Physics of Baryon-Rich Matter: Results and Opportunities for FAIR@GSI

Skopelos, May 2004

Peter Braun-Munzinger, GSI and TU, Darmstadt

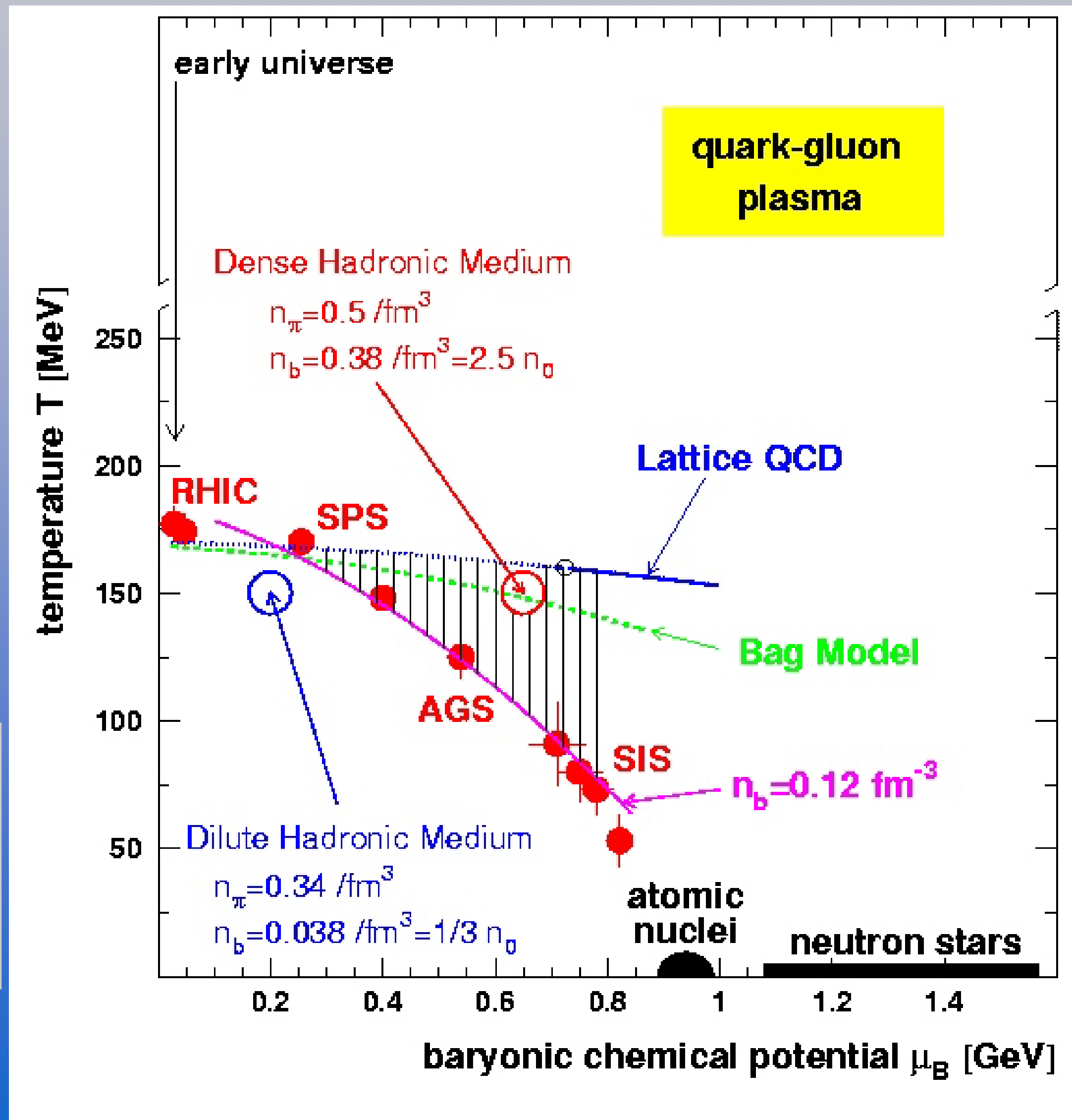
Outline

- Introduction
- Energy Dependence of Global Observables
- Strangeness and the Phase Boundary
- Lepton Pairs and Baryon Density
- Fluctuations
- Charm and J/y
- Exotica
- Summary

The QCD Phase Diagram and Chemical Freeze-out Points

- At SPSand RHIC: freeze-out near phase boundary
- Critical Point: somewhere between $0 < m_B < 700$ MeV

P. Braun-Munzinger, J. Stachel, J. Phys. G. 28 (2002) 1971

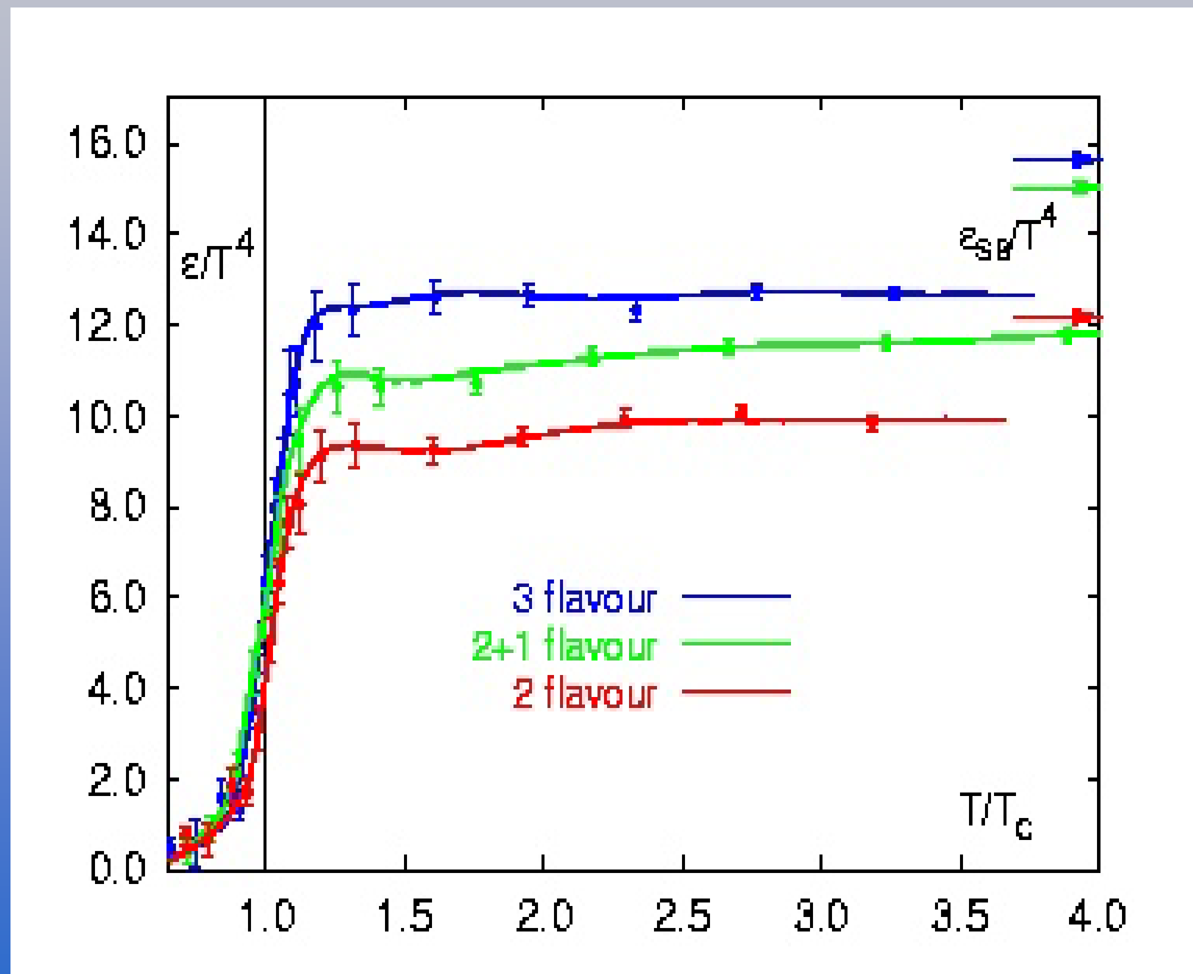


Chemical Equilibration must take place in the Hadronic Phase

- 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).
- For small m, T_{chem} and T_c practically coincide: pbm, J. Stachel, C. Wetterich, Phys. Lett. (in print, nucl-th/0311005), (see talk by Johanna Stachel).
- What about large m?

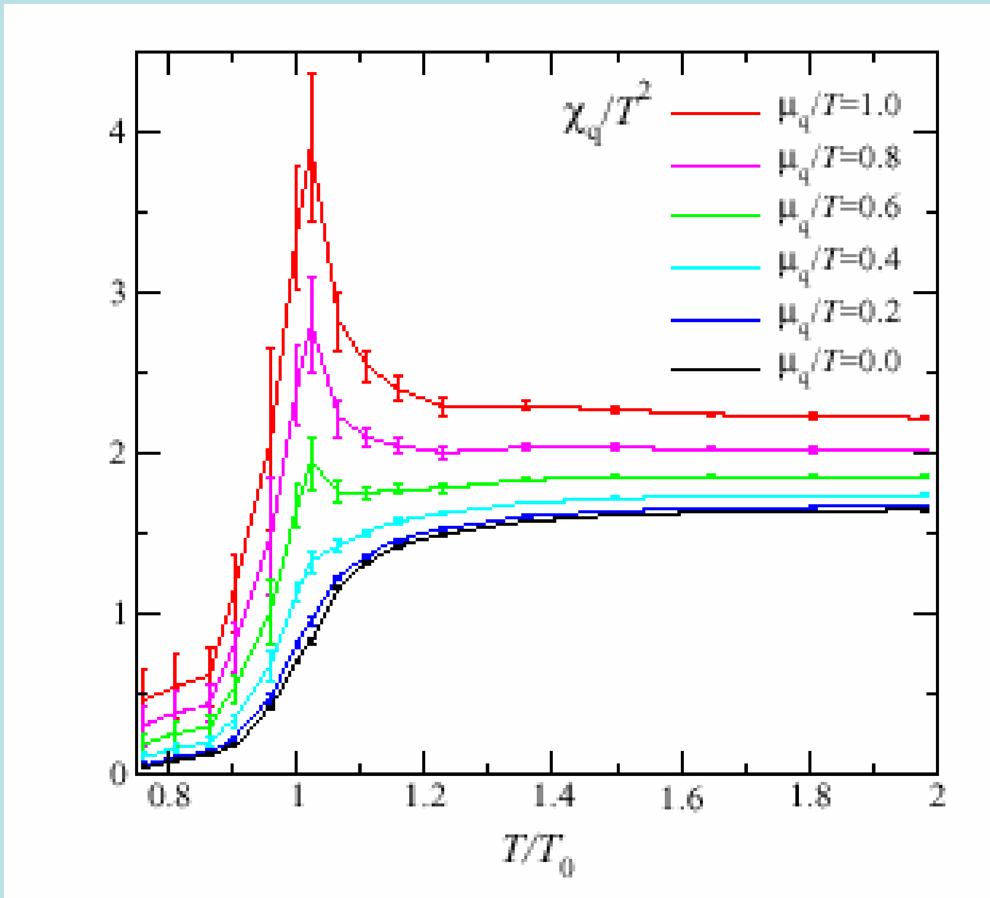
Energy Density from Lattice

- Calc. By Bielefeld group
- $T_c = 175 +/- 8$ MeV
- SB limit is never reached --> strong correlations
- $e_{crit} = 0.7$ GeV/fm^3



