Heavy Ion collisions at RHIC and LHC and cosmological implications

Sonia Kabana

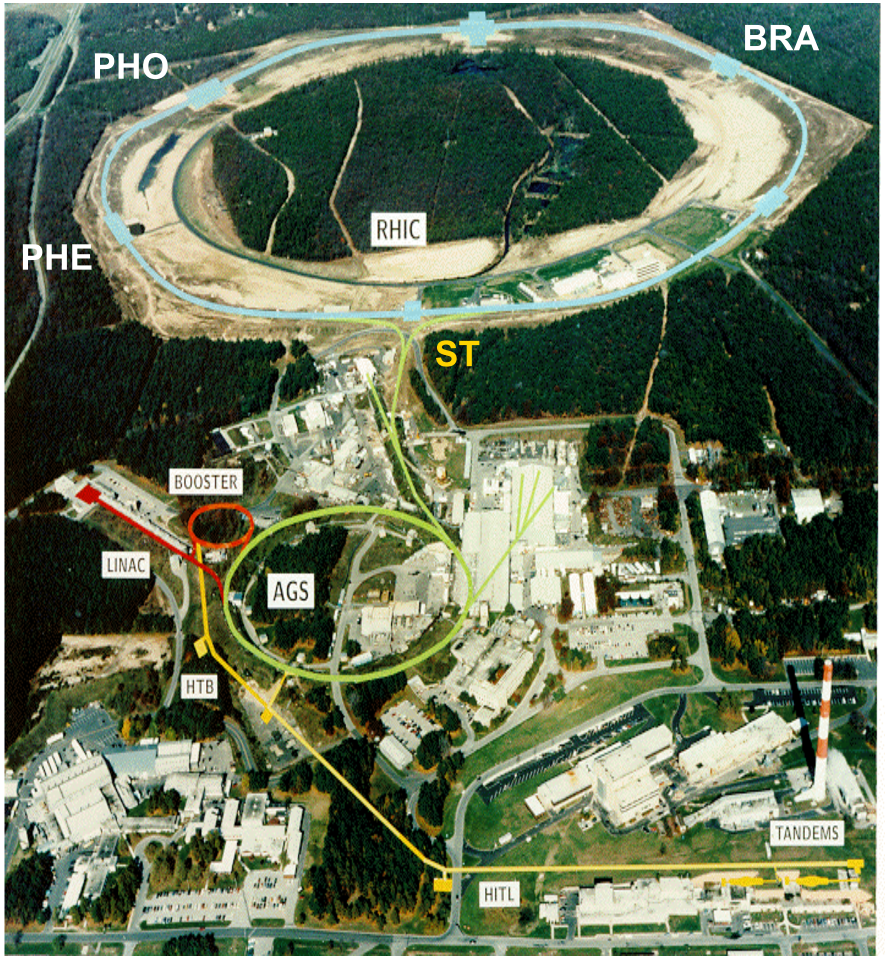
Laboratoire de Physique Subatomique et des technologies associees (SUBATECH) and University of Nantes, France

Corfu TR33 meeting on "Particles and the Universe"

17-21 September 2012, Corfu, Greece

BNL, Long Island, New York

CERN, Geneva



Outline

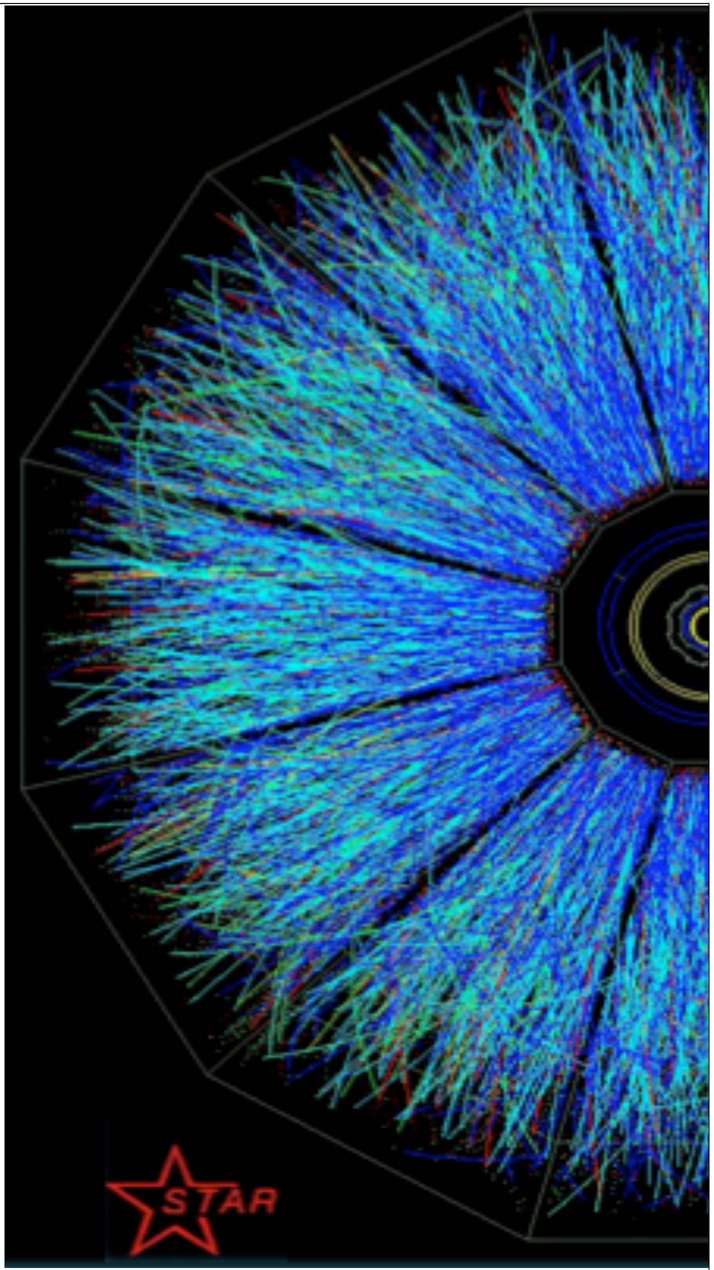
I Introduction

- A. The QCD phase transition
- B. The QCD Phase transition and the early universe
- C. Neutron stars/Quark stars
- D. The QCD phase transition and Heavy Ion collisions : Set the questions to answer

II A historical tour and latest hot news on selected physics items :

- A. Direct thermal photons
- B. Flow, strangeness
- C. Jet quenching
- D. Quarkonia

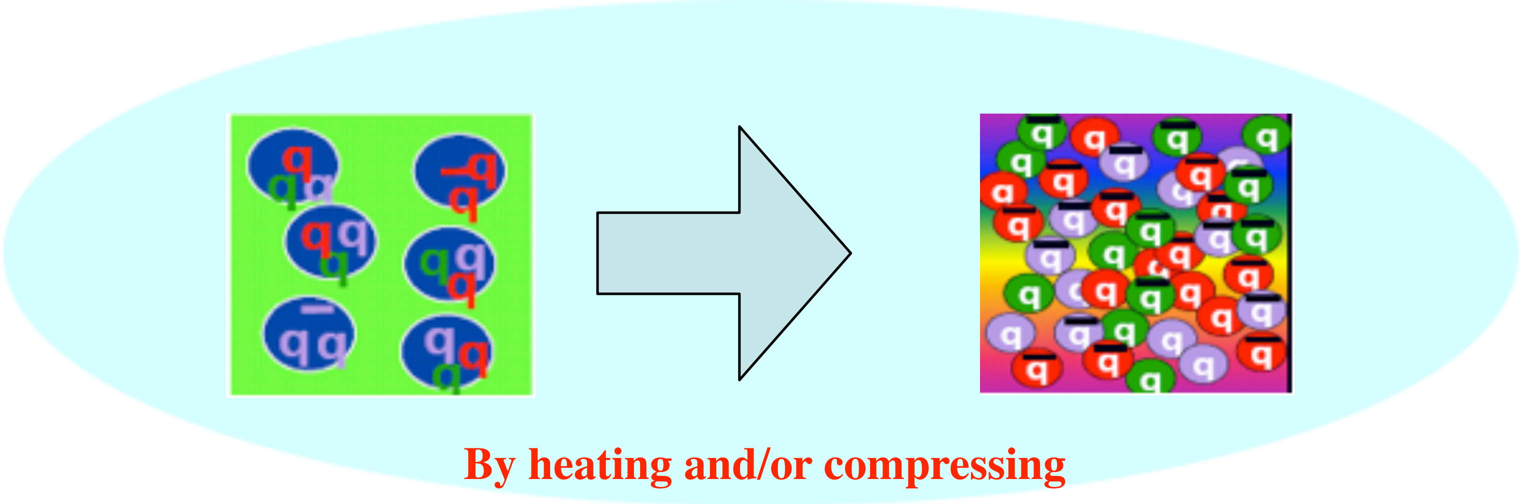
III Conclusions and Outlook



I Introduction

- The QCD phase transition

Initial idea : create matter at extreme conditions of high density colliding heavy ions



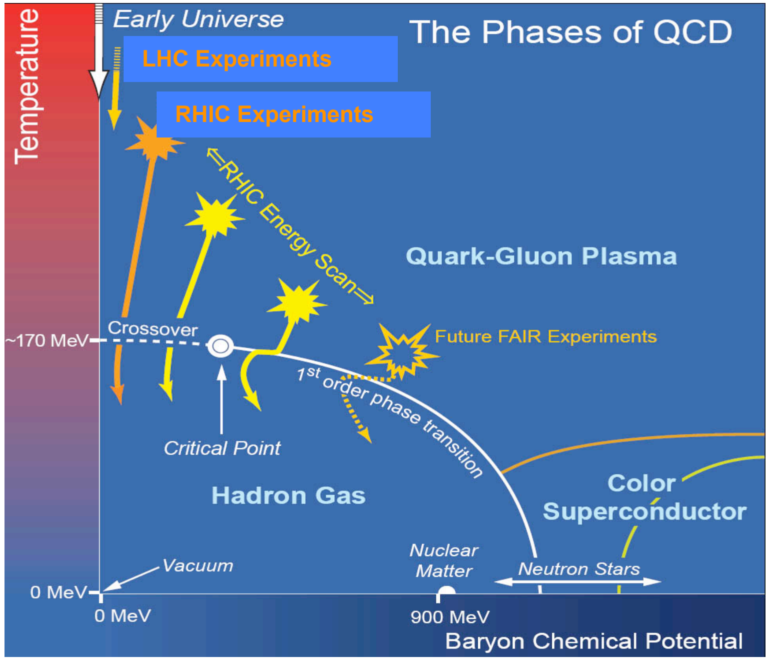
By heating and/or compressing

High Energy Heavy ion collisions ?

Interior of neutron stars - Quark stars ?

A search that started at the Bevalac, Berkeley (1970-), moving to Brookhaven Lab (1988-) and to CERN (1989-)

Physics goals: Mapping out the phases of QCD



This plot illustrates propositions and is not proven by measurement interpretation,

QCD on the lattice predicts a cross over at zero net baryon density and T(characteristic) of ~160-180 MeV energy density ~0.6-1GeV/fm^3

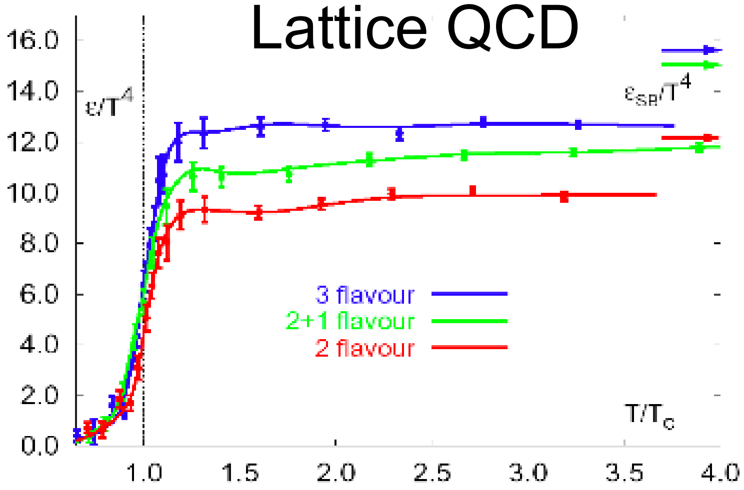
Other predictions: Tc~200 MeV (P.Minkowski, Czech. J. Phys. B40 (1990) 1003.

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

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

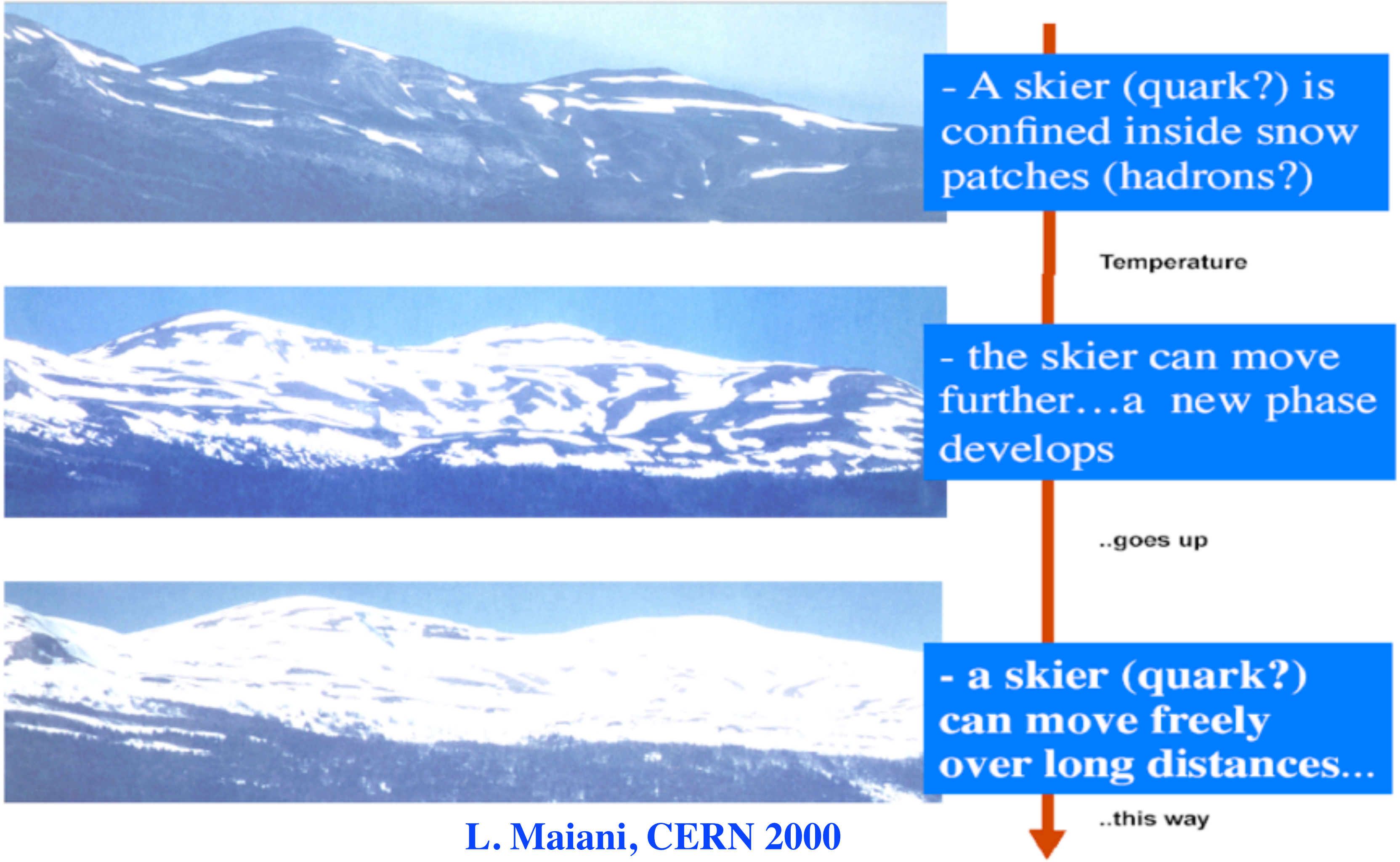
Study QCD matter under extreme conditions of densities and Temperatures

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)



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 seen from Jura



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

Temperature

- the skier can move further…a new phase develops

..goes up

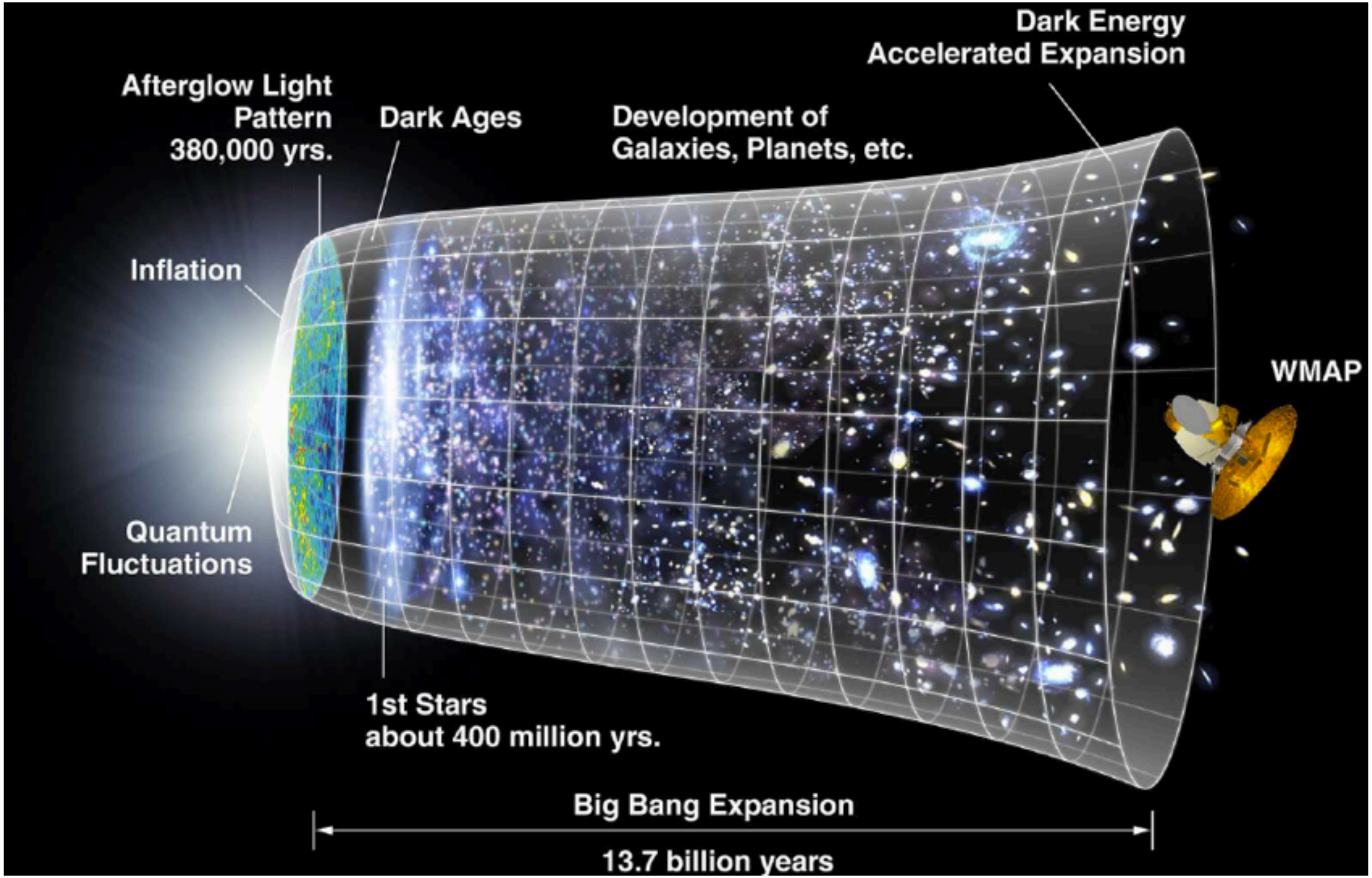
- a skier (quark?) can move freely over long distances…

..this way

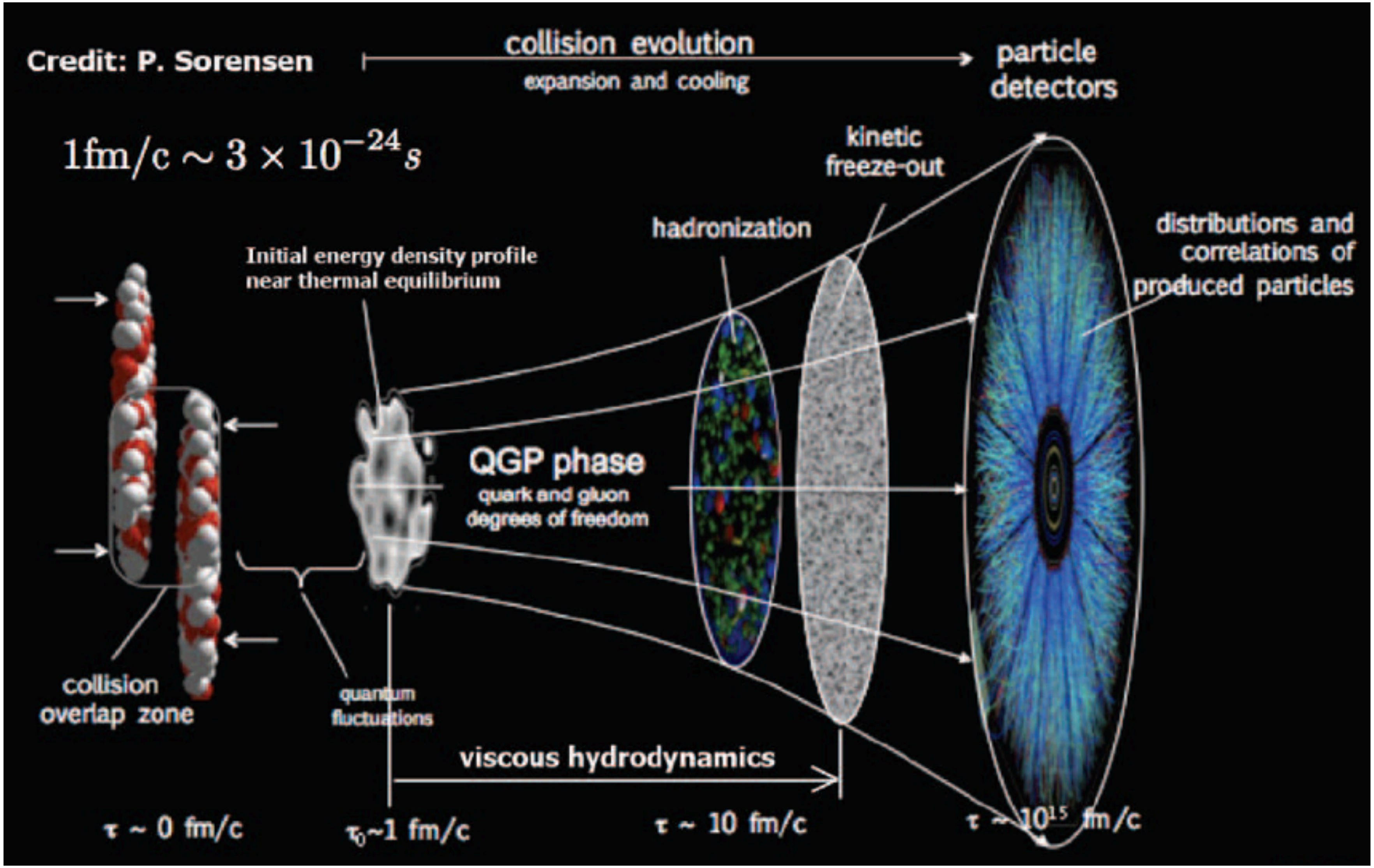
L. Maiani, CERN 2000

The QCD phase transition and the early universe

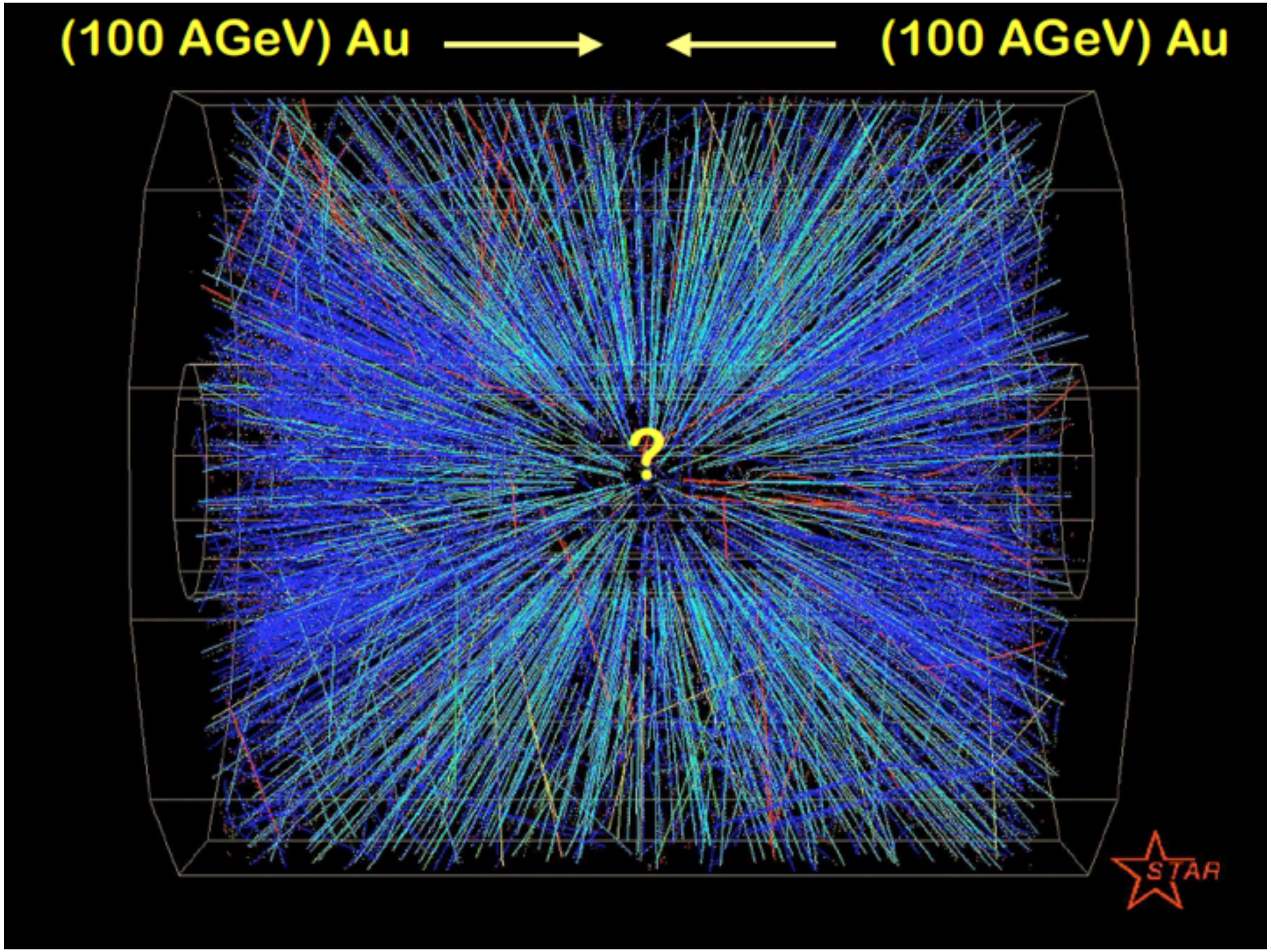
The Big Bang


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

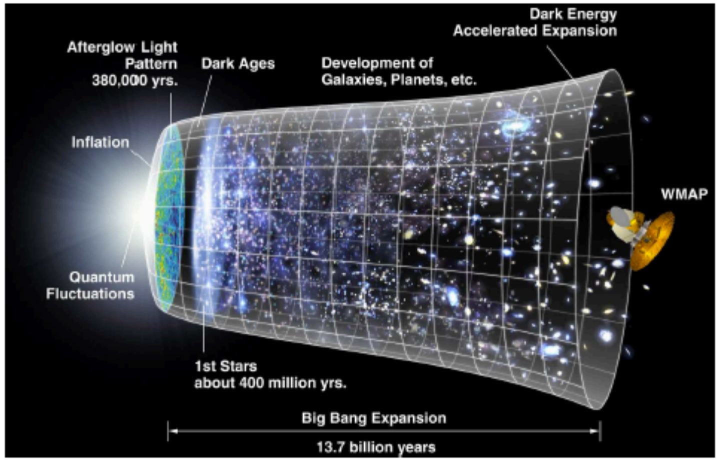
The little Bang

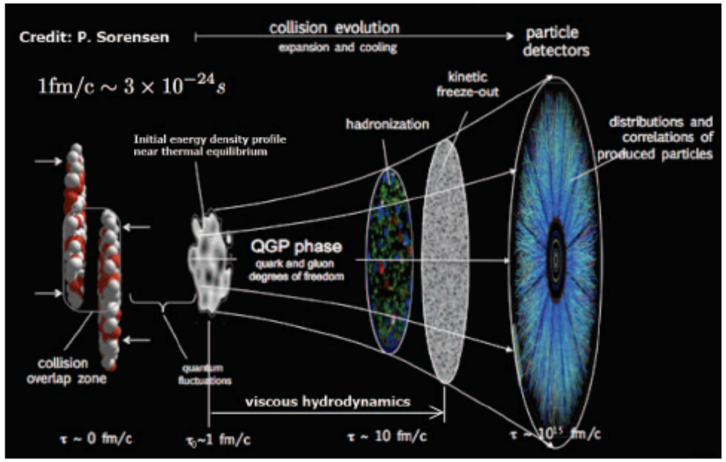


A little bang in STAR



Big bang vs little bang

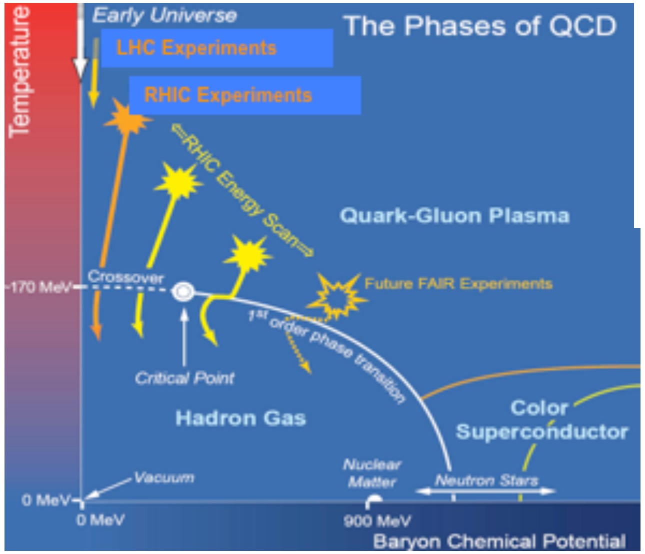


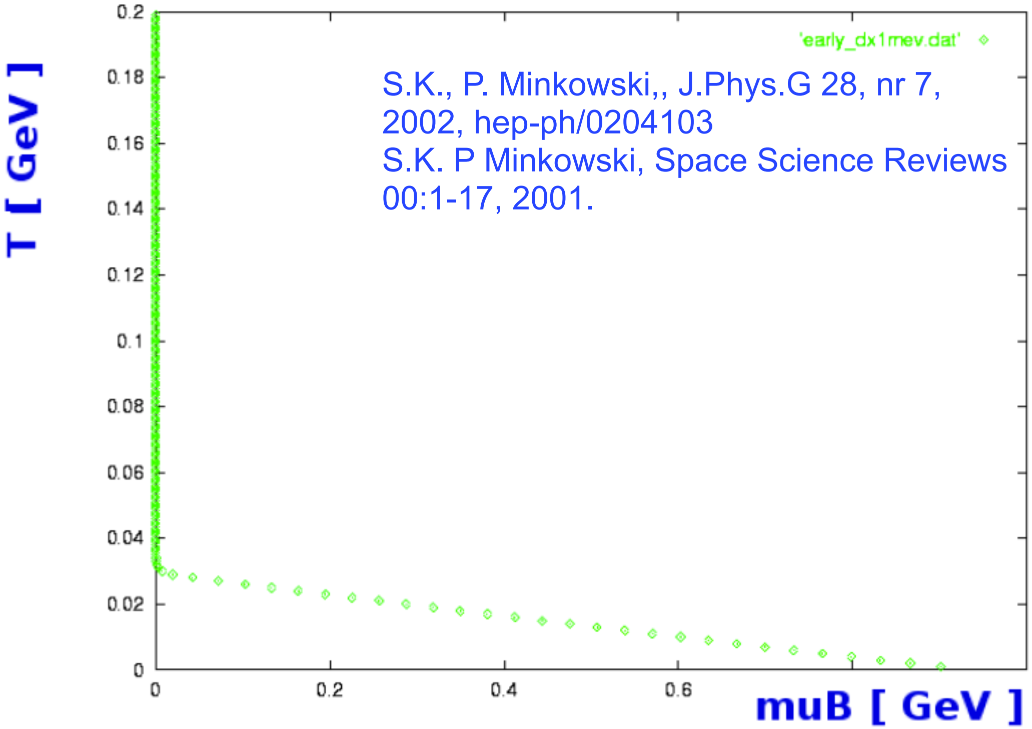


Similarities: - Expansion
- chemical freeze out (nucleosynthesis : hadrosynthesis),
- thermal freeze out happens after chemical freeze out
(Cosmic Microwave Background : hadron pT spectra)
- initial state quantum fluctuations leave imprints in the final state

Differences: - Expansion rates differ by many orders of magnitude.
Expansion is in 3d (not 4d).
Expansion is driven by pressure gradients (not gravity).
- Time scale in fm/c (not in billions of years)
- Distances measured in fm (not light years)

The path of the early universe through the (T, muB) plane

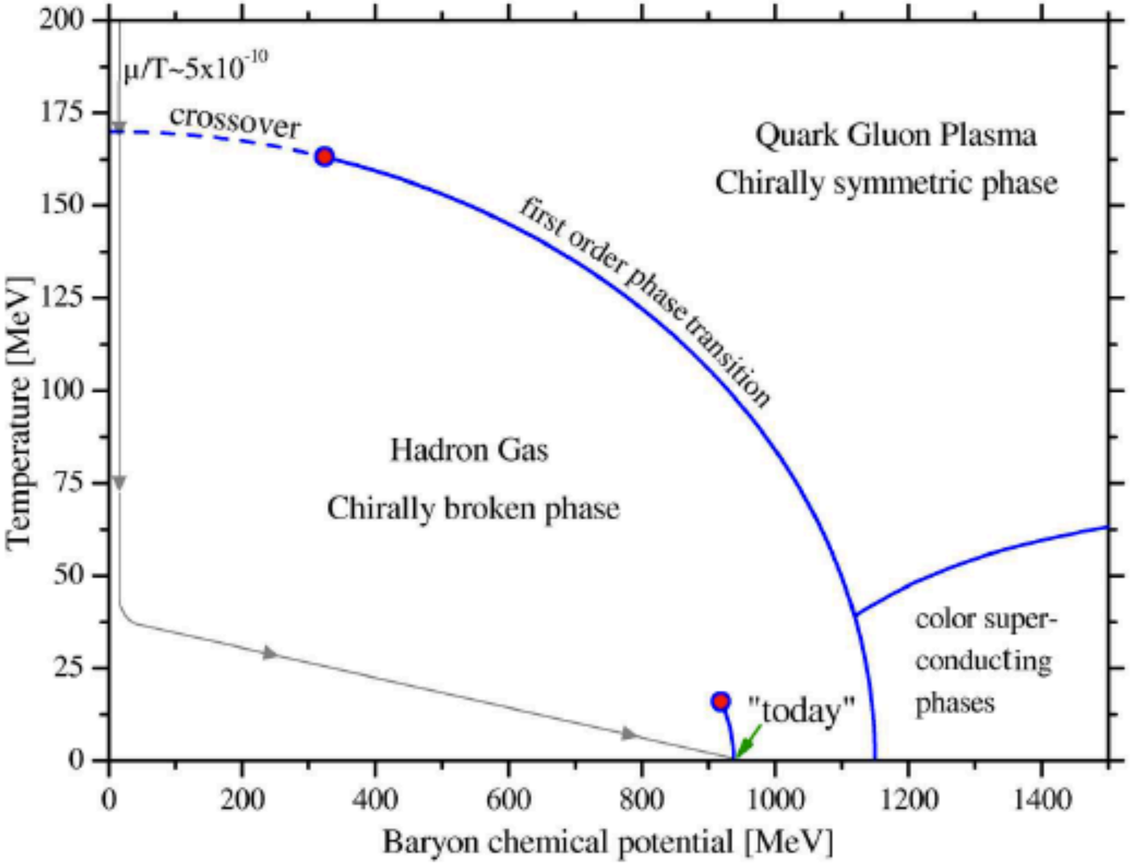




S.K., P. Minkowski,, J.Phys.G 28, nr 7, 2002, hep-ph/0204103
S.K. P Minkowski, Space Science Reviews 00:1-17, 2001.

