Search for the Critical Point and the Onset of Deconfinement

An Overview on the Experimental Status

7th International Workshop on
Critical Point and
Onset of Deconfinement
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GOETHE UNIVERSITÄT FRANKFURT AM MAIN
EMMI
HIC for FAIR
Helmholtz International Center

The QCD Phase Diagram

Topic of CPOD

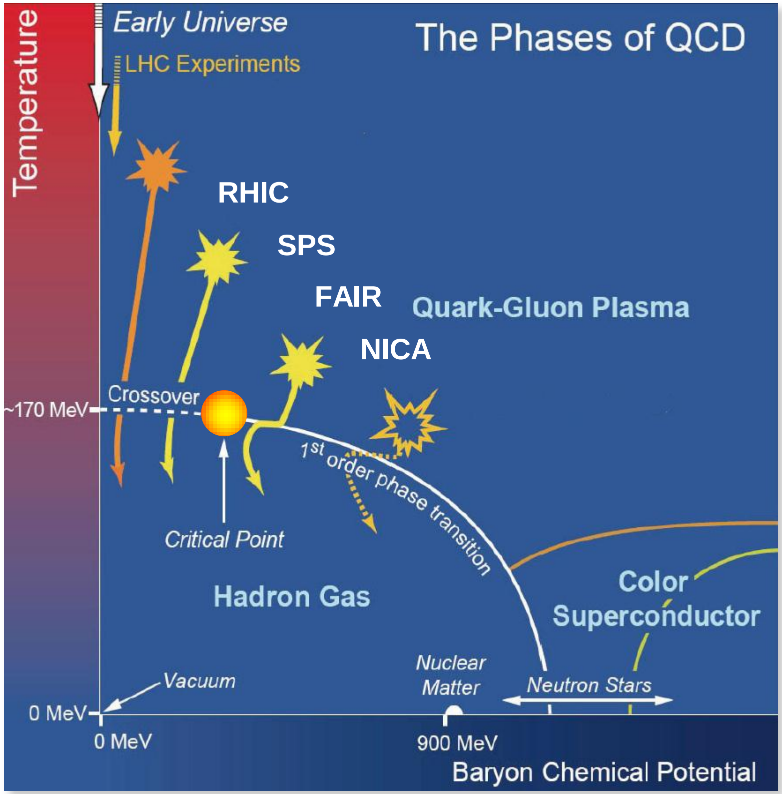
Part of phase diagram with $\mu_B > 0$
$\mu_B = 0$: LHC physics

Questions to experiments

1) Is it possible to locate the onset of deconfinement ?
2) Is there any evidence for a 1^{st} order phase transition ?
3) Can one find any indication for a possible critical point ?

Broad experimental program

Past: **SPS (and AGS)**
Present: **RHIC** and SPS
Future: FAIR and NICA



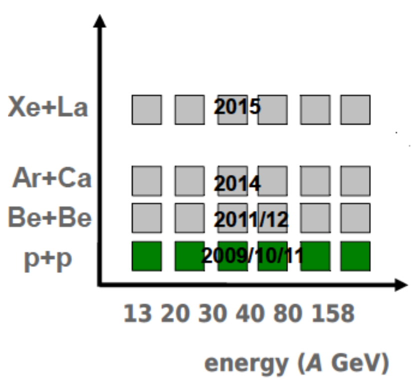
The QCD Phase Diagram
Experimental Access

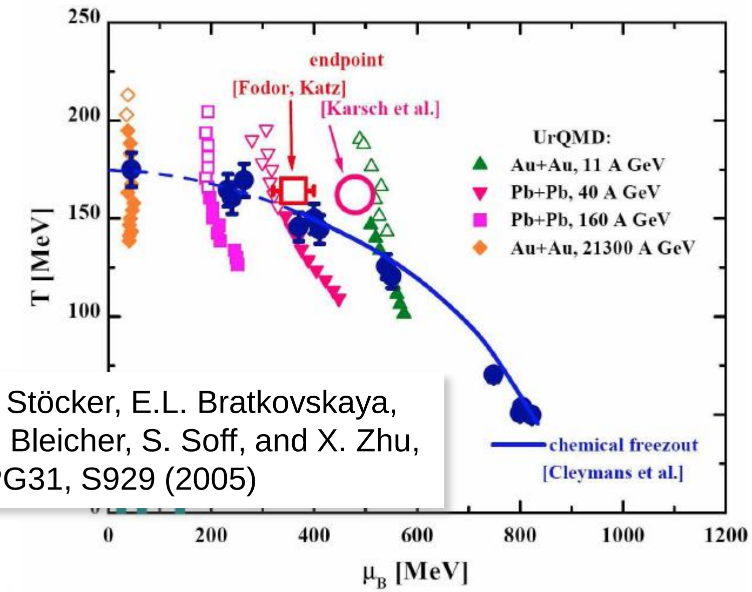
Control parameter: $\sqrt{s_{NN}}$
Allows to scan different regions of phase diagram

System freezes out at different positions along freeze-out curve

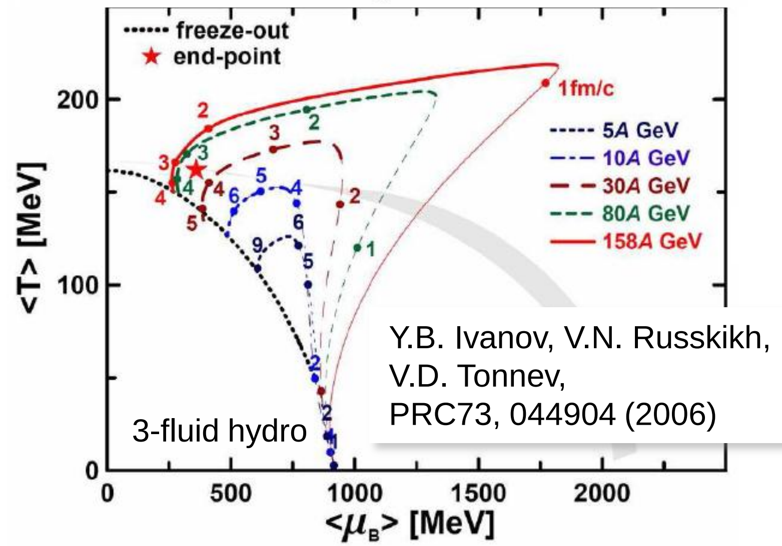
Trajectory might cross critical area

Variation of system size
Program of NA61@SPS



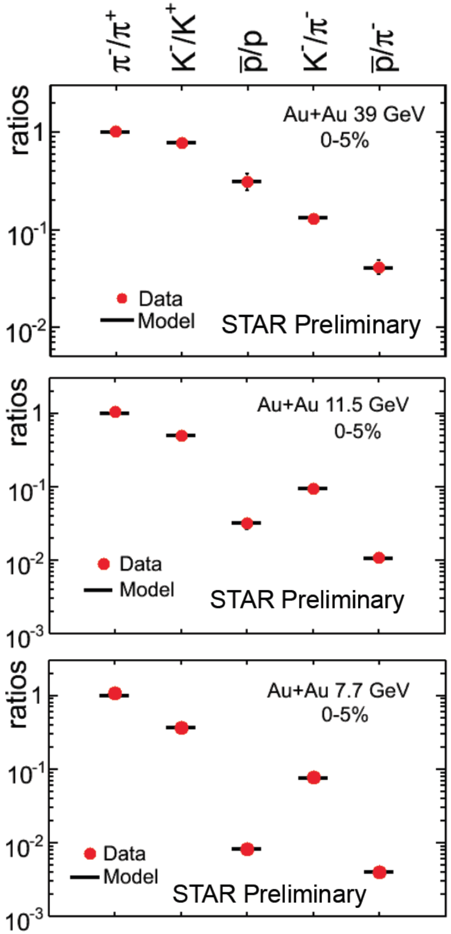


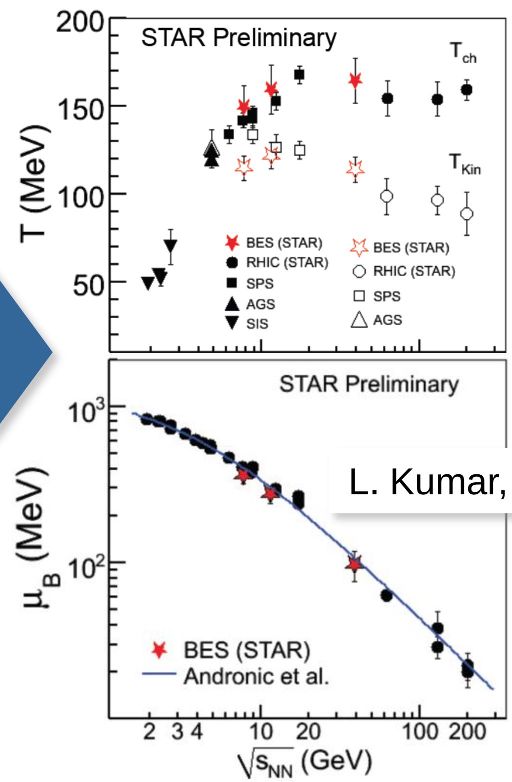
H. Stöcker, E.L. Bratkovskaya, M. Bleicher, S. Soff, and X. Zhu, JPG31, S929 (2005)



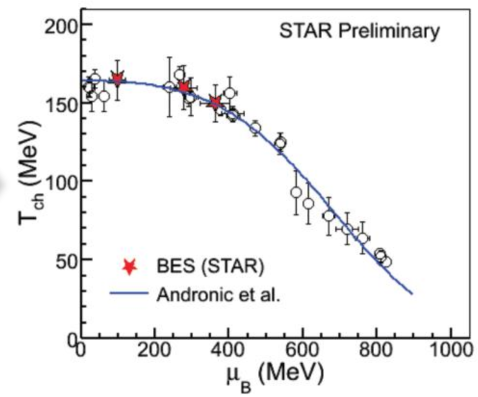
Y.B. Ivanov, V.N. Russkikh, V.D. Tonnev, PRC73, 044904 (2006)

The QCD Phase Diagram
Chemical Freeze-Out





L. Kumar, QM11



Statistical model fits

Freeze-out parameters:

V, T, μ_B, (γ_S)

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3p \left[e^{\sqrt{p^2+m_j^2}/T + \mu \cdot q_j/T} \pm 1 \right]^{-1}$$

Experimental Data
Beam Energy Scan at the CERN-SPS

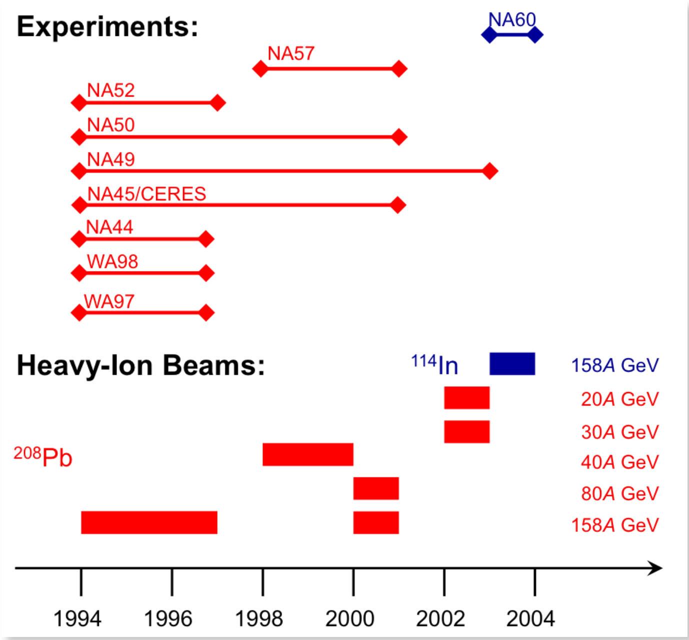
Energy scan program
Pb+Pb reactions

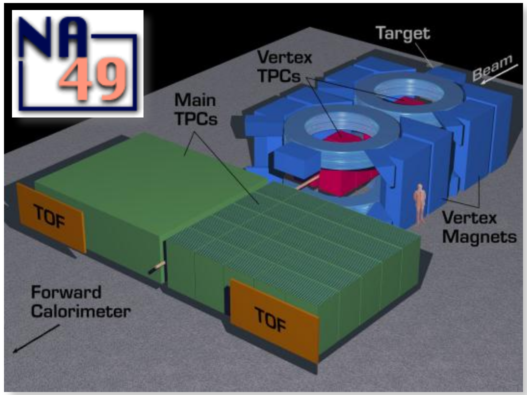
Year	1998 1999	2000	2002
$\sqrt{s_{NN}}$ (GeV)	8.8	12.3 17.3	6.3 7.6
E_{beam} (AGeV)	40	80 158	20 30

Covers ~250 MeV < μ_B < ~470 MeV

Experiments:
Fixed target setup

NA49 (all energies)
NA45 (40, 80, 158 AGeV)
NA57 (40, 158 AGeV)





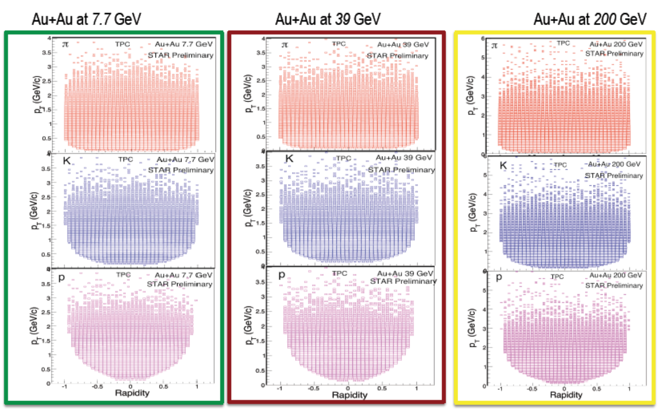
Experimental Access
Beam Energy Scan (BES) at RHIC

