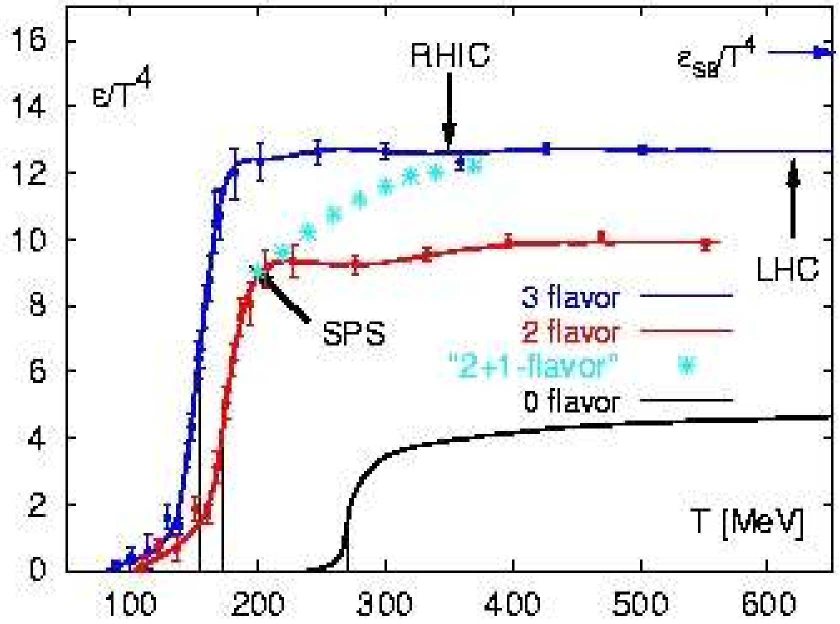
Ultrarelativistic nuclear collisions and the QCD phase boundary

- The QCD phase transition
- Hadron production and the chemical freeze-out curve
- Analysis near μ = 0
  - 2-body collisions don't equilibrate
  - the phase transition drives equilibration through multi-hadron collisions
- Recent results on the ρ meson spectral function
- Speculation about the phase boundary at large μ
- Nature of the QCD matter formed
  - a high density state opaque for fast partons: jet quenching
  - an ideal liquid? hydrodynamics and anisotropic flow – left out here
- Outlook

Korea, Sep. 2006

Peter Braun-Munzinger

Critical energy density and critical temperature



$T_c = 173 \pm 12$ MeV

$\varepsilon_c = 700 \pm 200$ MeV/fm^3

for the (2 + 1) flavor case:

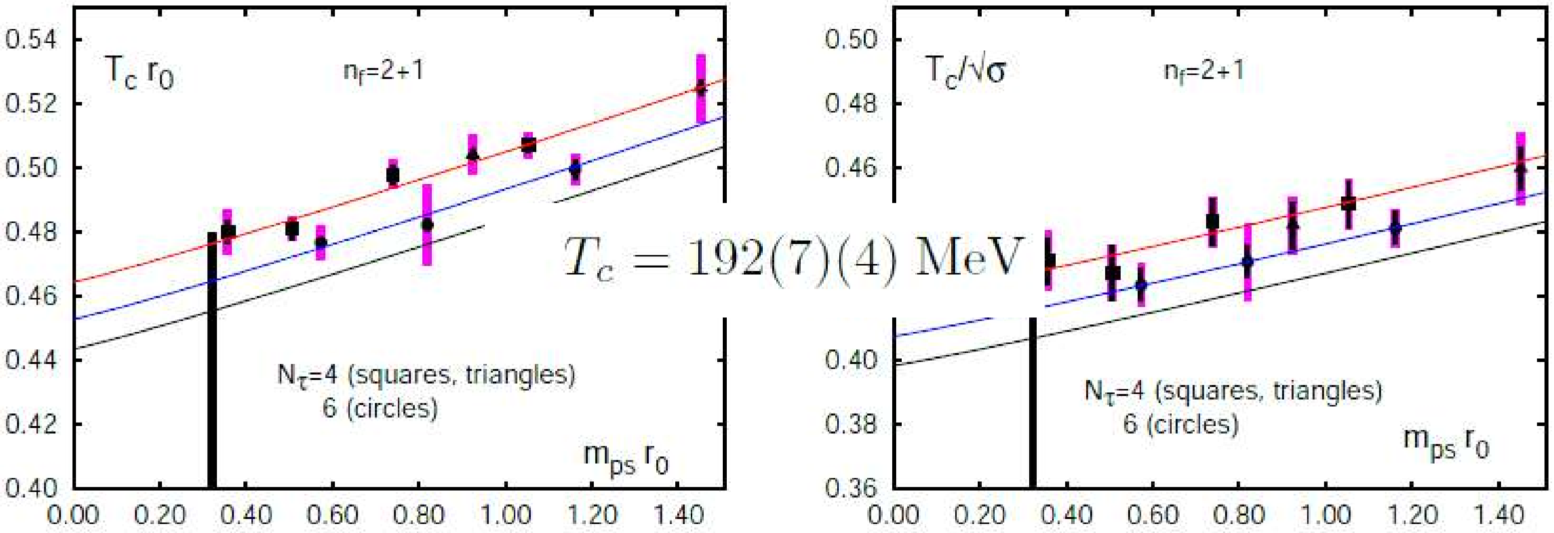
the phase transition to the QGP and its parameters are quantitative predictions of QCD.

The order of the transition is not yet definitively determined.

Lattice QCD calculations for $\mu_B = 0$
Karsch et al, hep-lat/0305025

Transition temperature: newest results

M. Cheng et al, hep-lat/0608013

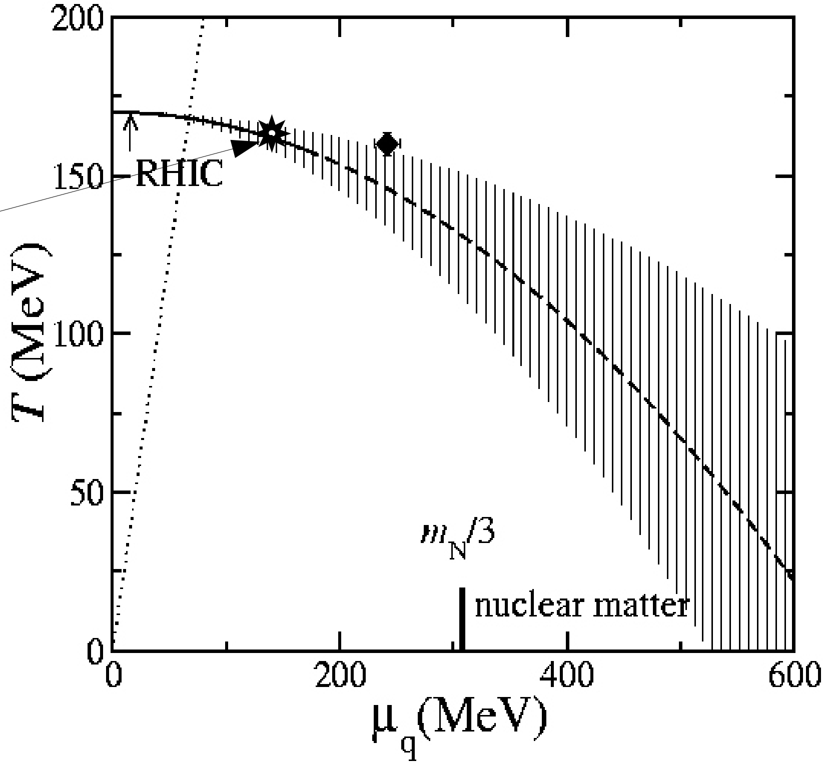


fix scale by determination of r_0 from bottomonium level splitting rather than by fitting pseudo-vector masses

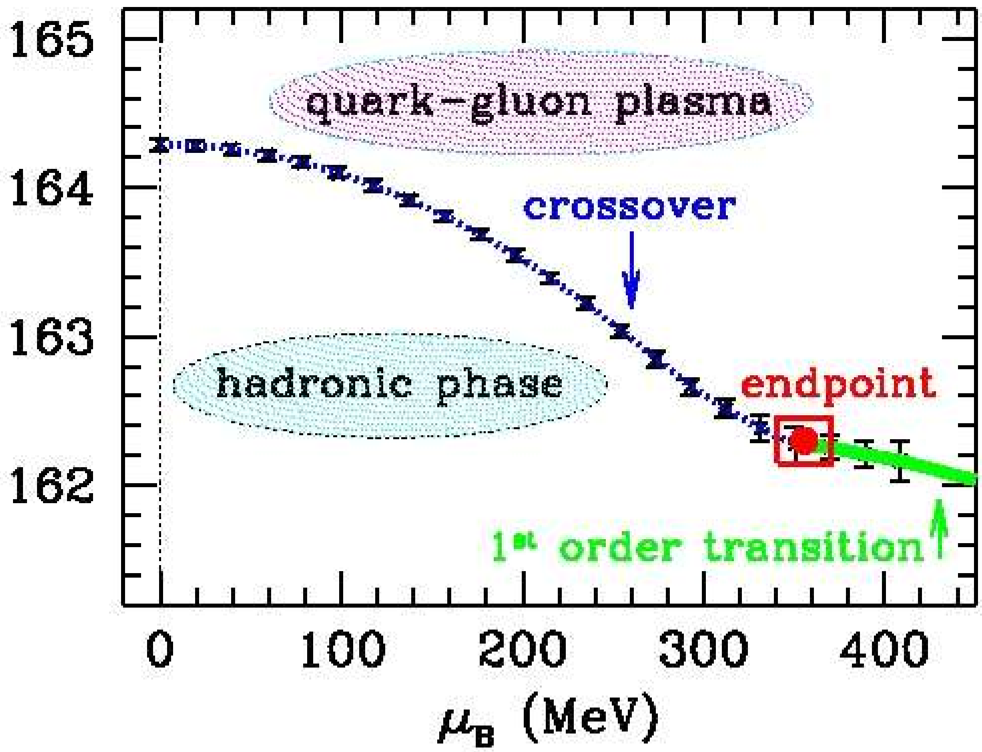
$$T_c = 192(7)(4)\ \mathrm{MeV}$$

The QCD phase boundary – recent results from lattice QCD

New endpoint



S. Ejiri et al, hep-lat/0312006

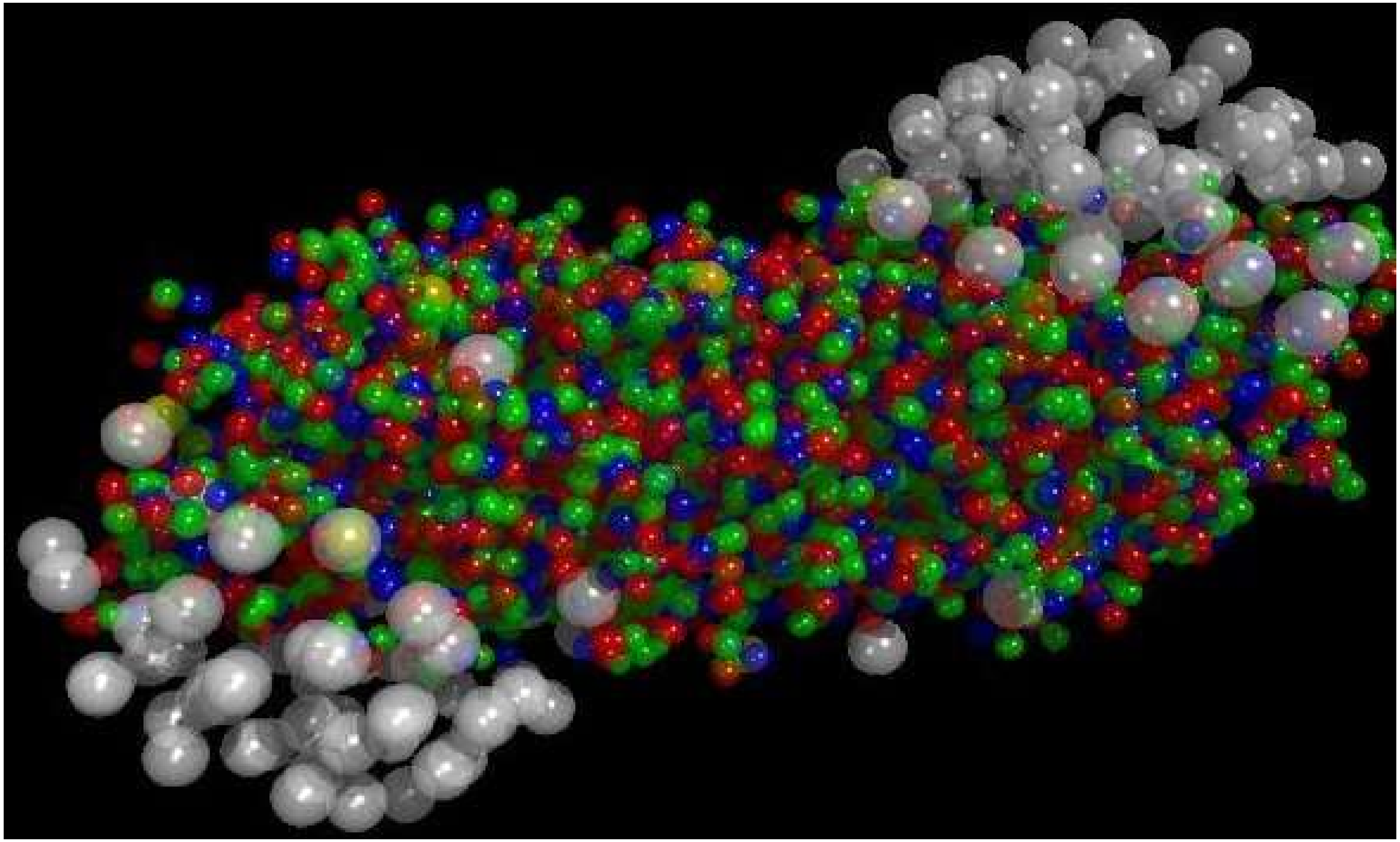


Z. Fodor, S. Katz, JHEP0404, (2004) 050;

Note: $3\,\mu_q = \mu_B$

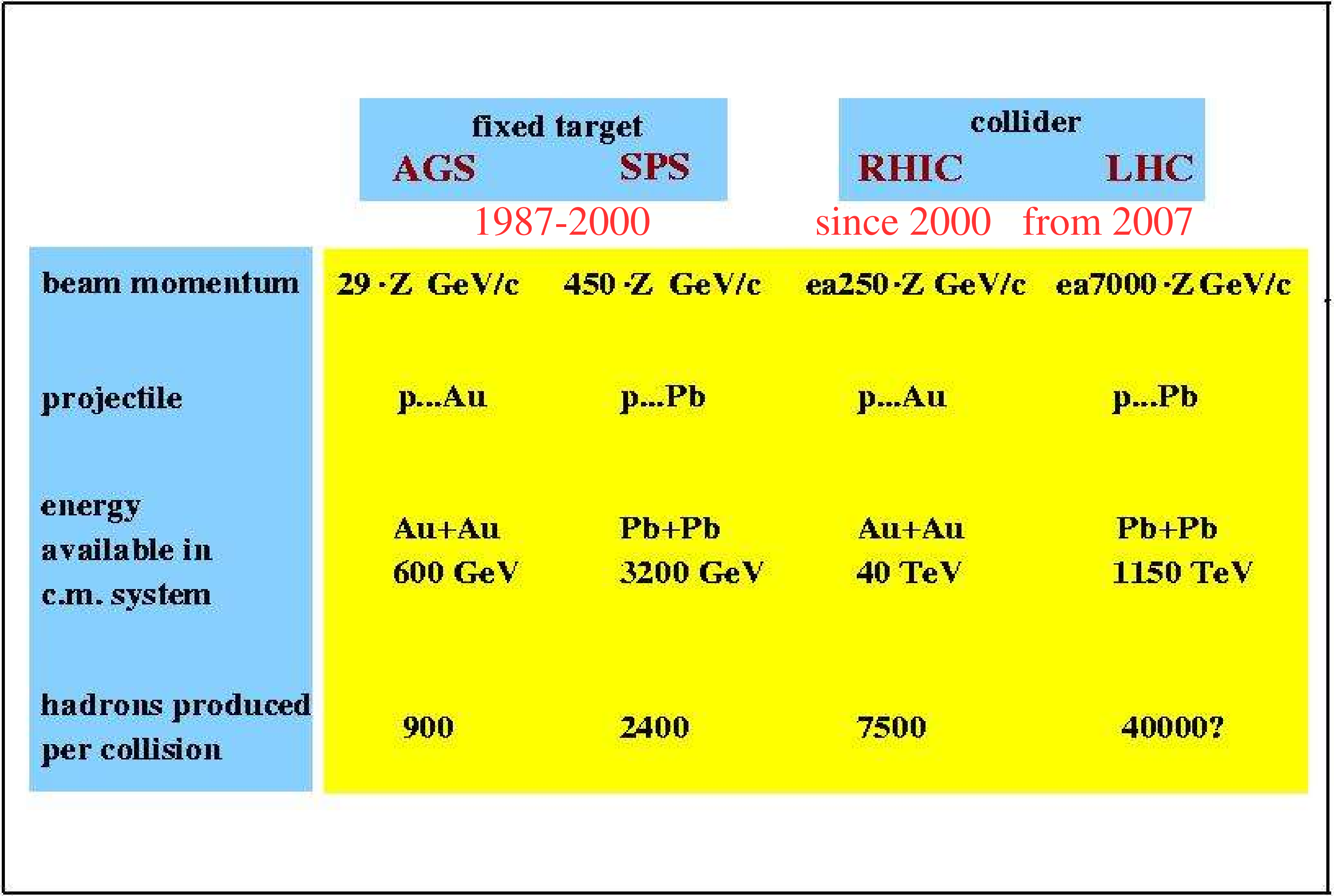
Tri-critical point not (yet) well determined theoretically

Press Release Feb. 2000: New State of Matter created at CERN



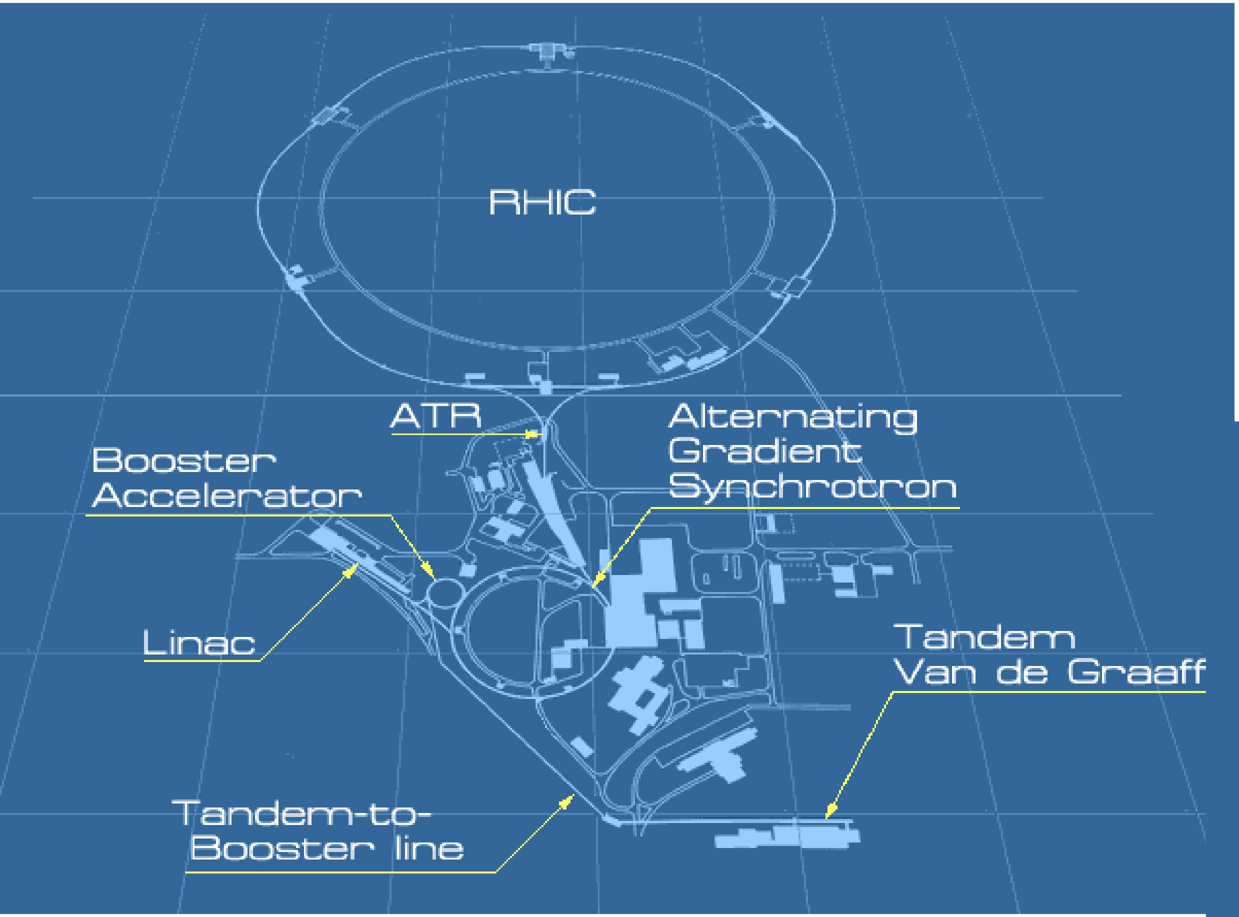
At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

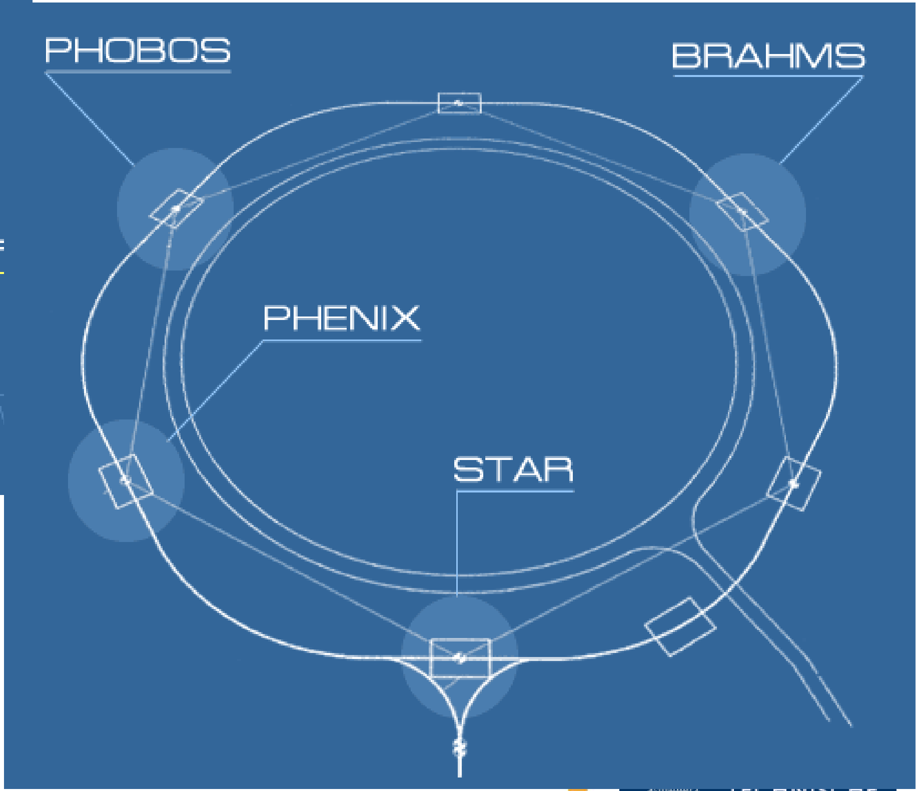
Accelerators where ultra-relativistic nuclei collide



	fixed target		collider	
	AGS	SPS	RHIC	LHC
	1987-2000		since 2000	from 2007
beam momentum	29 ·Z GeV/c	450 ·Z GeV/c	ea250 ·Z GeV/c	ea7000 ·Z GeV/c
projectile	p...Au	p...Pb	p...Au	p...Pb
energy available in c.m. system	Au+Au 600 GeV	Pb+Pb 3200 GeV	Au+Au 40 TeV	Pb+Pb 1150 TeV
hadrons produced per collision	900	2400	7500	40000?

