Heavy ion physics at the LHC

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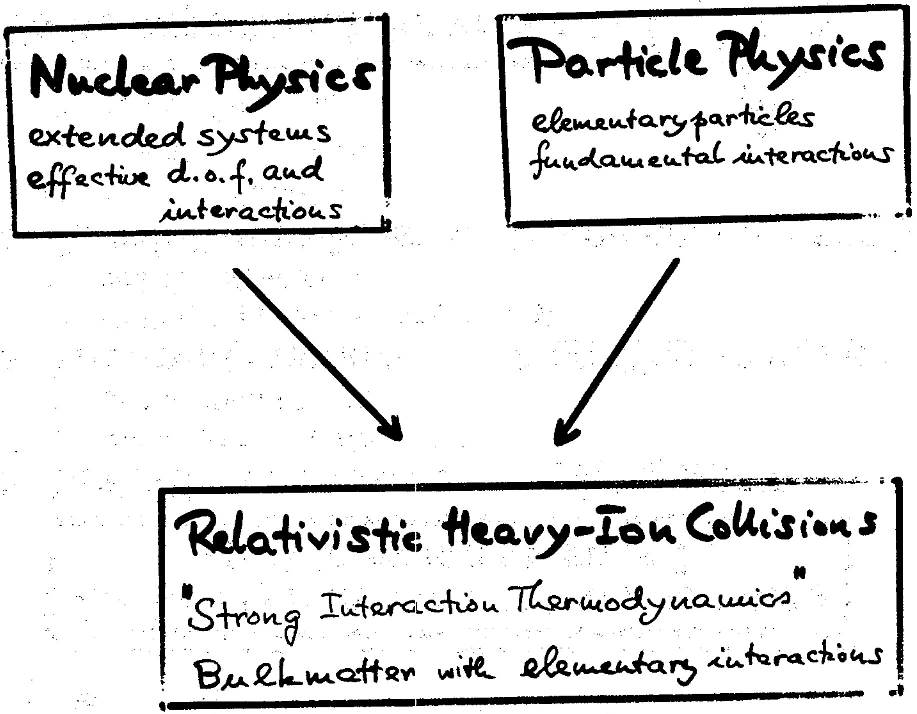
Heavy Ion Physics at the LHC

1. Aims
2. Global Features
3. Initial Conditions
4. Space - Time Evolution
5. Experimental Probes



Nuclear Physics
extended systems
effective d.o.f. and interactions

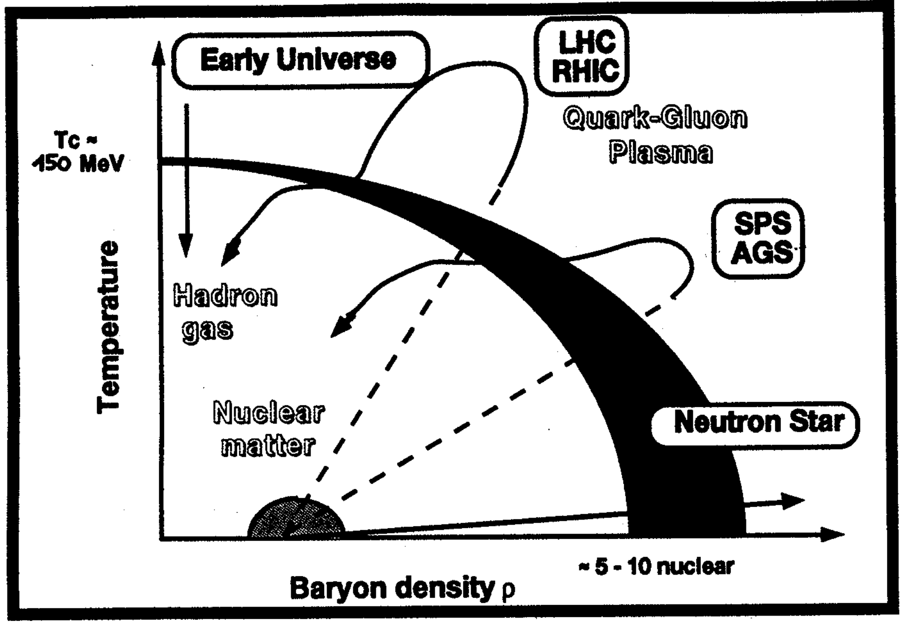
Particle Physics
elementary particles
fundamental interactions

Relativistic Heavy-Ion Collisions
"Strong Interaction Thermodynamics"
Bulkmatter with elementary interactions

Scale: $E \sim m_\pi \sim \Lambda_{QCD}$

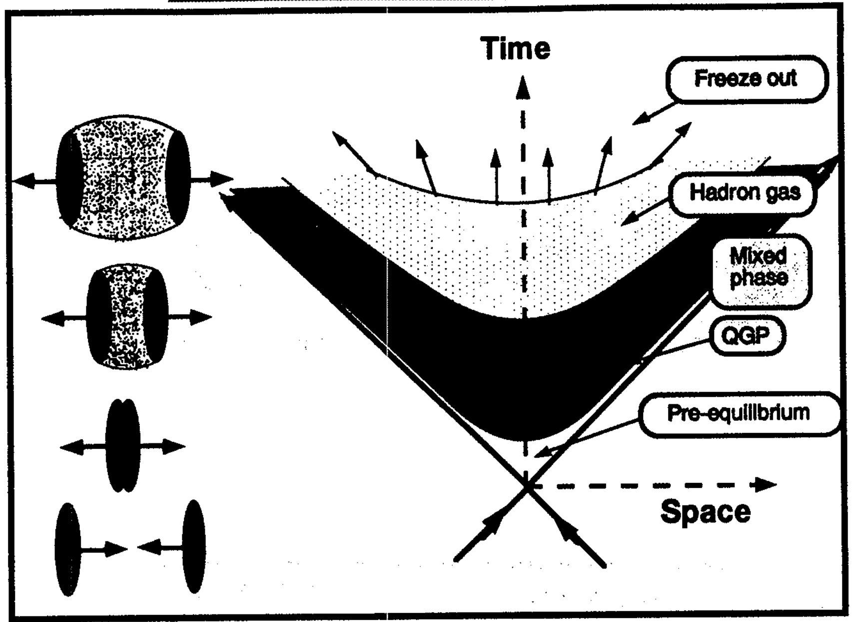
SOFT PHYSICS!