- **Path of early universe right after the QCD phase transition.**
- **Early universe undergoes a QCD phase transition or cross over**
- **The “big annihilation” starts at around 35 MeV**
- **High energy heavy ion experiments measure antimatter/matter ratios near 1 at T(chem fr out)=170 MeV**

The path of the early universe and the phase transition

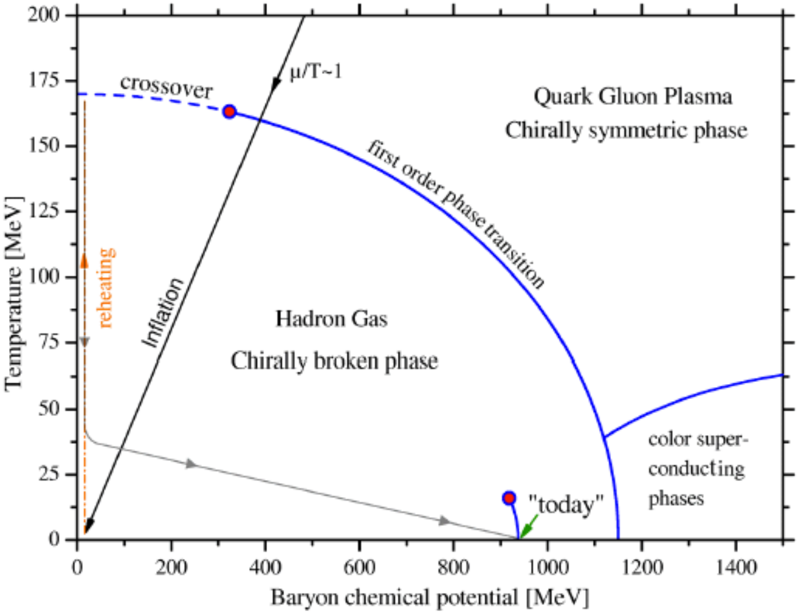


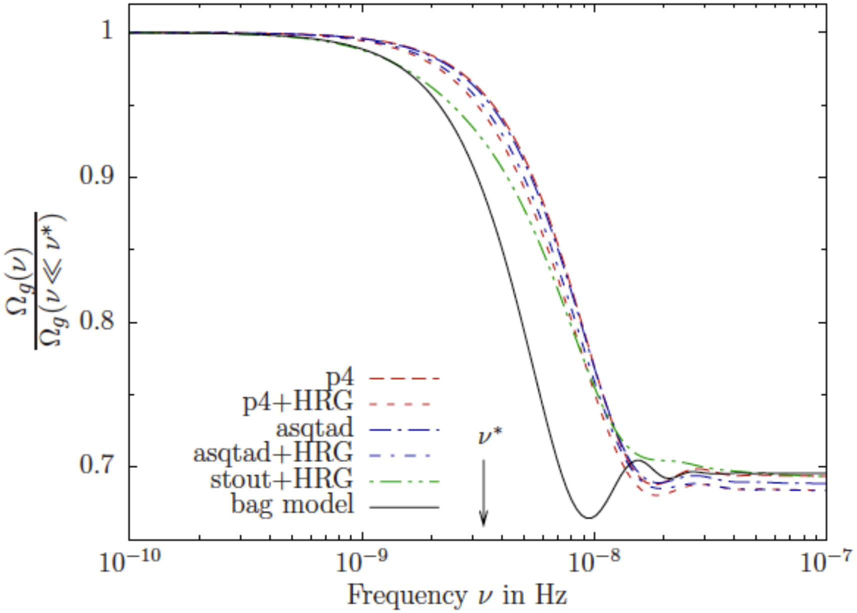
J. Schaffner-Bielich, arXiv: 1105.0339

J Rafelski et al, 2003, astro-ph/0211346

Consequences of a path of early universe through 1st order QCD phase transition

J. Schaffner-Bielich et al, arXiv:1105.0339





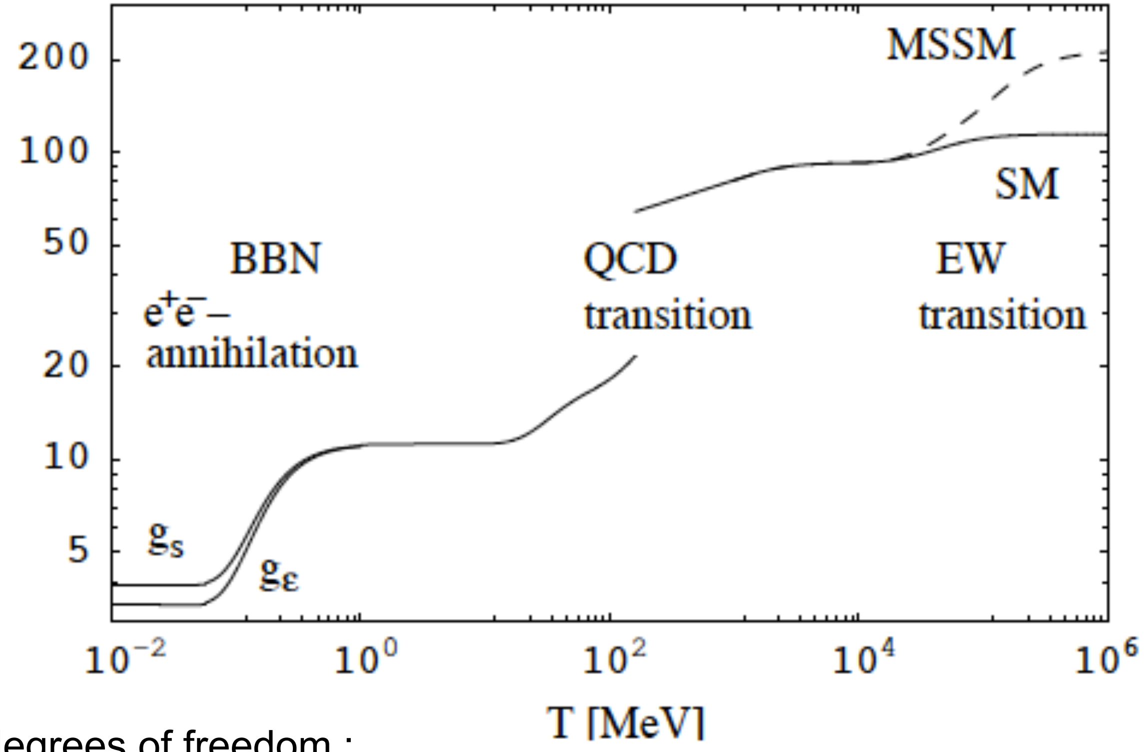
- Assuming a baryon asymmetry before QCD phase transition -> Early universe undergoes a 1st order transition at mB/T~1

- Some consequences: a strong suppression of Grav. Waves (GW) with frequencies above 10-8 Hz and the production of GW in bubble collisions and turbulences during the phase transition.

The effective number of degrees of freedom

D. Schwarz, arXiv:0303574

The effective number of degrees of freedom $g_\epsilon(T) = \epsilon(T)/(\pi^2/30T^4)$.



Full line: standard model of particle physics prediction

Change of degrees of freedom :
Electroweak transition 100-200 GeV, QCD transition 150-180 MeV
e+e- annihilation at ~170 keV

Could QCD relics be CDM candidates ?

Neutron stars/ Quark stars

Neutron stars

Neutron stars have density that can be much higher than nuclear density -> possibility of a quark core

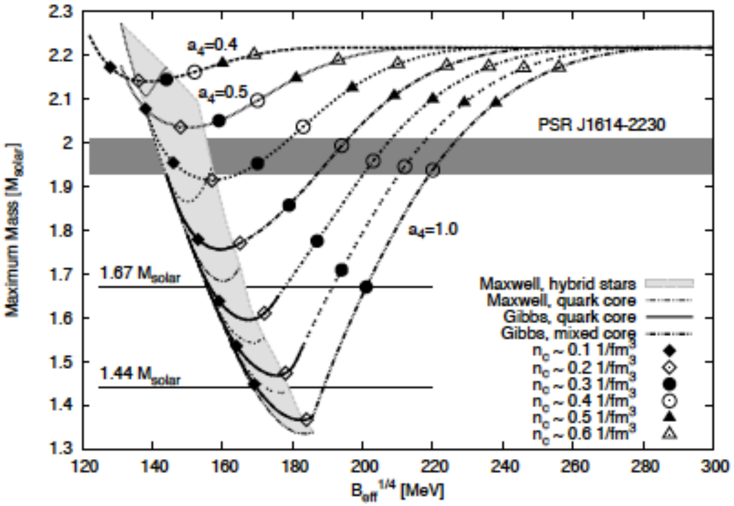
Strange quark matter : true state of matter ? (E Witten) -> Strange quark stars

S. Weissenborn et al, arXiv:1102.2869

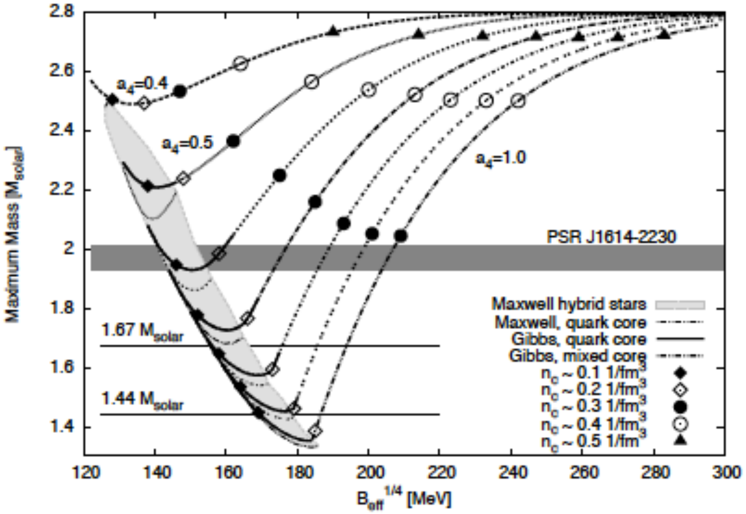
Pulsar PSR J1614-2230 with a mass of 1.97+-0.04 Solar masses, could be a strange star with stable strange quark matter if effects of strong coupling and color-superconductivity are taken into account.

Hybrid stars (with quark core and hadronic outer layer) have masses below hadronic and pure quark stars

Hybrid stars



Stars with hadronic matter



Do stable quark stars matter for Omega(matter) ?

Quark core - hadronic layer - H layer

Large range of possible masses from 1.8 to 375 solar masses for radii from 9 to 1200 km

Such objects maybe candidates for Dark Matter, if formed without affecting nucleosynthesis and CMB

For large masses (more than few solar masses) difficult to detect with grav. lensing

S.K., P. Minkowski,, J.Phys.G 28, nr 7, 2002, hep-ph/0204103
S.K. P Minkowski, Space Science Reviews 00:1-17, 2001.

H	Radius of dark ’star’ (km)	Mass of dark ’star’ (solar masses)	N_B ($N_B(sun)$)
$5\ 10^{-3}$	9.204	1.801	1.853
0.290	411	2.191	2.243
0.295	674	3.179	3.232
0.310	1061	12.63	12.68
0.50	1203	168.13	168.18
0.625	1208	271.06	271.11
0.75	1210	374.02	374.07

The QCD phase transition and Heavy Ion collisions : Set the questions to answer

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 and if yes which is the order, or is it a cross over ?

Which are the critical parameters ?

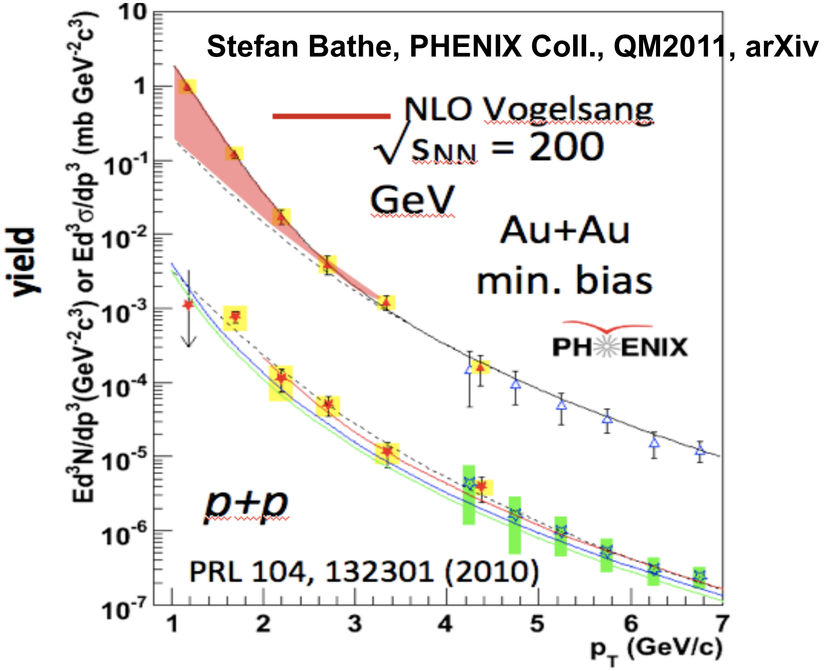
Is this state weakly or strongly interacting ?

Is there a critical point ?

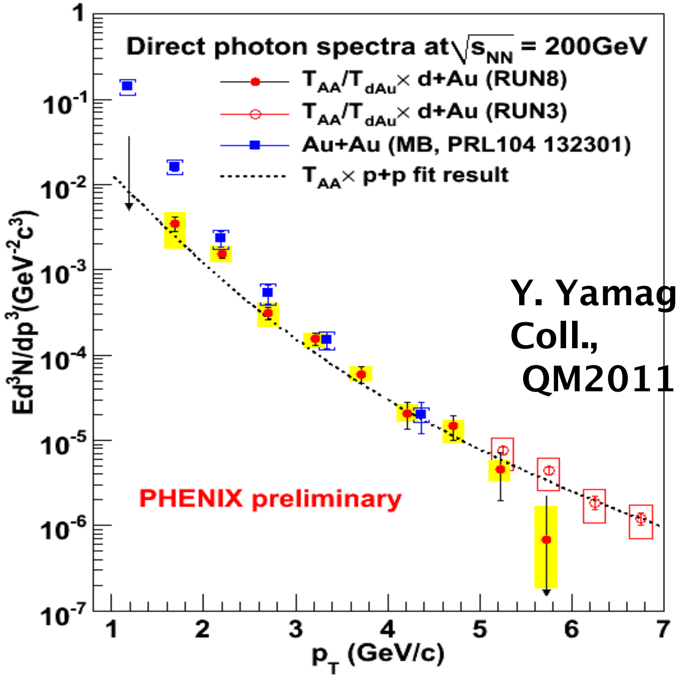
II A historical tour of selected physics results:

1. Direct thermal photons

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


Stefan Bathe, PHENIX Coll., QM2011, arXiv

PRL 104, 132301 (2010)



Y. Yamaguchi, PHENIX Coll.,
QM2011 poster

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 firmly established for the first time !

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

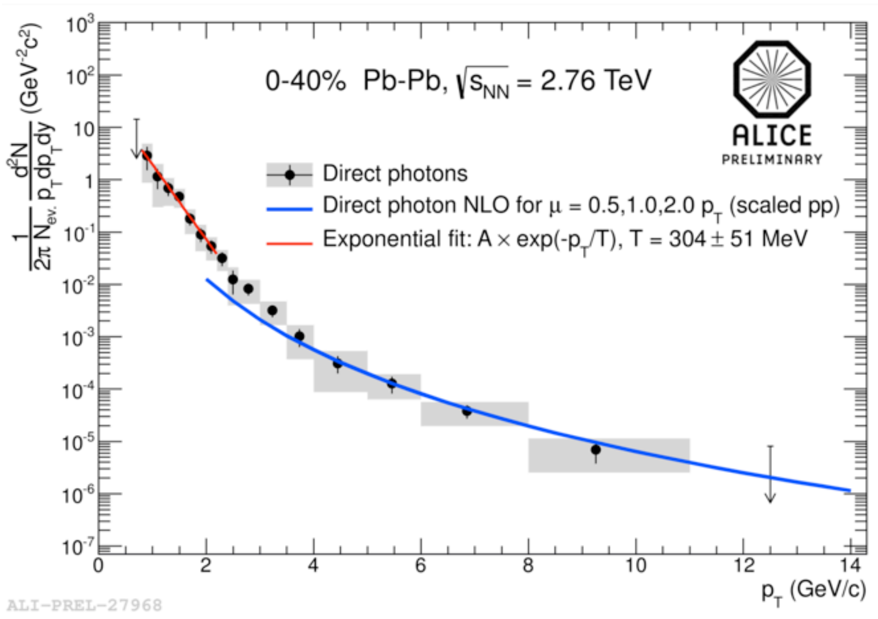
..collisions of gold ions ...have created matter at a temperature of about 4 trillion degrees Celsius ... about 250,000 times hotter than the center of the Sun. **This temperature is higher than the temperature needed to melt protons and neutrons into a plasma of quarks and gluons.**

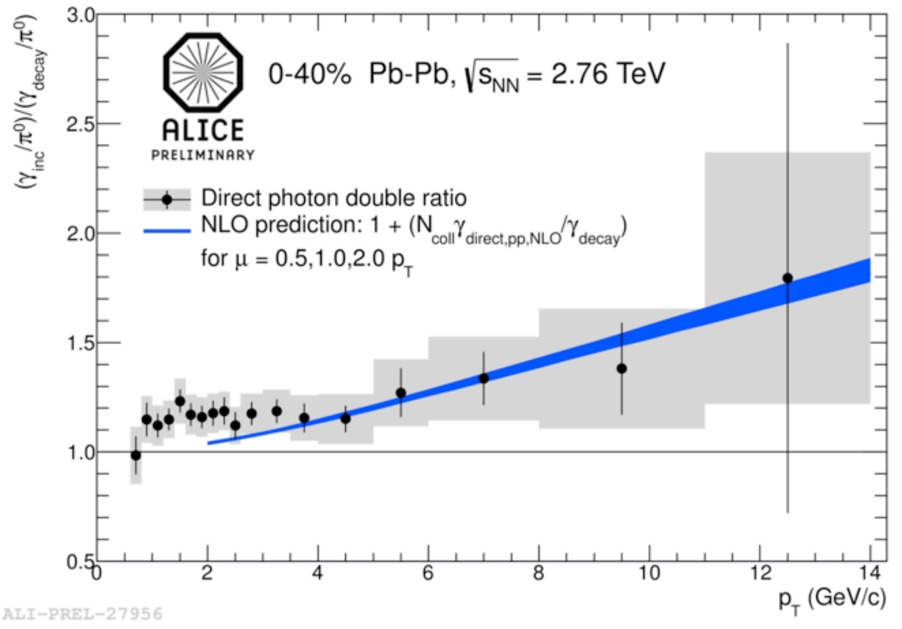
Thermalization seems to be achieved

Latest news: 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 $\sqrt{s}$ 2.76 TeV

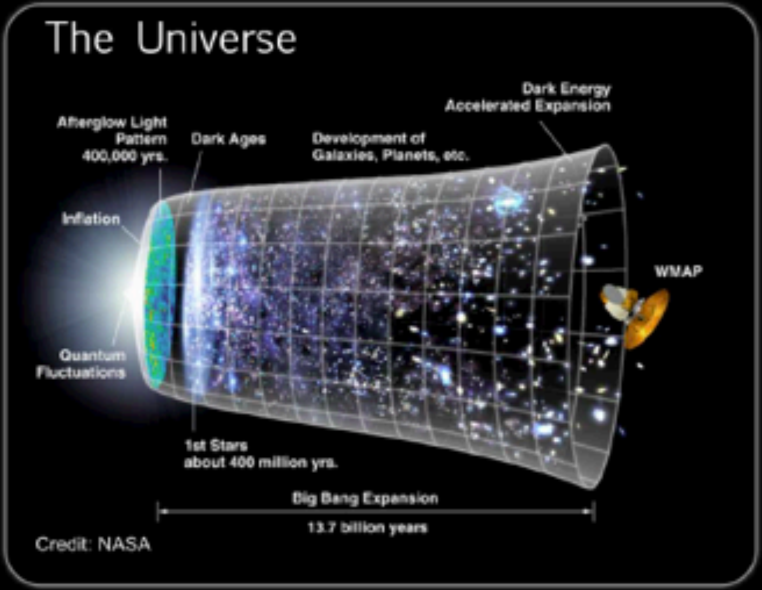
* PHENIX: *T* = 221±19±19 MeV
for 0–20% Au–Au at $\sqrt{s}$ 200 GeV

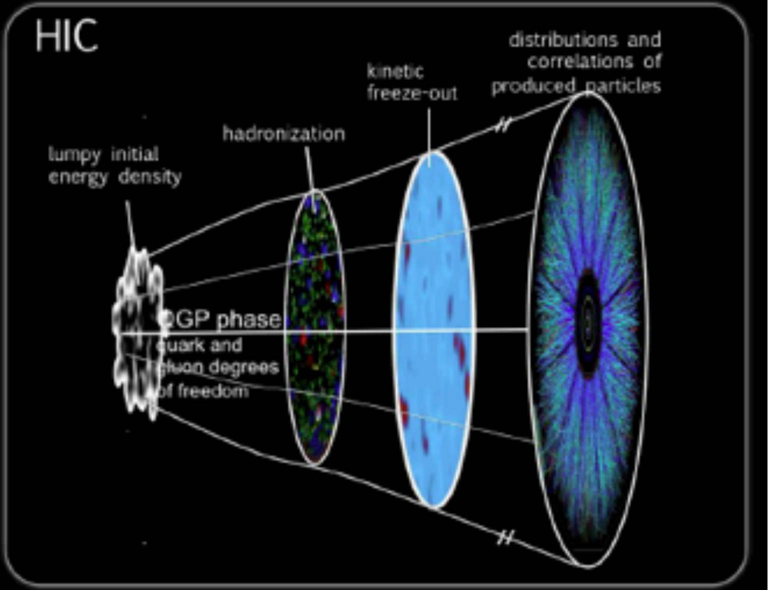
* *p*T < 2 GeV/*c*
~20% excess of direct photons

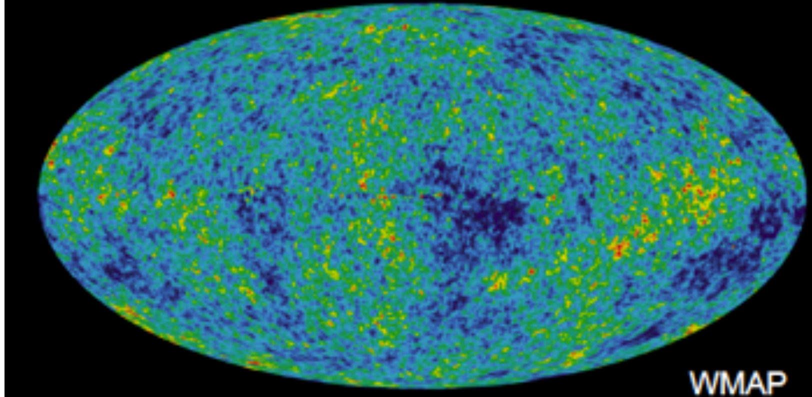
* *p*T > 4 GeV/*c*
agreement with *N*coll-scaled NLO

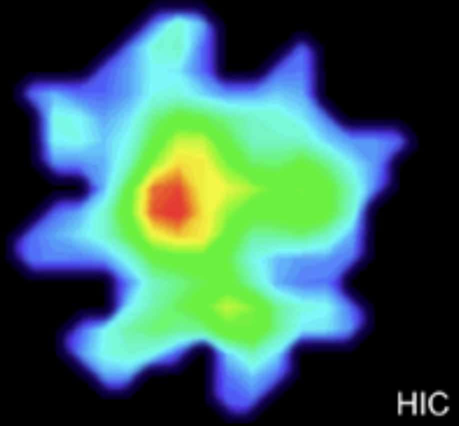
2. Flow, strangeness

The Big Bang vs the Little Bangs

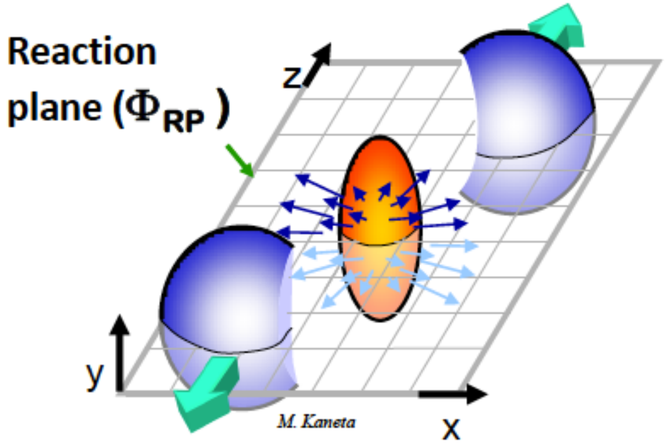


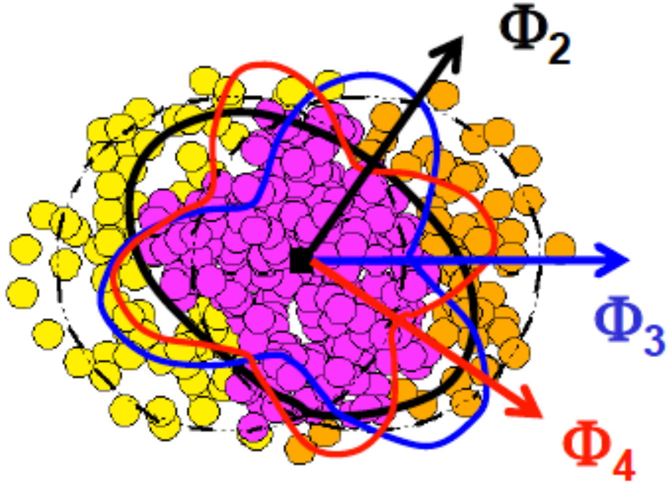






Flow coefficients vn, n=1,2,3..





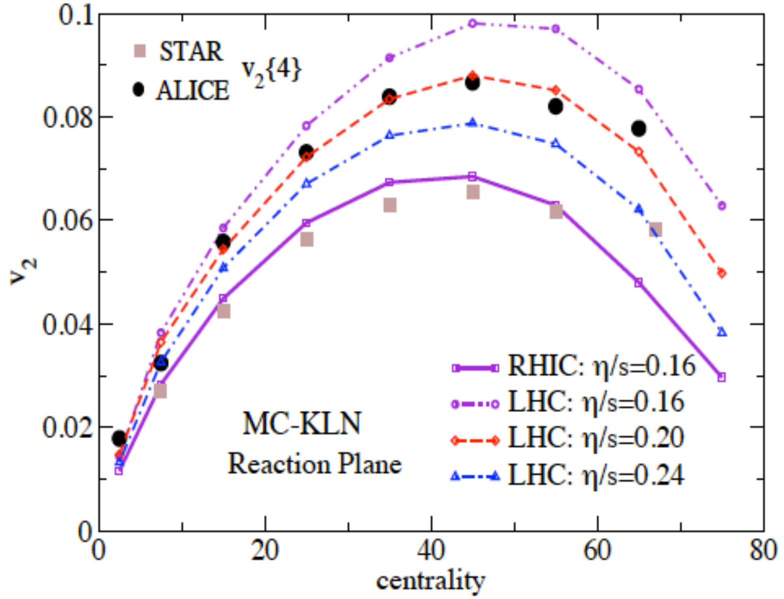
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

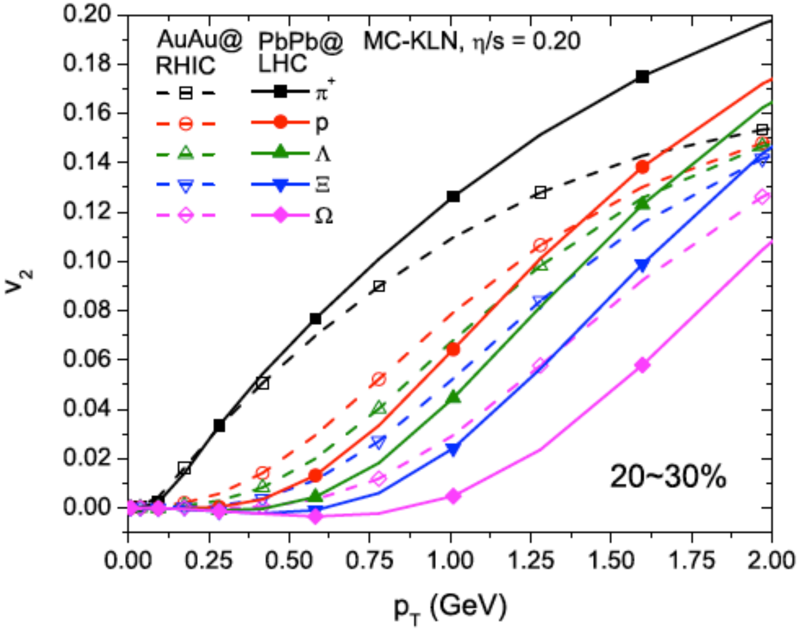
$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

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

Flow and shear viscosity

Shear viscosity estimates based on flow measurements
RHIC : the perfect liquid (see talk by U Heinz)





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

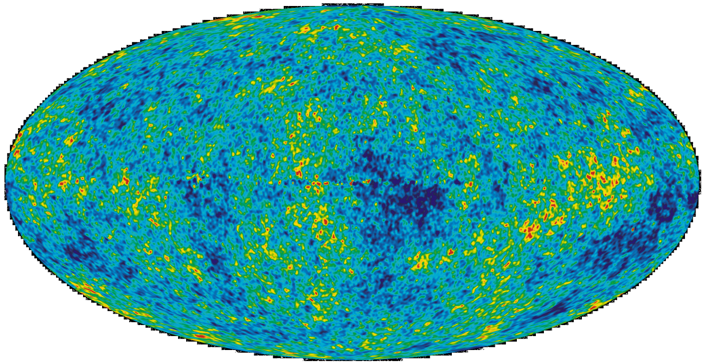
v2 of several identified hadrons, STAR sqrt(s)=200 GeV Au+Au and ALICE Pb+Pb 2.76 TeV

Model with η/s = 0.20 (for LHC)

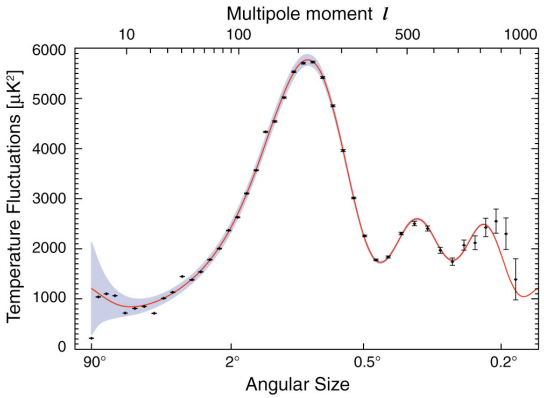
VISHNU : hybrid code = Viscous Israel-Stewart Hydrodynamics in 2+1 dimensions and UrQMD

T fluctuations in CMBR and v_n in sQGP

P Sorensen, STAR, QM2011

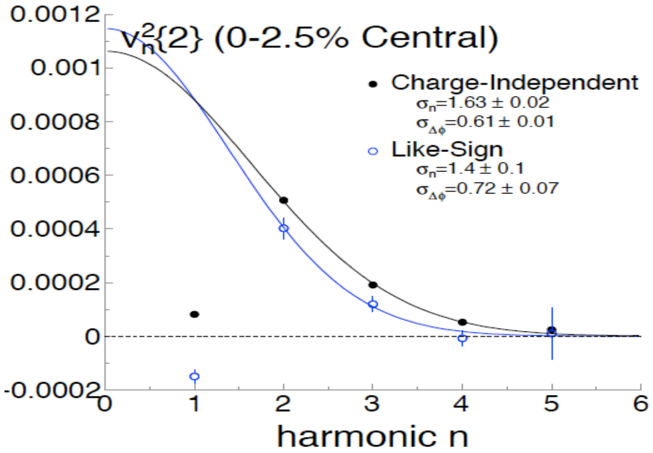


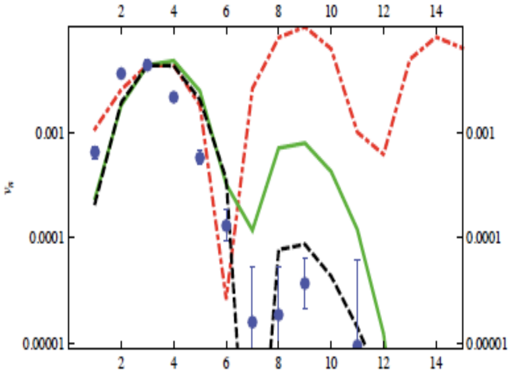
WMAP, Astrophys.J.Suppl.170:288,2007



$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

Kowalski, Lappi and Venugopalan,
Phys.Rev.Lett. 100:022303





P. Staig and E. Shuryak,
arXiv:1106.3243 Data ATLAS, QM2011

Analogous to the Power Spectrum extracted from the Cosmic Microwave Background Radiation

A.P. Mishra, R. K. Mohapatra, P. S. Saumia, A. M. Srivastava, Phys. Rev. C77: 064902, 2008
P. Sorensen, WWND, arXiv:0808.0503 (2008); J. Phys. G37: 094011, 2010

