
Наиболее значимые результаты коллаборации "Людмила" (1973-1990)

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Исследование взаимодействий антипротонов и антидейтронов с помощью 2-м жидководородной камеры «Людмила»

Жидководородная пузырьковая камера «Людмила» была изготовлена и испытана в ЛВЭ ОИЯИ, и в 1969 перевезена в ИФВЭ. Она была смонтирована на сепарированном пучке антипротонов ускорителя У-70 ИФВЭ при максимальном импульсе 22,4 ГэВ/с.

Характеристики камеры «Людмила»:

Рабочий объем $2,0 \times 0,6 \times 0,52 = 0,624 \text{ м}^3$.

Термическая изоляция: дюар объемом $7,5 \text{ м}^3$, пространство между стенками заполнено суперизолирующими слоями, давление в объеме -- 10^{-4} Торр

Механизм расширения: поршневого типа с поршнем диаметром 400 мм

Освещение: автоколлимационная система с использованием в качестве отражательного элемента сферического полосатого зеркала.

Фотографирование: 4 фотокамеры, расположенные по углам квадрата $460 \times 460 \text{ мм}^2$.

Магнитное поле: 2,5 Тл

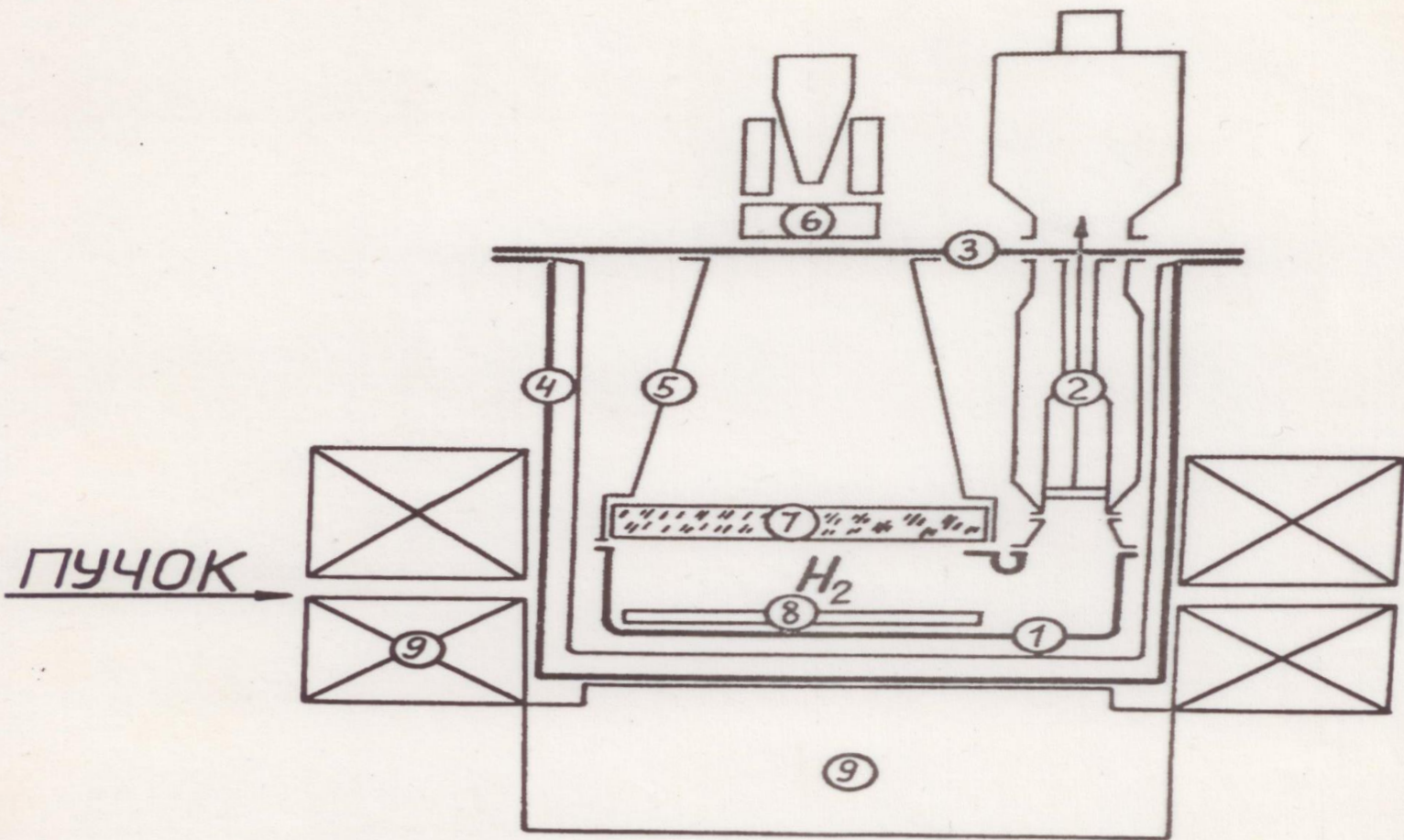
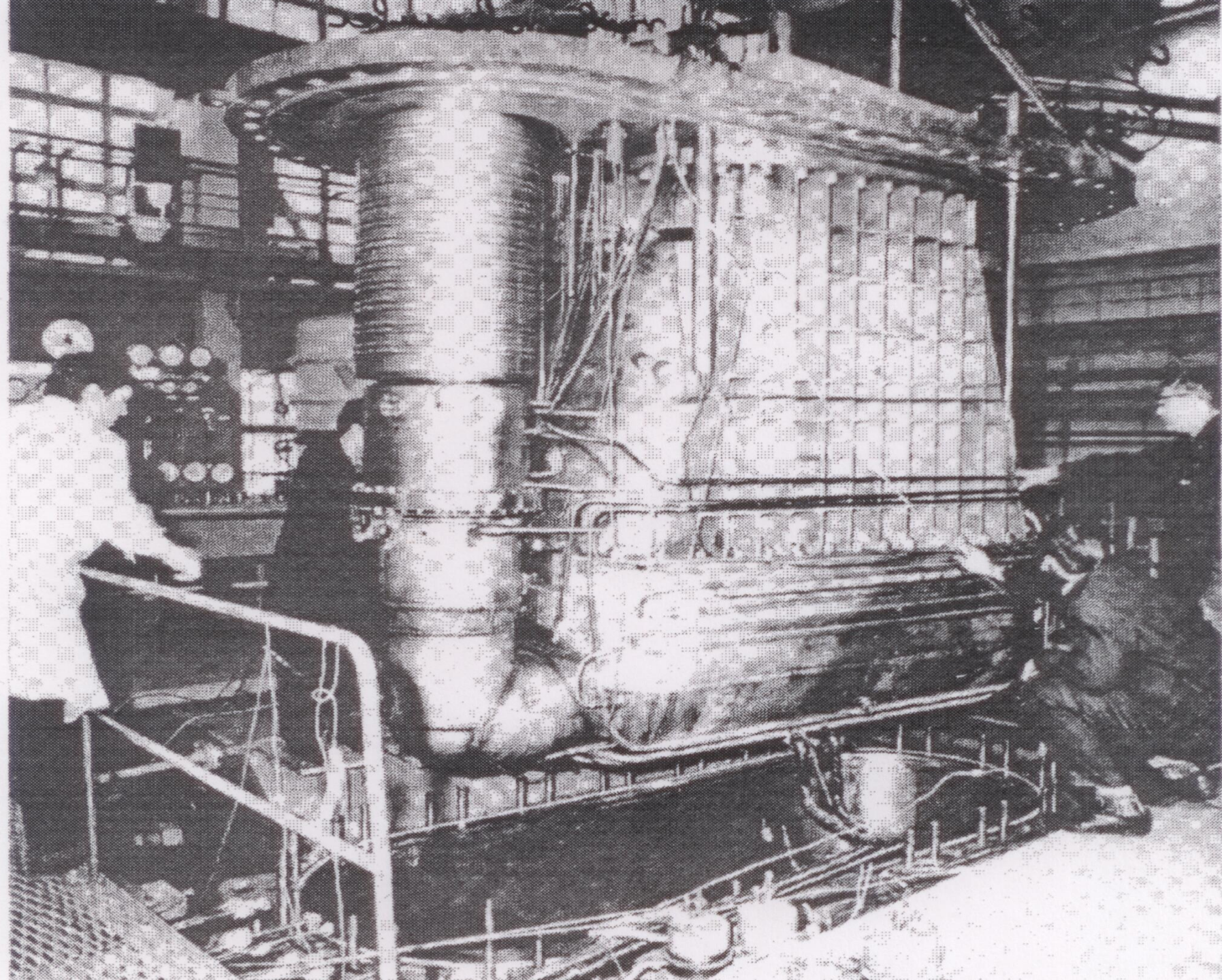
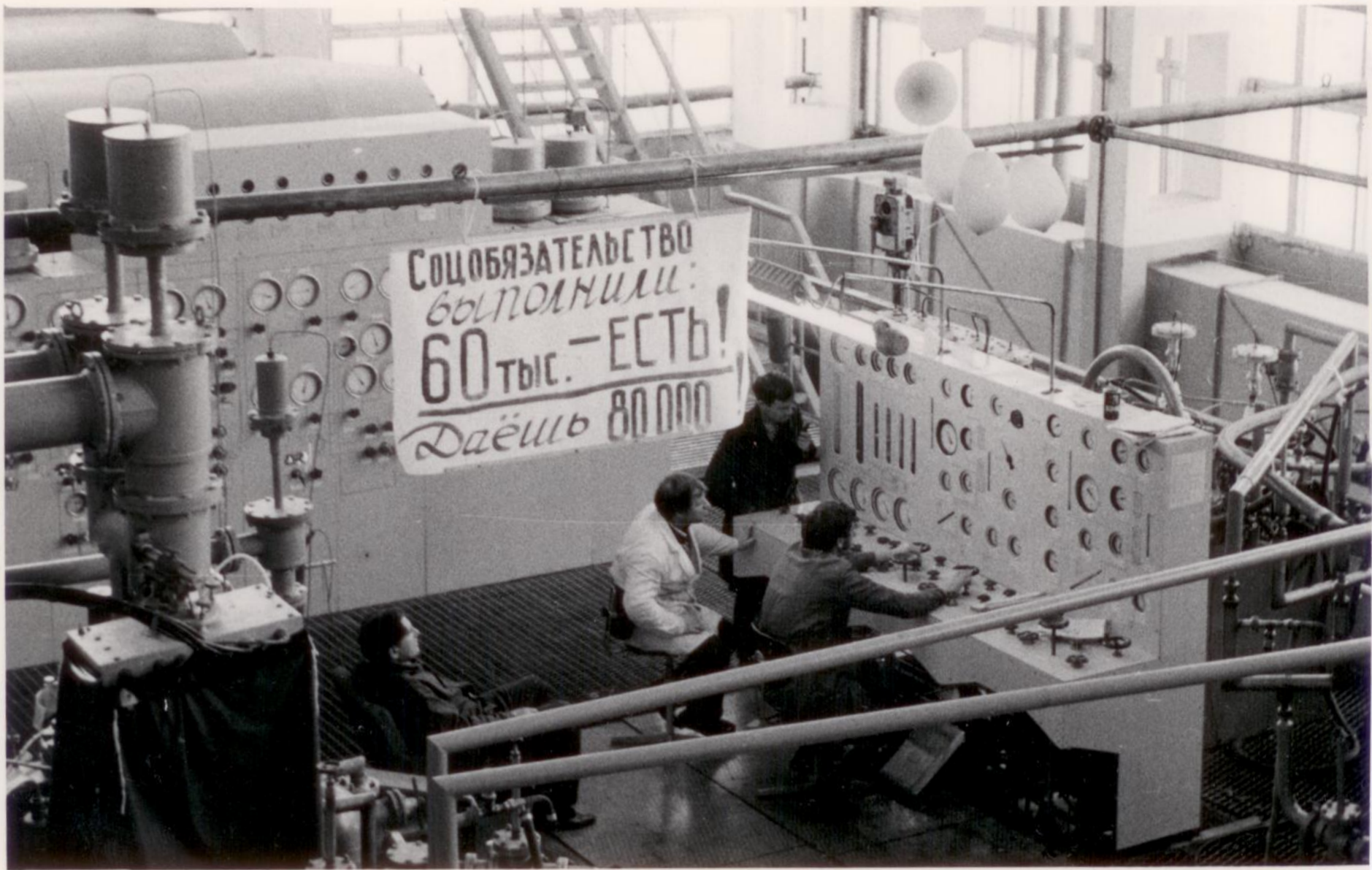


Рис. I. I Схематический чертеж водородной камеры "Людмила".

1. Корпус камеры
2. Механизм расширения
3. Крышка вакуумного кожуха
4. Дьюарная система изоляции
5. Конус
6. Стерефотоаппарат
7. Главное стекло
8. "Полосатый" растр
9. Магнит МС-7





СОЦОБЯЗАТЕЛЬСТВО
ВЫПОЛНИЛИ:
60 ТЫС. - ЕСТЬ!
ДАЁШЬ 80 000

При облучении было получено около 600 тыс. стереофотографий. Обработка данных проводилась в рамках международного сотрудничества, в которое кроме ОИЯИ входили институты Праги, Братиславы, Кошице, Алма-Аты, Хельсинки, Москвы, Тбилиси, Софии, Бухареста.

Первое

рабочее совещание сотрудничества состоялось в Дубне 14.11.1973.