Phase Diagram of Matter



- **Cosmology** $t \approx 10^{-5}$ s, $T \approx 200$ MeV
  density fluctuations during QCD phase transition
  - ⇨ nucleo-synthesis
  - ⇨ dark matter
  - ⇨ large scale structure of universe
- **Astrophysics** compressibility of matter
  - ⇨ stability of neutron stars
  - ⇨ dynamics of supernova explosions
- **High energy physics**
  - ⇨ symmetry breaking mechanisms
  - ⇨ origin of (constituent) masses
- **Nuclear physics**
  - ⇨ equation of state of matter
  - ⇨ collective phenomena (hydrodynamics)
  - ⇨ in medium effects (collective potentials)

Space-Time Evolution



Are heavy ions the right tool to study QCD-thermodynamics ?

- **Statistical concepts** => <u>'big' systems</u>
  - ⇨ many particles, Nch >> 1
  - ⇨ dimensions >> 1 fm
- **Thermodynamics** => <u>equilibrium system</u>
  - ⇨ lifetime > relaxation time > 1fm/c
  - ⇨ collisions/particle > 1
- **Quark-Gluon-Plasma** => <u>large energy density</u>
  - ⇨ $\varepsilon_c \approx 1$ GeV/fm^3
  - ⇨ $T_c \approx 150$ MeV
  - ⇨ $\rho_c \approx 5 - 10\ \rho_{(nucleus)}$

A

$\sqrt{s}$

To be experimentally verified !

Global Conditions

Multiplicity Densities (central region)

(A) $\overset{(-)}{p}p$ collisions:

Total multiplicity ($\frac{3}{2} \times N_{ch}$), minimum bias:

$$\boxed{\left.\frac{dN}{dy}\right|_{pp}^{\text{min. bias}} = \frac{3}{2} \times 0.876 \times \left(0.023 \ln^2 s - 0.25 \ln s + 2.5\right) \approx 0.9 \ln \frac{\sqrt{s}}{2 m_p}} \quad (s \text{ in GeV}^2)$$

CDF coll., Abe et al.
PR D41 (1990) 2330

(fits data from ISR to Tevatron, 20 GeV ≤ $\sqrt{s}$ ≤ 1800 GeV)

$\sqrt{s}$ (GeV)	SPS(17)	LHB(77)	RHIC(200)	LHC(6250)	LHC(16000)
$\left.\frac{dN}{dy}\right\|_{pp}^{\text{min. bias}}$	2.4	2.7	3.2	6.8	8.3

Note: SPS → LHC $\hat{=}$ ~factor 3 !

Tails of multiplicity distribution → 5-6 times minimum bias (CDF, PRL 64 (1990) 991)
(does not work for AA!)

$$\left.\frac{dN}{dy}\right|_{pp}^{\text{"central"}} (\sqrt{s} = 6250) \rightarrow 35 - 40$$

⇒ $\varepsilon \sim 4.5\ \text{GeV}/\text{fm}^3$ (see later), but only over small volume!

⇒ pp run useful and important check on finite volume effects!

(B) Nucleus-Nucleus collisions

Extrapolation to large A:

$$\boxed{\left.\frac{dN}{dy}\right|_{AA}^{\text{central collision}} = A^{1+\alpha} \left.\frac{dN}{dy}\right|_{pp}^{\text{min. bias}}}$$

α parametrizes "rescattering" or "cascading"

$\alpha(A, \sqrt{s})$ hard to estimate → large uncertainties in extrapolation

Limits on α:

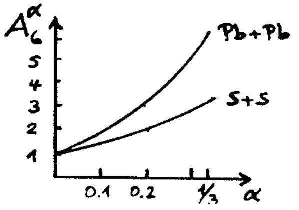
Empirical: at SPS, S+S vs p+p (NA35): $0 \leq \alpha \leq 0.05$
Pb+Pb expect $\alpha \simeq 0.1$
due to "rescattering"

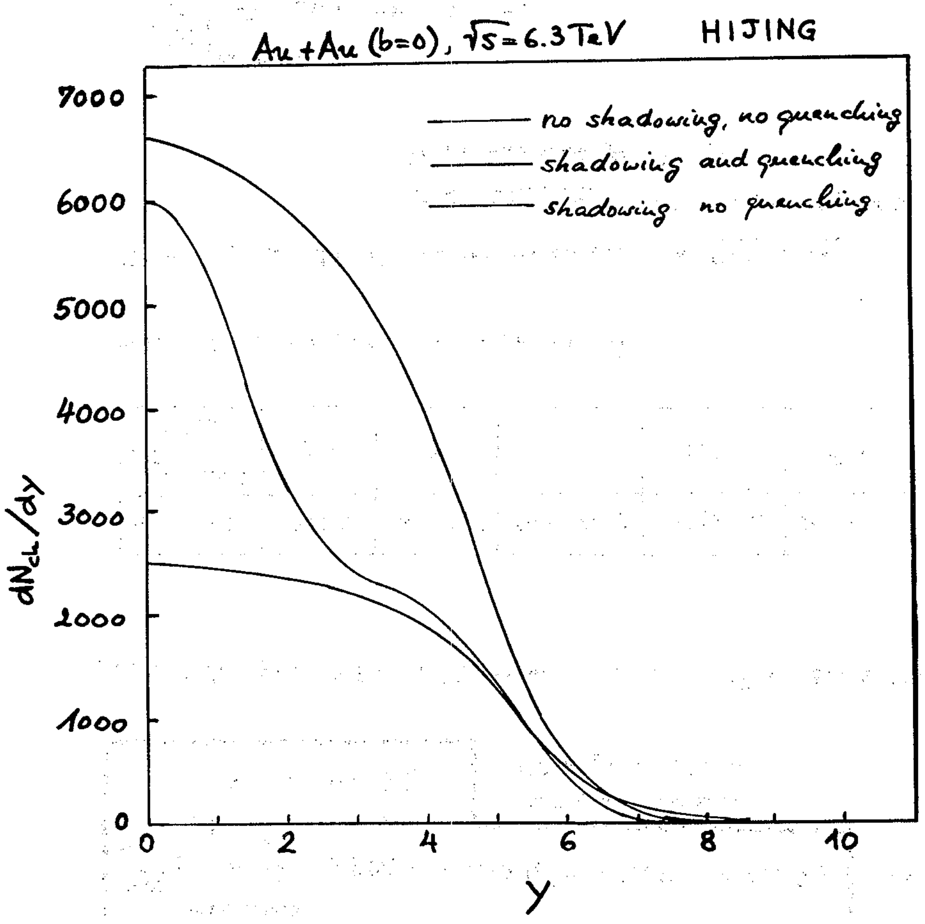
Theoretical: at high energies, expect semihard phenomena ("minijets") to dominate particle production
scales with $A^{4/3} \left(= \frac{A^2}{A^{2/3}}\right) \longrightarrow \alpha \to 1/3$

Thus expect α_{Pb+Pb} to grow from 0.1 to 0.33
as $\sqrt{s}$ grows from 20 GeV to ∞.

