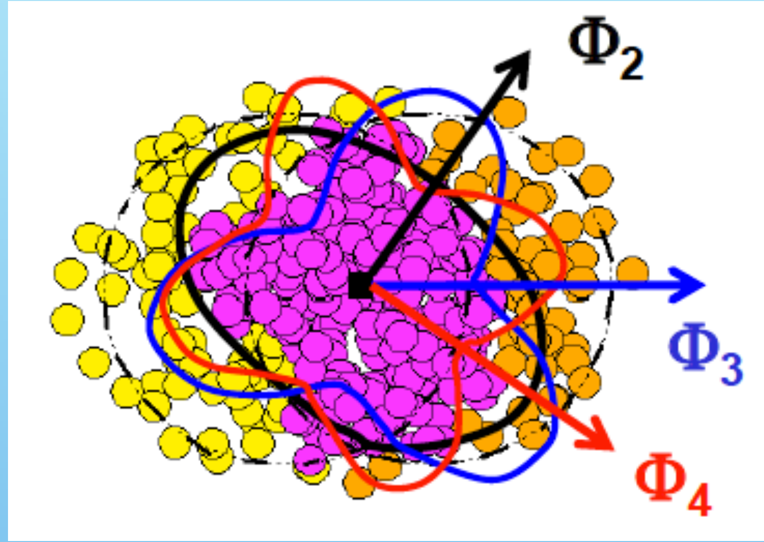
with particular emphasis at the future low energy scans coming up soon at RHIC, FAIR and NICA


BM@N (Detector)
Extracted beam
SPD
(Detector)
Collider
MPD
(Detector)
E-cooling
Internal target
Heavy Ion Linac
Ion source
LU-20
Booster
Nuclotron
Cryogenics
Magnet factory

Thank you very much for your attention

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





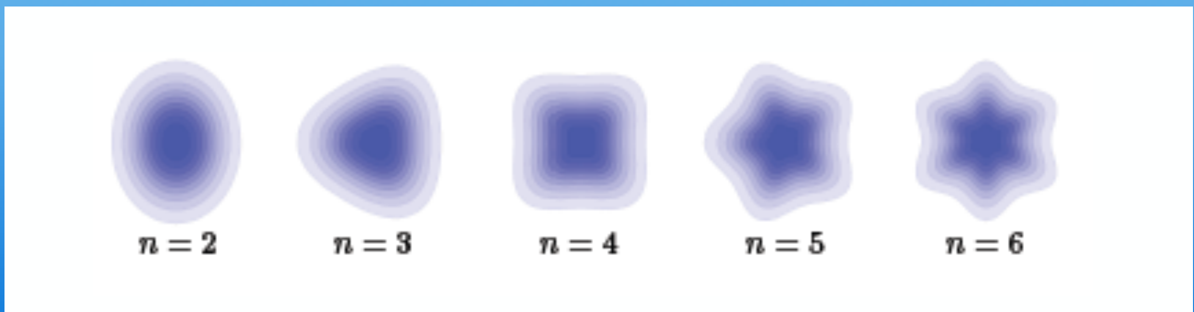
Matter in the overlapp area of two colliding nuclei gets compressed and heated

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

STAR goals

BES-II

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2 days	100M
9.8	4.5 (FXT)	589	2 days	100M
7.3	3.9 (FXT)	633	2 days	100M
5.75	3.5 (FXT)	666	2 days	100M
4.55	3.2 (FXT)	699	2 days	100M
3.85	3.0 (FXT)	721	2 days	100M

STAR BES-II goals

Table 8: Event statistics (in millions) needed in BES-II for various observables. This table update estimates originally documented in Ref. [45].

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-		160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400

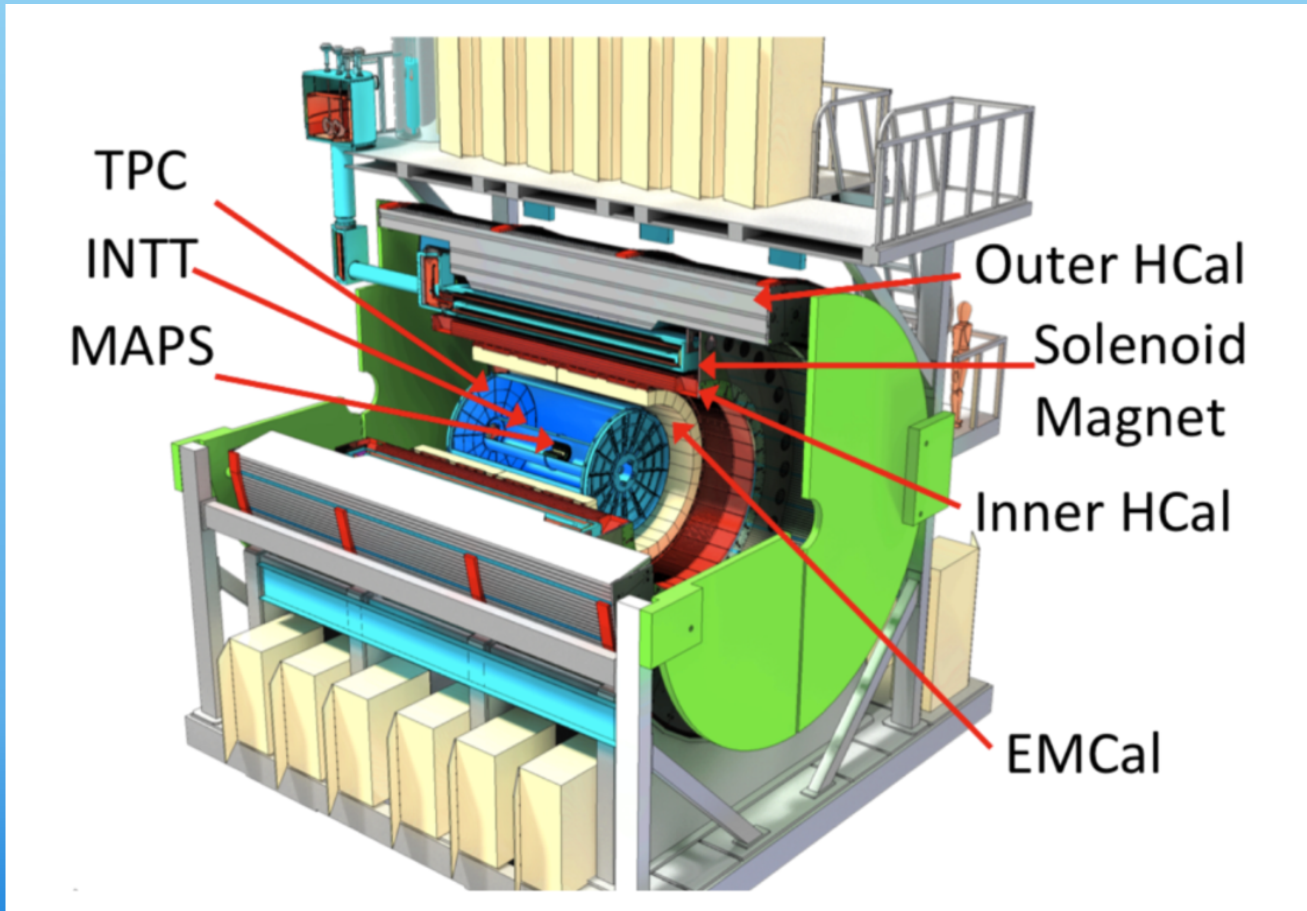
+100M for each FXT energy

Typically factor 20 more than for BES-I

* USA
* 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

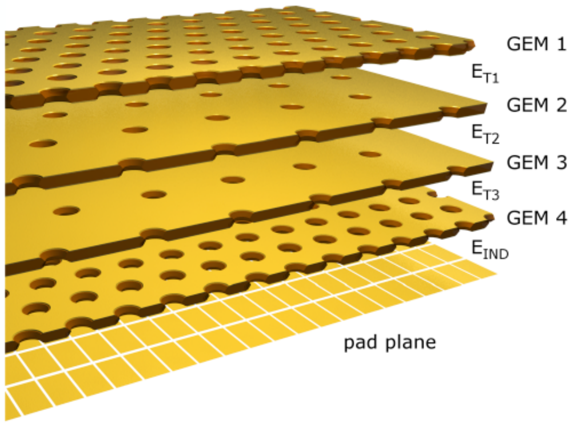


M. Connors,
Nucl.Phys. A967 (2017) 548-551

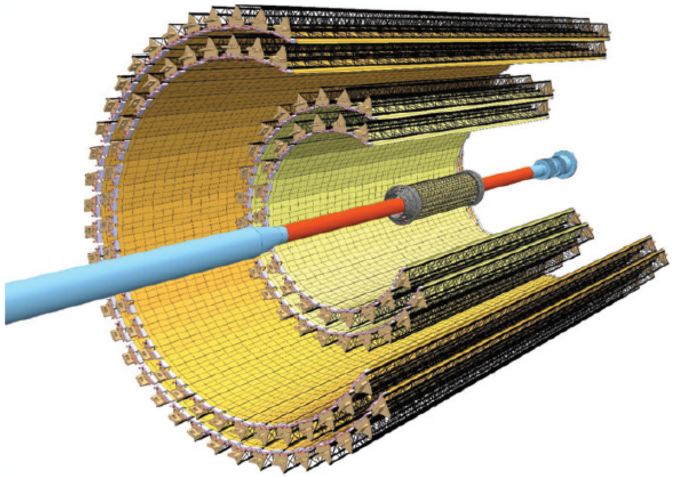
LHC experimental upgrades

ALICE upgrades for run-3

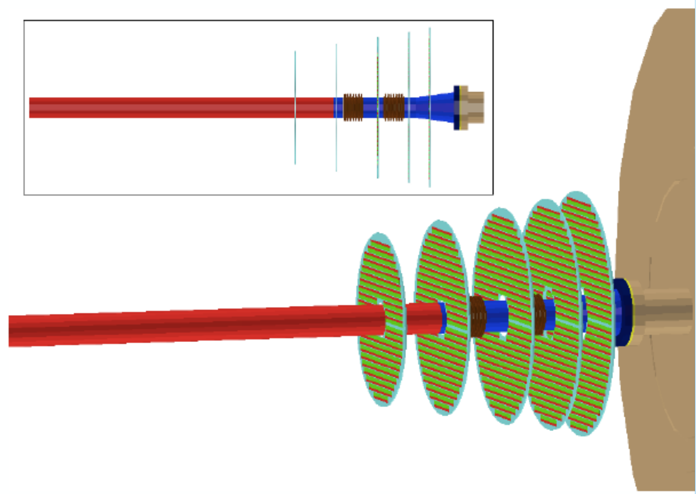
GEM-TPC



ITS

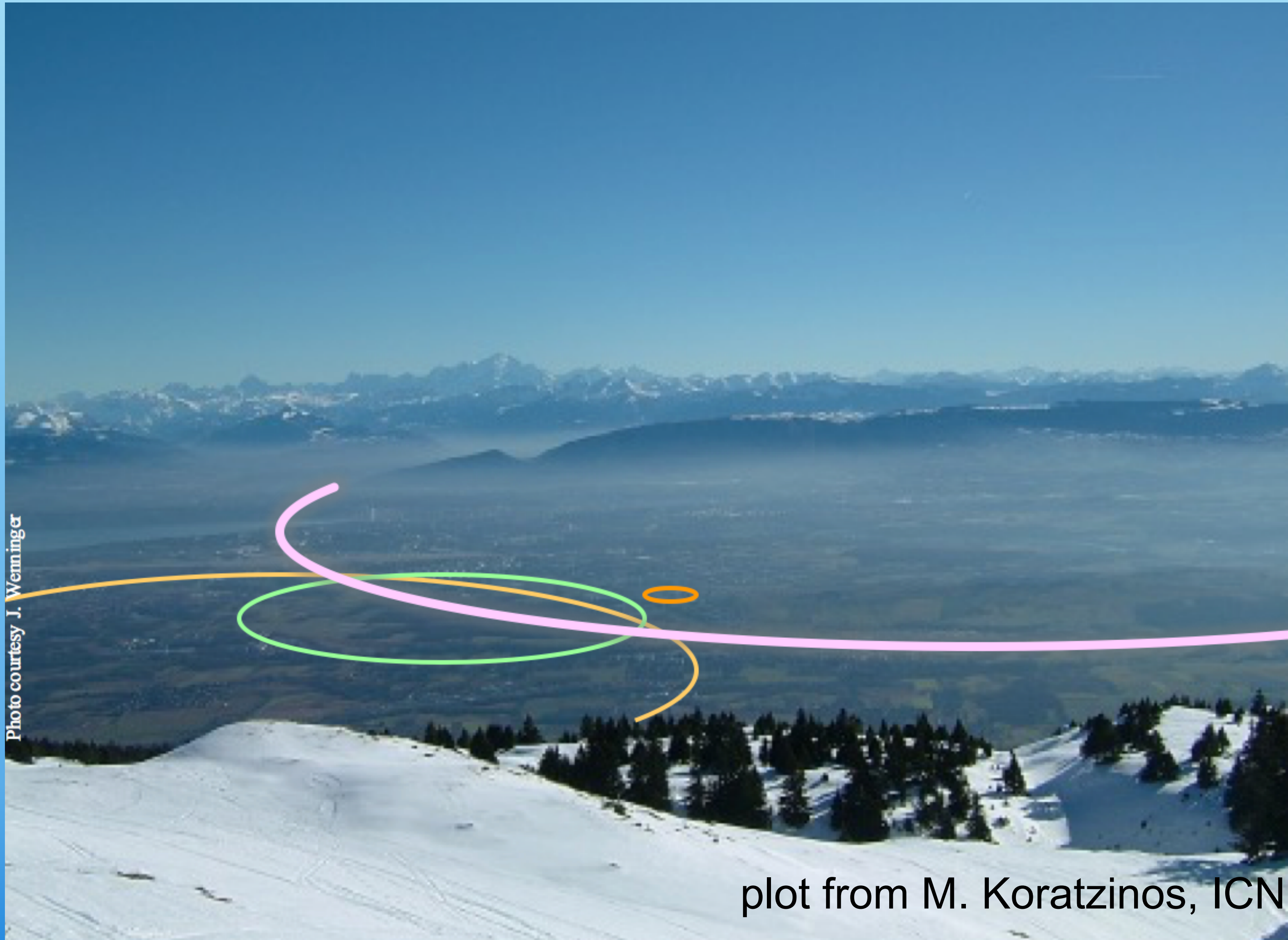


MFT



MFT: will provide secondary vertex reconstruction in forward rapidity
ITS : low pT reach and improved accuracy
High rate
The Upgrades will allow high statistics and high resolution strangeness measurements

A view into the far Future : FCC



plot from M. Koratzinos, ICNFP2017

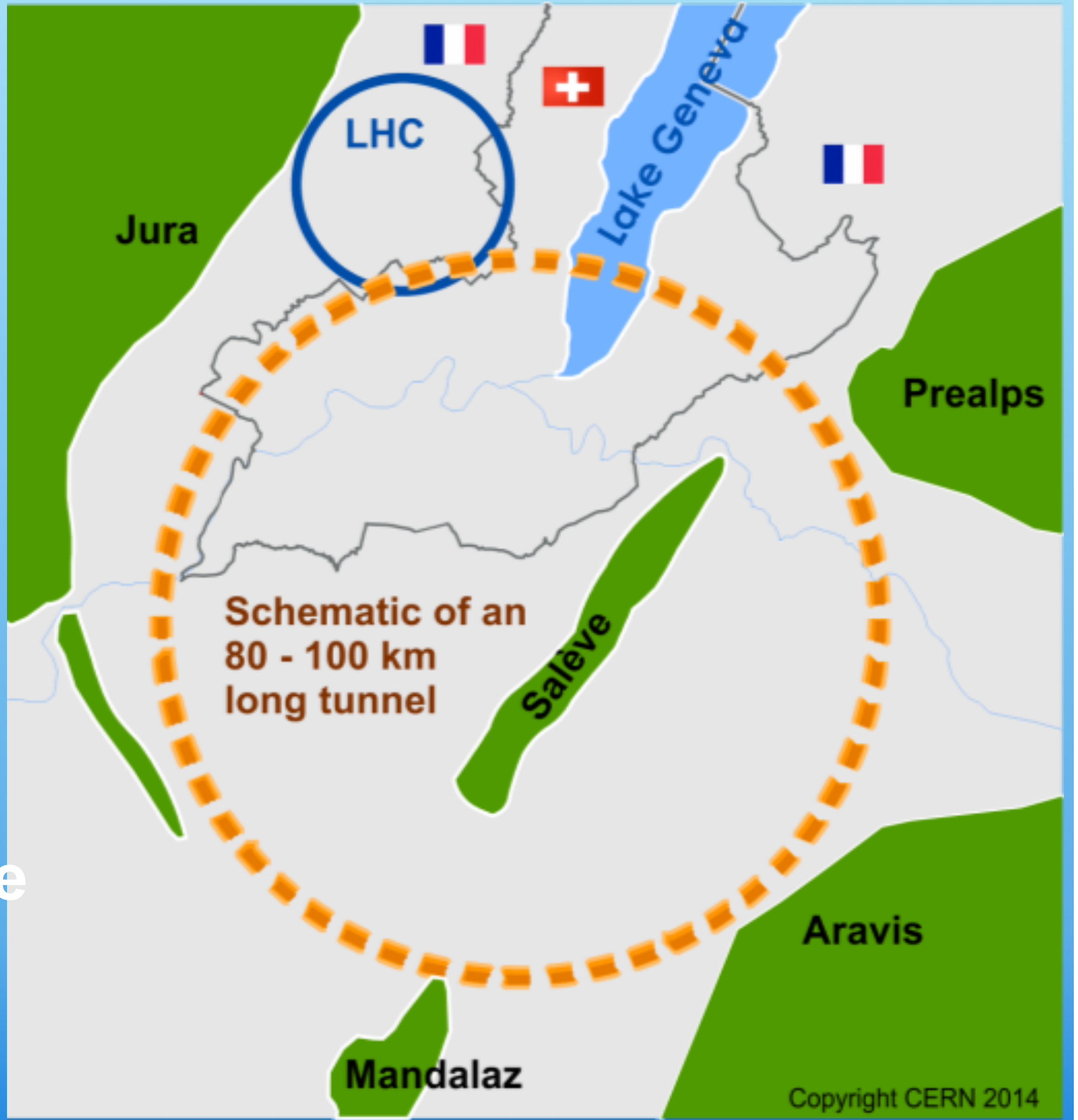
FCC: The Vision

~100 km tunnel, 16 T magnets
sqrt(s)= 100 TeV pp collisions

FCC-hh
FCC-ee
FCC-he

Possible first steps
*FCC-ee, E_CM=90-400 GeV
**HE-LHC* 16T 28 TeV
in LEP/LHC tunnel

FCC-AA : sqrt(s)NN=40 TeV

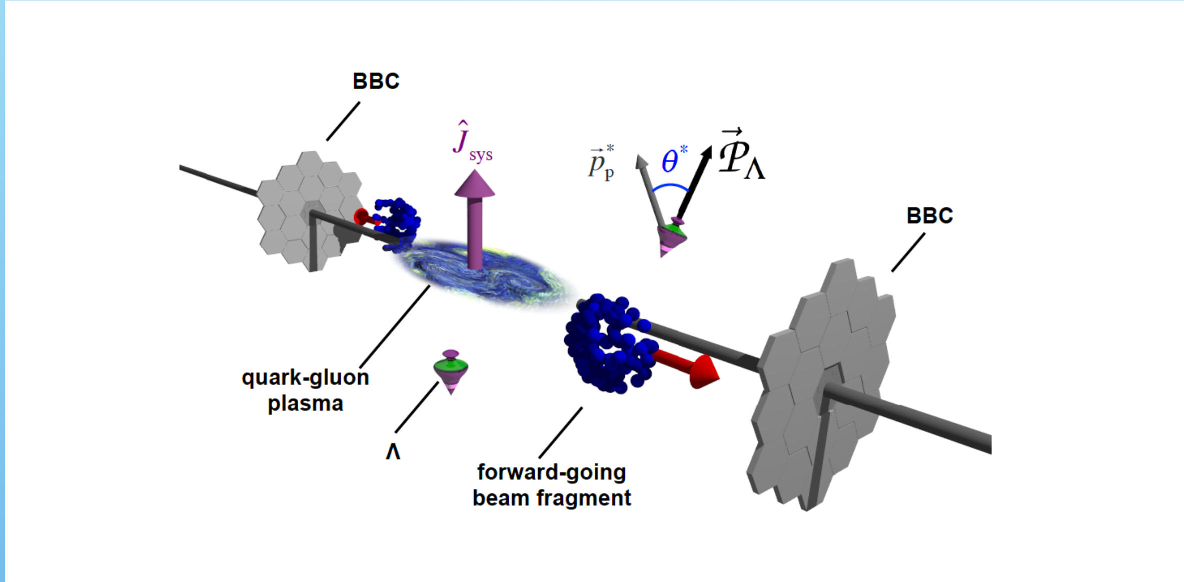


Strangeness related possible Highlight of FCC ? :
Strangelet production may be possible in FCC !