P. Staig et al, arXiv:1008.3139 [nucl-th]
A. Mocsy et al, arXiv:1008.3381 [hep-ph]
A. Adare [PHENIX], arXiv:1105:3928

Strangeness

Strangeness enhancement

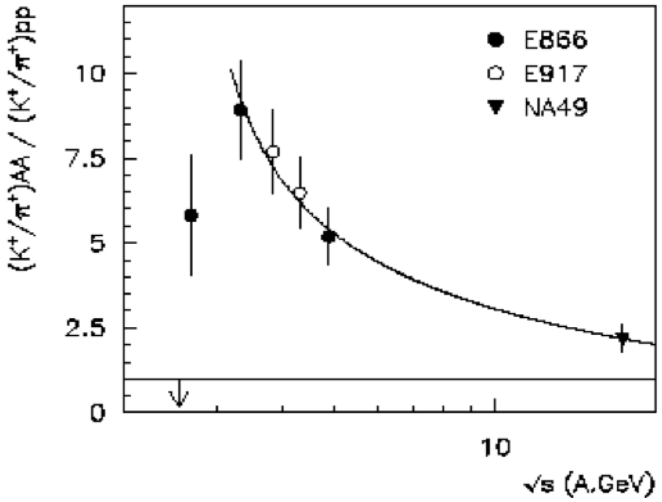
* **Strangeness enhancement was first discovered at the AGS at BNL, then at SPS at CERN**

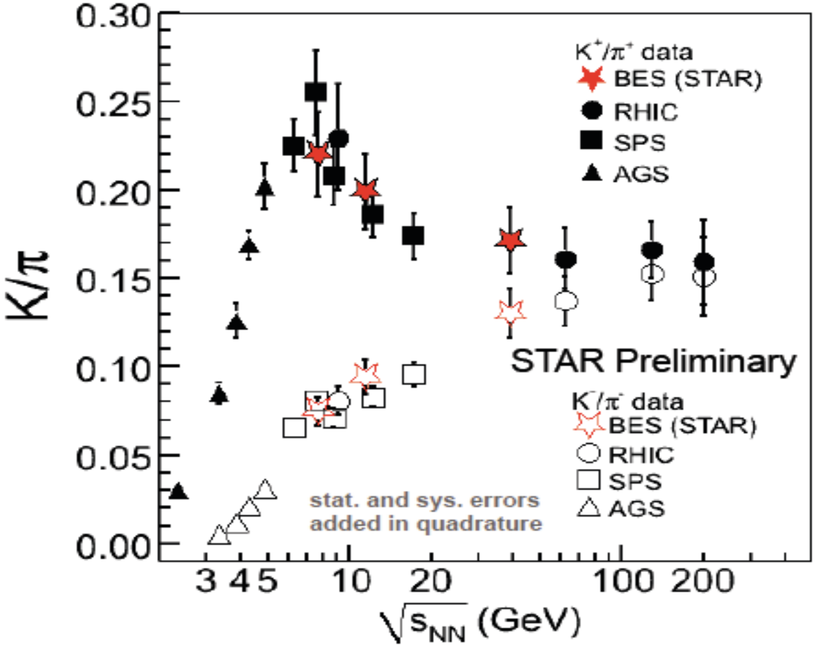
* **Expect to measure strangeness enhancement with increasing energy, and jumbing up above Tc**

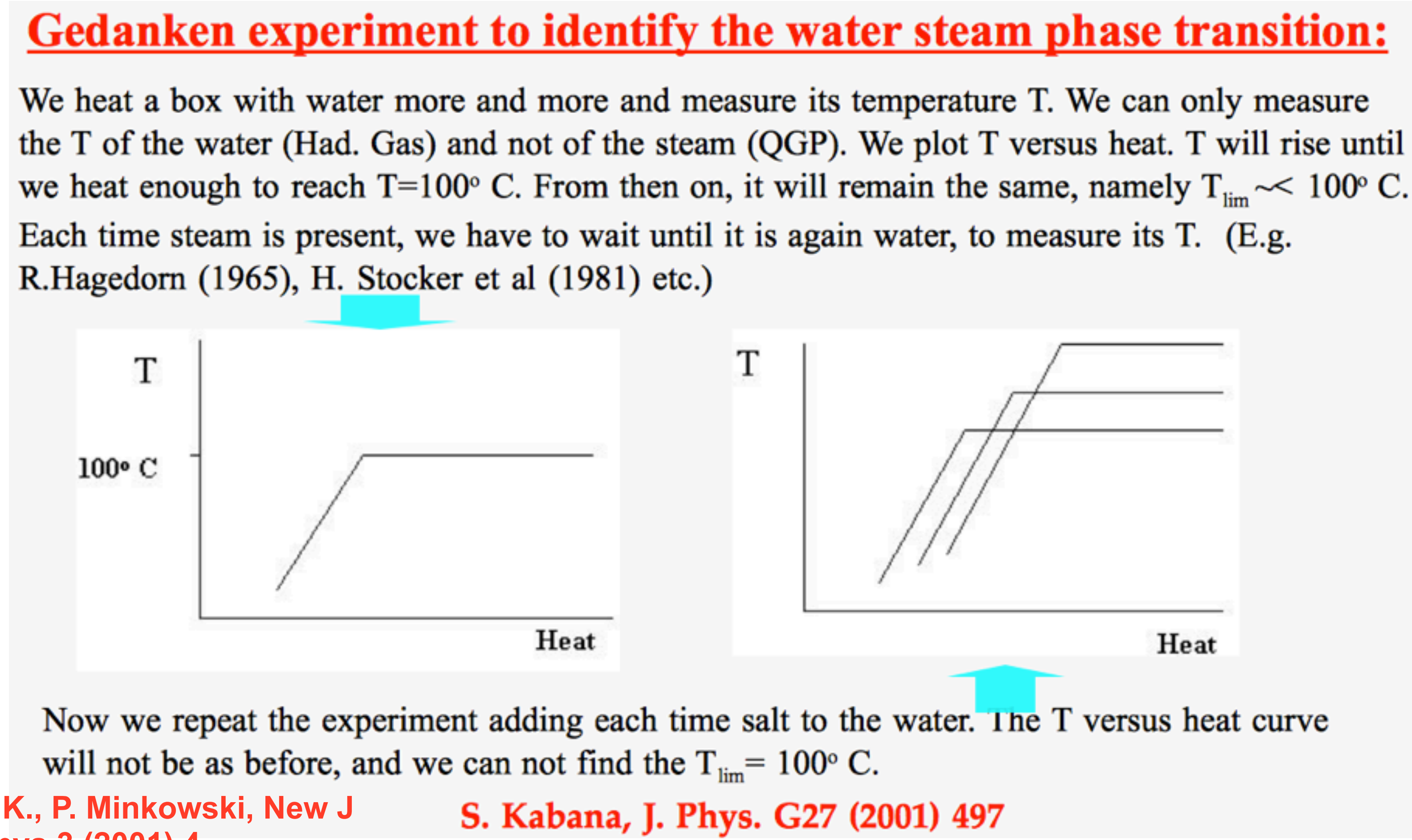
* **However, measurement showed strangeness enhancement increasing with decreasing energy from SPS to AGS !   (opposite to expectation)**

This was later established through the SPS (NA49, NA61) energy scan, and the last 3 years with the RHIC low energy scan (K+/pi+ “horn”, M. Gazdzicki, NA49).
However the maximum is not seen in the K-/pi- ratio.

However: the data points have each one a different muB !







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 $T_{lim} \lesssim 100^{o}$ 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 $T_{lim} = 100^{o}$ C.

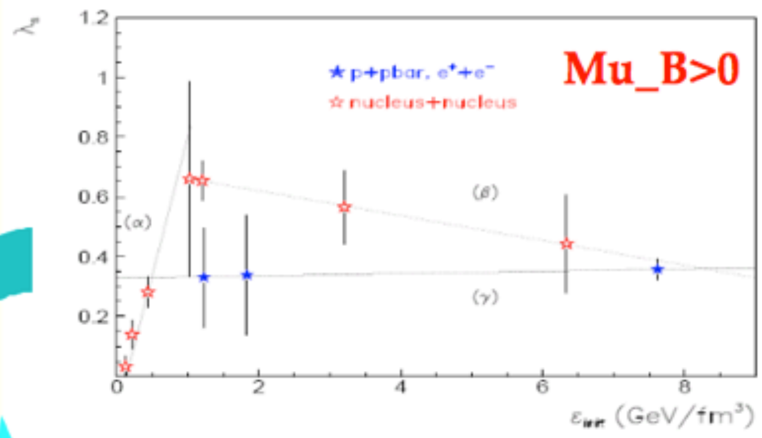
S. Kabana, J. Phys. G27 (2001) 497

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

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.

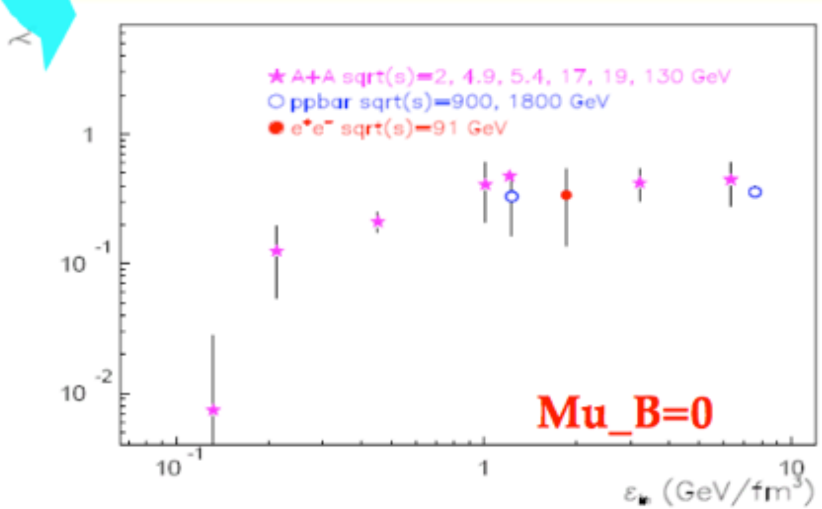
Extracting the salt out of the water

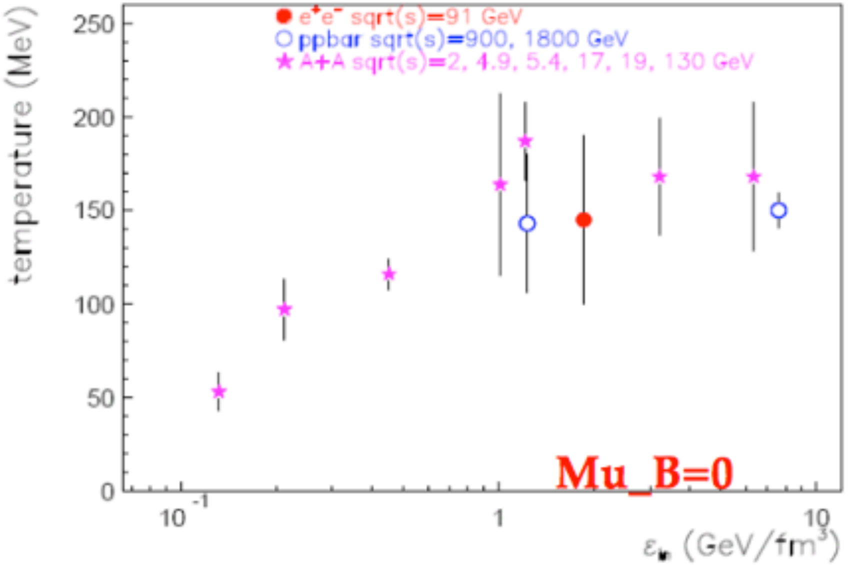


S. Kabana, P Minkowski, New J Phys 3 (2001) 4

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

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





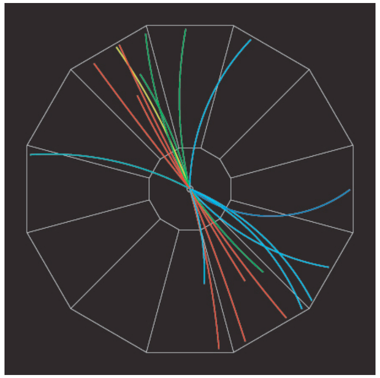
* The strangeness enhancement is not a primary signature of the phase transition, but it grows and saturates following the Temperature at muB=0

* 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

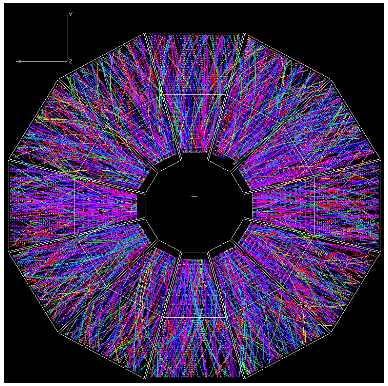
3. Jet quenching

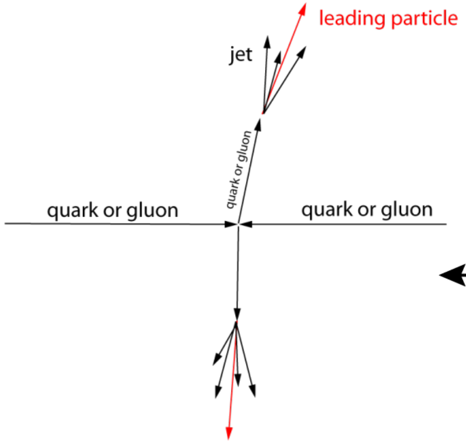
Jet quenching

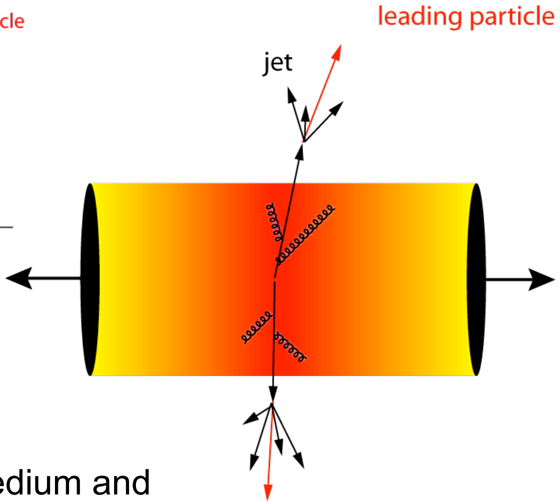
p+p Collision



Au+Au Collision







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

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

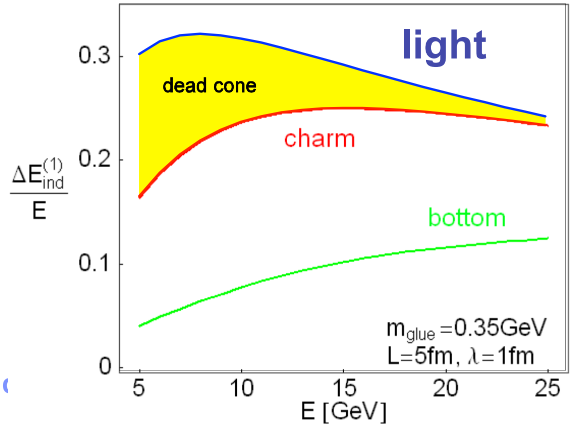
$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

N coll : Average number of NN collisions in AA collision

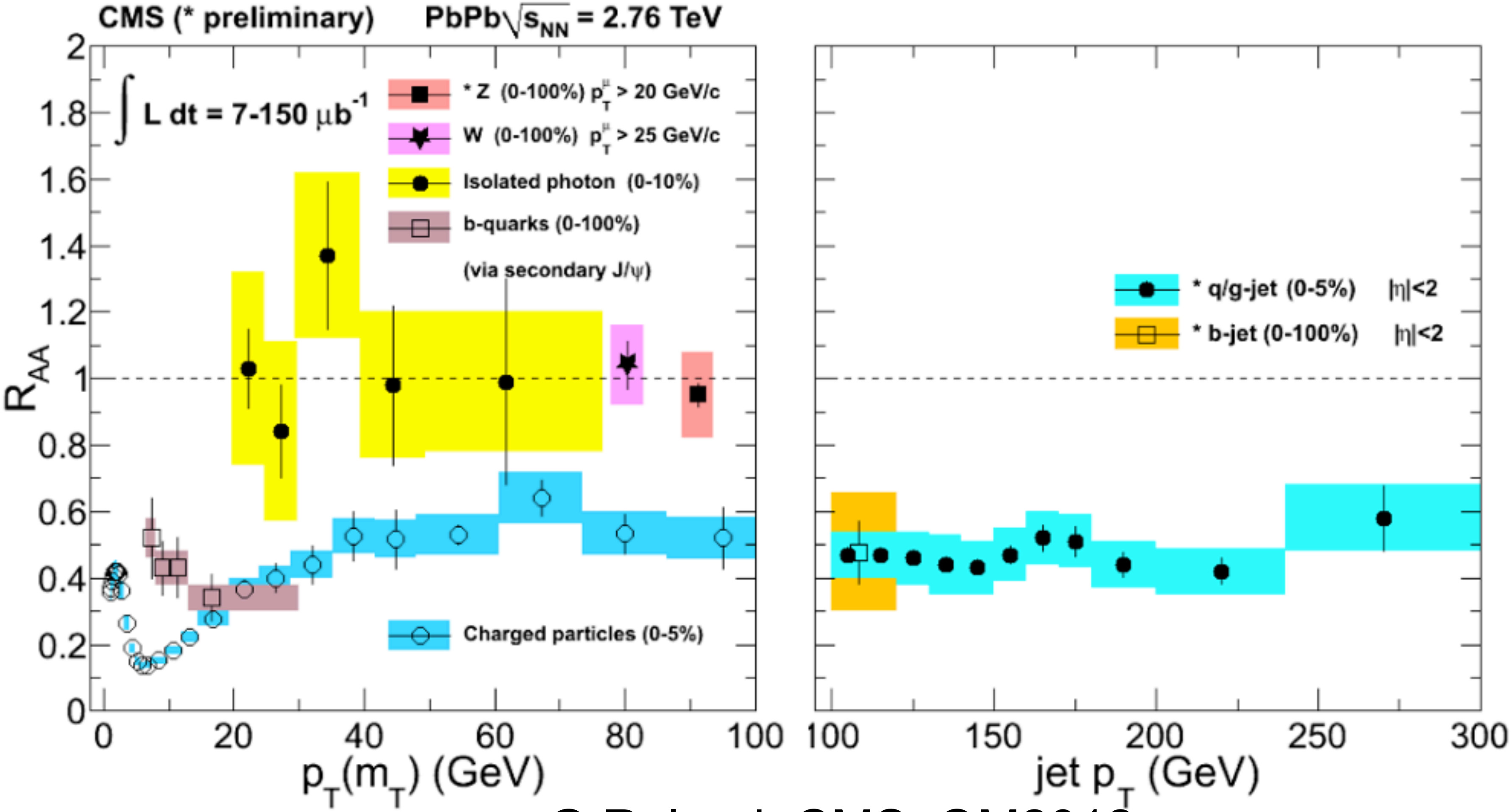
Suppression of jets in AuAu: $R_{AA} < 1$

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)

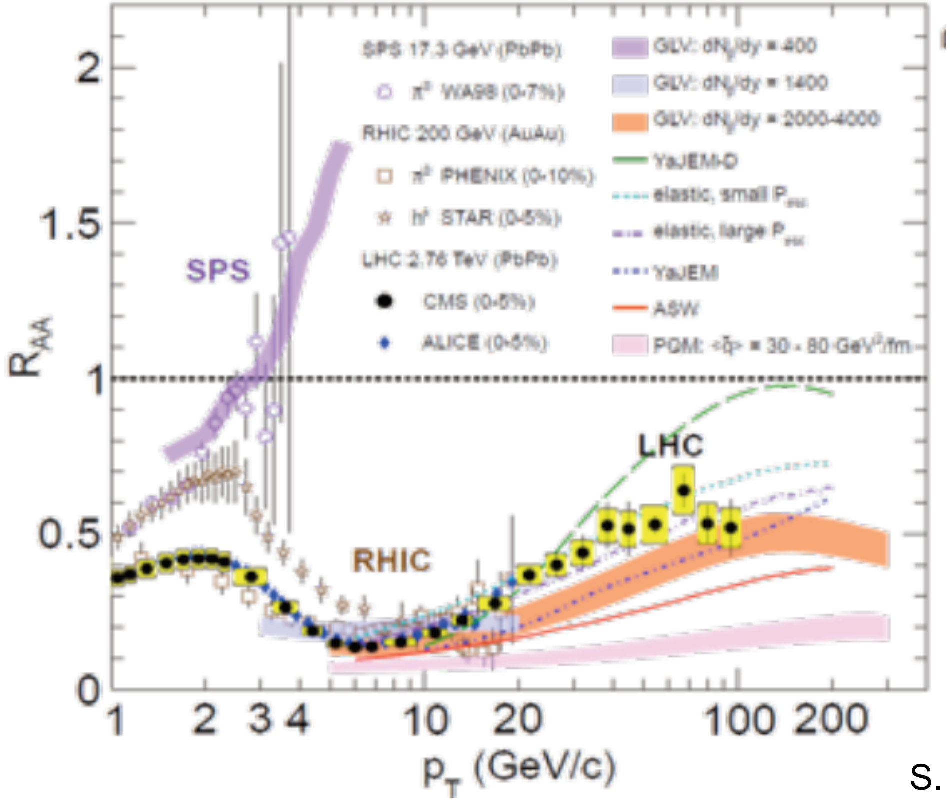


Latest news :
RAA suppression at the LHC



G Roland, CMS, QM2012

Nuclear suppression factor RAA : SPS, RHIC and LHC



S. Milov, J. Solana, QM2012

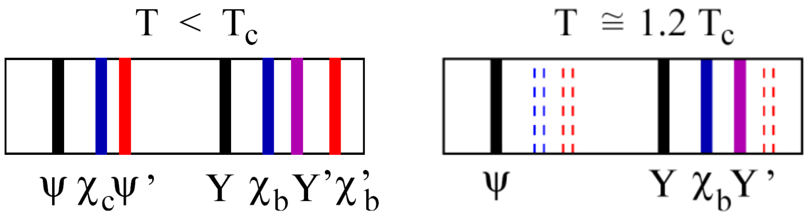
RAA compared to models for energy loss allows for an estimate of gluon density dN/dy(gluon)
Here as an example we get (GLV model):

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

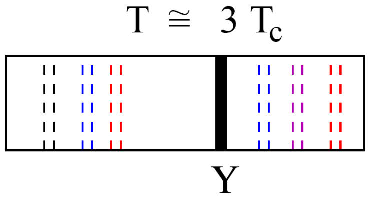
To estimate with confidence dN/dy(g), we should understand the mechanism of jet quenching via studies of its dependence from pT, energy, event plane, path length, centrality, quark mass etc

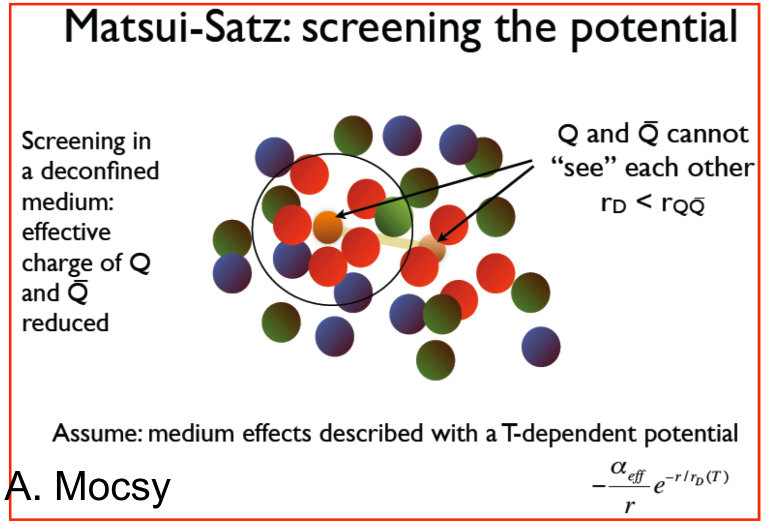
4. Quarkonia

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

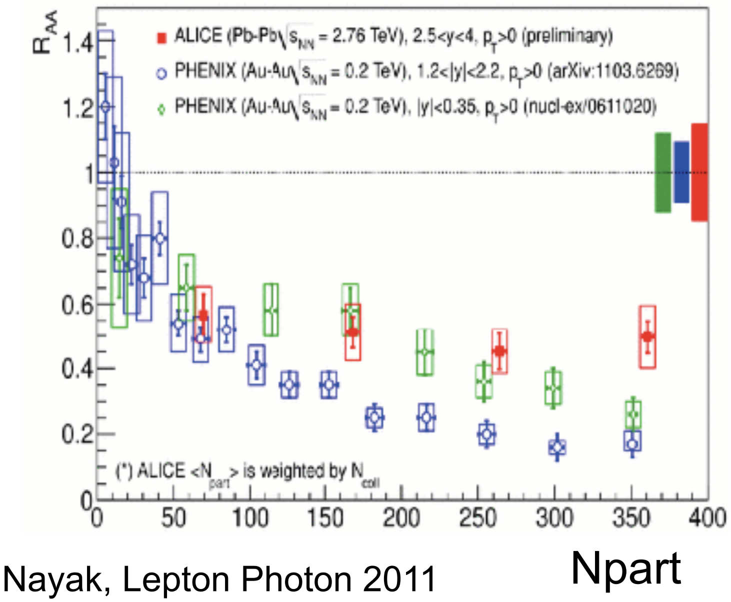
Quarkonia: Thermometer of QGP through hierarchy of T(dissociation)

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

ccbar

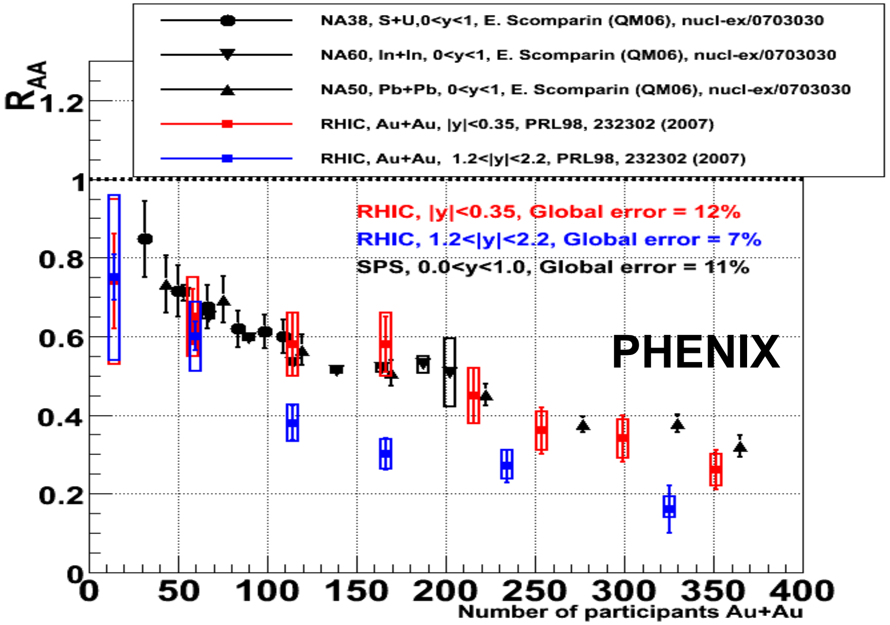
Collision energy dependence of J/Psi

RHIC vs LHC



T. Nayak, Lepton Photon 2011

RHIC vs SPS



J/Psi in forward y in ALICE less suppressed than J/Psi in forward rapidity in RHIC

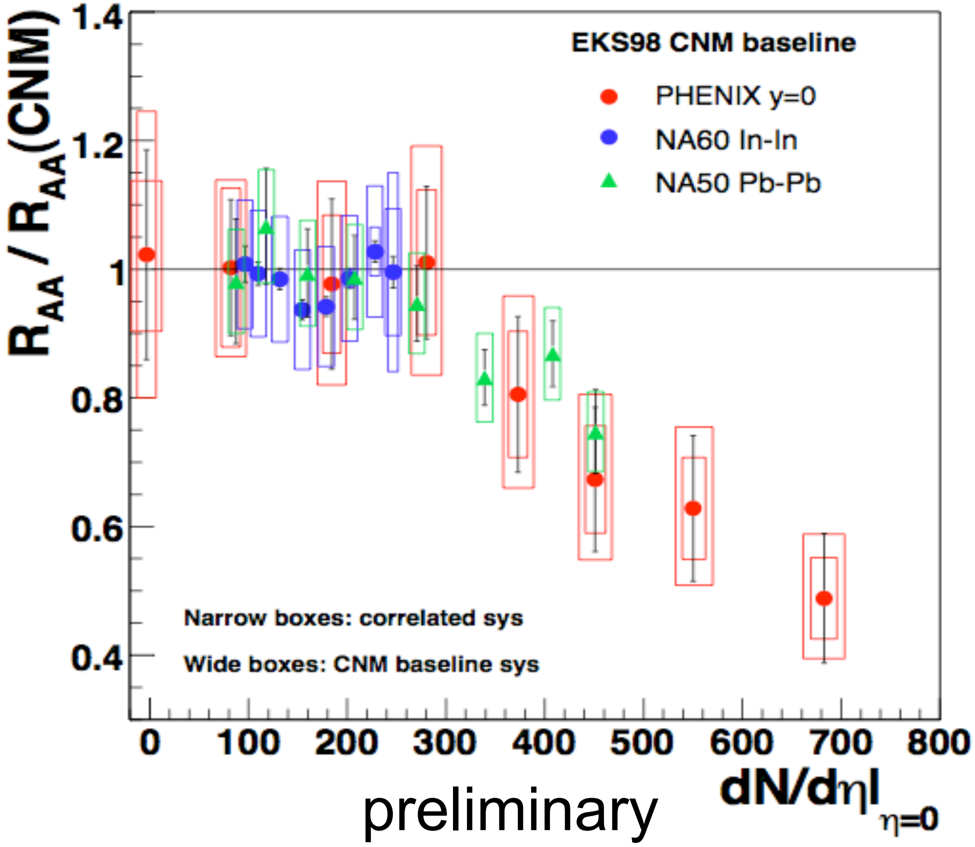
-> hint to recombination of J/Psi at the LHC

J/Psi at ycm is compatible between RHIC and SPS

Energy dependence: To compare J/Ψ at RHIC, SPS and LHC the

- **CNM effects must be estimated with p+A/d+A,**
- **one can look also ratio to open charm,**
- **use same feeding corrections,**
- **look also with x axis parameter that includes both the energy and centrality dependence like the initial energy density.**

The J/Psi RHIC-SPS-comparison -puzzle R Arnaldi



preliminary

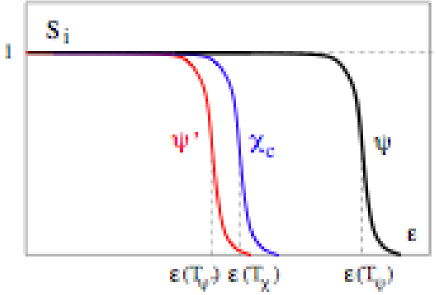
R Arnaldi, D Frawley, Trento 25-29 may 2009

-Divide out cold nuclear matter effects using not model but data (d+Au, p=Au)

- Plot as a function of dN/deta|eta=0 takes into account differences in energy in contrast to N_part.

