Results obtained with NeXSPheRIO

Frédérique Grassi

Instituto de Física-Univ. de São Paulo-Brazil

PLAN

- Smoothed Particle Hydrodynamics
  - Main ingredients
  - Improving (NeX)SPheRIO
  - More details on current version of (NeX)SPheRIO
- Overview of results at various energies
  - S+S
  - Pb+Pb
  - Au+Au
- Averaging I.C. vs. averaging final spectra
- Number of participants vs. impact parameter
- Effective K^+ temperature as function of $\sqrt{s}$
- Summary

Smoothed Particle Hydrodynamics

Main ingredients

- Method originally developped in astrophysics adapted to relativistic heavy ion collisions by C.E.Aguiar, T.Kodama, T.Osada & Y.Hama, J.Phys.G27(2001)75
- Advantage: incorporate any geometry in the initial conditions
  (in particular can be used to model event-by-event physics)
- Fluid divided in small volumes called "particles"
- Hydro. eq. become ordinary differential eq. for "particle" motion
- Each "particle" has attached to it, conserved numbers: entropy and baryon number

SPH representation for entropy and baryon number:

$$
\begin{aligned}
s(\tau,\vec{x}) &= \frac{1}{\tau\gamma}\sum_i \nu_i^s W(\vec{x}-\vec{x}_i;h),\\
n_b(\tau,\vec{x}) &= \frac{1}{\tau\gamma}\sum_i \nu_i^b W(\vec{x}-\vec{x}_i;h),
\end{aligned}
$$

ν_i^s (ν_i^b) entropy (baryonic number) of i-th particle

$\gamma = 1/\sqrt{1-v_x^2-v_y^2-\tau^2 v_\eta^2}$,

W interpolating kernel with width h.

(Note hyperbolic coordinates $\tau \equiv \sqrt{t^2-z^2}$, x, y and

$\eta \equiv 1/2 \cdot \ln[(t+z)/(t-z)]$)

Equations of motion for the SPH-particles:

$$
\begin{aligned}
\frac{d\vec{x}_i}{d\tau} &= \vec{v}_i,\\
\frac{d}{d\tau}\left(\gamma\nu^s\,\frac{P+\varepsilon}{s}\,\vec{\omega}\right)_i &= -\sum_j \nu_i^s\nu_j^s\left[\frac{P_i}{\tau\gamma_i^2 s_i^2}+\frac{P_j}{\tau\gamma_j^2 s_j^2}\right]\\
&\quad\times\vec{\nabla}_i W(\vec{x}_i-\vec{x}_j;h),
\end{aligned}
$$

where $\vec{\omega} = (v_x, v_y, \tau^2 v_\eta)$.

Improving (NeX)SPheRIO

- 1999-2001: only entropy conservation

  → SPheRIO (1st version)

  Aguiar,Kodama,Osada & Hama JPG27(2001)75

- 2000: initial conditions given by NeXus

  → NexSPheRIO

  Aguiar,Kodama,Osada & Hama NPA698(2002)639c

- 2000-2003: entropy+baryon nb. conservation
  eos w/o strangeness
  particle decays

  → SPheRIO & NeXSPheRIO (2nd version)

  Hama,Grassi,Socolowski,Aguiar,Kodama,Portugal,Tavares & Osada, 32th ISMD proc.; Gaździcki,Gorenstein, Grassi,Kodama & Socolowski, hep-ph/0309192; Andrade,Aguiar,Grassi,Hama,Kodama,Socolowski & Osada, submited

  RESULTS FROM THIS VERSION SHOWN HERE

- 2003-2004: eos w. strangeness (in progress)

- improved freeze out (planned)

More details on current version of (NeX)SPheRIO

- Equation of state: MIT bag+resonance gas with volume corrections
  Phase transition at 160 MeV

- Freeze out: Cooper-Frye formula for a given temperature
  $E\frac{d^3N}{dp^3} = \int_{\Sigma_{fo}} d\sigma \cdot p f(p \cdot u) \rightarrow \sum_i \frac{\nu_i^s \hat{n}_i \cdot p}{s_i |\hat{n}_i \cdot u_i|} f(p \cdot u_i)$
  sum over all SPH-particles on f.out surface
  $\hat{n}$ normal four-vector to this surface,
  $\propto (-\partial T/\partial\tau, -\partial T/\partial x, -\partial T/\partial y, -\partial T/\partial\eta)$.

- Initial conditions: NeXus provides $T^{\mu\nu}$, j^μ and u^μ on a $\tau_0 = 1fm$ surface for the SPH-particles
  H.J. Drescher, F.M.Liu, S.Ostapchenko, T.Pierog and K.Werner, Phys. Rev. C65 (2002) 054902

Overview of results at various energies:

h^- and $p - \bar{p}$

Usually in hydro.: smooth initial conditions are used, adjusted to reproduced some of the data

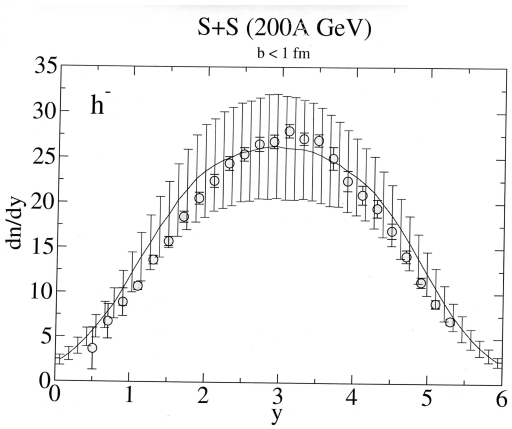
Here: Nexus provides I.C. and SPheRIO solves the hydro for that event, then process may be repeated

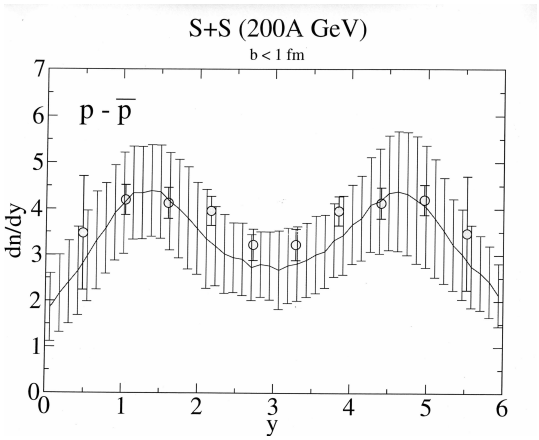
Only variable T_{fo}

S+S (200A GeV) spectra

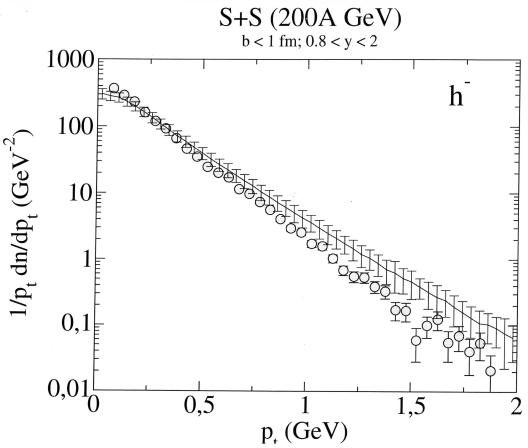
"error bars" indicate in fact fluctuation size (standard deviation)

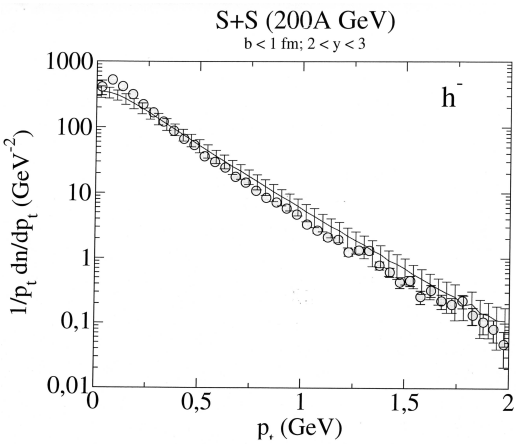
Rapidity distributions for h^- and $p - \bar{p}$, $b < 1fm$

