

# Recent results from NA60

## Rencontres QGP-France-09

Etretat, 15-18 sept. 2009

E. Scomparin  
for the NA60 collaboration

- Quarkonia measurements
- The  $\phi$  puzzle
- Thermal dimuon production
- Conclusions and perspectives

Comité d'organisation

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# Quarkonia measurements in p-A

- Study of **charmonium production/suppression** in pA collisions
  - Production models (CSM, NRQCD, CEM, ....)
  - Initial/final state nuclear effects (shadowing, dissociation,...)
  - Reference for understanding dissociation in a hot medium
- (Relatively) large amount of fixed-target data (SPS, FNAL, HERA)

**HERA-B** (I. Abt et al., arXiv:0812.0734)

p-Cu (p-Ti) p-W, 920 GeV,  $-0.34 < x_F < 0.14$ ,  $p_T < 5$  GeV

**E866** (M.J.Leitch et al., PRL84(2000) 3256)

p-Be p-Fe p-W 800 GeV,  $-0.10 < x_F < 0.93$ ,  $p_T < 4$  GeV

**NA50** (B. Alessandro et al., EPJC48(2006) 329)

p-Be p-Al p-Cu p-Ag p-W p-Pb, 400/450 GeV,  $-0.1 < x_F < 0.1$ ,  $p_T < 5$  GeV

**NA3** (J. Badier et al., ZPC20 (1983) 101)

p-p p-Pt, 200 GeV,  $0 < x_F < 0.6$ ,  $p_T < 5$  GeV

- New results from NA60  $\left\{ \begin{array}{l} \text{pA 158 GeV} \\ \text{pA 400 GeV} \end{array} \right.$

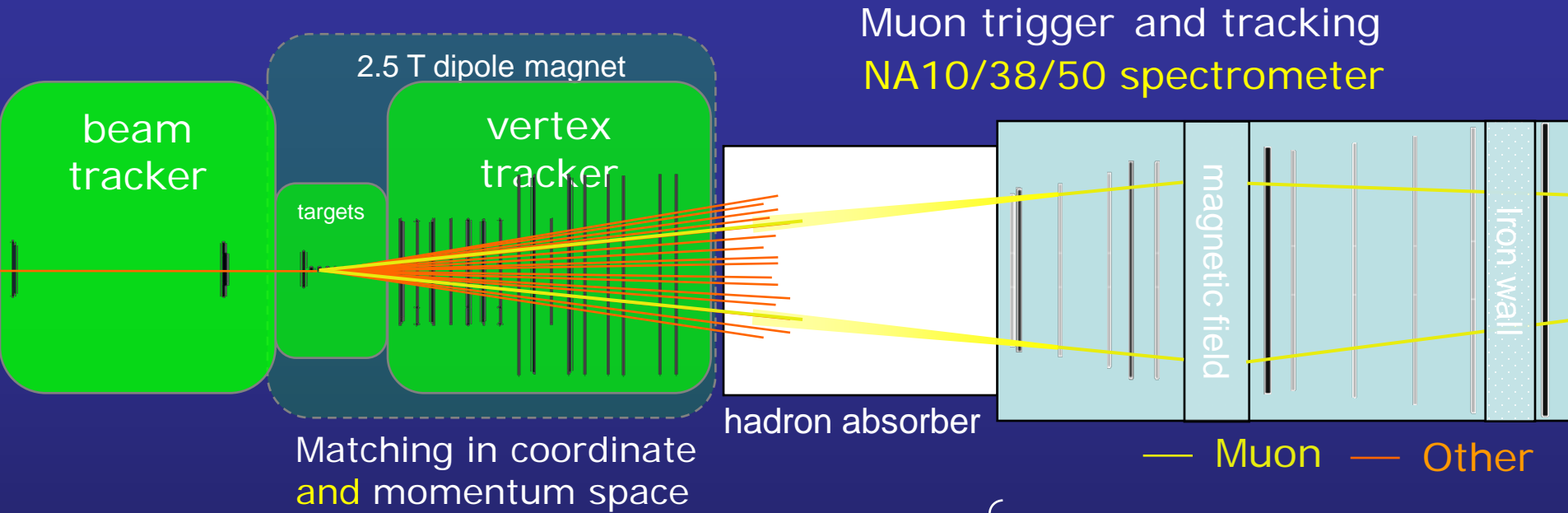
# NA60: pA at 158, 400 GeV

- Data taking at **158 GeV** (3-day long) largely motivated by the need of a **reference sample** taken in the same conditions of InIn (NA60) and Pb-Pb (NA50) data
- Data at **400 GeV** represent the **bulk of the NA60 p-A data taking**
- Results refer to:
  - Sub-sample with **same experimental set-up used at 158 GeV**
  - Useful as a **cross-check** (same energy/kinematic domain of a large statistics data sample collected by NA50)

**Kinematical window** used in this analysis

$$\bullet \quad 3.2 < y_{\text{lab}} < 3.7 \quad \left\{ \begin{array}{ll} 0.28 < y_{\text{cm}} < 0.78 & (158 \text{ GeV}) \\ -0.17 < y_{\text{cm}} < 0.33 & (400 \text{ GeV}) \end{array} \right.$$
$$\bullet \quad |\cos \theta_{\text{CS}}| < 0.5$$

# Apparatus and analysis



9 **subtargets**: Al-U-W-Cu-In-Be1-Be2-Be3-Pb

mixed A-order to limit possible z-dependent systematics

Estimate of differential distributions through **1-D acceptance correction**



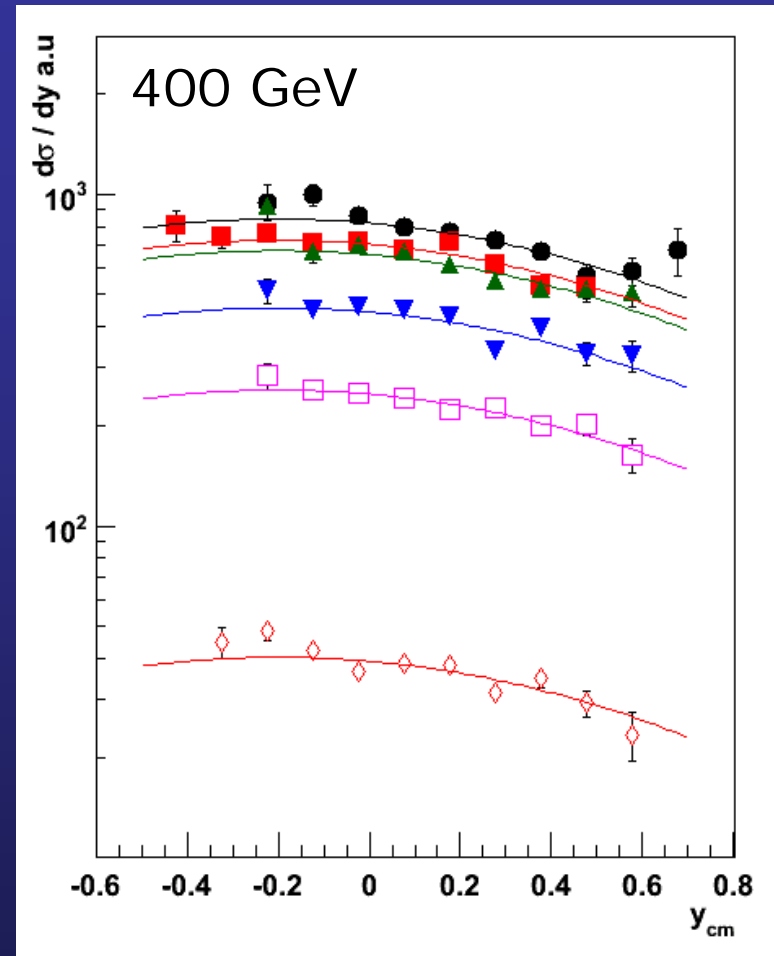
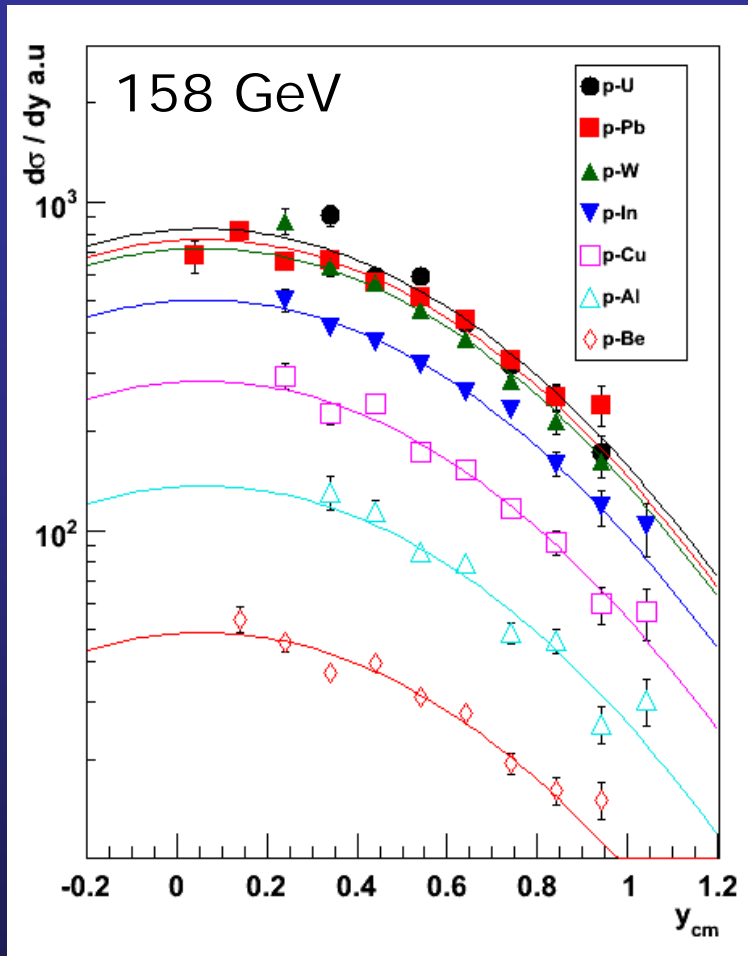
Distributions injected in the MC **iteratively tuned** on data

Estimate of nuclear effects through **relative cross sections** (luminosity factors **cancel out**)



$$\frac{\sigma_A^{J/\psi}}{\sigma_{Be}^{J/\psi}} = \frac{\frac{N_A^{J/\psi}}{N_A^{inc} \times N_A^{targ} \times A_A \times \epsilon_A}}{N_{Be}^{J/\psi}}}{\frac{N_{Be}^{inc} \times N_{Be}^{targ} \times A_{Be} \times \epsilon_{Be}}$$

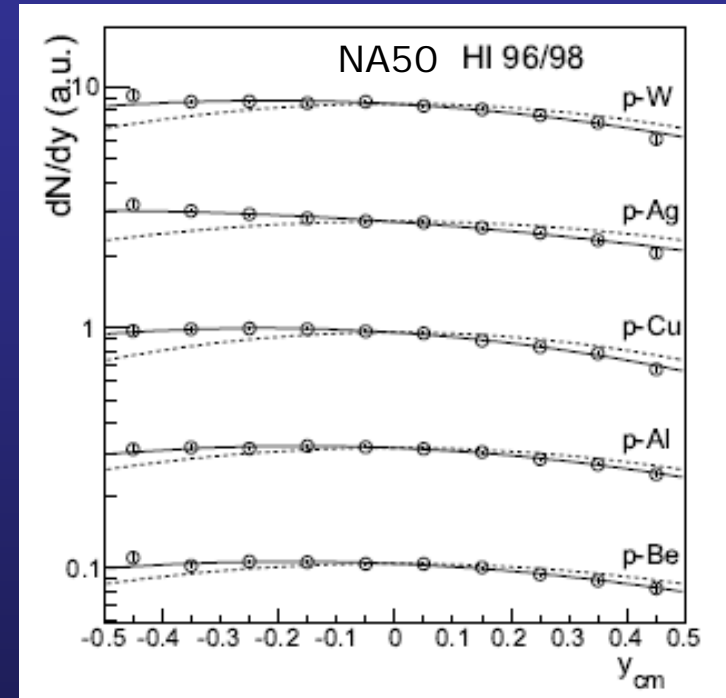
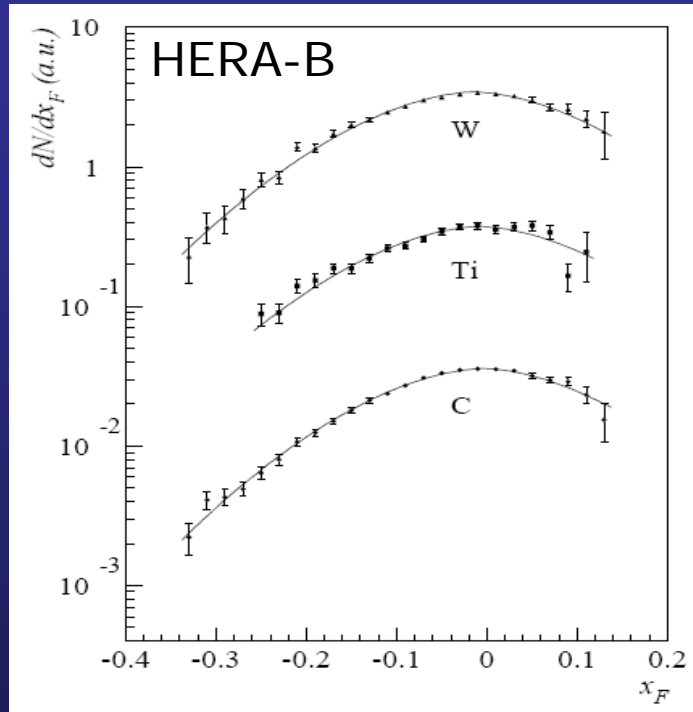
# Differential distributions: $dN/dy$



