High p_t Measurements at the SPS

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Hard Probes Asilomar

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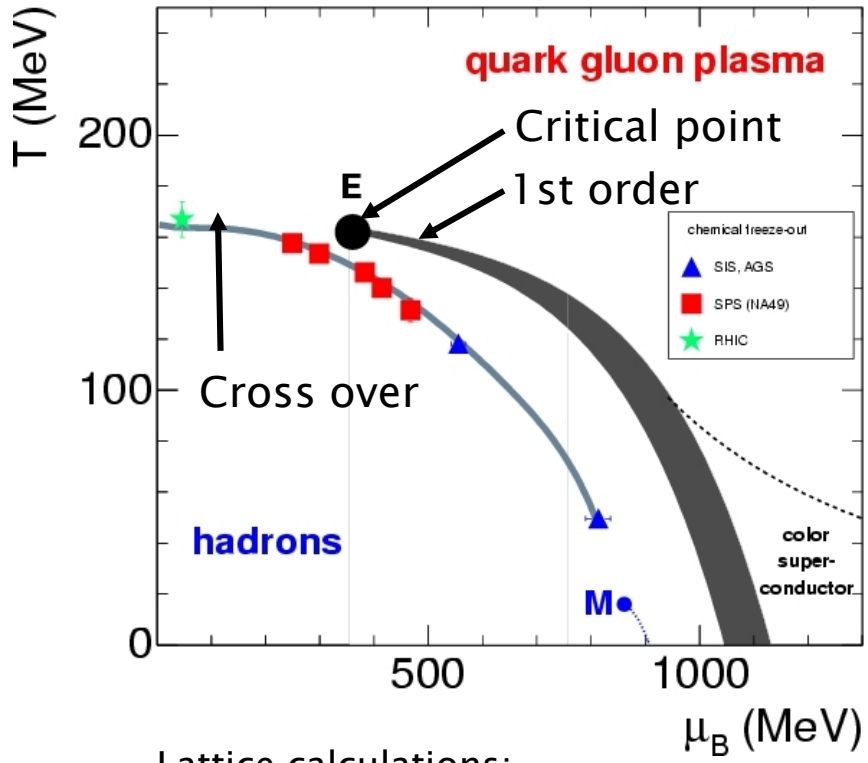
High p_t at the SPS

Chemical freeze-out points approach phase boundary at top SPS energies

Energy density at $\sqrt{s} = 17.3$ GeV: $\varepsilon_0 \approx 3 \mathrm{GeV/fm}^3$

Transition to QGP is likely to happen in this region

Any evidence for medium modifications of high p_t spectra ?



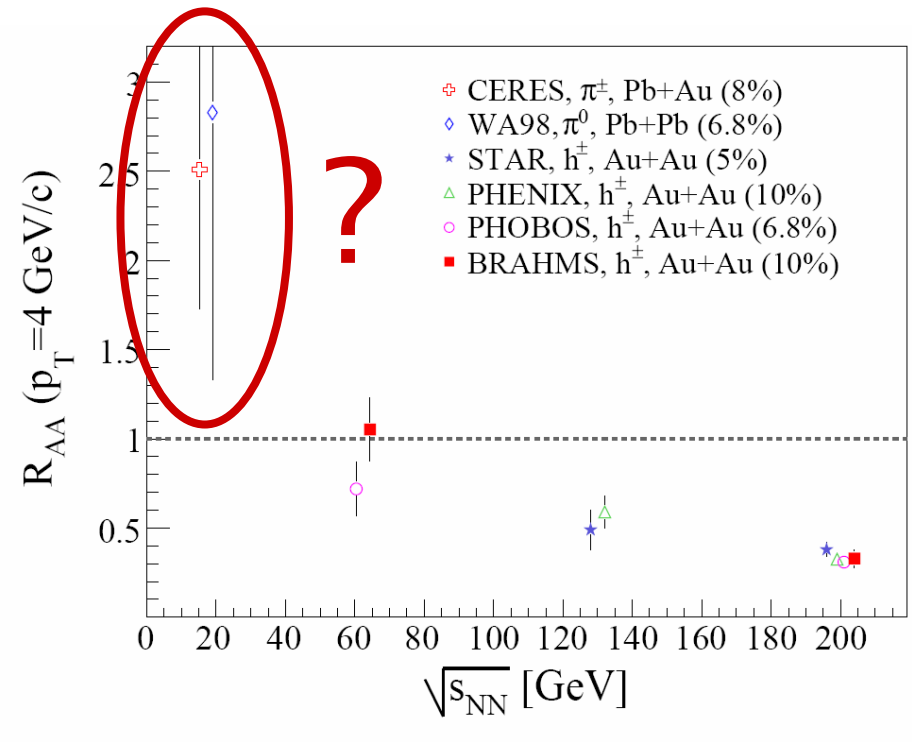
Lattice calculations:
Fodor and Katz
Bielefeld-Swansea group

Hadron gas fits (■):
J. Manninen et al.

High p_t at the SPS
Suppression seen at SPS?

Published R_{AA} show now indication for high-p_t suppression

$$R_{AA}(p_t) = \frac{\sigma_{inel}^{pp}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / (dp_t\, dy)}{d^2 \sigma_{pp} / (dp_t\, dy)}$$



BRAHMS
nucl-ex/0602018

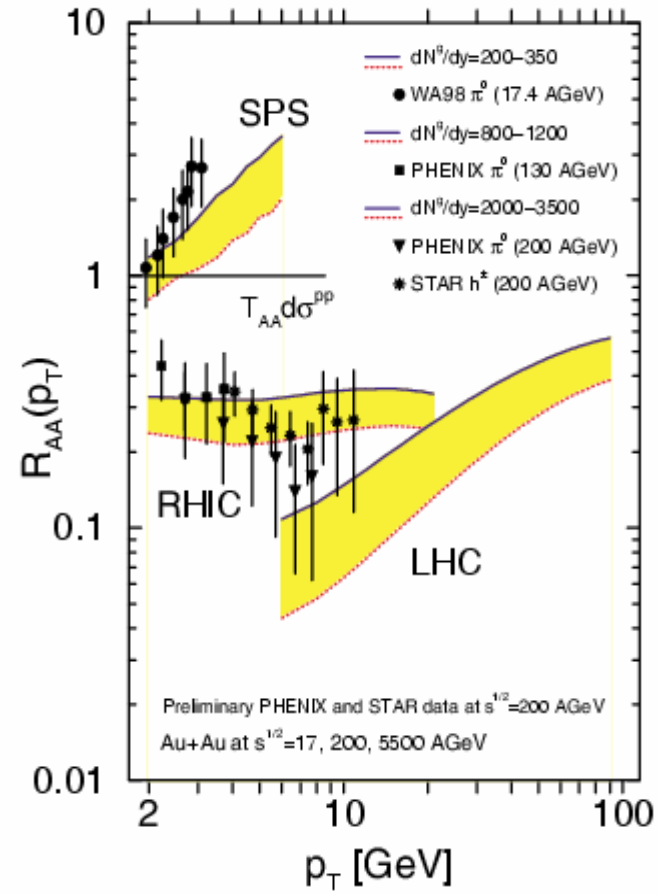
WA98
Eur. Phys. J. C23 (2002), 225.

CERES
nucl-ex/0407019.

High p_t at the SPS
Comparison to Theory

R_{AA} for π^0 above calculation including jet quenching + Cronin effect (dN_g/dy = 200 – 350)

I. Vitev and M. Gyulassy,
Phys. Rev. Lett. 89 (2002), 252301.



Problems:

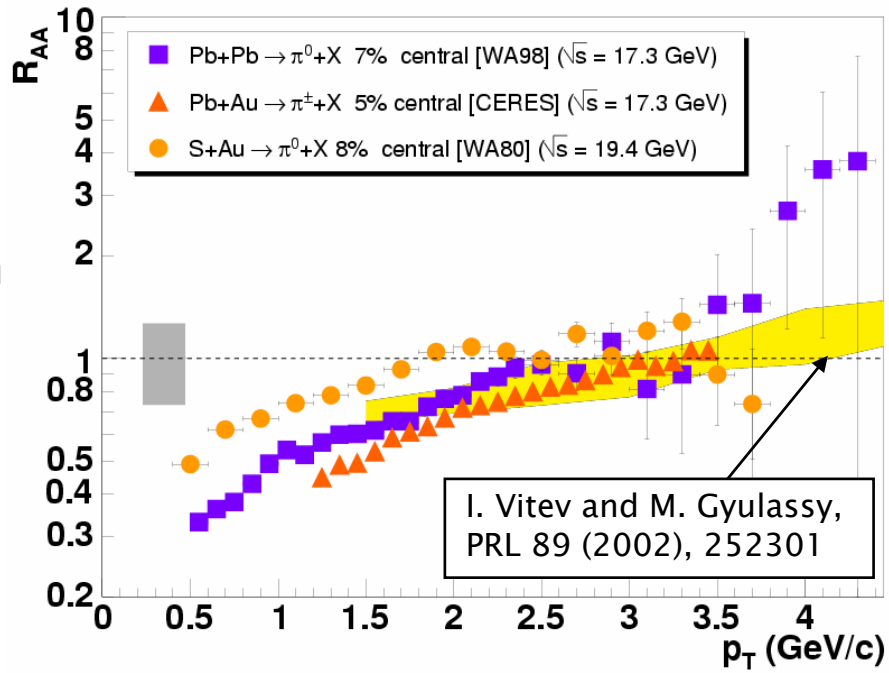
- Not consistent with R_{CP} of WA98
- p+p baseline very uncertain (extrapolation from other energies)

High p_t at the SPS
New look at old data

Update of pion R_{AA}

- Same central A+A data
- Reassessment of p+p reference
- → No Cronin-enhancement seen

D. D'Enterria,
Phys. Lett. B 596 (2004), 32.



Consistent with quenching calculation: dN_g/dy = 400–600

High p_t at the SPS
What is new at $\sqrt{s} = 17.3$ GeV?

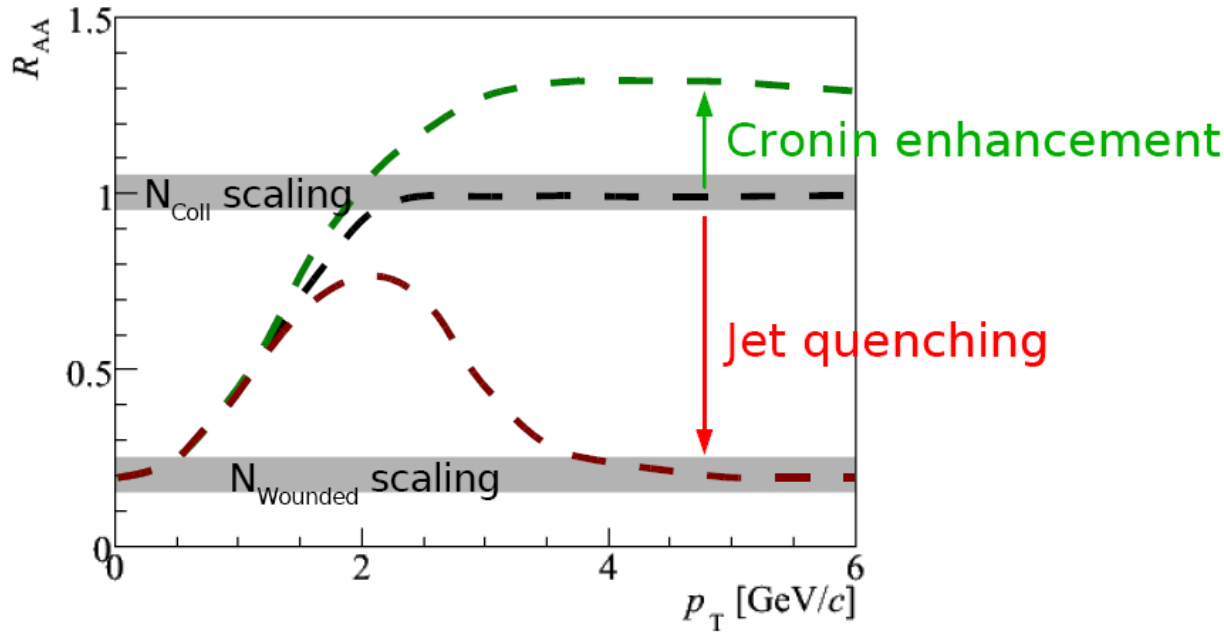
- R_{CP} for Pb+Pb at 158A GeV up to $p_t \approx 4$GeV/c
  - NA57: h^-, K^0_s, Λ, $\bar{\Lambda}$
  - NA49: $\pi^\pm$, $K^\pm$, p, $\bar{p}$