Заключительное

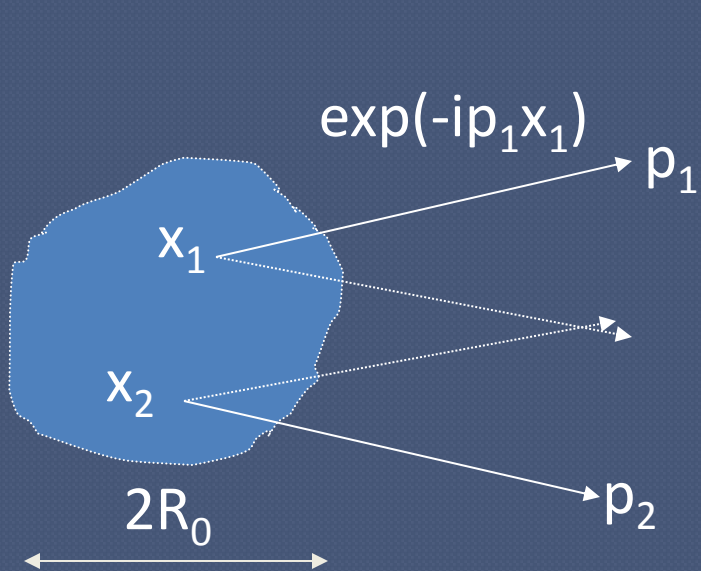
рабочее совещание состоялось в Стара Лесна 02.11.1990

KP'71-75:

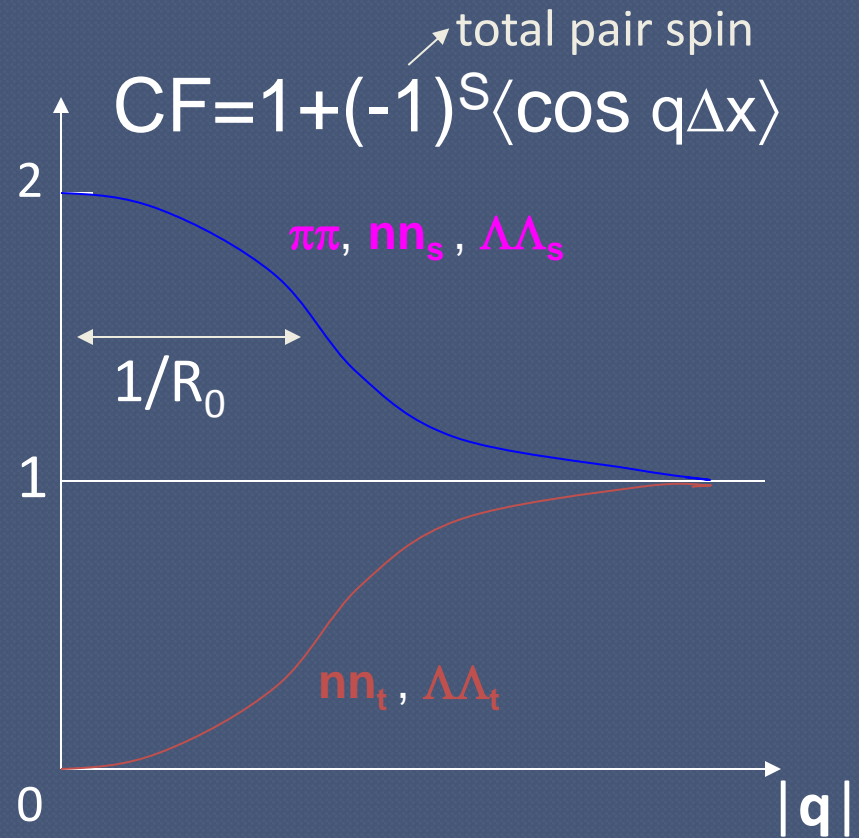
Correlation Femtoscopy

Fermi'34

momentum correlations of emitted particles are sensitive to space-time structure of the source due to **QS & FSI**



$$\Delta x = x_1 - x_2$$
$$q = p_1 - p_2$$



Интерференция тождественных частиц (Эффект Подгорецкого-Копылова)

Двухчастичная плотность в фазовом пространстве

$$W(p_1, p_2) = [1 + f(q, p)] W_0(p_1, p_2)$$

$$f(q, R, \tau) = \left[\frac{2J_1(Rq_T)}{Rq_T} \right]^2 \frac{1}{1 + (\tau q_0)^2}$$

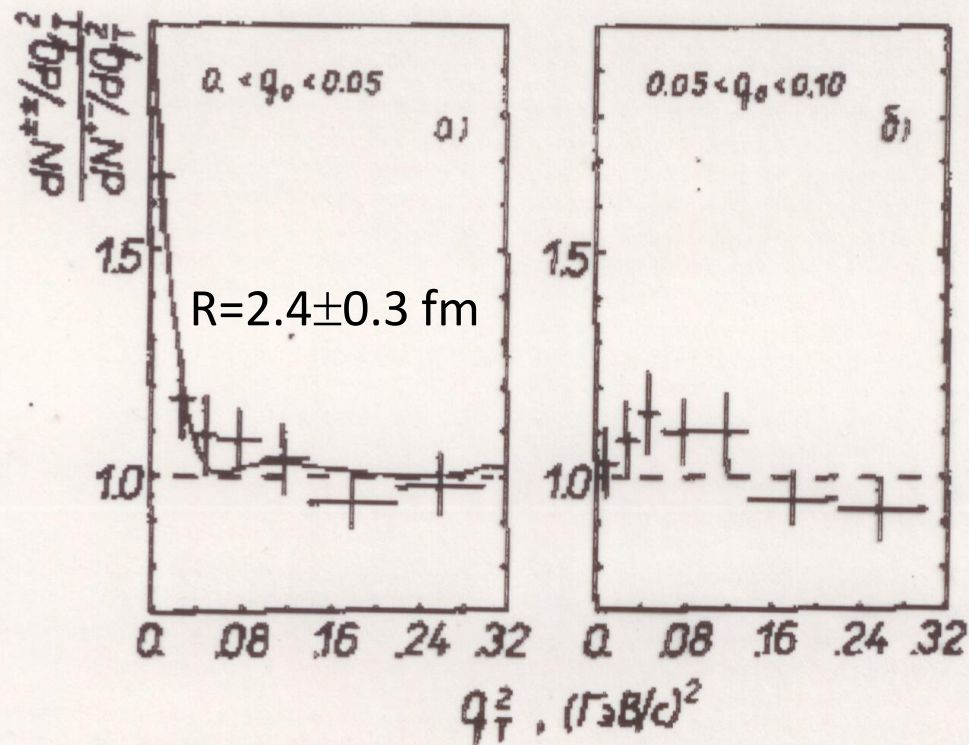
Static source:
disk of radius R
and lifetime τ

$$q_0 = |p_{01} - p_{02}| \quad q_T^2 = \vec{q}^2 - (\vec{q}\vec{n})^2$$

$$g(q_T^2) = b \left\{ 1 + \alpha \left[\frac{2J_1(Rq_T)}{Rq_T} \right]^2 \right\} \approx b \{ 1 + \alpha \exp[-(Rq_T/2)^2] \}$$

$$g = \left(\frac{dN^{\pm\pm}}{dq_T^2} \right) / \left(\frac{dN^{\pm}}{dq_T^2} \right)$$

A study of the interference effect in identical particle pairs for inclusive p-bar p interactions at 22.4 GeV/c
 Yad.Fiz. 27 (1978) 1556-1564



q_T^2 -распределения для различных интервалов q_0 .
 Кривая - результат подгонки выражением (8) (см. табл.2).

Observation of the dependence of the interference effect of identical pions on pion pair velocity in inclusive p-bar p interactions at 22.4 GeV/c
 Czech.J.Phys. B31 (1981) 475

$$CF = 1 + a \exp[-(Rq_T/2)^2 - \tau^2 q_0^2]$$

The interference parameters a , R , and τ in various v^2 -intervals.

v^2 -interval	N	a	R [fm]	τ [fm]
0· , 0·34	2887	0.13 ± 0.09	2.5 ± 1.7	0*)
0·34, 0·52	3404	0.64 ± 0.31	2.8 ± 0.8	3.0 ± 1.2
0·52, 0·64	3062	0.34 ± 0.14	1.4 ± 0.5	2.4 ± 1.0
0·64, 0·76	3451	0.85 ± 0.25	2.3 ± 0.5	2.5 ± 0.6
0·76, 1·	4093	$1. \pm 0.11^*)$	1.8 ± 0.2	0.6 ± 0.1 ←
0·34, 0·76	9917	0.64 ± 0.15	2.5 ± 0.4	2.8 ± 0.6 ←

*) On boundary.

Velocity dependence of the interference effect → an evidence of a non-static pion source

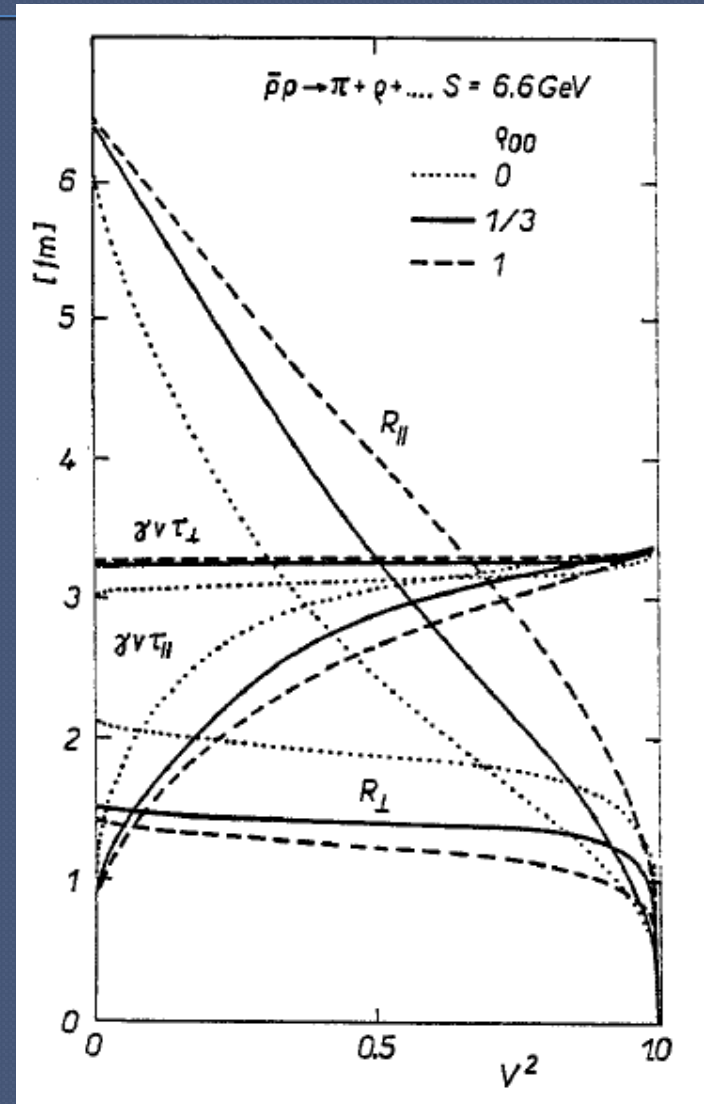
Example: pion + **Resonance** (ρ) model

$$l^* = \text{decay length in PRF} \\ = p_{\text{dec}} / (m_{\pi} \Gamma) \approx 3 \text{ fm}$$

$$q_0 = v q_L \rightarrow \gamma v \tau = \gamma r_L \approx l^*$$

Other examples of non-static models
(radii decreasing with the pair velocity):

strings
hydrodynamic expansion

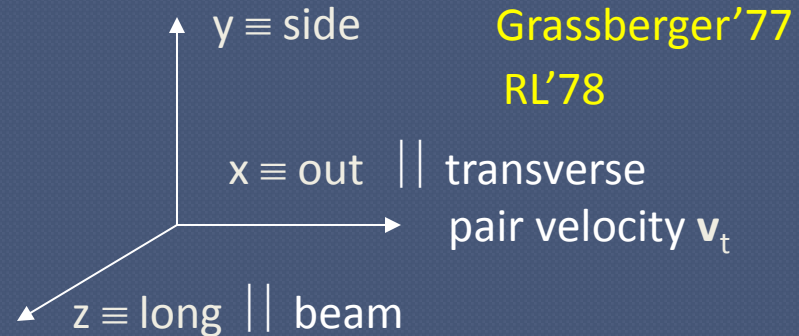


“General” parameterization at $|q| \rightarrow 0$

Particles on mass shell & azimuthal symmetry \Rightarrow 5 variables:

$$q = \{q_x, q_y, q_z\} \equiv \{q_{\text{out}}, q_{\text{side}}, q_{\text{long}}\}, \text{ pair velocity } v = \{v_x, 0, v_z\}$$

$$q_0 = \mathbf{q}\mathbf{p}/p_0 \equiv \mathbf{q}\mathbf{v} = q_x v_x + q_z v_z$$



$$\langle \cos \mathbf{q}\Delta\mathbf{x} \rangle = 1 - \frac{1}{2} \langle (\mathbf{q}\Delta\mathbf{x})^2 \rangle + \dots \approx \exp(-R_x^2 q_x^2 - R_y^2 q_y^2 - R_z^2 q_z^2 - 2R_{xz}^2 q_x q_z)$$

Interferometry or correlation radii:

$$R_x^2 = \frac{1}{2} \langle (\Delta x - v_x \Delta t)^2 \rangle, \quad R_y^2 = \frac{1}{2} \langle (\Delta y)^2 \rangle, \quad R_z^2 = \frac{1}{2} \langle (\Delta z - v_z \Delta t)^2 \rangle$$