- $y$ -distribution wider at 400 GeV, as expected
- Gaussian fit at 158 GeV gives  $\mu_y = 0.05$ ,  $\sigma_y = 0.51$
- Peak position not well constrained at 400 GeV
- Imposing  $\mu_y = -0.2$  (NA50 at 400 GeV)  $\sigma_y = 0.81$  (NA50 got 0.85)

# Comparison with previous experiments

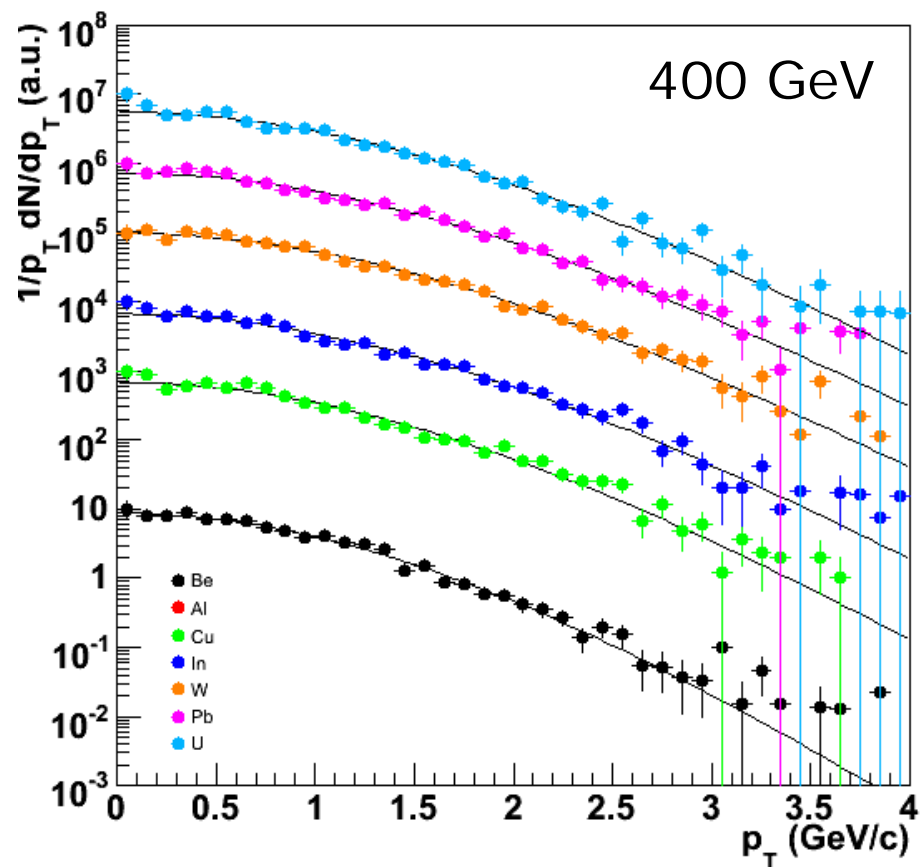
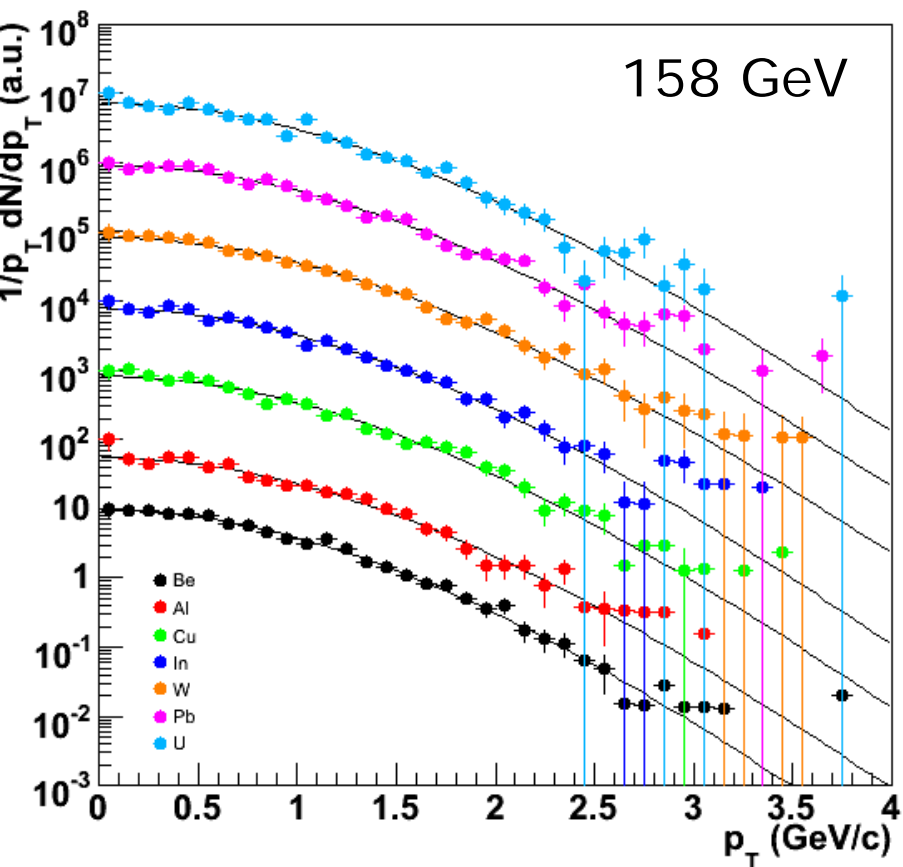
- HERA-B observes, at 920 GeV, a **displacement** of the center of the  $x_F$  distribution towards **negative** values, increasing with  $A$  (by a small amount,  $\Delta x_F < 0.01$ )



- NA50 observes, at 400 GeV, a **strong backward** displacement ( $\Delta y = 0.2$ , corresponding to  $\Delta x_F = 0.045$ )
- Mutually incompatible observations? NA60 data not precise enough to discriminate between the two scenarios

# Differential distributions: $dN/dp_T$

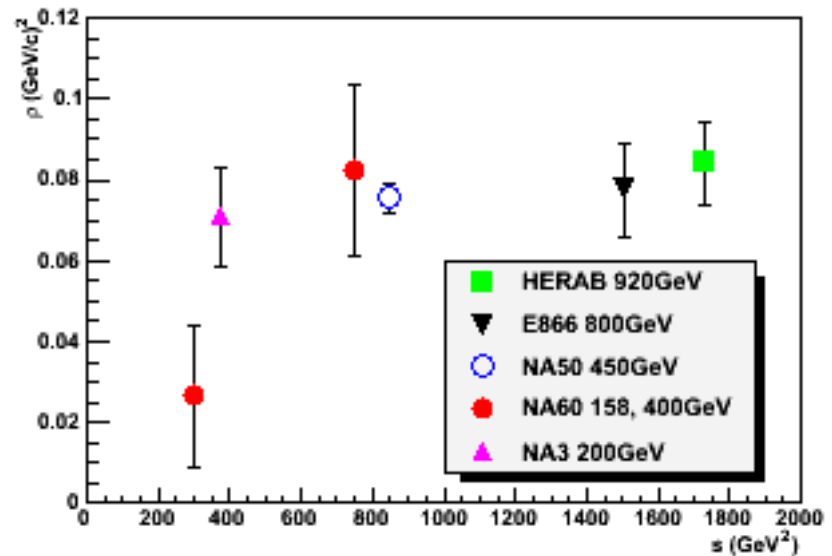
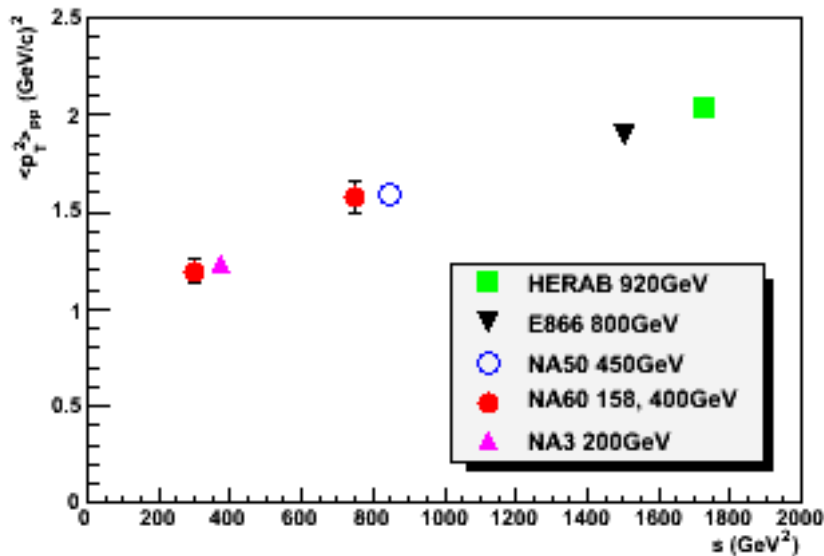
- $p_T$  broadening (Cronin effect) observed at both 158 and 400 GeV



# Comparison with previous experiments

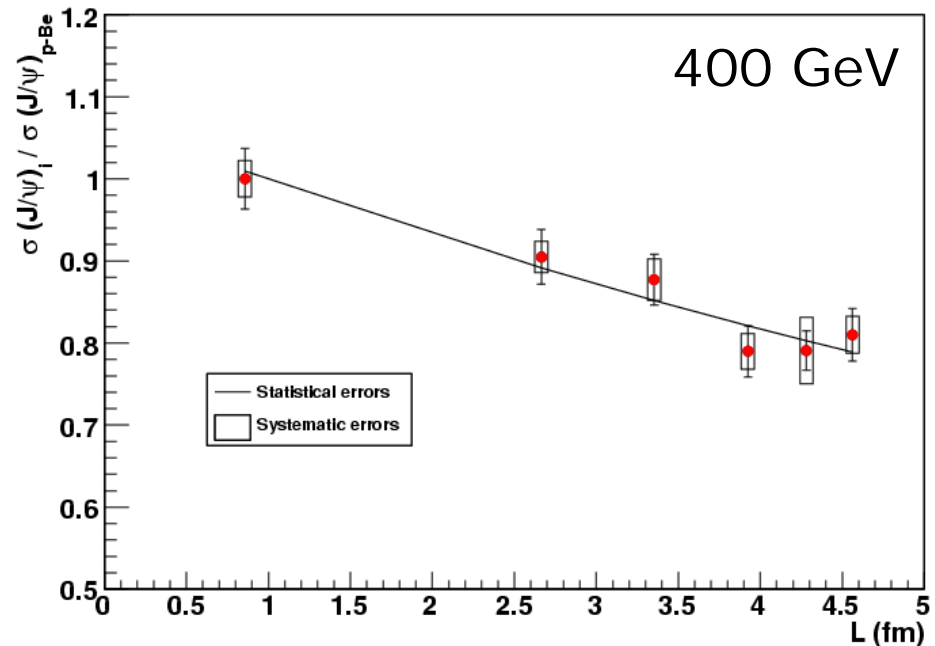
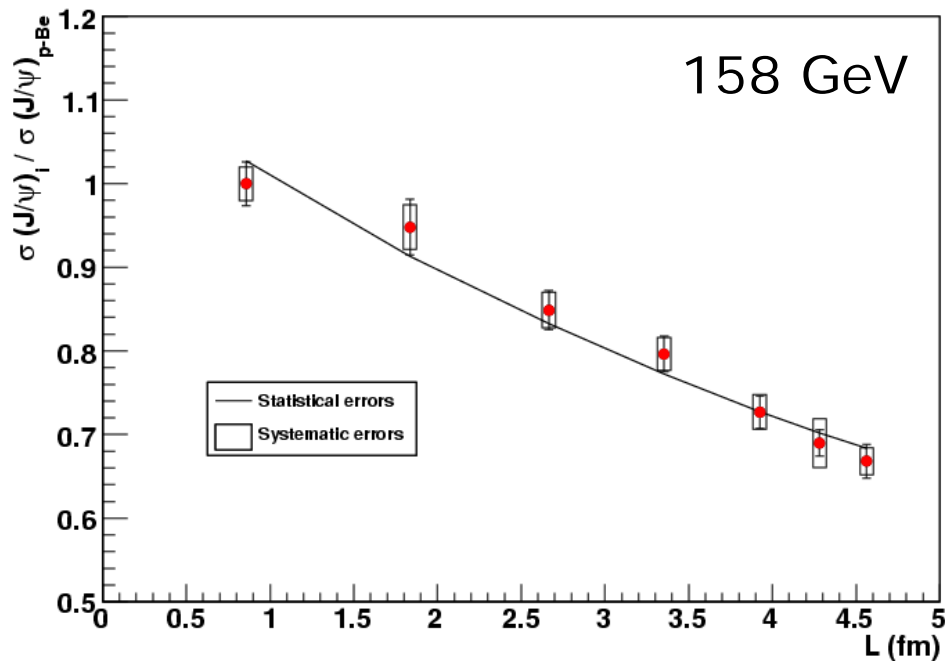
Fit  $\langle p_T^2 \rangle$  for various nuclei as

$$\begin{cases} \langle p_T^2 \rangle = \langle p_T^2 \rangle_{pp} + \alpha_{gN} \times L \\ \langle p_T^2 \rangle = \langle p_T^2 \rangle_{pp} + \rho(A^{1/3}-1) \end{cases}$$



- $\langle p_T^2 \rangle_{pp}$  shows an increase vs  $s$
- Does  $\rho$  increase with  $\sqrt{s}$  ?
  - Disagreement NA60 vs NA3 at low energy
  - Agreement NA60 vs NA50 at 400 GeV

# Relative cross sections vs A



- A-dependence fitted using the **Glauber model**
- **Shadowing neglected**, as usual (but not correct!) at fixed target