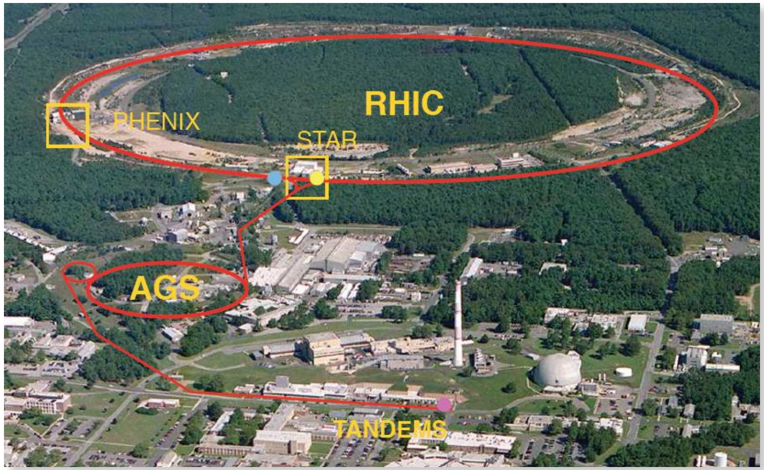
BES program of STAR
Au+Au reactions

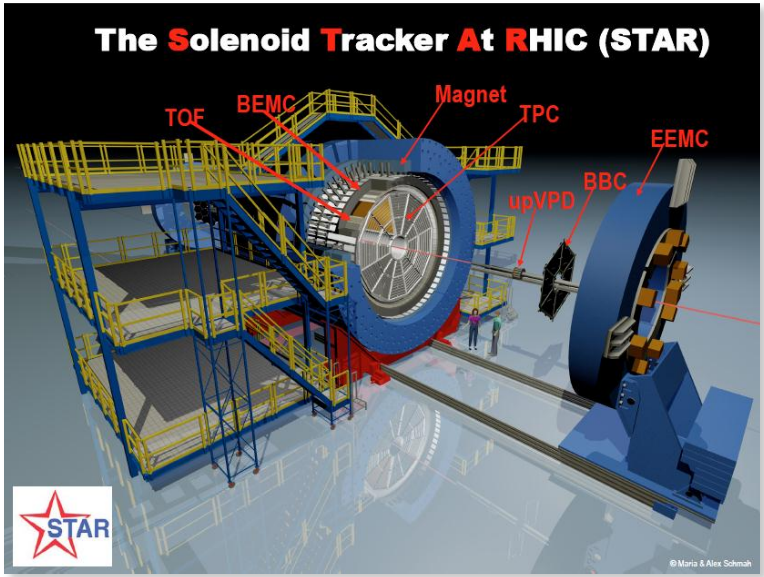
Year	2009	2010	2011	Planned
$\sqrt{s_{NN}}$ (GeV)	9.2	**7.7** **11.5** **39.0**	19.6 27.0	5.5 15.5?

Covers ~20 MeV < μ_B < ~400 MeV

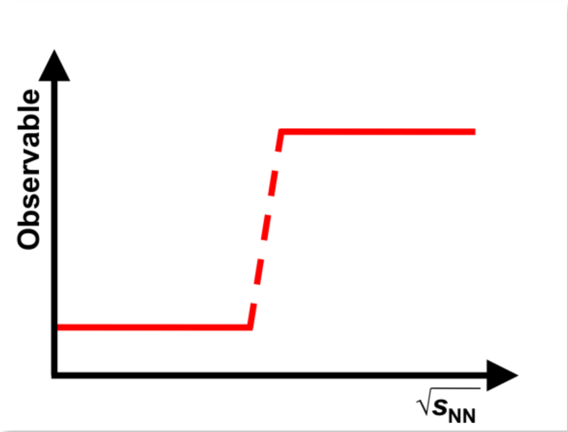
Collider geometry
⇒ Acceptance independent on $\sqrt{s_{NN}}$







Search for the Onset of Deconfinement



Sensitivity to EOS

HG → QGP: rapid change of the number of degrees of freedom

Flow observables

Radial flow: p_t spectra

Directed flow: collapse of proton v_1

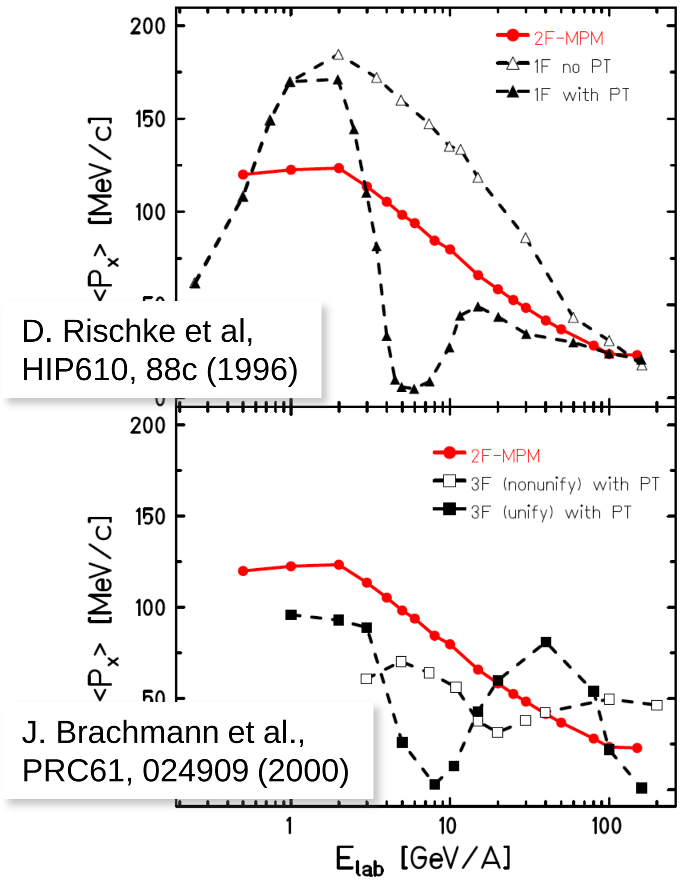
Elliptic flow: disappearance of partonic collectivity (NCQ-scaling)?

HBT radii

$\sqrt{s_{NN}}$ dependence of particle production

Statistical model of early stage

M. Gaździcki and M.I. Gorenstein, APPB30, 2705 (1999)



Onset of Deconfinement

NA49 Results

Structures in $\sqrt{s_{NN}}$ dep.

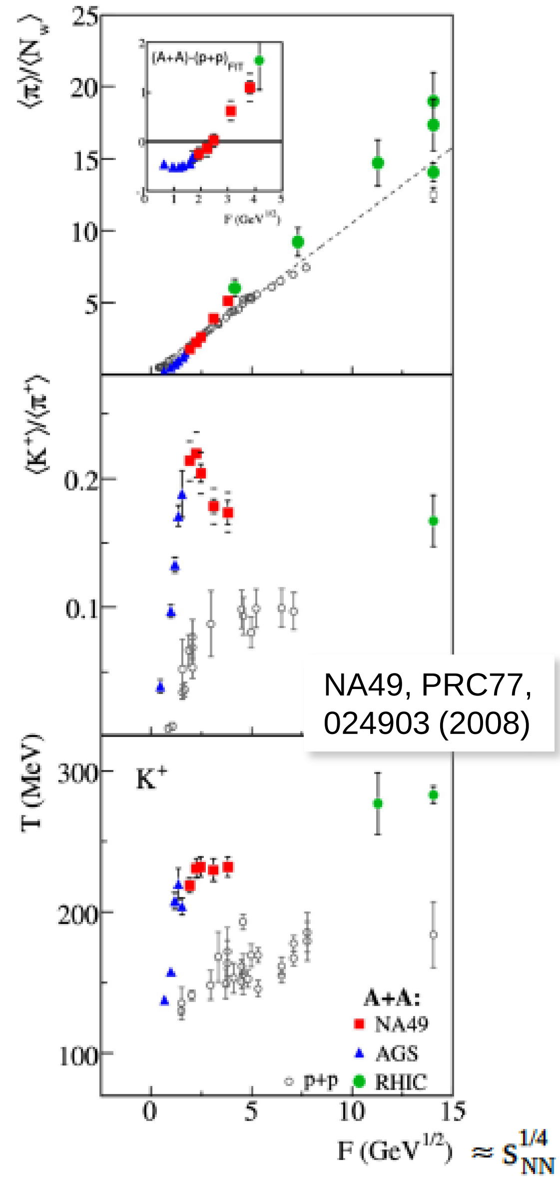
Increase of relative pion production

Sharp maximum in K^+/π^+ ratio

Change in of $\sqrt{s_{NN}}$ dep. of kaon slopes

Not seen in p+p

All occur at $\sqrt{s_{NN}} \approx 8$ GeV



NA49, PRC77, 024903 (2008)

Prominent structure in K^+/π^+ ratio

Not seen in p+p

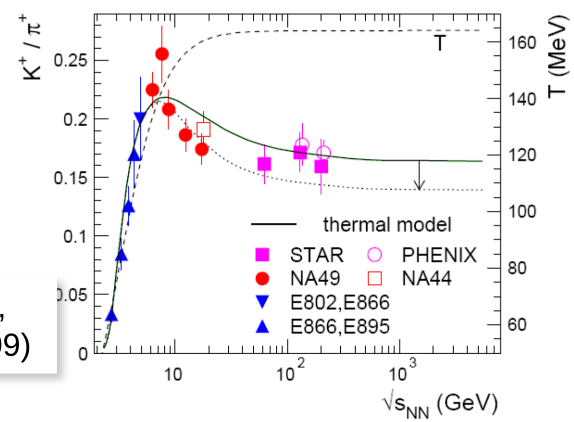
Not described by transport models

Good agreement between SPS and RHIC !

Proposed signature for PT

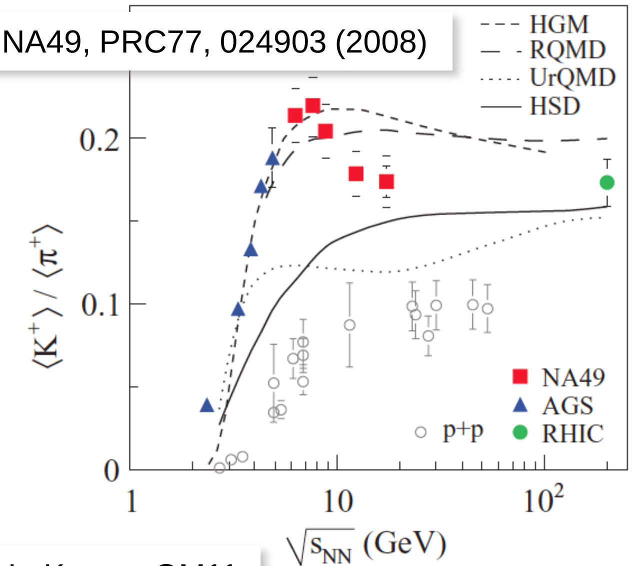
M. Gaździcki and M.I. Gorenstein, APPB30, 2705 (1999)

Recent statistical model curve:

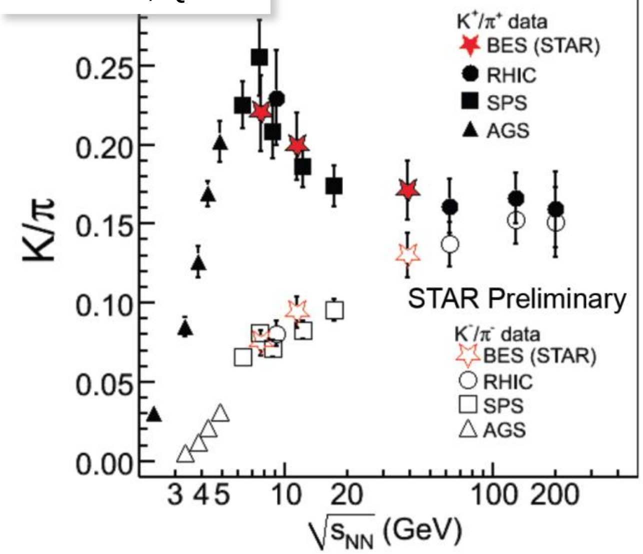


A. Andronic et al., PLB673, 142 (2009)

NA49, PRC77, 024903 (2008)