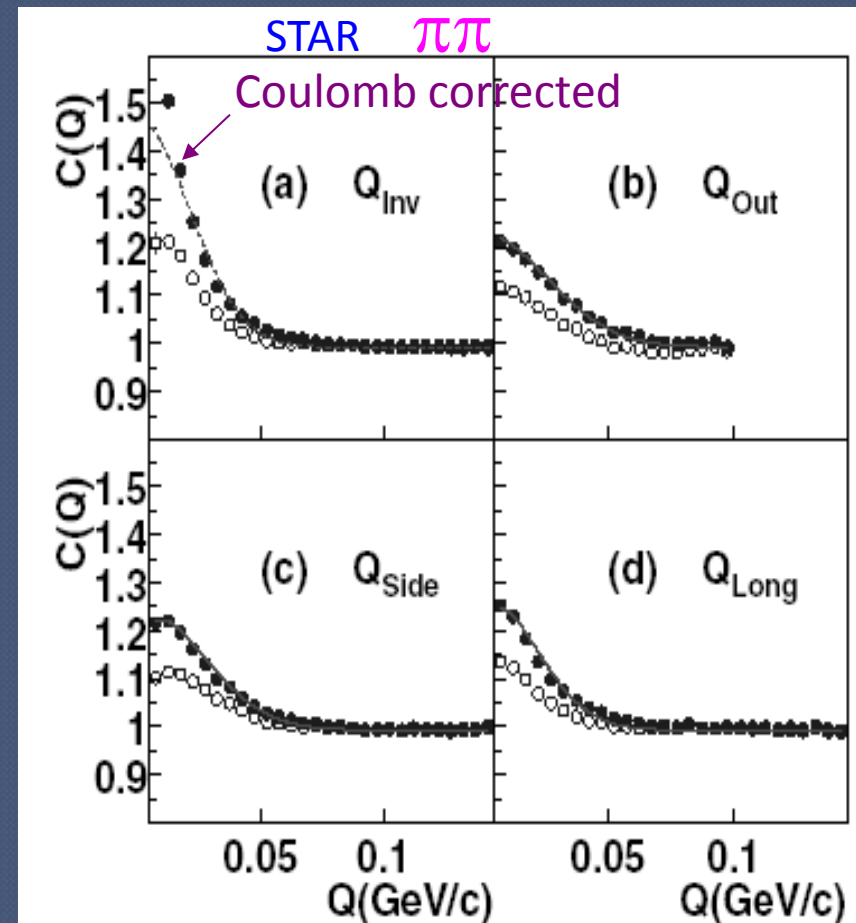
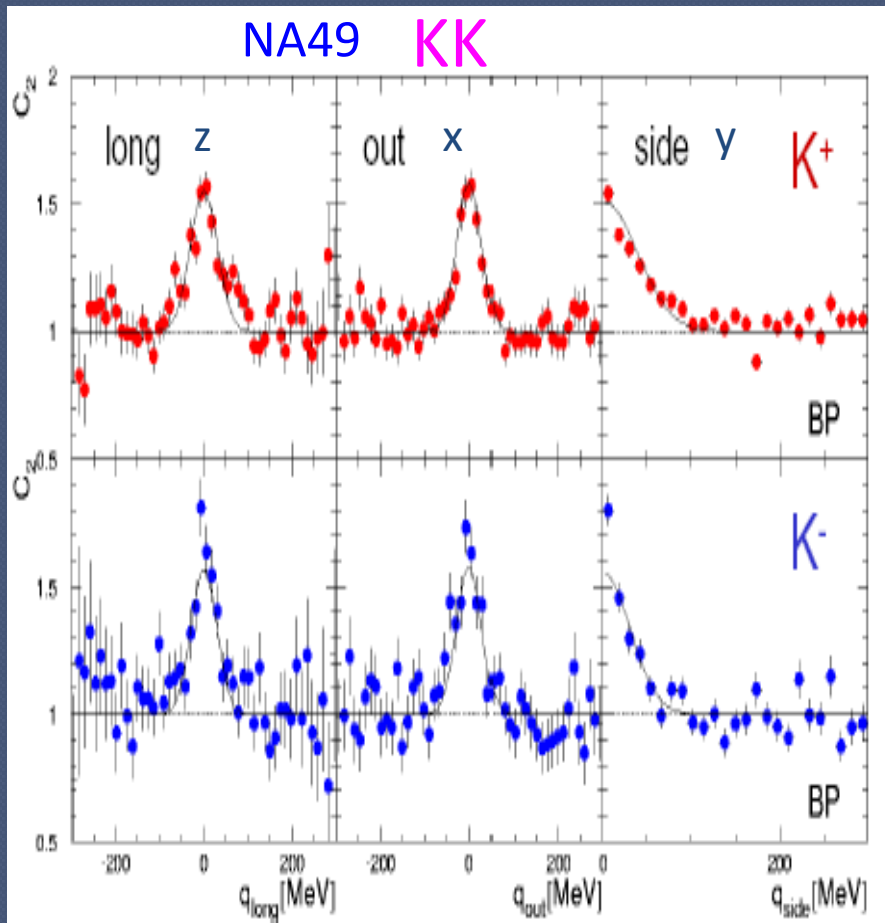
Podgoretsky'83; often called cartesian or BP'95 parameterization

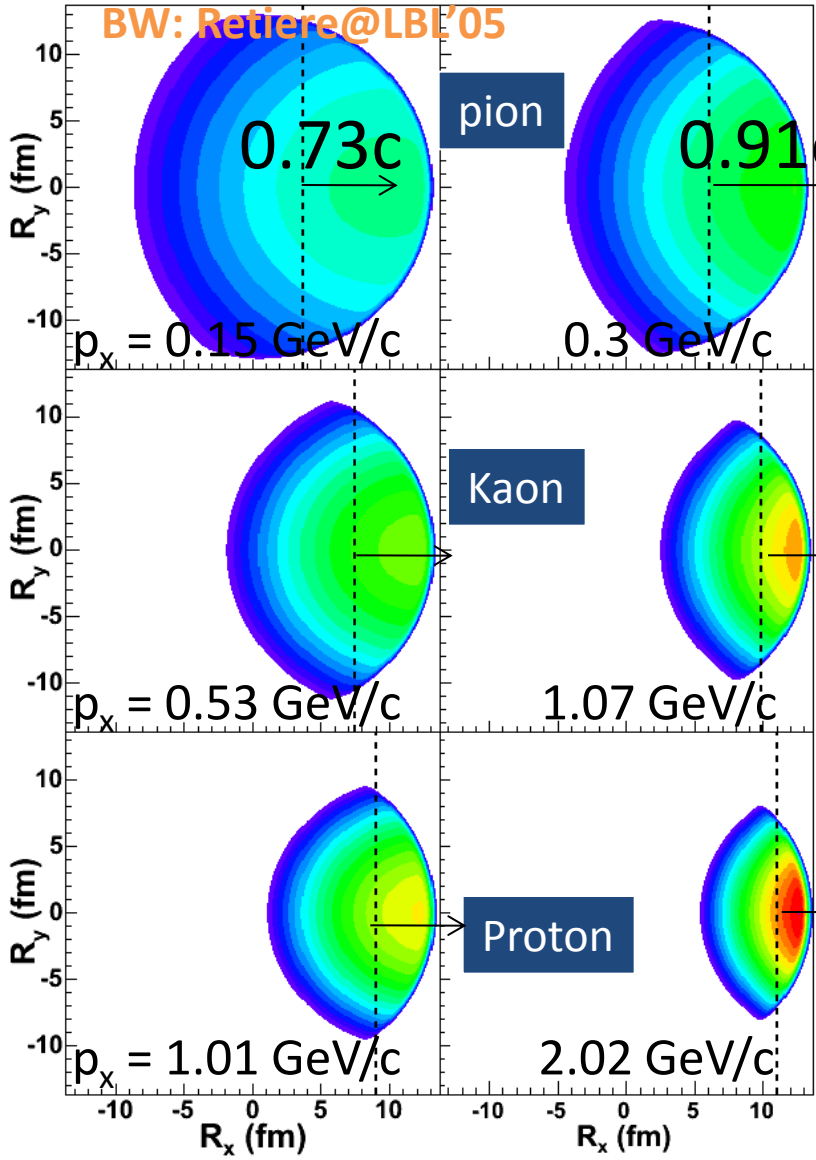
3-dim fit: $CF = 1 + \lambda \exp(-R_x^2 q_x^2 - R_y^2 q_y^2 - R_z^2 q_z^2 - 2R_{xz}^2 q_x q_z)$

Correlation strength or chaoticity

Interferometry or correlation radii

Examples of present data: NA49 & STAR





τ , $\Delta\tau$, Flow & Radii x-out, y-side, z-long

← Emission points at a given tr. velocity

$$R_z^2 \approx \langle \tau^2 \rangle (T/m_t) \quad R_y^2 = \langle y'^2 \rangle$$

$$R_x^2 = \langle x'^2 \rangle - 2v_x \langle x't' \rangle + v_x^2 \langle t'^2 \rangle$$

$$\langle t'^2 \rangle \approx \langle (\tau - \langle \tau \rangle)^2 \rangle \equiv \langle (\Delta\tau)^2 \rangle$$

For a Gaussian tr. density profile:

$$\rho(r) \sim \exp(-r^2/2R_G^2)$$

and a linear flow velocity profile:

$$\beta^F(r) = \beta_0 r / R_G \rightarrow$$

$$R_y^2 = R_G^2 / [1 + \beta_0^2 m_t / T]$$

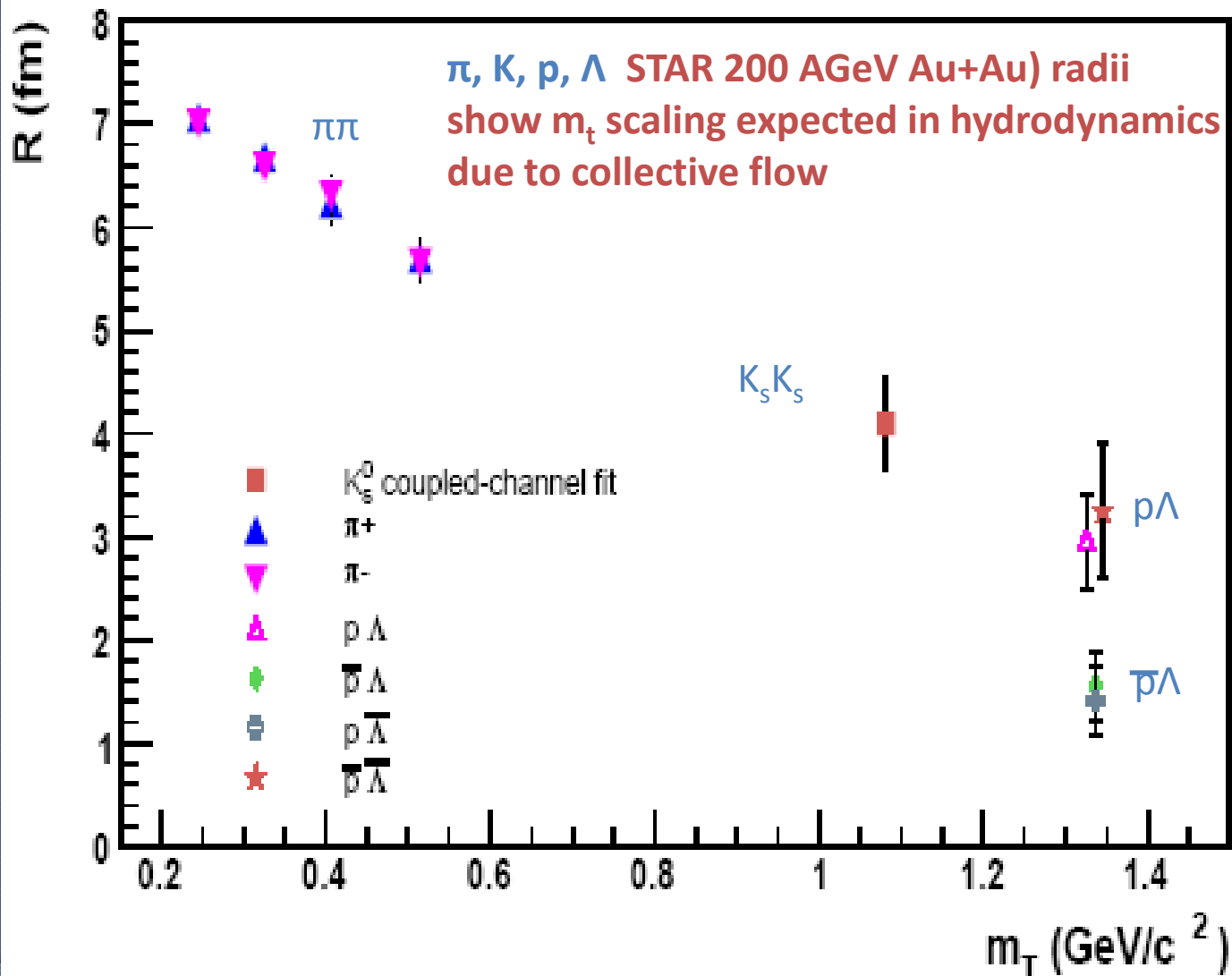
$$R_z \rightarrow \langle \tau \rangle = \text{evolution time}$$

$$R_x \rightarrow \Delta\tau = \text{emission duration}$$

$$R_x, R_y \rightarrow \beta_0 = \text{tr. flow velocity}$$

$$p_t\text{-spectra} \rightarrow T = \text{temperature}$$

m_t scaling of the invariant Gaussian radius \rightarrow universal transverse flow