$\sqrt{s}$ (GeV)	SPS(17)	LHB(77)	RHIC(200)	LHC(6250)
$\left.\frac{dN}{dy}\right\|_{Pb\,Pb}^{\text{central}}$	500-800	560-1000	670-2000	1400-8000
α (assumed)	0.0-0.1	0.0-0.1	0.0-0.2	0.0-0.33

Note: Important to measure A-dependence of multiplicity density
pp, SS, CuCu, PbPb





Initial Conditions

Energy and entropy densities (central region)

Issue: estimate initial parameters by extrapolating observed final phase-space density back in time

Uncertainties: How far back in time? (Formation and Equilibration time scales)

"Naive" approach: Longitudinal boost-invariance:

(i) Free streaming longitudinal expansion, no work done by pressure: (Bjorken, PR D27 (1983) 140)

$$\boxed{\varepsilon_0 = \frac{1}{V_0}\langle m_\perp\rangle \frac{dN}{dy} = \frac{\langle m_\perp\rangle}{\pi(1.2\,\mathrm{fm})^2\tau_0} A^{-2/3}\frac{dN}{dy}}$$

Factor $\langle m_\perp\rangle$ allows for collective transverse flow

$$\left.\begin{array}{ll}\tau_0 \approx 1\,\mathrm{fm}/c & \text{"formation time"}\\ \langle m_\perp\rangle \approx 0.5\,\mathrm{GeV} & \text{(from Tevatron data)}\end{array}\right\}\text{"conservative"}$$

(ii) Isentropic hydrodynamic expansion with longitudinal boost invariance (Hwa + Kajantie, PR D32 (1985) 1108)

$$\boxed{S_0 = \frac{1}{V_0}\,\underset{\substack{\uparrow\\ \text{pions}}}{3.6}\,\frac{dN}{dy} = \frac{3.6}{\pi(1.2\,\mathrm{fm})^2\underset{\substack{\uparrow\\ \text{"thermalization time"}}}{\tau_0}} A^{-2/3}\frac{dN}{dy}}$$

Note: For same τ_0, (ii) leads to larger ε, T than (i) above SPS energies

However, (ii) does not correct for entropy produced by resonance decays → overestimate of S_0

If τ_0 does not depend on A → $S, \varepsilon \sim A^{\alpha+1/3}$ (factor 6–35 for $A=200$:

→ Large A better than going into tails of pp!

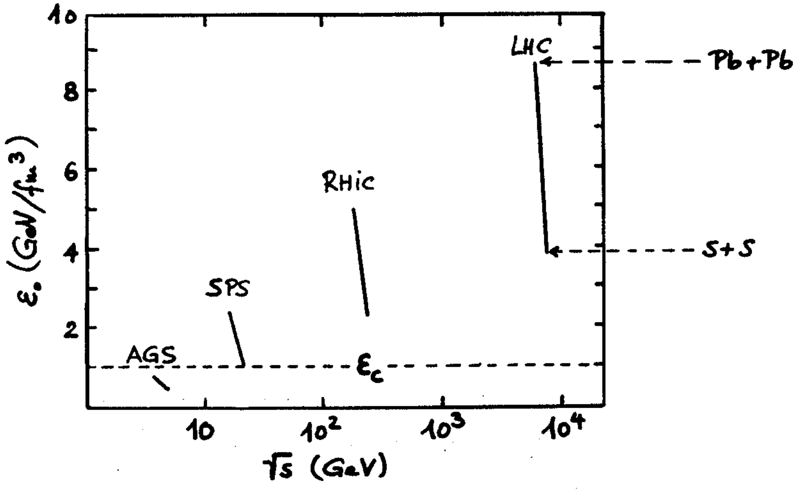
Caution: Event generators which give large α also give larger τ_0!

How to vary the initial energy density?

- vary $\sqrt{s}$ → very ineffective, since $\varepsilon_0 \sim \ln \sqrt{s}$
- vary A (pp, SS, CuCu, PbPb)
  - → changes ε_0 and V_0 simultaneously
- vary impact parameter at fixed (large) A (e.g. via E_T)
  - → changes only V_0 but leaves ε_0 essentially unchanged (Karsch + Satz, ZP C51 (91) 209

Initial energy density at $y = 0$
(Bjorken estimate)

for $\tau_0 = 1\,fm/c$
$\alpha = 0.1$ independent of $\sqrt{s}$



Handy formulae for Pb + Pb:

$$\varepsilon_0 = \mathbf{3.5} \left(\frac{1\,fm/c}{\tau_0}\right)\left(\frac{\langle m_\perp \rangle}{0.4\,GeV/c^2}\right)(208)^\alpha \; GeV/fm^3$$

$$s_0 = \mathbf{32} \left(\frac{1\,fm/c}{\tau_0}\right)(208)^\alpha \; fm^{-3}$$

Initial temperature (central region)

Use EOS of ideal quark-gluon gas, 3 massless flavors. $\mu_B = 0$ (see later)

(i) $\varepsilon = \frac{\pi^2}{30}\left(2\times 8 + \frac{7}{8}\times 2\times 3\times 3\times 2\right)T^4 + B$

$$\Rightarrow \boxed{T_{Bj} = \left(\frac{\varepsilon - B}{1953}\right)^{1/4}\,\mathrm{GeV}} \qquad (\varepsilon \text{ in GeV/fm}^3)$$

(ii) $s = \frac{2\pi^2}{45}\left(16 + \frac{7}{8}\times 36\right)T^3$

$$\Rightarrow \boxed{T_{HK} = \left(\frac{s}{2605}\right)^{1/3}\,\mathrm{GeV}} \qquad (s \text{ in fm}^{-3})$$

$\sqrt{s}$ (GeV)	SPS(17)	LHB(77)	RHIC(200)	LHC(6250)
T_{Bj} (MeV)	157-185	164-193	172-234	213-335
T_{HK} (MeV)	162-194	171-207	179-259	231-410

Note: These are average values;
T may be up to 20% higher in center of firetube.

