Review of the Physics of QGP

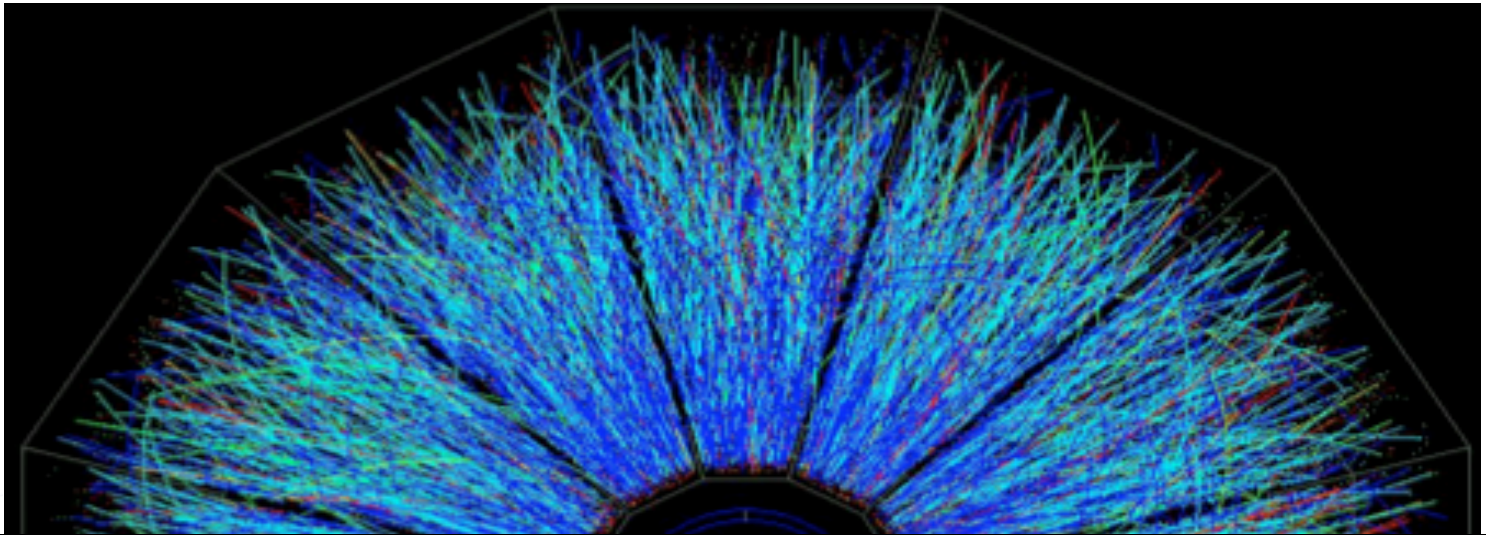
Sonia Kabana

Laboratoire de Physique Subatomique et des technologies associees (SUBATECH)
and University of Nantes, France

XXIX-th International Workshop on High Energy Physics

New Results and Actual Problems in Particle and Astroparticle Physics and Cosmology

26-28 June 2013, Protvino, Russia



Outline

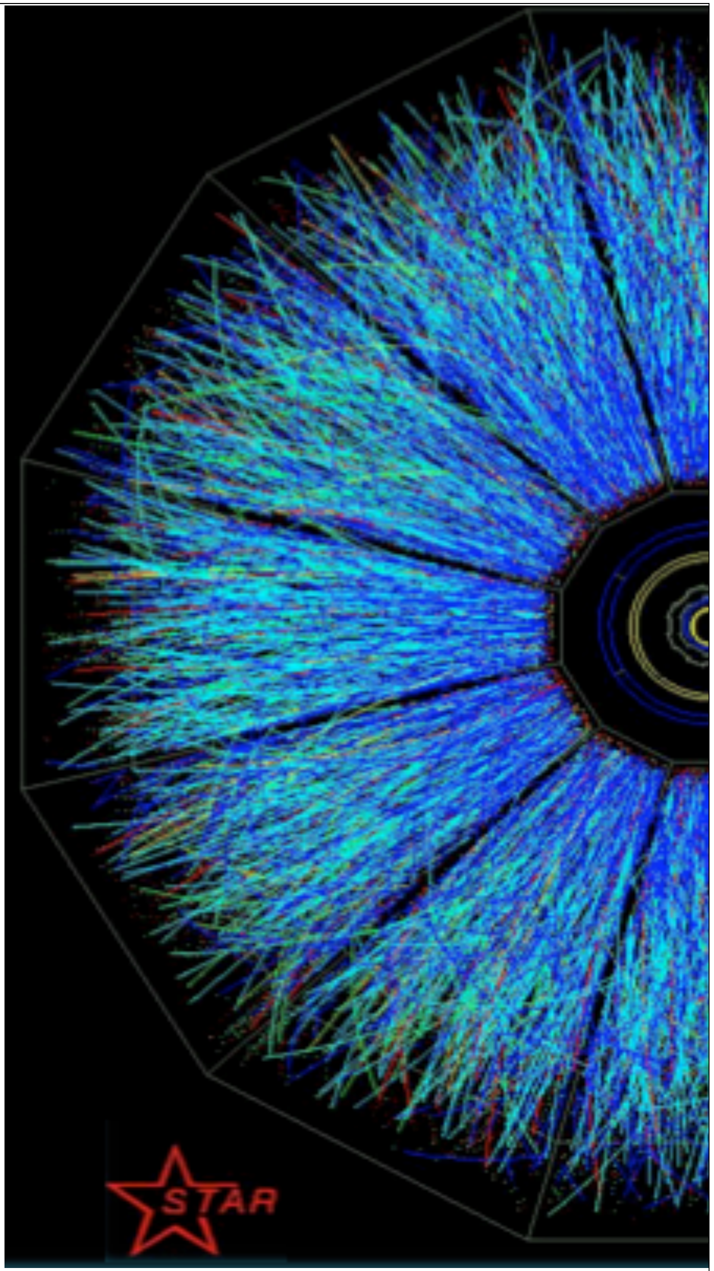
I Introduction

- Quark Gluon Plasma- Set the questions to answer

II Selected physics results :

1. Direct thermal photons
2. Flow, strangeness
3. Jet quenching
4. Quarkonia
5. New p+A data at the LHC

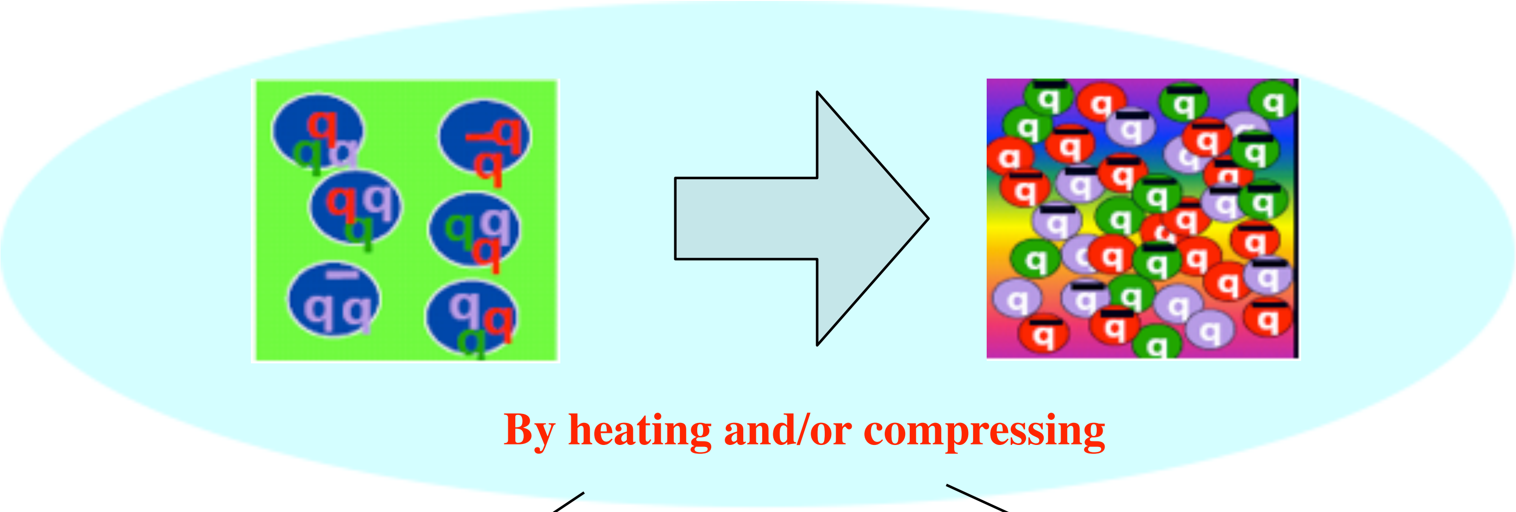
III Conclusions and Outlook



I Introduction

Quark Gluon Plasma

Quark Gluon Plasma is a state of matter in which quarks and gluons are no longer confined to color-neutral entities of hadronic size. (Term QGP : coined by Edward Shuryak)



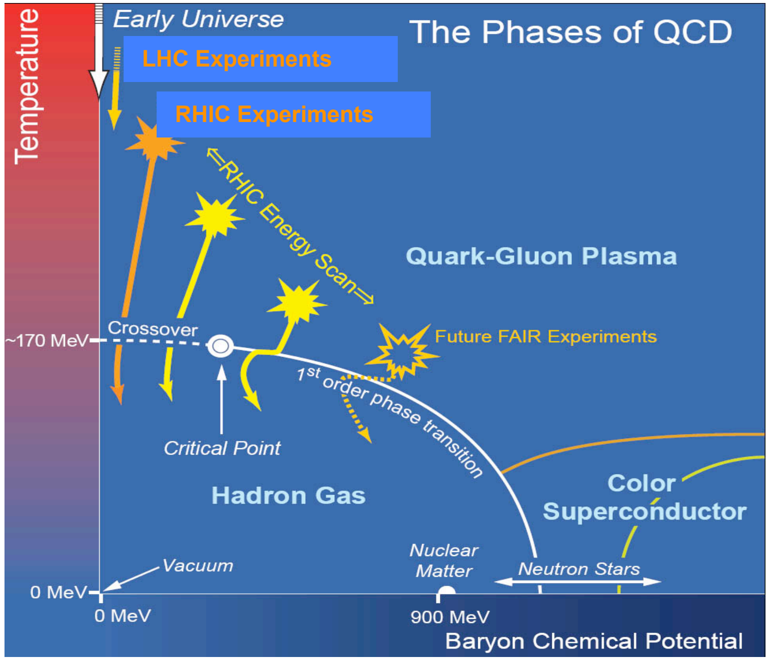
By heating and/or compressing

High Energy Heavy ion collisions ?

Interior of neutron stars - Quark stars ?

-> experimental program aiming to create matter at extreme conditions of high density and temperature colliding heavy ions

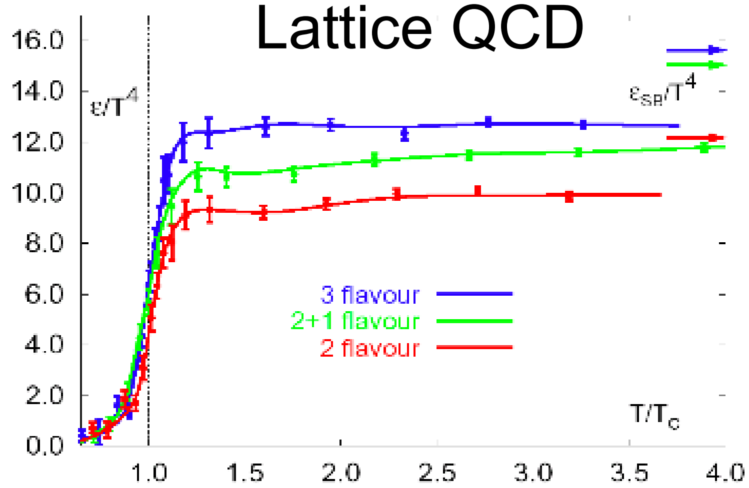
Physics goal: Mapping out the phases of QCD



Experimental program of Heavy Ion Collisions of last ~25 years aims to :

Study QCD matter under extreme conditions of densities and Temperatures

Reproduce a phase transition of the early universe at 10^{-6} sec after the Big Bang, between hadrons and quarks and gluons (Quark-Gluon-Plasma)



QCD on the lattice predicts a cross over at zero net baryon density and T(characteristic) of 154 +-9 MeV (HotQCD, 1111.1710) and 147-157 MeV (Budapest-Wuppertal).

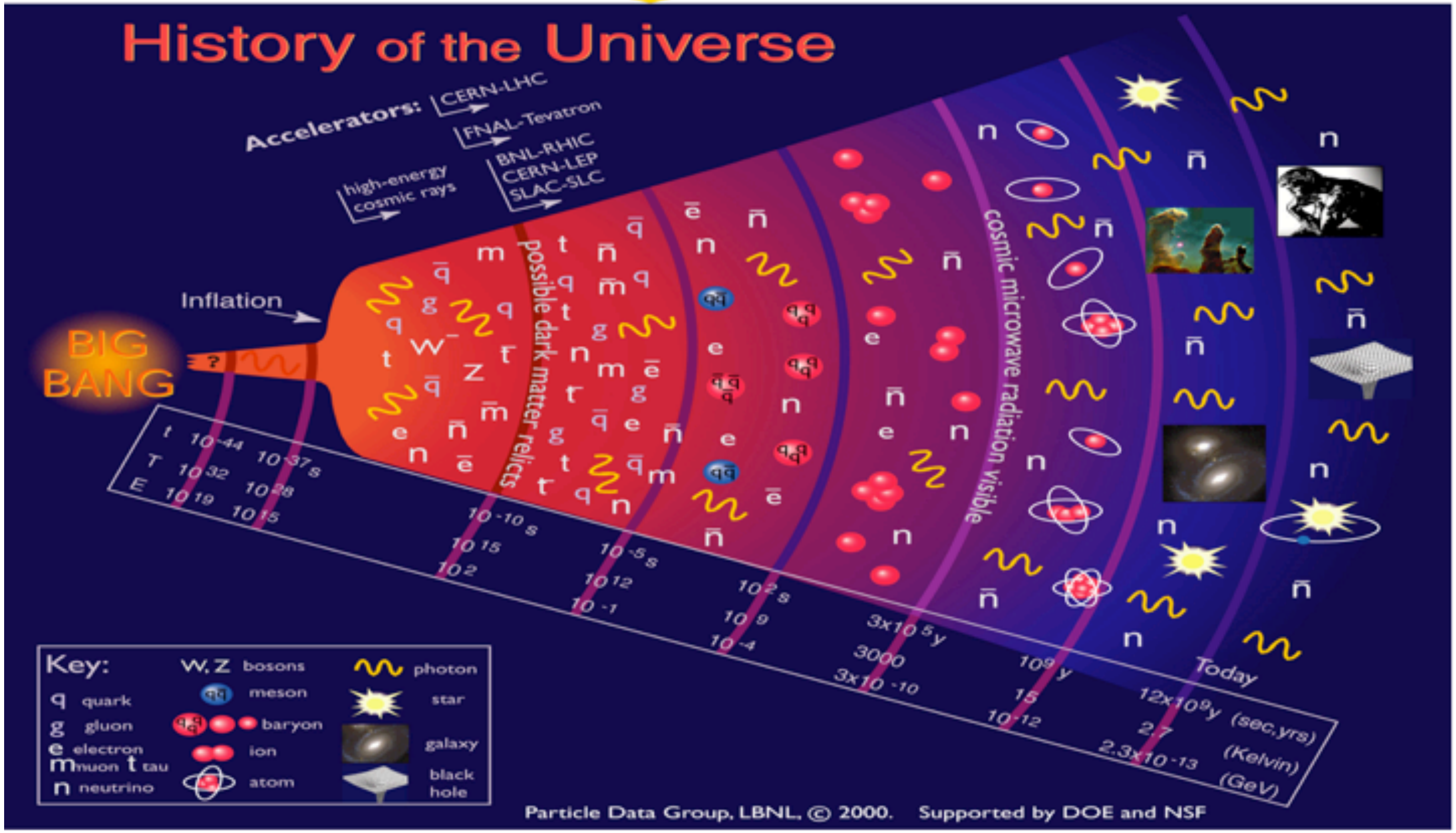
Other predictions: Tc~200 MeV (P.Minkowski, Czech. J. Phys. B40 (1990) 1003.

Historical note: Hagedorn predicted a limiting T(lim)~175 MeV

An energy scan from below potential Tc (SPS, RHIC BES, future accelerators) up to well above Tc (LHC) can reveal the nature of the phase diagram of QCD

QGP phase transition in the early univers

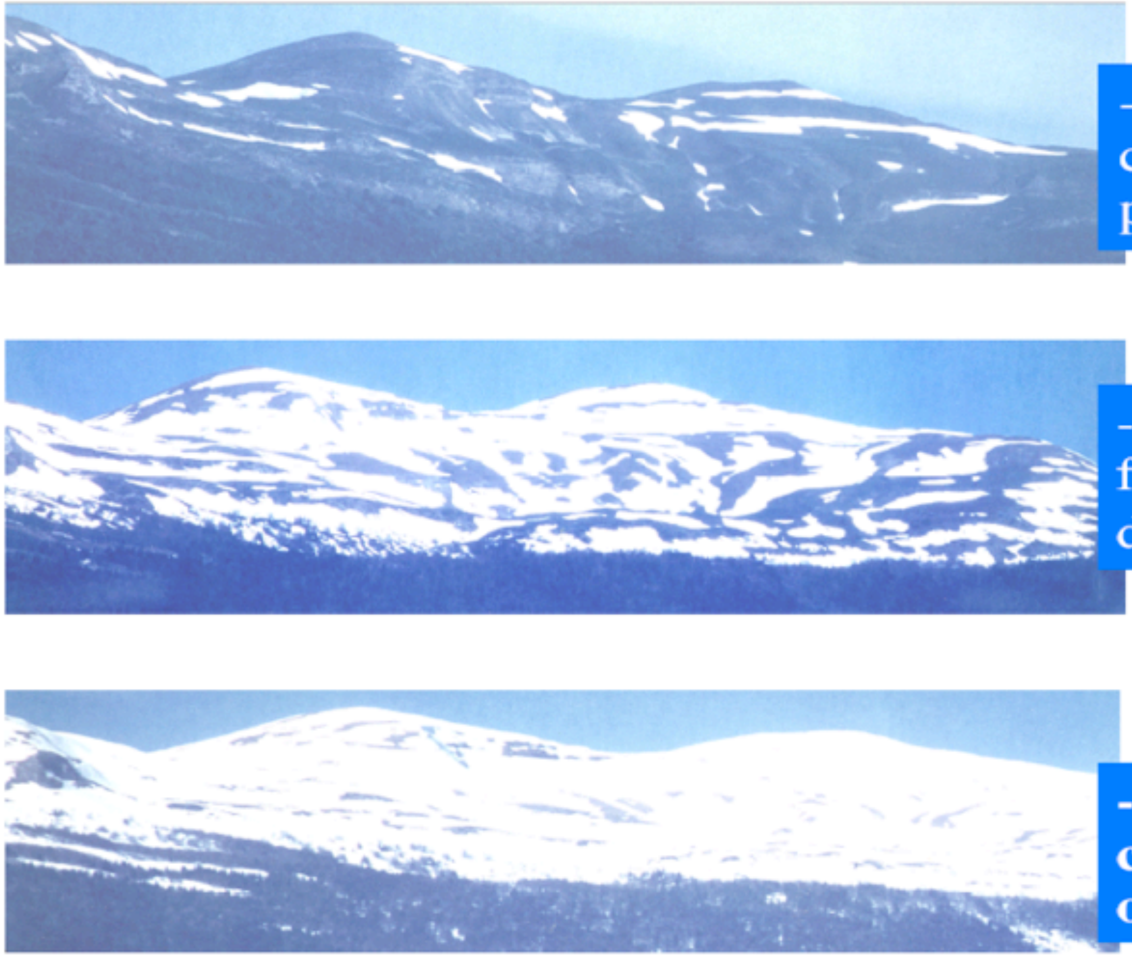
10-6 sec after Big Bang



Only phase transition of early universe accessible to experiments

(or cross over, according to Lattice QCD)

QGP seen from Jura



- A skier (quark?) is confined inside snow patches (hadrons?)