heavy ion collider RHIC – dedicated machine

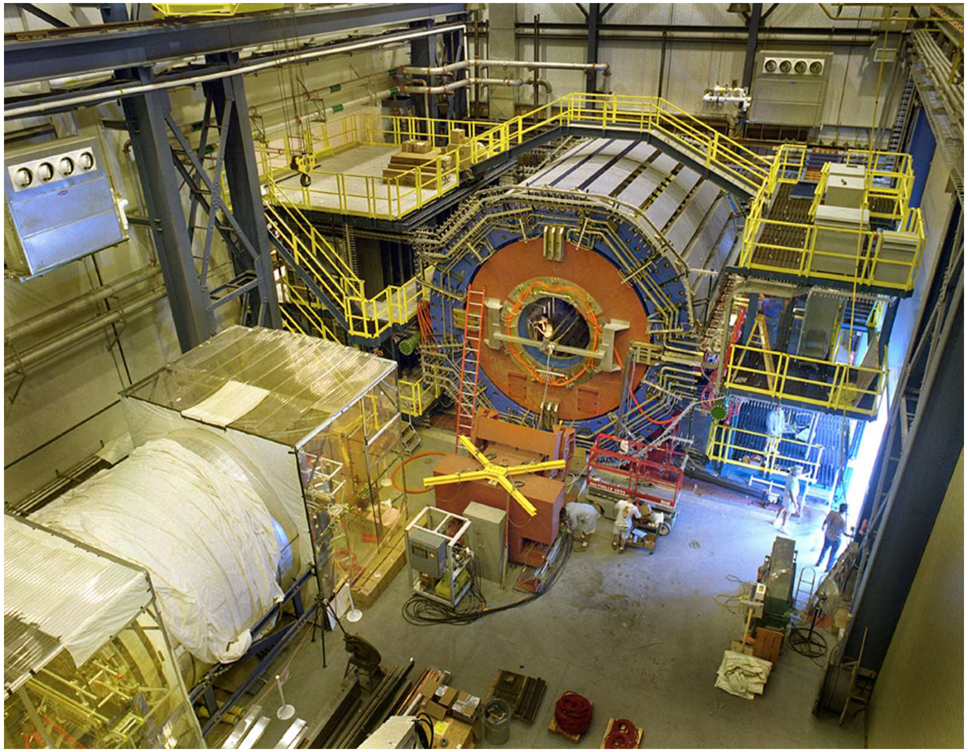




RHIC experiments: 2 large and 2 small

PHENIX: central 2 arm spectrometer plus forward/backward muon arms

STAR: large TPC at central rapidity

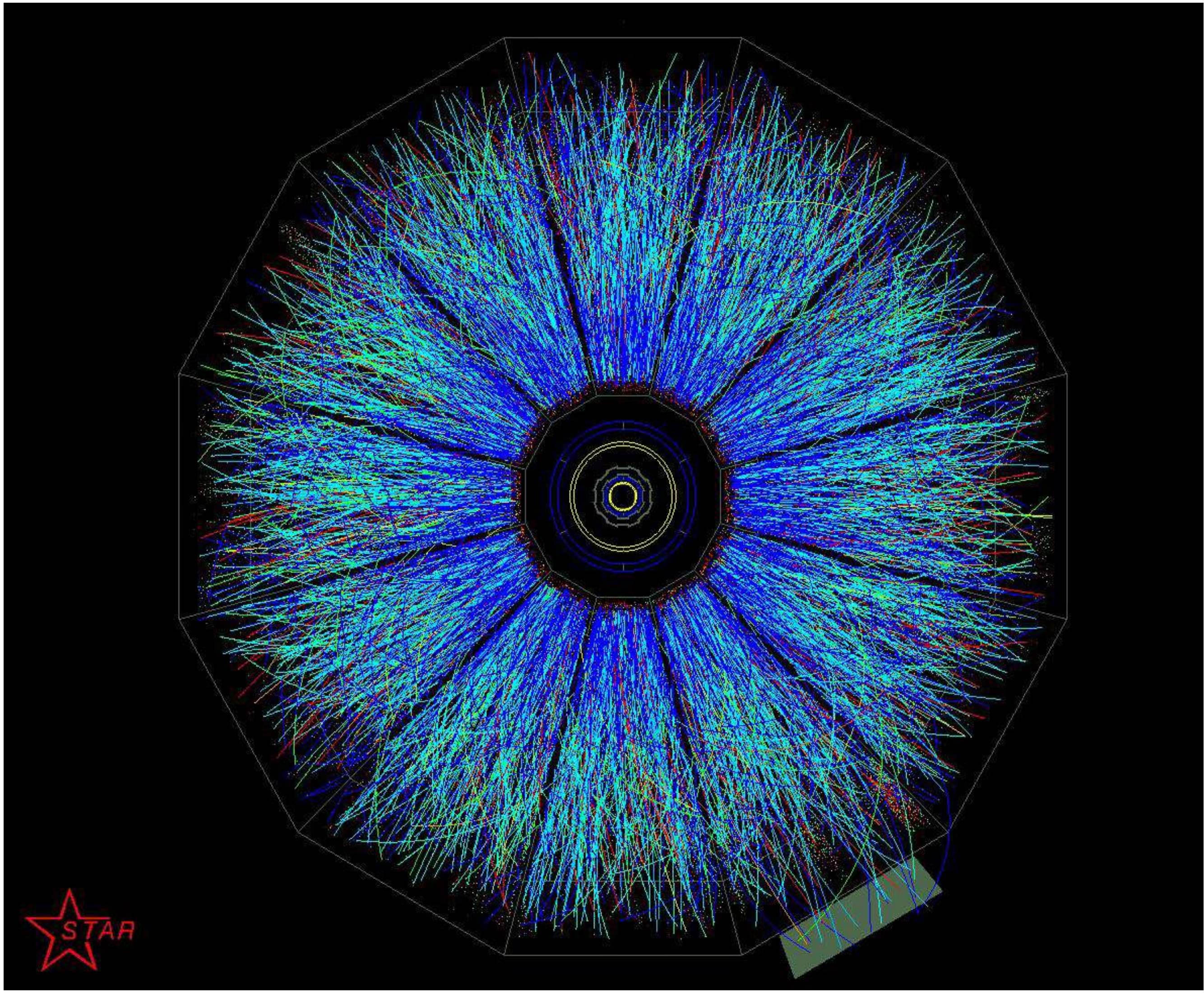


as well as PHOBOS and BRAHMS

STAR event display

in central AuAu collsions at RHIC $\sqrt{s}$ = 200 GeV about 7500 hadrons produced (BRAHMS)

about three times as much as at CERN SPS



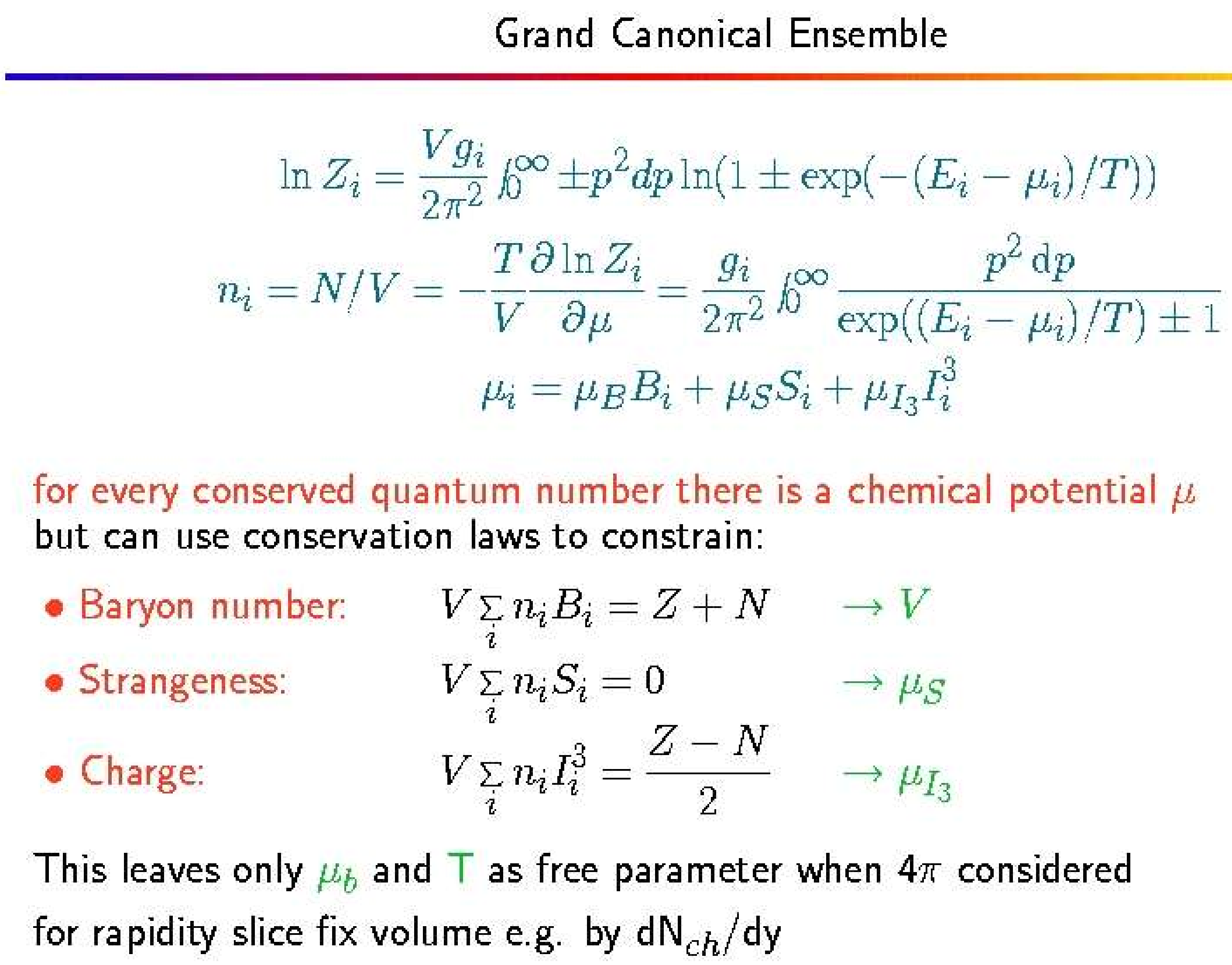
Hadron yields signal chemical equilibrium

- From AGS energy on, all hadron yields in central PbPb collisions reflect grand-canonical equilibration
- Strangeness suppression observed in elementary collisions is lifted

For a recent review see:

pbm, Stachel, Redlich, QGP3, R. Hwa, editor, Singapore 2004, nucl-th/0304013

Thermal model description of hadron yields



Grand Canonical Ensemble

$$\ln Z_i = \frac{V g_i}{2\pi^2}\int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i-\mu_i)/T))$$

$$n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,\mathrm{dp}}{\exp((E_i-\mu_i)/T) \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

for every conserved quantum number there is a chemical potential μ
but can use conservation laws to constrain:

- Baryon number: $V\sum_i n_i B_i = Z + N \quad \rightarrow V$
- Strangeness: $V\sum_i n_i S_i = 0 \quad \rightarrow \mu_S$
- Charge: $V\sum_i n_i I_i^3 = \frac{Z-N}{2} \quad \rightarrow \mu_{I_3}$

This leaves only μ_b and T as free parameter when 4π considered

for rapidity slice fix volume e.g. by dN_{ch}/dy

Fit at each energy provides values for T and μ_b

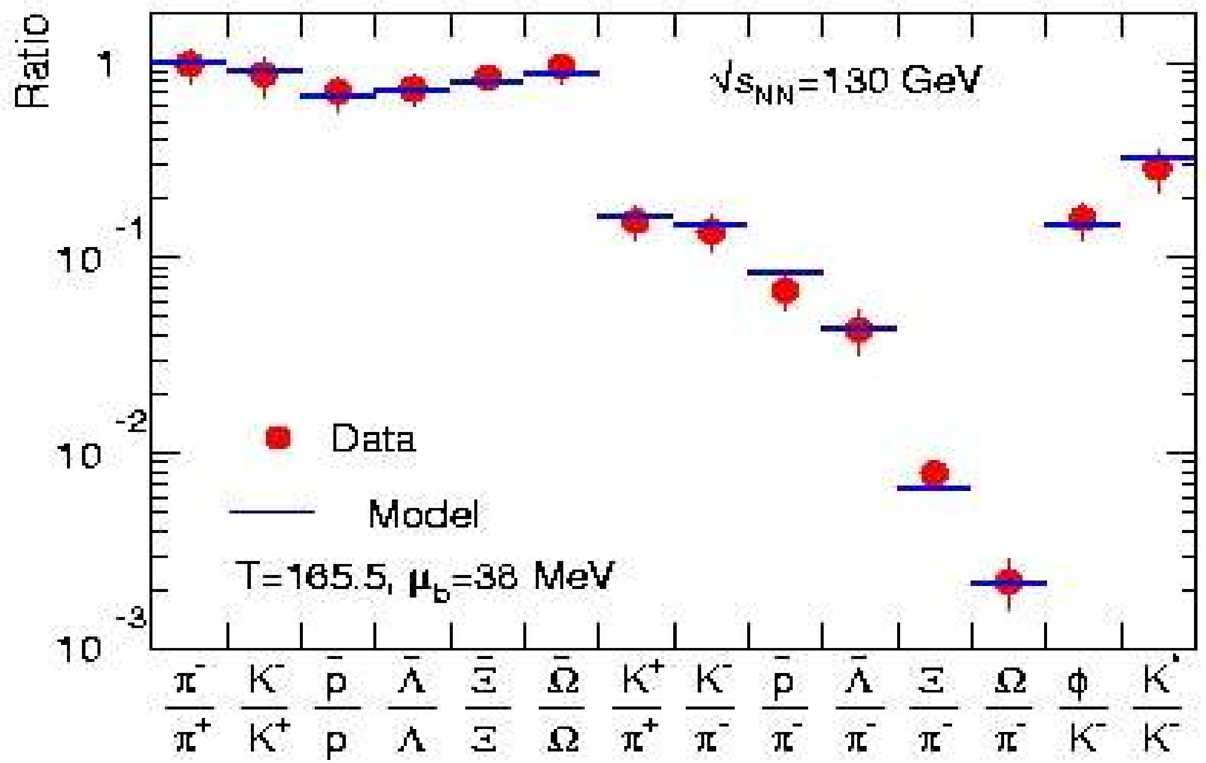
Hadro-chemistry at RHIC -- weakly decaying particles

All data in excellent agreement with thermal model predictions

chemical freeze-out at: T = 165 ± 8 MeV

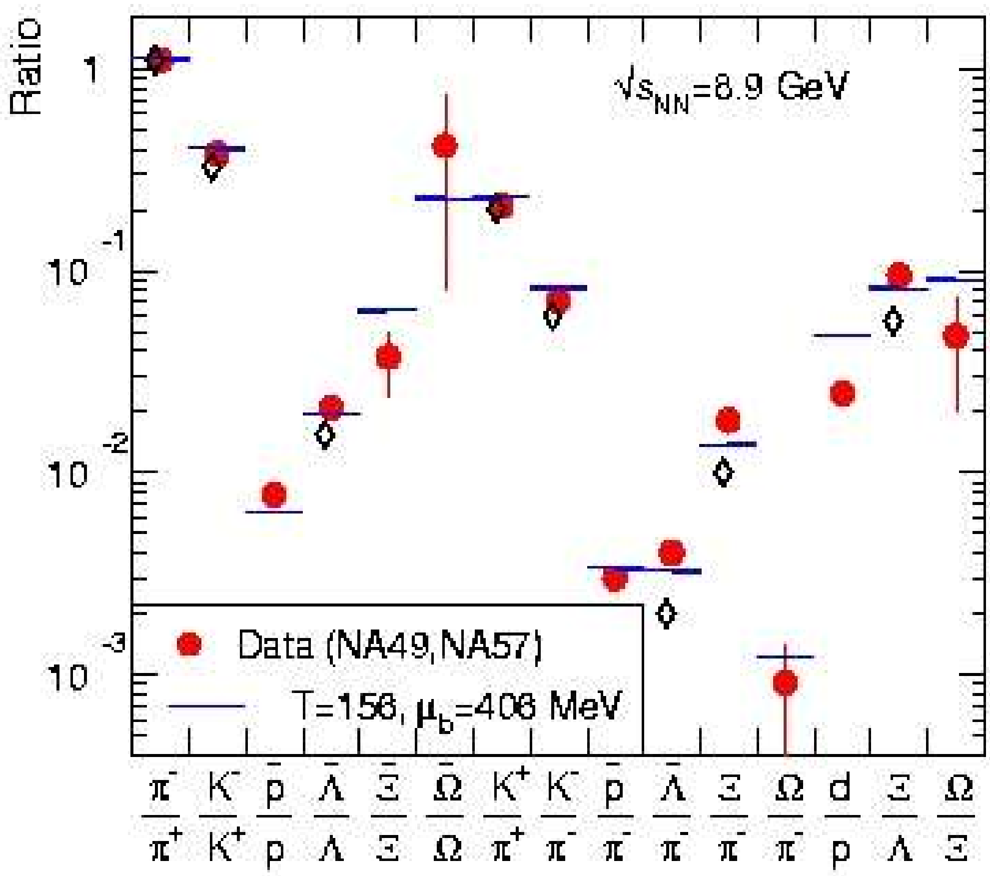
fit uses vacuum masses

most recent analysis: A. Andronic, pbm, J. Stachel, nucl-th/0511071 Nucl. Phys. A772 (2006) 167



pbm, d. magestro, j. stachel, k. redlich, Phys. Lett. B518 (2001) 41; see also Xu et al., Nucl. Phys. A698(2002) 306; Becattini, J. Phys. G28 (2002) 1553; Broniowski et al., nucl-th/0212052.

Hadro-chemistry at SPS



Data at 40 GeV/u Pb+Pb

central collisions

T = 156 MeV,

μ_b= 406 MeV

analysis from
Andronic, pbm,
Stachel,

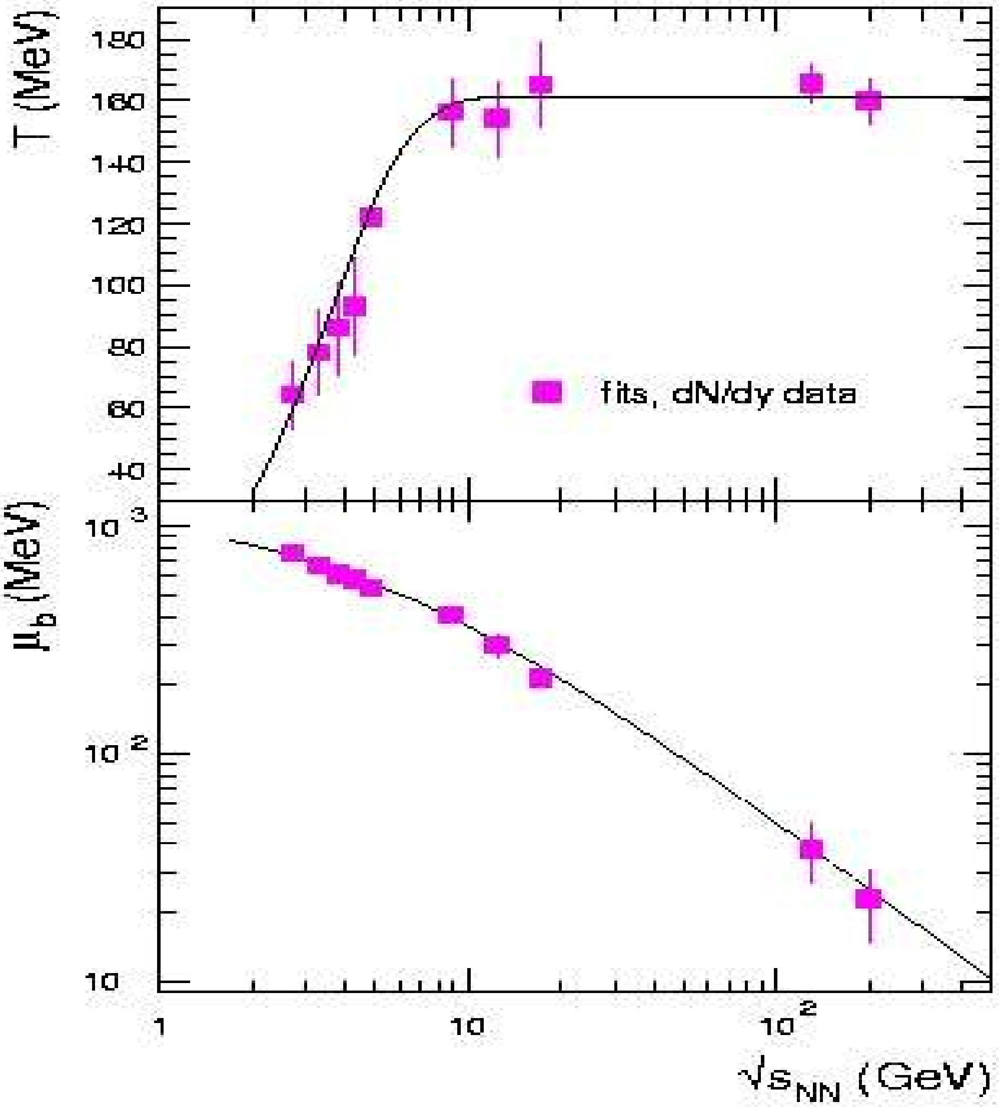
nucl-th/0511071

Nucl. Phys. A772
(2006) 167

Parameterization of all freeze-out points

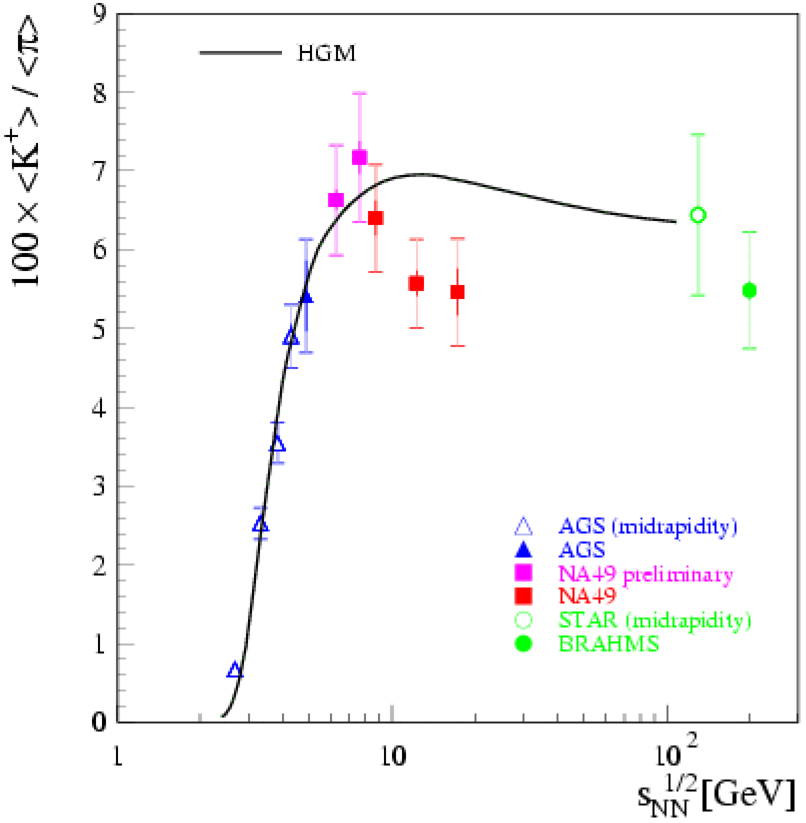
note: establishment of limiting temperature

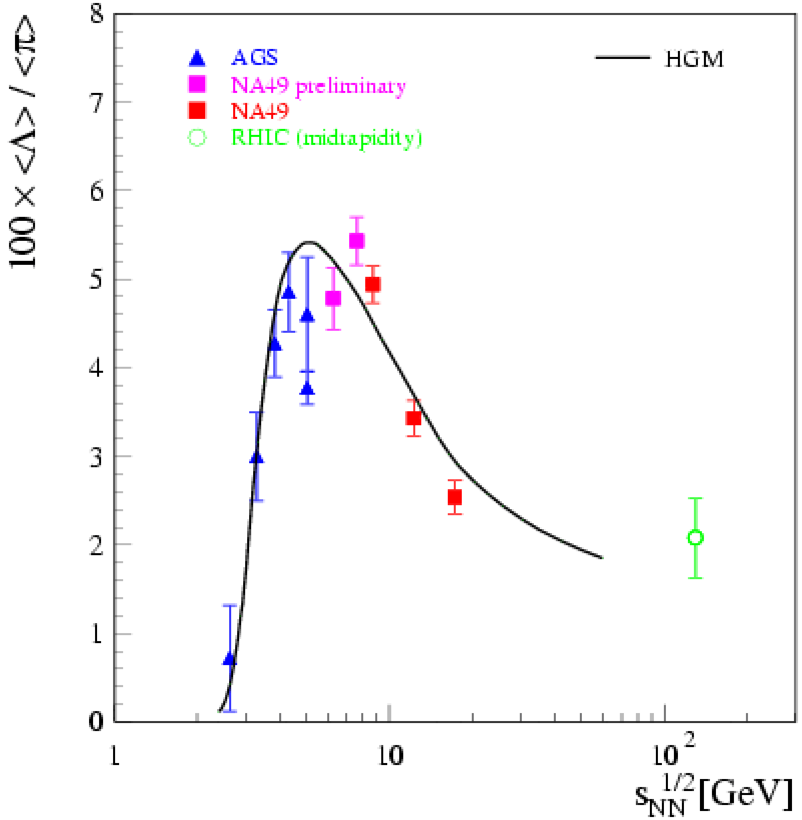
T_{lim} = 160 MeV



can use parameterization to predict particle ratios at all energies

Open Issue: the NA49 „horn“ in K/π

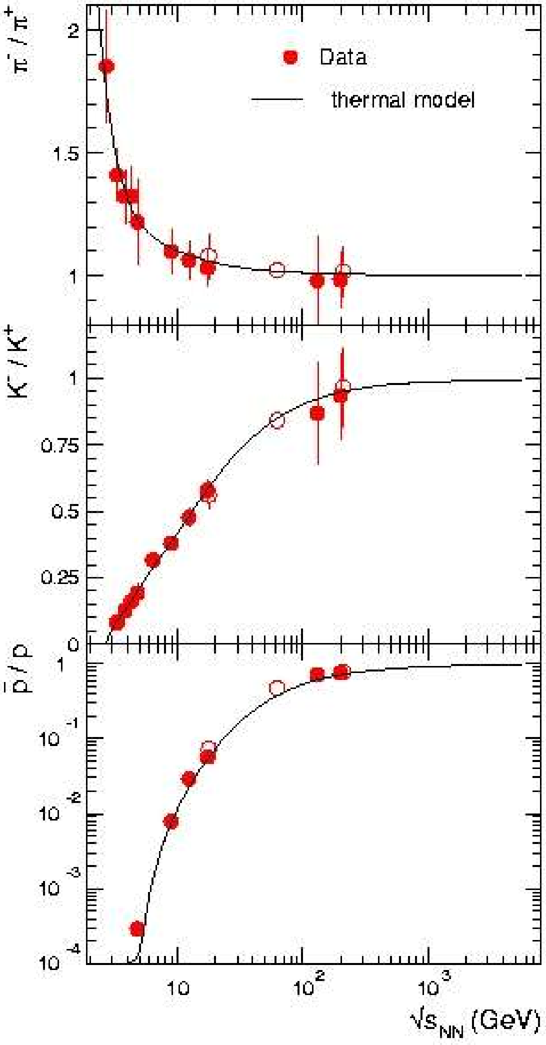


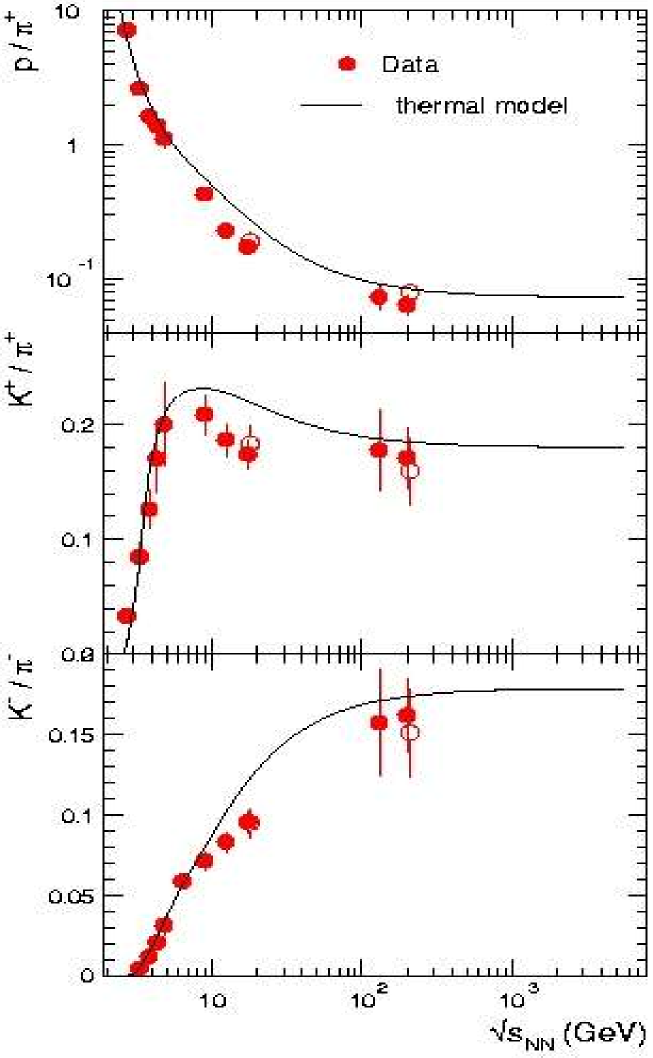


The structure near √s = 8 GeV is not reproduced but note: natural „ smearing“ is ≈ 3 GeV near √s = 8 GeV

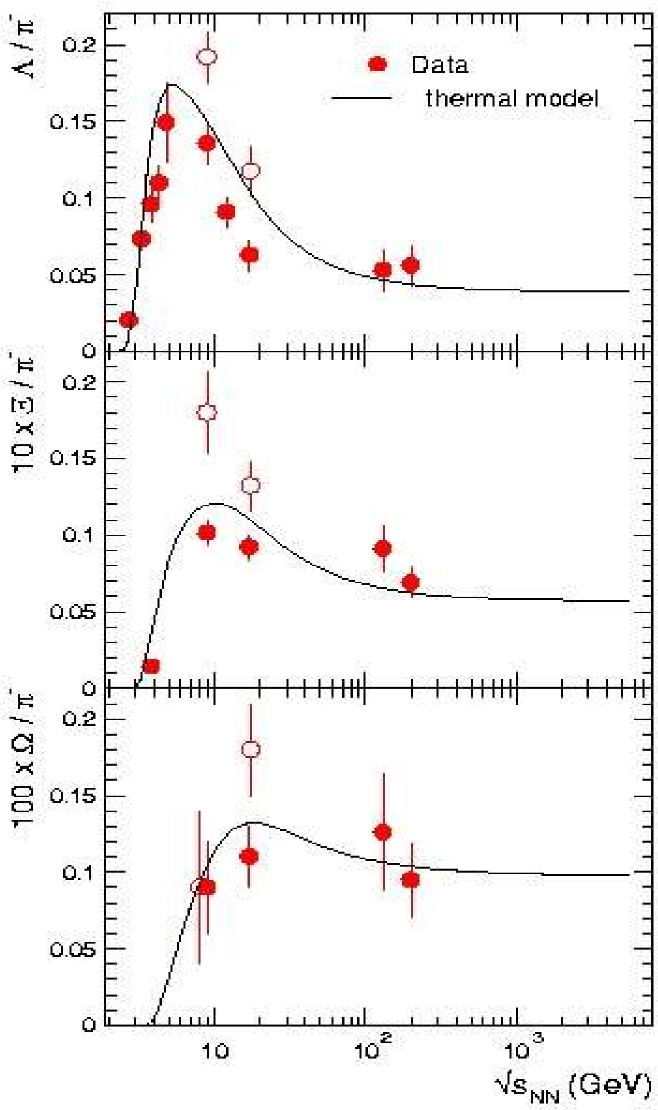
Strangeness undersaturated at 80 and 160 A GeV, saturated at all other energies?