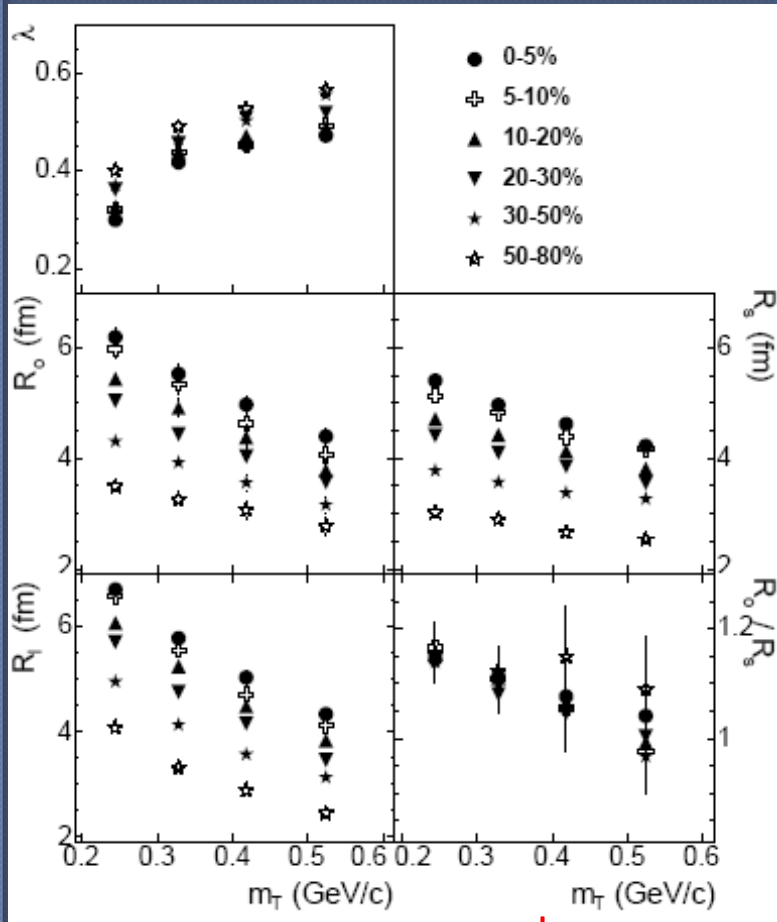
AGS → SPS → RHIC: $\pi\pi$ radii

Clear centrality & m_t dependence

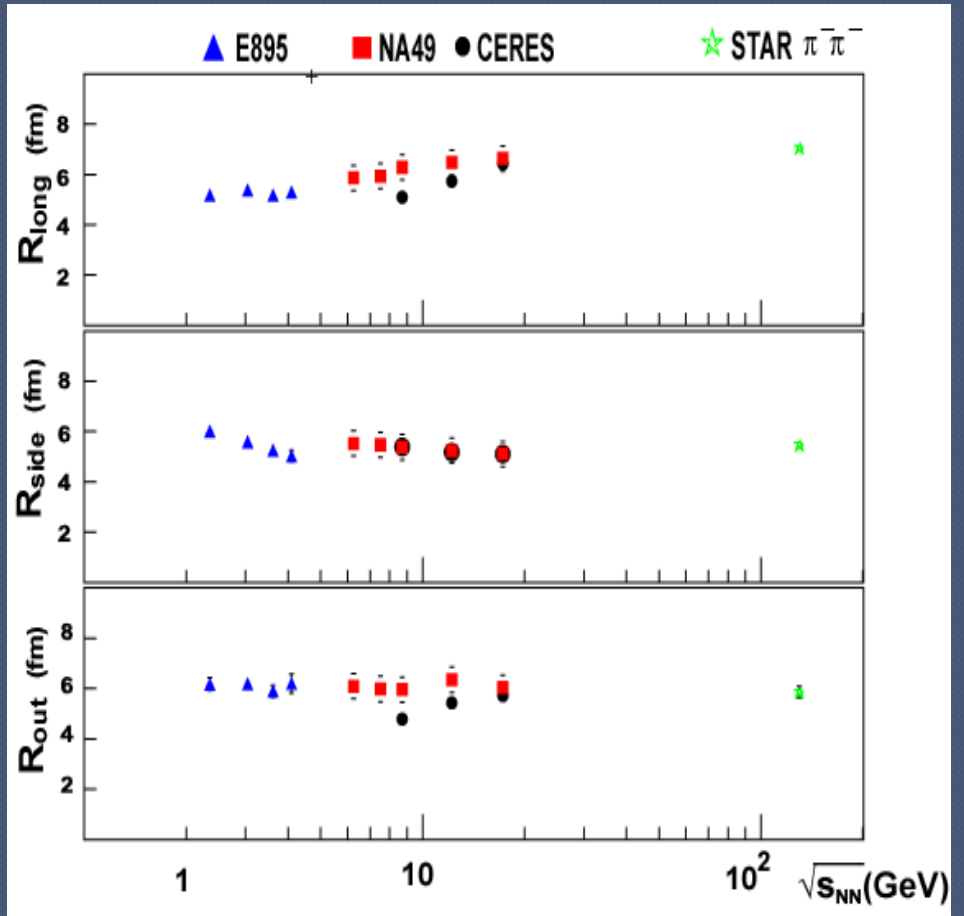
Weak energy dependence

STAR Au+Au at 200 AGeV

0-5% central Pb+Pb or Au+Au



$R \uparrow$ with centrality & \downarrow with m_t



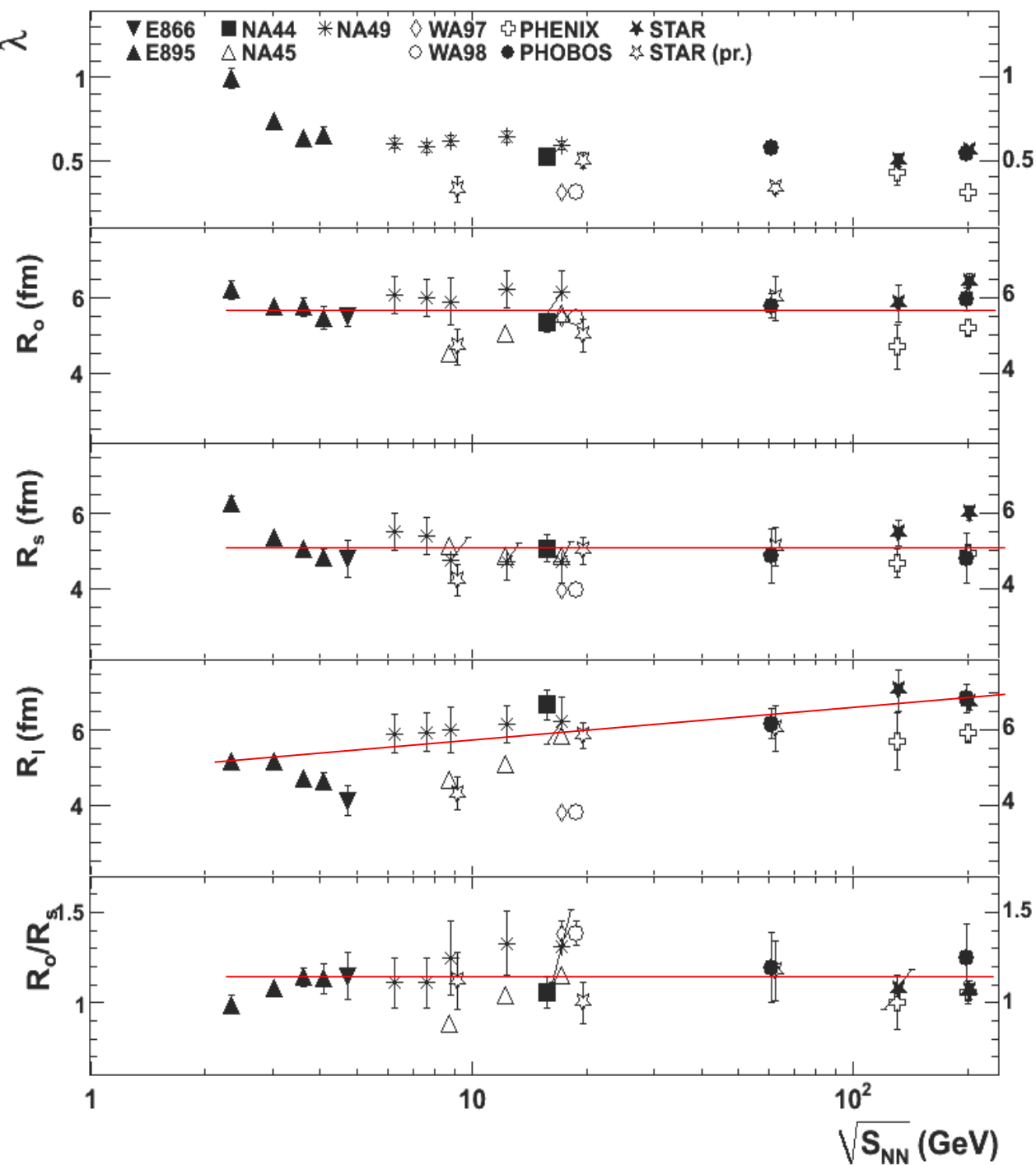
only R_{long} slightly \uparrow with energy

$$R_{side} \approx R / (1 + m_t \beta^2 / T)^{1/2}$$

→ tr. collective flow velocity β^F

$$R_{long} \approx \tau (T / m_t)^{1/2}$$

→ Evolution (freeze-out) time τ



Femto-puzzle I

Contradiction with transport and simple hydro calcul.

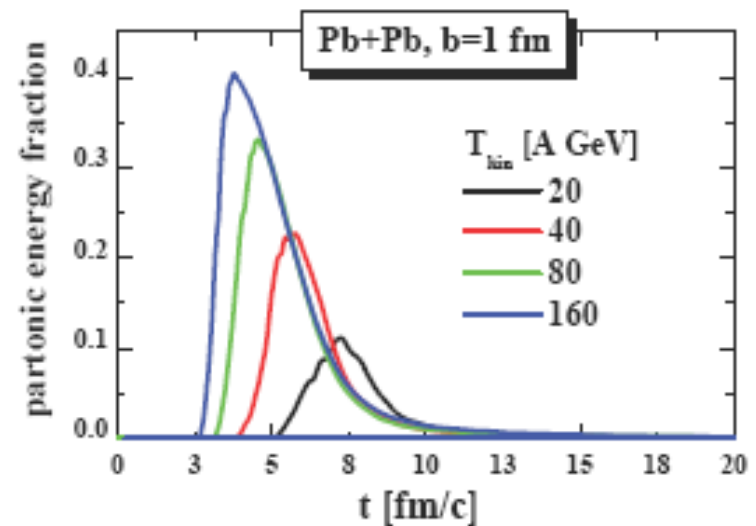
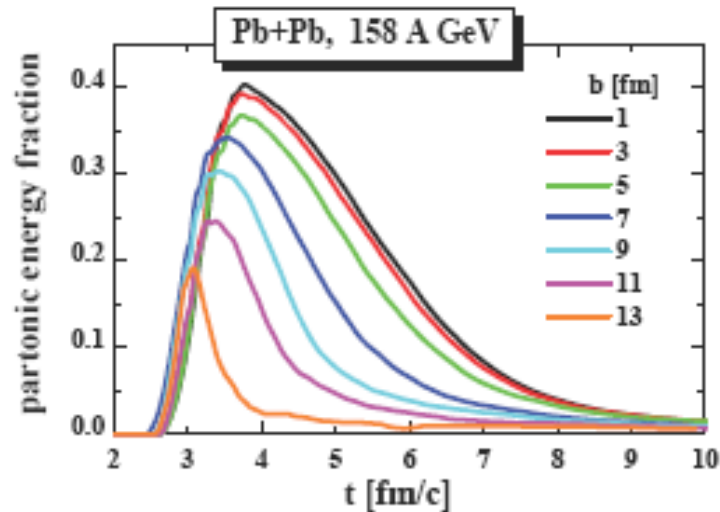
- Small space-time scales
- their weak energy dep.
- $R_{out}/R_{side} \sim 1$

Basically solved due to the initial flow increasing with energy (likely related to the increase of the initial energy density and partonic energy fraction)

Cassing – Bratkovskaya: Parton-Hadron-String-Dynamics

Perspectives at FAIR/NICA energies

partonic energy fraction vs centrality and energy

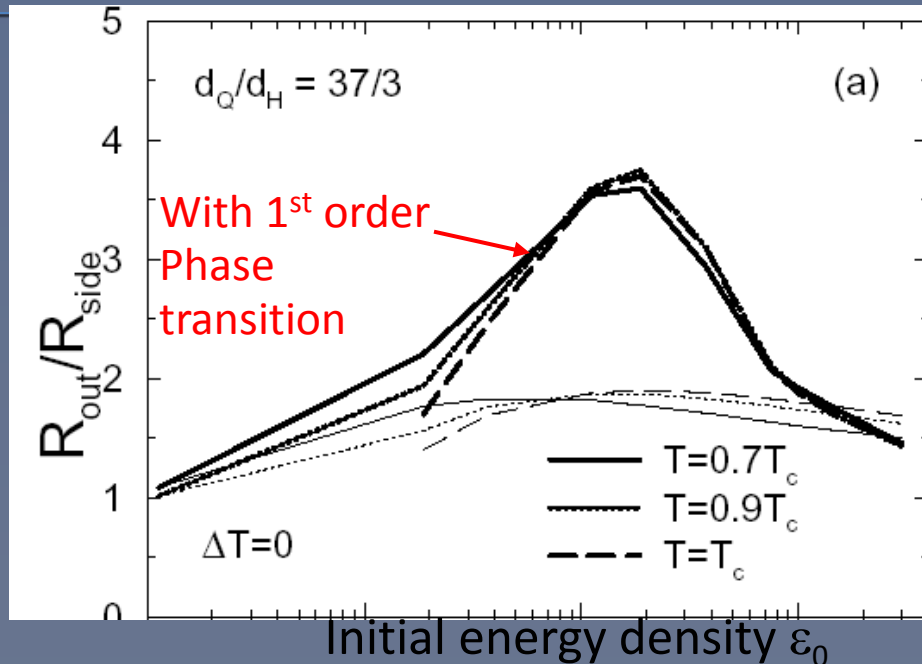


→ Dramatic decrease of partonic phase with decreasing energy and centrality !