Temperature

- the skier can move further…a new phase develops

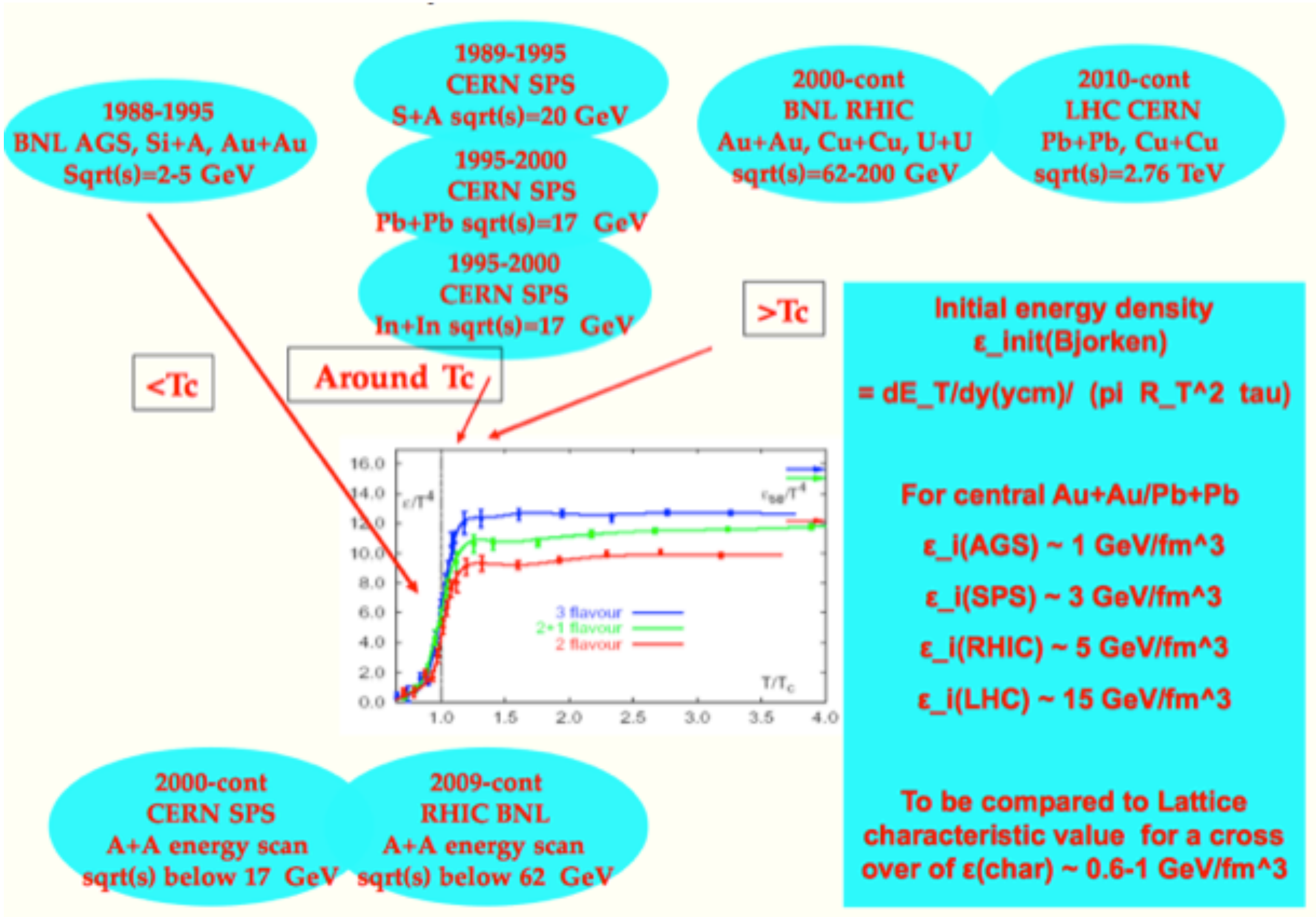
..goes up

- a skier (quark?) can move freely over long distances…

..this way

L. Maiani, CERN 2000

Experiments



1988-1995
BNL AGS, Si+A, Au+Au
Sqrt(s)=2-5 GeV

1989-1995
CERN SPS
S+A sqrt(s)=20 GeV

1995-2000
CERN SPS
Pb+Pb sqrt(s)=17 GeV

1995-2000
CERN SPS
In+In sqrt(s)=17 GeV

2000-cont
BNL RHIC
Au+Au, Cu+Cu, U+U
sqrt(s)=62-200 GeV

2010-cont
LHC CERN
Pb+Pb, Cu+Cu
sqrt(s)=2.76 TeV

<Tc

Around Tc

>Tc

Initial energy density
ε_init(Bjorken)

= dE_T/dy(ycm)/ (pi R_T^2 tau)

For central Au+Au/Pb+Pb

ε_i(AGS) ~ 1 GeV/fm^3

ε_i(SPS) ~ 3 GeV/fm^3

ε_i(RHIC) ~ 5 GeV/fm^3

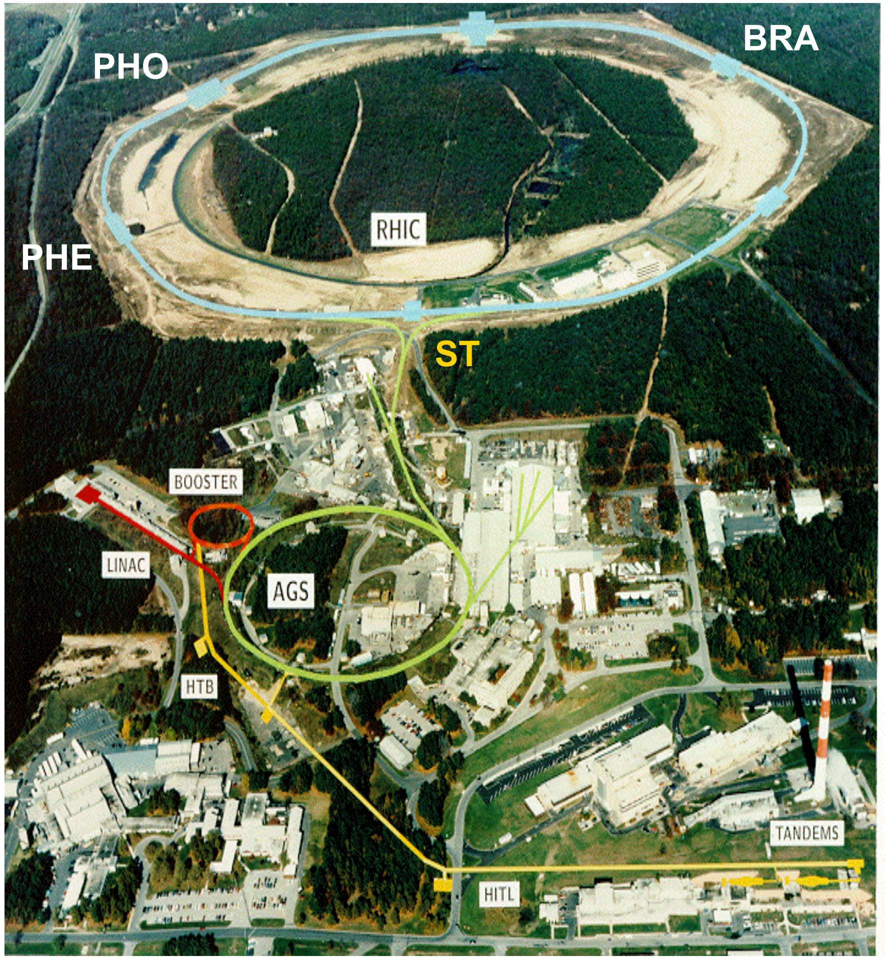
ε_i(LHC) ~ 15 GeV/fm^3

To be compared to Lattice characteristic value for a cross over of ε(char) ~ 0.6-1 GeV/fm^3

2000-cont
CERN SPS
A+A energy scan
sqrt(s) below 17 GeV

2009-cont
RHIC BNL
A+A energy scan
sqrt(s) below 62 GeV

BNL, Long Island, New York



CERN, Geneva

Signatures of the Quark Gluon Plasma

A. “Internal” Signatures originating “from the QGP itself” :

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

B. “External” Signatures of high pT probes altered by the QGP:

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

Historical Milestones of the search for the QCD phase transition

1988-89 AGS BNL and SPS CERN:

Discovery that strangeness is enhanced over pions in Si+Au and Au+Au collisions at sqrt(s)(NN)=1-5 GeV

K/π, Λ/π enhancement in A+A over p+A

2000 CERN press release:

Discovery of a new state of matter in A+A collisions at sqrt(s)(NN)=17, 19 GeV

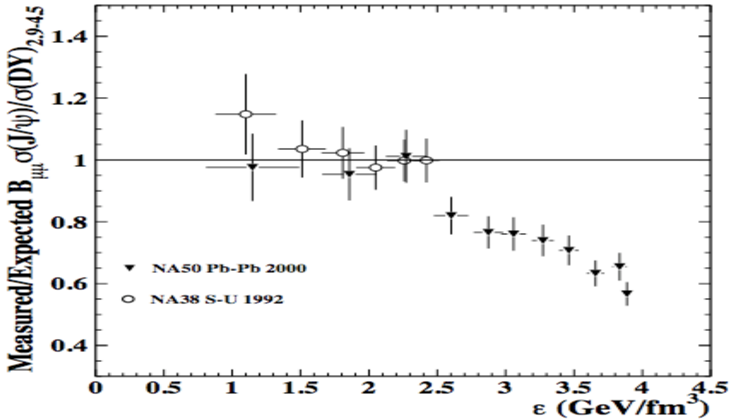
chi_c, Ψ', **J/Ψ suppression,**

T(direct γ)~200-300 MeV (model fit),

Strangeness enhancement including Omegas, Xis,

T(chem. fr. out)~170 MeV is located near Tc

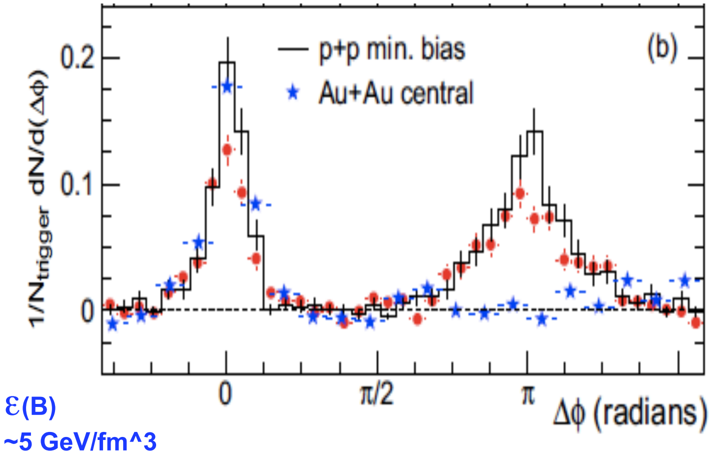
Discovery of J/Psi suppression
NA50 Coll. CERN SPS, 2000



ε(B)= ε(Bjorken)
~3.5 GeV/fm^3

Discovery of jet quenching, RHIC 2003

STAR



2003 BNL press release:

Discovery of jet quenching in Au+Au at √s(NN) = 200 GeV, large elliptic flow

Discovery of a strongly interacting QGP (sQGP)

sQGP found consistent with a perfect liquid

Applications of Anti de Sitter/Conformal Field Theory duality on sQGP

Marks a new era in QCD studies

ε(B)
~5 GeV/fm^3

Historical Milestones of the search for the QCD phase transition

Which are the critical parameters of the phase transition ?:

Several observables where suggestive of an onset of the QCD phase transition at energy lower than top SPS (19 GeV) energy, possibly with ε_c(Bjorken)~1 GeV/fm^3, motivating a low energy scan.

Low energy scan SPS (1999-), RHIC (2009-):

Study onset of transition, search for a possible critical point (as yet inconclusive and ongoing) and map out the QCD phase diagram.

2010: first PbPb collisions at the LHC !

Jet quenching, Quarkonia suppression

ε(B) ~16 GeV/fm^3

2010/11: RHIC upgrades accomplished

lead to largest data sample ever taken at RHIC (a billion Au+Au events) with highly enhanced identification capabilities due to new detectors

-> since 2009 like a "new RHIC collider and experiments"

2011: Y suppression discovered at RHIC and LHC
2012 : Sequential quarkonia suppression at the LHC
2013: First p+Pb run at LHC

Set the Questions :

Is there a dense hot matter of quarks and gluons build and which are its characteristics?

Is local thermalization achieved ?

Is there a phase transition or is it a cross over ?

If phase transition, which is the order ?

Which are the critical parameters ? (Critical temperature, density)

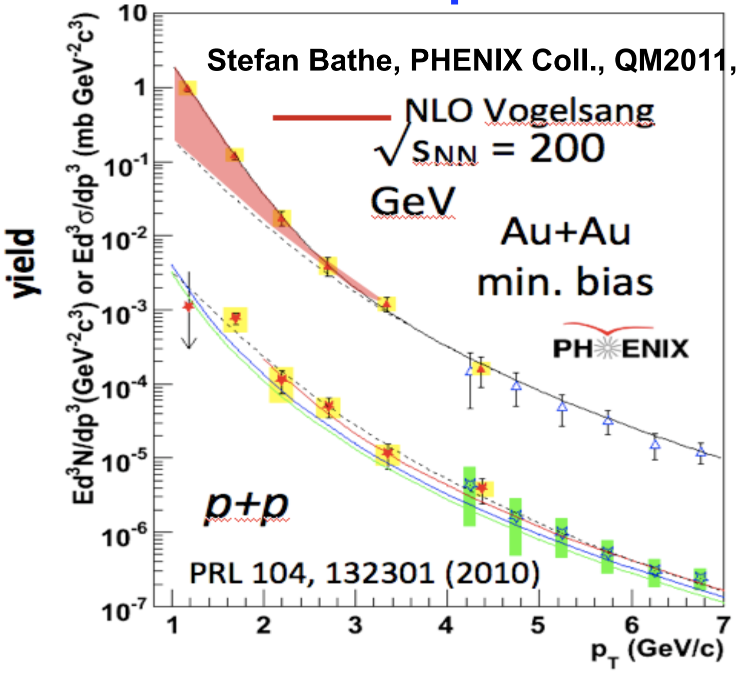
Is this state weakly or strongly interacting ?

Is there a critical point ?

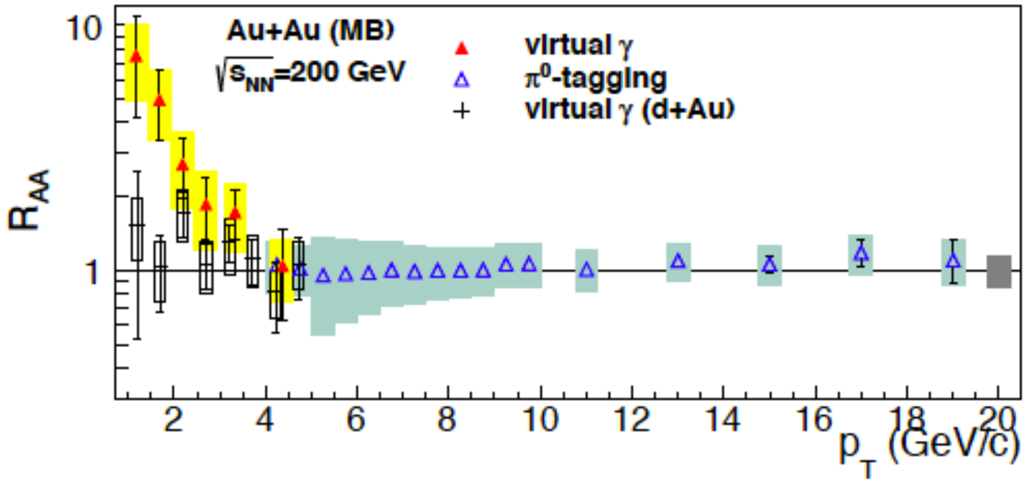
II Selected physics results:

1. Direct thermal photons

Direct photon excess in min bias Au+Au at 200 GeV


Stefan Bathe, PHENIX Coll., QM2011, arXiv

PHENIX arXiv 1208.1234
PHENIX PRL104, 132301, 2010



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 over p+p - Thermalization seems to be achieved

Direct thermal photons firmly established for the first time !

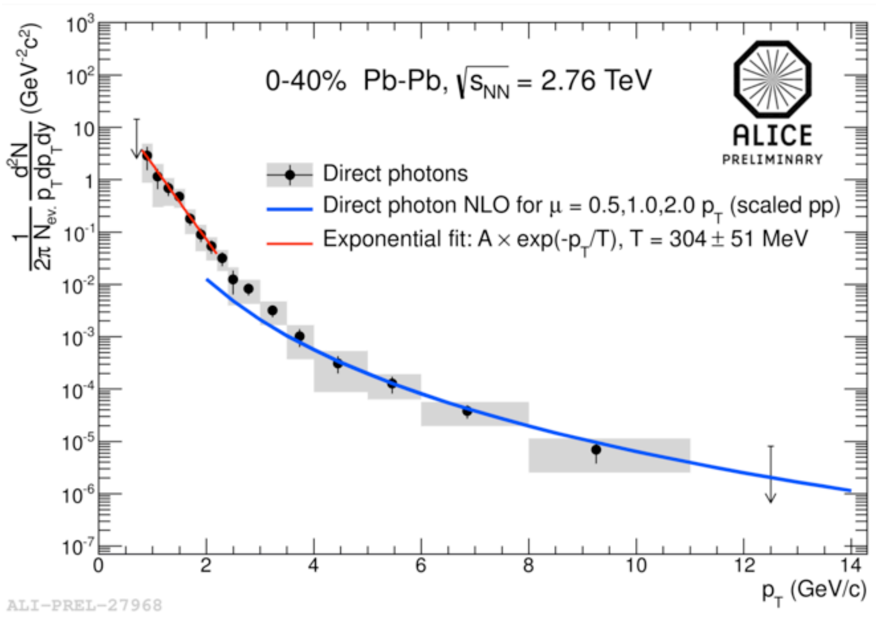
BNL press release, 15 Feb 2010 : 'Perfect' Liquid Hot Enough to be Quark Soup

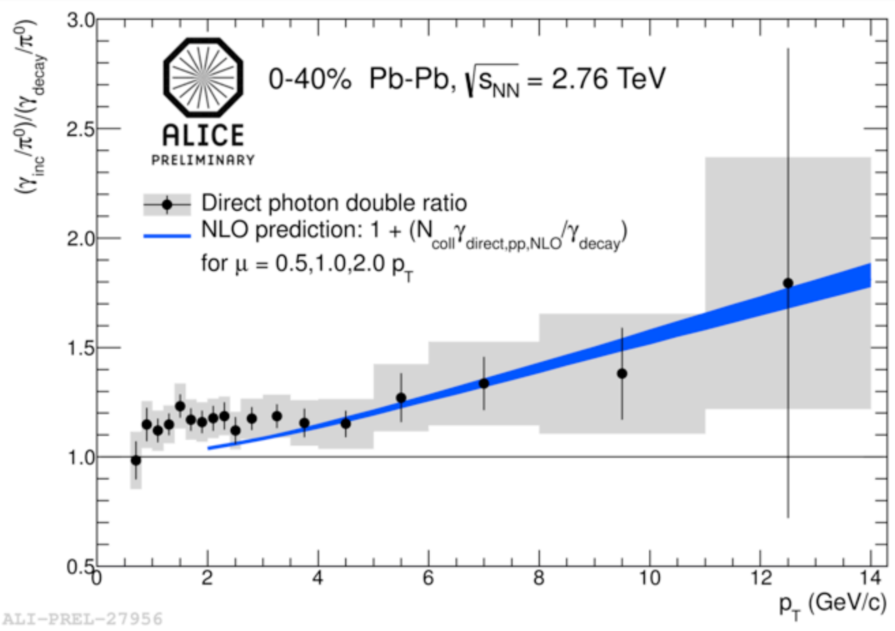
..collisions of gold ions ...have created matter at a temperature of about 4 trillion degrees Celsius ... about 250,000 times hotter than the center of the Sun. **This temperature is higher than the temperature needed to melt protons and neutrons into a plasma of quarks and gluons.**

T from direct photons at the LHC

RHIC result backed by LHC

K. Safarik, ALICE, QM2012





* Exponential fit for *p*T < 2.2 GeV/*c*
inv. slope *T* = 304±51 MeV
for 0–40% Pb–Pb at √*s* 2.76 TeV