Baryon Number Susceptibility

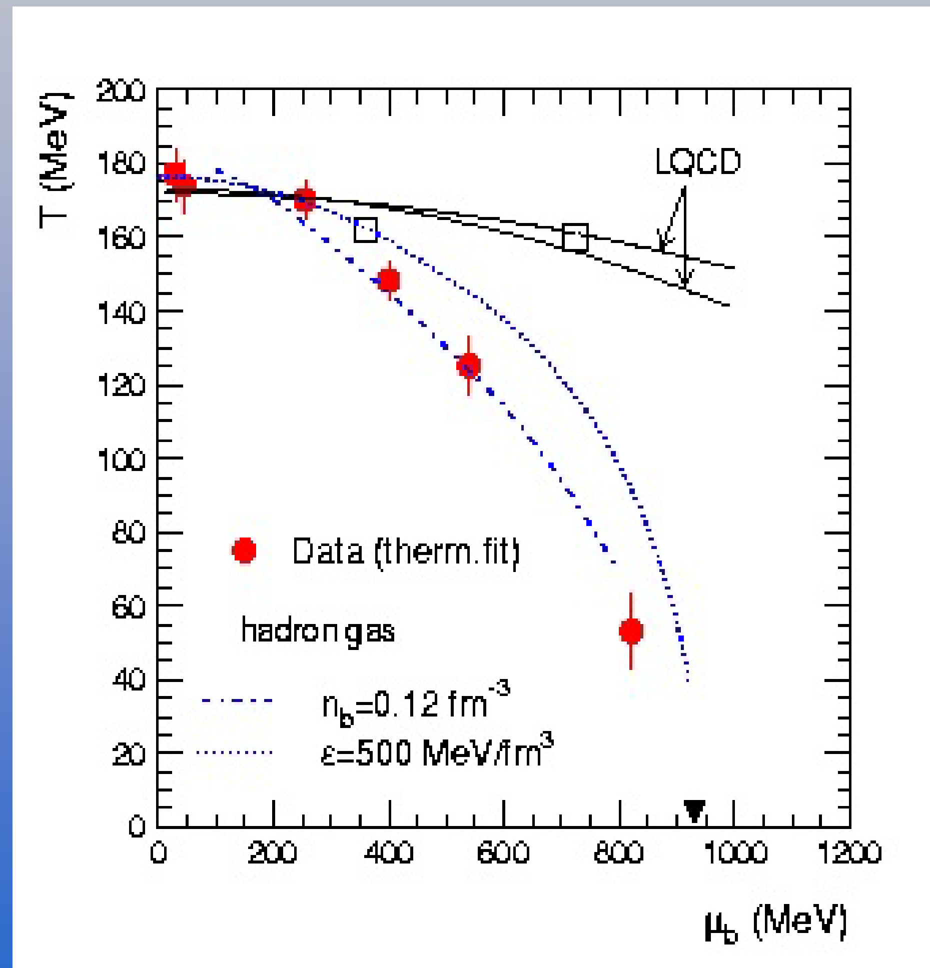
C. R. Allton et al, hep-lat 0305007



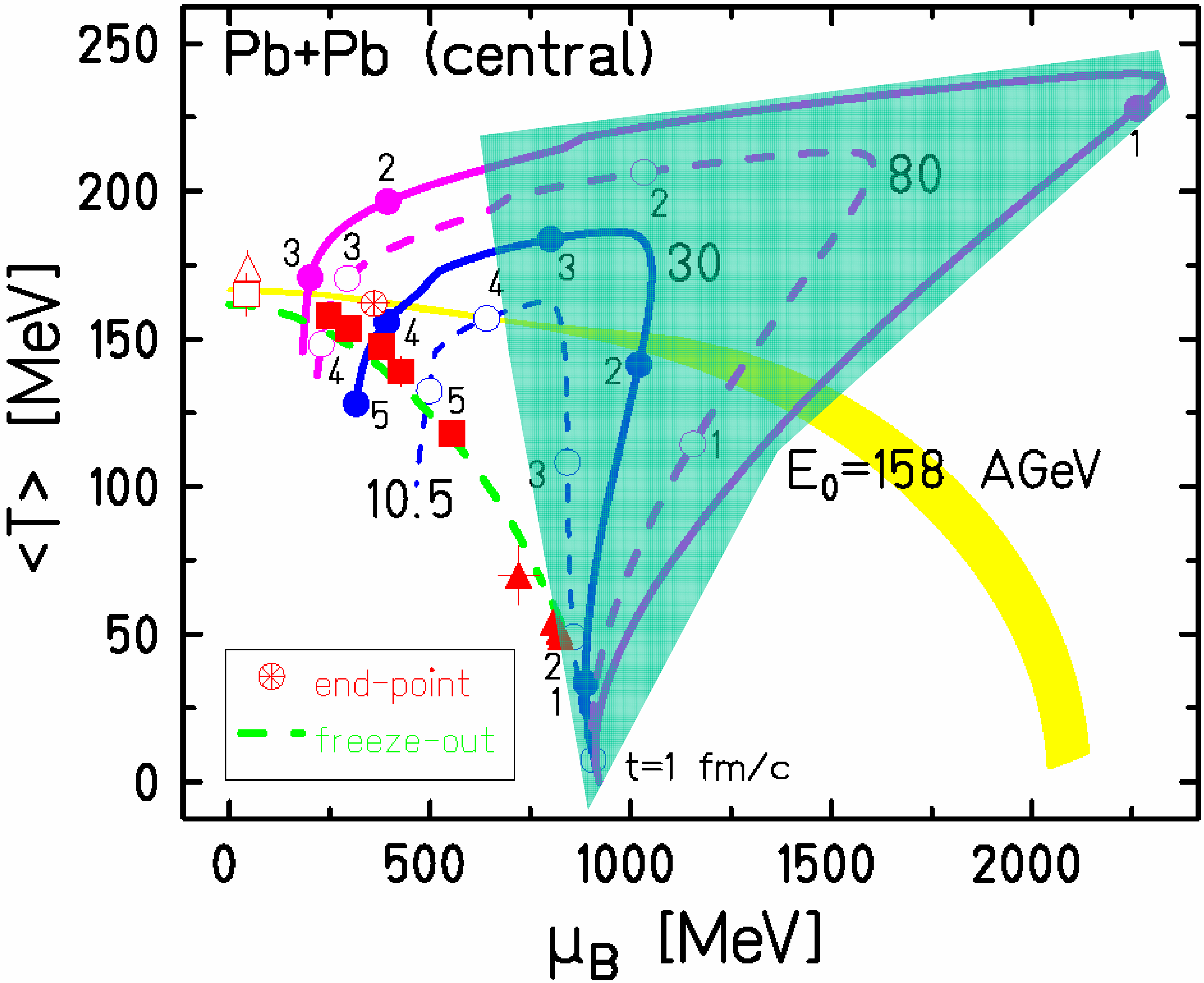
Lattice QCD :
maximal baryon number density fluctuations at T_C for $\square_q = T_C$
(m_B □ 480 MeV)

Where is Phase Boundary at large m?

- Is there a dense hadronic region between phase boundary and chem. Freeze-out points?
- Maybe phase boundary is line of constant energy density?



“Trajectories” (3 fluid hydro)



Hadron gas EOS

Warning:
System not initially
in
equilibrium!

Energy Dependence of Observables

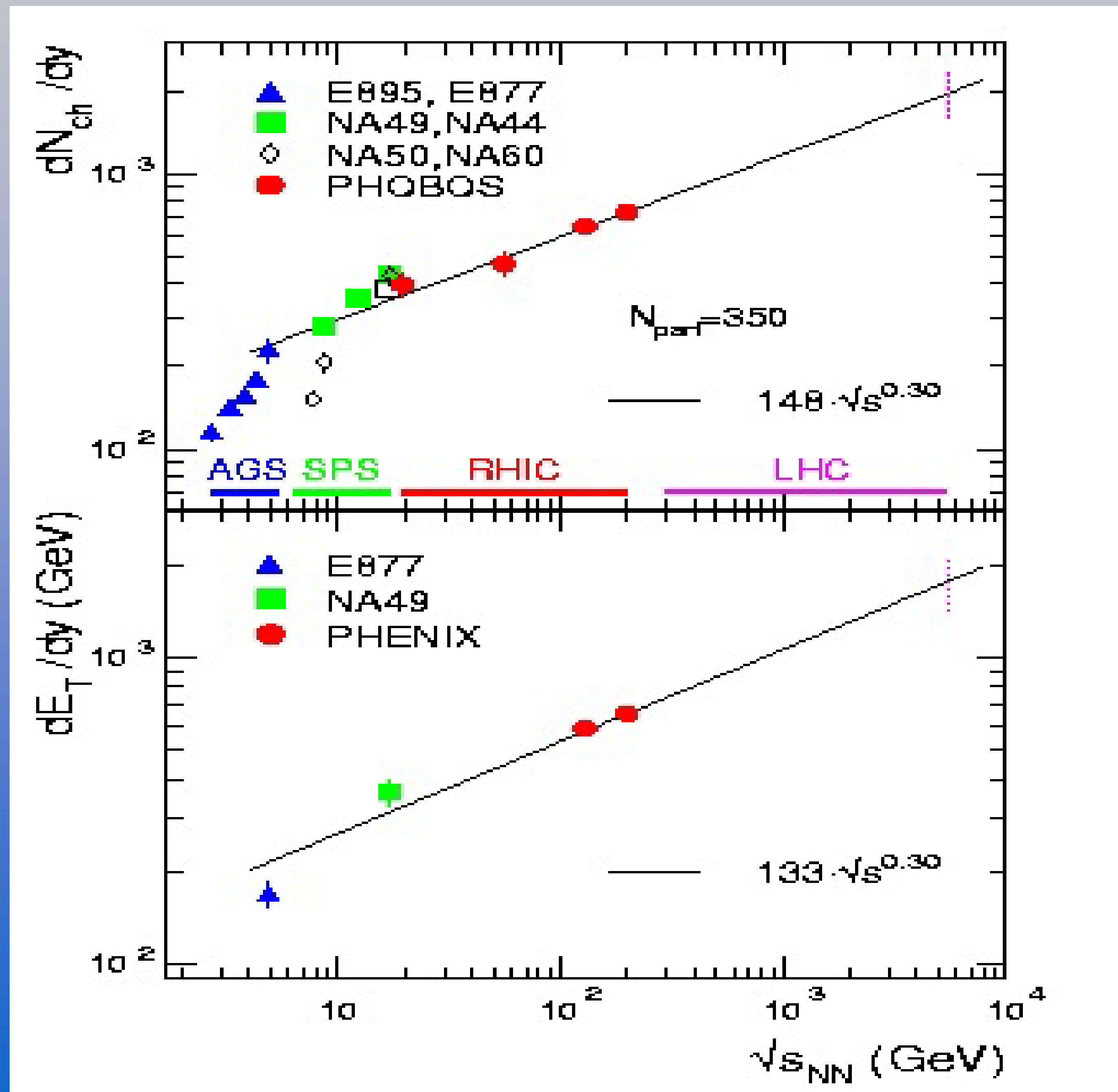
- Is everything smooth and monotonic, like in pp?
- Will consider global observables, strangeness, dileptons

Summary of dN_{ch}/dy

$dn_{ch/dy}$ is important input for the charm calculations

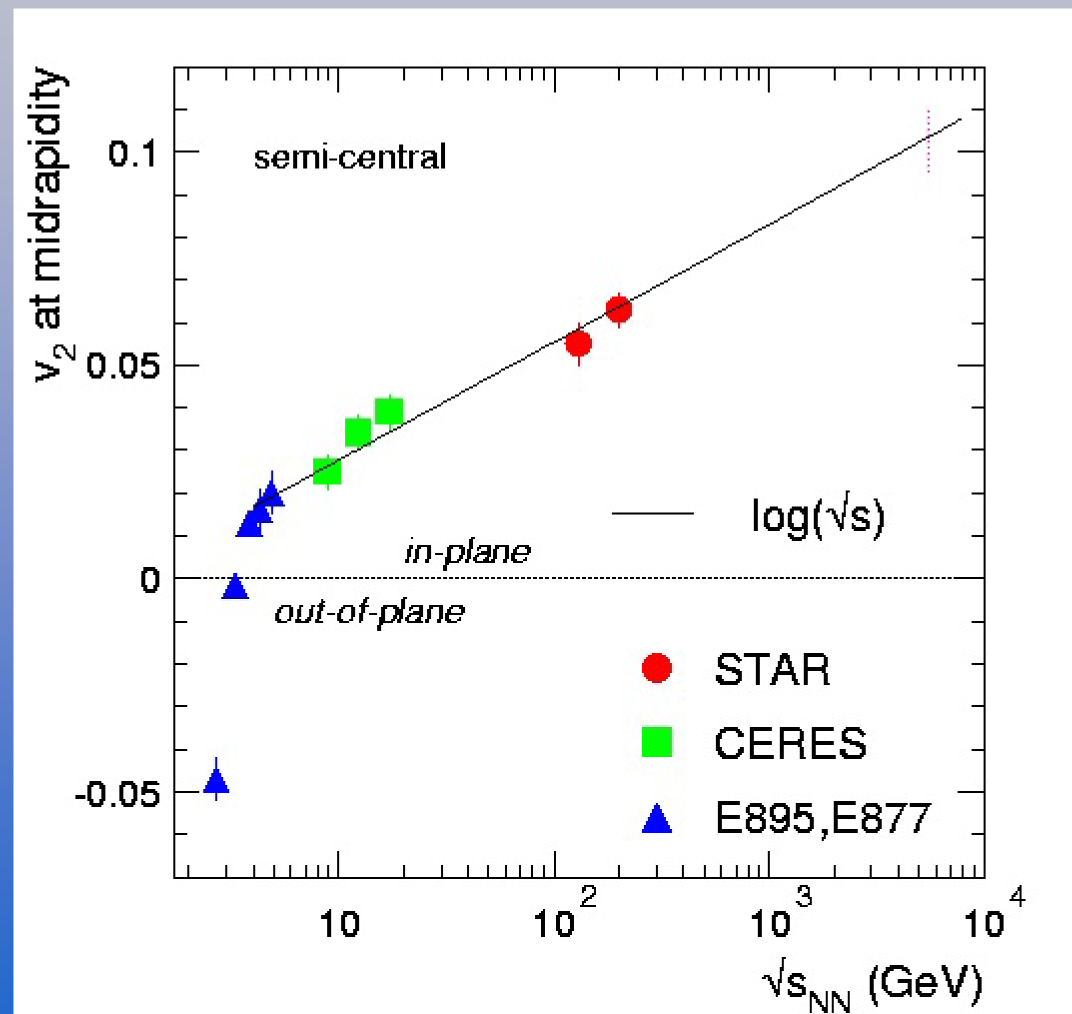
note: consistence among experiments not better than 15 %