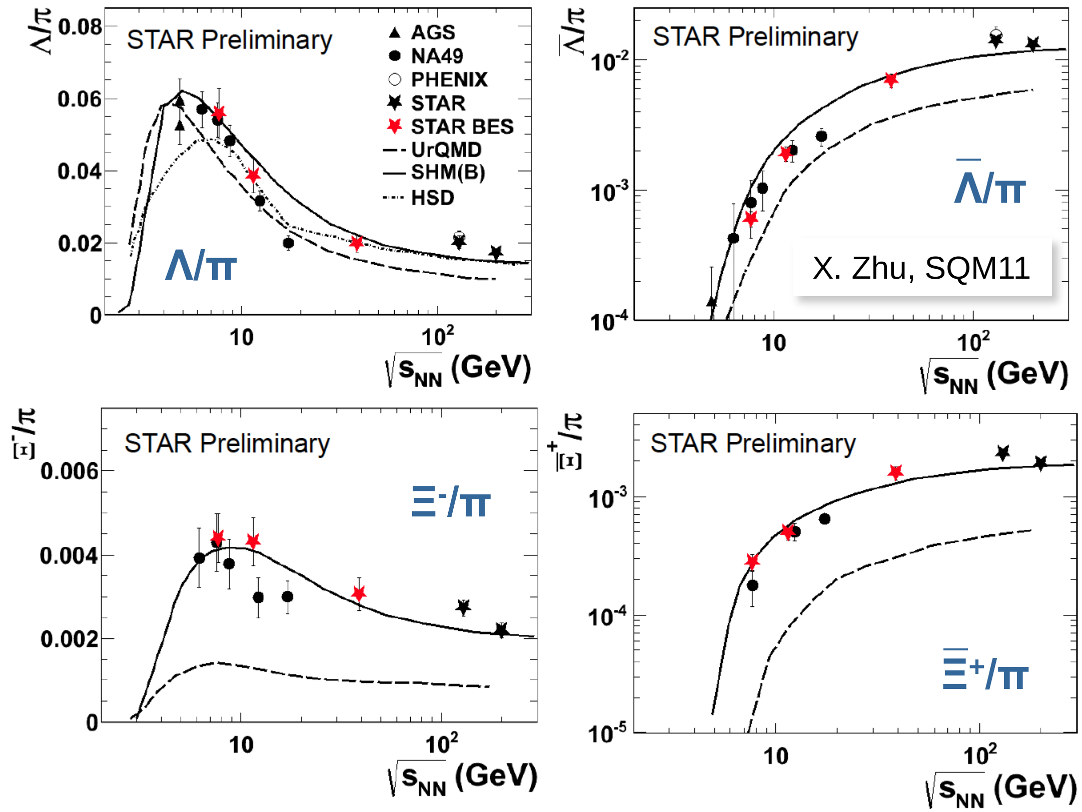


L. Kumar, QM11



Onset of Deconfinement

Strange Baryon to Pion Ratios

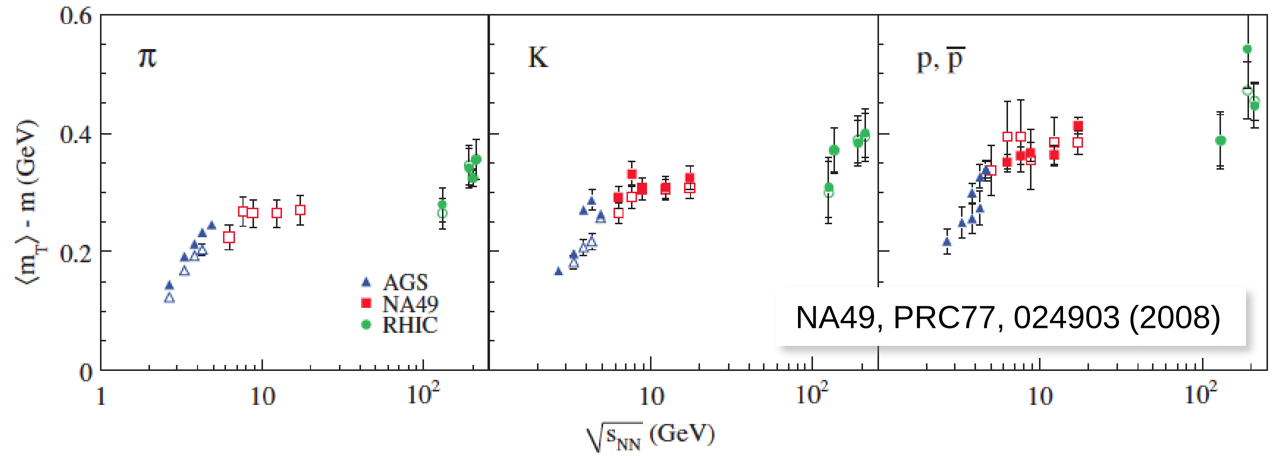


Good agreement between SPS and RHIC

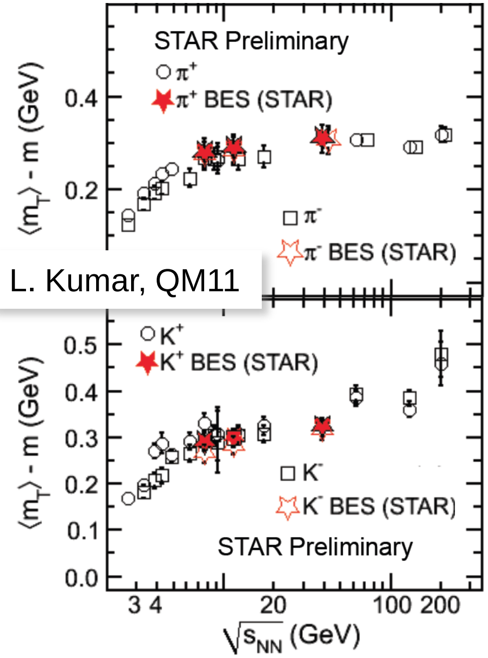
Close to statistical model curve

Onset of Deconfinement

Transverse Momentum Spectra: $\langle m_t \rangle - m_0$



NA49, PRC77, 024903 (2008)



L. Kumar, QM11

Evolution of radial flow

Steep increase at low energies

Moderate increase at higher energies

Good agreement between SPS and RHIC

Indicative for change in EOS?

Onset of Deconfinement

Kinetic Freeze-Out Parameter

Blast wave fits: T_{kin}, $\langle \beta_T \rangle$

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

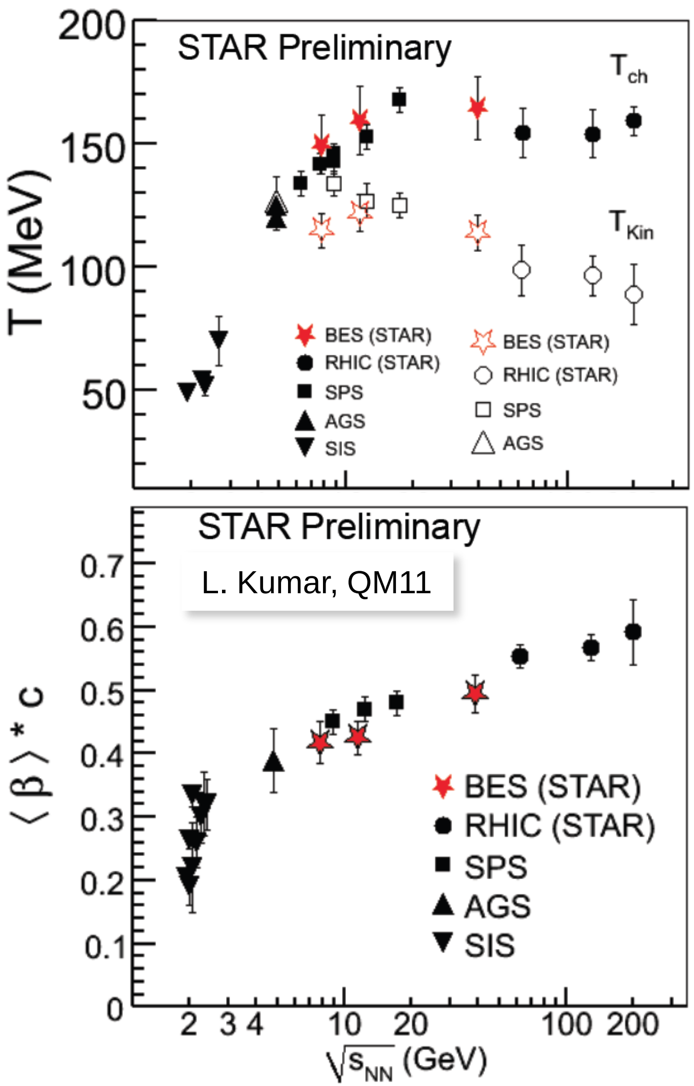
E. Schnedermann and U. Heinz, PRC50, 1675 (1994).

$T_{kin} < T_{ch}$ for $\sqrt{s_{NN}} > 10$ GeV

Difference increases with increasing energy (drop of T_{kin})
→ more time for cooling of system

Continuous increase of $\langle \beta_T \rangle$

Steep increase at low energies
Moderate increase at higher energies



Onset of Deconfinement

Directed Flow of (Anti-)Protons

Proton v_1 at mid-rapidity

Slope changes sign at $\sqrt{s_{NN}}$ = 8-10GeV

Antiproton v_1

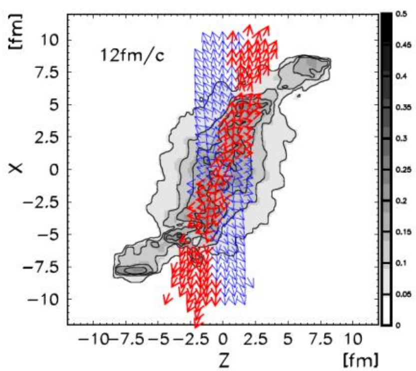
Different $\sqrt{s_{NN}}$ dependence

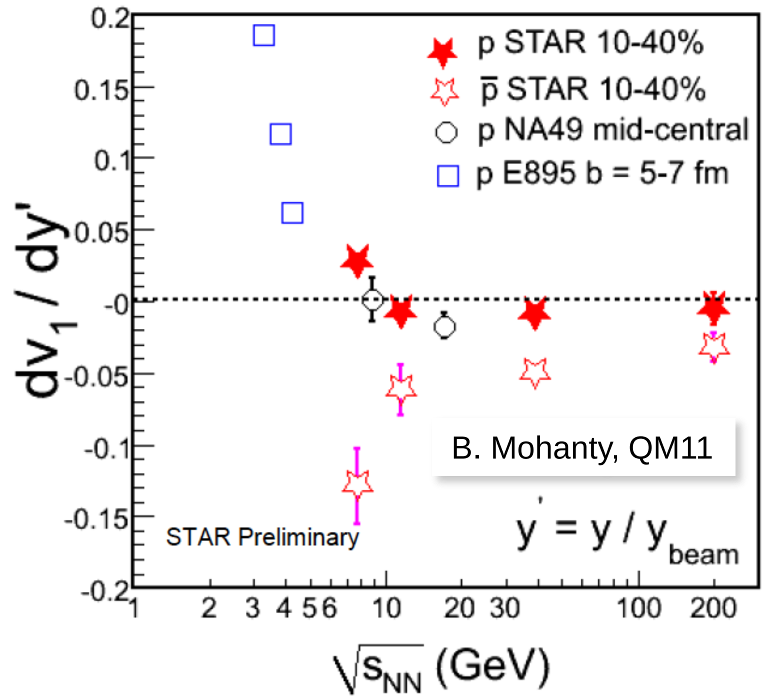
v_1 drops towards low energies

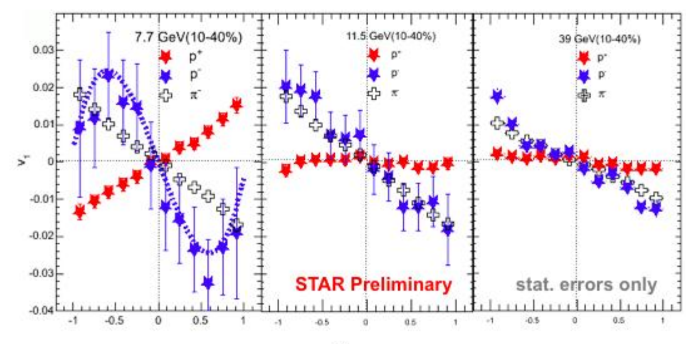
3rd flow component?

Sign of 1st order phase transition

L. Csernai, D. Röhrich, PLB458, 454 (1999)
J. Brachmann et al., PRC61, 024909 (2000)







Elliptic Flow: Particle - Antiparticle

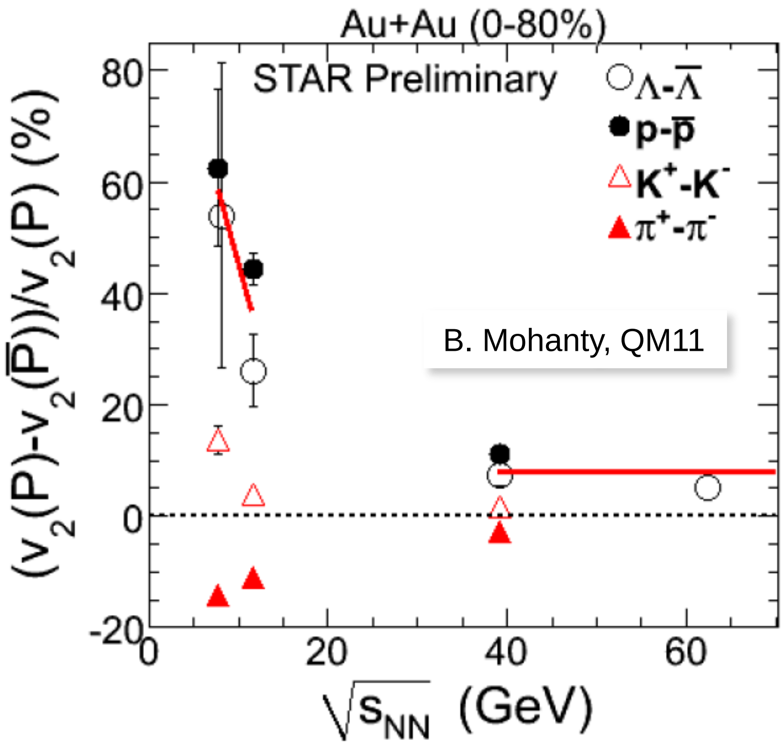
v_2(particle) – v_2(antiparticle)

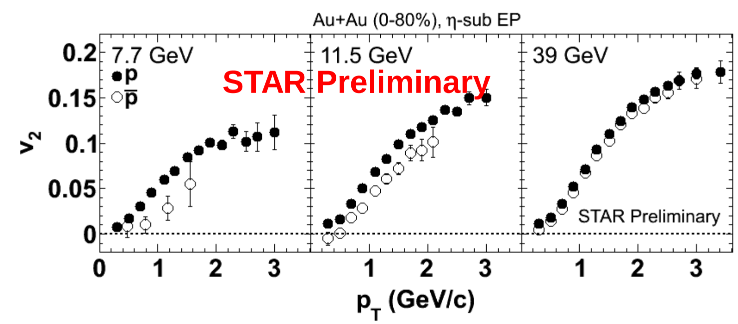
Difference increases towards low $\sqrt{s_{NN}}$

Effect stronger for baryons (p, Λ) than for mesons (π, K)

Continuous evolution

Absorption effects
Effect of high net-baryon density
... ?