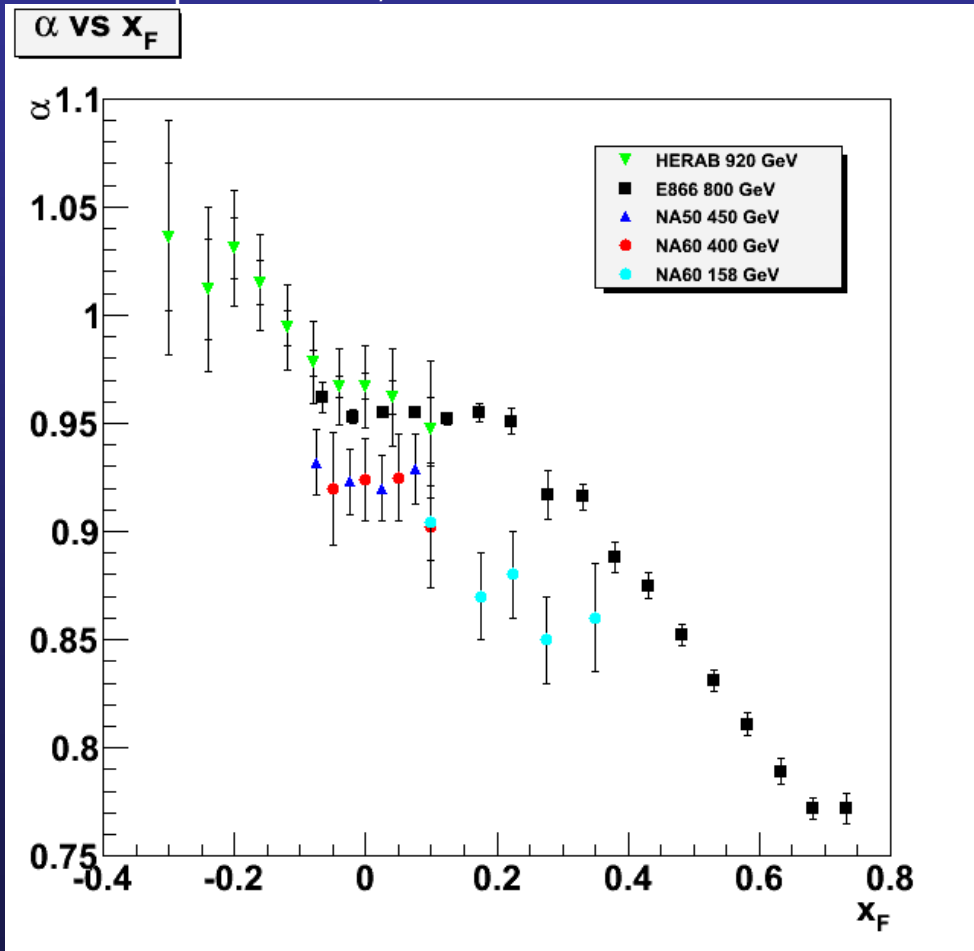
We get  $\left\{ \begin{array}{l} \sigma_{\text{abs}}^{J/\psi} (158 \text{ GeV}) = 7.6 \quad 0.7(\text{stat}) \quad 0.6(\text{syst}) \text{ mb} \\ \sigma_{\text{abs}}^{J/\psi} (400 \text{ GeV}) = 4.3 \quad 0.8(\text{stat}) \quad 0.6(\text{syst}) \text{ mb} \end{array} \right.$

Using  $\sigma_{pA} = \sigma_{pp} A^\alpha \left\{ \begin{array}{l} \alpha(158 \text{ GeV}) = 0.882 \quad 0.009 \quad 0.008 \\ \alpha(400 \text{ GeV}) = 0.927 \quad 0.013 \quad 0.009 \end{array} \right.$

# Comparison with other experiments (1)

- Recent results on  $\alpha$  vs  $x_F$  from HERA-B, together with older data from NA50, E866 (no NA3,  $\alpha$  biased by use of p-p)

E. Scomparin et al., arXiv:0907.3682



In the region close to  $x_F=0$ ,  
increase of  $\alpha$  with  $\sqrt{s}$

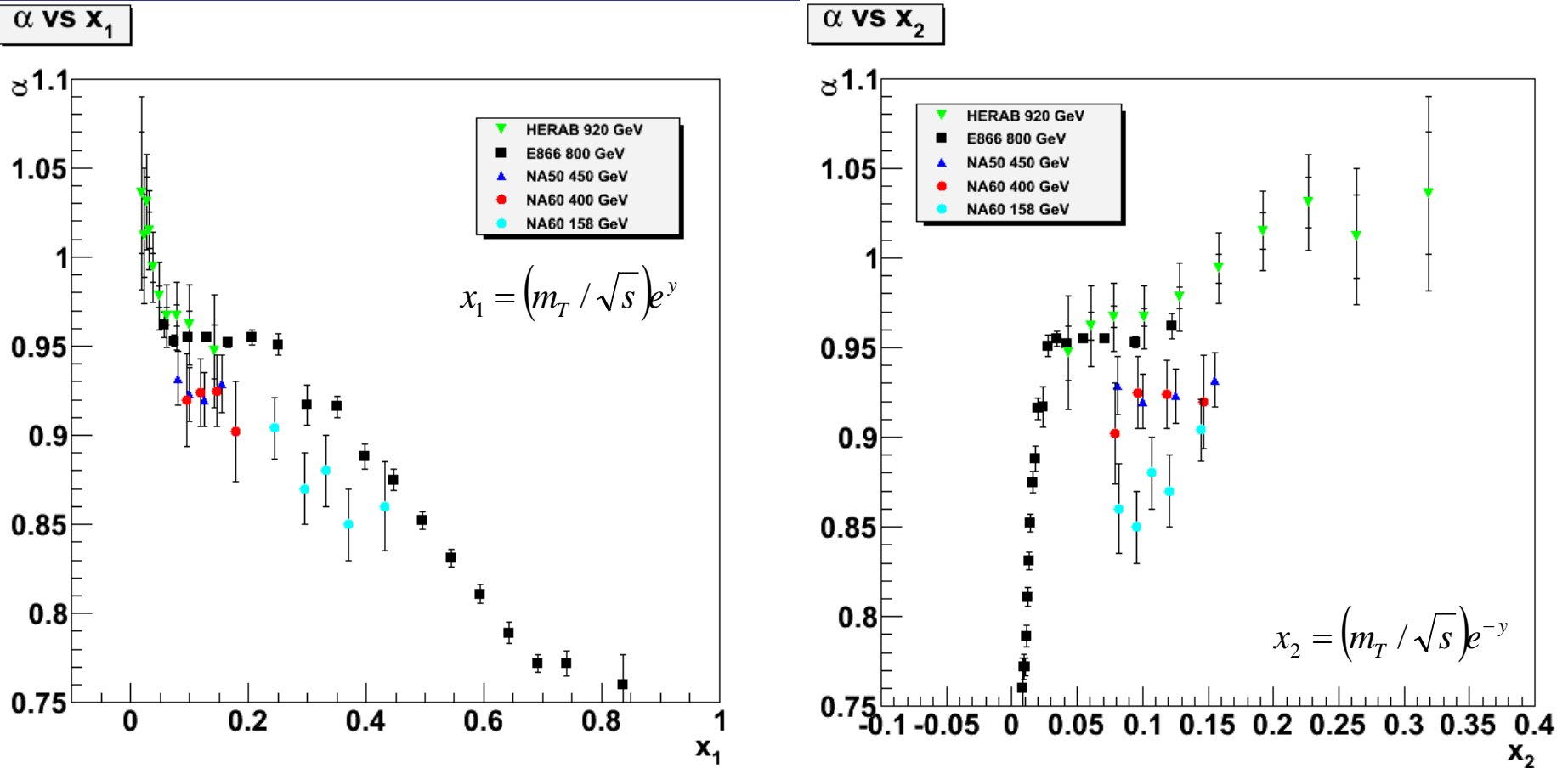
NA60

400 GeV: very good  
agreement with NA50

158 GeV: smaller  $\alpha$ ,  
hints of a decrease towards  
high  $x_F$  ?

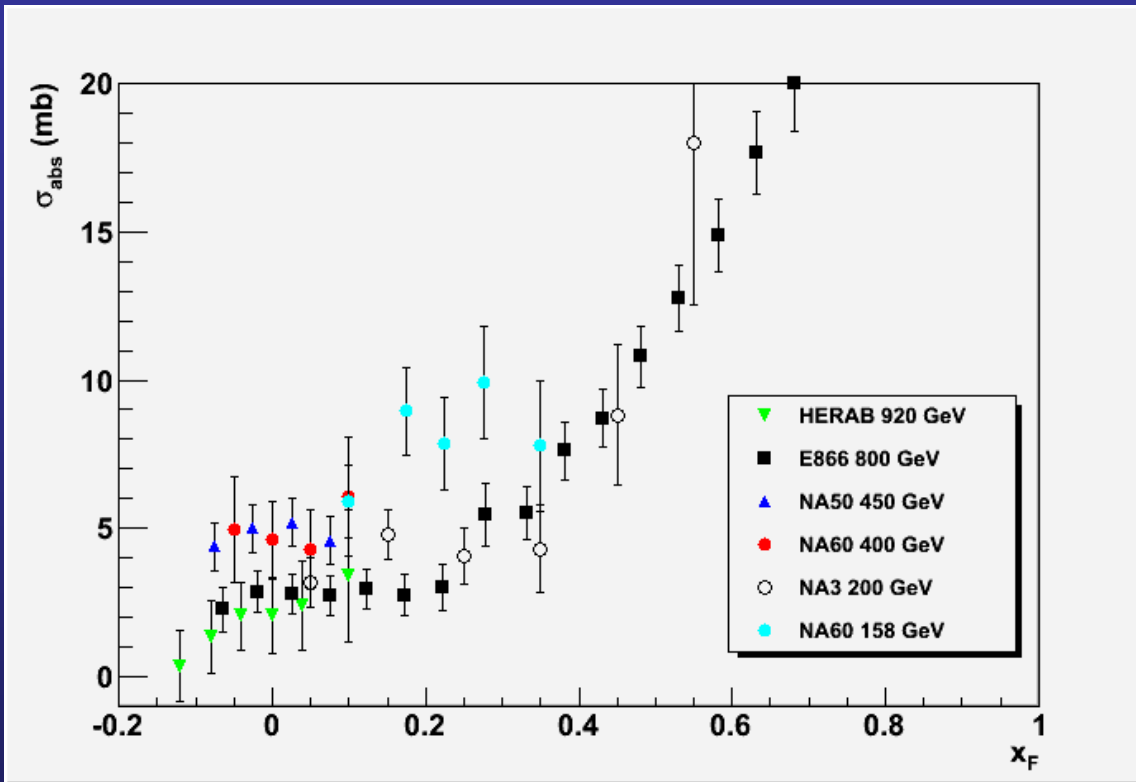
Systematic error on  $\alpha$  for the new NA60 points  $\sim 0.01$

# Comparison with other experiments (2)



- $\alpha$  pattern vs  $x_1$  at lower energies (400, 158 GeV) resembles HERA-B+E866, but systematically lower
- Shadowing effects and final state absorption scale with  $x_2$ , clearly other effects are present

# Comparison with other experiments (3)



$\sigma_{\text{abs}}^{J/\psi}$  calculated from cross section ratios for HERA-B, E866, NA3

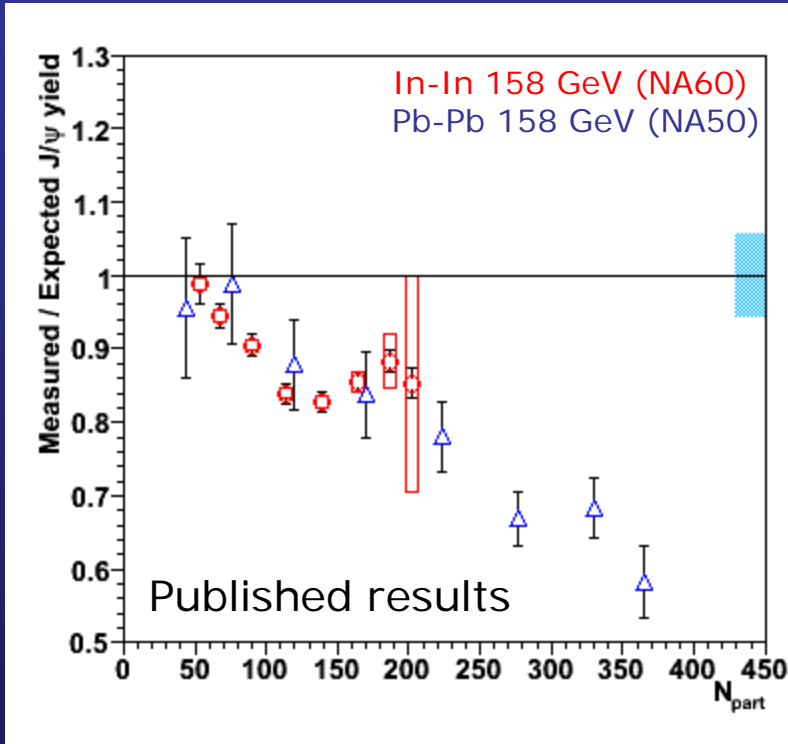
Increase of  $\sigma_{\text{abs}}^{J/\psi}$  with  $\sqrt{s}$ , but NA3 shows values closer to the high energy experiments (E866/HERA-B)

- Interpretation of results not easy, many competing effects (shadowing, final state absorption, energy loss, ...) affect charmonia production/propagation in nuclei
- First attempts of a systematic study start to appear (most recent C. Lourenco, R. Vogt and H. Woehri, JHEP 0902:014, 2009, see also F. Arleo and V.N. Tram, EPJC55(2008)449)