for details see: A. Andronic, pbm, hep-ph/0402291



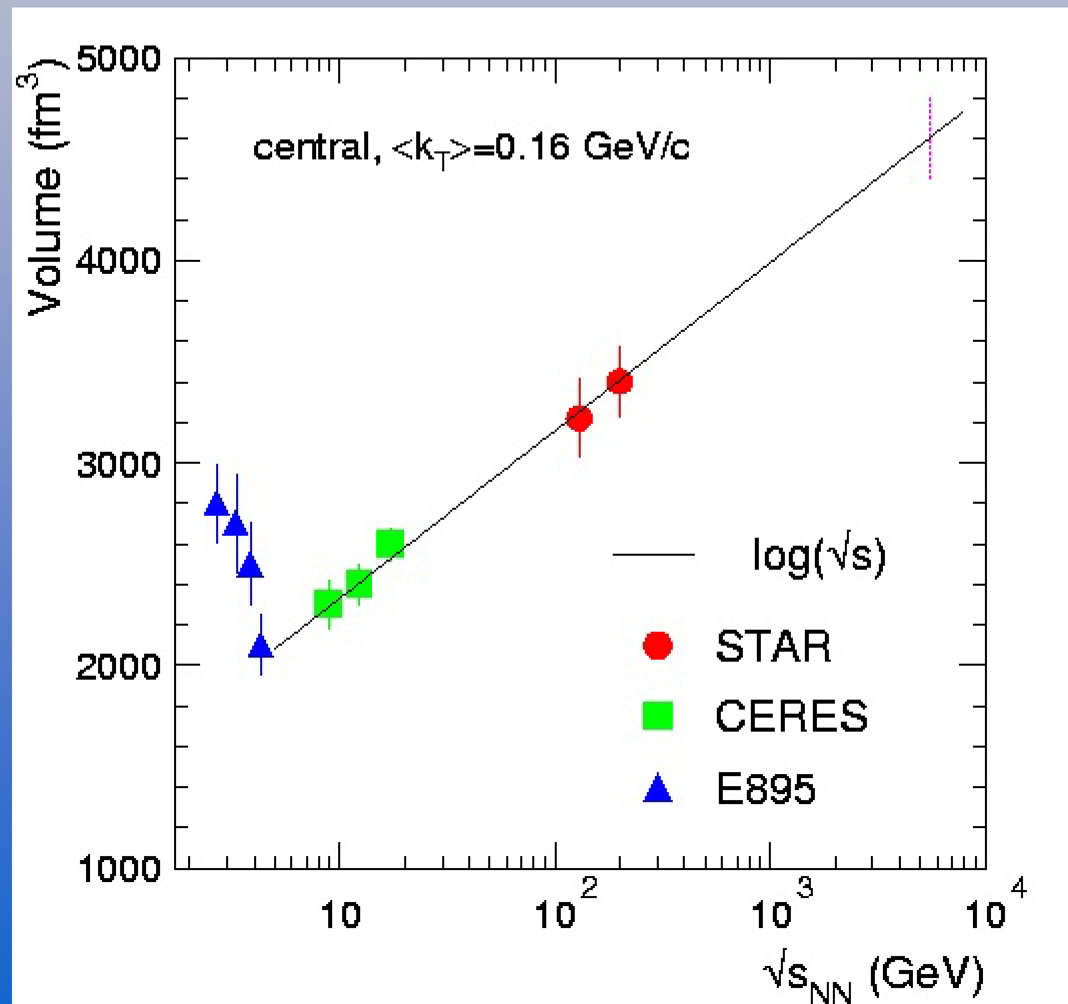
Anisotropic Flow

- Logarithmic energy dependence
- No visible anomalies



Volume from HBT

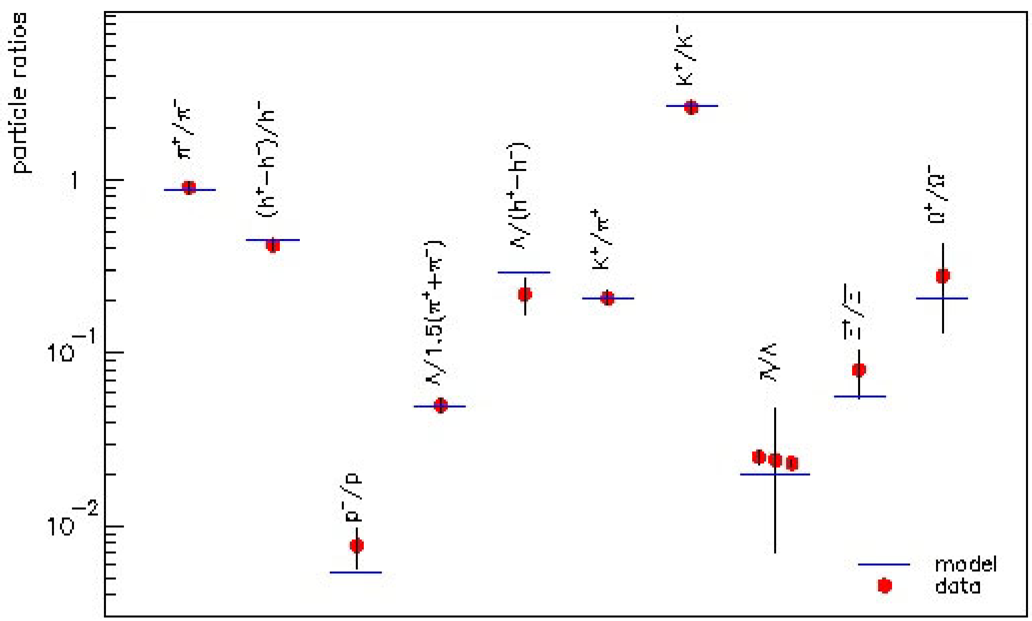
- Ceres PRL 90(2003)022301
- Structure explained as due to transition from baryon dominated to meson dominated regime
- But: implies very short mfp at thermal freeze-out: l_{mfp} = 1fm. Origin not well understood



Hadron Yields at SPS and Thermal Model

P. Braun-Munzinger, D. Magestro, J. Stachel, Dec. 02

central 40 A GeV/c Pb + Pb collisions - thermal model parameters: T = 148 MeV, μ_b = 400 MeV



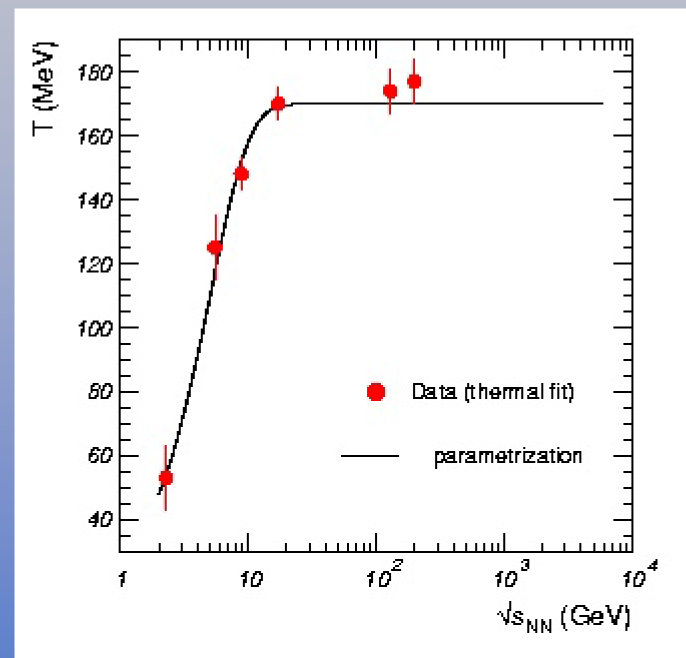
reduced $\chi^2 = 1.1$

Energy Dependence of T_{chem}

Saturation at $T \approx 170$ MeV

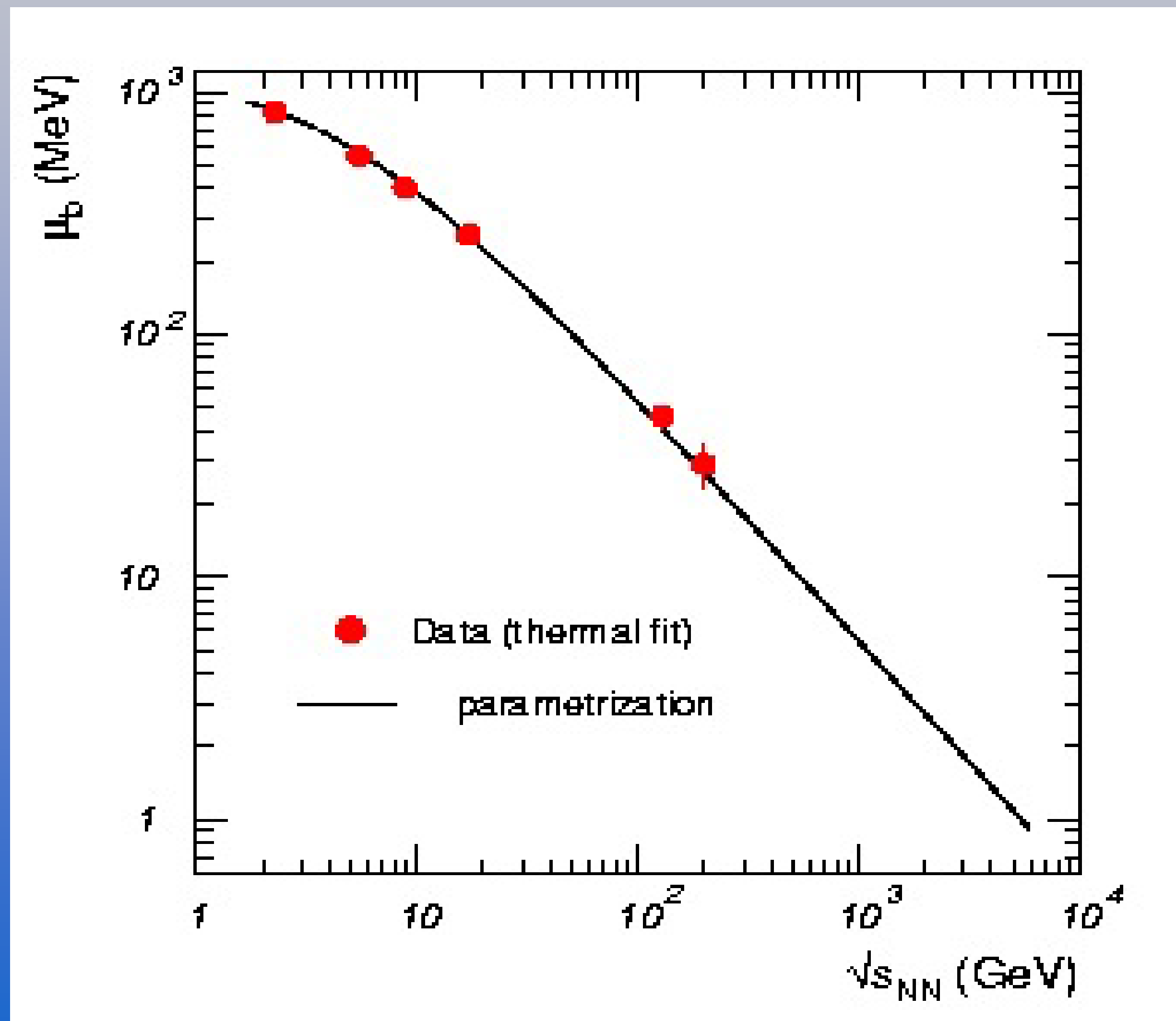
(top SPS energy)

Is the phase boundary reached there?

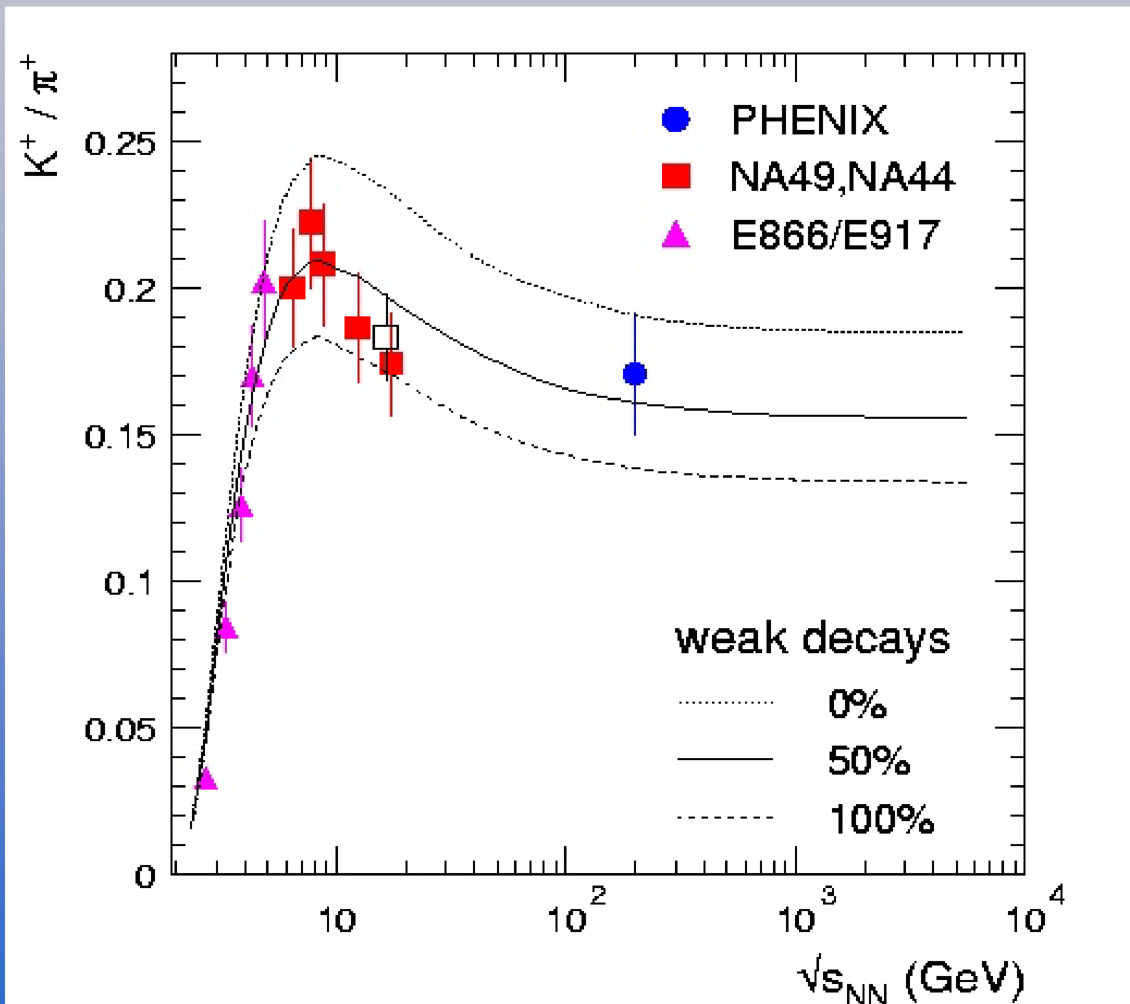


Parameterization of Energy Dependence of $\square_b$

the energy dependence of hadron production within the thermal model is done together with A. Andronic, see also hep-ph/0402291