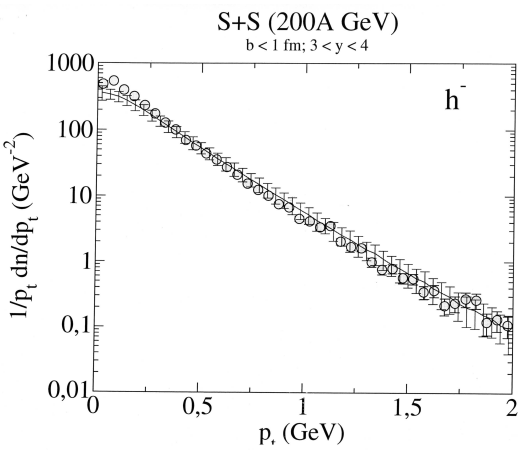


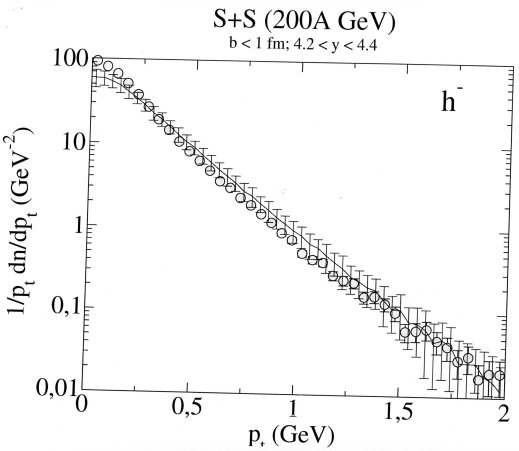


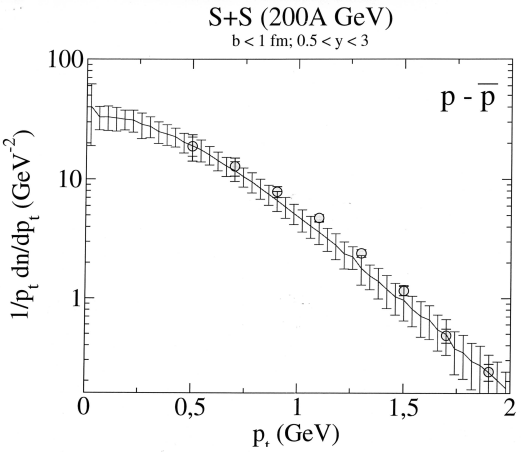
Transverse mass distribution for h^- in various y-window and $p - \bar{p}$, $b < 1fm$









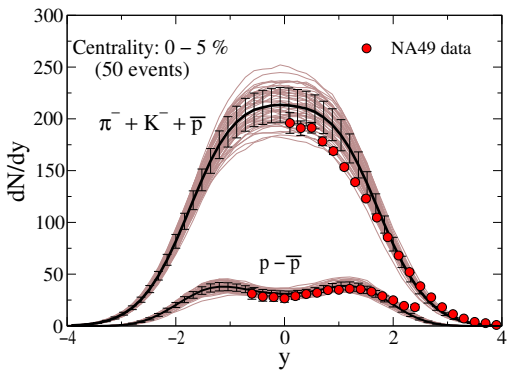


Conclusion: - sizable fluctuations event to event

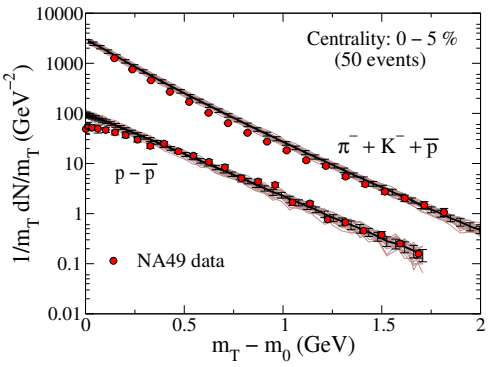
- average on events agrees with data

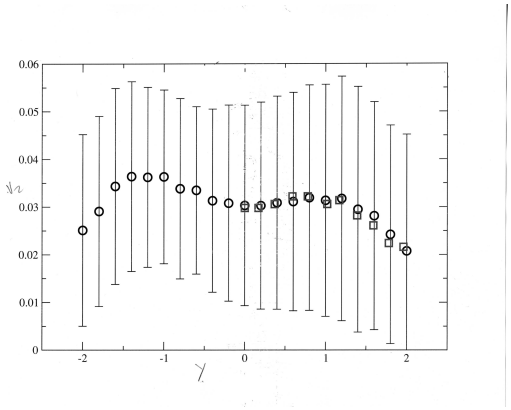
Pb+Pb (158A GeV) spectra

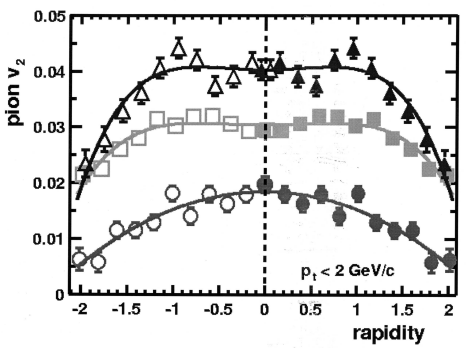
Rapidity Distributions (Pb+Pb, 17.3A GeV)

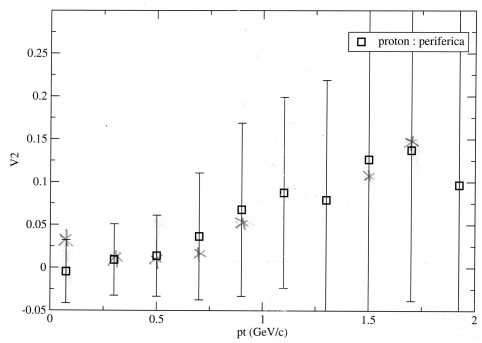


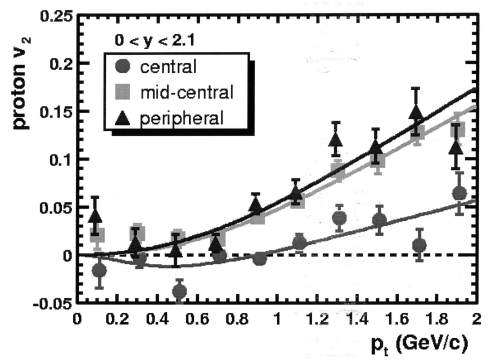
Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)







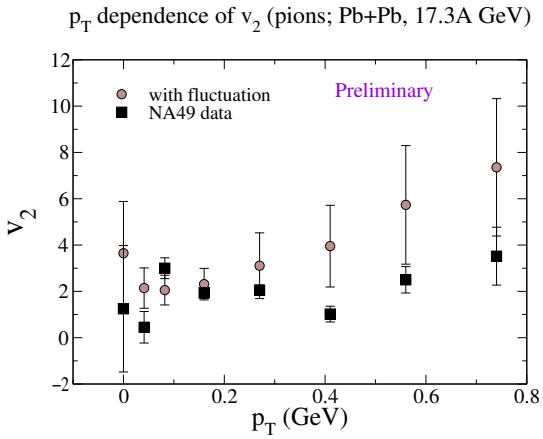


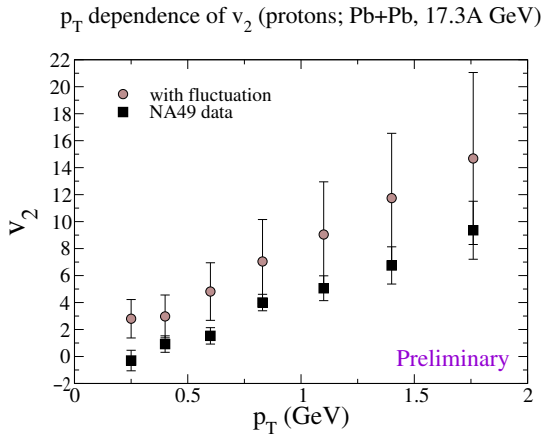


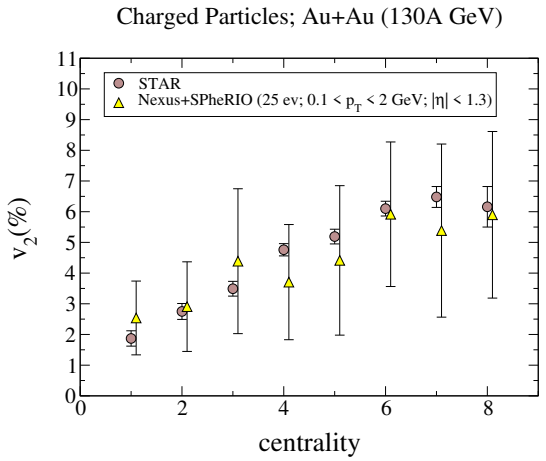
Conclusion: - sizable fluctuations event to event