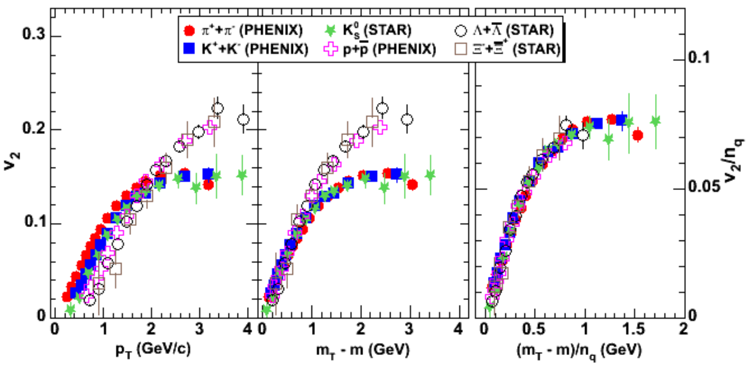
Onset of Deconfinement

Elliptic Flow: Disappearance of partonic collectivity ?

NCQ scaling of v_2

Indication for partonic flow

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

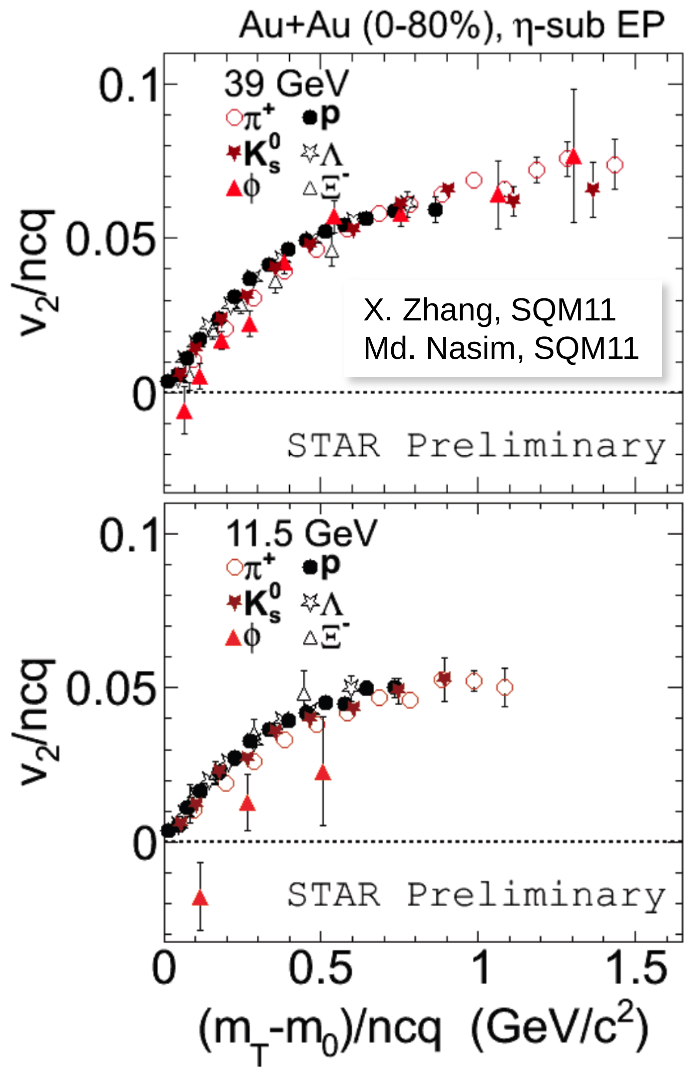


ϕ Meson seems to deviate at low energies

Scaling still ok at $\sqrt{s_{NN}}$ = 39 GeV

Low hadronic cross section of ϕ
→ less partonic flow seen ?

Breaking of NCQ scaling?

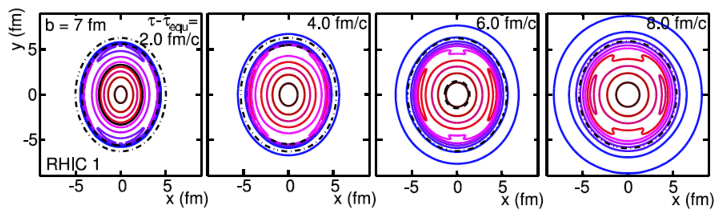


HBT radii vs. reaction plane

Freeze-out eccentricity:

$$\epsilon_f = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

In-plane pressure:
Initial eccentricity ⇒ spherical shape

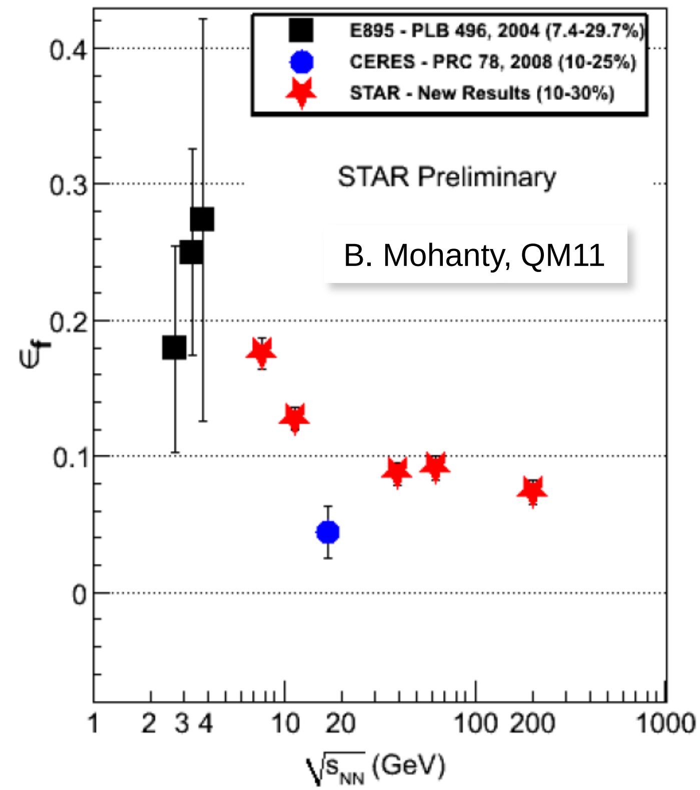


P.F. Kolb and U. Heinz, nucl-th/0305084

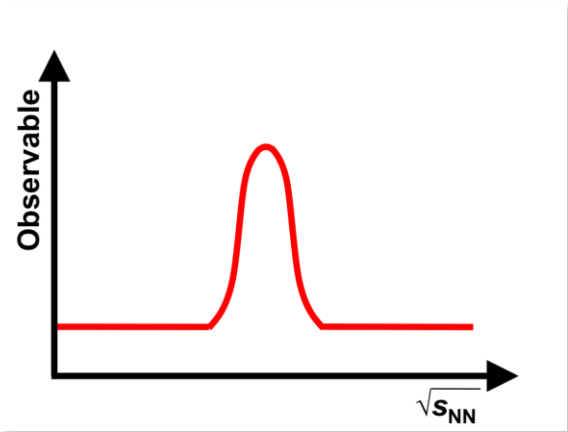
Sensitive to EOS (1st order PT)

Indication for non-monotonic behavior ?

How about integrated v_2 vs $\sqrt{s_{NN}}$?



Search for the Critical Point



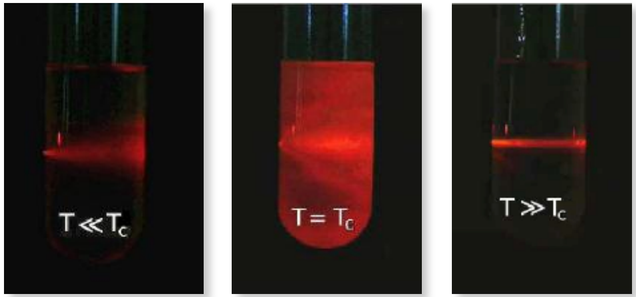
Critical opalescence
Correlation lengths and susceptibilities diverge

Heavy ion reactions
System size limited ⇒ critical region
Correlation length $\xi \approx$ radius of system

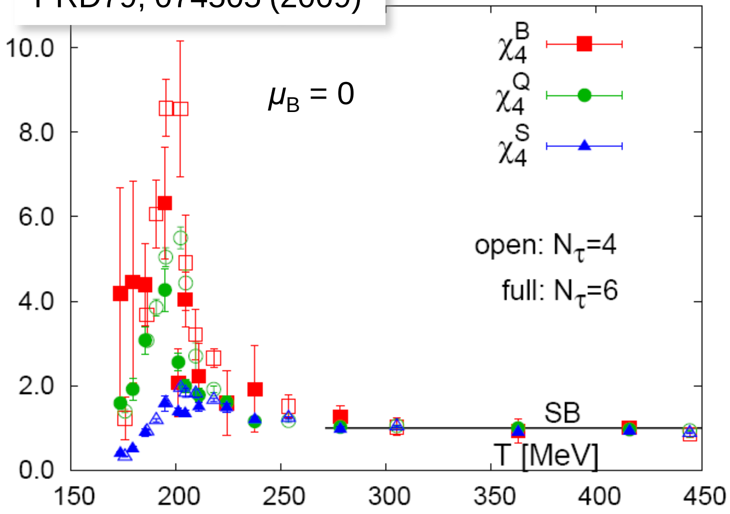
Enhanced fluctuations
Multiplicity
Average p_t
Particle ratios

Conserved quantities
Strangeness S
Baryon number B
Charge Q

Higher moments more sensitive



M. Cheng et al., PRD79, 074505 (2009)



Critical Point

Average p_t and Multiplicity Fluctuations

Average p_t fluctuations

Quantified by Φ_{pt}

$$\Phi_x \equiv \sqrt{\frac{\langle Z_x^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z_x^2}} \qquad Z_x \equiv \sum_{i=1}^{N_j}(x_i - \overline{x}) \qquad z_x \equiv x - \overline{x}$$

Multiplicity fluctuations

Quantified by scaled variance

$$\omega = \frac{Var(n\_)}{<n\_>} = \frac{<n\_^2> - <n\_>^2}{<n\_>}$$

No $\sqrt{s_{NN}}$ dependence seen

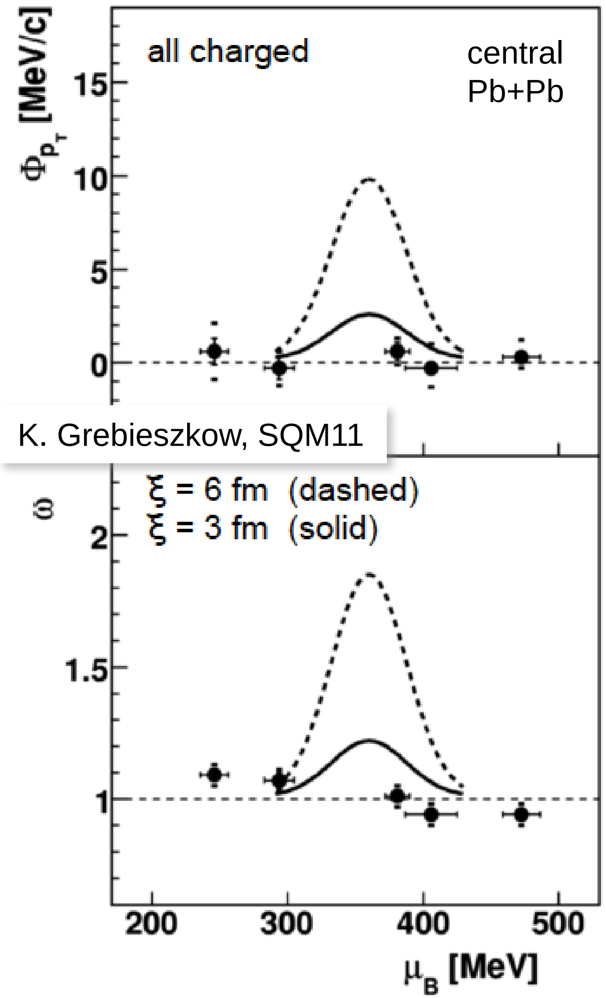
Critical point expectation

μ_B from stat. model fit:
F. Becattini et al.,
PRC73, 044905 (2006)

Position of critical point:
Z. Fodor and S. Katz
JHEP 0404, 050 (2004)

Amplitude of fluct. :
M. Stephanov et al.
PRD60, 114028 (1999)

Width of critical region:
Y. Hatta and T. Ikeda,
PRD67, 014028 (2003)



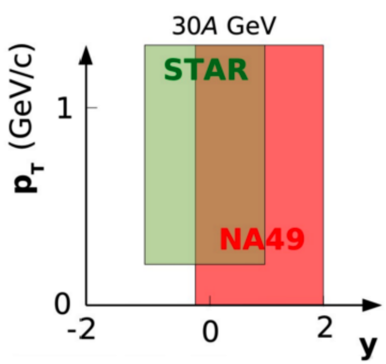
NA49, PRC79, 044904 (2009)