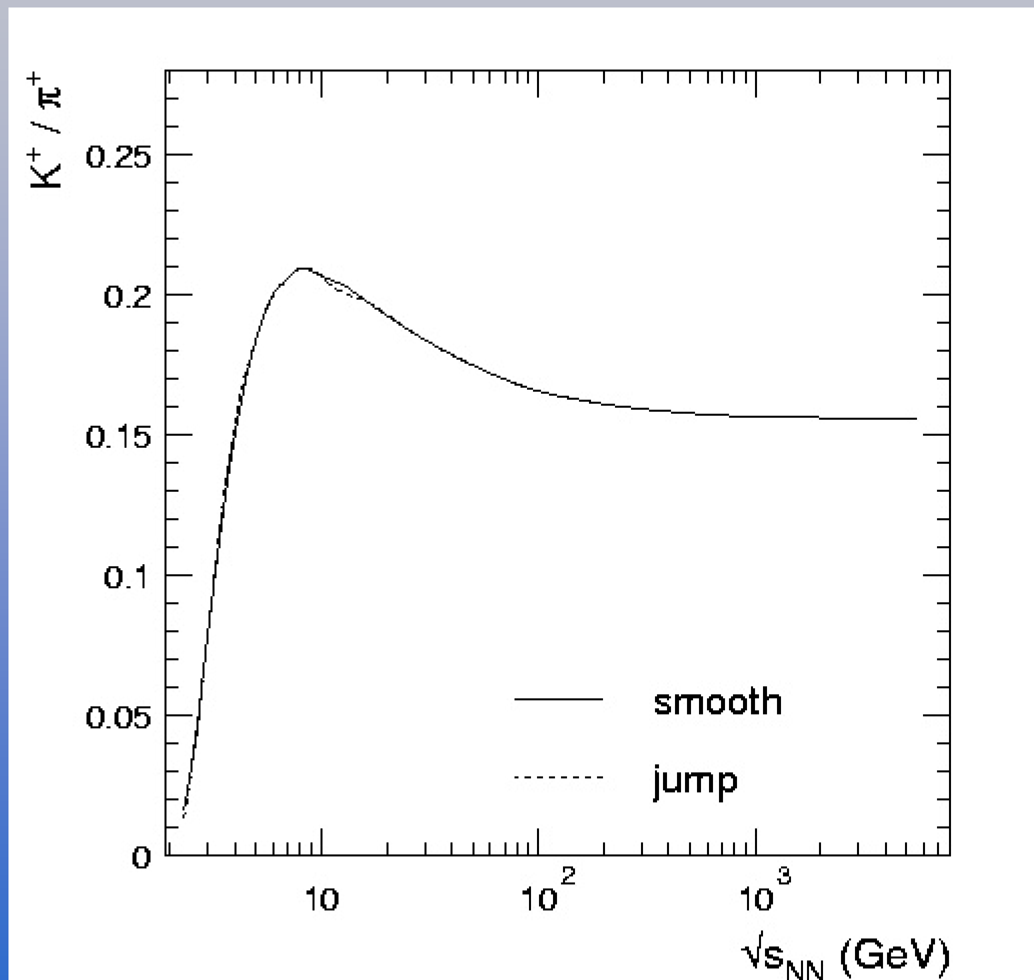


Energy Dependence of Particle Ratios

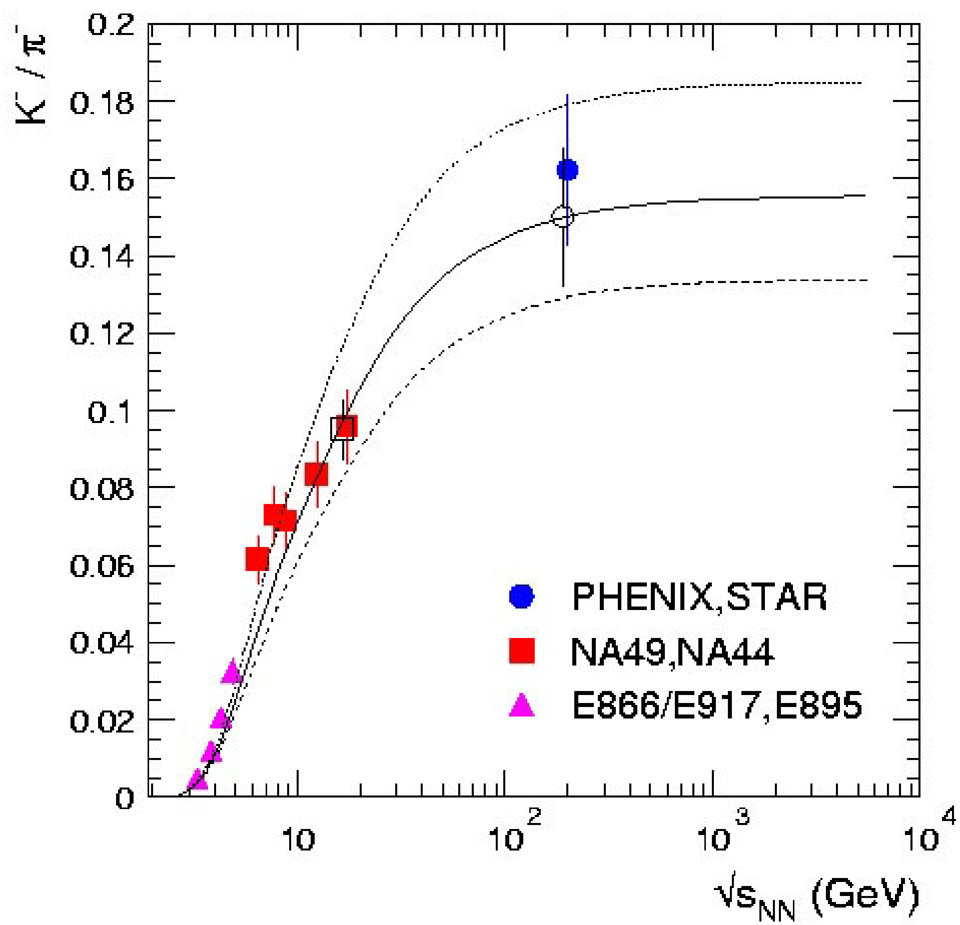


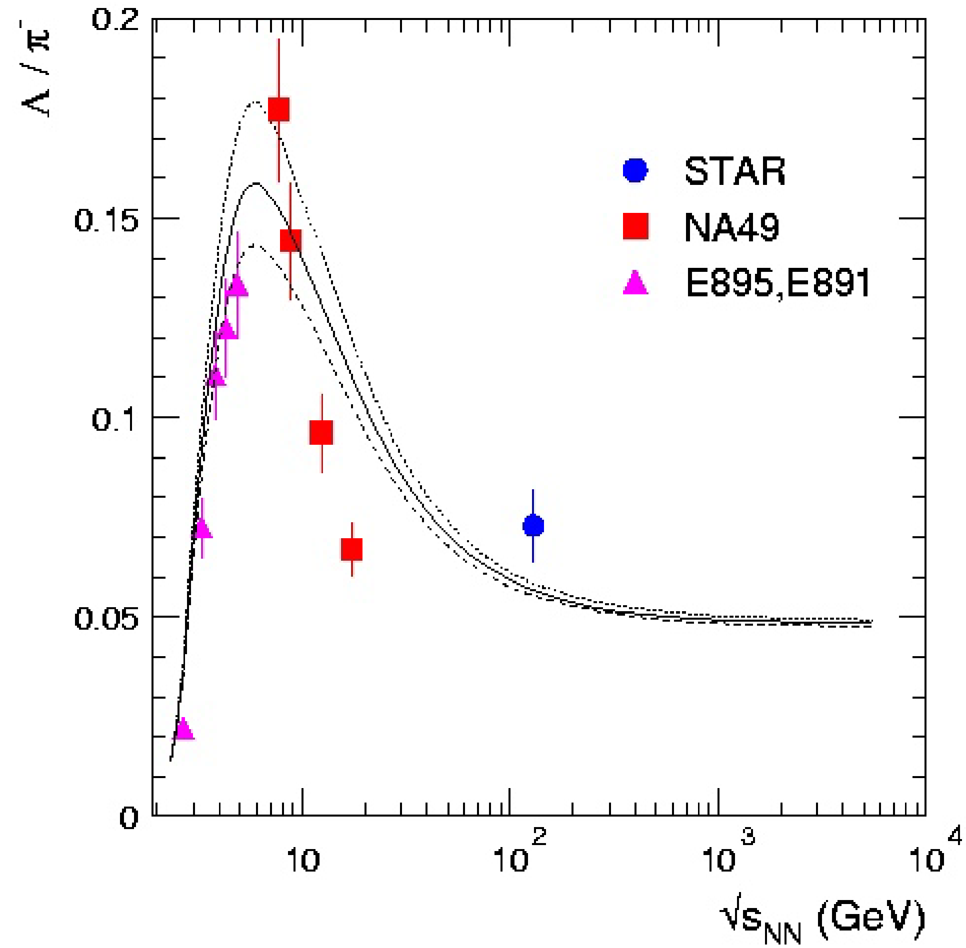
- Thermal model predictions: produce max. at correct energy, but measured shape not reproduced in detail
- Importance of feed-down corrections

Introduction of „Jump“: no change

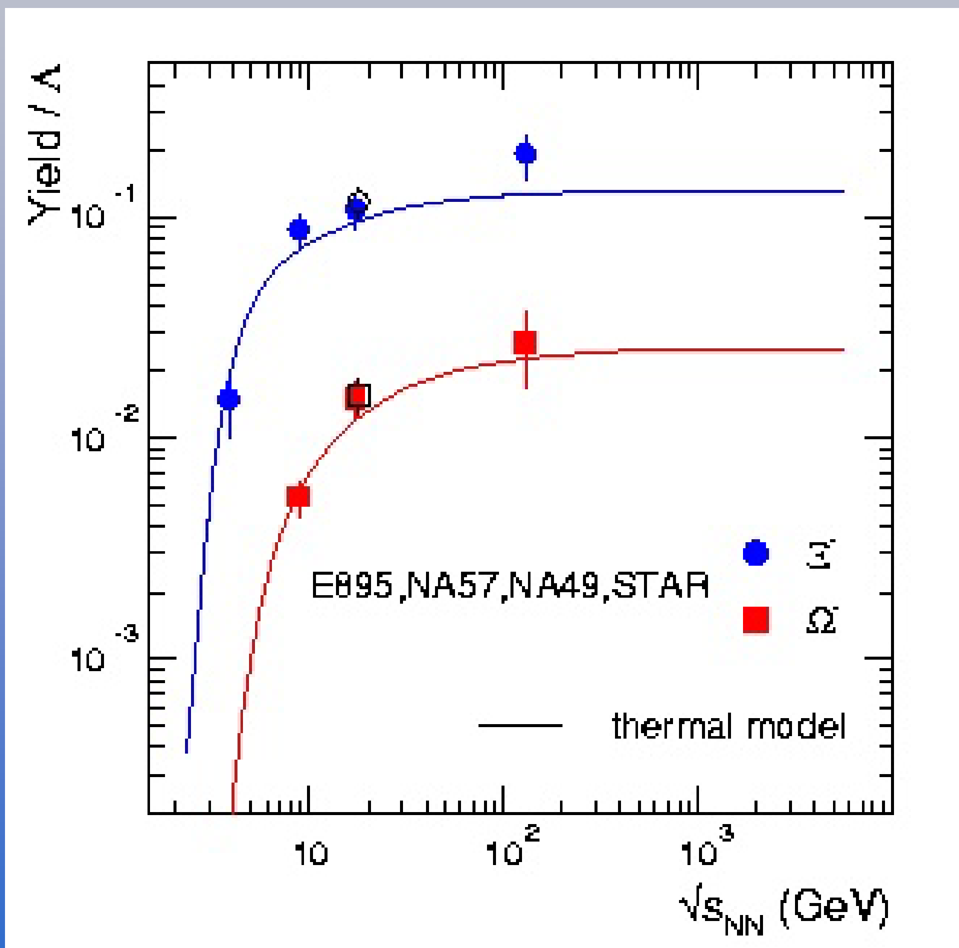


Other Particle Ratios





Multi-Strange Baryons



- Overall structure and magnitude well reproduced.
- Fine-tuning, i.e. simultaneous fit of all particle ratios at each energy, is still needed.

Summary on Strangeness

- NA49 anomaly is certainly not visible in all particle ratios.
- Overall size and magnitude of strangeness maximum is well reproduced.
- At RHIC energies, $T_{chem} = T_c$. Multi-particle reactions near phase transition drive equilibration. Example: KKKpp→WN$_{bar}$
- How far does the chemical freeze-out curve trace the phase boundary?
  - At 40 A GeV, consider KKKN→Wp. Can this drive equilibration near T_c? Note that between $10 < \sqrt{s} < 200$ GeV, the kaon density changes only by 50%. At 40 A GeV, the nucleon density is about 1/3 of the pion density.
  - Canonical suppression important only below 10 A GeV.