- average on events agrees with data

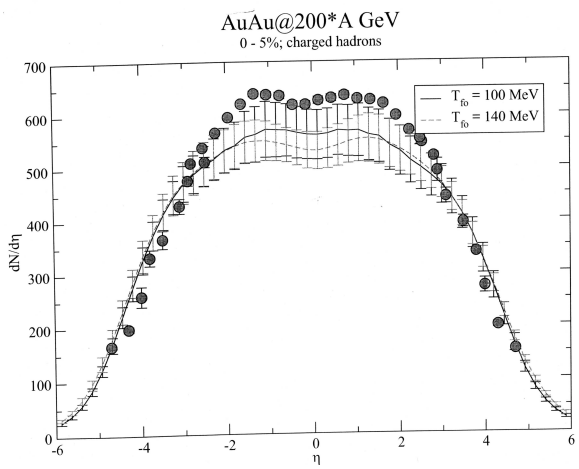
some (old) v_2 results for Pb+Pb

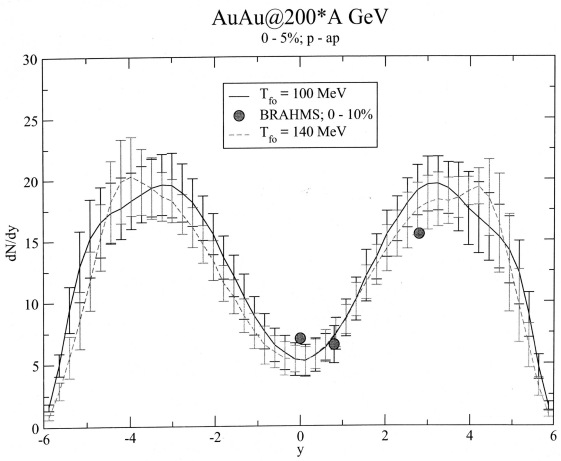


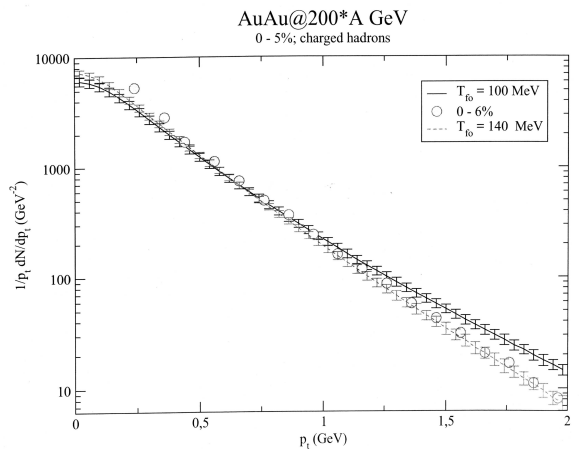


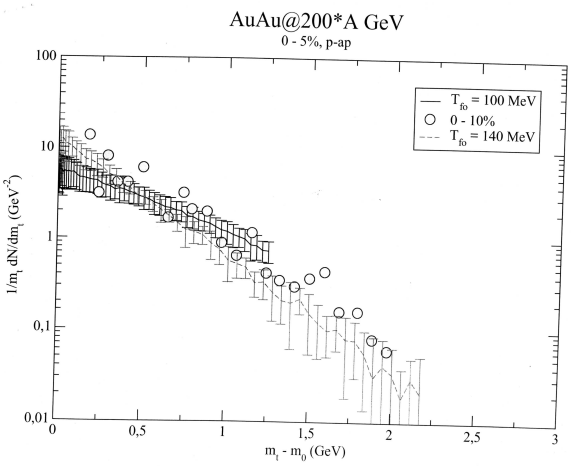


Au+Au (200A GeV in cms) spectra



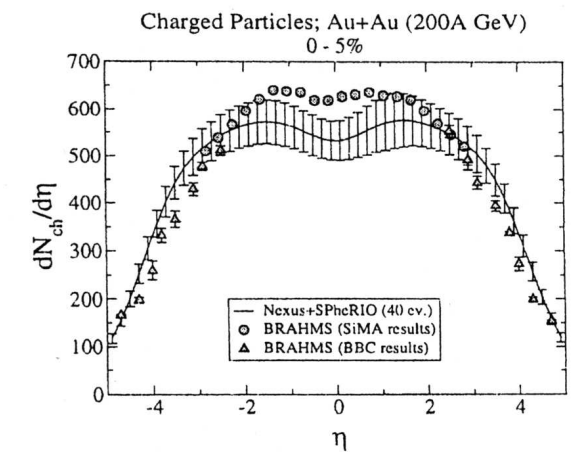


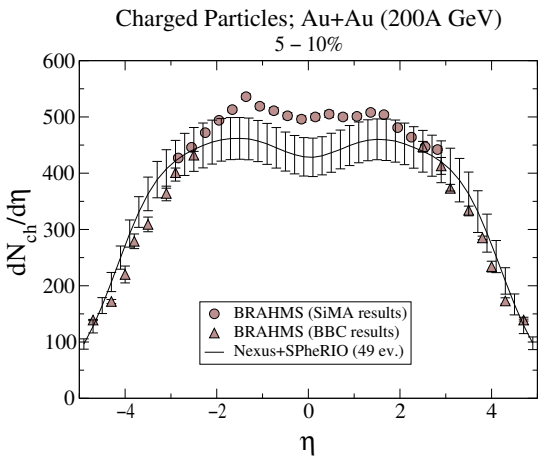


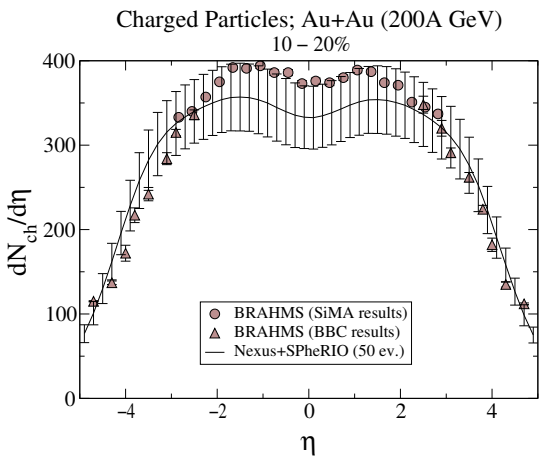


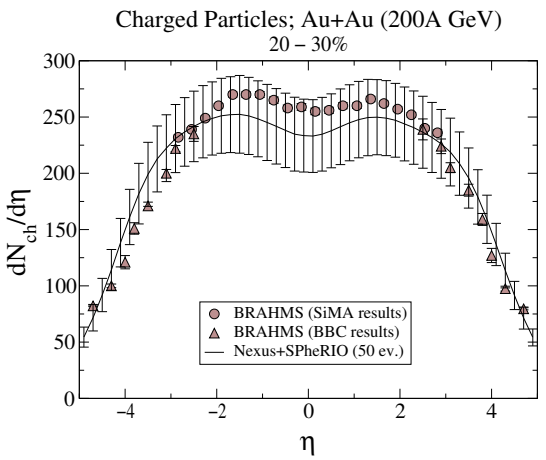
In most central window, charged hadrons pseudo-rapidity distribution, a little too low and too wide.

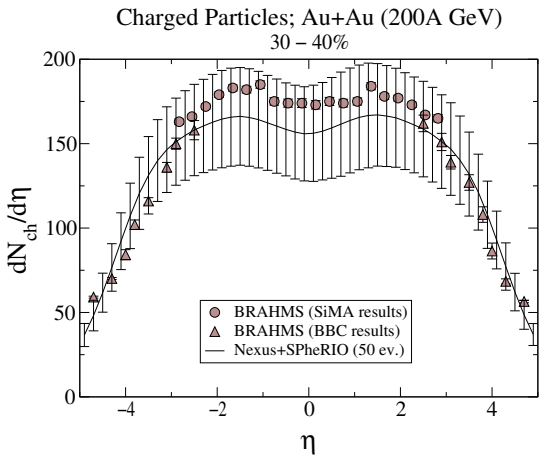
RESULTS FROM OLDER VERSION OF CODE

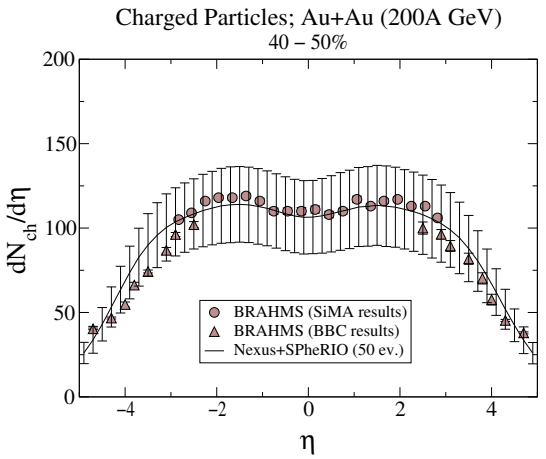


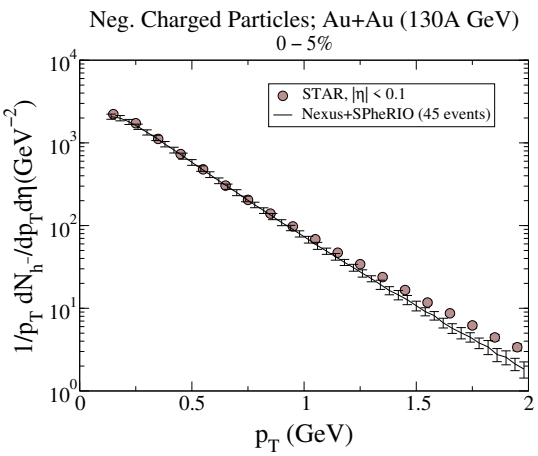


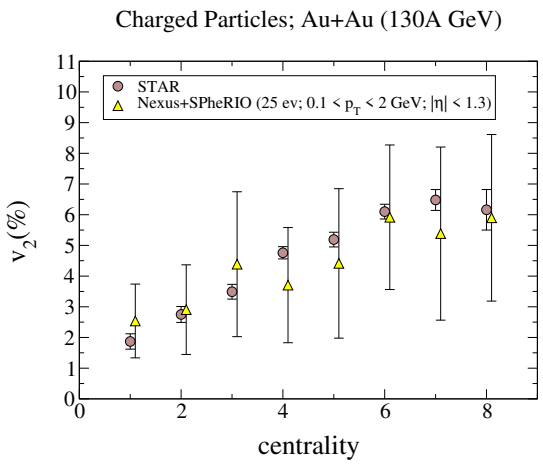






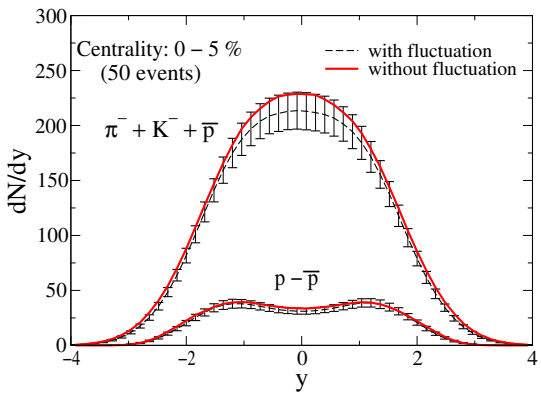



Neg. Charged Particles; Au+Au (130A GeV)
0 – 5%
STAR, |η| < 0.1
Nexus+SPheRIO (45 events)
1/p_T dN_h⁻/dp_T dη(GeV^-2)
p_T (GeV)