---> Cold nuclear matter absorbtion effect up to dN/deta|eta=0 = 300

---> Suppression of J/Psi above 300



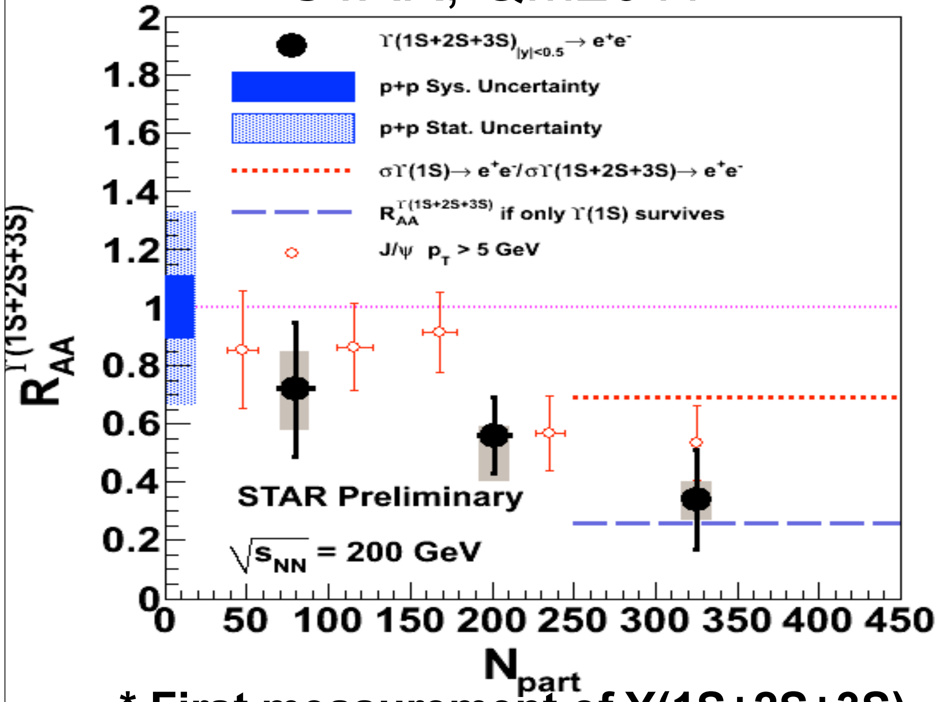
bbar

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

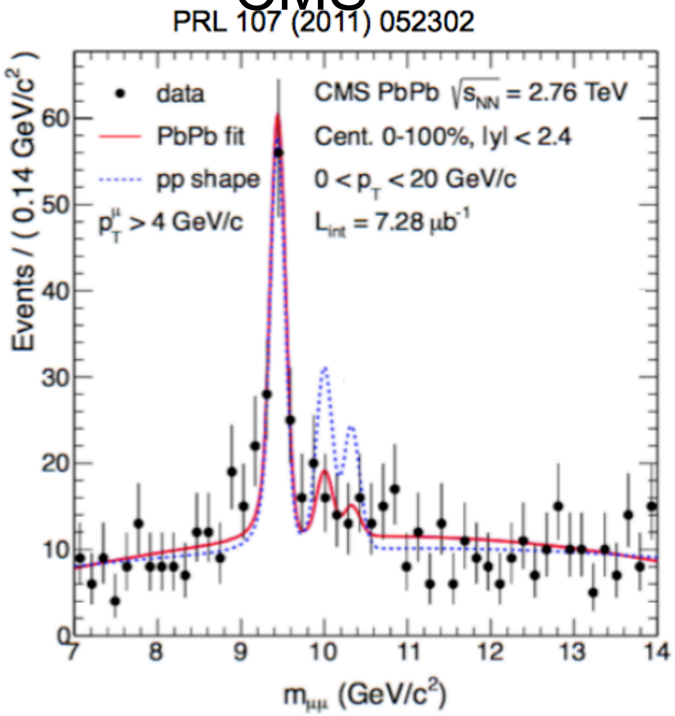
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

H Satz

STAR, QM2011



CMS



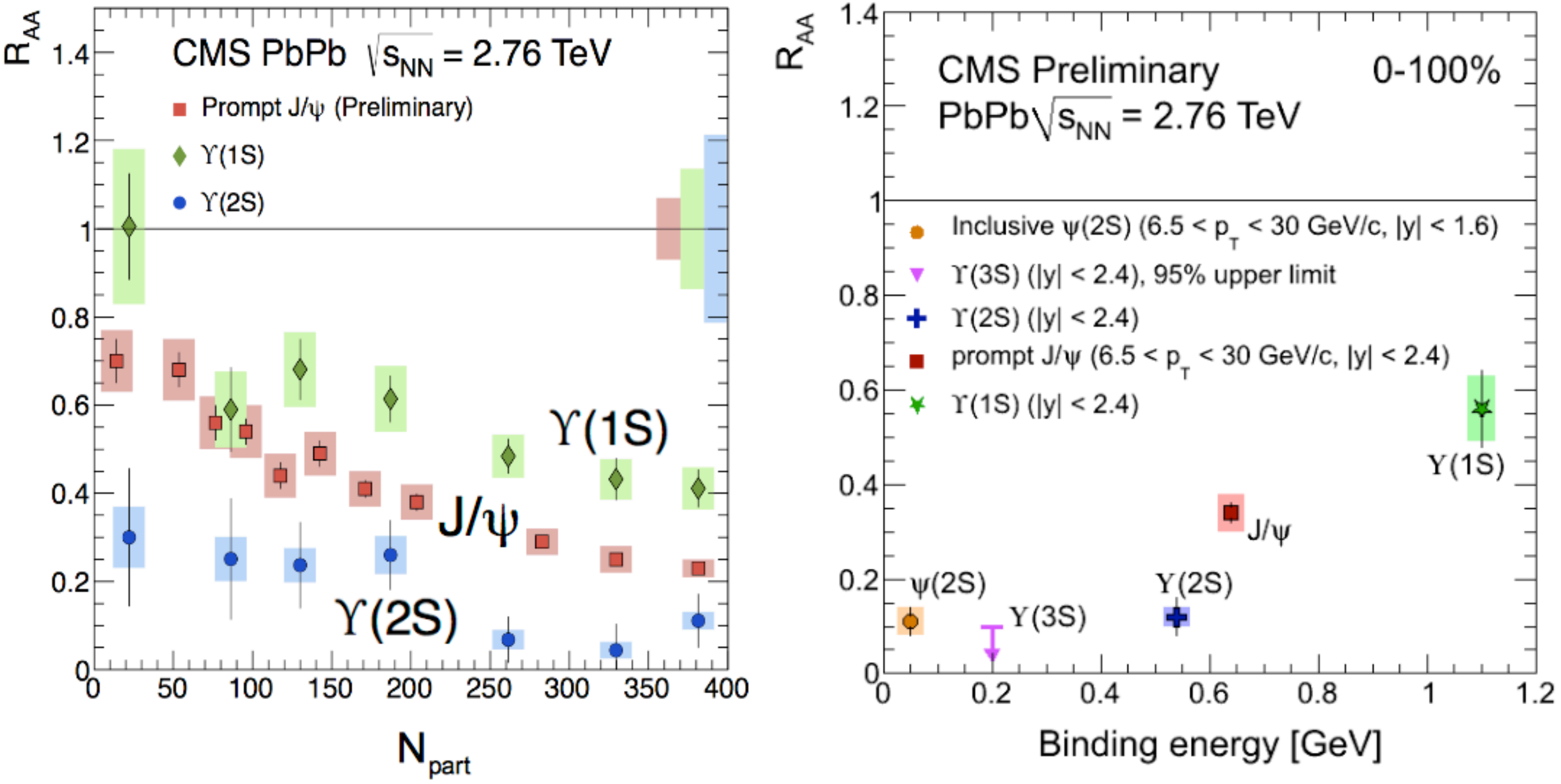
*** First measurement of Y(1S+2S+3S) suppression at RHIC.**

*** 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

G Roland, CMS, QM2012



Clear hierarchy in RAA of different quarkonium states

Expected in terms of binding energy

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

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

T(init) via quarkonia (needs p+A):
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

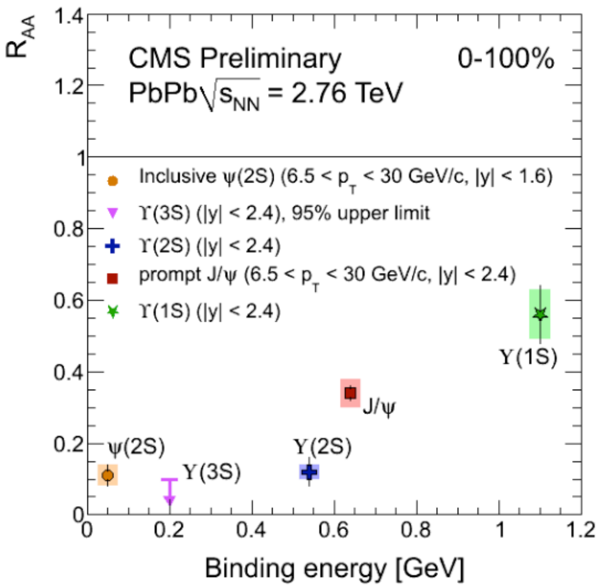
Is this state weakly or strongly interacting ?

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



Heavy Ion Collisions : After 25 years of searches for the QGP in 2012 we arrived at a culmination point with long awaited results.

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

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

to map out the QCD phase transition

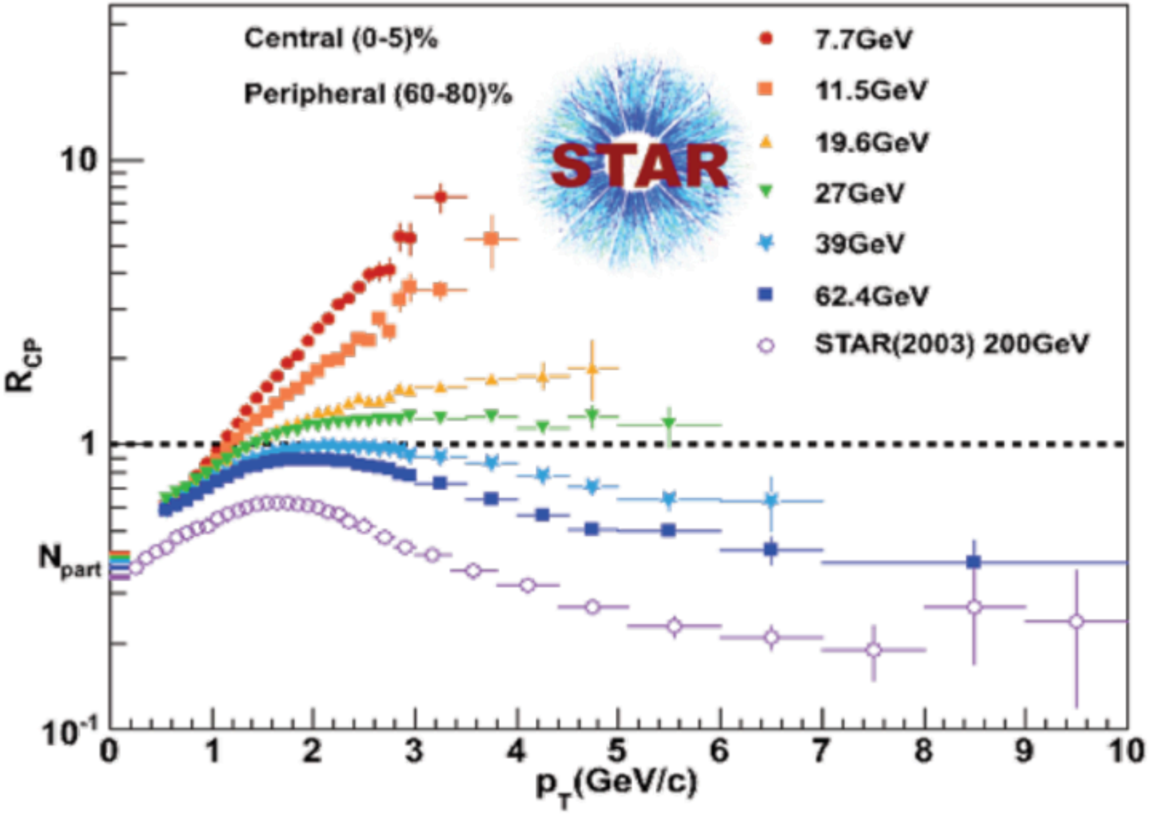
Cosmology:

The QCD phase transition and the early universe- possible consequences (Gravitational waves)

Neutron stars/quark stars ongoing theoretical and experimental work may allow to study the QCD phase diagram and set constraints (dark stars, dark QCD relics?)

Thank you very much for your attention

Collision energy dependence of “jet quenching” : at which energy is it “switched off” ?



S. Milov, J. Solana, STAR, BES, QM2012

RAA falls below 1 below 39 GeV

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 experiment and collider.

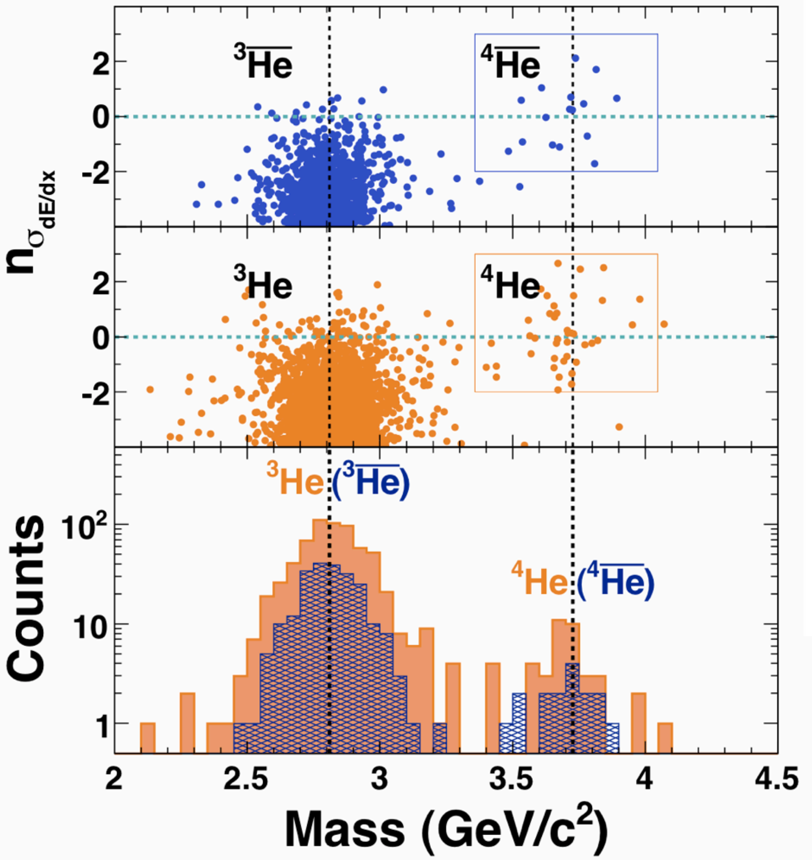
* RHIC short term: new upgrades for highly improved Heavy Flavour and quarkonia measurements.
* RHIC long term: BES II higher statistics for low energy scan, fixed target, eA

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

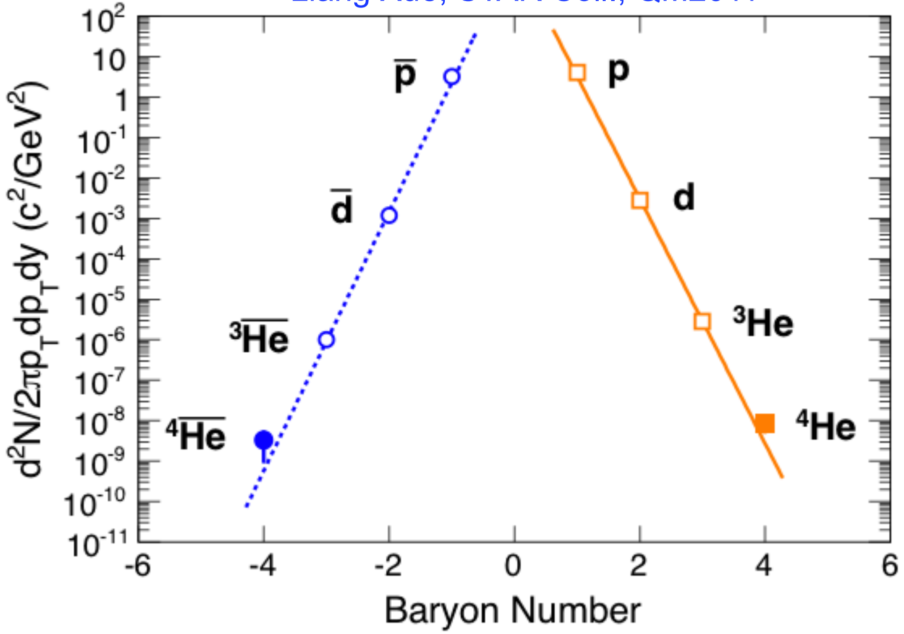
First observation ever of anti-^{4}He

Nature 473, 353-356, (19 May 2011) doi:10.1038/nature10079, ***STAR Collaboration***

The heaviest antimatter nucleus measured



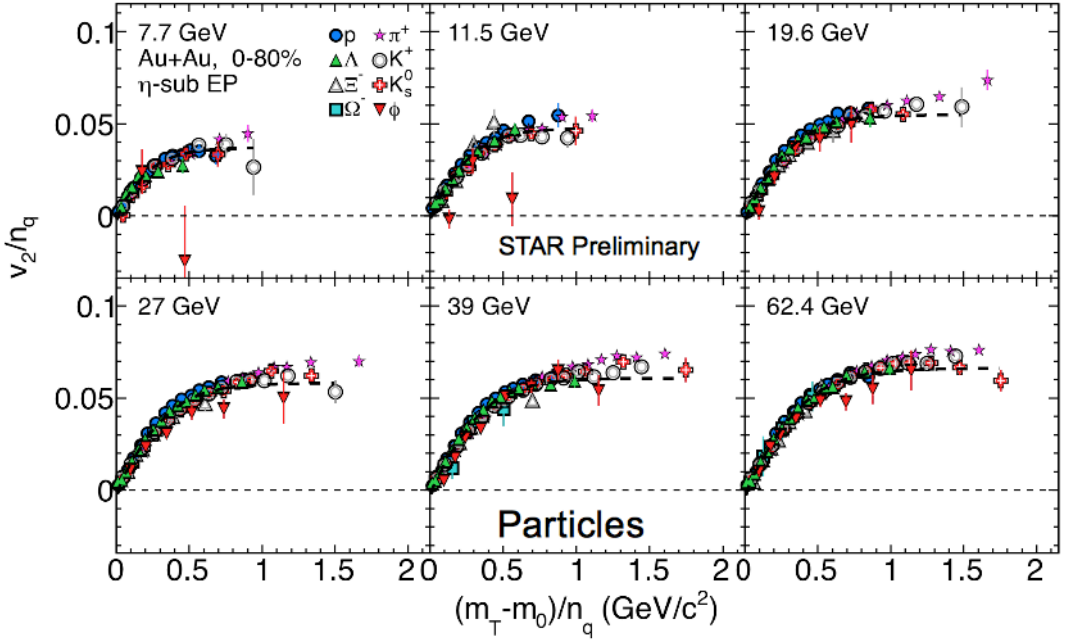
Liang Xue, STAR Coll., QM2011

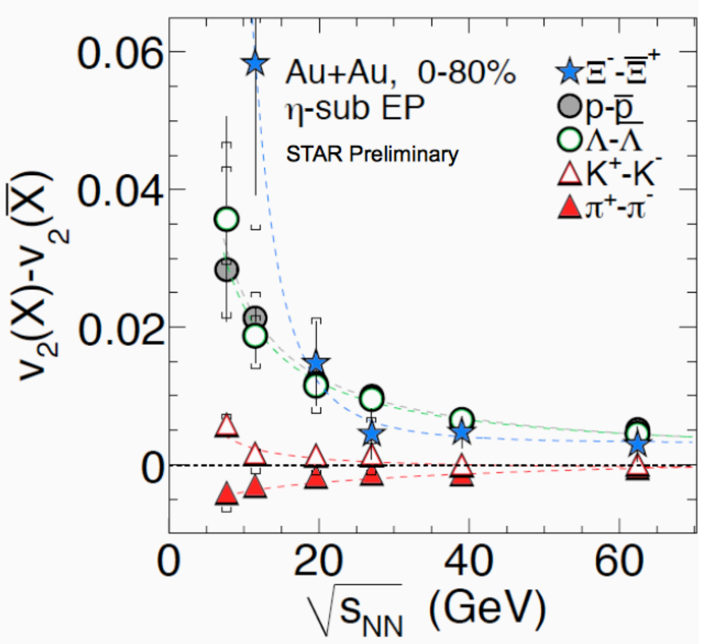


- **First measurement ever of 18 anti-^{4}He based on TPC+TOF+HLT**
- **Consistent with thermal & coalescence model expectation**

Sets the background for observation of antimatter in space

Number of constituent quarks scaling





nq= 2 for mesons, 3 for baryons
(same for antiparticles)

Shusu Shi, STAR, QM2012

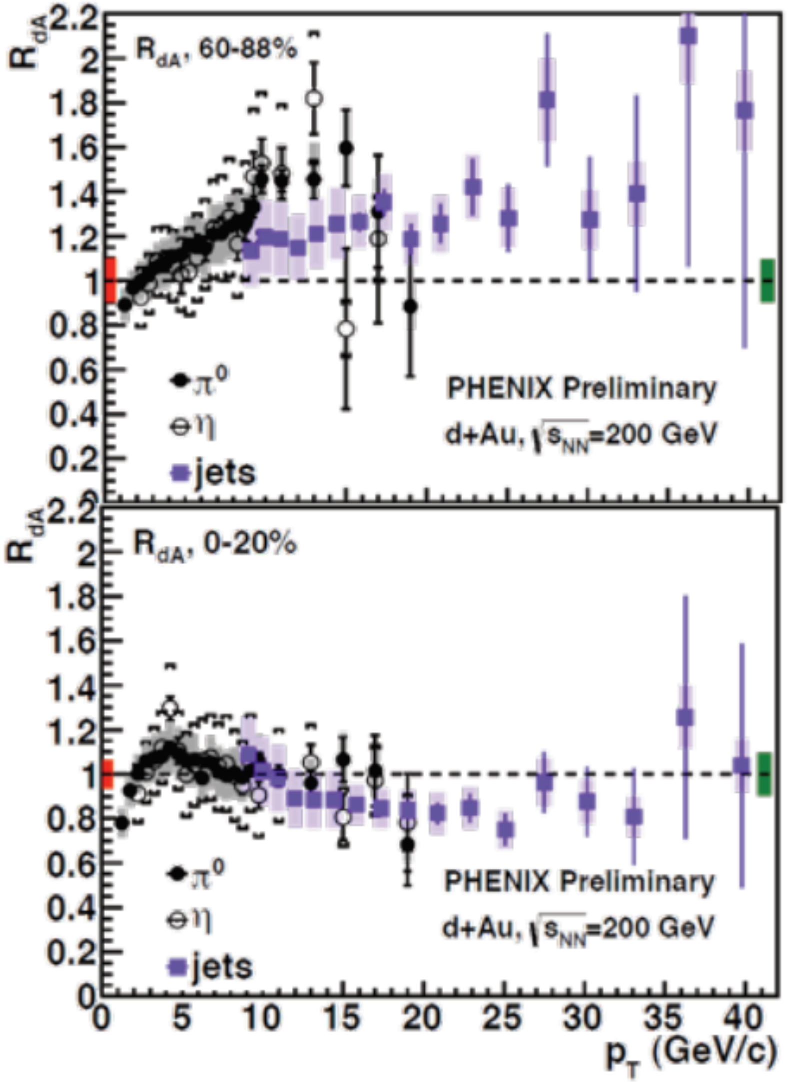
*** Scaling with the number of constituent quarks (NCQ) observed.**
This is in agreement with quark coalescence as dominant production mechanism of hadrons at the highest RHIC energies.

*** ϕ meson v2 deviates from other particles ~2σ at the highest pT data in 7.7 and 11.5 GeV ->**
NCQ scaling is broken at 11.5 GeV and below.
More data are needed at these energies for clear conclusion.

*** NCQ scaling is broken for particles minus antiparticles at low energies.**

Cold Nuclear Matter effects with d+Au

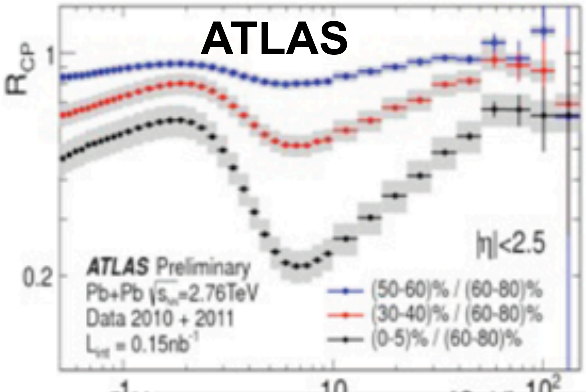
Milov, Solana, QM2012

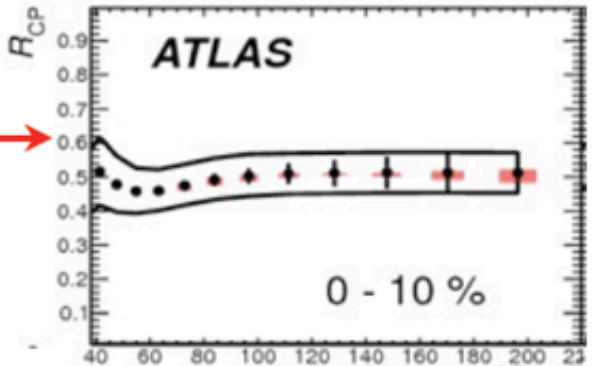


* Cold Nuclear Matter effects on jet quenching need to be taken into account at all energies

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

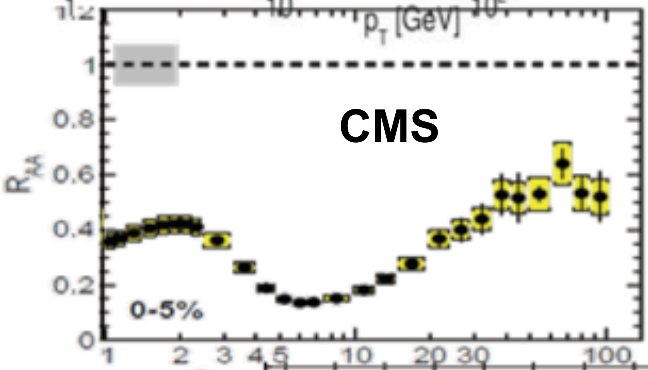
Similar suppression of hadrons and jets

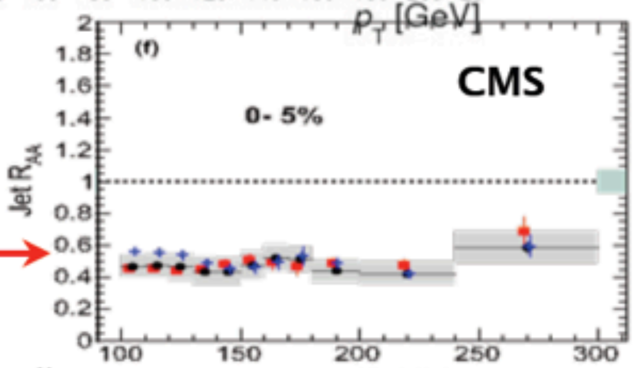


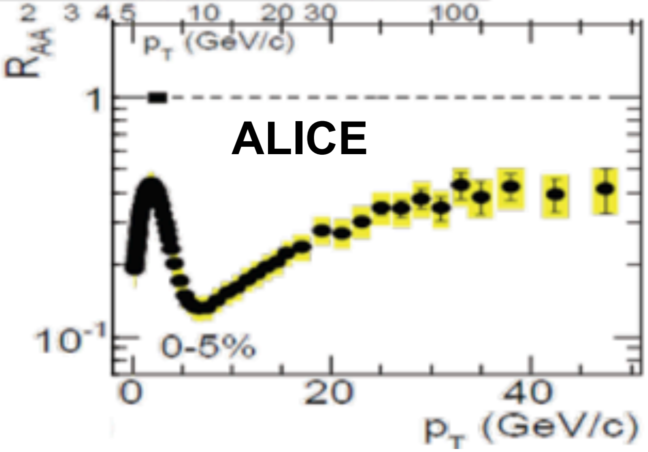


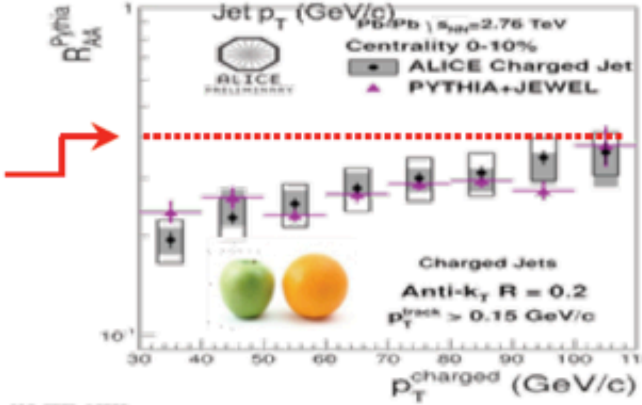
Left plots:
charged hadrons

Right plots:
reconstructed jets









ALICE
uses
tracks-jets

Milov,Solana,
QM2012

T(init) SPS, RHIC, LHC

*** SPS: measurement 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 at muB~1 MeV

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

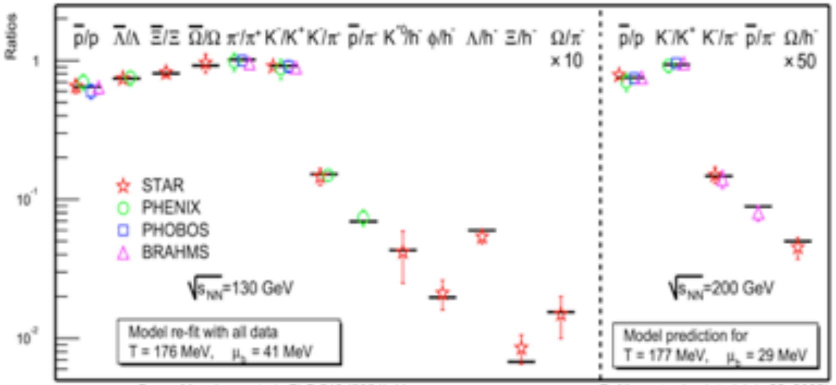
*** Low pT photons exhibit thermal spectrum, suggesting thermalization of their source**

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

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

Estimating the total strange to light quarks ratio

It has been observed that thermal models can describe the ratios of final state hadrons produced in A+A, e+e- and pp(ppbar) successfully.



Braun-Munzinger et al., PLB 518 (2001) 41

D. Magestro (updated July 22, 2002)

P.Braun Munzinger, J. Stachel et al

F. Becattini, C. Redlich, J. Cleymans et al

S. Kabana, P. Minkowski

J Rafelski, J. Lettessier, A Tounsi

Etc. (however results vary depending on free parameters gamma(s,q))

A T near 170-180 MeV has been found for SPS and RHIC : near Tc (lattice)

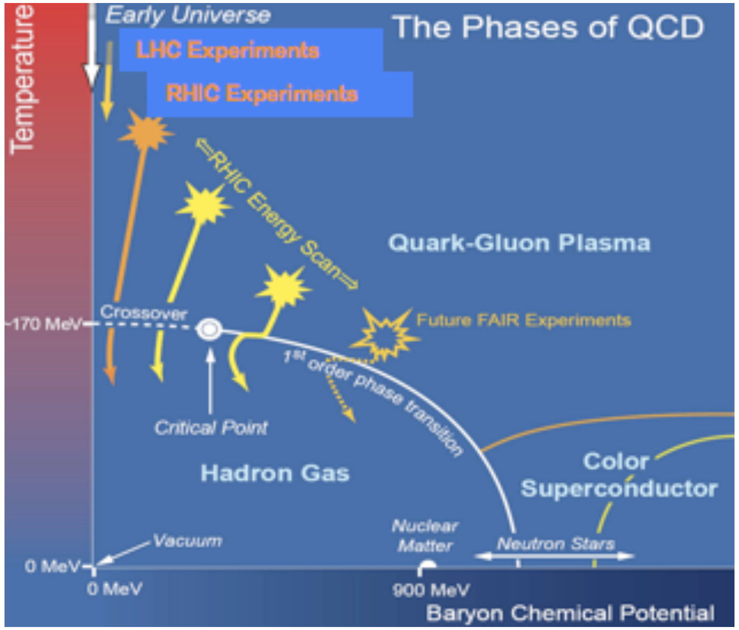
These models can be used to estimate the total strange/non strange newly produced quark ratio, namely the

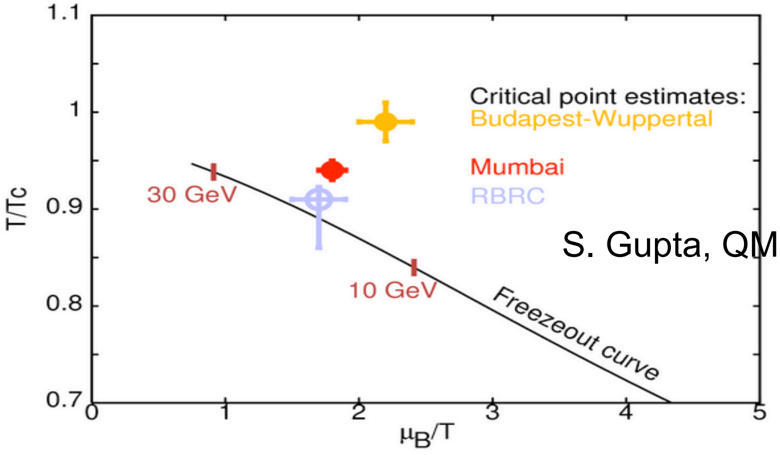
strangeness suppression factor (Wroblefski factor)

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

Beam Energy Scan at RHIC

Goal: Map out the QCD phase diagram searching for the onset of QGP signals and a possible critical point





S. Gupta, QM2011

RHIC beam energy scan with Au+Au and Cu+Cu (STAR, PHENIX) started with a test run in 2008/09

sqrt(s)= 7.7, 11.5, 19.6, 22.4, 27, 39, (62, 130, 200) GeV

Observables

Search for the onset of QGP signals :

Scaling of v2 pT dependence with nr of quarks

Flow coefficients vs energy

Quarkonia suppression

Strangeness to light hadrons (K/pi) Energy dependence

Signature for softening of EOS

v1, v2...

Search for fluctuations near a critical point:

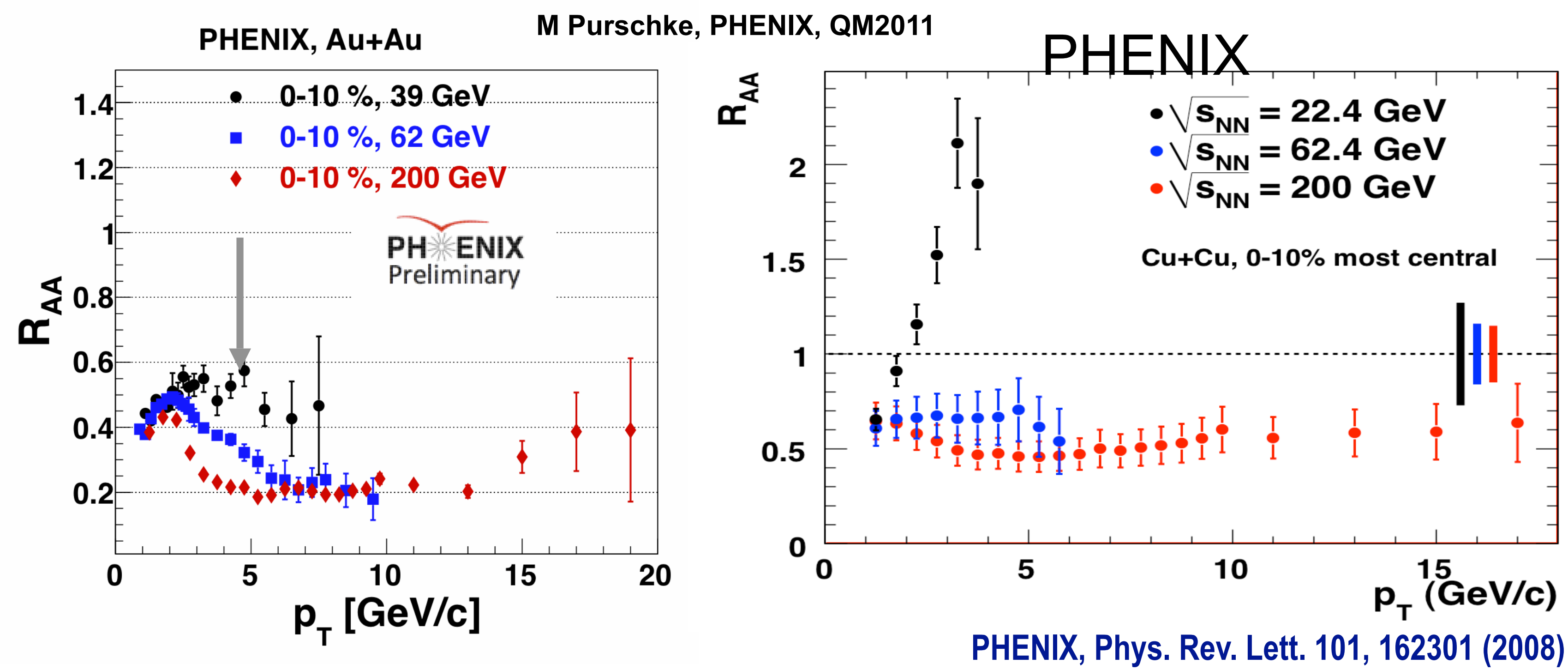
http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493 arXiv:1007.2613

At which collision energy is the onset of R_AA suppression ?