- Azimuthal correlations à la PHENIX
  - CERES: Pb+Au $$\frac{1}{N_{trig}}\frac{dN^{AB}}{d\Delta\phi} = \frac{J(\Delta\phi)}{\int(C(\Delta\phi')d(\Delta\phi'))}\frac{N^{AB}}{N^{A}}$$

    $2.5\ \text{GeV/c} < p_t^{\text{trigger}} < 4.0\ \text{GeV/c}$
    $1.0\ \text{GeV/c} < p_t^{\text{assoc.}} < 2.5\ \text{GeV/c}$

- Ratios of identified particles
  - NA49: p/π^+, $\bar{p}/\pi^-$, Λ/K^0_s

Baseline Measurements
Cronin Effect and Jet Quenching



"Not so really high p_t" at the SPS ($p_t \leq 4 - 4.5$ GeV/c)

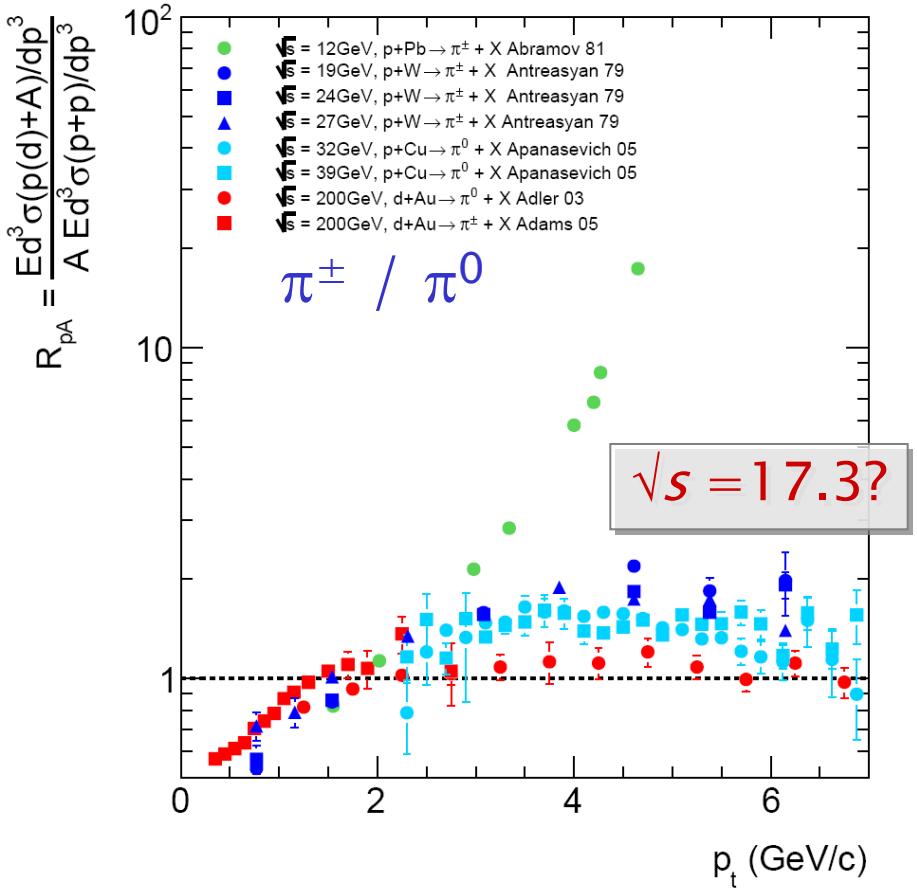
Interplay between Cronin enhancement and possible jet quenching effects

→ *Baseline measurements in p+p <u>and</u> p+A important!*

Baseline Measurements
Cronin Effect in p(d)+A Data

Nuclear enhancement factor for min. bias p(d)+A

$$R_{pA} = \frac{1}{A}\frac{Ed^3\sigma(p(d)+A)/dp^3}{Ed^3\sigma(p+p)/dp^3}$$



Clear energy dependence of enhancement factor

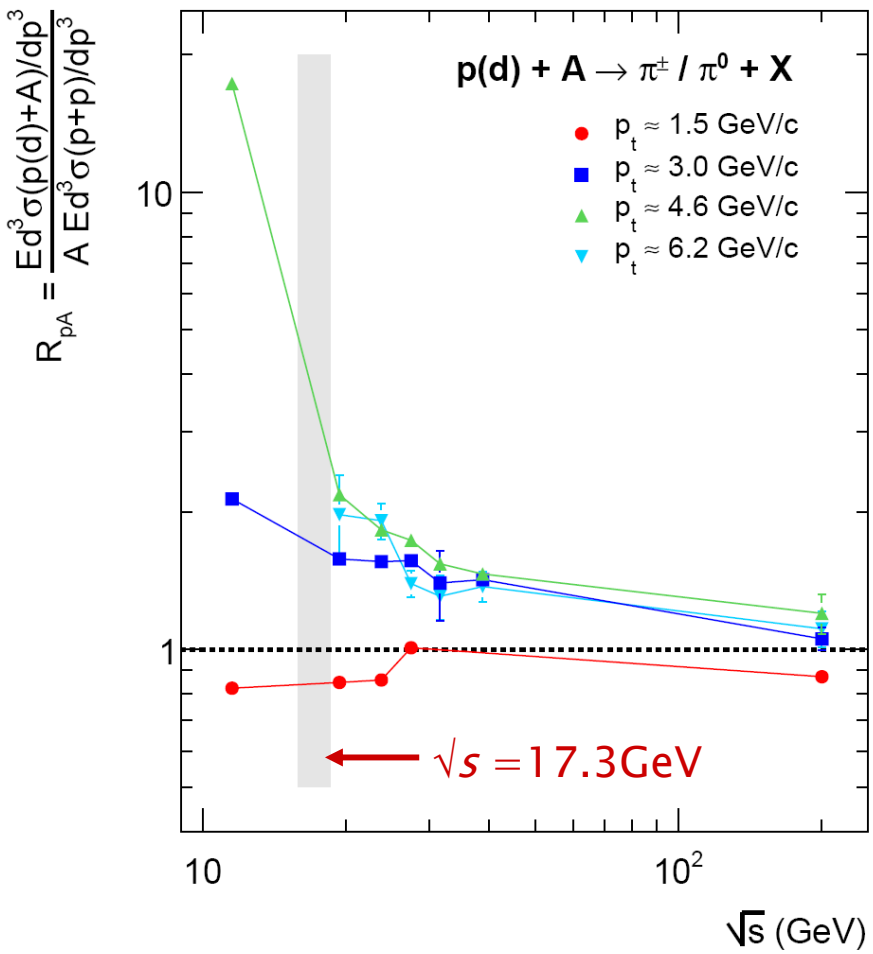
Baseline Measurements
Energy Dependence of Cronin Effect

R_{pA} increases by factor ~5 between RHIC (200GeV) and $\sqrt{s}$ = 19.4GeV

Even stronger increase towards lower energies indicated by Serpukhov data!

R_{pA} at $\sqrt{s}$ = 17.3GeV?

Measurement needed (WA98: p+C/Pb)



Baseline Measurements
p+p Data

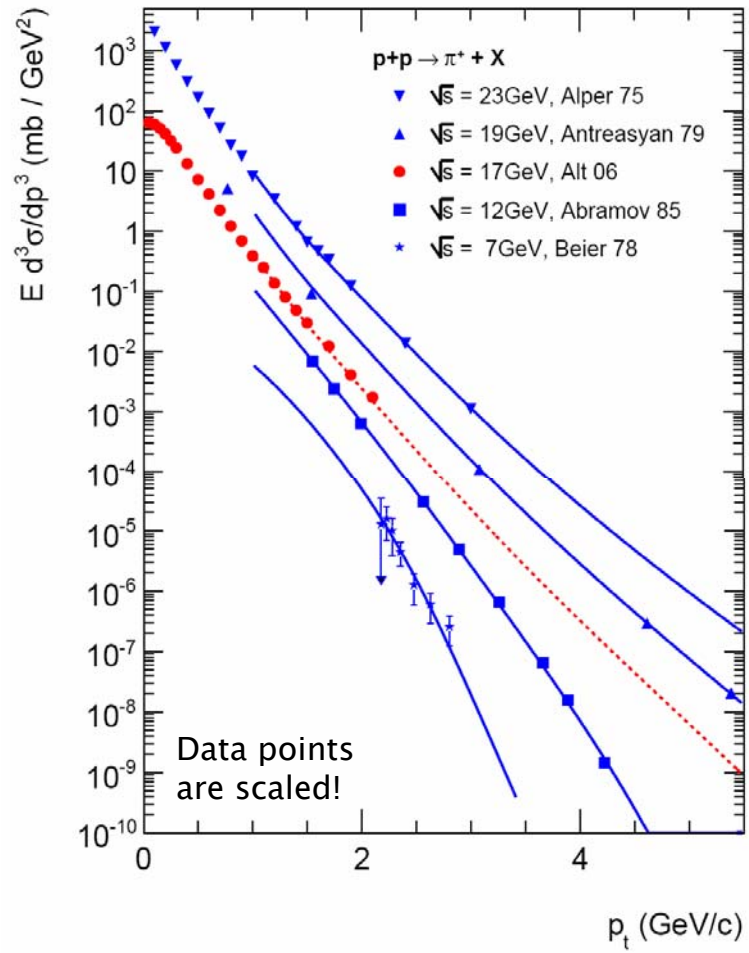
Shape of p_t-spectra in high-p_t region changes around SPS energies

Kinematical effects become important at lower $\sqrt{s}$

→ Difficult to parametrize

Especially for charged particles, where data are sparse

<u>But</u>: More data available for π^0



Only existing p+p reference @ $\sqrt{s}$ =17.3GeV:
p+p → $\pi^{\pm}$ + X by NA49 p_t < 2.1 GeV/c!
Eur. Phys. J. C45 (2006) 343

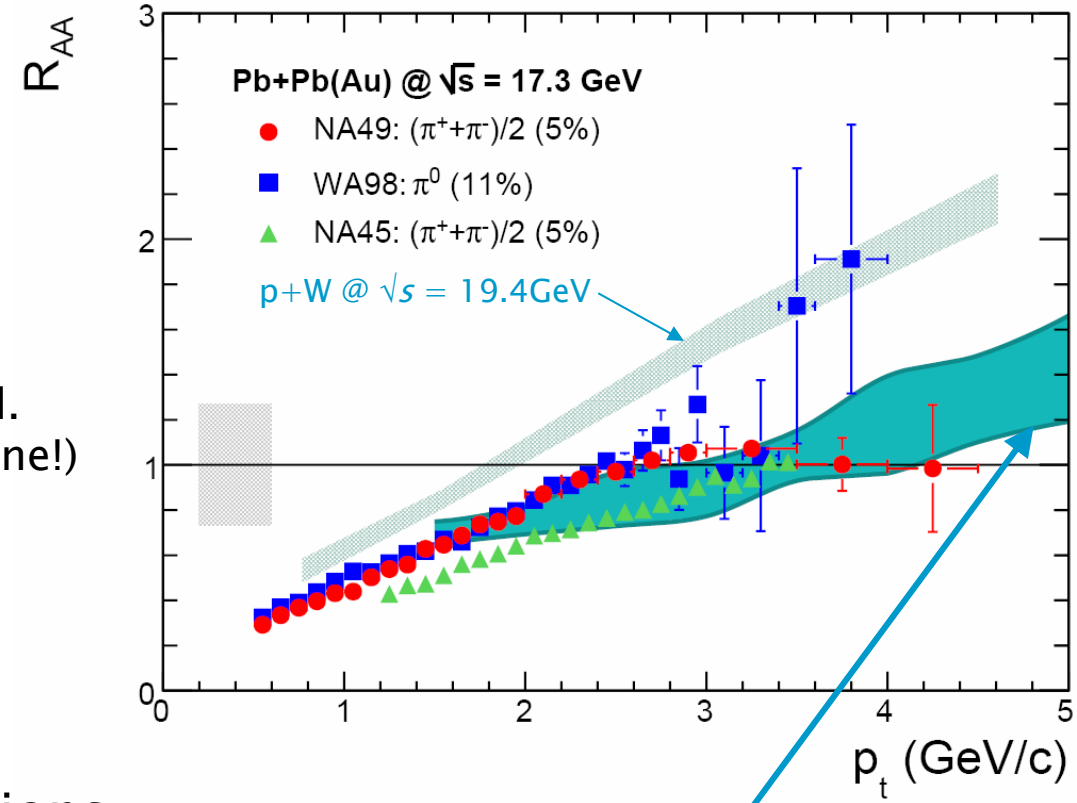
Comparison Central Pb+Pb ↔ p+p
R_{AA} @ $\sqrt{s}$ = 17.3GeV Update

R_{AA} = 1 up to p_t = 4.2GeV/c

Consistent with energy loss scenario

(Assumption: Blattnig et al. provides proper pp-baseline!)