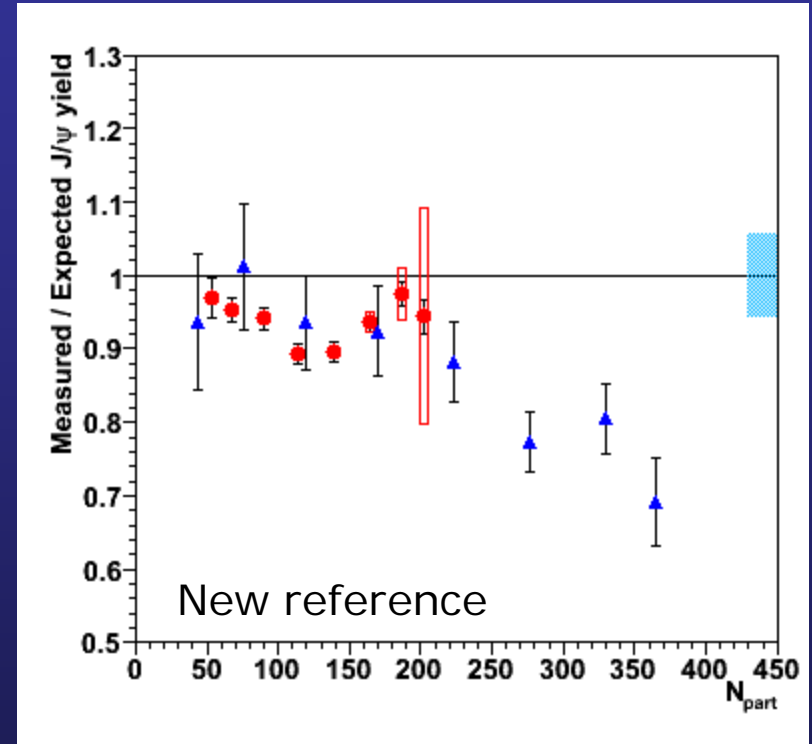
# Comparison with AA results

➔  $\sigma_{\text{abs}}^{J/\psi} (158 \text{ GeV}) > \sigma_{\text{abs}}^{J/\psi} (400 \text{ GeV})$

➔ smaller anomalous suppression with respect to previous estimates



B. Alessandro et al., EPJC39 (2005) 335  
R. Arnaldi et al., PRL99 (2007) 132302



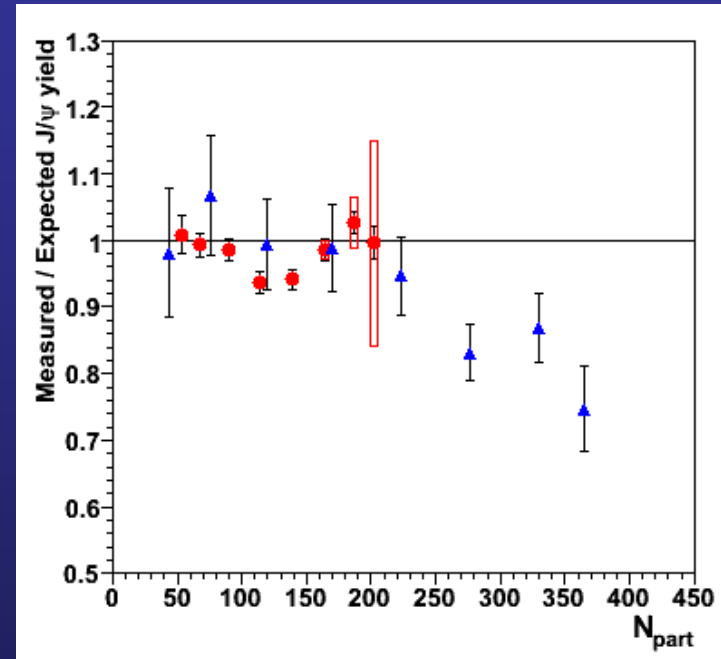
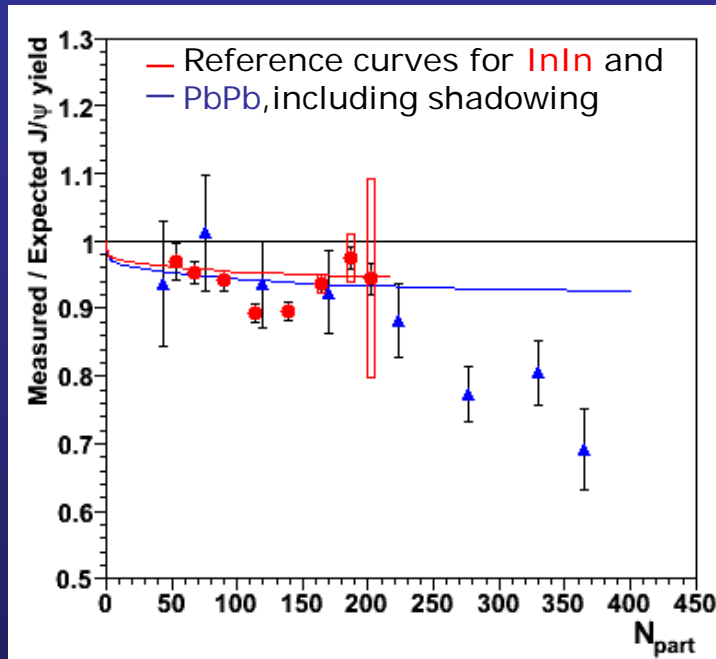
R. Arnaldi et al., arXiv:0907.5004

➔ Anomalous suppression in In-In  $\leq 10\%$

➔ Anomalous suppression in Pb-Pb up to 30%

# Anti-shadowing contribution

- ➔ In AA collisions the **initial state** effects (shadowing) affect not only the **target**, but also the **projectile**  
➔ to be included in the extrapolation of the reference from pA to AA



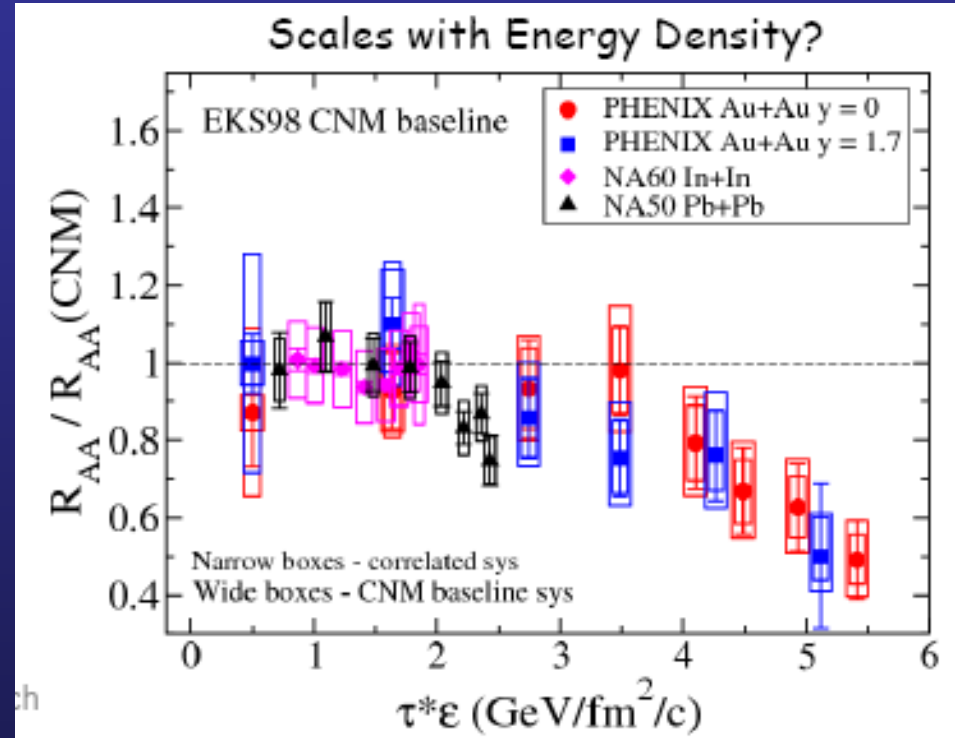
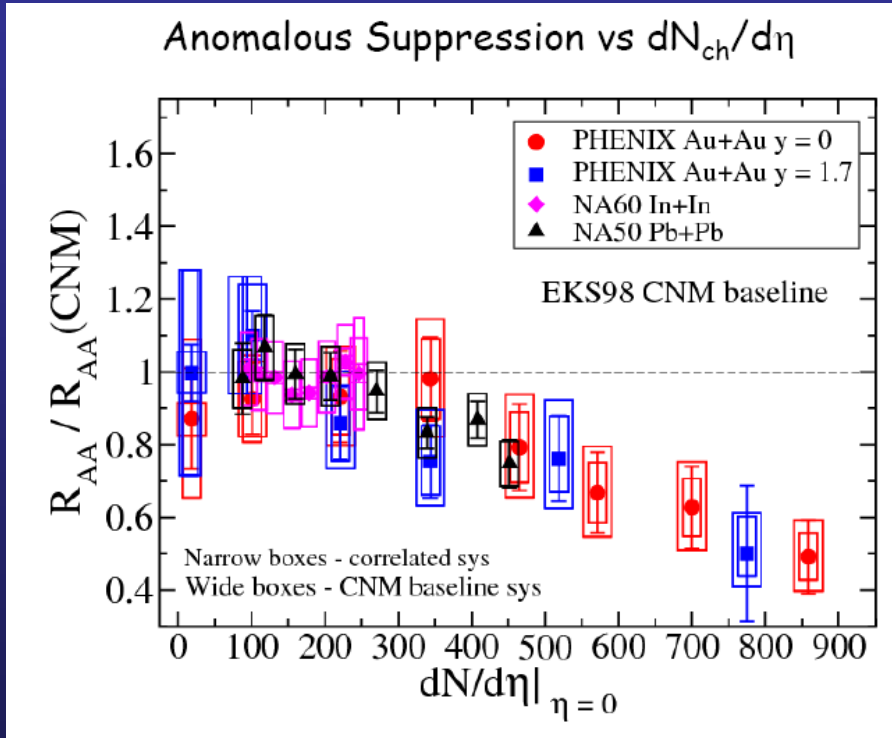
- ➔ Even in absence of anomalous suppression, the use of the standard reference (no shadowing) induces a 5-10% suppression signal  
➔ **sizeable effect**
- ➔ Using the new reference (shadowing in the projectile and target)
- Central Pb-Pb: still anomalously suppressed
  - In-In: almost no anomalous suppression?
- R. Arnaldi et al., arXiv:0909.2199

# SPS vs RHIC

- For the first time we have:
  - RHIC d-Au data with decent statistics
  - SPS p-A data at the same energy of A-A

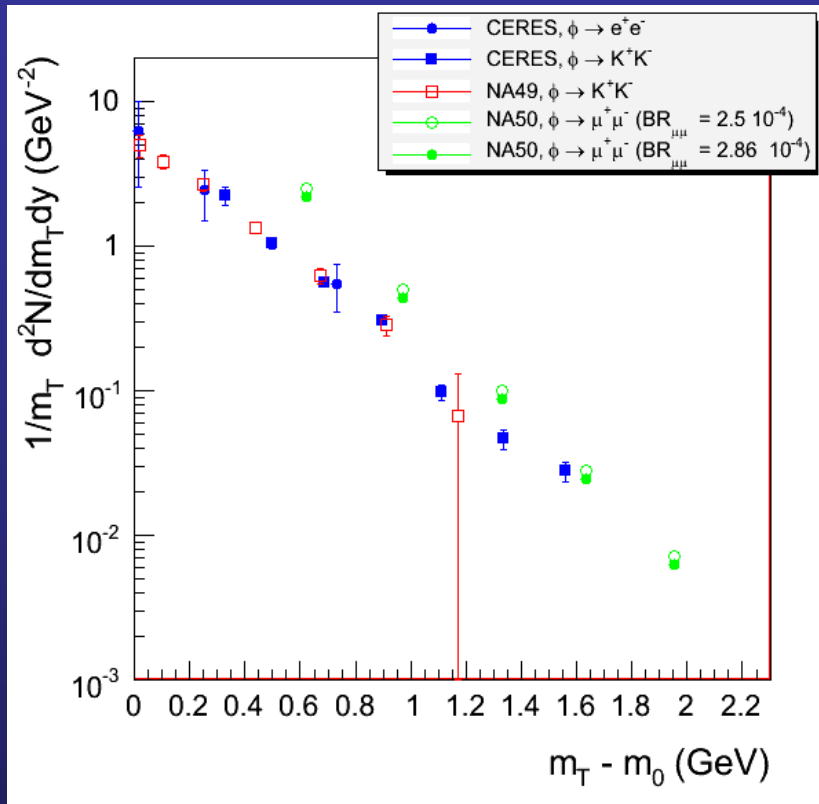


Compare anomalous suppression vs various variables



- Is there any scaling behaviour ?
- Relative systematics being evaluated (delicate, needs more work)

# The $\phi$ -puzzle for Pb-Pb collisions at the SPS



Historic facts on  
NA49  $\phi \rightarrow KK$  vs NA50  $\phi \rightarrow \mu\mu$

Yields in hadronic channel lower than in leptonic channel by factor  $\sim 4$  in central collisions

Inverse slopes in central Pb-Pb collisions

Hadronic (low  $p_T$ )  $\sim 300$  MeV

Leptonic (high  $p_T$ )  $\sim 230$  MeV

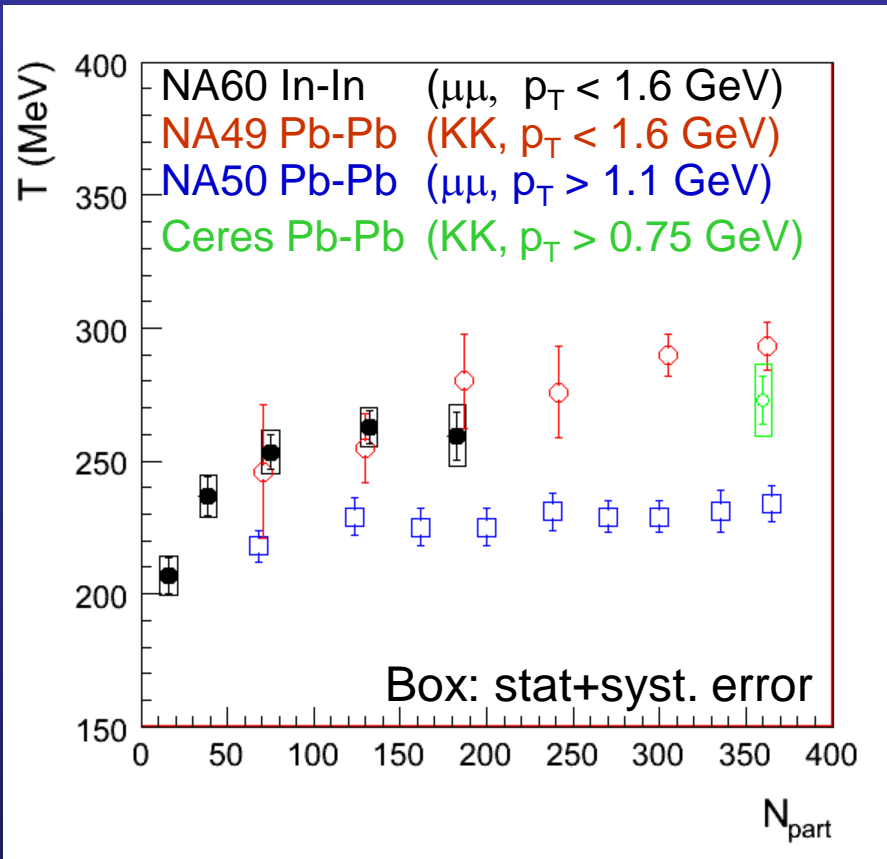
$\Rightarrow$   $\phi$  puzzle: in-medium effects on  $\phi$  and kaons + kaon absorption and rescattering leading to reduced yield and hardened  $p_T$  spectrum in hadronic channel?

