Energy and System Size Dependence of Hadron Production from NA49

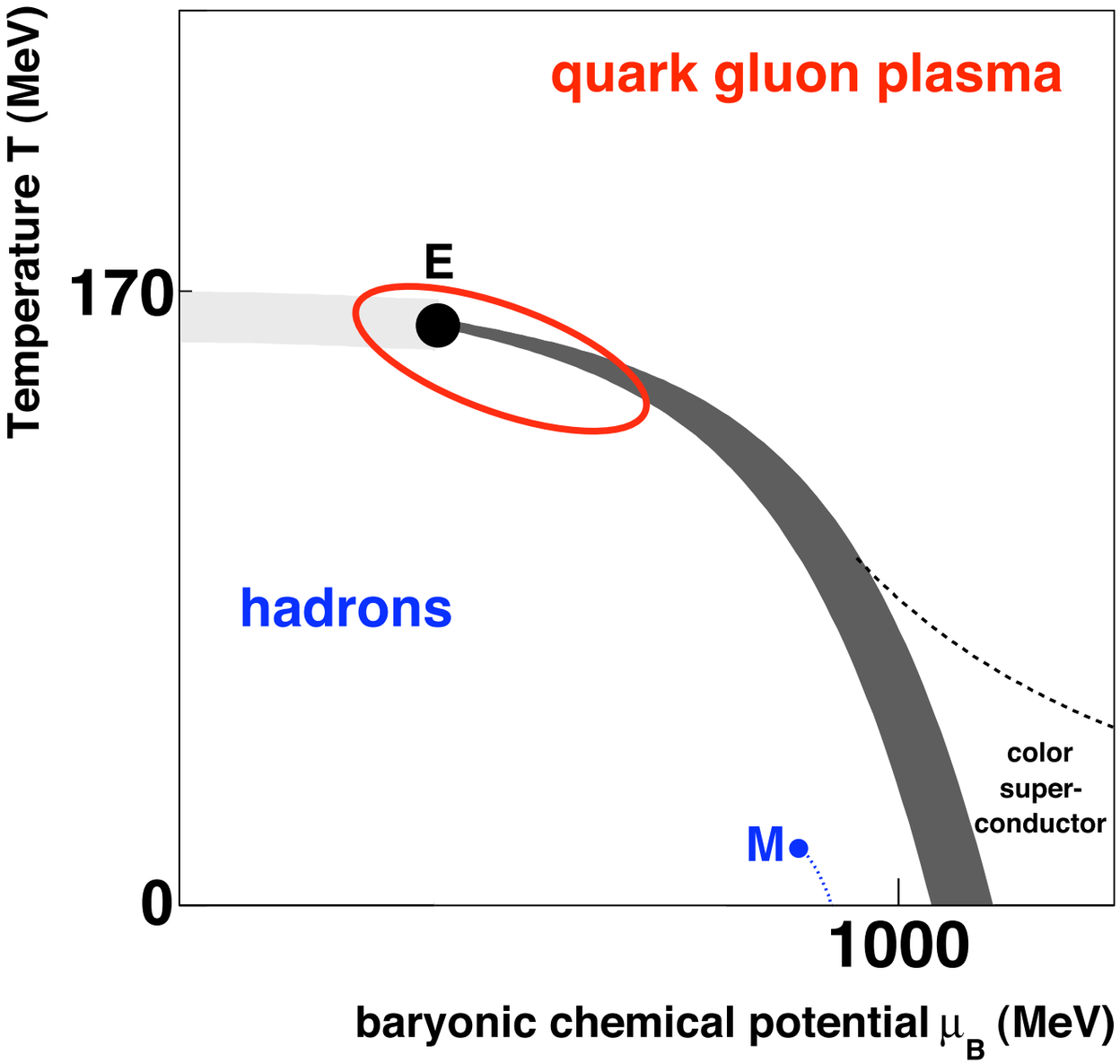
Michael K. Mitrovski

Outline

1. Introduction.
2. The NA49 experiment.
3. Search for structures in the energy dependence to discover a signal of onset of deconfinement
    a. Particle yields and spectra
    b. Anisotropic flow
    c. Bose-Einstein correlations
4. Conclusion.

Fluctuations (see Talk of Tim Schuster)

Phase Diagram of Strongly Interacting Matter



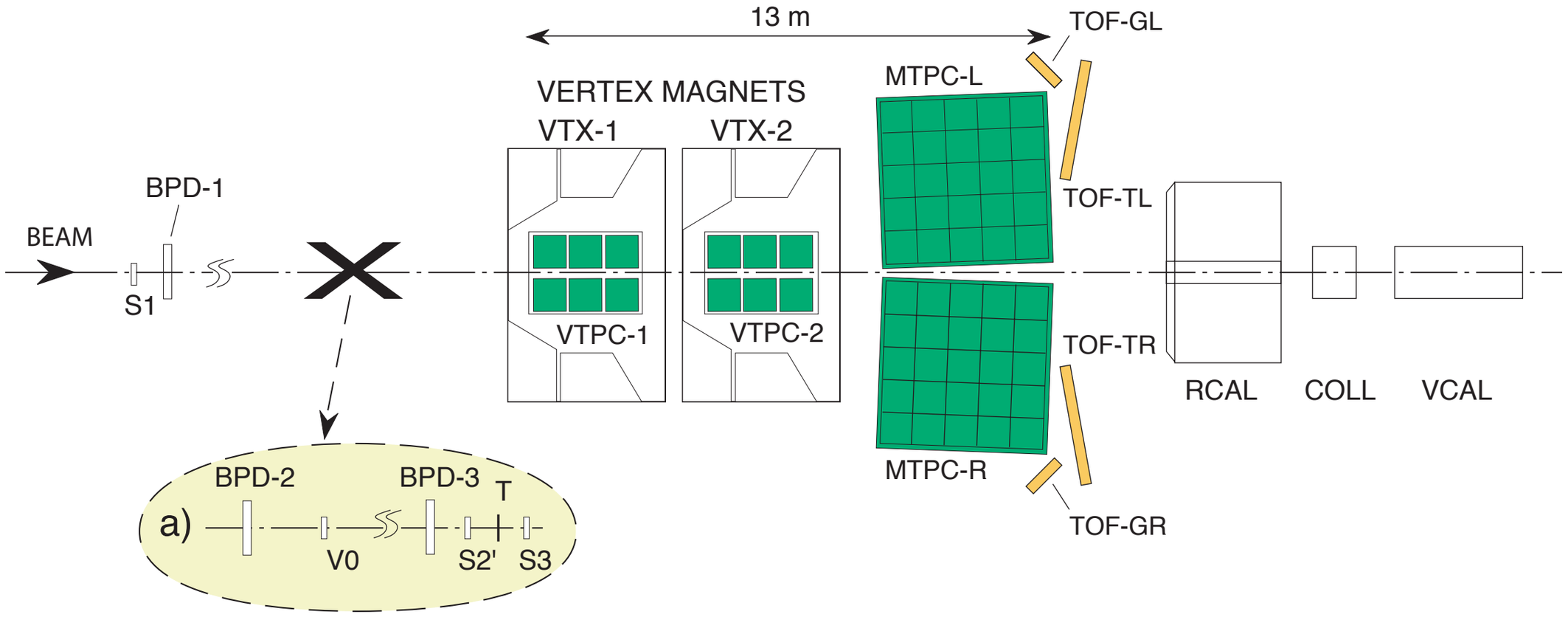
- Is a phase transition reflected in hadronic observables?
- NA49 at CERN SPS allows to explore an essential part of the phase diagram
  - In order to search for the onset of deconfinement NA49 started in 1997 the energy scan program
  - E_{cm} = 6.3 - 17.3 GeV

Critial Point and crossover from Lattice-QCD:
Fodor et. al.:JHEP 0404 (2004) 050

The CERN Accelerator Complex

- E_{CM} from 6.3 - 17.3 GeV.
- Beam species from proton to Pb.

The NA49 Experiment



- **Large acceptance hadron spectrometer:**
  - **TPC: Q, $\vec{x}$, $\vec{p}$, dE/dx**
  - **TOF: time of flight**
- **Centrality by the Veto-Calorimeter.**

- **pions, kaons and protons: dE/dx in TPCs + TOF (mid-rapidity).**
- **K^0_s,Λ,Ξ,Ω : decay topology + inv. mass. + dE/dx**
- **φ, K^*, Λ^* : inv. mass. + dE/dx**

Collected A+A Data

E_{CM}	System	Centrality	Statistics
17.3 GeV	Pb+Pb	10%, 23%	800k, 3M
		min. bias	410k
	C+C, Si+Si	15%, 12%	220k, 300k
	p+p	min. bias	6.8M
12.3 GeV	Pb+Pb	7%	300k
8.7 GeV	Pb+Pb	7%	600k
		min. bias	750k
	C+C, Si+Si	66%, 29%	240k, 130k
7.6 GeV	Pb+Pb	7%, 35%	440k, 230k
6.3 GeV	Pb+Pb	7%, 35%	360k, 330k

Scenarios for the Onset of Deconfinement

a) Particle yields and spectra

- **"Horn", "Step" and "Kink": Equilibration at early stage of both hadron gas and QGP.**
  (Gazdzicki, Gorenstein:APP B30 (1999) 2705)

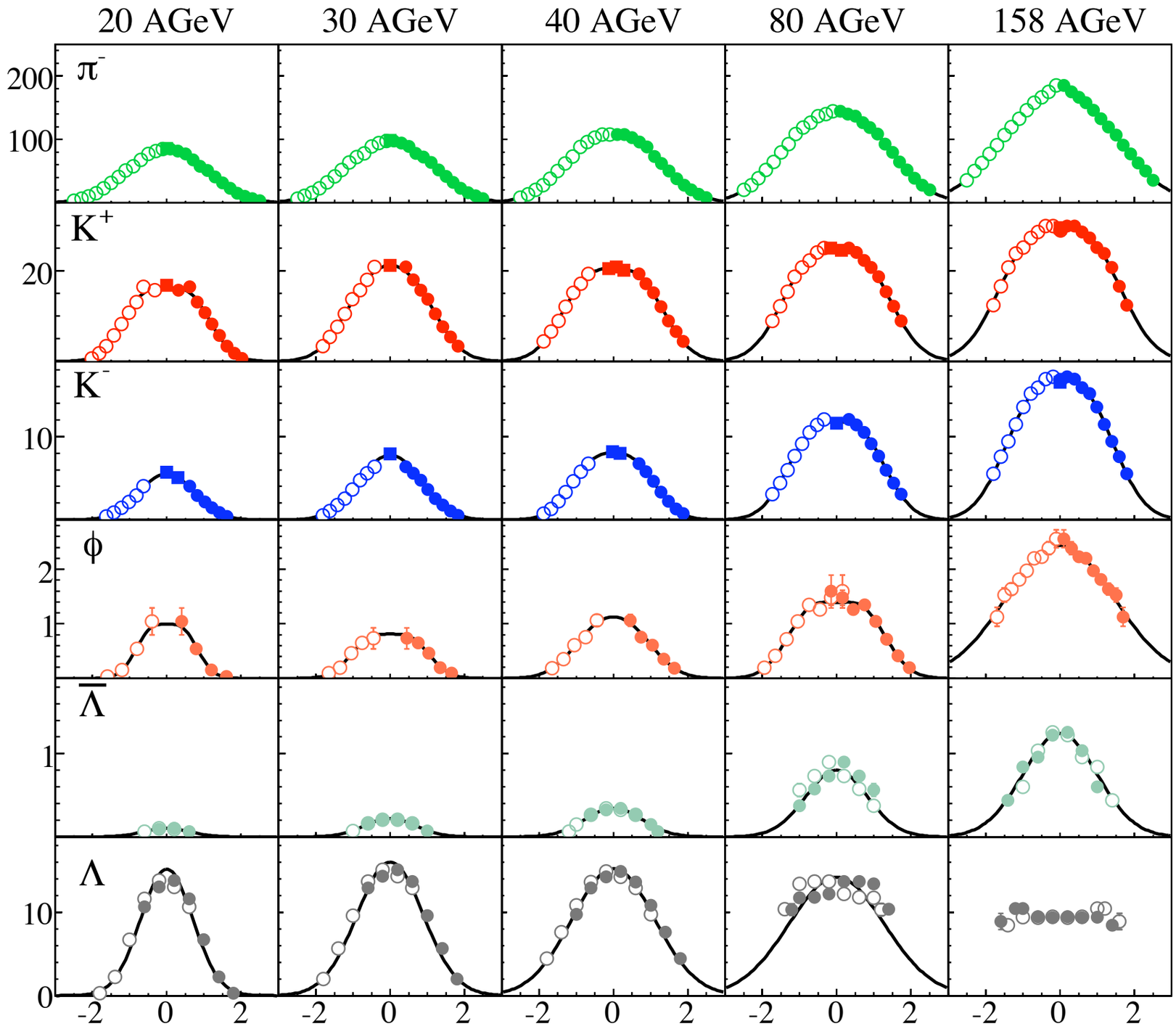
- **Minimum in the sound velocity: Observation of the softest Point in the EoS.**
  (Bleicher:arXiv:hep-ph/0509314)

- **Experimental access: Systematic study of (strange) hadron production as a function of energy and system size.**

b) Anisotropic flow

c) Bose-Einstein correlations

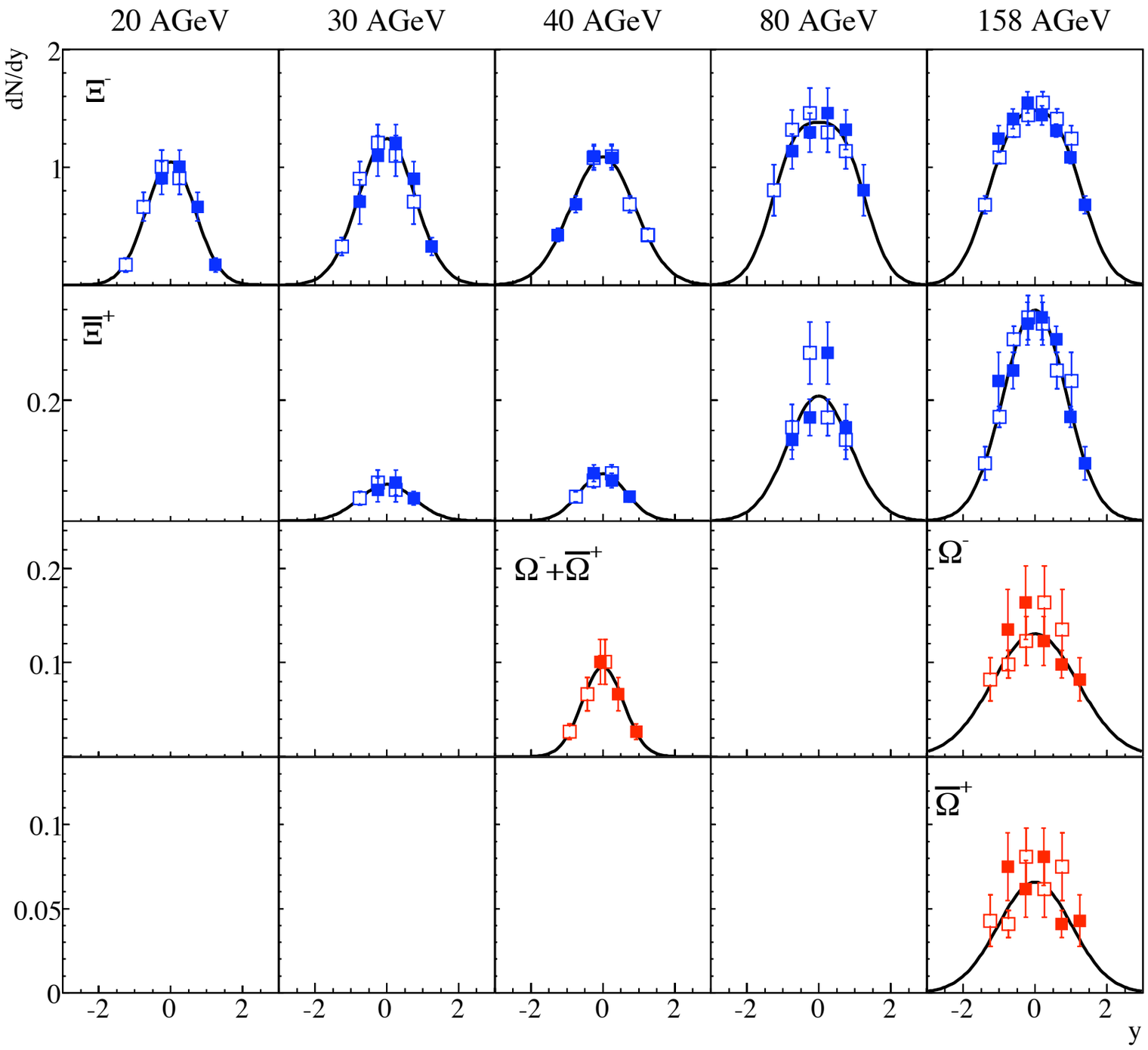
Rapidity Spectra



- **(Double-) Gaussian shape for all particles, with exception of Λ at higher energies.**

NA49 Ref.: [1], [2], [8], [10]