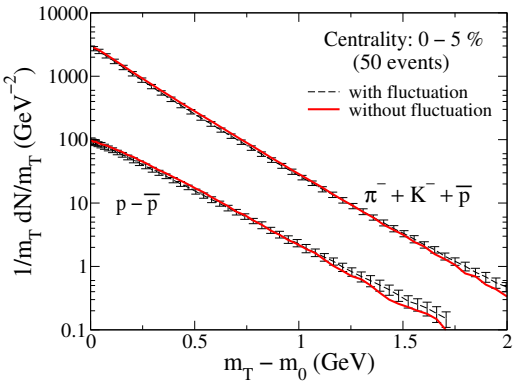

Charged Particles; Au+Au (130A GeV)
STAR
Nexus+SPheRIO (25 ev; 0.1 < p_T < 2 GeV; |η| < 1.3)
v_2(%)
centrality

Averaging I.C. vs. averaging final spectra

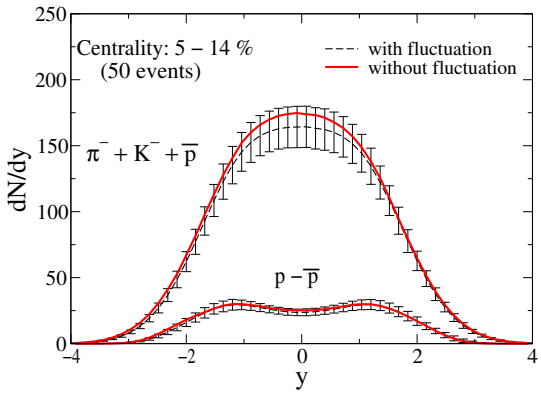
Rapidity Distributions (Pb+Pb, 17.3A GeV)



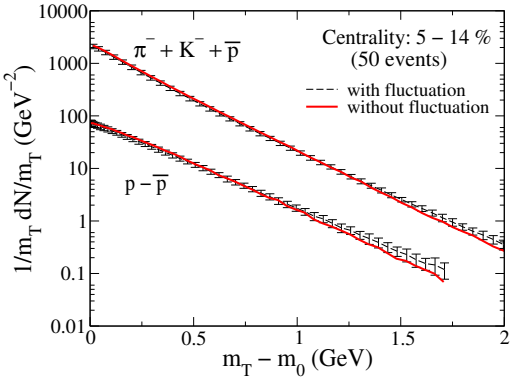
Transverse–Mass Distributions (Pb+Pb,17.3A GeV)



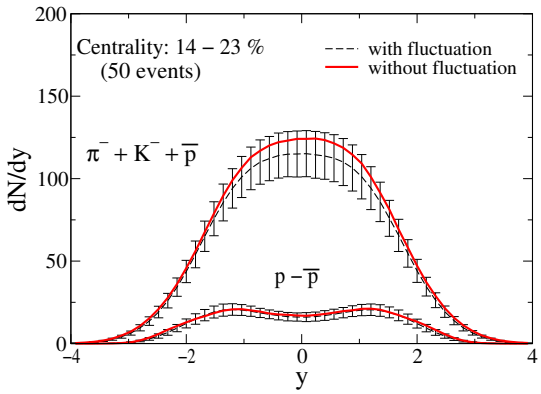
Rapidity Distributions (Pb+Pb, 17.3A GeV)



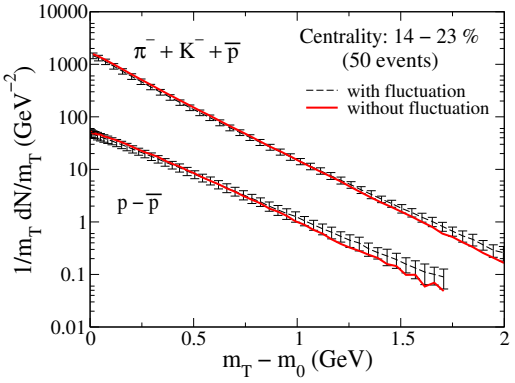
Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)



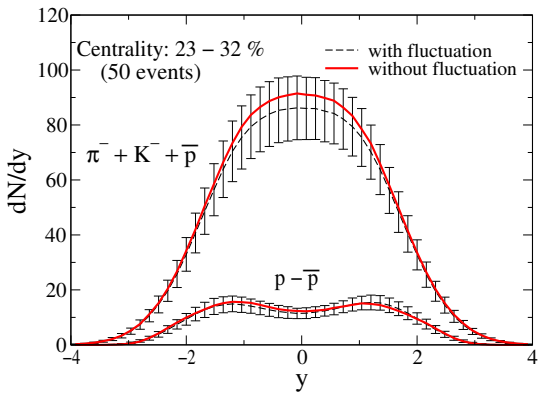
Rapidity Distributions (Pb+Pb, 17.3A GeV)



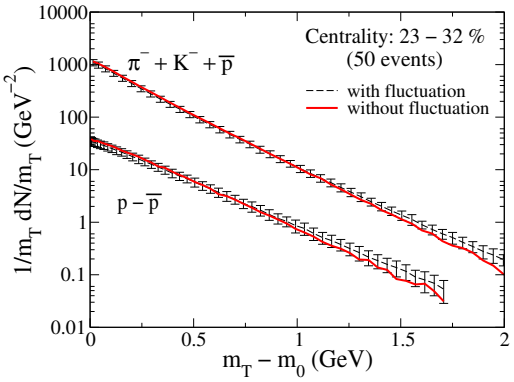
Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)



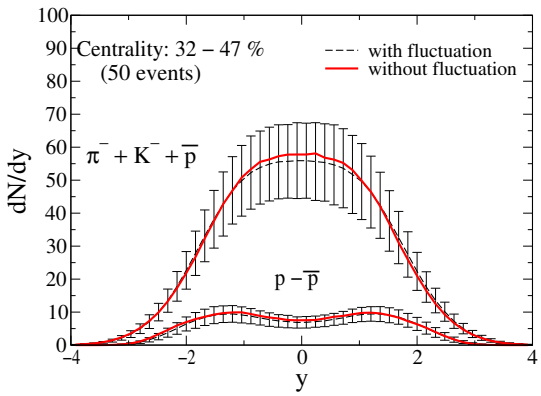
Rapidity Distributions (Pb+Pb, 17.3A GeV)



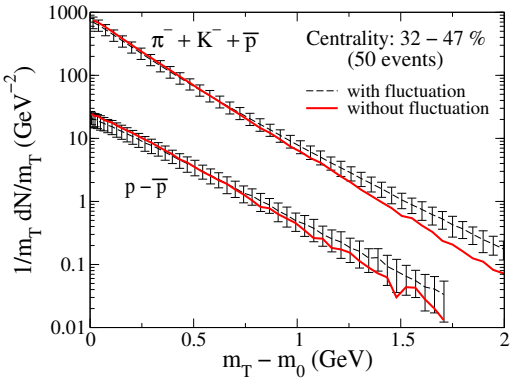
Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)



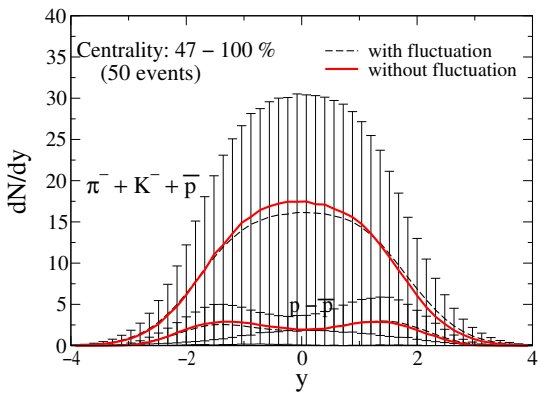
Rapidity Distributions (Pb+Pb, 17.3A GeV)