Femtoscopic signature of QGP onset

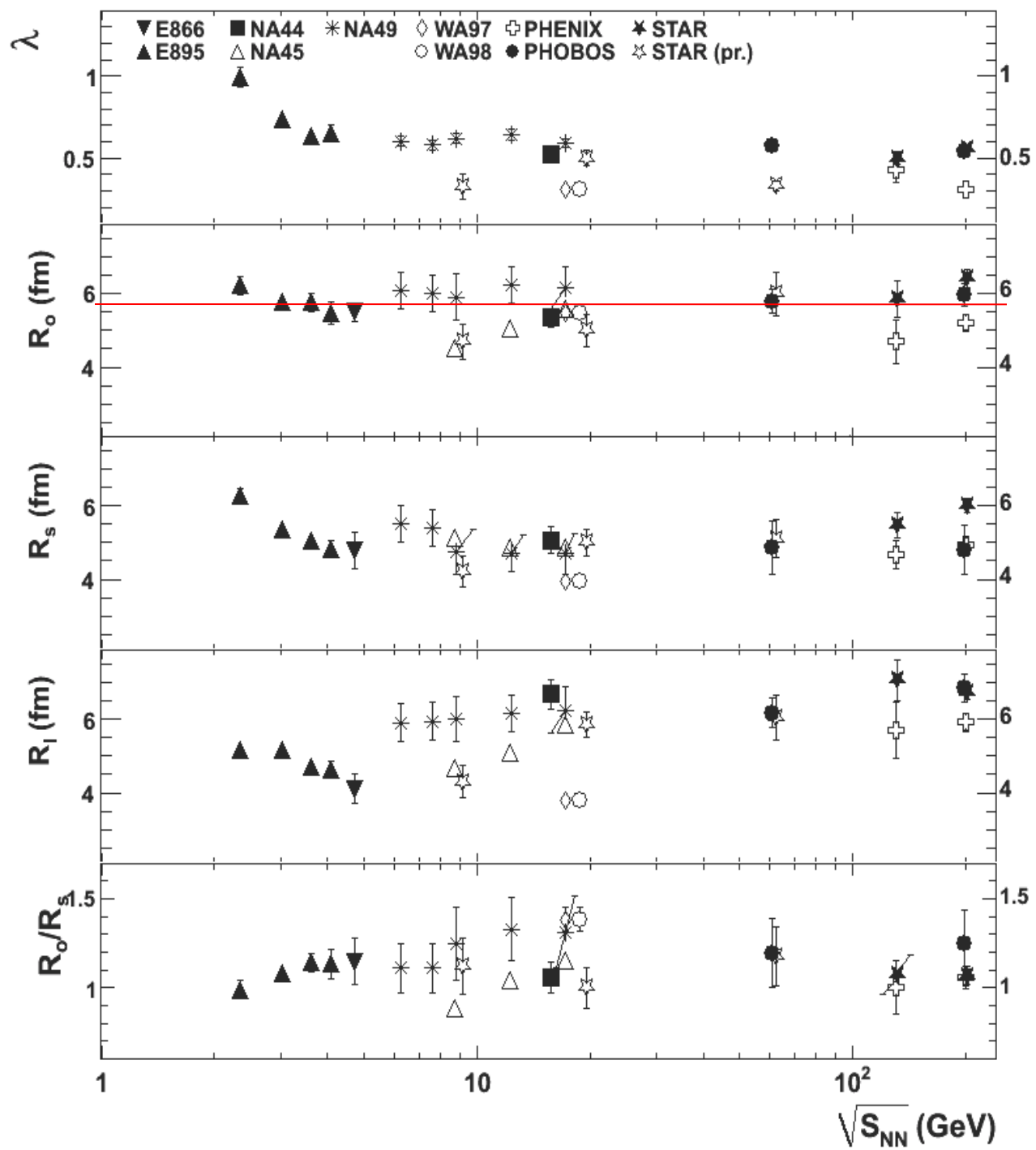
3D 1-fluid Hydrodynamics

Rischke & Gyulassy, NPA 608, 479 (1996)



Long-standing signature of QGP onset:

- **increase in $\Delta\tau$, R_{OUT}/R_{SIDE}** due to the Phase transition
- hoped-for “turn on” as QGP threshold in ϵ_0 is reached
- $\Delta\tau$ decreases with decreasing Latent heat & increasing tr. Flow
(high ϵ_0 or initial tr. Flow)

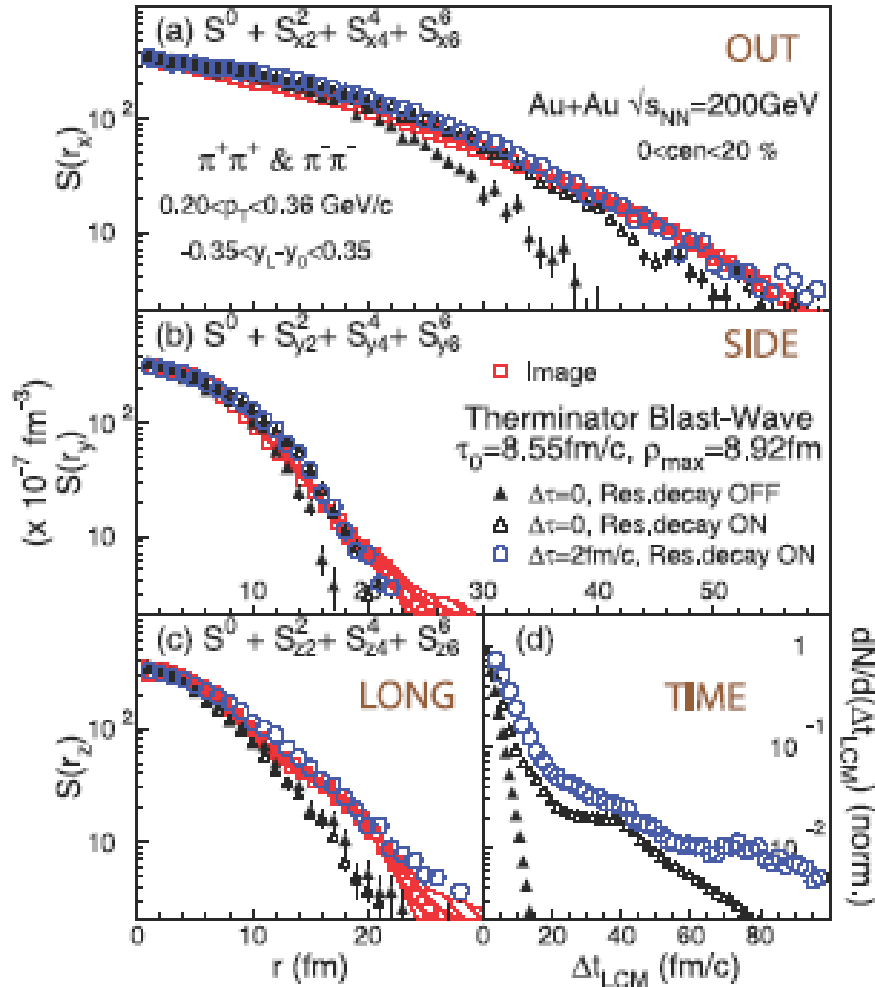


Femto-puzzle II

No signal of a bump in R_{out} near the QGP threshold (expected at AGS-SPS energies) !? – likely solved due to a decrease of partonic phase at these energies

Imaging

Source Compared to Terminator Model



Kisiel *et al.* PRC73(06)064902

PHENIX PRL100(08)232301

Emission smeared out with

$$\frac{dN}{d\tau'} = \frac{\theta(\tau' - \tau)}{\Delta\tau} \exp[-(\tau' - \tau)/\Delta\tau]$$

$\Delta\tau \sim 2 \text{ fm}/c$ needed

Distribution of emission pts
 in Longitudinal CM time t_{LCM} .

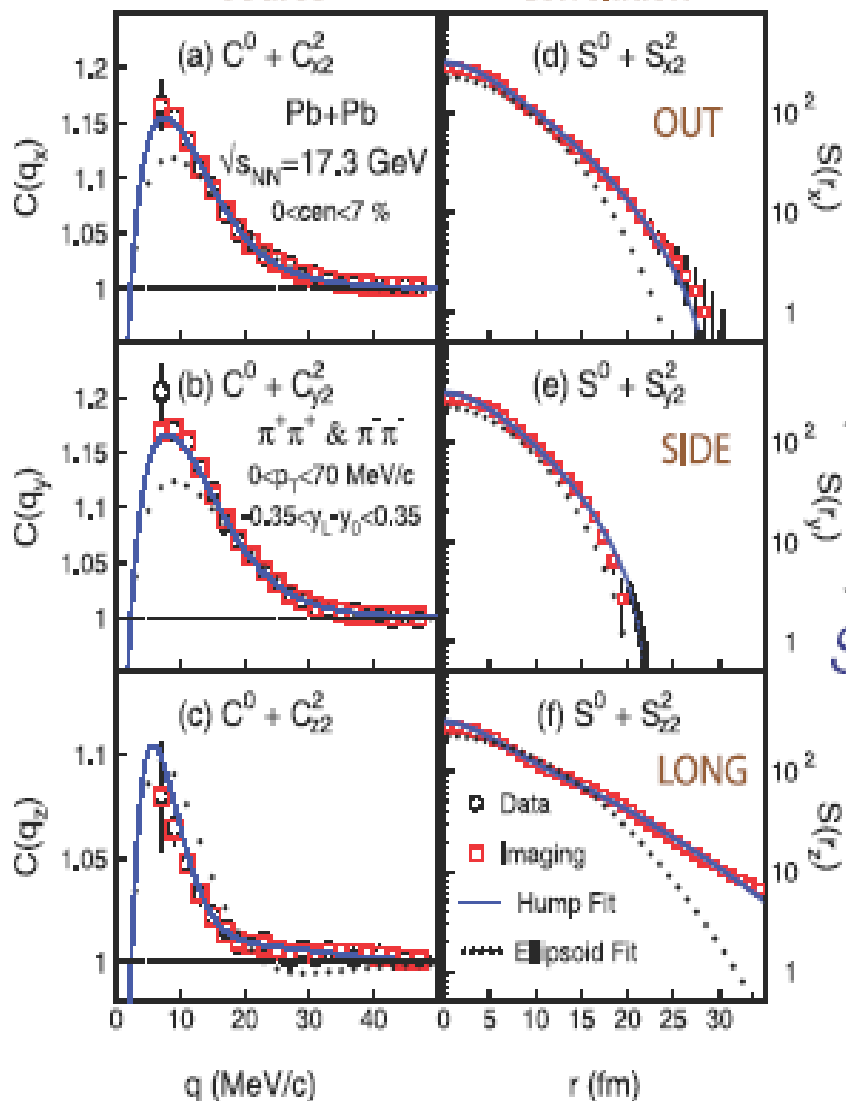
$\langle |t_{\text{LCM}}| \rangle \sim 12 \text{ fm}/c$



Source & Correlation for Different Directions

Source

Correlation



NA49 arXiv:0809.1445

Harmonic decomposition & analysis of individual harmonics

Imaging: test of consistency

Hump function with short + long-range structure:

$$S(r) = \lambda \exp \left[-f_s \left(\frac{x^2}{4\Delta_{xs}^2} + \frac{y^2}{4\Delta_{ys}^2} + \frac{z^2}{4\Delta_{zs}^2} \right) - f_l \left(\frac{x^2}{4\Delta_{xl}^2} + \frac{y^2}{4\Delta_{yl}^2} + \frac{z^2}{4\Delta_{zl}^2} \right) \right]$$

$$f_s = 1/[1 + (r/r_0)^2], f_l = 1 - f_s$$

Ellipsoid: just anisotropic Gaussian...



Conclusions and prospects related to Correlation Femtoscopy

- ◉ Wealth of data on correlations of various particle species ($\pi^\pm, K^\pm, p^\pm, \Lambda, \Xi$) is available & gives unique space-time info on production characteristics including collective flows
- ◉ Absence of fluctuation & femtoscopic signals of CP and 1-st order PT at $\sqrt{s_{NN}} < 10$ GeV is likely due to a dramatic decrease of partonic phase with decreasing energy
- ◉ Search for the effects of QGP 1-st order PT (onset and CP) can be successful only in dedicated high statistics and precise experiments like **NICA** and FAIR allowing, particularly, to search (beyond the usual Gaussian radii) for the enlarged emission duration

Образование мезонных резонансов

Анализ спектра эффективных масс " $\pi^+\pi^-$ " и " K^+K^- "

$$\frac{d\sigma}{dM} = \frac{\sigma_i}{I_i} BW(M) \cdot BG(M) + \frac{\sigma_{BG}}{I_{BG}} BG(M)$$

$$i = \rho^0, f_2, \phi$$

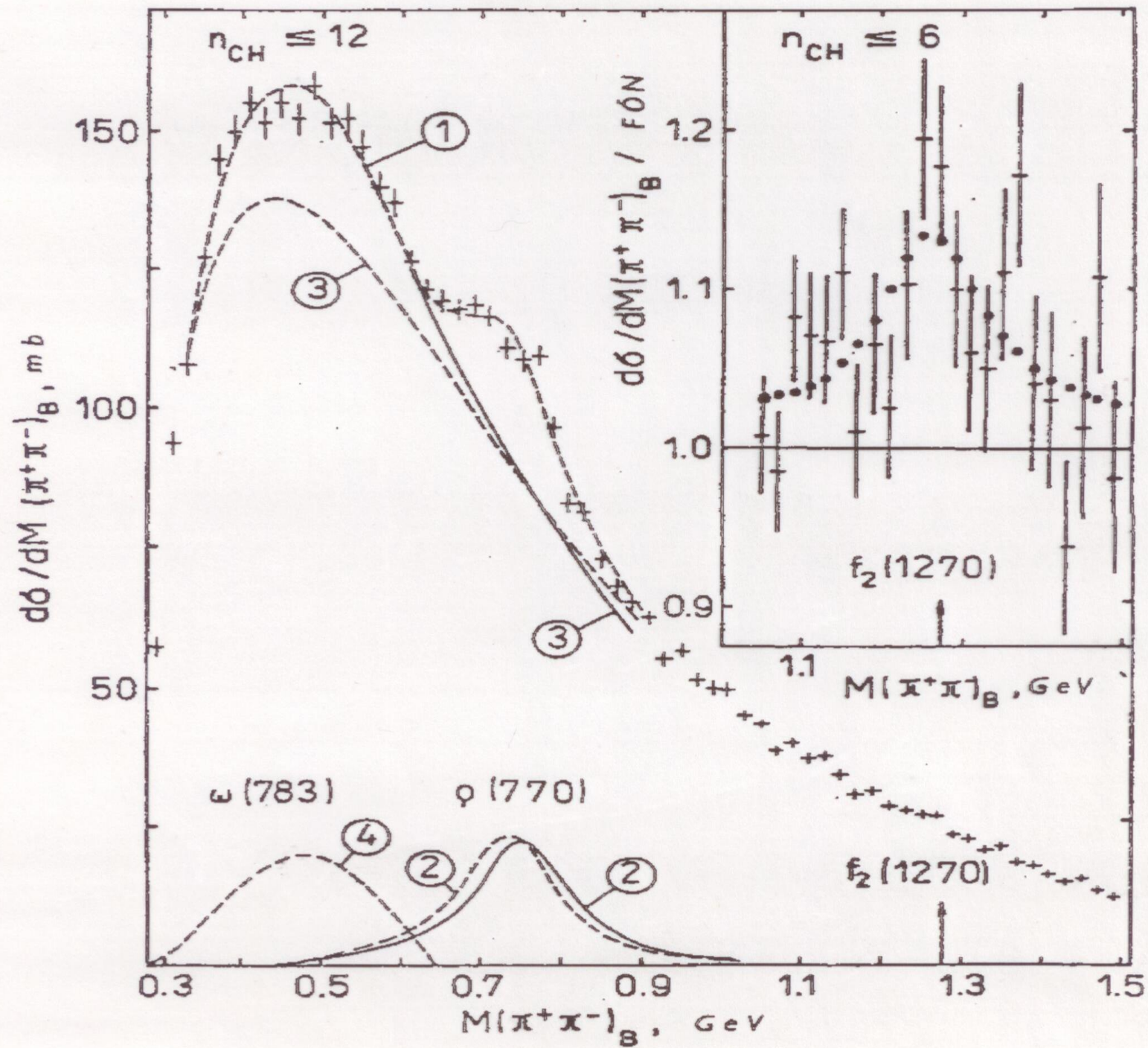
$$BW(M) = \frac{M}{q(M)} \Gamma(M) / [(M^2 - M_0^2)^2 + M_0^2 \Gamma^2(M)]$$