Au+Au

Cu+Cu

PHENIX



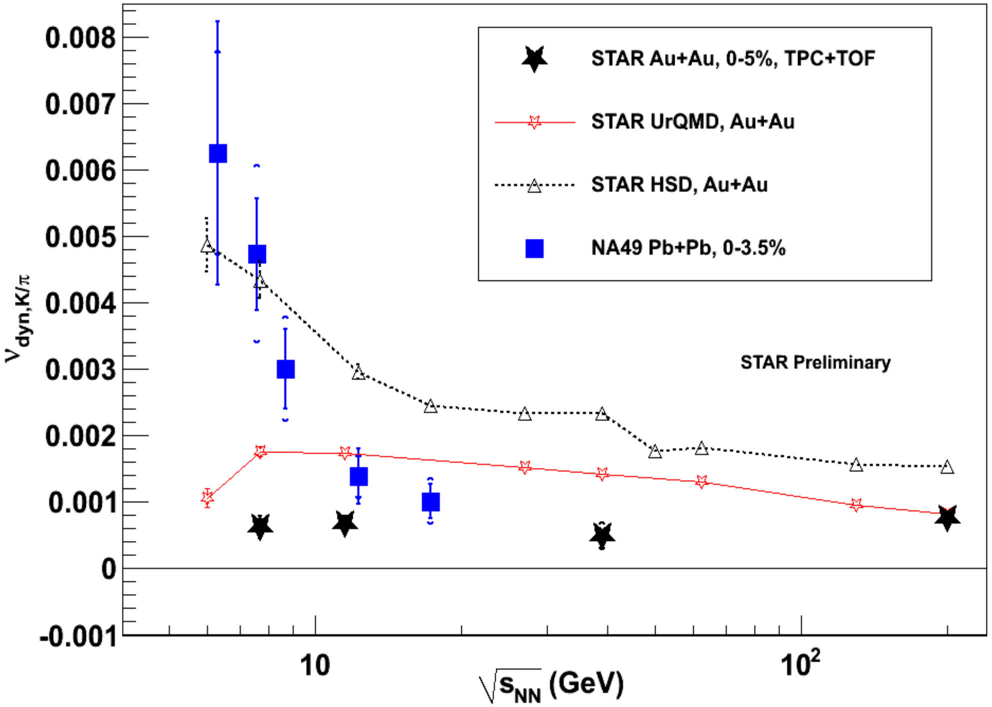
PHENIX, Phys. Rev. Lett. 101, 162301 (2008)

R_{AA} suppressed also at 39 GeV

R_{AA} at 62 GeV approaches value of RAA in 200 GeV at high p_T

No Suppression in Cu+Cu at 22.4 GeV

Search for fluctuations of the K/pi ratio in BES



NA49, PRC79 (2009) 044910

Terence Tarnowsky, STAR, QM2011
M Mitrovski, HEP2011

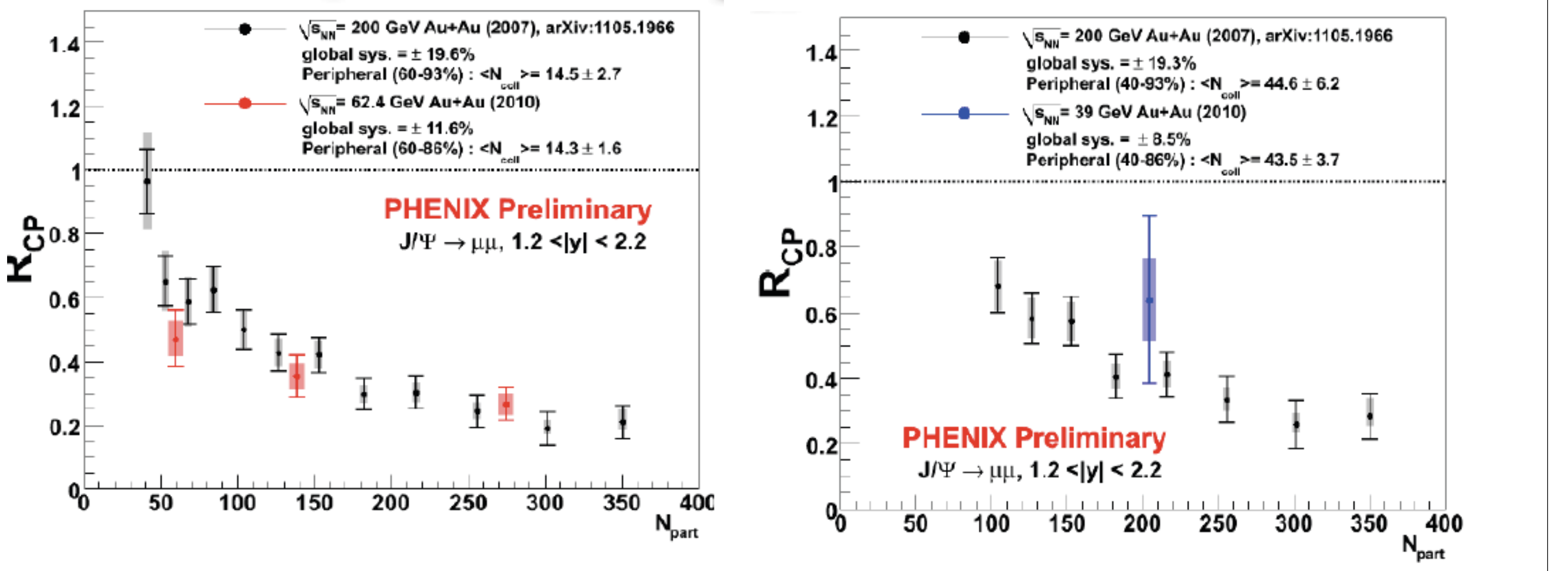
STAR TPC+TOF
π: 0.2 < p_T < 1.4 GeV/c
K; 0.2 < p_T < 1.4 GeV/c

- **No strong energy dependence of K/π fluctuations in central 0-5% Au + Au collisions at sqrt(s)= 7.7, 11.5, 39, 200 GeV observed in STAR data**

- **Difference between STAR and NA49 may be due to different (pT,y) acceptance, or particle identification - issue to be clarified**

At which energy is the onset of J/Psi suppression?

C da Silva, PHENIX, QM2011



Same detector, rapidity range and centrality

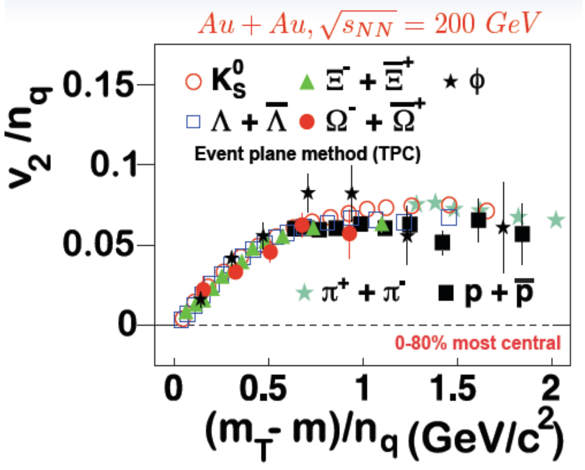
No p+p reference for 62 and 39 GeV

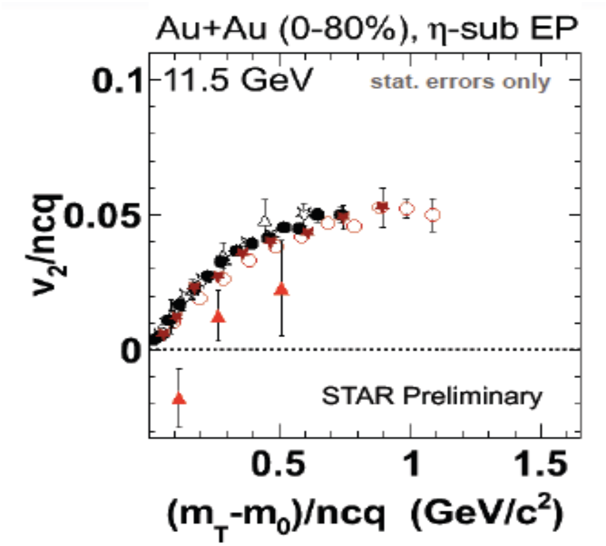
J/Psi suppression similar at these energies within errors

However cold nuclear matter effects are expected to be different

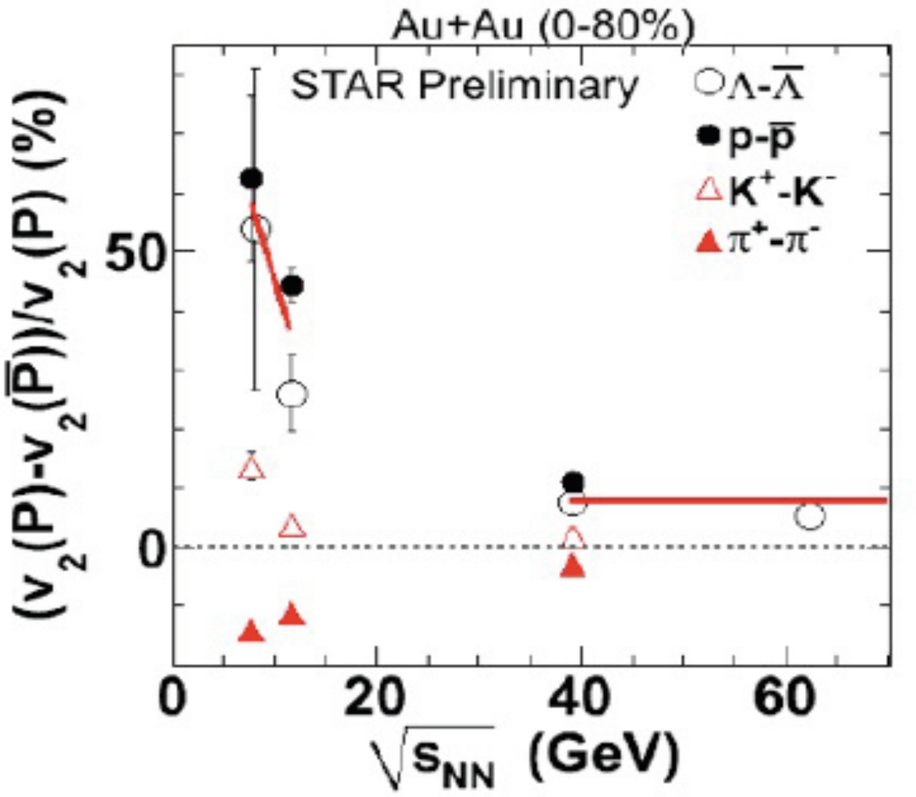
At which energy brakes the scaling of v2 with the nr of constituent quarks ?

M Mitrovski, STAR, HEP2011





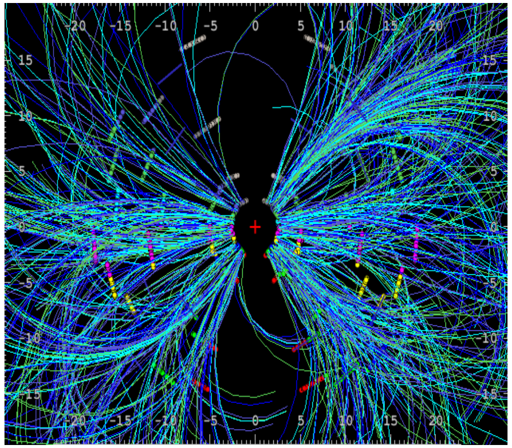
A. Schmah, STAR, QM2011



NCQ scaling seems to be broken for particles and antiparticles at lower energies (7,7, 11.5 GeV)

The phi meson does not follow the trend of other mesons at 11.5 GeV

Outlook
- near term



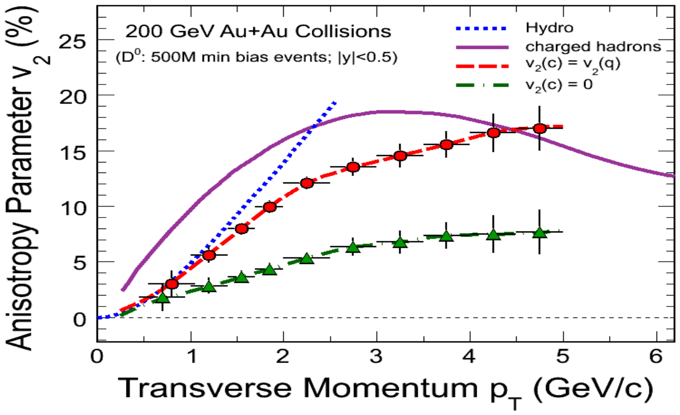
Several major upgrades by STAR and PHENIX :

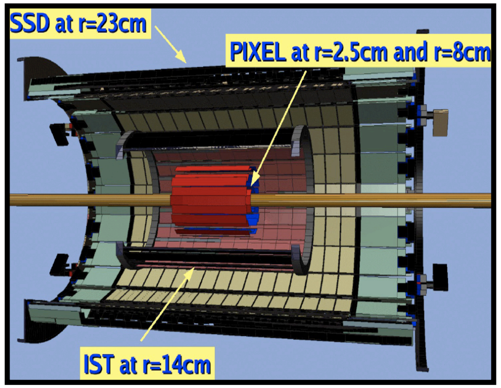
PHENIX: new silicon vertex detector commissioned with +p, took Au+Au data in 2011

STAR: new silicon vertex detector under construction designed to reach a DCA resolution of ~30 microns (Heavy Flavour Tracker). Data taking 2014.

Myon Telescope, later : forward instrumentation

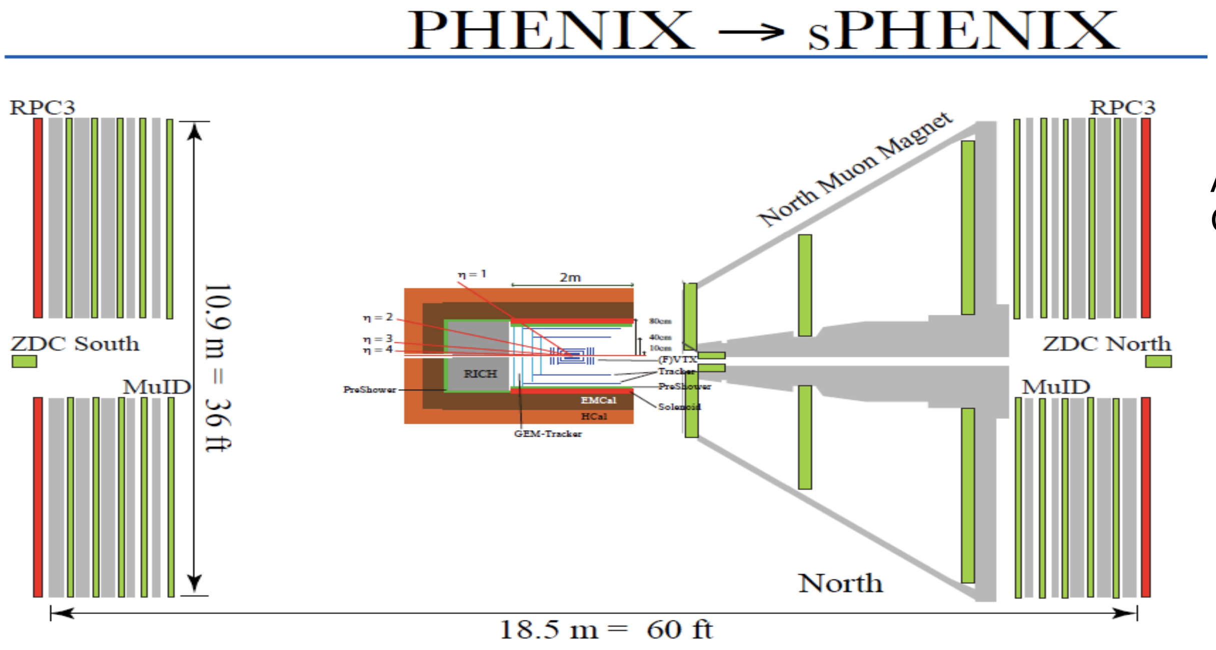
Physics capabilities of HFT





Outlook - long term

PHENIX -> sPHENIX : hadronic calorimeter at ycm

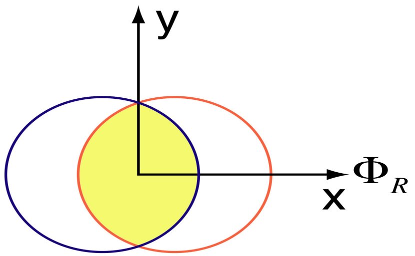


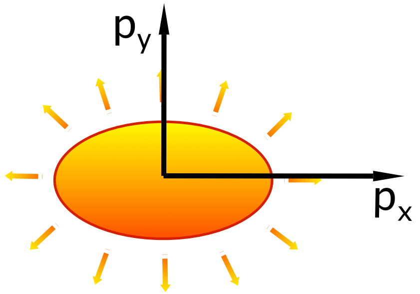
A. Sickles, PHENIX, QM2011

STAR -> eSTAR (optimization for e+A collisions) : Hcal and a new tracker for the e

Flow

- spatial anisotropy ⇒ momentum anisotropy





Fourier decomposition of the momentum space particle distributions in the x-y plane

v_2 is the 2nd harmonic Fourier coefficient

The v2 for hadrons :

- scales with nr of consituent quarks suggesting partonic degrees of freedom of their source and

- is consistent with low viscosity (hydro, AdS/CFT)

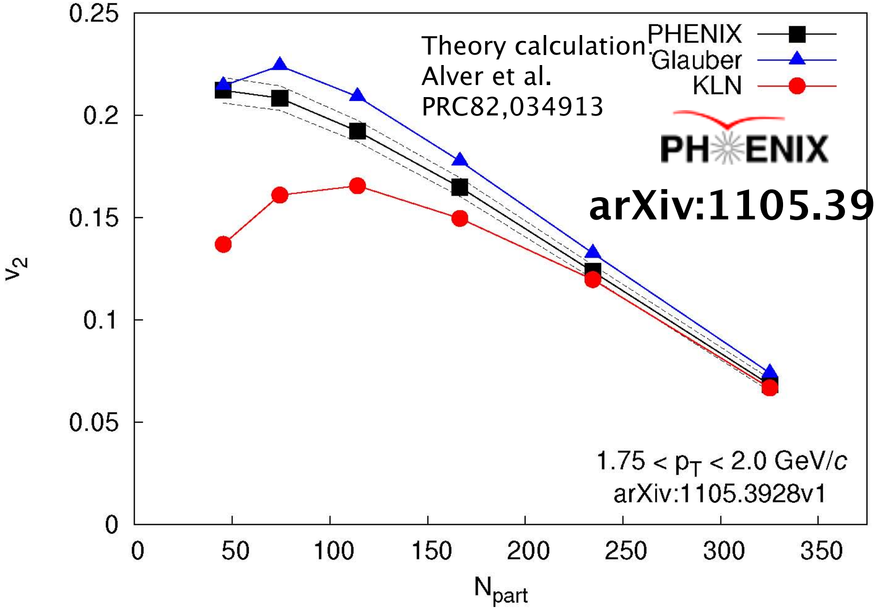
→

How is v2 for direct thermal photons?

v_3 disentangles initial state and η/s

Stefan Bathe for PHENIX, QM2011

v_2 described by Glauber and CGC

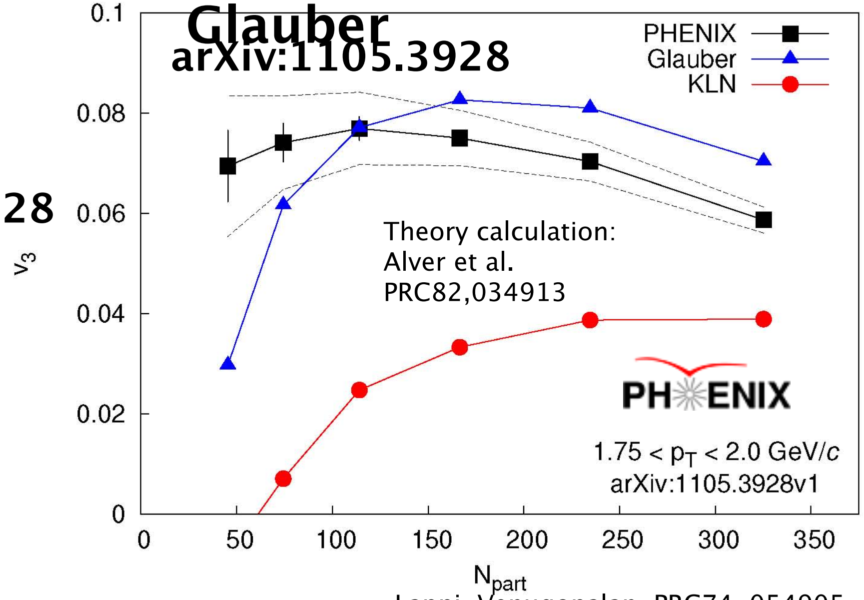


Theory calculation:
Alver et al.
PRC82,034913

arXiv:1105.3928

v_3 described only by Glauber

arXiv:1105.3928



Theory calculation:
Alver et al.
PRC82,034913

Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

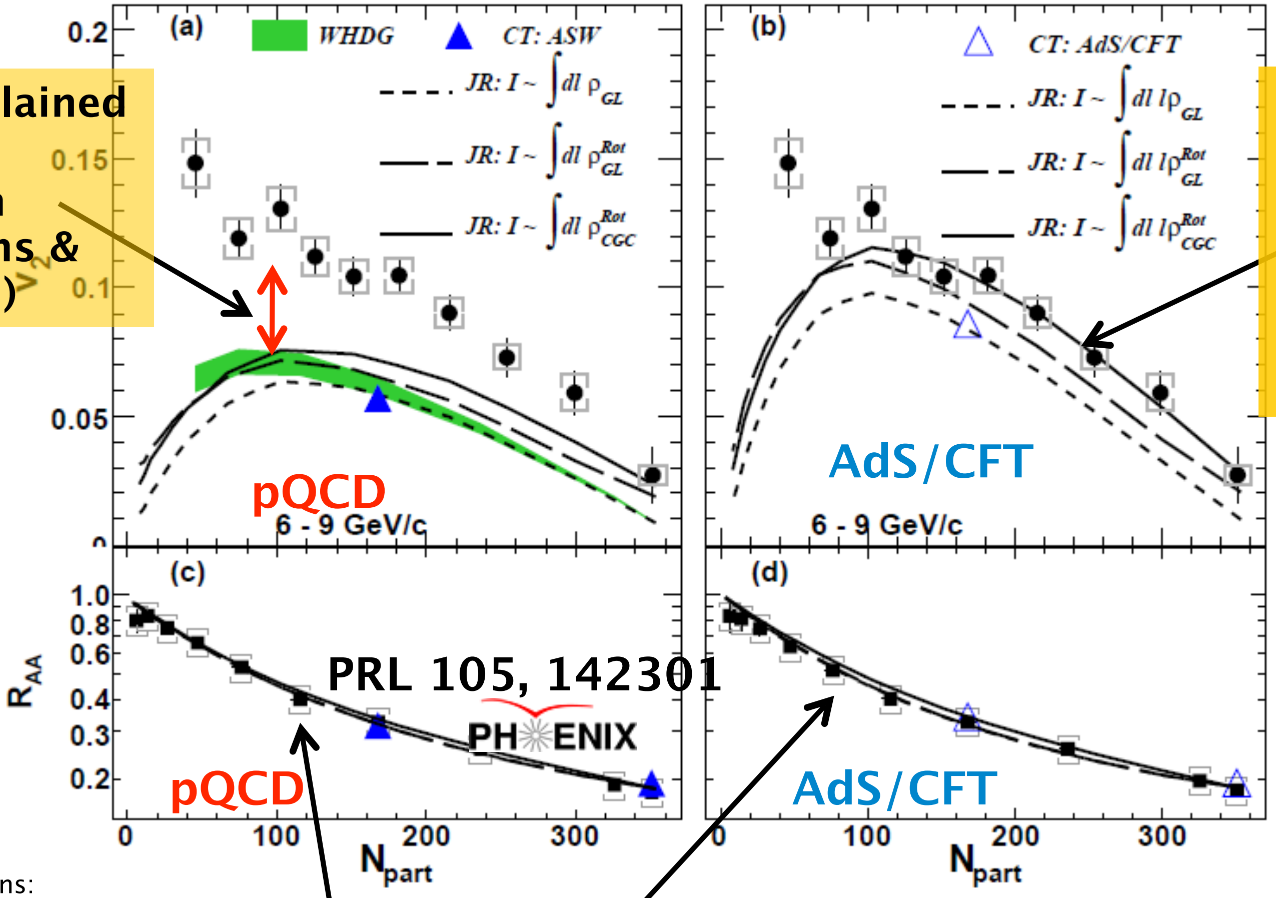
- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

⟵ Two models ⟶

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

Which is the path-length dependence of de/dx ?

S Bathe, M Purschke, PHENIX, QM2011



v_2 not explained by pQCD (even with fluctuations & saturation)

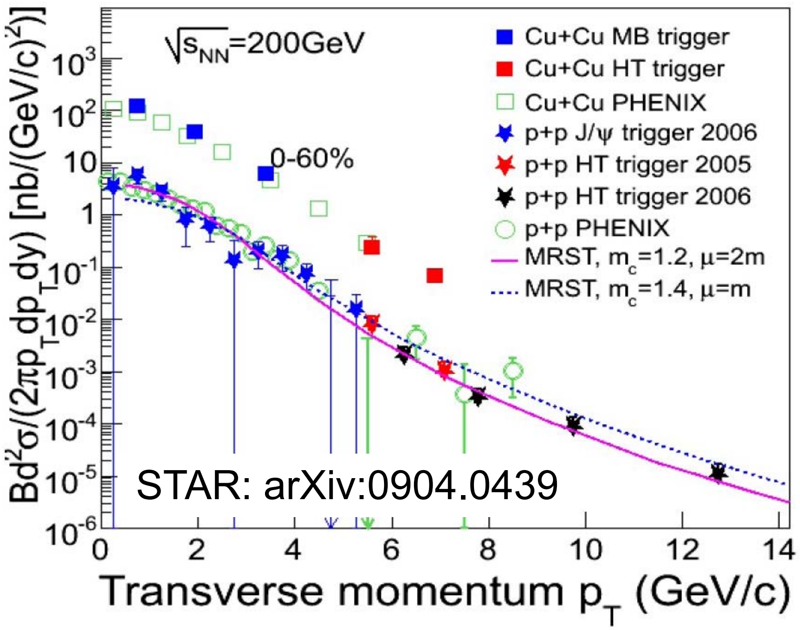
v_2 explained by cubic path length dependence (like AdS/ CFT)

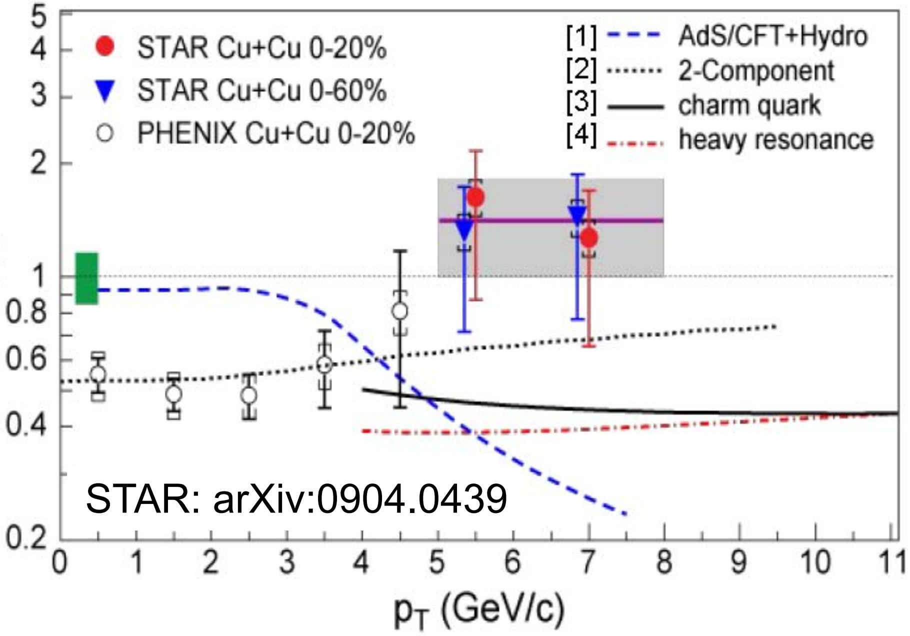
While R_{AA} explained by both models

Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645

v_2 data favors $dE/dx \sim l^3$ (like AdS/ CFT)

J/ψ in p+p and Cu+Cu 200 GeV





- **R_{AA}(p_T>5 GeV/c) = 1.4± 0.4±0.2**
- Consistent with no suppression at high p_T

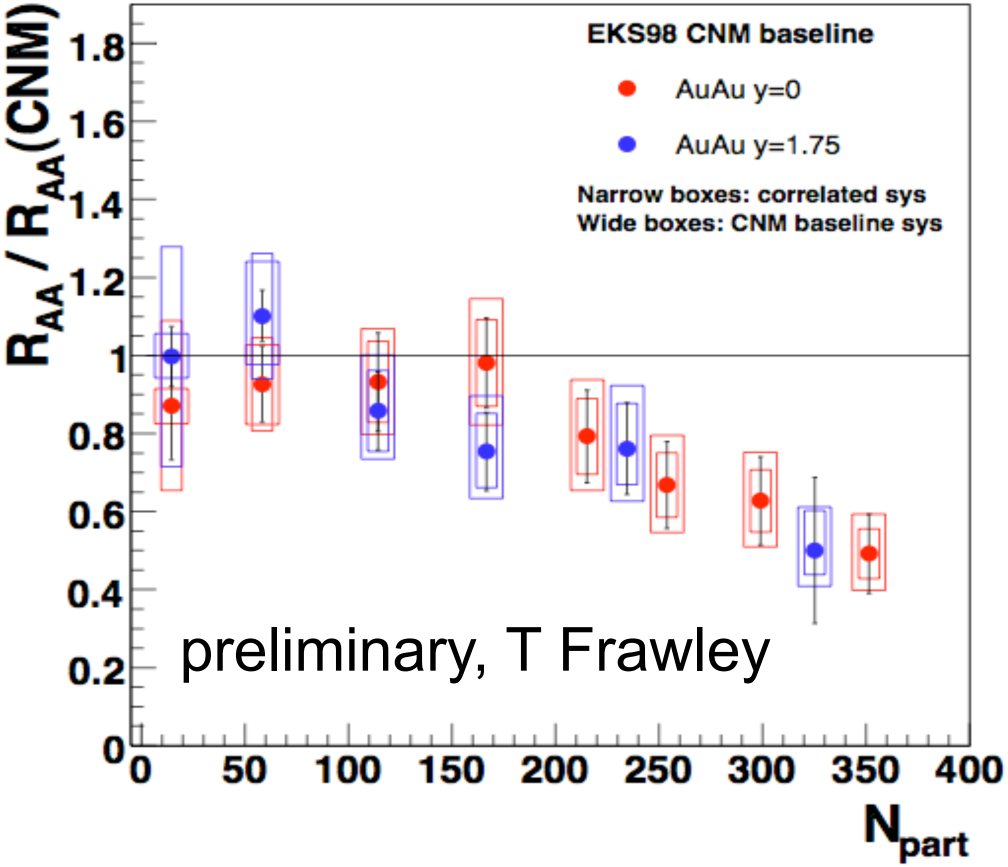
A. Adil and I. Vitev, Phys.Lett. B649, 139 (2007),
S. Wicks et al., Nucl. Phys. A784, 426 (2007)

•Inconsistent with AdS/CFT+Hydro and “heavy resonance” models

•Two component model+J/ψ form. time+ B feed down describes the trend well

R. Rapp, X. Zhao, nucl-th/0806.1239

RHIC J/Psi "y"-puzzle, T Frawley



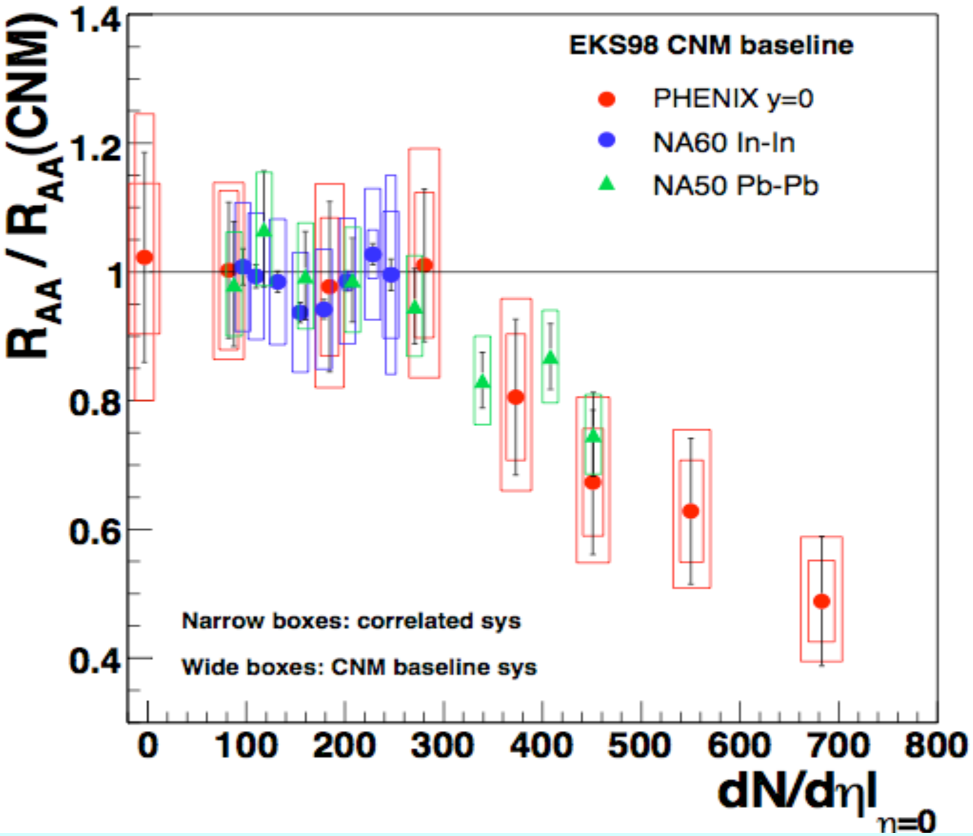
T Frawley, (PHENIX) workshop ECT*,Trento, May 24-29 2009

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 N uclear Matter) at y=0 and y=1.75

The J/Psi RHIC-SPS-comparison -puzzle R Arnaldi



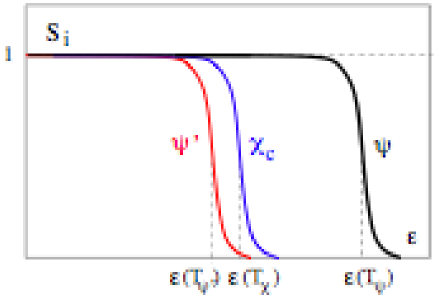
R Arnaldi, D Frawley, Trento 25-29 may 2009

-Divide out cold nuclear matter effects using not model but data (d+Au, p=Au)

- Plot as a function of dN/deta|eta=0 takes into account differences in energy in contrast to N_part.

---> Cold nuclear matter absorbtion effect up to dN/deta|eta=0 = 300

---> Suppression of J/Psi above 300



J/ψ suppression at low p_T maybe from excited stats (ψ', χ_c) F. Karsch, D. Kharzeev and H. Satz, PLB 637, 75 (2006); B. Alessandro et al. (NA50), Eur. Phys. J. C 39 (2005) 335; R. Arnaldi et al. (NA60), Quark Matter 2005; PHENIX: Phys.Rev.Lett.98, 232301,2007.