$\mu \neq 0$ will somewhat reduce T.

$$\boxed{T_i \sim 2T_c}$$

Baryon density (central region)

Energy loss of high energy protons through Pb target: $\delta y = 2 - 2.5$

Additional energy loss in Pb-Pb collisions via cascading.

Event generators (RQMD, VENUS, DTUNUC): $\delta y = 3.5$ (?)

→ figure

Schematic model (→ figure)

$$\frac{dN_B}{dy}(y=0) = \begin{cases} \frac{2A}{y_p} & y_{proj} < \delta y \\ \frac{2A}{\delta y}\left(2 - \frac{y_p}{\delta y}\right) & \delta y < y_p < 2\delta y \\ 0 & y_p > 2\delta y \end{cases}$$

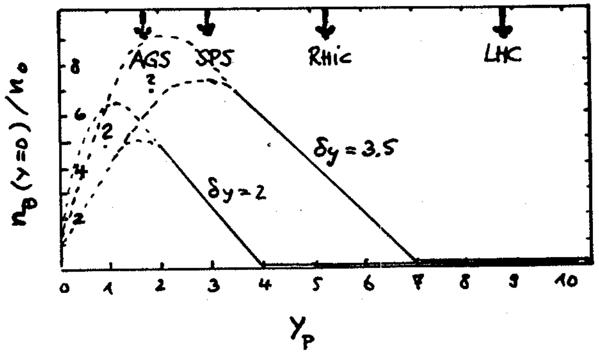
For $y_p \gtrsim \delta y$ onset of transparency

→ baryon density at $y=0$ begins to drop

Bjorken scaling expansion near $y=0$:

$$\frac{n_B(y=0)}{n_0} = \frac{1}{n_0}\frac{1}{\pi(1.2\,\mathrm{fm})^2\tau_0}A^{-2/3}\frac{dN_B}{dy}(y=0)$$

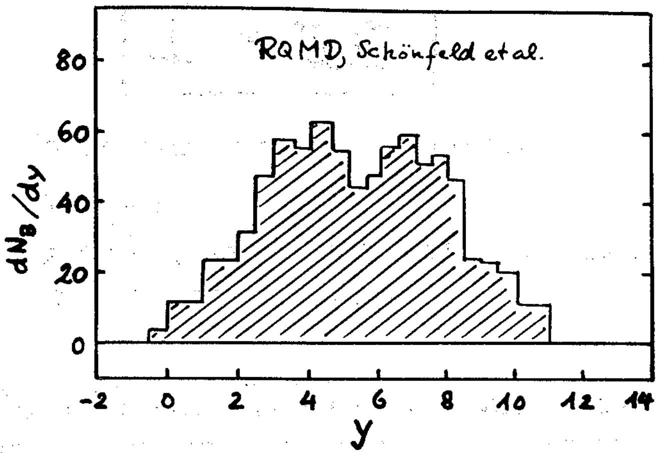
Baryon density at $y=0$:



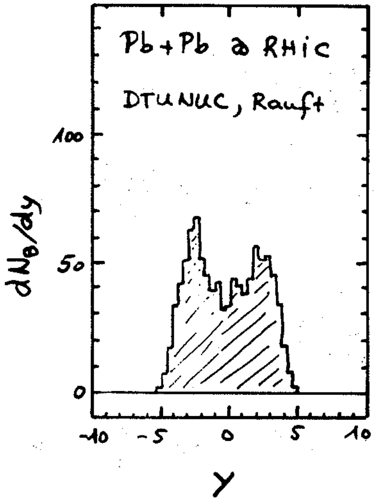
Note: Baryon density in fragmentation regions may be much higher!