$$\Gamma(M) = \frac{M}{M_0} \Gamma_0 [q(M) / q(M_0)]^{2J+1}$$

Учет отражения распада $\omega \rightarrow \pi^+\pi^-\pi^0$

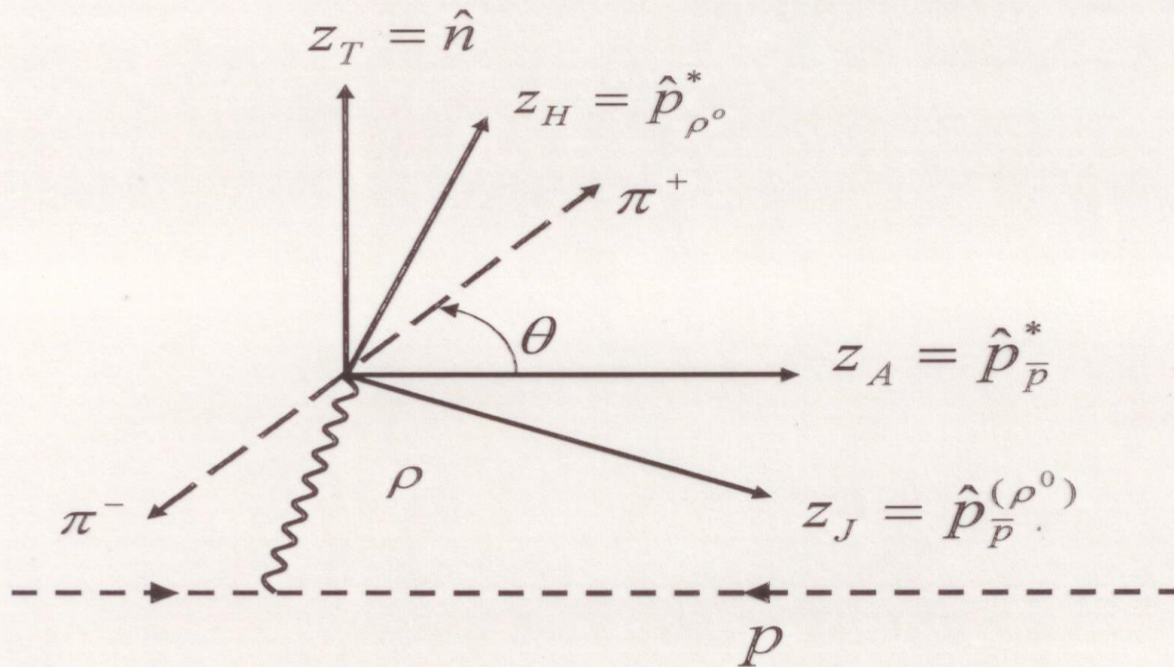
$$\frac{d\sigma}{dM} = \frac{\sigma_\omega}{I_\omega} R_\omega(M) \quad R_\omega(M) = q_{+-}^3 P_0^3$$

	$\bar{p}p(22,4)$	$pp(24)$	$\bar{p}p$ анниг.
$\sigma(\rho^0)$ мб	$8,92 \pm 0,82$	$3,70 \pm 0,24$	$5,22 \pm 0,85$
$\sigma(\omega)$ мб	$9,19 \pm 1,11$	$2,78 \pm 0,33$	$6,41 \pm 1,16$
$\sigma(f_2)$ мб	$1,09 \pm 0,12$	$0,64 \pm 0,11$	$0,45 \pm 0,33$

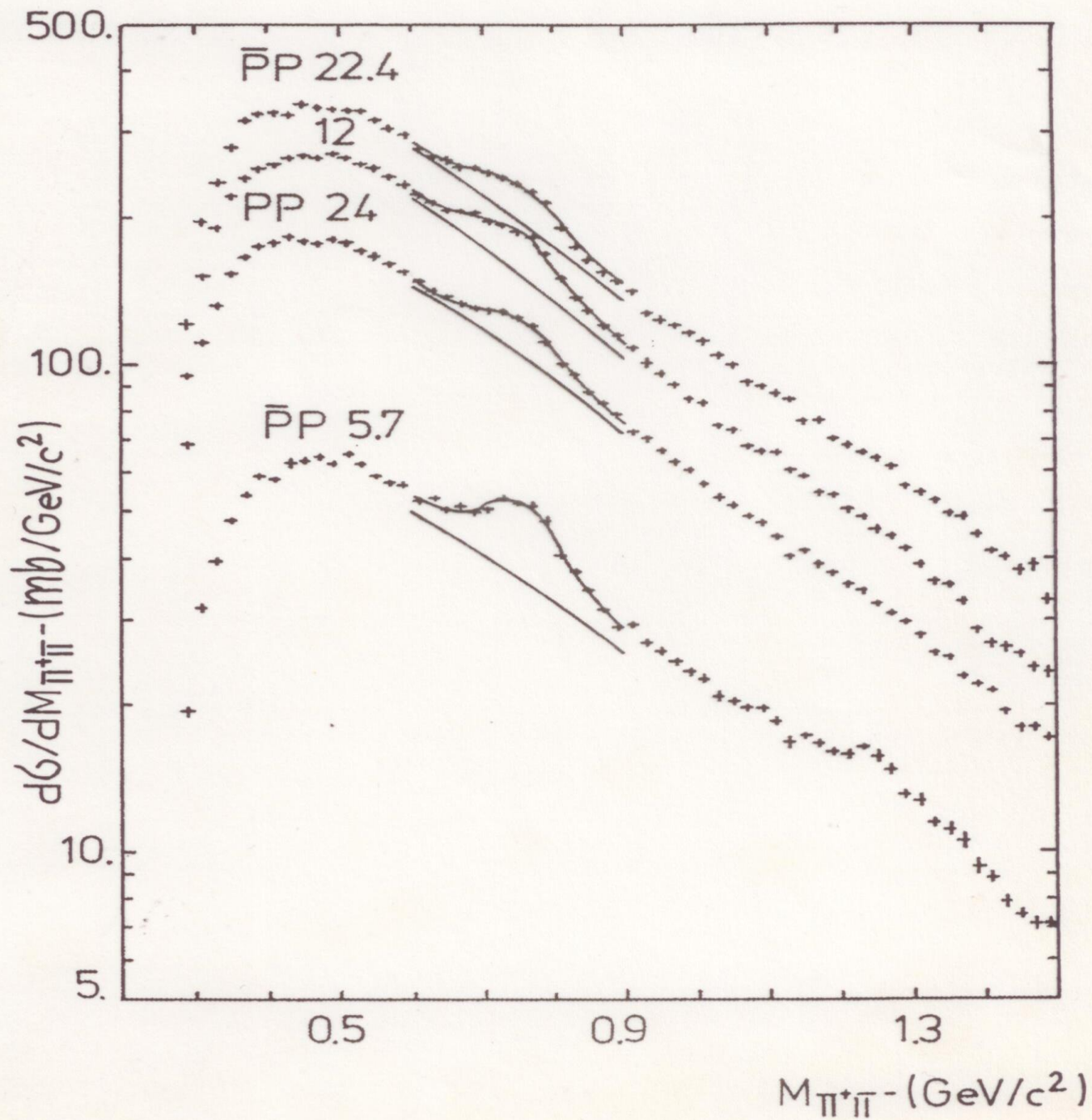


Спиновые эффекты при образовании ρ^0 - мезонов

Study of ρ^0 meson spin alignment in $\bar{p}p$ and pp interactions
 NPB 294 (1987) 1037



$$\frac{d\sigma}{d\cos\theta} = \frac{1}{2} \left[1 + \frac{1}{2} (1 - 3\rho_{00}) (1 - 3\cos^2\theta) \right]$$



A strong ρ^0 -meson spin alignment observed in the transverse system ($z \perp$ production plane): $\rho_{00}^T > 1/3$