* PHENIX: *T* = 221±19±19 MeV
for 0–20% Au–Au at √*s* 200 GeV

* *p*T < 2 GeV/*c*
~20% excess of direct photons

* *p*T > 4 GeV/*c*
agreement with *N*coll-scaled NLO

T(init) SPS, RHIC, LHC

* SPS: (not firmly established)
-> T(dir γ)~200-300 MeV (model fit) at muB~200 MeV

* RHIC:
First clear measurement of T(RHIC)=221+-19+-19 MeV (measurement)
-> T(RHIC)~300-600 MeV (model fit) at muB~20 MeV

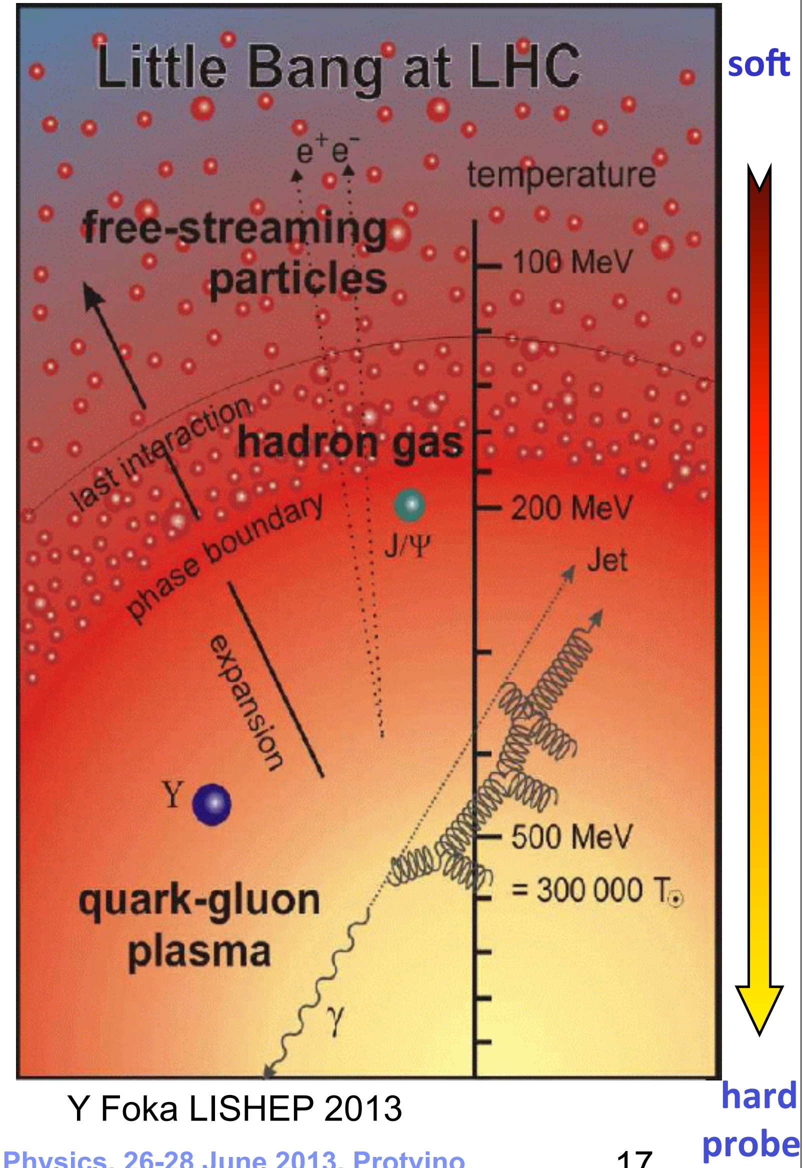
* LHC:
Highest measured temperature:
-> T(LHC)=304+-51 MeV (measurement) at muB~1 MeV

* SPS, RHIC, LHC: T(chem. freeze out)~170 MeV is similar to Tc

* Low pT photons exhibit thermal spectrum, suggesting thermalization of their source

* The initial T at SPS, RHIC, LHC is higher than Tc

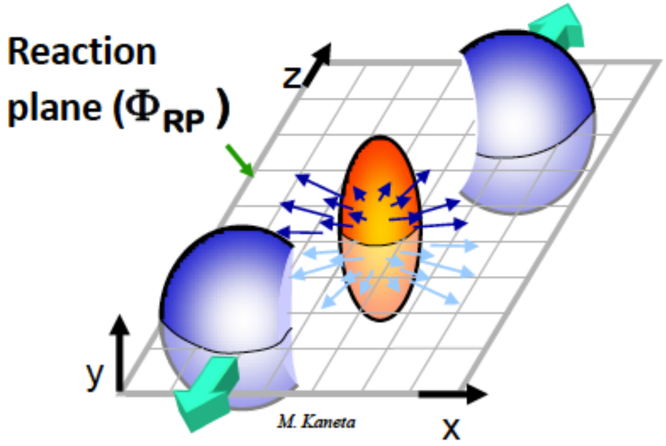
* The initial T rises with collision energy from SPS to RHIC to LHC

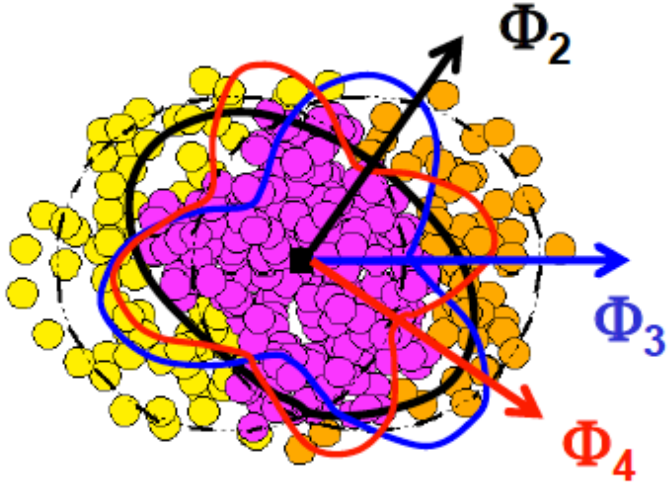


Y Foka LISHEP 2013

2. Flow, strangeness

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



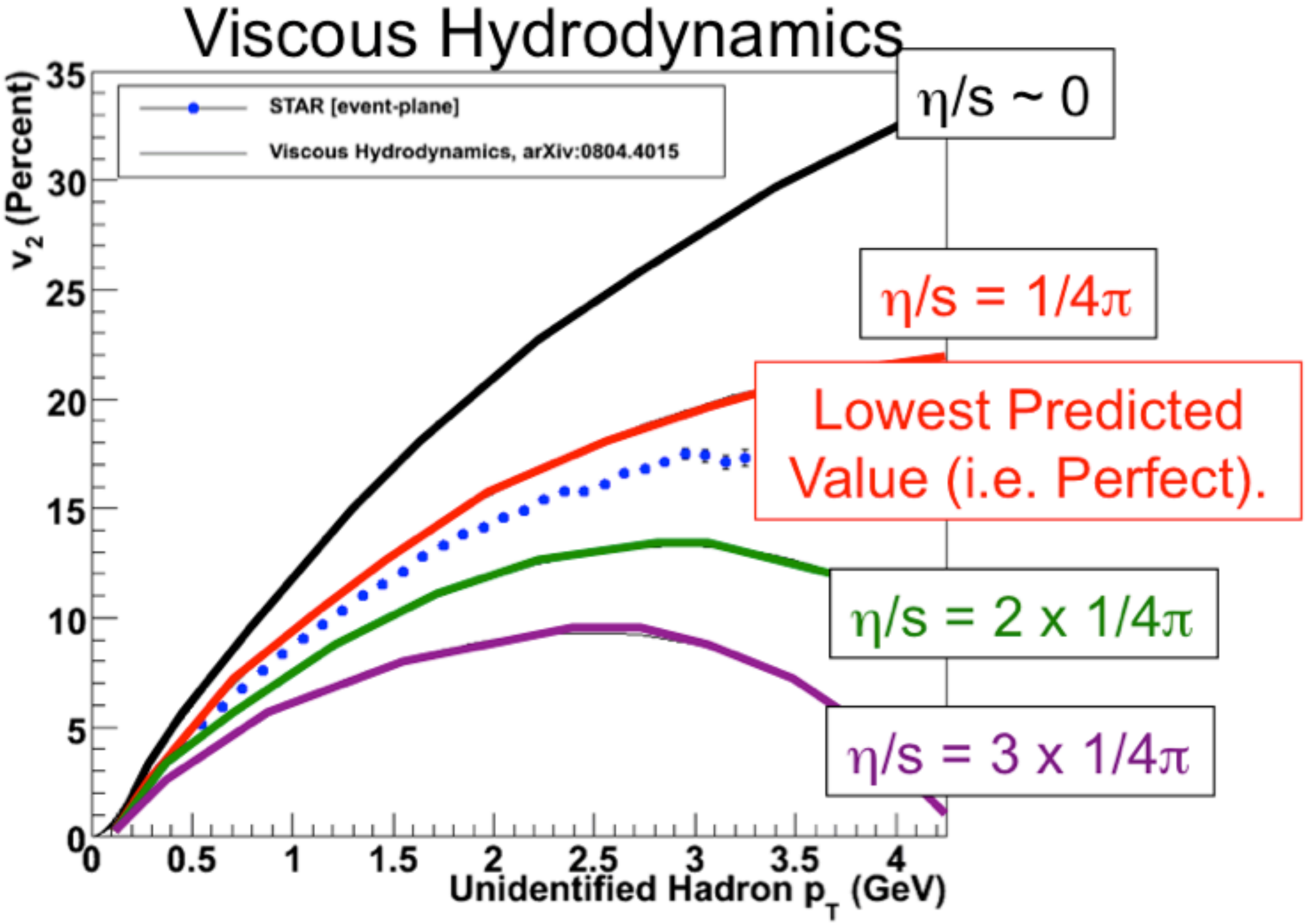


$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

$$v_n = < \cos[n(\phi - \Phi_n)] >$$

* Initial shape of the interaction region (v2 - elliptic flow)
* Initial spatial fluctuations of interacting nucleons (higher order vn)

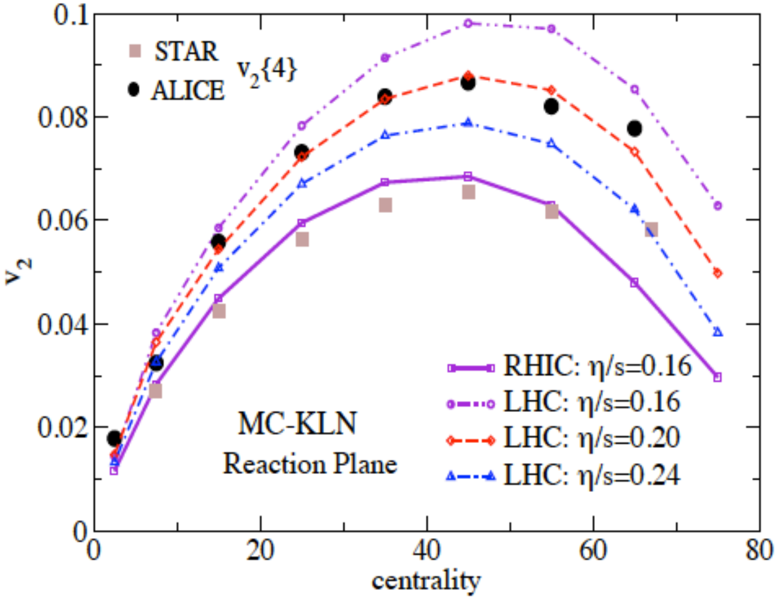
Extracting the Shear Viscosity of QGP



M. Luzum et al, PRC 78 034915 (2008)

Flow and shear viscosity

Shear viscosity estimates based on flow measurements
RHIC : the perfect liquid

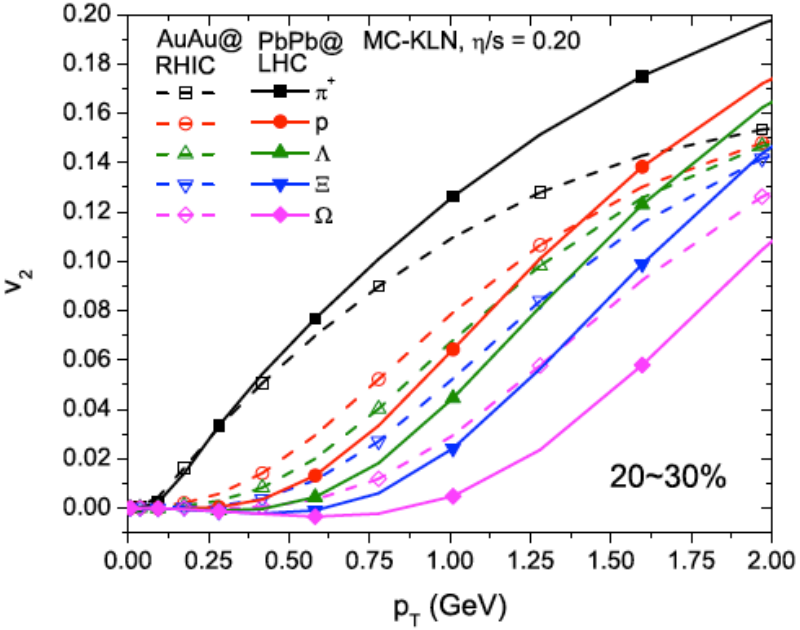


pT integrated v2 of charged hadrons, STAR sqrt(s)=200 GeV Au+Au and ALICE Pb+Pb 2.76 TeV ->

η/s (Au+Au 200 GeV RHIC) = 0.16
η/s (Pb+Pb 2.76 TeV LHC) = 0.20

U. Heinz, arXiv:1106.6350 and references therein

Lower limit from AdS/CFT: 1/4pi=0.0796



v2 of several identified hadrons, STAR sqrt(s)=200 GeV Au+Au and ALICE Pb+Pb 2.76 TeV

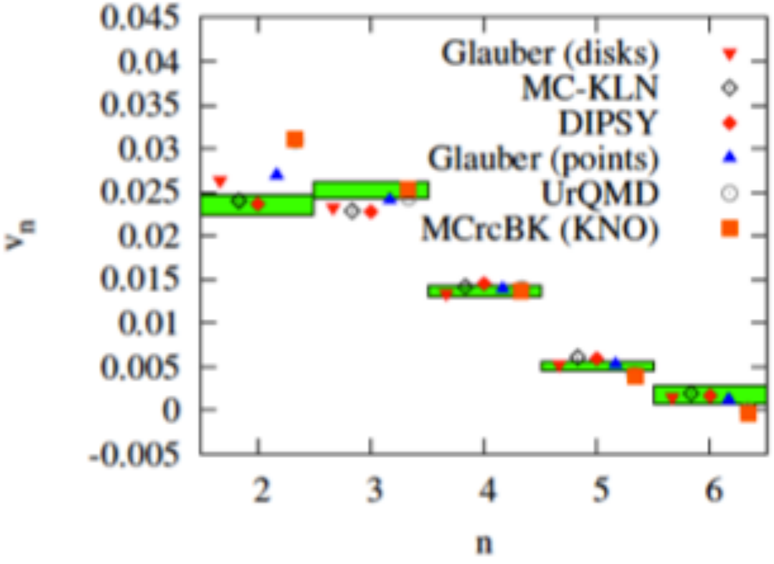
Model with η/s = 0.20 (for LHC)

VISHNU : hybrid code = Viscous Israel-Stewart Hydrodynamics in 2+1 dimensions and UrQMD

EXTRACTING η/s FROM v_n IN CENTRAL COLLISIONS

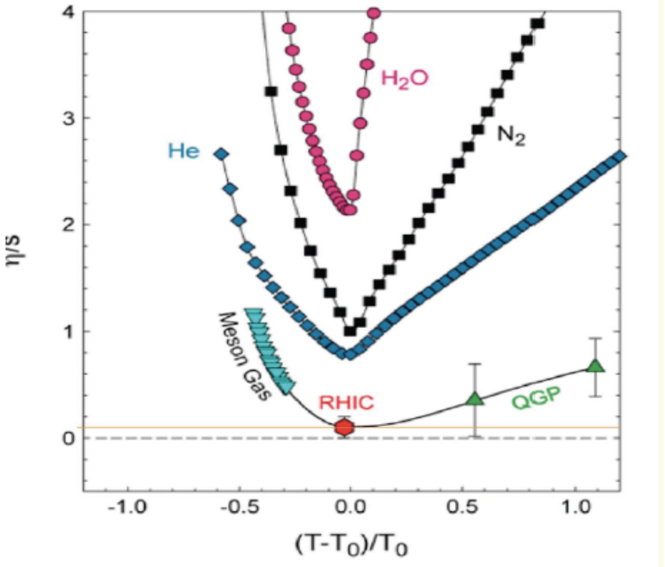
M. Luzum, QM2012

ATLAS, 0-1% central Pb+Pb, pT inegrated vn



Experimental uncertainties	±0.020
Initial eccentricity	±0.050
$v_n/\varepsilon_n =$ constant	$\sim$ ±0.010
Thermalization time	±0.030
Initialization of shear tensor	±0.005
Initial flow	±0.050
Equation of State	±0.015
Second-order transport coeff.	±0.005
Bulk Viscosity	$\sim$ ±0.010
Deviation from boost-invariance / longitudinal fluct.	$\sim$ ±0.005
Viscous correction to f.o. distribution	±0.015
Other aspects of freeze out	$\sim$ ±0.025

Y Foka LISHEP 2013



- A simultaneous fit of v_2–v_6 gives a preferred extracted η/s for each initial condition
- Range of results quantifies uncertainty

Result for LHC (preliminary) :

$$0.07 \leq \eta/s \leq 0.43$$

Connection to η/s ➔ RHIC values close to the lower theoretical bound of 1/4π (hbar=c=1)

Strangeness

Strangeness enhancement

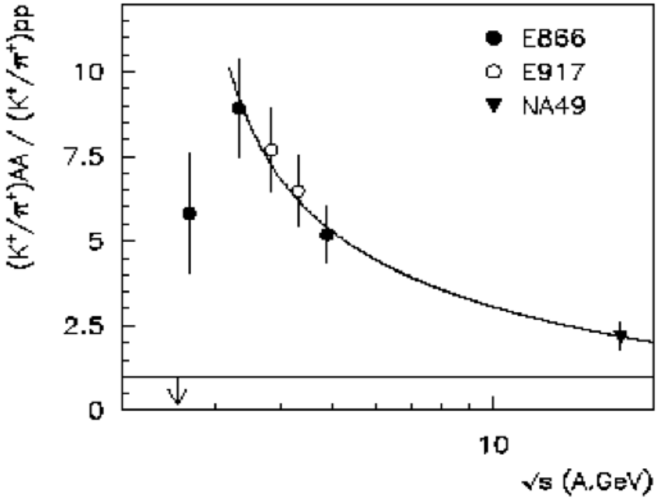
* **Strangeness enhancement was first discovered at the AGS at BNL, then at SPS at CERN**

* **Expect to measure strangeness enhancement with increasing energy, and jumbing up above Tc**

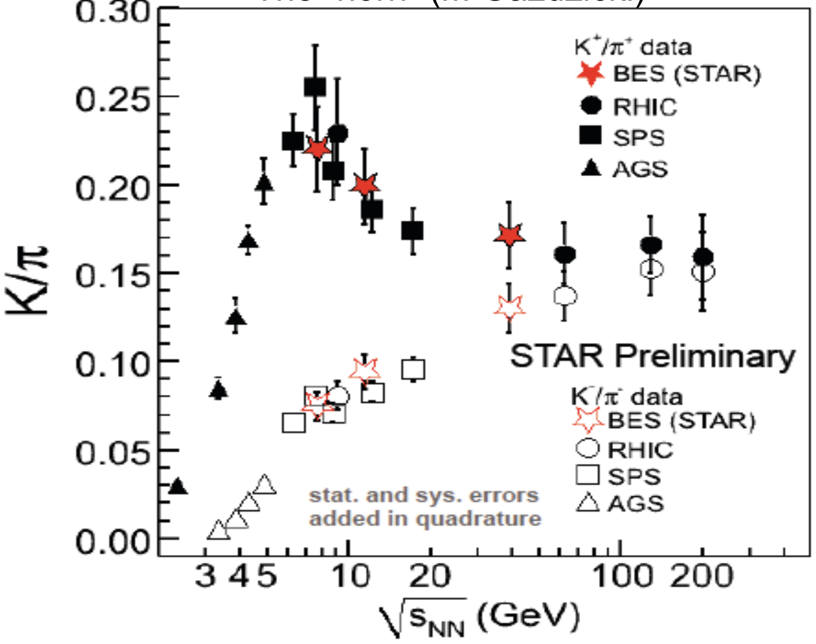
* **However, measurement showed strangeness enhancement increasing with decreasing energy from SPS to AGS (opposite to expectation)**

This was later established through further measurements in the SPS (NA49, NA61) energy scan, and the last few years with the RHIC low energy scan

However the maximum is not seen in the K-/pi- ratio.