NA49
A. Laszlo et al., nucl-ex/0510054



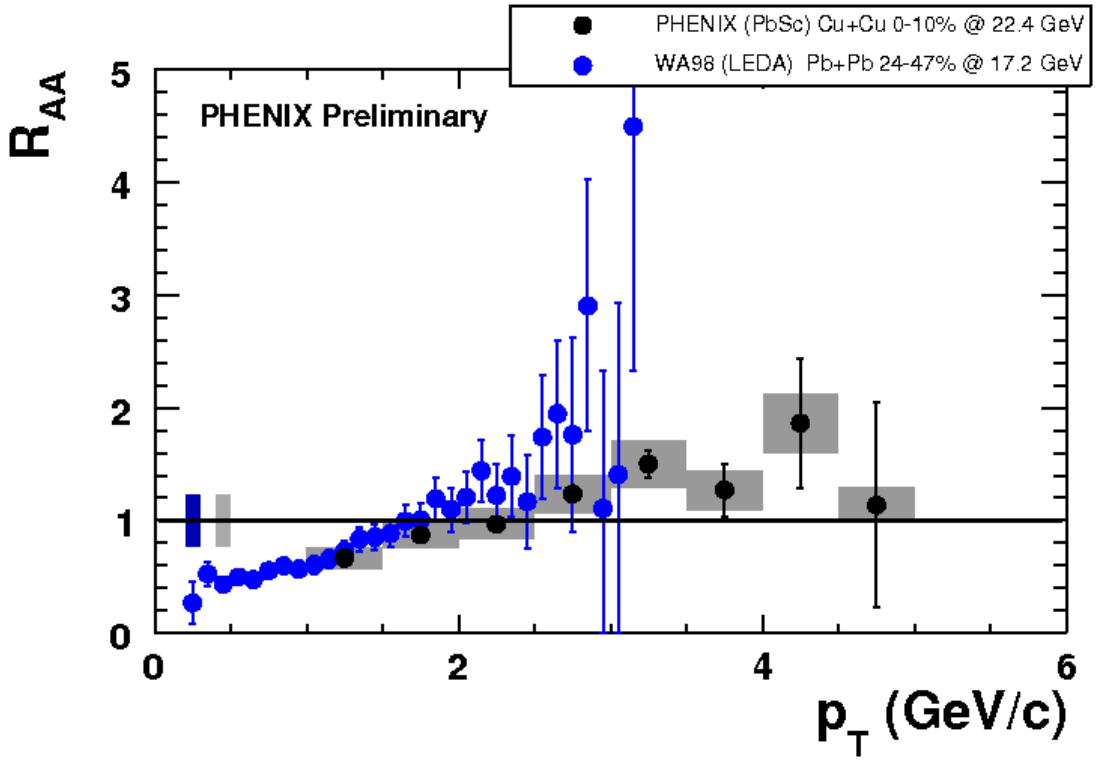
But: For final conclusions a p+p measurement up to $p_t \approx$ 4GeV/c is needed!

Theoretical prediction with energy loss
dN_g/dy = 400-600 + Cronin + shadowing

I. Vitev and M. Gyulassy, PRL 89 (2002), 252301

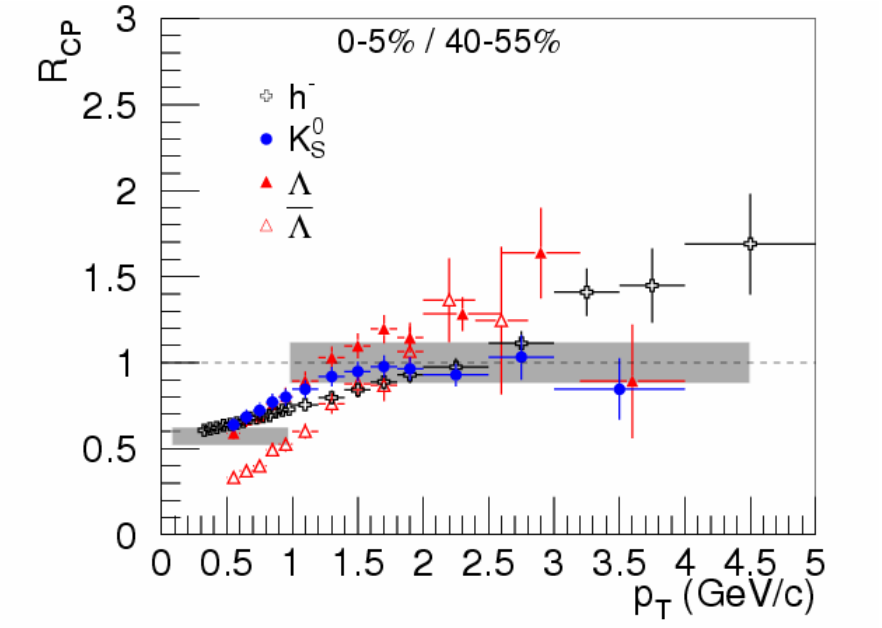
Comparison Central Pb+Pb ↔ p+p
R_{AA} Comparison to RHIC @ $\sqrt{s}$ = 22.4GeV

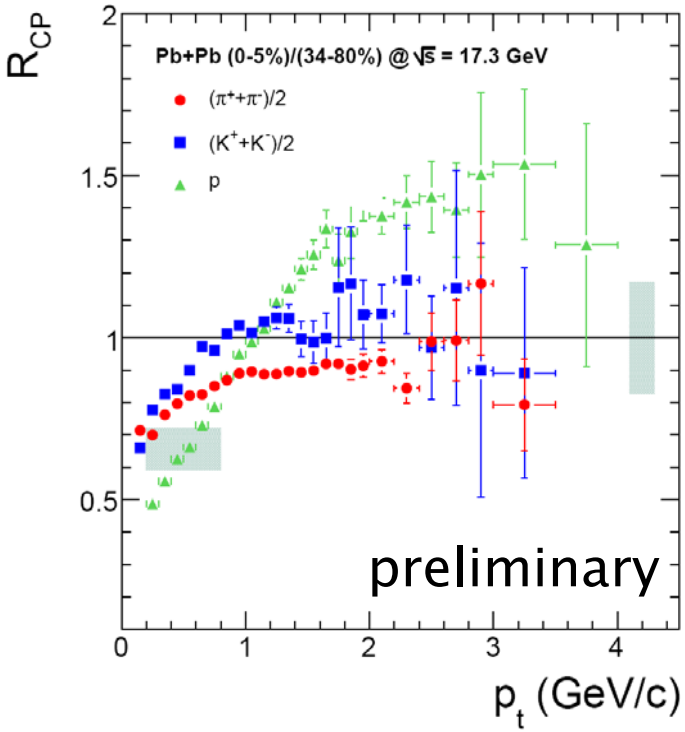
Recent Cu+Cu data @ $\sqrt{s}$ = 22.4GeV support $R_{AA} \approx 1-1.5$ above p_t = 2GeV/c



PHENIX
C. Klein-Bösing et al., nucl-ex/0606013

Central ↔ Peripheral Pb+Pb
New Data @ $\sqrt{s}$ = 17.3GeV





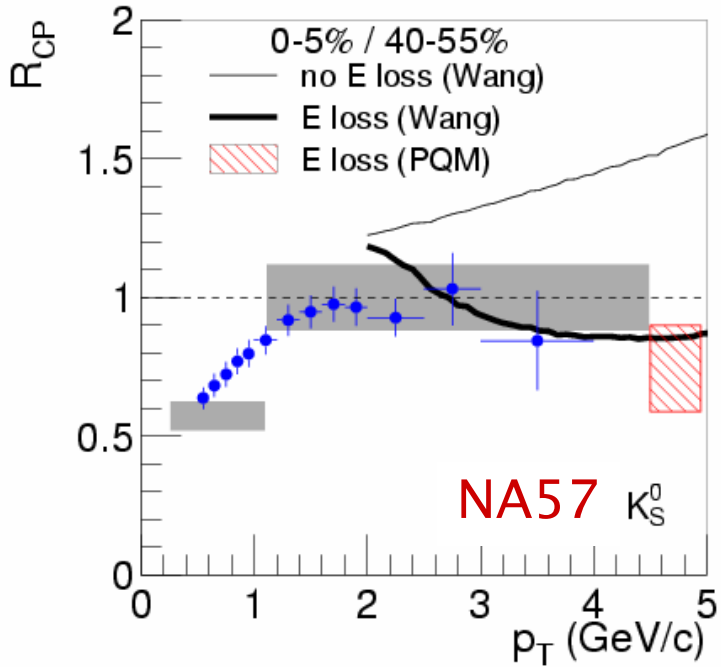
NA57
Phys. Lett. B623 (2005), 17

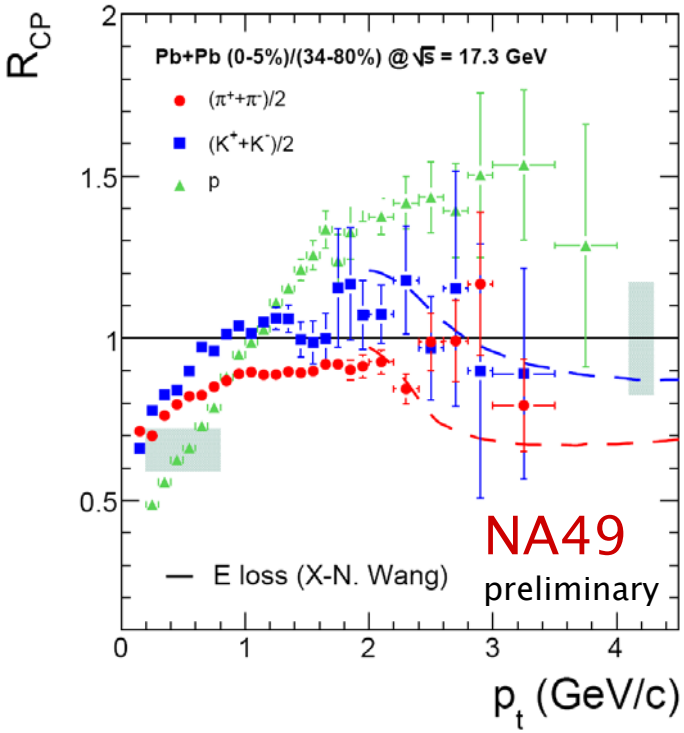
NA49
A. Laszlo et al.,
nucl-ex/0510054

R_{CP} for h^-, K^0_s, Λ, $\bar{\Lambda}$

R_{CP} for $\pi^\pm$, $K^\pm$, p

Central ↔ Peripheral Pb+Pb
Comparison to Theory





Consistent with quenching scenario

Mass Ordering: $R_{CP}(\Lambda,p) > R_{CP}(K^0_s,\pi)$

Similar as observed at RHIC

Calculations:

X.N. Wang, PRC68 (2001) 064910, PRL81 (1998) 2655, PLB595 (2004) 165, priv. com.