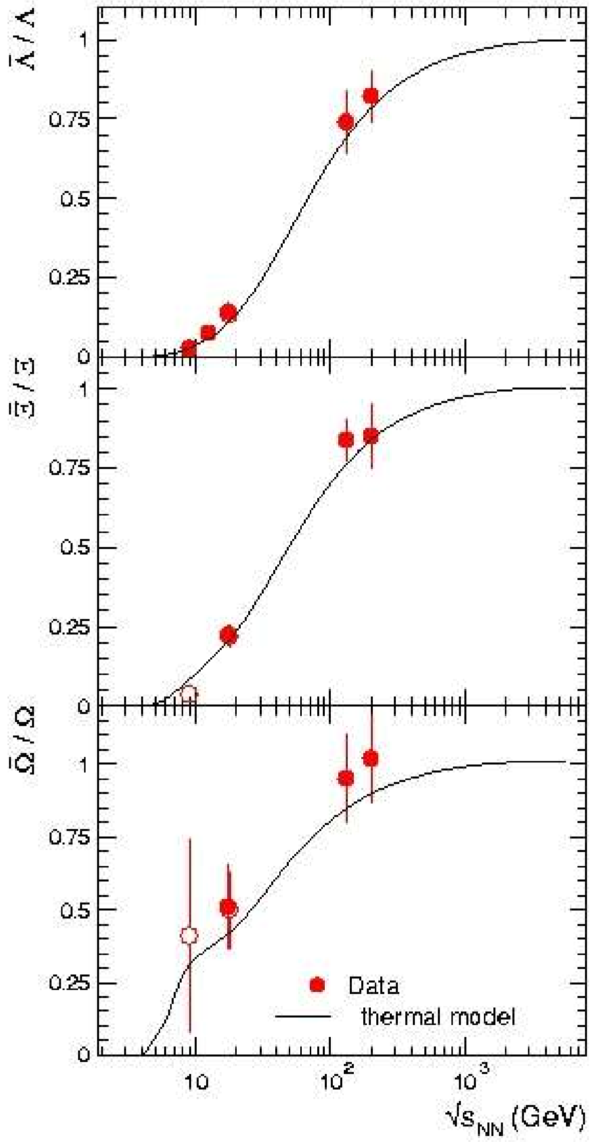
excitation functions and thermal model predictions





excitation functions and thermal model predictions





Peter Braun-Munzinger

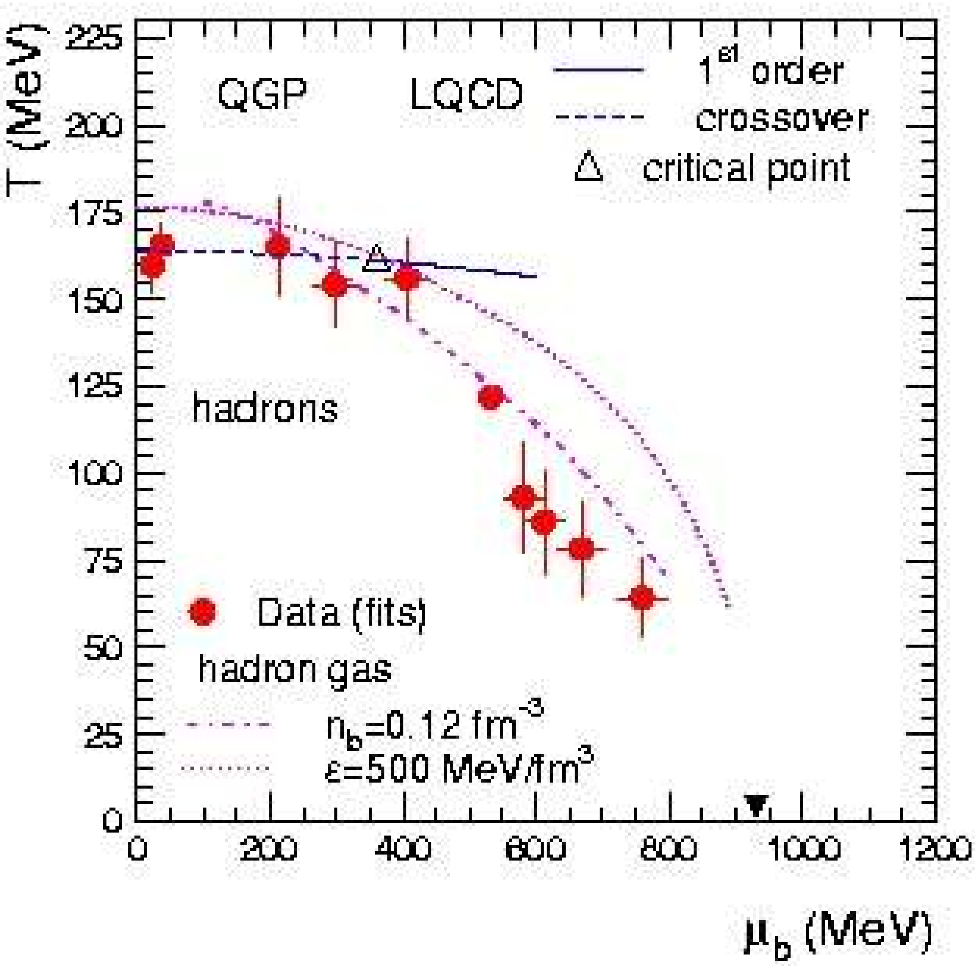
Strangeness equilibration at RHIC energies

- Strangeness fully saturated (except maybe near top SPS energy???)
- Freeze-out points are very close to phase boundary
- Deal with multi-strange baryons

The QCD phase diagram and chemical freeze-out (I)

Main result: chemical freeze-out points seem to delineate the QCD phase boundary at small μ (< 400 MeV)

can this be used to determine the critical temperature of the QCD phase transition?



How is chemical equilibration achieved? Our Scenario

- Strangeness saturation takes place in the QGP phase.

- Phase transition is crossed from above.

- Near T_c new dynamics associated with collective excitations will take place and trigger the transition.

- Propagation and scattering of these collective excitations (Goldstone bosons) is expressed in the form of multi-hadron scattering. Near T_c multi-hadron processes will therefore be dominant. Chemical equilibrium is reached via these multi-hadron scattering events.

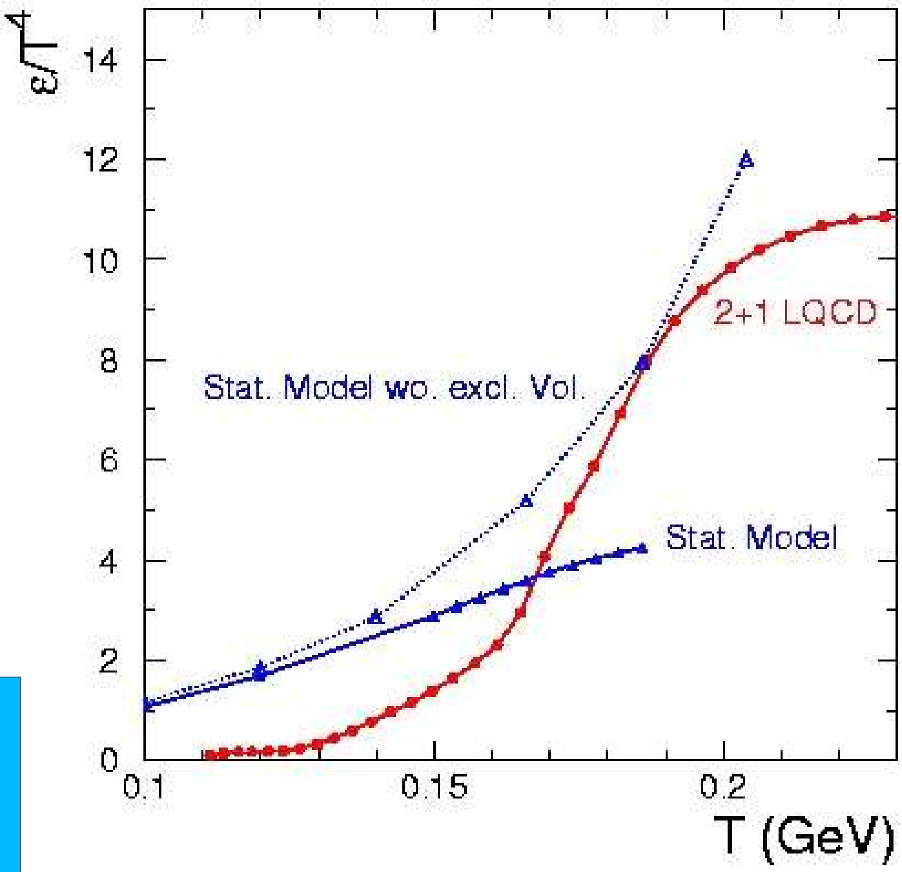
Chemical Equilibration must take place in the Hadronic Phase

- Hadron yields determined by Boltzmann factors with 'free' vacuum masses.
- Particle distribution in QGP phase has no 'memory' of vacuum hadron masses .
- Relative yields are not determined by the strange quark mass but by individual strange hadron masses (at fixed T and m).
- But: the number of strange quarks is determined in the QGP phase! Equilibrium then implies redistribution of strange quarks.

Chemical freeze-out takes place at T_c!

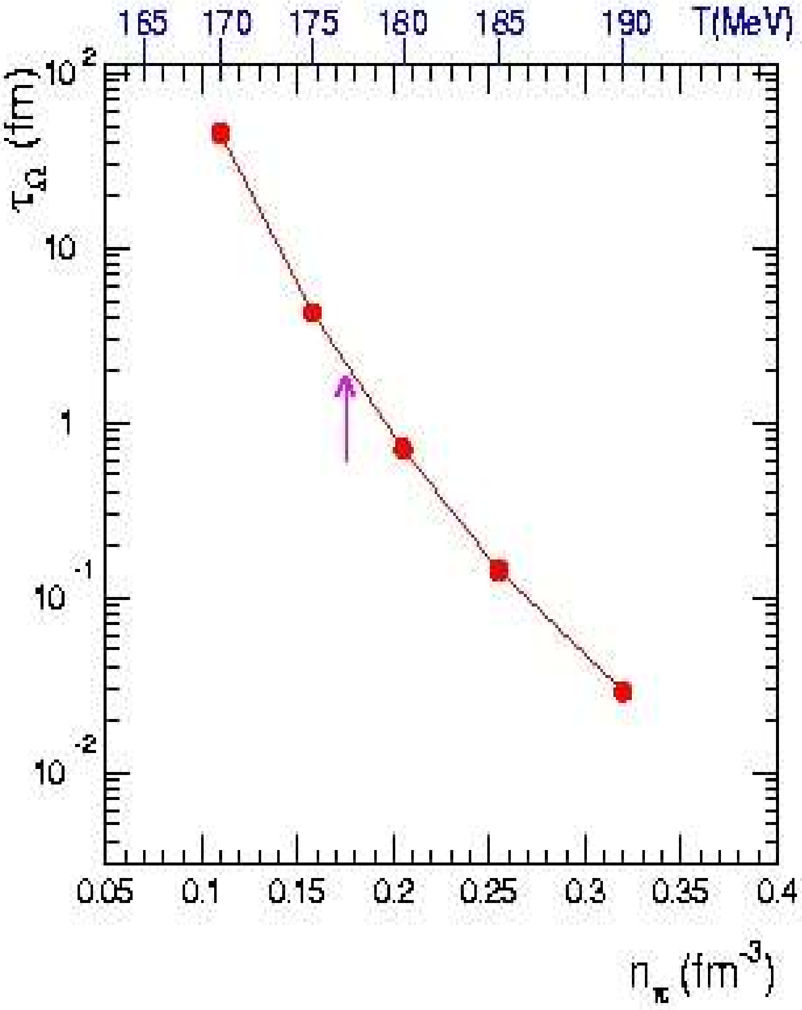
- Two-body collisions are not sufficient to bring multi-strange baryons into equilibrium.
- The density of particles varies rapidly with T near the phase transition.
- Multi-particle collisions are strongly enhanced at high density and lead to chem. equilibrium very near to $T_{c.}$

pbm, J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005



Lattice QCD calcs.
By F. Karsch et al.

Density dependence of characteristic time for strange baryon production



- Near phase transition particle density varies rapidly with T.
- For small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within a very narrow temperature window.

pbm, J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005

Chemical freeze-out determines T_c for small

phase transition brings multi-strange (and all other hadrons) into equilibrium

chemical freeze-out temperature closely coincides with critical temperature

determination of a fundamental QCD parameter from experiments on hadron production in ultra-relativistic nuclear collisions

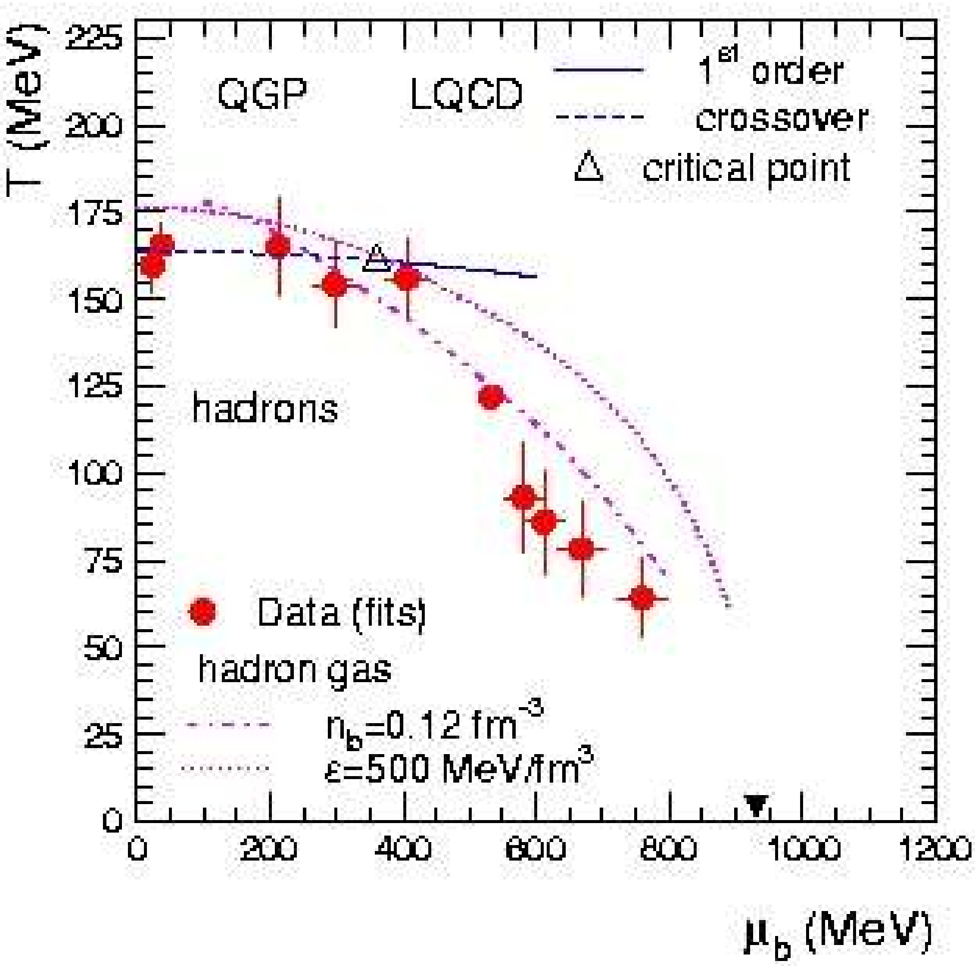
$$\mathbf{T_c = 160\ (+12\ -16)\ MeV}$$

2 sigma discrepancy with latest lattice results needs to be sorted out!

The QCD phase diagram and chemical freeze-out (II)

Data are nearly described by curve of constant critical energy density

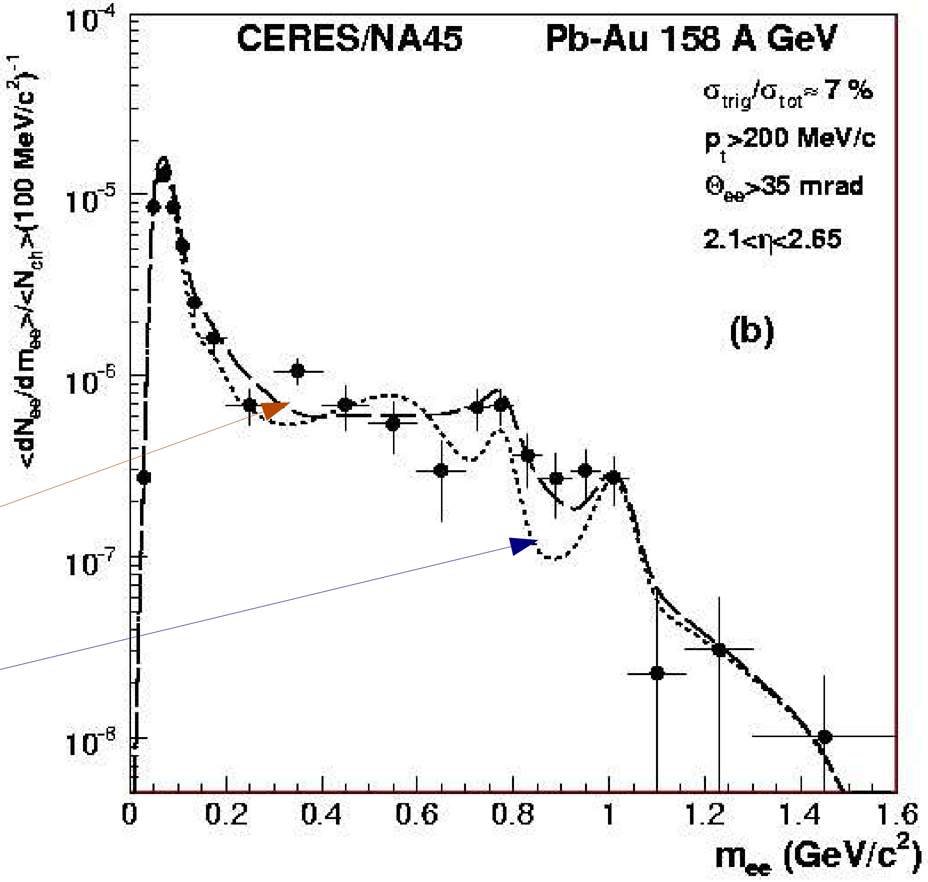
Conjecture: chemical freeze-out points delineate the QCD phase boundary also at larger μ down to AGS energy



Strongly decaying resonances – e^+e^- decays from CERES

- final result with 4 % mass resolution
- ω and φ strength close to thermal model prediction
- anomalous low mass continuum – modified ρ

- theories with medium modified ρ



Rapp-Wambach scenario

vs

Brown-Rho scenario

CERES coll.,
to appear very soon

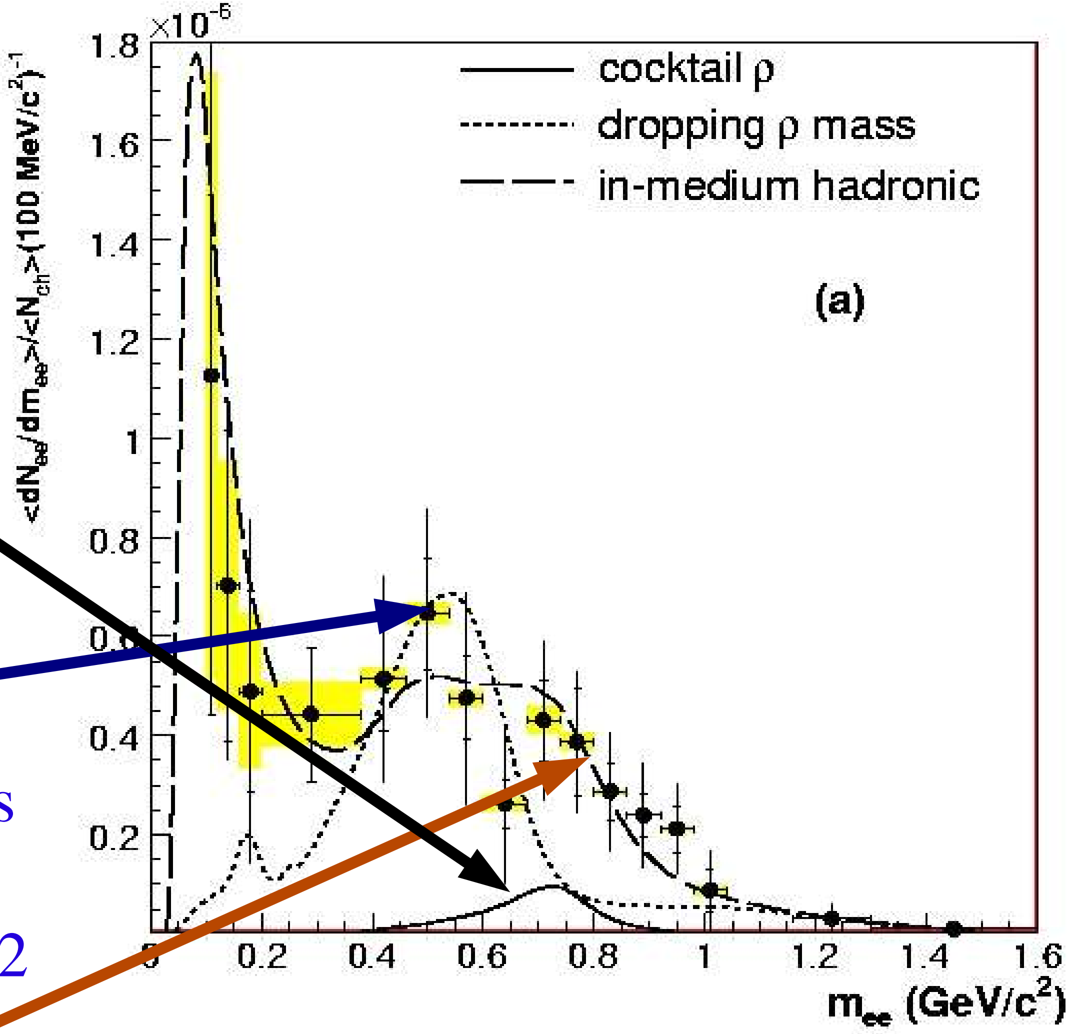
e^+e^- decays from CERES and ρ spectral function