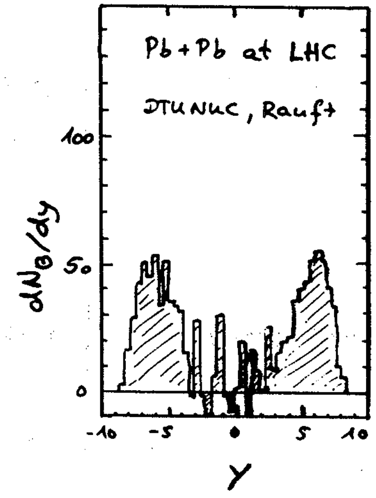
Pb + Pb at RHIC

net baryon density



net baryon density



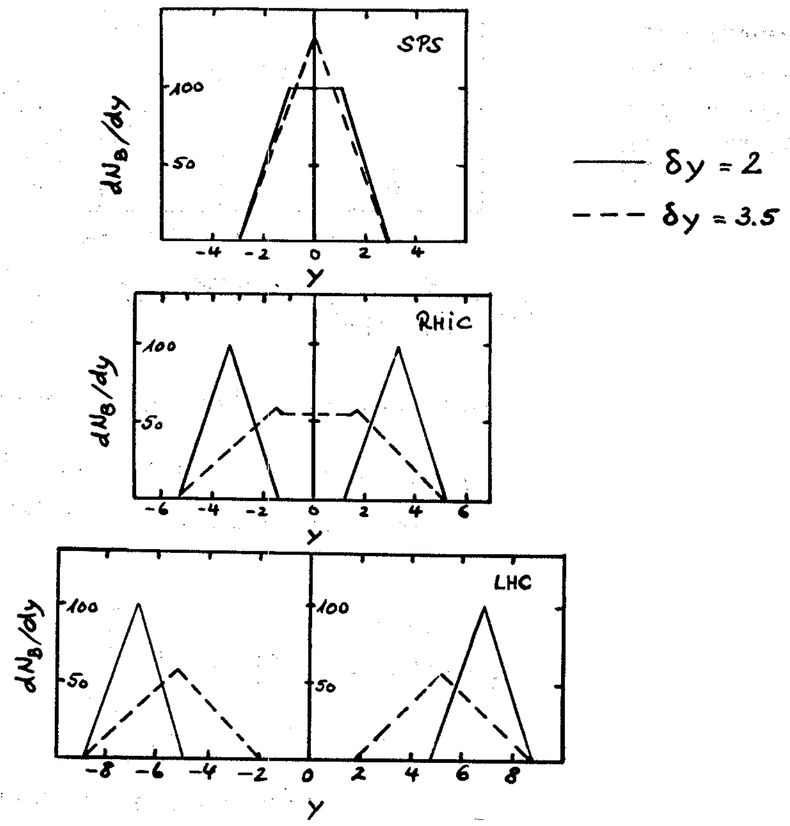


↑

large fluctuations due to strong B-$\bar{B}$ production

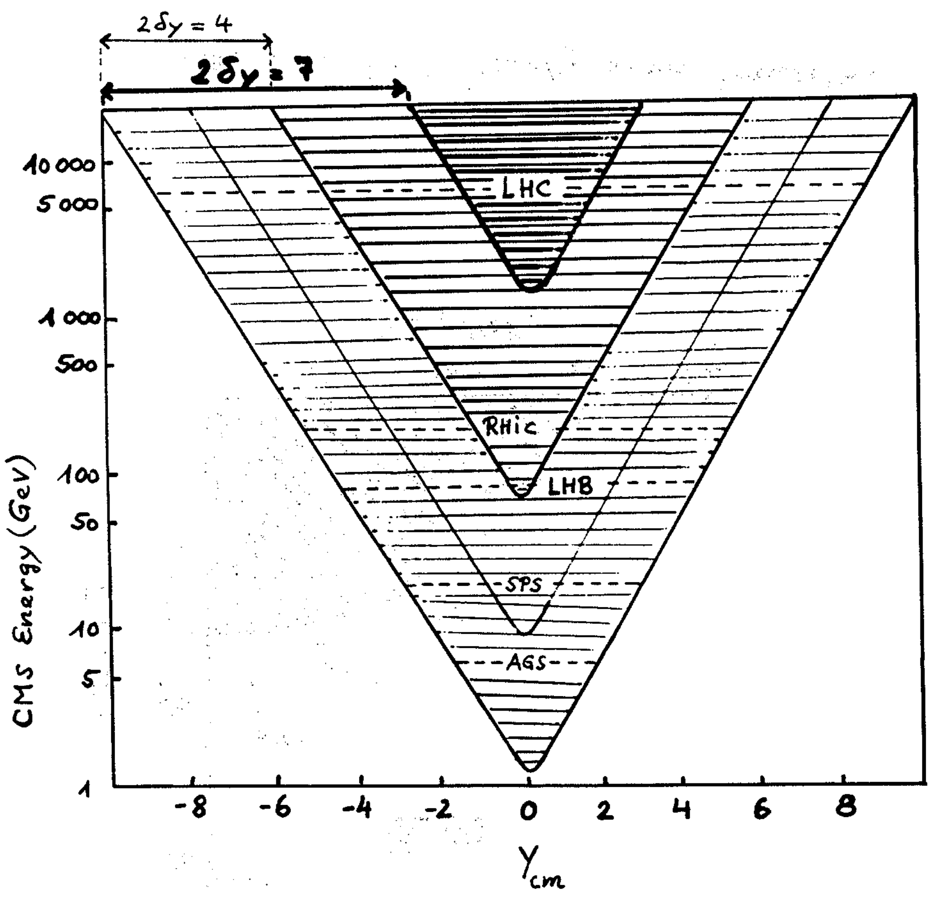
Event generators

Net baryon density (schematic)



(H. Satz, CERN-TH 6216/91)

Central rapidity gap



$\Rightarrow$ Expect: Physics $\approx$ const. in $y \in [-2,2]$

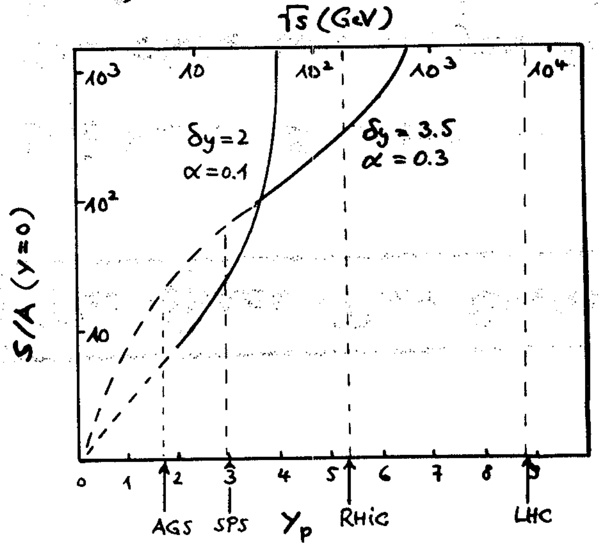
But: To check picture, measure $\frac{dN}{dy}$ (no particle id.) in larger region (-5 to +5 ?)
(plateau ? Gaussian ?)

How well can we reproduce the Early Universe in the laboratory ?

Specific entropy: $\left(S/A\right)_{\text{Early Universe}} = 10^{9 \pm 1}$

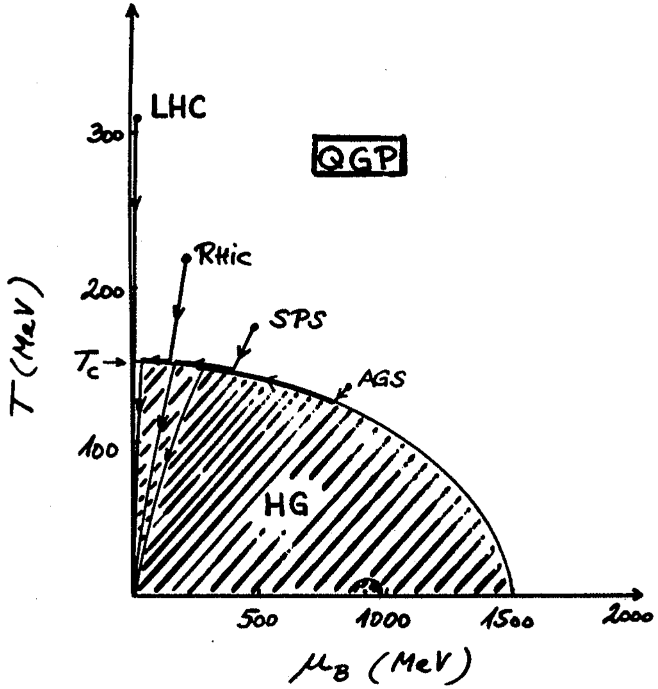
Nuclear collisions at $y=0$:

$$\frac{S}{A} \approx \frac{3.6 \frac{dN}{dy}}{\frac{dN_B}{dy}}$$



Even if $\frac{dN_B}{dy}$ = flat (??), we have at LHC $S/A\,(y=0) \sim 10^3$, i.e. about 5 times as usual as at RHic and more than 30 times as usual as at SPS.