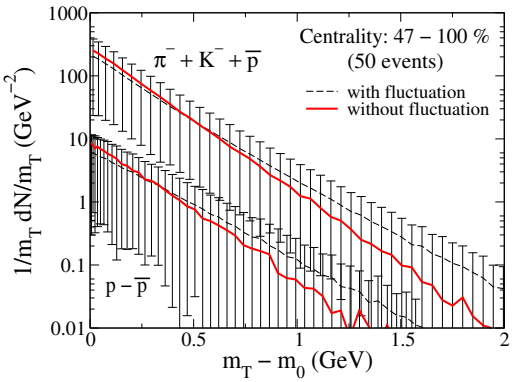
Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)



Rapidity Distributions (Pb+Pb, 17.3A GeV)



Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)



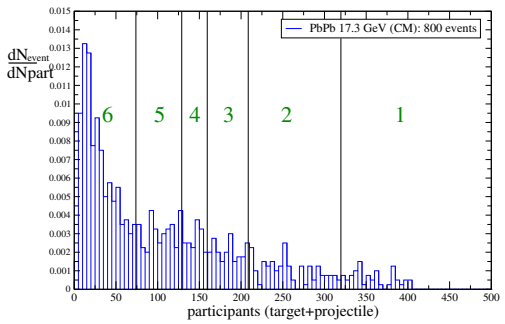
Conclusion: - averaging I.C. leads to higher rapidity distribution than averaging final spectra (≤ 10 %

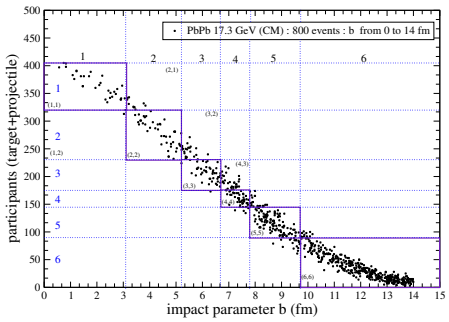
- transverse mass spectra are not very different.

Nb. of participants vs. impact parameter

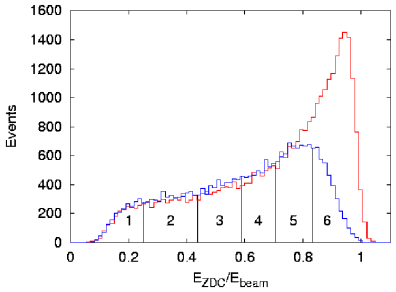
Centrality windows are defined
- in experiments, using E_{ZDC}, participant number, multiplicities
- in hydro, using impact parameter (generally)
$\rightarrow$ is it comparable?

Run NexSPheRIO 800 times



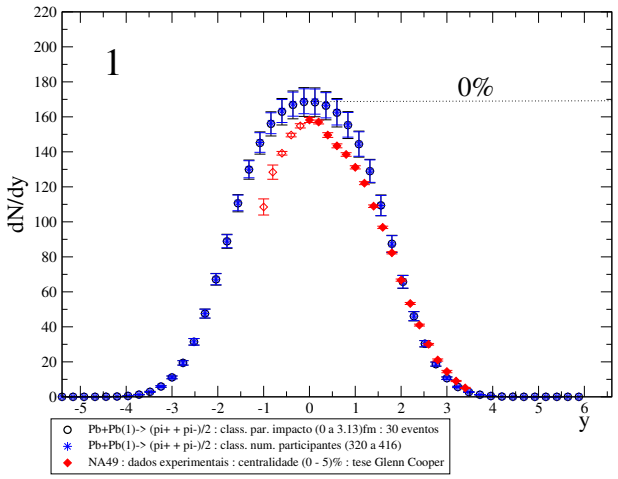


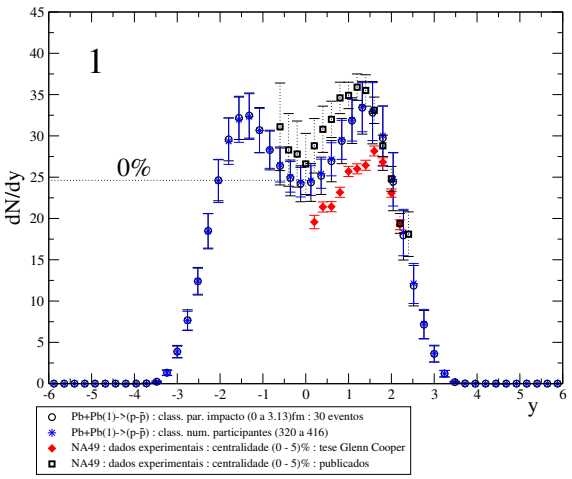
Choice of windows made to approximate NA49 choice

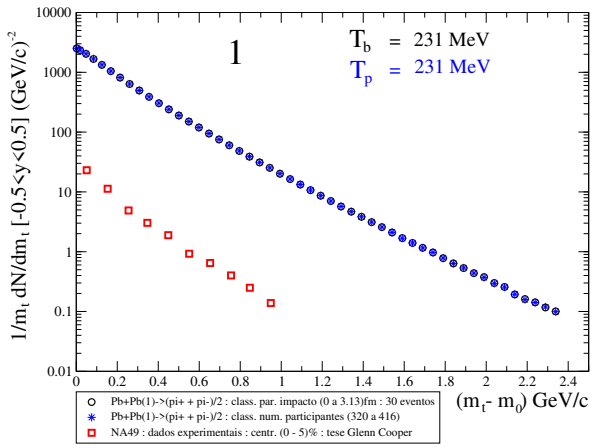


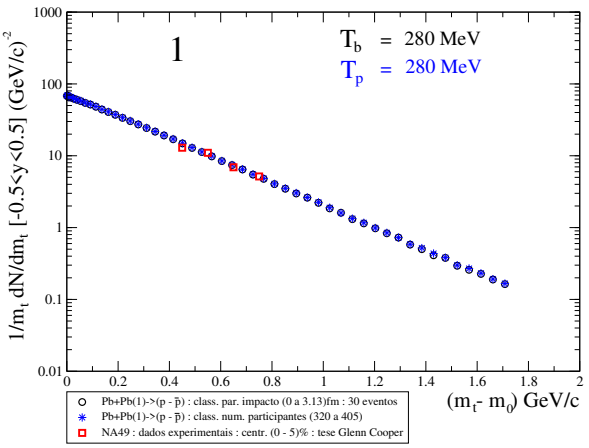
Different particle distributions expected for a window in N_{part} and the corresponding window in b, because mean number of participants are different.

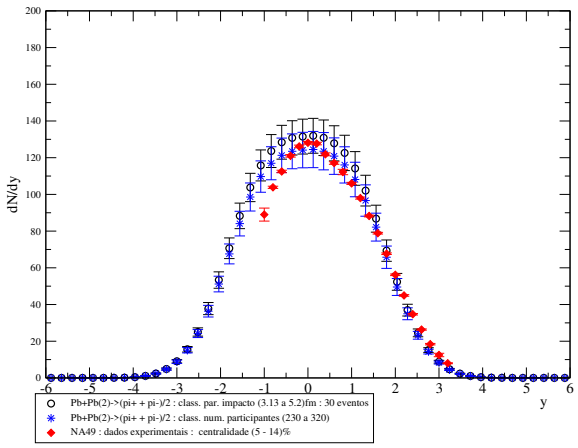
NA49 classification			N_{part} classification		b classification	
	central.	$< N_{part} >$	N_{part}	$< N_{part} >$	b (fm)	$< N_{part} >$
1	0-5%	362 $\pm$ 12	320-416	358	0-3.1	364
2	5-14%	304 $\pm$ 16	230-320	268	3.1-5.2	289
3	14-23%	241 $\pm$ 16	175-230	200	5.2-6.7	220
4	23-31%	188 $\pm$ 16	145-175	158	6.7-7.8	171
5	31-48%	130 $\pm$ 14	90-145	116	7.8-9.7	117
6	48-100%	72 $\pm$ 8	0-90	35	9.7-14	35

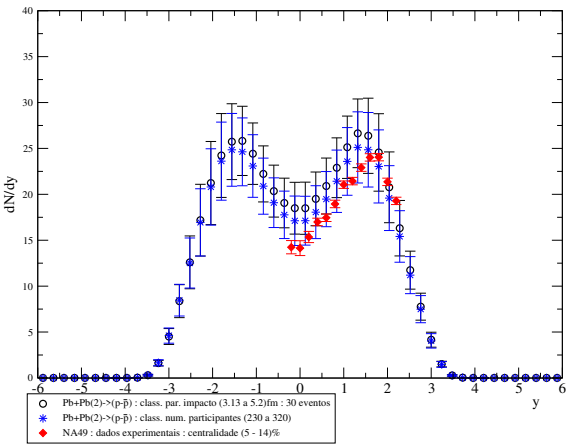

1
0%
dN/dy
y
Pb+Pb(1)-> (pi+ + pi-)/2 : class. par. impacto (0 a 3.13)fm : 30 eventos
Pb+Pb(1)-> (pi+ + pi-)/2 : class. num. participantes (320 a 416)
NA49 : dados experimentais : centralidade (0 - 5)% : tese Glenn Cooper