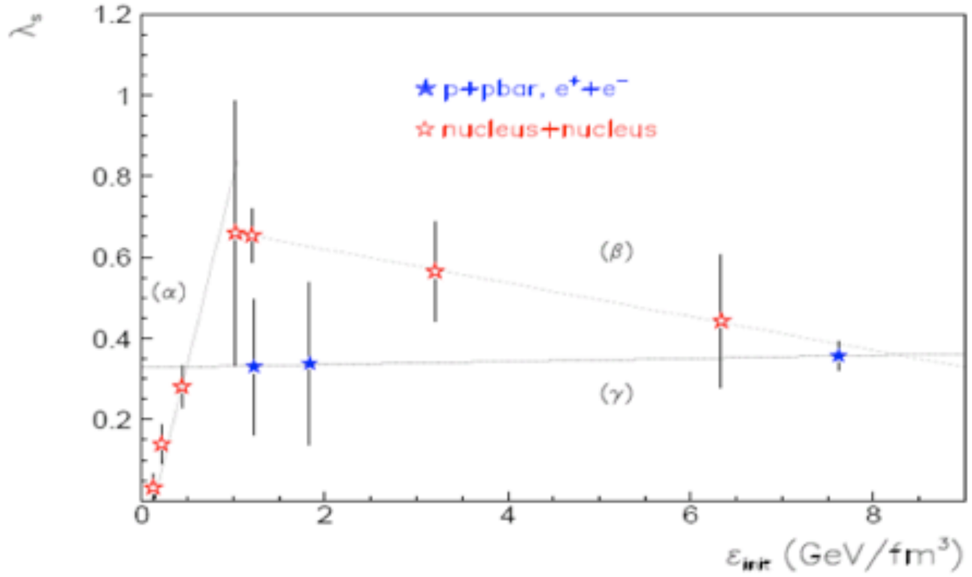
The “horn” (M Gazdzicki)



Strangeness suppression factor as a function of initial Bjorken energy density

S. Kabana, Eur. Phys. J C21 (2001) 545

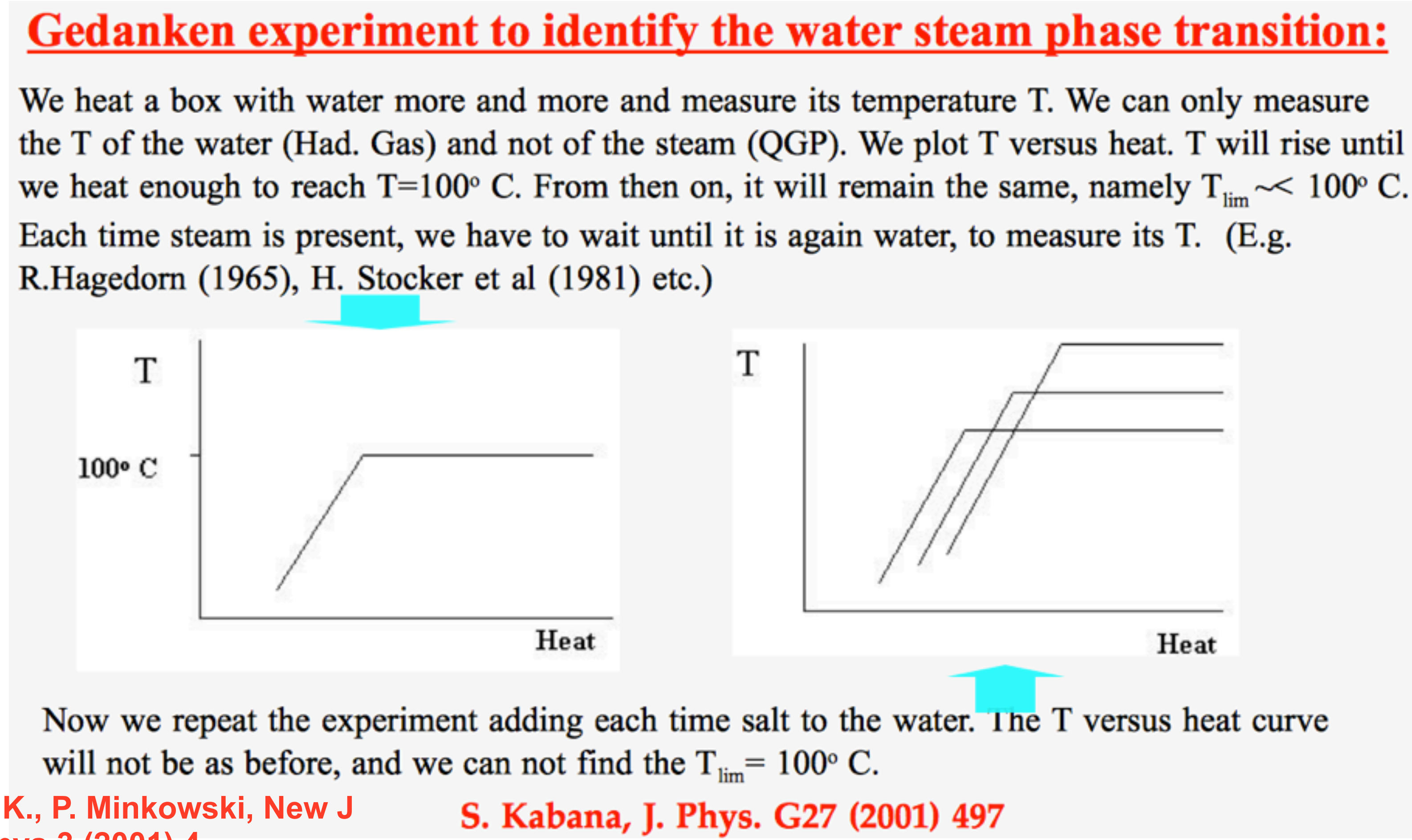
S.K., P. Minkowski, New J Phys 3 (2001) 4



$$\lambda_S = \frac{\langle s\bar{s}\rangle}{0.5(\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)}$$

- Lambda_s is enhanced in A+A over ppbar, e+e-
- Maximum of lambda_s near 40 GeV Pb+Pb (remember the horn)

Is this enhancement due to the QCD phase transition ?



Gedanken experiment to identify the water steam phase transition:

We heat a box with water more and more and measure its temperature T. We can only measure the T of the water (Had. Gas) and not of the steam (QGP). We plot T versus heat. T will rise until we heat enough to reach T=100° C. From then on, it will remain the same, namely $T_{\text{lim}} \sim< 100°$ C. Each time steam is present, we have to wait until it is again water, to measure its T. (E.g. R.Hagedorn (1965), H. Stocker et al (1981) etc.)

Now we repeat the experiment adding each time salt to the water. The T versus heat curve will not be as before, and we can not find the $T_{\text{lim}} = 100°$ C.

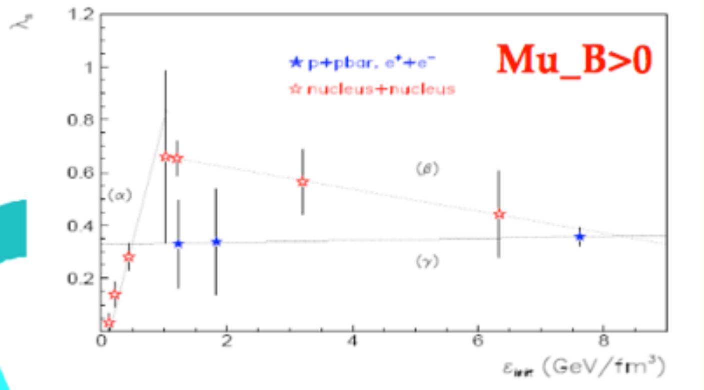
S.K., P. Minkowski, New J Phys 3 (2001) 4

S. Kabana, J. Phys. G27 (2001) 497

The baryochemical potential is like salt for hadronic systems.

Therefore, in order to measure a unique curve of T at freeze-out as a function of ε(init) in hadronic particle systems, one has to use the same conditions, with the same μB, the simplest one beeing μB=0.

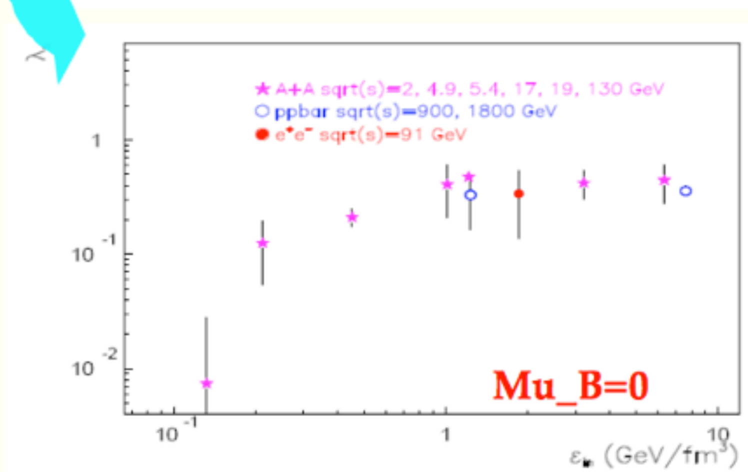
Extracting the salt out of the water

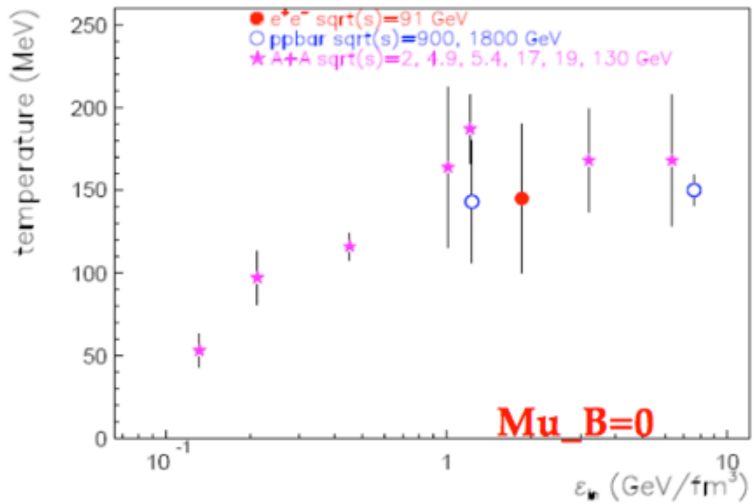


S. Kabana, P Minkowski, New J Phys 3 (2001) 4

S. Kabana, Eur. Phys. J C21 (2001) 545

e_I(onset of saturation) = 1+-0.3 GeV/fm^3



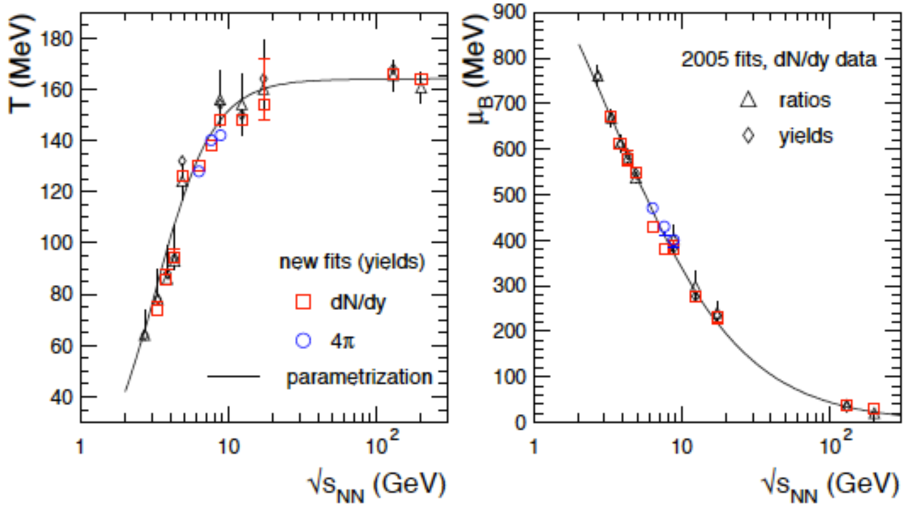


* Maximum of lambda_s near e=1 GeV/fm^3 at muB>0 : a consequence of sqrt(s) dependence of mub and T

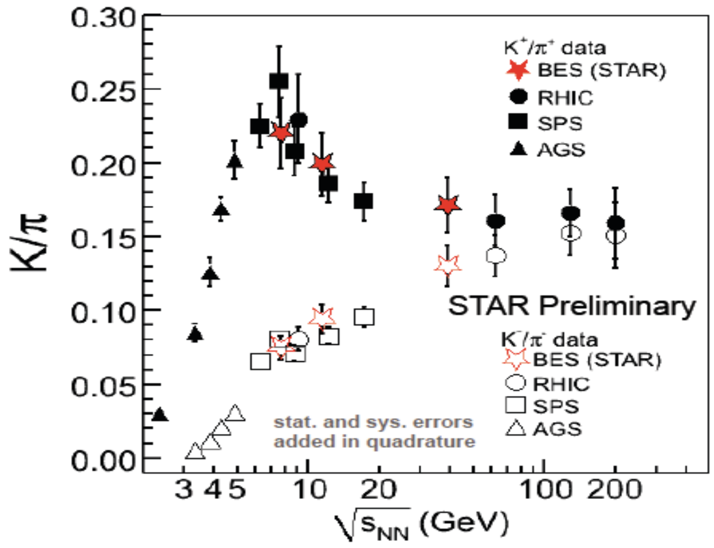
* The strangeness enhancement at mub=0 grows and saturates following the Temperature at muB=0

* The increase and saturation of the T at μB=0 near 1 GeV/fm^3 can be interpreted as onset of a phase transition at μB=0

Thermal fit results to hadron ratios ar freeze out



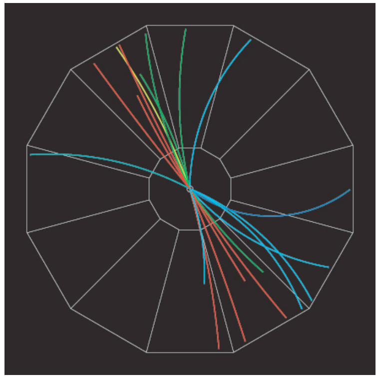
A Andronic et al, arXiv 0911.4806



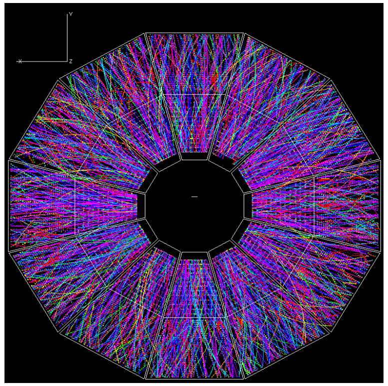
3. Jet quenching

Jet quenching

p+p Collision



Au+Au Collision

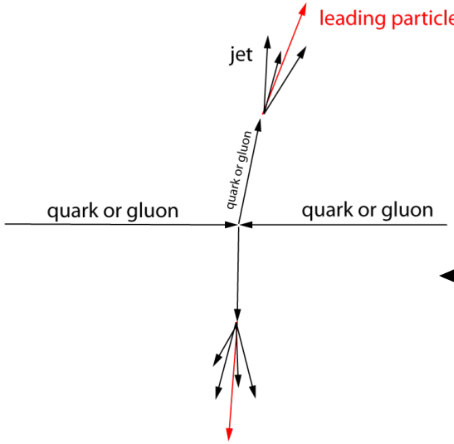


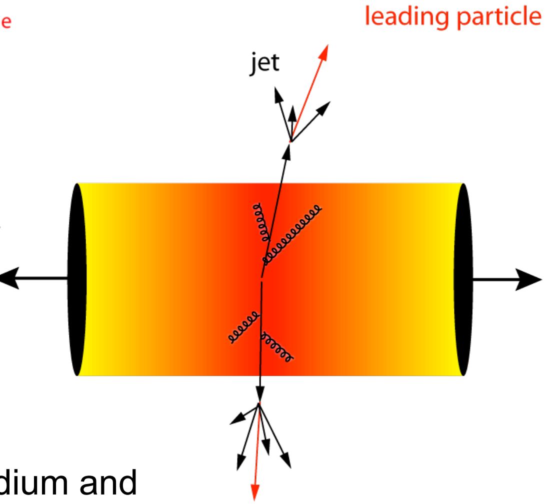
We compare A+A to expectations from p+p, using the “nuclear modification factor” R_{AA} defined as:

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

N coll : Average number of NN collisions in AA collision

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

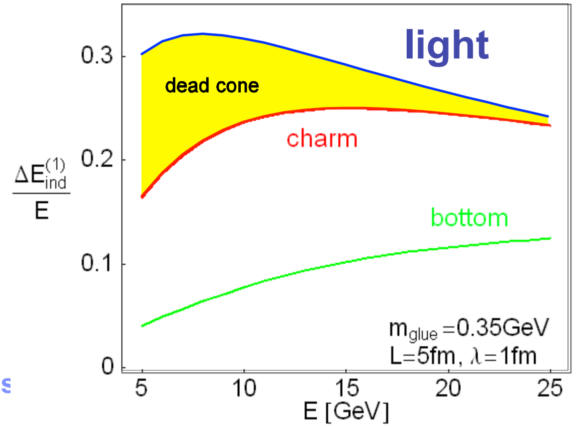




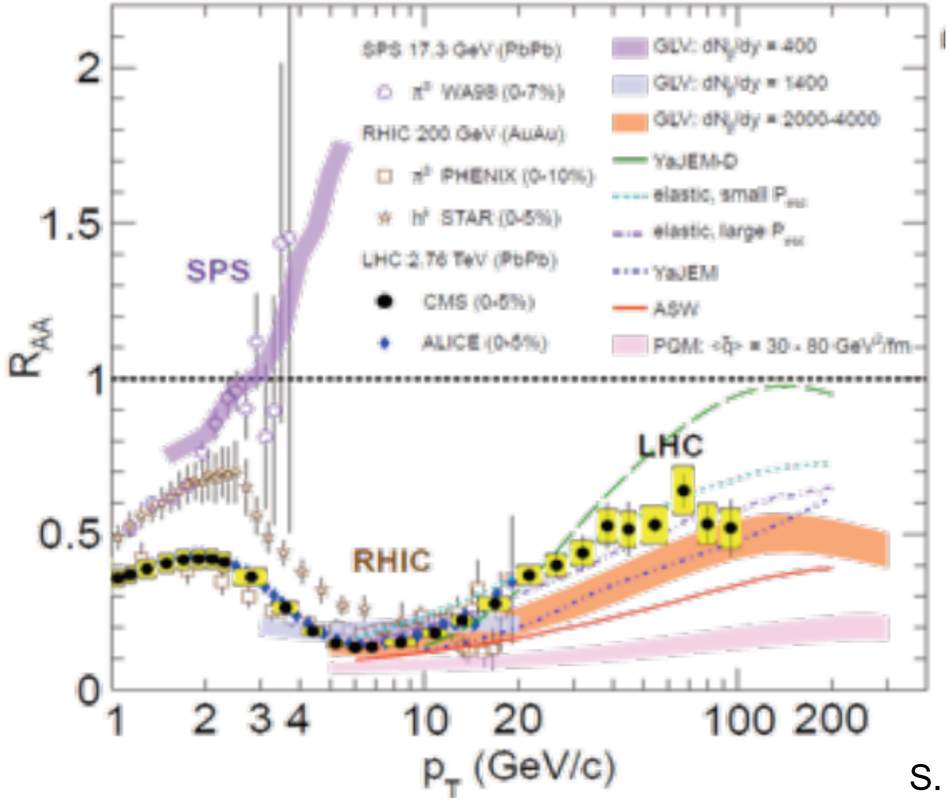
Partons interact with the medium and loose energy through eg gluon radiation

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)