PQM: A. Dainese, C. Loizides, G. Paic, EPJC38 (2005) 495

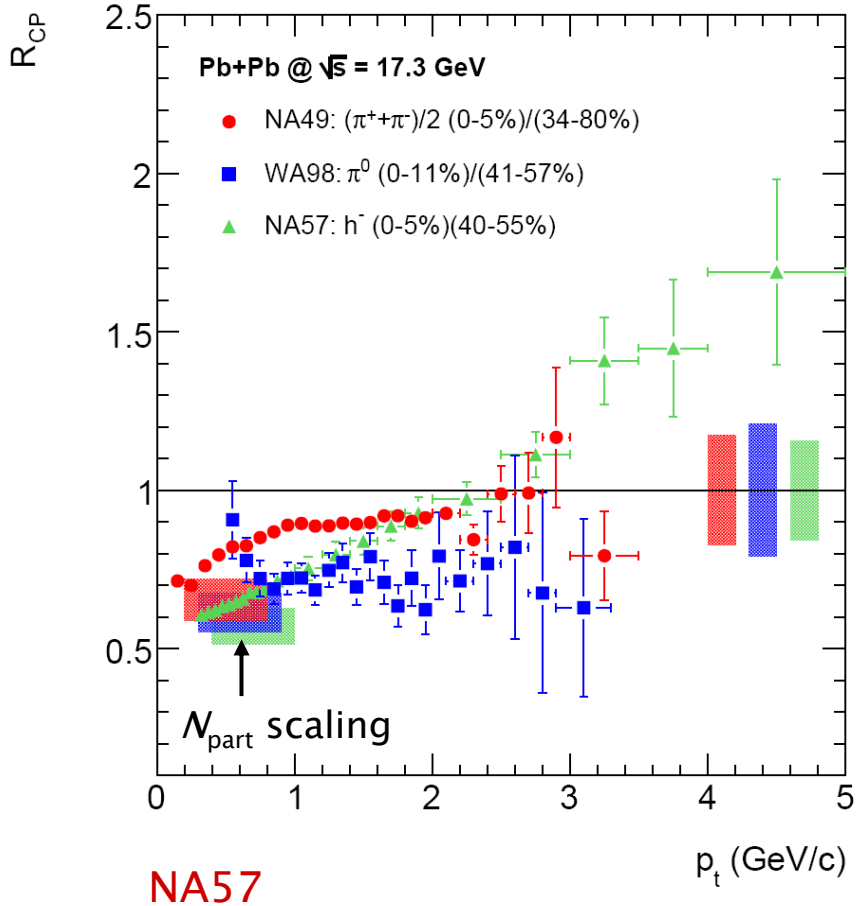
Central ↔ Peripheral Pb+Pb
Pions and h^- @ $\sqrt{s}$ = 17.3GeV

$R_{CP}(h^-) > 1$ above $p_t = 3$GeV/c

Kaon contribution?

$R_{CP}(\pi^0, \text{WA98}) < R_{CP}(\pi^\pm, \text{NA49})$

Note different centrality ranges



NA49
A. Laszlo et al., nucl-ex/0510054

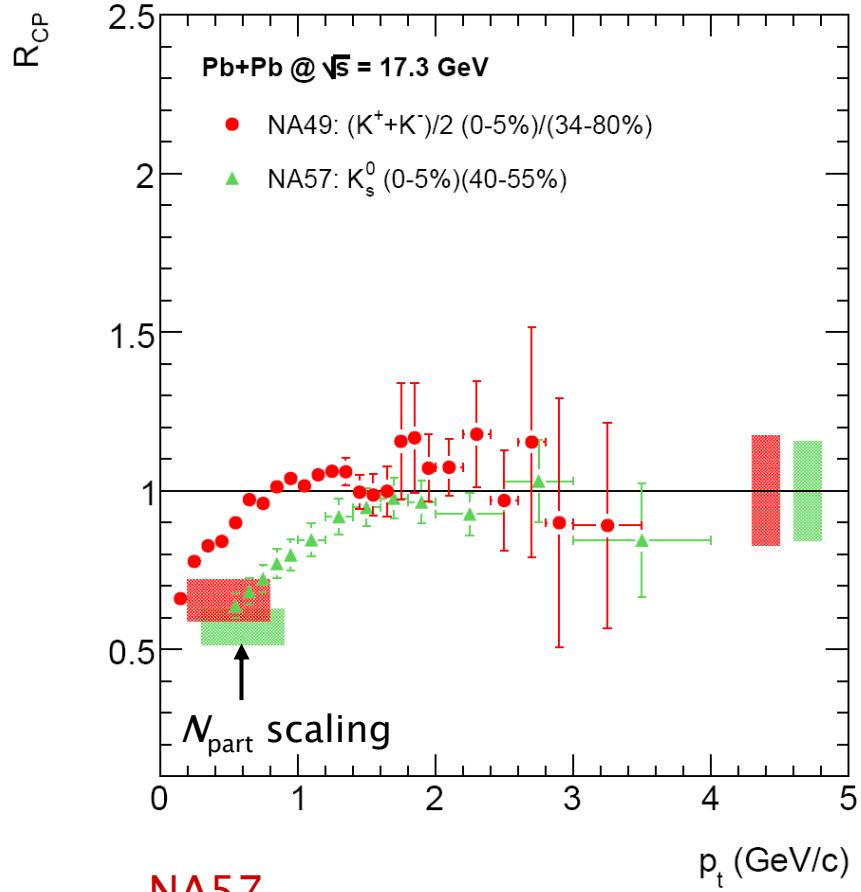
WA98
Eur. Phys. J. C23 (2002), 225.

NA57
Phys. Lett. B623 (2005), 17

Central ↔ Peripheral Pb+Pb
Kaons @ $\sqrt{s}$ = 17.3GeV

K^0_s(NA57) and $K^{\pm}$(NA49) agree above p_t = 1.5GeV/c

But: discrepancies at lower p_t

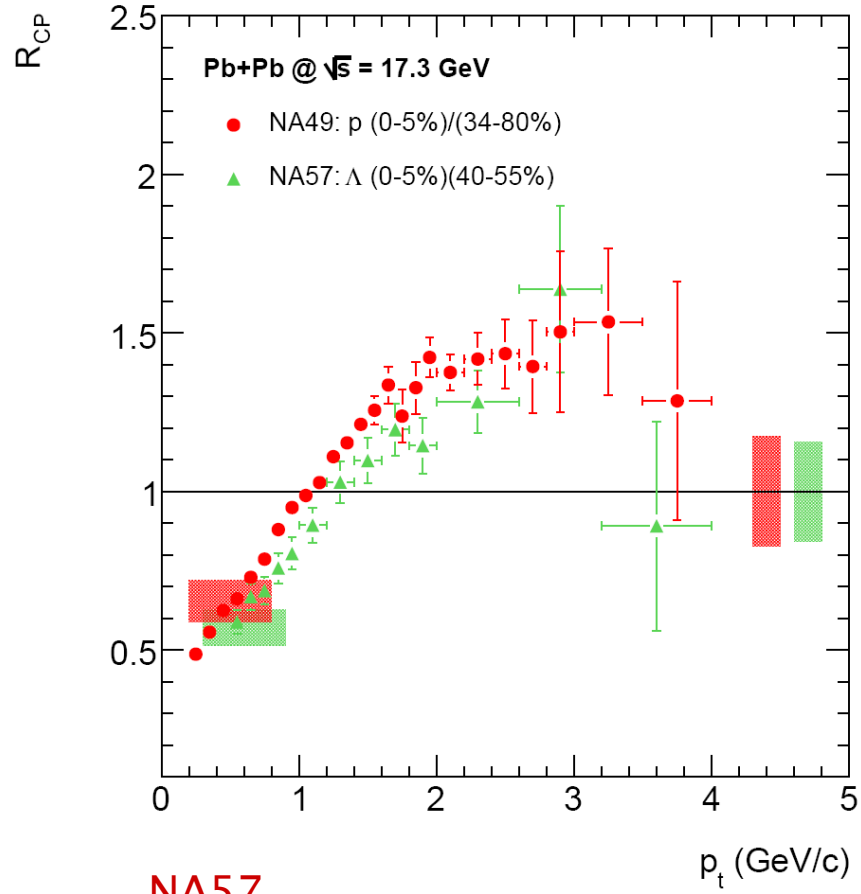


NA49
A. Laszlo et al., nucl-ex/0510054

NA57
Phys. Lett. B623 (2005), 17

Central ↔ Peripheral Pb+Pb
Protons and Λ @ $\sqrt{s}$ = 17.3GeV

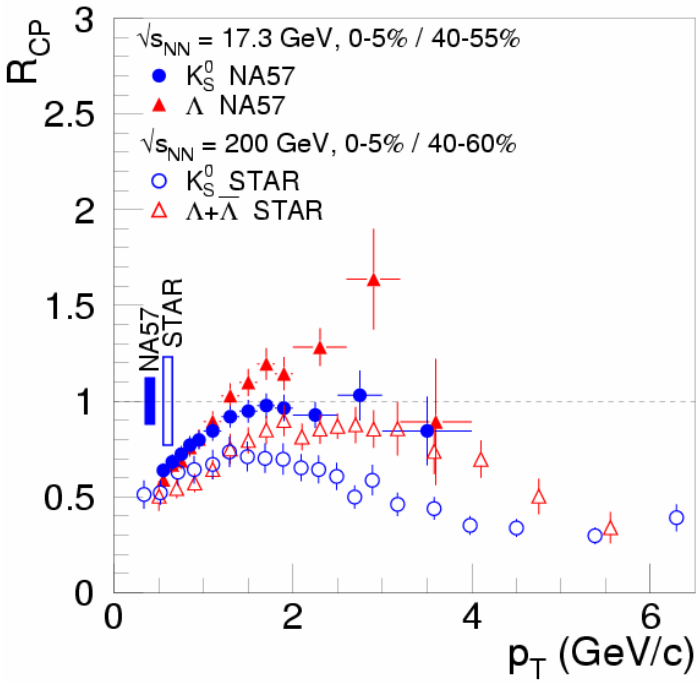
Good agreement between R_{CP}(p, NA49) and R_{CP}(Λ, NA57)



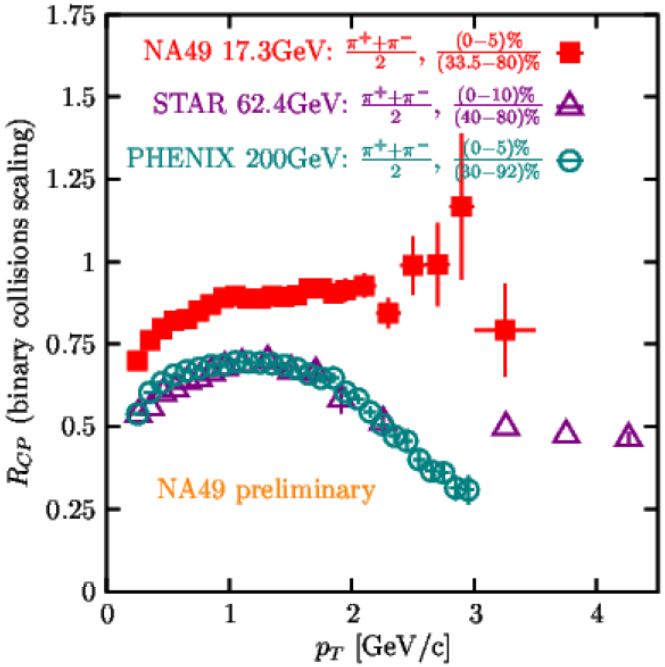
NA49
A. Laszlo et al., nucl-ex/0510054

NA57
Phys. Lett. B623 (2005), 17

Central ↔ Peripheral Pb+Pb
Comparison SPS to RHIC



NA57
Phys. Lett. B623 (2005), 17



NA49
A. Laszlo et al.,
nucl-ex/0510054

Clear energy dependence of R_{CP}

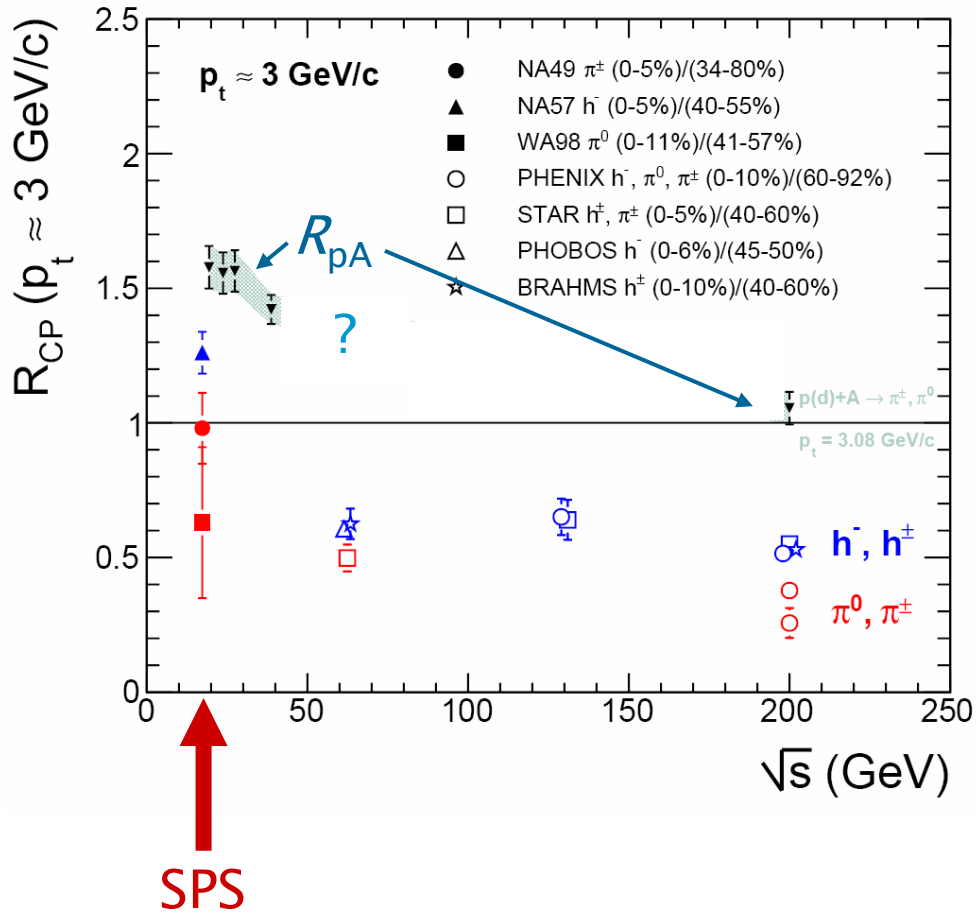
Central ↔ Peripheral Pb+Pb

Energy Dependence of R_{CP} for Pions and h⁻

Strongest drop of R_{CP} between $\sqrt{s}$ = 17.3GeV and $\sqrt{s}$ = 62.4GeV

Similar energy dependence in R_{pA}?