60% of all J/Psi comes from direct J/ψ. While 30% of all J/Psi come from χ_c and 10% ψ'

χ_c and ψ' T(dissociation) ~Tc, while J/Psi T(dissociation)~ 2.1 T_c

--> suppression of J/Psi observed, maybe due to χ_c and ψ' dissociation

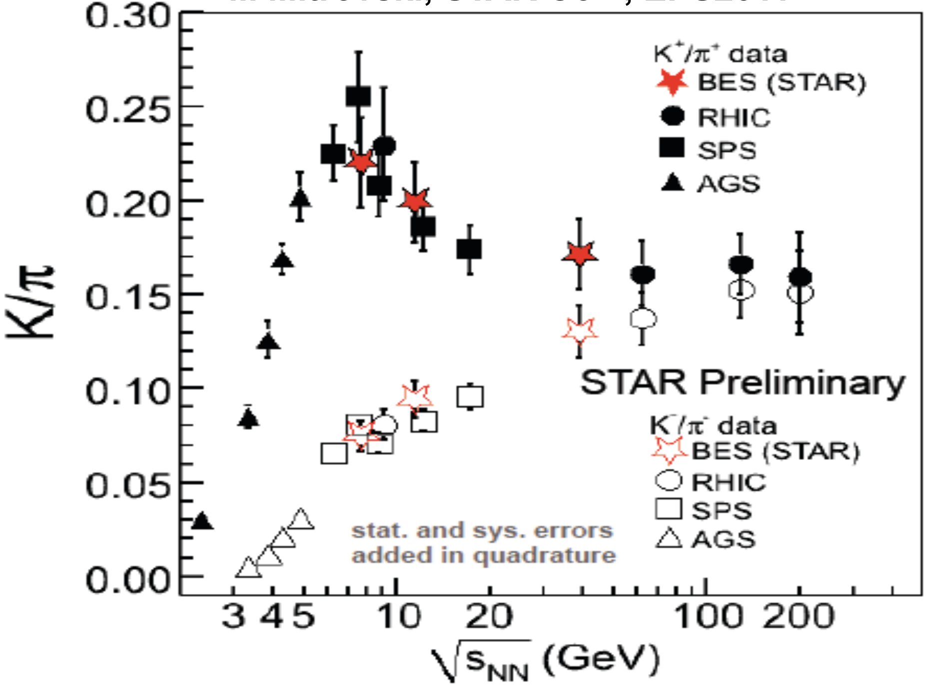
--> directly produced J/Psi may not be suppressed at RHIC

--> expect more suppression at LHC due to direct J/Psi dissociation

(but must account for c,cbar coalescence-> J/Psi)

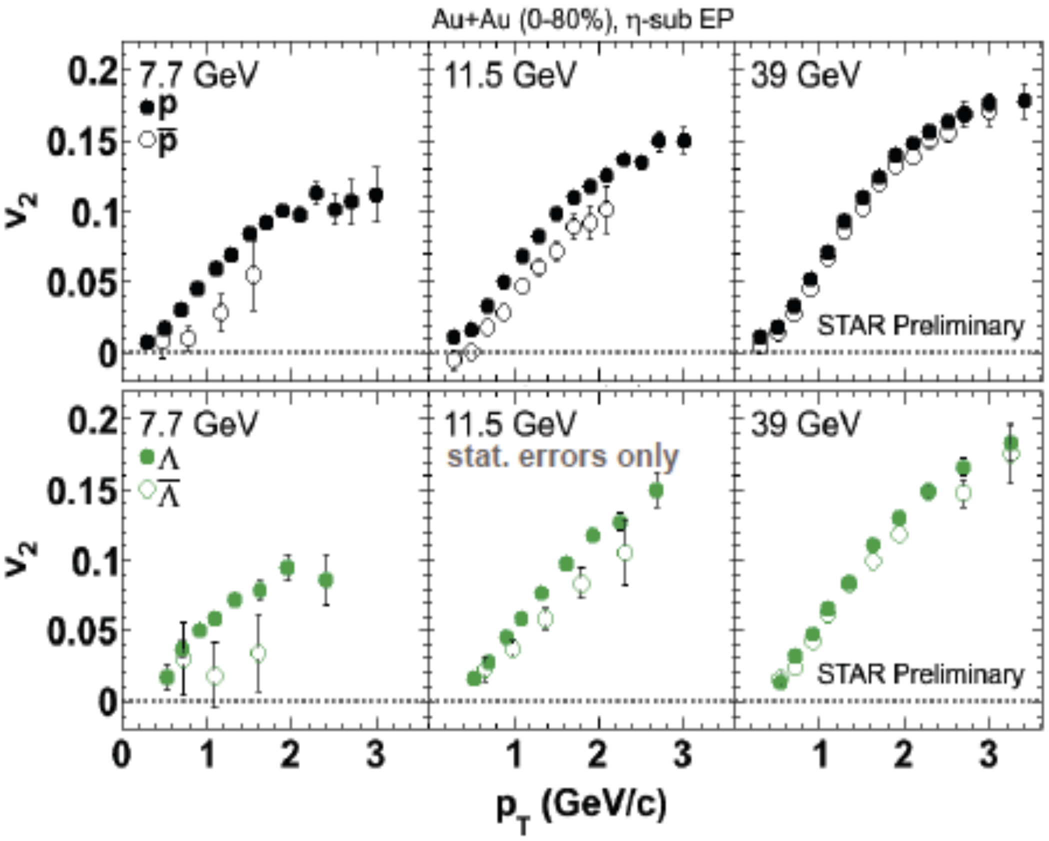
What can we learn from the K/pi ratio energy dependence?

M Mitrovski, STAR Coll., EPS2011

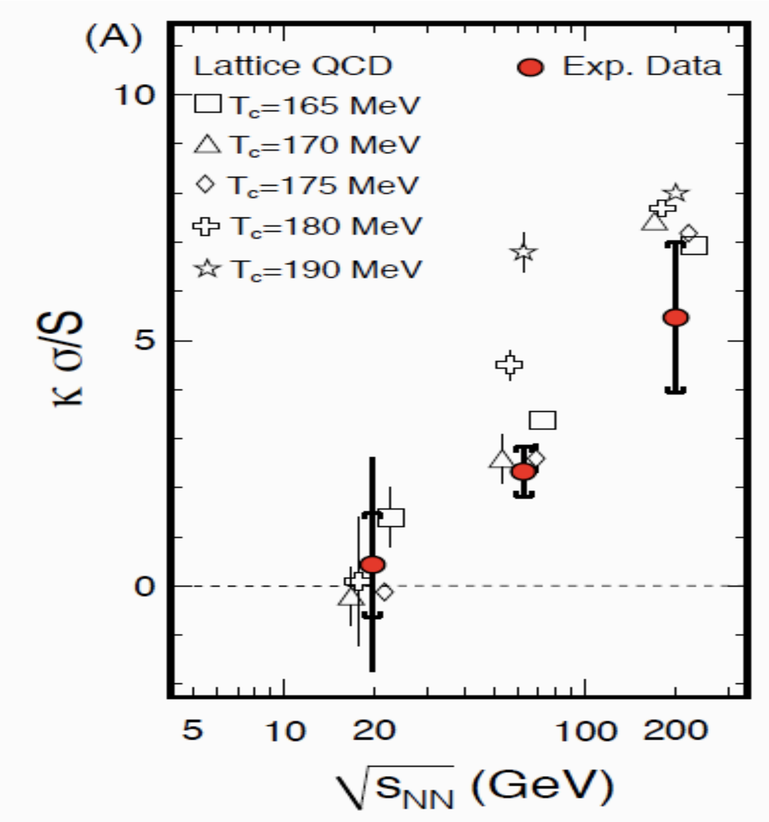


- New STAR data on K/pi are in agreement with previous SPS measurements
- Maximum of K+/pi+ ratio near sqrt(s)=7 GeV, not seen in the K-/pi- in A+A, neither in p+p

v2 BES


Au+Au (0-80%), η-sub EP
7.7 GeV
● p
○ $\bar{p}$
11.5 GeV
39 GeV
STAR Preliminary
7.7 GeV
● Λ
○ $\bar{\Lambda}$
11.5 GeV
stat. errors only
39 GeV
STAR Preliminary
v_2
0.2
0.15
0.1
0.05
0
0
1
2
3
p_T (GeV/c)

Extraction of Tc from data comparing to lattice
Press release LBNL June 2011



Sourendu Gupta, et al., Science 332,1525 (2011)

arXiv:1105.3934

k= kurtosis

S=skewness

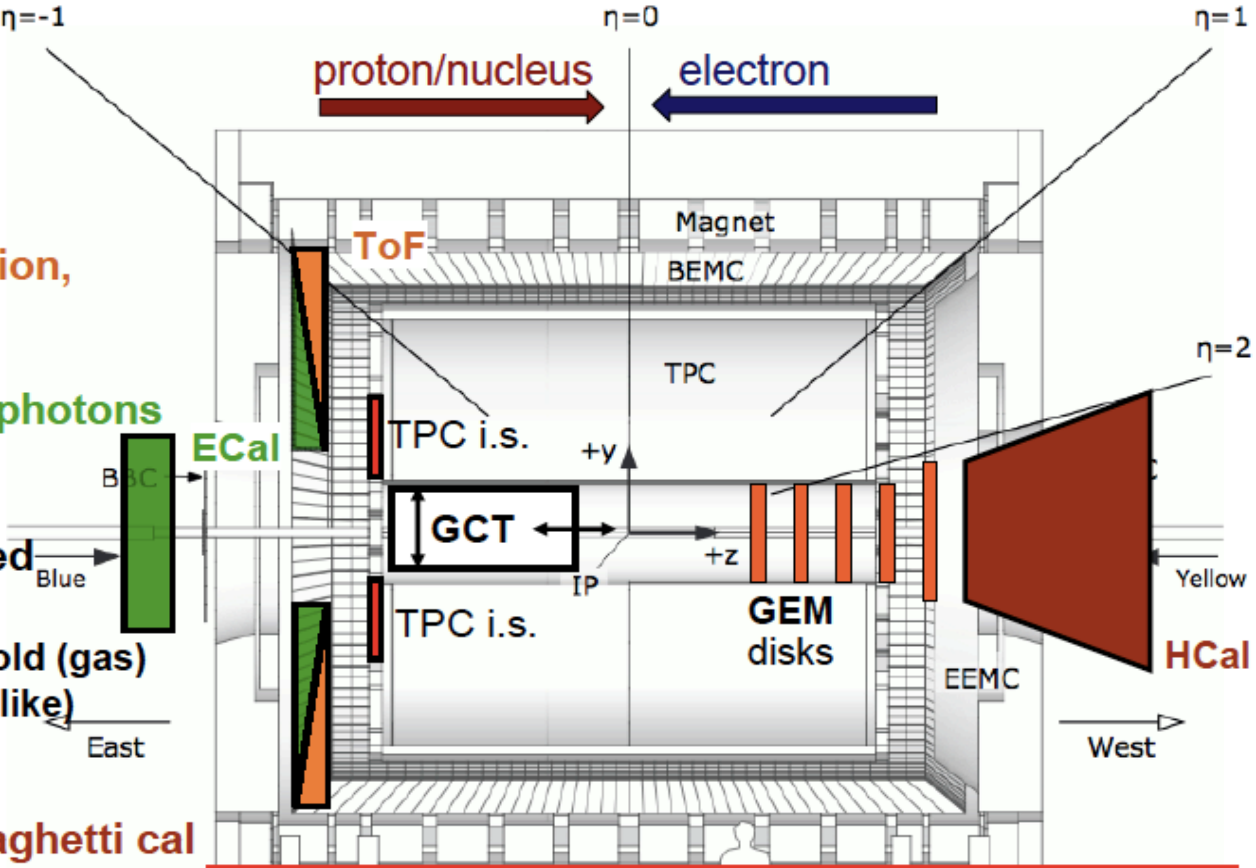
Ratio kσ/S is independent of Volume

First estimate of Tc at μ_B=0, from comparison of data (at nonzero μ_B) to lattice :

Tc=175+1 -7 MeV

S Gupta, Lepton Photon 2011

Evolving from *STAR* into *eSTAR*



ToF: π , *K* identification, t_0, electron

ECal: electrons and photons

GCT: a compact tracker with enhanced electron capability

Combine high-threshold (gas) Cherenkov with TPC(-like) tracking

HCal: W powder, spaghetti cal

GCT: LOI toward multi-institution R&D effort

HCal: R&D proposal

Presented to EIC Generic Detector R&D Panel

Simulations ahead:

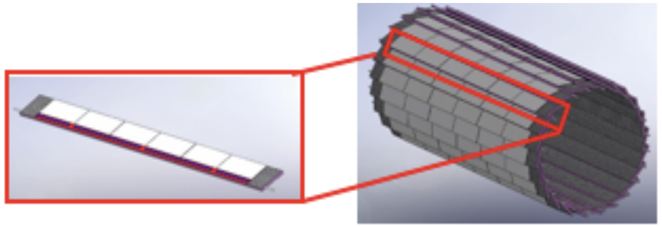
eSTAR task force formed

STAR Science for the Decade – QM2011 – Carl Gagliardi 16

The Heavy Flavour Tracker

The STAR collaboration has proposed a new silicon vertex detector composed by :

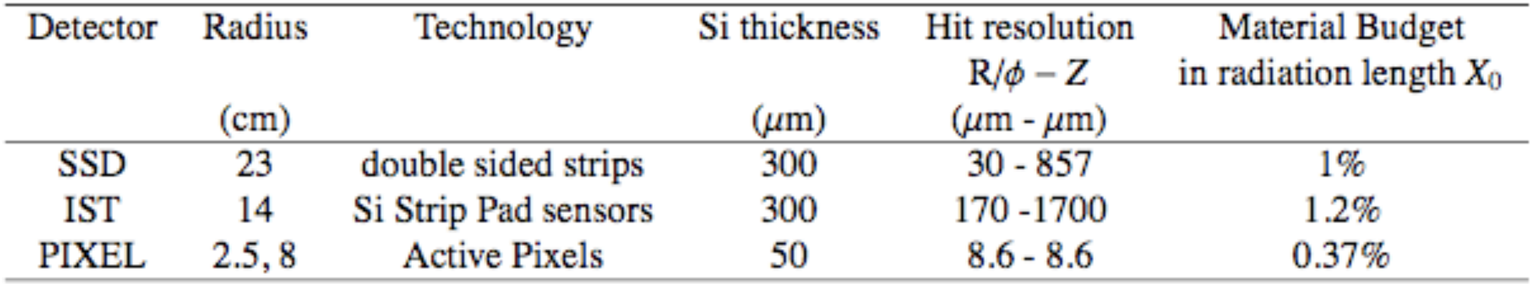
- The existing **SSD** : a single layer of double-sided silicon strips detector located at a radius of 22 cm from the beam axis.
- **IST** :1 intermediate layer of single sided strips : it aimed to guide tracks from the SSD through PIXEL detector. It is composed by 24 liquid cooled ladders equipped with 6 silicon strip-pad sensors.



- **PIXEL** detector : The goal of this detector is to measure with great accuracy the track pointing resolution and to find secondary decays. It is made by 2 layers of 18.4μm x 18.4μm CMOS Active Pixel sensors.

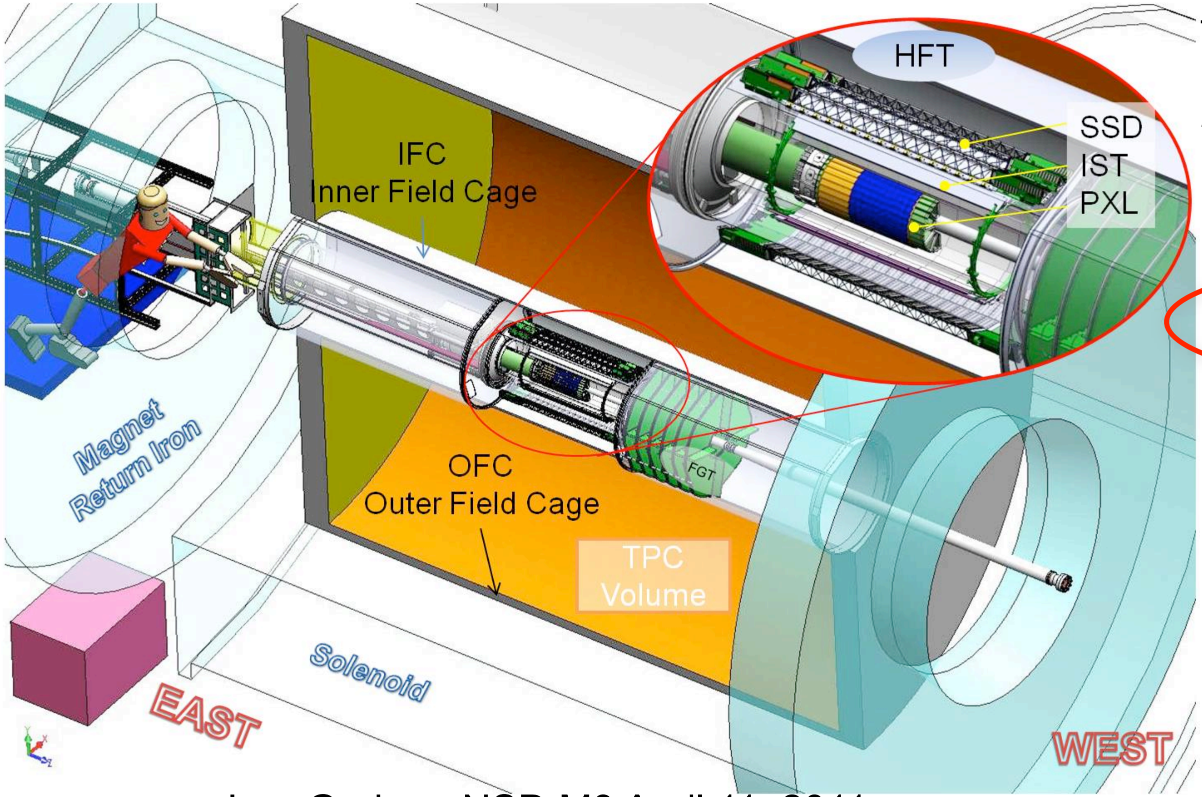
E. Anderssen et al. , A Heavy Flavor Tracker for STAR (http://rnc.lbl.gov/hft/docs/hft_final_submission_version.pdf)

J Bouchet et al, poster, QM2009, arXiv:0907.3407



Detector	Radius (cm)	Technology	Si thickness (μm)	Hit resolution R/$\phi - Z$ (μm - μm)	Material Budget in radiation length X_0
SSD	23	double sided strips	300	30 - 857	1%
IST	14	Si Strip Pad sensors	300	170 -1700	1.2%
PIXEL	2.5, 8	Active Pixels	50	8.6 - 8.6	0.37%

The Pixel Detector for Inner Detector Upgrades



Leo Greiner, NSD M3 April 11, 2011

TPC – Time Projection Chamber

HFT – Heavy Flavor Tracker

- SSD – Silicon Strip Detector
  - r = 22 cm
- IST – Inner Silicon Tracker
  - r = 14 cm
- PXL – Pixel Detector
  - r = 2.5, 8 cm

PXL:

High granularity (~20 microns pixel pitch)

Short integration time (<200 microsec)

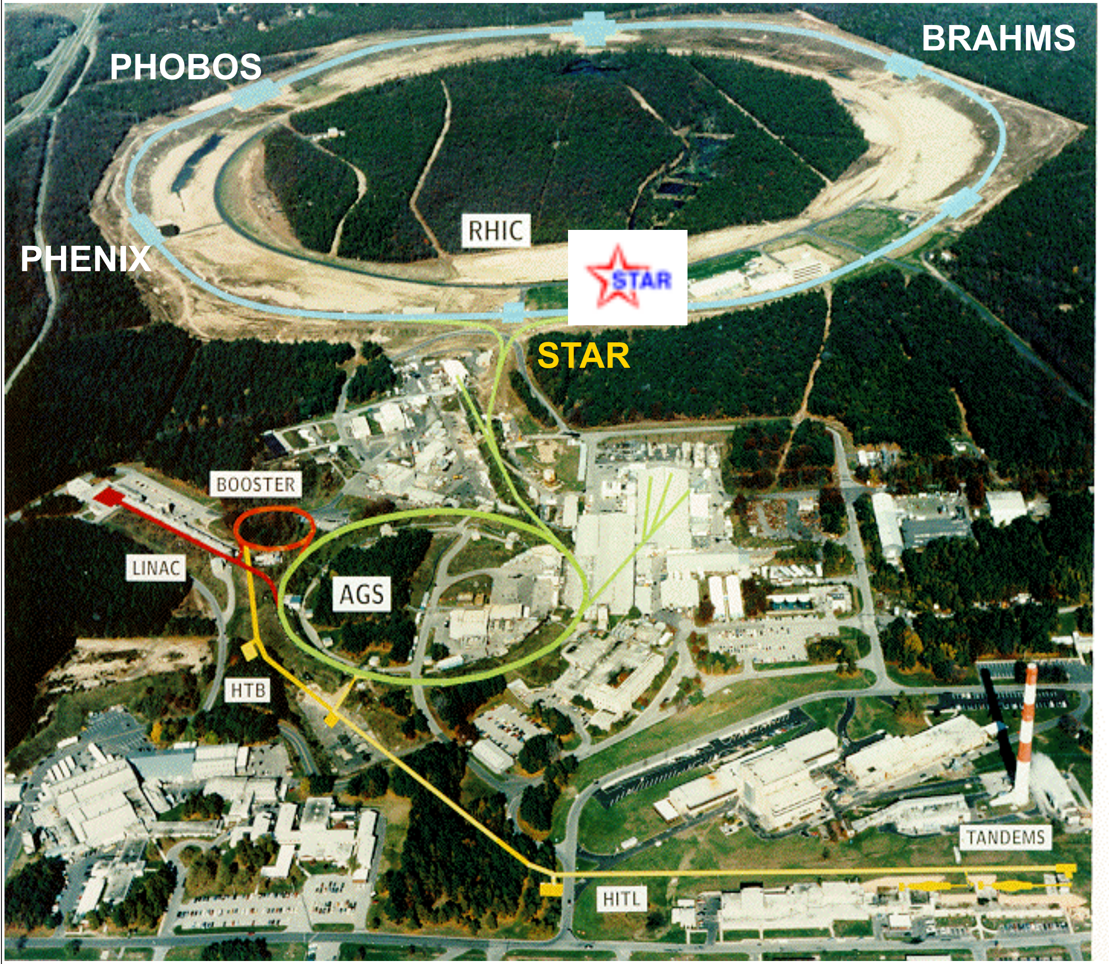
thin sensors (50 microns, 0.37% X0)

We track inward from the TPC with graded resolution:

TPC ~1mm → SSD ~300μm → IST ~250μm → PXL <30μm → vertex

Relativistic Heavy Ion Collider

RHIC site in BNL on Long Island, USA

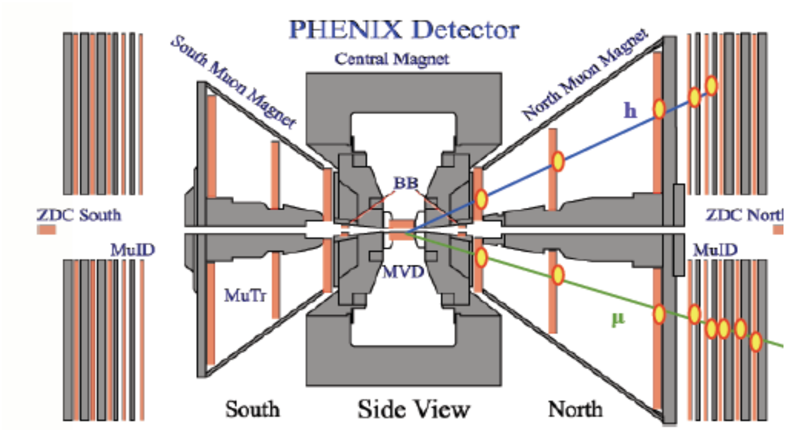


RHIC has been exploring nuclear matter at extreme conditions over the last decade
2000-2011

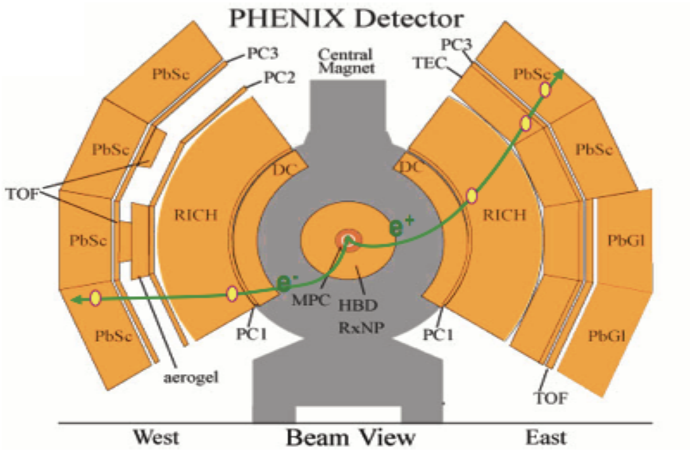
4 experiments:
STAR PHENIX
BRAHMS PHOBOS

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

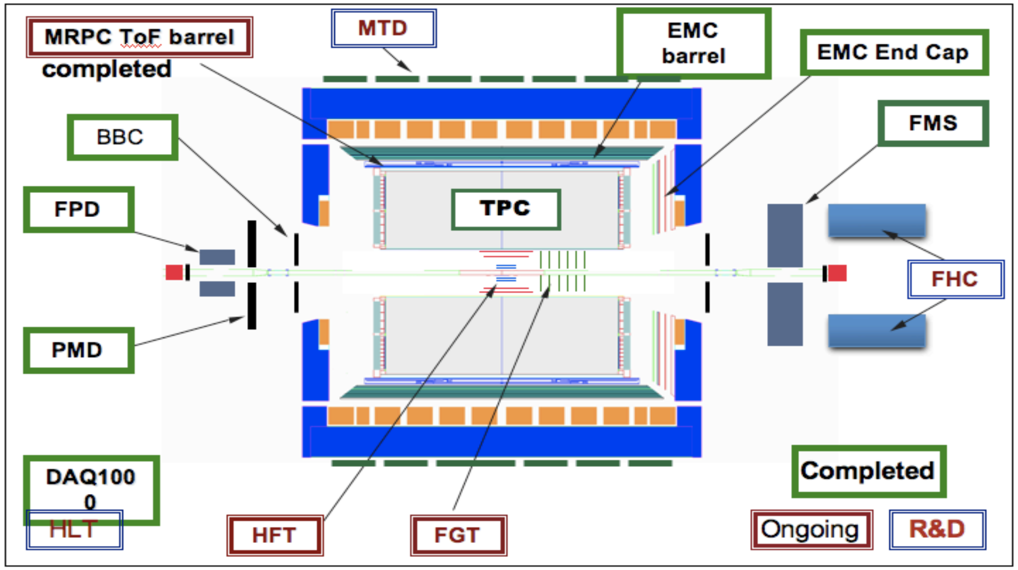
STAR and PHENIX detectors at RHIC



1.2<|y|<2.2 ΔΦ=2π



|y|<0.35 ΔΦ=2xπ/2



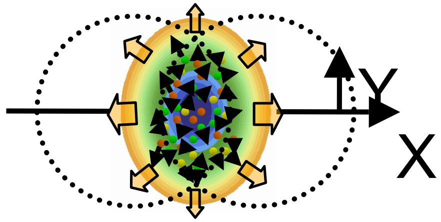
STAR : TPC, Em cal , TOF cover midrapidity, full azimuthal angle coverage

Direct photon elliptic flow in min bias Au+Au at 200 GeV

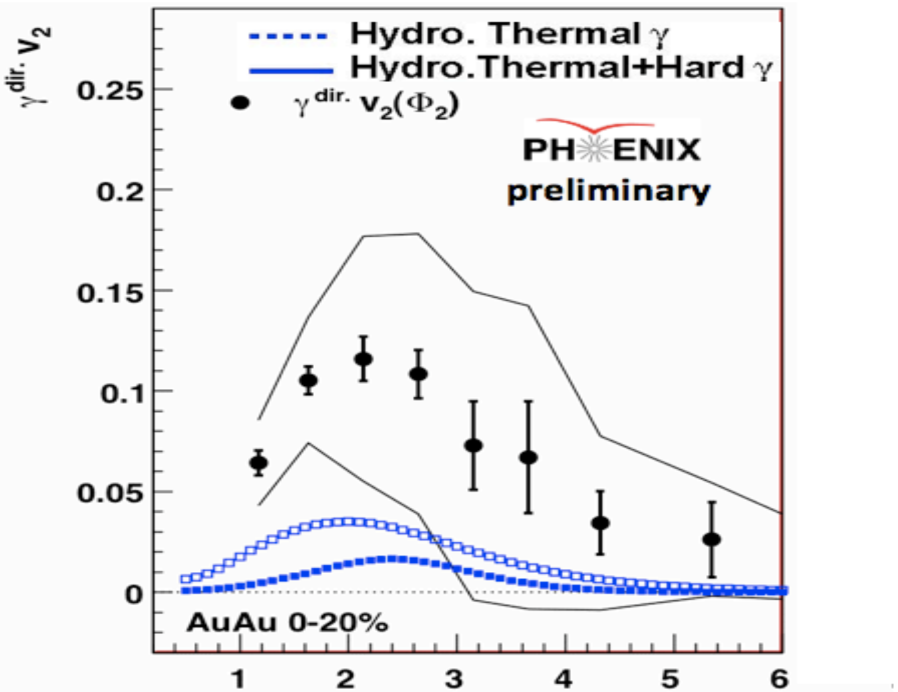
What we expect from theory ?

Expected v2 of prompt photons depends on emission time:

Small at early time (flow not build up), larger at later time (like hadrons)



Stefan Bathe, PHENIX, QM2011



Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

Chatterjee, Srivastava PRC79, 021901 (2009)

Direct photon v2 =

inclusive photon v2 - decay photon v2

PHENIX measurement :

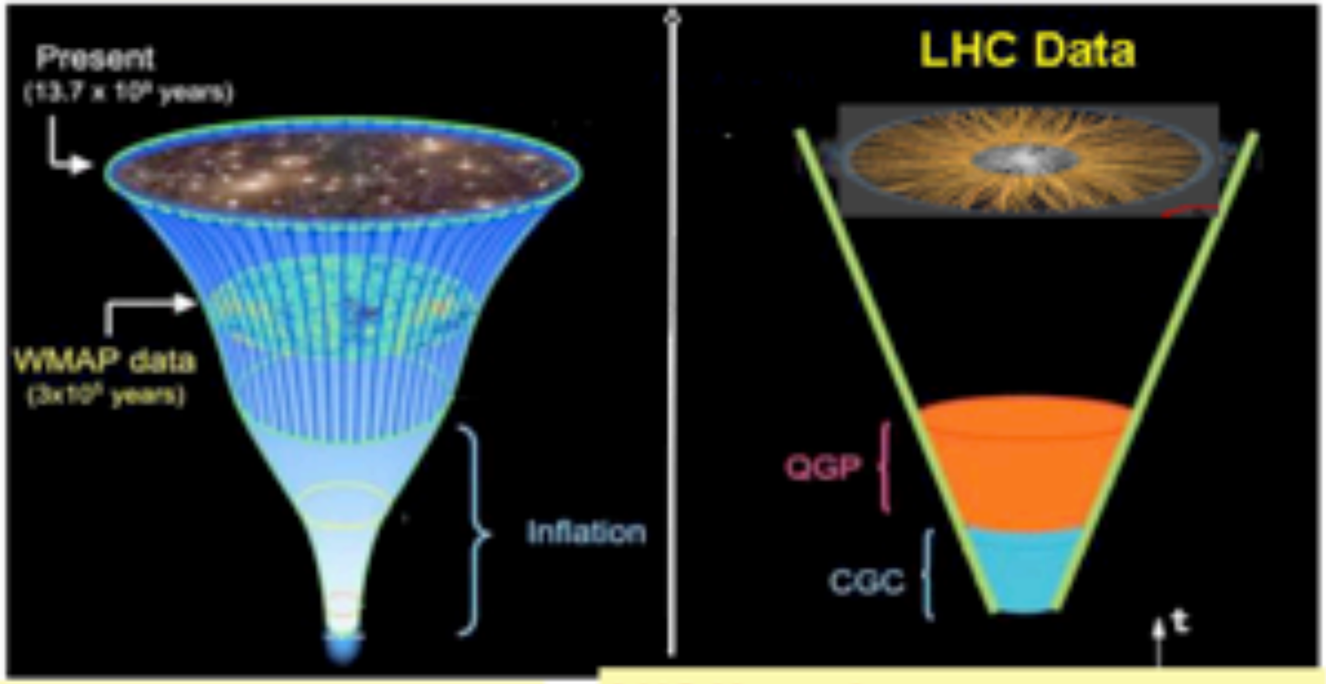
Large direct photon v2 observed at low pT, where thermal photons dominate (~0.15 at pT~2.5 GeV)

v2 -> 0 at high pT where prompt photons dominate

Models underpredict direct photon v2

Challenge to theorists

BIG BANG LITTLE BANG



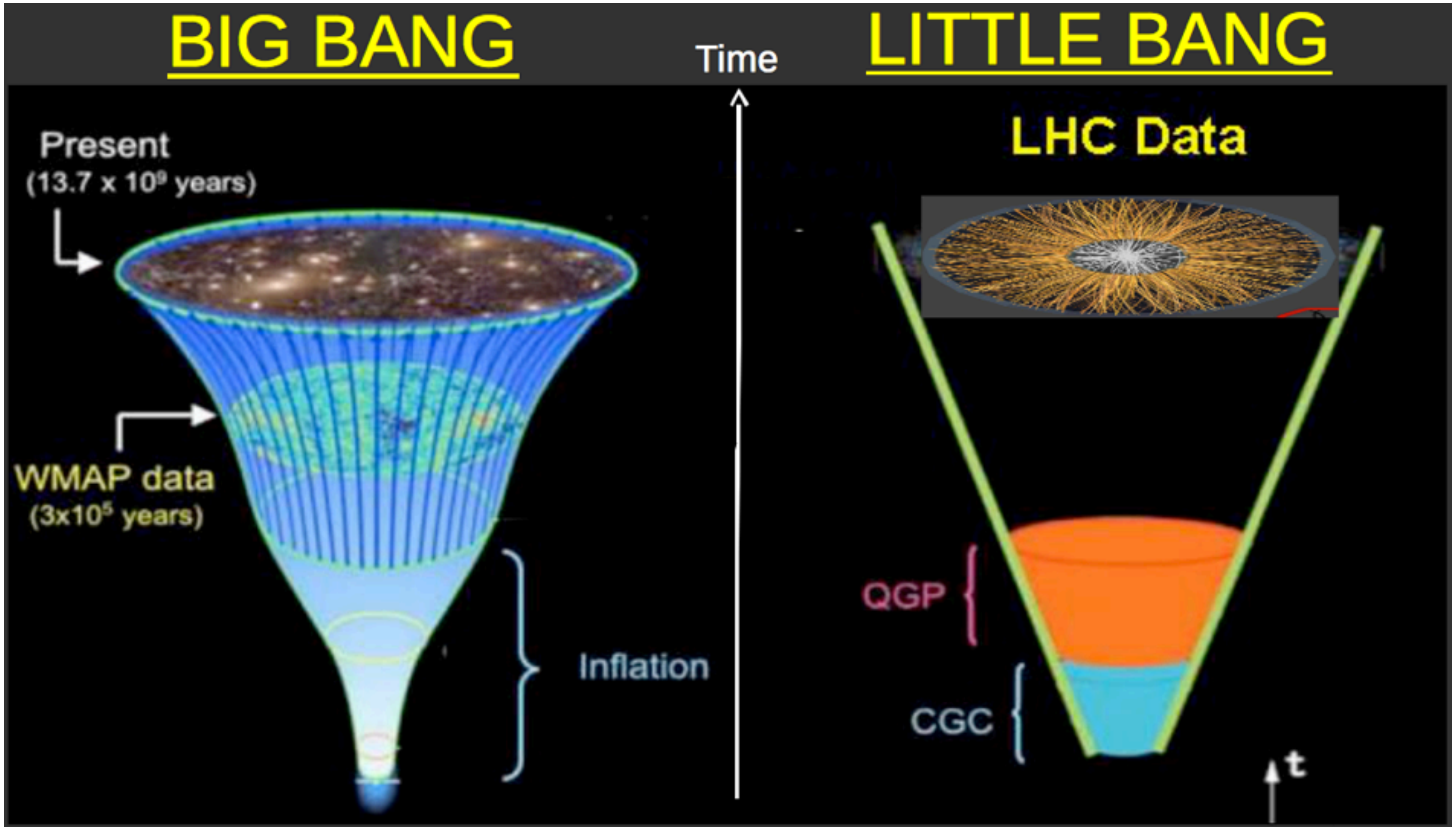
WMAP:

Temperature Fluctuations of the Cosmic Microwave Background.

