Subthreshold production of ϕ mesons in heavy-ion collisions with FOPI

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- ϕ mesons in nucleus-nucleus collisions
- Production of ϕ at 1.5 .. 2A GeV: yields and slopes
- Systematics of the ϕ data
- Summary

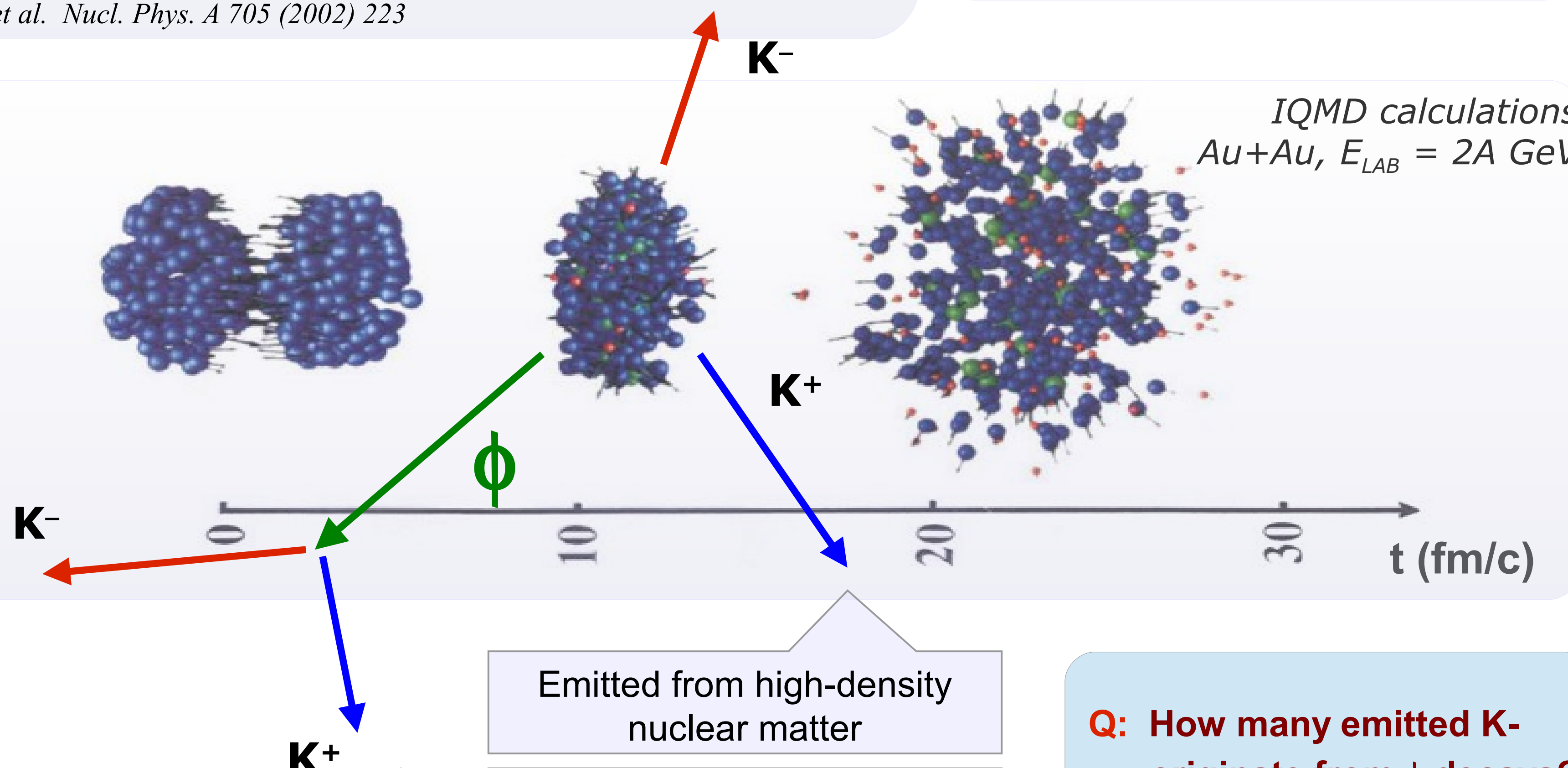
ϕ mesons in nucleus-nucleus collisions

- ϕ ($s\bar{s}$) : m = 1019 MeV
- $E_{thr\ NN}$ = 2.6 GeV (below threshold for the GSI experiments)
- Considered production channels for subthreshold energies :

$$BB \rightarrow \phi BB \quad , \quad B = [\Delta, N]$$
$$\pi B \rightarrow \phi B \quad , \quad \rho B \rightarrow \phi B$$
$$\pi N^* \rightarrow \phi N \quad , \quad \rho\pi \rightarrow \phi$$

H.W. Barz et al. Nucl. Phys. A 705 (2002) 223

- $c\tau$ = 50 fm
- $\phi \rightarrow K^+K^-$ (BR = 49%)
- Yield of K^- is comparable to ϕ

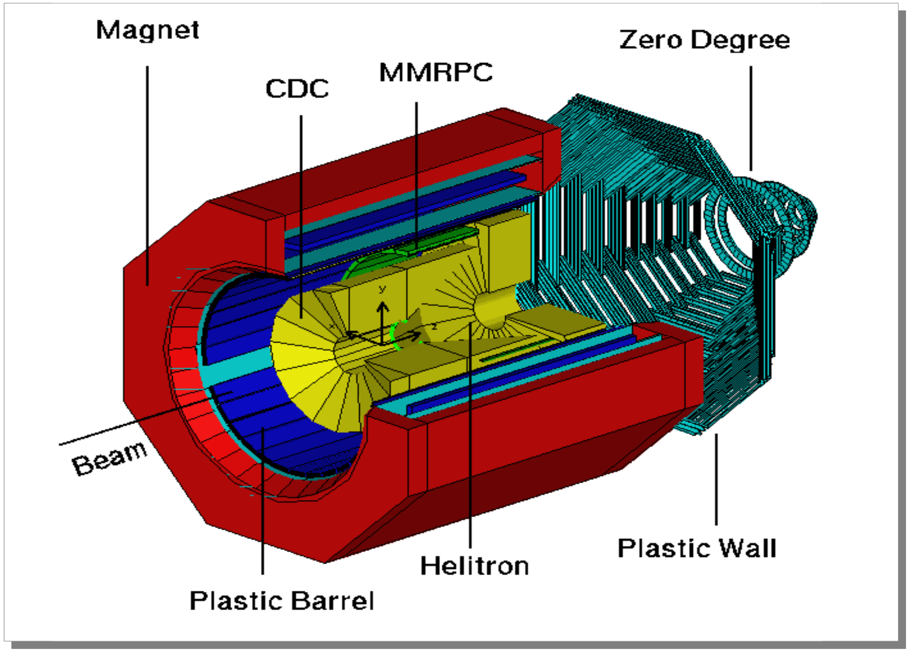


Emitted from high-density nuclear matter

Emitted (mainly) in vacuum

Q: How many emitted K- originate from ϕ decays?