- standard hadronic (cocktail) ρ meson very small compared to observations

spectral function strongly enhanced in hot medium

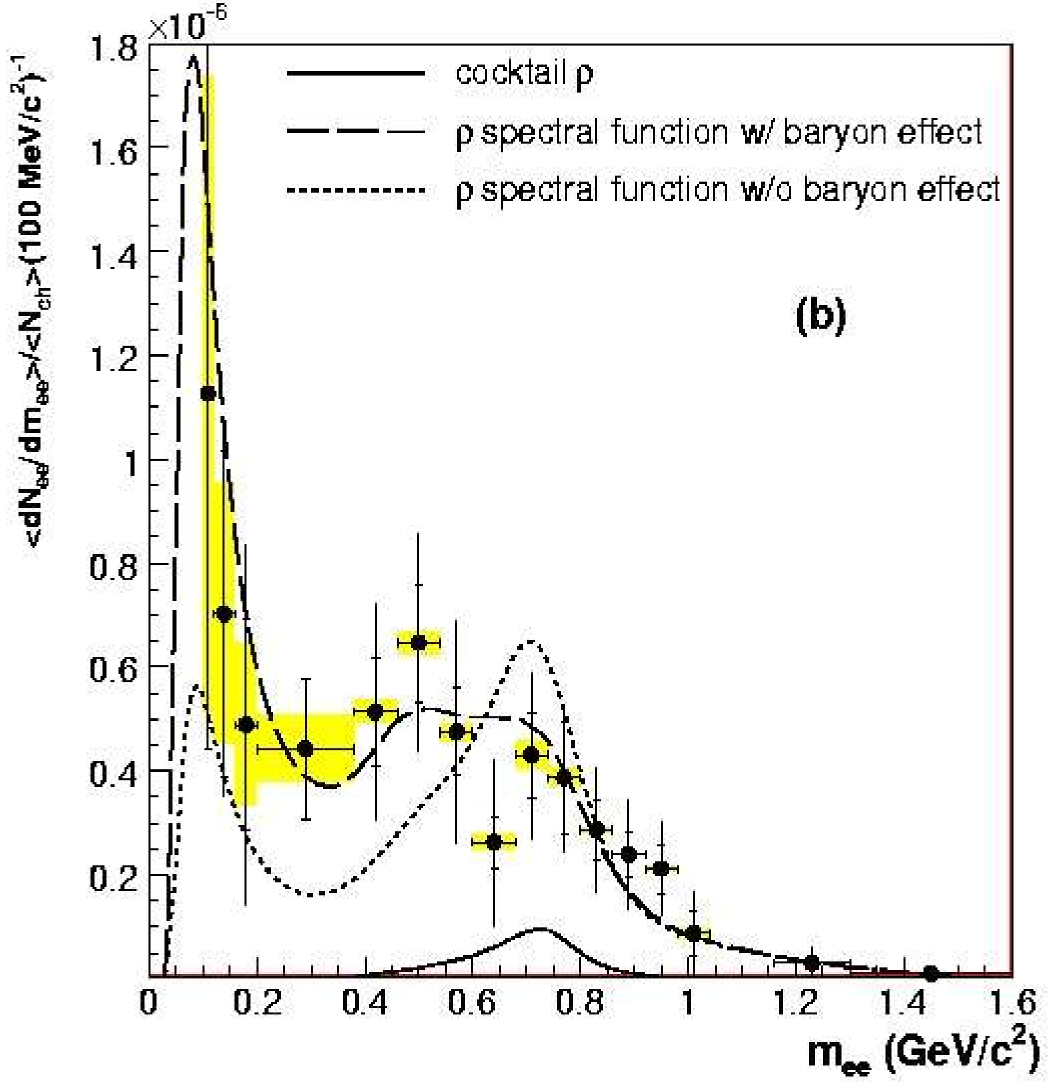
- Brown-Rho scenario
  not including BR scaling in terms of the vector manifestation, Brown and Rho, nucl-th/0509002

- Rapp-Wambach scenario



e^+e^- decays from CERES and ρ spectral function

- pure temperature effect on spectral function not in agreement with observations
- interaction of baryons with ρ mesons near T_c leads to good agreement with data
- considerable overlap between ρ and A_1 spectral function – indication of chiral symmetry restoration near T_c

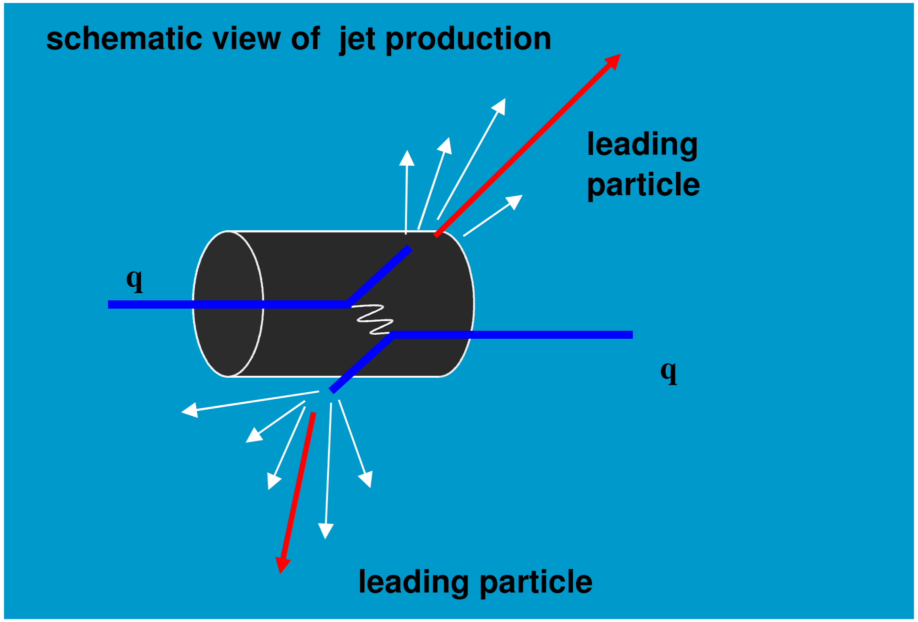


Jet quenching

- suppression of high p_t particles in AA relative to pp collisions
- disappearance of jet-like correlations
- connected to large gluon density in hot (QGP) fireball

Jet quenching

- Hard parton scattering observed via leading particles
- Expect strong $\Delta\phi = \pi$ azimuthal correlations



However, the scattered partons may loose energy (~ several GeV/fm) in the colored medium

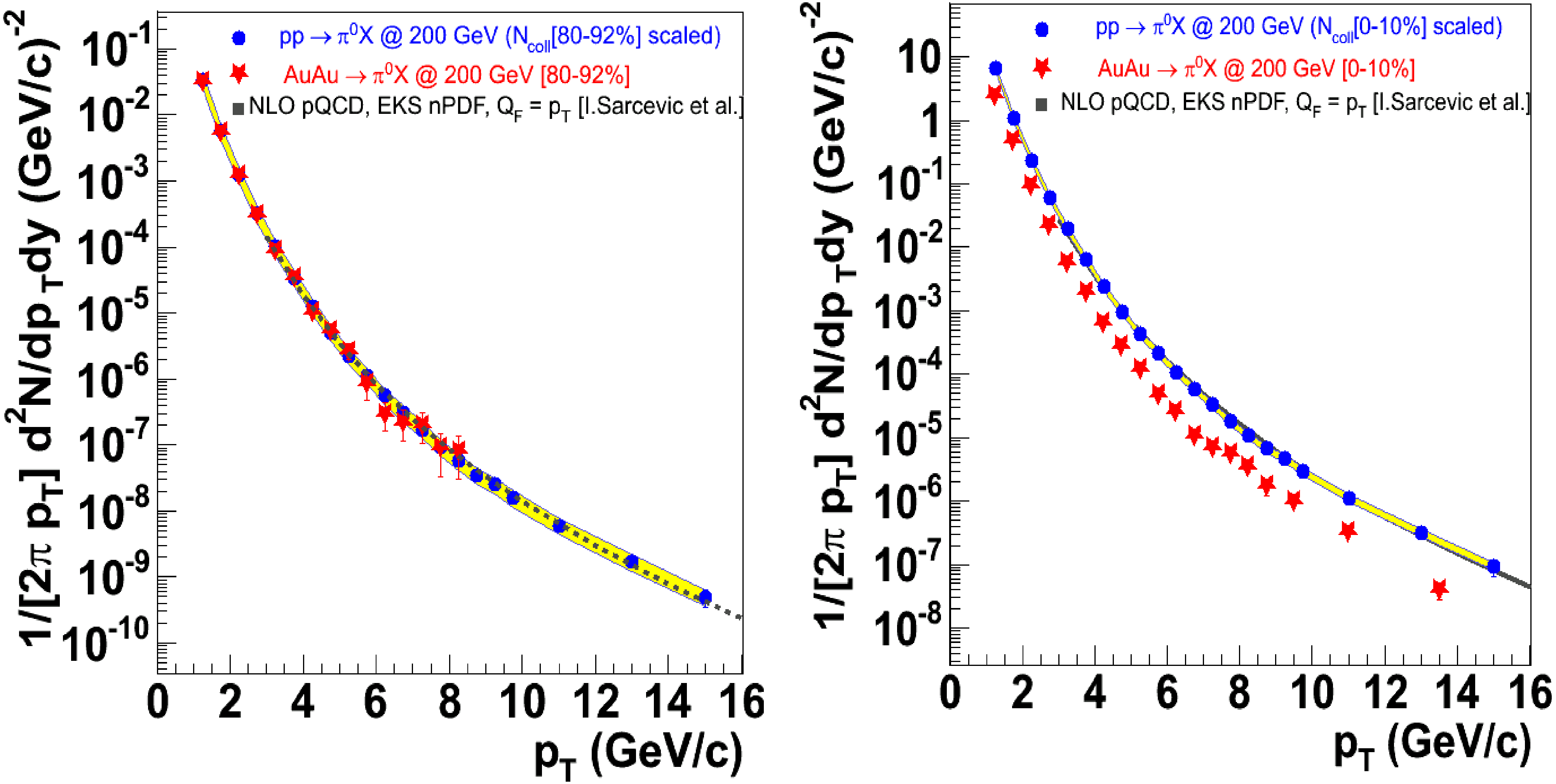
→ momentum reduction (fewer high p_T particles in jet)

→ no jet partner on other side

Jet Quenching

spectra suppressed at high p_t in AuAu relative to pp

proton data scaled to AuAu with appropriate number of binary collisions



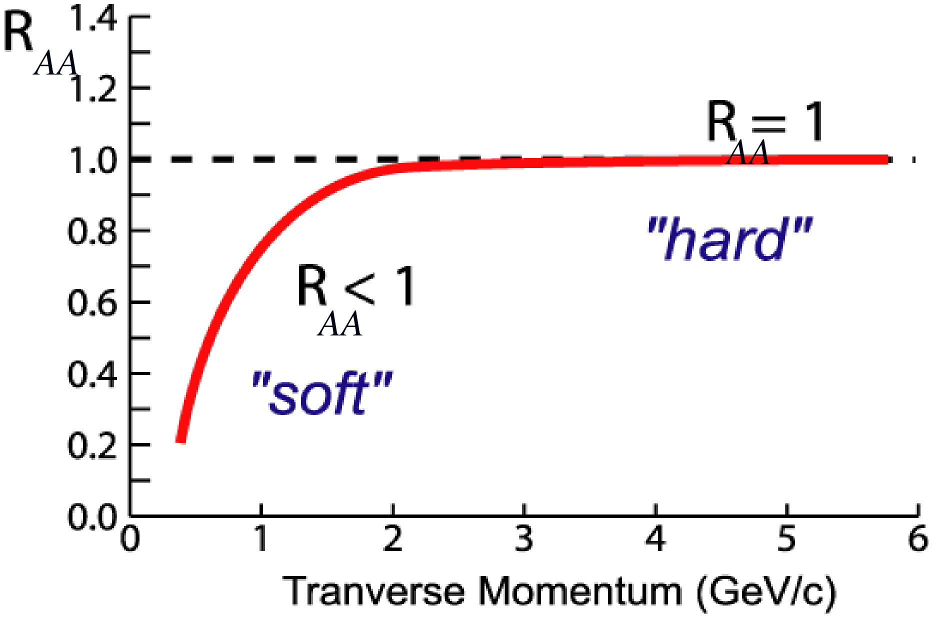
PHENIX PRL 91 (2003) 072305 and 241803

Definition of R_{AA}

R_{AA} = medium/vacuum

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_Td\eta}{T_{AA}d^2\sigma^{NN}/dp_Td\eta}$$

$\langle N_{binary}\rangle / \sigma_{inel}^{p+p}$



no medium effects:

$R_{AA} < 1$ in regime of soft physics

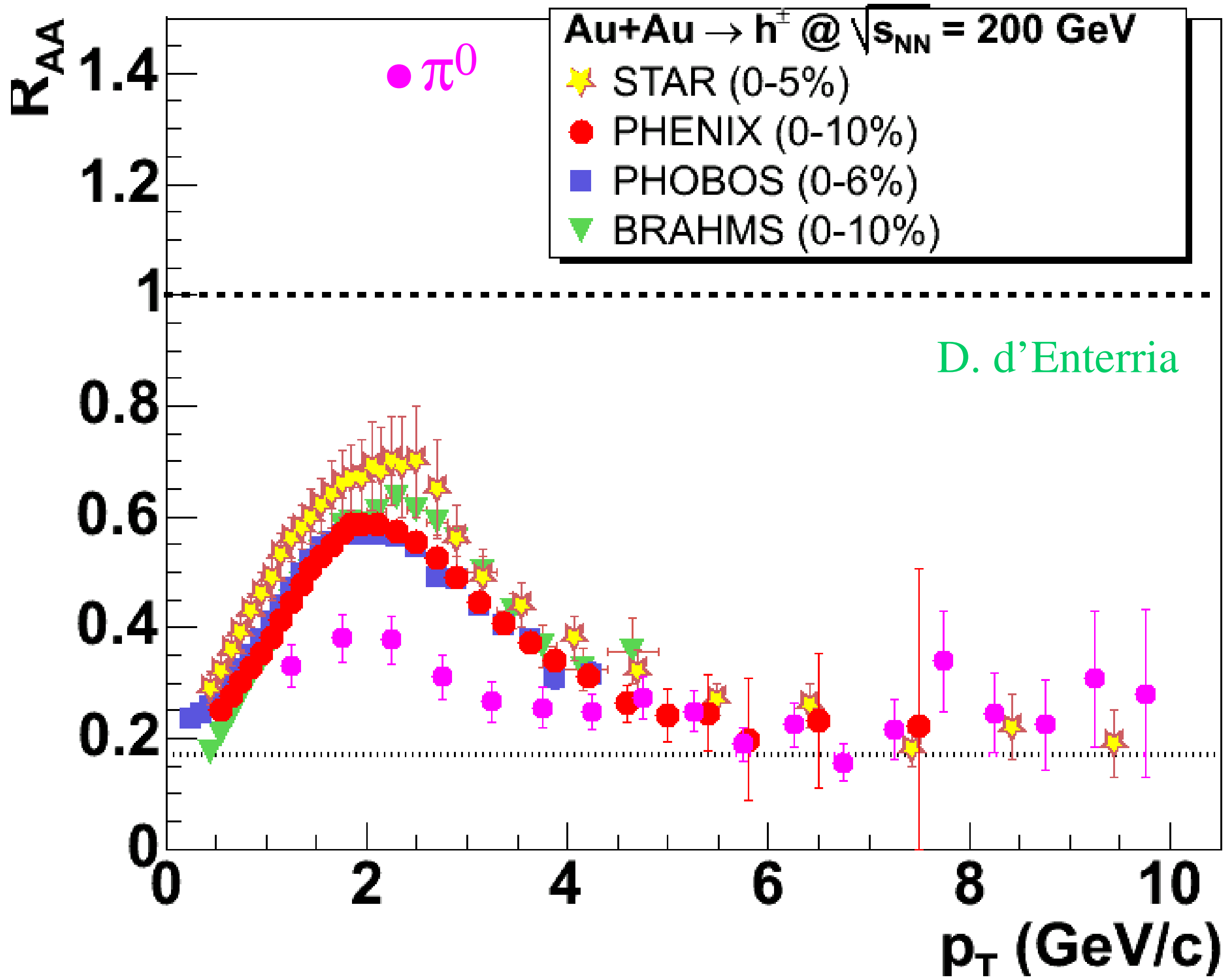
$R_{AA} = 1$ at high-p_T where hard scattering dominates

Suppression:

$R_{AA} \ll 1$ at high-p_T

high p_t suppression seen by all RHIC experiments

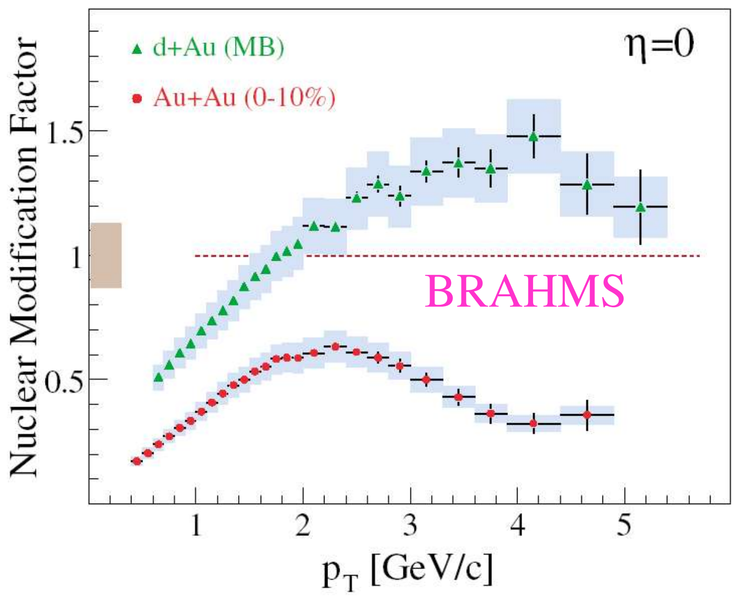
R_{AA}=yield(AuAu)/N_{coll} yield(pp)

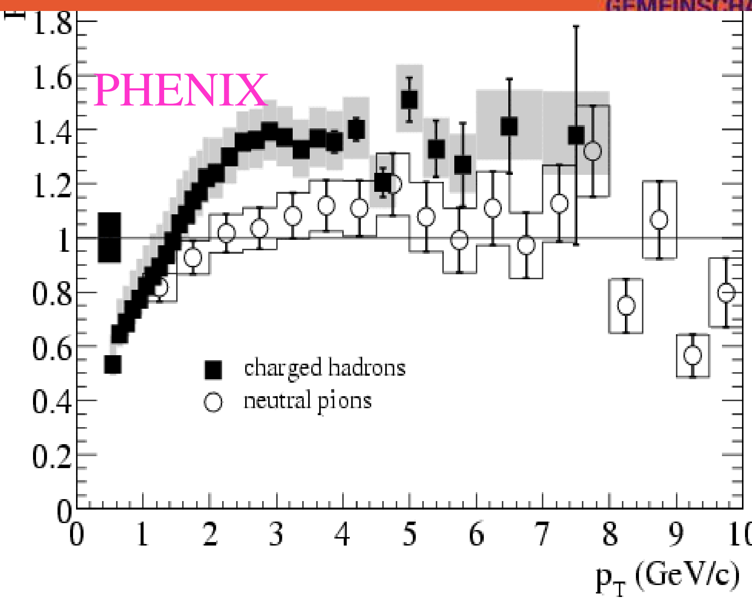


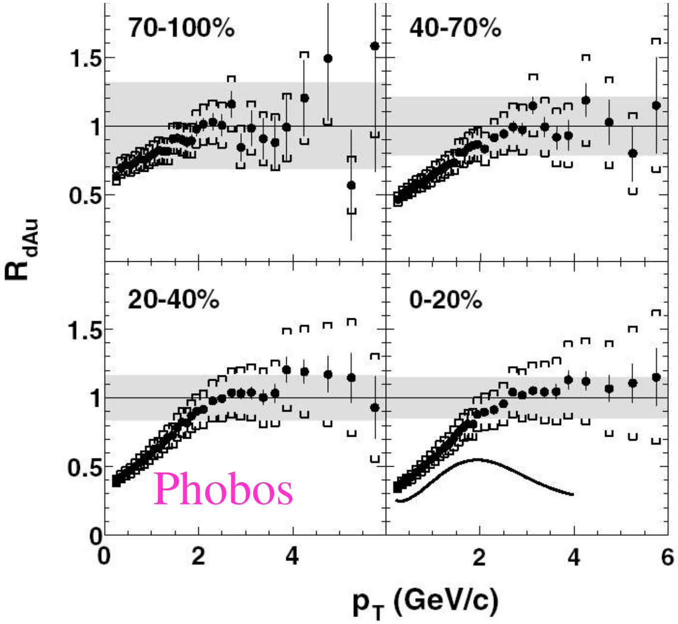
- all expts. see large suppression in AuAu
- π^0 lower than $h^{\pm}$
- no suppression in dAu rather Cronin enhancement → medium effect, not incoming partons

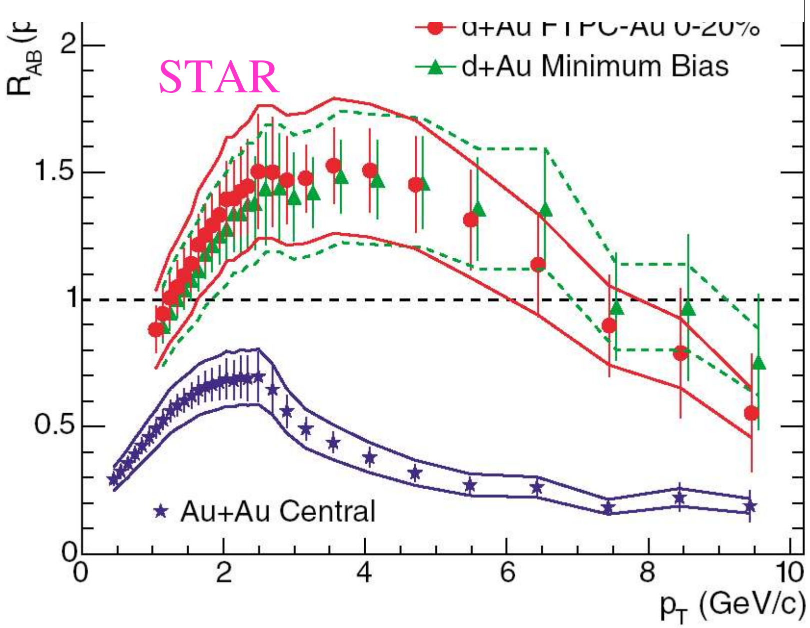
- reasonable agreement between 4 experiments

No suppression in d-Au collisions



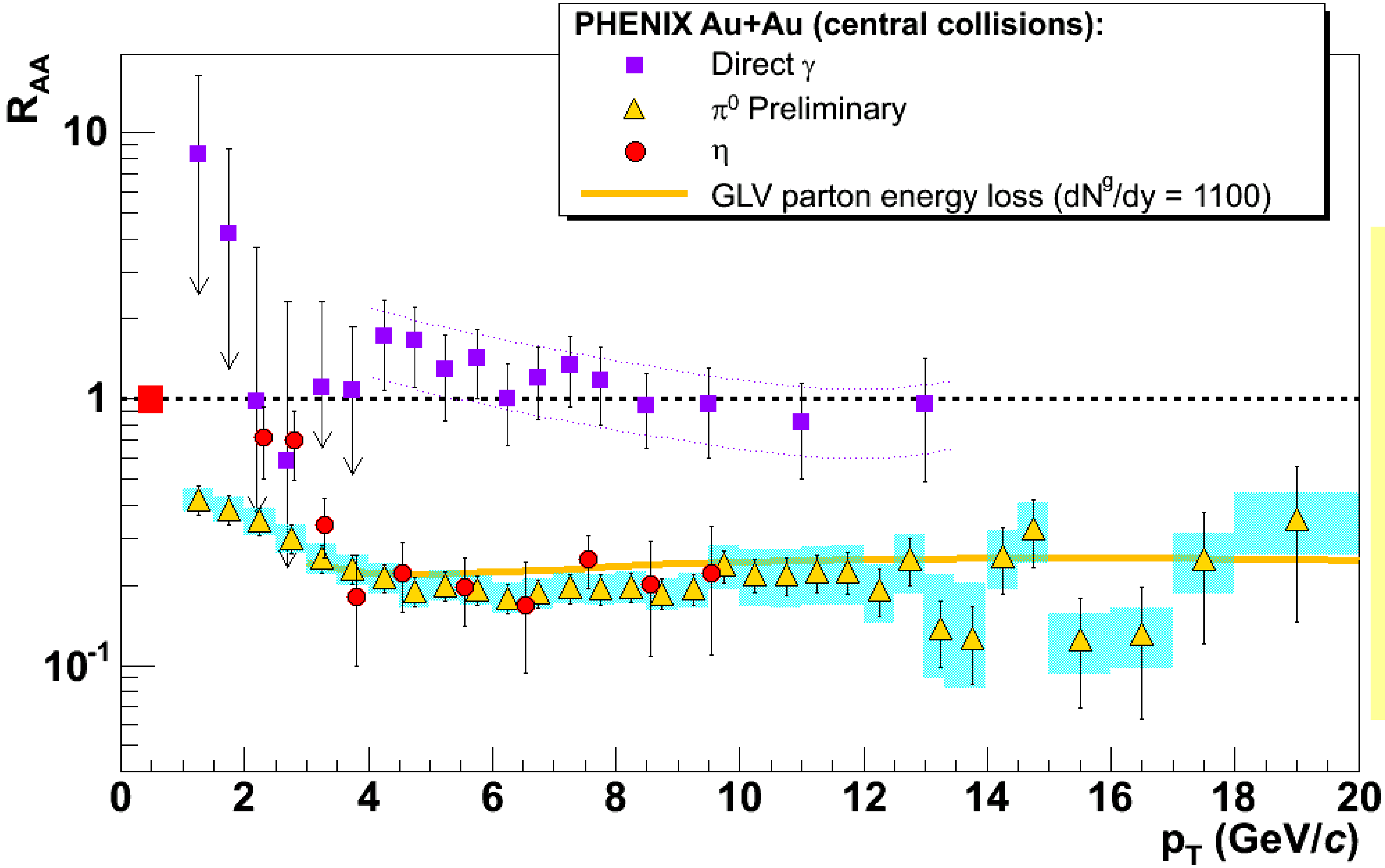






Conclusion: suppression is due to the medium in the final state (QGP)