Lambdas, Antilambdas and Vorticity

Vorticity measurement in Au+Au collisions at RHIC 20-50% centrality

STAR, Nature, 2017, 1701.06657



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

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

H: Λ / Anti-Λ

P_{H} : Λ / Anti-Λ polarizatin vector in the hyperon rest frame

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

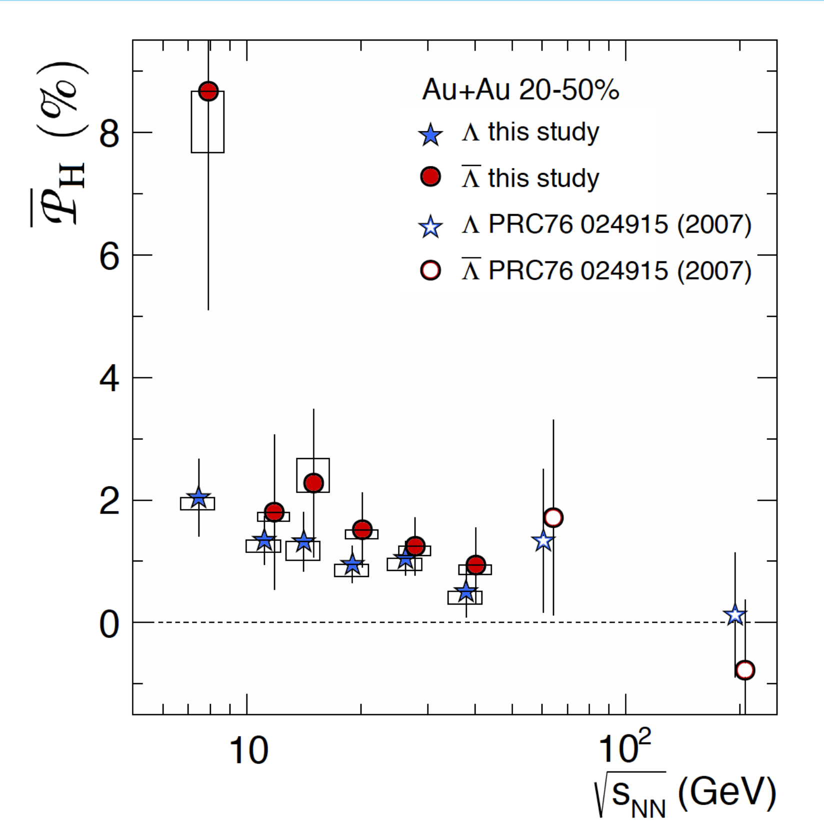
Average projection of the Polarization on J(sys) is extracted:

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

noted here as "global polarization"

sQGP vorticity measured to be maximal

P_H: average polarization with H: Λ or Anti-Λ



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.)

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

With T the temperature. The vorticity found is

ω= (9±1) 10^{21} s-1

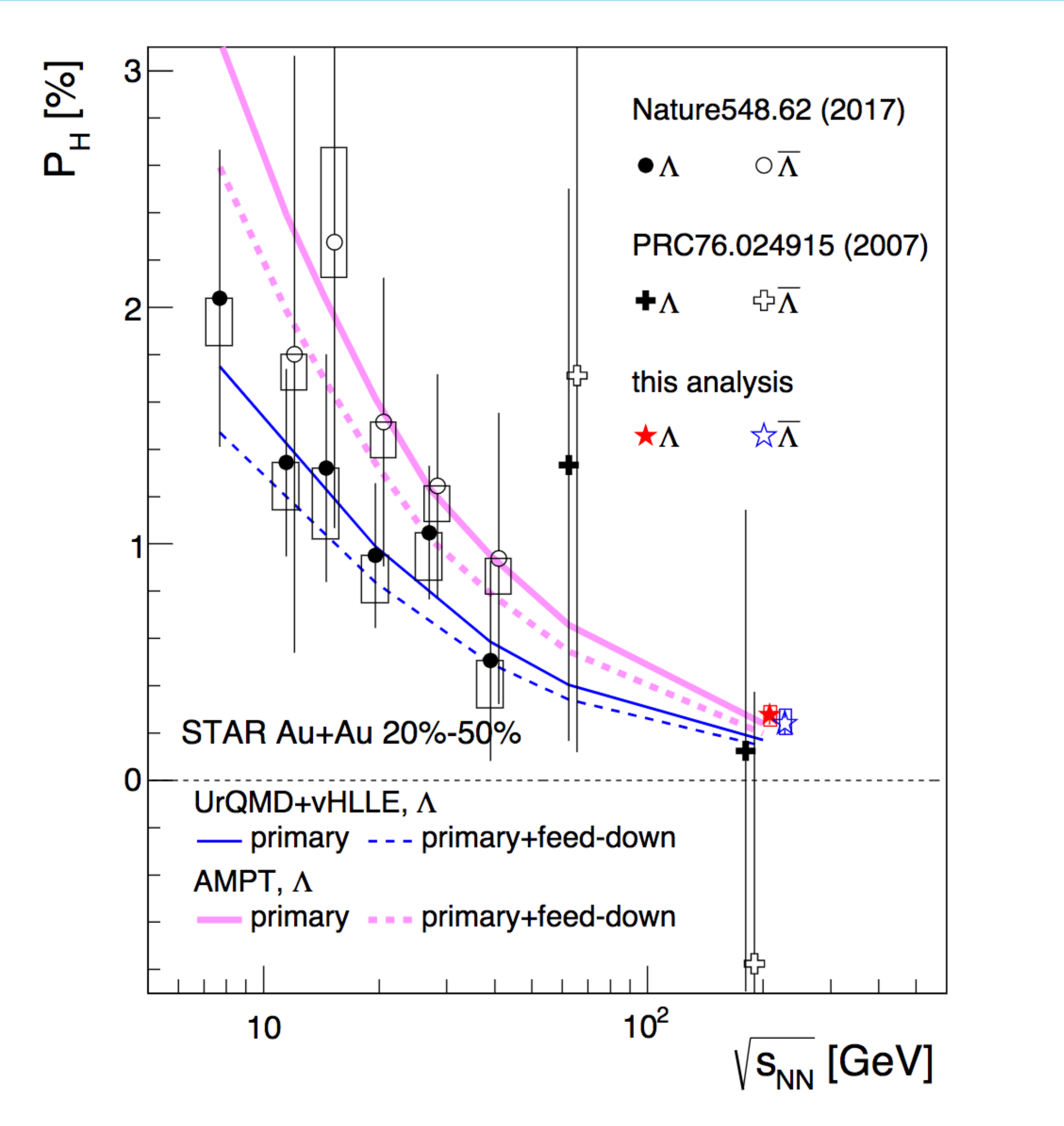
with an additional systematic error of a factor of 2 which by far surpasses the vorticity of all known fluids

For example solar subsurface flow has omega= 10-7 s-1, and superfluid nanodroplets omega=10ˆ7 s-1

* The Quark Gluon Plasma produced in heavy ion collisions is
- hotter
- least viscous
- and has larger vorticity, from all fluids ever produced in the laboratory !


nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
First observation of fluid vortices formed by heavy-ion collisions
PAGES 34 & 62
SUBATOMIC SWIRLS
CLIMATE CHANGE
PARIS AGREEMENT
Time for nations to match words with deeds
PAGE 25
BOOKS
SUMMER SELECTION
Recommended reading for the holiday season
PAGE 28
STEM CELLS
YOUTHFUL SECRETS
How the hypothalamus helps to control the ageing process
PAGE 52
NATURE.COM/NATURE
3 August 2017
Vol. 548, No. 7665

New STAR results on global polarization of Λ, Anti-Λ in Au+Au at 200 GeV Λ,



1805.04400

High precision measurement of a finite Λ and Anti-Λ global polarization of the level of 0.1-0.5% (depending on centrality) in Au+Au at 200 GeV

Global polarization increases with decreasing collision energy

sQGP

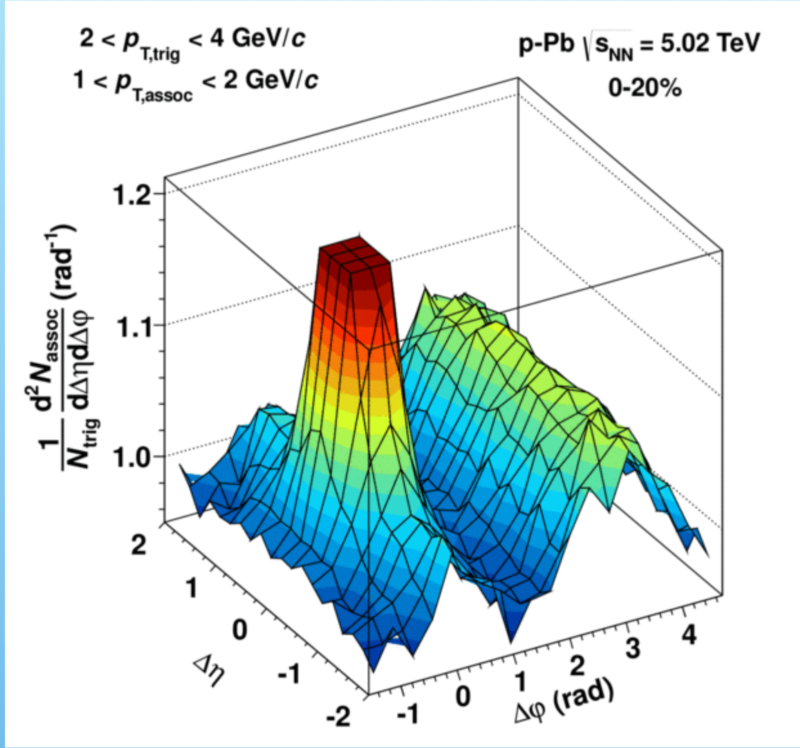
* **The Quark Gluon Plasma produced in heavy ion collisions is an extraordinary state of matter :**

- **100,000 times hotter than the core of the sun (T ~ 200 MeV, 2.3x10ˆ{12} K).**

- **least viscous than any observed fluid -> the Perfect Fluid**

- **with larger vorticity by many orders of magnitude than all fluids produced in the laboratory**

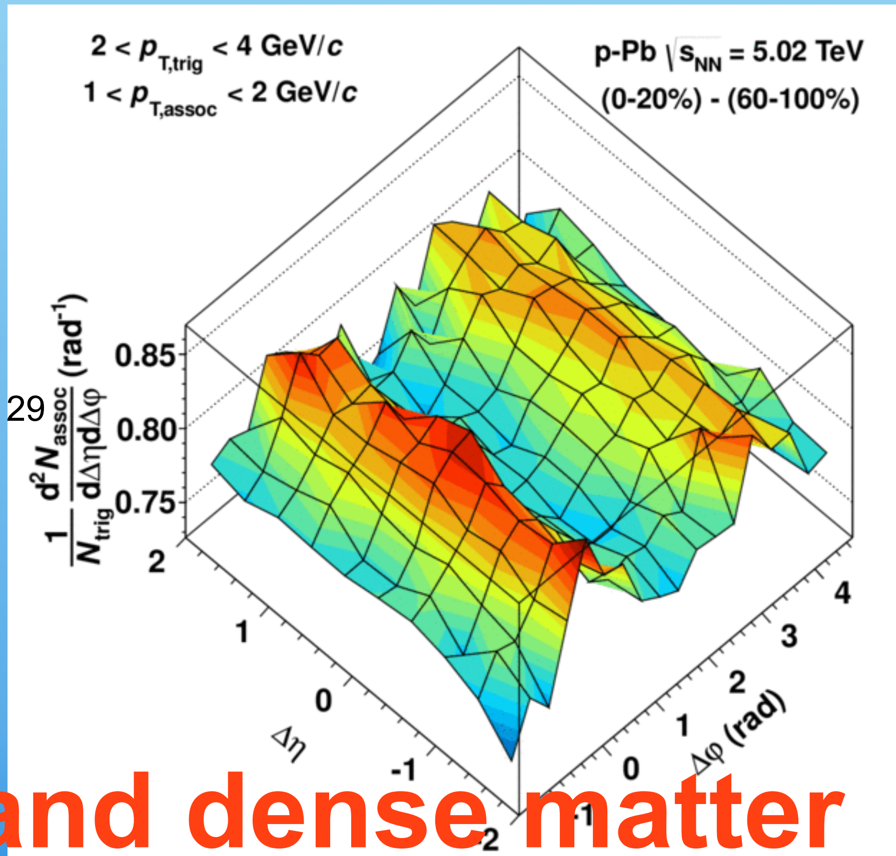
The ridge in p+p, p+A, A+A



ALICE PLB719 (2013) 29

First observed by CMS
PLB718 (2013) 795

After taking out jet-effects: Double Ridge



* Interpretation of ridge structure in p+p, p+Pb remains open

CGC ? hydrodynamic flow ?

Possibility of hot and dense matter formation in small systems ?

1986-2000: Discovery of a new state of matter at CERN

$$\varepsilon_{Bj}(\tau) = \frac{1}{A\tau}\frac{dE_T(\tau)}{dy},$$

Evidence:

* ccbar suppression

* Strangeness enhancement

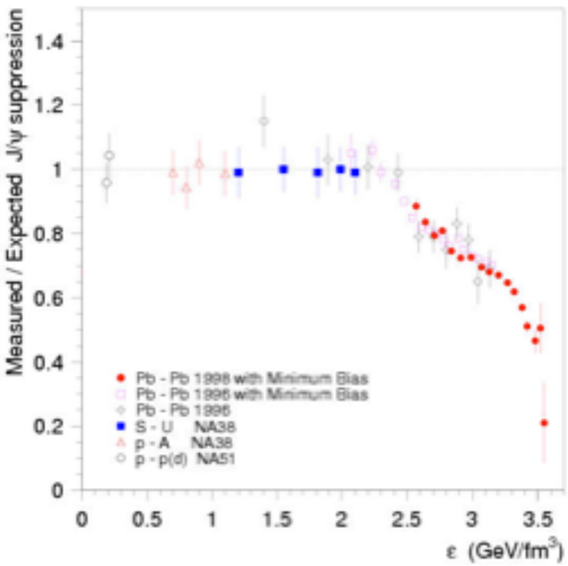
* T(chem. freee out) ~ T (critical

* Direct gammas consistent with T > Tcritical

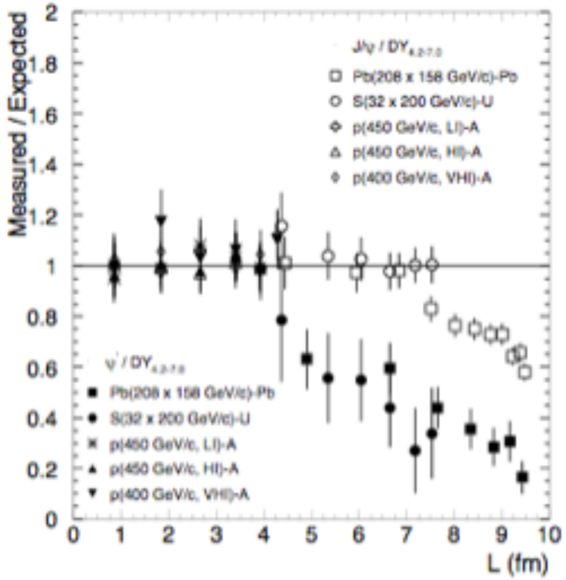
and other results

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

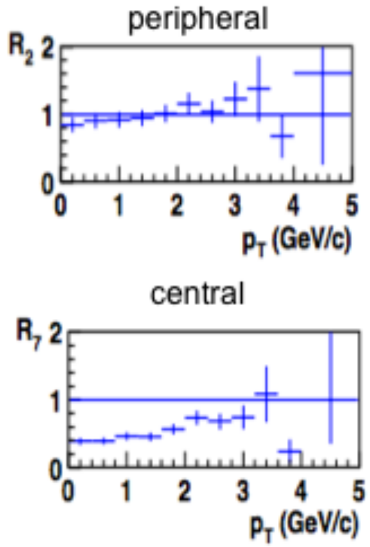
NA50, Phys Lett B 477 (2000) 28



Eur Phys J C 49 (2007) 559



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



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

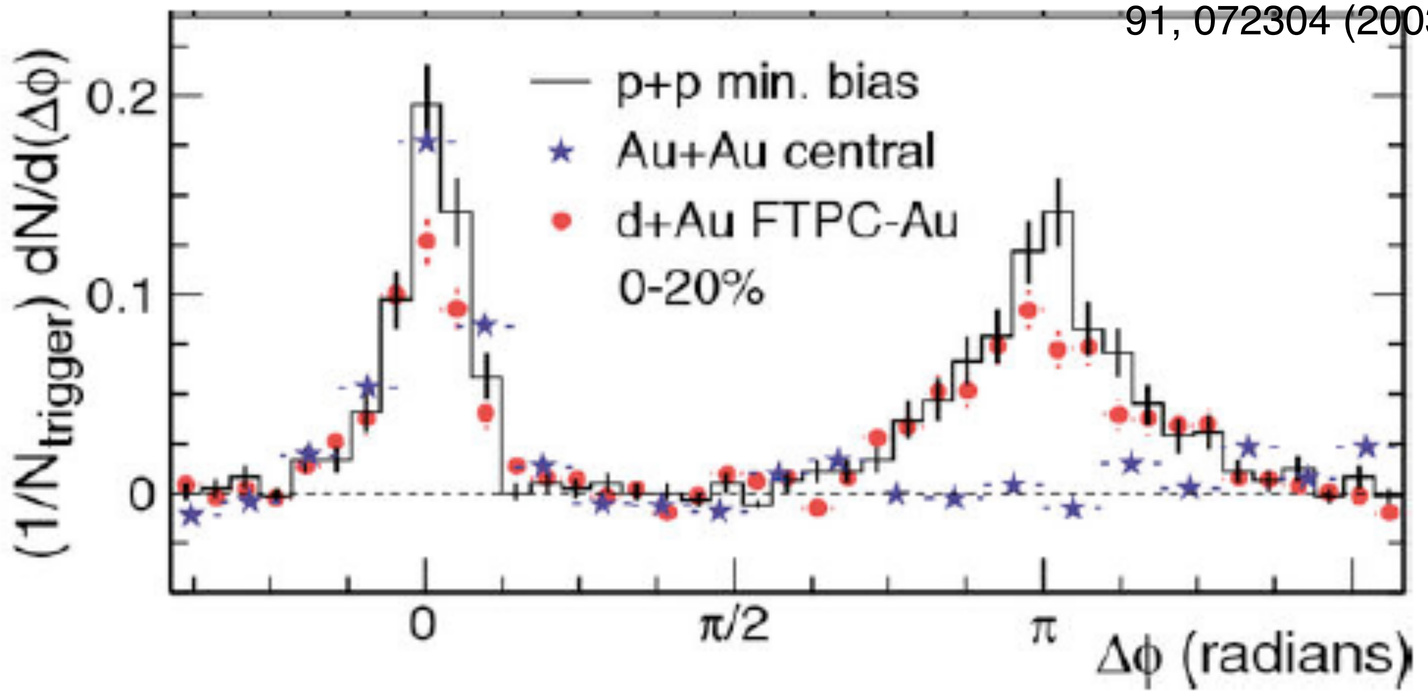
* **Psi prime is suppressed from 1.23 GeV/fm^3 on**
* **J/Psi is suppressed from ~2.4 GeV/fm^3 on**
* **J/Psi supression occurs mainly at low pT**

CERN press release 2000

2000-2003: Discovery of strongly interacting QGP and of jet quenching at RHIC

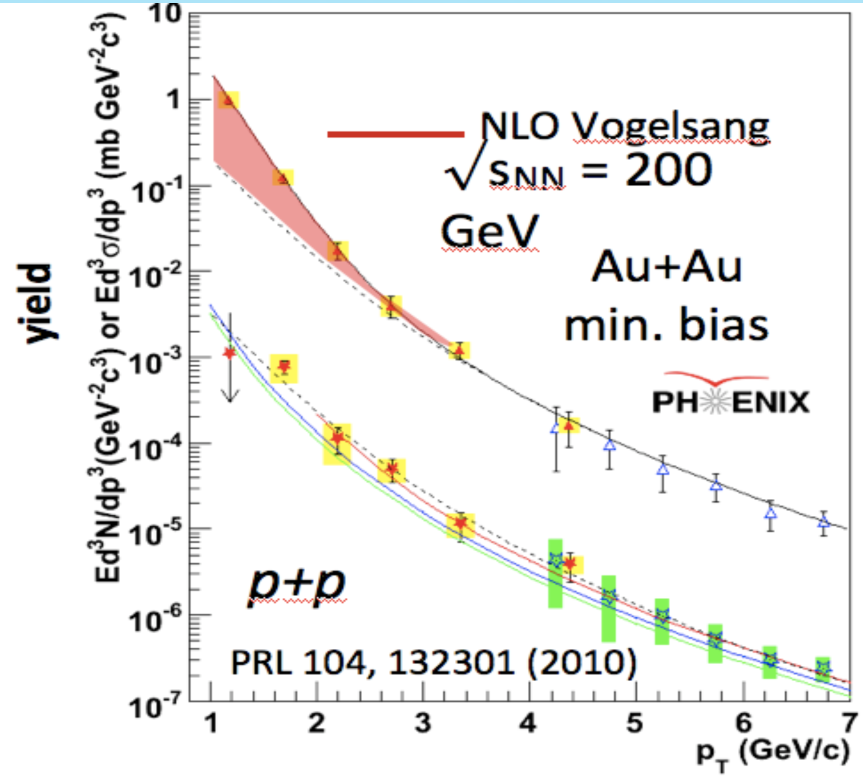
RHIC white papers for the 4 RHIC experiments: 2005

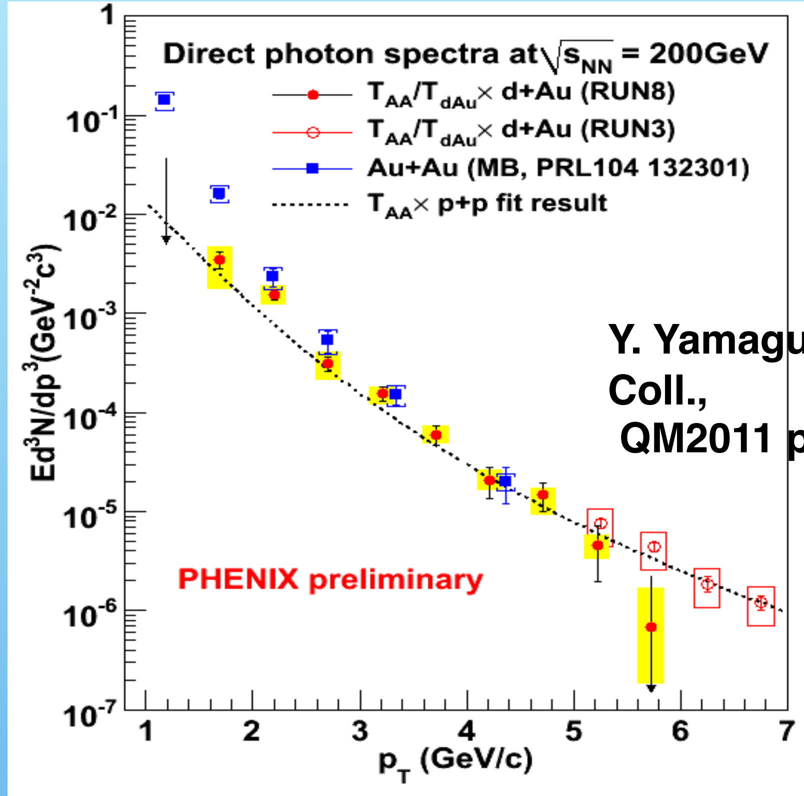
STAR Phys. Rev. Lett. 91, 072304 (2003), nucl-ex/0306024.



Dihadron correlations for pT(trig)=(4,6 GeV) and pT(associated)=(2 GeV,pT(trig))

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





Y. Yamaguchi, PHENIX Coll., QM2011 poster

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

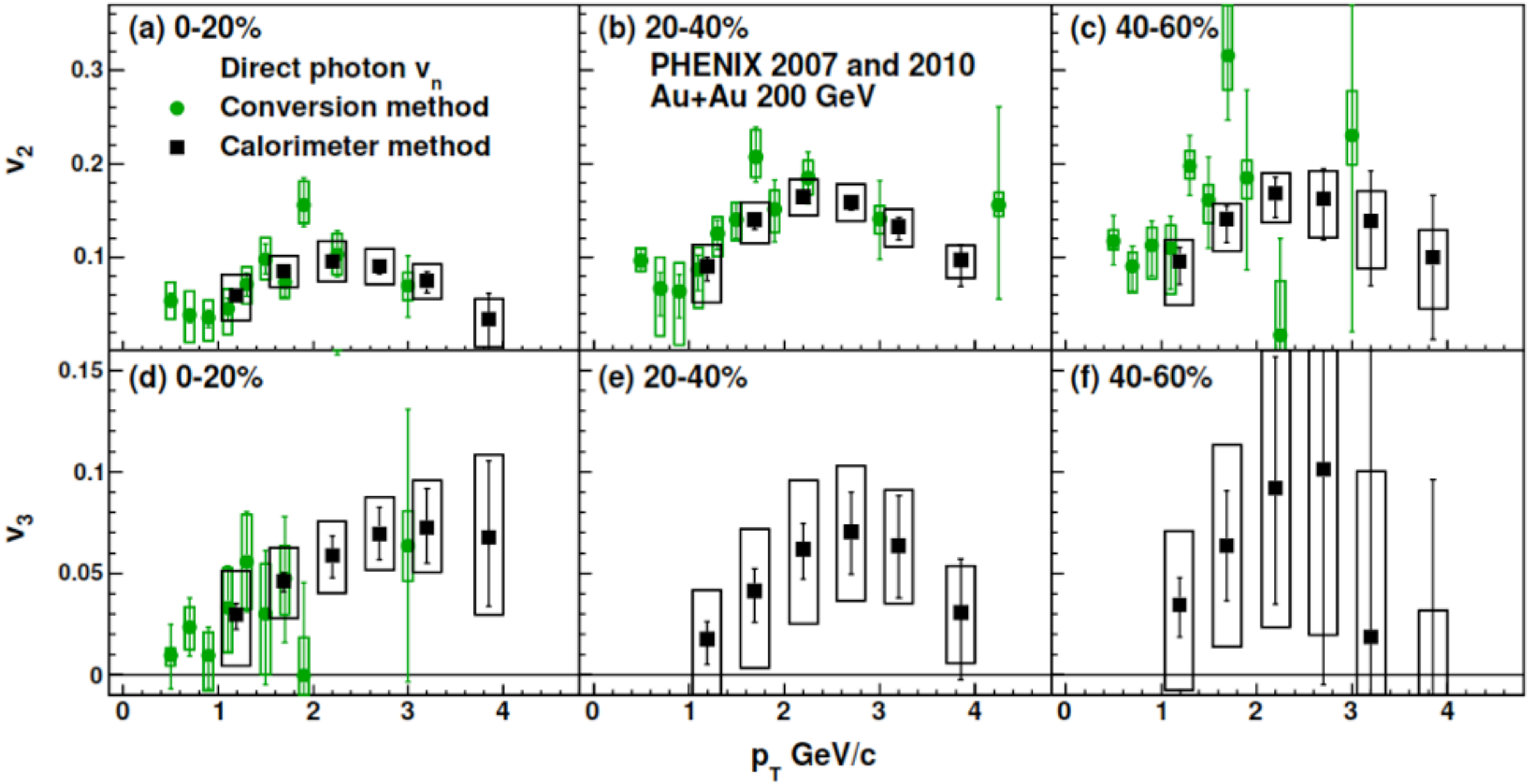
Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope 220 ± 20 MeV -->
T(init) from hydrodynamic models : 300-600 MeV, depending on thermalization time

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

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

PHENIX, arXiv:1509.07758

Anisotropic emission of direct photons

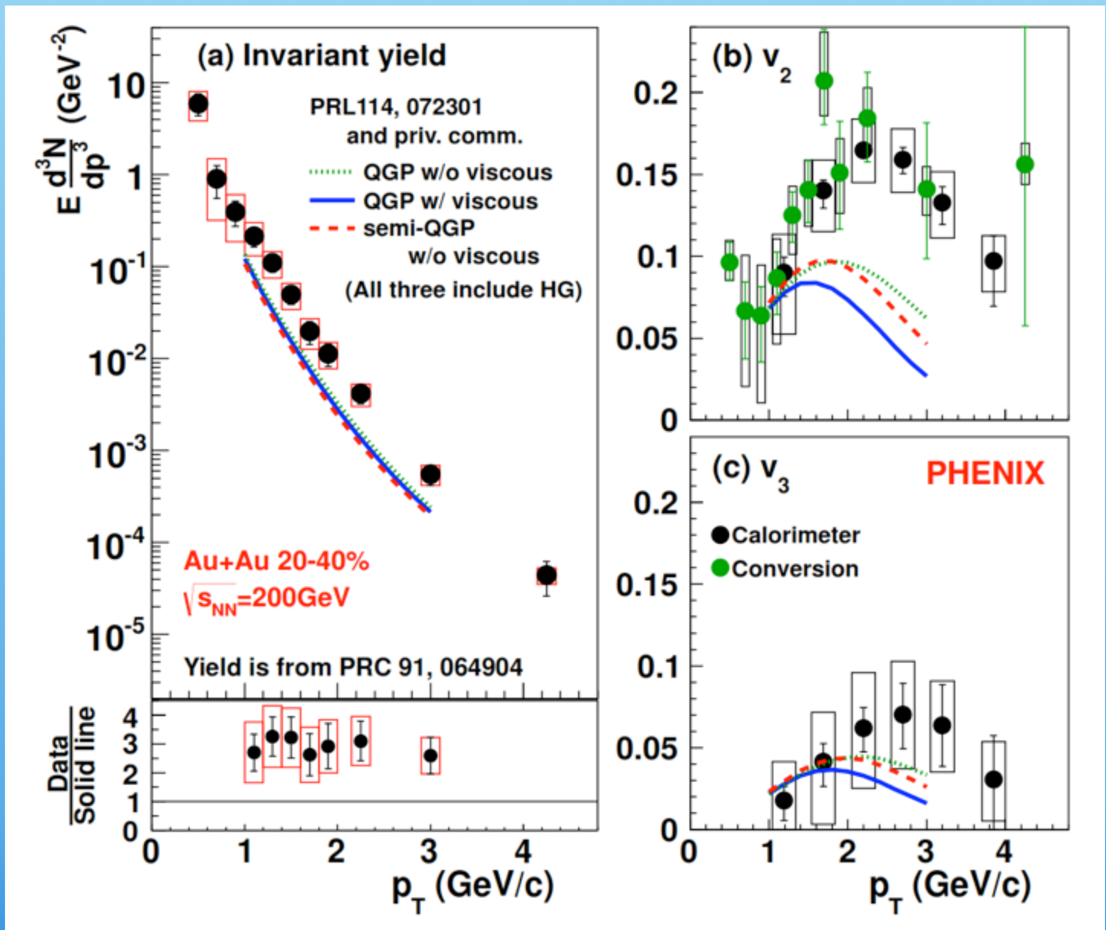


Large v_2 and v_3 of direct photons in Au+Au at 200 GeV studied vs pT and centrality

Direct photons vs models

Example: viscous hydro + thermal emission

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

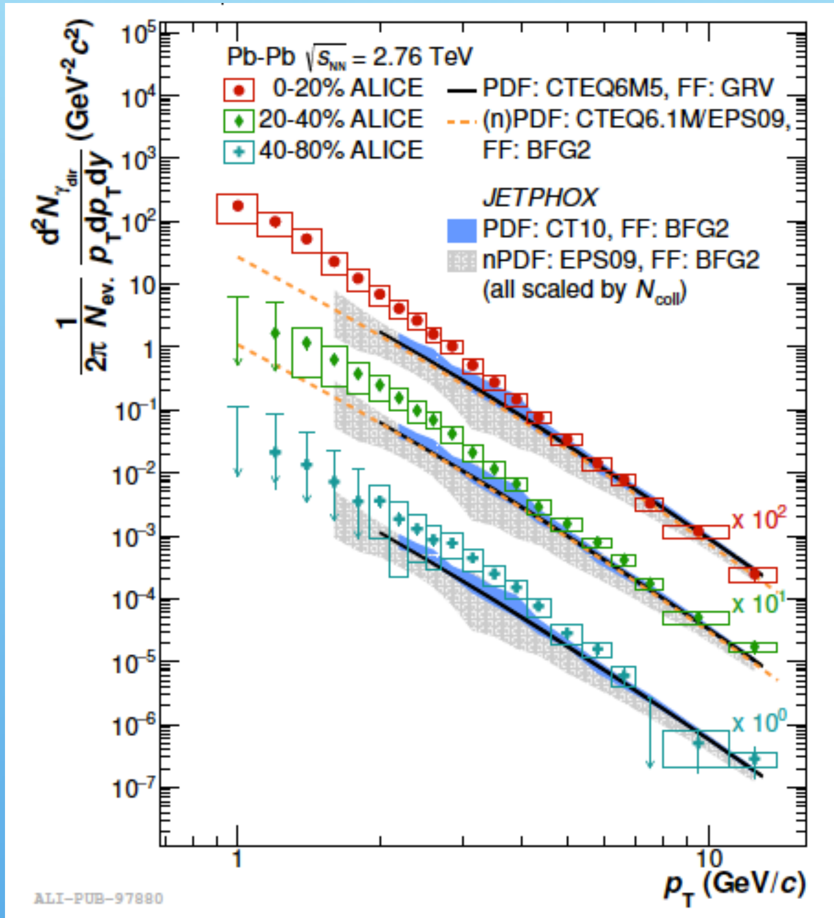


Thermal direct photons with large flow v2, v3: challenge for models

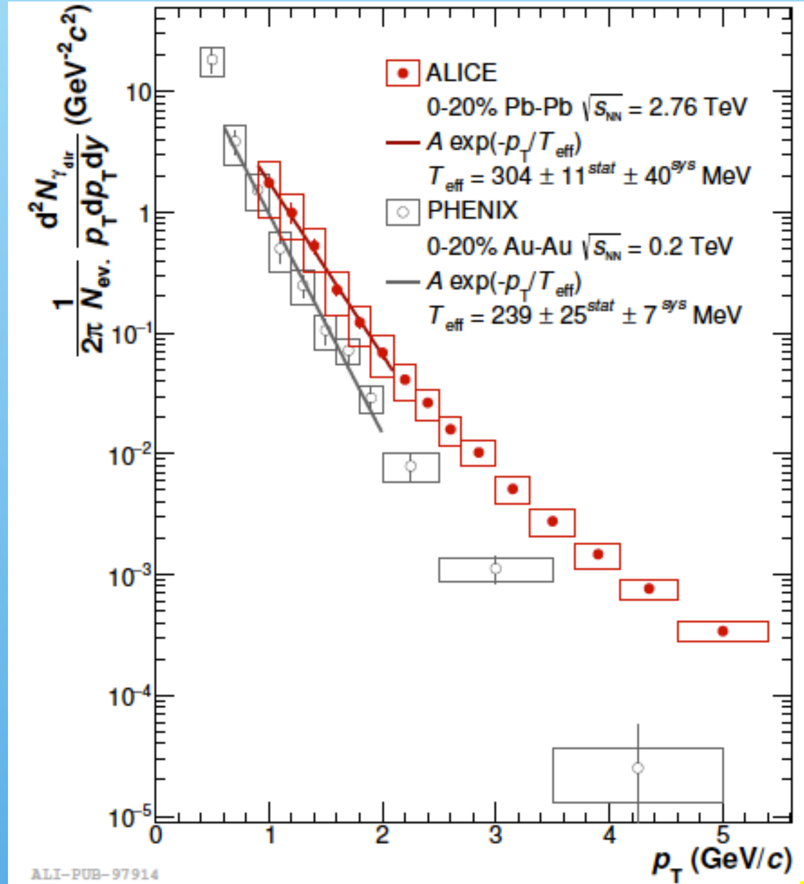
ALICE direct photons 2015

ALICE: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)