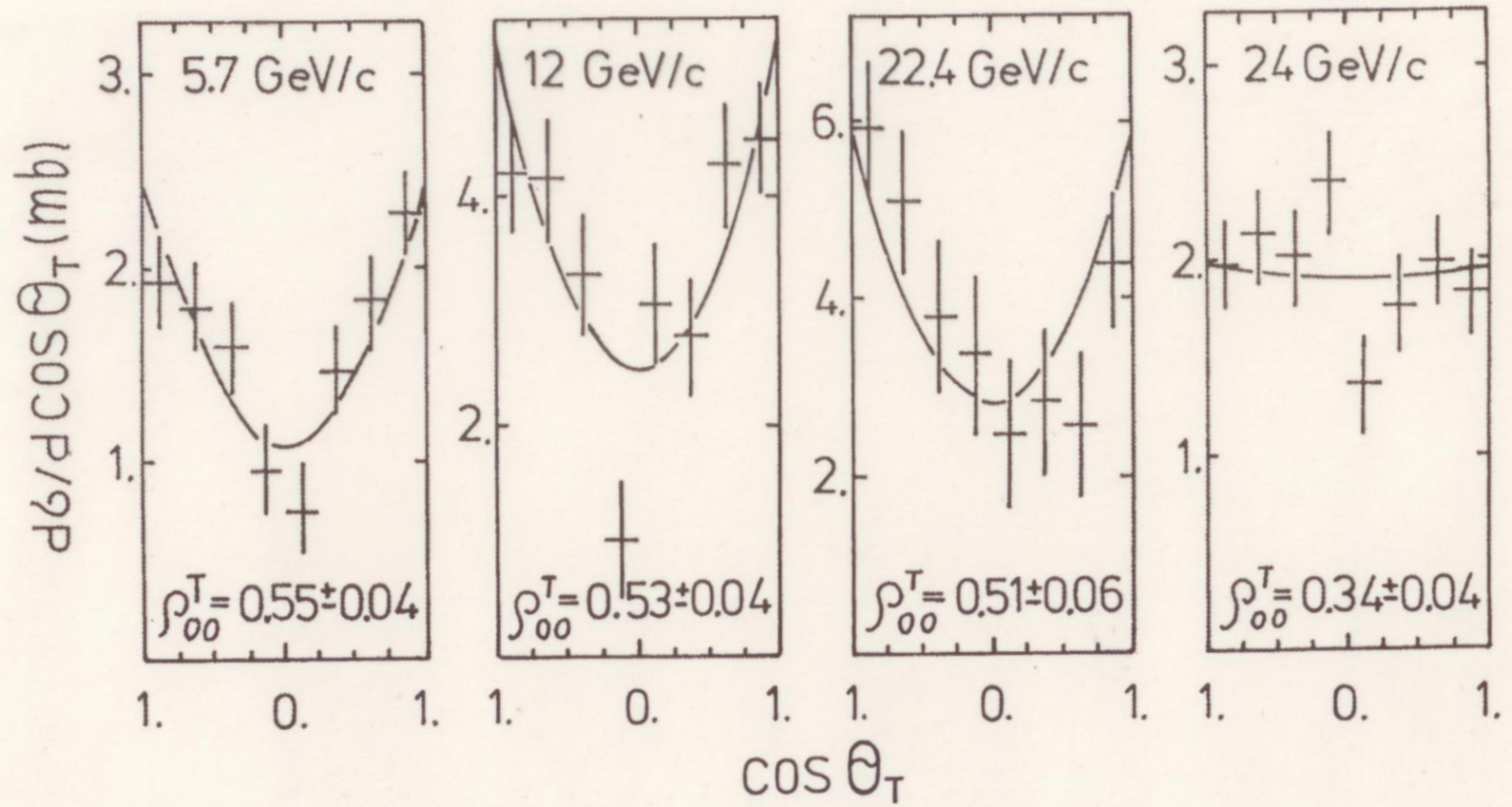


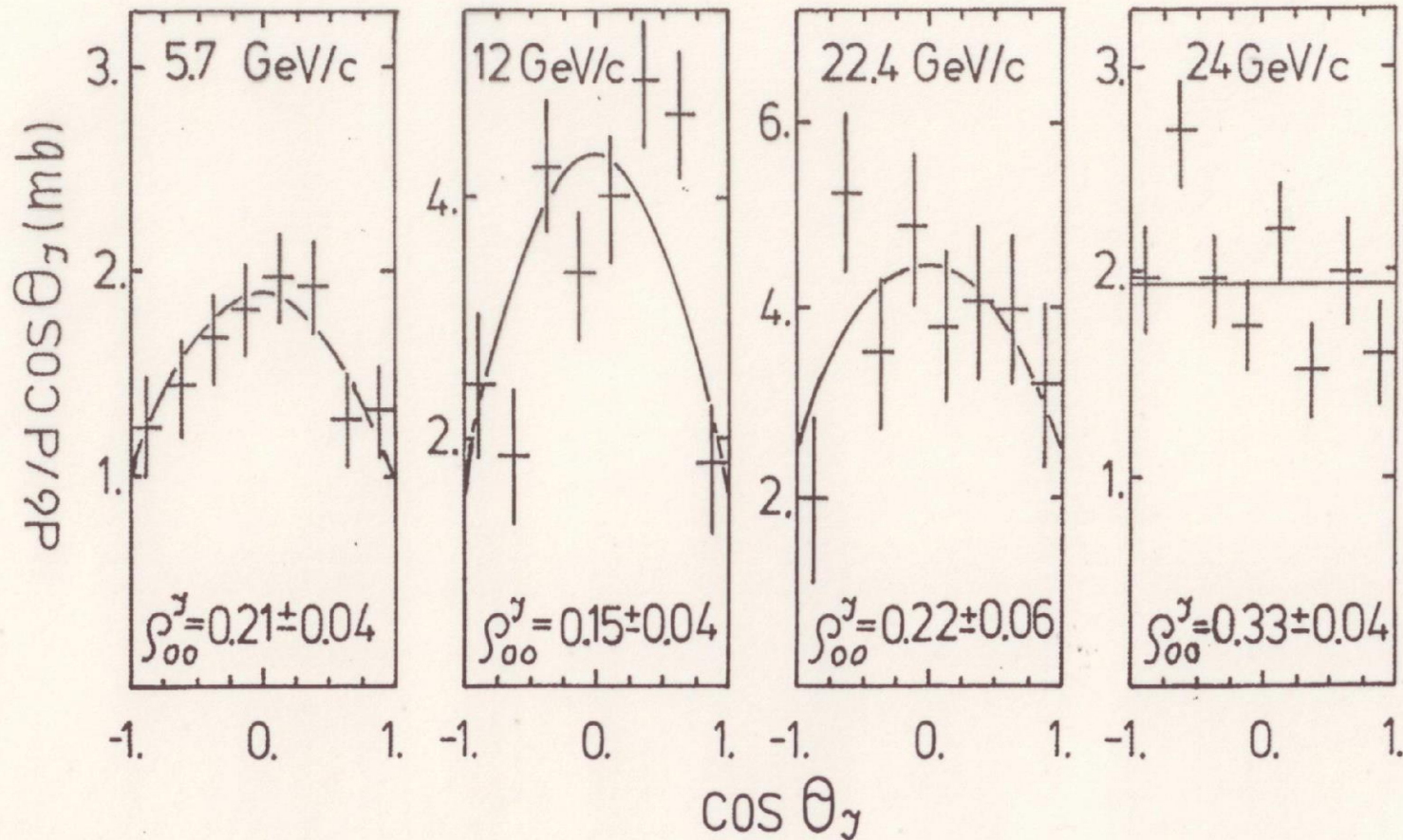
Fig. 3

Relating spin density matrix in transverse system
and any system with the z-axis in production plane

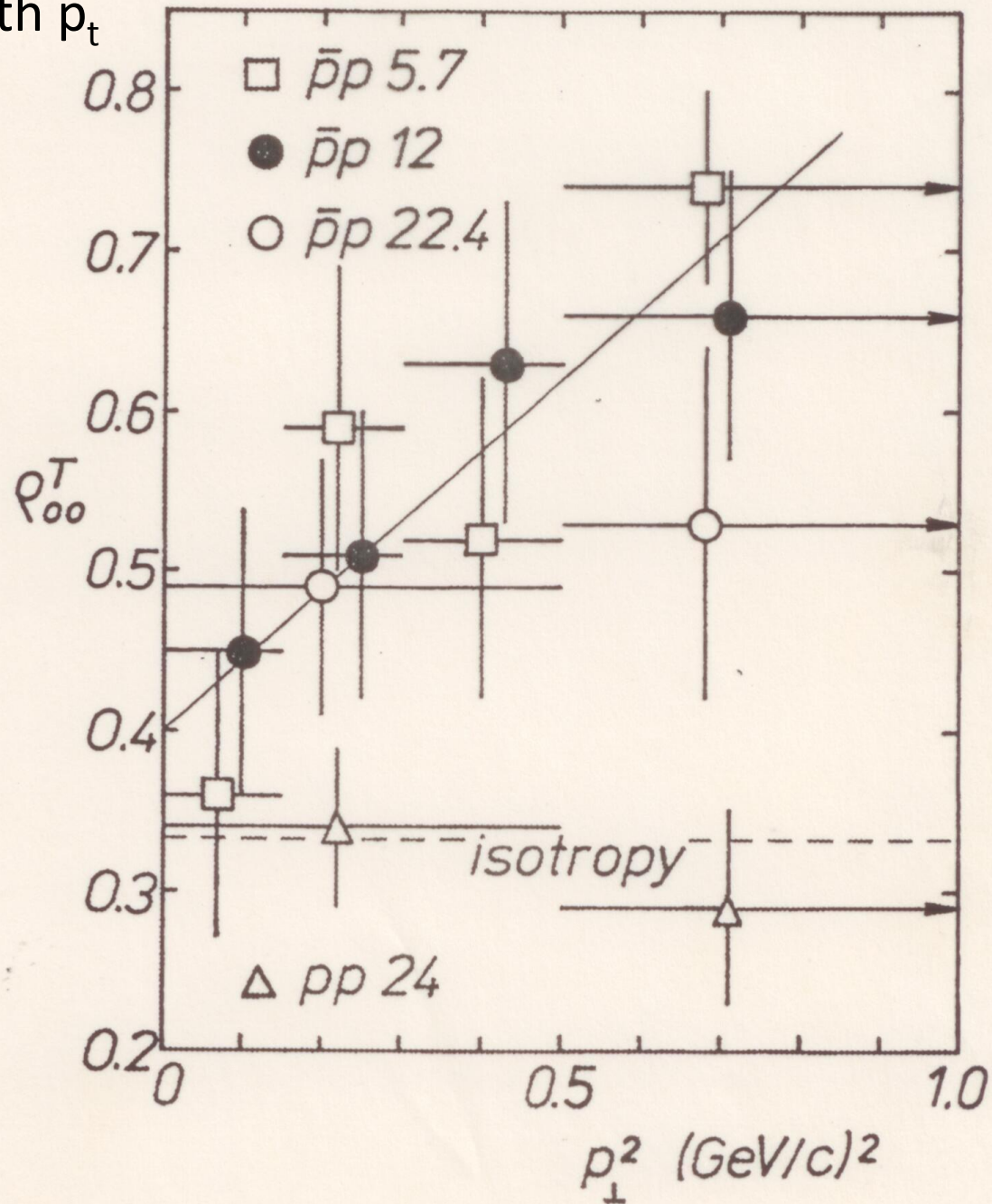
$$\rho_{00}^T = \rho_{11} + \rho_{1-1}$$

$|\rho_{1-1}| \leq \rho_{11} \leq \frac{1}{2} \Rightarrow$ a large ρ_{00}^T requires a small $\rho_{00} = 1 - 2\rho_{11}$

OK



As expected, the spin alignment in transverse system increases with p_t



At 12 GeV/c a clear spin alignment effect is seen also in the events with identified protons: $\rho_{00}^T = 0.65 \pm 0.12$

⇒ The effect is not due to annihilation

Being absent (or small) in pp it is likely related with VV contribution in the quark fusion (recombination) model

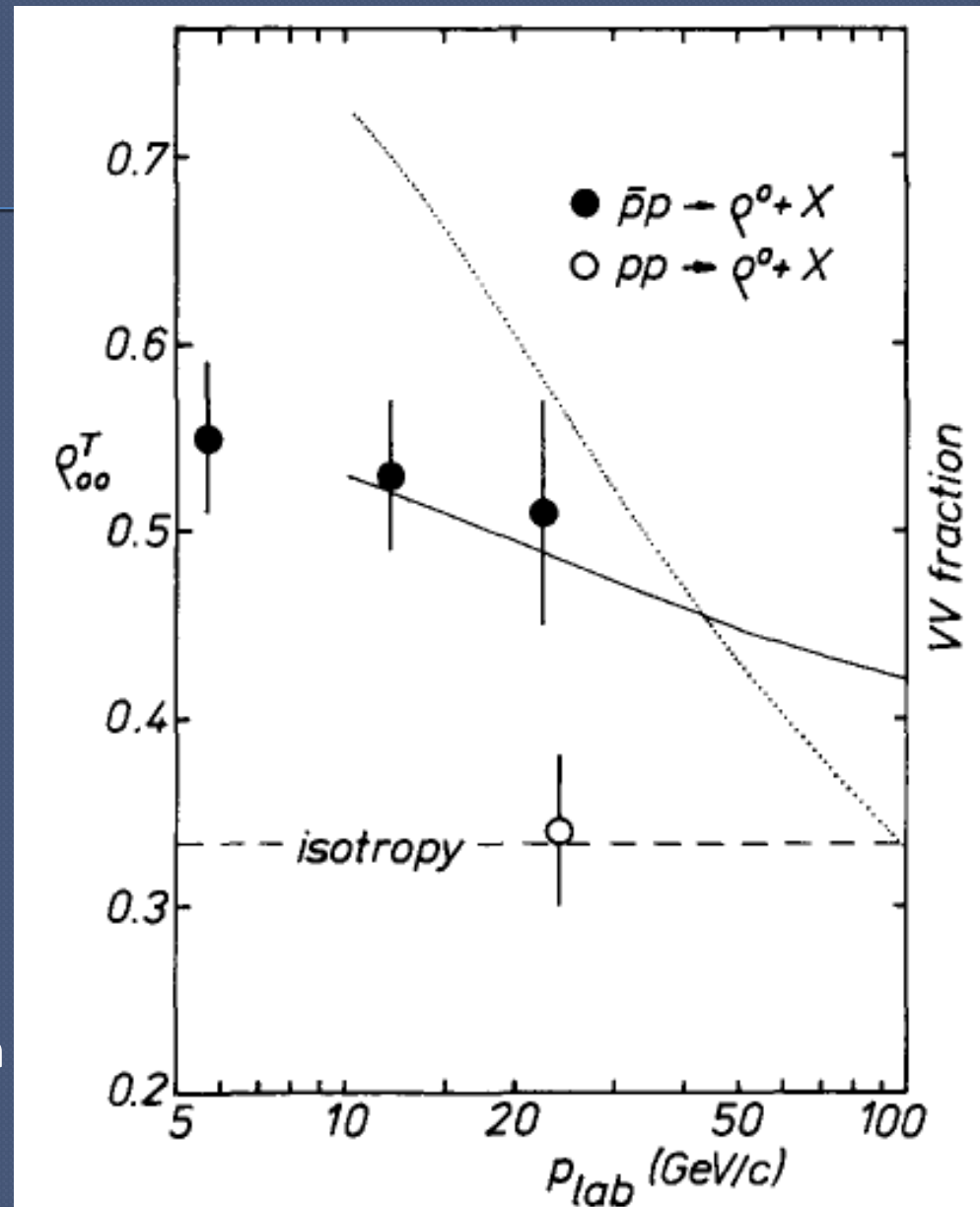
The model describes the data assuming $\rho_{00}^T = 0.6$ for VV fusion
 $\rho_{00}^T = 1/3$ for VS, SS fusion

A possible alignment mechanism is the quark polarization in the confining field:

$$\rho_{00}^T = (1 - \varepsilon_i \varepsilon_j) / (3 + \varepsilon_i \varepsilon_j) \quad \text{for } ij \text{ fusion}$$

$$\varepsilon_i = -\varepsilon_j = \varepsilon_V > 0 \quad \text{for VV fusion}$$

$$\varepsilon_i = -\varepsilon_j = \varepsilon > 0 \quad \text{for SS fusion } (\varepsilon \ll \varepsilon_V)$$



Conclusions and prospects related to the spin-alignment effect

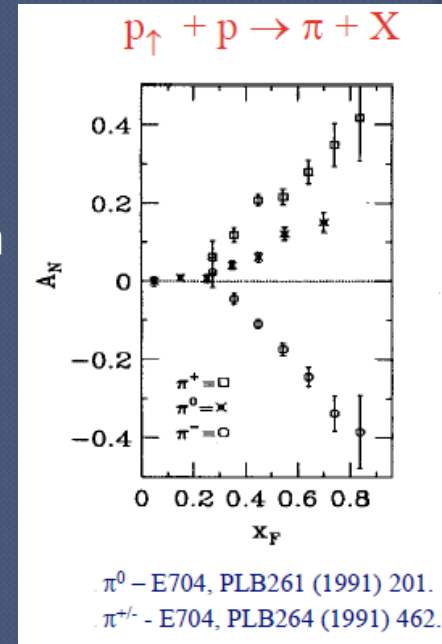
- The quark (polarization) model is supported by a large transverse hyperon polarization observed in the K-fragmentation:

$$P_{\Lambda} = 3/2 P_{\Xi} = \varepsilon_V > 0$$

- Assuming that the quark polarization arises due to an elastic interaction with the color field (i.e. $P_q = A_q$), one can explain also the polarization asymmetry observed in the fragmentation of polarized protons to mesons; e.g., using SU(6) WF one has for $p \uparrow \rightarrow \pi$ ($P_u = -2P_d = 2/3$):

$$A_{\pi^+} = -2A_{\pi^-} = 2A_{\pi^0} = 2/3 \varepsilon_V > 0$$

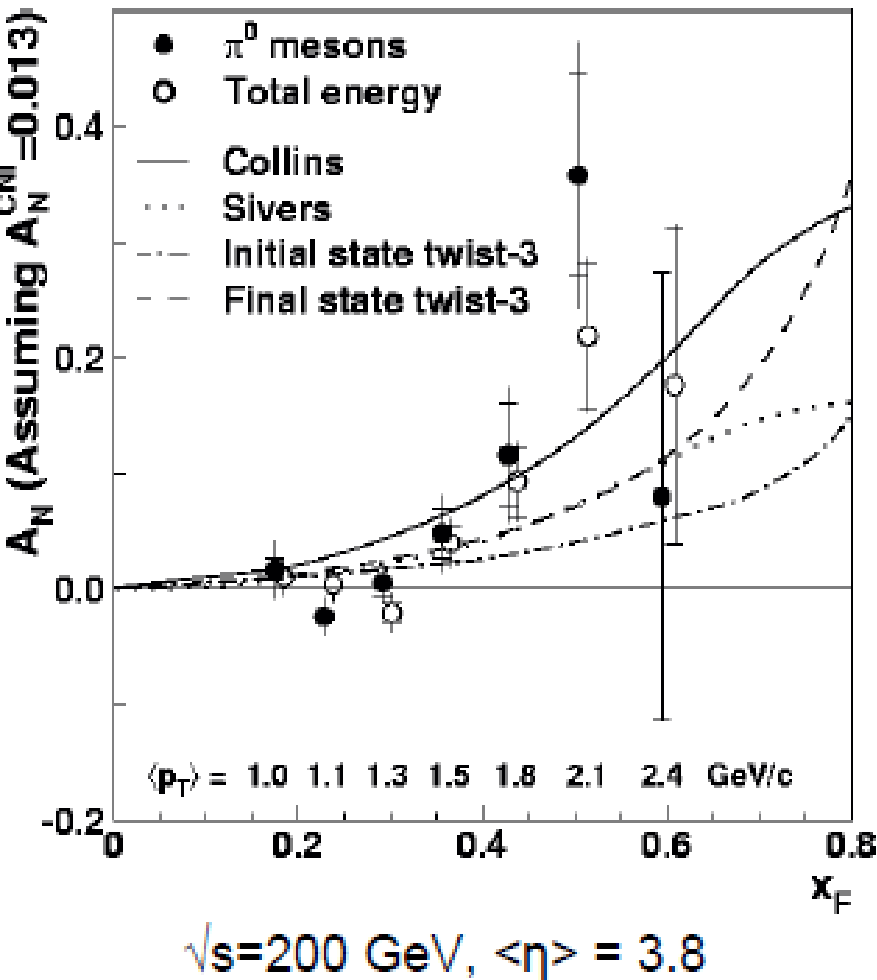
- To clarify the mechanism of the observed spin alignment effect as well as the role of a possible coherence of the amplitudes, one has to study the effect for other vector mesons (ω ?) in various reactions