Leading hadrons and hard photons



matter opaque until p_t(hadron) = 20 GeV

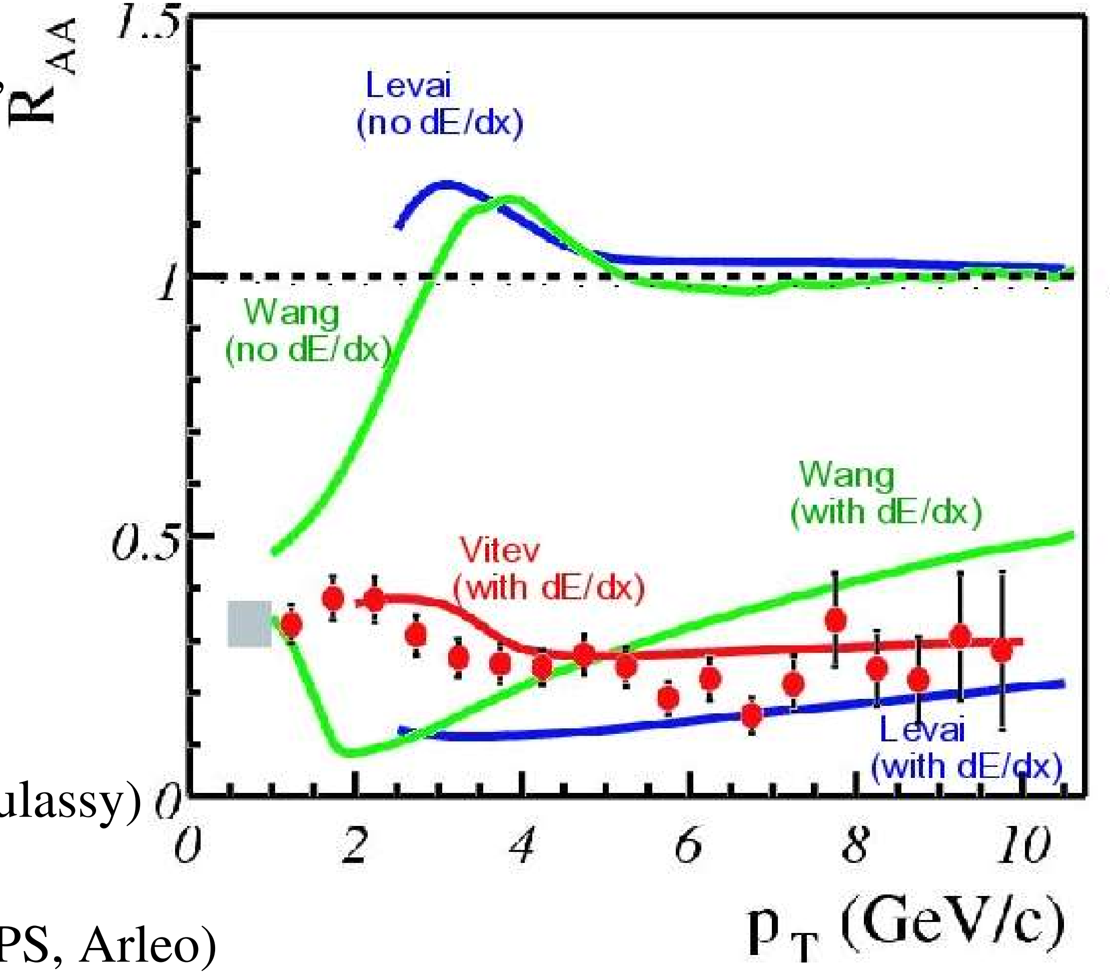
→

p_t(parton) > 30 GeV

- Direct photons are not suppressed, follow pQCD predictions.
- Common suppression for π^0 and η.
- $\varepsilon > 15$ GeV/fm^3; $dN_g/dy > 1100$

Suppression predicted due to energy loss of partons in hot matter "jet quenching"

H. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne, D. Schiff, Nucl. Phys. B483 (1997) 291 and 484 (1997) 265
energy loss of high energy parton traversing color charged medium ->
medium induced gluon radiation
in high energy limit
$\Delta E \approx \alpha_s \mu^2 L^2/\lambda\ (1 + O(1/N))$



implemented in models in different ways:
high initial densities $dN_g/dy=1100$ (Vitev/Gyulassy)
large opacities $\langle n \rangle = L/\lambda \approx 3\text{-}4$ (Levai et al.)
transport coefficients $q_0=3.5$ GeV/fm^2 (BDMPS, Arleo)
plasma temperature T = 400 MeV (G. Moore)
medium induced radiative energy loss
dE/dx(expanding)=0.25 GeV/fm or dE/dx(static source)=14 GeV/fm (S.N.Wang)

Parton energy loss - continued

results up to now include only gluon radiation

recent investigations imply large contributions from elastic collisions (K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, Phys. Lett. B637 (2006) 179, hep-ph/0512300; A. Adil, M. Gyulassy, W.A. Horowitz, S. Wicks, nucl-th/0606010)

energy loss of heavy quarks not consistent with observations

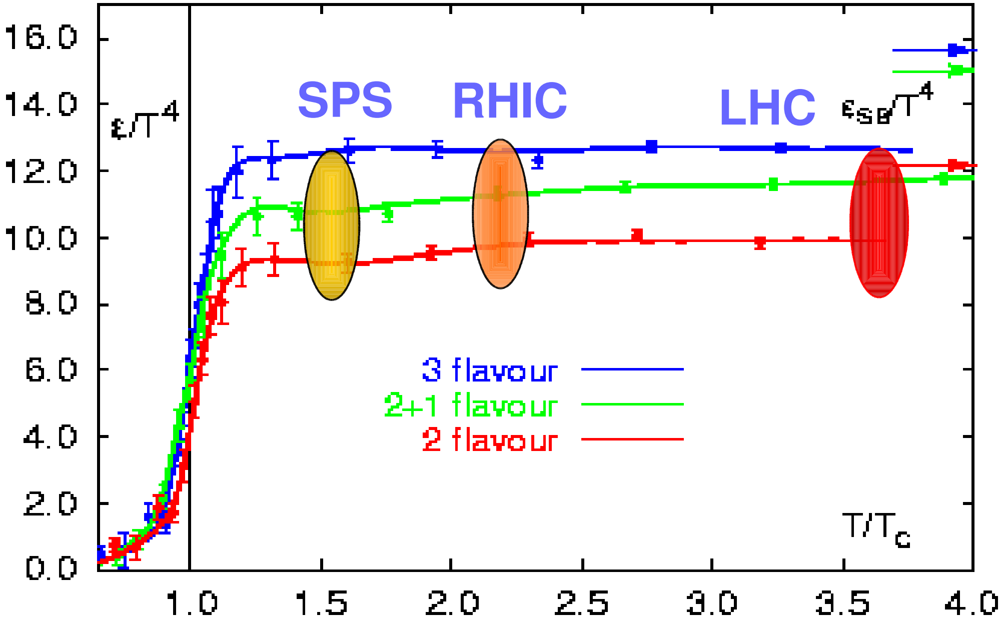
see talk by Johanna Stachel

jet quenching indicative of gluon rapidity density

	$\tau_0[fm]$	$T[MeV]$	$\varepsilon[GeV/fm^3]$	$\tau_{tot}[fm]$	dN^g/dy
SPS	**0.8**	**210-240**	**1.5-2.5**	**1.4-2**	**200-350**
RHIC	**0.6**	**380-400**	**14-20**	**6-7**	**800-1200**
LHC	**0.2**	**710-850**	**190-400**	**18-23**	**2000-3500**

I. Vitev, JPG 30 (2004) S791

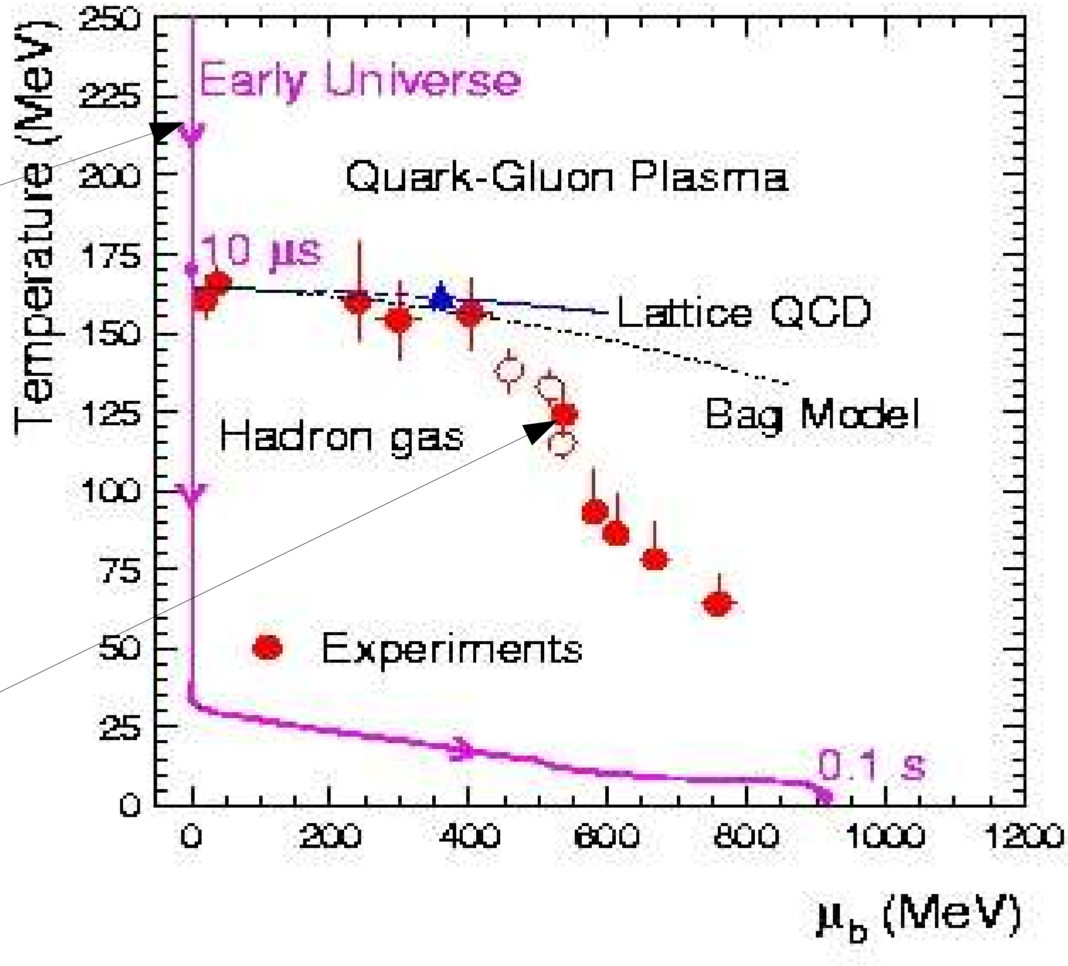
- **Estimates consistent with hydrodynamic analysis**



Further directions to explore the phases of QCD

High temperature regime:
ALICE@ LHC

High density – moderate
temperature regime
CBM@ FAIR-GSI

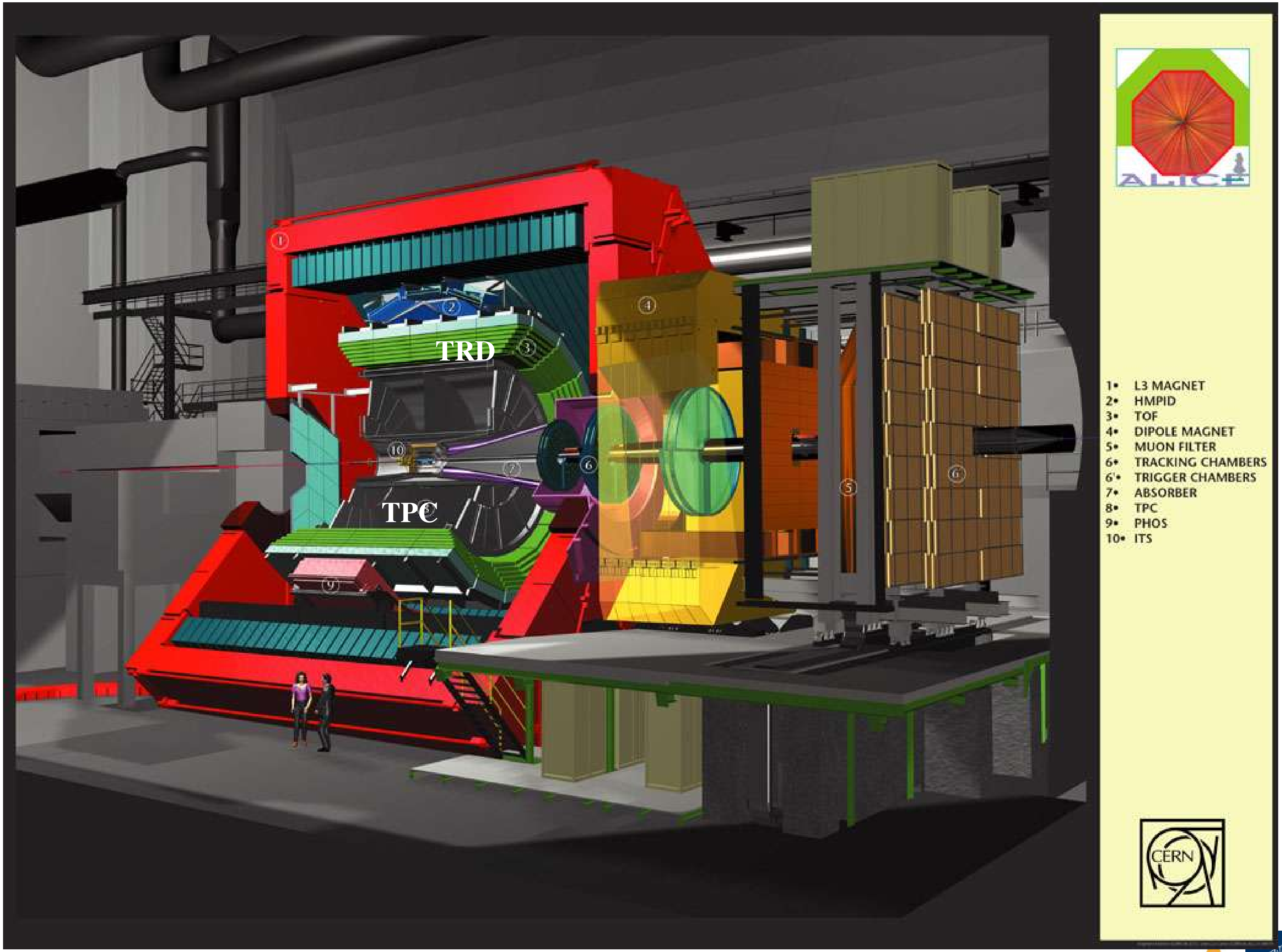


Apropos LHC

- Physics to start in late 2007
- ALICE is the dedicated heavy ion experiment
- ATLAS and CMS decided to join in heavy ion program – emphasis on hard processes
- 25 fold increase in cm energy over RHIC – large discovery potential
- $T_{max} > 600$ MeV, $\varepsilon_{max} > 500$ GeV/fm^3 – plasma tomography, heavy quark energy loss, complete quarkonium spectroscopy, determination of deconfinement, ...
- QCD at high field strength -- color glass condensate

see talk in this symposium
by Johanna Stachel

ALICE - Overview

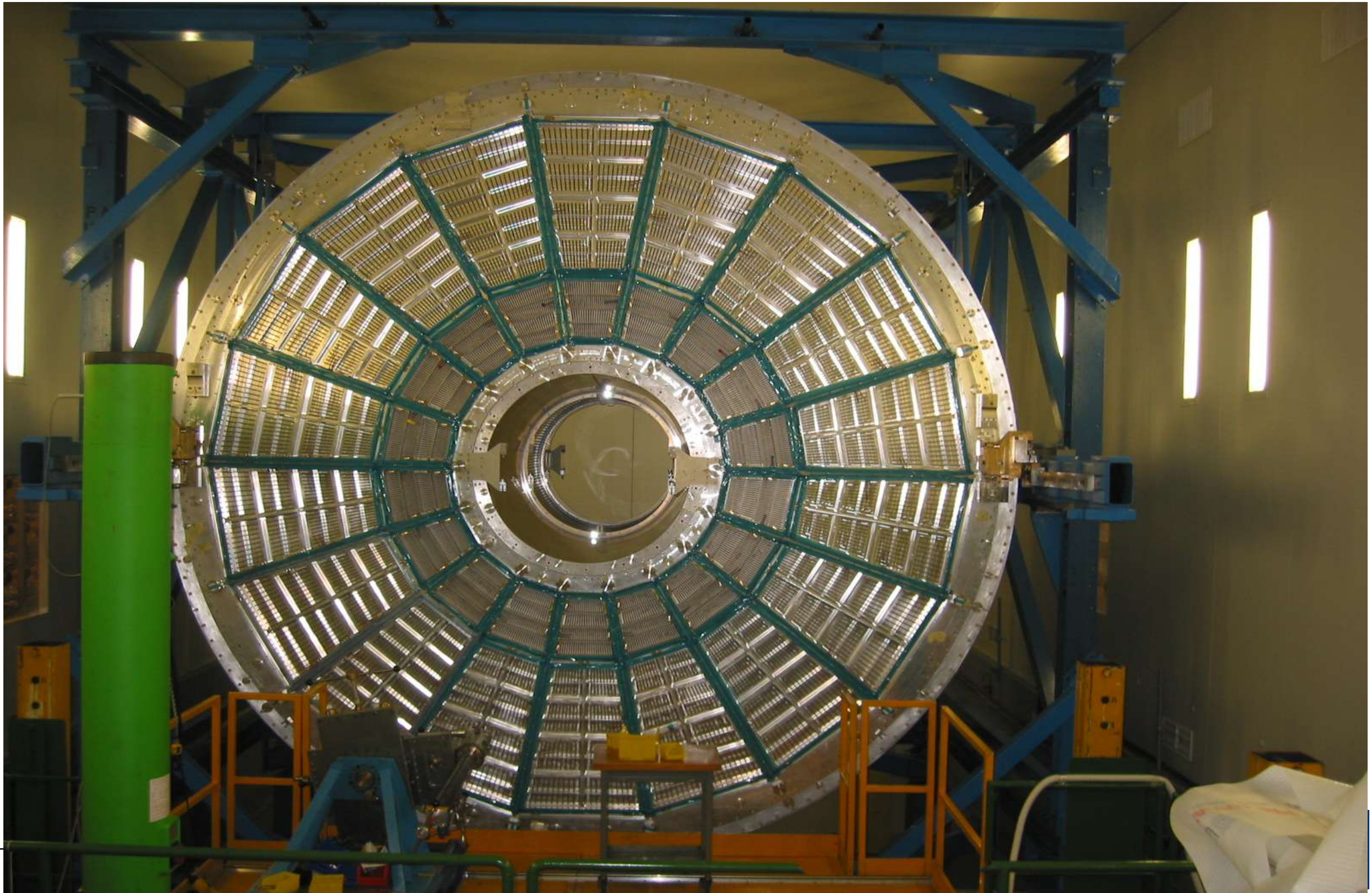


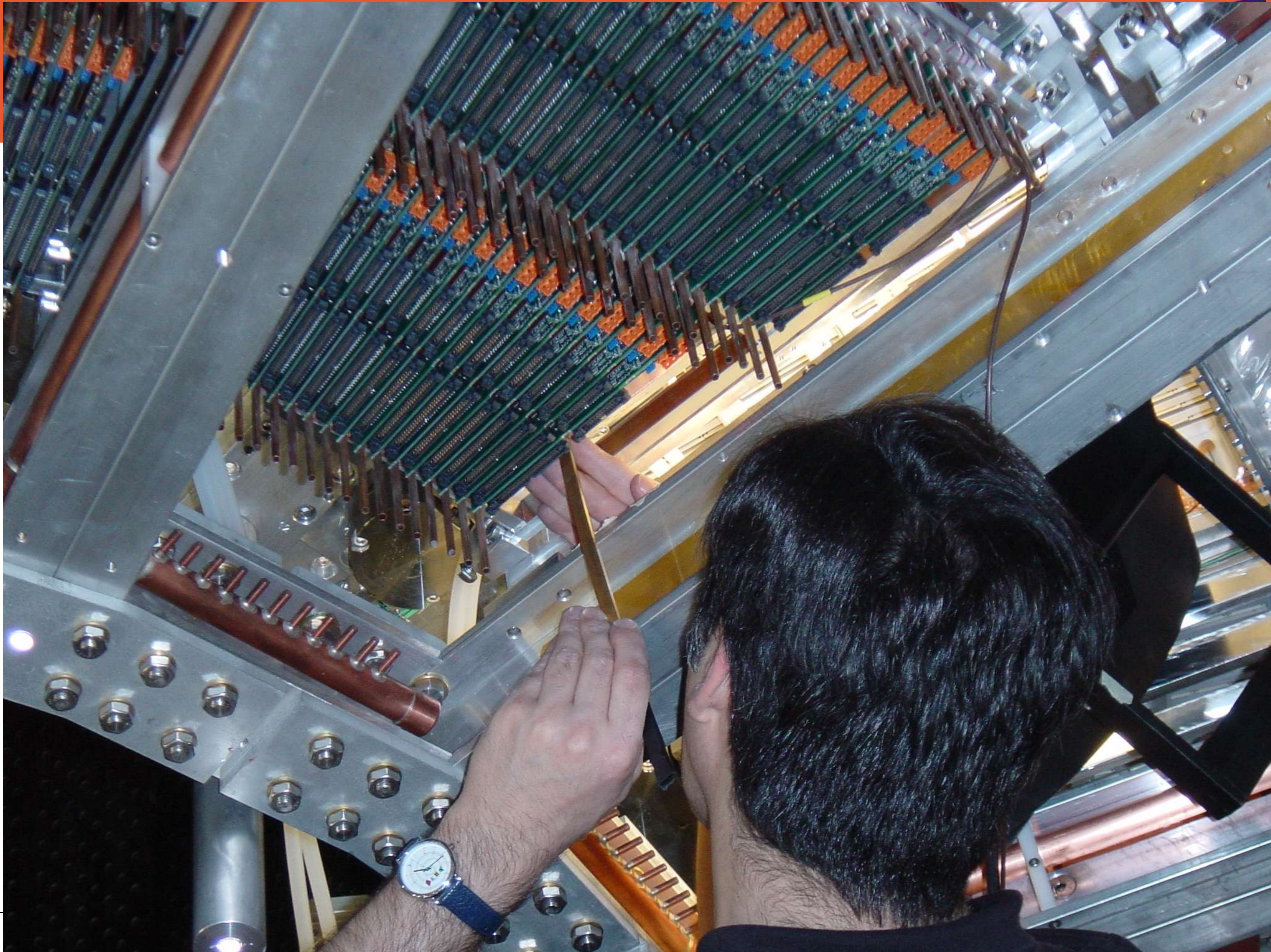
The charm and challenge of modern detectors: a fisheye's view into the ALICE TPC

ALICE

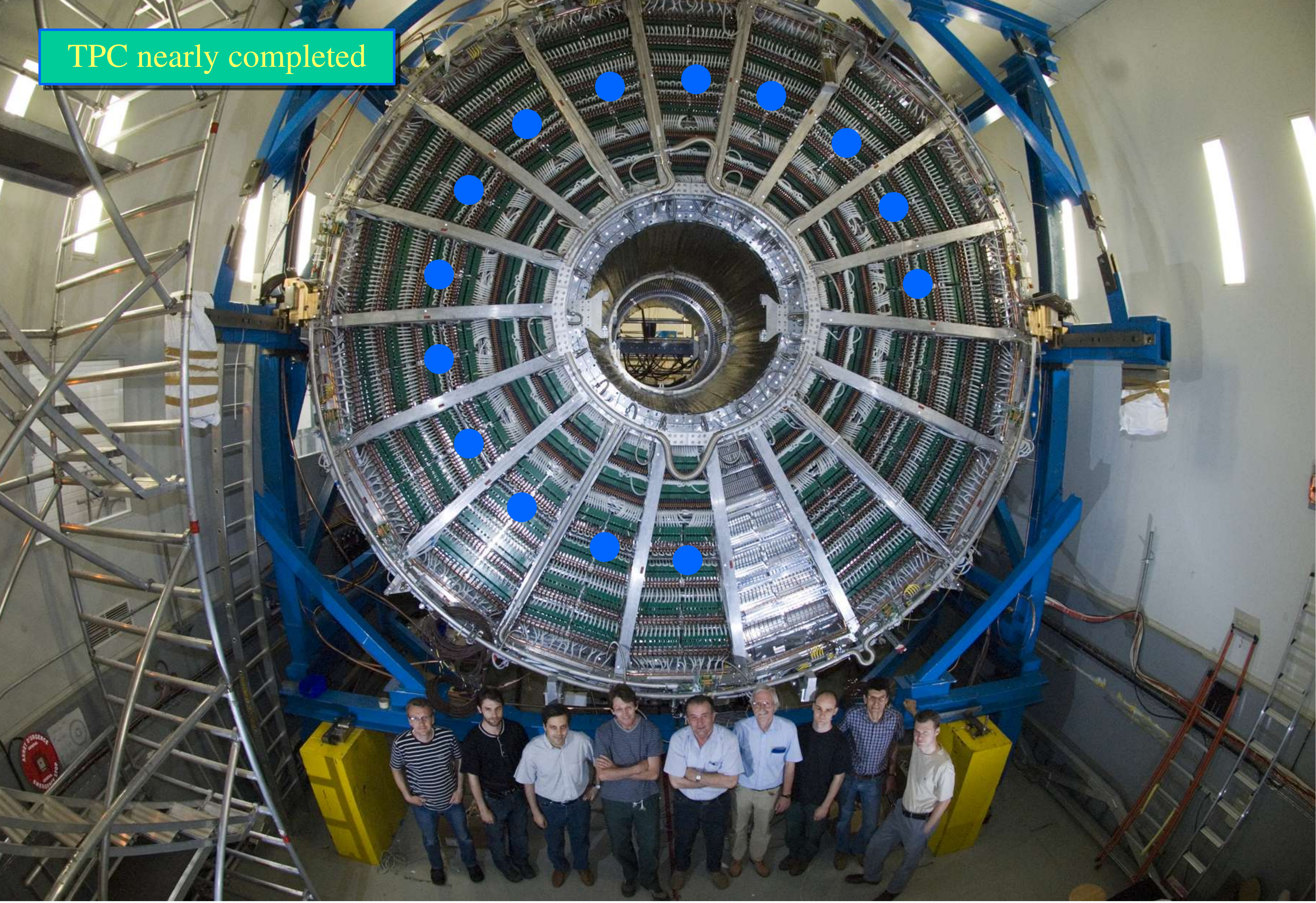
bmb+f - Förderschwerpunkt
ALICE
Großgeräte der physikalischen
Grundlagenforschung

Status of TPC (Feb. 2006)