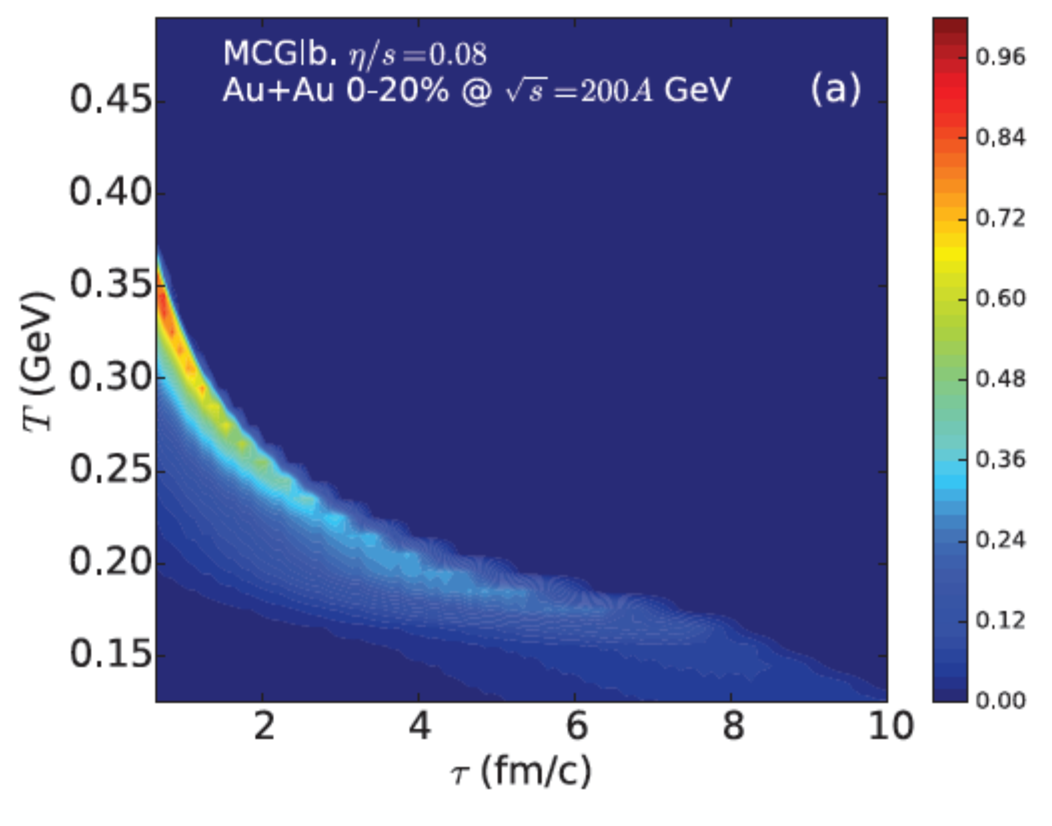
T(dir. photons) at RHIC and LHC is > than critical Tcrit~154 MeV

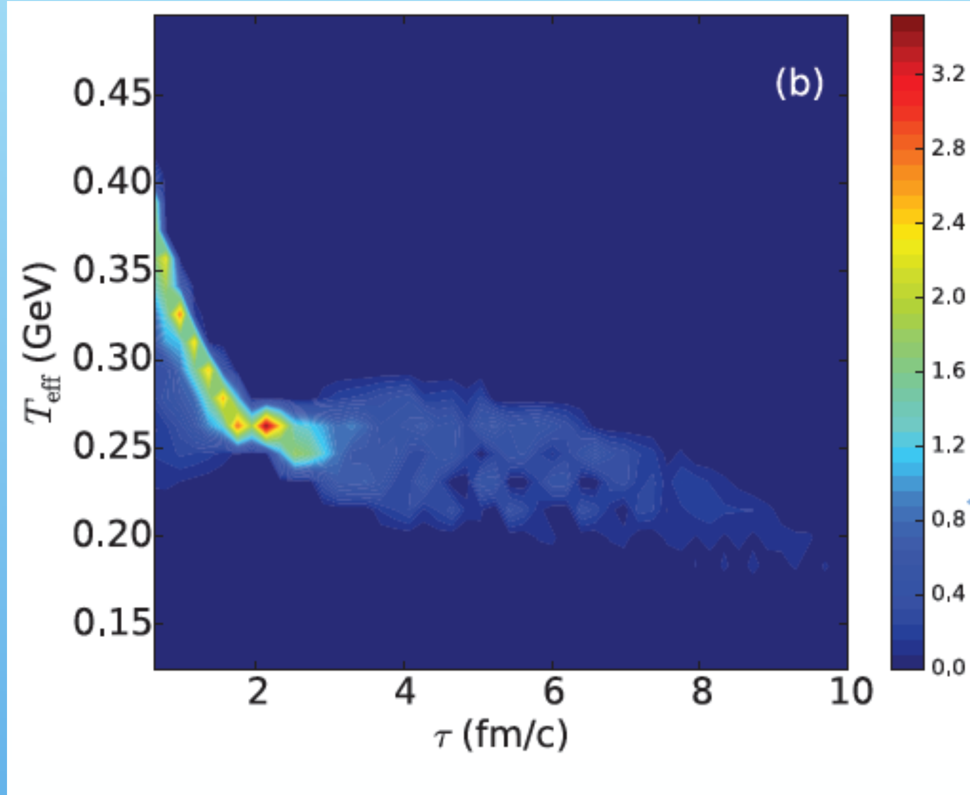
The real initial T of the source is higher than the measured T

Theory on direct photons

RHIC

C. Gale et al, 1308.2440



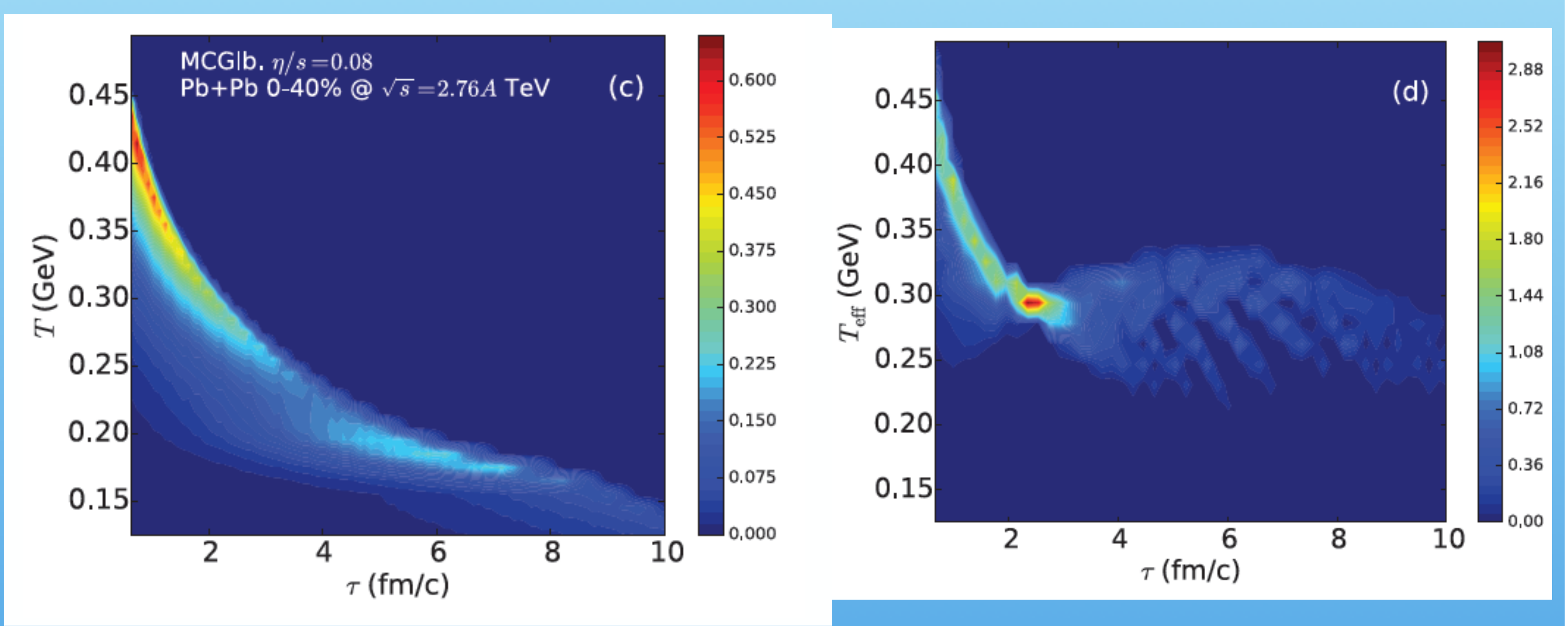


The 3rd dimension in these plots is cross section of photons

$$\frac{dN^{\gamma} / dydTd\tau}{dN^{\gamma} / dy}$$

Theory on direct photons

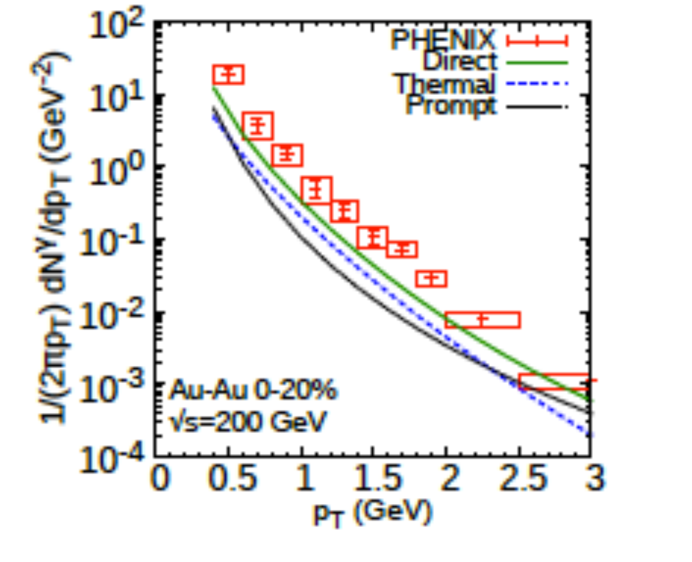
LHC

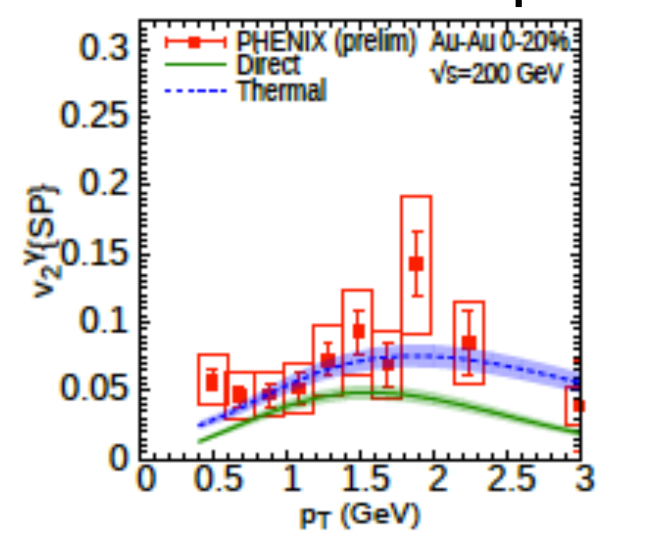


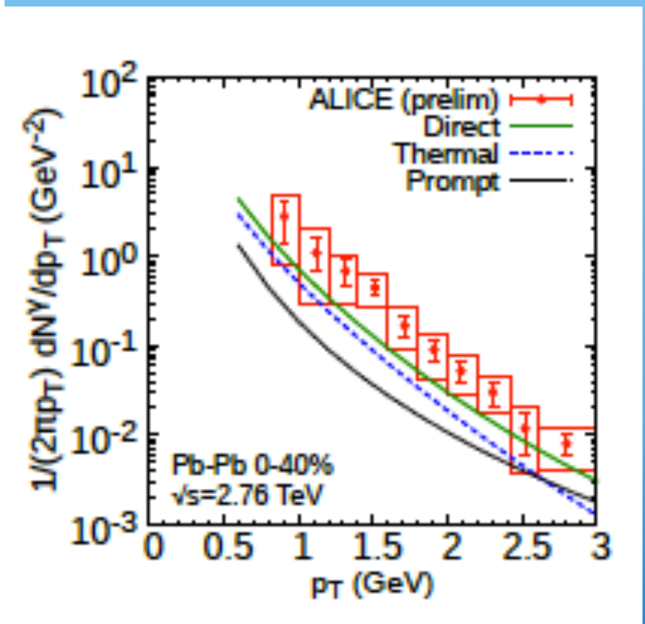
C. Gale et al, 1308.2440

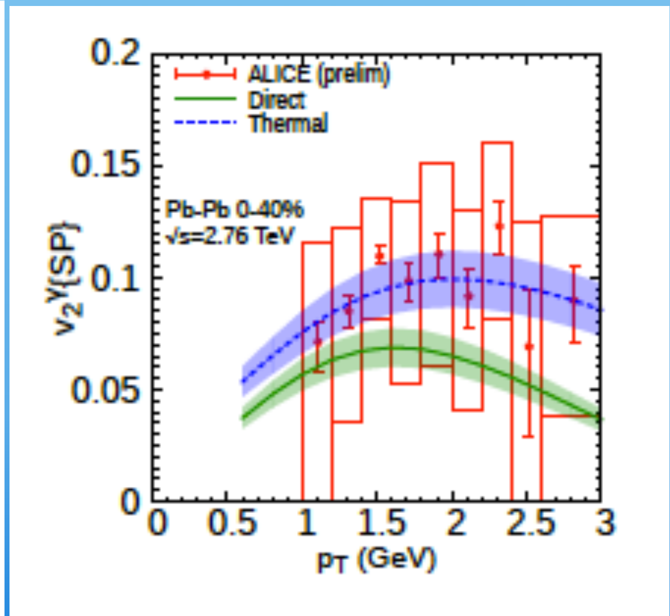
Direct photons flow too

J. F. Paquet et al, 1509.06738









Difficult for models to describe both cross section and v2 flow of direct photons

Hydrodynamic model describes approx. the v2 data at RHIC and LHC.

Suggests that excess of direct photons is due to thermal photons

Photons as a thermometer

range of photon emission	fraction of total photon yield	
	AuAu@RHIC 0-20% centr.	PbPb@LHC 0-40% centr.
$T = 120\text{-}165$ MeV	17%	15%
$T = 165\text{-}250$ MeV	62%	53%
$T > 250$ MeV	21%	32%
$\tau = 0.6 - 2.0\,\text{fm/c}$	28.5%	26%
$\tau > 2.0\,\text{fm/c}$	71.5%	74%

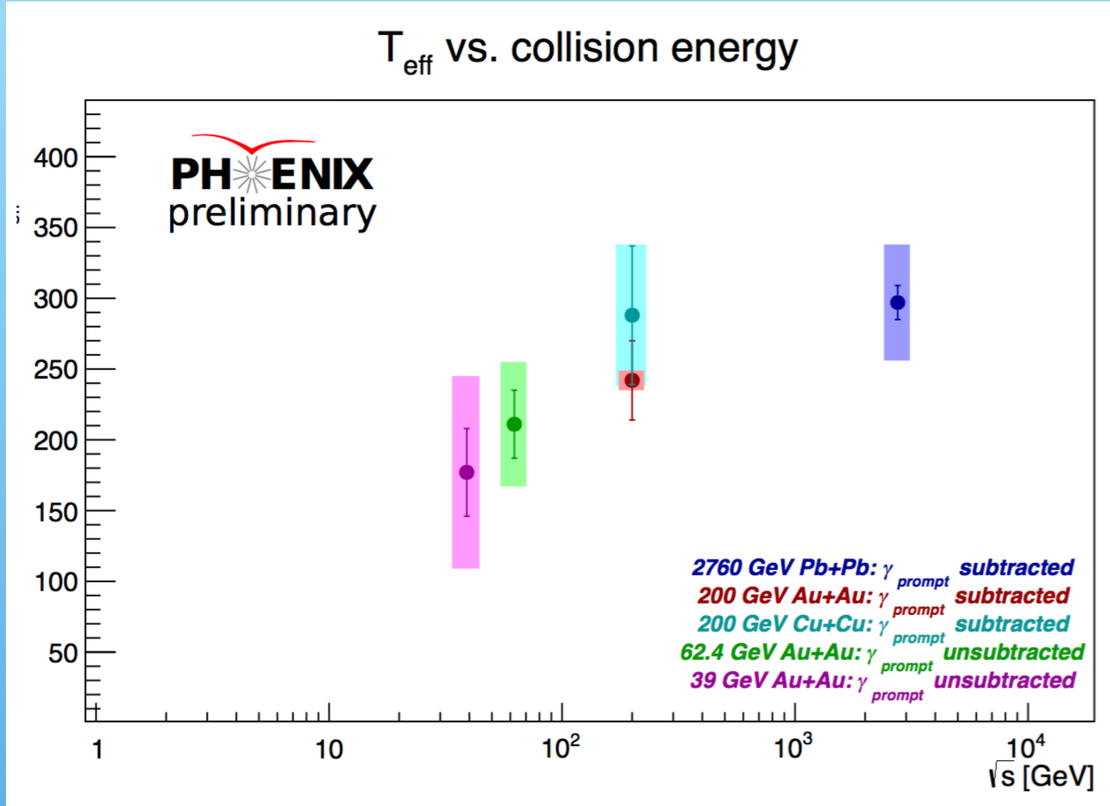
C. Gale et al, 1308.2440

*** Most photons at RHIC and LHC are emitted from time near Tc**
*** Their effective temperature is enhanced by strong radial flow (effective temperature of hadrons decaying into photons are above Tc due to mass dependence of radial flow).**
*** However a very high temperature early initial collision stage is required to generate this radial flow**

Conclusions:
*** Photons can be used as a thermometer**
*** T>Tc is reached**
*** More model calculations needed to fit the data and extract the T(init)**