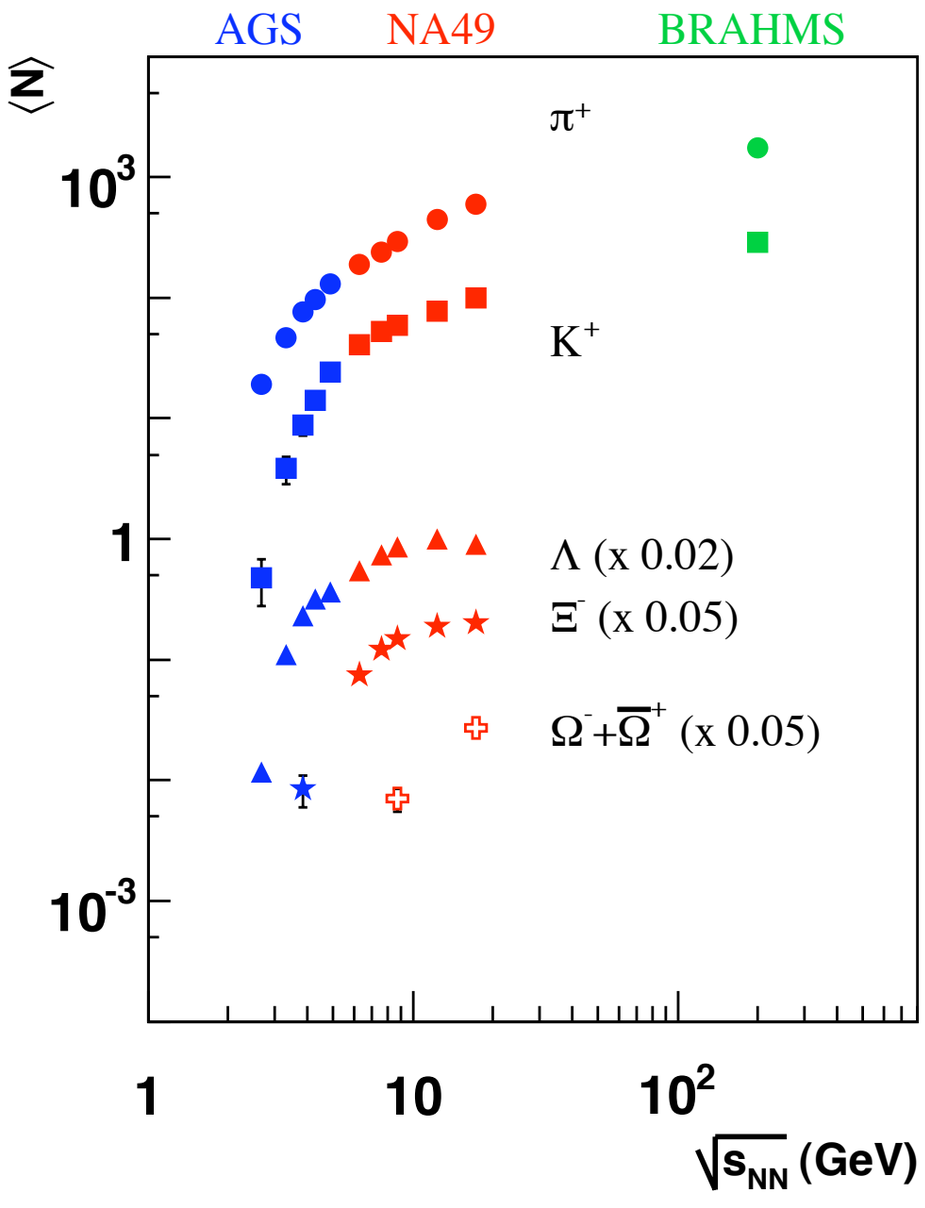
Rapidity Spectra

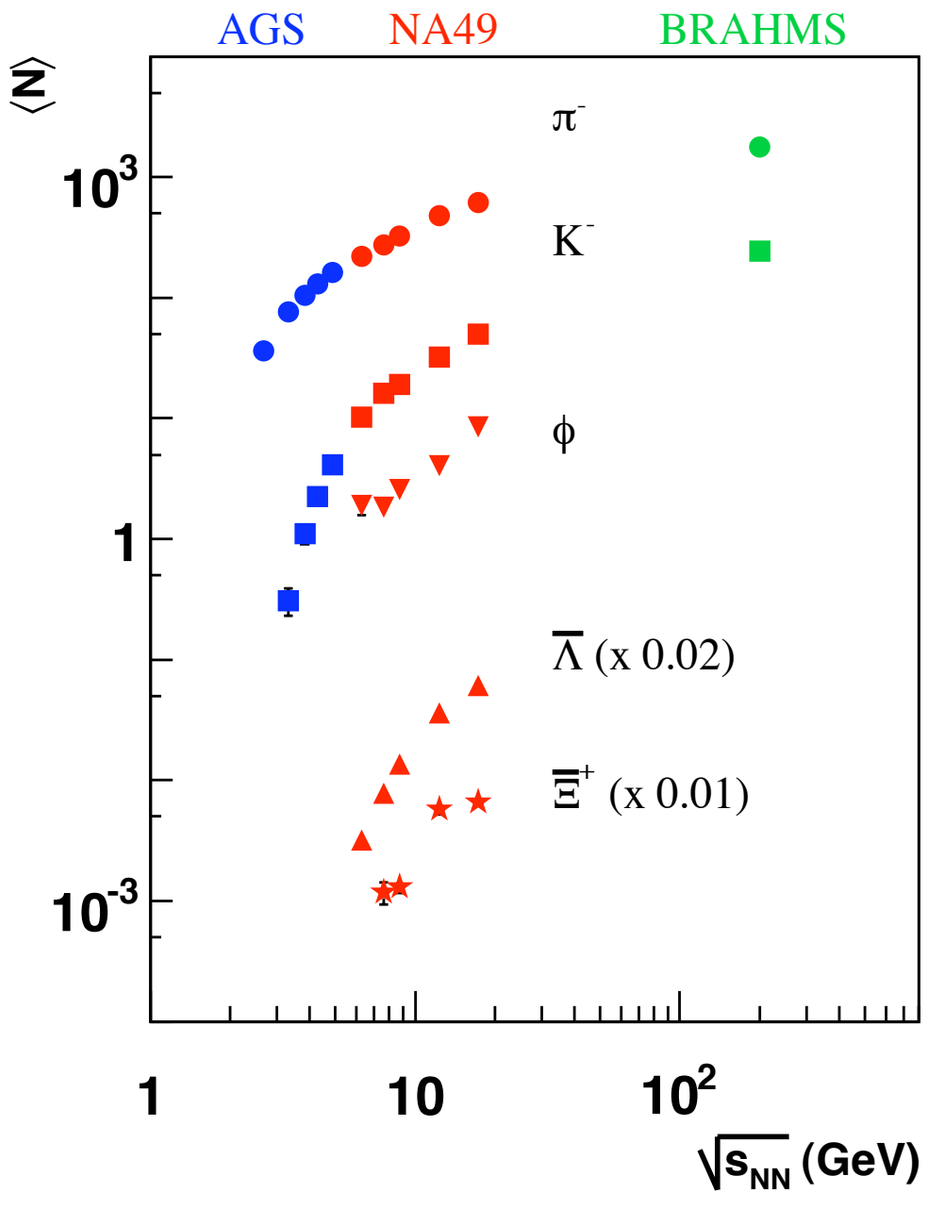


- **First measurements of Ξ and Ω rapidity spectra.**
- **Shape is ≈ Gaussians.**

NA49 Ref.: [7], [9]

4π Particle Yields

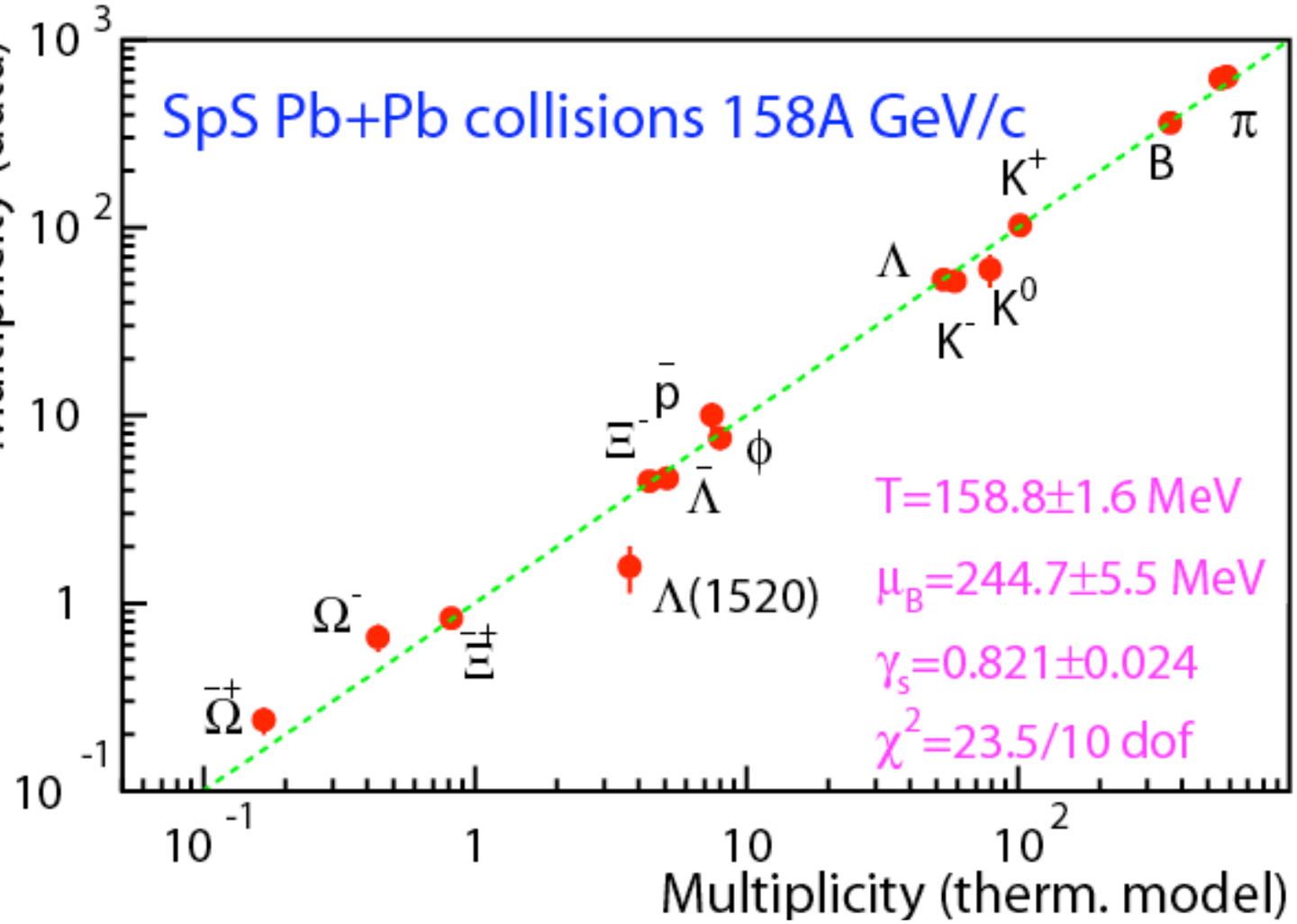




- **Weak energy dependence for Λ at SPS.**

NA49 Ref.: [1]-[11]

Statistical Model

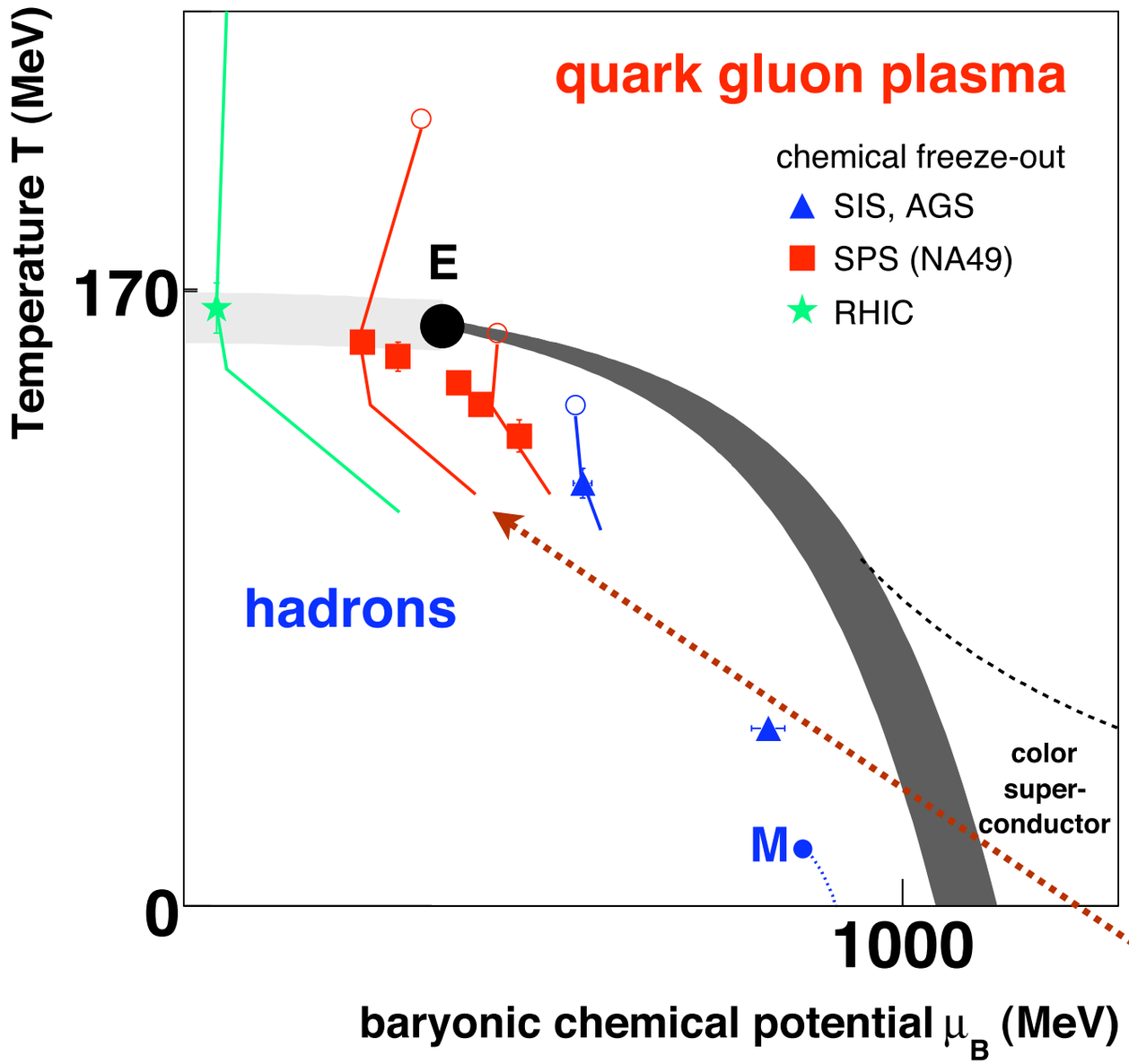


- **Assumption of chemical equilibrium at freeze-out.**
- **Particle production can be described with a few parameters: V, T, μ_B, γ_S.**
- **Extract chemical freeze-out parameters → phase diagram.**

$$\langle n_i \rangle = \frac{(2J_i+1)\ V}{(2\pi)^3} \int d^3p\ \frac{1}{\gamma_s^{-S_i} exp[(E_i - (\mu_B + \mu_S + \mu_Q))/T] \pm 1}$$

Model:
Becattini et al. :PR C73 (2006) 044905

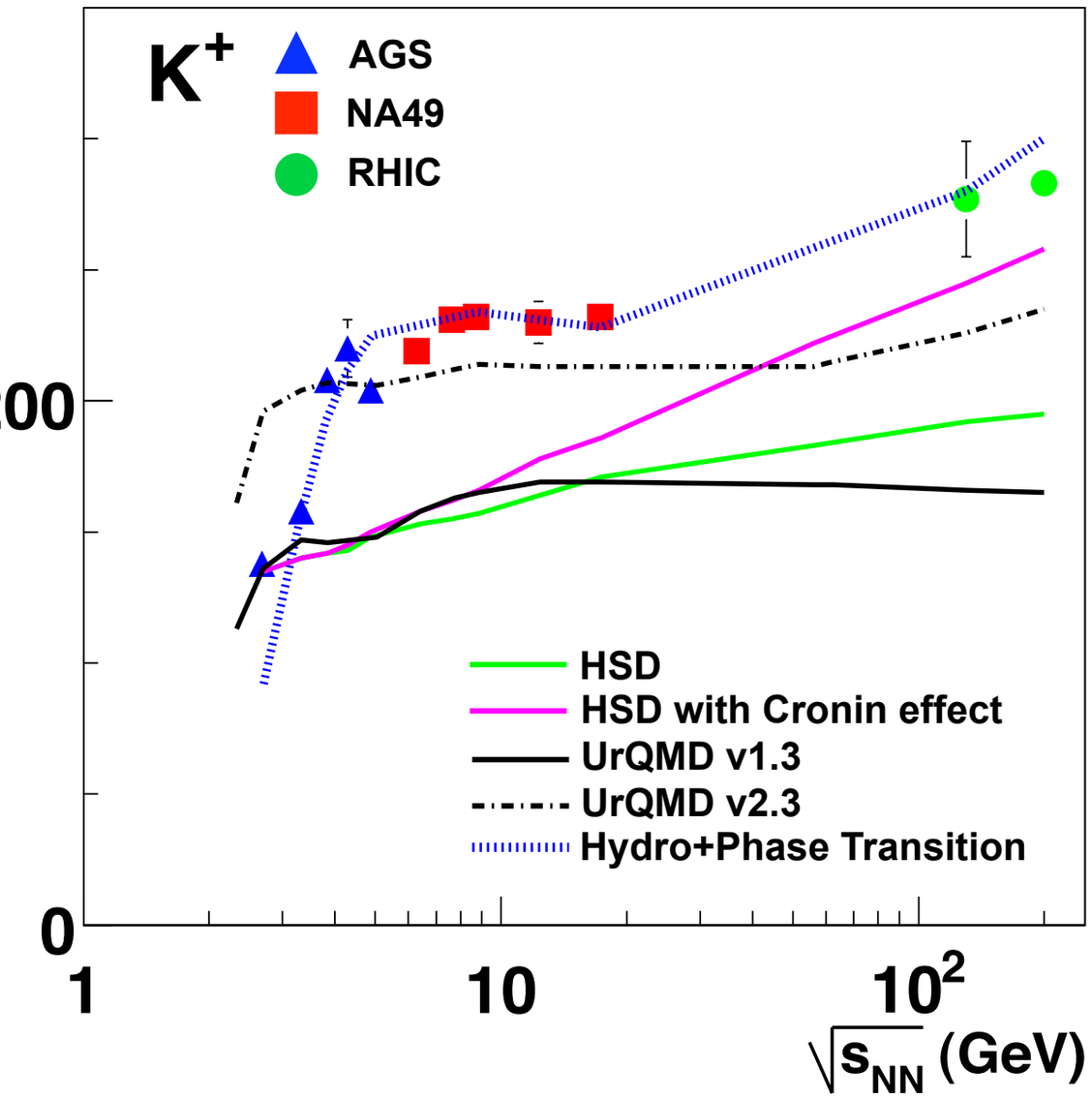
Phase Diagram of Strongly Interacting Matter