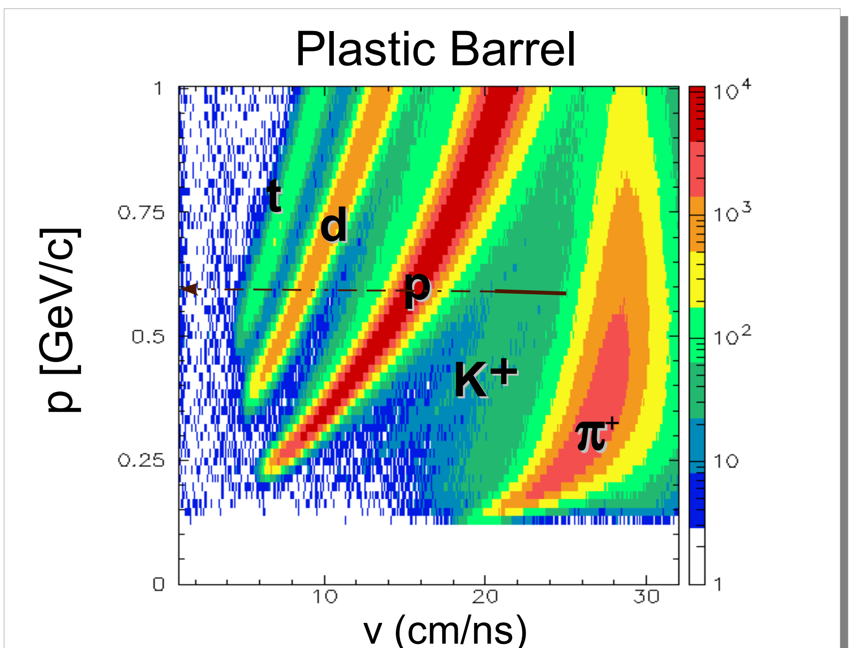
FOPI experimental setup

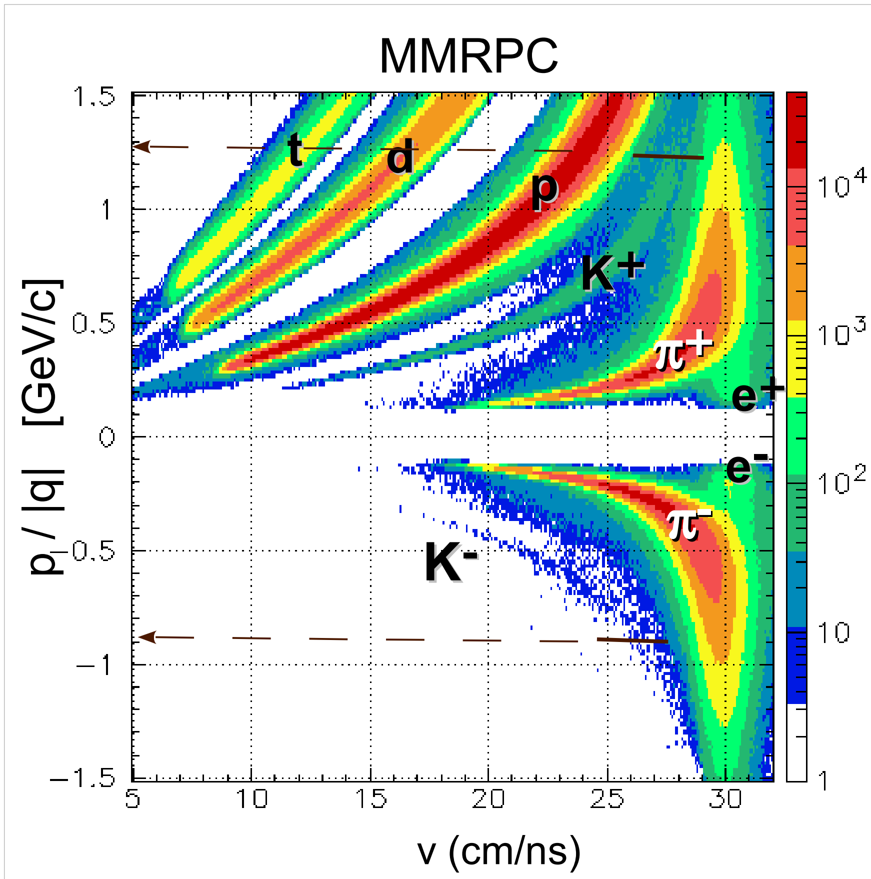


- Nearly 4π coverage
- Drift chambers: CDC, Helitron

  ToF : Plastic Barrel, RPC

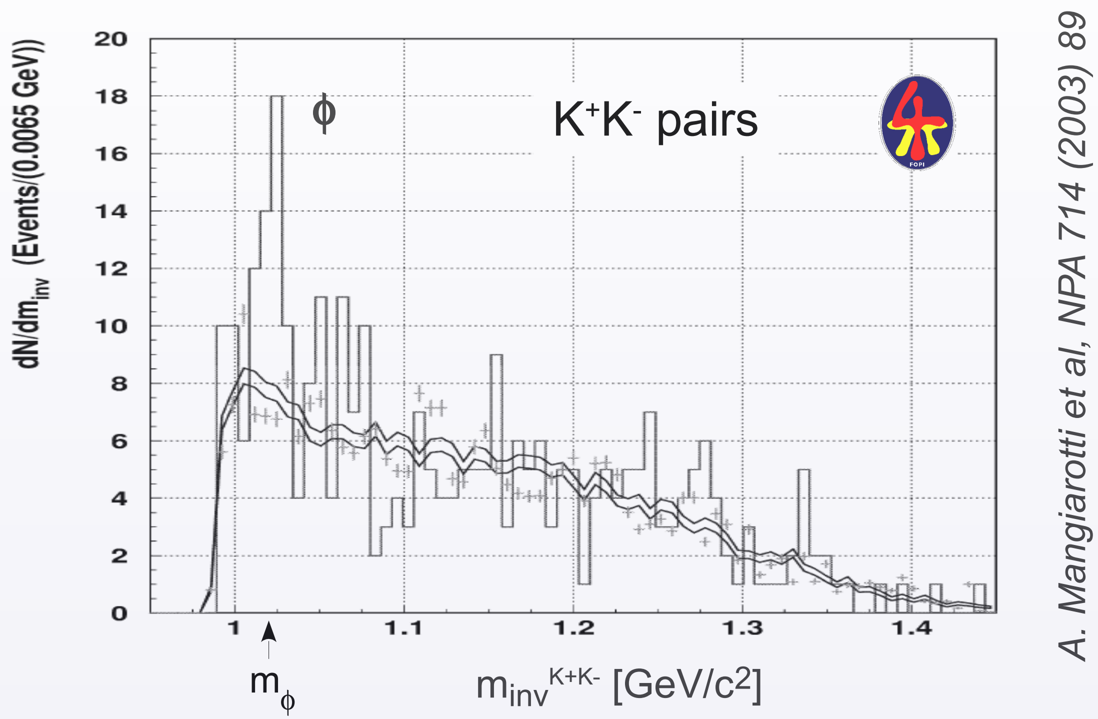
  Forward: Plastic Wall, Zero Degree
- Direct PID of $\pi^{\pm}$, $K^{\pm}$, p, d, t, ^{3,4}He





Ni+Ni @ 1.93A GeV

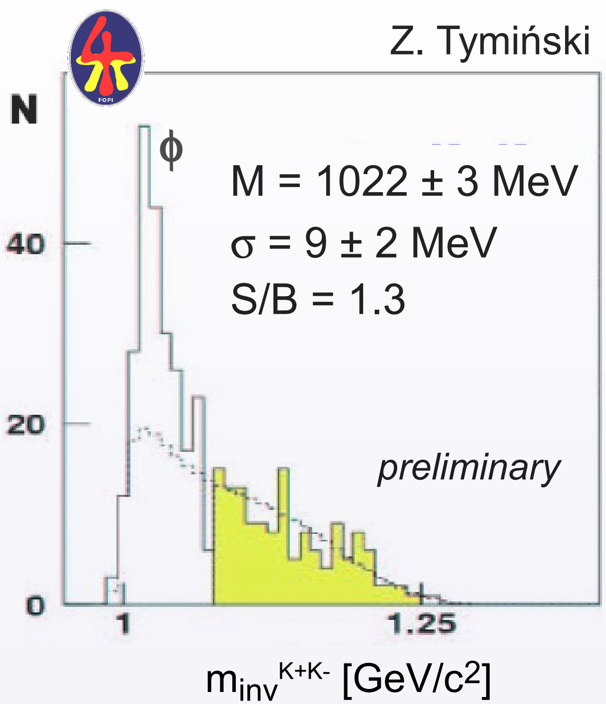
- First measurement: FOPI, 1995
- Trigger: 12% most central events



- Number of ϕ = 23 ± 7 ± 2
- ϕ yield depends on Temperature, which was not found due to scarce statistics.
- But within T $\in$ [70, 130] MeV, $P(\phi) = (1.2 .. 4.5) \cdot 10^{-3}$ (first estimate)

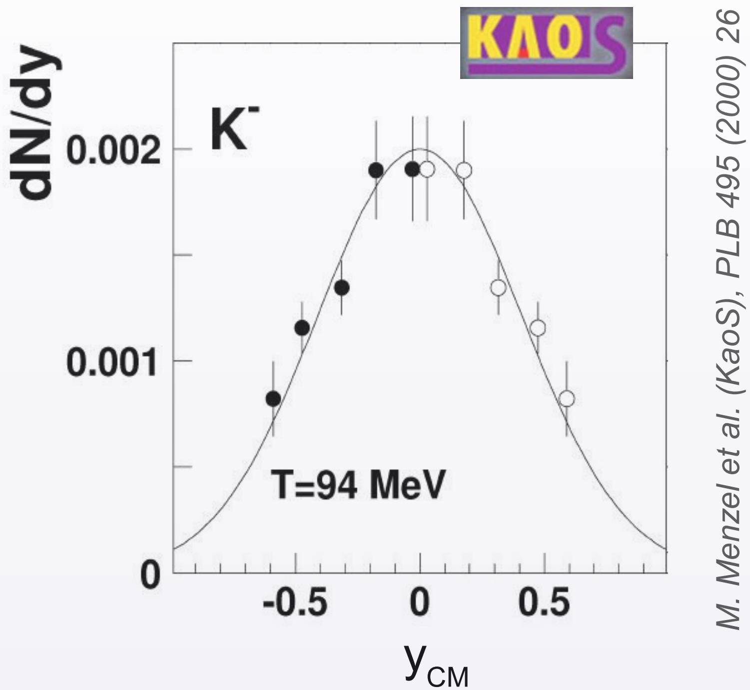
Ni+Ni @ 1.93A GeV

- Trigger: 20% most central events



- Number of ϕ = 100 ± 17 ± 20
- ϕ yield per triggered event: $(6 \pm 1 \pm 2) \cdot 10^{-4}$

- K^- from KaoS, central collisions



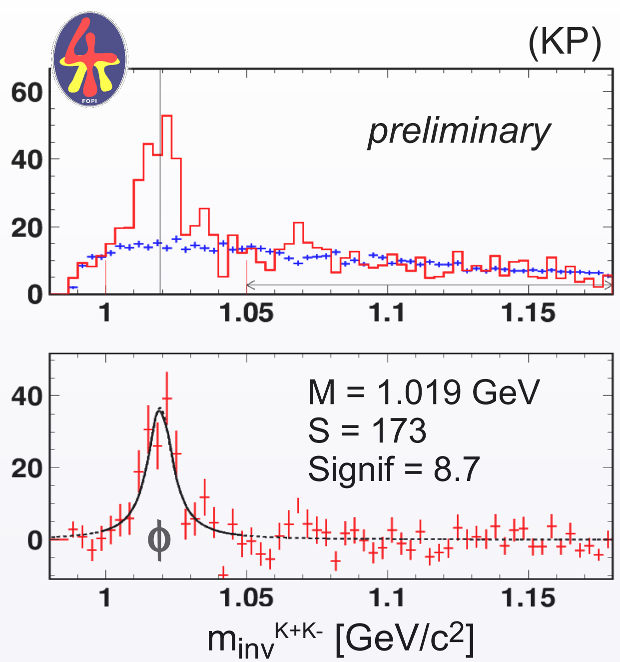
- K^- yield per triggered event: $(2.1 \pm 0.4) \cdot 10^{-3}$