Latest results from RHIC Beam Energy Scan: direct photons

effective T(from direct photons)



PHENIX, Dheepali Sharma QM2017

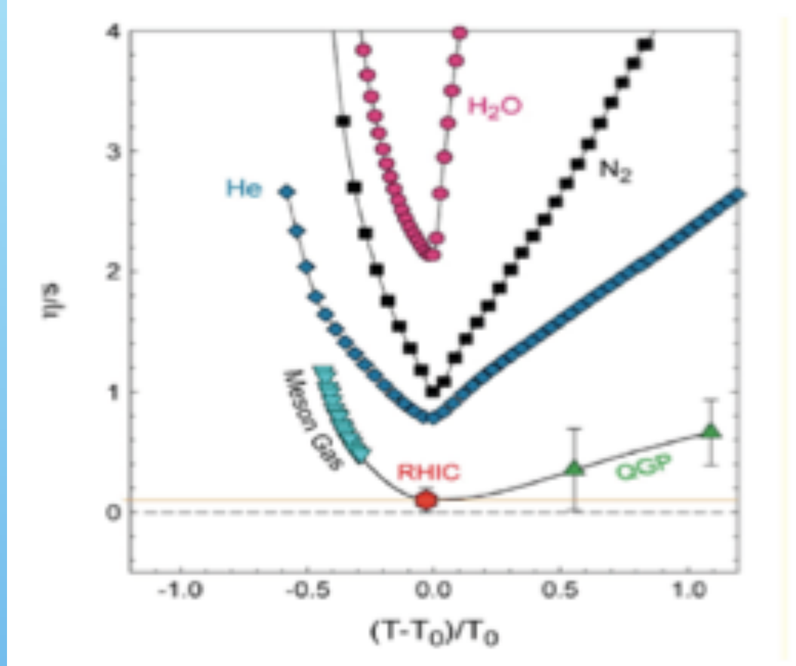
3. Collectivity, Flow, Strangeness

Flow and shear viscosity

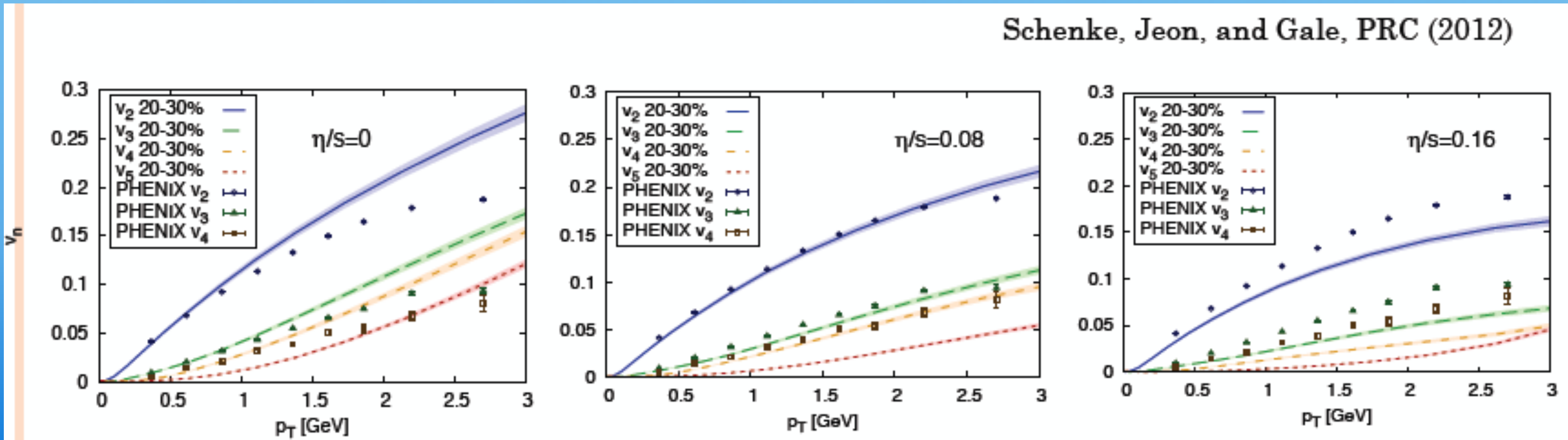
- 2003: discovery at RHIC of large flow and first extraction of shear viscosity -> RHIC white papers

- QGP : a perfect liquid

- strongly interacting QGP



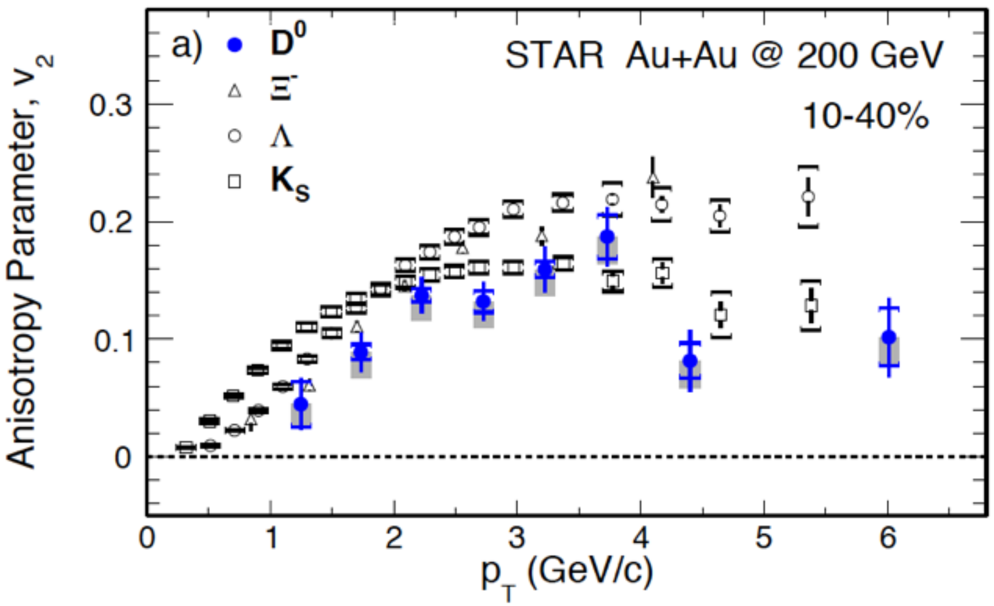
PHENIX



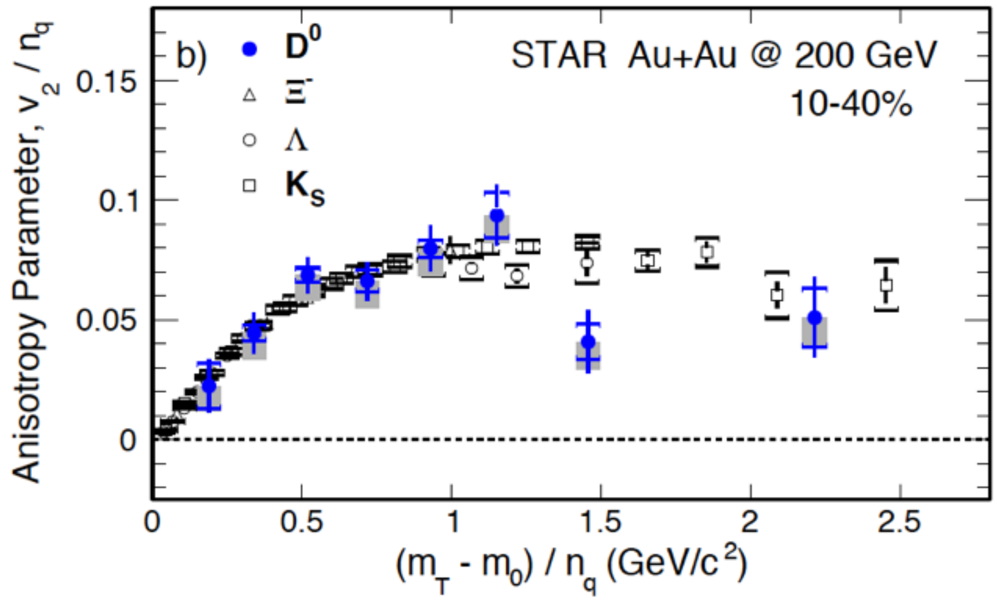
New D0 v2 from STAR Heavy Flavor Tracker

1701.06060, STAR

Mass ordering



NCQ scaling

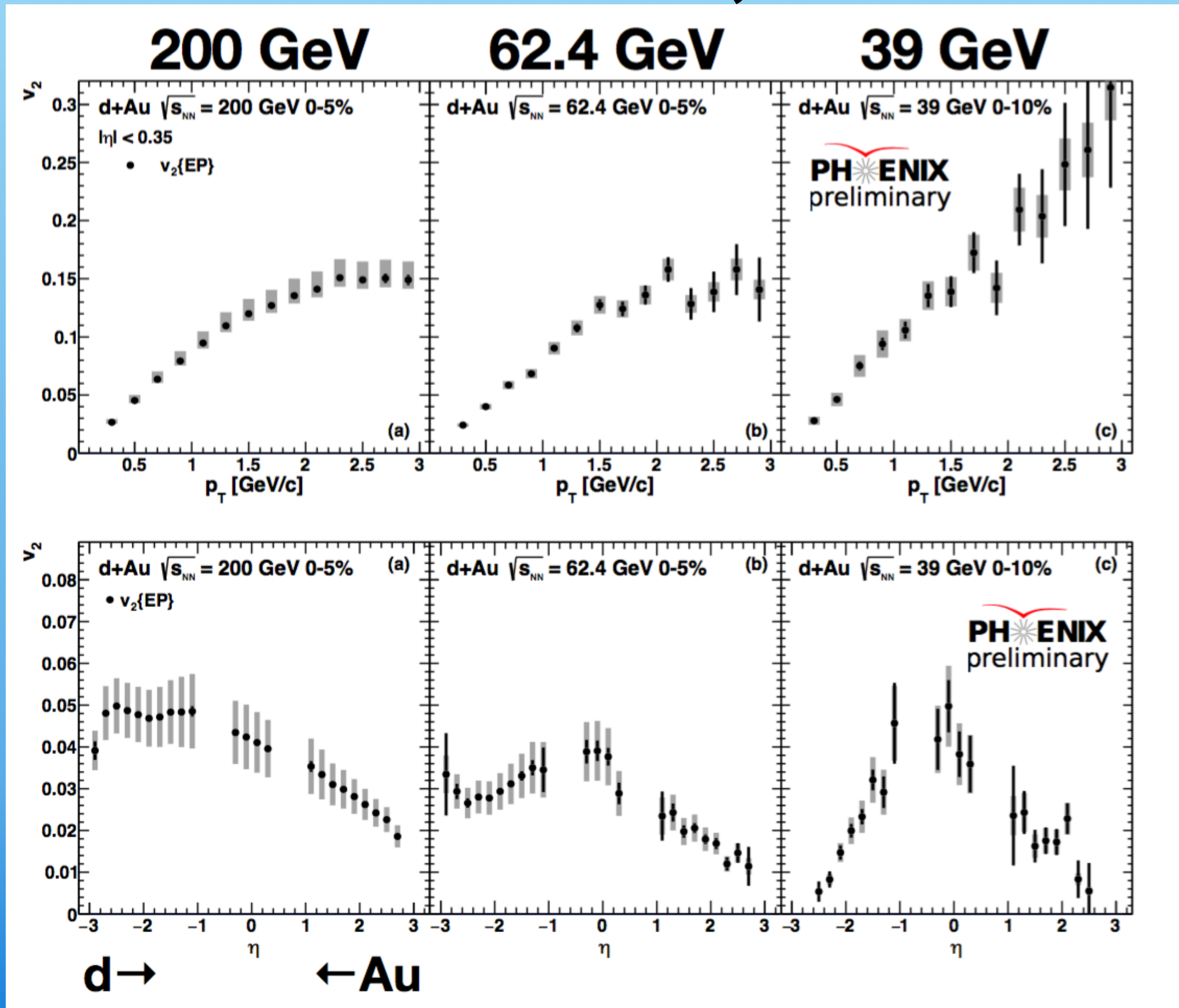


v2 of D0 in Au+Au follows Number-of-Constituent-Quarks scaling of other hadrons

-> Evidence for thermalization of charmed mesons

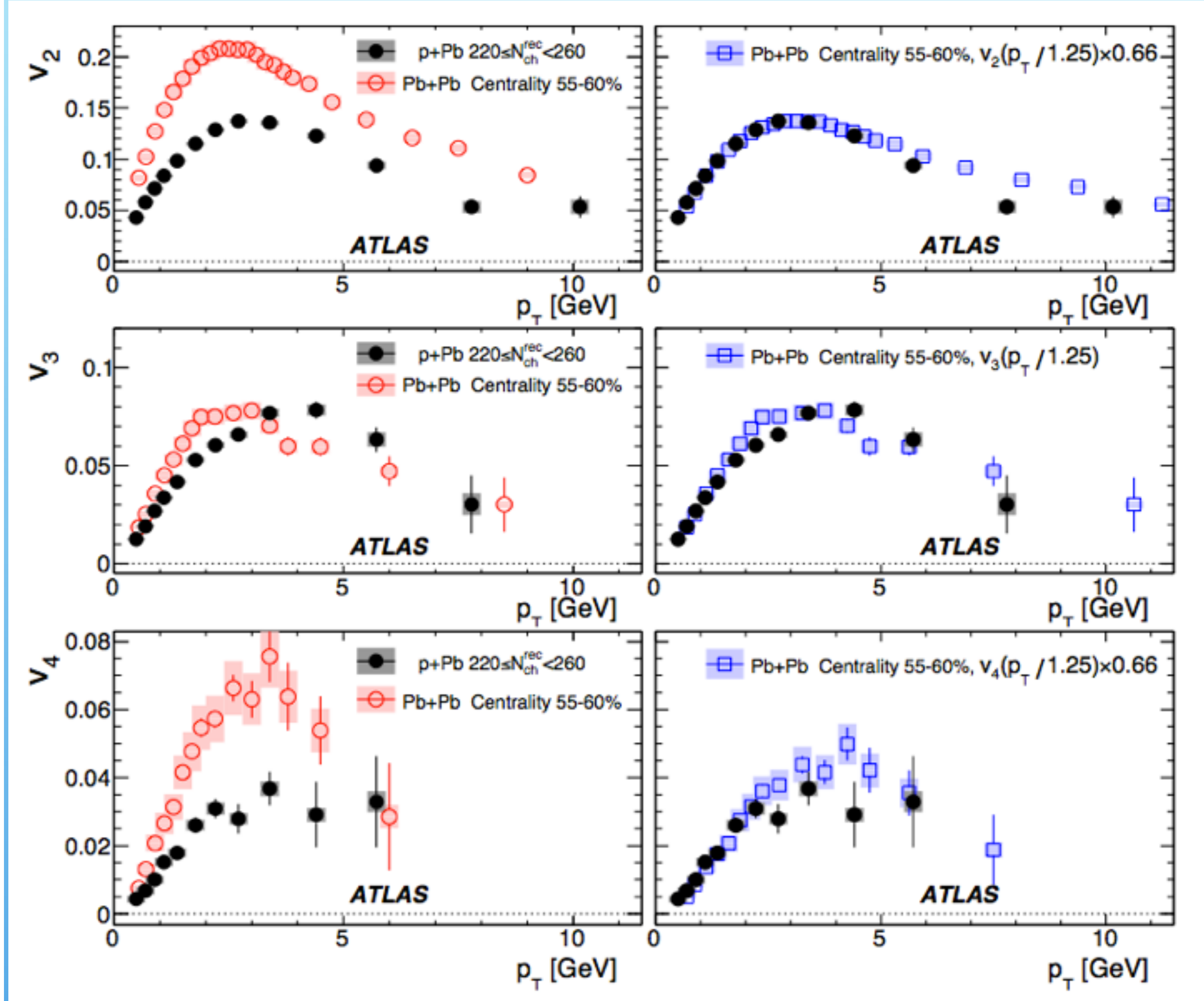
Small Systems

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



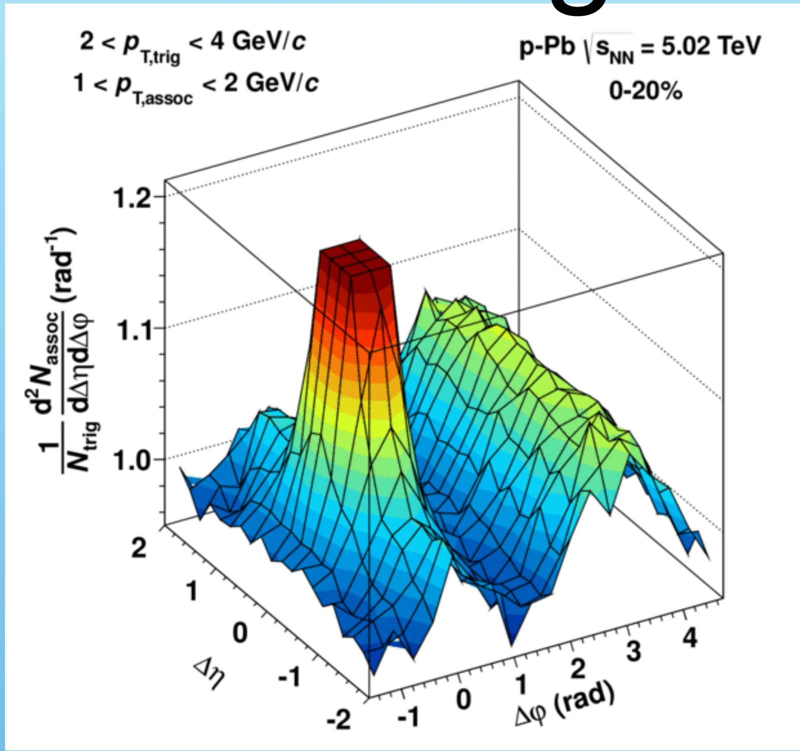
Results from ATLAS 1409.1792

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 ?