- **Chemical freeze-out points approach phase boundary at top SPS energies.**
- **Look for signatures for the onset of deconfinement and the critical point.**

Critial Point and crossover from Lattice-QCD:
Fodor et. al.:JHEP 0404 (2004) 050

Inverse Slope Parameter

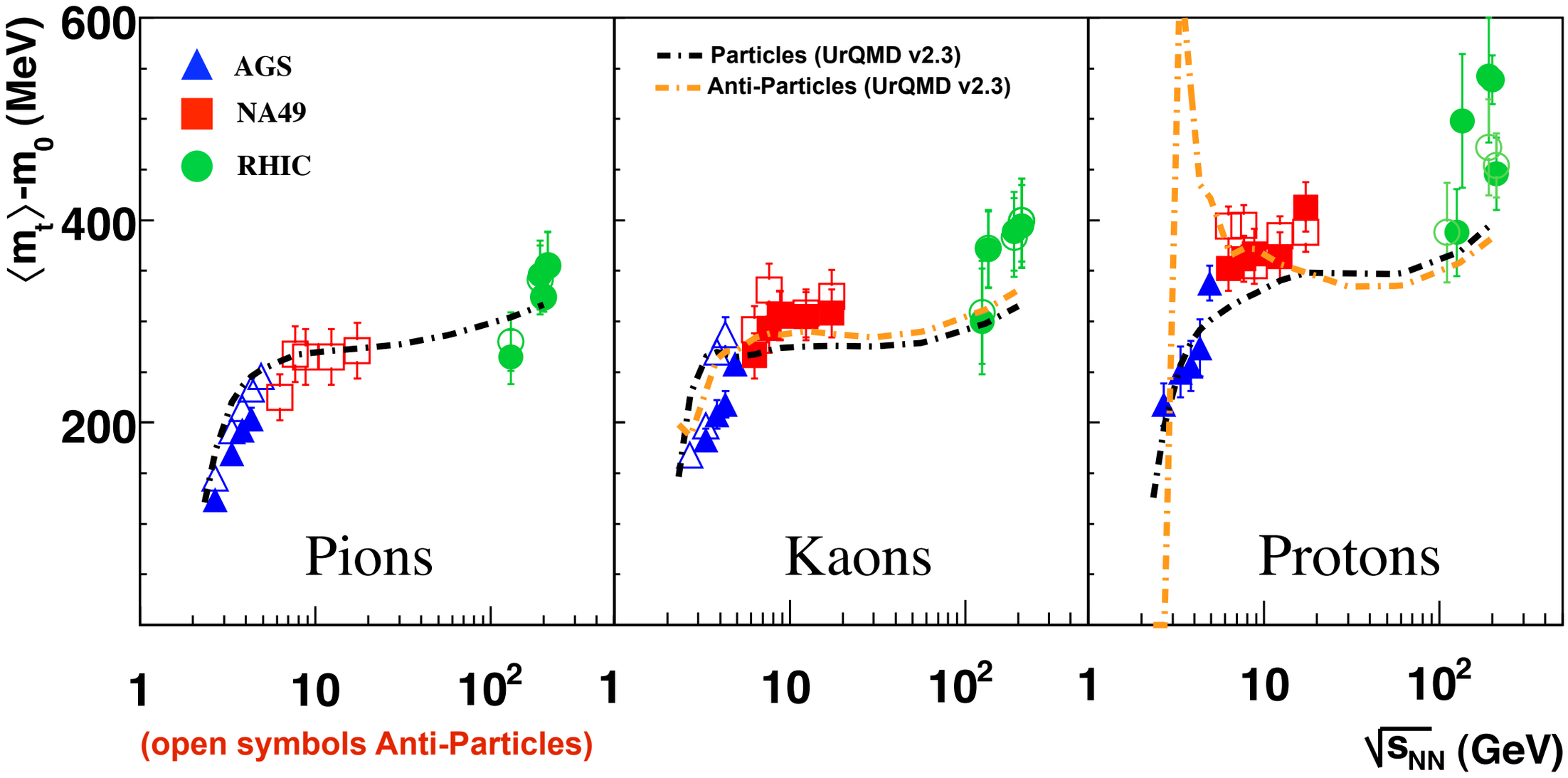


- A step-like dependence is observed at SPS energies.
- Large deviation between various string-hadronic models
  - UrQMD v2.3 describes the data approximatly
- Model with 1st order phase transition describe the spectra well.

HSD:Bratkovskaya et al.:PRC 69 (2004) 054907
UrQMD:Bleicher et al.:arXiv:0805.0567
Hydro+Phase+Phase Transition:Gazdzicki et al.:BJP 34 (2004) 322

NA49 Ref.: [1], [2]

$\langle m_t \rangle - m_0$



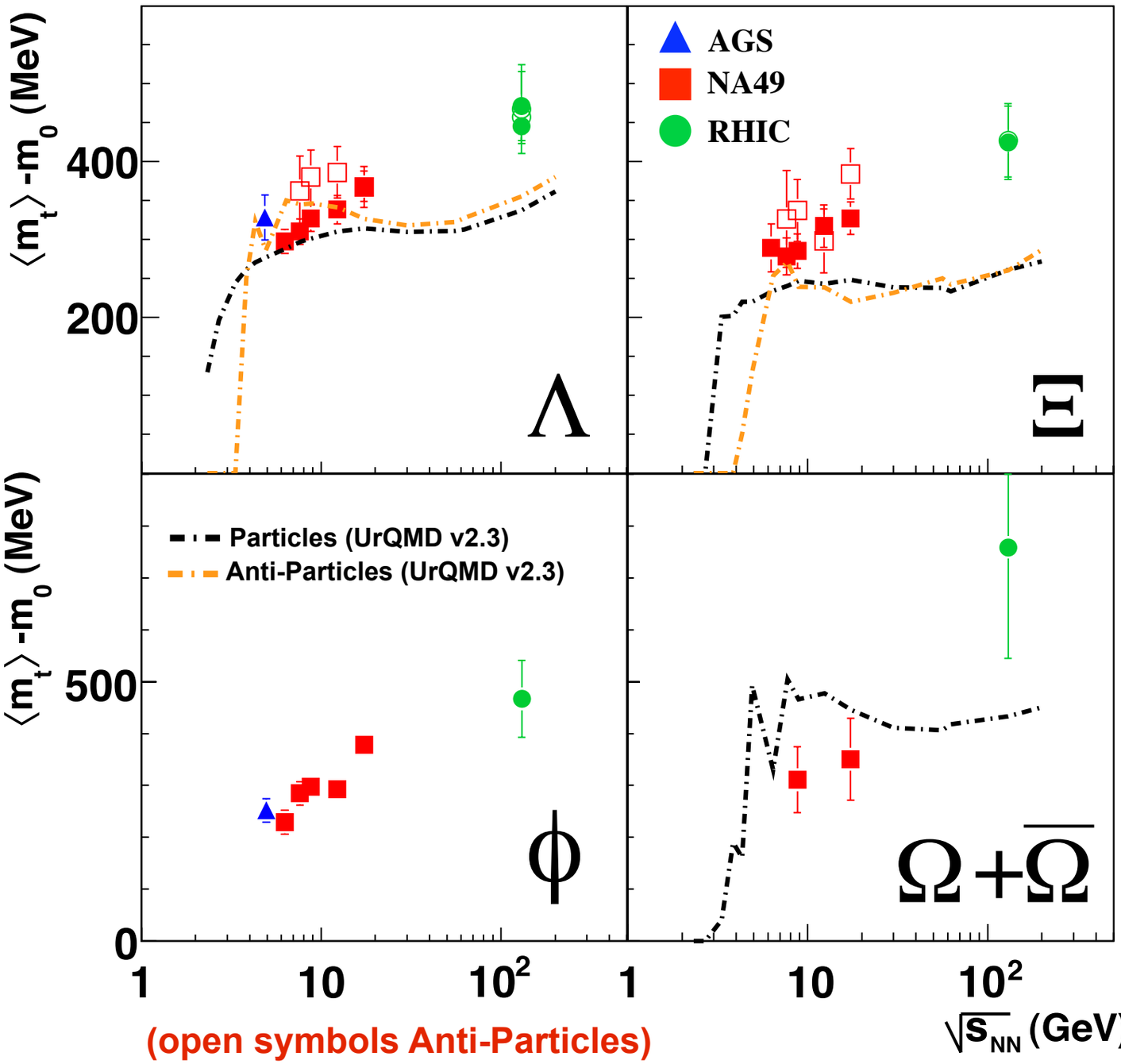
(open symbols Anti-Particles)

- The step-like behaviour is seen for Pions, Kaons and Protons
  - → UrQMD 2.3 reproduces approximately the data
  - → Signature of change of EoS due to phase transition?

UrQMD:Bleicher et al.:arXiv:0805.0567

NA49 Ref.: [1]-[4]

$\langle m_t \rangle - m_0$



- **No significant energy dependence of $\langle m_t \rangle - m_0$ in SPS energy range**

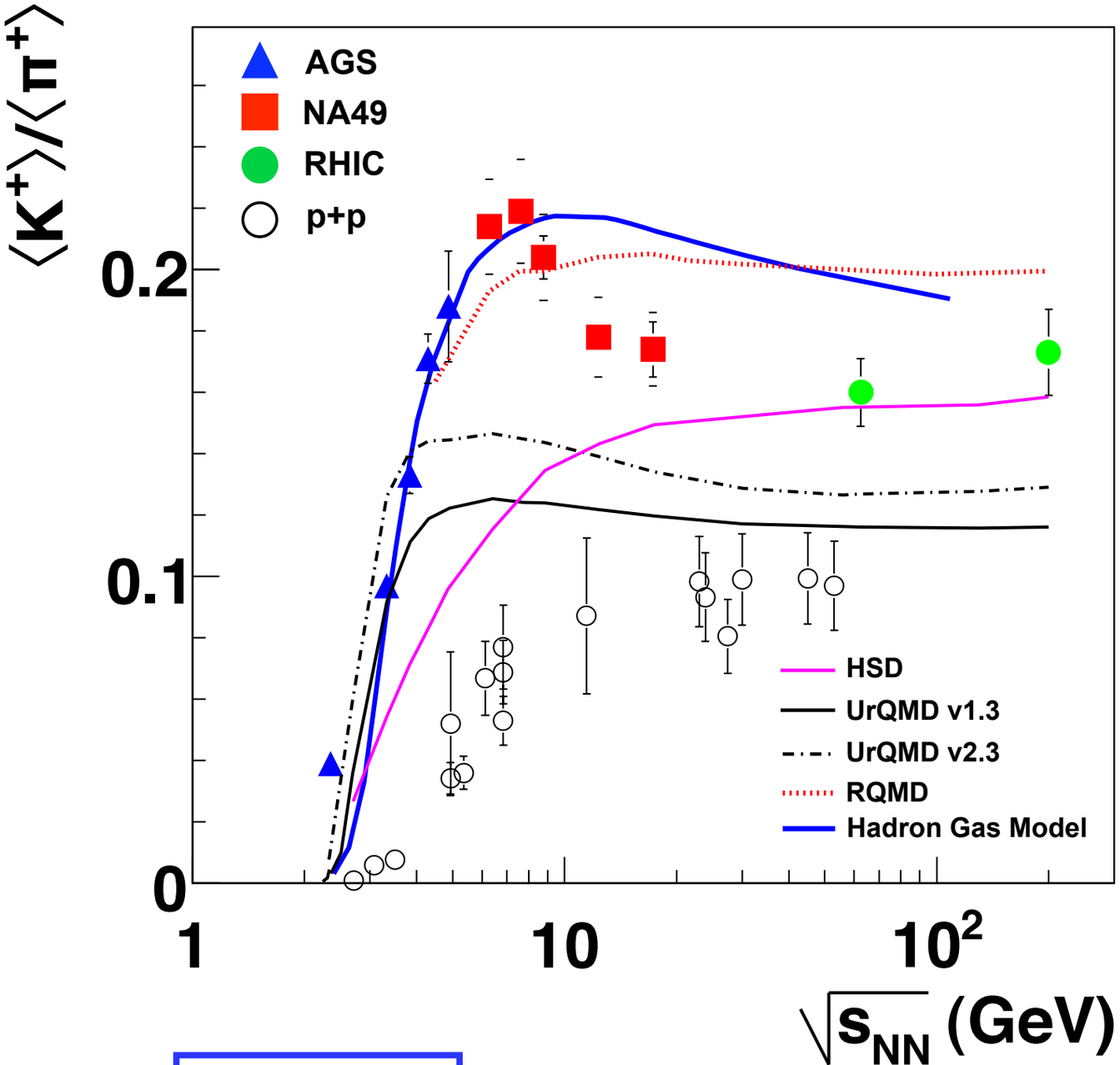
→ **Missing measurements for heavier particles at FAIR energies**

→ **FAIR up to $\sqrt{s_{NN}}$ = 10 GeV (E=45 *A*GeV)**

UrQMD:Bleicher et al.:arXiv:0805.0567

NA49 Ref.: [5], [7]-[10]

4π Particle Ratios

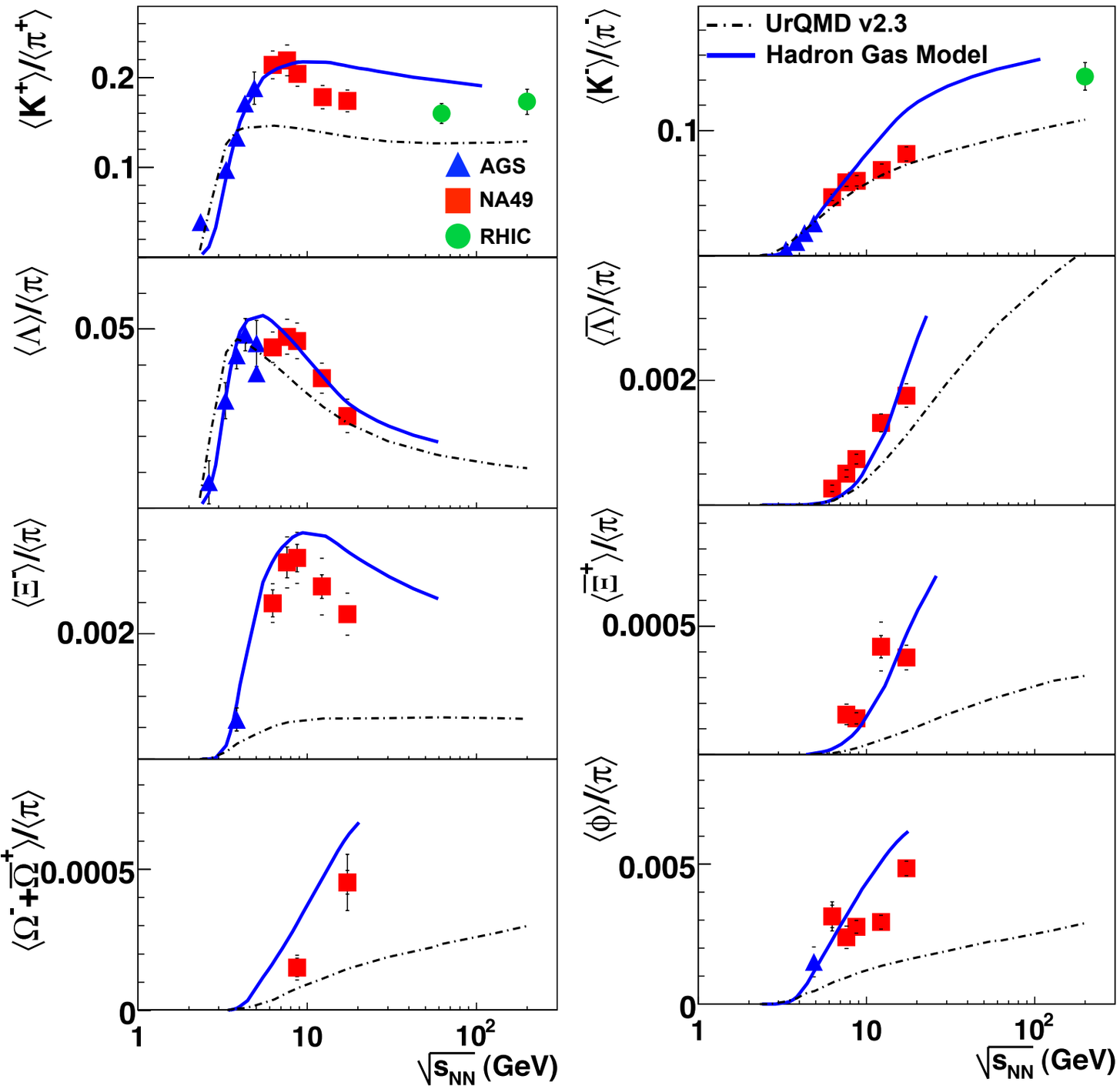


- Non-monotonic structure in A+A, not visible in p+p.
- Large deviation between various string-hadronic models.
- Hadron gas model reproduces the trend in the AGS and lower SPS region, but overestimate it at higher SPS and RHIC energies.