→ d+Au at 62.4GeV needed



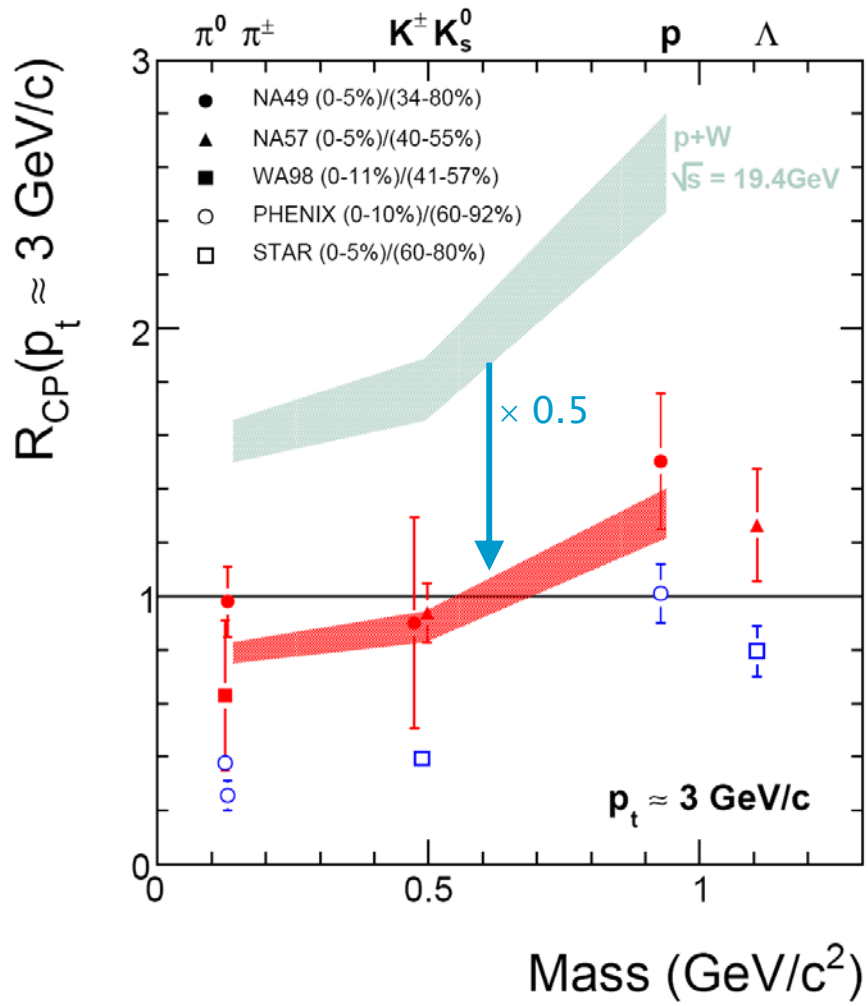
Central ↔ Peripheral Pb+Pb
Mass Dependence of R_{CP}

Clear mass ordering of R_{CP} observed @ $\sqrt{s}$ = 17.3.GeV

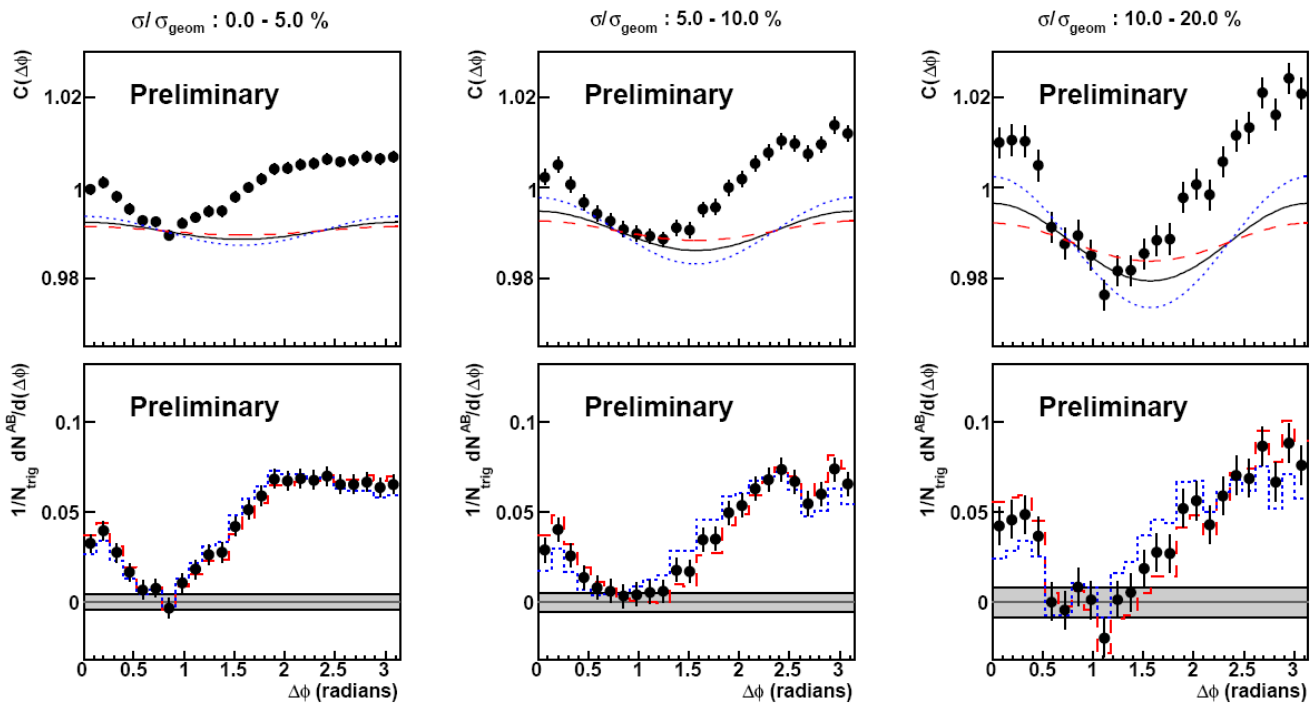
$R_{CP}(p,\Lambda) > R_{CP}(K) \geq R_{CP}(\pi)$

Similar as seen at RHIC (200GeV) and in p+A data

$R_{CP}(p_t=3) \approx ½\ R_{pA}(p_t=3)$ at SPS energies



Azimuthal Correlations
CERES: Pb+Au @ $\sqrt{s}$ = 17.3GeV



$2.5\ \mathrm{GeV/c} < p_t^{\mathrm{trigger}} < 4.0\ \mathrm{GeV/c}$
$1.0\ \mathrm{GeV/c} < p_t^{\mathrm{assoc.}} < 2.5\ \mathrm{GeV/c}$

Flow contribution by ZYAM method

$$C(\Delta\phi) = \frac{Y_{same}(\Delta\phi)}{Y_{mixed}(\Delta\phi)} \times \frac{\int Y_{mixed}}{\int Y_{same}}$$

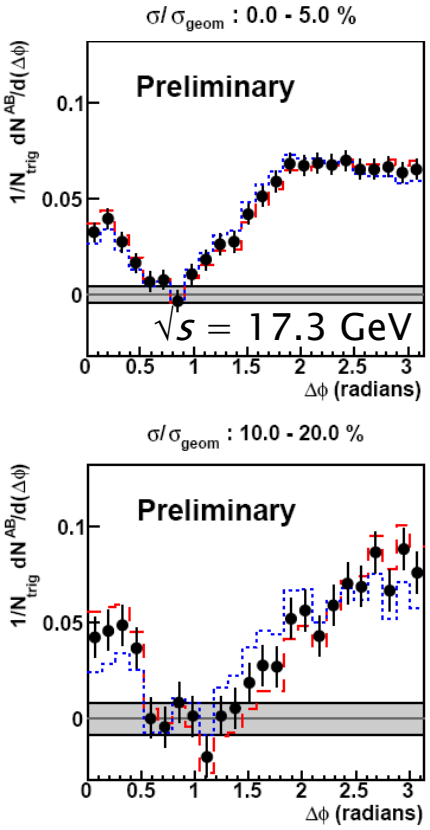
$$\frac{1}{N_{trig}} \frac{dN^{AB}}{d\Delta\phi} = \frac{J(\Delta\phi)}{\int (C(\Delta\phi')d(\Delta\phi'))} \frac{N^{AB}}{N^{A}}$$

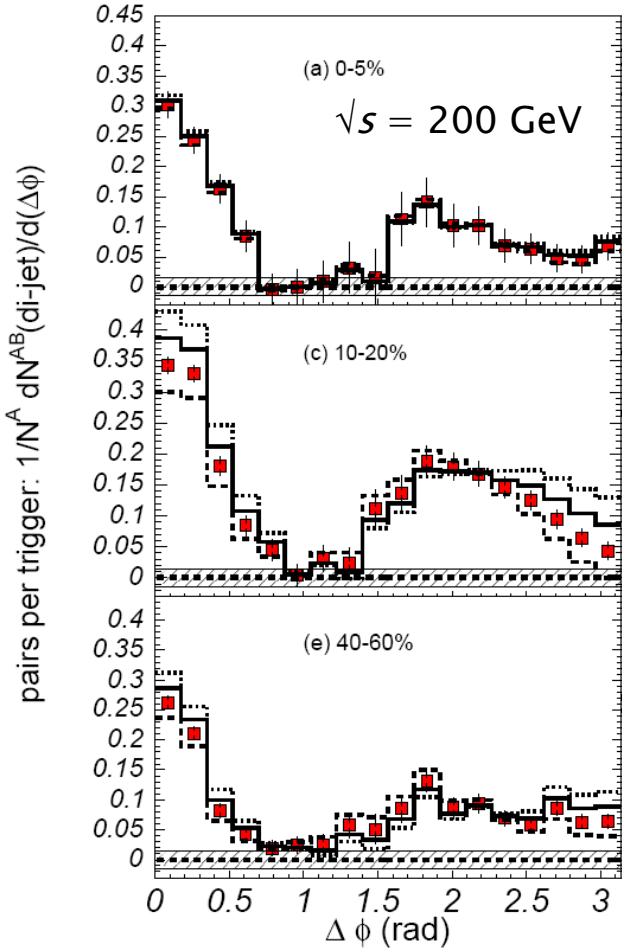
CERES
M. Płoskoń et al.,
nucl-ex/0511043