First A_N Measurement at STAR

prototype FPD results

STAR collaboration
Phys. Rev. Lett. **92** (2004) 171801



Similar to result from E704 experiment
($\sqrt{s}=20$ GeV, $0.5 < p_T < 2.0$ GeV/c)

Can be described by several models available as predictions:

- ◆ Sivers: spin and k_{\perp} correlation in parton distribution functions (initial state)
- ◆ Collins: spin and k_{\perp} correlation in fragmentation function (final state)
- ◆ Qiu and Sterman (initial state) / Koike (final state): twist-3 pQCD calculations, multi-parton correlations

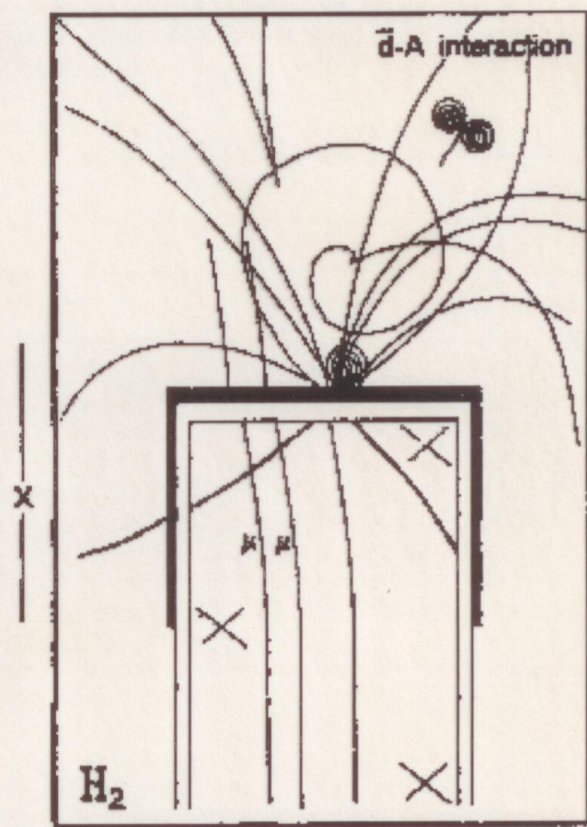
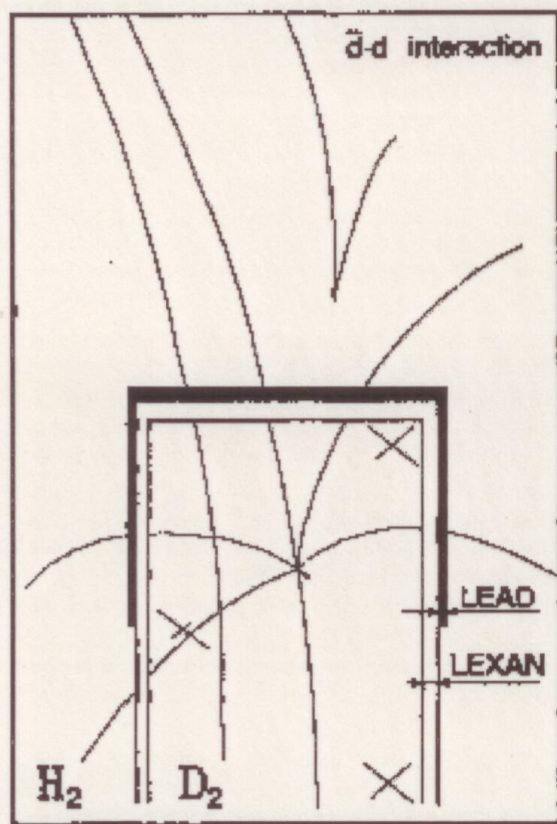
– **Contemporary language:**
 k_t -dependent PDF's or PFF's

Параметры в объеме камеры (ЖВК) и мишени (ТЧМ)

Deuteron TST inside HBC

	ЖВК	ТЧМ
Температура (К)	27,2	31,0
Статическое давление (кг/ кв.см)	5,9	5,9
Давление при расширении	2,8	2,5
Плотность пузырьков на 1 см	40	20

При этих условиях треки заряженных частиц наблюдались в обоих объемах одновременно.



Показаны типичные примеры $\bar{d}d$ - и $\bar{d}A$ -взаимодействий в установке.

Результаты анализа dd - и $\bar{d}d$ - взаимодействий

- Распределения по множественности и топологические сечения dd и $\bar{d}d$

- Оценка доли многократных процессов в dd и $\bar{d}d$ (10% и 12%)

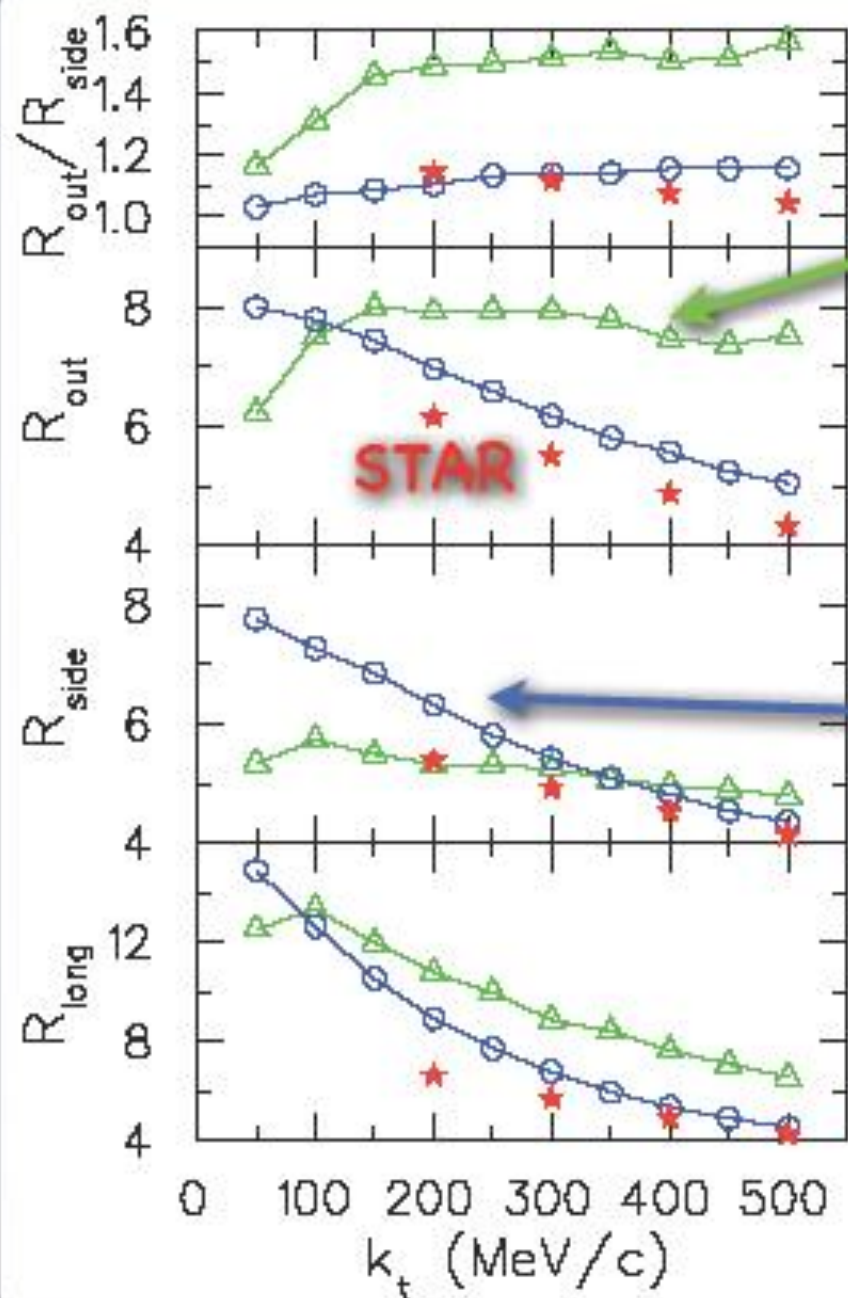
- Анализ разности топологических сечений $\bar{d}d$ и dd указывает на подавляющий вклад процессов $\bar{d}d$ -аннигиляции, в которых аннигилирует одна $\bar{N}N$ -пара. Верхняя оценка полной $\bar{d}d$ -аннигиляции составляет примерно 1,5% от неупругого сечения.

- Получены характеристики pp и $\bar{p}p$ квазисвободных взаимодействий.

- Получены инклюзивные характеристики

Λ и K^0_s в $\bar{d}d$ -, $\bar{d}C$ -, и $\bar{d}Pb$ -взаимодействиях

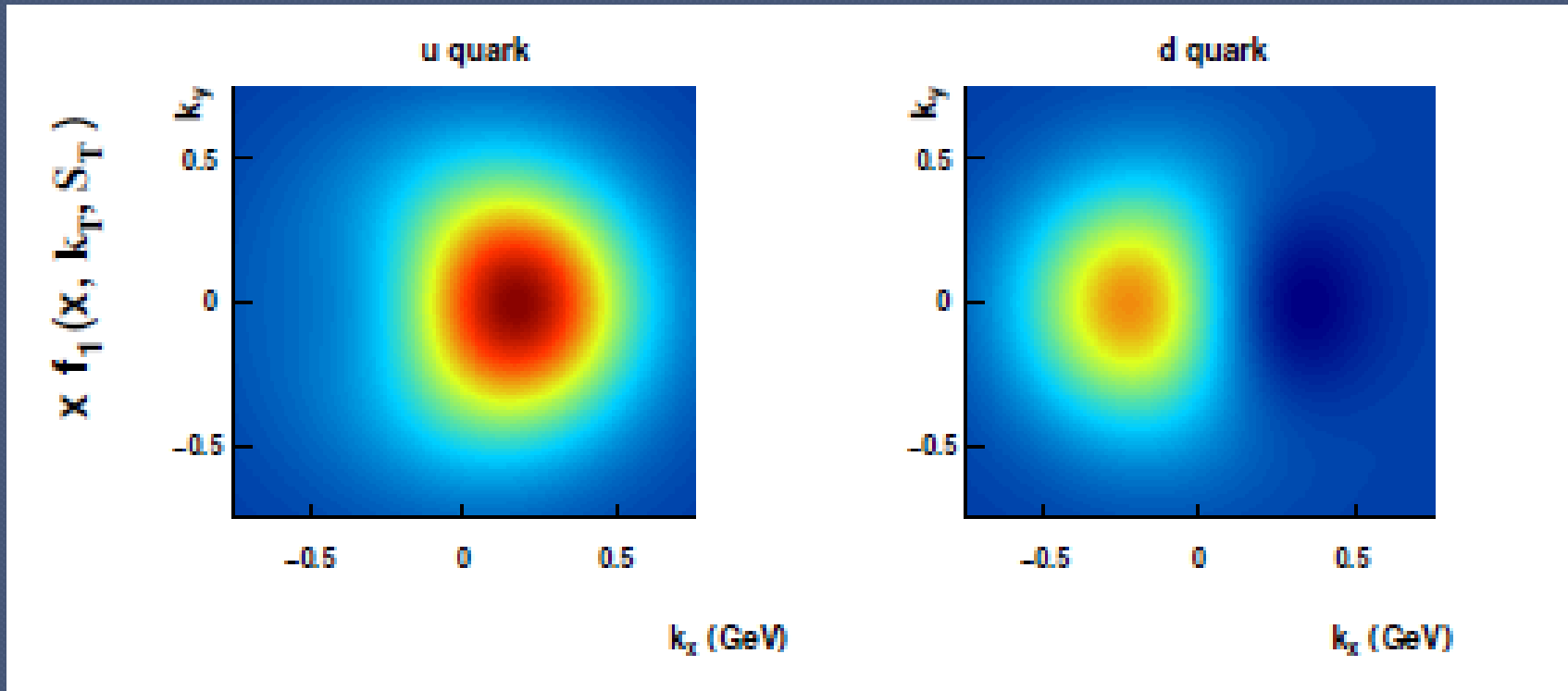
Спасибо за внимание !



Ideal Hydro,
no pre-acceleration
 Bass+Nonaka

Add:
 Pre-acceleration from CGC
 Shear + Bulk Viscosity
 Better EoS
 Better Coupling to Cascade
 Better hadronic chemistry

Sivers PDF: Correlation between quarks' k_t and proton's transverse spin



Quark densities in transverse momentum plane for a proton polarized in the +y direction. Up and down quarks orbiting in opposite directions??