NA49 Ref.: [1], [2]

HSD:Bratkovskaya et al.:PRC 69 (2004) 054907
UrQMD:Bleicher et al.:arXiv:0805.0567
RQMD:Sorge et al.:NPA 498 (1989) 567
Hadron Gas:Cleymans et al.:PRC 60 (1999) 054908

4π Particle Ratios



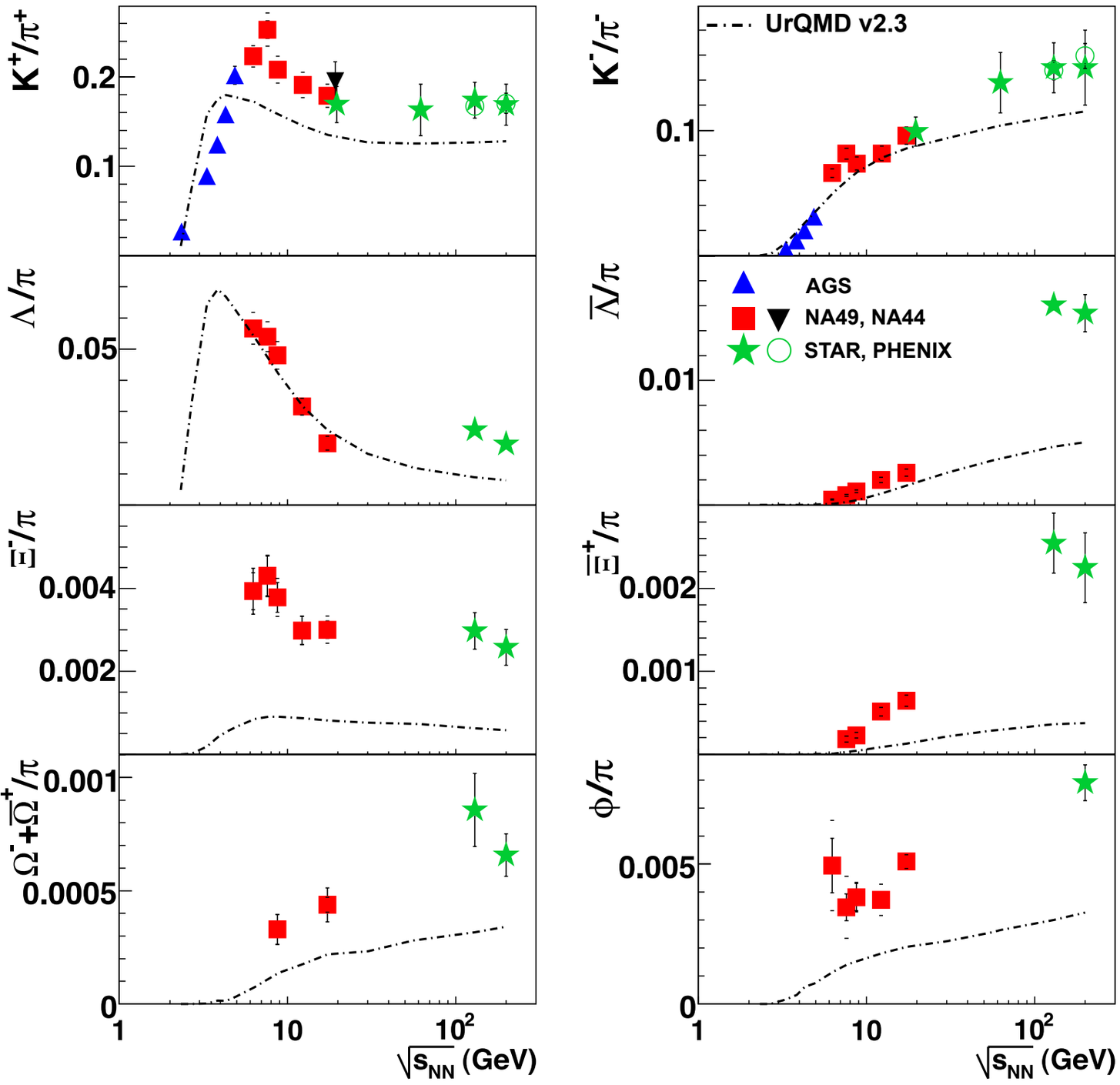
- Maximum for K^+, Λ, Ξ^- at low SPS energies.
- Increase of K^-, $\bar{\Lambda}$, $\bar{\Xi}^+$, Φ, $\Omega^-+\bar{\Omega}^+$ from AGS to RHIC energies.

UrQMD:Bleicher et al.:arXiv:0805.0567
Vogel:Private communication
Hadron Gas:Cleymans et al.:PRC 60 (1999) 054908

$$\langle\pi\rangle = 1.5 \cdot (\langle\pi^+\rangle + \langle\pi^-\rangle)$$

NA49 Ref.: [1]-[11]

Midrapidity Particle Ratios



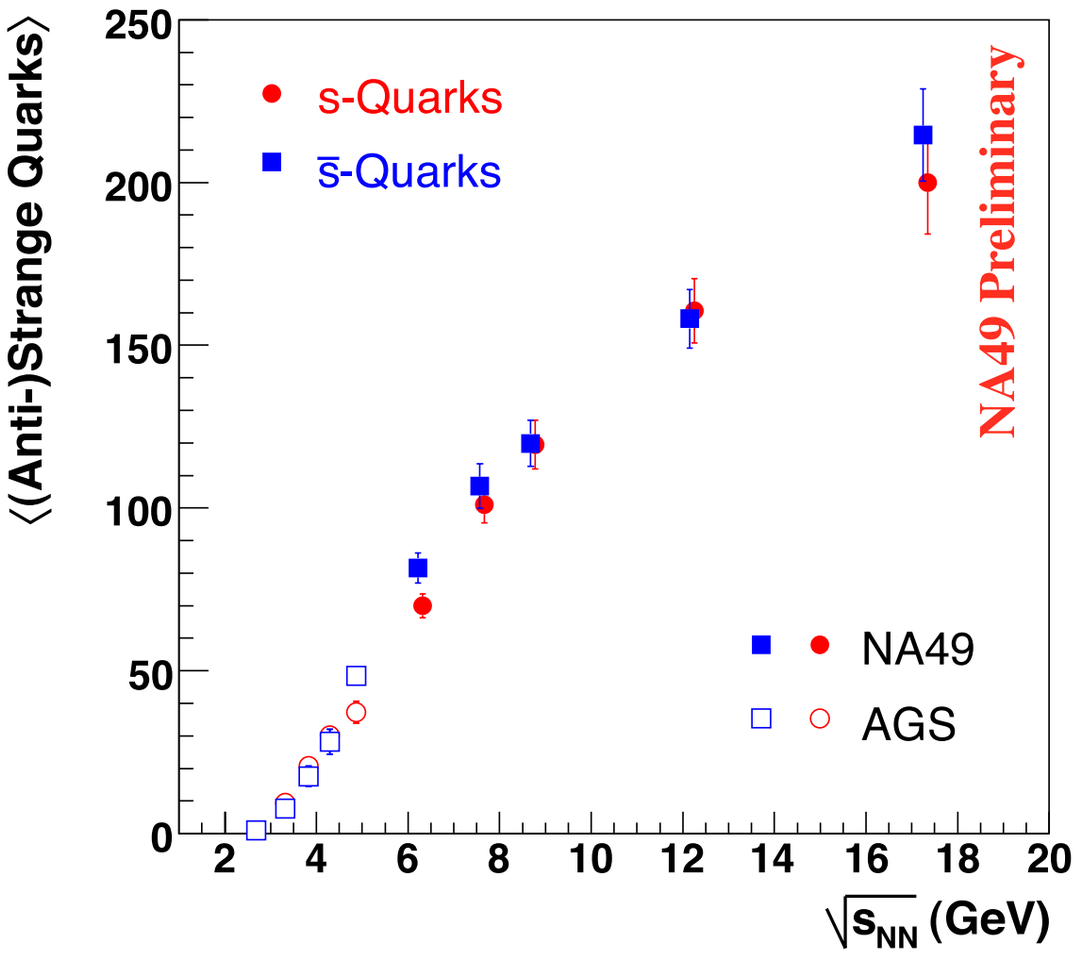
- Maximum for K^+, Λ, Ξ^- at low SPS energies.
- Increase of K^-, $\bar{\Lambda}$, $\bar{\Xi}^+$, Φ, $\Omega^-+\bar{\Omega}^+$ from AGS to RHIC energies.

UrQMD:Bleicher et al.:arXiv:0805.0567
Vogel:Private communication

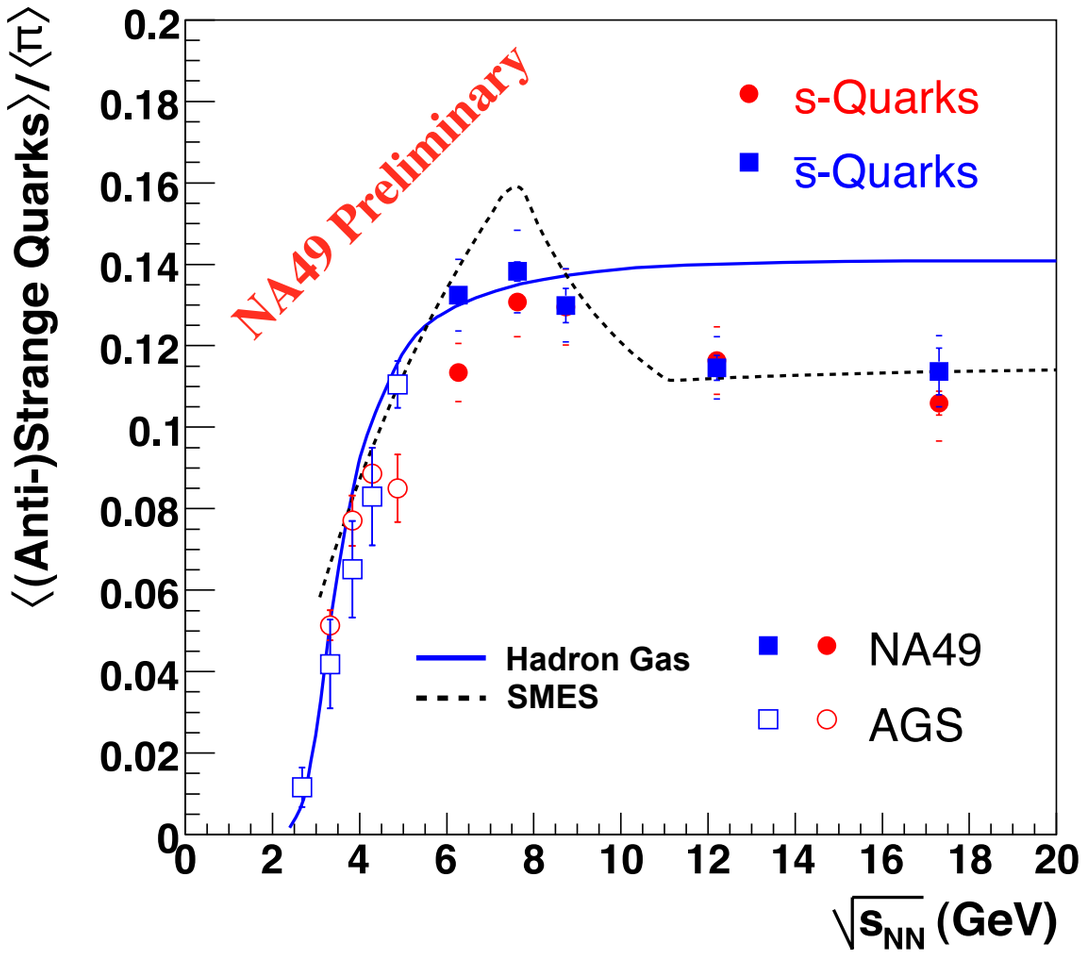
$$\pi = 1.5 \cdot (\pi^+ + \pi^-)$$

NA49 Ref.: [1]-[11]

Comparison s- and s̄-carriers



- Consistent results for s and s̄ quarks.
- Energy dependence of strangeness is changing at 30 *A*GeV.



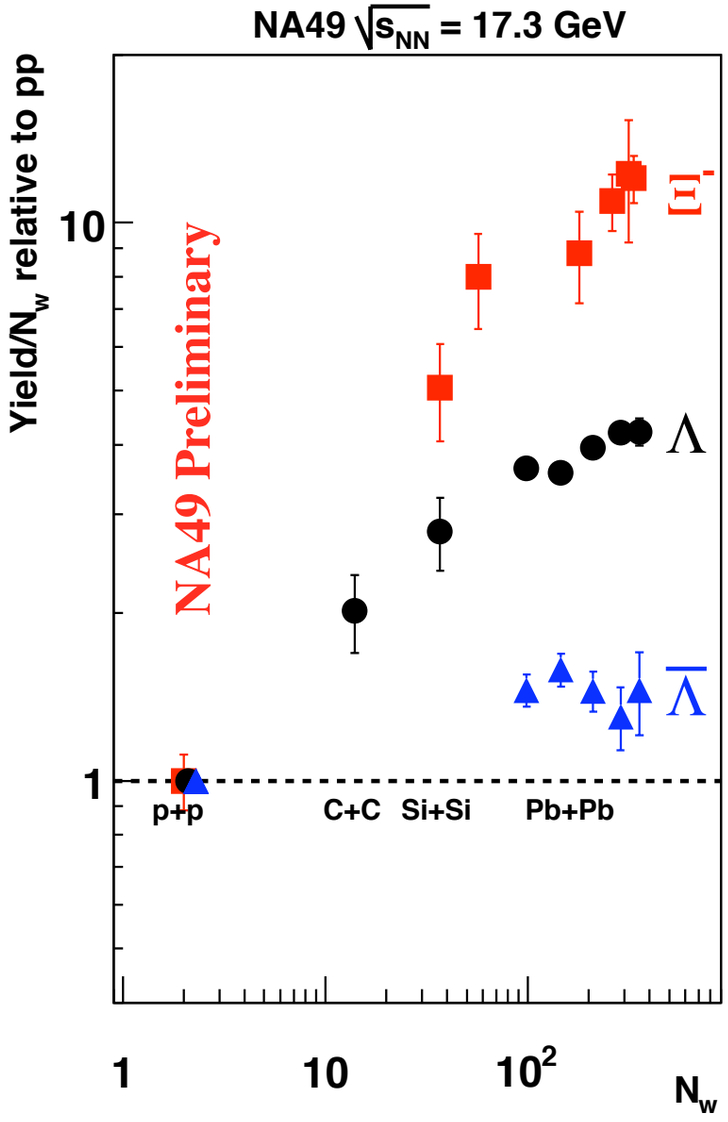
- Maximum in strangeness/π ratio.
- Not reproduced by hadron gas models.
- Can be described assuming the onset of deconfinement.

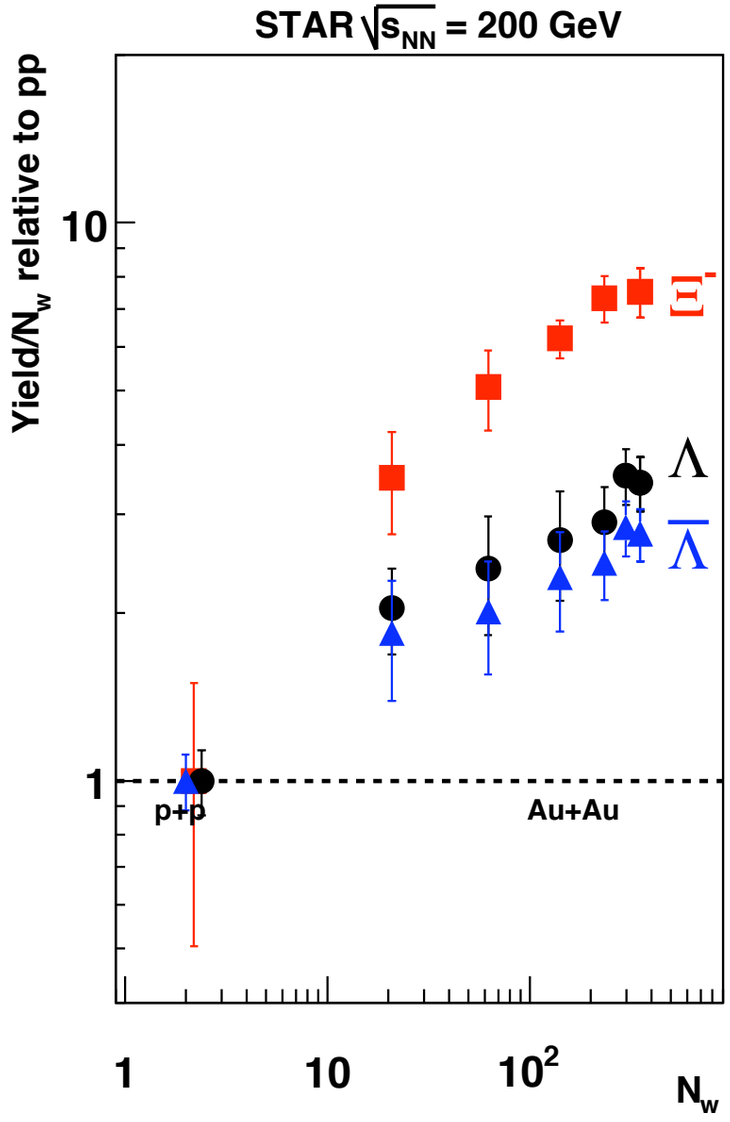
(1) $\langle K^0 \rangle \approx \langle K^+ \rangle$, $\langle \overline{K^0} \rangle \approx \langle \overline{K^-} \rangle$ due to isospin symmetry
(2) empirical factor $\langle \Sigma^\pm \rangle \approx 0.6 \langle \Lambda \rangle + \Sigma^0$
(3) From hadron gas model if not measured

s-quark carriers :	s̄-quark carriers :
K^-, $\overline{K^0}$ 1)	K^+, K^0 1)
$\Lambda+\Sigma^0$, $\Sigma^\pm$ 2)	$\overline{\Lambda+\Sigma^0}$, $\overline{\Sigma^\pm}$ 2)
Ξ^-, Ξ^0, Ω^- 3)	$\overline{\Xi^+}$, $\overline{\Xi^0}$, $\overline{\Omega^+}$ 3)

Hadron Gas:Cleymans et al.:PRC 60 (1999) 054908
SMES:MG et al.:APP B30 (1999) 2705

Hyperon Enhancement





- Strong increase of yields with centrality (NA57 observes similar behavior).
- Enhancement stronger for Ξ than for Λ and $\overline{\Lambda}$.
- Stronger enhancement at SPS than at RHIC energies.
- Shape for Λ and $\overline{\Lambda}$ is different at SPS compared to RHIC energies.

$$Enhancement = \left(\frac{Yield}{N_W}\right)_{A+A} \Big/ \left(\frac{Yield}{N_W}\right)_{p+p}$$