Details: Talk by
M. Płoskoń,
parallel session II

Azimuthal Correlations
Comparison SPS ↔ RHIC

CERES





$2.5\ \mathrm{GeV/c} < p_t^{\mathrm{trigger}} < 4.0\ \mathrm{GeV/c}$

$1.0\ \mathrm{GeV/c} < p_t^{\mathrm{assoc.}} < 2.5\ \mathrm{GeV/c}$

PHENIX

nucl-ex/0507004

Azimuthal Correlations
Centrality Dependence of Widths

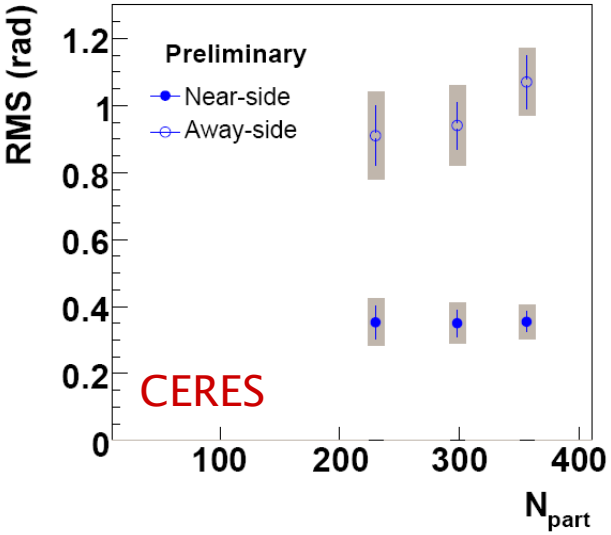
Broad away side structure

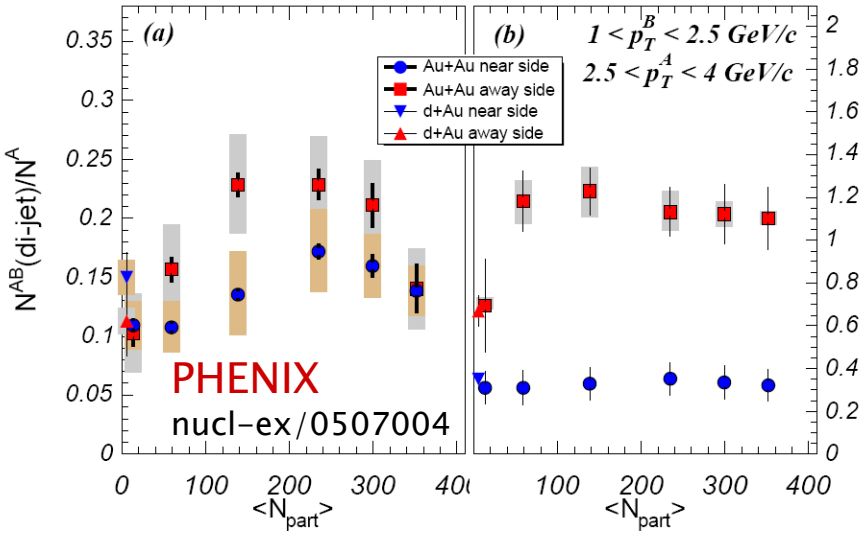
Broader than pp-like di-jet expectation (e.g. PHYTIA)

No significant centrality dependence of RMS

Modification of away side shape seen also at SPS

Effect of partonic interaction with medium?



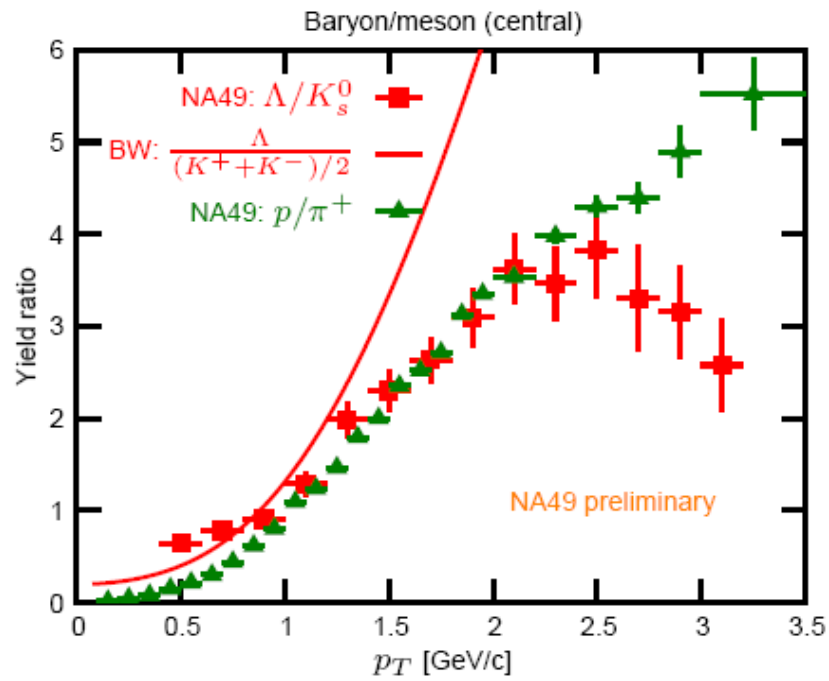


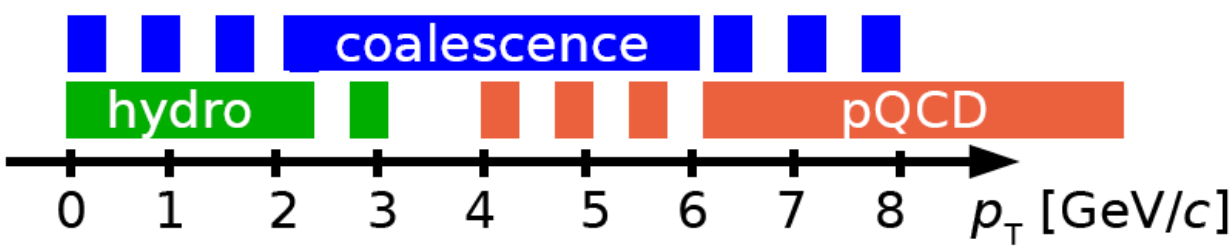
Baryon / Meson Ratios at High-p_t
Coalescence Picture

Baryon/meson ratio increases with p_t

Similar to RHIC

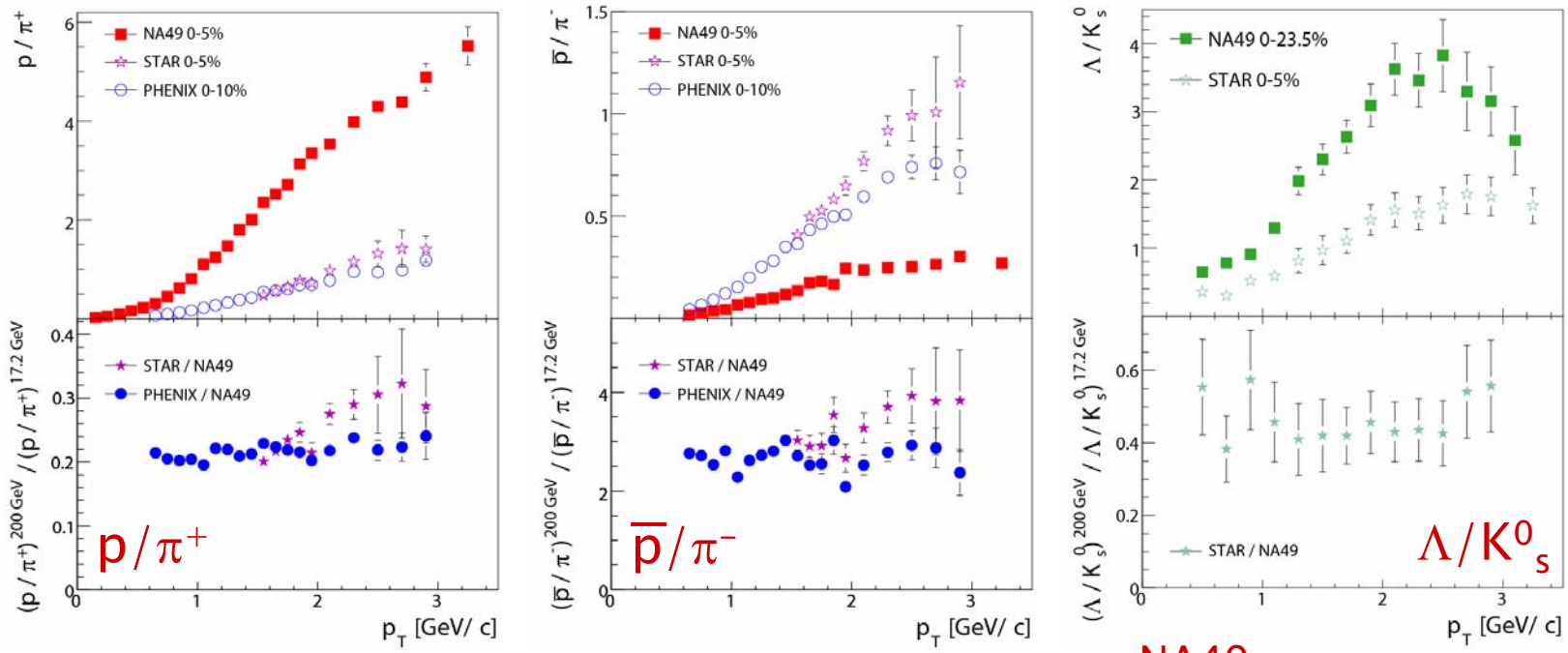
Coalescence models applicable at SPS?





NA49
A. Laszlo et al., nucl-ex/0510054

Baryon / Meson Ratios at High-p_t
Comparison to RHIC



NA49
T. Schuster et al., nucl-ex/0606005

STAR
nucl-ex/0601042

PHENIX
Phys. Rev. C 69 (2004), 034909

p_t-dependence of baryon/meson ratio appears to be energy independent

Baryon / Meson Ratios at High-p_t

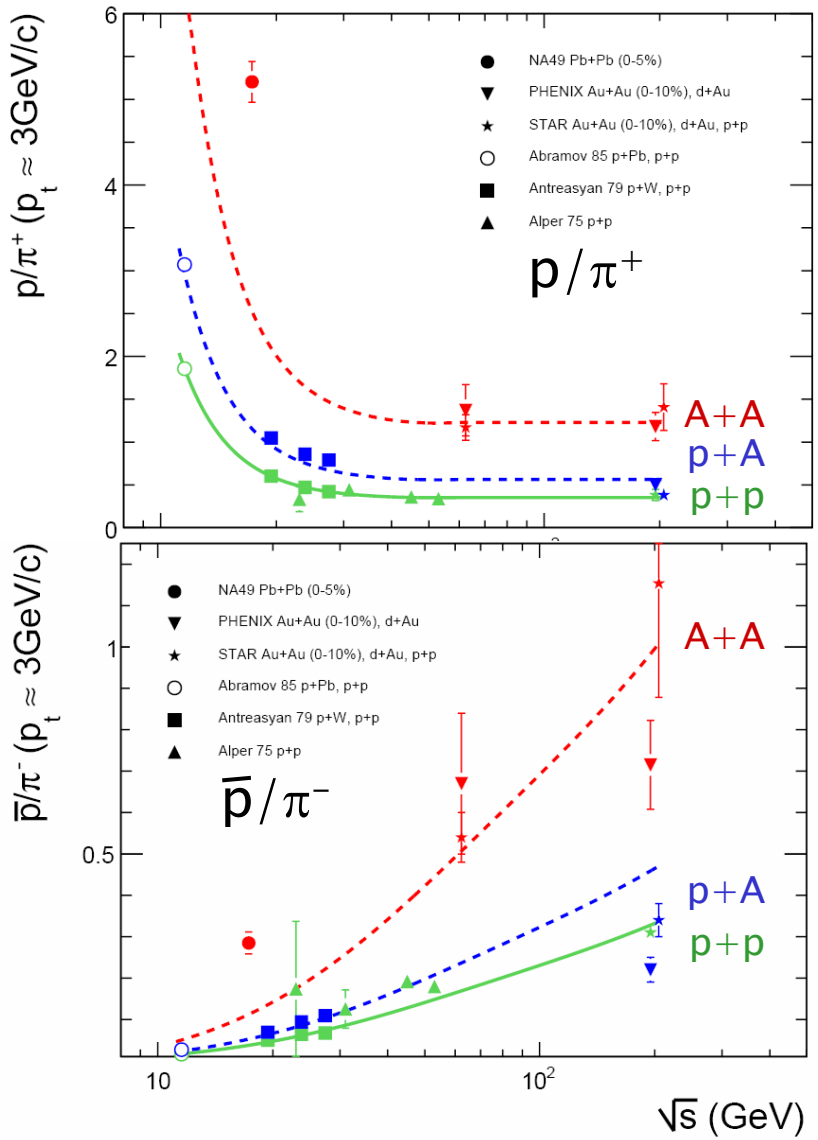
Energy Dependence of p/π^+ and $\bar{p}/\pi^-$

p/π^+ ratio at $p_t = 3$GeV/c increases rapidly towards lower energies

stronger increase than in p+p (A)!