More recently:

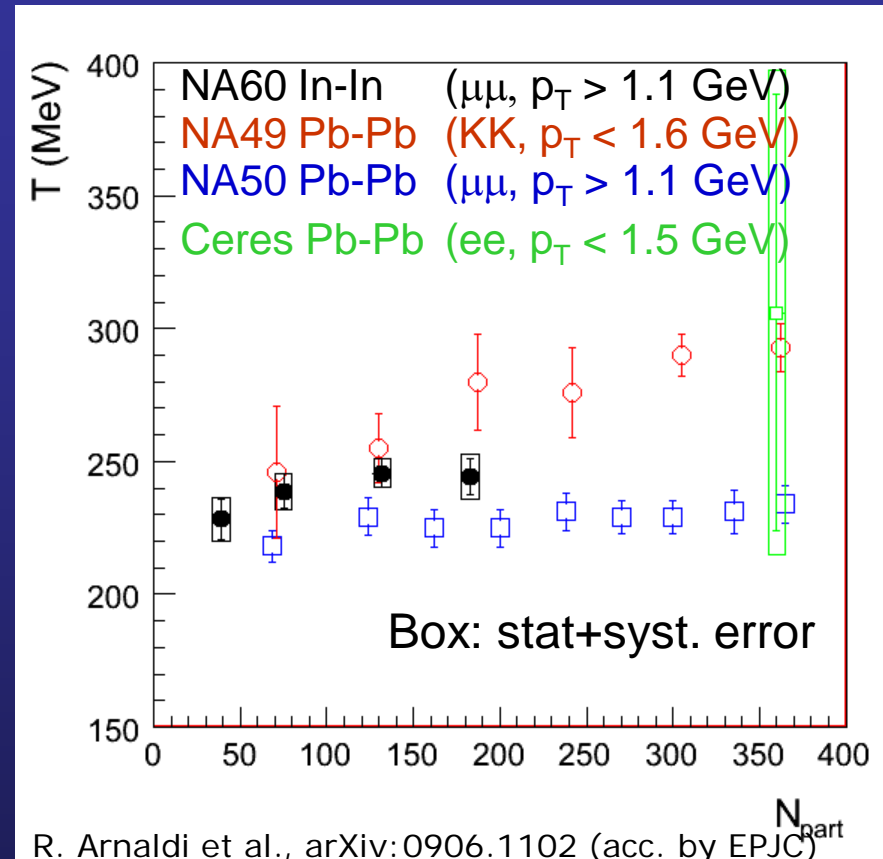
- CERES hadronic yield and inverse slope similar to NA49. Within large errors leptonic yield also compatible with NA49  $\Rightarrow$  No  $\phi$  puzzle?
- New NA50 analysis confirms previous results within 8%

# T slopes in In-In and Pb-Pb collisions

NA60 fits at low  $p_T$  (NA49 range)



NA60 fits at high  $p_T$  (NA50 range)



R. Arnaldi et al., arXiv:0906.1102 (acc. by EPJC)

NA60 low vs high  $p_T$ : maximal difference in T slopes only  $\sim 15$  MeV presumably related to radial flow

well below difference between NA50 and NA49 ( $\sim 70$  MeV) in the most central bin  $\Rightarrow$  significant extra hardening of hadronic channel beyond radial flow?

# $\phi \rightarrow \mu\mu$ : multiplicity

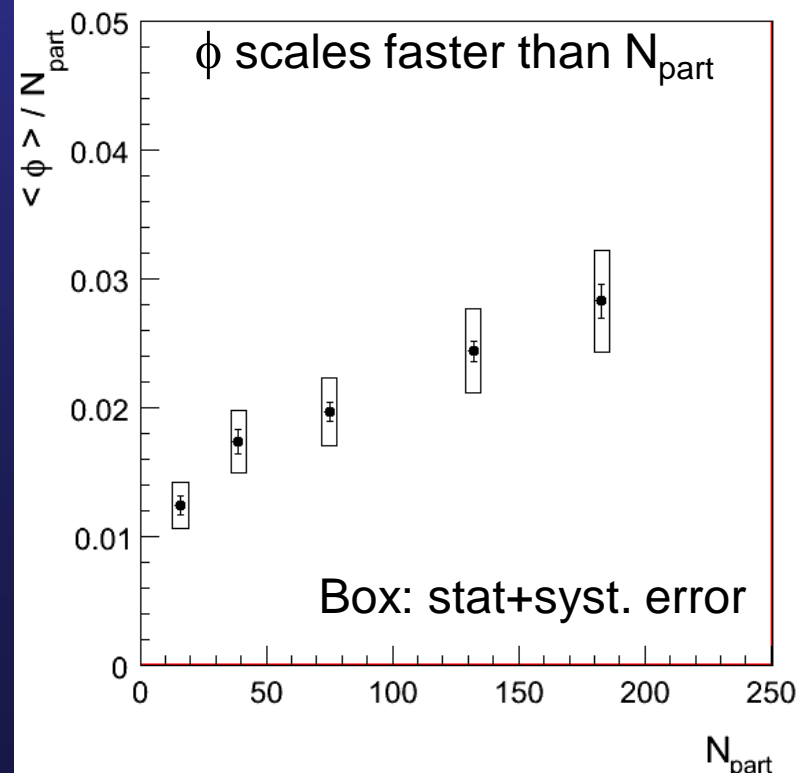
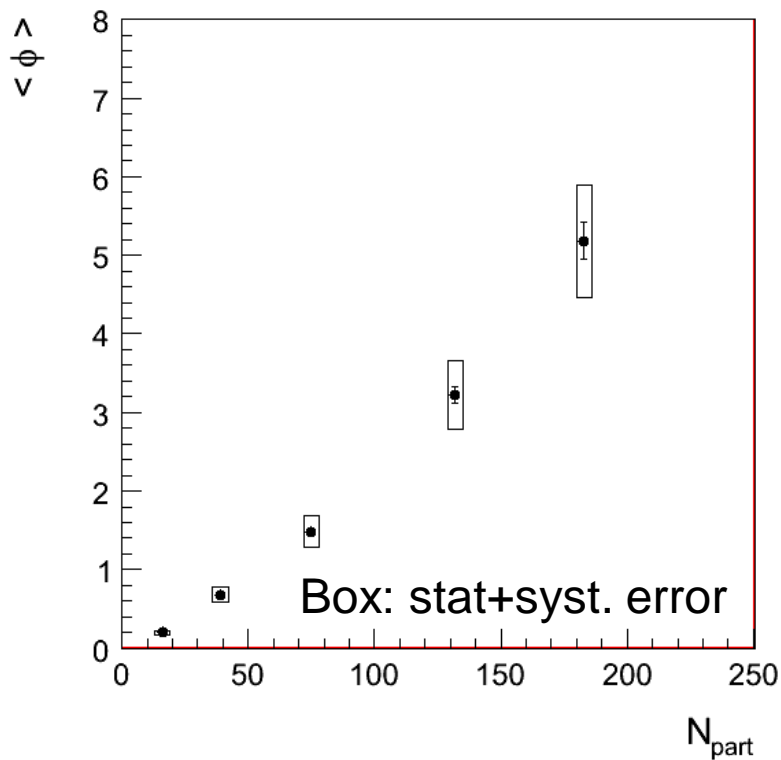
Multiplicity determined either directly with the cross section measurement or extracted using the  $J/\psi$  (corrected for the nuclear and anomalous suppression)

Results in full phase space and corrected for  $BR_{\mu\mu} = 2.86 \cdot 10^{-4}$

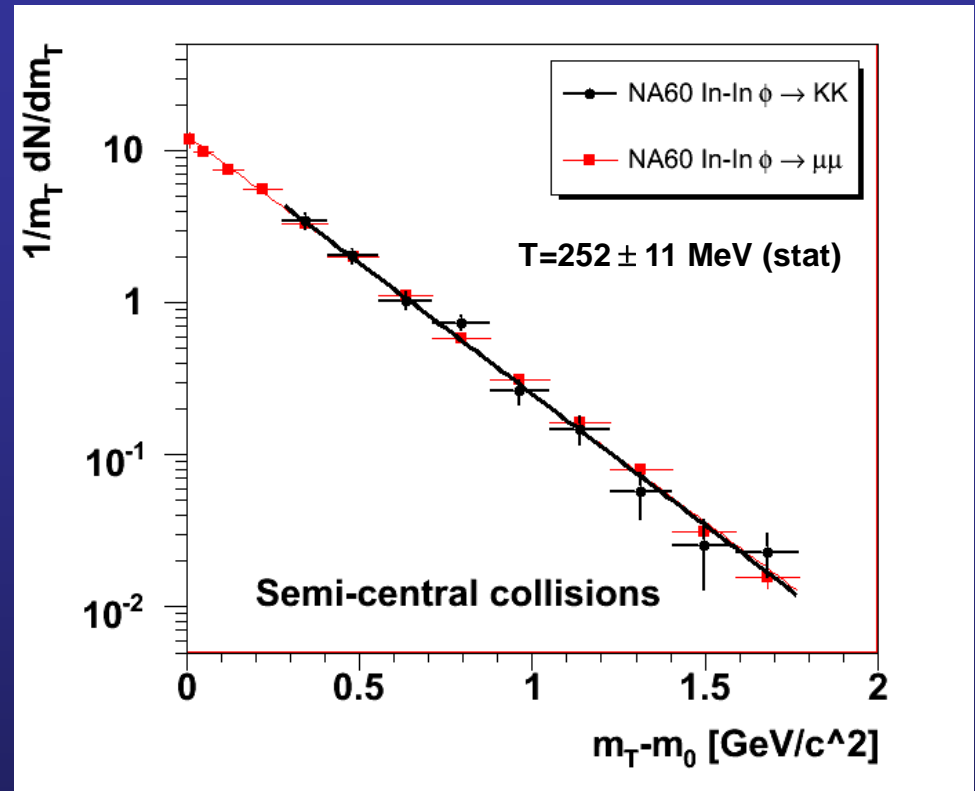
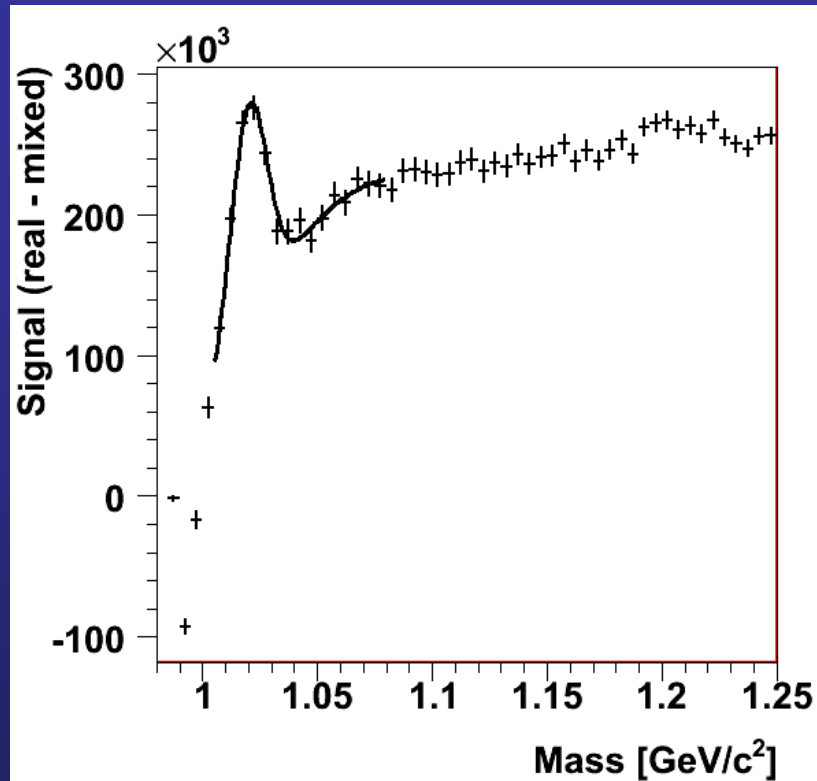
Yield integrated in centrality:

- Direct method:  $\sigma_\phi = 7.01 \pm 0.05 \pm 0.7 \text{ b}$      $\langle \phi \rangle = 1.62 \pm 0.01 \pm 0.16$
- $J/\psi$  Calibration:     $\langle \phi \rangle = 1.48 \pm 0.04 \pm 0.2$

Centrality dependence (average of the 2 methods)