Energy Dependence of Dilepton Production

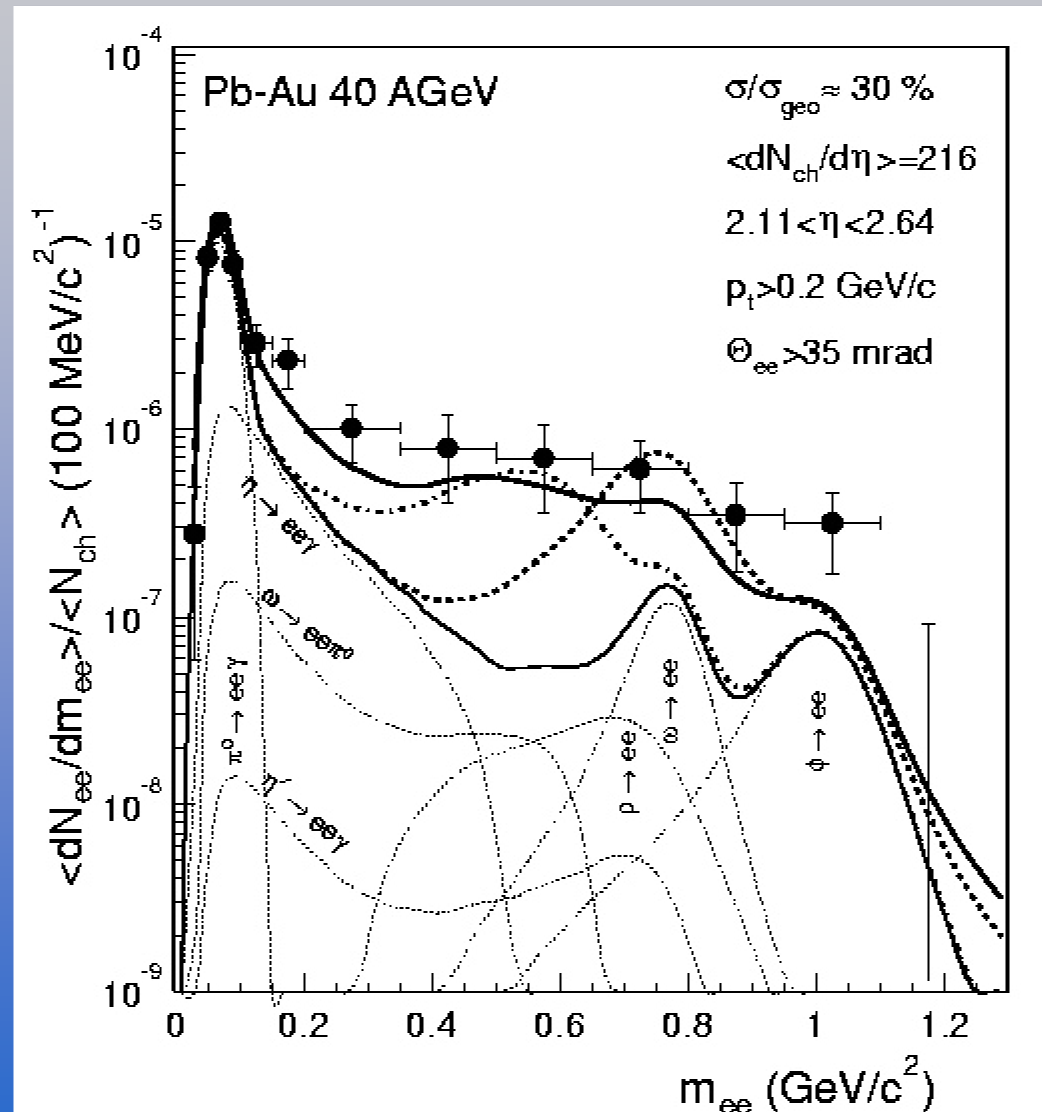
- For heavy systems, only data from CERES
- Preliminary data for In+In from NA60 and for C+C from HADES

CERES Results

Data at 40 A GeV, Pb-Au

PRL 91(2003)042301
first data with partially
equipped TPC, mass resolution
dm/m = 7%

enhancement: 5.9±2.9
(stat. + sys.)



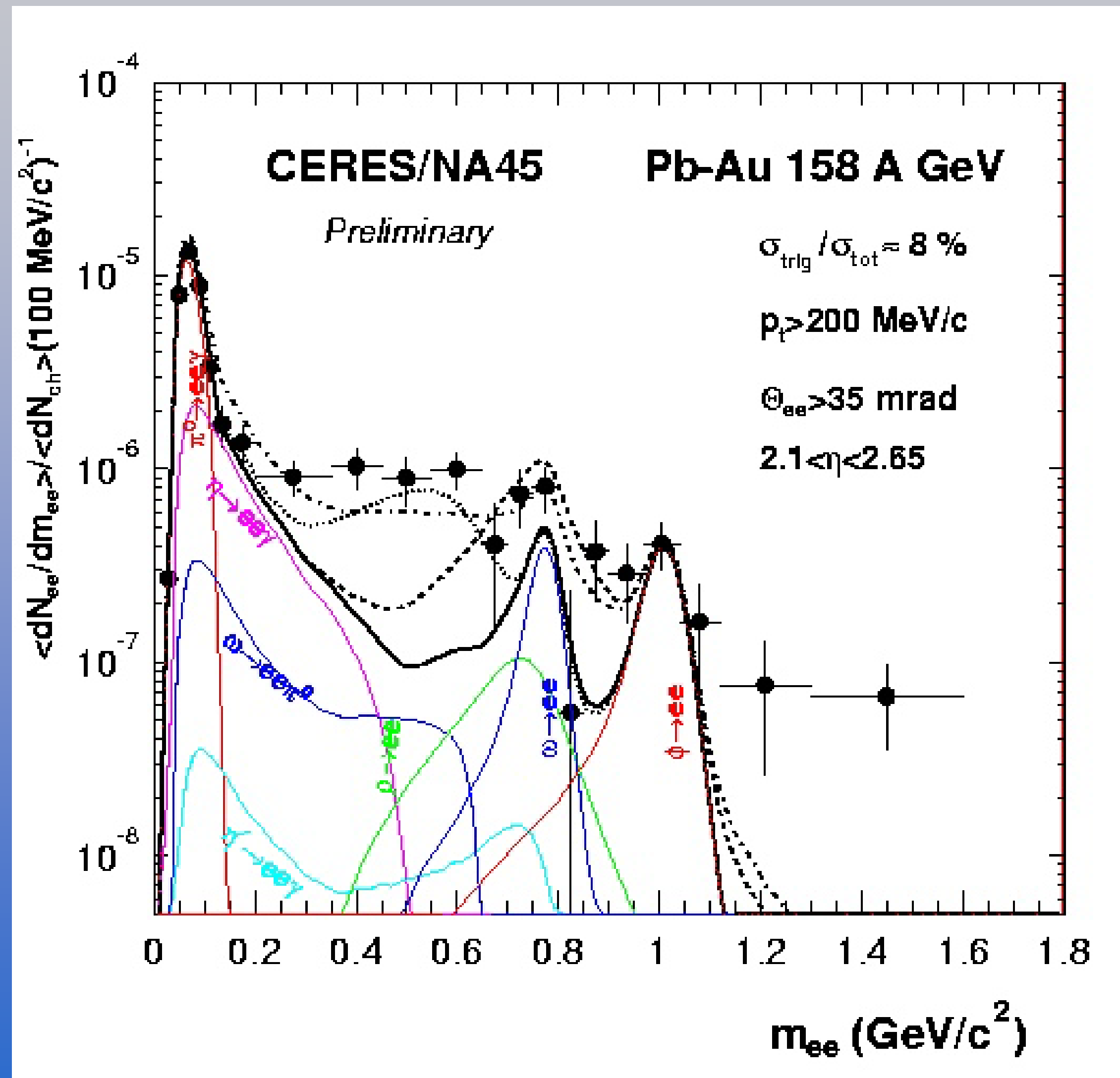
New CERES Results

Data at 160A GeV, Pb-Au QM2004, J.Phys. G(in print)
First data with fully calibrated TPC, mass resolution dm/m = 4%
enhancement: 3.1±0.3 (stat.)

First evidence for w and f.

Can Brown-Rho scaling be distinguished from the Rapp-Wambach scenario?

f meson yield in agreement with NA50 data.



Summary on Dileptons

- Weak energy dependence
- Baryon density at chem. freeze-out: $r_b = 0.12/fm^3$ at all energies
- Is the r modified because of
  - Brown-Rho scaling in the baryon-dense fireball?
  - Hadronic cooking with baryons (Rapp-Wambach)?
  - Interactions in the strongly coupled liquid above T_c (Brown et al., hep-ph-0405114)?
  - Interactions in a long-lived mixed phase?
- Are the di-leptons generated by quark-antiquark annihilation in the plasma?

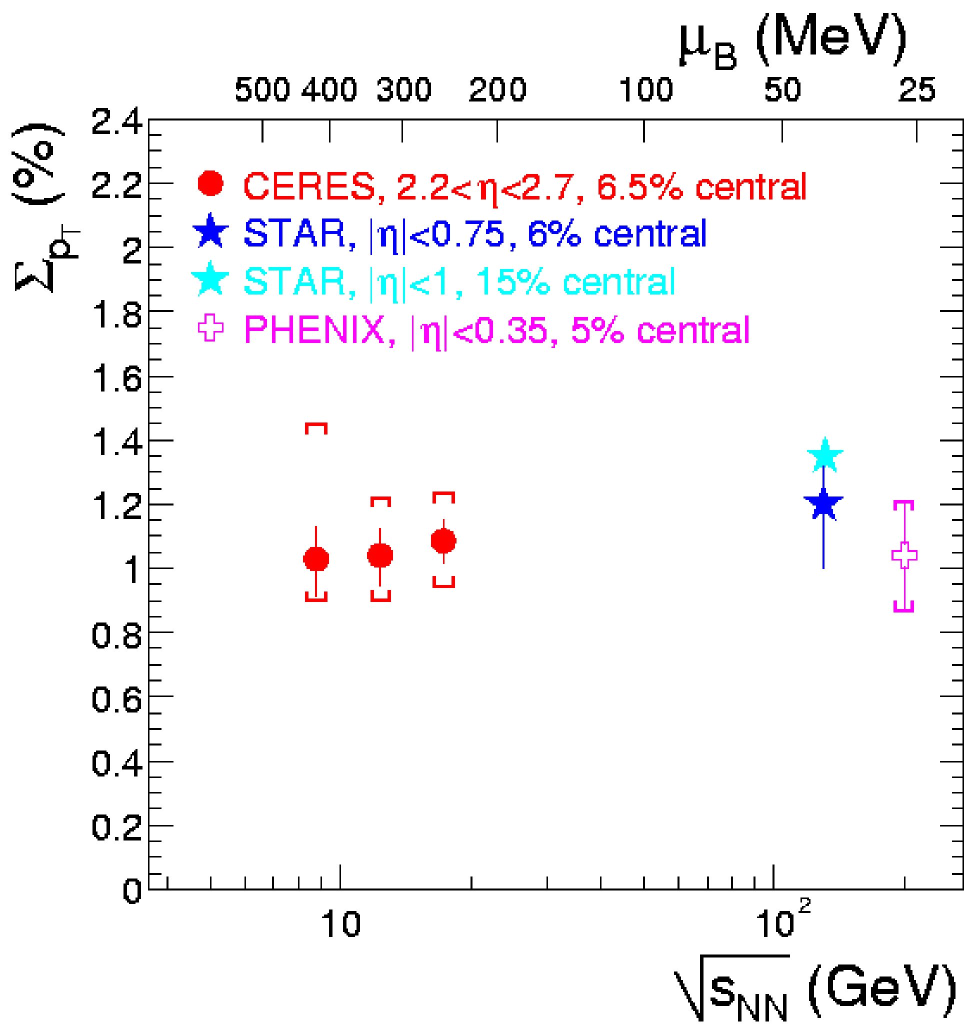
Precision experiments at several energies are needed

Fluctuations

- Is there a critical point, and if so, where?
- Can it be located by observing critical fluctuations?

The critical point of QCD

...should show up as a peak in the excitation function (Stephanov, Raja



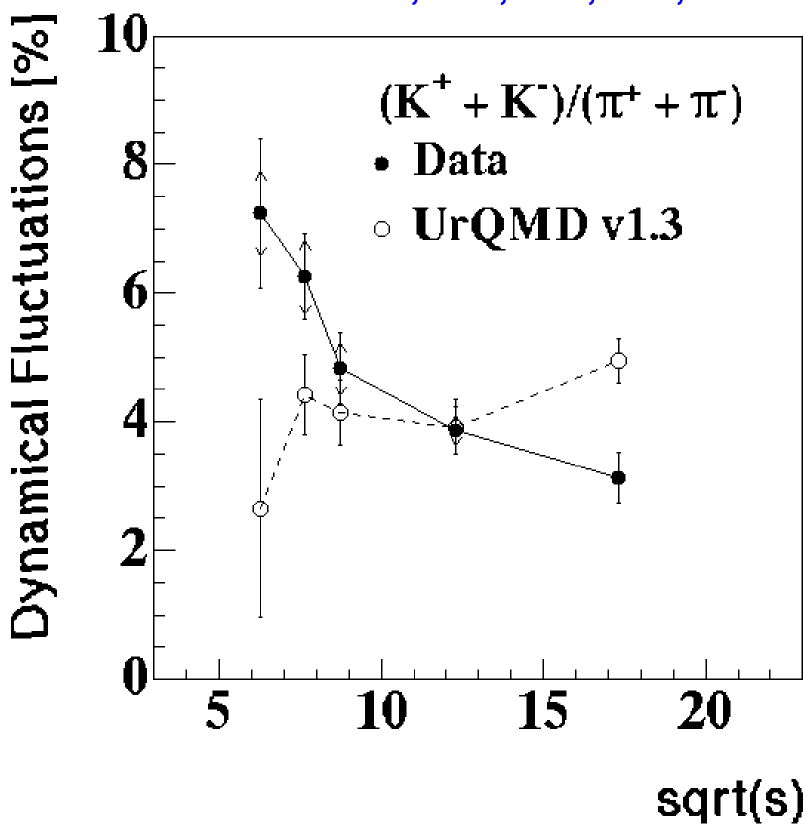
H. Sako (CERES, nucl-ex/0403037), also: Nucl.Phys. A727(2003)97