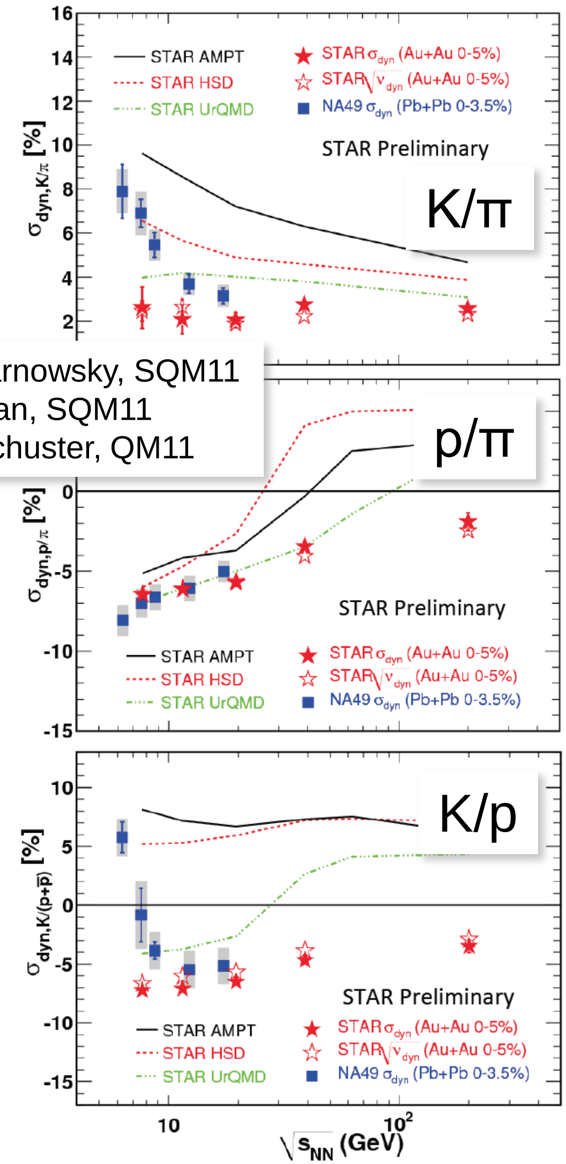
Critical Point
Particle Ratio Fluctuations

Sensitivity to CP ?
No evidence for non-monotonic behavior in energy dependence

Comparison NA49 ↔ STAR
Good agreement for p/π
Deviations for K/π + K/p at lowest $\sqrt{s_{NN}}$
NA49, PRC83, 061902 (2011)
NA49, PRC79, 044910 (2009)
STAR, PRL103, 092301 (2009)

Difficult to resolve due to different acceptances:

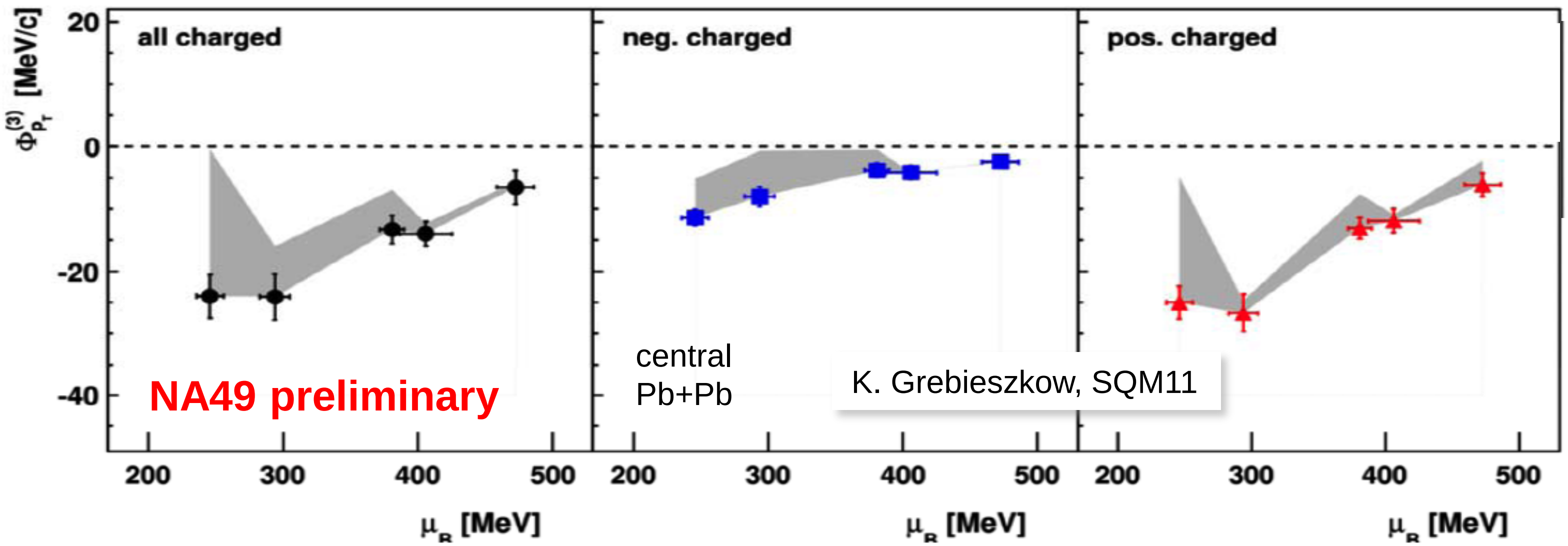




T. Tarnowsky, SQM11
J. Tian, SQM11
T. Schuster, QM11

Critical Point

Higher Moments of ⟨p_t⟩-Fluctuations



3[rd] moments as a function of $\sqrt{s_{NN}}$

$$\Phi^{(n)}_{p_t} = \left(\frac{\langle Z^2_{p_t}\rangle}{\langle N\rangle}\right)^{1/n} - \left(\bar{z}^n_{p_t}\right)^{1/n}$$

$$z_{p_t} = p_t - \bar{p}_t \qquad Z_{p_t} = \sum_{i=1}^{N}(p_t - \bar{p}_t)$$

Sensitive to higher power of correlation length *ξ*

E. g. $\langle N^4\rangle \propto \xi^7$ compared to $\langle N^2\rangle \propto \xi^2$

S. Mrówczynski
PLB **465**, 8 (1999)

M.A. Stephanov
PRL **102**, 032301 (2009)

Critical Point

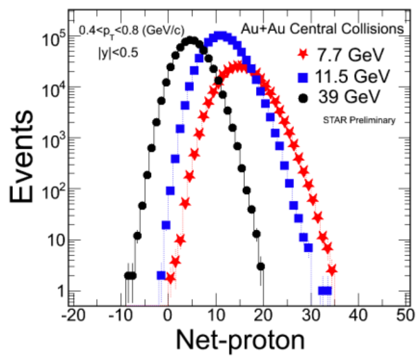
Higher Moments of Net-Proton Fluctuations

Baryon number fluctuations

Conserved quantity

Higher moments more sensitive to divergent correlation lengths

Measure of non-Gaussian behavior



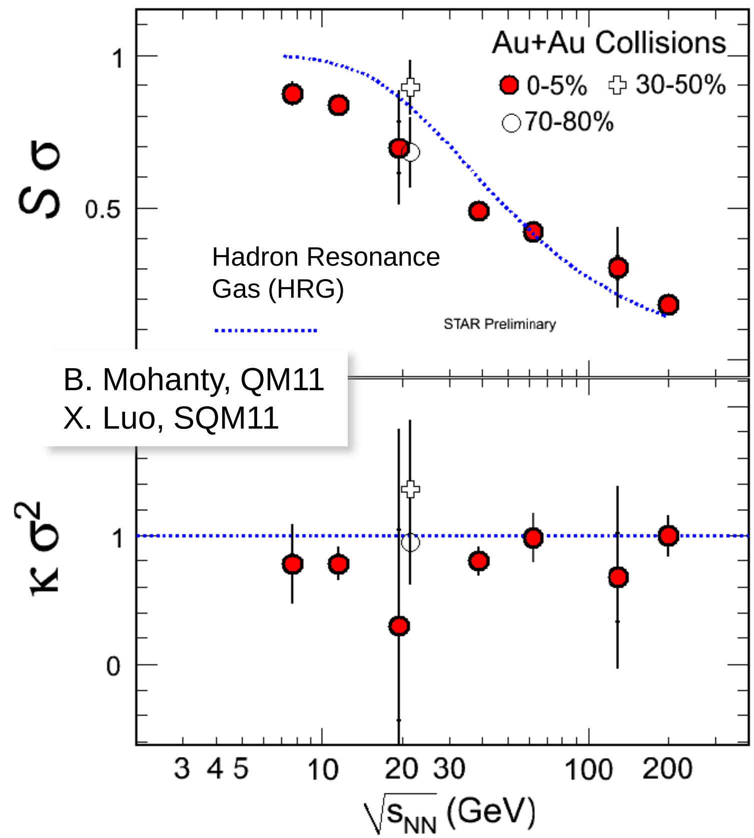
Connected to susceptibilities

$S\sigma = \chi^3_{\mathrm{B}}/\chi^2_{\mathrm{B}} \qquad K\sigma^2 = \chi^4_{\mathrm{B}}/\chi^2_{\mathrm{B}}$

Volume effects cancel

Smooth evolution

Departs from HRG at low $\sqrt{s_{NN}}$



B. Mohanty, QM11
X. Luo, SQM11

STAR, PRL105, 022302 (2010)

Critical Point

System Size Dependence of Multiplicity Fluctuations

Multiplicity fluctuations

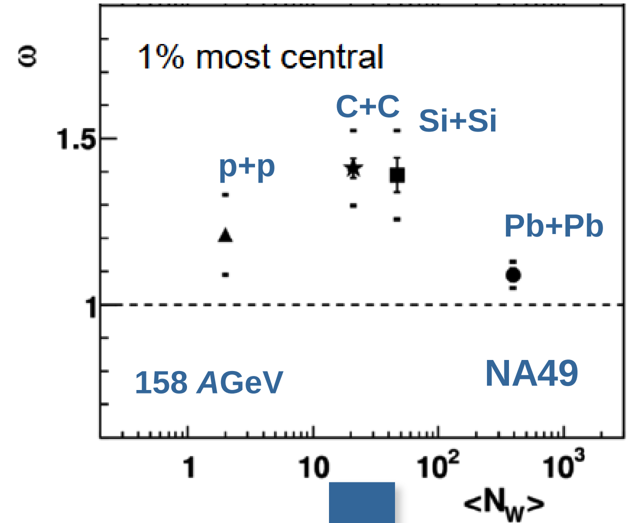
Quantified by scaled variance

$$\omega = \frac{Var(n_-)}{< n_- >} = \frac{< n_-^2 > - < n_- >^2}{< n_- >}$$

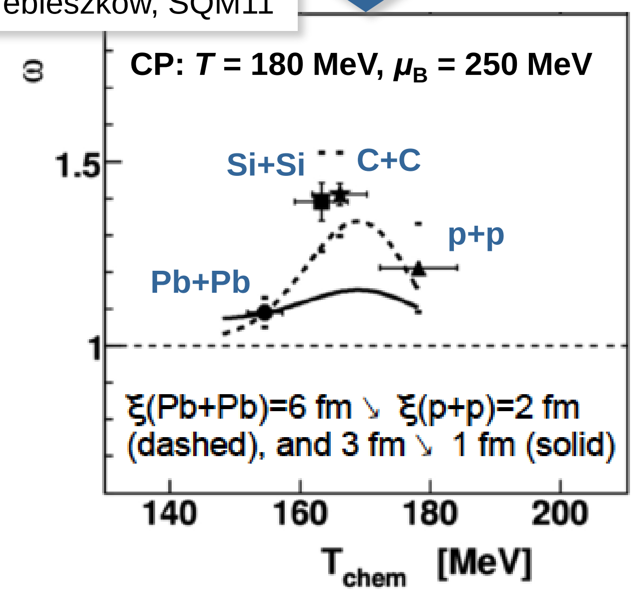
Clear change with N_w seen

Maximum for C+C and Si+Si

Connection to CP possible?