Nuclear suppression factor RAA : SPS, RHIC and LHC



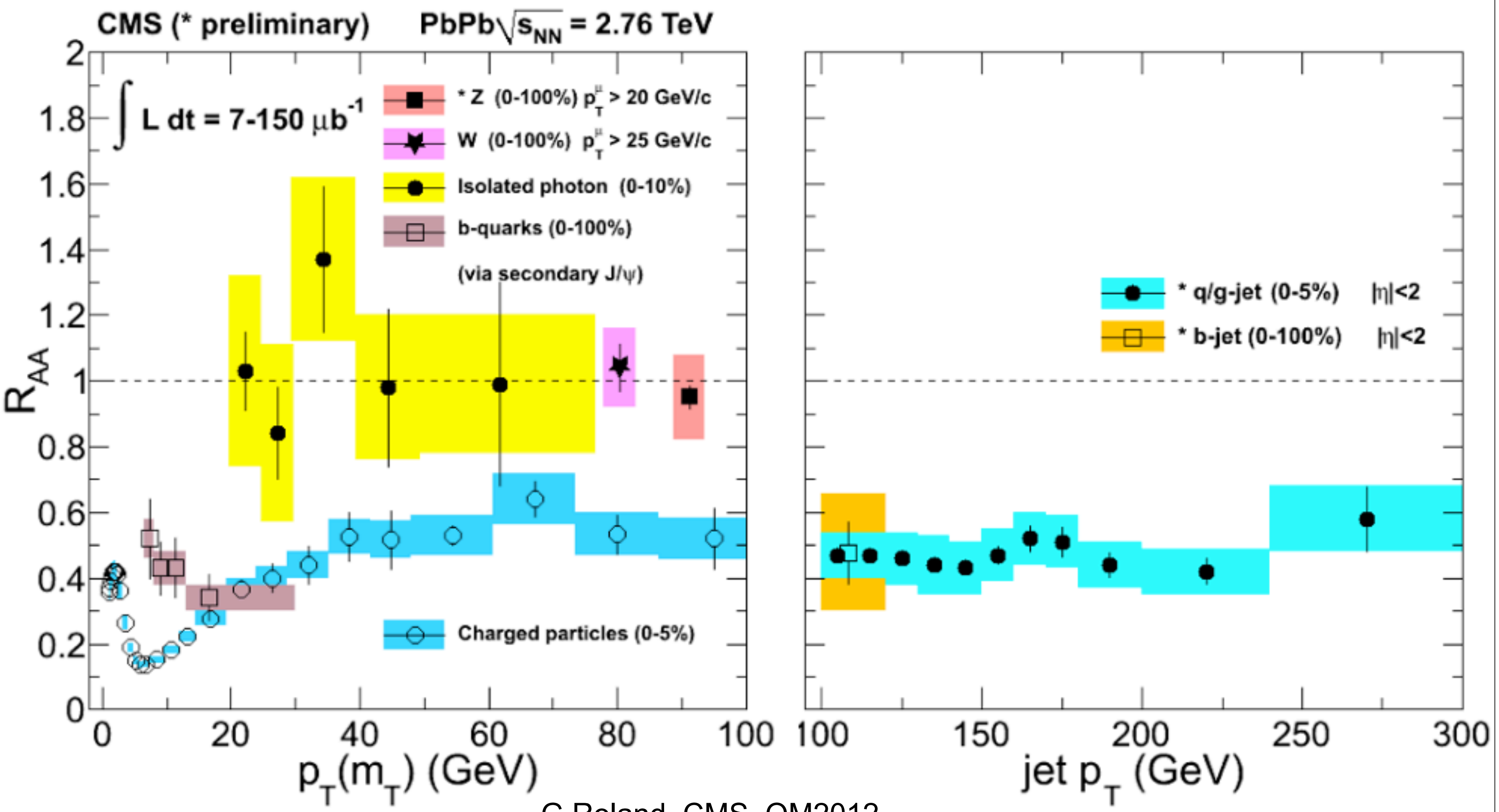
S. Milov, J. Solana, QM2012

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

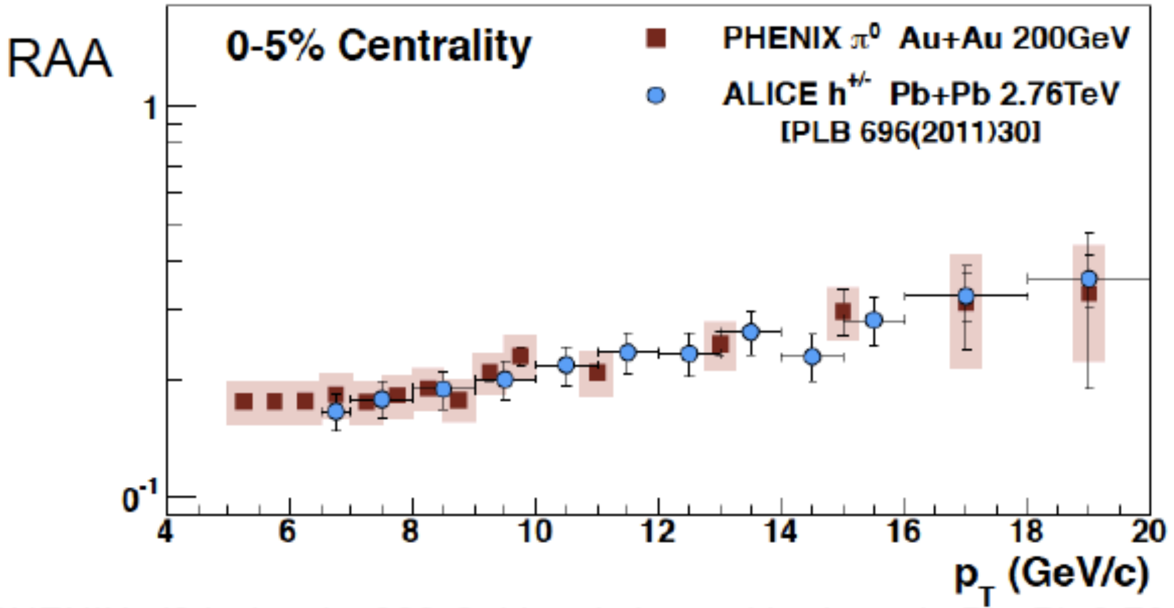
RAA suppression at the LHC



G Roland, CMS, QM2012

RHIC vs LHC

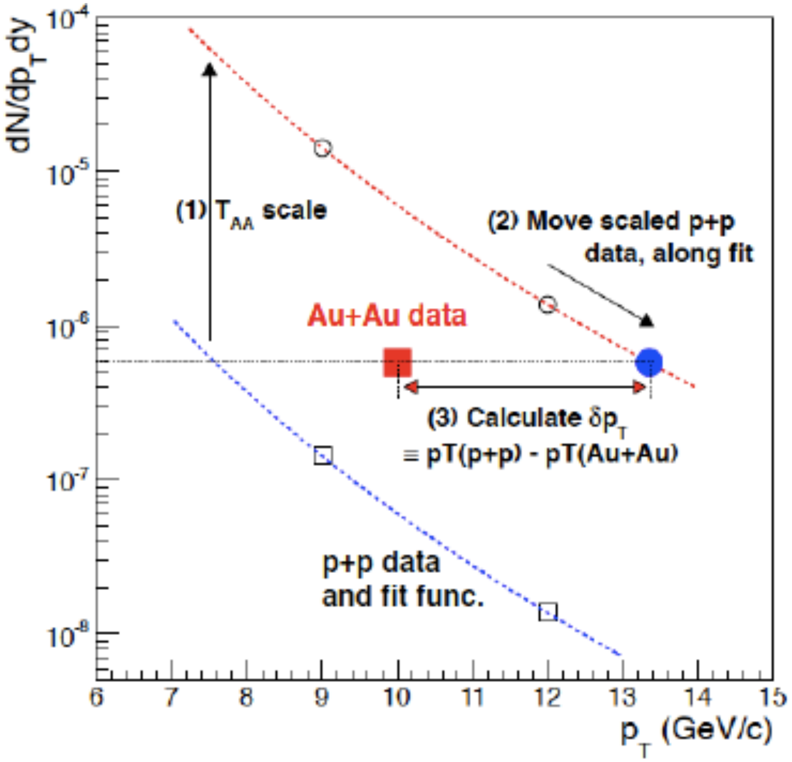
Sakaguchi, PHENIX, QM2012

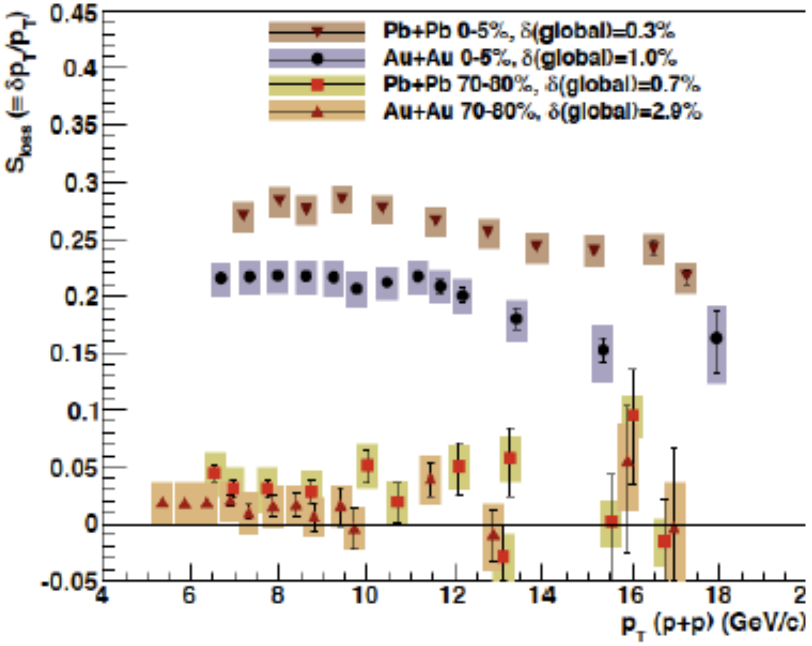


PHENIX pi0 in Au+Au 200 GeV and charged hadrons in Pb+Pb 2.76 TeV 0-5% look very similar

Fractional momentum loss from PHENIX

arXiv:1208.2254



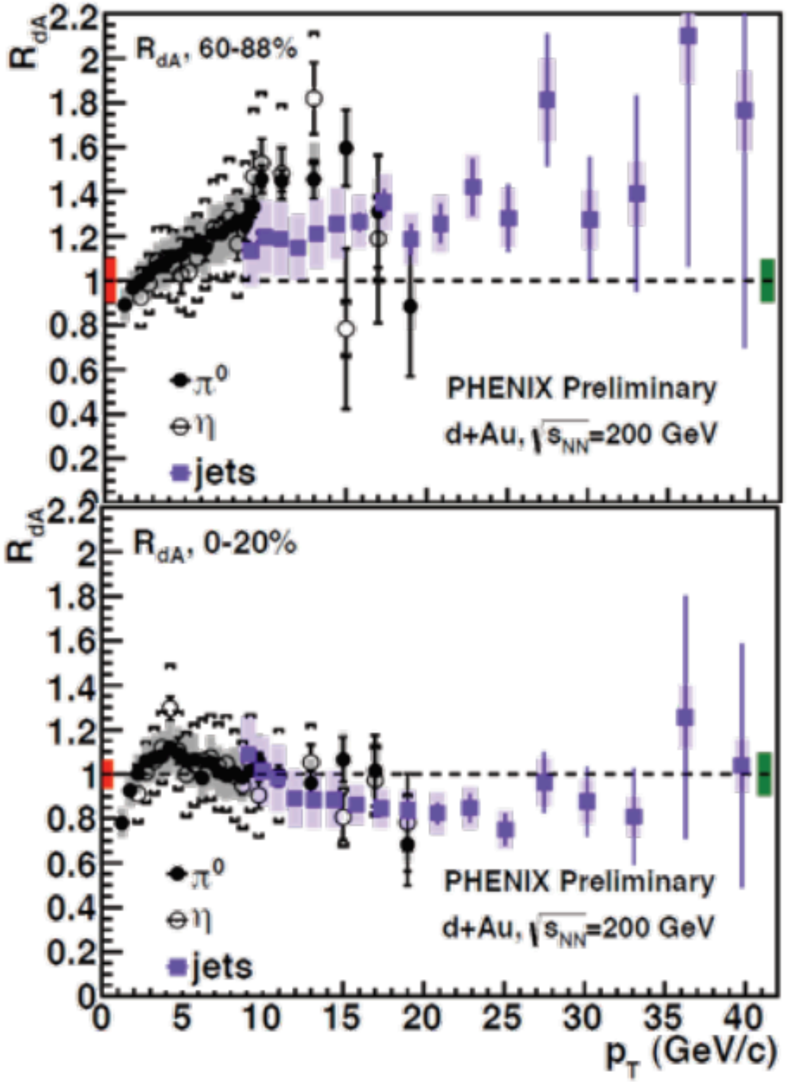


Measure fractional momentum loss instead of RAA

- Different dpT/pt for RHIC and LHC, for same RAA
- dpt/pt is 25% higher for ALICE
- dpt/pt decreases slightly with increasing pt (where rise of RAA occurs)

Cold Nuclear Matter effects with d+Au

Milov, Solana, QM2012



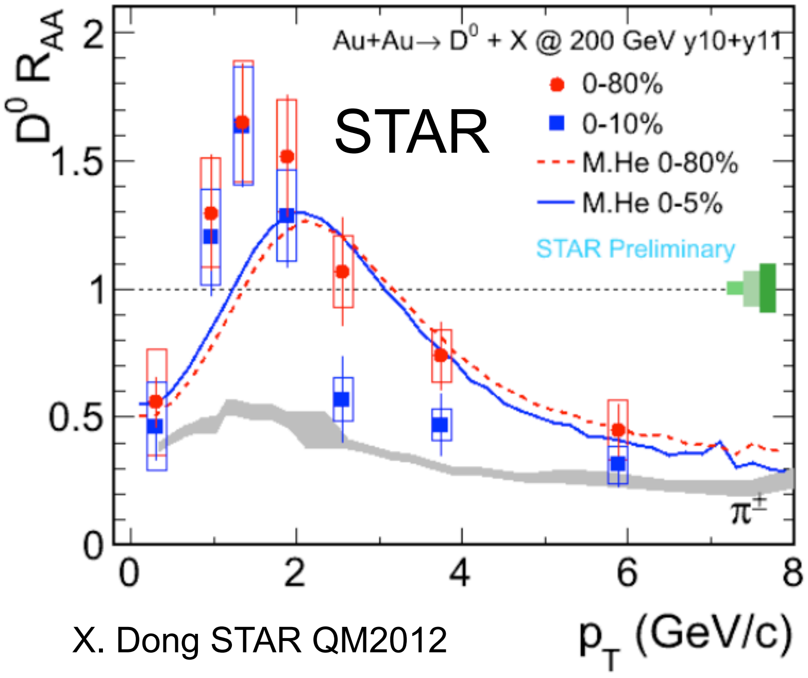
* Cold Nuclear Matter effects on jet quenching need to be taken into account at all energies

* p+A will be taken in LHC this year (end 2012)

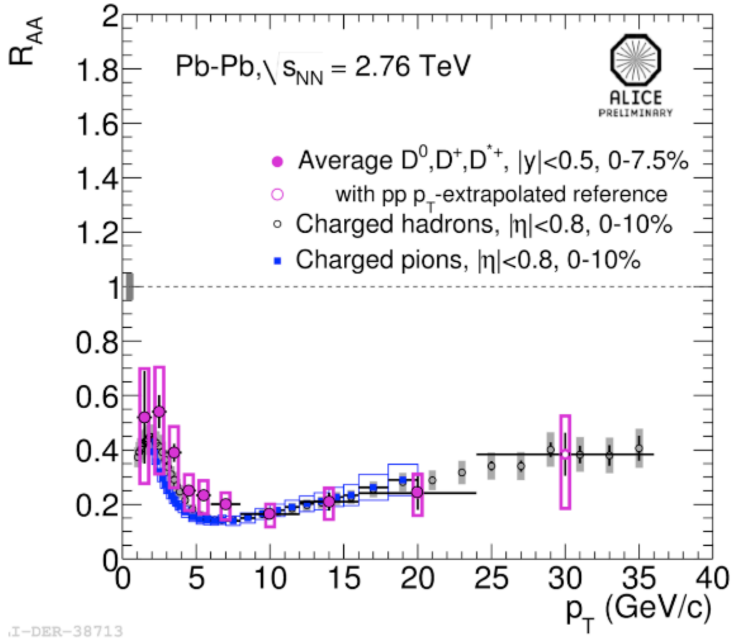
Quenching of open charm and pions

The RAA of Charm and Beauty are both suppressed at RHIC and LHC.

*** Puzzle at RHIC since few years:**
(b+c) -> e suppression is similar to that of charged hadrons (STAR, PHENIX).



X. Dong STAR QM2012

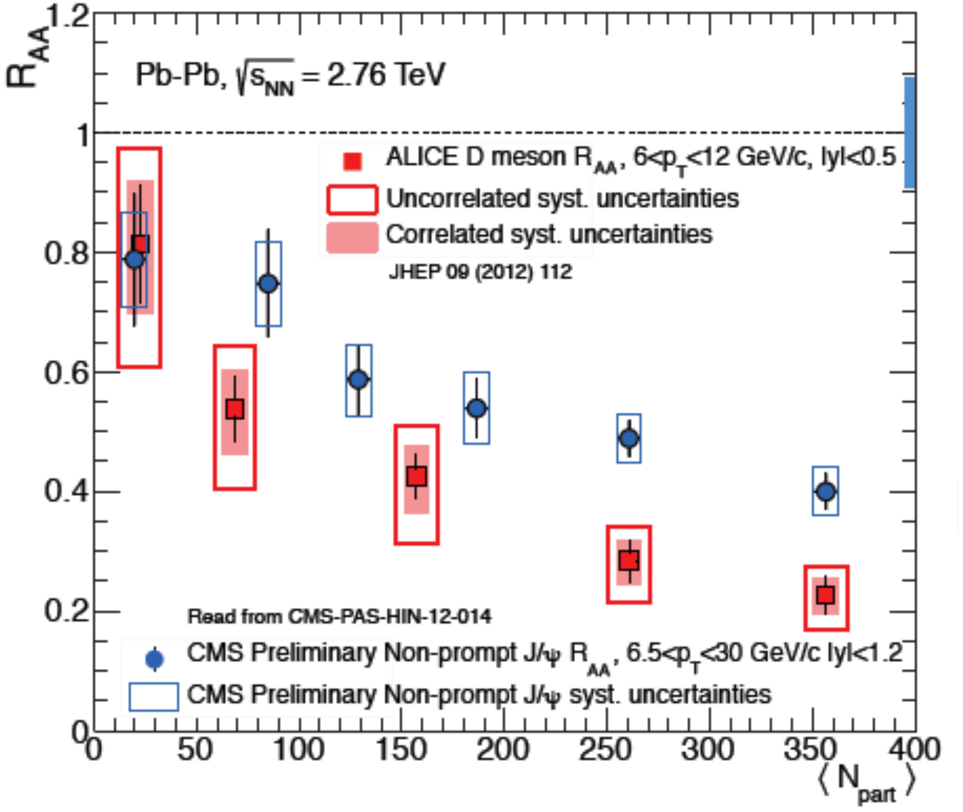


K Safarik, ALICE, QM2012

*** The RAA of D0 at RHIC (STAR) is suppressed after pT=3 GeV, and is similar to the RAA of charged hadrons at pT~6 GeV.**