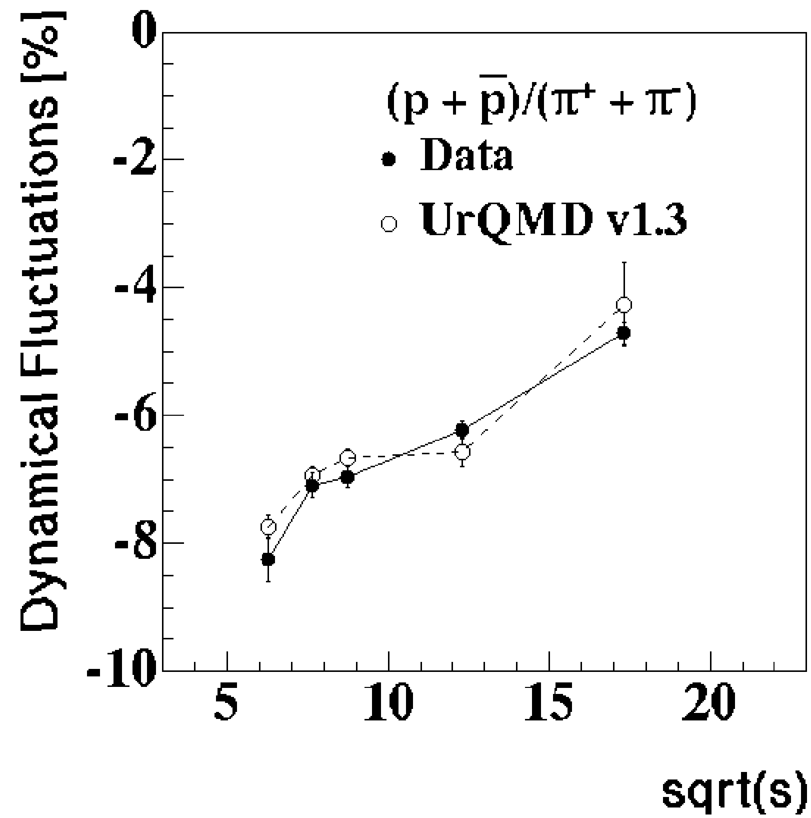
- No indication for the critical point so far
- Scan between SPS and RHIC
- 20 and 30 GeV/c from NA49
- GSI SIS 300

Particle ratio fluctuations

Christof Roland (NA49)

Pb-Pb 20, 30, 40, 80, 158 AGeV/c





K/π fluctuations increase towards lower beam energy
(another 'horn', but with max. at a different energy?)

p/π fluctuations explained by resonance decays

Summary on fluctuations

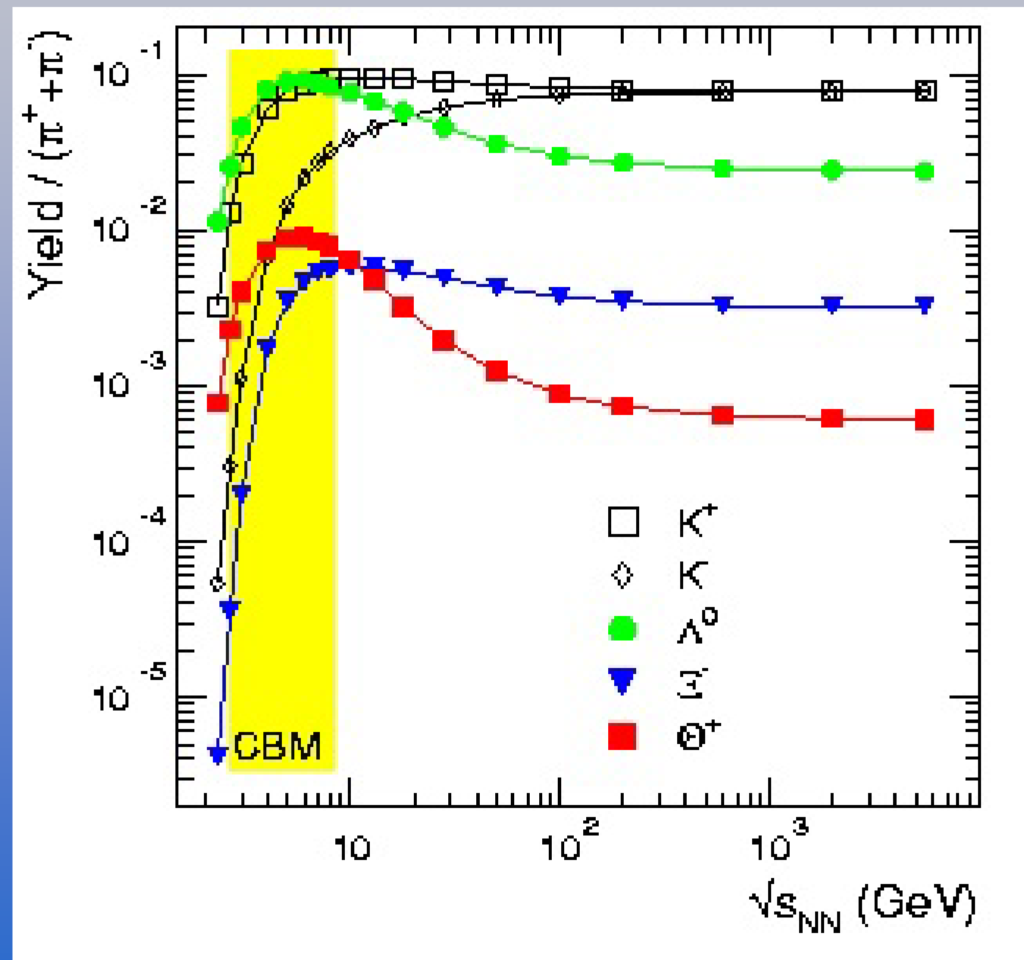
- Anomalous (non-statistical) fluctuations are observed, but:
  - No indication for a critical point so-far.
- Is the strong coupling near T_c resonsible for damping of all fluctuations?

Exotica

- Deeply bound kaonic states
- The penta-quark family
- Multi-quark-antiquark clusters
- .....

Penta-Quark Yields

At SIS300 energies, penta-quark yields exceed those for X-baryons!



High Density nuclear systems with Isovector deformation

Dote, Horiuchi, Akaishi, Yamazaki, Prog. Theo. Phys. Suppl. 149(2003)221

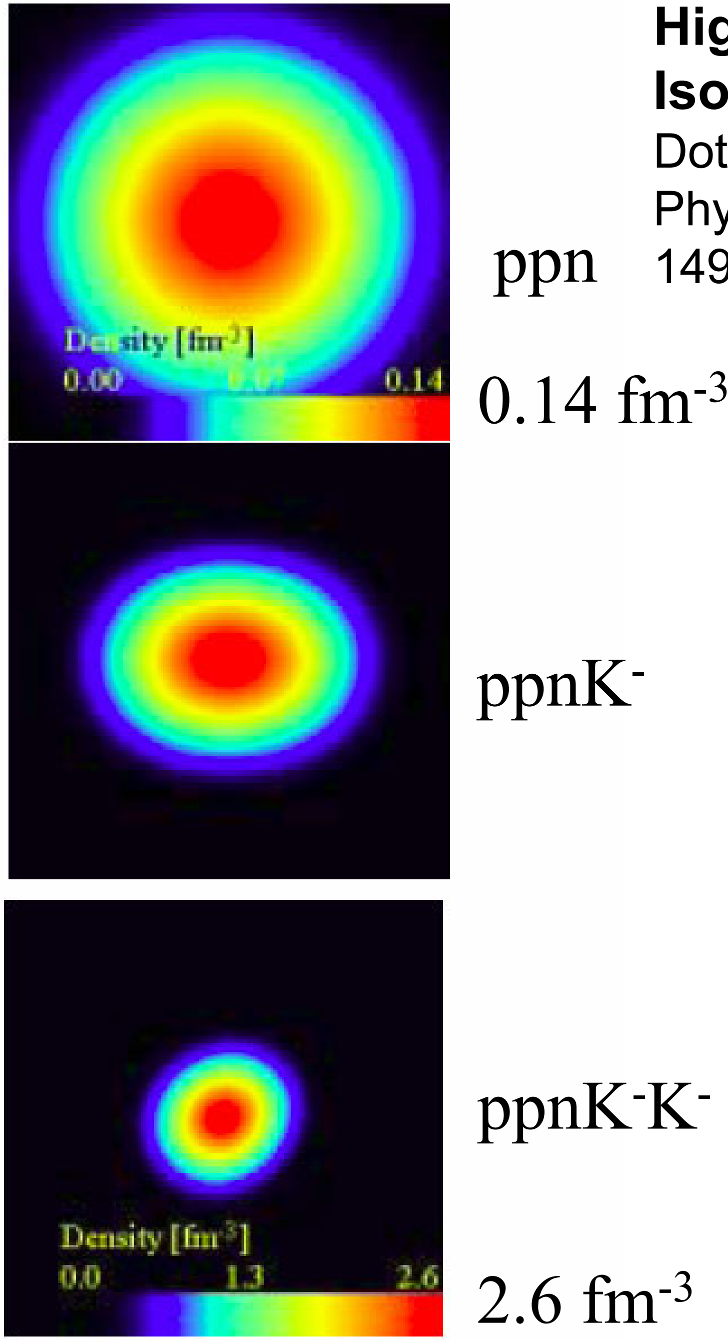


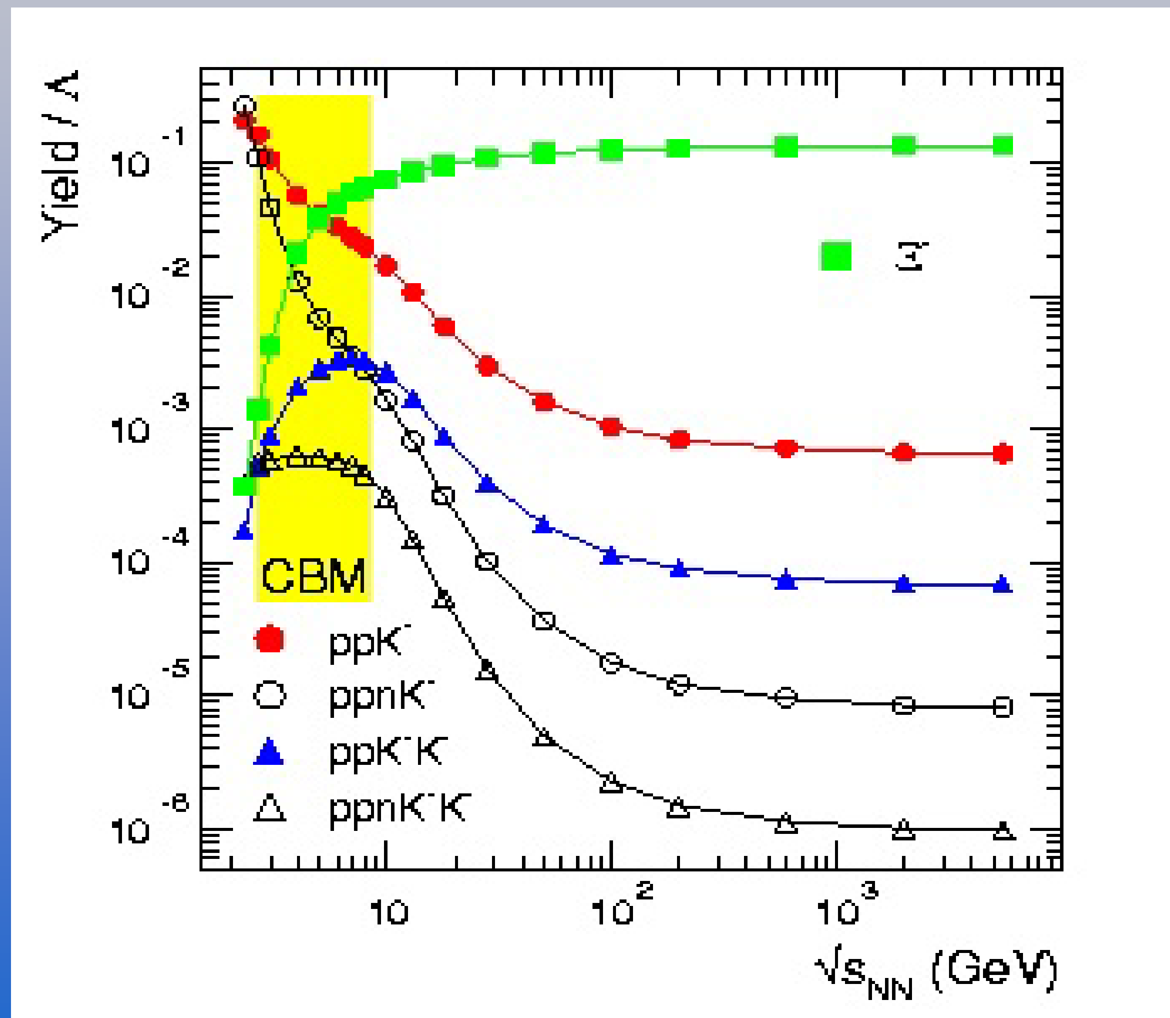
FIG. 2: Calculated density contours of ppn, ppnK$^-$ ar ppnK$^-$K$^-$.