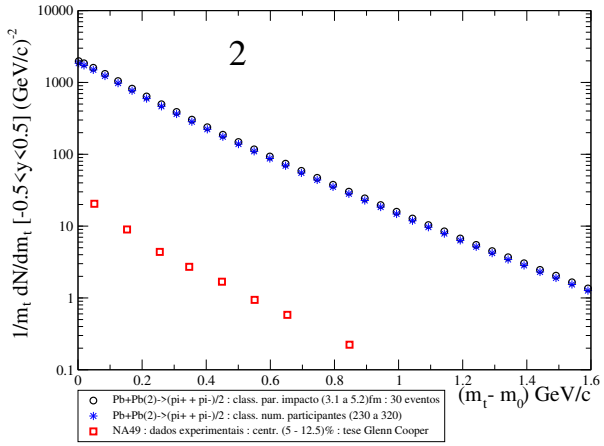

1
0%
dN/dy
y
Pb+Pb(1)->(p-p̄) : class. par. impacto (0 a 3.13)fm : 30 eventos
Pb+Pb(1)->(p-p̄) : class. num. participantes (320 a 416)
NA49 : dados experimentais : centralidade (0 - 5)% : tese Glenn Cooper
NA49 : dados experimentais : centralidade (0 - 5)% : publicados

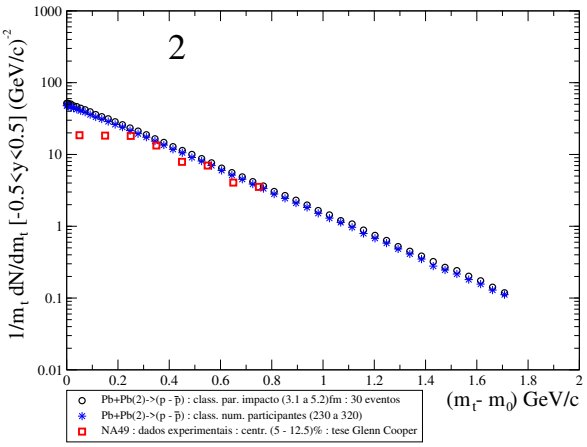

1
T_b = 231 MeV
T_p = 231 MeV
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(1)->(pi+ + pi-)/2 : class. par. impacto (0 a 3.13)fm : 30 eventos
Pb+Pb(1)->(pi+ + pi-)/2 : class. num. participantes (320 a 416)
NA49 : dados experimentais : centr. (0 - 5)% : tese Glenn Cooper

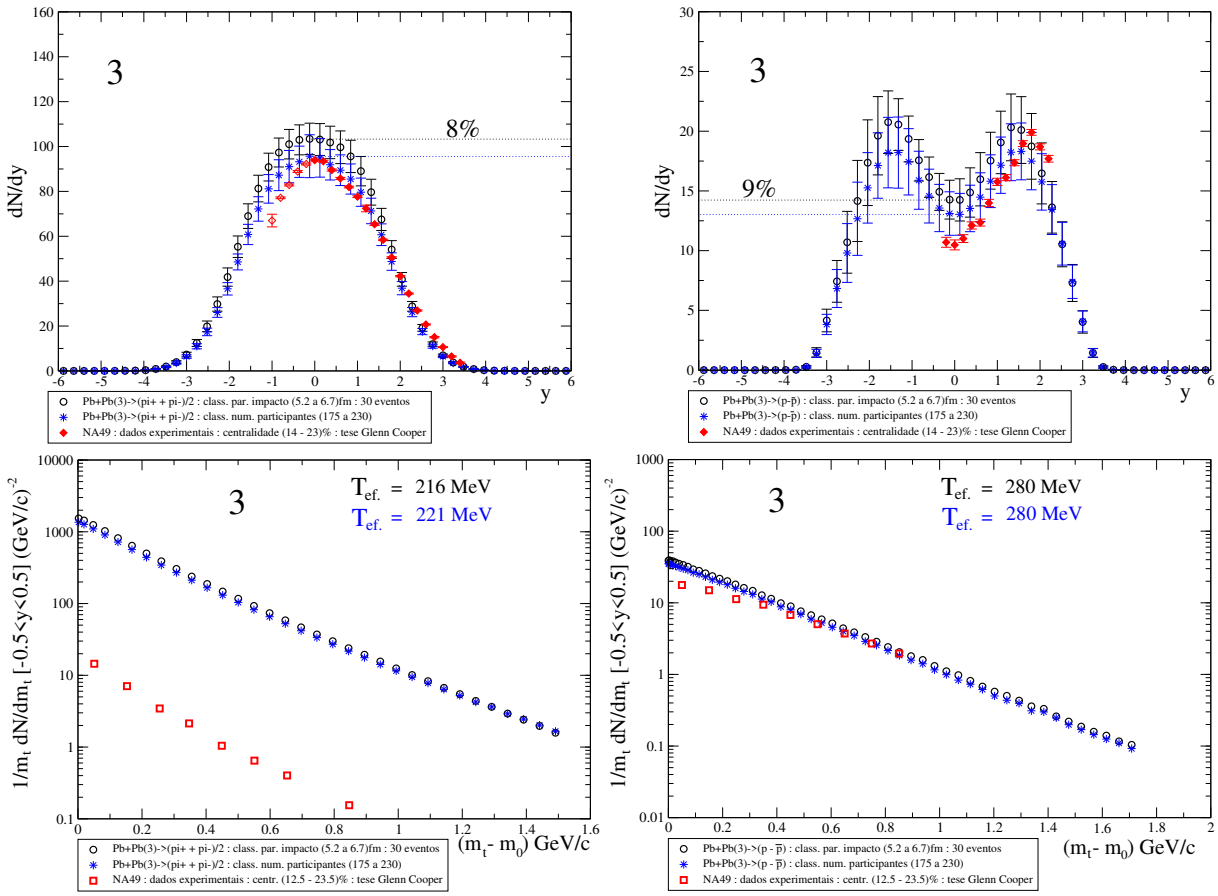

1
T_b = 280 MeV
T_p = 280 MeV
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(1)->(p - p̄) : class. par. impacto (0 a 3.13)fm : 30 eventos
Pb+Pb(1)->(p - p̄) : class. num. participantes (320 a 405)
NA49 : dados experimentais : centr. (0 - 5)% : tese Glenn Cooper

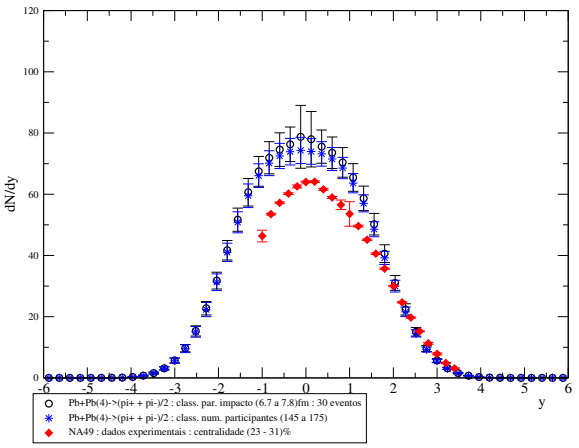

dN/dy
y
Pb+Pb(2)->(pi+ + pi-)/2 : class. par. impacto (3.13 a 5.2)fm : 30 eventos
Pb+Pb(2)->(pi+ + pi-)/2 : class. num. participantes (230 a 320)
NA49 : dados experimentais : centralidade (5 - 14)%

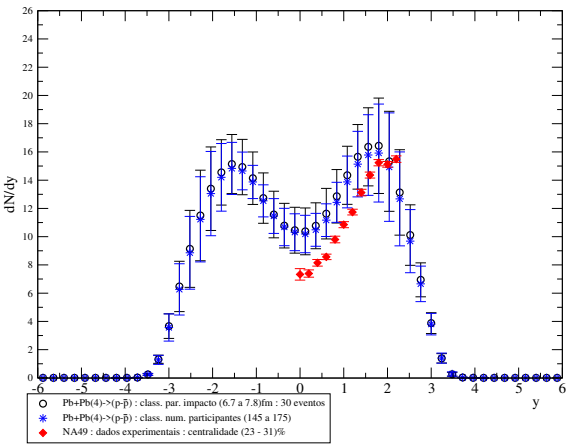

dN/dy
y
Pb+Pb(2)->(p-p̄) : class. par. impacto (3.13 a 5.2)fm : 30 eventos
Pb+Pb(2)->(p-p̄) : class. num. participantes (230 a 320)
NA49 : dados experimentais : centralidade (5 - 14)%

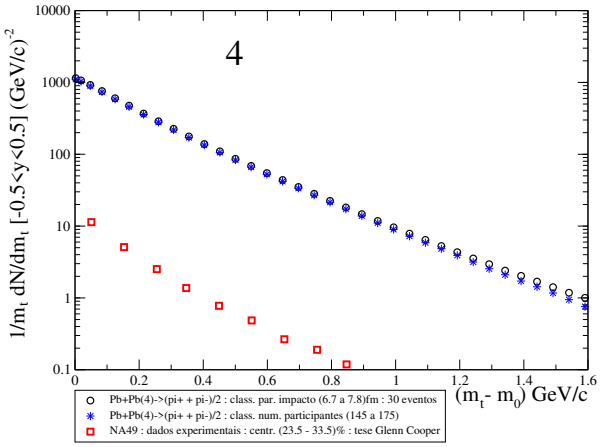

2
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(2)->(pi+ + pi-)/2 : class. par. impacto (3.1 a 5.2)fm : 30 eventos
Pb+Pb(2)->(pi+ + pi-)/2 : class. num. participantes (230 a 320)
NA49 : dados experimentais : centr. (5 - 12.5)% : tese Glenn Cooper