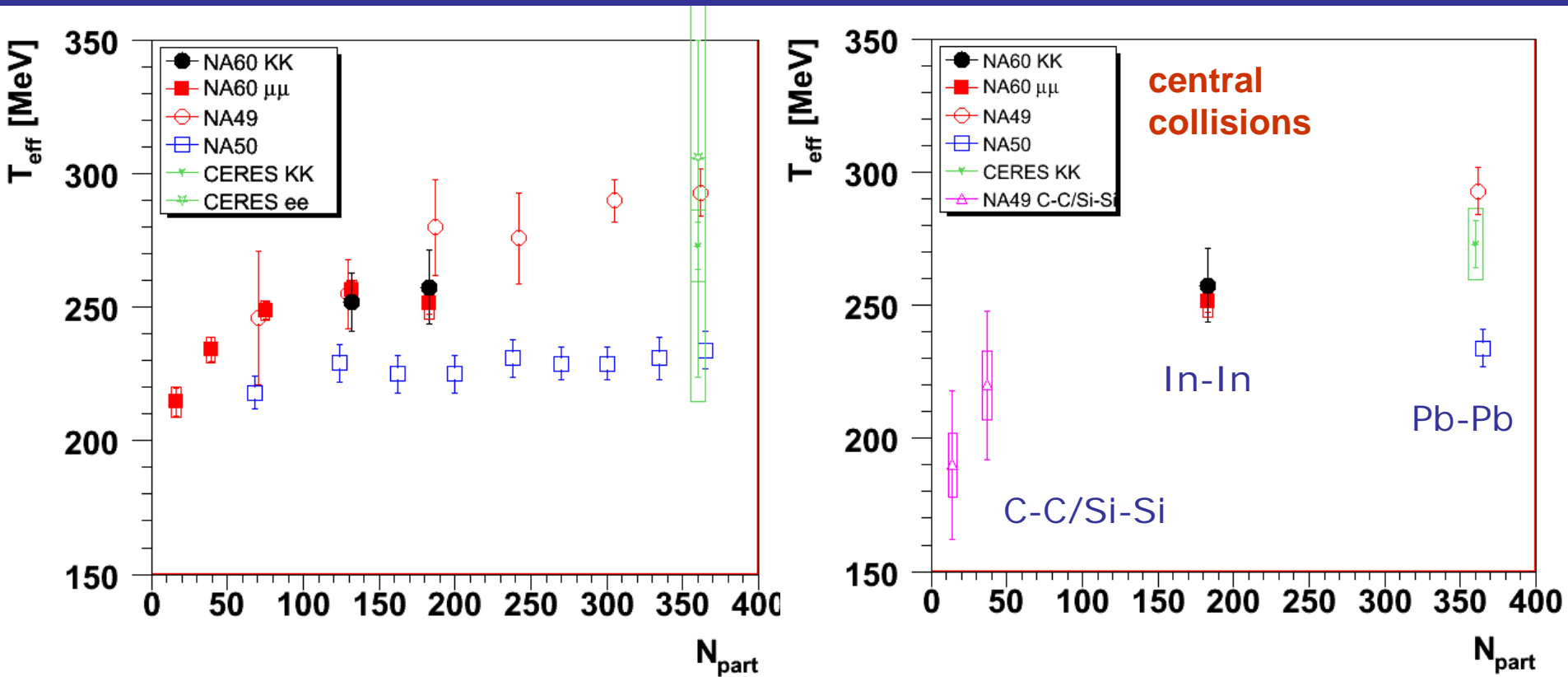


# $\phi \rightarrow KK$ and comparisons with $\phi \rightarrow \mu\mu$ (T)



- Background subtraction via mixed events (checked on like-sign)
- Analysis restricted to  $p_T > 0.9$   $\text{GeV}/c$
- Clear **agreement** between the  $m_T$  distributions measured in In-In collisions in the **hadronic** and **dileptonic** channels

# $T_{\text{eff}}$ vs other measurements



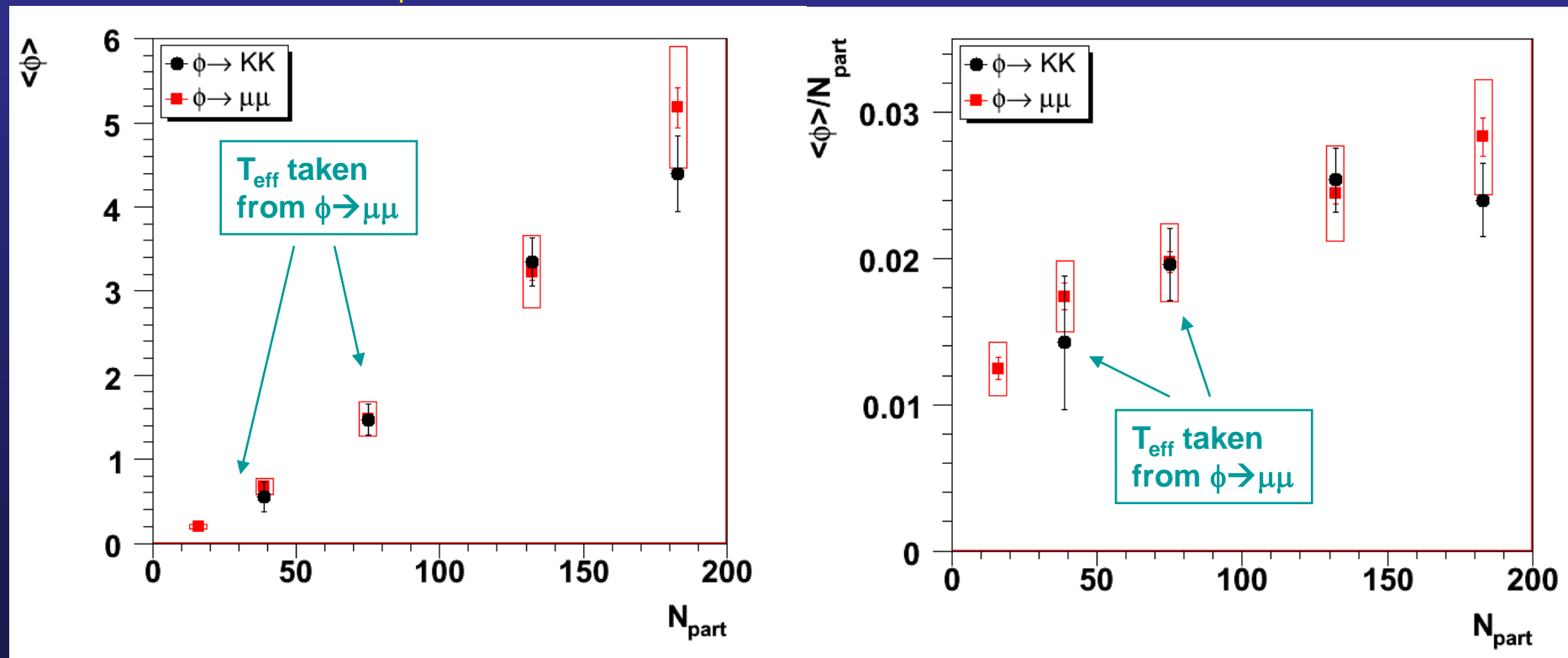
In **In-In** the measurements in kaon and muon pairs are in agreement

**Central collisions:** NA49 and CERES (KK) in Pb-Pb are above the In-In result by about 30 MeV  
 The difference between NA50 and NA49 results is  $\sim 70$  MeV  
 Radial flow alone cannot describe the difference

# Yield vs $N_{\text{part}}$ in KK compared to $\mu\mu$

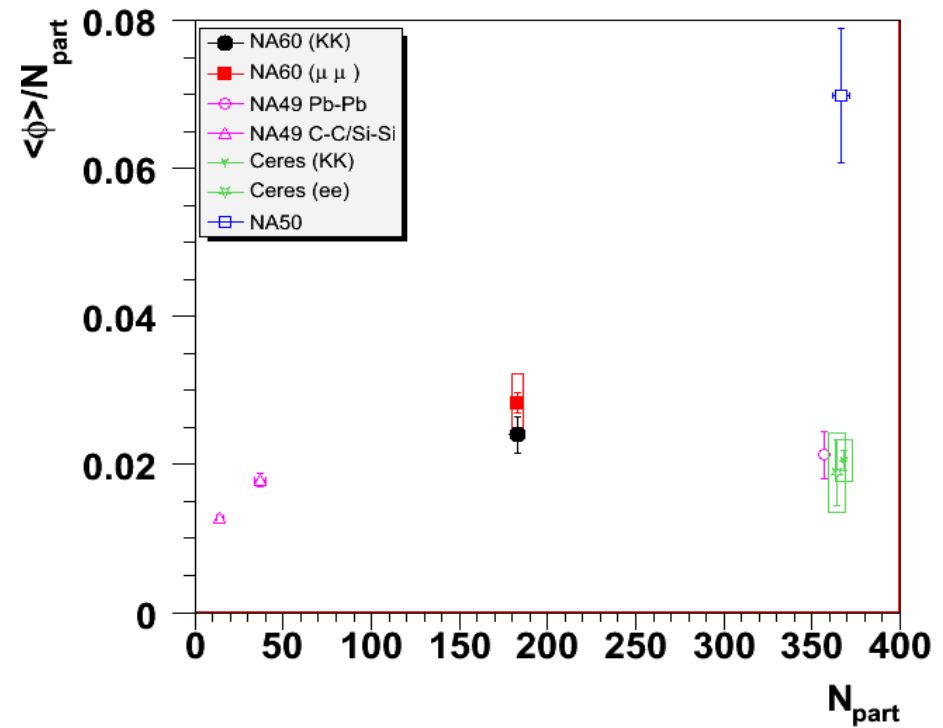
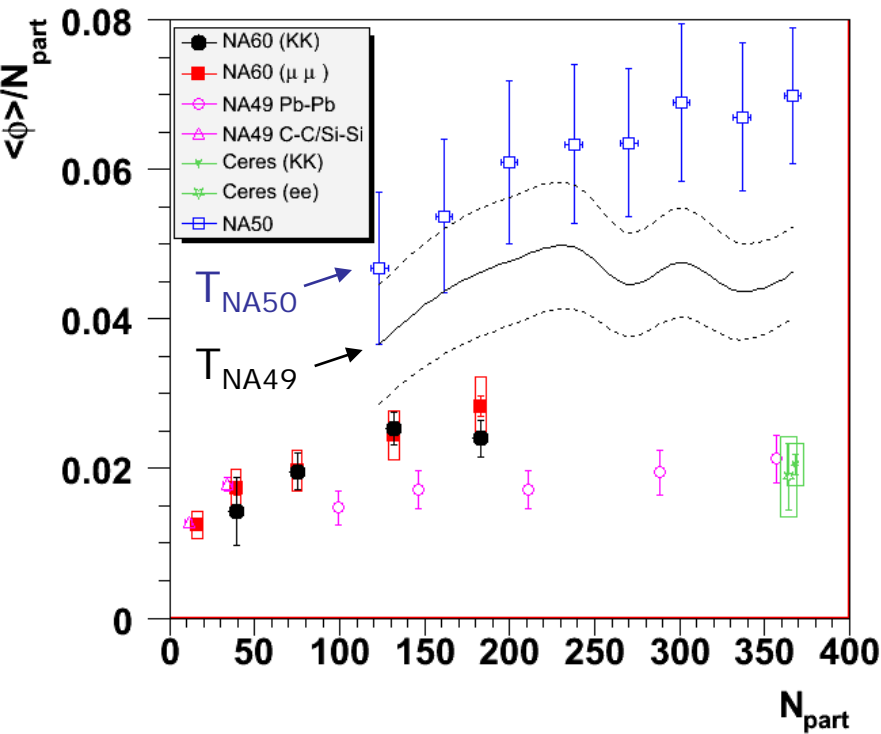
- Determine  $N_\phi$  integrated for  $p_T > 0.8$  GeV/c for each centrality bin
- Correct for the integrated acceptance in  $4\pi$  and for the branching ratio  $T_{\text{eff}}$  from KK in (semi)central, from  $\mu\mu$  in (semi)peripheral collisions
- $N_\phi$  is then divided by the number of events in that centrality bin

$\phi$  multiplicity vs  $N_{\text{part}}$  in the kaon channel agrees with the results in muons



Only statistical errors (syst of the order of 0.2 on  $\langle \phi \rangle$ )

# $\phi \rightarrow KK$ and comparison with $\phi \rightarrow \mu\mu$ ( $\langle\phi\rangle$ )



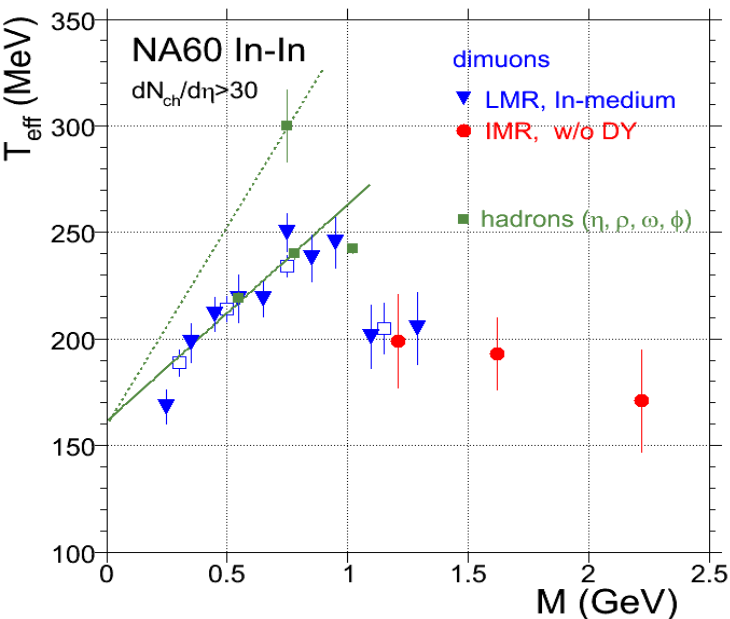
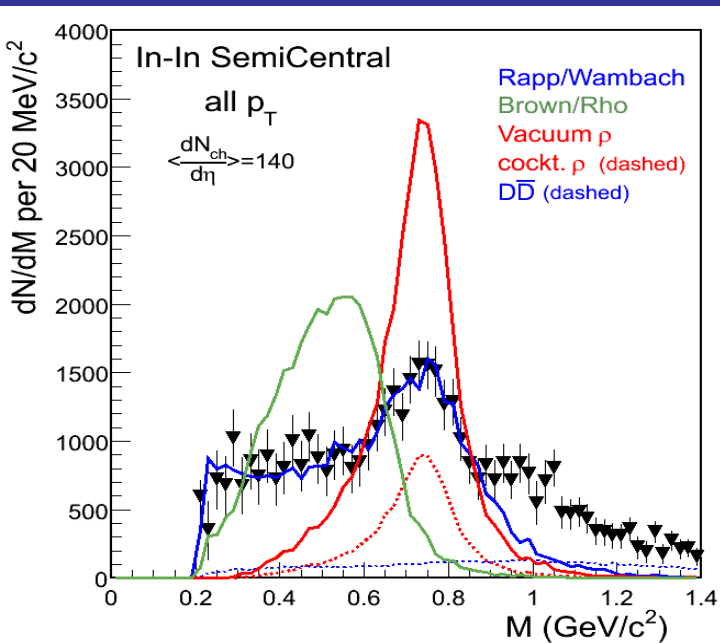
• Comparison **between various systems** for central collisions **difficult**