How to study K$^-$ clusters

$$
\begin{array}{ll}
i) & ppK^- \to \Lambda + p, \\
ii) & ppnK^- \to \Lambda + d, \\
iii) & pppK^- \to \Lambda + p + p, \\
iv) & ppnnK^- \to \Lambda + t, \\
v) & pppnK^- \to \Lambda + {}^3\mathrm{He}, \\
vi) & ppK^-K^- \to \Lambda + \Lambda, \\
vii) & pppK^-K^- \to \Lambda + \Lambda + p, \\
viii) & pppnK^-K^- \to \Lambda + \Lambda + d.
\end{array}
$$

Excitation Function for such Clusters

Calculations with thermal model give measurable yields at SIS300



Multi-quark-antiquark clusters

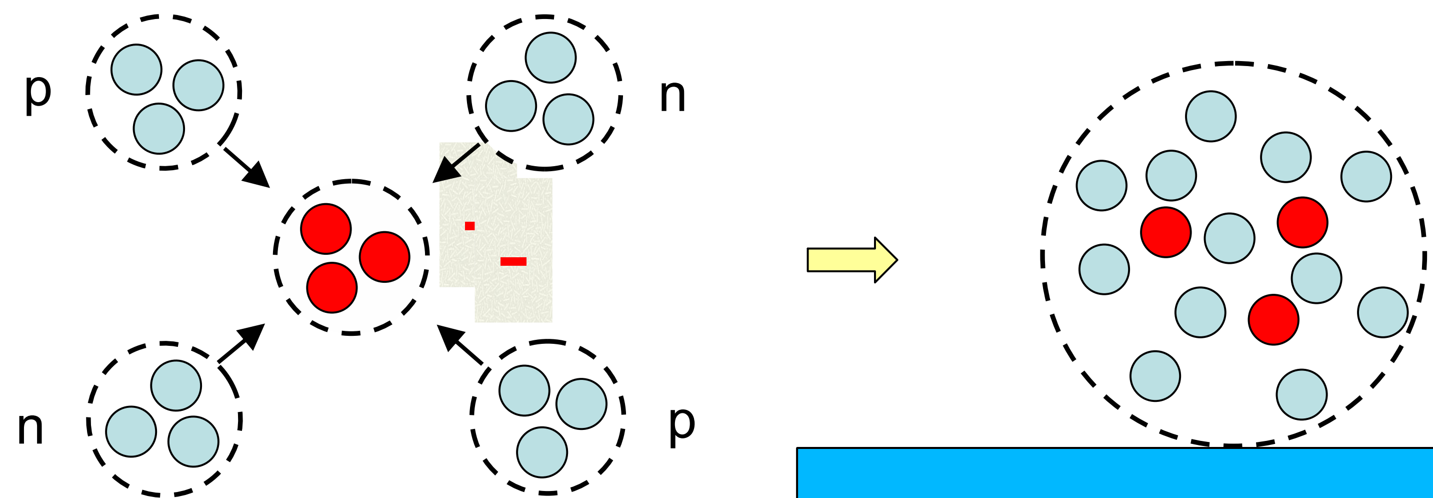
I.N.Mishustin et al. Nucl-th/0404026

An antibaryon (n_bar, anti-lambda) acts as a strong attractor for surrounding Nucleons may force them to move towards the center of a nucleus

High density cloud containing n_bar and few nucleons is in fact a relatively cold peace of quark-gluon plasma

E.g. the whole ^{4}He nucleus could be transformed into deconfined phase by a deeply bound p_bar

$\bar{p} + {}^4He$



$12q\,3\bar{q}$

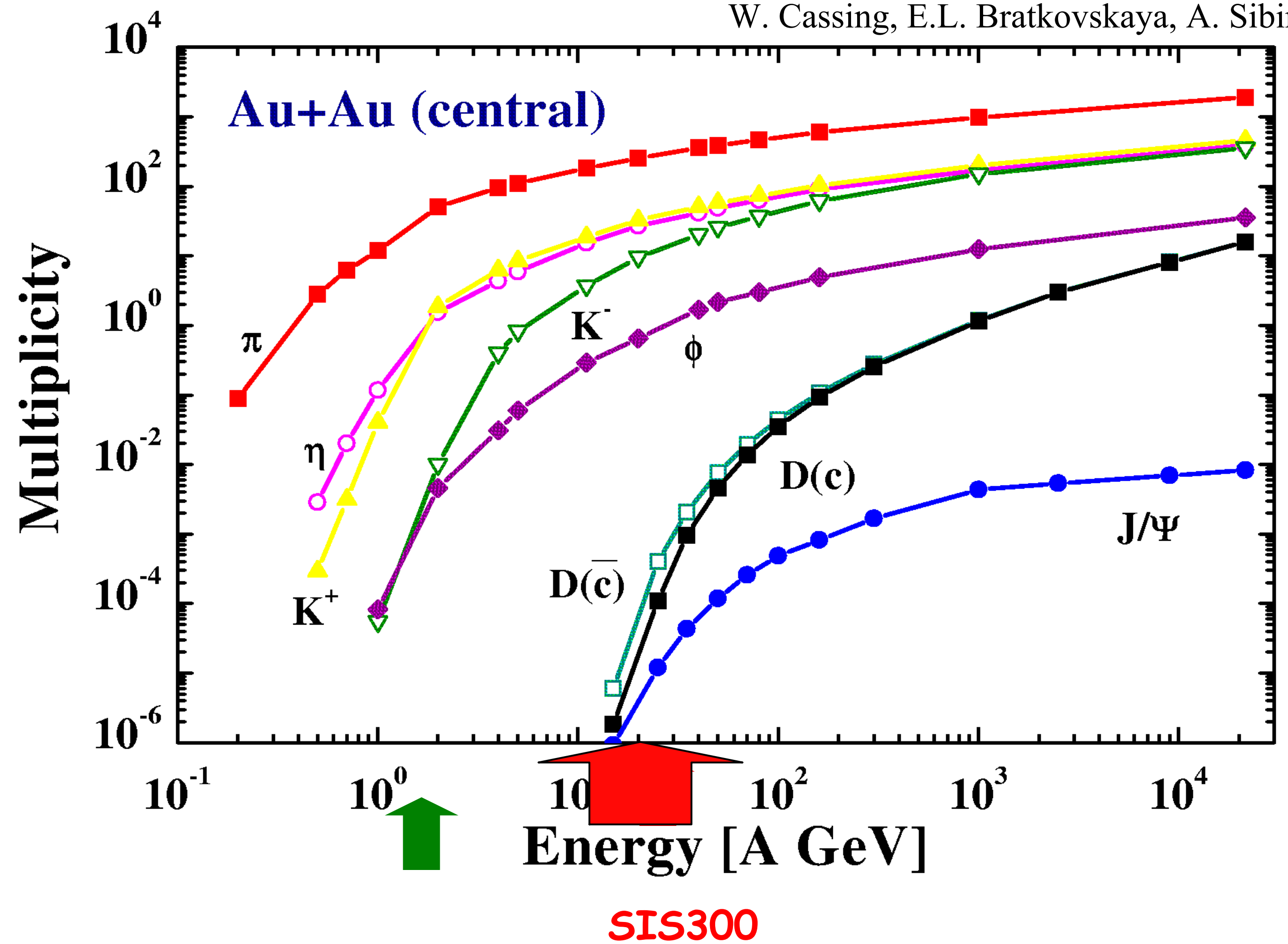
No exp. Indications so-far for such states

Open and Hidden Charm Mesons

- J/y: plasma suppression or interaction with dense baryonic medium?
- D-mesons: is near threshold production a tool to measure medium modifications?

Meson production in central Au+Au collisions

W. Cassing, E.L. Bratkovskaya, A. Sibirtsev



Theory

Charm production near threshold may probe the D-meson mass change in the baryon-rich fireball

Effects of baryon density

D-Meson mass splitting

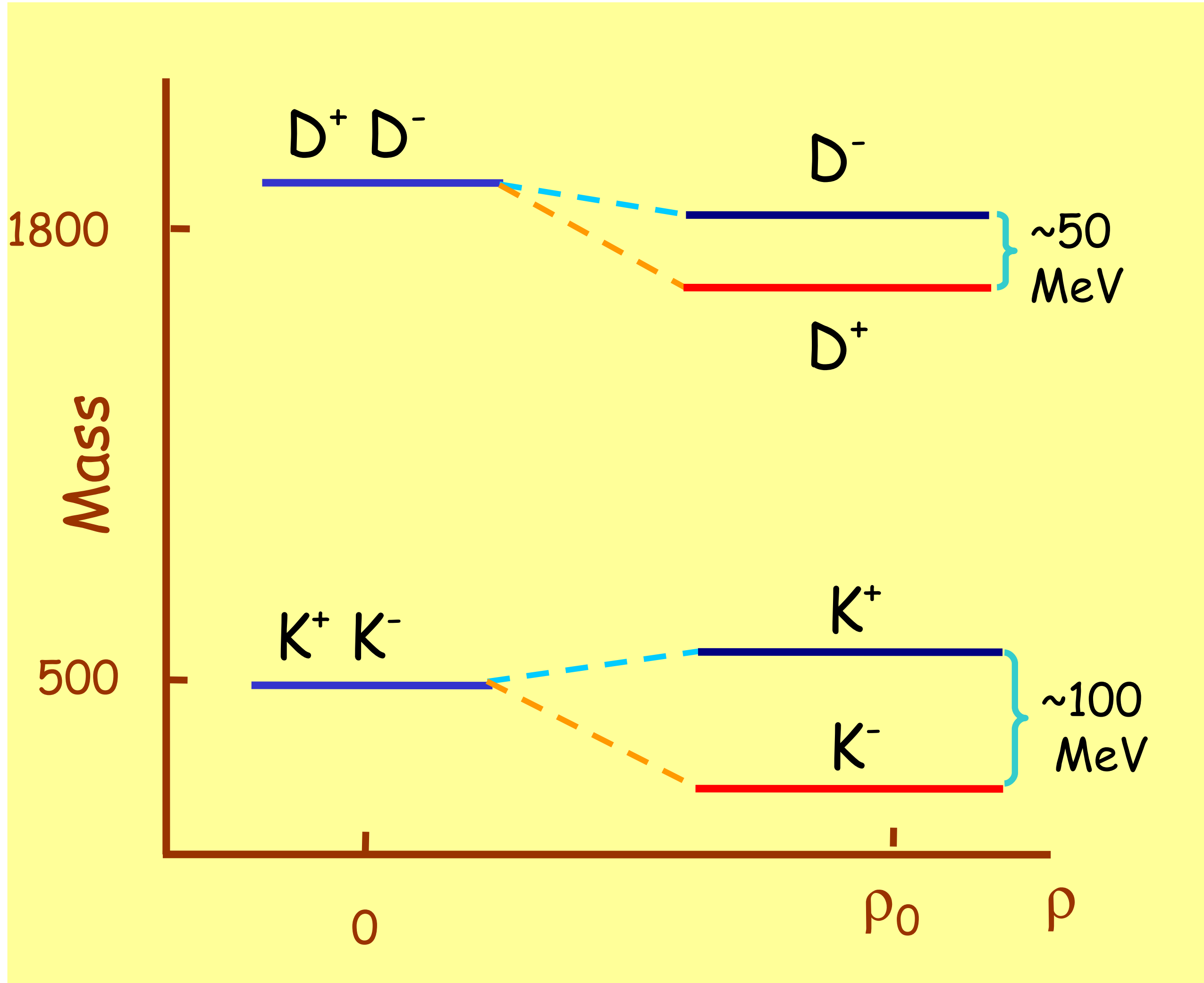
at $n_B \neq 0$

$|D^-\rangle = |d\bar{c}\rangle$

$|D^+\rangle = |c\bar{d}\rangle$

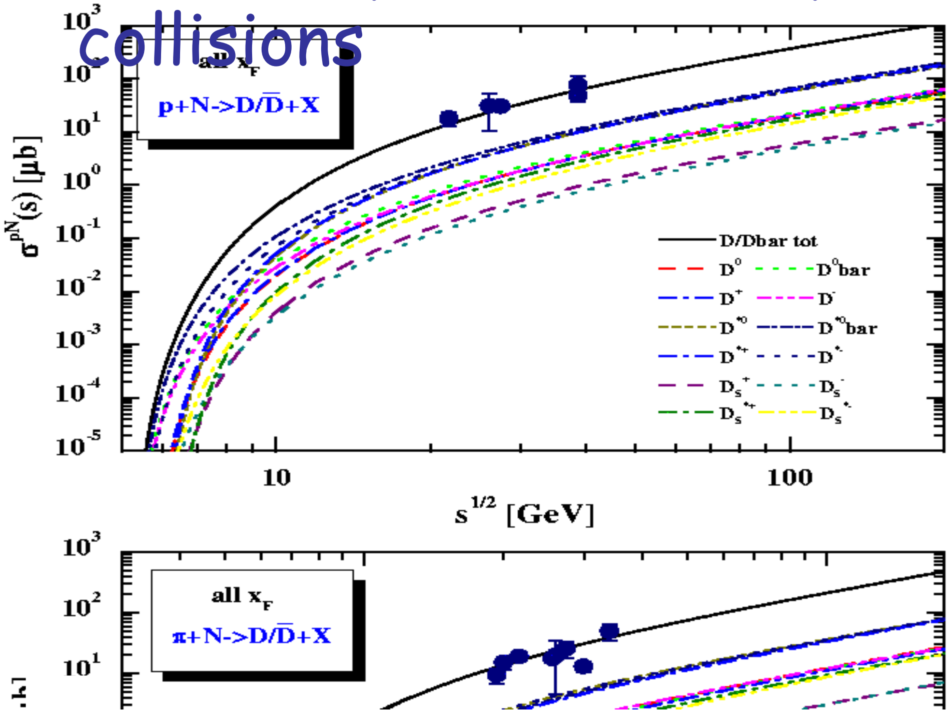
Explore D-meson properties in dense matter at energies around charm threshold

$E \approx 10\text{-}30\,AGeV$



Charmed mesons

D meson production in pN collisions



Some hadronic decay modes

$D^{\pm}$ ($c\tau$ = 317 μm):

$D^+ \rightarrow K^0\pi^+$ (2.9±0.26%)

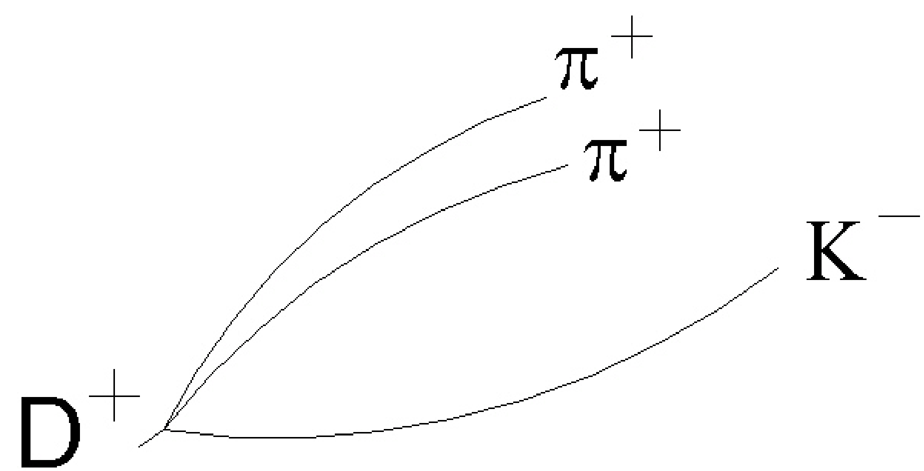
$D^+ \rightarrow K^-\pi^+\pi^+$ (9 ± 0.6%)