→ $\frac{\phi}{K^-} = 29 \pm 7 \pm 10\%$

→ 14 ± 3 % of K^- originate from ϕ decays

Ni+Ni @ 1.93A GeV

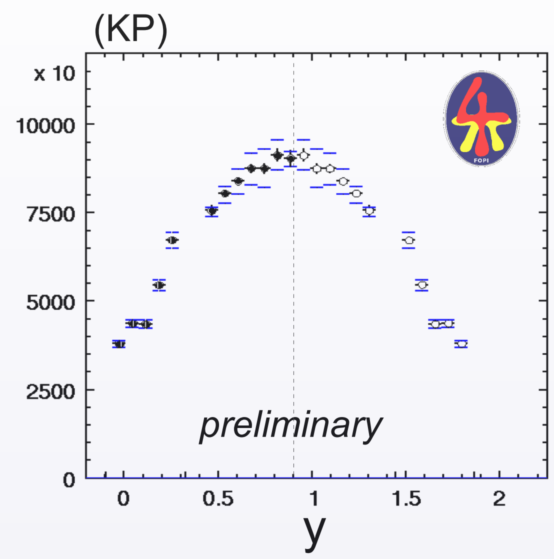
- Trigger: 50% most central events

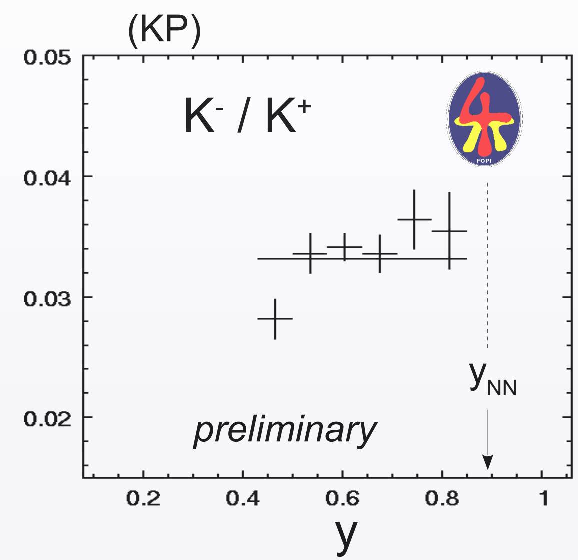


- Number of ϕ = 173
  Significance = 8.7

- ϕ yield per triggered event:
  $(4.4 \pm 0.4 \pm 1.3) \cdot 10^{-4}$

- $$\frac{\phi}{K^-} = \frac{\phi}{K^+} \Big/ \frac{K^-}{K^+}$$





- K^+ yield per triggered event:
  $(3.87 \pm 0.10 \pm 0.12) \cdot 10^{-2}$

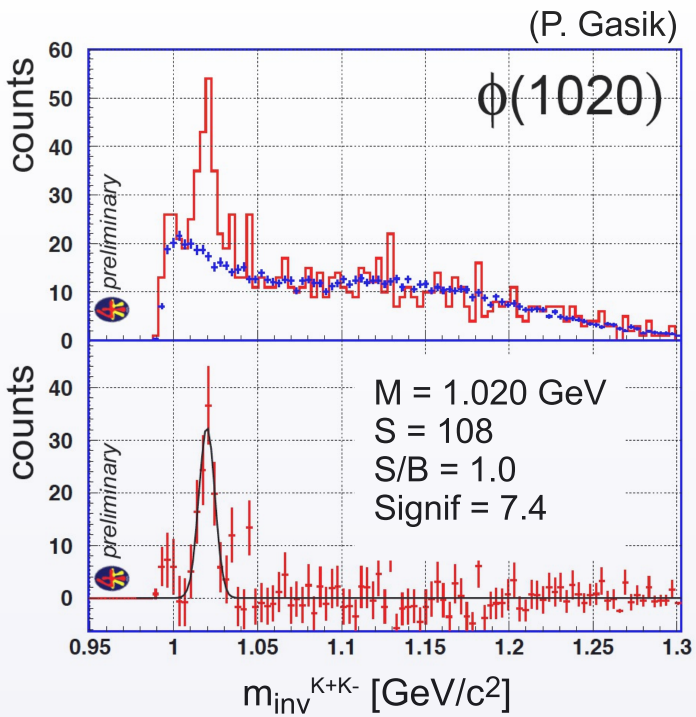
- K^-/K^+ ratio (in the measurable range)
  $(3.32 \pm 0.07 \pm 0.13) \cdot 10^{-2}$

→ $$\frac{\phi}{K^-} = 34 \pm 3 \pm 11\ \%$$

→ $17 \pm 2 \pm 5\%$ of K^- originate from ϕ decays

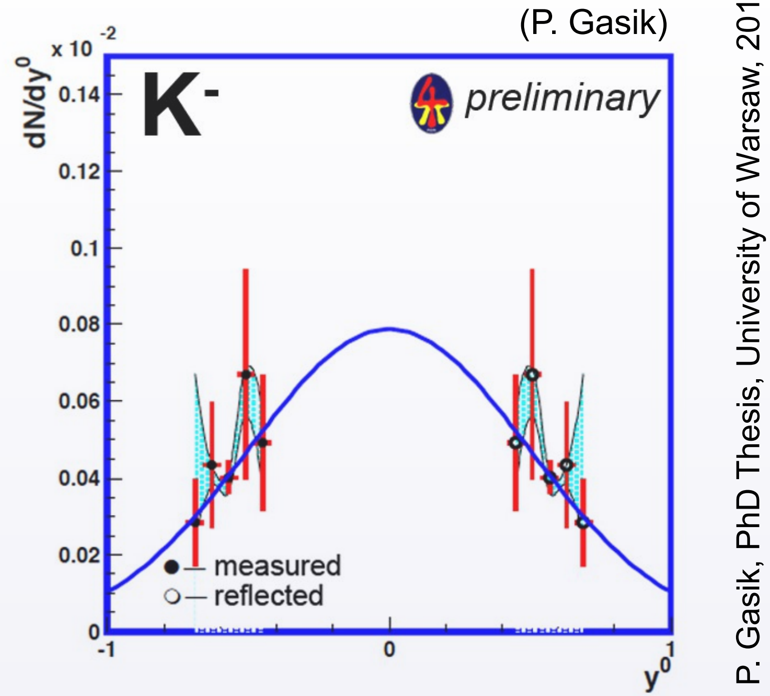
Al+Al @ 1.9A GeV

- Trigger: 9% most central events



- Number of ϕ = 108 ± 15
  Significance = 7.4

- ϕ yield per triggered event:
  $(3.3 \pm 0.5 \pm 0.6) \cdot 10^{-4}$



- Number of K^- = 3090 ± 60

- K^- yield per triggered event:
  $(1.1 \pm 0.3 \pm 0.2) \cdot 10^{-3}$

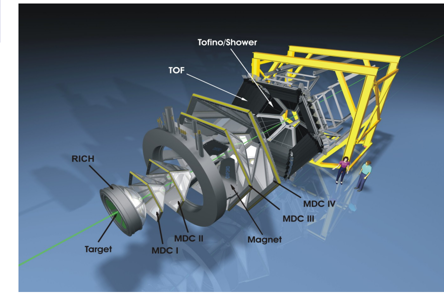
$$\frac{\phi}{K^-} = 30 \pm 8 \pm 5 \ \%$$

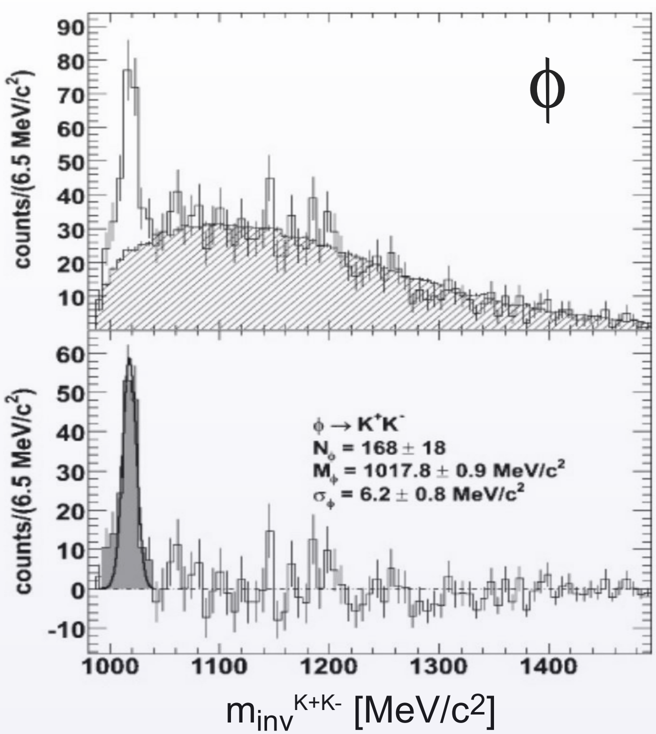
15 ± 4 % of K^- originate from ϕ decays

Ar + KCl @ 1.756A GeV

HADES

- Trigger: 35% most central events

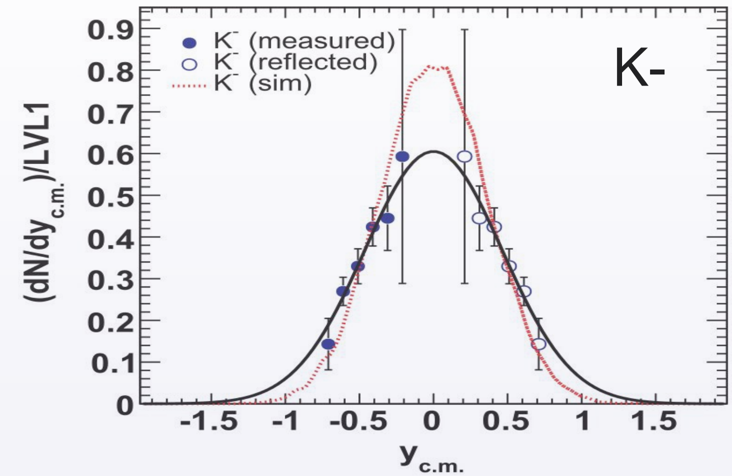




- Number of ϕ = 168 ± 18
- ϕ yield per triggered event:

  $(2.6 \pm 0.7 \pm 0.1) \cdot 10^{-4}$

G. Agakishiev et al., PRC 80, 025209 (2009)



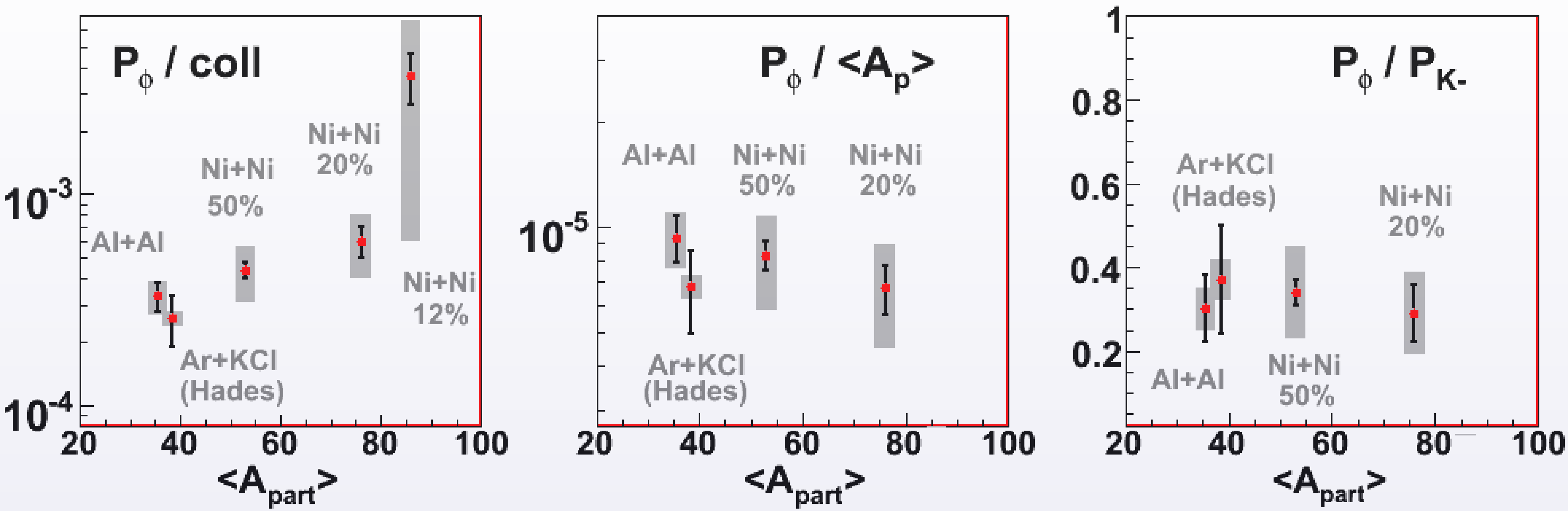
- K^- yield per triggered event:

  $(7.1 \pm 1.5 \pm 0.3) \cdot 10^{-4}$

→ $$\frac{\phi}{K^-} = 37 \pm 13 \pm 3 \ \%$$

→ 18 ± 6 % of K^- originate from ϕ decays

Systematics of subthreshold ϕ meson production

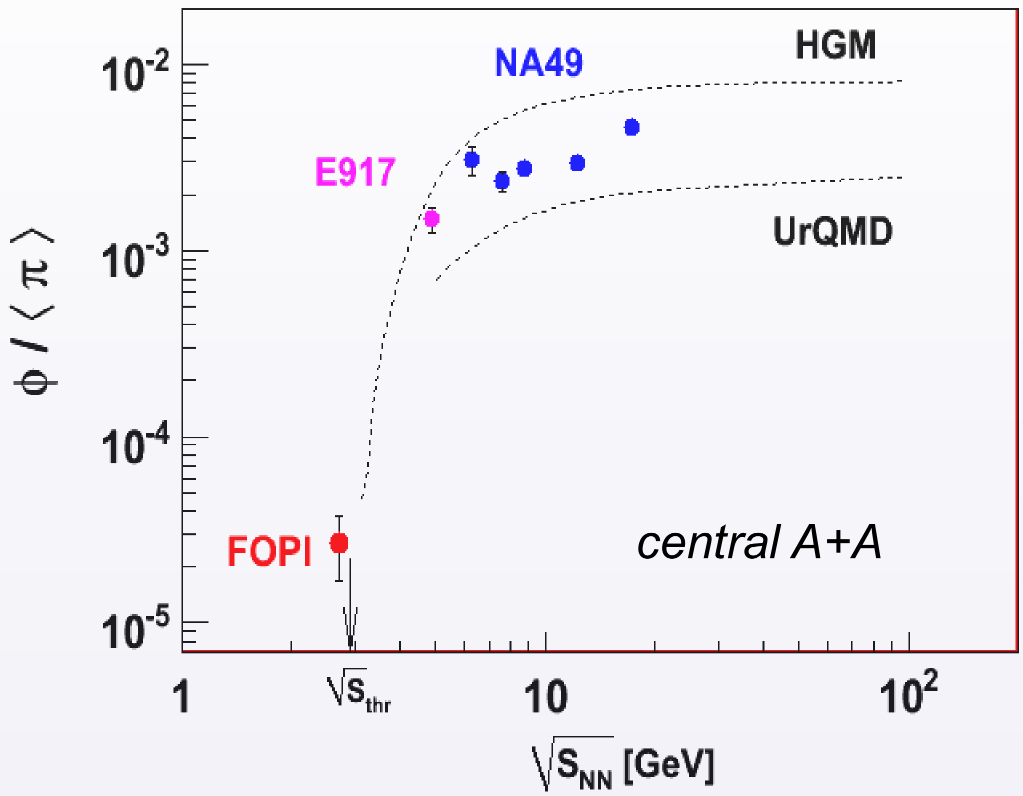


- Conclusion: regardless of system size and exact beam energy,

$$\frac{\phi}{K^-} \approx \frac{1}{3} \quad \Rightarrow \quad \frac{1}{6} \text{ of } K^-$$

are produced from ϕ decays

ϕ / <π> excitation function



C. Alt et al. (NA49), Phys. Rev. C **78**, 044907 (2008)
B. Back et al. (E917), Phys. Rev. C **69**, 054901 (2004)

- HGM = Hadron Gas Model

  (statistical, equilibrium)

- UrQMD 1.3 (transport)

  $\sqrt{S} \in (5, 200)$ GeV

  $K^+K^- \rightarrow \phi$ (~ 70%)

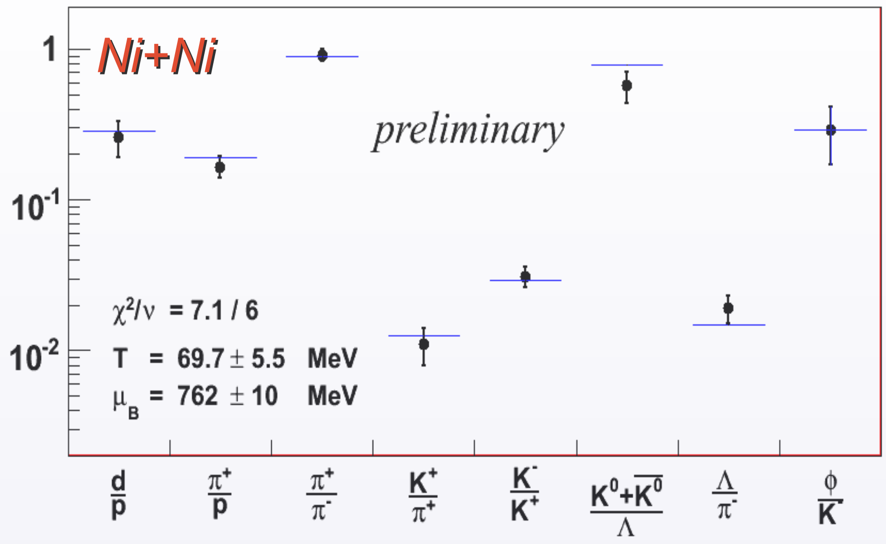
- BUU (transport)

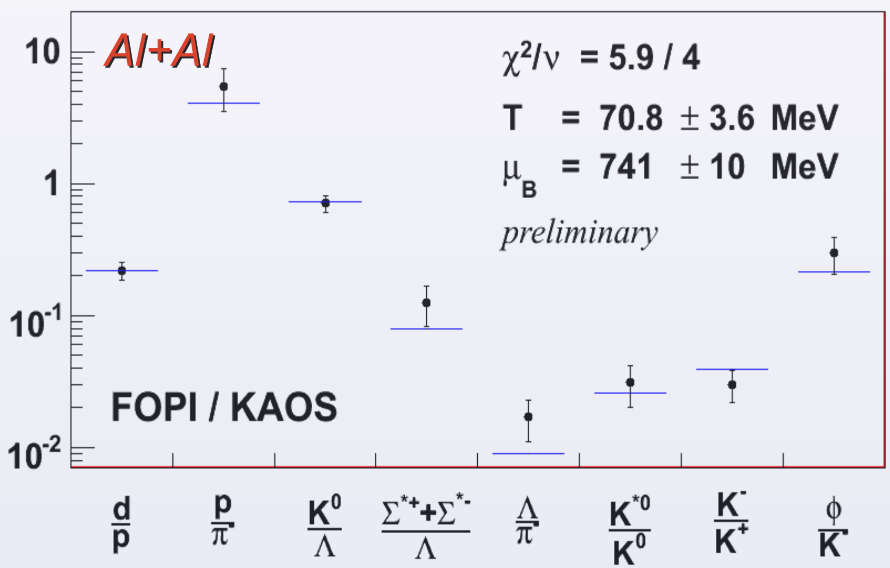
  Ni+Ni, $\sqrt{S}$ = 2.67 GeV

$\rho B \rightarrow \phi B$	(53%)
$BB \rightarrow \phi BB$	(21%)
$\pi B \rightarrow \phi B$	(17%)