K. Grebieszkow, SQM11



Critical Point

Di-Pion (Sigma) Intermittency

$\pi^+\pi^-$ Pairs above di-pion threshold

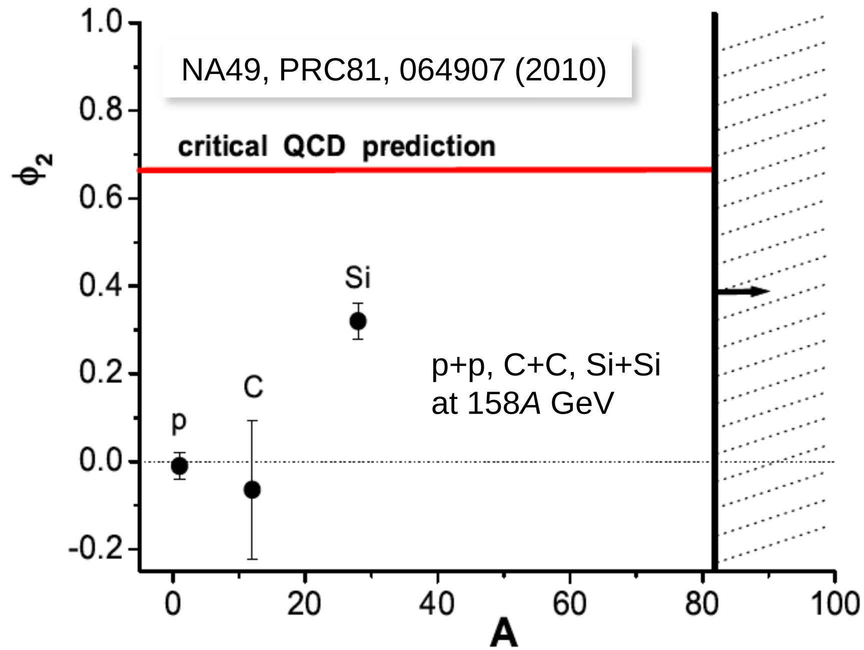
$$(2m_\pi + \epsilon_1)^2 \leq (p_{\pi^+} + p_{\pi^-})^2 \leq (2m_\pi + \epsilon_2)^2$$

Factorial moments $F_2(M)$
M: Number of bins in p_t

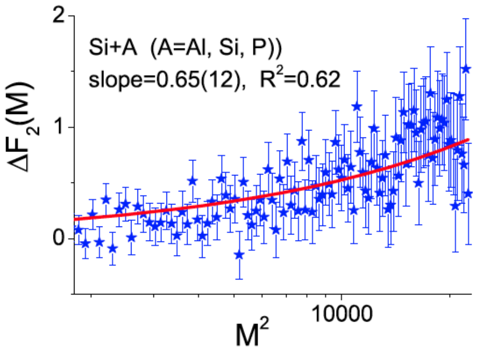
Subtract mixed event background
$\Rightarrow \Delta F_2(M)$

Search for power law behavior
$\Delta F_2(M) \sim (M^2)^{\Phi 2}$
Φ_2 : critical exponent

$\Phi_2 > 0$ for Si+Si
Coulomb effects become
an issue for larger systems



Analysis with identified protons:



Outlook

NA61 / SHINE at the CERN-SPS

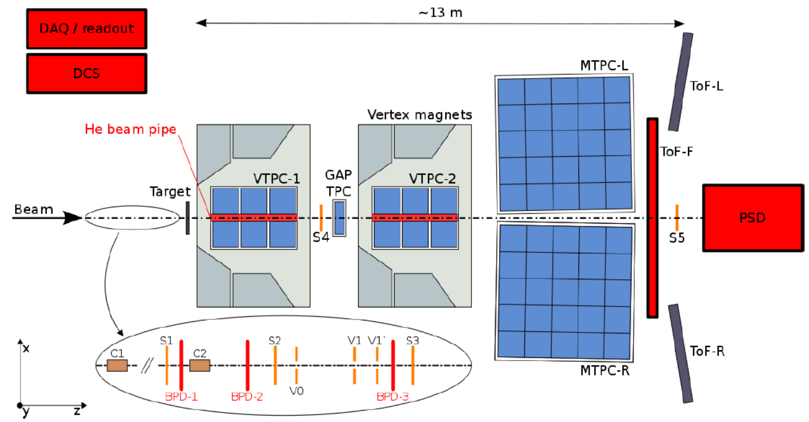
Upgrade of NA49 setup

Faster readout
Projectile Spectator Detector (PSD)
Secondary ion beam line
(fragment separator)

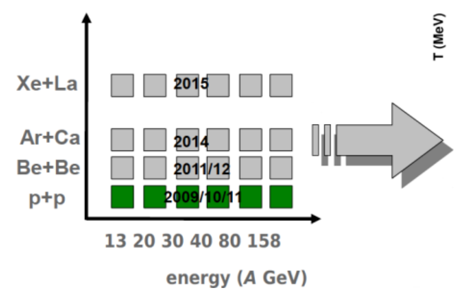
Program

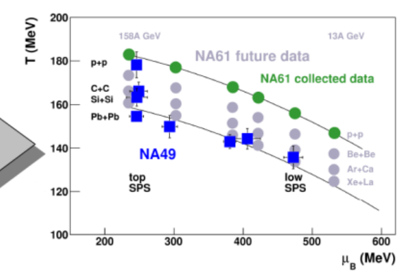
2D scan: energy + system size

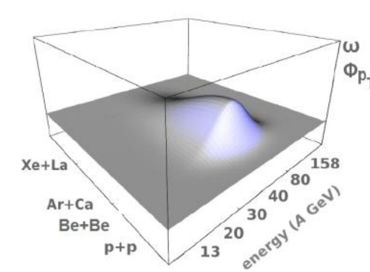
Already done: p+p energy scan, p+C
Start with Be+Be this year



top view – not to scale
upgrades marked in red







Outlook
CBM at FAIR

Compressed Baryonic Matter

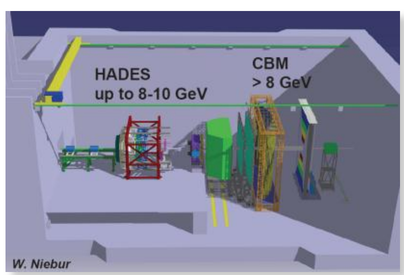
Fixed target experiment at SIS-100/300
Ion beams with highest luminosity 10^9/s
Beam energies 10 – 45 *A*GeV
Begin 2019

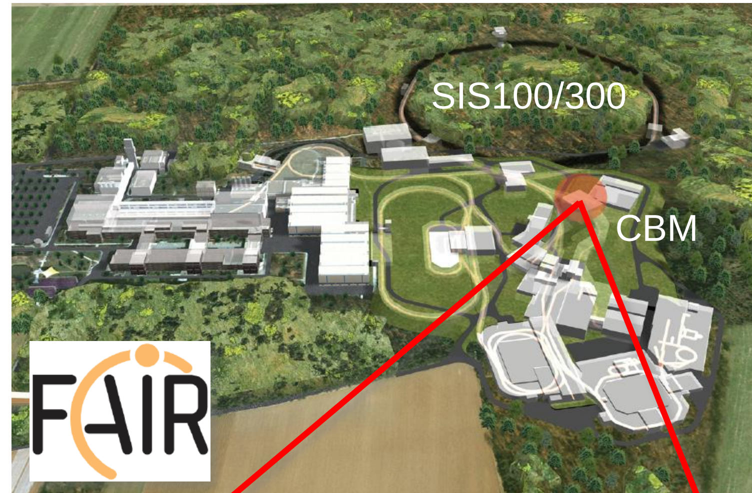
Program

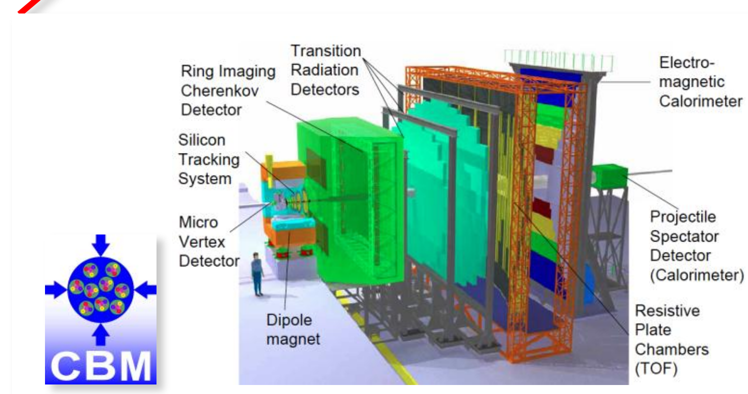
Rare probes: J/ψ, open charm
Multi-strange baryons
Di-leptons, photons
All hadronic observables

Startup with SIS-100

HADES @ FAIR
E_{beam} < 10 *A*GeV







Outlook

NICA at JINR (Dubna)

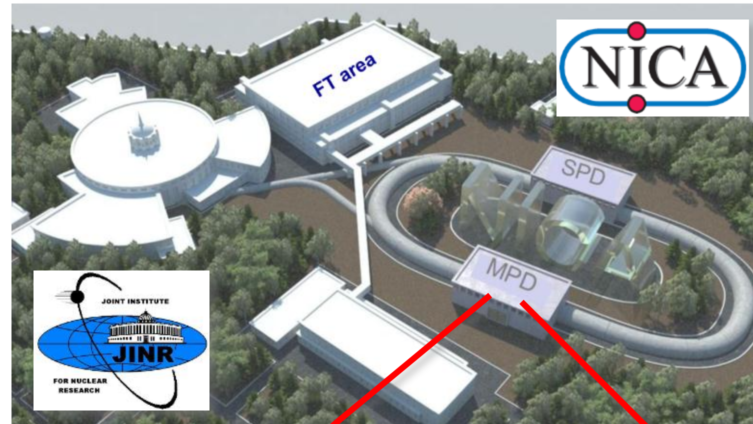
NICA: Nuclotron based Ion Collider fAcility

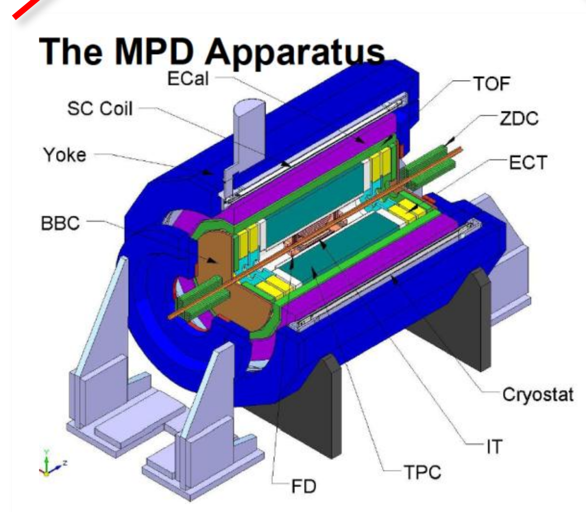
Collider with $\sqrt{s_{NN}}$ = 4–11 GeV
Luminosity ~ 10^{27} $cm^{-2}s^{-1}$ for $^{179}Au^{79+}$
Begin 2017

Fixed target @ Nuclotron (BM@N)
(joint GSI-JINR effort)
$\sqrt{s_{NN}} \approx 3.5$ GeV, begin 2015

Program

Systems with highest baryon density
Critical point
Quarkyonic phase
Chiral symmetry restoration





Conclusions

Already a wealth of data on the market

Energy scan at the CERN-SPS (NA49)
Beam Energy Scan (BES) at RHIC (STAR)
Good agreement between experiments (except K/π and K/p fluct. at low $\sqrt{s_{NN}}$)

Onset of deconfinement

Many interesting and non-trivial structures
K^+/π^+ ratios, radial flow, directed flow of (anti)protons
Onset of partonic collectivity observable?

Search for the critical point

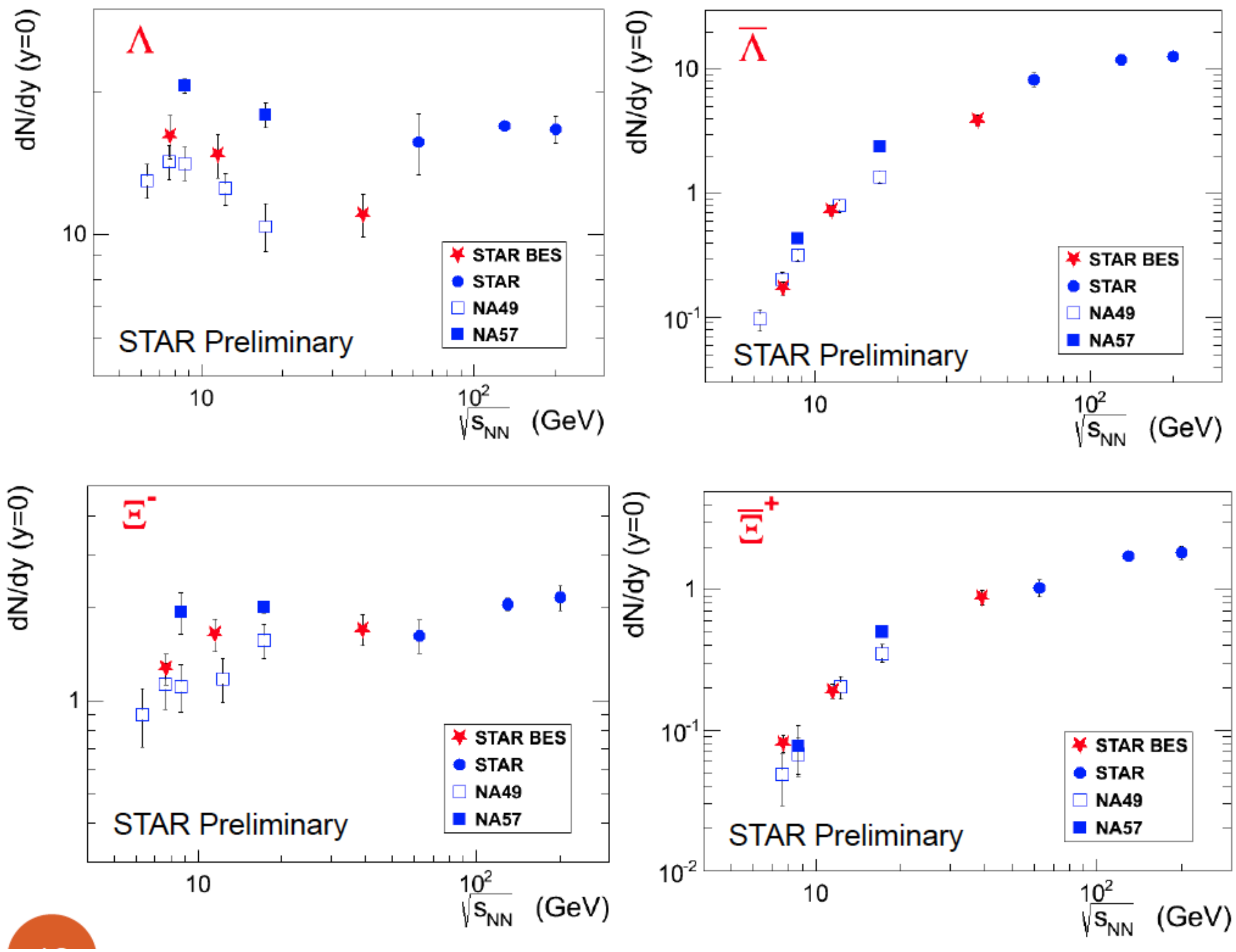
Many promising ideas being tested
Higher moments, conserved quantities (e.g. net-protons)
No clear evidence yet

Much more to come in the future

BES (STAR) and CERN (NA61)
FAIR (CBM) and NICA (MPD)

Many Thanks!
M. Bleicher, F. Diakonos, M. Gaździcki, B. Mohanty, H.G. Ritter, P. Seyboth, N. Xu, ...