Phase diagram with expansion trajectories for matter produced at $y \approx 0$ in various accelerators



Only with LHC "safely" above transition!

The Space-Time Evolution

Lifetimes & Sizes –

How close can we get to the thermodynamic limit?

Lifetimes

Plasma lifetime:

- determined by entropy conservation:
  $$s(\tau)\, V(\tau) \;\geq\; s_0 V_0$$
- initially only longitudinal expansion:
  $$V(\tau) \sim \tau$$

→ upper limit: $s_0 \tau_0 \leq s_{had} \tau_{had}$ (no mixed phase)

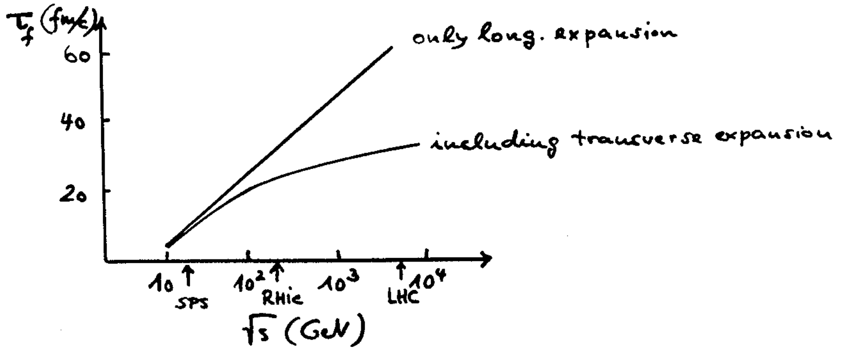
$$\rightarrow \tau_{had} \gtrsim \frac{s_0}{s_{had}} \tau_0 = \frac{d_{QGP} T_i^3}{d_{HG}^{eff} T_c^3} \tau_0 \approx \underset{\uparrow}{8} \left(\frac{T_i}{T_c}\right)^3 \tau_0 \sim \ln\sqrt{s}$$

including 3 flavors + resonances

- transverse rarefaction shock cuts plasma life short
  $$\tau_T = \frac{R_A}{c_{shock}} \sim (3\text{-}4) R_A \sim 20 - 30 \text{ fm/c for Pb}$$

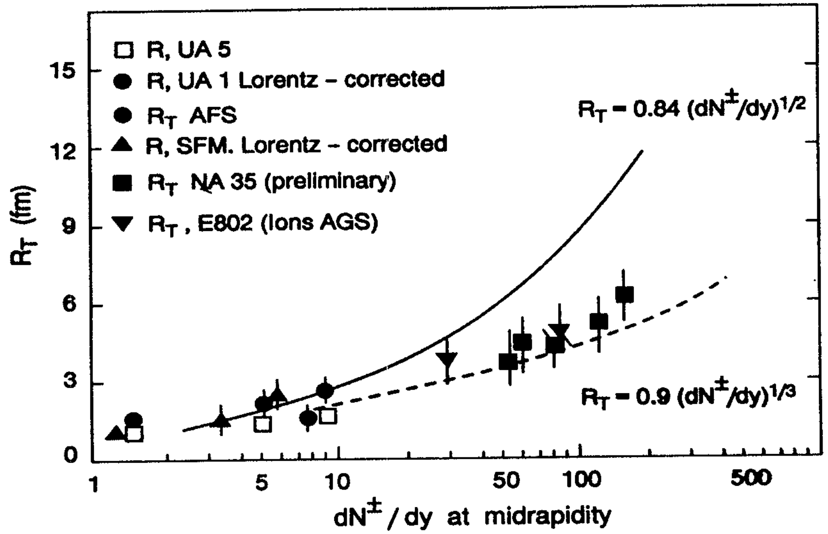
- after hadronization → 3-d expansion
  → very rapid decoupling

⇒ at high energies: total lifetime dominated by plasma phase ?



Size at freeze-out

2-pion HBT interferometry data:



Simple model to "explain" this:

Freeze-out at fixed τ_f, determined by transition temperature T_c

- $V_f = \pi R_f^2 \tau_f = \frac{V_0 s_0}{s_f} = \frac{1}{s_f} \cdot 3.6 \frac{dN}{dy} \xrightarrow[\frac{dN}{dy} = 2000 - 8000]{T_c = 150\,\text{MeV}} \underline{(0.8 - 3.4) \times 10^4 \text{ fm}^3 !}$
- Since $\tau_f \sim R_f \Rightarrow R_f \sim \left(\frac{dN}{dy}\right)^{1/3}$

Consequences:

For $\frac{dN}{dy}(LHC) = 2000 - 8000$ ⇒ $R_f(LHC) = 10 - 20$ fm
$= \underline{(1.5 - 3) \times R_{Pb}}$

[For $\frac{dN}{dy}(RHIC) = 700 - 2000$ ⇒ $R_f(RHIC) = 8 - 10$ fm $= \underline{(1 - 1.5) \times R_{Pb}}$]

Two words of caution:

1) Due to rapid longitudinal expansion volume elements which are separated in y by more than 1 unit are causally disconnected

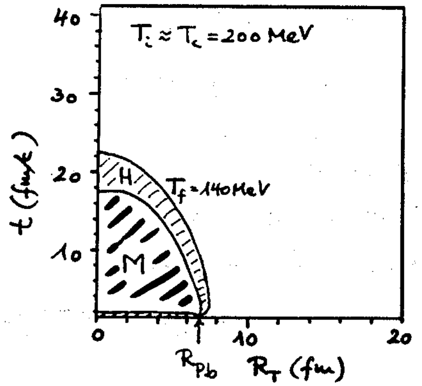
→ Causally connected volume at freeze-out is about factor 20 smaller

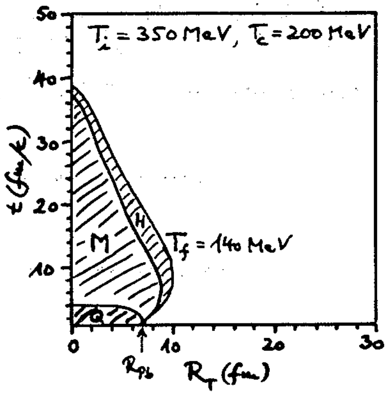
2) Freeze-out does not occur instantaneously at τ_f = const.