  H.W. Barz et al. (BUU) ,
  Nucl. Phys. A 705 (2002) 223

ϕ and analysis of yield ratios





- **Ni+Ni @ 1.9A GeV** :
  8 independent ratios involving
  p, d, π^+, π^-, K^+, K^-, K^0, Λ, ϕ

- **Al+Al @ 1.9A GeV** :
  8 independent ratios involving
  p, d, π^-, K^+, K^-, K^0, Λ, Σ^*, ϕ

Statistical Model

→ Grand Canonical ensemble;

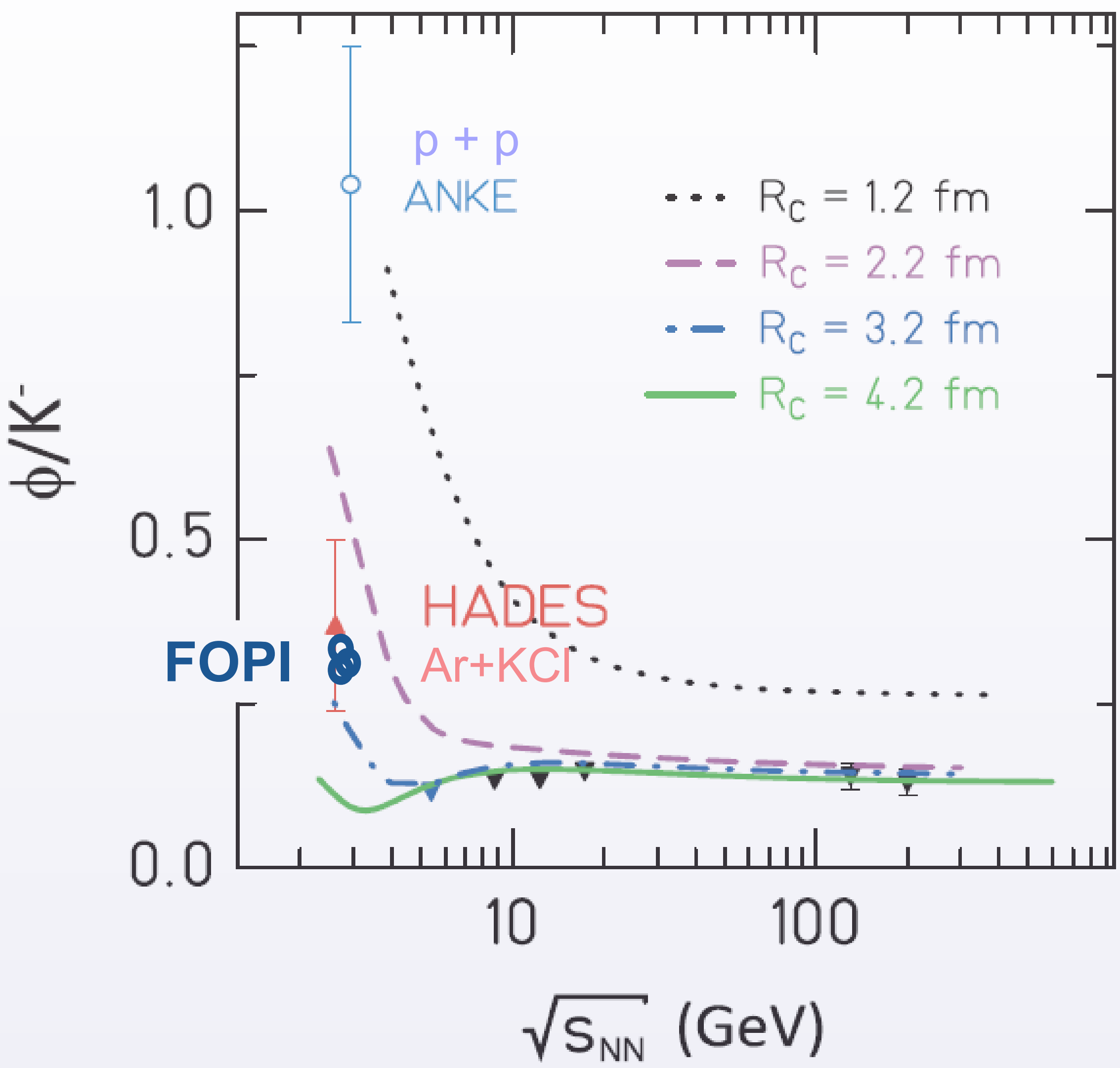
→ For S≠0, Canonical ensemble

→ calc: THERMUS code

S.Wheaton, J.Cleymans , hep-ph/0407175

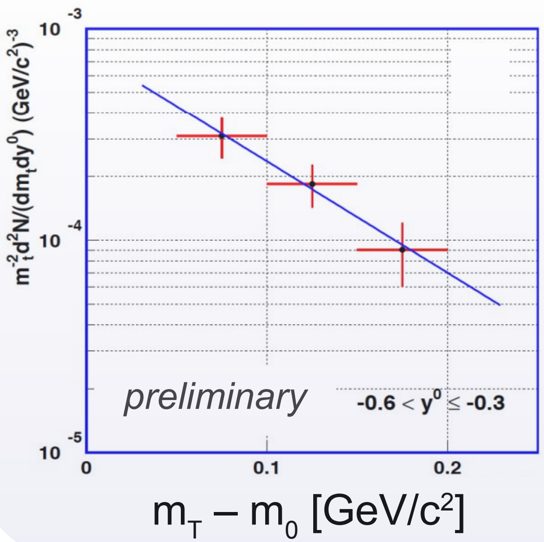
→ *SM* fitting quite well

ϕ/K^- within the statistical model approach



J. Cleymans et al. PLB **603**, 146 (2004)   G. Agakishiev et al., PRC 80, 025209 (2009)

ϕ mesons: inverse slopes



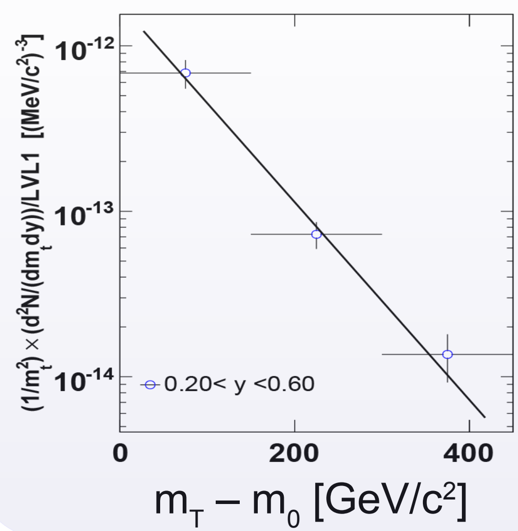
Al+Al @ 1.9A GeV

T_B = 83 ± 26 MeV

Assuming:

$$T_B(y) = \frac{T_{eff}}{\cosh(y - y_{CM})}$$

T_{eff} = 91 ± 20 MeV

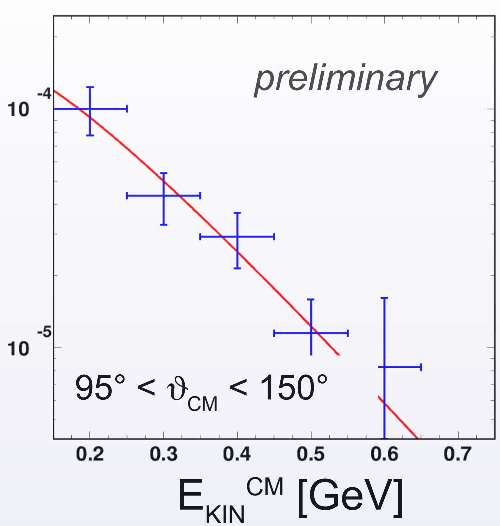


Ar+KCl @ 1.9A GeV

Assuming:

$$T_B(y) = \frac{T_{eff}}{\cosh(y - y_{CM})}$$

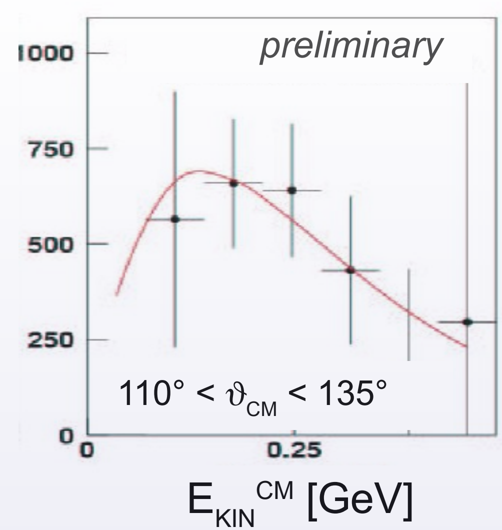
T_{eff} = 84 ± 8 MeV



Ni+Ni @ 1.9A GeV

50% most central σ

T = 108 ± 14 ± 16 MeV

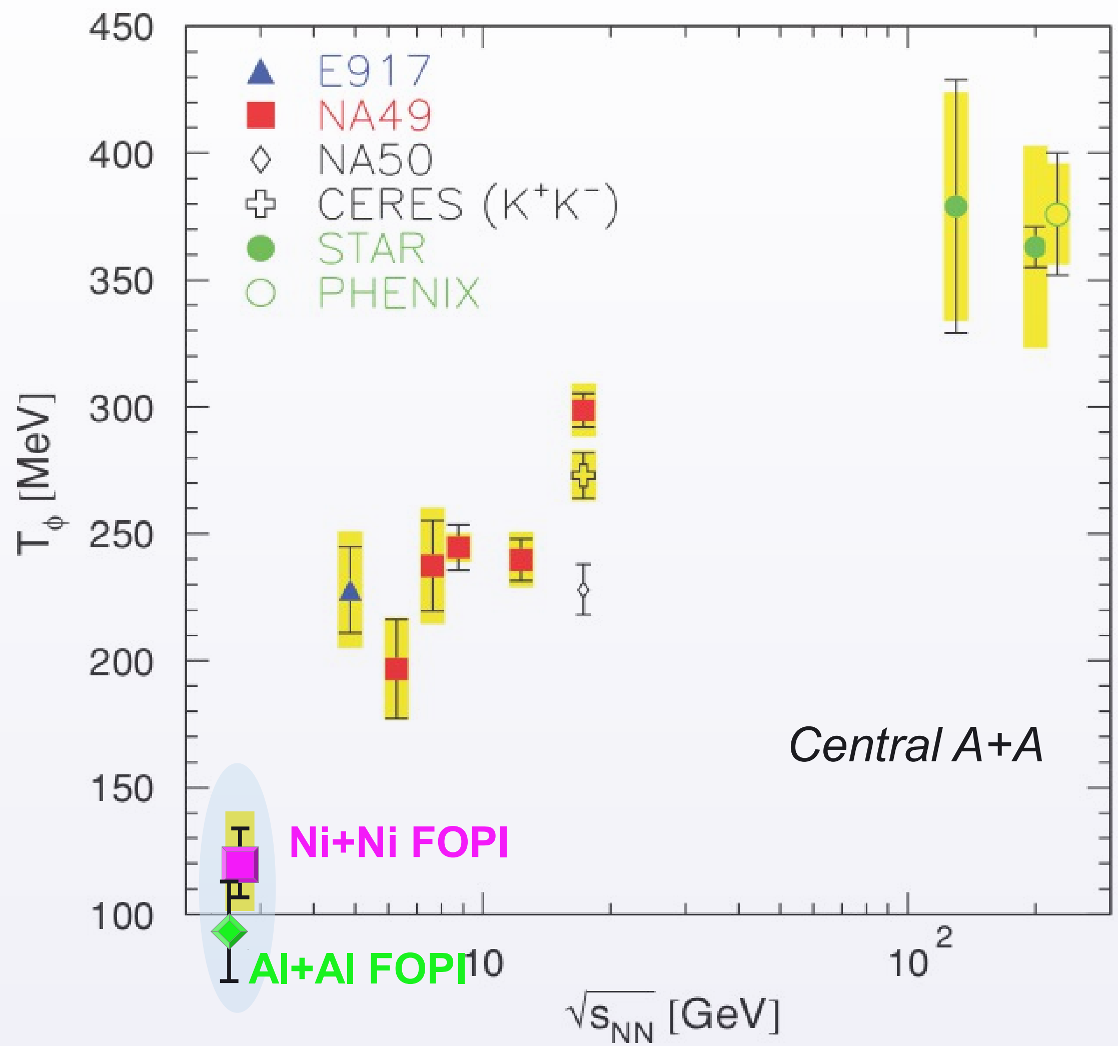


Ni+Ni @ 1.9A GeV

20% most central σ

T = 120 ± 12 ± 20 MeV

T_ϕ excitation function



C. Alt et al. (NA49), Phys. Rev. C **78**, 044907 (2008)
B. Back et al. (E917), Phys. Rev. C **69**, 054901 (2004)

Summary

- At E_{beam} = 1.5 .. 2A GeV, ϕ mesons from five data sets were measured:
  - FOPI: Al+Al and Ni+Ni (3 different centrality classes) @ 1.9A GeV
  - HADES: Ar+KCl @ 1.756A GeV

- ϕ meson yields: (0.3 .. 1.3) · 10^{-3} per triggered event

  → P(ϕ) seems to scale with $\langle A_{participants} \rangle_b$

- $\frac{\phi}{K^-}$ ratio seems to be stable ($\frac{1}{3}$) and independent from E_b, $\langle A_{part} \rangle$.

  → About $\frac{1}{6}$ of K^- originate from decays of ϕ

- First insights into the ϕ phase space:

  → Inverse slopes of ϕ : 85 .. 120 MeV

- Statistical model vs yield ratios → T, μ parameters
- Excitation functions of ϕ / K^- , $\phi / \langle \pi \rangle$, and T_ϕ

Thank You!

Backup slides

Strangeness production and absorption

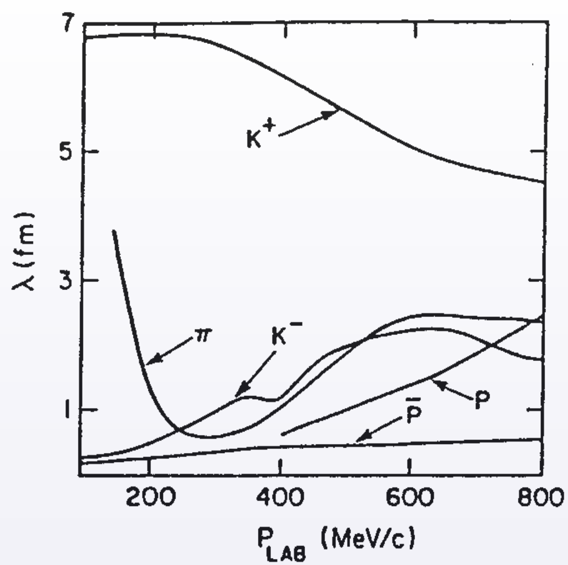
	K^+	K^-	ϕ
Production (primary)	$BB \to BYK^+$ $T_{pp \to p\Lambda K+}$ = *1.58 GeV*	$BB \to BBK^+K^-$ $T_{pp \to ppK+K-}$ = *2.5 GeV*	$BB \to BB\phi$ $T_{pp \to ppK+K-}$ = *2.6 GeV*
Production (secondary)	$\pi B \to YK^+$	$\pi Y \to (\Sigma^* \to)\ BK^-$ $BY \to NK^-\Lambda$ $BY \to BBK^-$ $\pi B \to BK^+K^-$ $\phi \to K^+K^-$	$\pi B \to B\phi$ $\rho B \to B\phi$ $\pi N^* \to N\phi$ $\rho\pi \to \phi$ $K^+K^- \to \phi$ *negligible*
Absorption Elastic scat. (char. exch.)	$K^+Y \to \pi B$ $K^+B \leftrightarrow K^+ B$ $K^+n \leftrightarrow K^0 p$	$K^-B \to \pi Y$ $K^-B \leftrightarrow K^-B$ $K^-p \leftrightarrow \bar{K}^0 n$	$\phi N \to K\Lambda$ $\phi N \to \phi N$

[B] = *p, n, N, N**, *Δ*

[Y] = *Λ, Σ*

Yields from	Ni + Ni (1.93 GeV)
B + B	3.5×10^{-4}
π + B	2.9×10^{-4}
ρ + B	8.9×10^{-4}
$\pi + \rho$	1.6×10^{-4}
π + N(1520)	0.5×10^{-4}
Total yield	1.7×10^{-3}

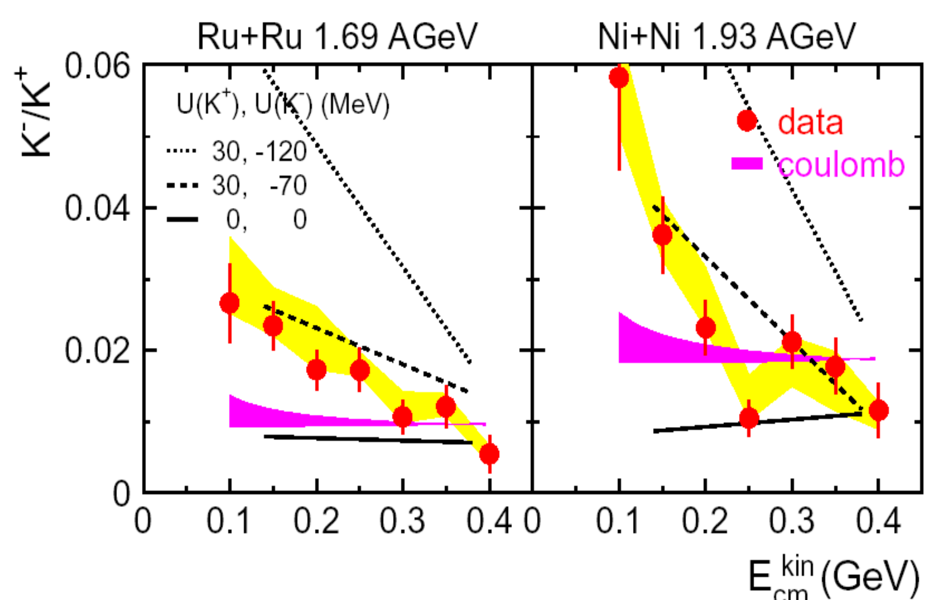
H.W. Barz et al. (BUU) ,
Nucl. Phys. A 705 (2002) 223



C.B. Dover, G.E. Walker
Phys. Rep. **89** (1982) 1

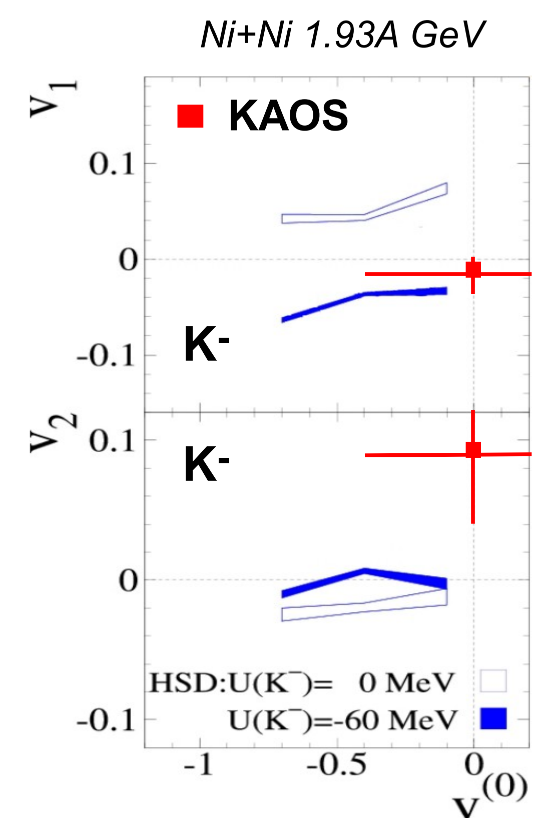
Examples of mixing of different sources of K-