•  $\langle\phi\rangle/N_{part}$ :

- In-In much lower than NA50 (with various assumptions on  $T$ )
- Slightly higher than NA49/CERES in kaon pairs and dielectrons
- $\mu\mu$  (NA50) vs KK (NA49) in Pb-Pb still leave room for a physical effect  
However, CERES measurements in kaons and dielectrons agree

**No  $\phi$ -puzzle in In-In collisions at the SPS  
New measurement in Pb-Pb would be important**

# Thermal dimuons in In-In collisions



- Invariant mass region  $M < 1$  GeV: thermal dilepton production largely mediated by the broad vector meson  $\rho$  via  $\pi\pi \rightarrow \rho \rightarrow \gamma \rightarrow \mu\mu$  annihilation. **Hadronic** nature supported by the rise of radial flow up to  $M = 1$  GeV

- $M > 1$  GeV: sudden fall of radial flow of thermal dimuons occurs, naturally explained as a transition to a qualitatively different source, i.e. mostly **partonic** radiation,  $qq \rightarrow \gamma \rightarrow \mu\mu$

R. Arnaldi et al., Phys. Rev. Lett. 96 (2006) 162302

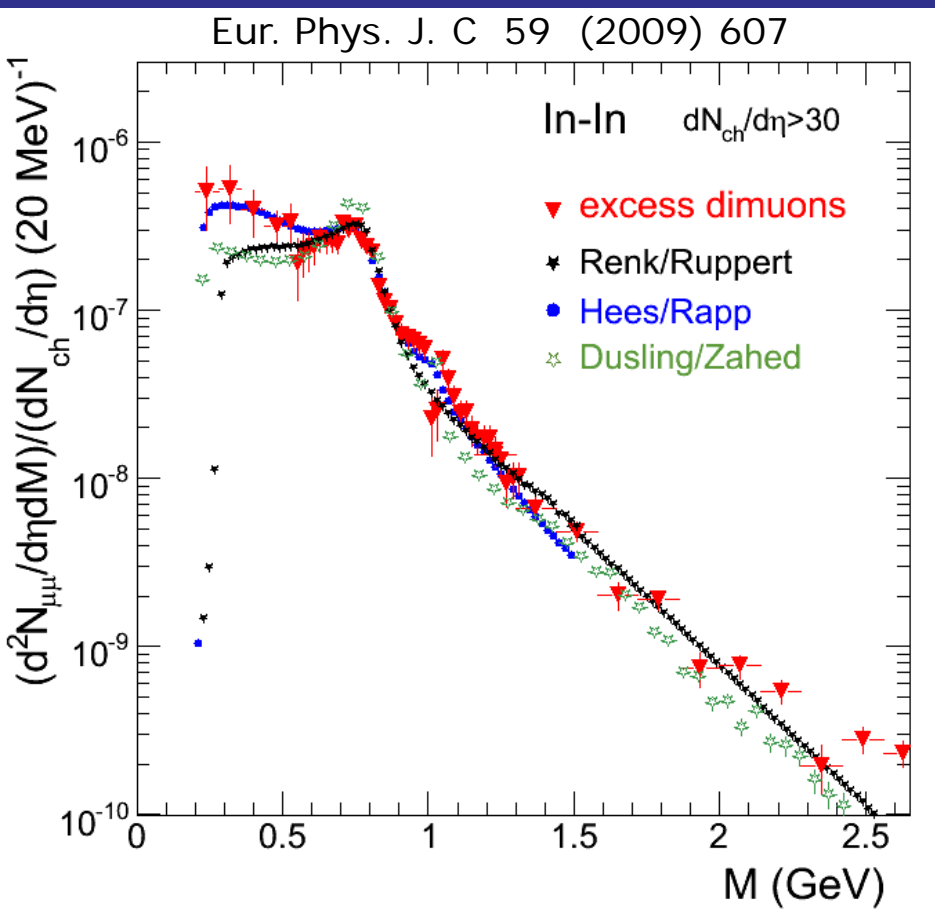
R. Arnaldi et al., Phys. Rev. Lett. 100 (2008) 022302

# Thermal radiation, mass spectrum

All known sources (hadro-cocktail, open charm, DY) subtracted

Acceptance corrected spectrum ( $p_T > 0.2$  GeV)

Absolute normalization  $\rightarrow$  comparison to theory in absolute terms!



thermal  $\pi\pi \rightarrow \gamma \rightarrow \mu\mu$  ( $M < 1$  GeV)

&&

thermal  $qq \rightarrow \gamma \rightarrow \mu\mu$  ( $M > 1$  GeV)

suggested dominant by  $T_{\text{eff}}$  vs  $M$   
(supported by R/R, D/Z)

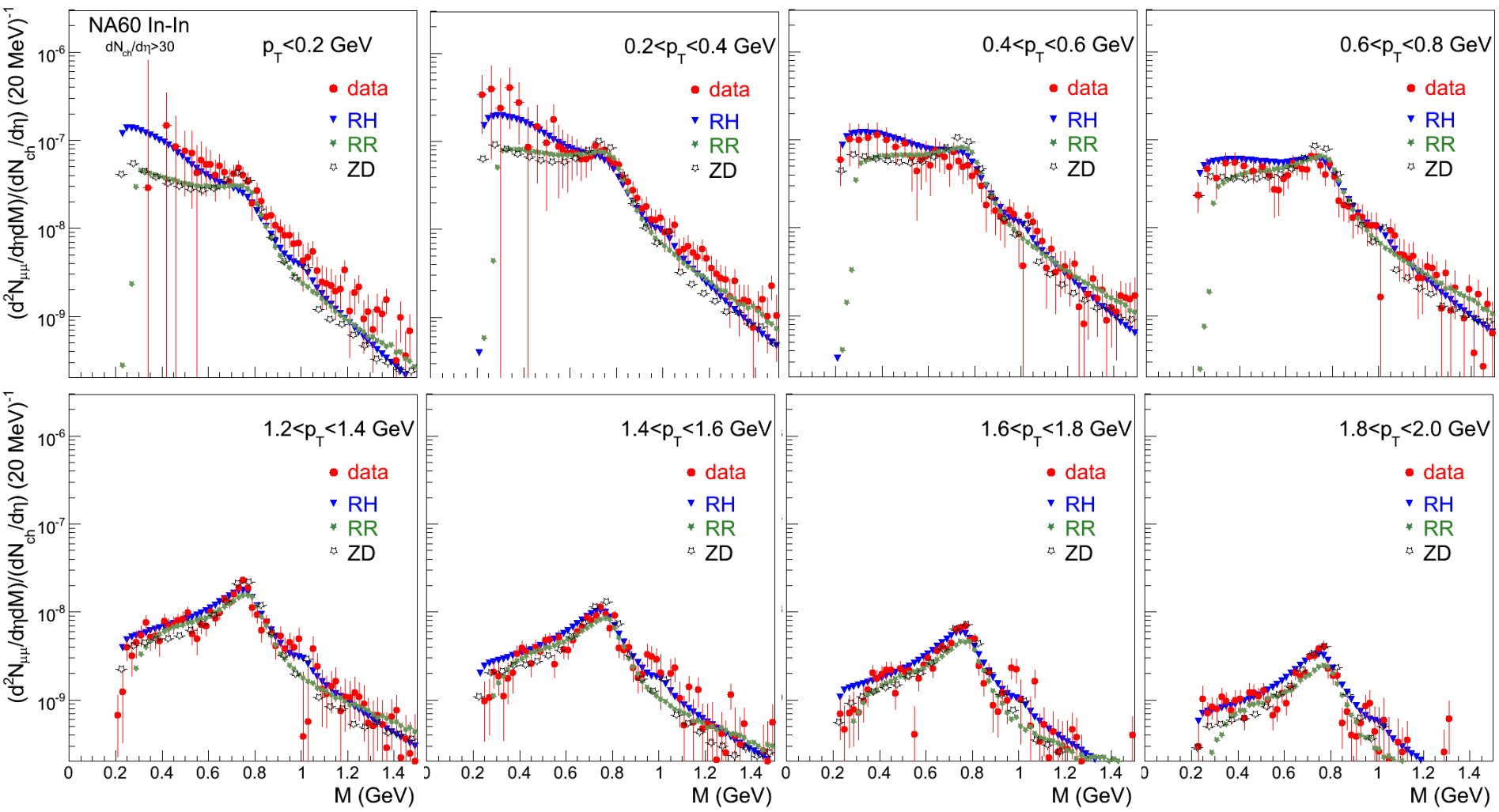
also multipion processes (H/R)

**Planck-like** mass spectrum;  
falling exponentially

**Agreement** with theoretical  
models up to 2.5 GeV!

# Excess vs $p_T$ : comparison to theory

S. Damjanovic et al., J.Phys. G 35(2008)104036



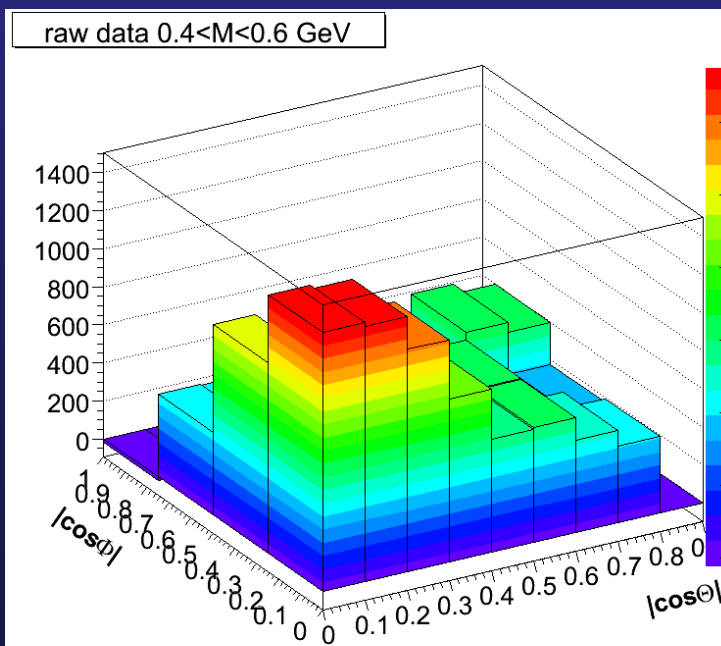
- Absolute normalization both for theory and data
- Differences at low masses reflect differences in the tail of  $\rho$  spectral function
- Differences at high masses,  $p_T$  reflect differences in flow strength

# Thermal radiation – angular distributions

- General formalism for the description of an angular distribution

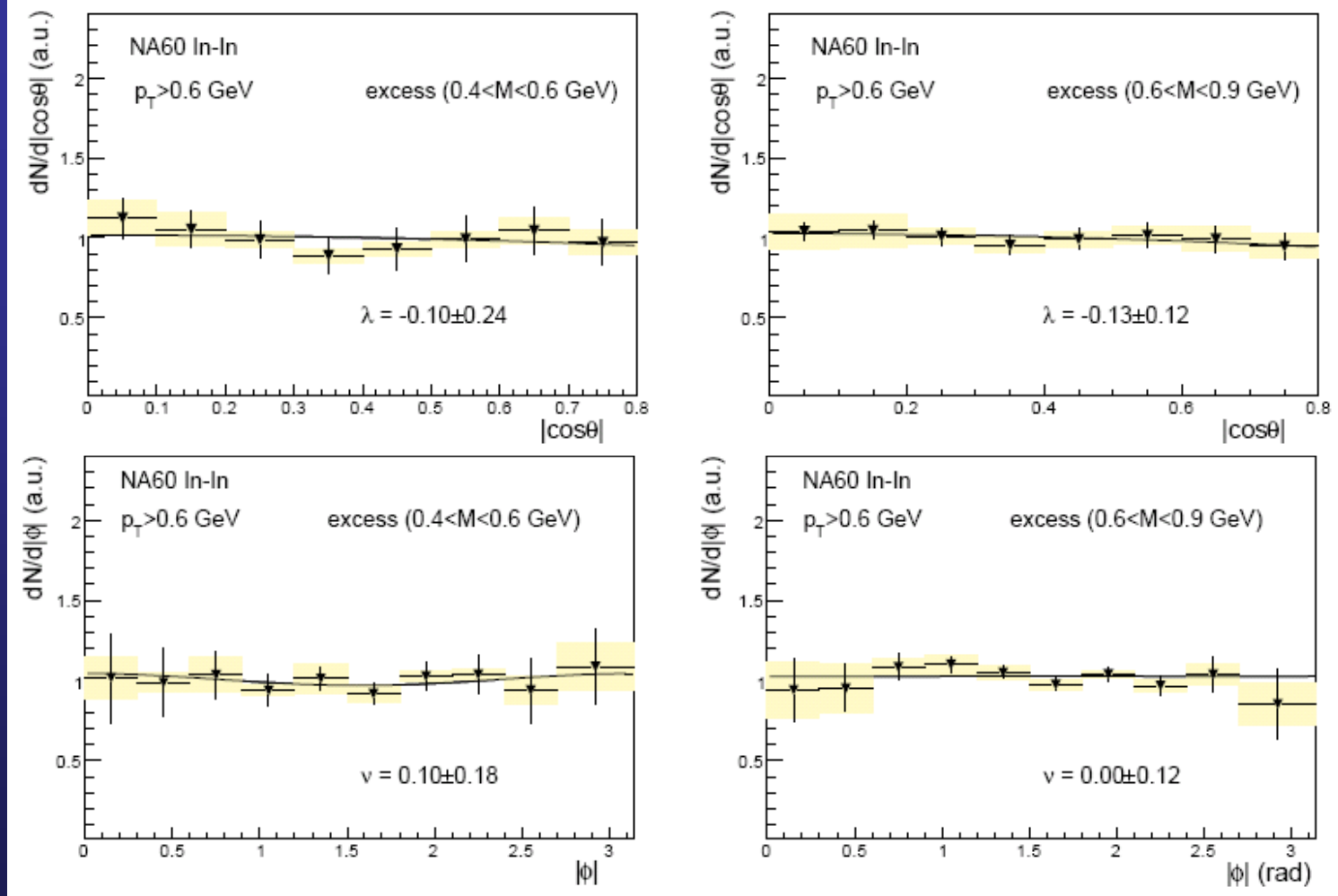
$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta d\phi} = \left( 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right)$$