$\bar{p}/\pi^-$ ratio at $p_t = 3$GeV/c decreases smoothly towards lower energies

weaker decrease than in p+p (A)!



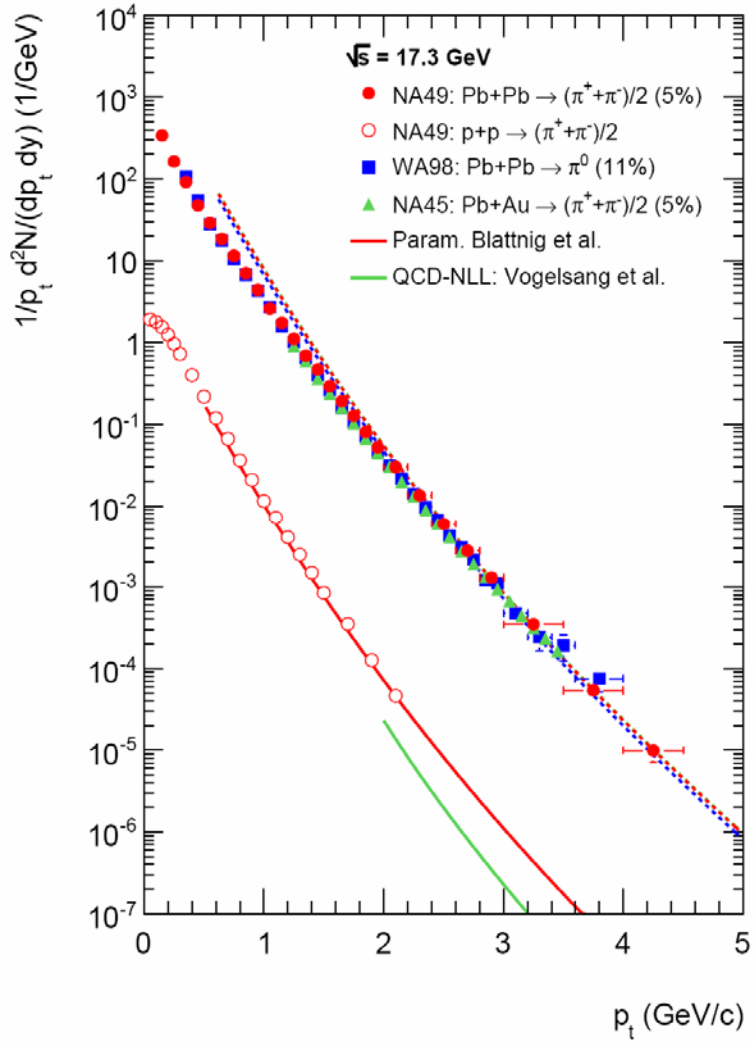
Summary

- *Baseline measurements*
  - Solid p+p and p+A baseline missing!
    - p+p (NA49): $p_t < 2.1$GeV/c
    - p+A: Ongoing re-analysis of WA98 data ($p_t < 3$-3.5GeV/c)
  - Important, since spectral shape strongly $\sqrt{s}$ dependent at SPS
- *Evidence for high p_t suppression at SPS?*
  - R_{AA} consistent with jet quenching + Cronin (<u>but</u>: see above)
  - Supported by new measurements of R_{CP} (NA57 and NA49)
  - "Suppression" relative to p+A $\approx$ 0.5! (RHIC@200GeV $\approx$ 0.2)
- *Azimuthal correlations*
  - CERES results qualitatively similar to RHIC
  - Indications for partonic interaction with medium
- *Baryon / meson comparison*
  - Mass dependence of R_{CP}, large p/π^+- and Λ/K^0_s-ratios
  - Test for quark coalescence models

Thanks!

Baseline Measurements
p+p Parametrization

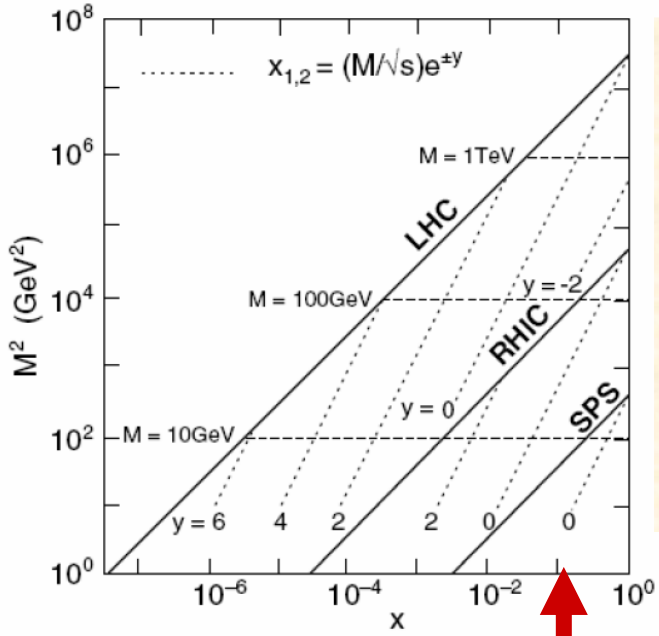
High-p_t pion spectra
in central Pb+Pb
at $\sqrt{s}$ = 17.3GeV

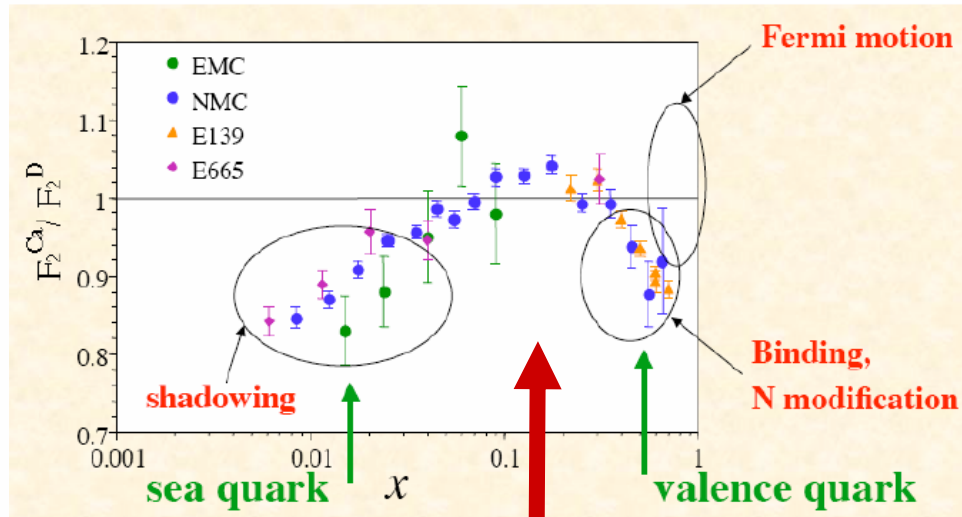


π^0-Parametrization by Blattnig et al.,
as suggested in:
D. d'Enterria, Phys. Lett. B 596 (2004), 32.

QCD-NLL: D. de Florian and W. Vogelsang,
Phys. Rev. D 71 (2005), 114004.