LHC Heavy Ions:

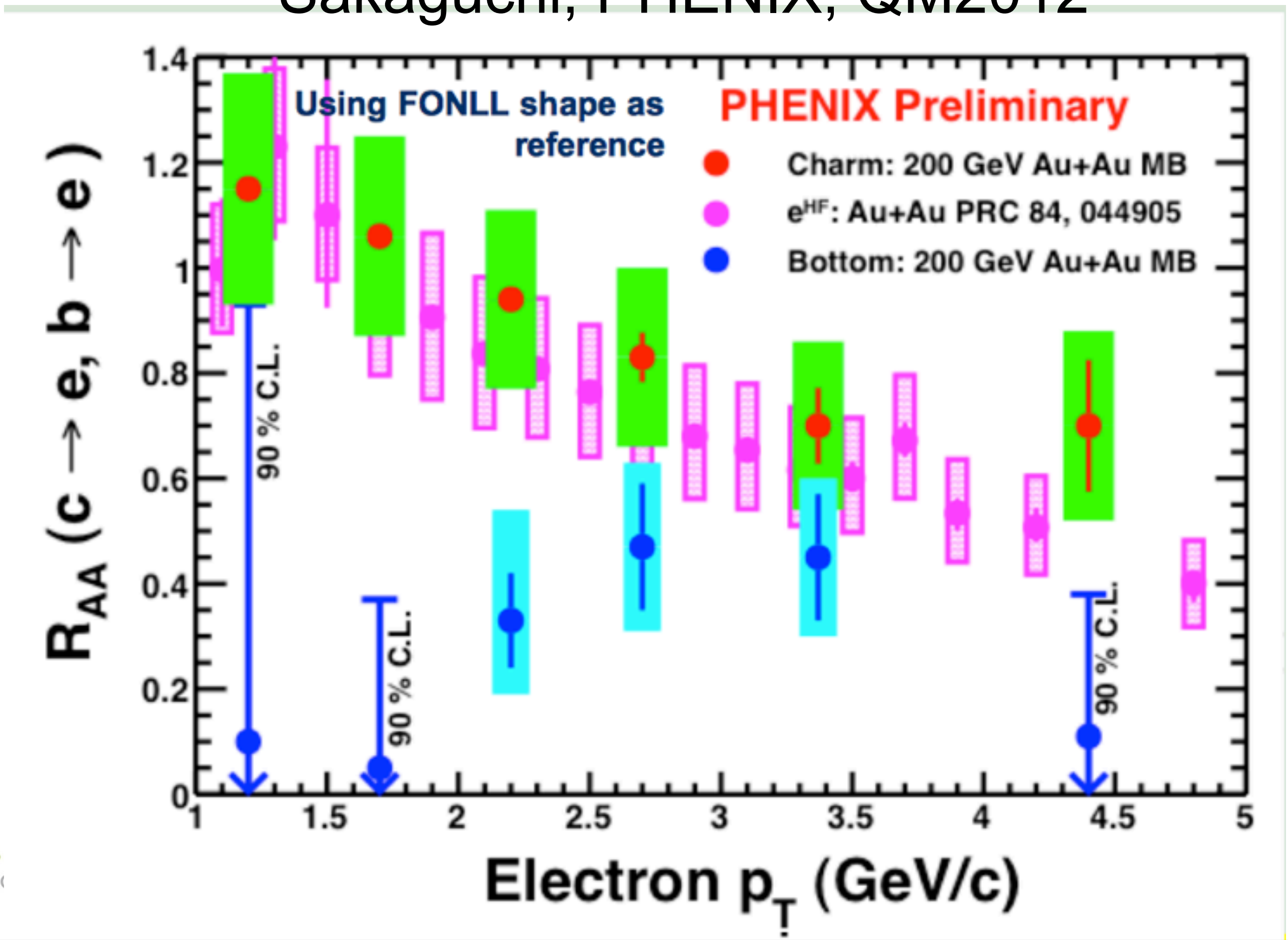
Event-by-Event FLUCTUATIONS of:

- **Conserved Quantities (Net Charge, Net baryon number ....)**
- **Mean pT, Temperature ....**

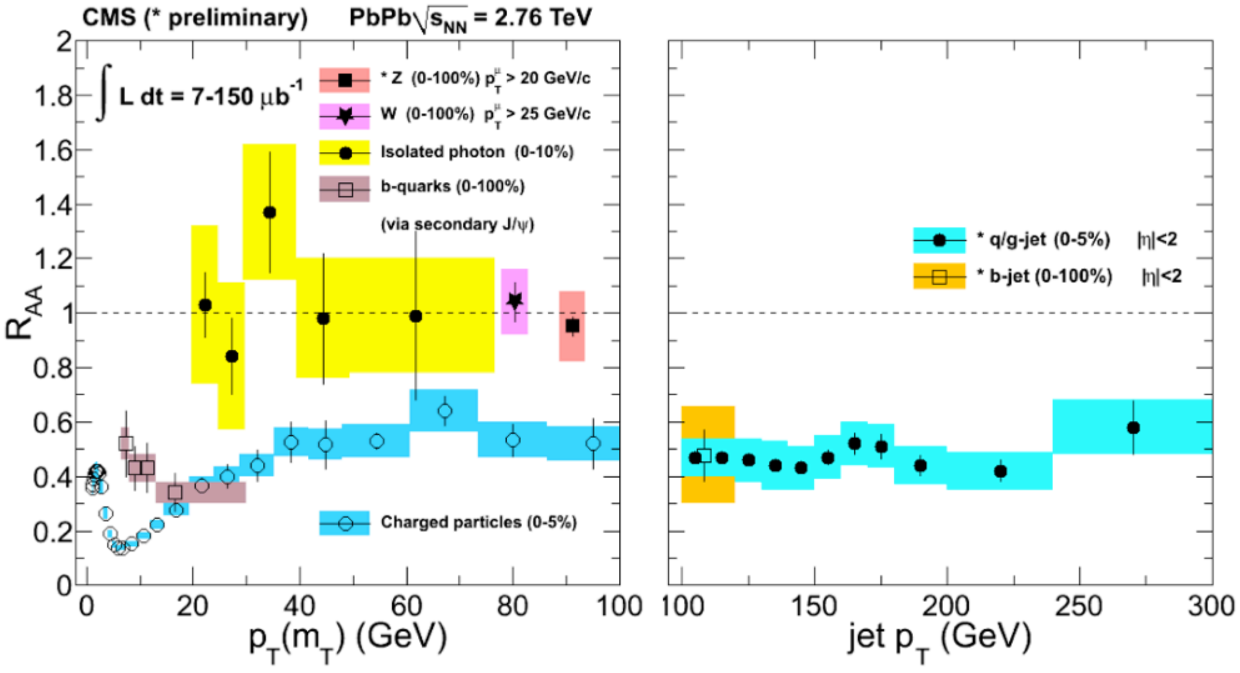

BIG BANG
Time
LITTLE BANG
Present
(13.7 x 10⁹ years)
WMAP data
(3x10⁵ years)
Inflation
LHC Data
QGP
CGC
t

B and C quenching measured in MB Au+Au at 200 GeV

Sakaguchi, PHENIX, QM2012



Quenching of beauty measured via J/Psi and b-jets



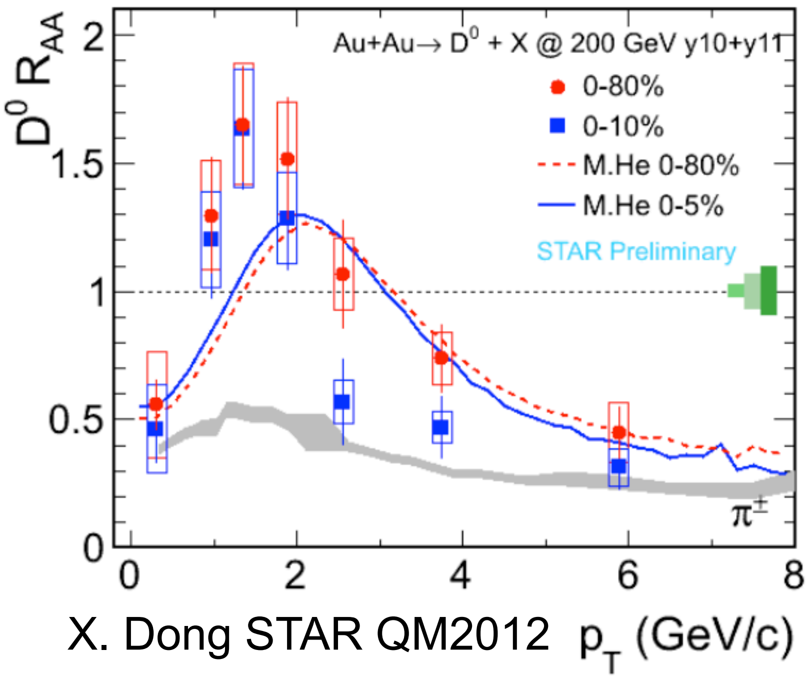
G Roland,
CMS,
QM2012

Note: centrality for b-measurements is different tan for charged hadrons

Quenching of charm and beauty

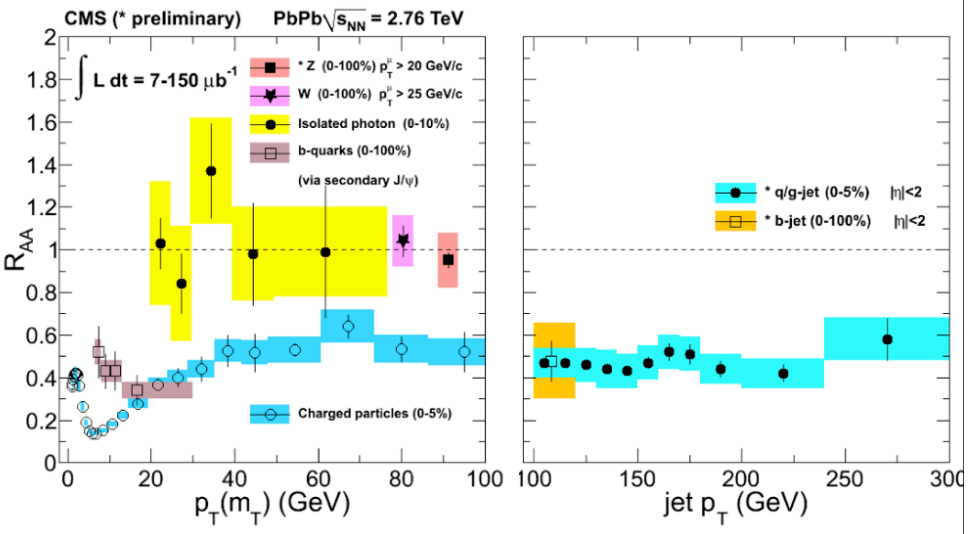
*** The RAA of Charm and Beauty are both suppressed at RHIC and LHC.**
*** Puzzle at RHIC since few years: (b+c) -> e suppression is similar to that of charged hadrons (STAR, PHENIX).**

c measurements



X. Dong STAR QM2012

b measurements



G Roland, CMS, QM2012

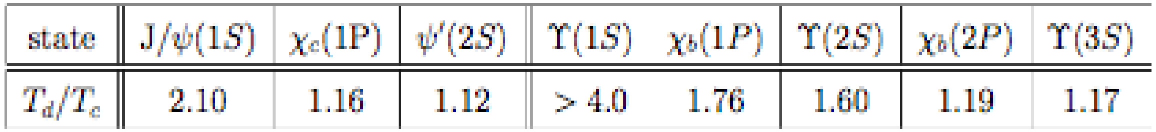
Note: the centrality for b-measurements is different than for charged hadrons

*** 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.**

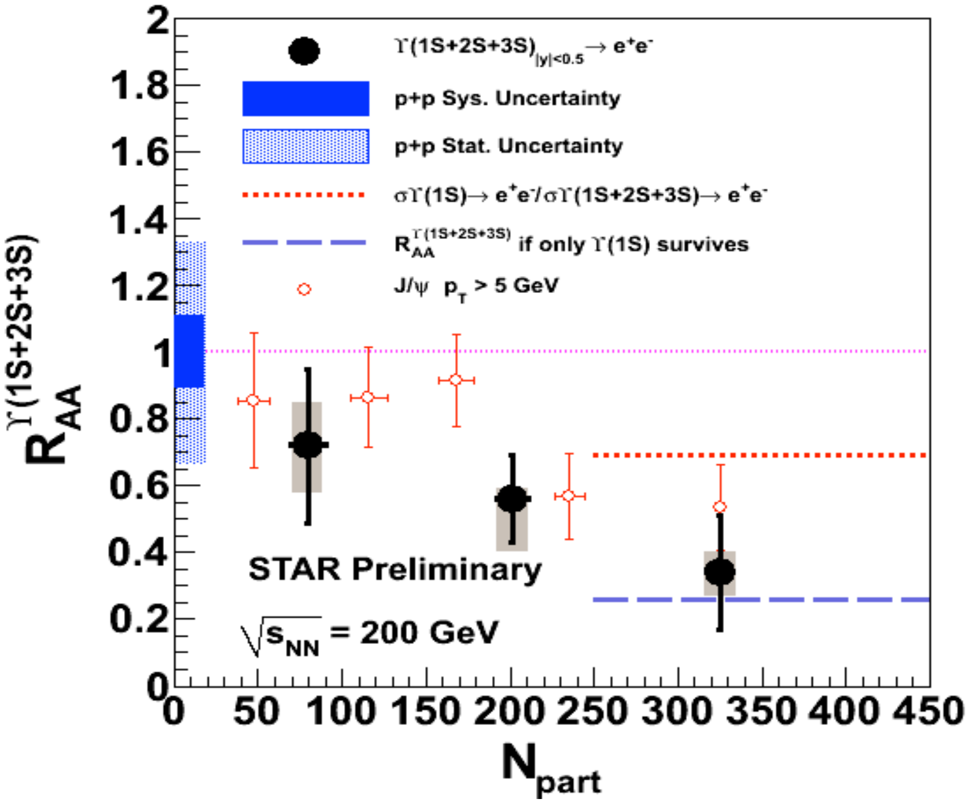
First measure of Y suppression in Au+Au at 200 GeV

Rosi Reed, STAR, flash talk,

poster QM2011



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



- Υ(1S+2S+3S) suppression at central collisions

  -Similar suppression with high p_T J/ψ

- First measurement of Υ suppression at RHIC

- RAA at most central point is in agreement with only Y(1S) surviving

- Statistical uncertainty will be improved by factors 2 to 3 for Au+Au 2011 and p+p 2009 respectively

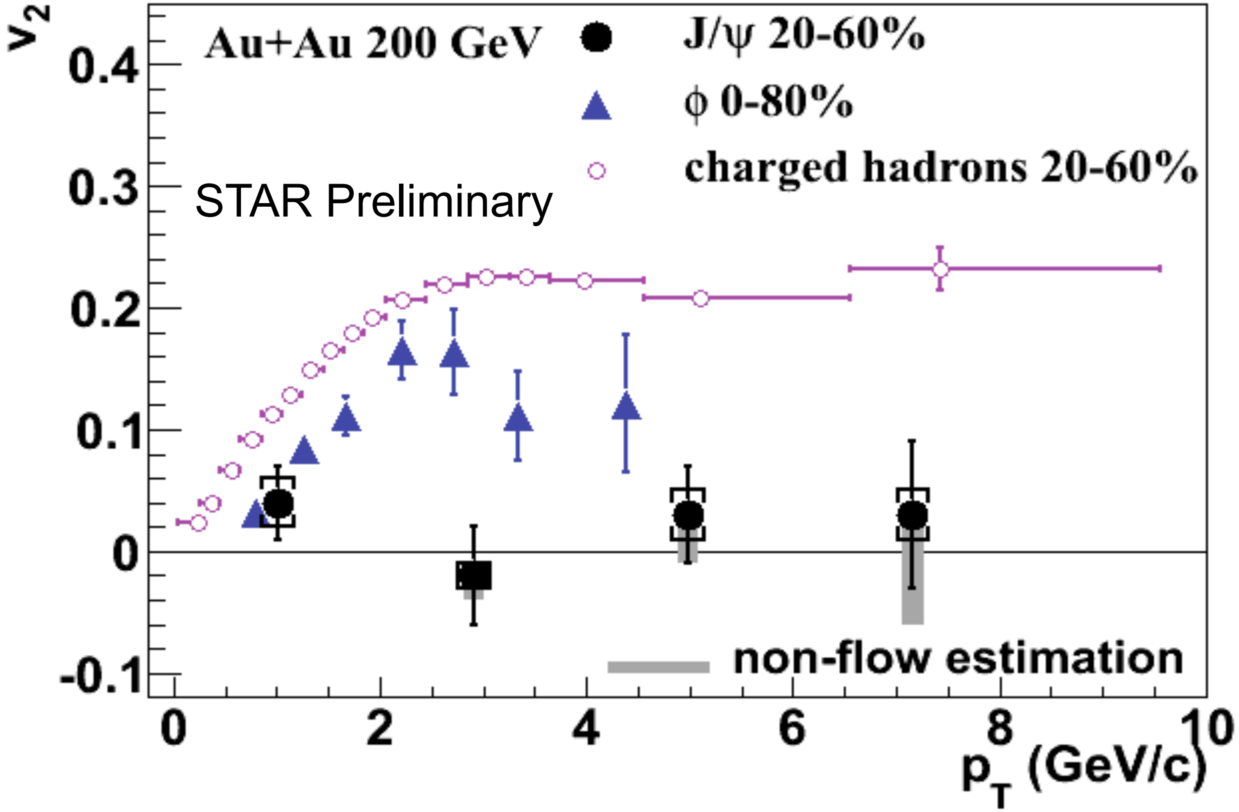
Energy dependence of Y suppression:

Pb+Pb at the LHC : Y(2S+3S)/Y(1S) suppression observed (CMS, QM2011)

Does the J/Ψ flow ?

Zebo Tang, STAR, QM2011

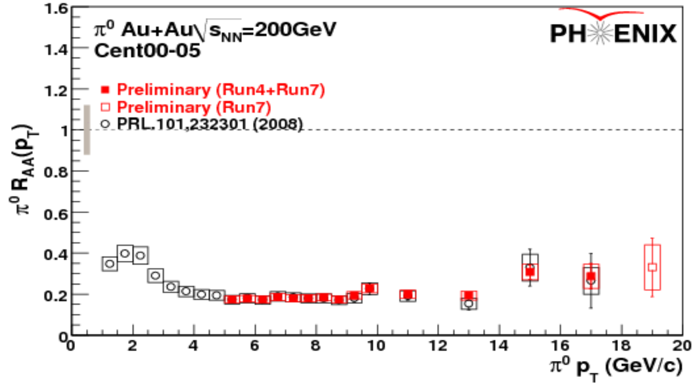
charged hadrons, STAR, ***PRL93****, 252301 (2004)*
ϕ, STAR, ***PRL99****, 112301 (2007)*



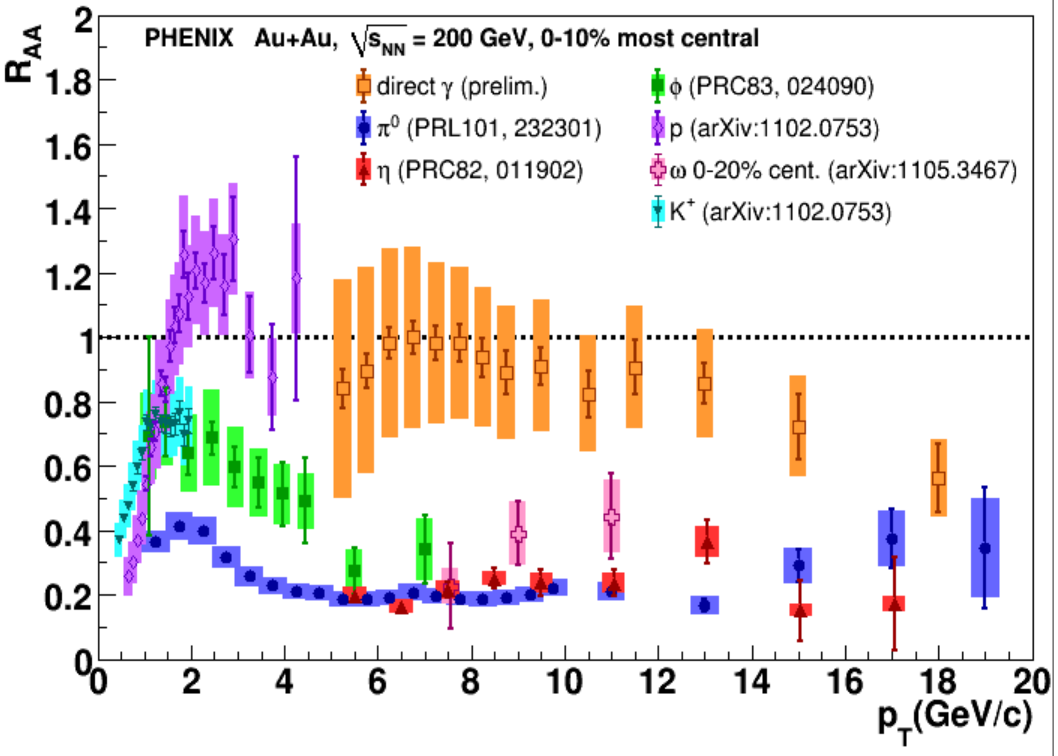
- *J/ψ* **v_2 ~ 0 up to p_T ~ 8 GeV/c in mid-central 20-60%**

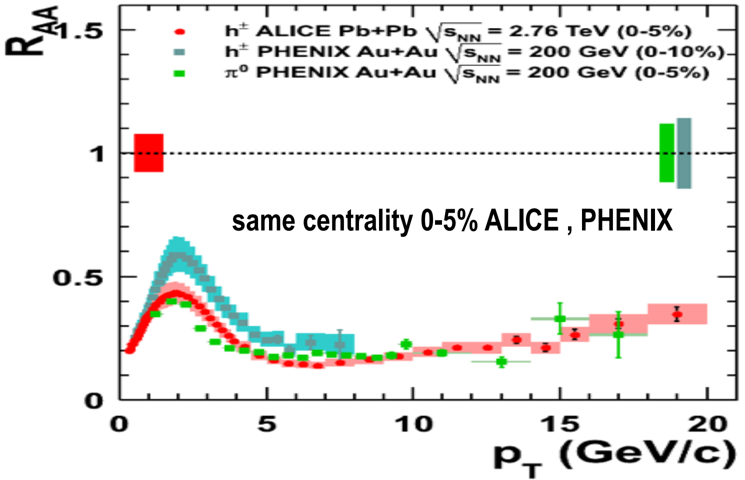
➡ **Disfavors coalescence from thermalized charm quarks at RHIC**

Collision energy dependence of RAA
Nuclear modification factor R_{AA} at RHIC vs LHC



M Purschke, PHENIX, QM2011

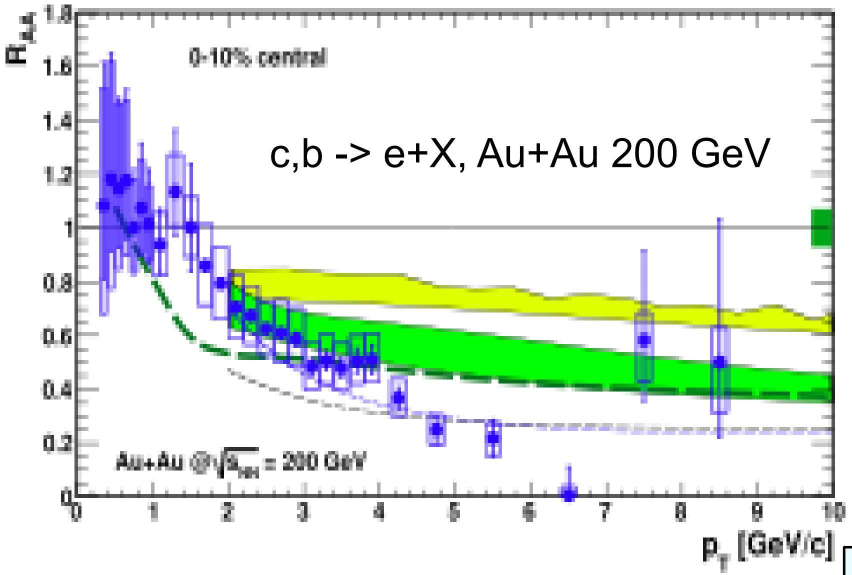




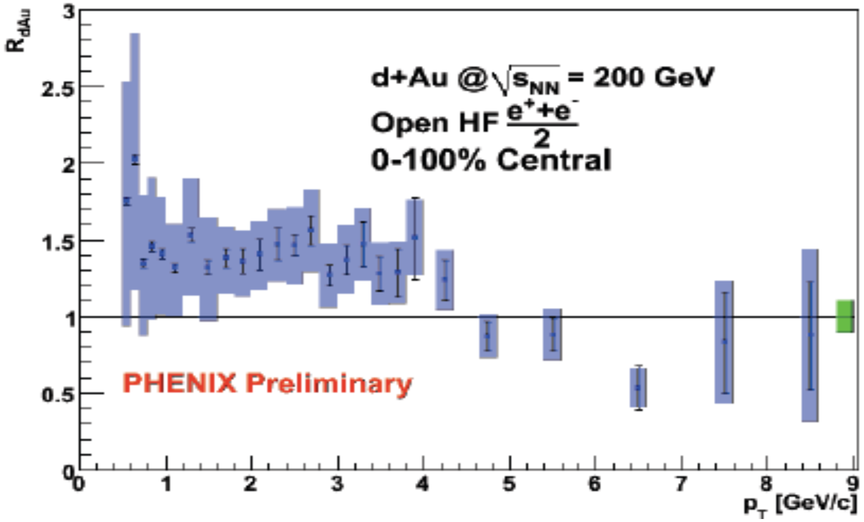
- R_{AA} measured up to p_T = 20 GeV/c in central Au+Au
- R_{AA} (of π0, η, ω) ≈ 0.2 in central Au+Au at high p_T (>5 GeV)
- The R_{AA} looks very similar between RHIC and LHC
- **No suppression for direct gammas below p_T 13 GeV**

Which is the mass dependence of E loss ?
RAA of electrons from heavy flavour decays

Data from : **A Adare et al, PHENIX, 2010, arXiv:1005.1627**
Similar result in STAR, PRL 98 (207) 192301, erratum 2011



C Da Silva, M. Durham, PHENIX,QM2011



Thick dashed line: BDMPS (D,B)->e
Upper band: DGLV (D,B)->e radiative dedx
Lower band: DGLV collisional+rad. dedx
Thin dashed curves: DGLV only D->e+X

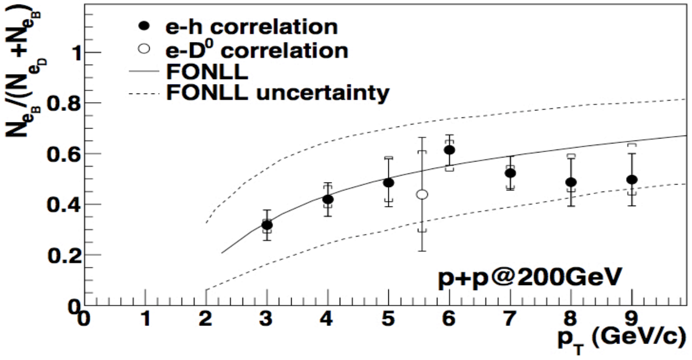
* Is the suppression of R_{AuAu} coming from cold nuclear matter effects ? - New preliminary d+Au data from PHENIX shows that this is not the case

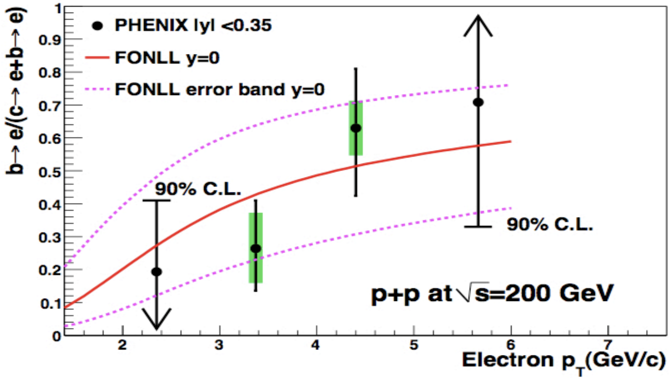
* RAA of open c,b -> e in Cu+Cu 0-20% and periph. Au+Au shows little suppression (not shown)

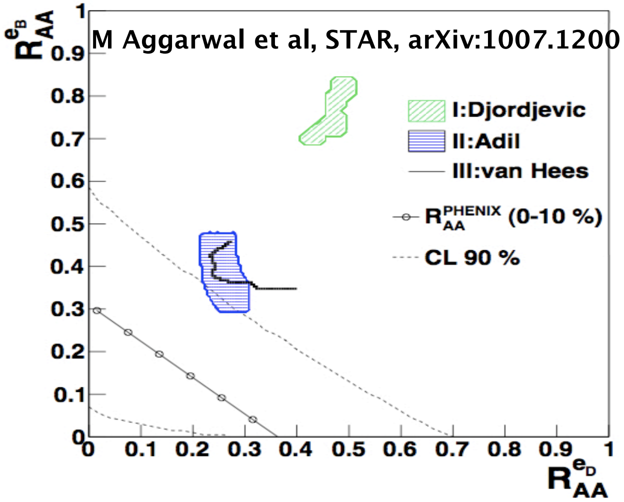
Mesons and NonPhotonicElectrons (NPE) from heavy flavour decays exhibit similar suppression
→ mass dependence of energy loss not as expected from models for radiative de/dx
Challenge to the theory
Adding collisional dE/dx improves the agreement with data
--> Need to disentangle charm and beauty

Disentangling beauty and charm

Confidence level contours for the nuclear modification factor R_AA for beauty and charm are determined from R_AA of NPE (Phenix) and the B/(C+B) measurement from e-h and e-D0 correlations for pT>5 GeV (STAR).






M Aggarwal et al, STAR, arXiv:1007.1200

I: (M.Djordjevic et al, PLB 632, 81, 2006) radiative energy loss with initial g density dN/dy(g)=1000. This model is excluded by the data.

II: (Adil, Vitev,PLB649,139,2007) collisional dissociation of D and B mesons in the QGP causes suppression of R_AA.

III: (van Hees et al,PRC73,034913,2006) Large elastic scattering cross section associated with resonance states of D and B mesons in the QGP.

Contribution of electrons from beauty become ~50% at ~5 GeV pT in p+p collisions

R_AA(e_B) < 1 even if R_AA(e_D)=0 -->Beauty and Charm are both suppressed in Au+Au

Measurements of B and C in Au+Au are crucial -> Silicon detectors upgrades STAR and PHENIX

Set the Questions to answer :

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

Is local thermalization achieved ?

Is there a phase transition or cross over ?

If phase transition, which are the critical parameters ? (Tc)

If phase transition, which is the order of the transition ?

Is this state weakly or strongly interacting ?

Which are the characteristics of this state? (T, density, energy density, viscosity, pressure, lifetime, volume, freeze out conditions)

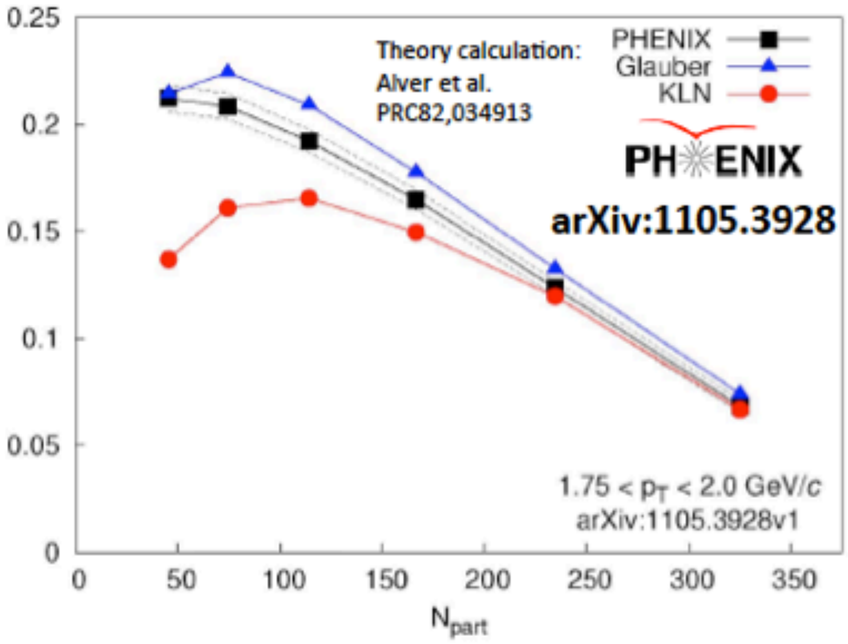
Is there a critical point ?

Which is the phase diagram of QCD ?