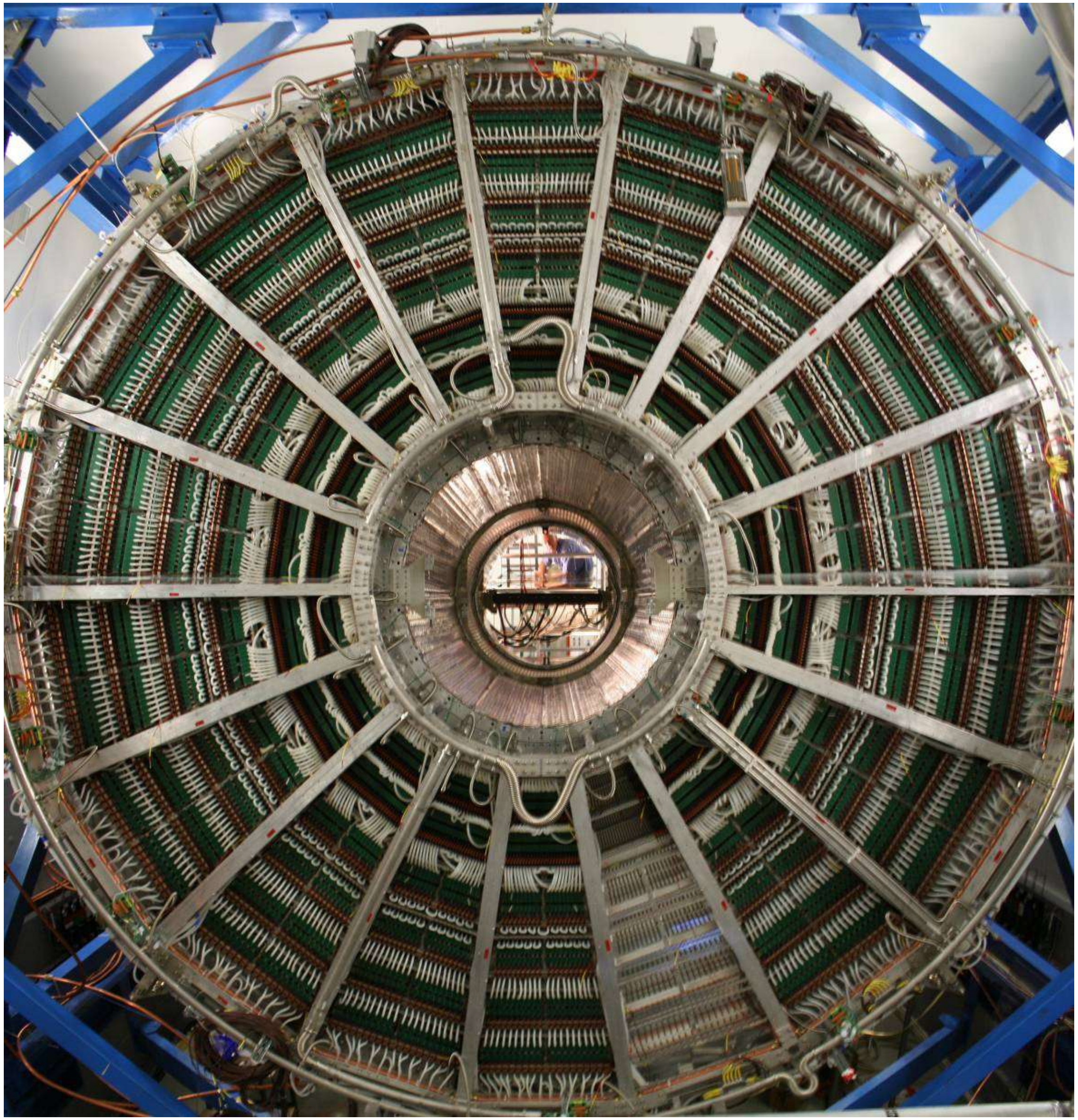


TPC nearly completed

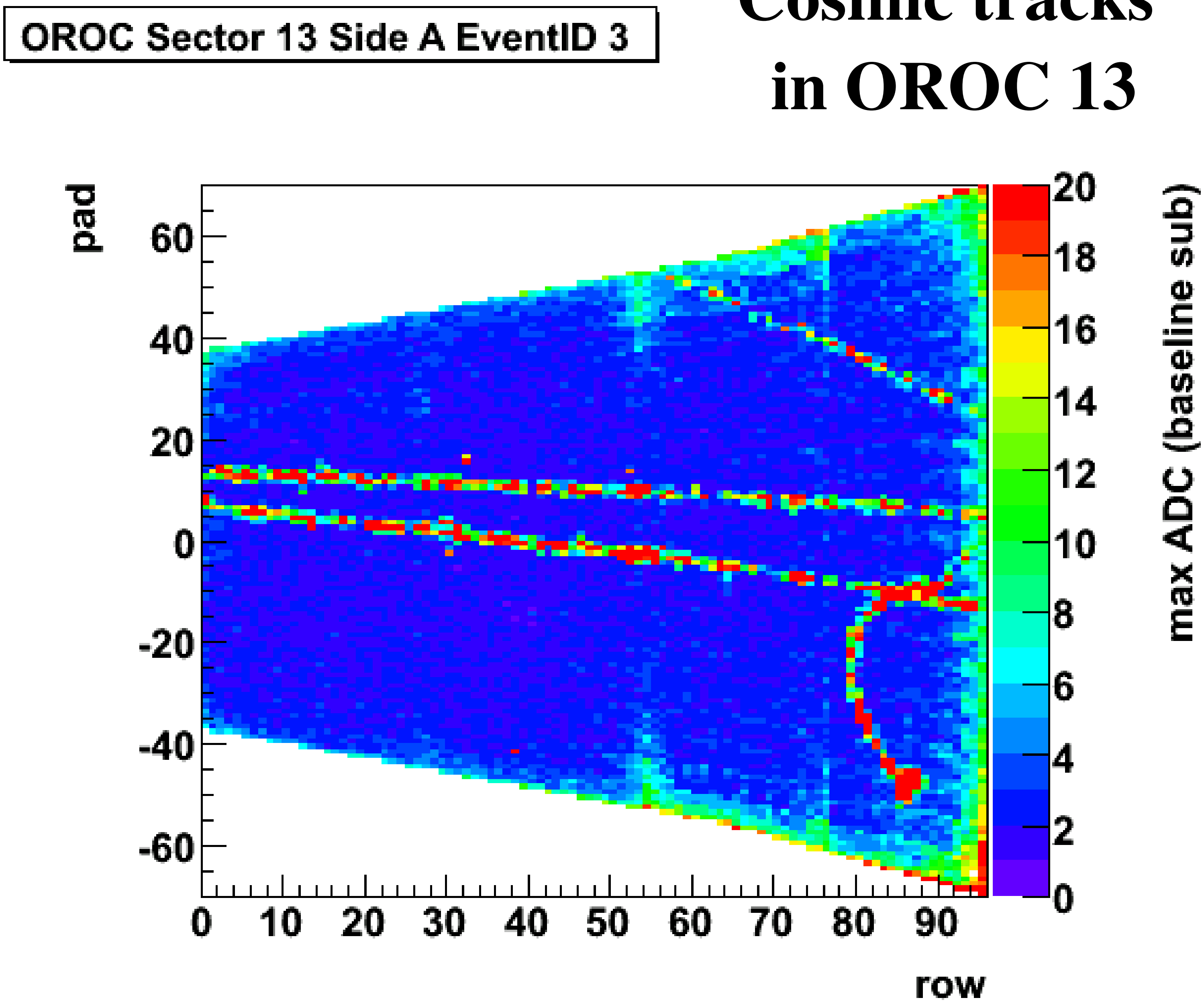


The ALICE TPC has entered the commissioning phase

- 2006/Q1: Frontend electronics installation
  - 72 readout chambers
  - 4356 FEE cards
  - 557,568 channels
  - up to 1000 time bins each
- Commissioning above ground since May
  - Gas system: 95 m^3 $Ne/CO_2/N_2$ (90/10/5), now few ppm O_2
  - test 2 sectors at a time
  - Full data chain
  - Cosmics tracks
  - Laser tracks
  - Noise $\sigma \sim 0.7 - 0.8$ ADC cts
- Move to cavern in December

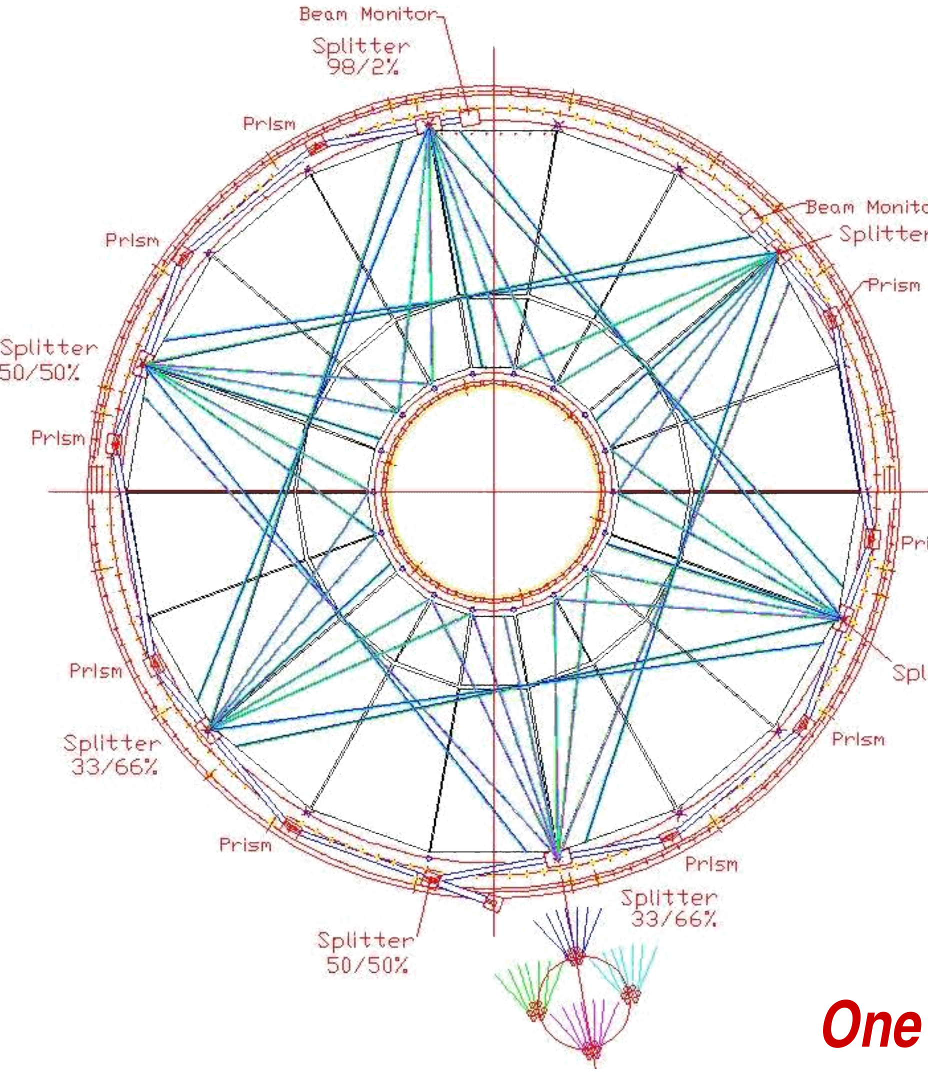


Cosmic tracks in OROC 13

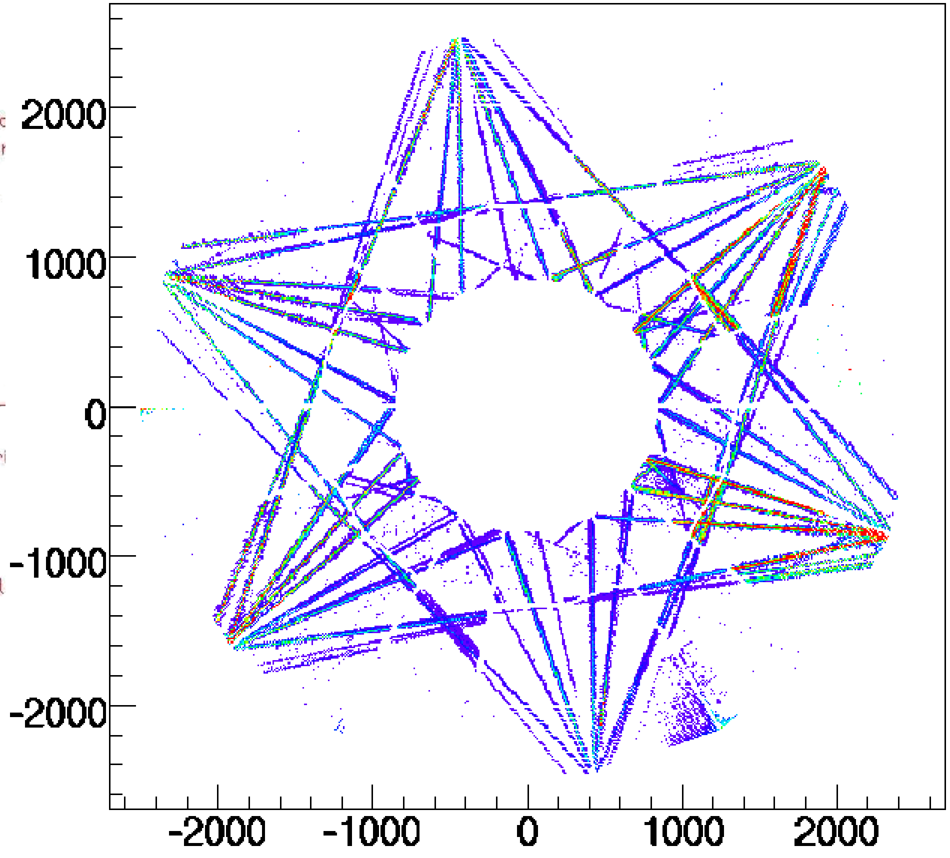


Laser system

Design Side A



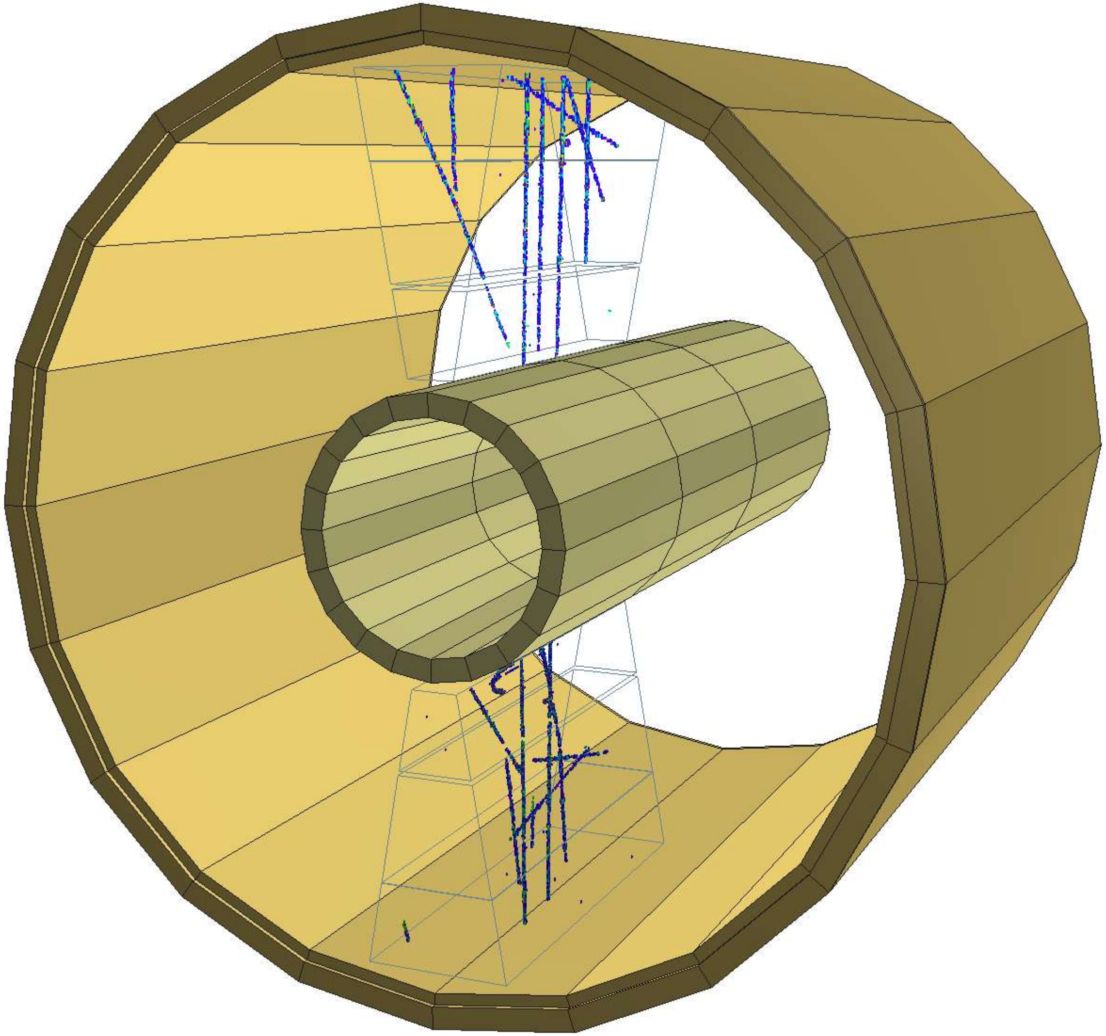
Measured Side A



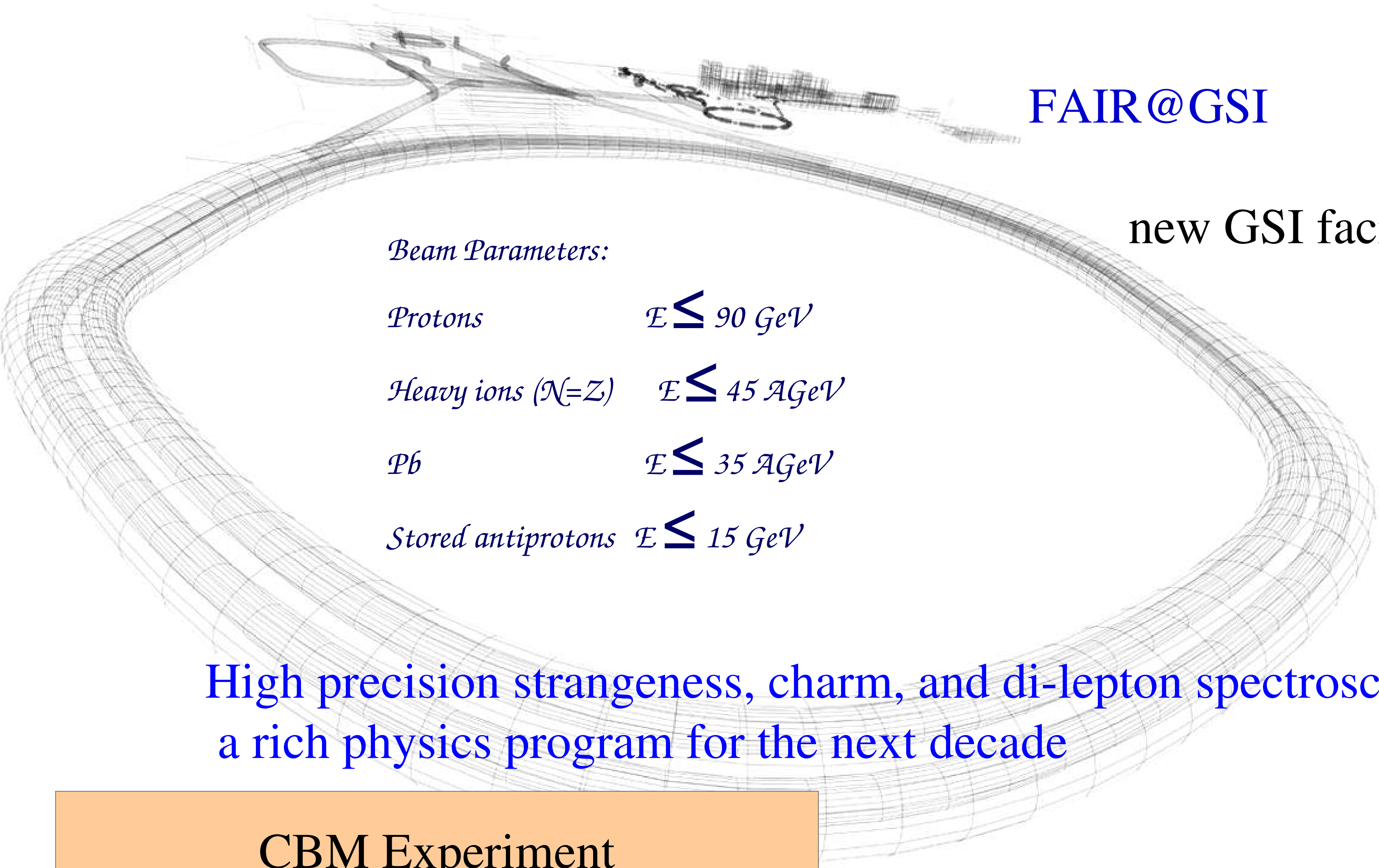
One laser installed on the floor

TPC Status now

- Phase1 of commissioning completed
- tracking performance as in Technical Design Report
- long term tests of detectors and electronics to follow
- installation of TPC into ALICE from Dec. 2006 on



Exploration of the QCD phase diagram in the baryon-rich region



FAIR@GSI

new GSI facility

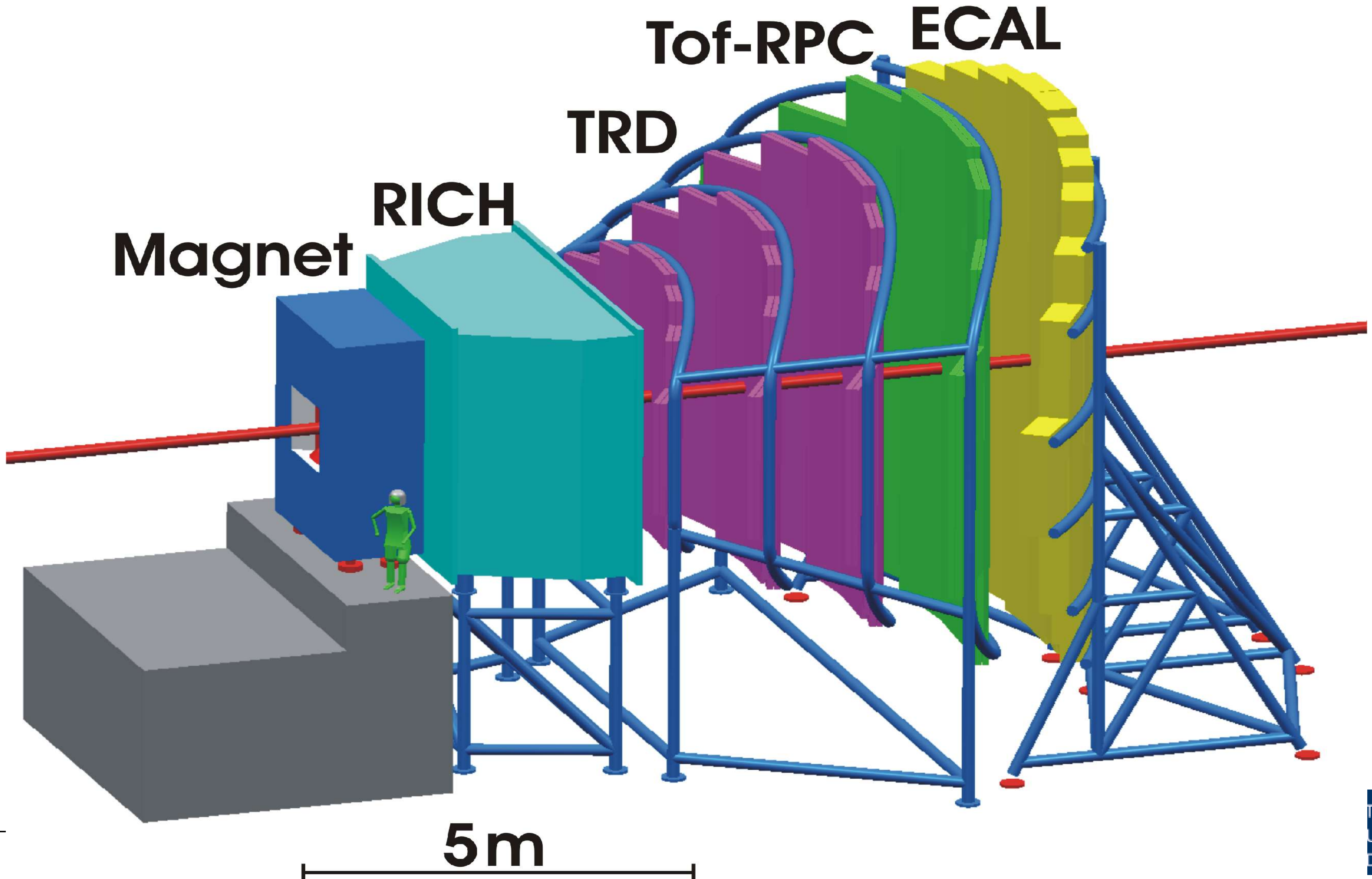
Beam Parameters:

Protons	$E \leq 90$ GeV
Heavy ions (N=Z)	$E \leq 45$ AGeV
Pb	$E \leq 35$ AGeV
Stored antiprotons	$E \leq 15$ GeV

High precision strangeness, charm, and di-lepton spectroscopy: a rich physics program for the next decade

CBM Experiment

The CBM Experiment



Conclusions and Outlook

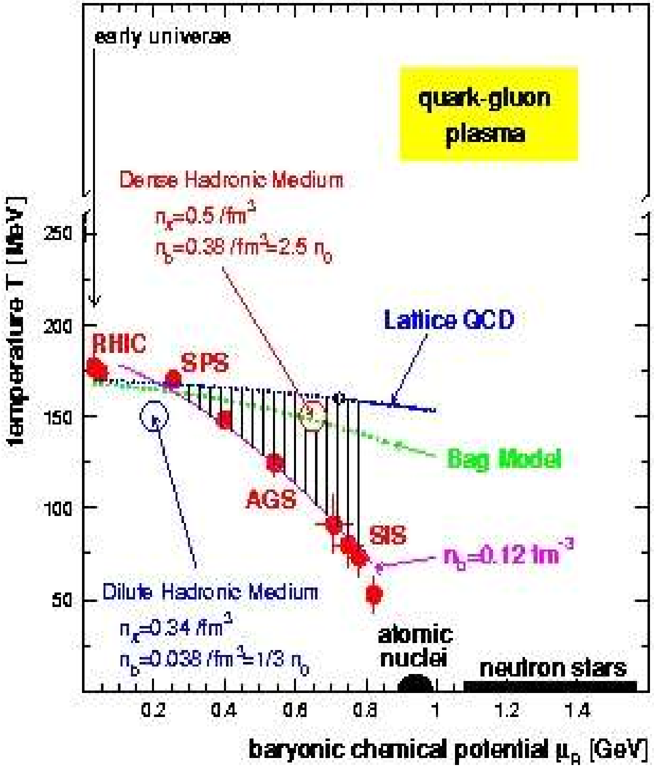
- Chemical equilibration of multi-strange hadrons is obtained through multi-hadron collisions near (during) the phase transition.
- Chemical freeze-out at RHIC and top SPS energy coincides with phase boundary from LQCD.
- Experimental determination of critical temperature:
  $T_c = T_{chem}$ +12 -16 MeV = 160 (+12 – 16) MeV --- confront LQCD
- ρ meson spectral function: dramatic change near the phase boundary
- Jet quenching: matter is very dense and opaque for fast partons
- Some open questions for FAIR, SPS, RHIC:
  - Is QGP ideal liquid near T_c?
  - Where is phase boundary at lower energies?
  - Is the full chemical freeze-out curve coincident with the phase boundary?
  - Where is the critical end-point?