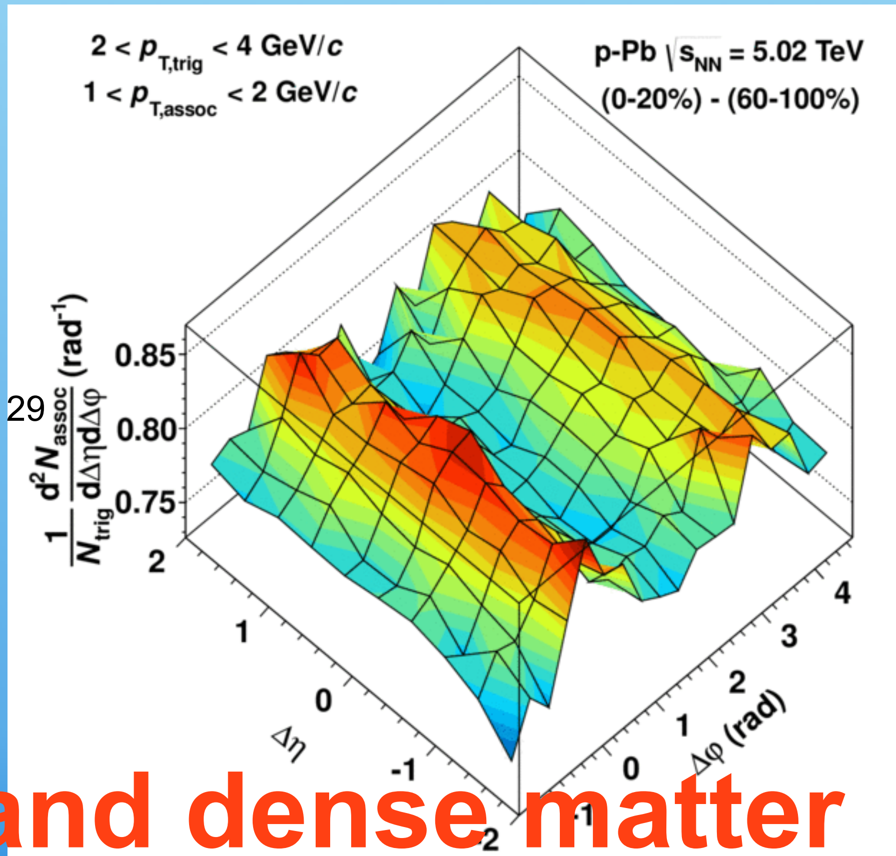
The ridge in p+p, p+A, A+A



First observed by CMS
PLB718 (2013) 795

ALICE PLB719 (2013) 29

After taking out jet-effects: Double Ridge

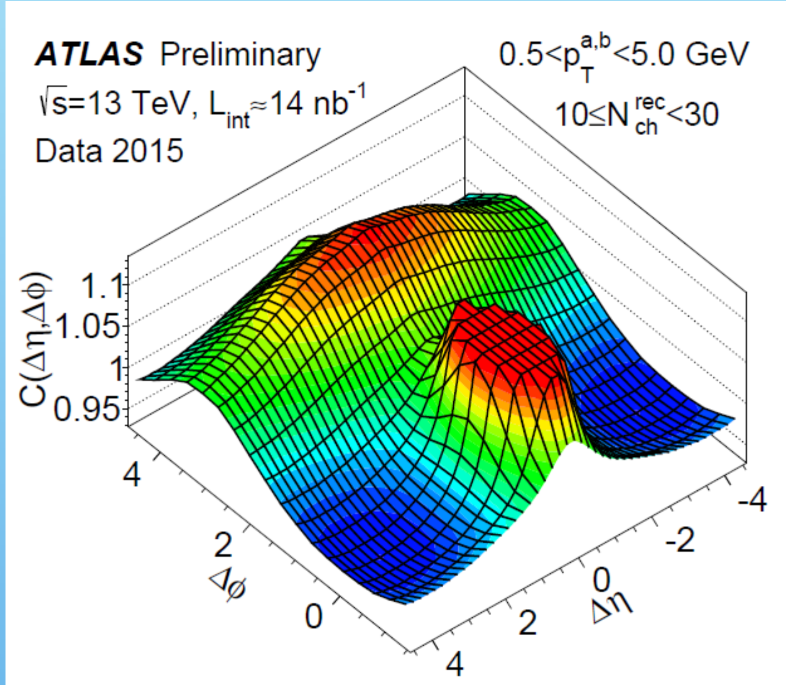


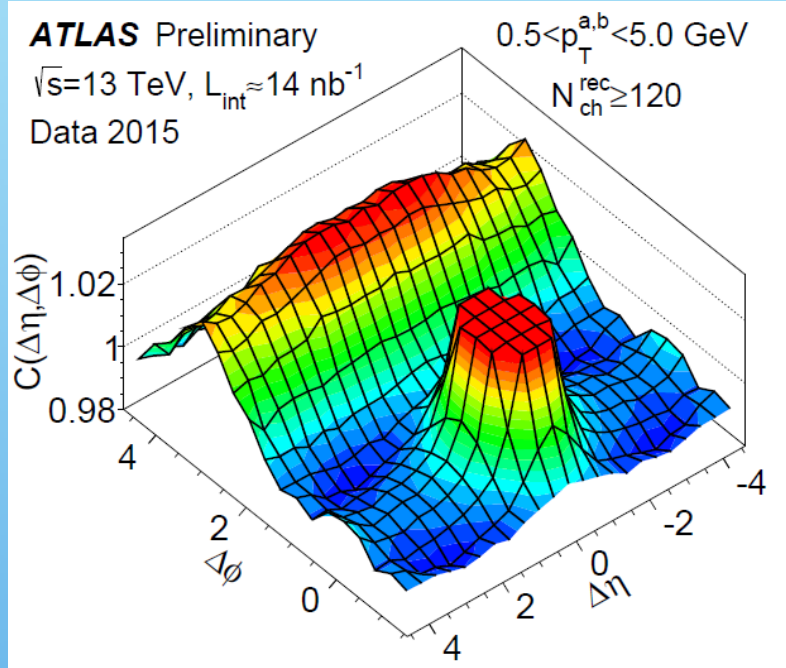
* Interpretation of ridge structure in p+p, p+Pb remains open

CGC ? hydrodynamic flow ?

Possibility of hot and dense matter formation in small systems ?

Run-2 news: the ridge seen in p+p collisions at 13 TeV





Low mult

High mult

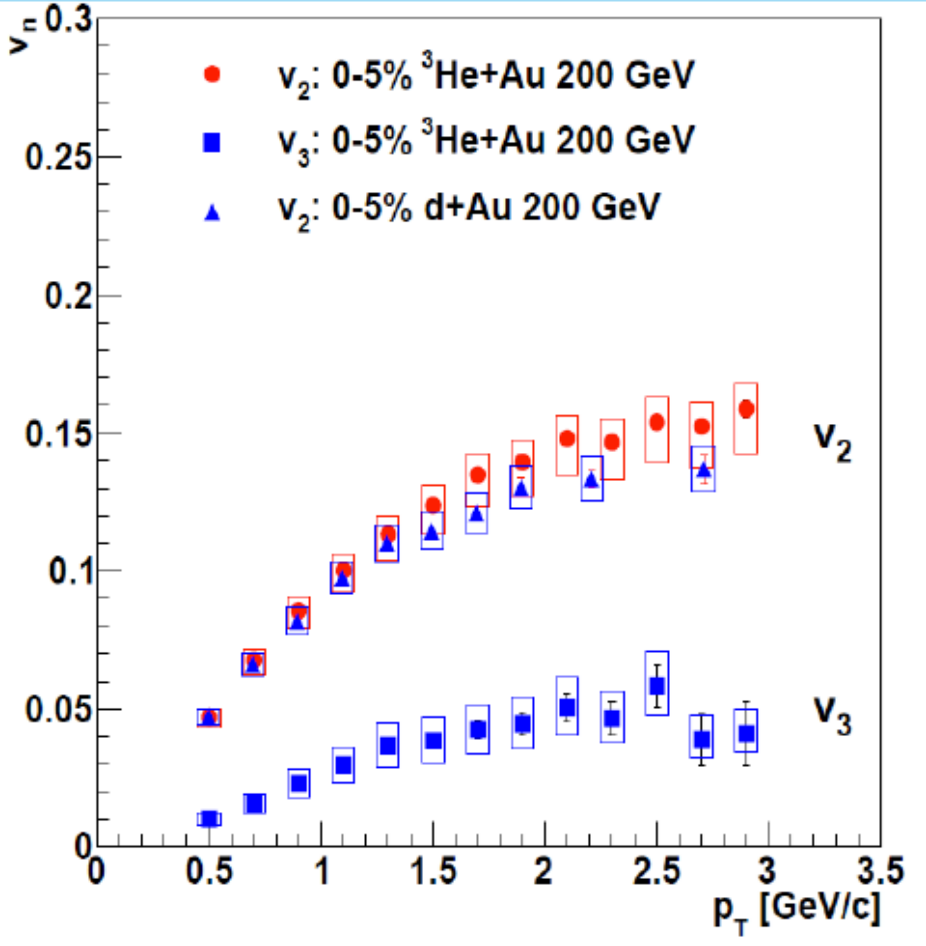
M. Arratia et al , ATLAS EPS2015

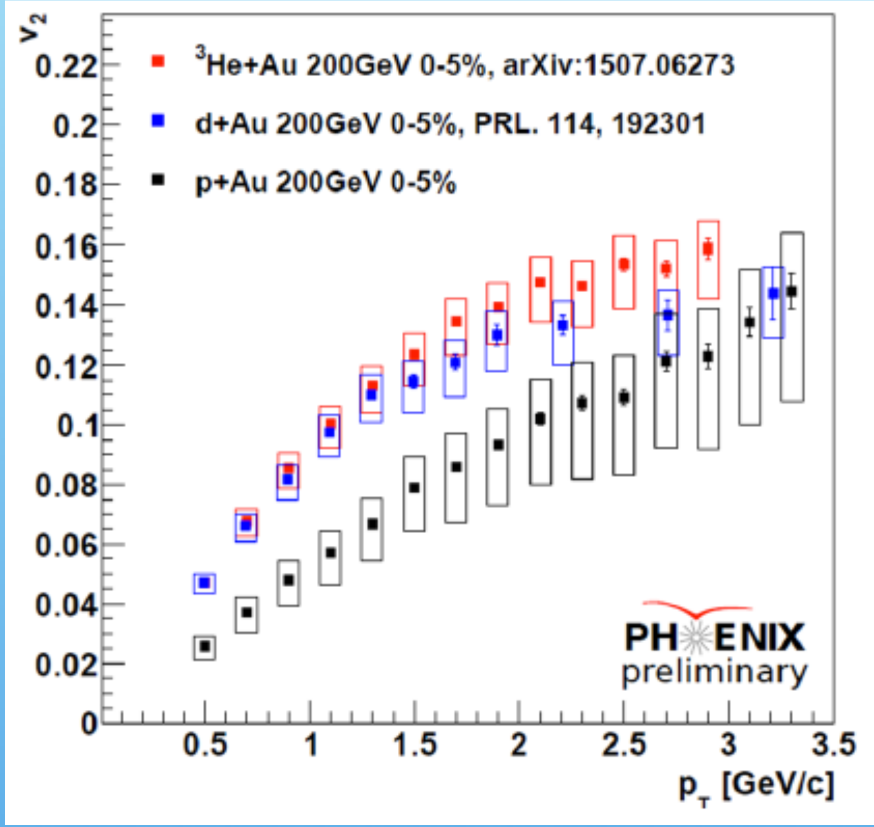
Ridge: Similar in p+p 13 and 7 TeV

QGP forming in small systems ?

RHIC: First results from 2015 p+Au run and results from 2014 3He+Au at 200 GeV

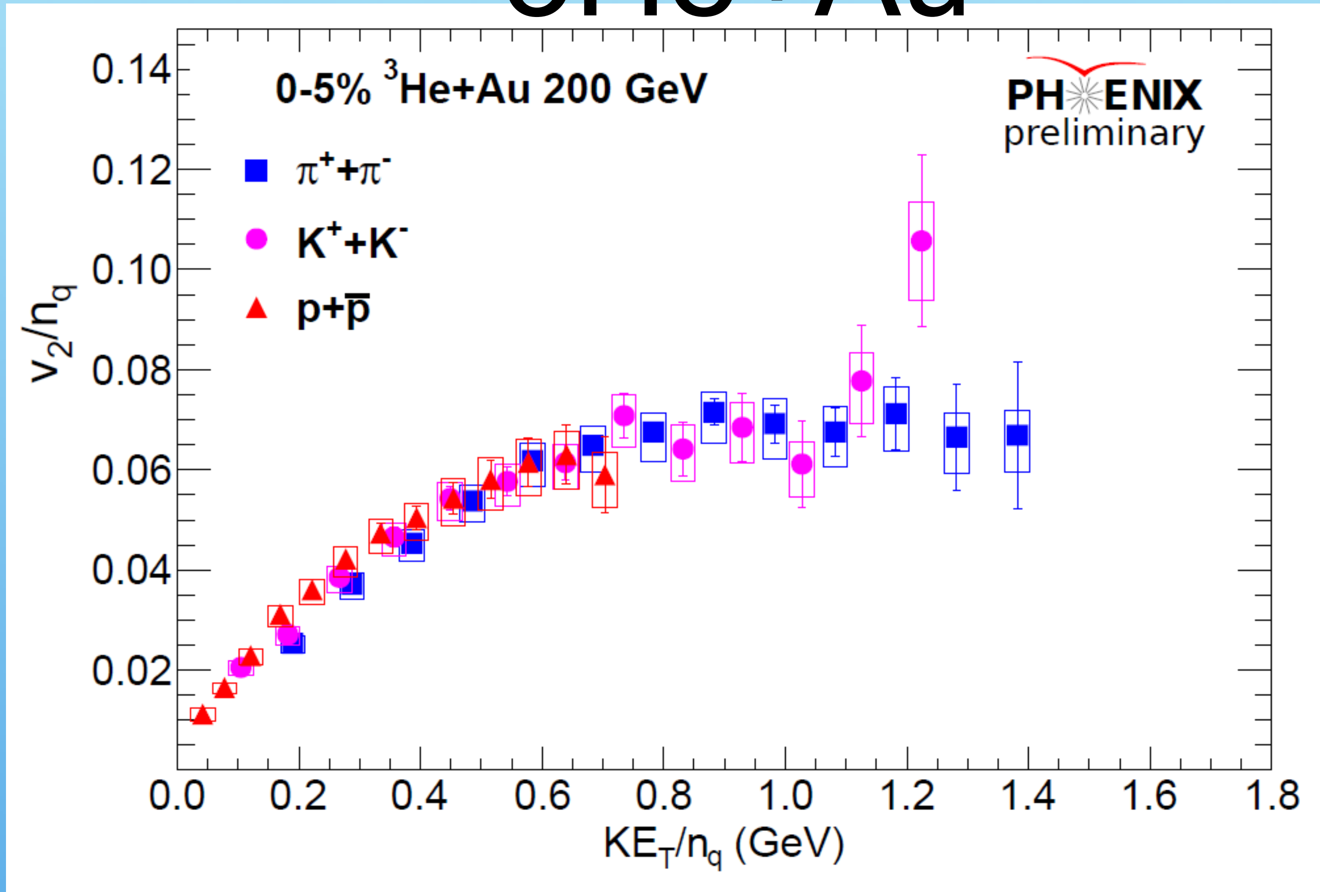
PHENIX 3HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)