*** The RAA of D0 at LHC (ALICE) is suppressed and is similar to the RAA of charged hadrons at high pT.**

Indication for mass dependence of energy loss comparing beauty and



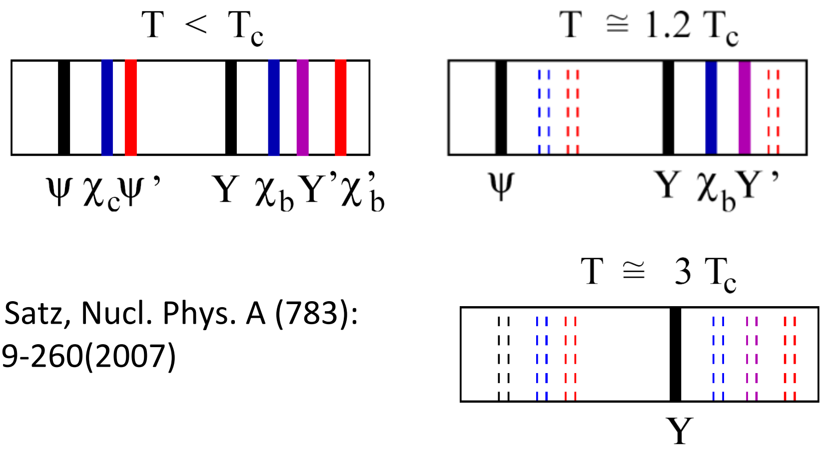
J/ψ: from B, $6.5<p_T<30$ GeV/c

D: $6<p_T<12$ GeV/c

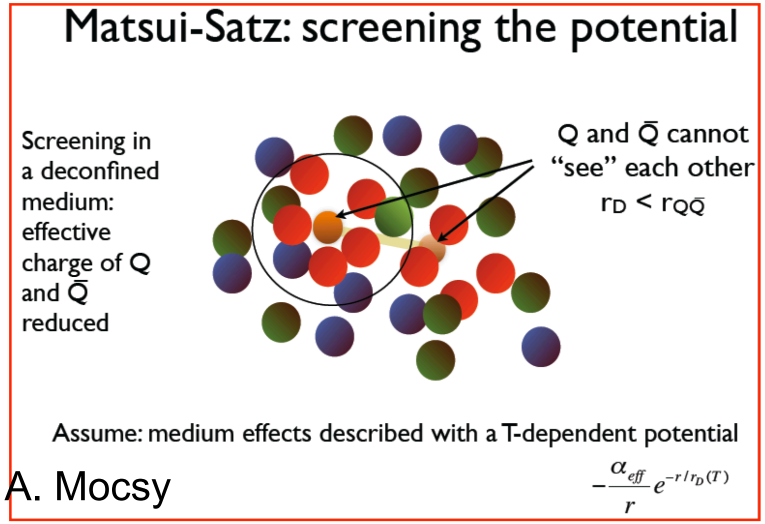
A Rossi LHCP 2013

4. Quarkonia

Quarkonia



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



Matsui-Satz: screening the potential

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

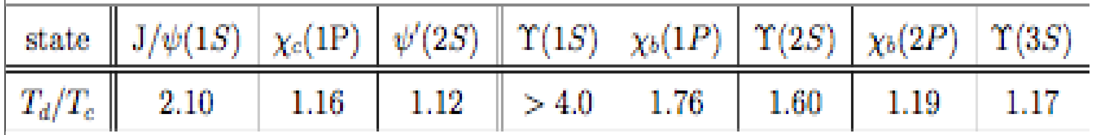
Q and $\bar{Q}$ cannot "see" each other

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

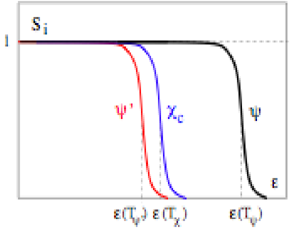
Assume: medium effects described with a T-dependent potential

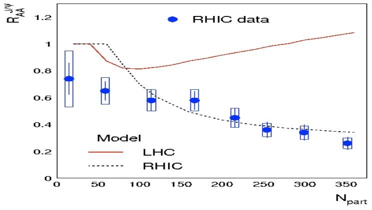
$$-\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$$

A. Mocsy



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 through hierarchy of T(dissociation)

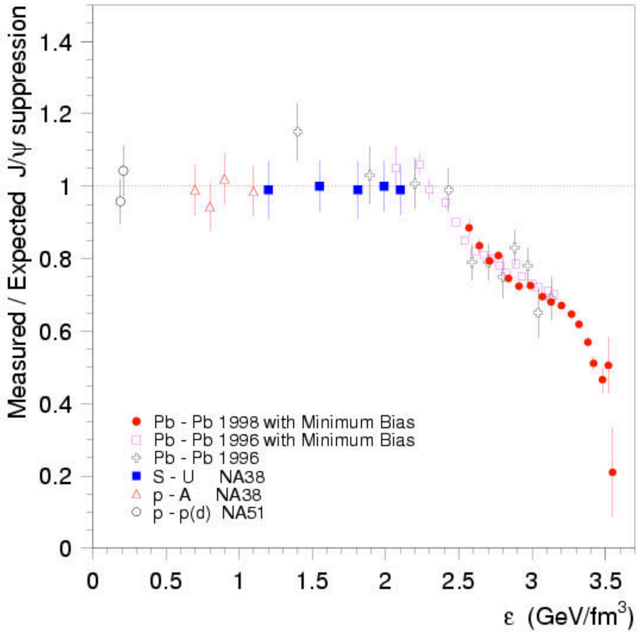
Many effects play a role like dissociation in QGP, cold matter absorbtion, recombination/coalescence from c, cbar, feeding

Quarkonia measure T of QGP in "units" of Td/Tc
Direct photons measure T of QGP
T(freeze out) from ratios vs e(Bjorken) give access to Ec -> Tc

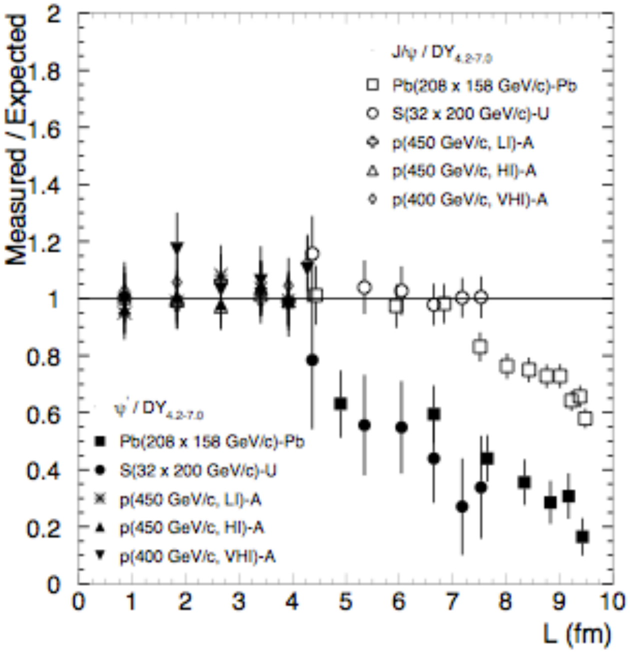
ccbar

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

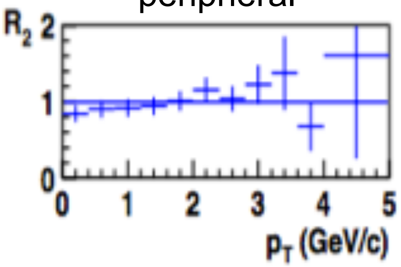


Eur Phys J C 49 (2007) 559

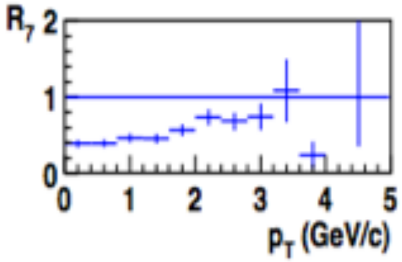


J/Psi/DY n-bin/1st bin

peripheral



central



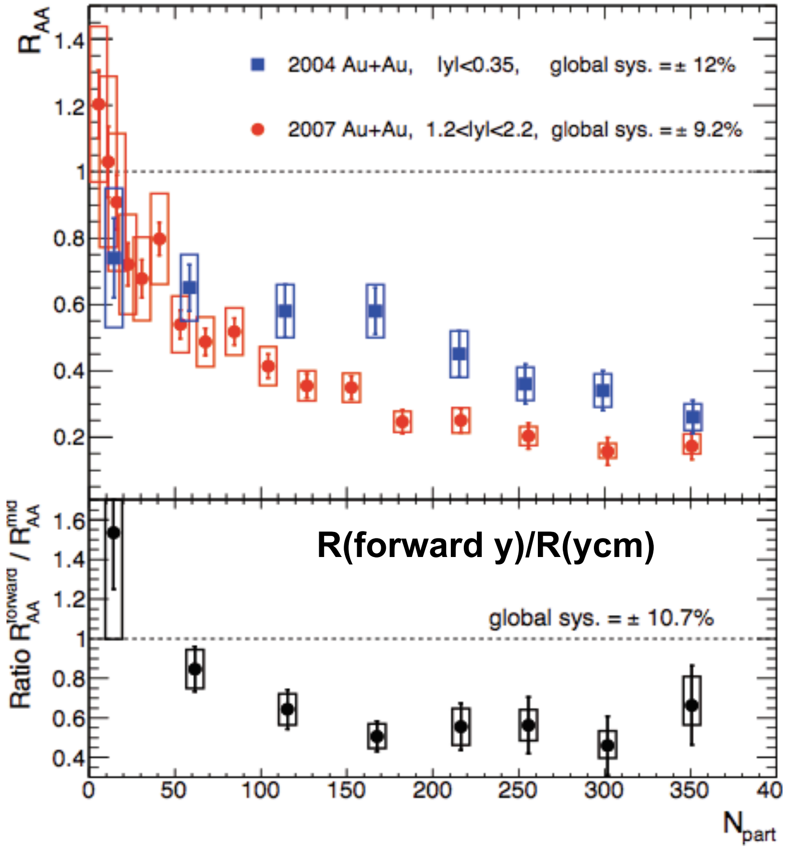
A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

- **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**

RHIC: The J/Ψ “puzzle” (1) : rapidity dependence

J/Psi at forward y in Au+Au, PHENIX, arXiv:1103.6269

C da Silva, PHENIX, QM2011



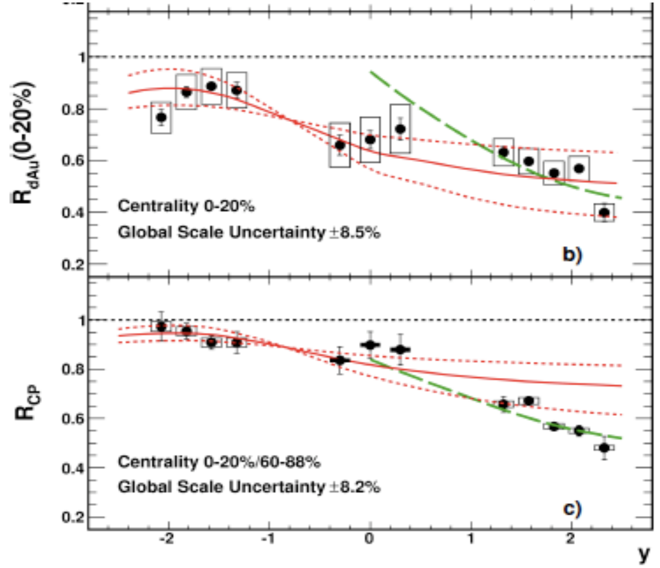
- **Suppression doesn’t increase with local density**
  - R_{AA} (|y|<0.35) > R_{AA} (1.2<|y|<2.2)

*** Data on J/Ψ in forward rapidity 1.2-y-2.2 show larger J/Ψ suppression with respect to midrapidity**

*** If J/Ψ from ψ’ and χ_c decays is fully suppressed RAA drops to 0.6 -> implies other source of suppression is present too**

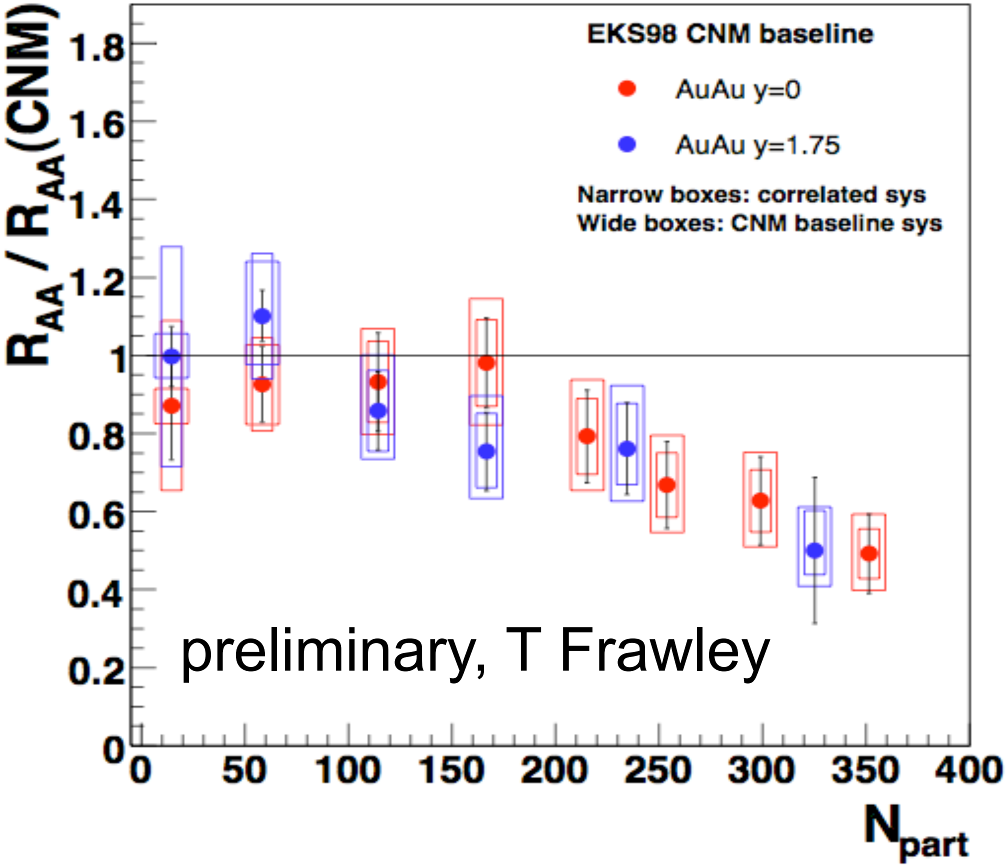
- **PHENIX has measured the y-dependance of R(dAu) and R(CP) of J/Ψ in d+Au (arXiv:1010.1246).**

PHENIX, arXiv:1010.1246



--> y-dependent CNM effects should be corrected in Au+Au before discussing the y-dependence of J/Psi suppression

RHIC J/Psi "y"-puzzle



T Frawley, (PHENIX) workshop
ECT*,Trento, May 24-29 2009

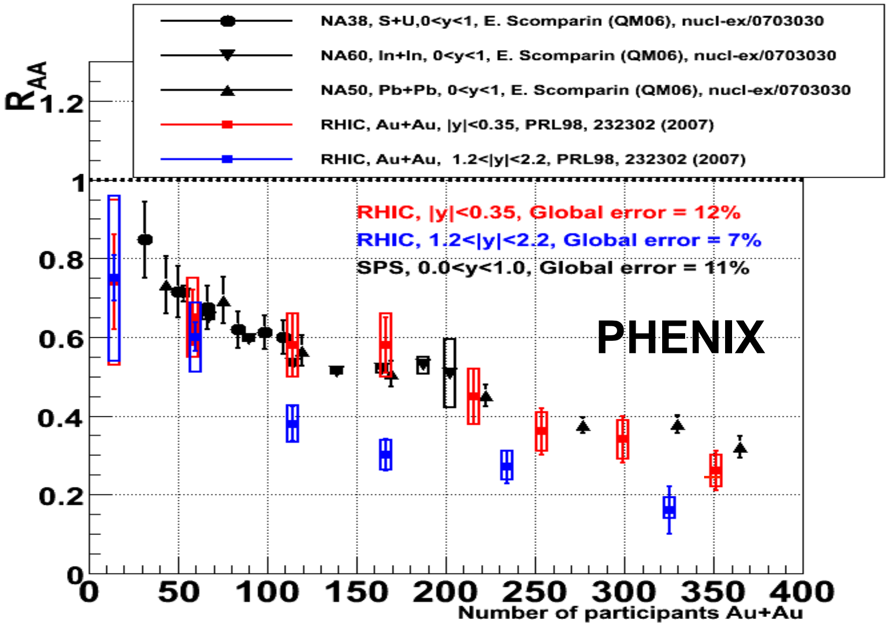
Analysis of d+Au data of run 2009 in terms of sigma_abs to account for all nuclear matter effects

→sigma_abs increases from midrapidity to forward rapidity

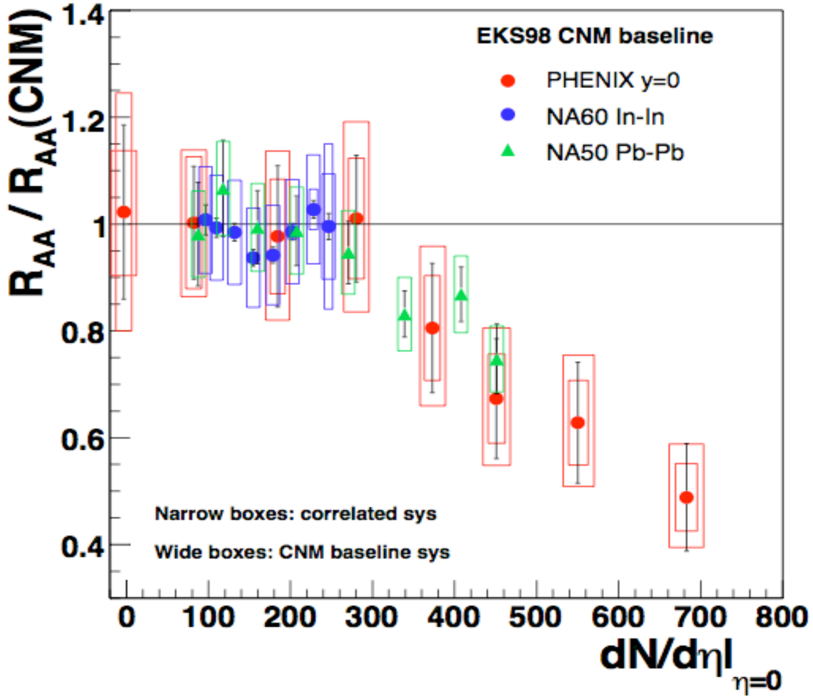
→ Agreement of J/Psi R_AA/R_AA(Cold Nuclear Matter) at y=0 and y=1.75

RHIC J/Psi “puzzle (2): Collision energy dependence

RHIC vs SPS



R Arnaldi, D Frawley, Trento 25-29 may 2009



J/Psi at ycm is compatible between RHIC and SPS

-> Suppression does not increase with local density

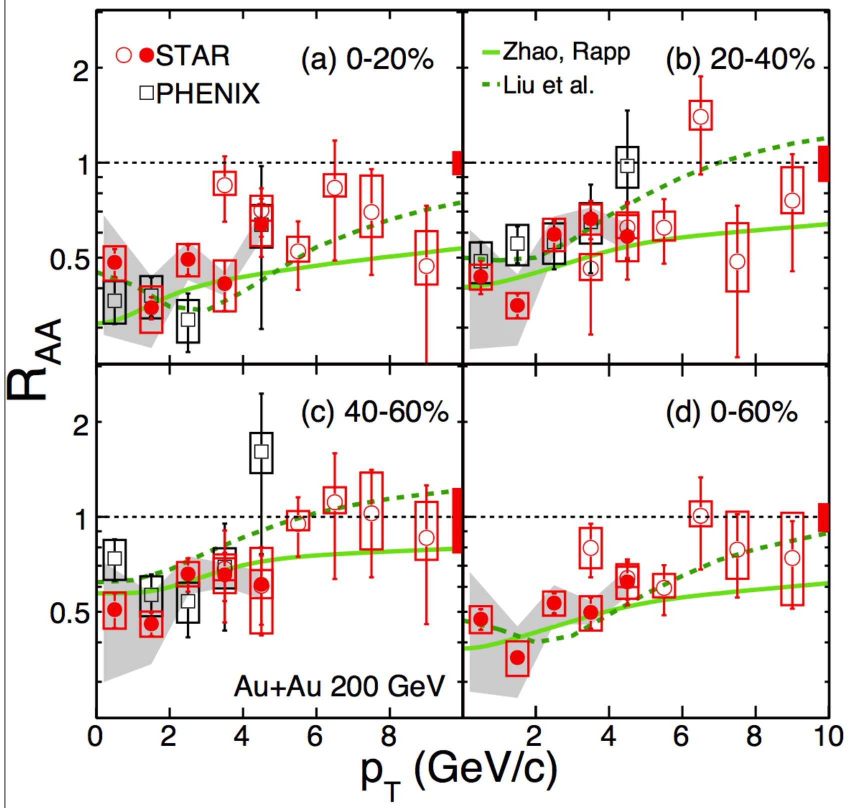
However, Cold Nuclear Matter (CNM) effects are not corrected and may be y and collision energy dependent.