- $d\sigma/d\cos\theta d\phi$  is the differential decay angular distribution in the rest frame of the virtual photon wrt a suitably chosen axis (use Collins-Soper reference frame in the following)
- A completely random orientation of annihilating pions (as expected for thermal radiation) would lead to  $\lambda = \mu = \nu = 0$
- **Analysis done in  $\cos\theta - \phi$  space** with different binnings in  $[dN/d\cos\theta d\phi]_{m \times n}$  to study the systematics
- After background subtraction and subtraction of known sources, acceptance correction in:
  - 2-dim  $\cos\theta - \phi$  space
  - 1-dim projections
- The two methods give **consistent results**



# Polarization of dileptons

R. Arnaldi et al., PRL 102 (2009) 222301

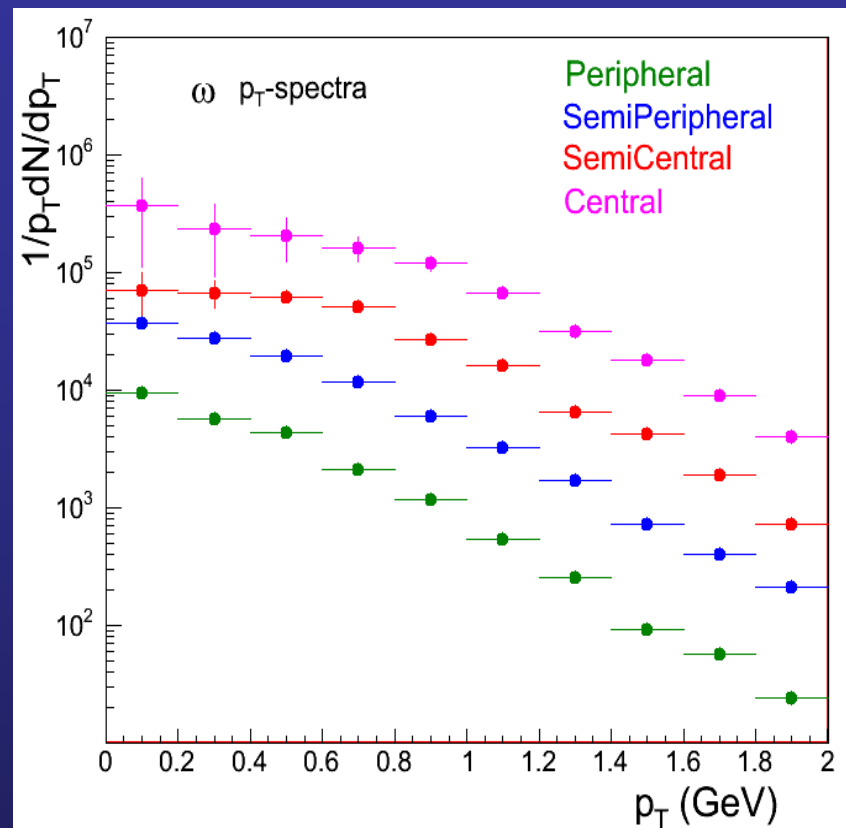
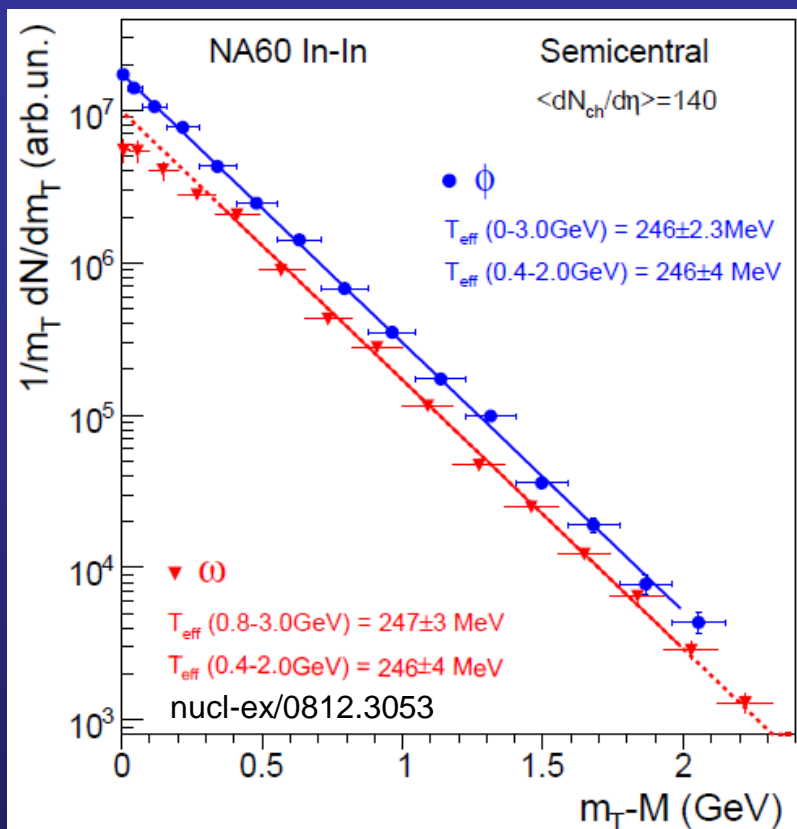


$\mu$  consistent with zero

- Polarization of the muon excess (in the Collins-Soper frame) for  $m \leq m_\phi$   
→ Lack of any polarization in excess (and in hadrons) **supports emission from thermalized source.**
- Statistical error dominant

# Evidence of $\omega$ in-medium effects?

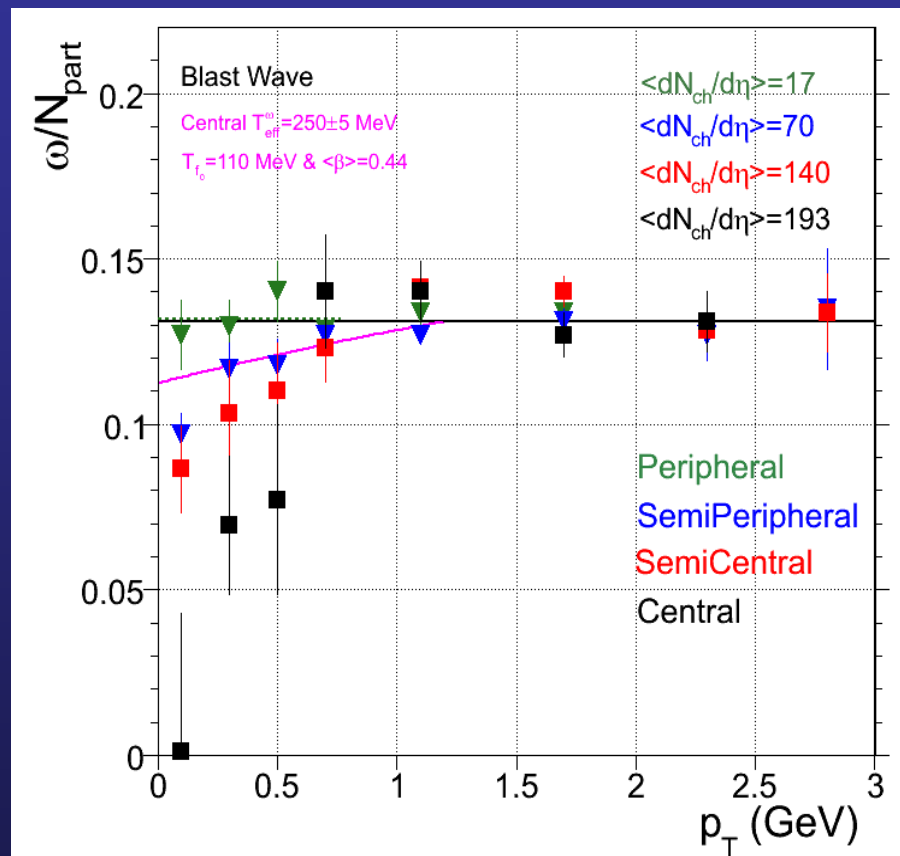
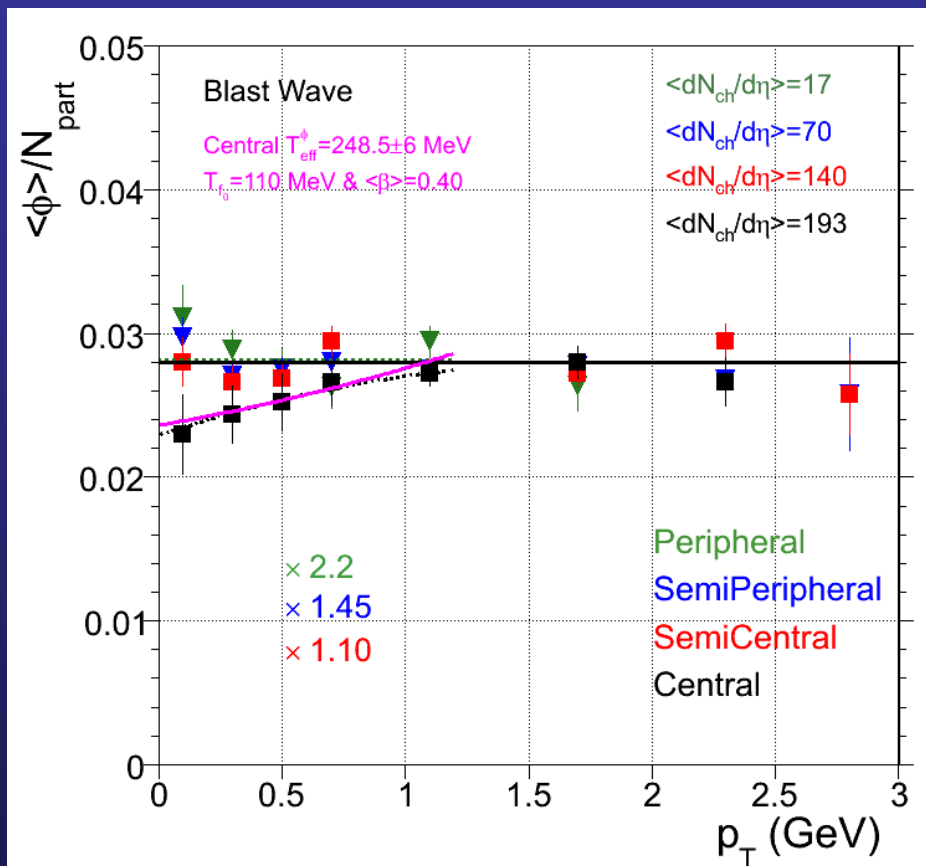
R. Arnaldi et al., Eur.Phys.J.C61: 711-720,2009



- Flattening of the  $p_T$  distributions at low  $p_T$ , developing very fast with centrality.
- Low- $p_T$   $\omega$ 's have more chances to decay inside the fireball ?
- Appearance of that yield elsewhere in the spectrum, due to  $\omega$  mass shift and/or broadening, unmeasurable due to masking by the much stronger  $\pi\pi \rightarrow \mu\mu$  contribution.
- Disappearance of yield out of narrow  $\omega$  peak in nominal pole position  
 $\Rightarrow$  Can only measure disappearance

# Results on $\omega$ yield suppression

- Determine suppression vs  $p_T$  with respect to  $dN/dm_T^2 \sim \exp(-m_T/T_{eff})$  (extrapolated from  $p_T > 1 \text{ GeV}/c$ )
- Account for difference in flow effects using the results of the Blast Wave analysis



$\phi$ : depletion for central collision **consistent with radial flow**

$\omega$ : strong centrality-dependent suppression at low  $p_T$ , **beyond flow**

# Conclusions

- NA60: a successful third-generation heavy-ion experiment at the CERN SPS (pA collisions 158/400 GeV, InIn 158 GeV/nucleon)
- Lots of new results (only a selection presented today), including:
  - Measurement of  $\rho$  spectral function in nuclear collisions
  - Radial flow of thermal dimuons (LMR + IMR)
  - Polarization of thermal radiation
  - $\omega$  in-medium effects
  - $\eta$  and  $\omega$ -decay e.m. form factors
  - Solution of IMR puzzle (DD vs DY, Helios-3 NA38/NA50)
  - Investigation (solution?) of  $\phi$  puzzle
  - Measurement of cold nuclear matter effects on  $J/\psi$  at 158 GeV
  - Study of anomalous  $J/\psi$  suppression in light(er) nuclear systems
  - Polarization of  $J/\psi$ , in pA and AA collisions
- Most NA60 results would be nicely complemented by
  - a Pb-Pb data taking
  - an extension of the measurements towards lower energy