D^0 ($c\tau$ = 124.4 μm):

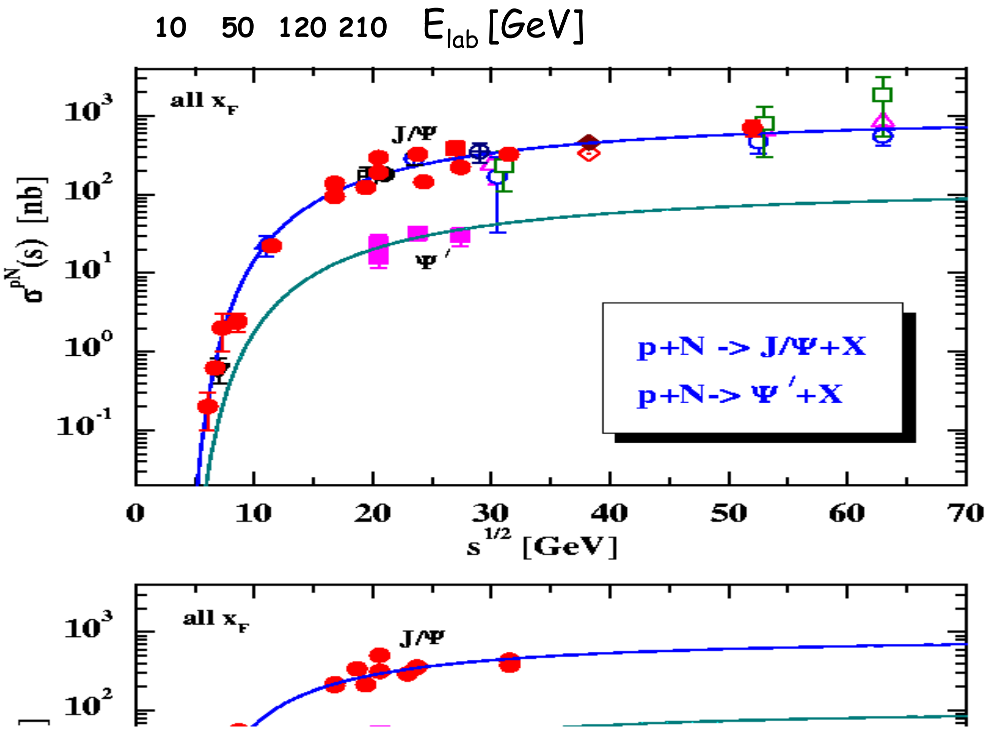
$D^0 \rightarrow K^-\pi^+$ (3.9 ± 0.09%)

$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ (7.6 ± 0.4%)

Measure displaced vertex
with resolution of ≈ 30 μmm !



J/ψ experiments: a count rate estimate

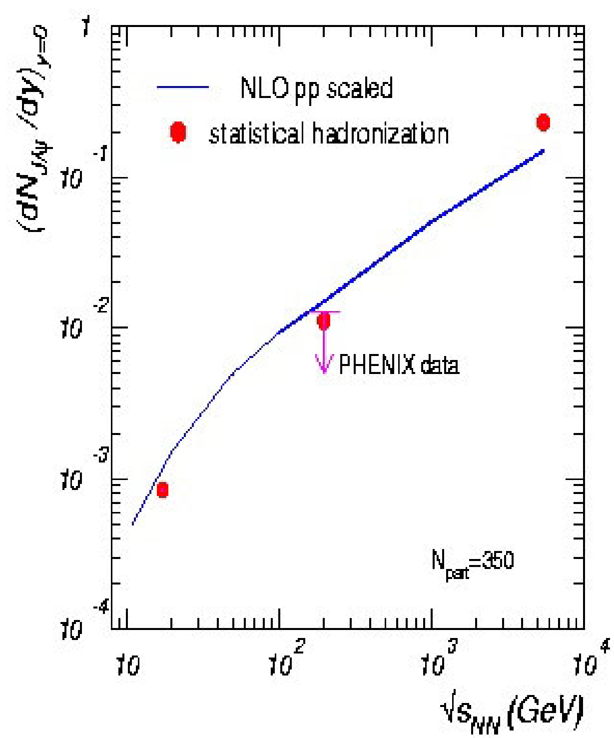


Count rate estimate for J/y production at 30 A GeV: some 10000/week in CBM (see talk by V. Friese)

Physics question: anomalous (QGP) suppression vs hadronization at the phase boundary.

Energy Dependence of J/y Production

J/ψ Excitation Function



Pb–Pb (Au–Au) central collisions

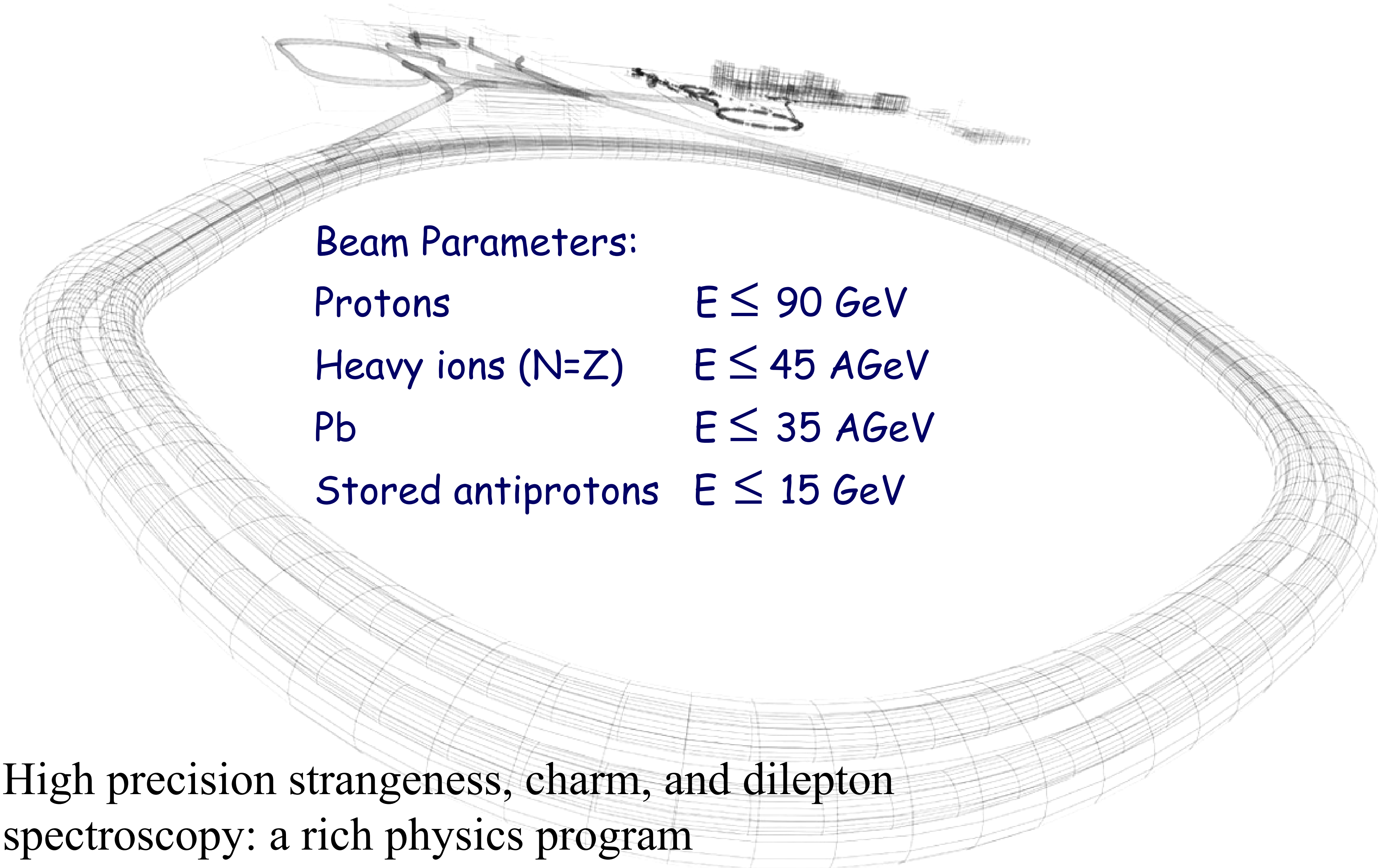
⟶ Transition from Suppression to Enhancement

⟶ more precise data needed !

RHIC Energy in Balance Region

LHC Energy: Enhancement as Fingerprint of Deconfinement

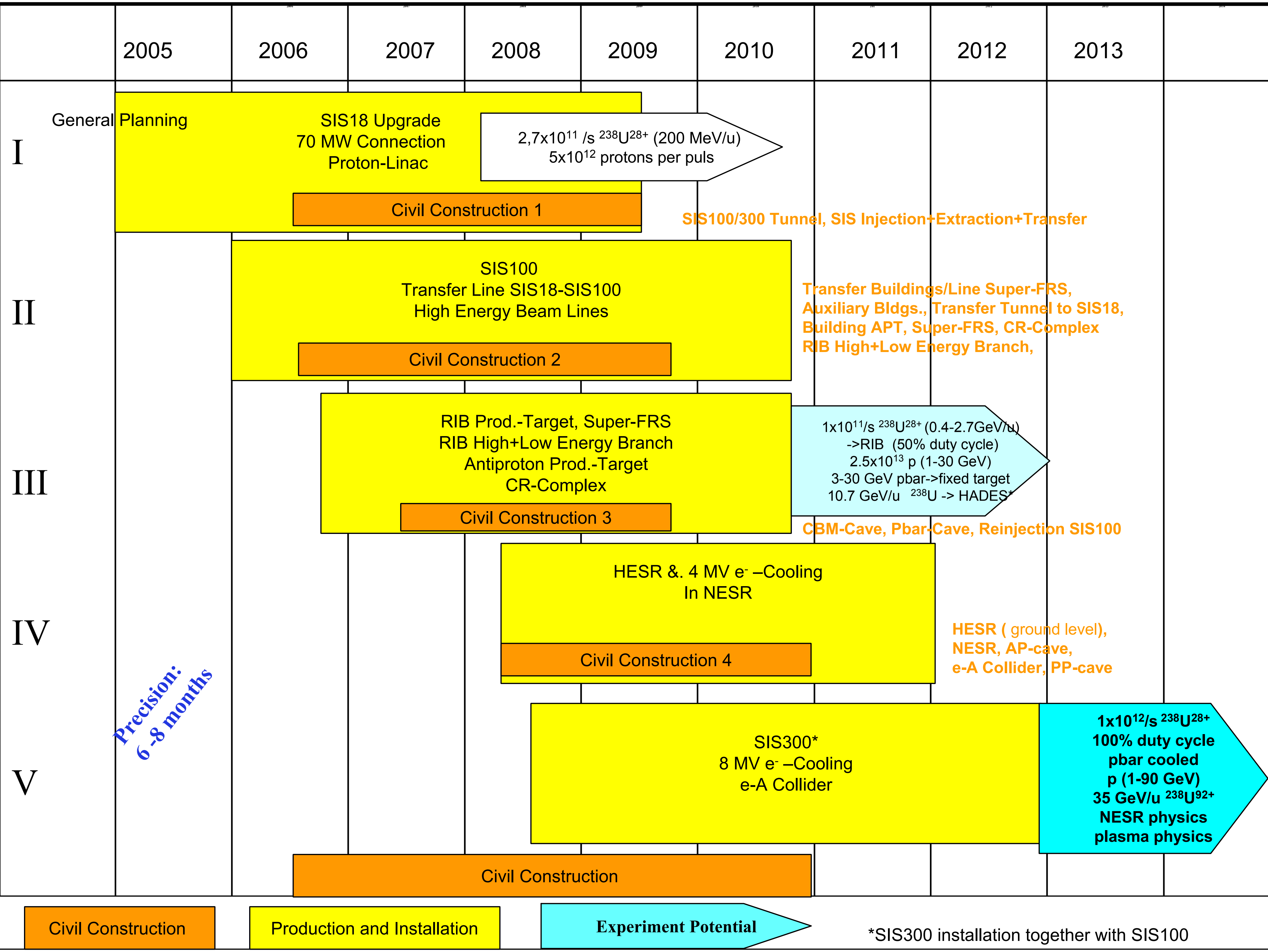
Exploration of the QCD Phase Structure in the Baryon-Rich Region



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 dilepton spectroscopy: a rich physics program



2005
2006
2007
2008
2009
2010
2011
2012
2013
I
General Planning
SIS18 Upgrade
70 MW Connection
Proton-Linac
2,7x10^11 /s 238U28+ (200 MeV/u)
5x10^12 protons per puls
Civil Construction 1
SIS100/300 Tunnel, SIS Injection+Extraction+Transfer
II
SIS100
Transfer Line SIS18-SIS100
High Energy Beam Lines
Civil Construction 2
Transfer Buildings/Line Super-FRS,
Auxiliary Bldgs., Transfer Tunnel to SIS18,
Building APT, Super-FRS, CR-Complex
RIB High+Low Energy Branch,
III
RIB Prod.-Target, Super-FRS
RIB High+Low Energy Branch
Antiproton Prod.-Target
CR-Complex
Civil Construction 3
1x10^11/s 238U28+ (0.4-2.7GeV/u)
->RIB (50% duty cycle)
2.5x10^13 p (1-30 GeV)
3-30 GeV pbar->fixed target
10.7 GeV/u 238U -> HADES*
CBM-Cave, Pbar-Cave, Reinjection SIS100
IV
HESR &. 4 MV e- –Cooling
In NESR
Civil Construction 4
HESR (ground level),
NESR, AP-cave,
e-A Collider, PP-cave
V
Precision:
6 -8 months
SIS300*
8 MV e- –Cooling
e-A Collider
1x10^12/s 238U28+
100% duty cycle
pbar cooled
p (1-90 GeV)
35 GeV/u 238U92+
NESR physics
plasma physics
Civil Construction
Civil Construction
Production and Installation
Experiment Potential
*SIS300 installation together with SIS100