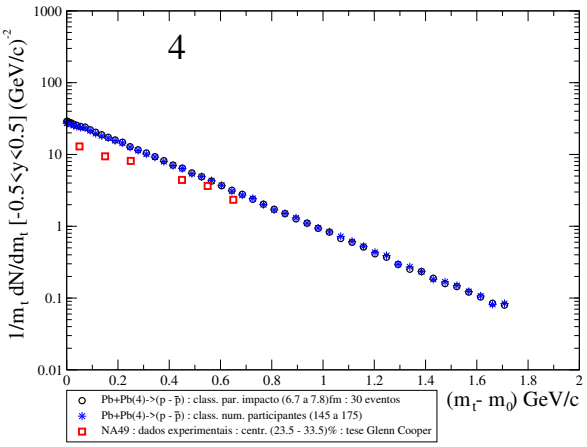

2
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(2)->(p - p̄) : class. par. impacto (3.1 a 5.2)fm : 30 eventos
Pb+Pb(2)->(p - p̄) : class. num. participantes (230 a 320)
NA49 : dados experimentais : centr. (5 - 12.5)% : tese Glenn Cooper

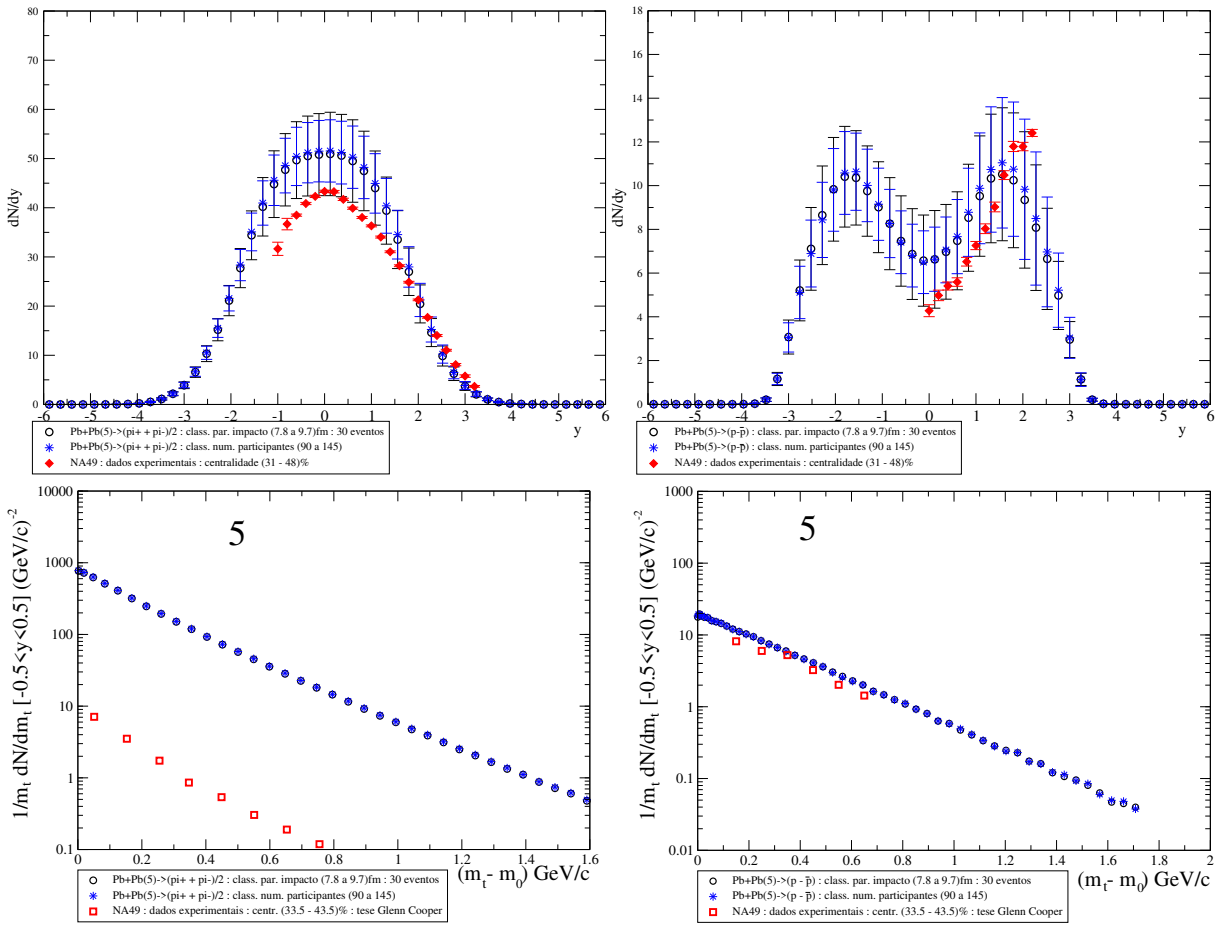

3
8%
dN/dy
y
Pb+Pb(3)->(pi+ + pi-)/2 : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(pi+ + pi-)/2 : class. num. participantes (175 a 230)
NA49 : dados experimentais : centralidade (14 - 23)% : tese Glenn Cooper
3
9%
dN/dy
y
Pb+Pb(3)->(p-p̄) : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(p-p̄) : class. num. participantes (175 a 230)
NA49 : dados experimentais : centralidade (14 - 23)% : tese Glenn Cooper
3
T_ef. = 216 MeV
T_ef. = 221 MeV
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t - m_0) GeV/c
Pb+Pb(3)->(pi+ + pi-)/2 : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(pi+ + pi-)/2 : class. num. participantes (175 a 230)
NA49 : dados experimentais : centr. (12.5 - 23.5)% : tese Glenn Cooper
3
T_ef. = 280 MeV
T_ef. = 280 MeV
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t - m_0) GeV/c
Pb+Pb(3)->(p - p̄) : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(p - p̄) : class. num. participantes (175 a 230)
NA49 : dados experimentais : centr. (12.5 - 23.5)% : tese Glenn Cooper

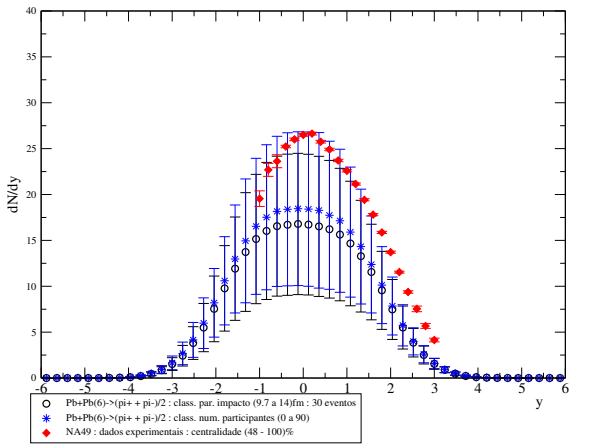

dN/dy
y
Pb+Pb(4)->(pi+ + pi-)/2 : class. par. impacto (6.7 a 7.8)fm : 30 eventos
Pb+Pb(4)->(pi+ + pi-)/2 : class. num. participantes (145 a 175)
NA49 : dados experimentais : centralidade (23 - 31)%

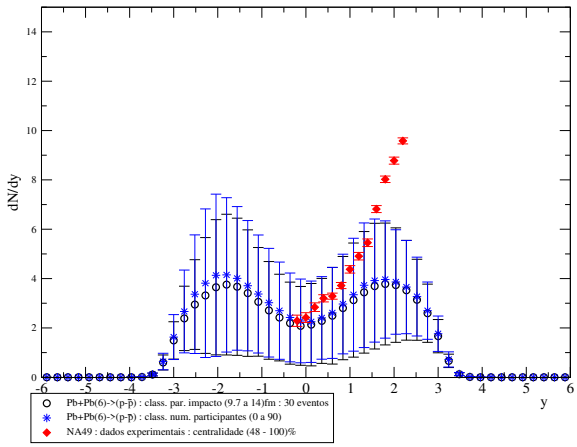

dN/dy
y
Pb+Pb(4)->(p-p̄) : class. par. impacto (6.7 a 7.8)fm : 30 eventos
Pb+Pb(4)->(p-p̄) : class. num. participantes (145 a 175)
NA49 : dados experimentais : centralidade (23 - 31)%