Also the Npart-axis misses the energy dependence.

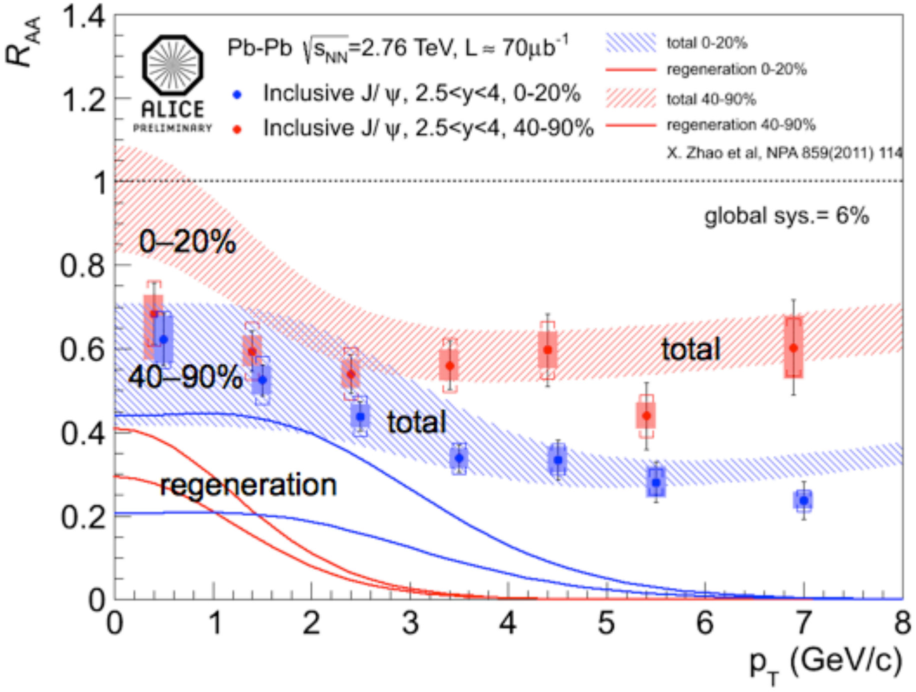
- Attempt to correct cold nuclear matter effects using data (d+Au, p+Au) (preliminary)
- Plot as a function of dN/d(eta) at (eta=0) takes into account differences in energy in contrast to Npart.

J/Psi p_T dependence - RHIC and LHC

Ch Powell, STAR, Kruger2012



K Safarik, ALICE, QM2012



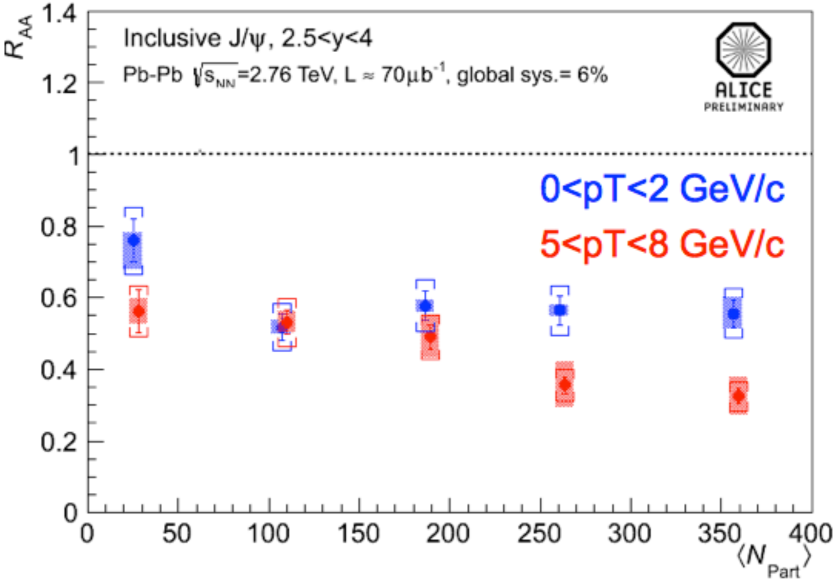
*** RHIC most central collisions:**
J/Psi is more supressed at low pT

*** LHC most central collisions (blue points):**
J/Psi is less supressed at low pT

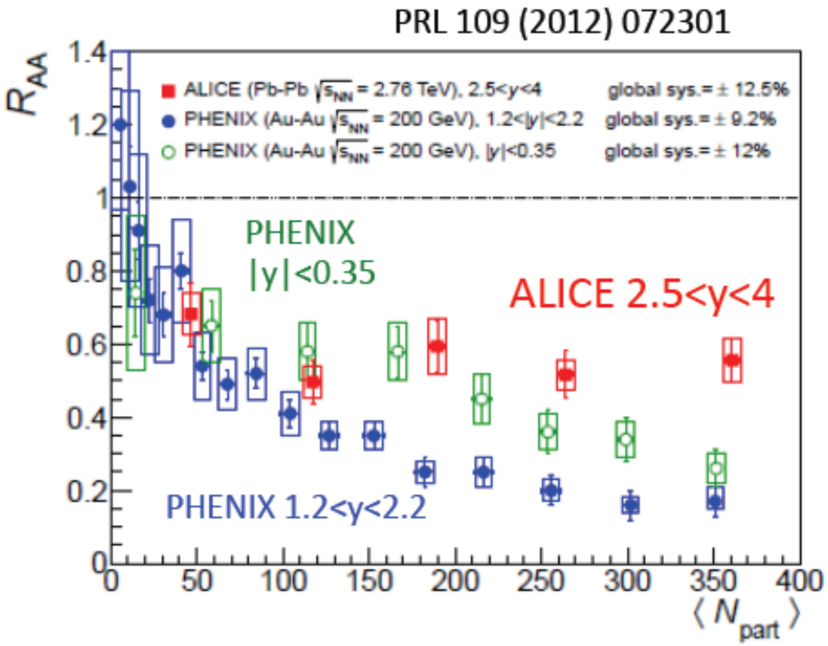
Opposite trend

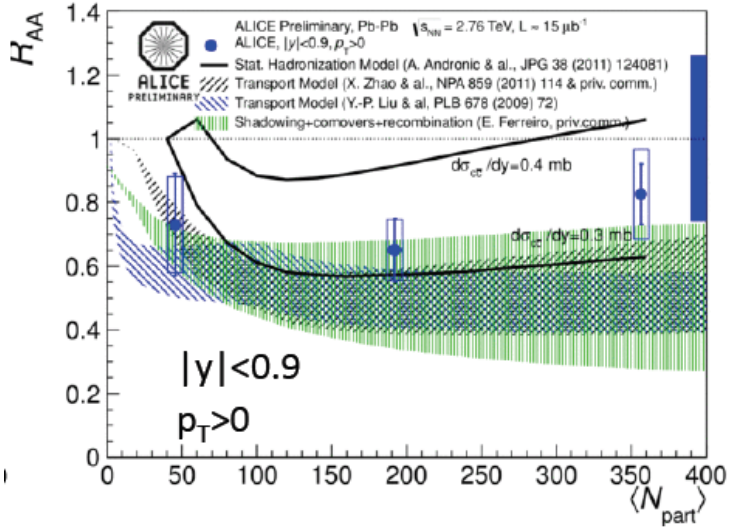
J/Psi Npart and pT dependence

K Safarik, ALICE, QM2012



PRL 109 (2012) 072301





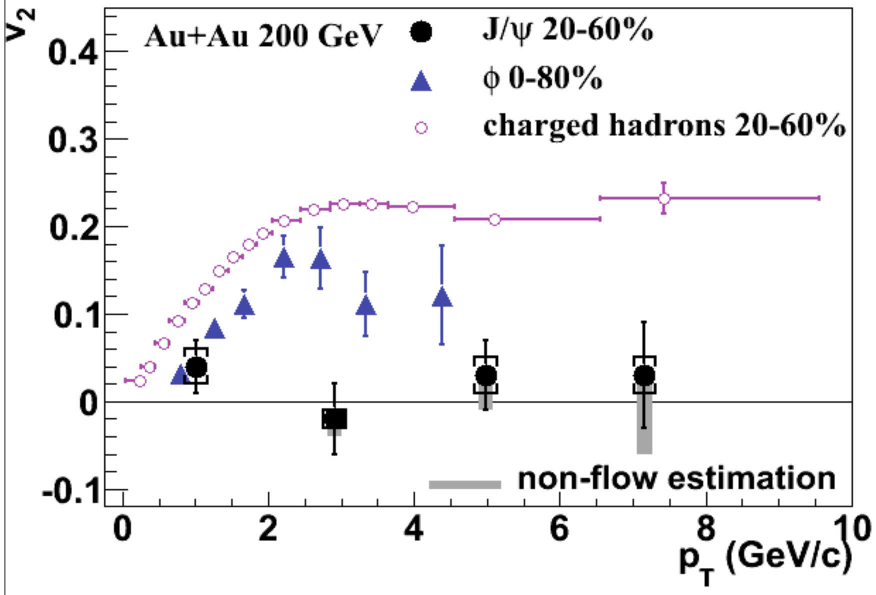
**Most central collisions:
Low pT J/Psi at LHC is less suppressed than RHIC data**

Even more so at low pT and at |y|<0.9

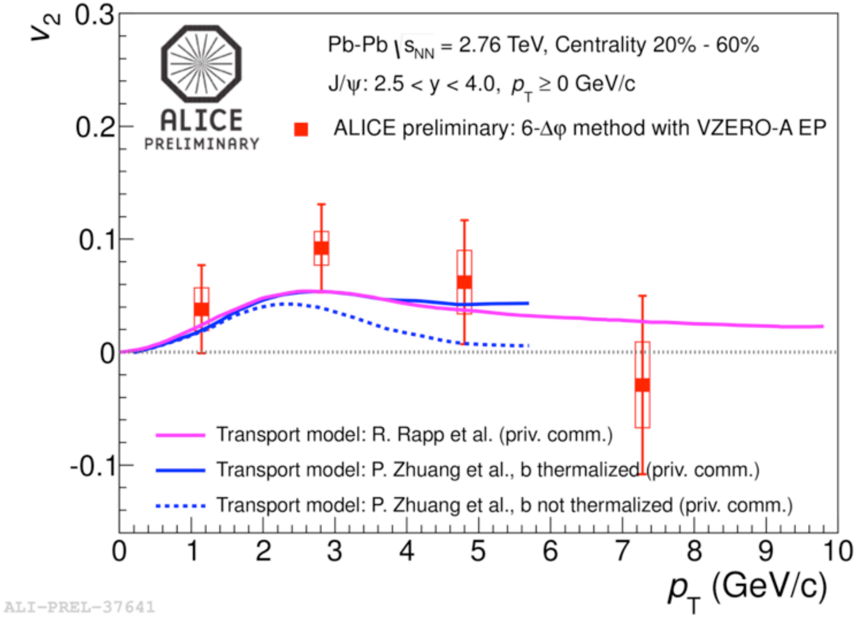
Indication of J/Psi regeneration at LHC at low pT?

Elliptic flow of J/Psi at RHIC and LHC

Zebo Tang, STAR, QM2011



K Safarik, ALICE, QM2012



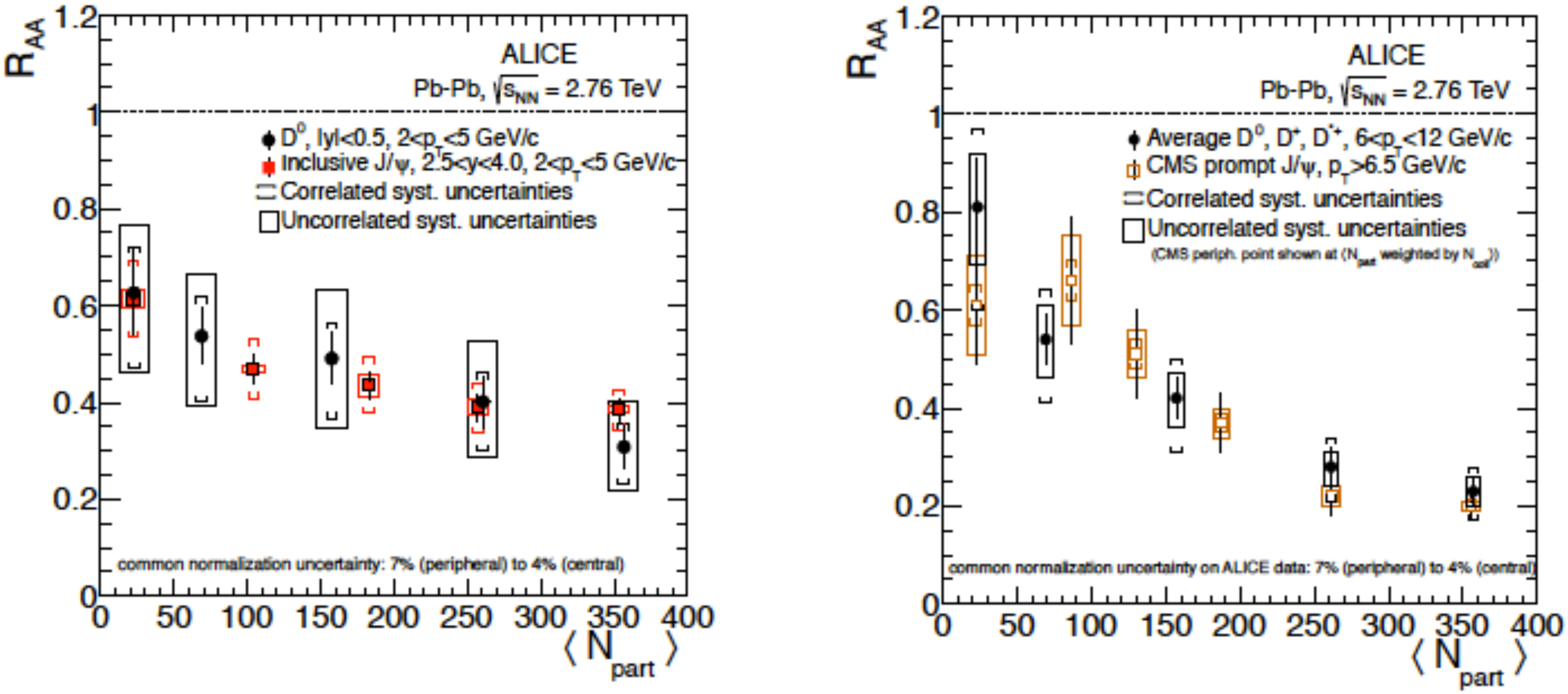
- *J/ψ* v_2 ~ 0 up to p_T ~ 8 GeV/c in mid-central 20-60%

➡ **Disfavors coalescence from thermalized charm quarks at RHIC**

- **_J/ψ_ produced by recombination of thermalized quarks is expected to have non-zero elliptic flow (ssuming charm quark sflow)**
- **Measurements give a hint for non-zero v2**
- **Qualitative agreement with models including recombination**
- **Complementary to RAA results**

➡ **Suggests coalescence from thermalized charm quarks at LHC**

J/Psi compared to open charm - LHC

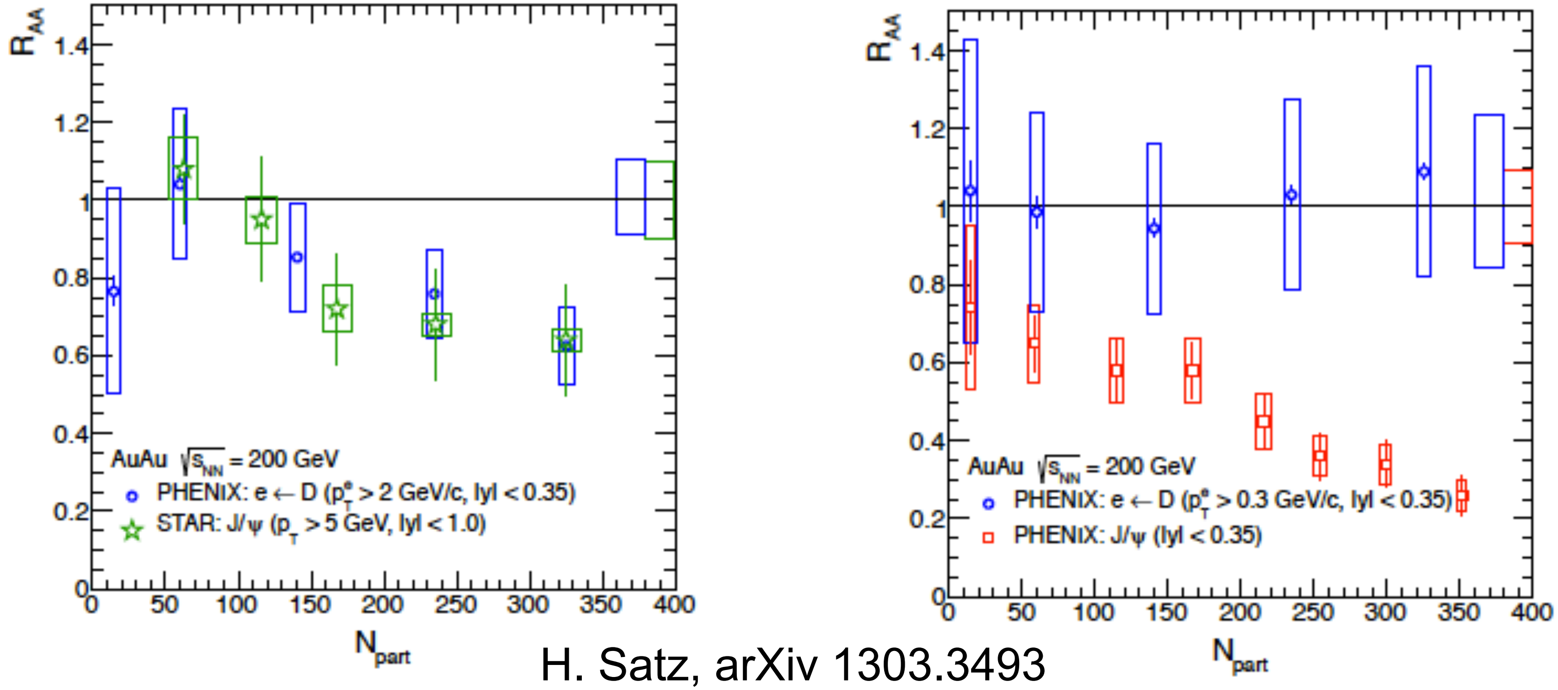


H. Satz, arXiv 1303.3493

J/Psi seems to be neither suppressed nor enhanced with respect to open charm at all centralities, at intermediate (pT=2-5 GeV) and high pT>6.5 GeV

However experiments should compare more precisely within exactly same acceptance (here different y) and at low pT too

J/Psi compared to open charm - RHIC

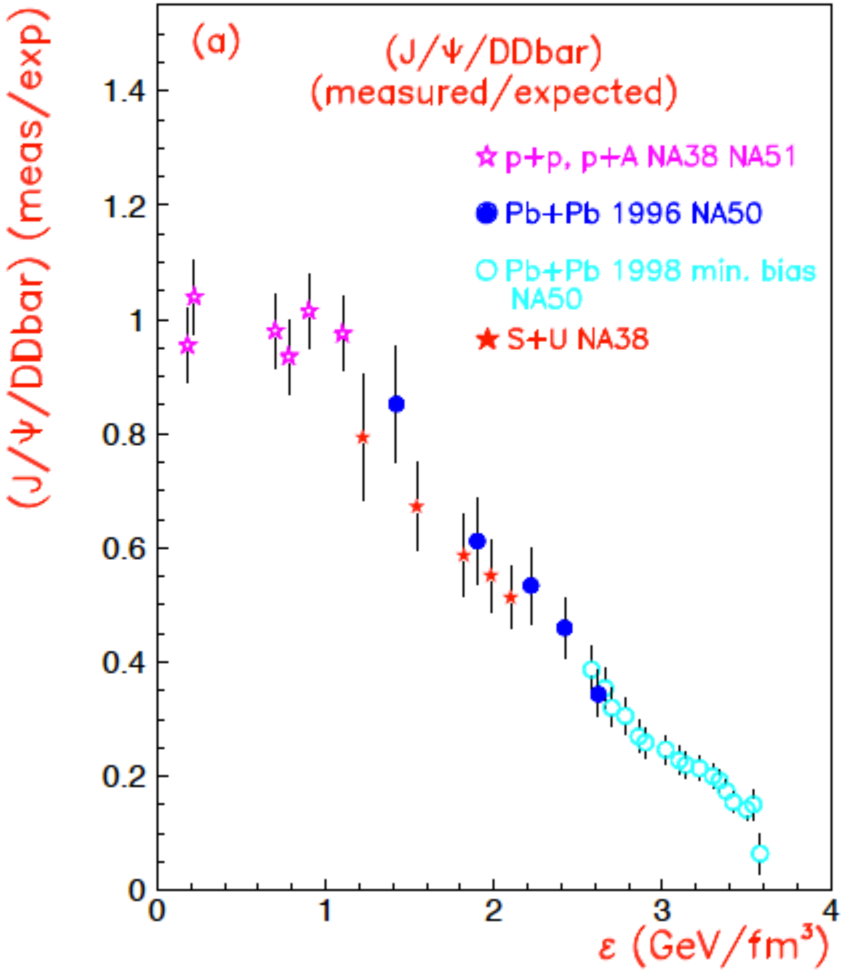


H. Satz, arXiv 1303.3493

*** J/Psi seems to be neither suppressed nor enhanced with respect to open charm at all centralities at high pT (However pT range is not exactly the same)**