→ volume decreases by sequential freeze-out

Example: 2+1 dim. hydrodynamics, v. Gersdorff, Kataja, Ruuskanen, McLerran 1987

Freeze-out surface:

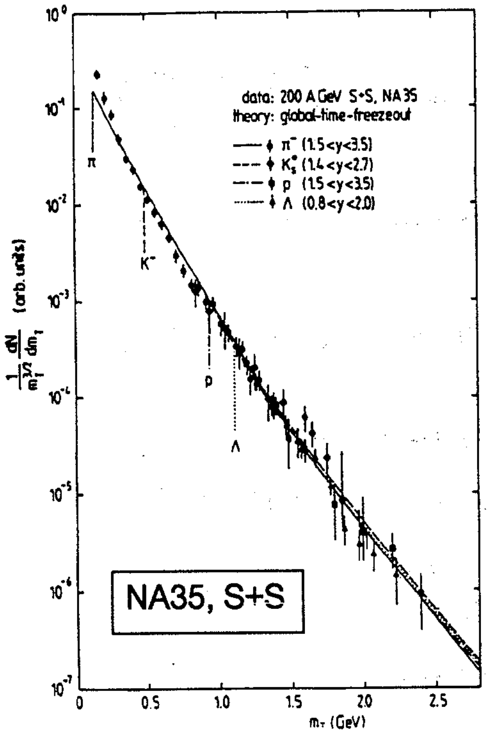


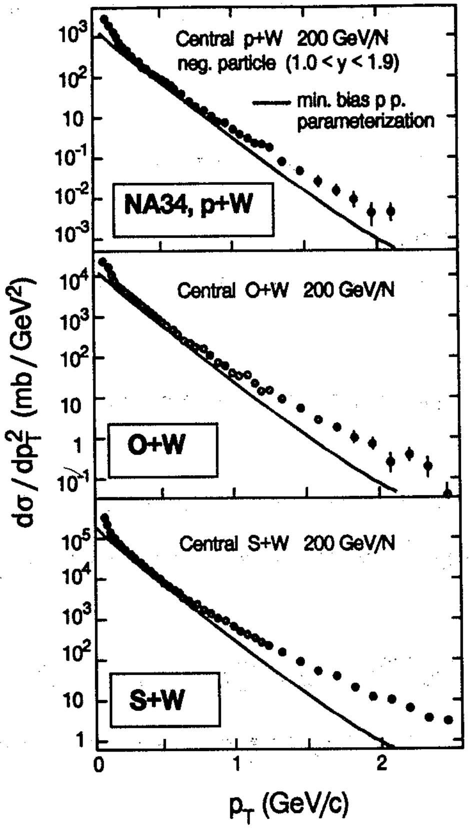


→ NA35 result $R_T(S+S) \approx 2 \times R_S$ very surprising!

Experimental Probes

Global features of P_t Spectra





- **identified particles (π,K,Λ):**
  - ⇨ universal slope (m_t-scaling), T≈ 200 MeV (pp: T ≈150 MeV)
  - ⇨ consistent with thermalization (+ collective flow) ?

    AGS (E802) $p_t(p) > p_t(K^+) > p_t(K^-) \approx p_t(\pi)$

    CERN (NA34) $p_t(K^+) > p_t(K^-)$ at $y \approx y_{target}$
- **neg. particles(π):** (good statistics, large range in p_t)
  - ⇨ big enhancement from p-p -> p-W

    at low pt < 250 MeV (resonance decays, Δ, ρ, ω...)

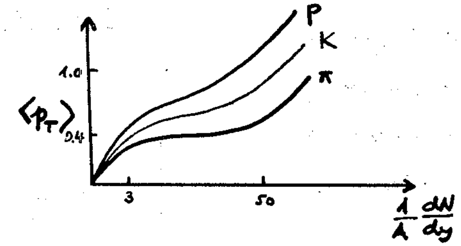
    at high pt > 1 GeV **CRONIN** effect, FNAL ('75)

    (increases with centrality and with A_P, A_T) rescattering, flow

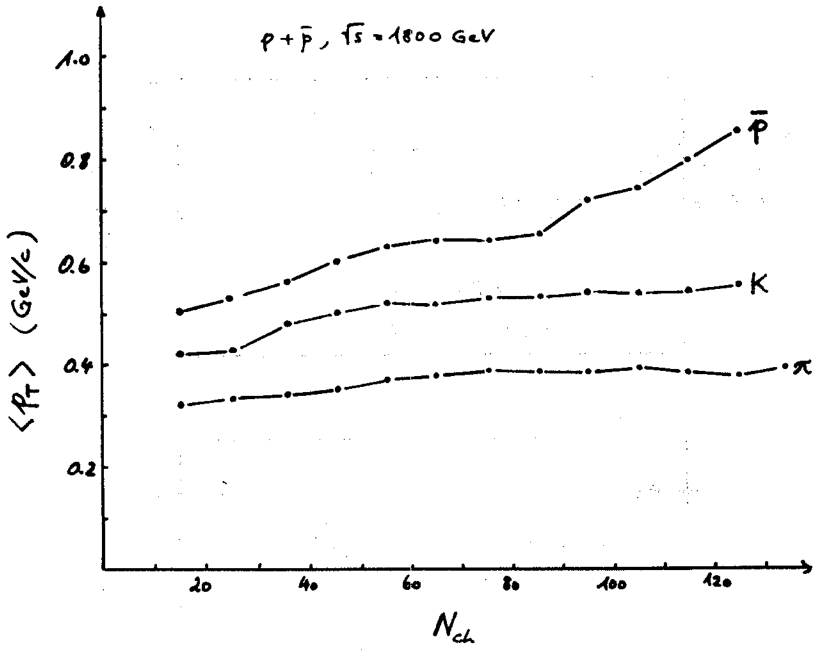
p_T - Spectra:

- 1^{st} order phase transition ⟷ characteristic "saddle point" in $\langle p_T \rangle$ vs. $\frac{dN}{dy}$ plot → Fig.
- Transverse flow → flattening of p_T-spectra + curvature → Fig.

  → larger $\langle p_T \rangle$ for heavier hadrons



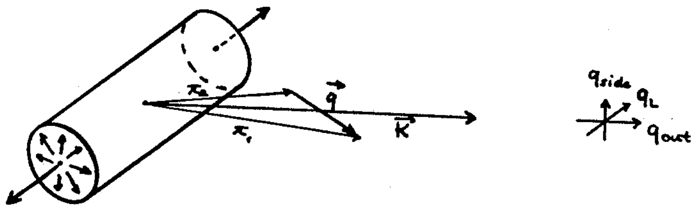
(Kataja et al.)