Progress in determination of
fundamental QCD parameters
from nuclear collisions next major step: ALICE@LHC

Extra slides

What about lower beam energies?

- at top SPS energy numbers work out nearly the same as at RHIC
- at 40 A GeV/c pion and kaon densities lower by 1/3 → τ_Ω increases by factor 12
- but: other reactions involving baryons must come into play at high baryon density: $N\rho KKK \rightarrow \Omega\pi$ or $N\pi\pi KKK \rightarrow \Omega\rho$



A remark on critical energy density

- Along the Fodor-Katz phase boundary, critical energy density increases with increasing μ
- At $\mu = 0$, $\varepsilon_{crit} = 0.6$ GeV/fm^3
- At $T = 160$ MeV and $\mu = 650$ MeV, $\varepsilon_{crit} \approx 2.7$ GeV/fm^3 calc. within hadron resonance gas model, no excluded volume correction
- There are 1.46 baryons/fm^3 and 0.44 mesons/fm^3 at this point

Phase boundary at $\mu = 650$ MeV is very likely at lower T

Evaluation of multi-strange baryon yield

consider situation at T_{ch}=176 MeV first

- rate of change of density for n_{in} ingoing and n_{out} outgoing particles

$$r(n_{in}, n_{out}) = \bar{n}(\mathrm{T})^{n_{in}} |\mathcal{M}|^2 \phi$$

with

$$\phi = \prod_{k=1}^{n_{out}} \left(\int \frac{d^3 p_k}{(2\pi)^3 (2E_k)} \right) (2\pi)^4 \delta^4 \left(\sum_k p_k^\mu \right)$$

- The phase space factor ϕ depends on $\sqrt{s}$
  needs to be weighted by the probability $f(s)$ that multiparticle scattering occurs
  at a given value of $\sqrt{s}$
  evaluate numerically in Monte-Carlo using thermal momentum distribution

- typical reaction: $\Omega + \bar{N} \rightarrow 2\pi + 3K$
  assume cross section equal to measured value for $p + \bar{p} \rightarrow 5\pi$
  relevant $\sqrt{s} = 3.25$ GeV → σ=6.4 mb

- compute matrix element and use for rate of $2\pi + 3K \rightarrow \Omega + \bar{N}$

Evaluation of multi-strange baryon yield

reaction $2\pi + 3K \rightarrow \Omega + \bar{N}$ leads to

$$r_\Omega = 0.00014 \text{ fm}^{-4} \text{ or } r_\Omega / n_\Omega = 1/\tau_\Omega = 0.46/\text{fm}$$

$\Rightarrow$ can achieve final density starting from 0 in 2.2 fm/c!

similarly one obtains

for $3\pi + 2K \rightarrow \Xi + \bar{N}$ $\tau_\Xi = 0.71$ fm/c

and

for $4\pi + K \rightarrow \Lambda + \bar{N}$ $\tau_\Lambda = 0.66$ fm/c

What about pp and e+e- collisions?

- Thermal fits describe hadron yields with T ~ 160 MeV
- Hadronization may be pre-thermalization process
- But: multi-strange baryons can only be reproduced by ad-hoc strangeness suppression factor implying incomplete equilibration

Analysis of pp collisions

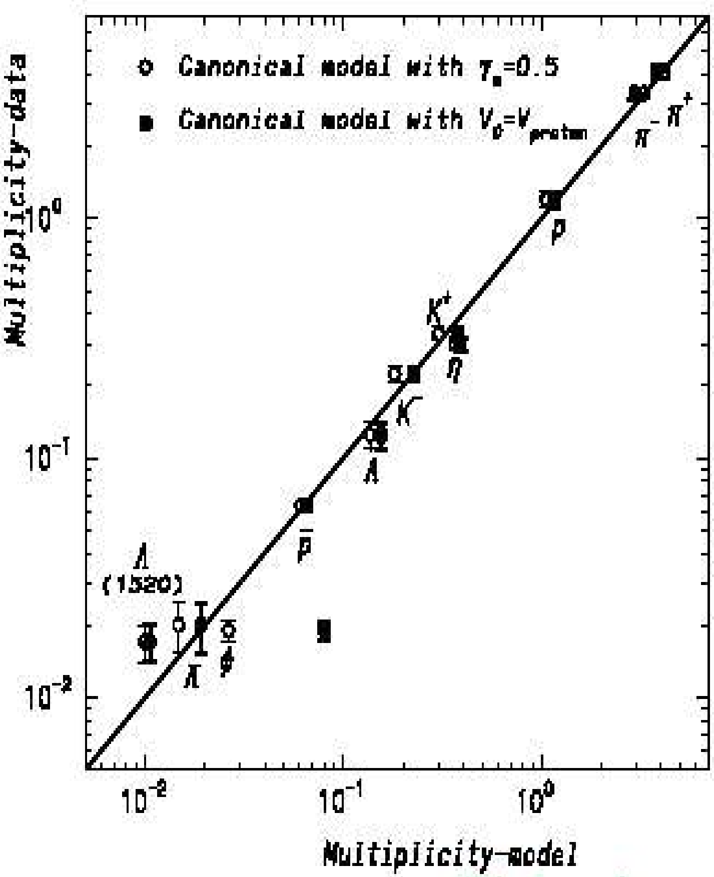
F. Becattini, Z. Phys. C69 (1996) 485; F. Becattini and U. Heinz, Z. Phys. C76 (1997) 269

pp data, $\sqrt{s} = 27.6$ GeV

canonical (volume) suppression vs γ_s factor (non-equilibrium), T = 165 MeV

Analysis by K. Redlich, see pbm, Stachel, Redlich, nucl-th/0304013

γ_s factor needed to describe ϕ production



Observed strangeness suppression is **not** described by equilibrium thermo-dynamics

pp and e+e- continued

- Suppression factor of 2 implies Omega baryons are factor 8 off the equilibrium value
- Suppression is not due to canonical thermodynamics (phi problem, K. Redlich)
- Multi-meson fusion not effective since no high density phase
- 'Temperature' in pp and e+e- reflects hadronization but not phase transition.
- The existence of a medium in AA collisions also leads to the result that T is not universal (at T = 160 MeV as in e+e- and pp) but varies with μ: T=140 MeV at μ = 400 MeV, e.g.

2-body collisions are not enough

typical densities at T_{ch}: ρ_π =0.174/fm^3 (incl. res.) ρ_K =0.030/fm^3 ρ_Ω = 0.0003/fm^3

- To maintain equilibrium even for 5 MeV below T_{ch} need relative rate change

$$\left|\frac{\bar{r}_\Omega}{n_\Omega} - \frac{\bar{r}_K}{n_K}\right| = \tau_\Omega^{-1} - \tau_K^{-1} = (1.10 - 0.55)/\mathrm{fm} = 0.55/\mathrm{fm}.$$

  So, Ω density needs to change by 100 % within 1 fm/c

- Typical reactions with large cross sections of 10 mb and relative velocity of 0.6 give

  $\Omega + \pi \rightarrow \Xi + K$ → $\bar{r}_\Omega/n_\Omega = n_{\bar{\pi}}\langle v_r \sigma\rangle$=0.086/fm

  $\pi + \pi \rightarrow K + \bar{K}$ (σ=3mb) → $\bar{r}_K/n_K = 0.18$/fm

  i.e. much too slow to maintain equilibrium even over Δ T = 5 MeV!

- Even much more difficult: to produce large Ω abundancy

  assume hadronization like in pp, factor 8 too few Ωs, to produce them within 1 fm/c

  need reactions that provide $\bar{r}_\Omega/n_\Omega$=1.0 ⇒ not with 2-body reactions

- Consensus in the literature: Koch, Müller, Rafelski, Phys. Rep. 142(1986), C. Greiner, S. Leupold, J.Phys.G27(2001)L95; P. Huovinen, J. Kapusta, nucl-th/0310051

Check numerics via detailed balance

- Initially manifestly nonequilibrium situation - start with practially zero Ω density
- As equilibrium is approached
  rates $3K + 2\pi \rightarrow \Omega + \bar{N}$ and $\Omega + \bar{N} \rightarrow 3K + 2\pi$ have to become equal
- back and forth reactions scale very differently with pion density
  $\rightarrow$ only at one density can they be equal
- to explicitly check these rates now use pion, kaon, nucleon densities before strong decays,
  i.e. without resonance feeding
  (for all resonances corresponding rates have to be calculated accordingly)
- find: creation of Ω with $r_\Omega / n_\Omega = 3.4\ 10^{-3}/\text{fm}$
  and annihilation of Ω with $r_\Omega / n_\Omega = 1.4\ 10^{-3}/\text{fm}$

for equal rates reduce density by 25 %
reduce T by 2-3 MeV or excluded volume a bit larger

Variation of fireball temperature with time

Values chosen appropriate for RHIC Au + Au collisions

- Assume: T_{ch}=176 MeV
  density decrease between chemical and thermal freeze-out: 30 %
- Two-pion correlation data: R_{side} =5.75 fm, R_{long}=7.0 fm, mean β_t =0.5, β_{long}=1
- Isentropic expansion → $\tau_f = 0.9 - 2.3$ fm, $T_f = 158 - 132$ MeV
  (uncertainty due to variation in density profile)
- Near T_c: rate of decrease in temperature $|\dot{T}/T| = \tau_T^{-1} = (13 \pm 1)$ % /fm

What about centrality dependence of chemical equilibration?

- Apparent chemical temperature depends little on centrality.
- The importance of multiple collisions should decrease with decreasing particle density, i.e. lower centrality.
- This is expressed in the data as change in γ_s .
- Note: $\gamma_s = 0.8$ reduces Ω yield by factor of 2.

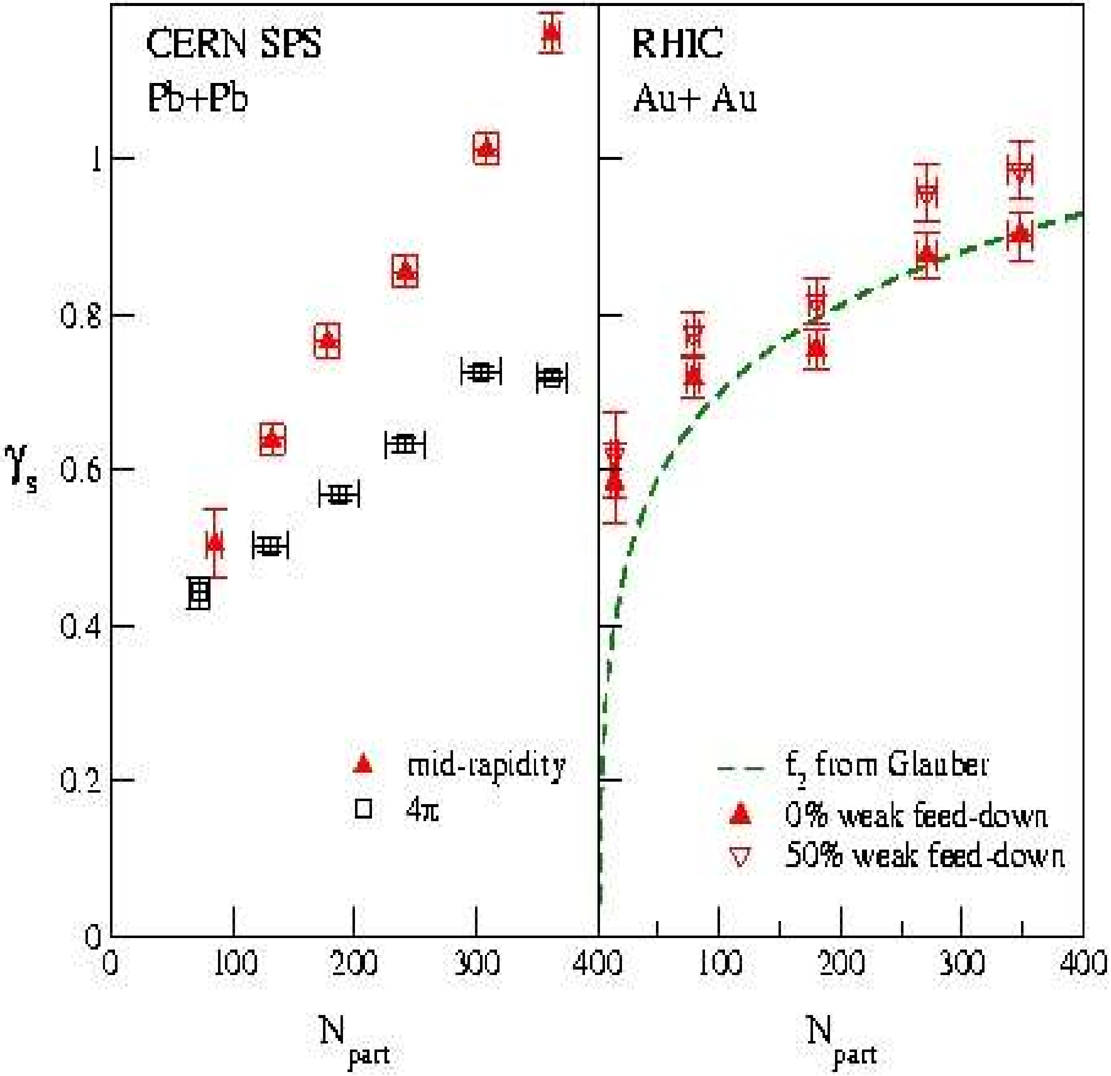
Centrality dependence of γ_s

Cleymans, Kämpfer, Steinberg, Wheaton, hep-ph/0212335

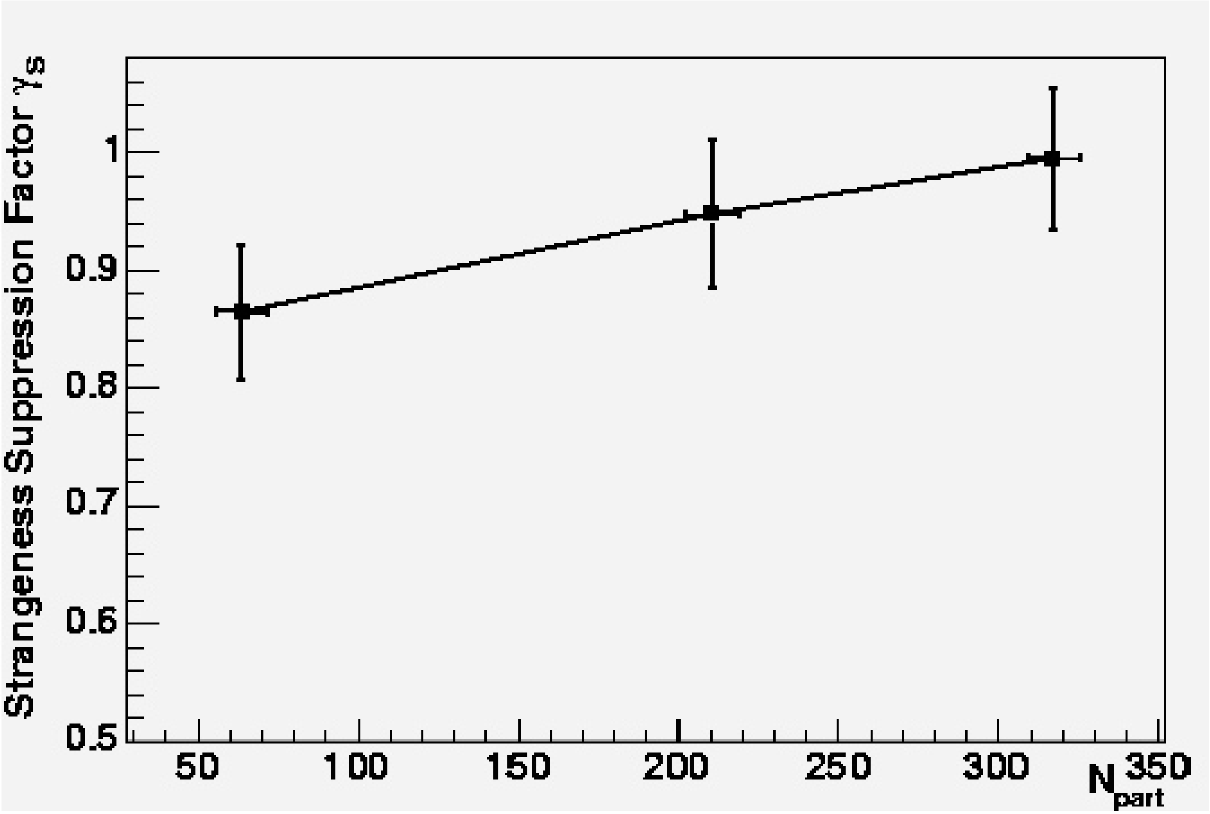
Fit μ_B and γ_S to π, K, p yields

f_2 fraction of N_{part}

with multiple collisions



Centrality dependence of γ_s

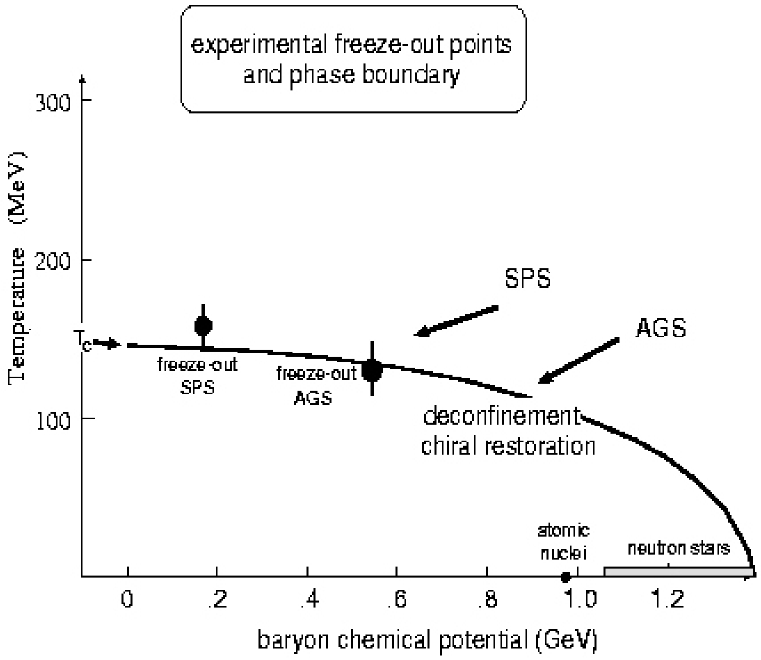


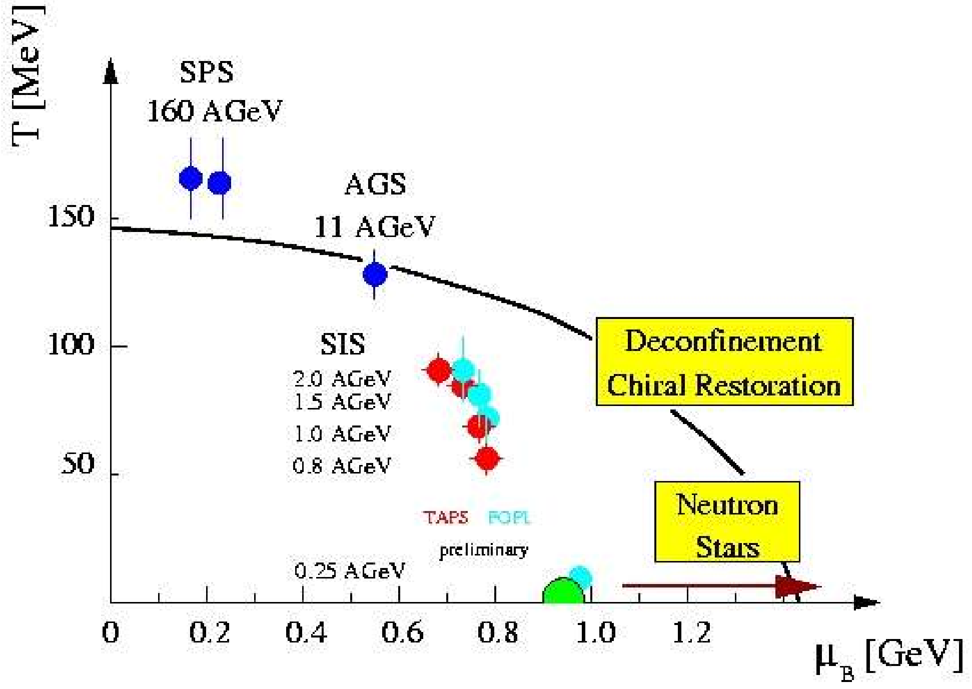
S. Wheaton et al, SQM04,
Au+Au analysis, RHIC energy

increasing N_{part} → increasing particle density

→ chemical equilibration is reached

Establishing the chemical freeze-out curve





The first plot: pbm, Stachel
Phys. Lett. B365 (1996)1
Nucl. Phys. A606 (1996) 320

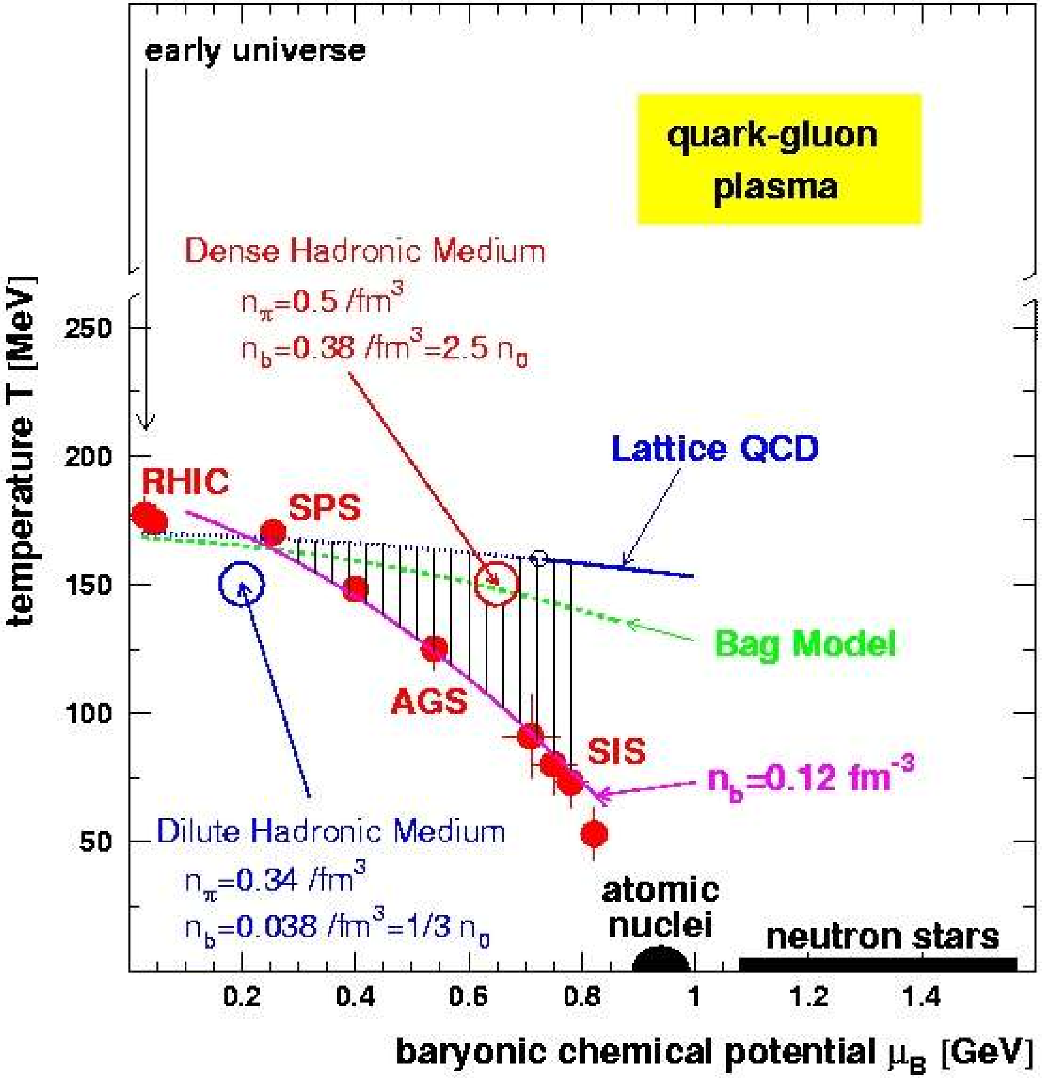
The full curve:
pbm, Stachel, QM1997
Nucl. Phys. A638 (1998)3c