*** J/Psi seems to be significantly suppressed with respect to open charm at low pT in central Au+Au events (same acceptance here)**

J/Psi compared to “open charm” - SPS



Here the enhancement of dimuons in the intermediate mass(mu+ mu-) region (1.6 -2.5 GeV) is assumed to be due to open charm

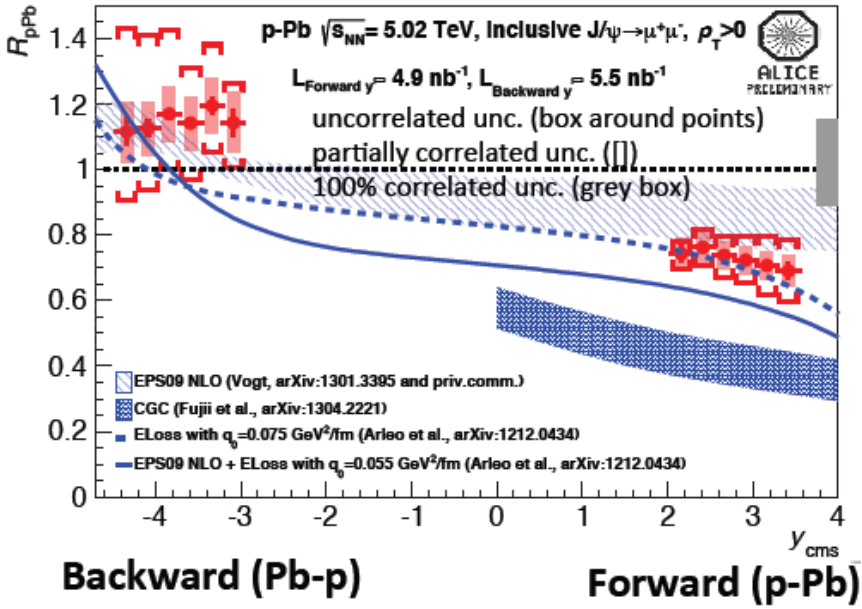
Consequences: The J/Psi over the DDbar estimate is suppressed already at 1 GeV/fm^3, namely near the critical energy density for the QGP phase transition

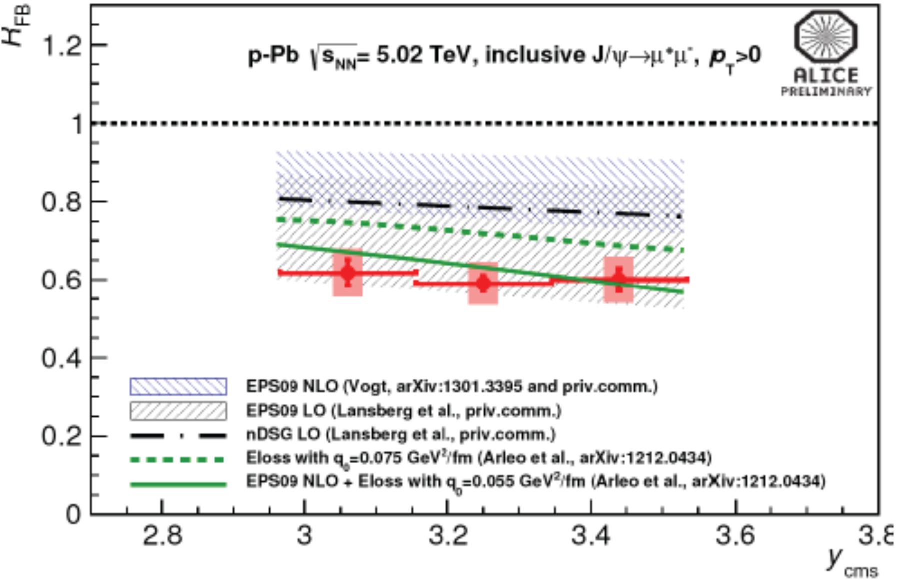
-> open charm and chi_c measurement at SPS energy needed to interpret the SPS data

-> AFTER/CHIC

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

Latest news from LHC: J/Psi in p+Pb collisions





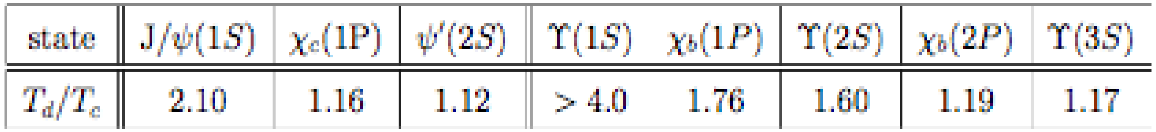
Rossi,LHCP, May 2013

* Shadowing+Energy loss models describe the data on forward-backward ratio relatively well

* Shadowing alone or energy loss alone seem to overestimate the forward-backward ratio data

bbar

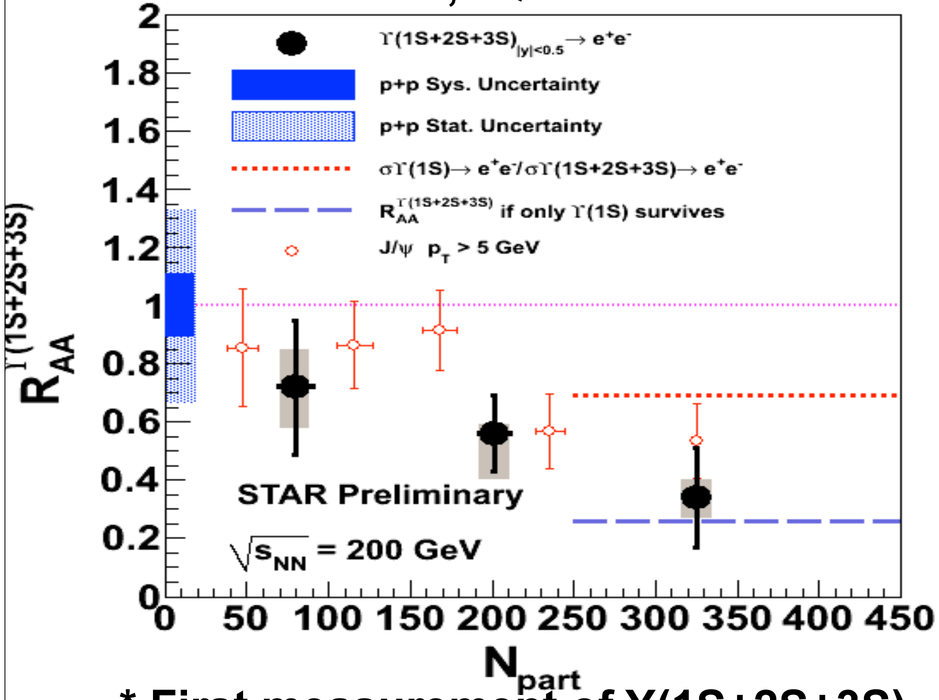
Y suppression was discovered in 2011 at same time at RHIC and LHC



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

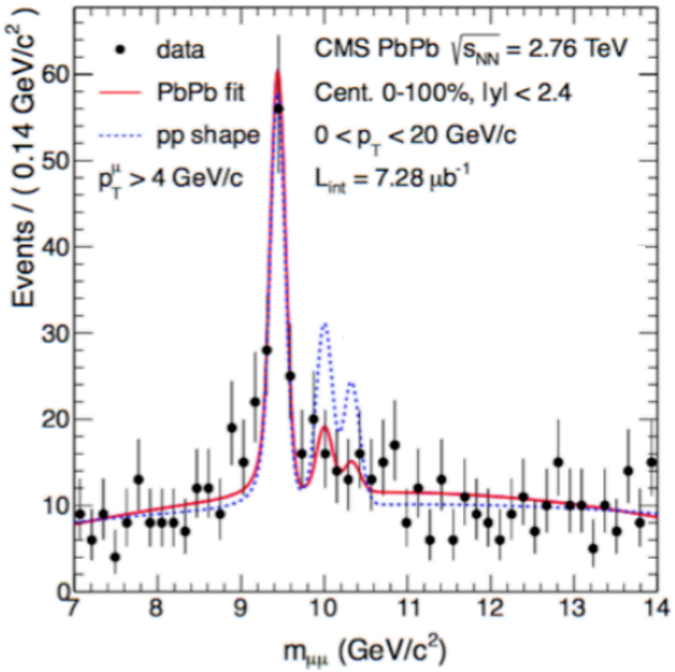
H Satz

STAR, QM2011



CMS

PRL 107 (2011) 052302



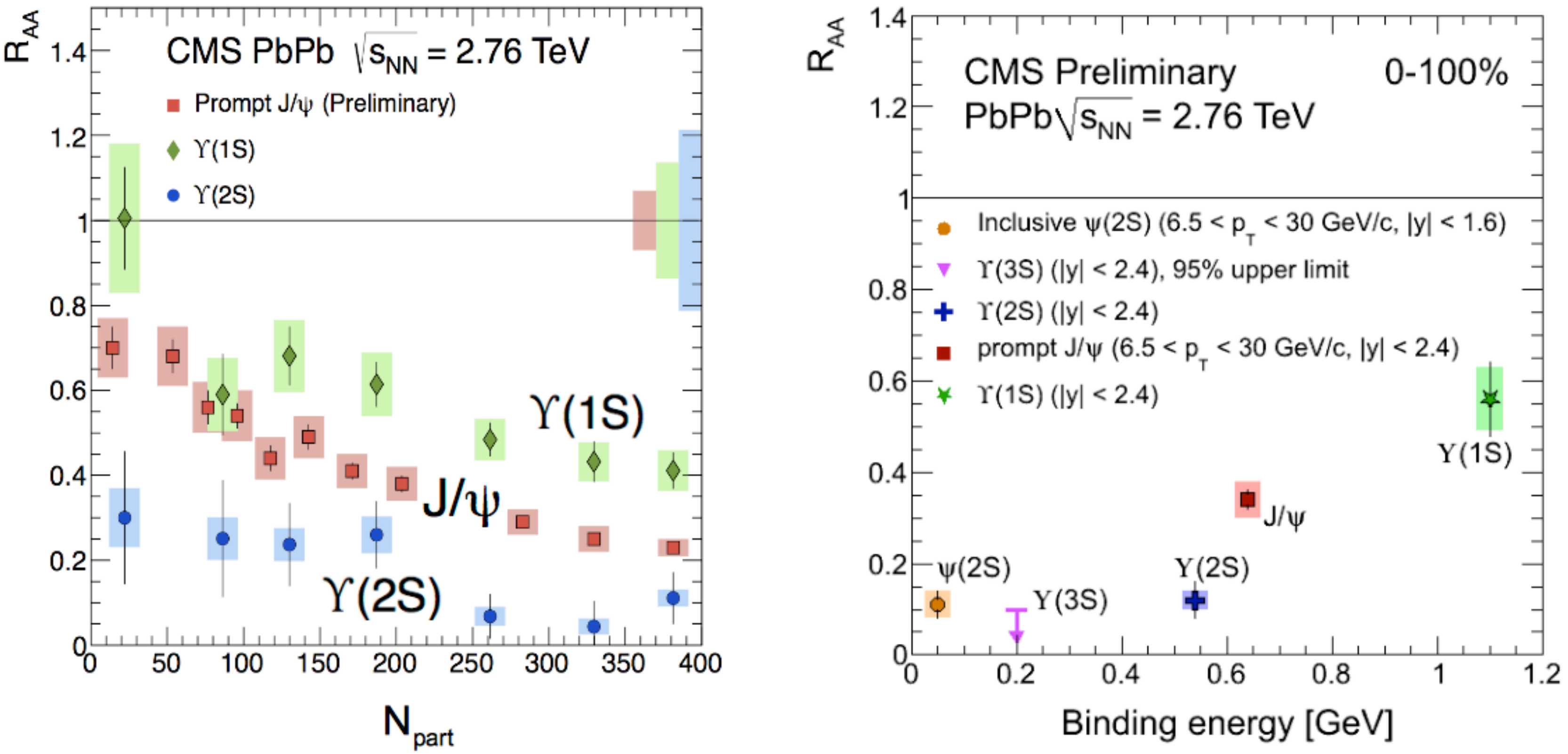
*** First measurement of Y(1S+2S+3S) suppression at RHIC.**

*** RAA of most central point is in agreement with only Y(1S) surviving**

Indication of suppression of Y(2S+3S) with respect to Y(1S) (2010 data)

Y suppression - thermometer at LHC

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



G Roland, CMS, QM2012 and PRL 109, 222301 (2012)

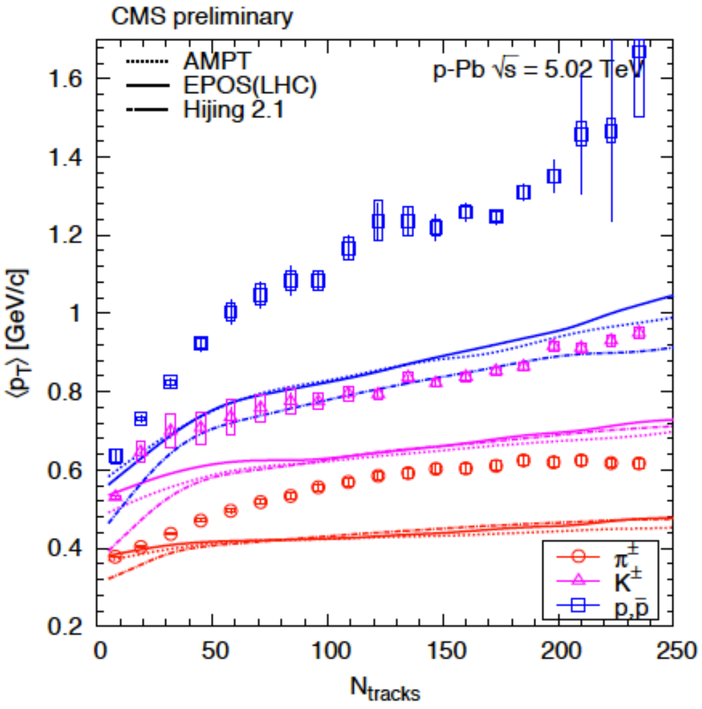
Clear hierarchy in RAA of different quarkonium states

If confirmed (using p+A for CNM effects, feeding corrections, open beauty) is an outstanding discovery for the Heavy Ion field

New p+Pb data at LHC

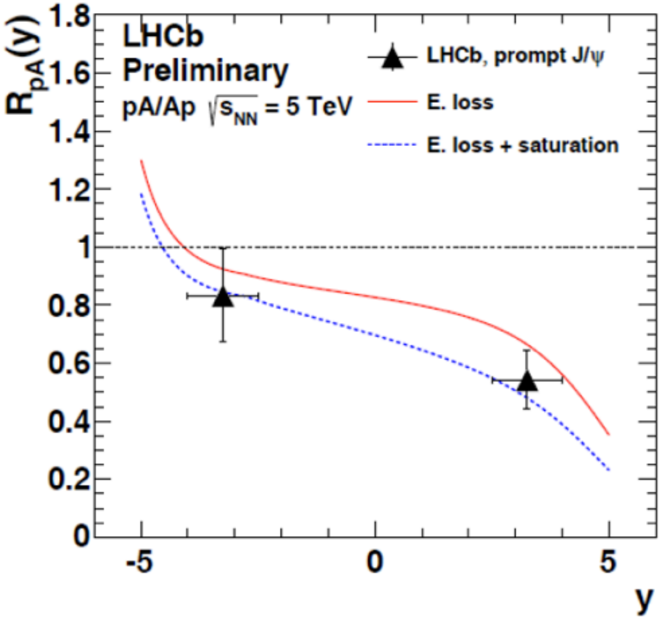
New p+Pb data

CMS



LHCb

Nuclear attenuation factor $R_{pA}(y)$



Theoretical predictions:
JHEP 1303 (2013) 122
[arXiv:1212.0434]

F Jing, LHCb, Trento May 2013

Data in large
disagreement with models

F Sikler, CMS, Trento May 2013

III Conclusions and outlook

Back to the Questions :

Is there a dense hot matter of quarks and gluons build ?

Yes: Temperature:

T(init) from direct gammas=230, 300-600 MeV (models) at SPS and RHIC > Tc
increasing with energy, up to the raw measurement of 300 MeV at LHC > Tc
T(chemical freeze out) ~ Tc

Potential future estimates of T(QGP) via quarkonia (needs p+A and further analysis):
Tdissoc of Y(1S) > 450 MeV, Tdissoc of Y(2S) > 245 MeV (P. Petreczky) in agreement with direct thermal photon measurement of T

Energy density:
ε(Bjorken at tau=1fm/c)= 3, 5, 16 GeV/fm^3 at SPS, RHIC, LHC.
At RHIC and LHC thermalization happens earlier than 1 fm/c and energy density is much higher (hydro models).

Density (not yet settled) :
dN/dy(gluon) through jet quenching is ongoing work.
As an example GLV: dN/dy=400,1400,2000-4000 at SPS, RHIC, LHC

v2 scaling with the number of constituent quarks (not yet settled)

Is local thermalization achieved ?

Yes : Thermal direct photons at low pT measured
Hydrodynamic behaviour.
Thermal model fits to the hadron ratios (is not a direct evidence for initial thermalization)

Is there a phase transition and if yes which is the order, or is it a cross over ?

Quarkonia suppression in QGP, jet quenching, thermal direct photons, T vs energy density: signs of a new phase.
Furthermore the energy scan has found that QGP signatures found at high energy are switched off at low energies.
(Nr of Constituent Quark scaling, quenching, T(chem. freeze out) falls below its limiting value.)
More data and analysis are needed and forthcoming.

Which are the critical parameters ?

“Critical Bjorken energy density” from (T vs ε_Bj) around 0.5-1 GeV/fm^3, corresponding to sqrt(s) around 10 GeV (muB=0 case included) and Tc~160-200 MeV --> motivated building new colliders NICA and FAIR and the Beam Energy Scan at SPS and RHIC

Is this state weakly or strongly interacting ?

It is strongly interacting : sQGP
v2, shear viscosity : η/s=0.07-043 (LHC)
This is backed up by theory asymptotically free only at very large T/Tc.

Is there a critical point ?

Not yet established, SPS and RHIC are on their way to look.

Conclusions and outlook

After 25 years of searches for the QGP we have arrived at a culmination point with long awaited results.

In the following detailed studies of matter at high density and temperature can be envisaged with existing and new detectors and accelerators.

In the next few years new data will allow to establish these results and add possible new discoveries at:

- high energy and low muB (RHIC,LHC)
- low energies and high muB (Beam Energy Scans at RHIC, SPS and the new colliders NICA and FAIR)

to map out the QCD diagram

Outlook

* LHC : p+A data, A+A data
Precision studies of the characteristics of the sQGP
Full LHC energy measurements at sqrt(s)=5 TeV
Upgrades of LHC experiments and collider.
AFTER-CHIC fixed target with LHC beam to measure chi_c etc

* RHIC short term: new upgrades for highly improved Heavy Flavour and quarkonia measurements (PHENIX silicon det., STAR HFT 2014, STAR Muon det.).
* RHIC long term: BES II higher statistics for low energy scan, fixed target, eA

New facilities:
* NICA in Dubna, FAIR at GSI Germany: new facilities to measure the low energy regime of Heavy Ion collisions

Thank you very much for your attention