Backup


Λ
dN/dy (y=0)
10
STAR BES
STAR
NA49
NA57
STAR Preliminary
10
10^2
√s_NN (GeV)
Λ̄
dN/dy (y=0)
10
1
10^-1
STAR BES
STAR
NA49
NA57
STAR Preliminary
10
10^2
√s_NN (GeV)
Ξ-
dN/dy (y=0)
1
STAR BES
STAR
NA49
NA57
STAR Preliminary
10
10^2
√s_NN (GeV)
Ξ̄+
dN/dy (y=0)
1
10^-1
10^-2
STAR BES
STAR
NA49
NA57
STAR Preliminary
10
10^2
√s_NN (GeV)

X. Zhu, SQM11

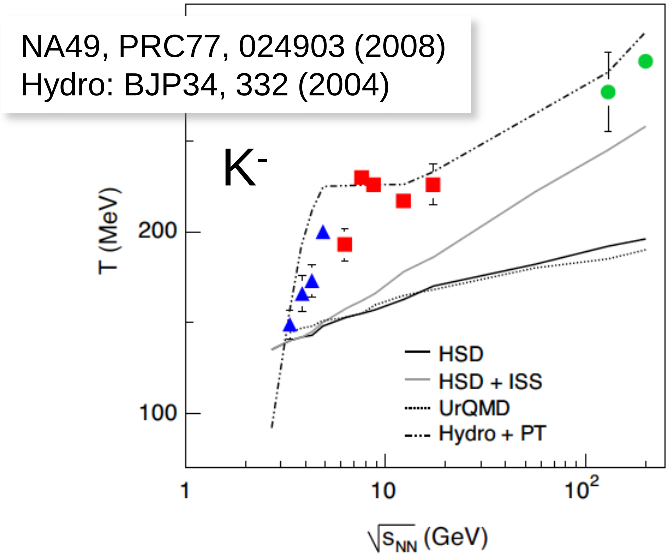
Onset of Deconfinement

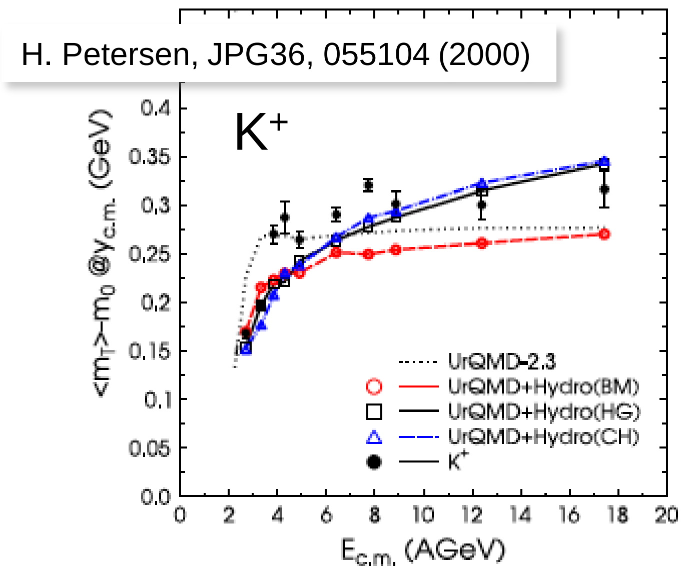
Model Comparisons to p_t Spectra

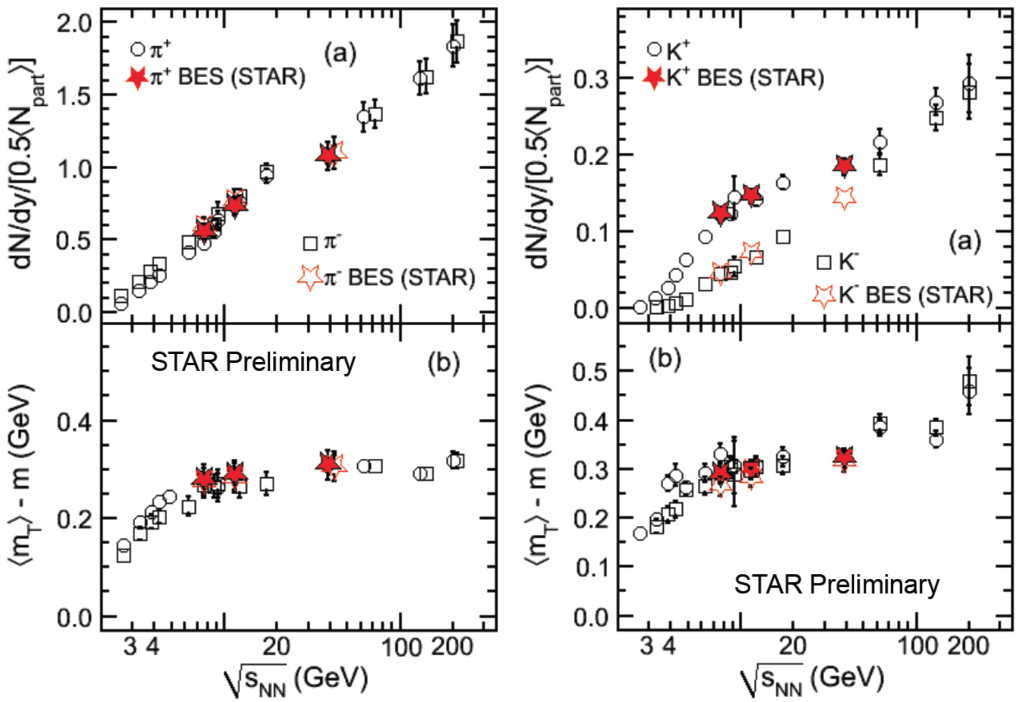
Transport models
HSD, UrQMD1.6
Do not match data (except UrQMD2.3)

Hydro models
Structure consistent with change of EOS
1^{st} order phase transition

But:
Strong influence of freeze-out description
Difficult to establish unique connection



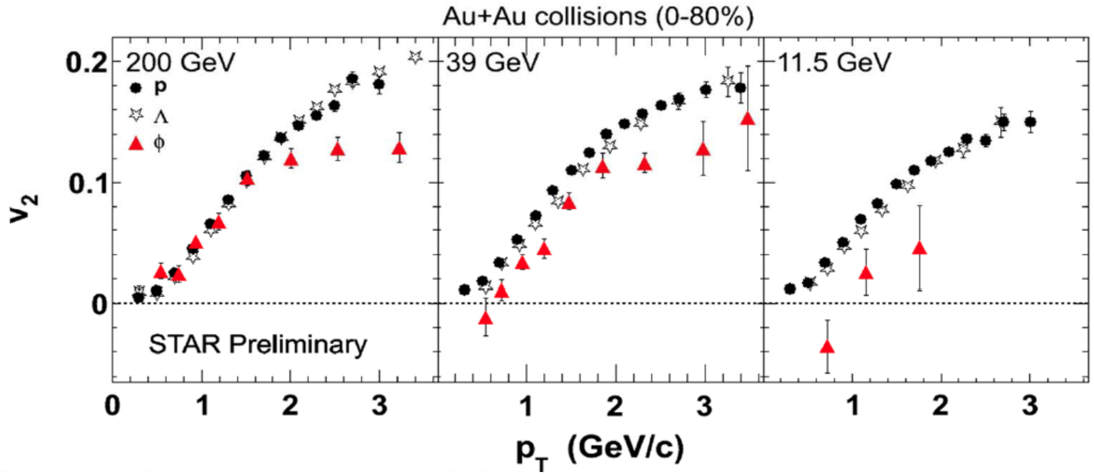




π+
π+ BES (STAR)
(a)
π-
π- BES (STAR)
dN/dy/[0.5⟨Npart⟩]
STAR Preliminary
(b)
⟨mT⟩ - m (GeV)
√sNN (GeV)
K+
K+ BES (STAR)
K-
K- BES (STAR)

Onset of Deconfinement

Elliptic Flow: ϕ Meson



X. Zhang, SQM11
Md. Nasim, SQM11

p_t-Spectra

Sensitive to radial flow

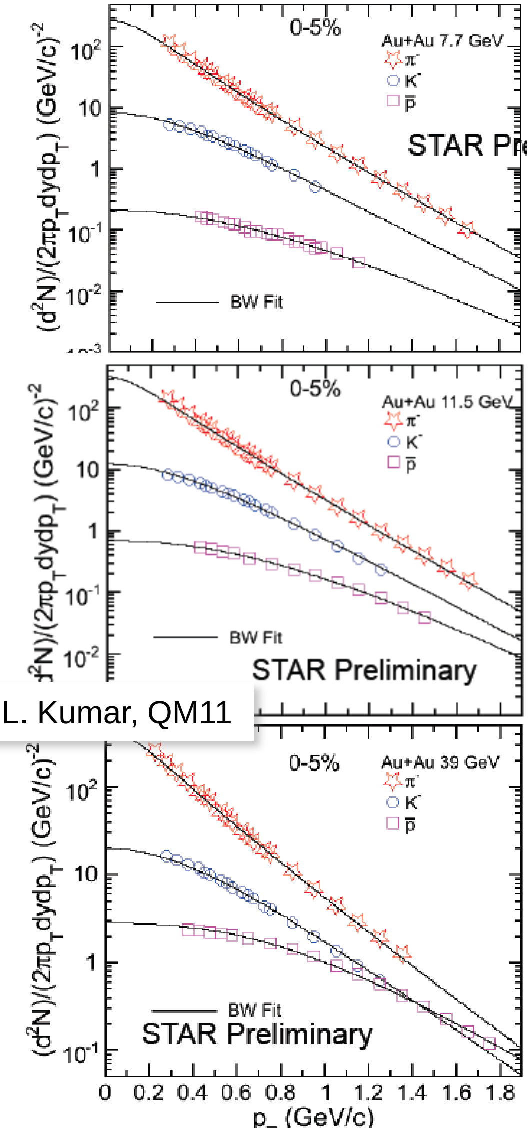
→ mass dependence

Blast wave fits: T_{kin}, $\langle\beta_T\rangle$

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

E. Schnedermann and U. Heinz, PRC**50**, 1675 (1994).

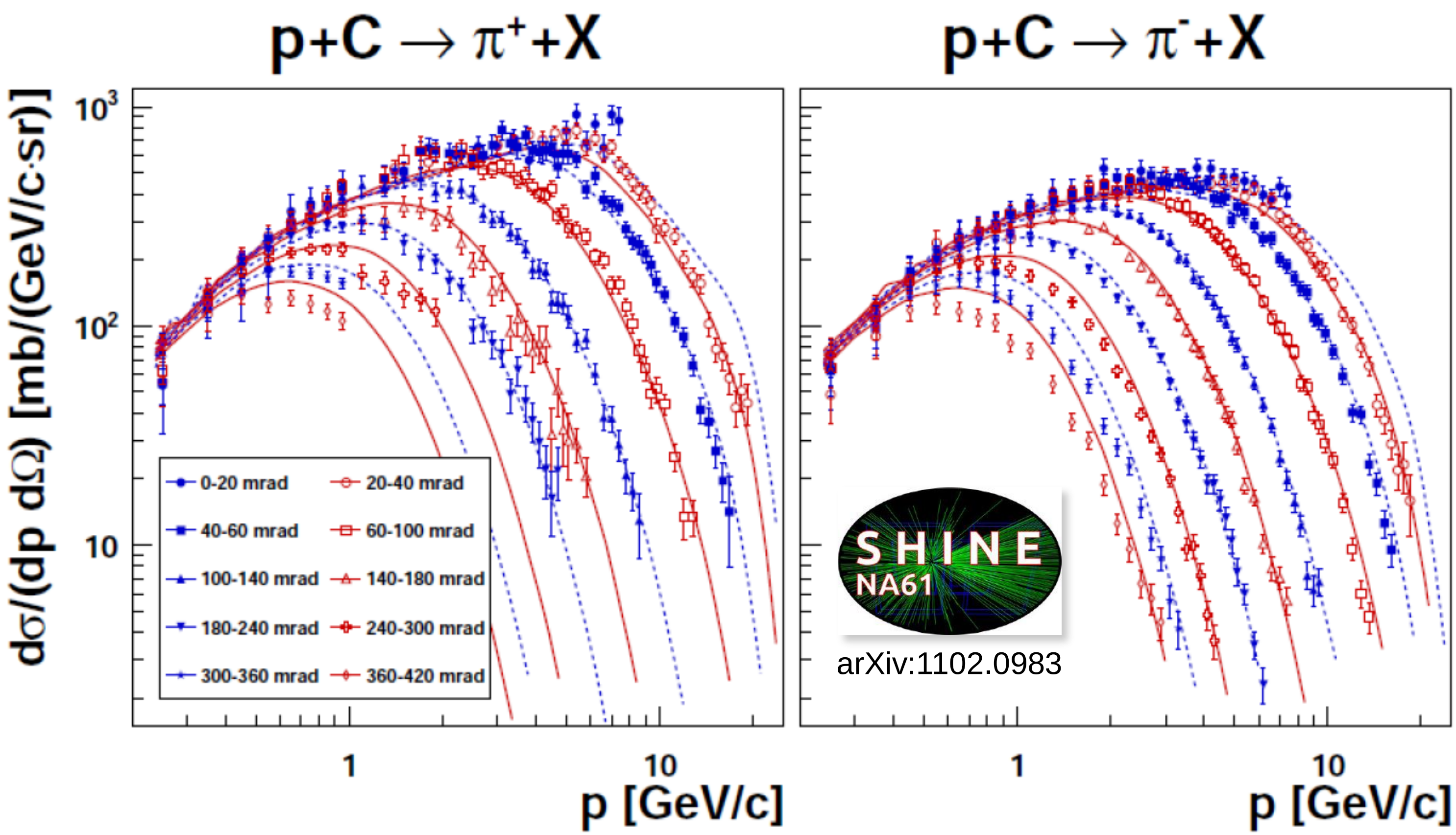
Resonance feed down usually ignored !