NA49 Ref.: [9], [12]

Scenarios for the Onset of Deconfinement

a) Particle yields and spectra

b) Anisotropic flow

- **Proton antiflow near midrapidity.**

  (Stöcker:NPA 750 (2005) 121,
  Brachmann et al.:PRC 61 (2000) 024909,
  Csernai et al.:PLB 458 (1999) 454)

- **Collapse of Proton v_2 at midrapidity.**

  (Stöcker:NPA 750 (2005) 121)

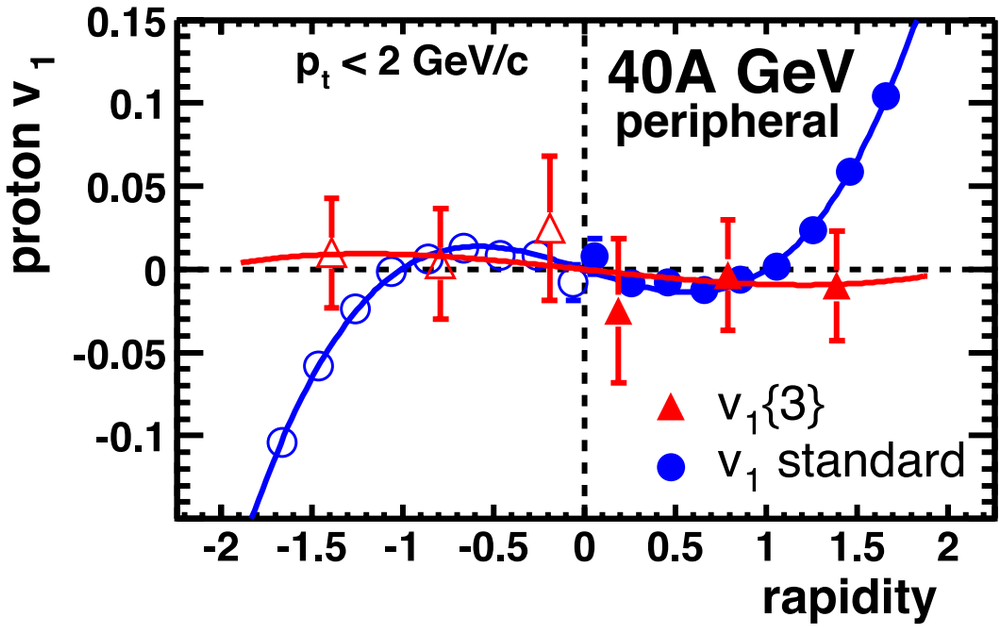
- **Weakening of v_2 as a function of E_{cm}.**

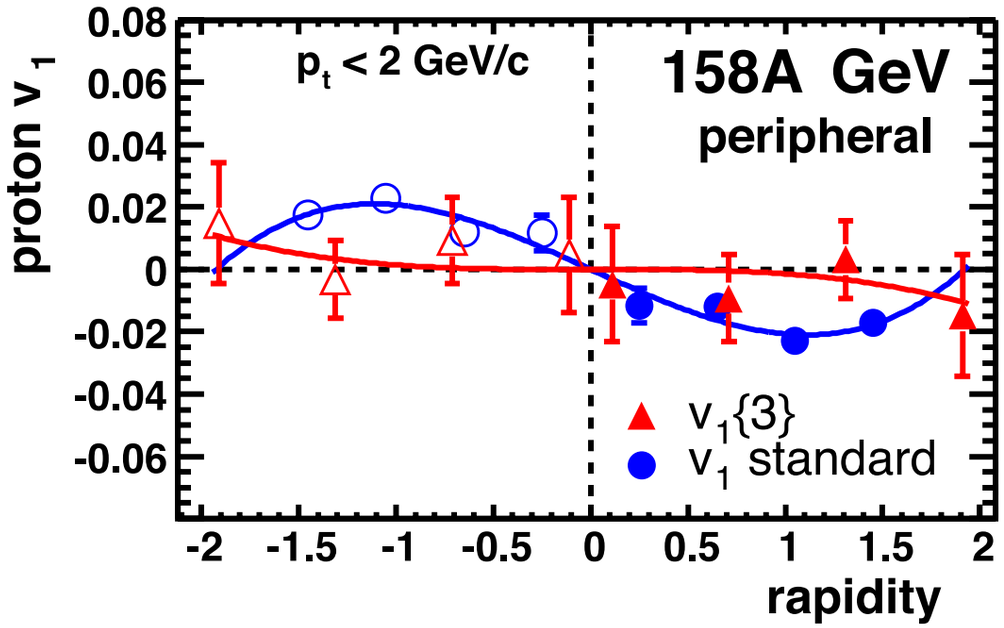
  (Kolb et al.:PRC 62 (2000) 054909)

- **Experimental access: Systematic study of hadron v_1 and v_2 as a function of energy and centrality.**

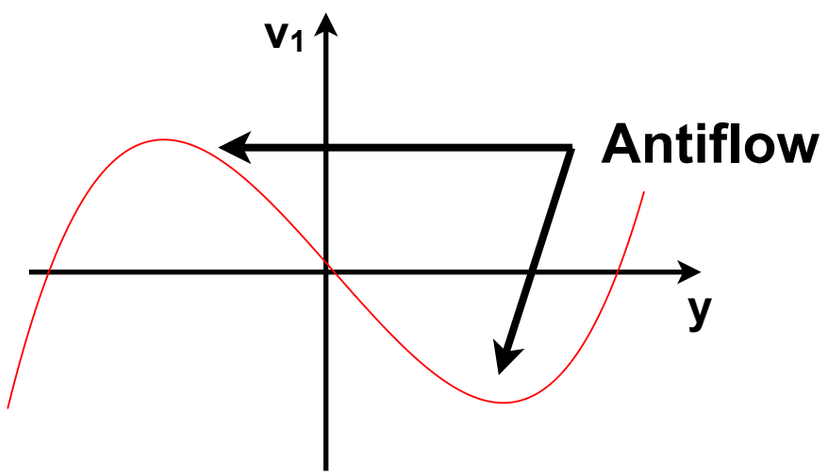
c) Bose-Einstein correlations

Directed Flow of Protons





- At 40 *A*GeV a difference in the shape of v_1 for peripheral collisions is visible by using different flow analysis techniques.
- At 158 *A*GeV a same difference is visible between the different analysis methods like at 40 *A*GeV.



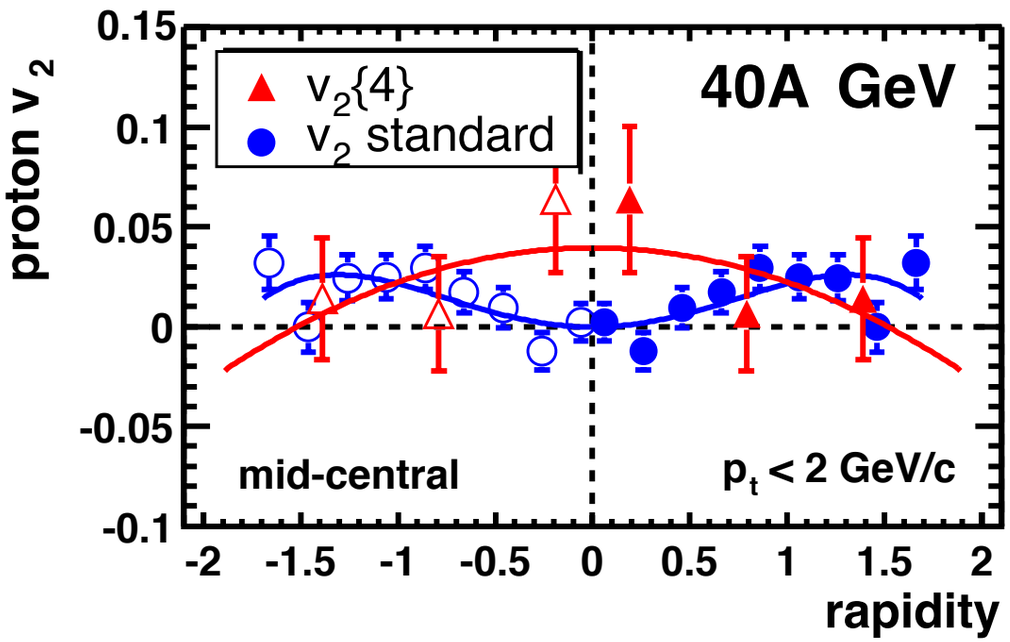
⇒ No clear conclusion can be drawn whether antiflow is visible in the v_1 of Protons.

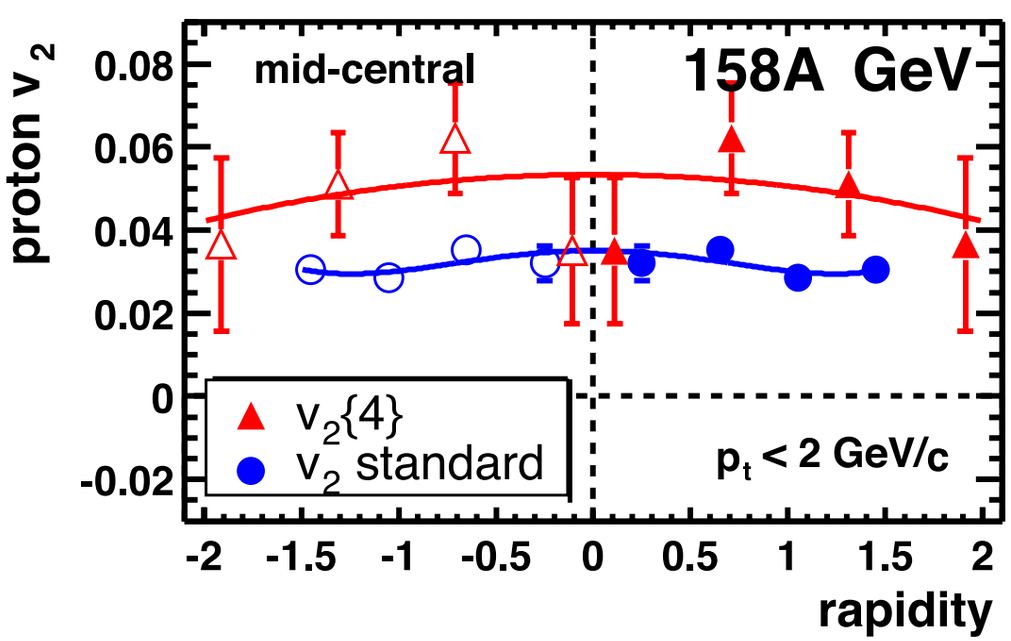
Csernai et al.:PLB 458 (1999) 454
Stöcker:NPA 750 (2005) 121
Brachmann et al.:PRC 61 (2000) 024909

$peripheral : \sigma/\sigma_T = 43.5\% -$

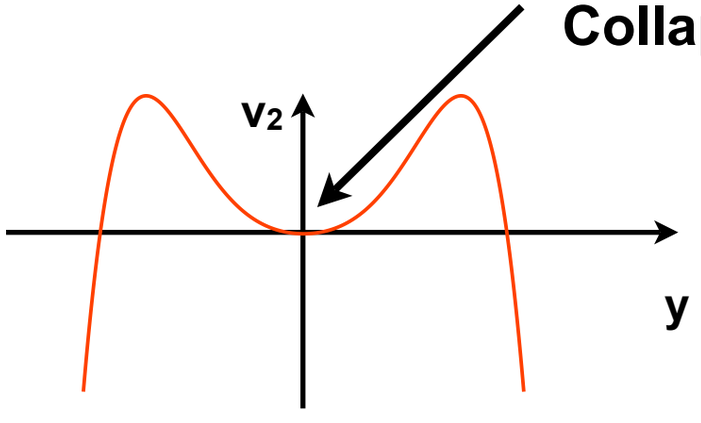
NA49 Ref.: [15]

Elliptic Flow of Protons





- At 40 *A*GeV a difference in the shape of v_2 for central collisions is visible by using different flow analysis techniques.
- At 158 *A*GeV the elliptic flow is too small to use four-particle cumulants due to statistical fluctuations.



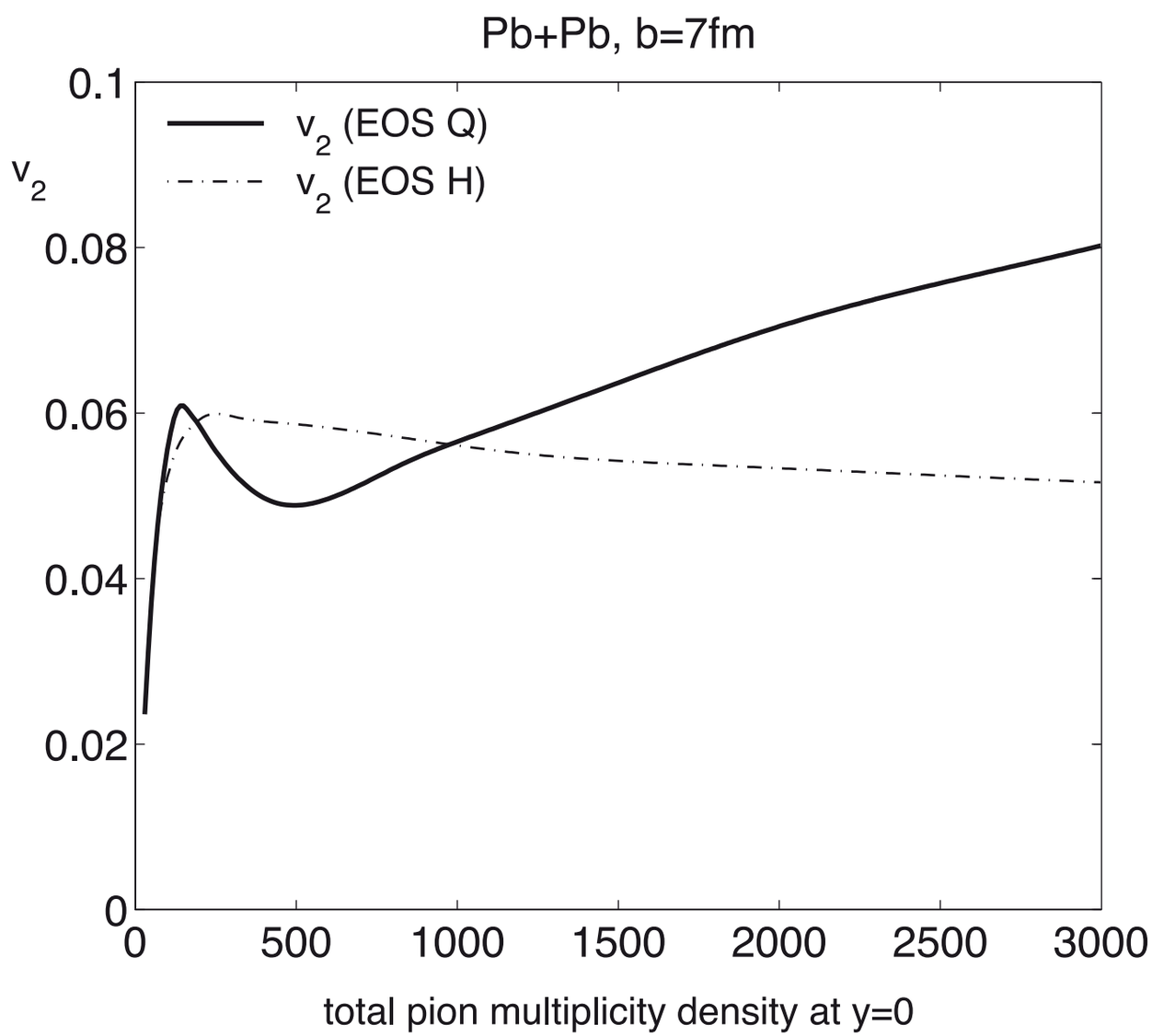
Collapse ⇒ **No clear conclusion can be drawn whether the collapse of Proton v_2 is visible.**

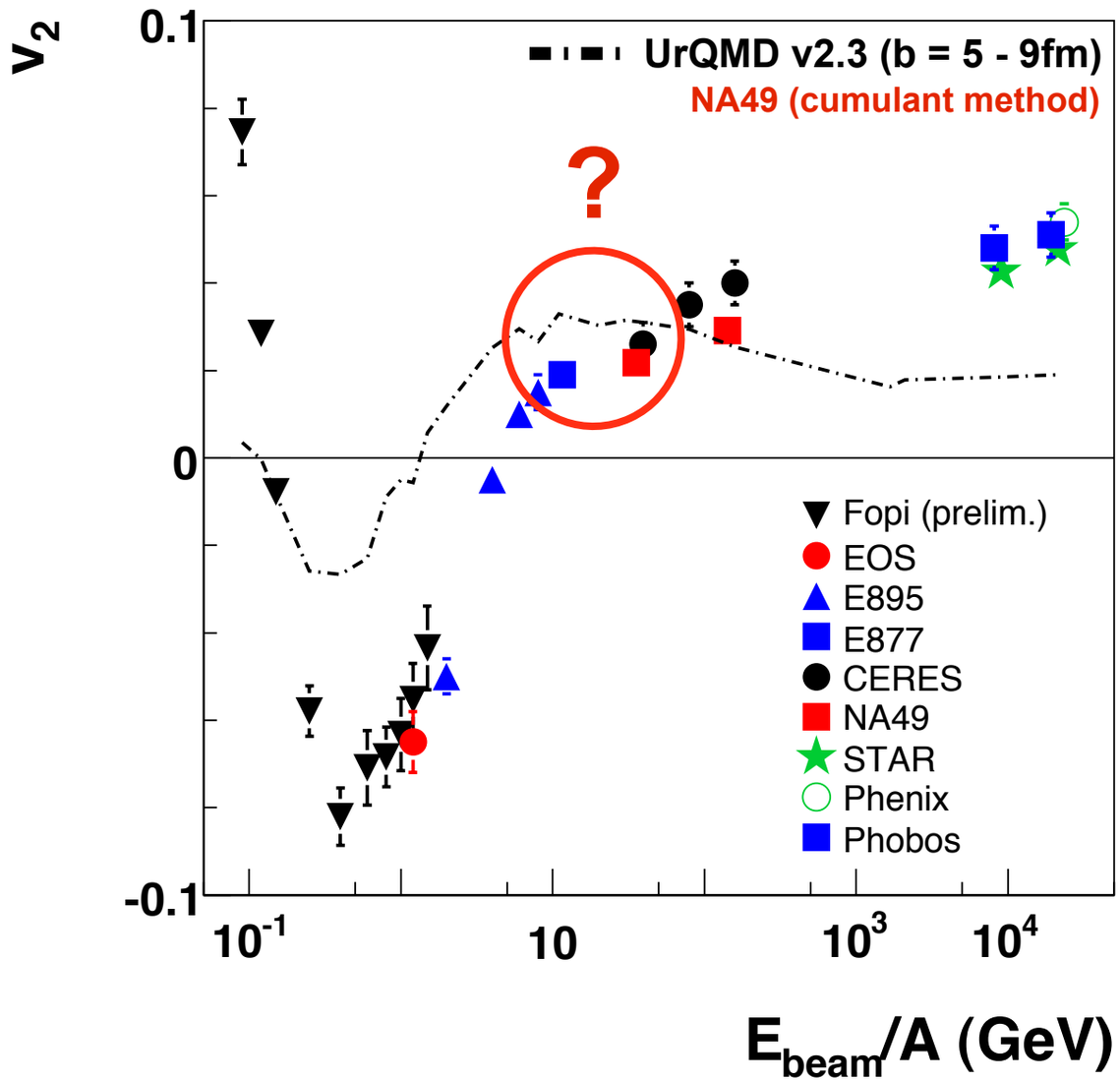
Stöcker:NPA 750 (2005) 121

$mid-central : \sigma/\sigma_T = 12.5\% - 43.5\%$

NA49 Ref.: [15]