Chemical freeze-out curve – the view as of 2002

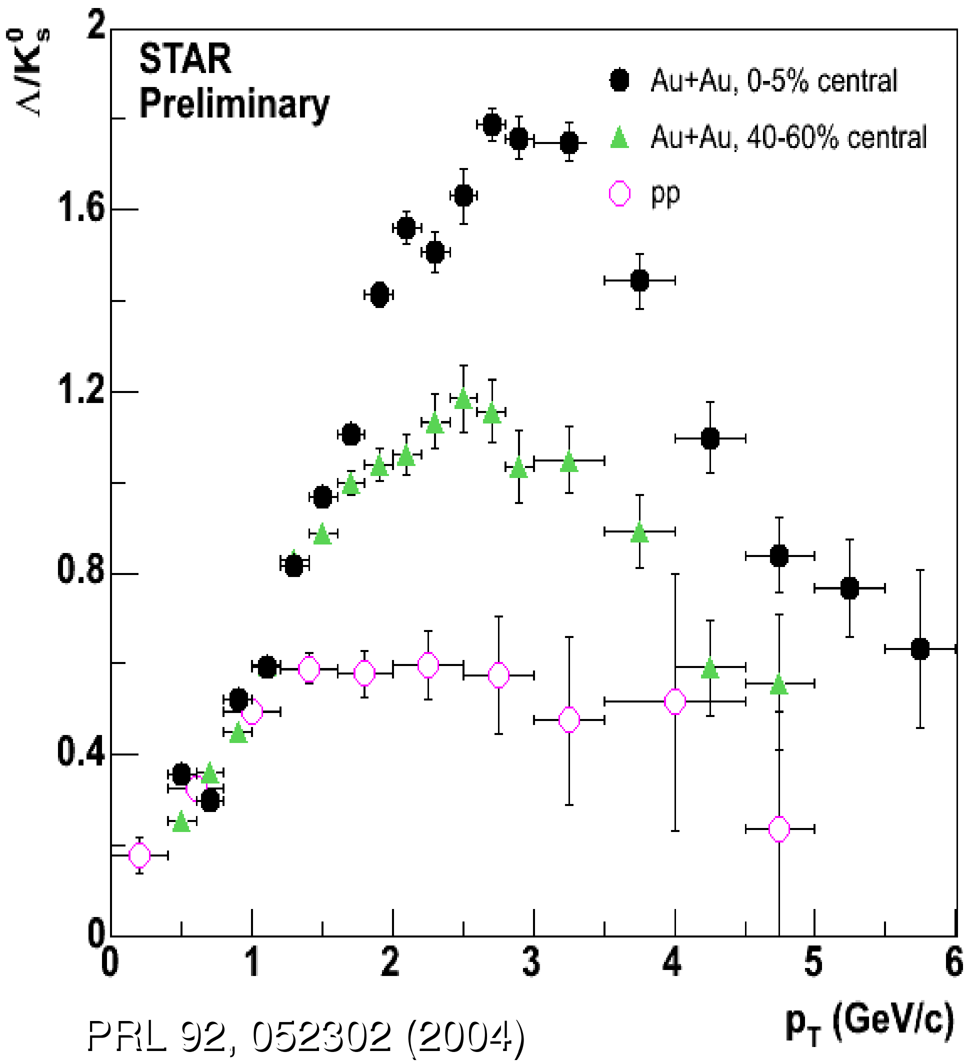
P. Braun-Munzinger, J. Stachel,
J. Phys. G. 28 (2002) 1971
chem. freeze-out at constant total
baryon density

J. Cleymans, K. Redlich,
Phys. Rev. Lett. 81(1998)5284
chem. freeze-out at constant
energy/particle

Note: for μ < 300 MeV,
LQCD phase boundary
coincides
with freeze-out curve



suppression pattern depends on hadronic species



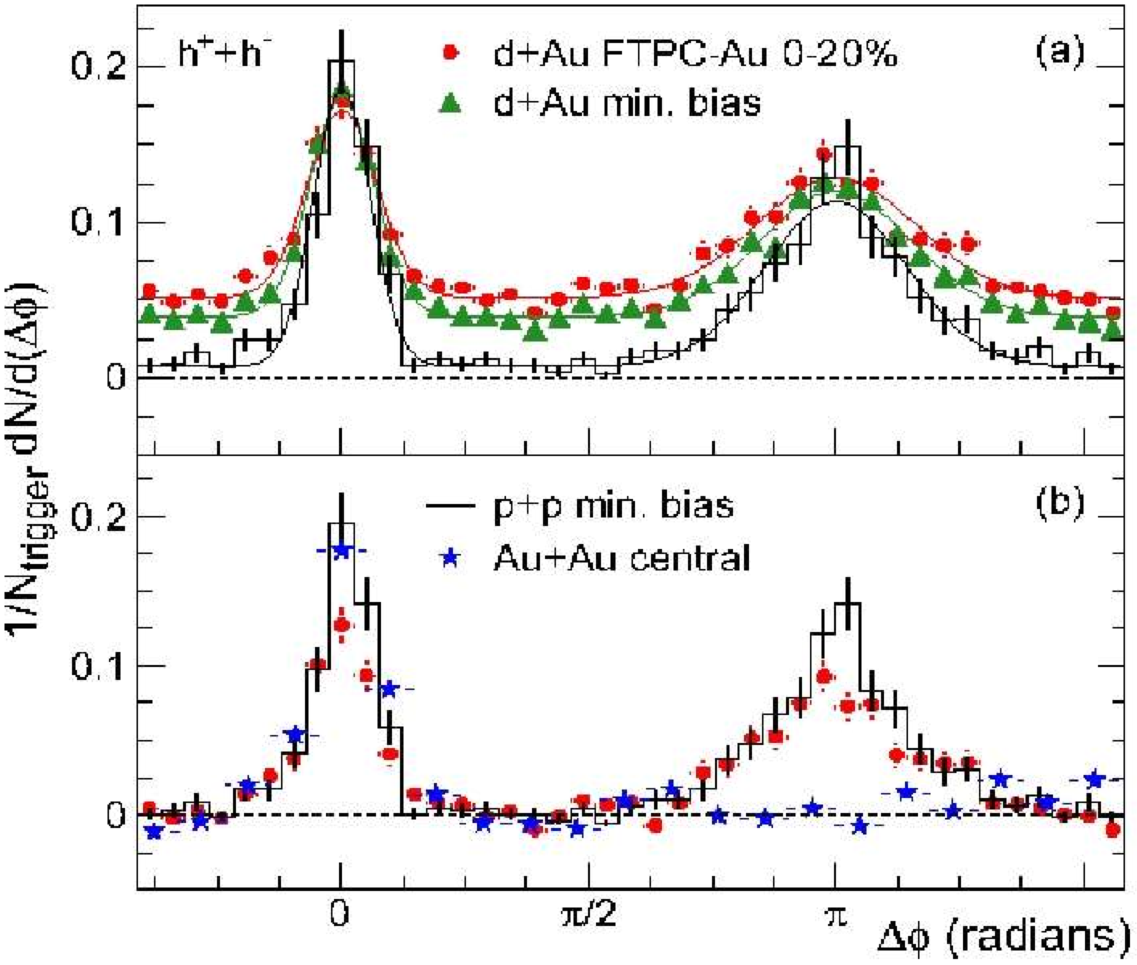
PRL 92, 052302 (2004)
J.Phys. G30, S963 (2004)

observed early on: protons exceed number of pions at 2 GeV/c

general feature for all baryons?

very cleanly shown recently for Λ as compared to K^0_s while pp shows normal fragmentation
coalescence of valence quarks?

Azimuthal correlations of high p_t particles

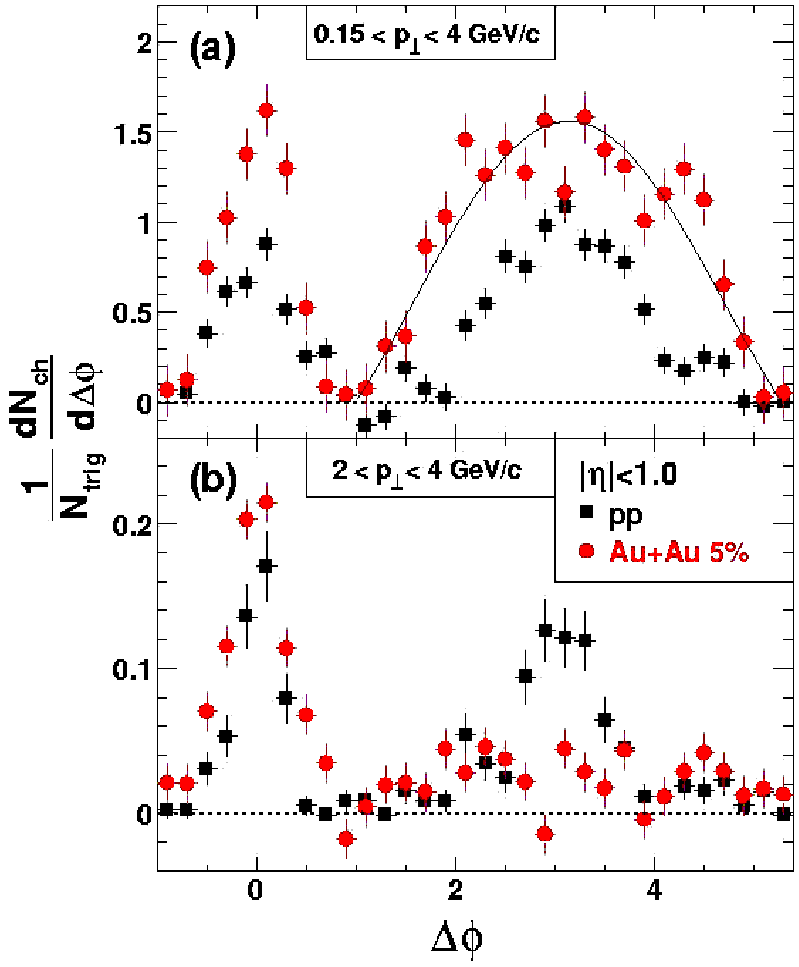


trigger particle: 4-6 GeV/c
correlated with all others
with p_t=2-4 GeV/c

STAR: PRL 91 (2003) 072304

away-side associated hadrons at lower p_t

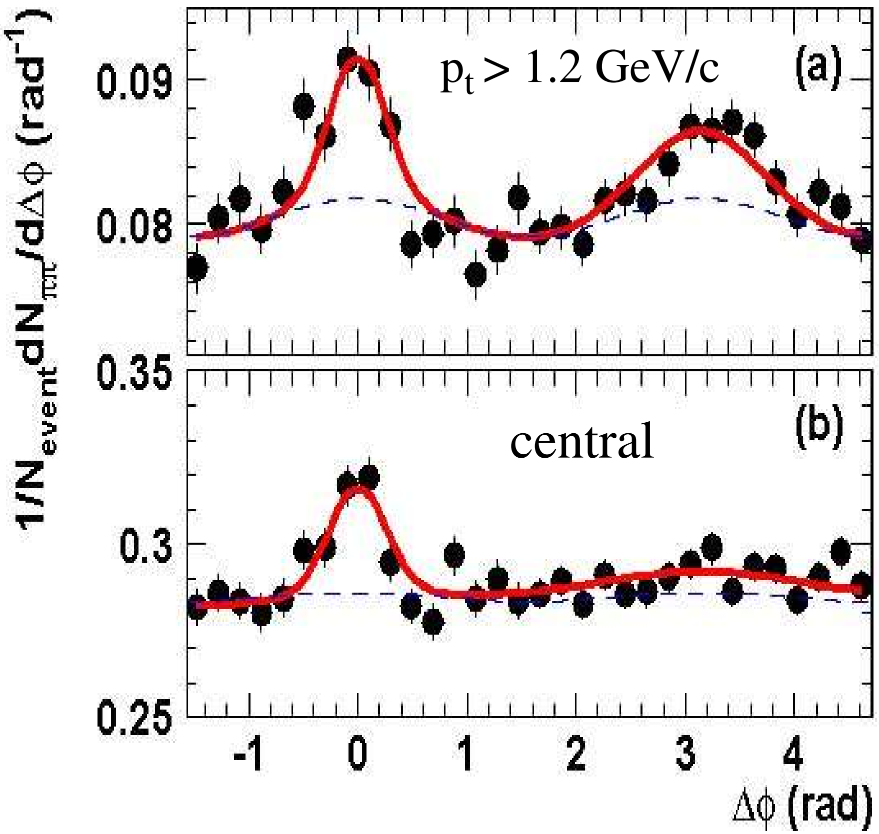
STAR 200 GeV nucl-ex/0501016



$4 < p_T(\text{trig.}) < 6$ GeV/c

$\sqrt{s} = 17.2$ GeV

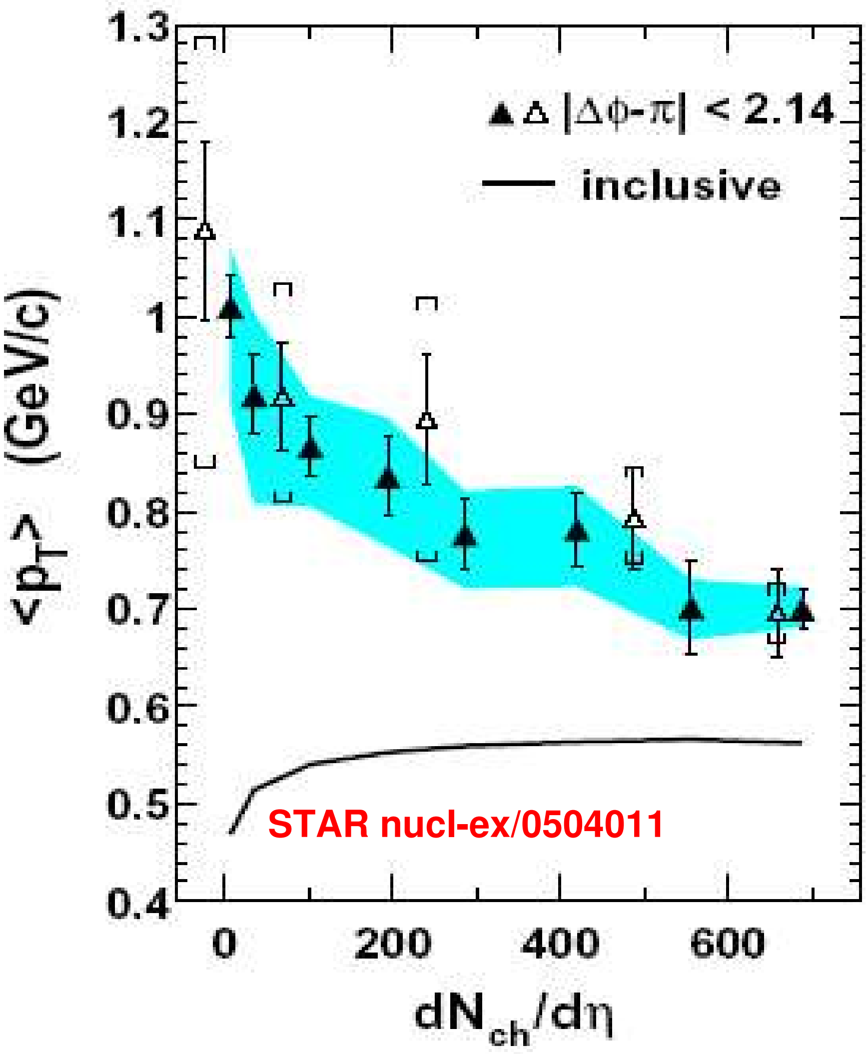
CERES/NA45 PRL92(2004)032301



shape of away side peak changes (broadens)

momenta reduced

mean p_t in cone opposite to leading trigger particle



for central collisions mean p_t on opposite side looks nearly thermalized

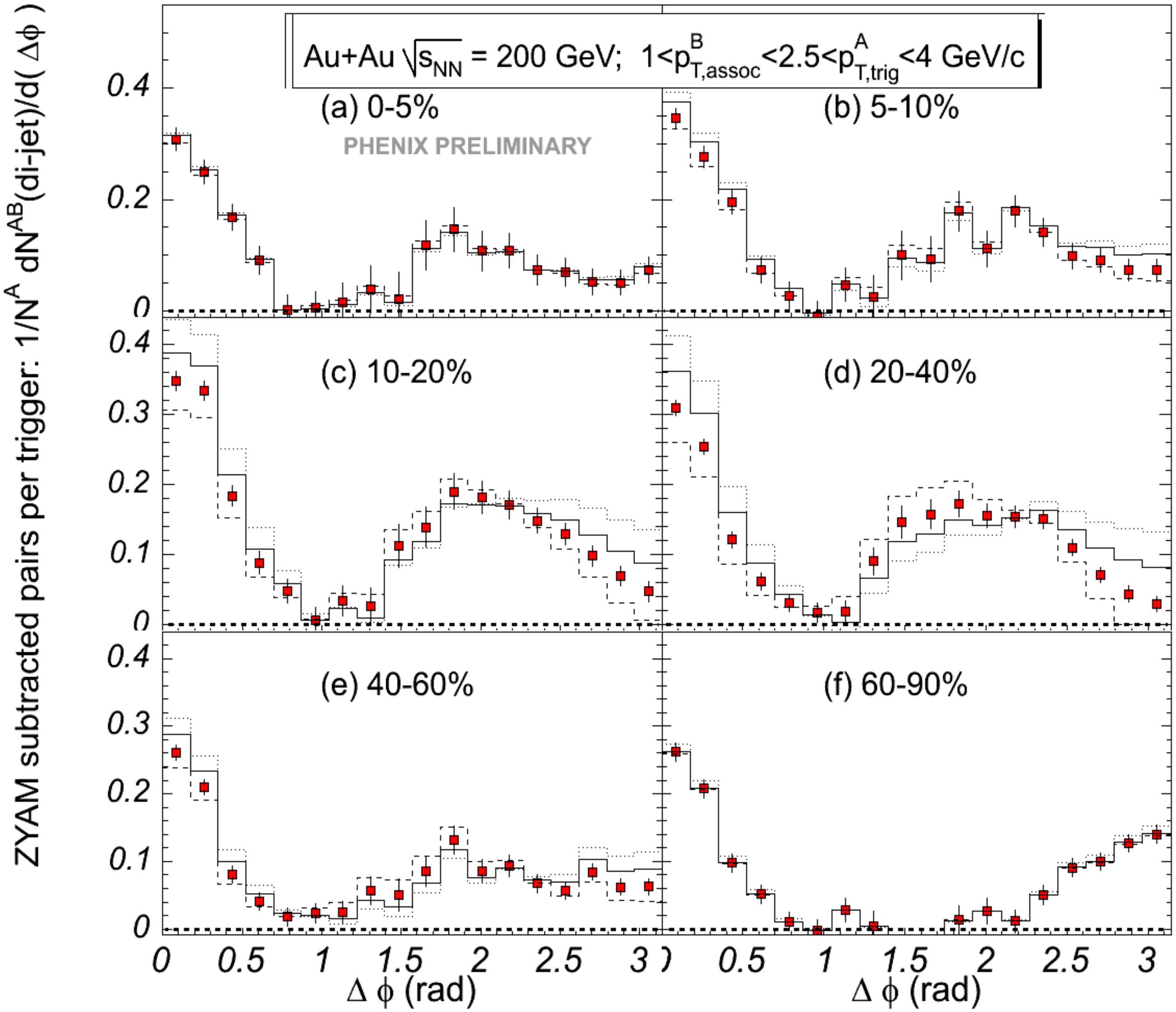
$\sqrt{s_{NN}}$ = 200 GeV Au+Au results:

Closed symbols ⇔ $4 < p_T^{trig} < 6$ GeV/c

Open symbols ⇔ $6 < p_T^{trig} < 10$ GeV/c

Assoc. particles: $0.15 < p_T < 4$ GeV/c

opening angle correlations between high p_t particles



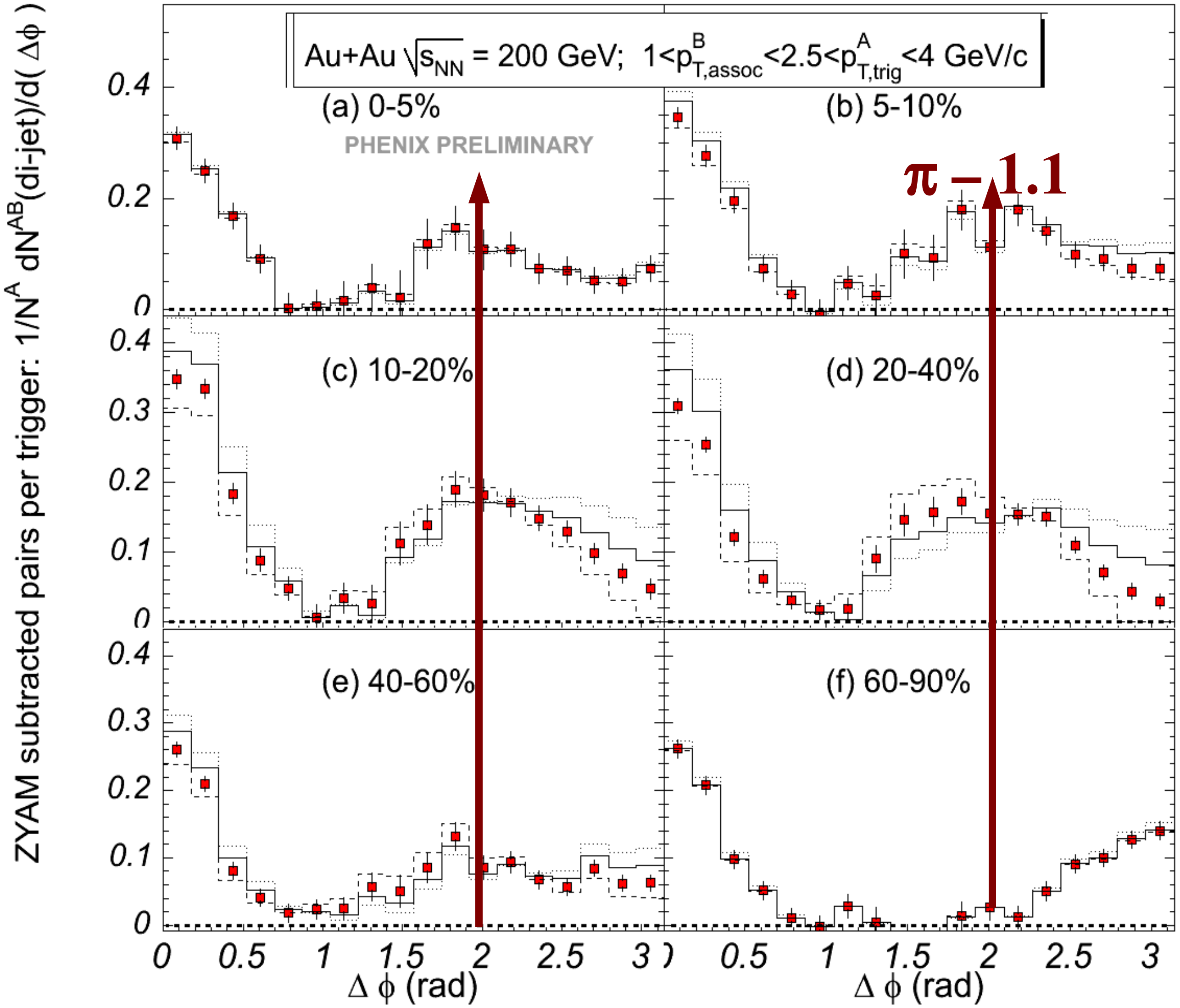
when asking for softer particle opposite hard trigger particle: dip (2 σ) at $\Delta\varphi = \pi$ except for most peripheral bin

N.N.Ajitanand, Proc. Int. Conf. Phys. & Astrophys. of QGP, Kolkata Feb. 2005

Mach cone due to sonic boom from quenched jets?

original idea:
Stöcker/Greiner 1976
for nuclear reactions;
Stöcker 2004:
60º cone for jets in QGP

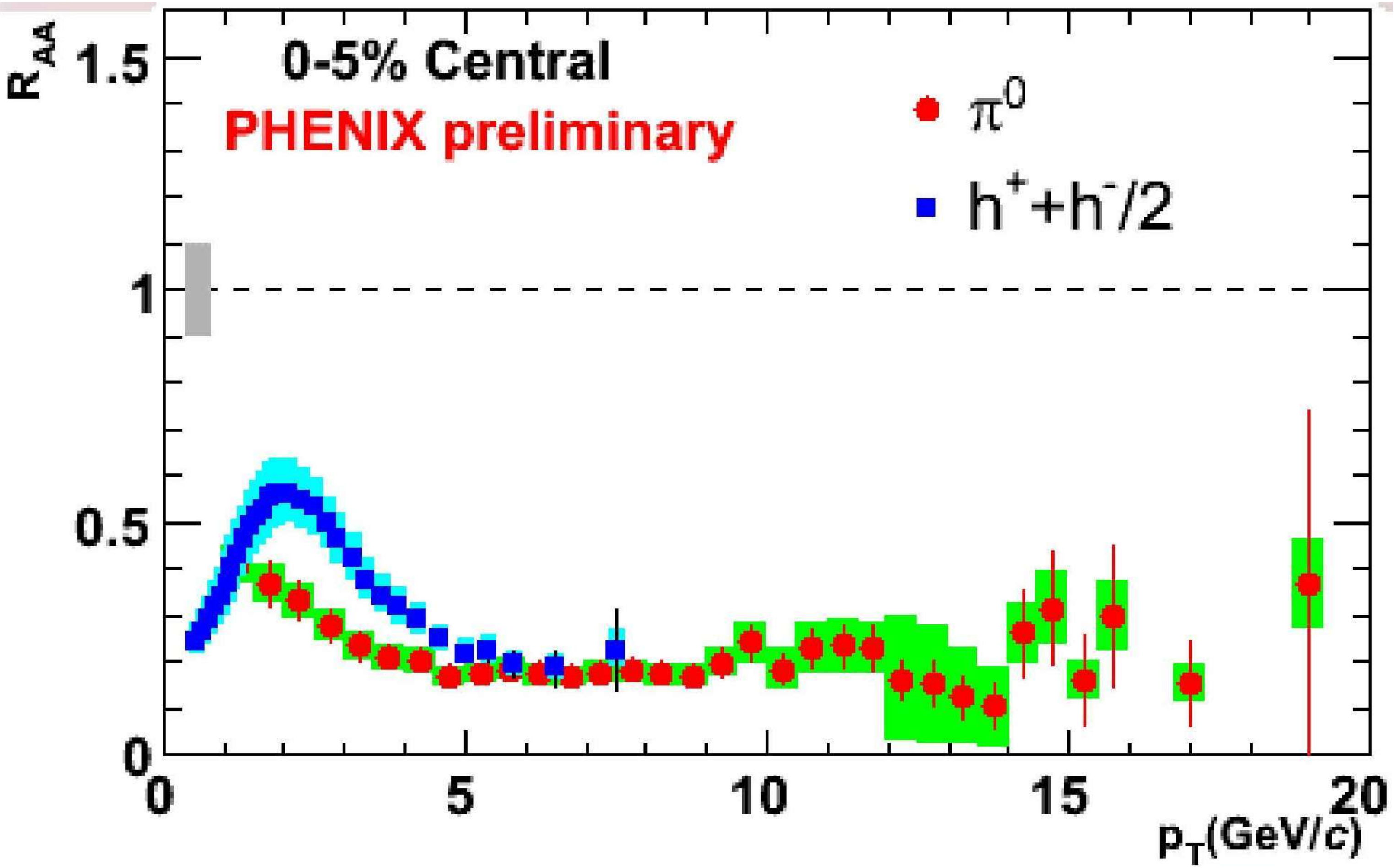
J.Casalderrey-Solana,E. Shuryak, D. Teaney,hep-ph/0411315



if this can be established
far reaching consequences:
sensitivity to speed of
sound and EOS

experimental challenge:
can one see cone in 2d?
rel to reaction plane?

The matter is opaque up to at least 20 GeV.



- Suppression is very strong (R_{AA}=0.2!) and flat up to 20 GeV/c
- Anomaly in charged hadrons (blue) is due to baryons (recombination vs fragmentation)