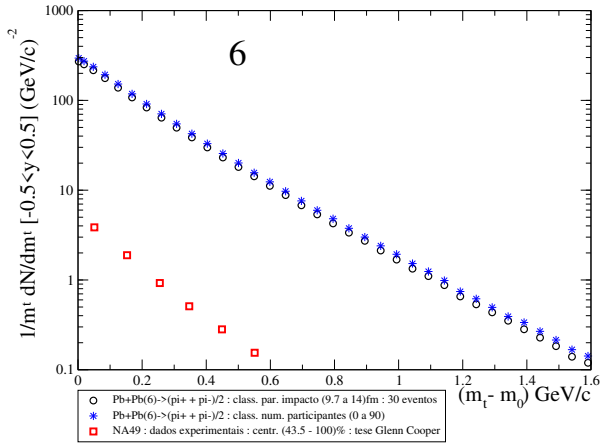

4
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(4)->(pi+ + pi-)/2 : class. par. impacto (6.7 a 7.8)fm : 30 eventos
Pb+Pb(4)->(pi+ + pi-)/2 : class. num. participantes (145 a 175)
NA49 : dados experimentais : centr. (23.5 - 33.5)% : tese Glenn Cooper

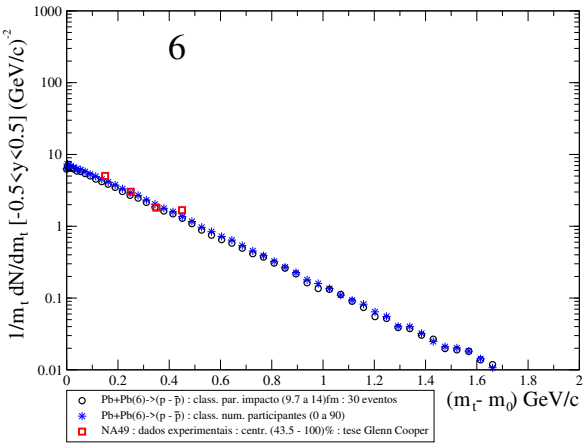

4
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(4)->(p - p̄) : class. par. impacto (6.7 a 7.8)fm : 30 eventos
Pb+Pb(4)->(p - p̄) : class. num. participantes (145 a 175)
NA49 : dados experimentais : centr. (23.5 - 33.5)% : tese Glenn Cooper


dN/dy
y
Pb+Pb(5)->(pi+ + pi-)/2 : class. par. impacto (7.8 a 9.7)fm : 30 eventos
Pb+Pb(5)->(pi+ + pi-)/2 : class. num. participantes (90 a 145)
NA49 : dados experimentais : centralidade (31 - 48)%
dN/dy
y
Pb+Pb(5)->(p-p̄) : class. par. impacto (7.8 a 9.7)fm : 30 eventos
Pb+Pb(5)->(p-p̄) : class. num. participantes (90 a 145)
NA49 : dados experimentais : centralidade (31 - 48)%
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
5
(m_t- m_0) GeV/c
Pb+Pb(5)->(pi+ + pi-)/2 : class. par. impacto (7.8 a 9.7)fm : 30 eventos
Pb+Pb(5)->(pi+ + pi-)/2 : class. num. participantes (90 a 145)
NA49 : dados experimentais : centr. (33.5 - 43.5)% : tese Glenn Cooper
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
5
(m_t- m_0) GeV/c
Pb+Pb(5)->(p - p̄) : class. par. impacto (7.8 a 9.7)fm : 30 eventos
Pb+Pb(5)->(p - p̄) : class. num. participantes (90 a 145)
NA49 : dados experimentais : centr. (33.5 - 43.5)% : tese Glenn Cooper


dN/dy
y
Pb+Pb(6)->(pi+ + pi-)/2 : class. par. impacto (9.7 a 14)fm : 30 eventos
Pb+Pb(6)->(pi+ + pi-)/2 : class. num. participantes (0 a 90)
NA49 : dados experimentais : centralidade (48 - 100)%


dN/dy
y
Pb+Pb(6)->(p-p̄) : class. par. impacto (9.7 a 14)fm : 30 eventos
Pb+Pb(6)->(p-p̄) : class. num. participantes (0 a 90)
NA49 : dados experimentais : centralidade (48 - 100)%


6
1/mt dN/dmt [-0.5<y<0.5] (GeV/c)-2
(mt- m0) GeV/c
Pb+Pb(6)->(pi+ + pi-)/2 : class. par. impacto (9.7 a 14)fm : 30 eventos
Pb+Pb(6)->(pi+ + pi-)/2 : class. num. participantes (0 a 90)
NA49 : dados experimentais : centr. (43.5 - 100)% : tese Glenn Cooper


6
1/mt dN/dmt [-0.5<y<0.5] (GeV/c)-2
(mt- m0) GeV/c
Pb+Pb(6)->(p - p̄) : class. par. impacto (9.7 a 14)fm : 30 eventos
Pb+Pb(6)->(p - p̄) : class. num. participantes (0 a 90)
NA49 : dados experimentais : centr. (43.5 - 100)% : tese Glenn Cooper

Conclusion: - for the rapidity disitribution, the difference between both approaches can be up to 12 %.

- for the transverse mass ditribution, there is little difference

- under progress: v_2 comparison and multiplicity classification.

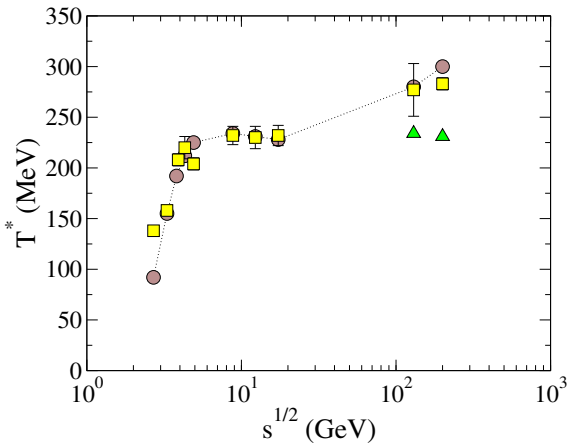
- On this subject see also:
Broniowski & Florkowski, Phys.Rev. C65 (2002) 024905 (nucl-th/0110020)

Effective K^+ temperature as function of $\sqrt{s}$

Motivation:Gorenstein,Gazdzicki,Bugaev PLB567(2003)175
argue that behaviour of $T_{eff}^{K^+}(\sqrt{s})$ comes from QGP

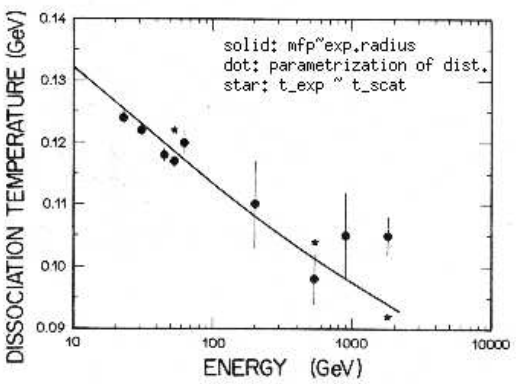
- choose a $\sqrt{s}$
- I.C.= average over 30 NeXus events
- Run SPheRIO
- Stop at freeze out temperature $T_{f.o.}(\sqrt{s})$ (SEE BELOW)
- Compute K^+ distribution and extract its T_{eff}
- Compare with its experimental value

$\sqrt{s}$	T_0	ε_0	T_{fo}	$\bar{v}_T$	T^*
2.7	98	0.75	85	0.067	92
3.3	128	0.66	94	0.28	155
3.8	131	1.01	97	0.41	192
4.3	135	1.38	115	0.37	212
4.9	140	1.55	120	0.39	225
8.8	198	4.06	143	0.32	234
12.3	248	9.04	147	0.32	231
17.3	265	11.37	149	0.32	228
130	279	12.86	128	0.52	280
			155	**0.34**	**234**
200	277	12.48	125	0.56	300
			155	**0.34**	**231**



Conclusion: decreasing $T_{f.o.}(\sqrt{s})$ is required by data, it implies
$\rightarrow$ longer expansion time IN THE HADRONIC PHASE for increasing $\sqrt{s}$
$\rightarrow$ larger effective temperature $T_{eff}^{K^+}(\sqrt{s})$
= different from common vue that longer expansion time in the QGP phase is responsible for increase in $T_{eff}^{K^+}(\sqrt{s})$

Decreasing $T_{f.o.}(\sqrt{s})$ predicted in the past: see Hama & Navarra Z.Phys.C53(1992)501 and Navarra, Nemes, Ornik & Paiva, Phys.Rev.C45(1992)R2552



SUMMARY

NeXSPheRIO combines initial conditions given by NeXus with a hydrodynamical solution provided by SPheRIO.

- Predictions for rapidity spectra and transverse mass distributions of pions and $p - \bar{p}$ agree with S+S, Pb+Pb at CERN and Au+Au from RHIC (except perhaps the most central window at RHIC).

  Under progress: elliptic flow, HBT

- Fluctuations in initial conditions from event to event lead to large fluctuations in rapitidy distributions

- Using averaged initial conditions leads to higher rapitidy distributions than running various events and then making the average of their individual rapitidy distribution (as happens experimentally)

- Using a classification of centrality windows in participant number (as obtained e.g. experimentally) rather than in impact parameter (as doable in hydrodynamics) lead to up to 12 % difference in rapitidy distributions.

- Increase in $T_{eff}^{K^+}(\sqrt{s})$ seems related to decrease of $T_{f.o.}(\sqrt{s})$ and larger expansion in HADRONIC PHASE rather than larger expansion in QGP phase.