Energy Dependence of Elliptic Flow





Kolb et al.:PRC 62 (2000) 054909
UrQMD:Petersen private communication

Scenarios for the Onset of Deconfinement

a) Particle yields and spectra

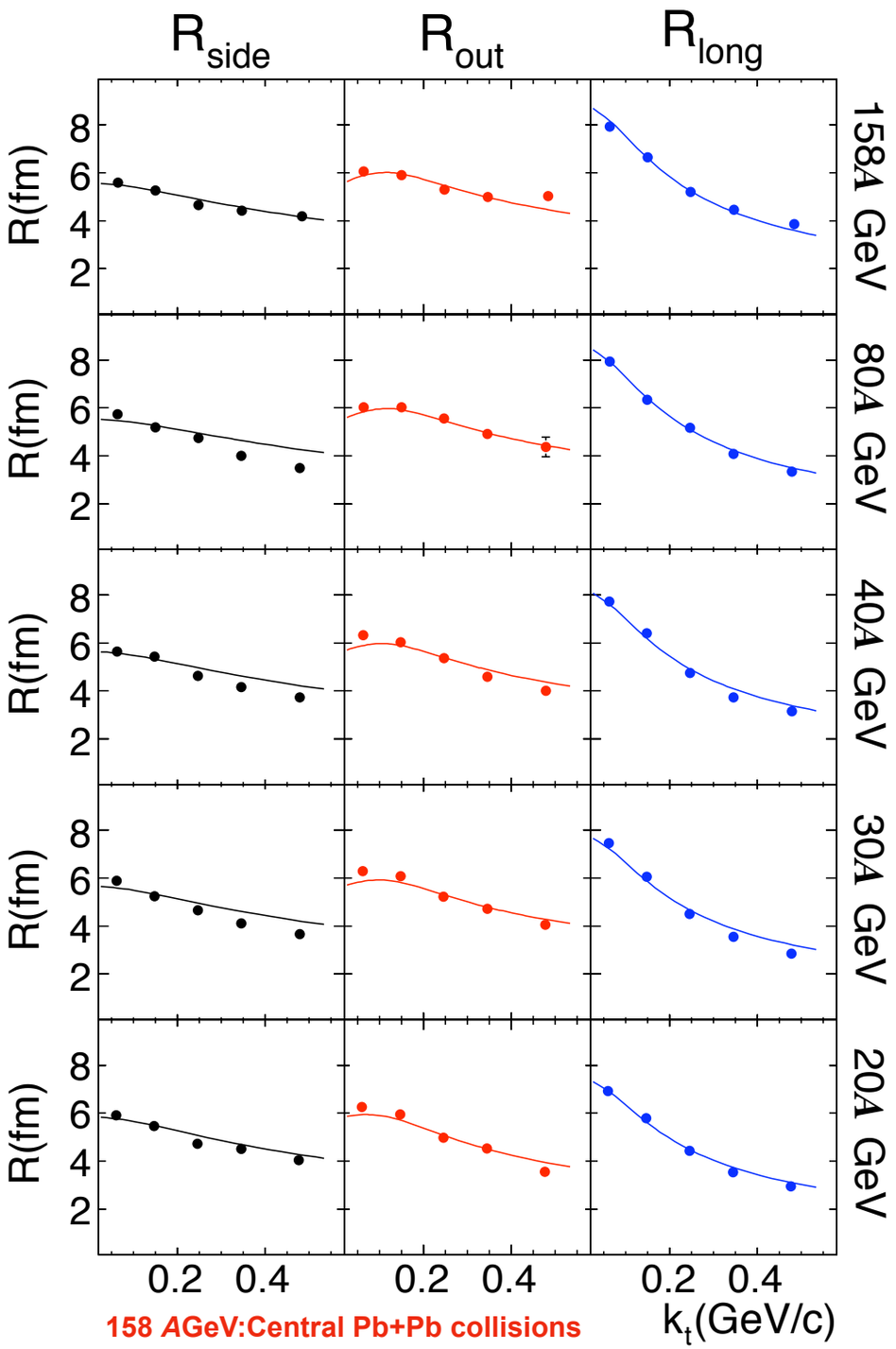
b) Anisotropic flow

c) Bose-Einstein correlations

- **Enhancement of R_{Out}/R_{Side}.**
  (Rischke,Gyulassy:NPA 608 (1996) 479)

- **Experimental access: Systematic study of two-particle correlations as a function of energy.**

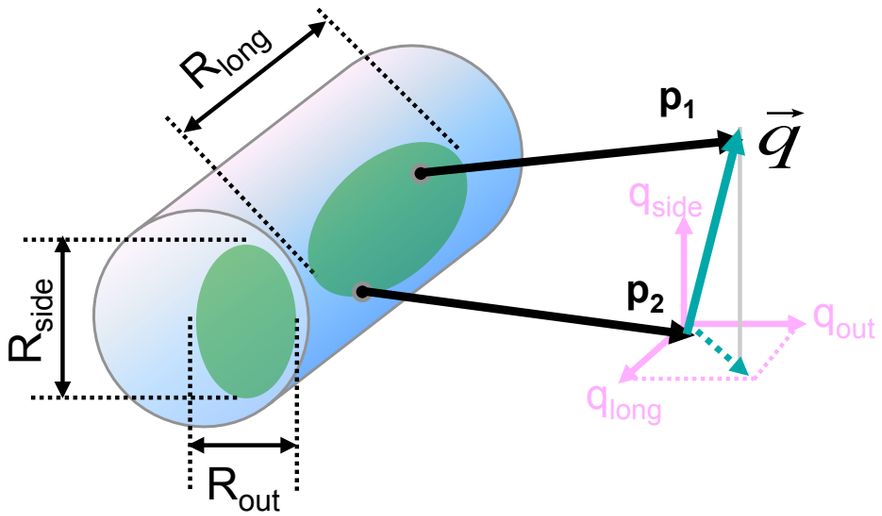
Bose-Einstein Correlations



- **Measurement of the two-pion correlation function to extract the three-dimensional source radii:**

$$C_2(p_1,p_2) = \frac{P(p_1,p_2)}{P(p_1)P(p_2)} = \frac{real\ event\ pairs}{mixed\ event\ pairs}$$

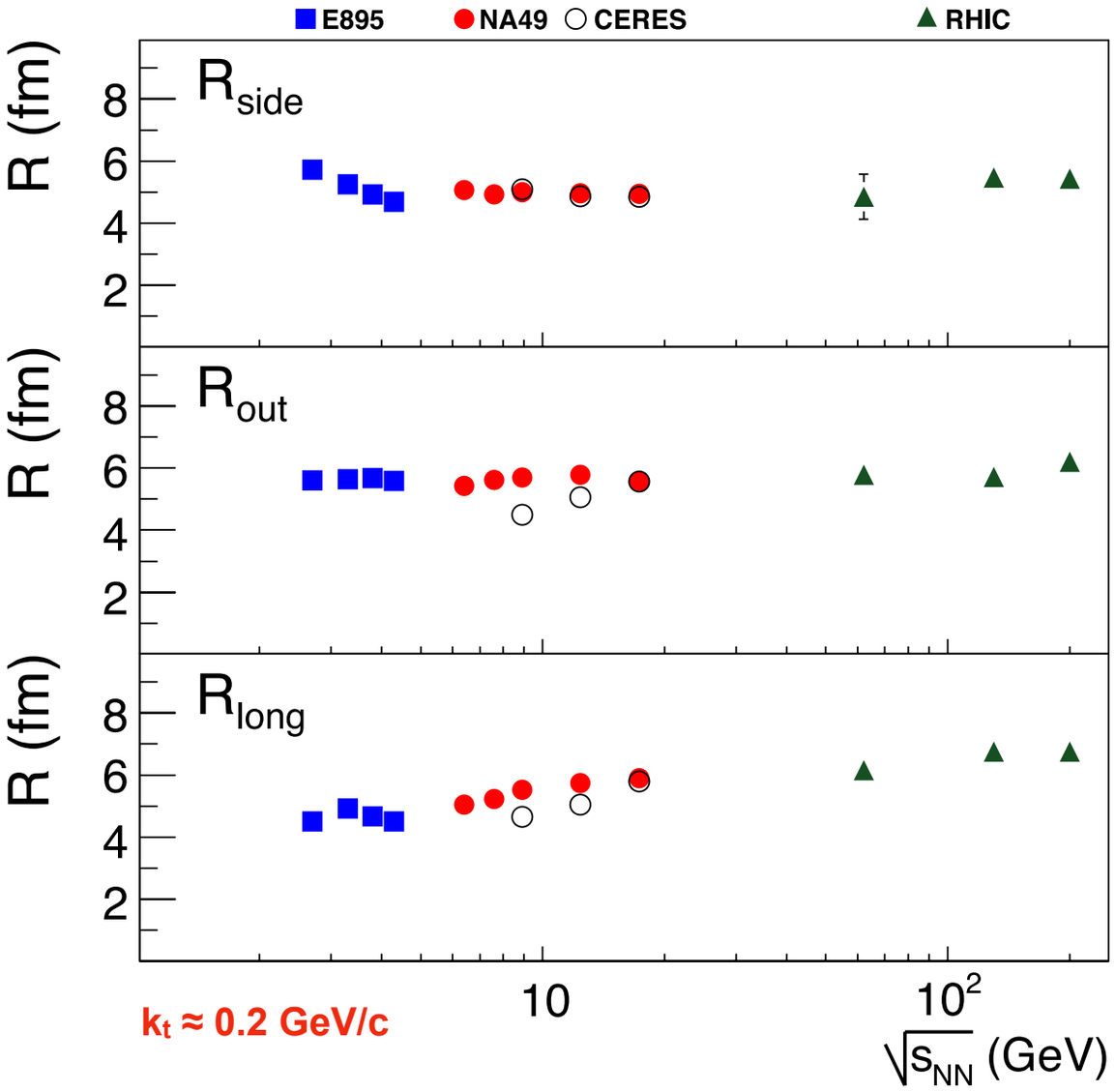
- **Combines „Blast wave“ fit to HBT radii and transverse mass spectra.**
- **The model fits the date quite well, except from R_{side} at high k_t.**



Fit function:
Retière,Lisa:PRC 70 (2004) 044907

NA49 Ref.: [16]

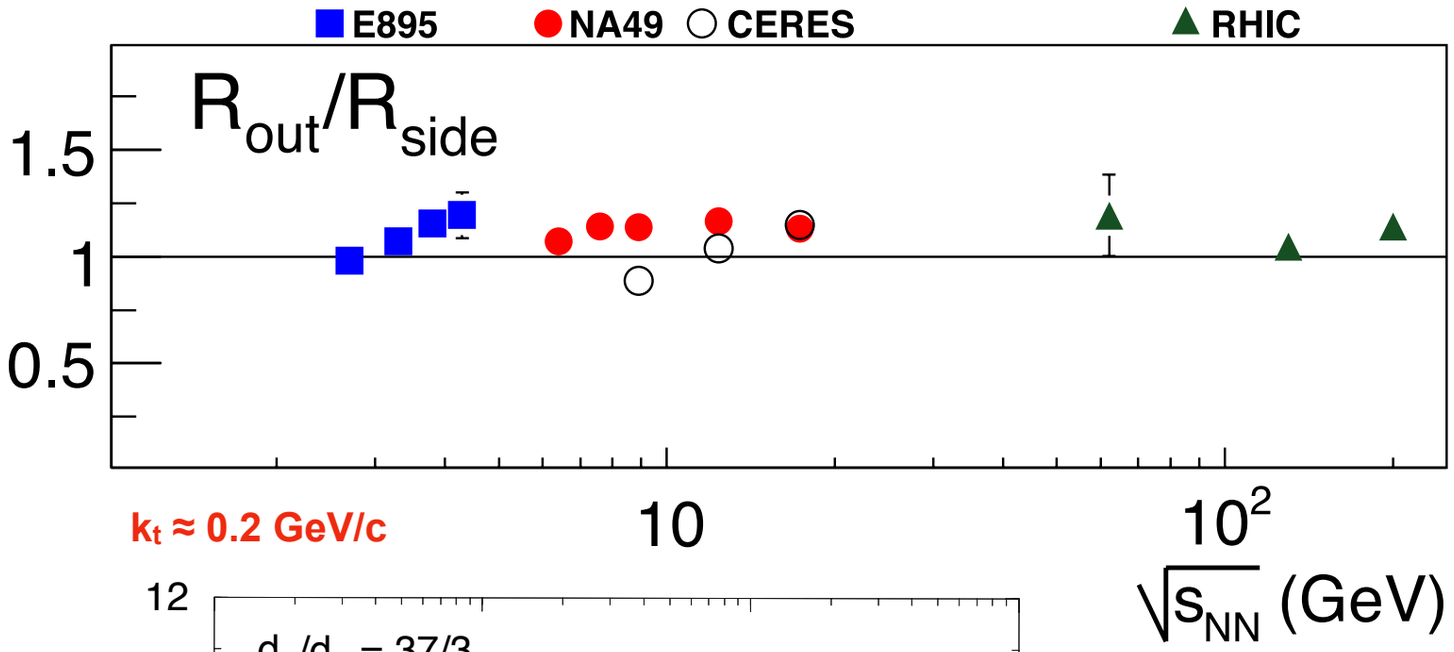
Energy Dependence of HBT-Radii

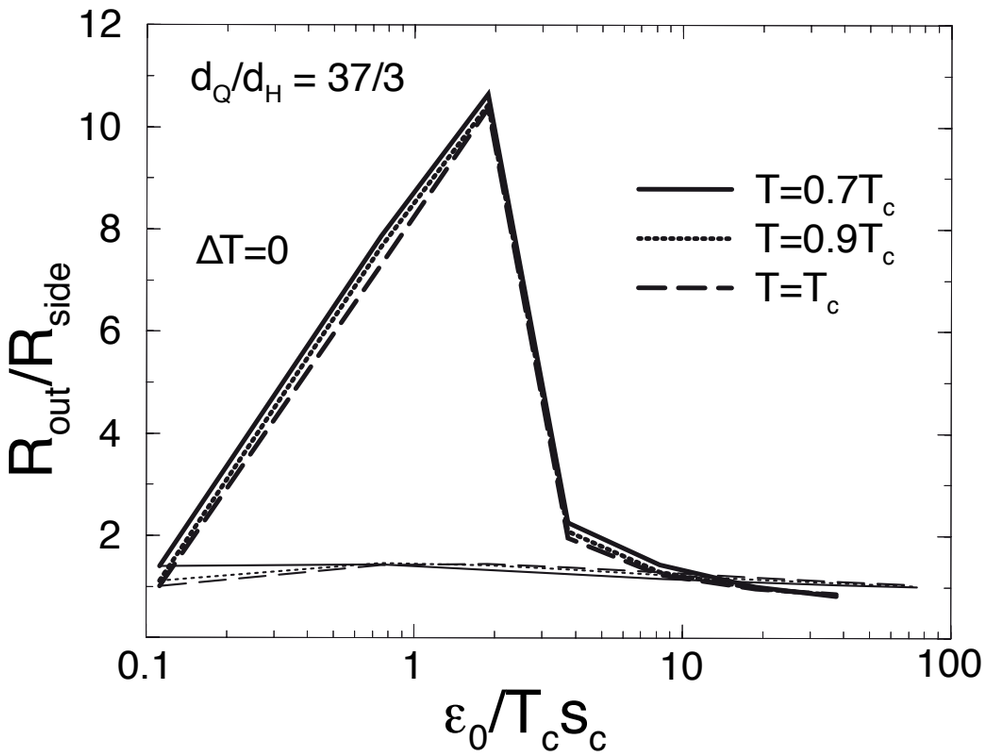


- **No energy dependence is observed for the HBT-Radii from AGS to RHIC energies, expect for R_{long}.**

NA49 Ref.: [16]

Energy Dependence of HBT-Radii





- **No energy dependence is observed for R_{out}/R_{side} from AGS to RHIC energies.**
- **Predicted signal for onset of deconfinement is not observed.**
- **No indication for $R_{Out} >> R_{Side}$ (1st order transition, soft point of EoS).**
- **Interpretation of the HBT data is still under discussion.**

Rischke,Gyulassy:NPA 608 (1996) 479

NA49 Ref.: [16]

Conclusion

a) Particle yields and spectra

- Comprehensive results on particle production from NA49.
- Indication of a "Step" structure observed in $\langle m_t \rangle - m_0$.
- The strangeness to π ratio shows a "Horn" at low SPS energies.