High p_t at the SPS
Kinematical Regime

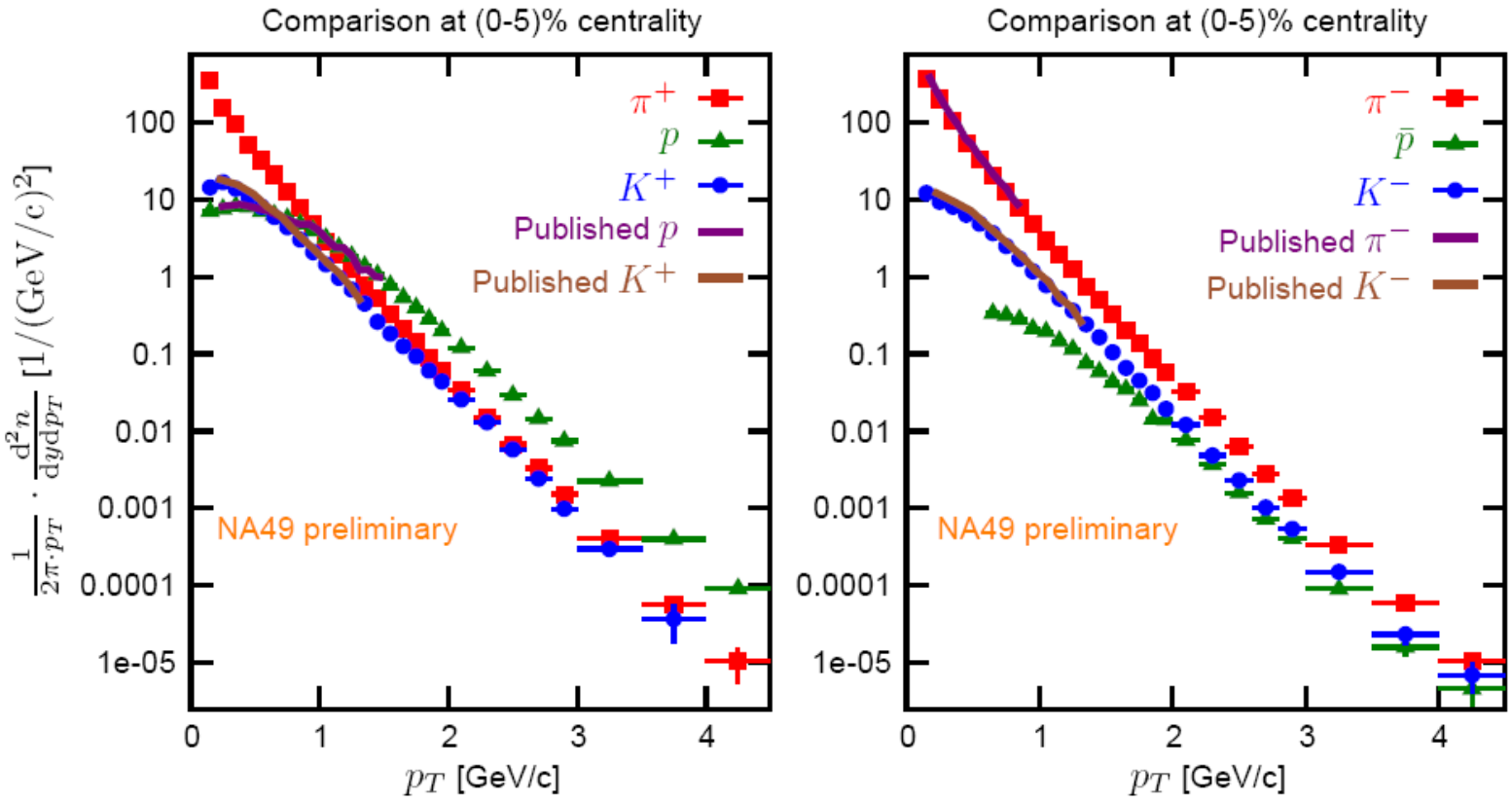




Bjørken-x region ≈ 0.1

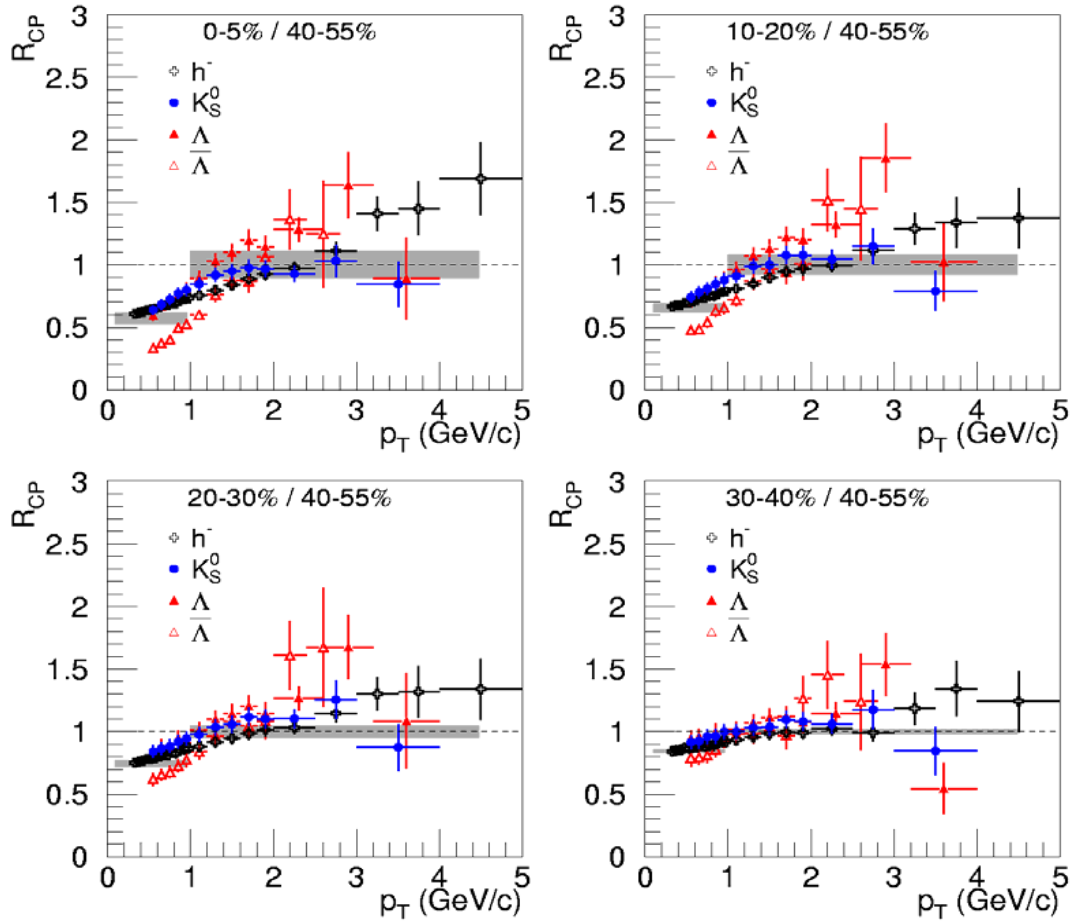
Anti-shadowing region

High p_t at the SPS
New NA49 data at $\sqrt{s} = 17.3$ GeV



Central ↔ Peripheral Pb+Pb
Centrality Dependence of R_{CP}

No dramatic centrality dependence of R_{CP} observed

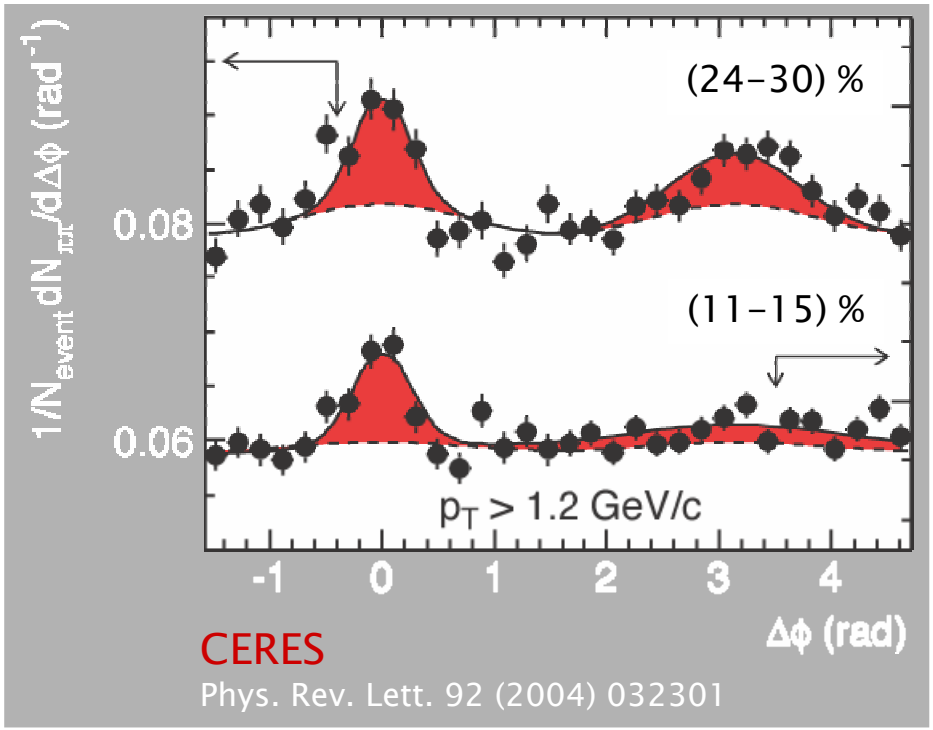


NA57
Phys. Lett. B623 (2005), 17

Azimuthal Correlations
Published Data by CERES

Azimuthal correlations for Pb+Au at 158*A* GeV

Semi-hard two particle correlation on top of flow component ?



Away side peaks broadens with centrality

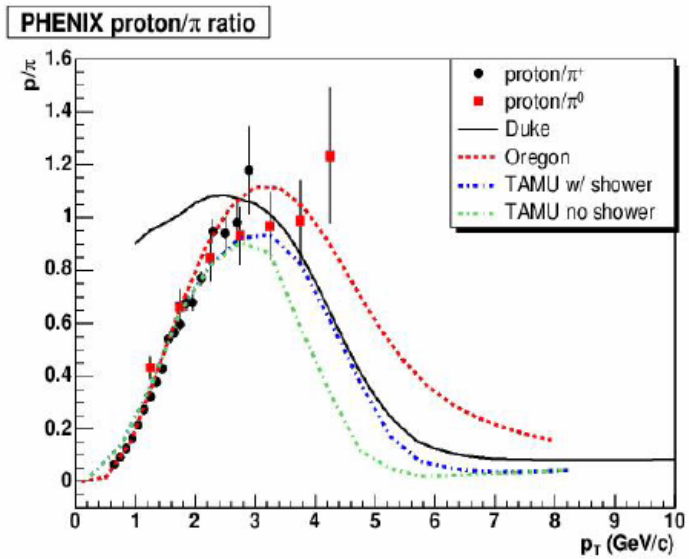
- In-medium parton scattering?
- Same picture as at RHIC?

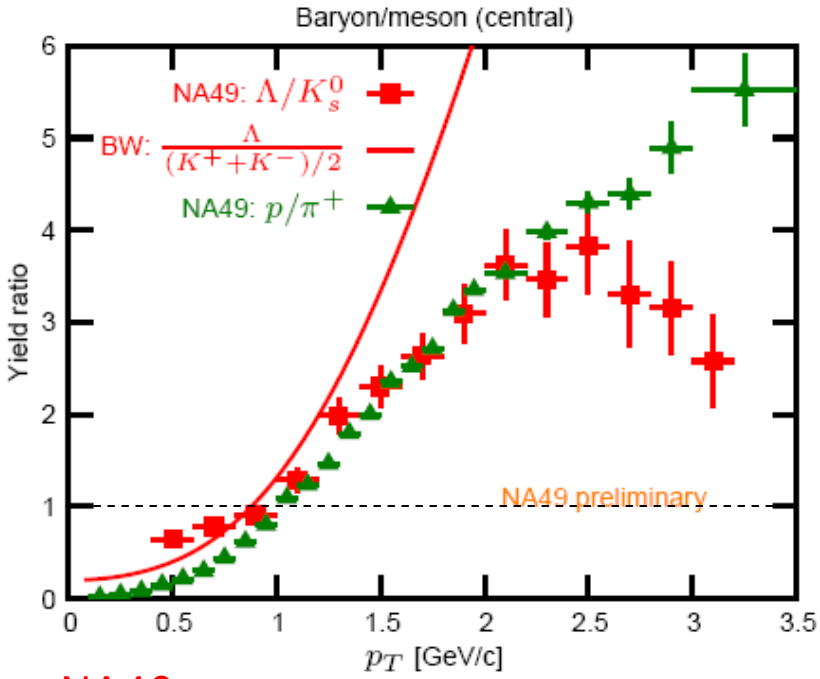
Baryon Meson Ratios at High-p_t
Coalescence Picture

Baryon/meson ratio increases with p_t

Similar to RHIC

Coalescence models applicable at SPS?

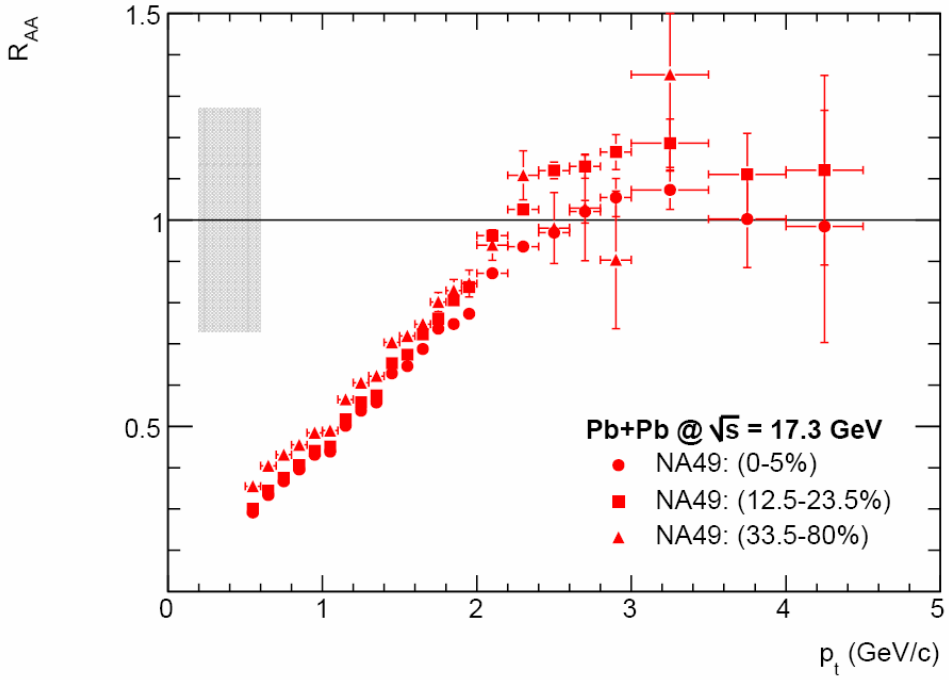


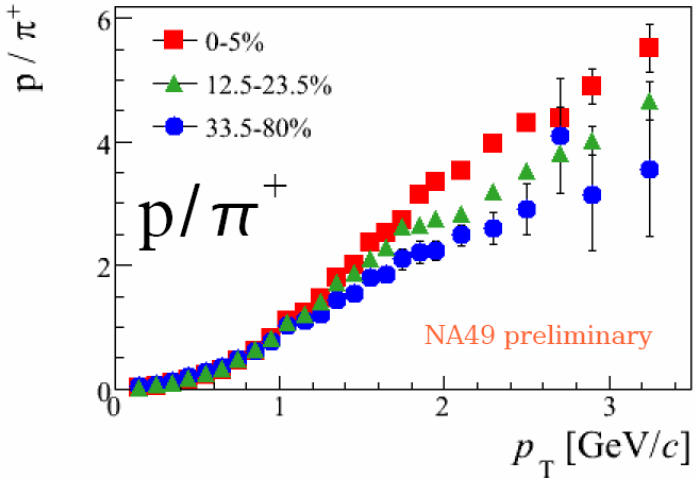
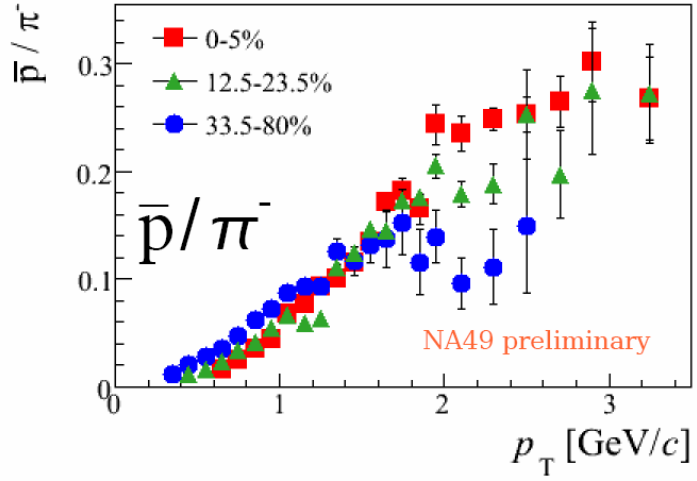


NA49
A. Laszlo, QM05
T. Schuster

Comparison Central Pb+Pb ↔ p+p

R_{AA} Centrality Dependence



Baryon / Meson Ratios at High-p_t

Centrality Dependence of p/π^+ and $\bar{p}/\pi^-$