L. Kumar, QM11

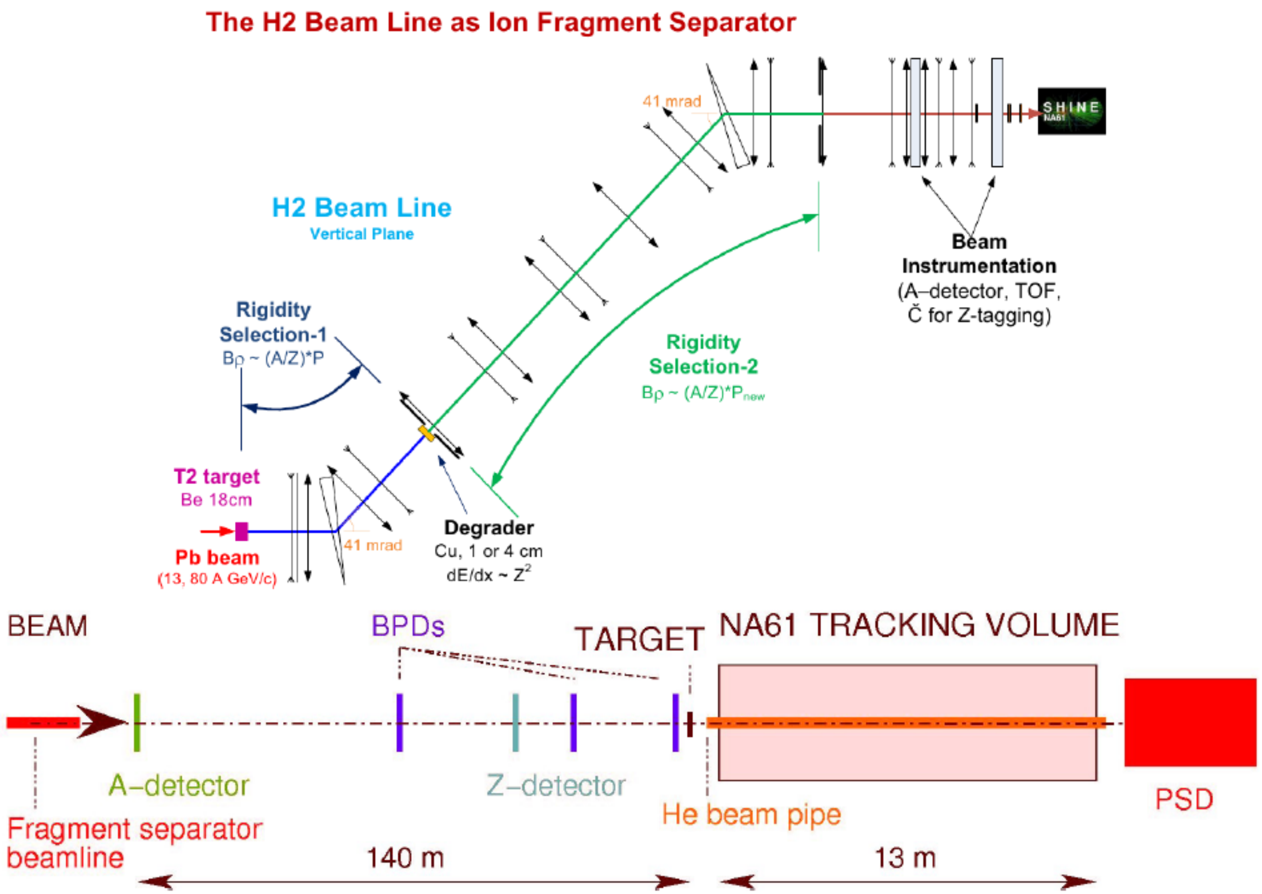
Outlook

NA61 / SHINE at the CERN-SPS



Pilot data 2007: p+C at 31 GeV/c

Comparison to FLUKA2008



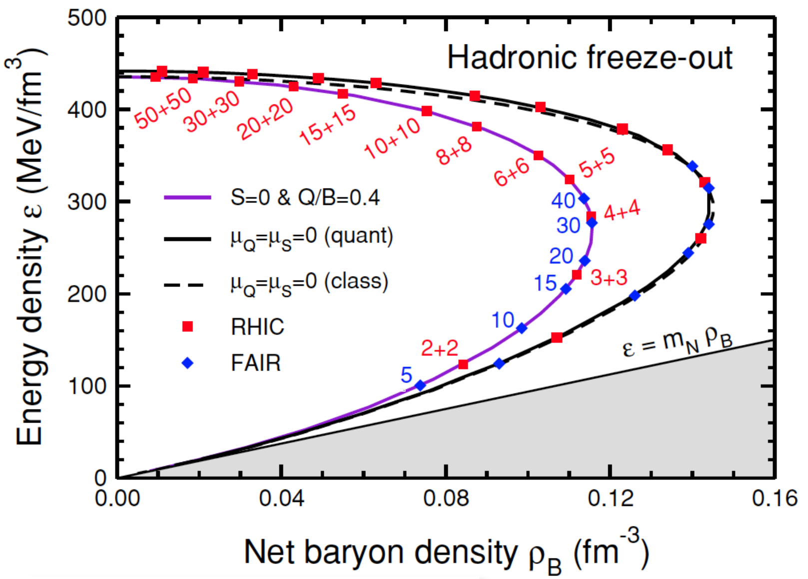
A. Aduszkiewicz, SQM11

The QCD Phase Diagram

High Baryon Density

Net baryon density

Reaches maximum in interesting regions of $\sqrt{s_{NN}}$



J. Randrup and J. Cleymans, PRC74, 047901 (2006)

Critical Point

Theoretical Predictions

Critical region

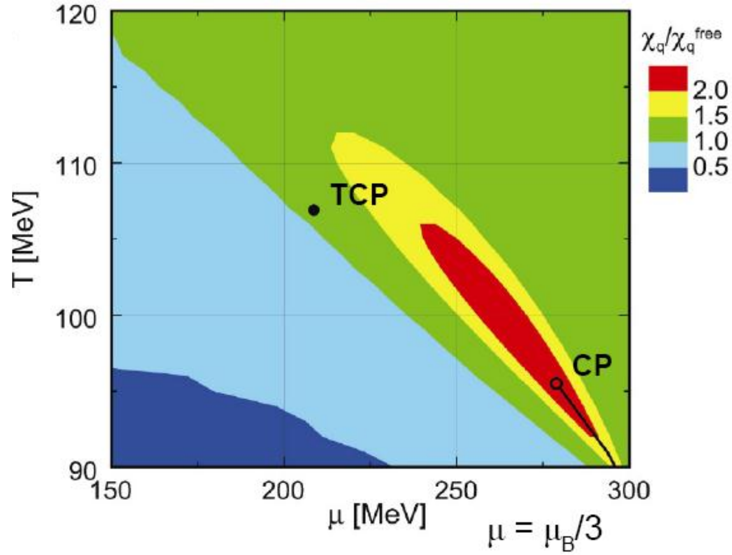
Larger area in T - μ_B plane

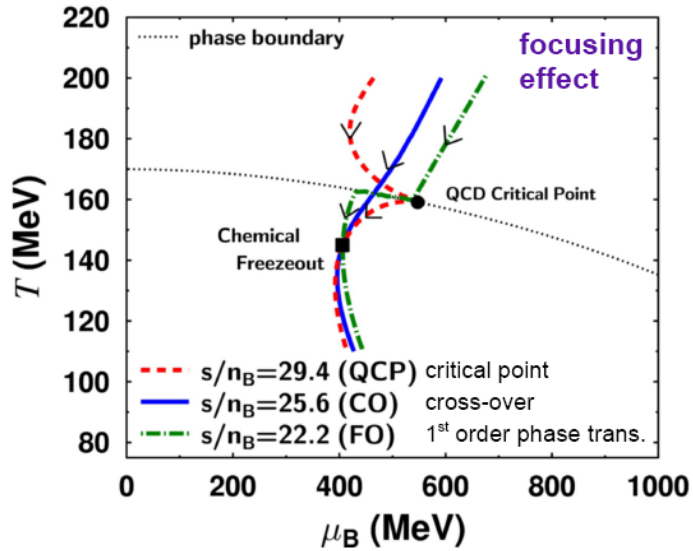
Y. Hatta and T. Ikeda,
Phys. Rev. D67,
014028 (2003)

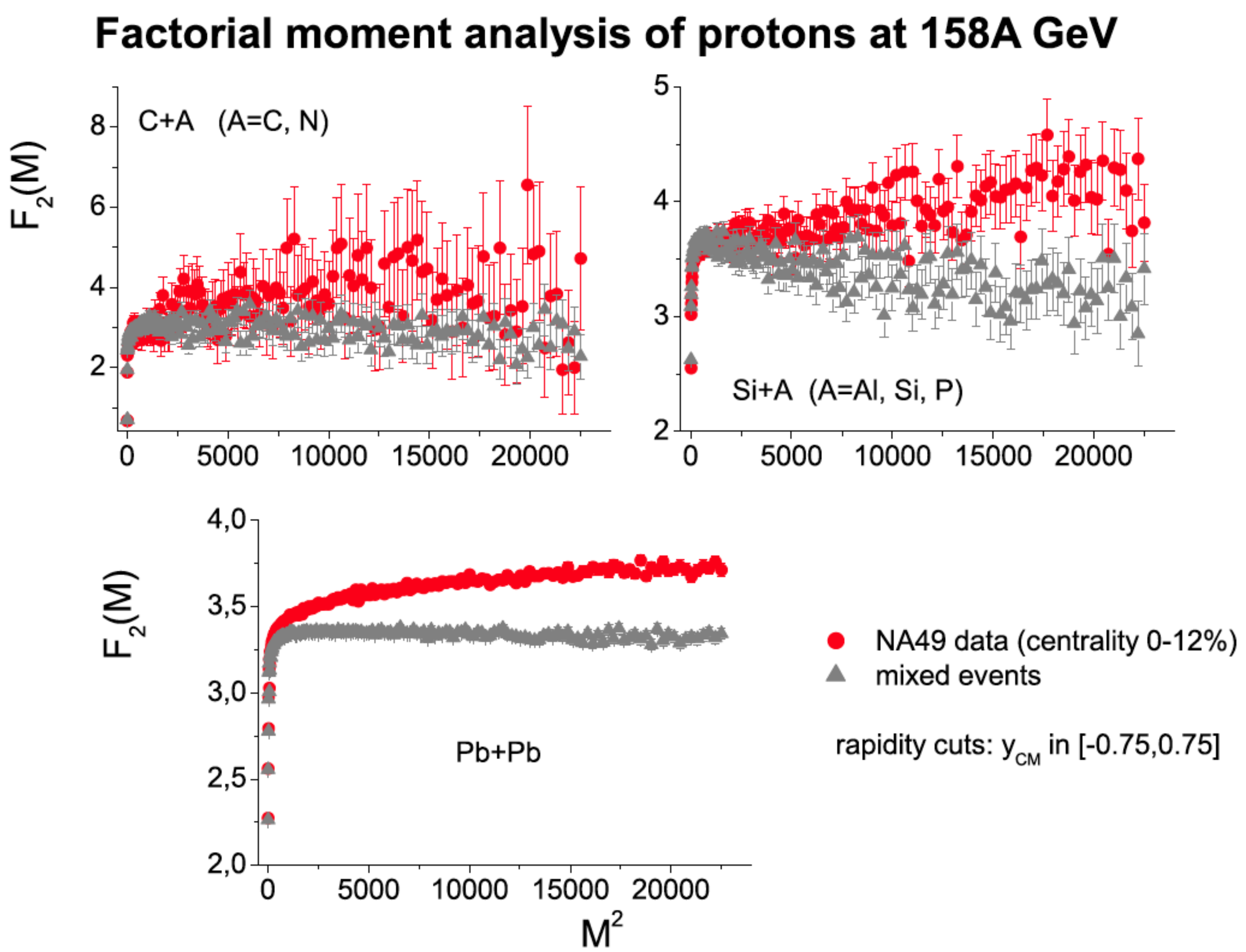
Focusing effect

Proximity of critical point might influence isentropic trajectories (n_B/s = const.)

Askawa et al.,
Phys. Rev. Lett. 101,
122302 (2008)






Factorial moment analysis of protons at 158A GeV
C+A (A=C, N)
Si+A (A=Al, Si, P)
Pb+Pb
F2(M)
M2
NA49 data (centrality 0-12%)
mixed events
rapidity cuts: yCM in [-0.75,0.75]

The correlator $\Delta F_2(M)$ for 3 considered systems at 158A GeV