Large v2, v3 components in 0-5% 3He+Au, d+Au and p+Au from 2015 run

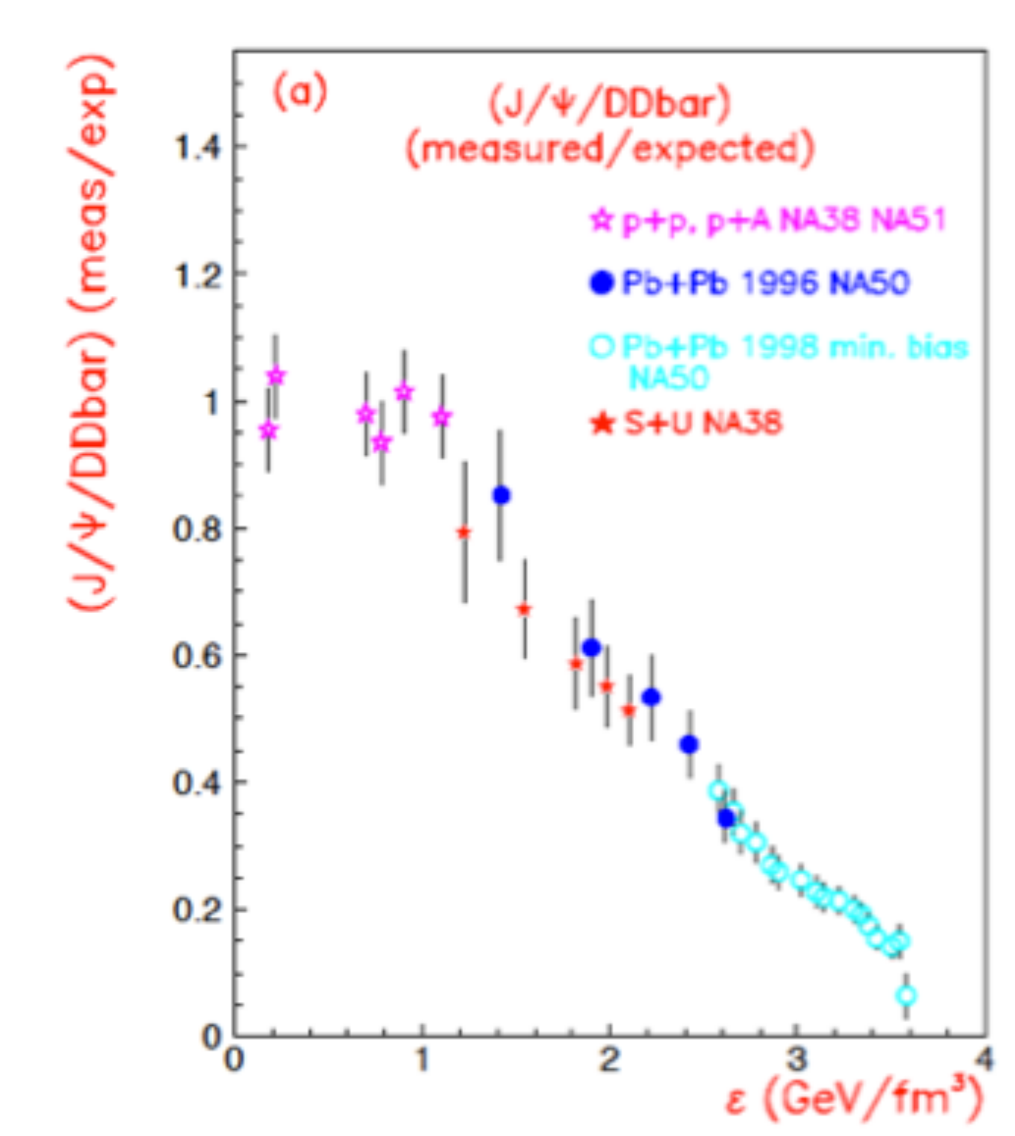
Number of quark scaling in 3He+Au



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

Measured ratio of J/Psi to D mesons at SPS



S.K., New J. of Physics, Vol. 3, (2001), 16, arXiv 0004138

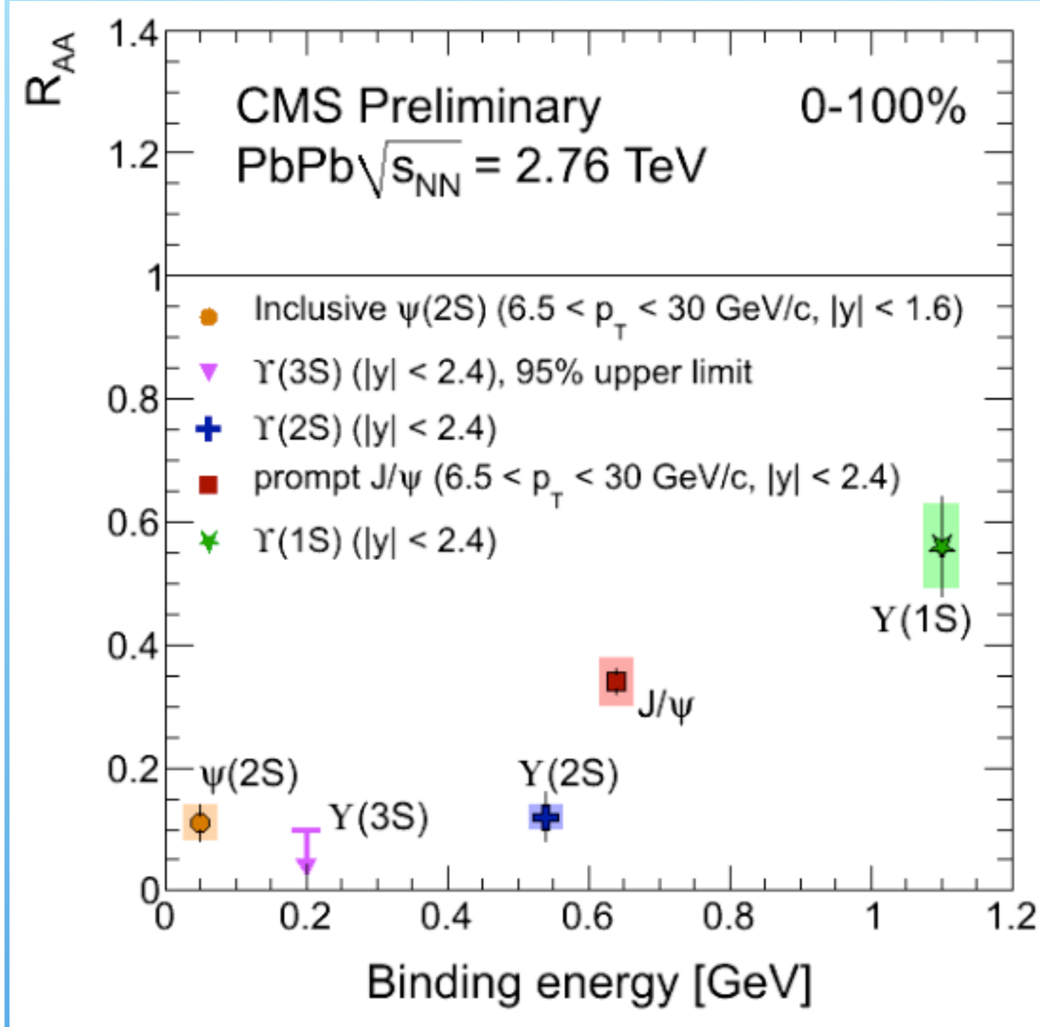
- Open charm measured by dimuons in region 1.6-2.5 GeV

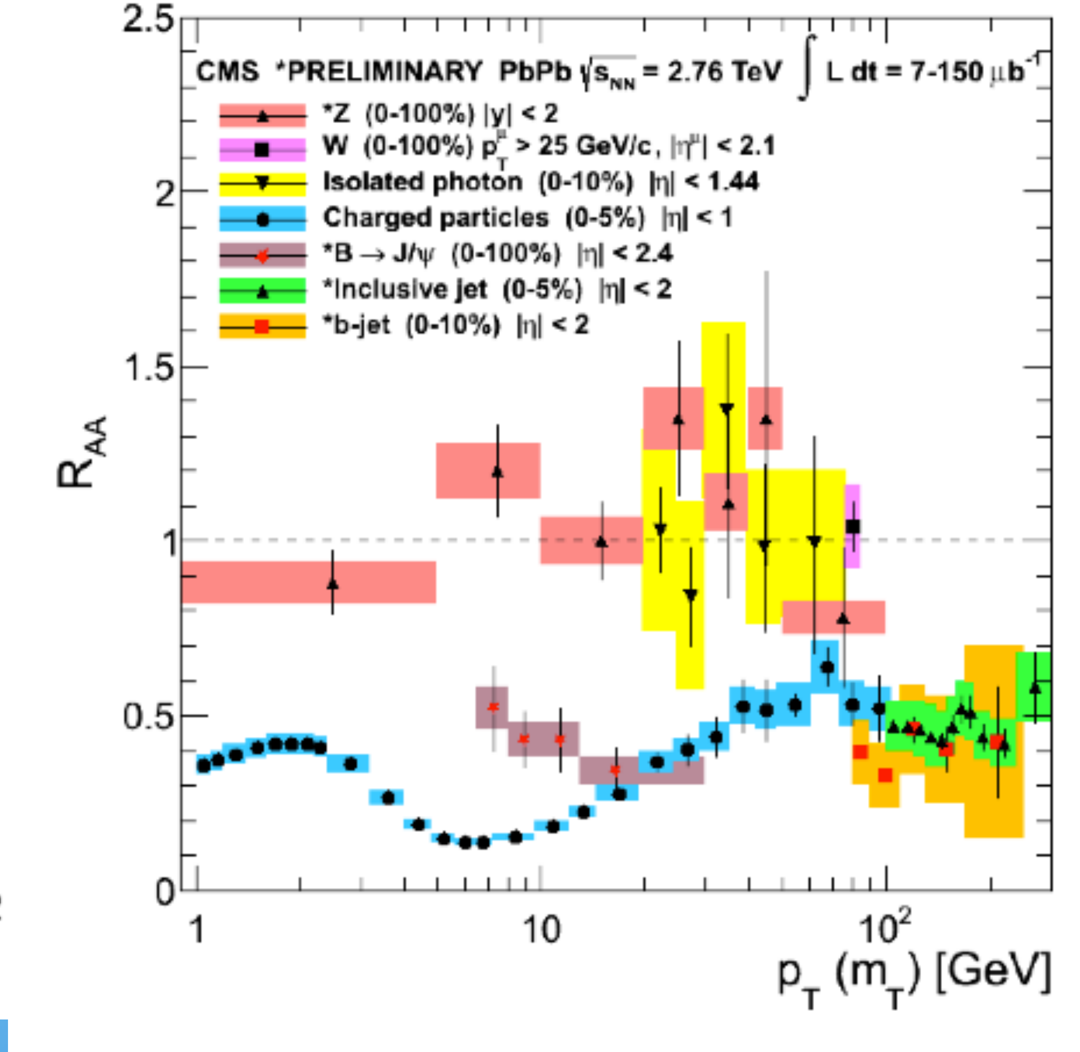
The J/Psi/(DDbar) estimate is suppressed at 1 GeV/fm^3

Need open charm measurements at low energy to understand quarkonia onset of suppression

Would be nice to get chi_c measurements at energies at or below RHIC to disentangle screening vs other mechanisms of quarkonia suppression
LHCb SMOG program will address this at ~ top SPS energy (F Fleuret et al).

M. Jo et al CMS,
Etretat QGP 2014





Y(1S) in PbPb seem less suppressed than open beauty in PbPb (needs better stat)

Y(2S), Y(3S) in PbPb more suppressed than open beauty in PbPb

Multi-parameter estimates from a variety of data

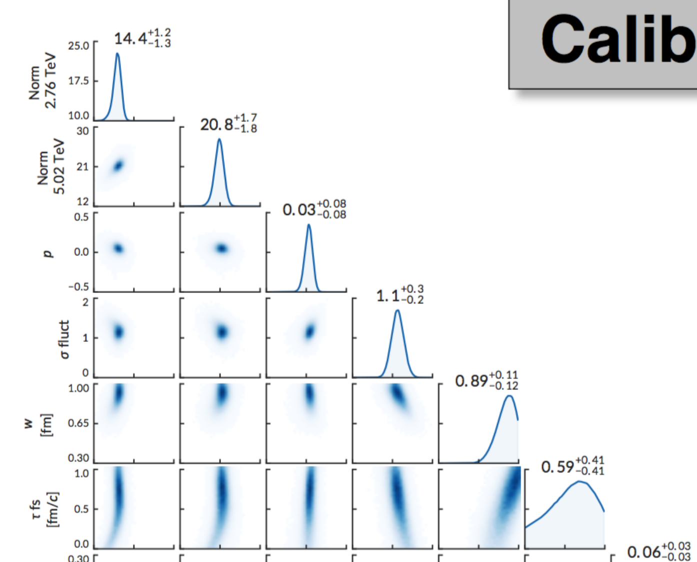
Multiple parameter estimation

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

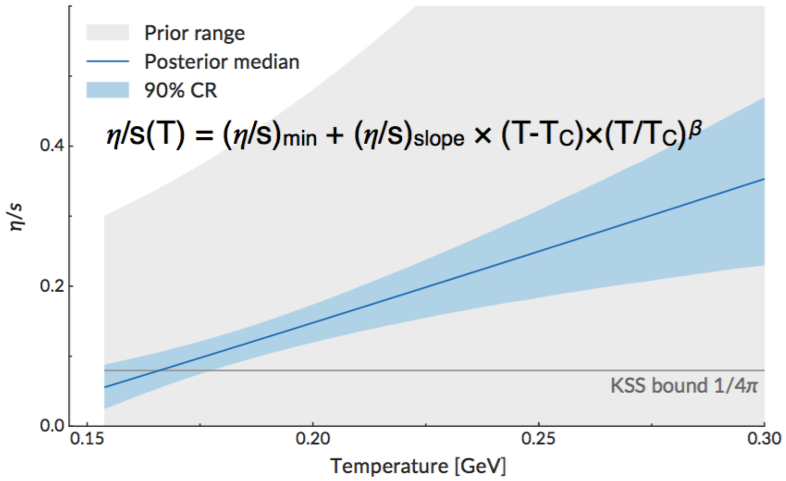
Example of results I: Review: S. Bass, QM2017,

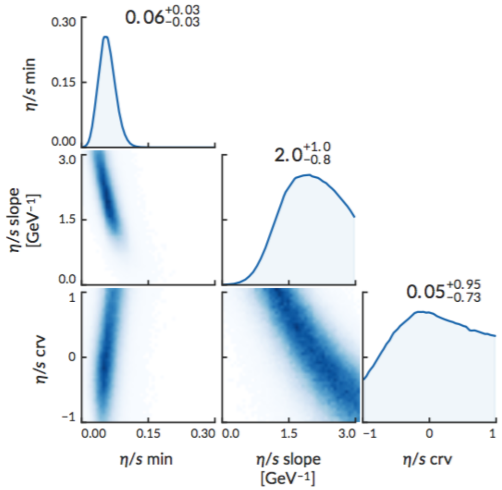
Temperature Dependence of Shear & Bulk Viscosities

temperature dependent shear viscosity:

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

▸ **RHIC data may disambiguate further**



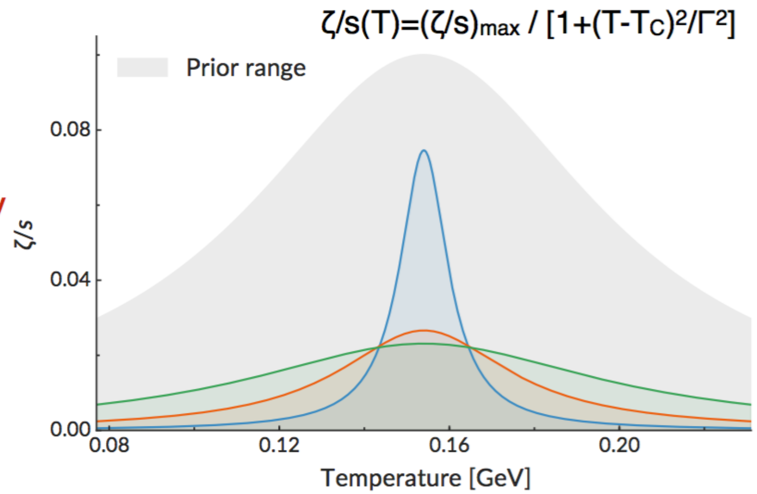


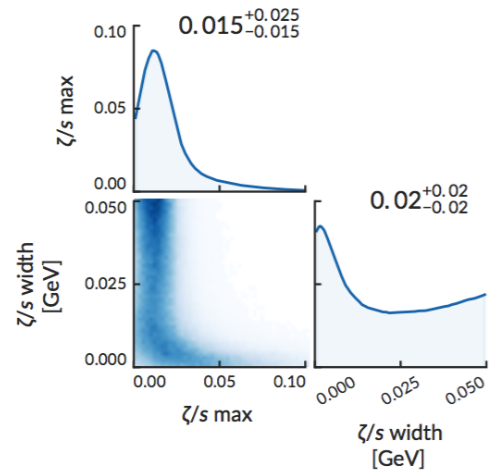
temperature dependent bulk viscosity:

- 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

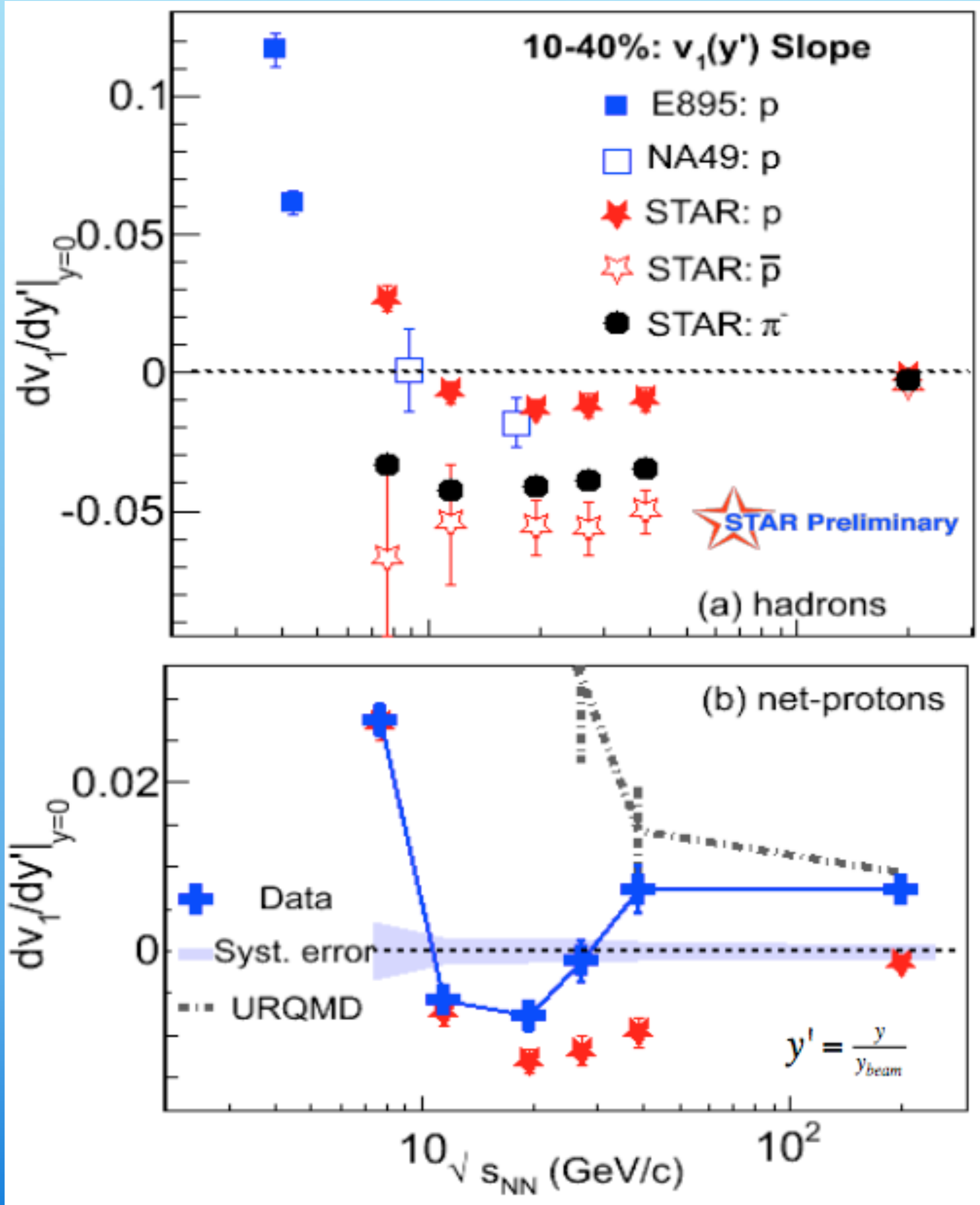
Review: S. Bass, QM2017,

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

6. Beam energy scan

Directed flow of protons



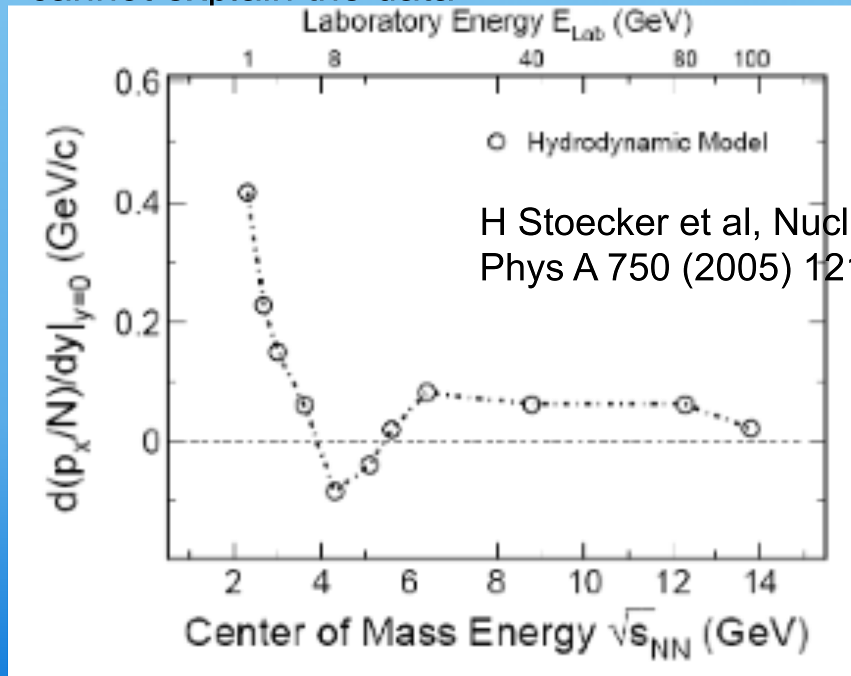
* Directed flow slope is sensitive to a 1st order transition