- ϕ influences investigation of U_{KN} potential



K. Wiśniewski *et al.* (FOPI), EPJ A9, 515(2000)

- K- flow and ϕ flow mix together



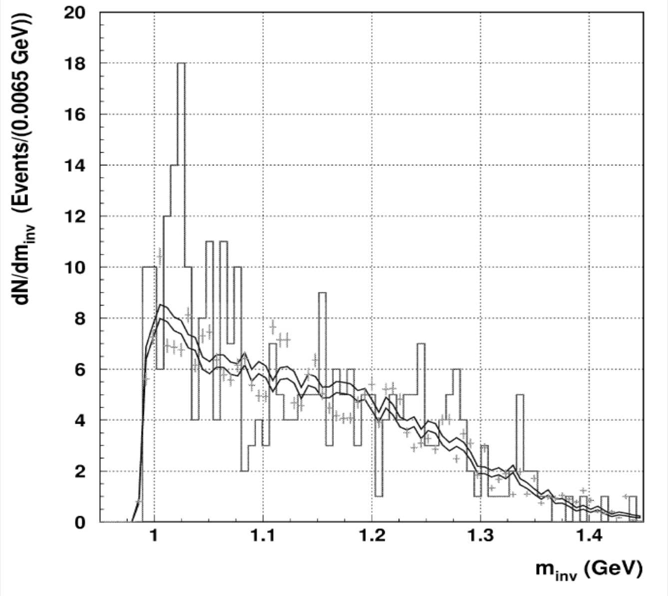
KAOS: *F. Uhlig et al., PRL 95, 012301(2005)*

First ϕ's from Ni+Ni : 1995 session

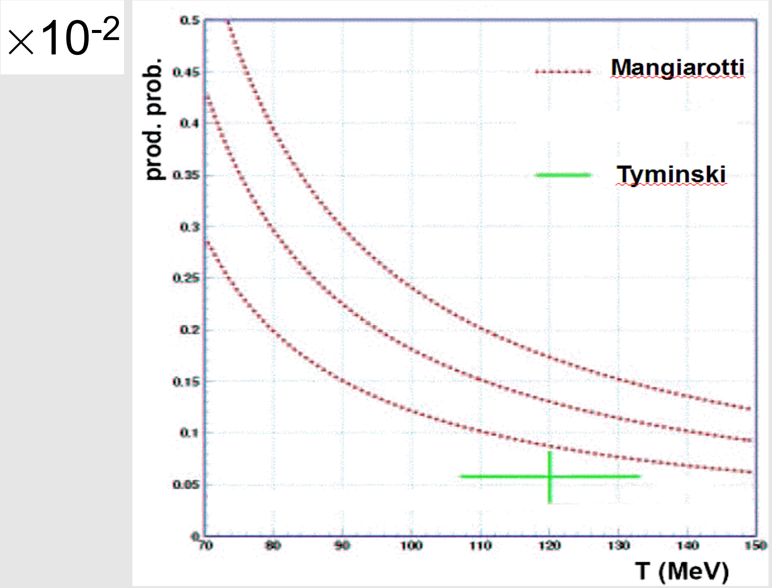
- Ni+Ni @ 1.93A GeV
  (A. Mangiarotti)

→ *Trig: 12% most centr. ($<A_{part}>=86$)*

→ $N_{\phi} = 23 \pm 7 \pm 2$



→ ***P_{ϕ}** / collision : depends on T_{ϕ}*



$T_{\phi} = 70$ MeV → $(\mathbf{4.5} \pm 1.4 \pm 2.2) \cdot \mathbf{10^{-3}}$

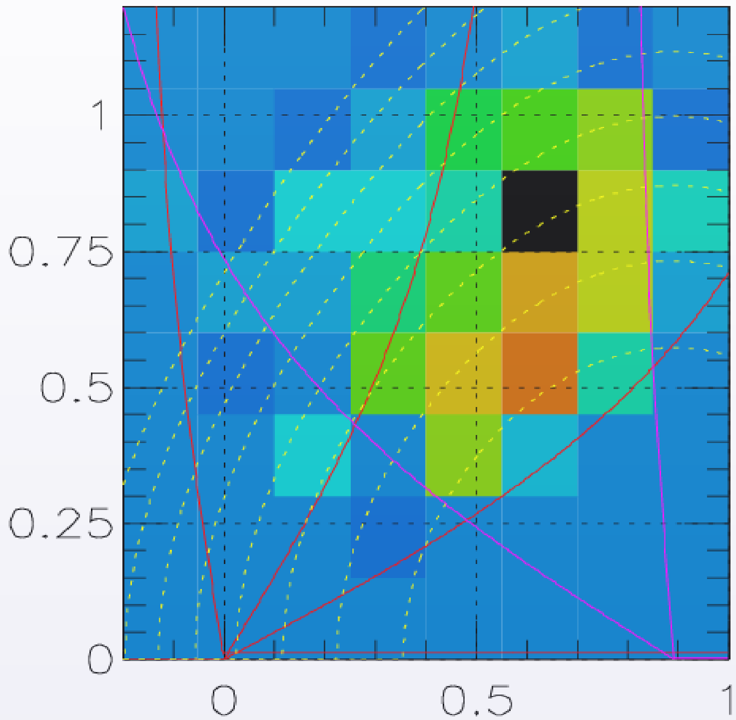
$T_{\phi} = 130$ MeV → $(\mathbf{1.2} \pm 0.4 \pm 0.6) \cdot \mathbf{10^{-3}}$

First (but only) ϕ data published:

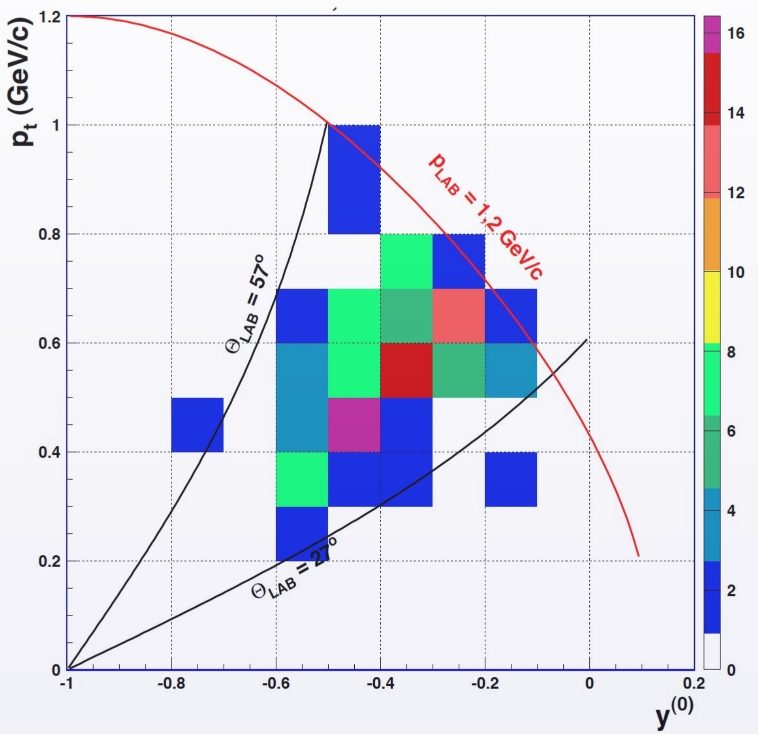
A. Mangiarotti et al, NPA 714 (2003) 89

Ni+Ni @ 1.9A GeV

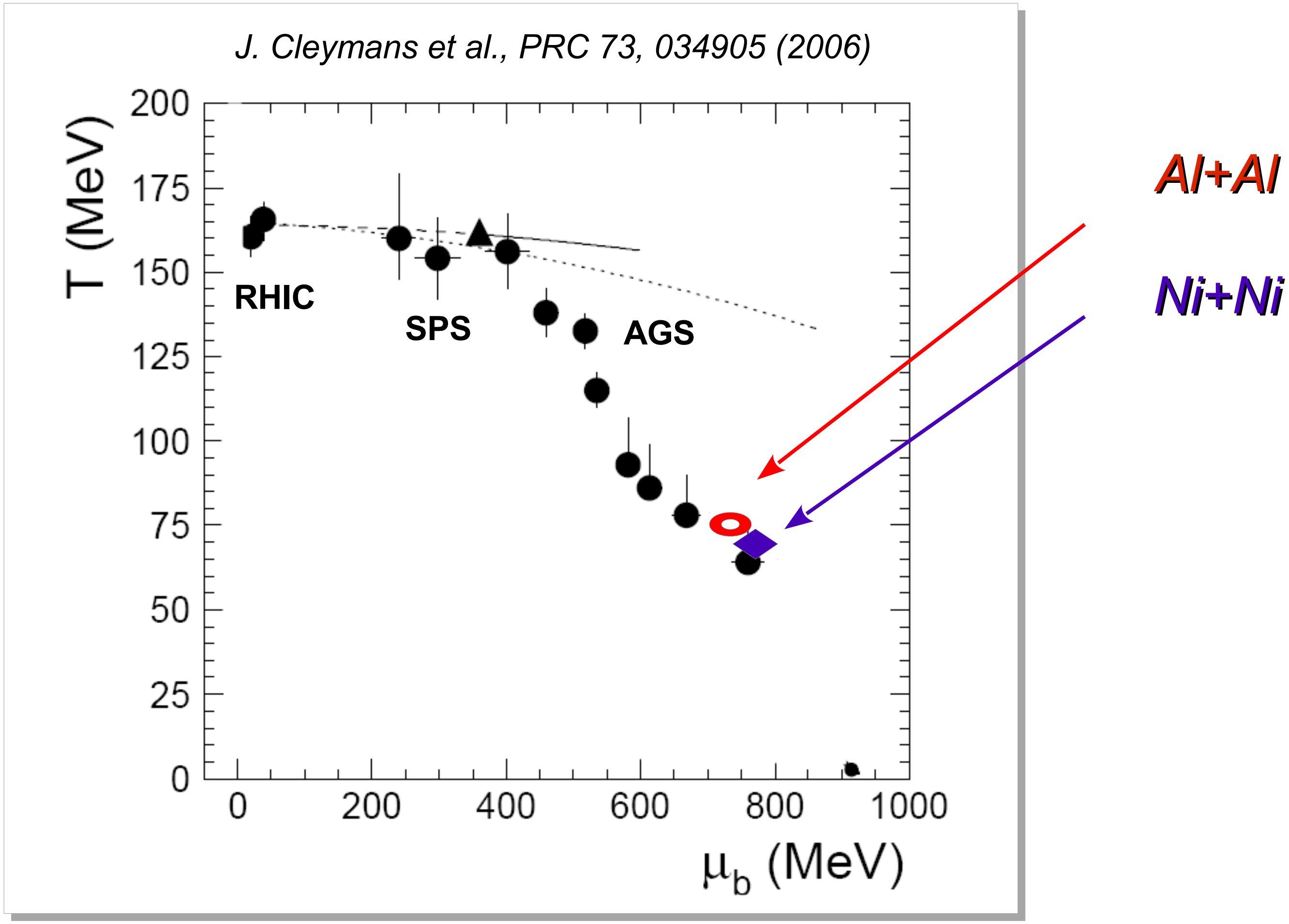
50% most central σ



Al+Al @ 1.9A GeV

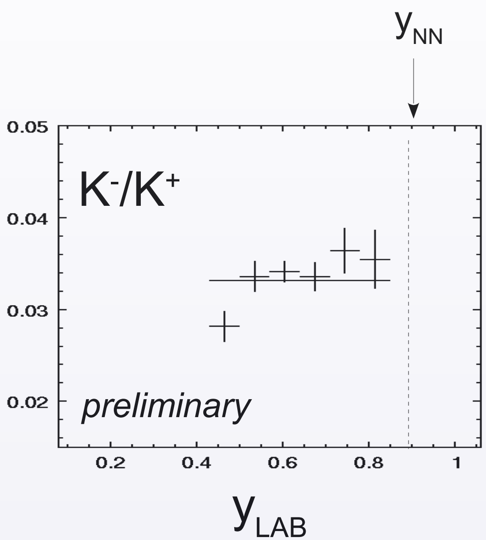


Freeze-out in phase diagram

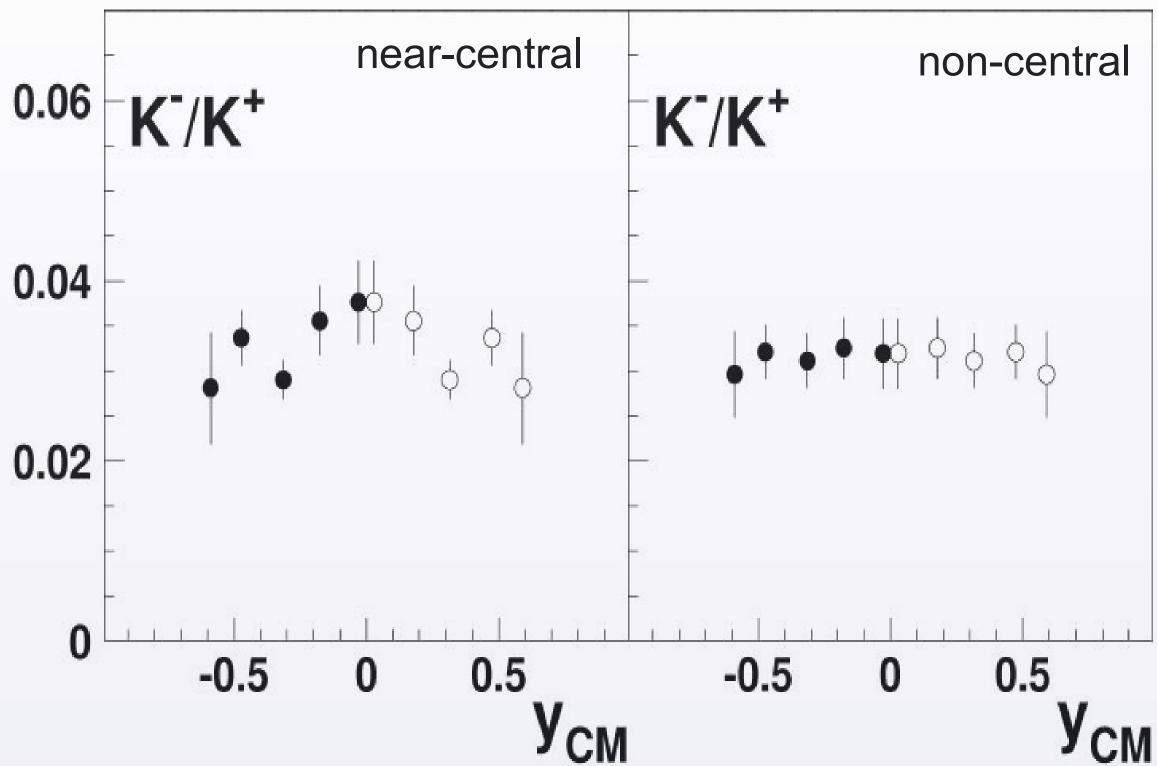


K-/K+ ratio for Ni+Ni from FOPI and KaoS

FOPI



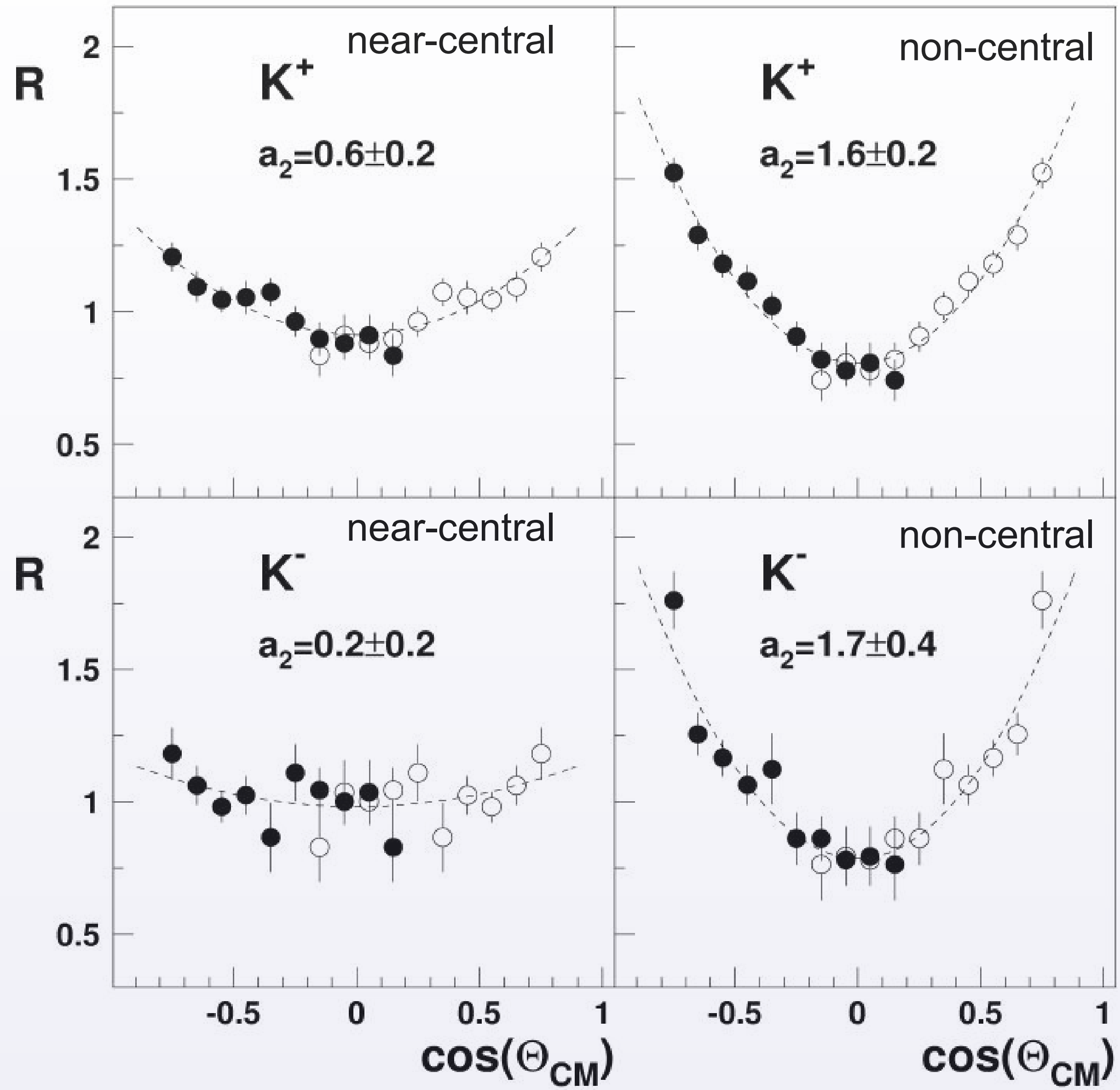
KaoS



M. Menzel et al. (KaoS), Phys Lett B 495 (2000) 26

Azimuthal anisotropy of Kaons from Ni+Ni @ 1.93A GeV

$$R(\theta_{CM}) = \frac{\sigma_{measured}(\theta_{CM})}{\sigma_{Isotropic}(\theta_{CM})}$$



M. Menzel et al. (KaoS), Phys Lett B 495 (2000) 26