+

⇒ Indication for the onset of deconfinement at low SPS energies

b) Anisotropic flow

- Sufficient data for conclusion and to verify the v_1 antiflow for Protons and the weakening of v_2.
- Better measurements for v_1 and v_2 are needed for low SPS energies (RHIC low energy and/or FAIR).

?

c) Bose-Einstein correlations

- R_{Side}, R_{Out} and R_{Long} shows no energy dependence (5 fm).
- R_{Out}/R_{Side} is constant with energy. No anomalous structure is observed.

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The NA49 Collaboration

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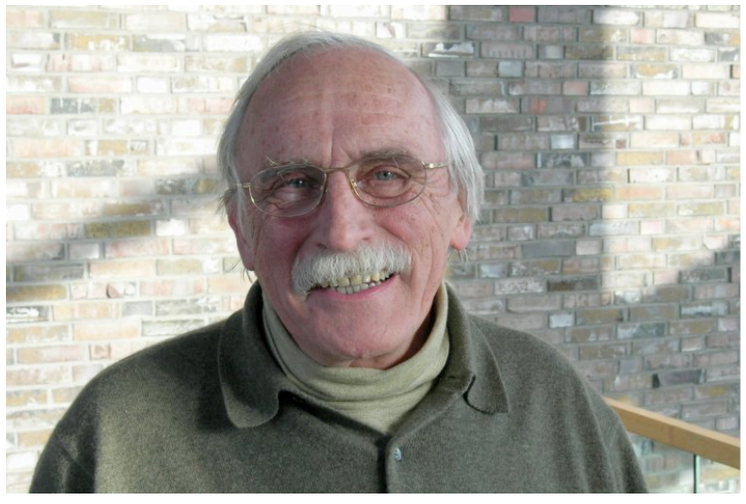
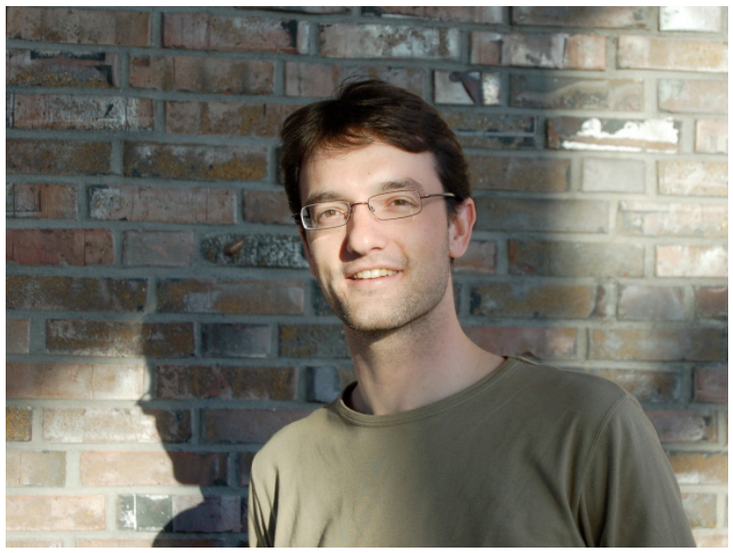
[1] C. Alt et al.:PRC 66 (2002) 054902
[2] C. Alt et al.:PRC 77 (2008) 024903
[3] C. Alt et al.:PRC 73 (2006) 044910
[4] T. Anticic et al.:PRC 69 (2004) 024902
[5] T. Anticic et al.:PRL 93 (2004) 022302
[6] S. V. Afanasiev et al.:PLB 538 (2002) 275
[7] C. Alt et al.:arXiv:0804.3770
[8] C. Alt et al.:arXiv:0806.1937
[9] C. Alt et al.:PRL 94 (2005) 192301
[10] S. V. Afanasiev et al.:PLB 491 (2000) 59
[11] C. Alt et al.:PRL 94 (2005) 052301
[12] M. Mitrovski:JPG 32 (2006) 43
[13] G. Stefanek: PoS CPOD2006 (2006) 30
[14] C. Alt et al.:PRC 75 (2007) 044901
[15] C. Alt et al.:PRC 68 (2003) 034903
[16] C. Alt et al.:PRC 77 (2008) 064908

The New Hope for the RHIC Low Energy Run in STAR

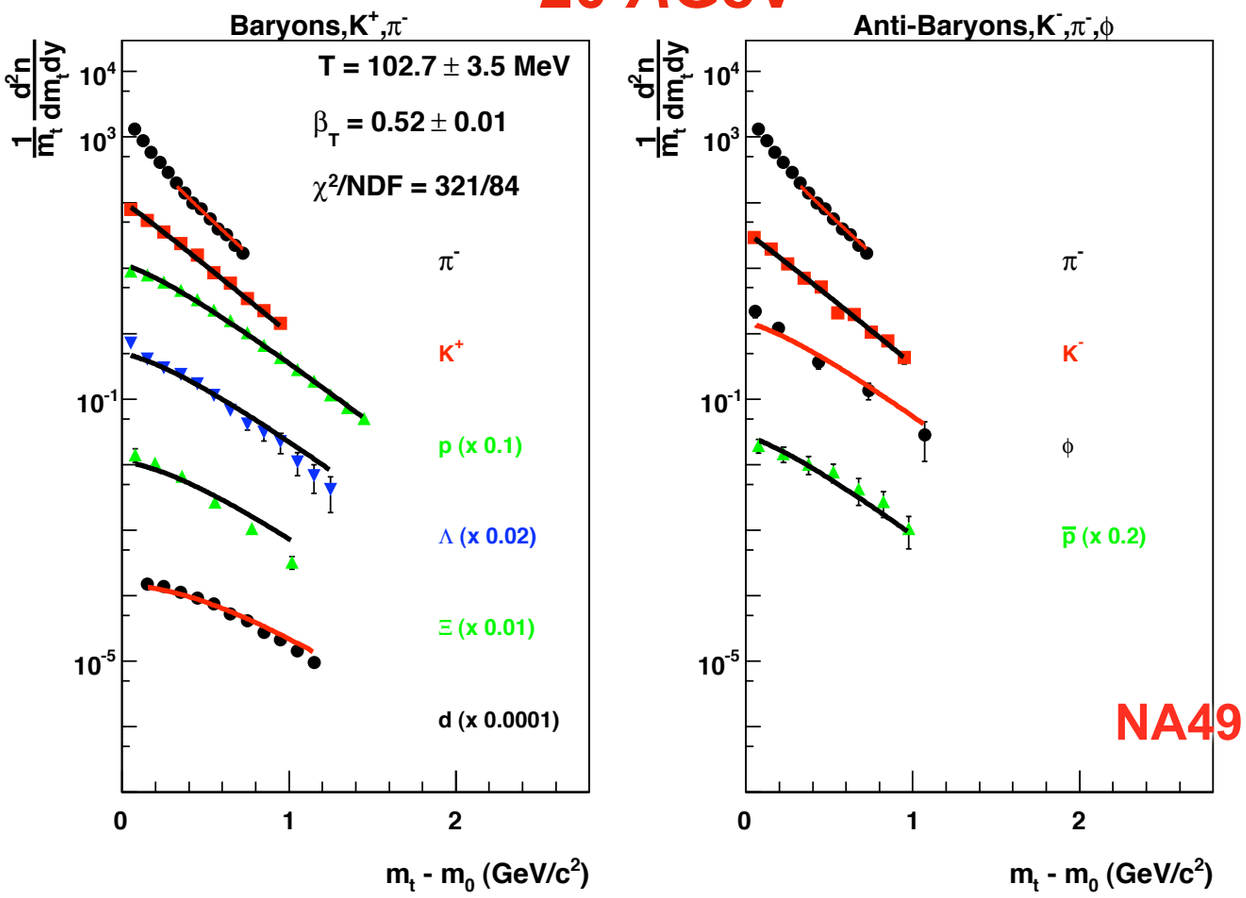




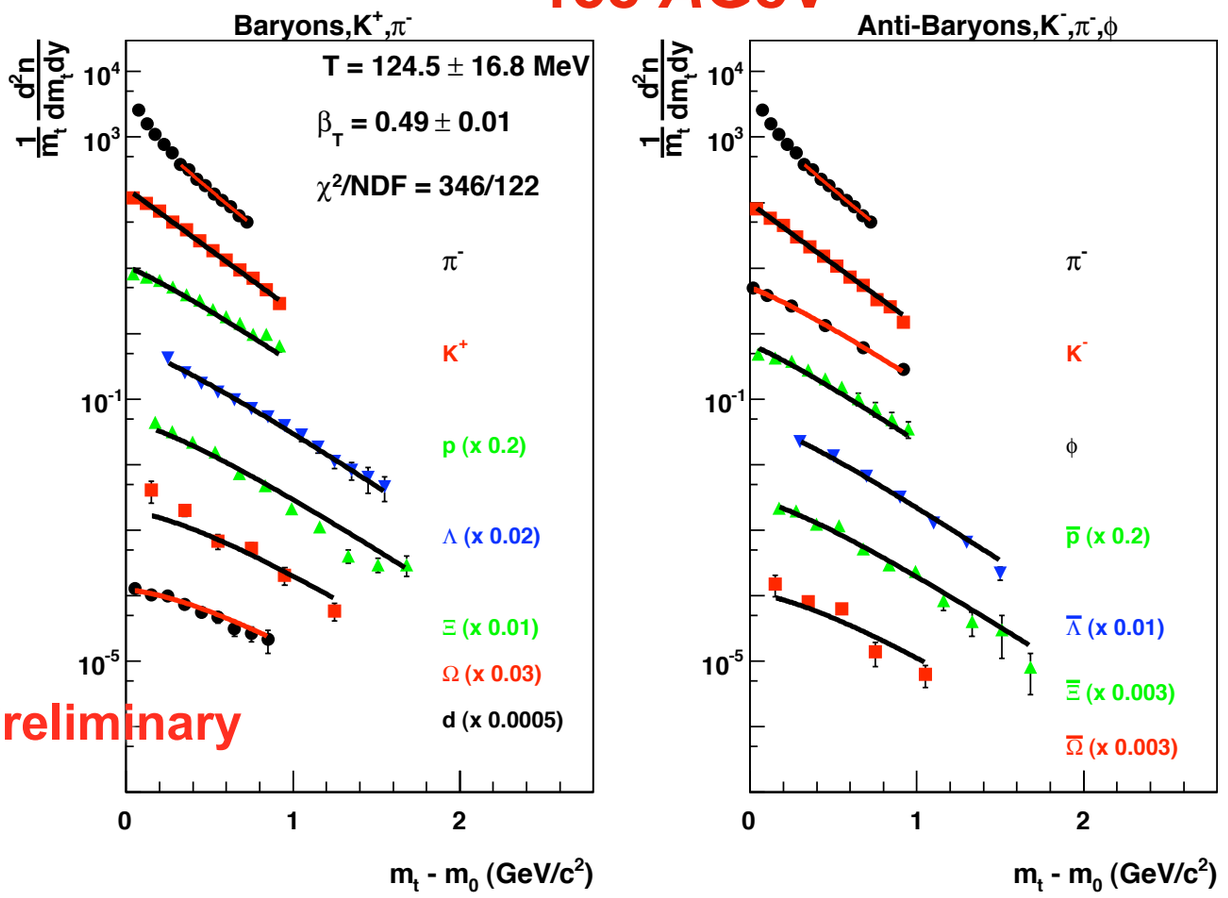
The End

Kinetic Freeze-Out

20 *A*GeV



158 *A*GeV



NA49 Preliminary

20 *A*GeV:Central 7% Pb+Pb

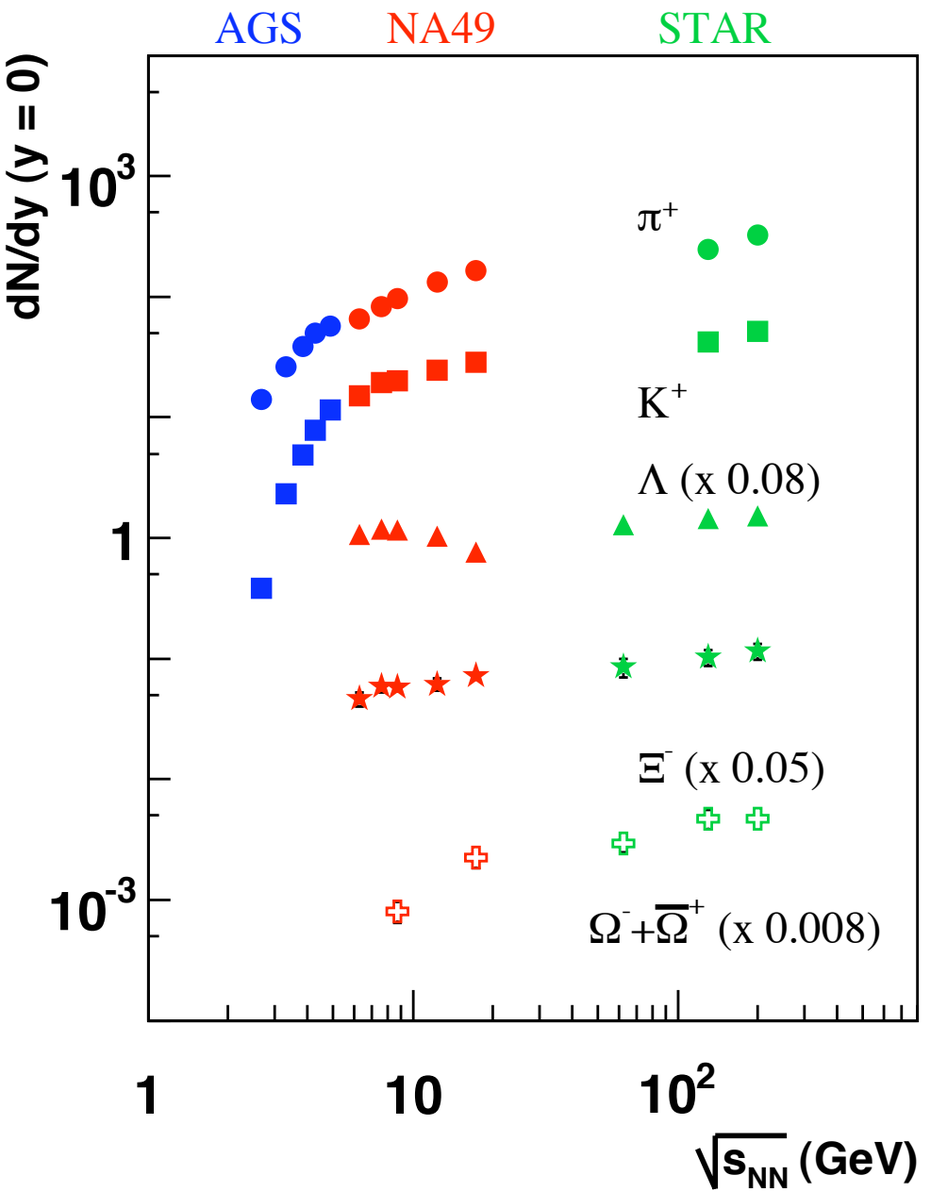
158 *A*GeV:Central 5%,10%,23.5% Pb+Pb

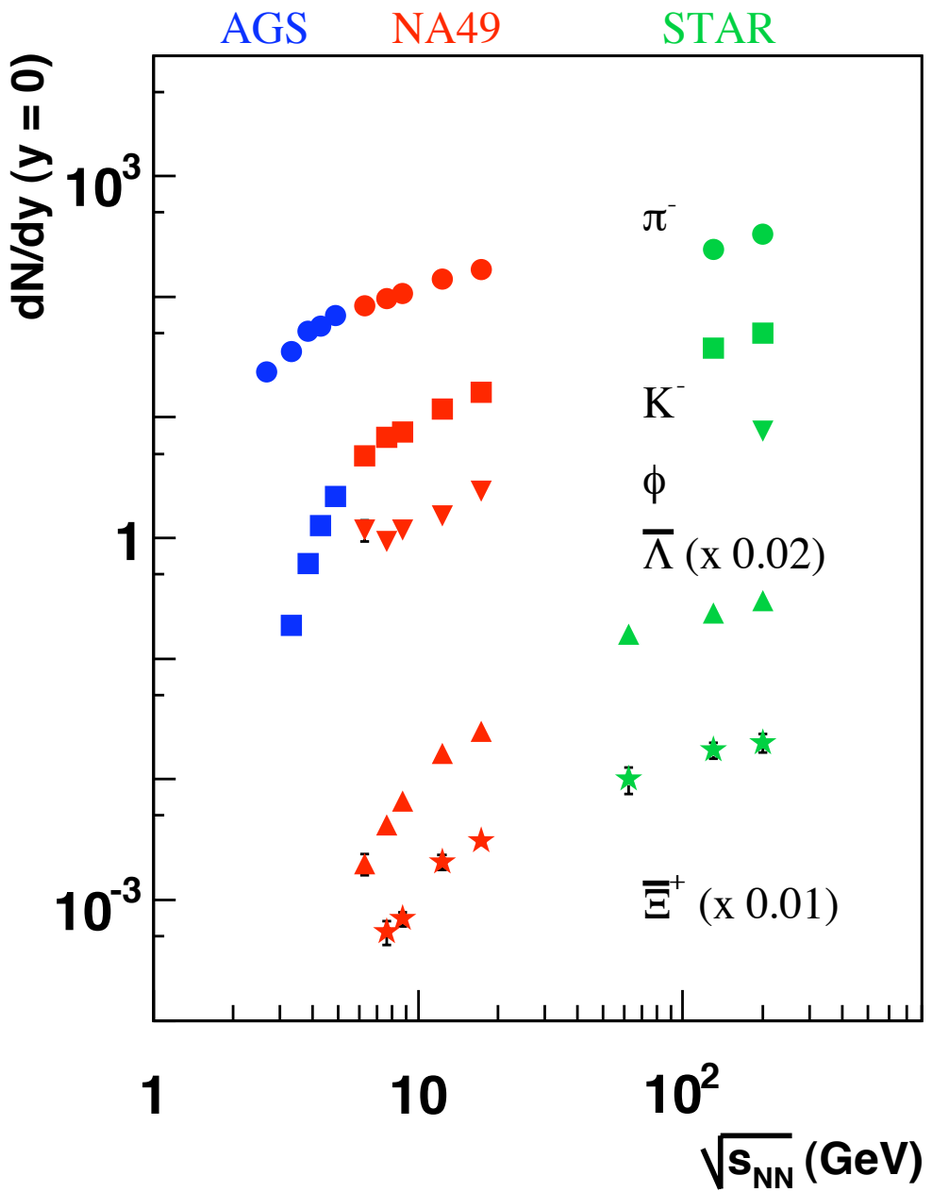
Fit function:
Retière,Lisa:PRC 70 (2004) 044907

NA49 Ref.: [1]-[11]

- Radial flow fit (“Blast Wave”).
- “kinetic” freeze out at T ≈ 100 - 120 MeV, $\langle\beta_T\rangle \approx 0.5$ at SPS.