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

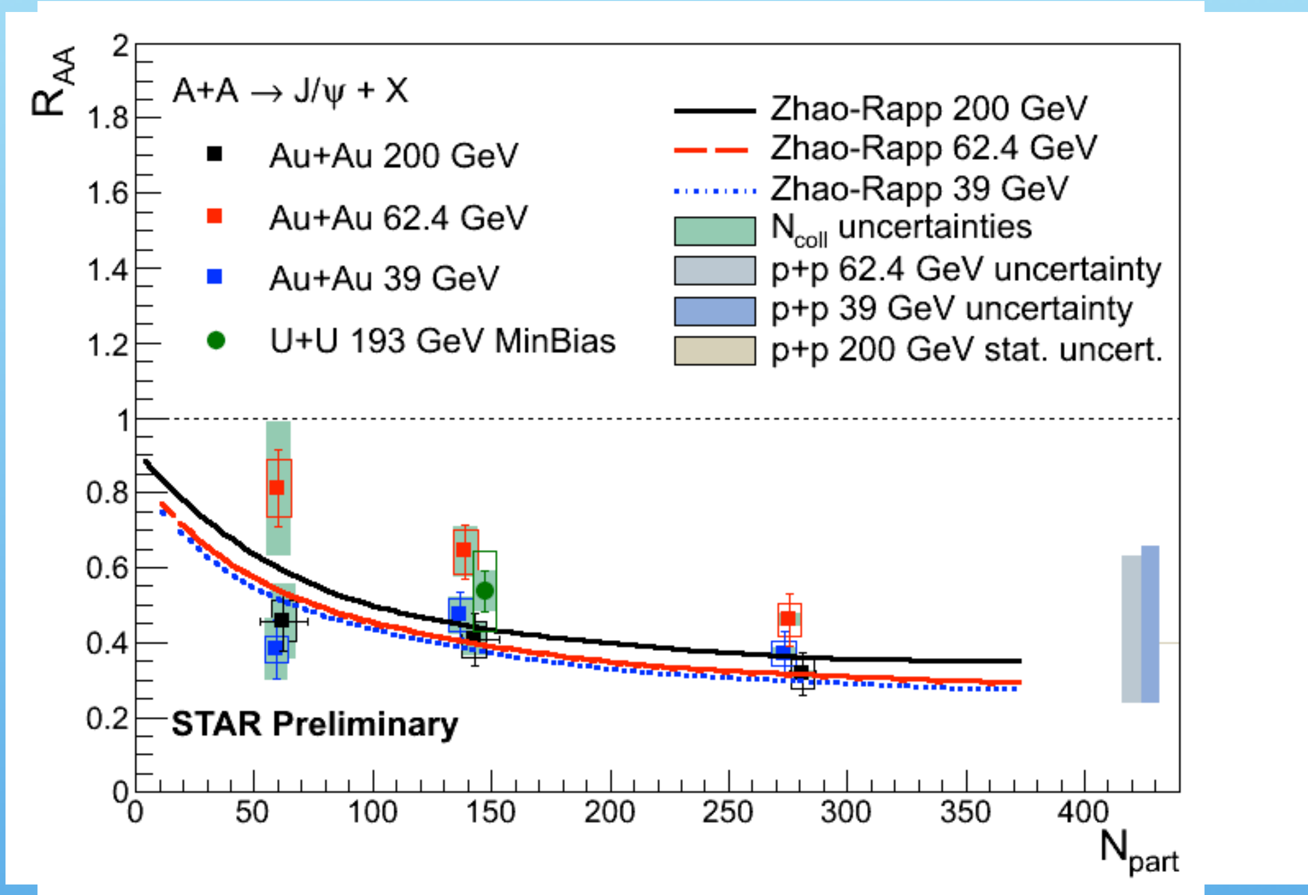
Pions and antiprotons have always negative v1 slopes.

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

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



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

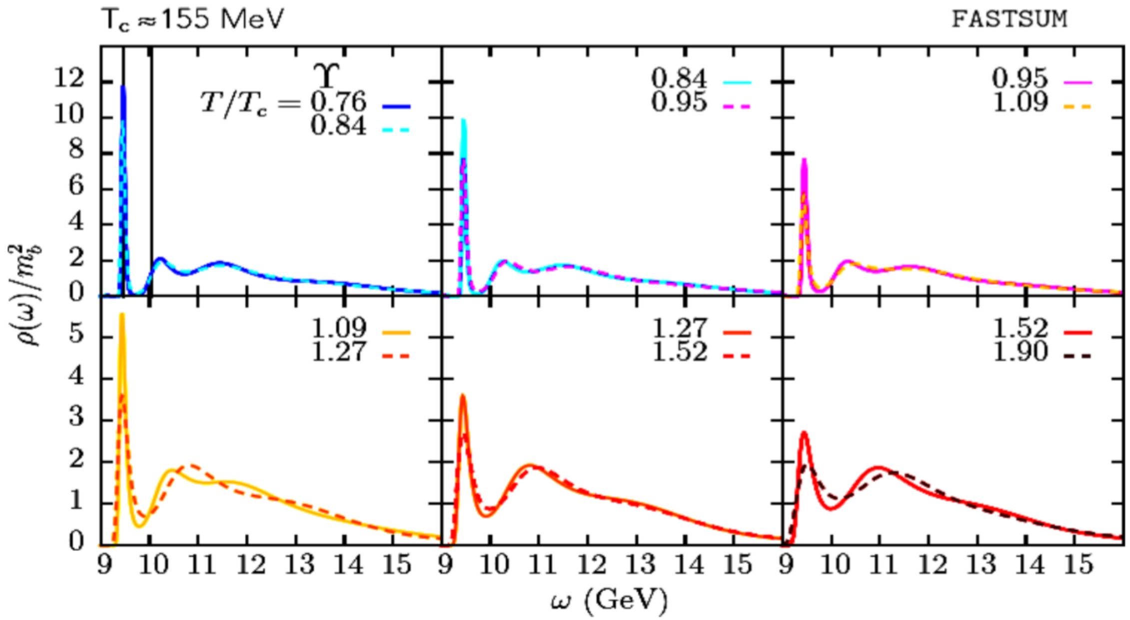
FCC quarkonia

- p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV

D. d Enterria, QM2017

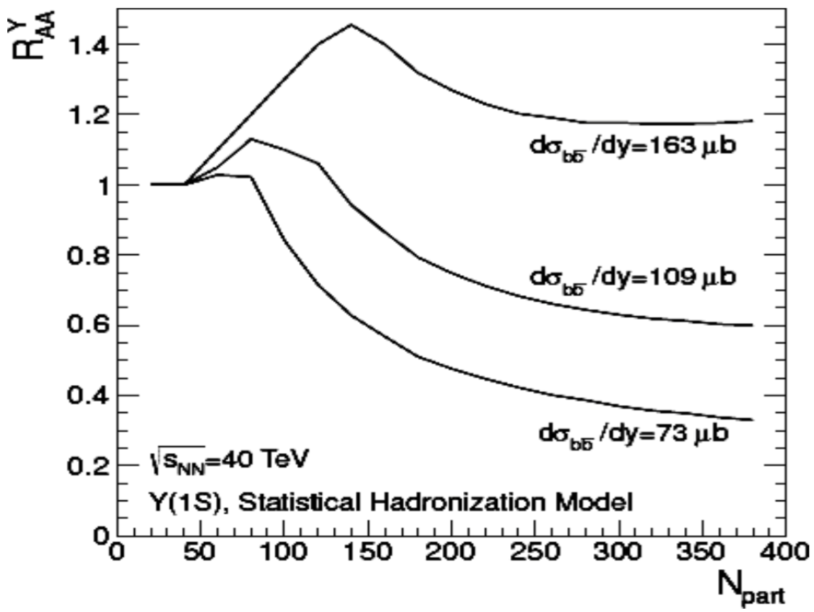
- FCC-AA (T_0~1GeV) can probe Y(1S) "melting" expected by latt-QCD at T=4–5 T_c

[G. Aarts et al, JHEP 07 (2014) 097]



- Density of bbbar pairs large enough for Y(1S) recombination?

[A.Andronic, et al., JPG38 (2011) 124081]

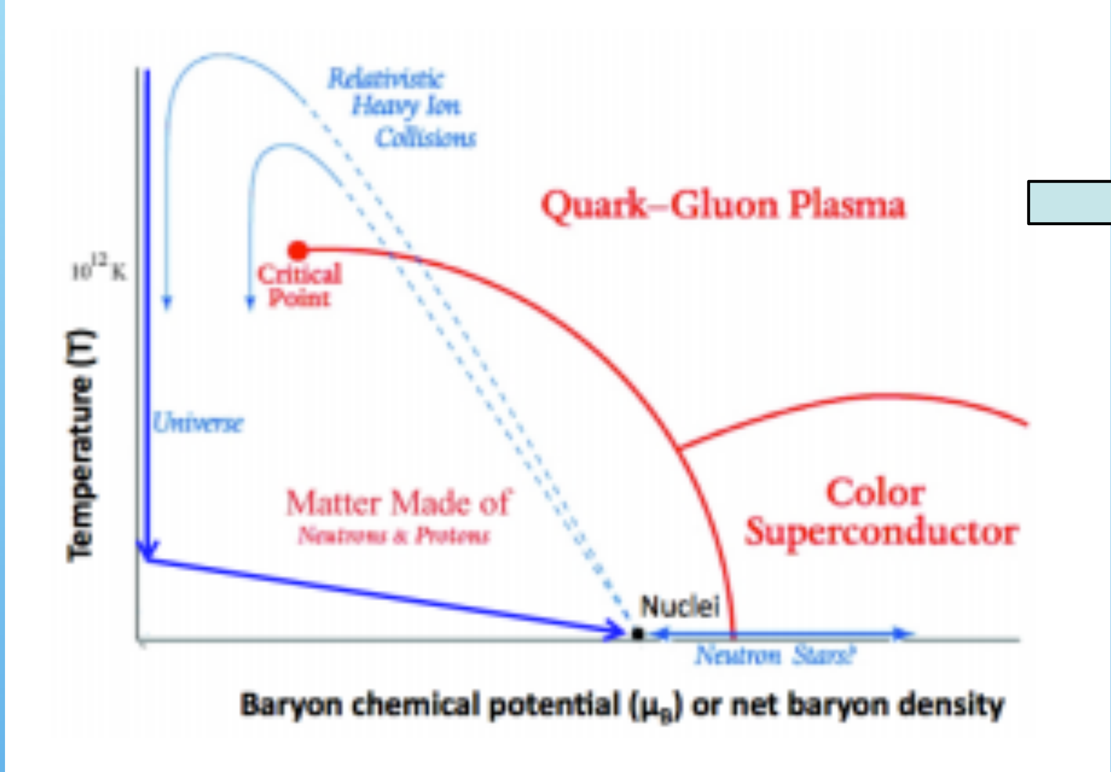


FiXed Target program energies

Collider Energy	Fixed-Target Energy	Single beam A GeV	Center-of-mass Rapidity	μ_B (MeV)
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	*721*

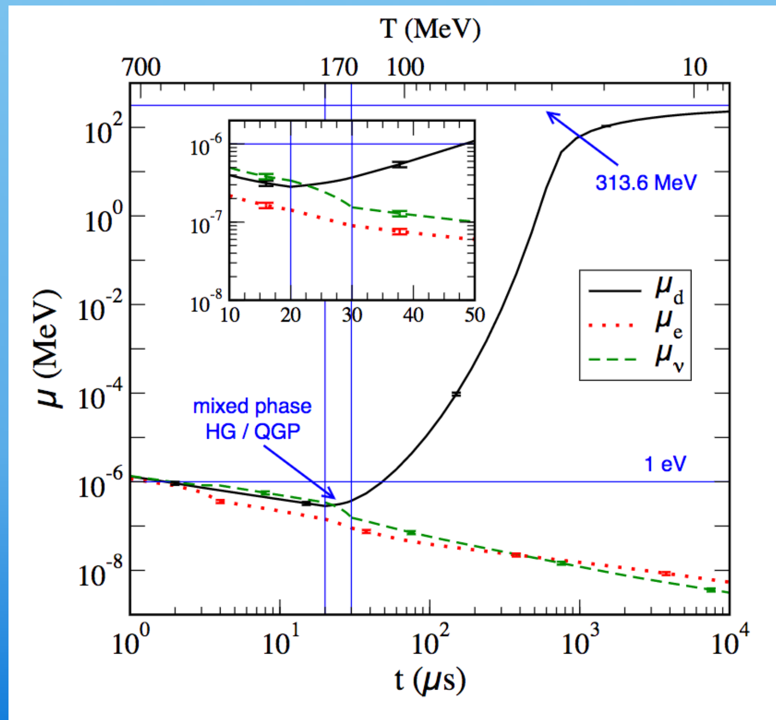
The QCD Phase Diagram and the Path of Early Universe through this diagram

Plot from review by Ph. Rosnet,1510.04200



First calculation and plot of the Path of Early Universe in (T, mu-B) plane was done by Uli Heinz and later from
S.K., P. Minkowski, J Phys G 28 (2002) 2063-2067, hep-ph/0204103 (fig. 1).
S.K. P. Minkowski, Space Sci.Rev. 100 (2002) 175-192

Later calculation: M Fromerth, J. Rafelski, astro-ph/0211346



NA57, PbPb sqrt(s)=17 GeV

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

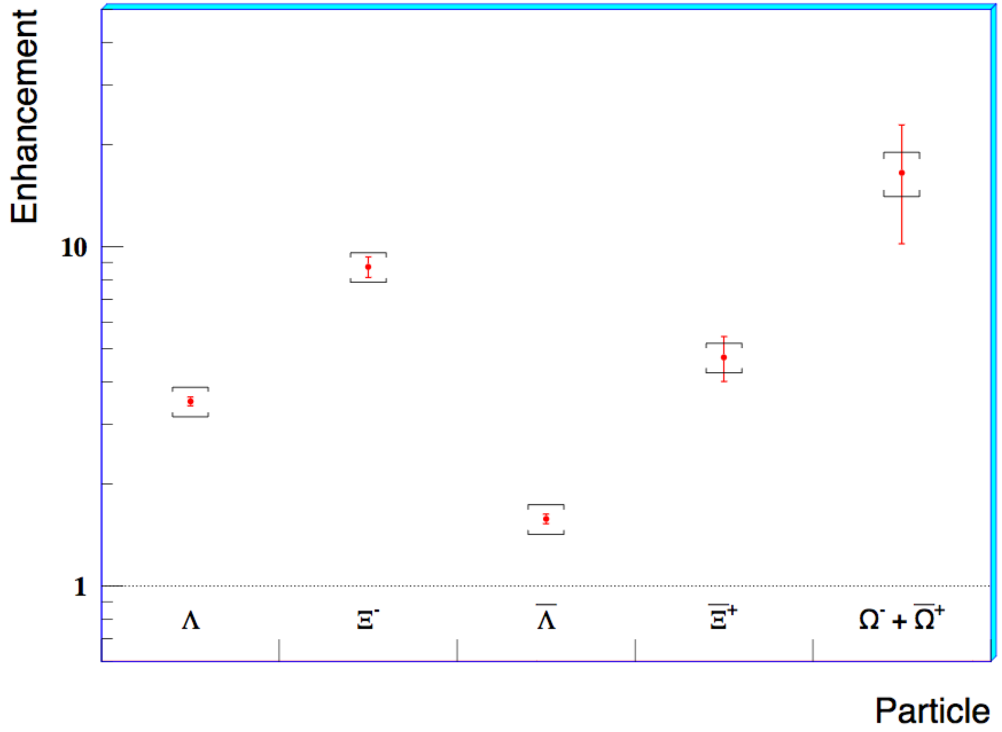


Figure 7. Hyperon enhancement versus strangeness content for 53% most central Pb–Pb events. Errors on the pBe yields have been propagated. The symbol ⊔ shows the systematic error. Due to the limited statistics in the pBe sample the $\Omega^-$and $\overline{\Omega}^+$signals have been combined.

First measurement of strange (anti)baryons Xi, Omega by WA97

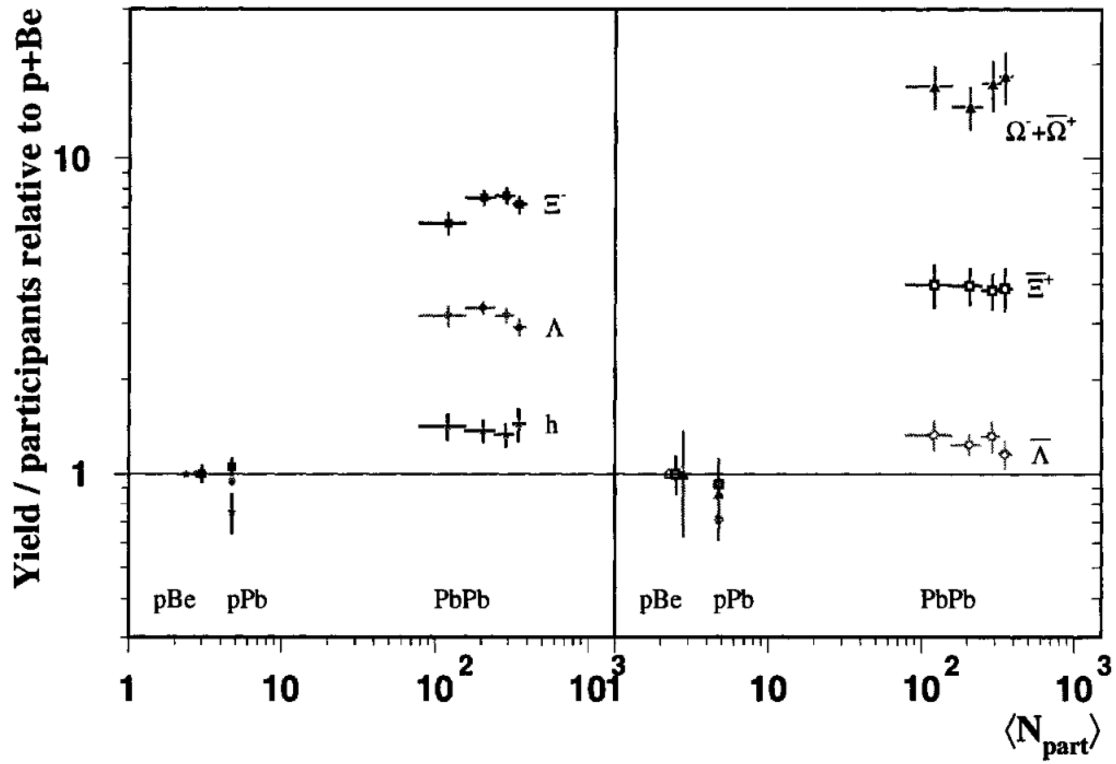


Figure 3. Yield per participant as a function of the number of participants for different particles.

Nuclear Physics A663&664 (2000) 717c-720c

Enhancement increases with strangeness content