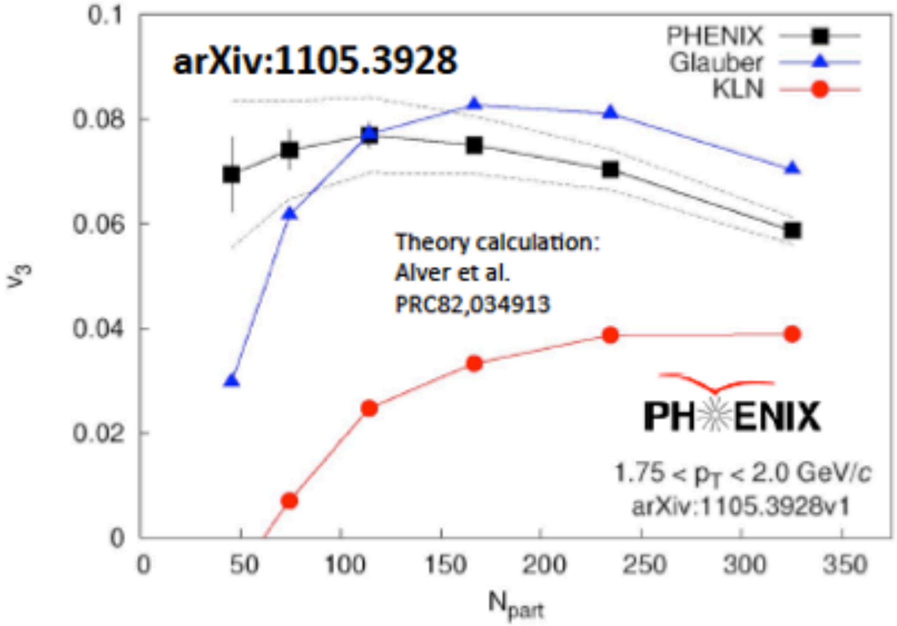
v_3 disentangles initial state and η/s

Stefan Bathe for PHENIX, QM2011

v_2 described by Glauber and CGC



v_3 described only by Glauber



- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

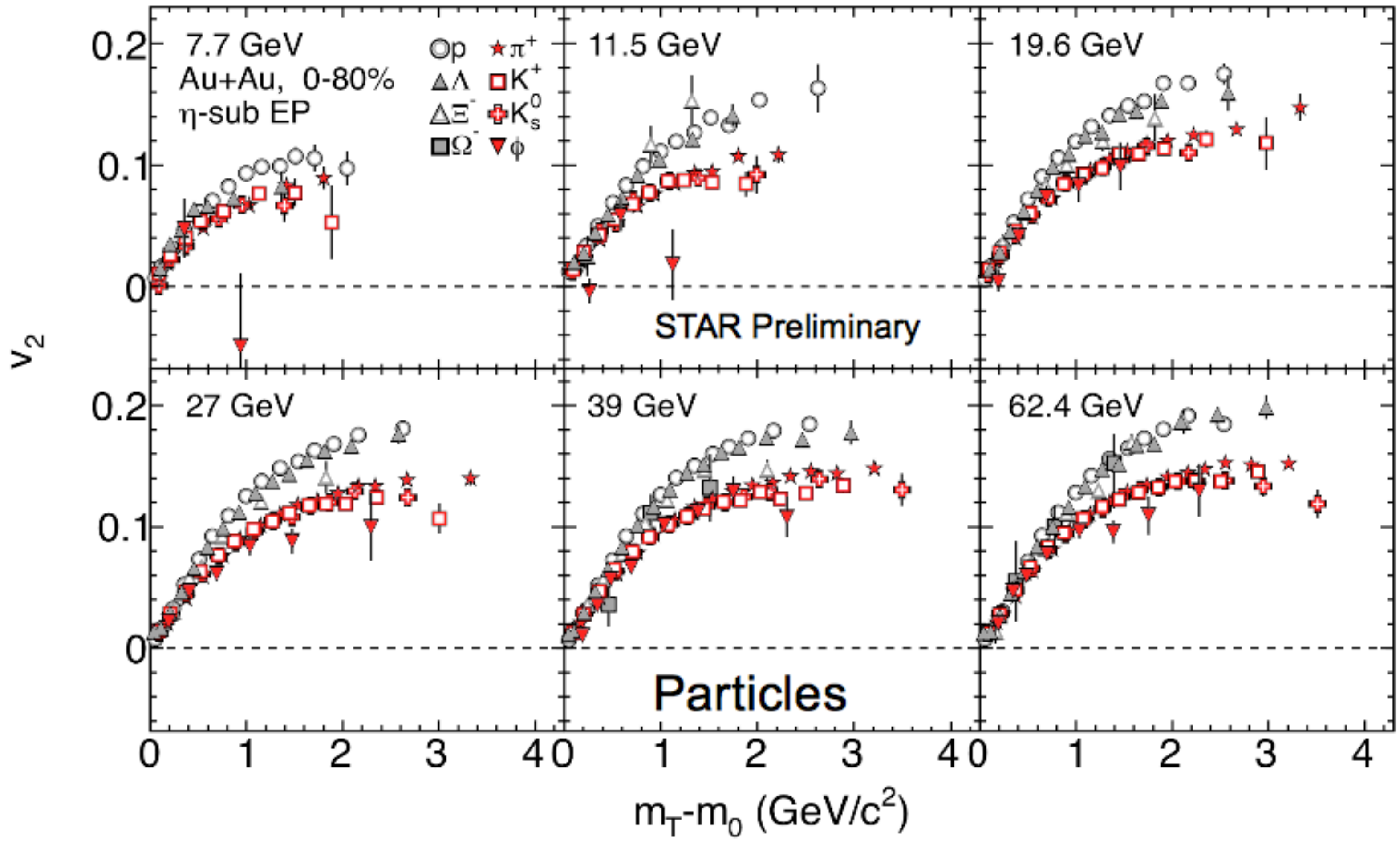
← Two models →

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

AdS/CFT predicts $\eta/s=1/4\pi$

Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

Shusu Shi et al, STAR, QM2012



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

2003 BNL press release:

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

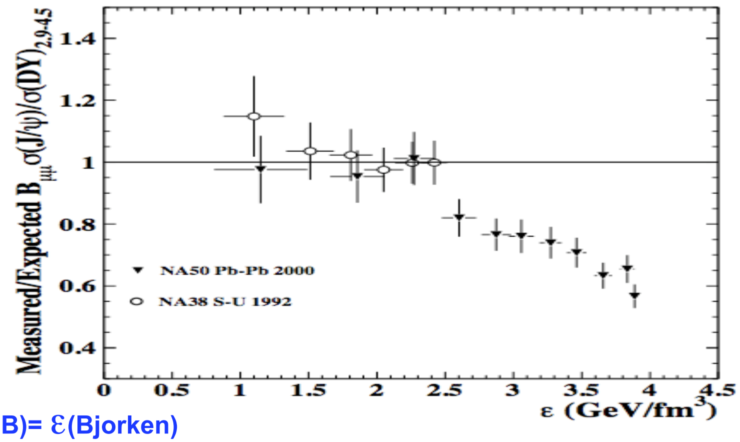
Discovery of a strongly interacting QGP (sQGP)

sQGP found consistent with a perfect liquid

Applications of AdS/CFT duality on sQGP

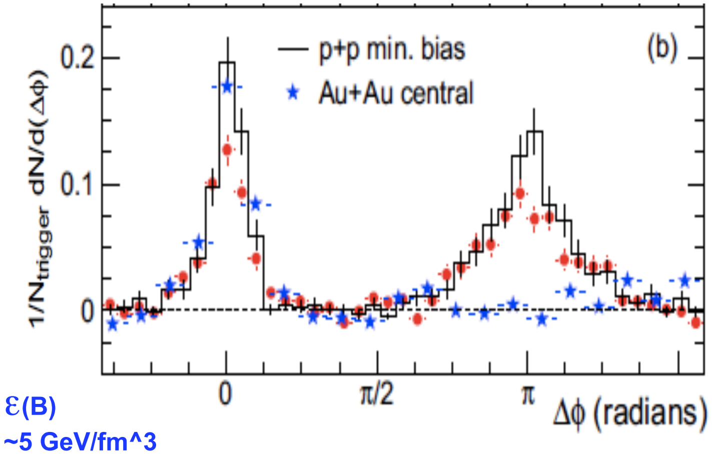
Marks a new era in QCD studies

J/Psi suppression, NA50 Coll.



Ɛ(B)= Ɛ(Bjorken) ~3.5 GeV/fm^3

STAR



Ɛ(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 !

2011: large data sample collected

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 billon Au+Au events) with highly enhanced identification capabilities due to new detectors

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

2011: Y suppression discovered at RHIC and LHC

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

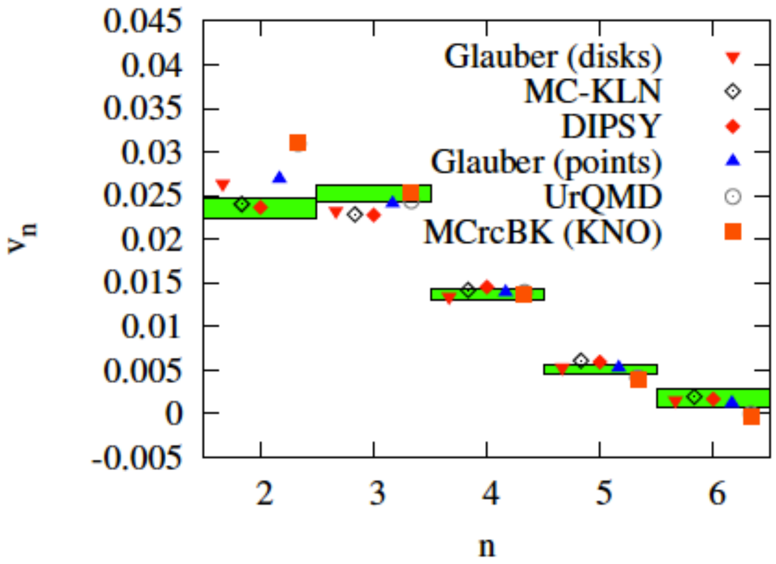
--> Goal is to achieve a combination of many signatures

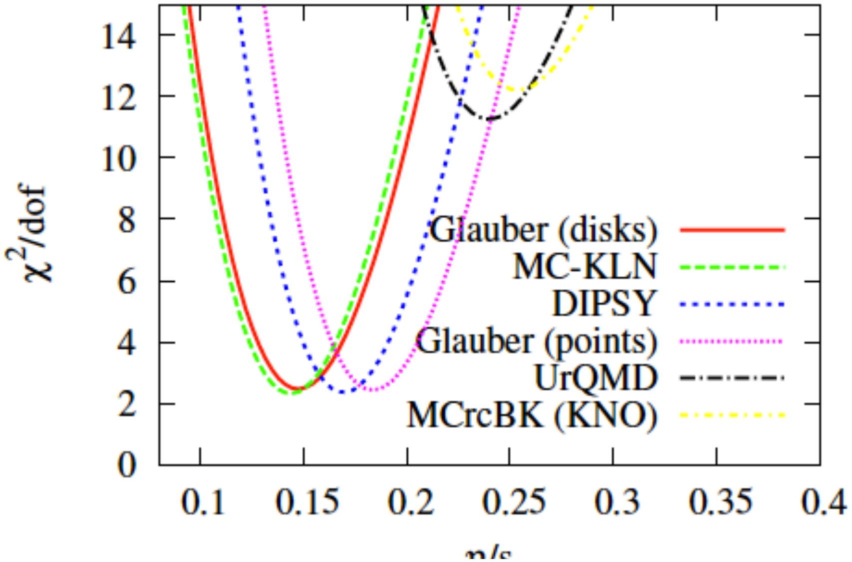
EXTRACTING η/s FROM v_n IN CENTRAL COLLISIONS

M. Luzum, QM2012

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

(Also see U Heinz et al) for vn fits





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

Experimental uncertainties	±0.020
Initial eccentricity	±0.050
$v_n/\varepsilon_n =$ constant	~ ±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	~ ±0.010
Deviation from boost-invariance / longitudinal fluct.	~ ±0.005
Viscous correction to f.o. distribution	±0.015
Other aspects of freeze out	~ ±0.025

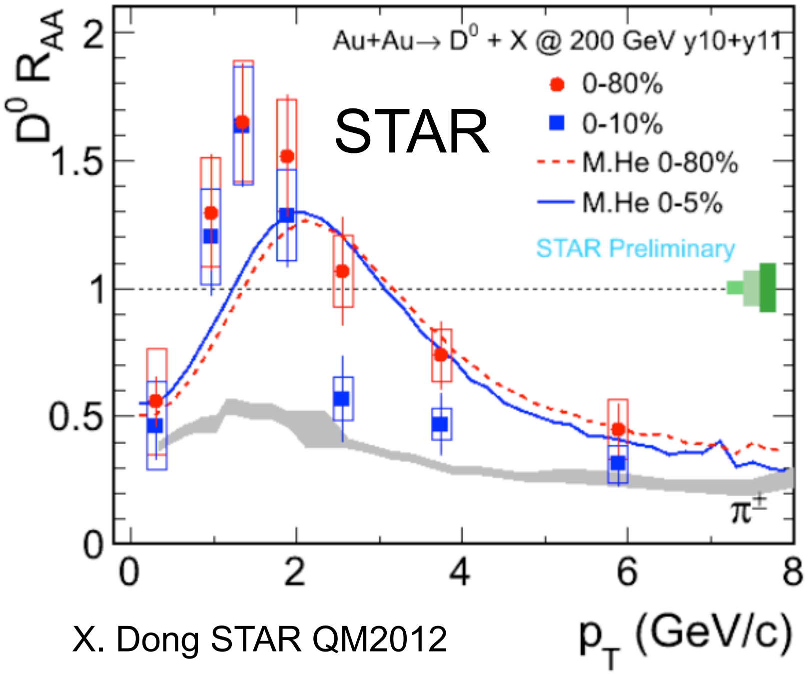
Result for LHC (preliminary) :

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

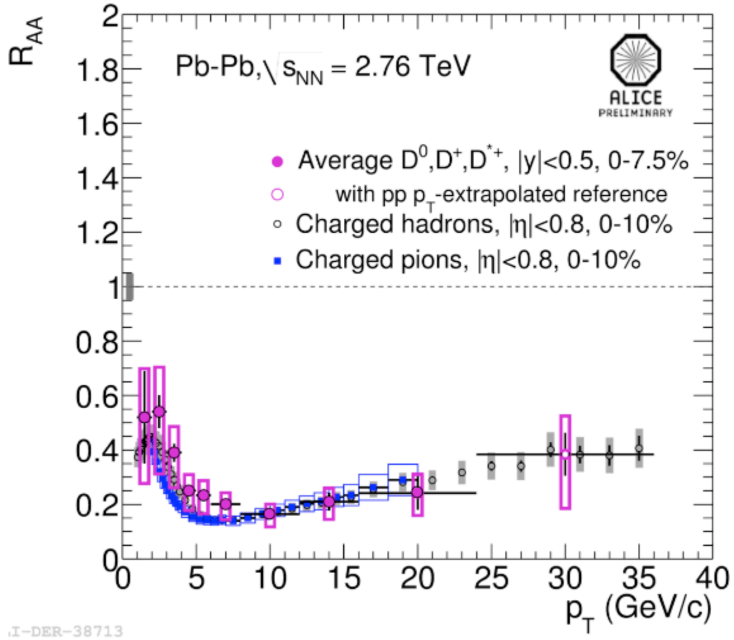
Quenching of open charm and beauty

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

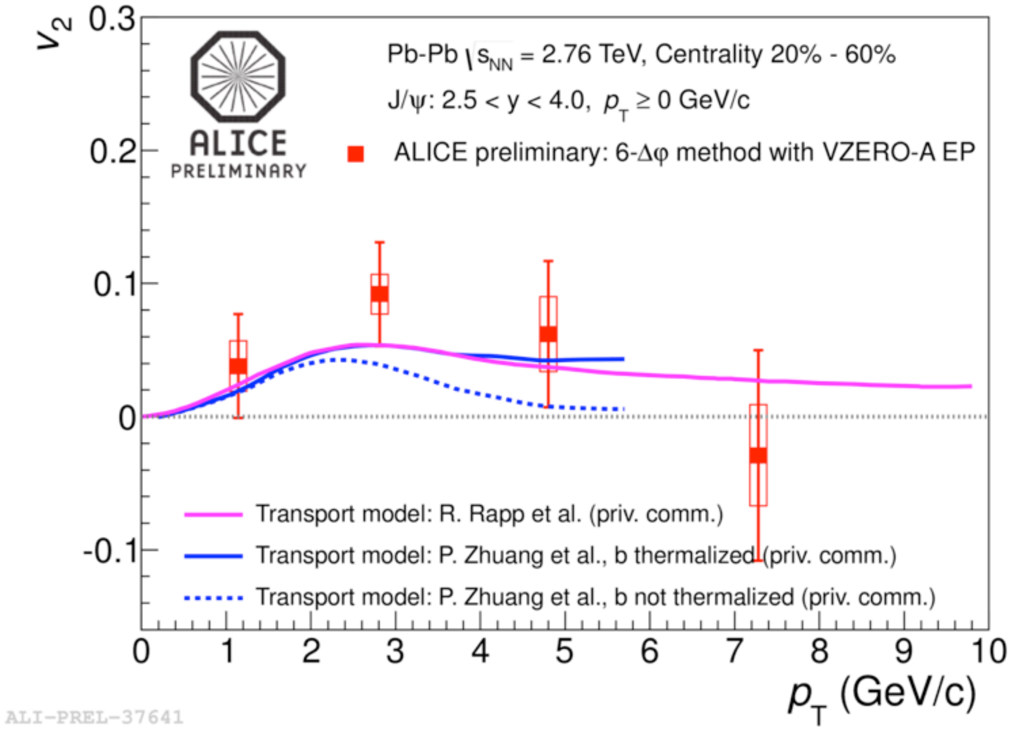


K Safarik, ALICE, QM2012

*** 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.**

elliptic flow of J/Psi at LHC



K Safarik,
ALICE,
QM2012

J/y produced by recombination of thermalized c-quarks should have non-zero elliptic flow

– measurements give a hint for non-zero *v2*

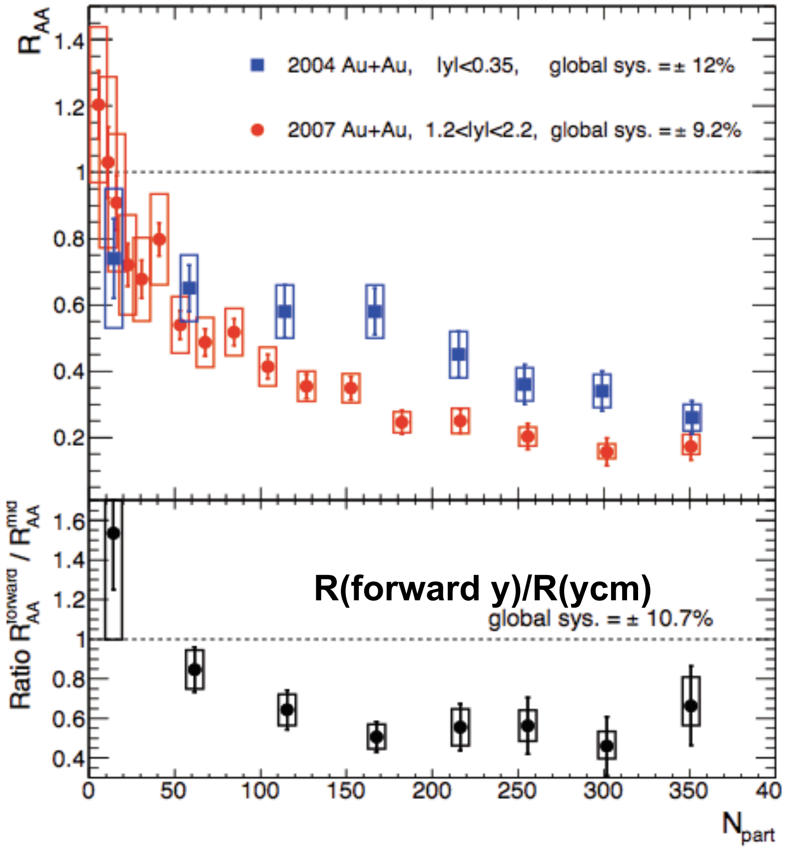
– qualitative agreement with transport models, including regeneration

– complementary to indications obtained from J/y *RAA* studies

The J/Ψ puzzle at RHIC

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

C da Silva, PHENIX, QM2011



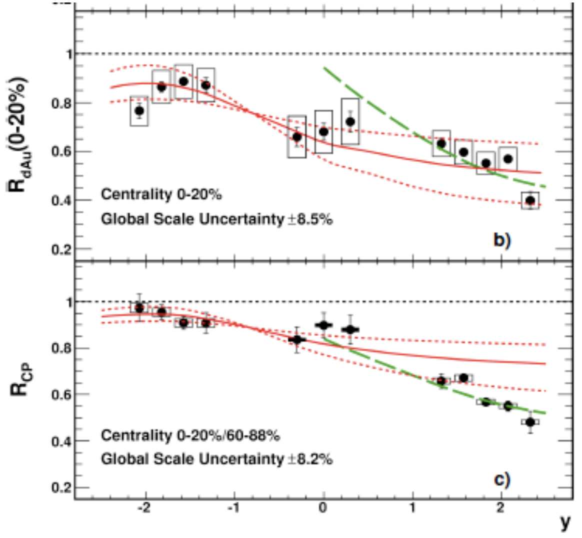
- Suppression doesn't increase with local density
  - –R_{AA} ($|y|<0.35$) > R_{AA} ($1.2<|y|<2.2$)
  - –R_{AA} (RHIC, $|y|<0.35$) ≈ R_{AA} (SPS)

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

*** If J/Ψ from ψ' and χ_c decays is fully suppressed RAA drops to 0.6**

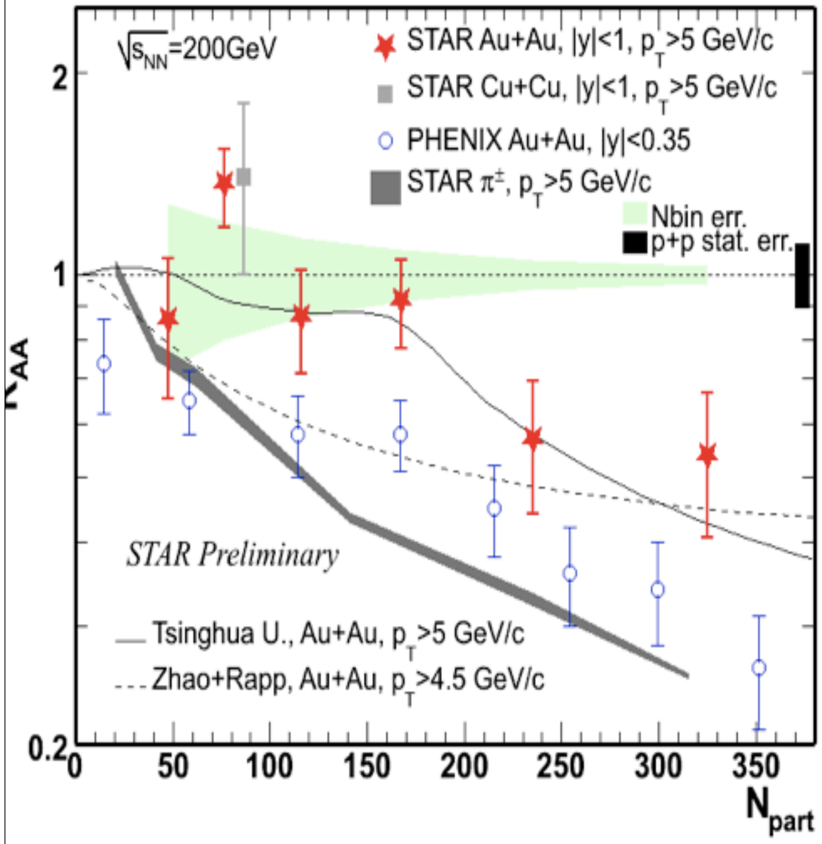
• PHENIX has measured the y-dependance of R(dAu) and R(CP) of J/Ψ in d+Au (arXiv:1010.1246).

PHENIX, arXiv:1010.1246

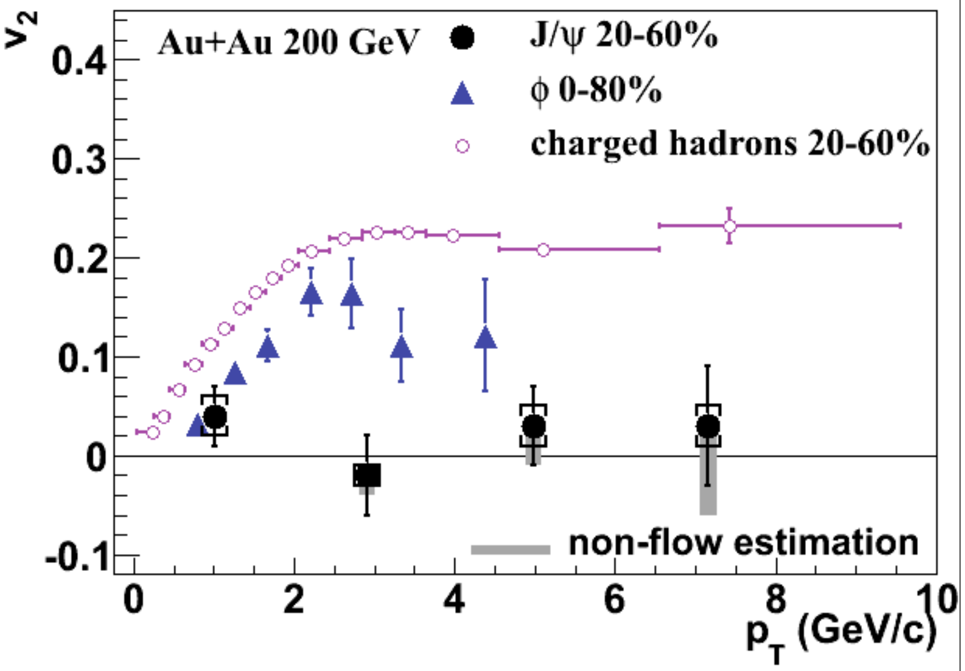


J/Psi in A+A, p_T and Npart dependence

Zebo Tang, STAR, QM2011



Zebo Tang, STAR, QM2011



* Suppression in central collisions at high p_T

* Low pT(Phenix data in blue) is more suppressed

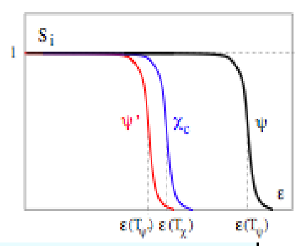
RAA systematically higher at high p_T

- *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 suppression and coalescence

J/ψ suppression at low p_T maybe from excited stats (ψ', χ_c) F. Karsch, D. Kharzeev and H. Satz, PLB 637, 75 (2006); B. Alessandro et al. (NA50), Eur. Phys. J. C 39 (2005) 335; R. Arnaldi et al. (NA60), Quark Matter 2005; PHENIX: Phys.Rev.Lett.98, 232301,2007.

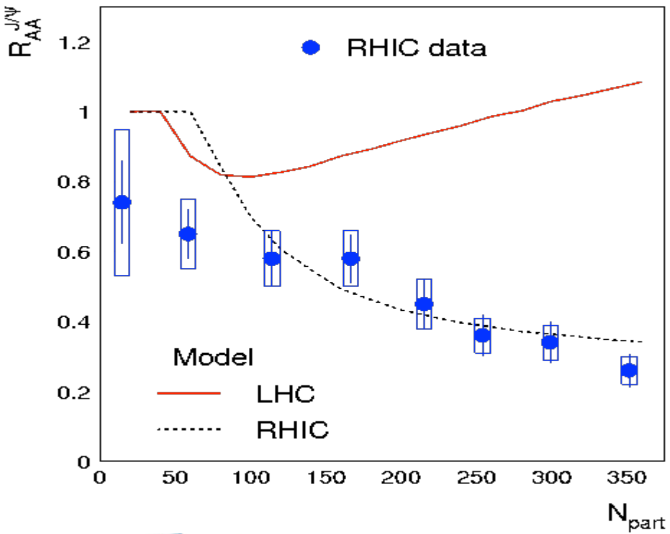


60% of all J/Psi comes from direct J/ψ. (30% of all J/Psi come from χ_c and 10% ψ')
χ_c and ψ' T(dissociation) ~Tc, while J/Psi T(dissociation)~ 2 Tc

Suppression of J/Psi observed, maybe due to χ_c and ψ' dissociation
Directly produced J/Psi may not be suppressed at SPS and RHIC
One can then expect more suppression at LHC due to direct J/Psi dissociation
(but must account for possible c,cbar coalescence-> J/Psi)

J/Psi assumed completely suppressed and resurrected by c,cbar "coalescence"

A Andronic et al, Phys Lett B 652 2007, p 259



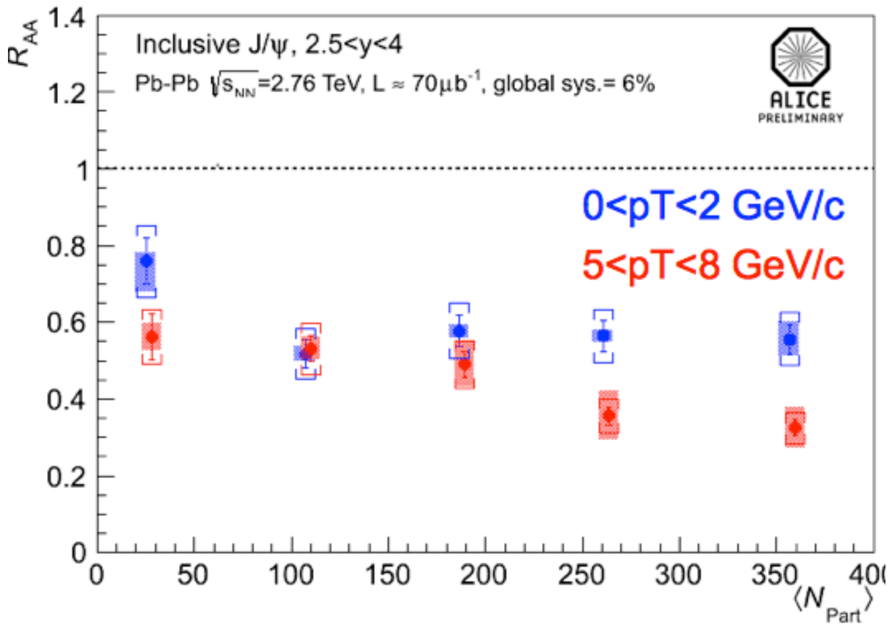
- **J/Psi is assumed to be completely suppressed at RHIC**
- **R_AA(J/Psi) is then estimated for the process of c, cbar coalescence to J/Psi, within a thermal model**

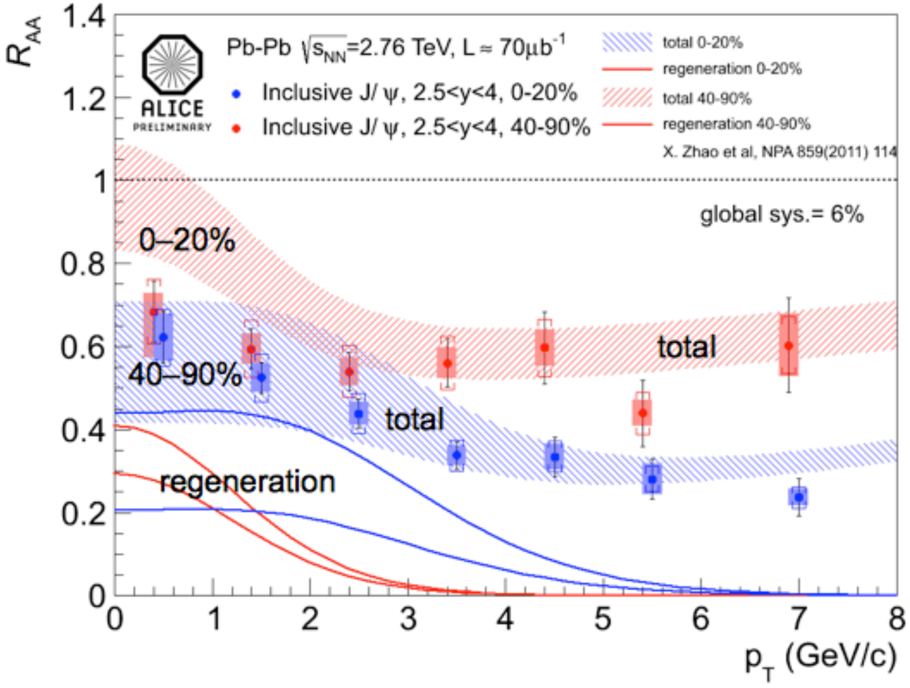
→This estimate can describe R_AA(J/Psi) at RHIC

→ It predicts a great enhancement of R_AA(J/Psi) at LHC

J/Psi in A+A, p_T and Npart dependence

K Safarik, ALICE, QM2012



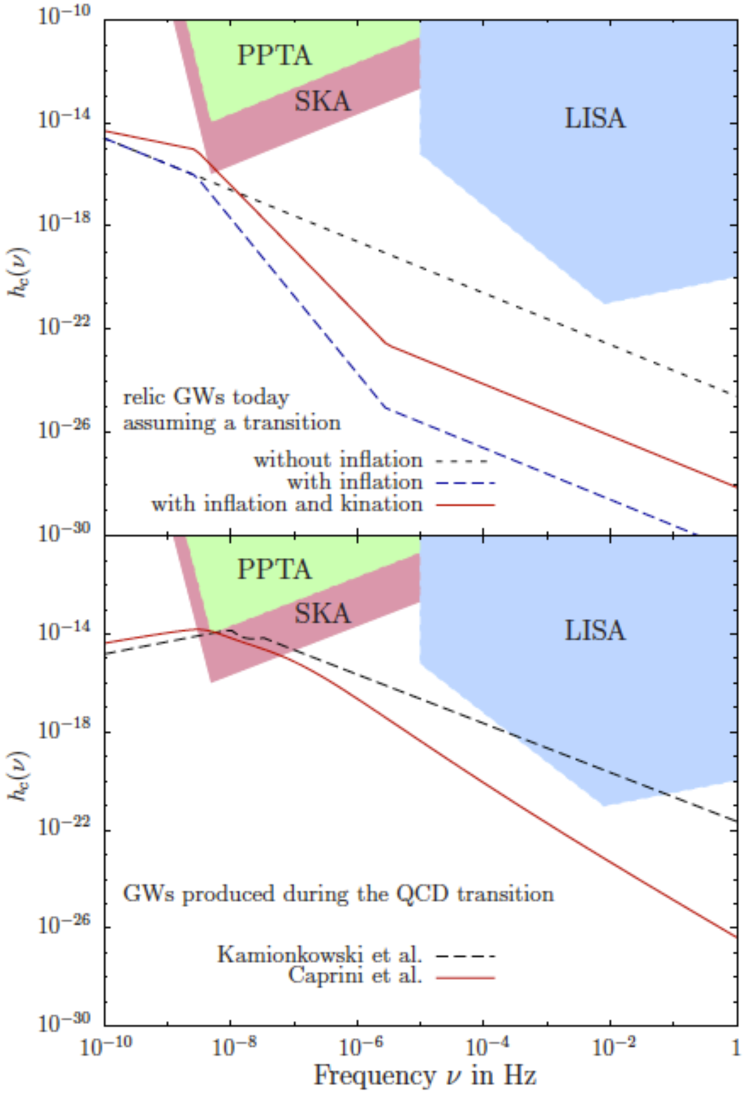


Low pT is less suppressed
RAA of J/Psi smaller at low pT, in central collisions ->

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

At low *p*T ~50% J/y from recombination

Gravitational waves may allow to distinguish between types of phase transition



Upper plot: Cross over case comparing to inflation and kination (assuming a long period of domination of kinetic energy of a scalar field).

Lower plot: Grav Waves emanating from bubble collisons and turbulences during a 1st order QCD phase transition

Comparison to sensitivity of experiments: SKA (Square Kilometer Array), PPTA (Parks Pulsar Timing Array), LISA (Laser Interferometer Space Antenna)

J. Schaffner-Bielich et al, arXiv:1105.0339

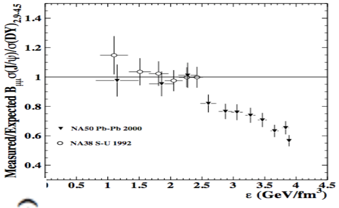
Historical Milestones of the search for the QCD phase transition

2000 CERN press release:

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

Ψ’, J/Ψ suppression, T(direct γ)~335 MeV, T(chem. fr. out)~170 MeV near Tc

J/Psi suppression, NA50 Coll.



Ɛ(B)= Ɛ(Bjorken) ~3.5 GeV/fm^3

2003 BNL press release:

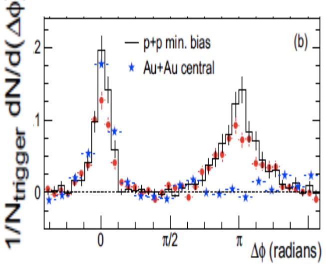
Discovery of jet quenching in Au+Au at √s(NN) = 200 GeV, large elliptic flow

Discovery of a strongly interacting QGP (sQGP)

sQGP found consistent with a perfect liquid - a non anticipated result !

Applications of AdS/CFT duality on sQGP

Marks a new era in QCD studies



STAR

Ɛ(B) ~5 GeV/fm^3

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 in agreement with lattice QCD, motivating a low energy scan.

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

Study onset of transition, search for a possible critical point and map out the QCD phase diagram.

2010: first PbPb at the LHC !

Discovery of Y suppression in 2011 at RHIC and LHC

Hierarchy of bbar and ccbar suppression patterns (2012, LHC)

Ɛ(B) ~16 GeV/fm^3