Midrapidity Particles Yields

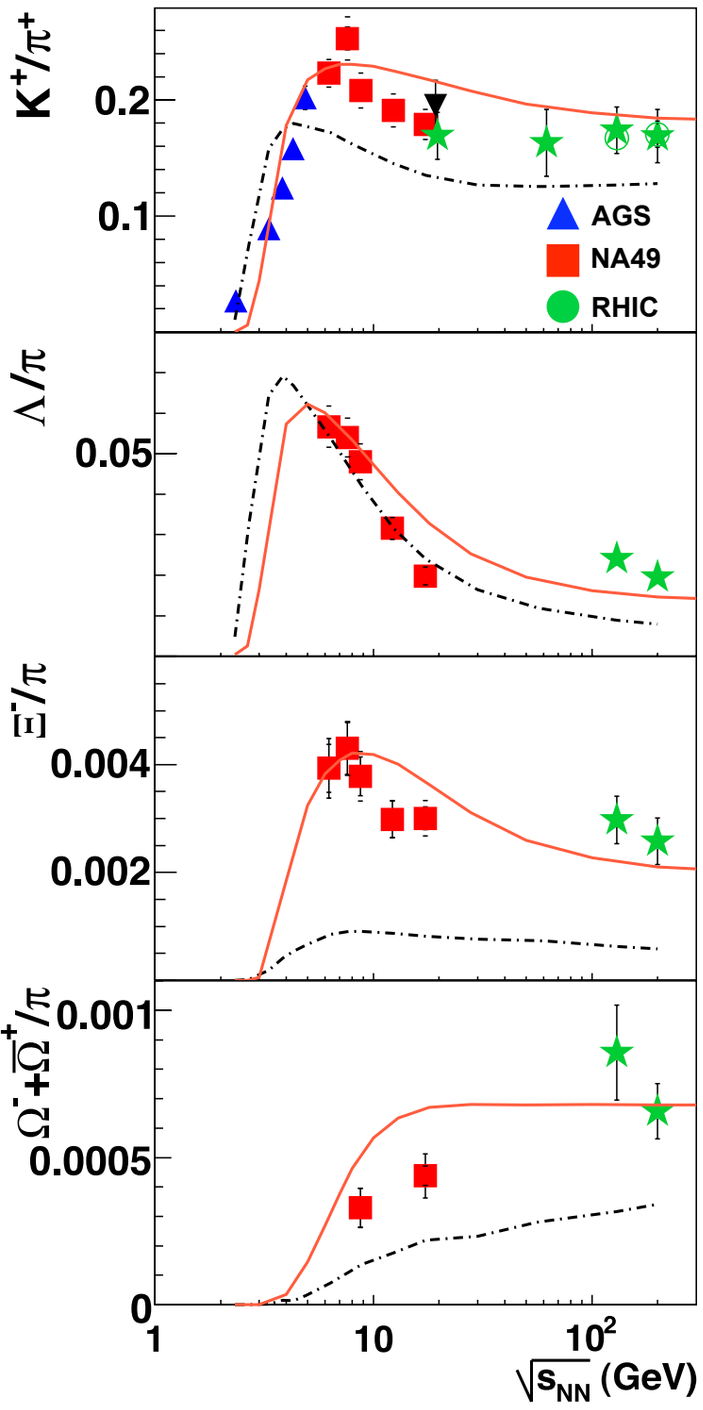


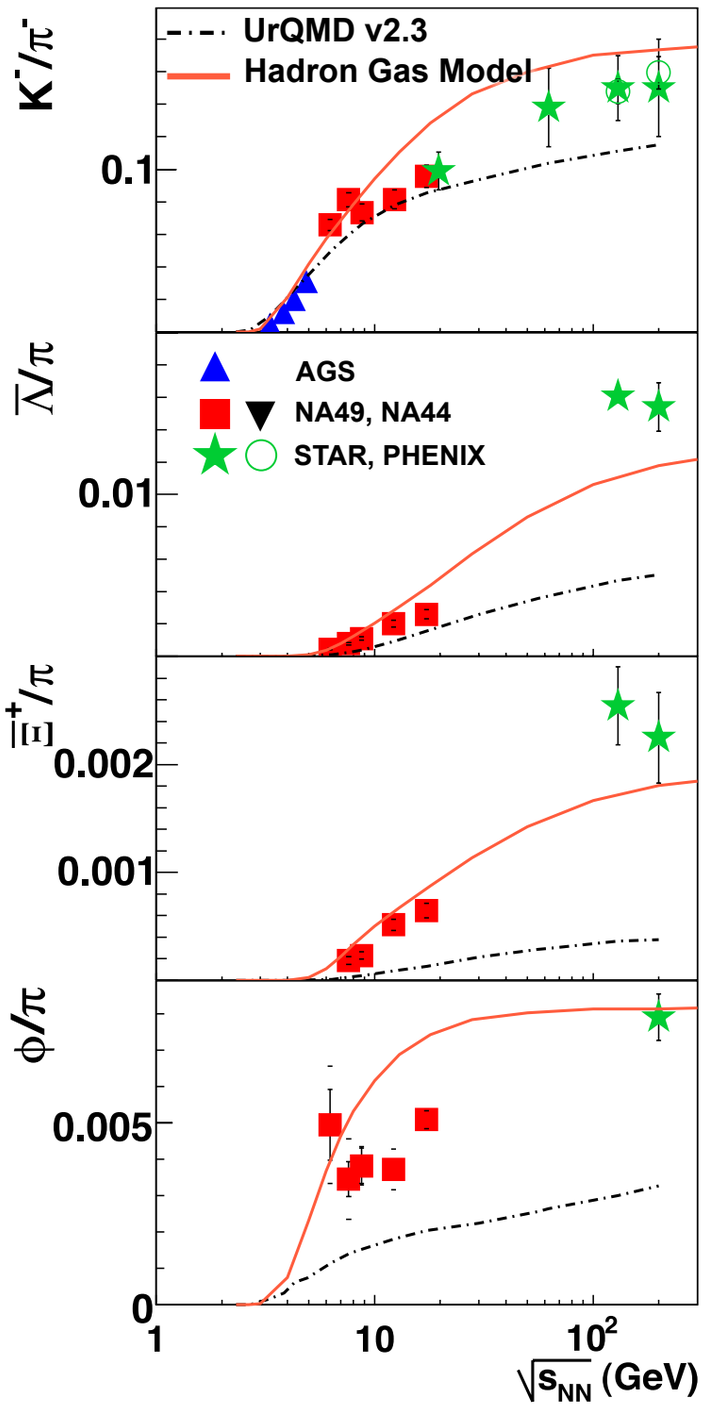


- **Energy dependence is weaker for hyperons than for anti-hyperons.**

NA49 Ref.: [1]-[11]

Midrapidity Particle Ratios





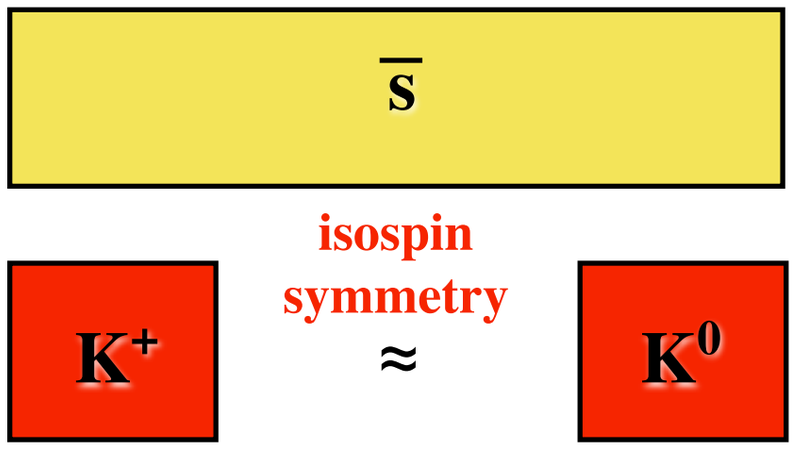
- Maximum for K^+, Λ, Ξ^- at low SPS energies.
- Increase of K^-, $\bar{\Lambda}$, $\bar{\Xi}^+$, Φ, $\Omega^-+\bar{\Omega}^+$ from AGS to RHIC energies.
- Hadron gas model is designed to fit 4π yields and could only fit midrapidity values if the system is boost invariant.

UrQMD:Bleicher et al.:arXiv:0805.0567
Vogel:Private communication
Hadron Gas:Andronic et al.:NPA 772 (2006) 167

$\pi = 1.5 \cdot (\pi^+ + \pi^-)$

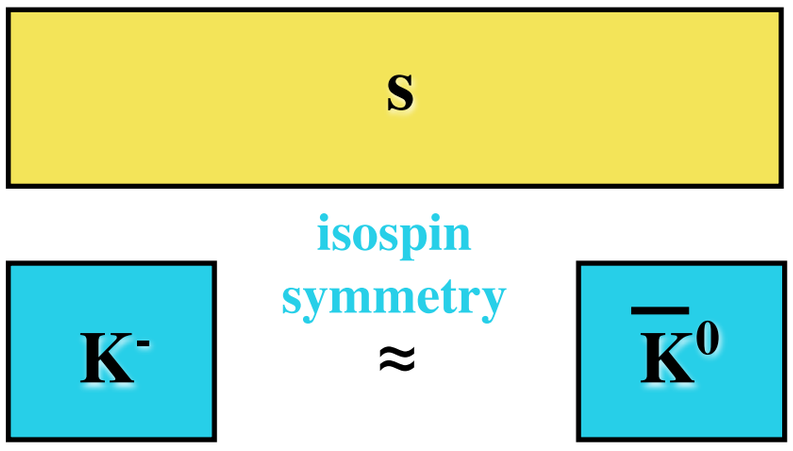
NA49 Ref.: [1]-[11]

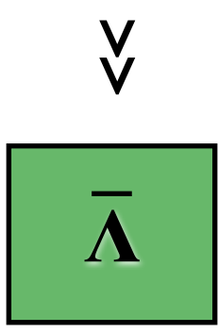
Main Strangeness Carrier



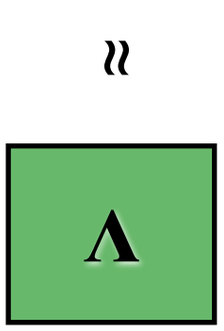
strangeness
conservation

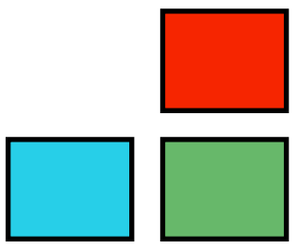
=





high baryon
density

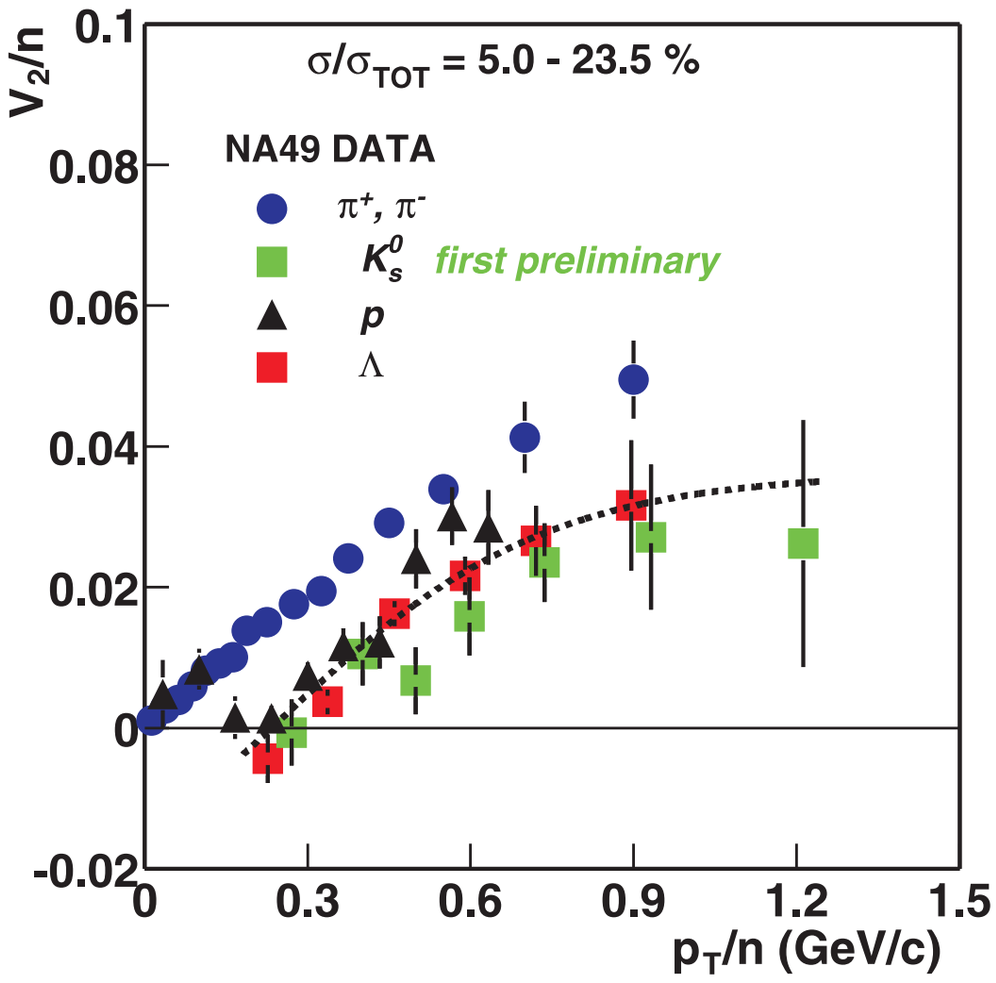




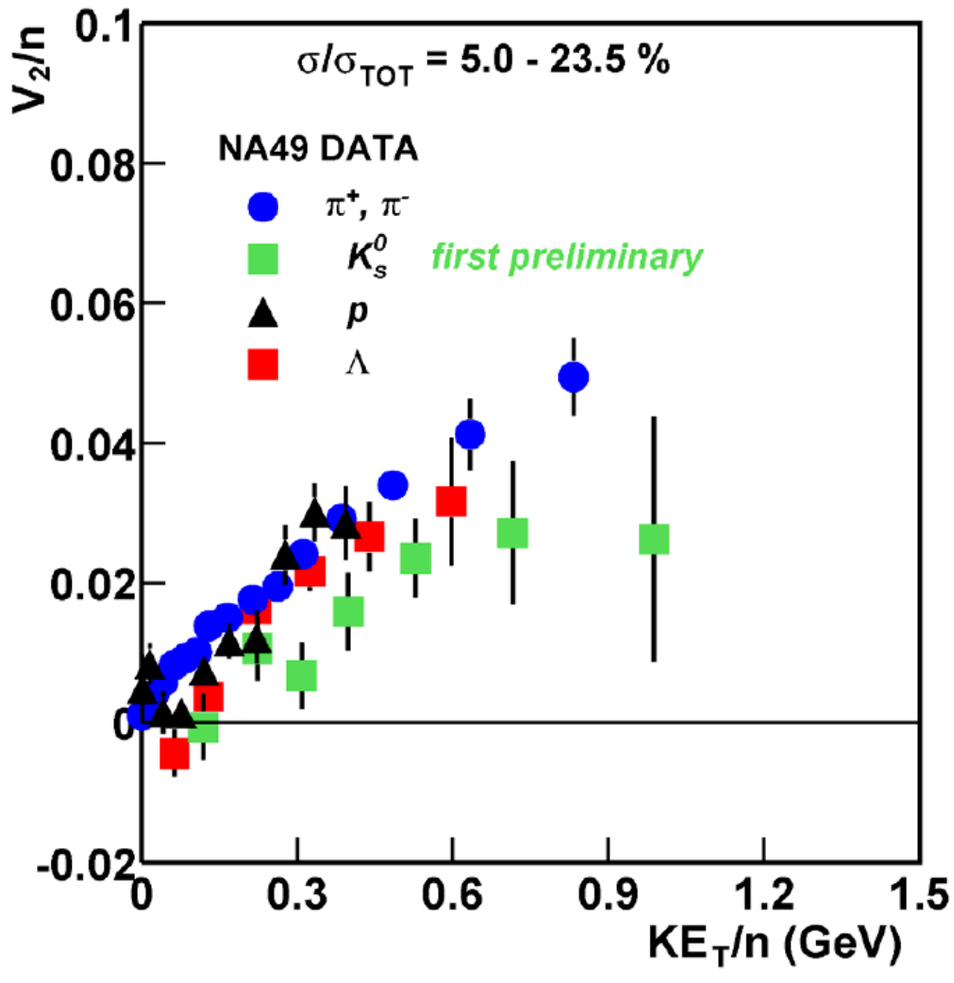
Sensitive to strangeness content only

Sensitive to strangeness content and baryon density

Elliptic Flow Quark Number Scaling



- No Quark number scaling of v_2 at SPS (Quark coalescence picture).
- Scaling seems to work for p, Λ and K^0_s but not for π.
- At SPS the pt-range is too low compared to RHIC results.



- Scaling with KE_t/n works for π, p and Λ.
- K^0_s is below the others.
- Also no clear quark number scaling when scaling with KE_t/n (too large errors).

NA49 Ref.: [13]