E735 (FNAL) (T. Alexopoulos et al. PRL 64 (90) 991)

Geometry & Dynamics at Freeze-Out

→ HBT Interferometry



Parametrize 2-particle-correlation function as

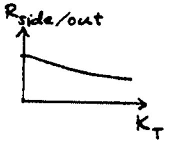
$$C(\vec{q},\vec{K}) = 1 \pm \lambda e^{-q_L^2 R_L^2(\vec{K}) - q_{side}^2 R_{side}^2(\vec{K}) - q_{out}^2 R_{out}^2(\vec{K})}$$

The parameters $R_i(\vec{K})$ ($i = L, side, out$) contain the following information (schematically): (Pratt, Sinyukov, Hama, Gyulassy...)

$R_{side}(K_T \to 0)$ ⟶ transverse size at freezeout R_T^f

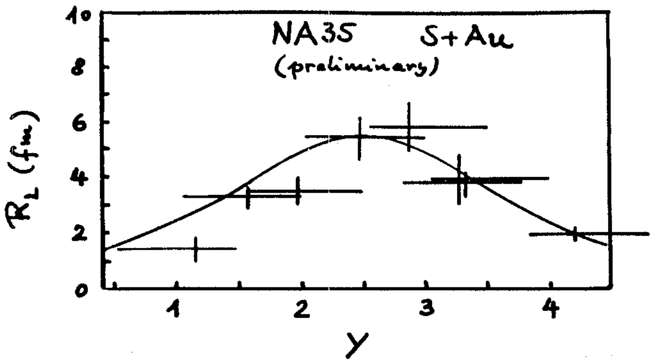
$R_{out} - R_{side}$ ⟶ duration of particle emission $\Delta\tau_f$

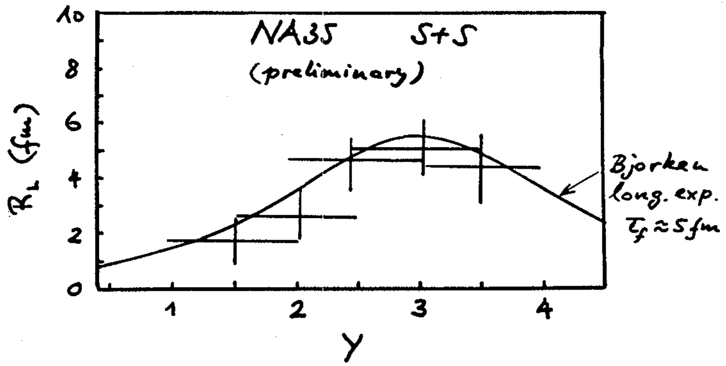
$\left.\begin{matrix} R_{side}(K_T) \\ R_{out}(K_T) \end{matrix}\right\}$ ⟶ transverse expansion:

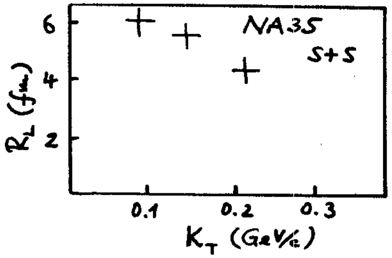


$R_L \overset{\text{in local rest frame}}{=} \sqrt{\frac{2T_f}{m_T}} \frac{1}{\frac{du_z}{dz}}$ ⟶ longitudinal expansion and decoupling time τ_f

$\sim \sqrt{2 T_f}$ (for Bjorken expansion)







K_T-dependence of R_L supports longitudinal flow (Salzburg, preliminary)

- $R_{out} \approx R_{side}$ → $\Delta\tau_f \lesssim 2$ fm/c rapid freeze-out
- No positive sign of transverse flow yet due to small statistics at large K_T

Strangeness Production – Approach to Chemical Equilibrium

UA5 - Compilation
+ AA data

Need:
- $\frac{K^\pm}{\pi^\pm}$, $\frac{\phi}{\rho^0}$, ...
- $\frac{\Lambda}{p}$, $\frac{\Xi}{\Lambda}$, $\frac{\Omega}{\Xi}$, $\frac{\bar\Lambda}{\bar p}$, $\frac{\bar\Xi}{\bar\Lambda}$, $\frac{\bar\Omega}{\bar\Xi}$, ...
- Systematics with $p_\perp$ ($m_\perp$) , Y , A_p , A_T !
  + centrality

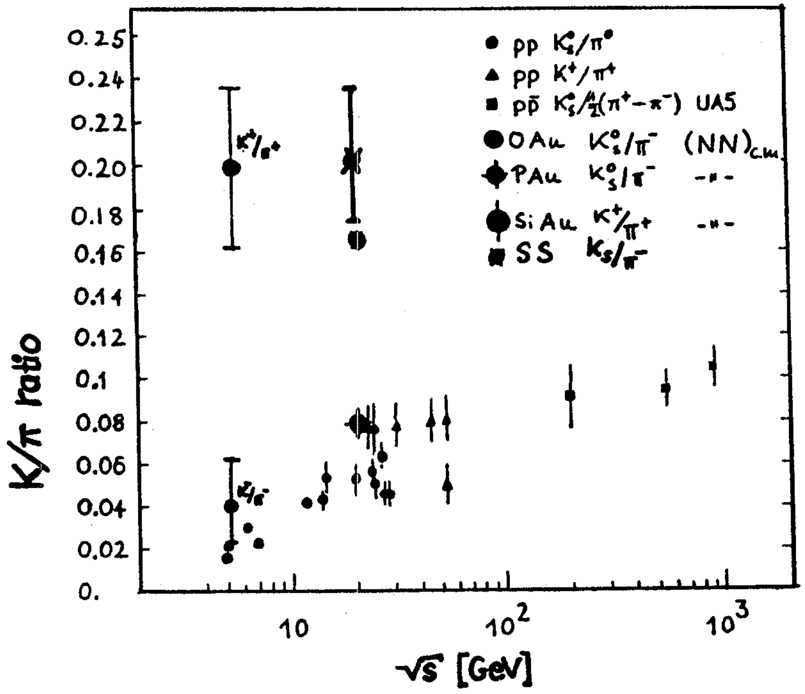
to sort out mechanisms:

- hadronic rescattering (e.g. associated production $N + \pi \to K Y$)
- hadronization of QGP (topological hadronization mechanism for $B - \bar{B}$ production ?)

different equilibration time scales!

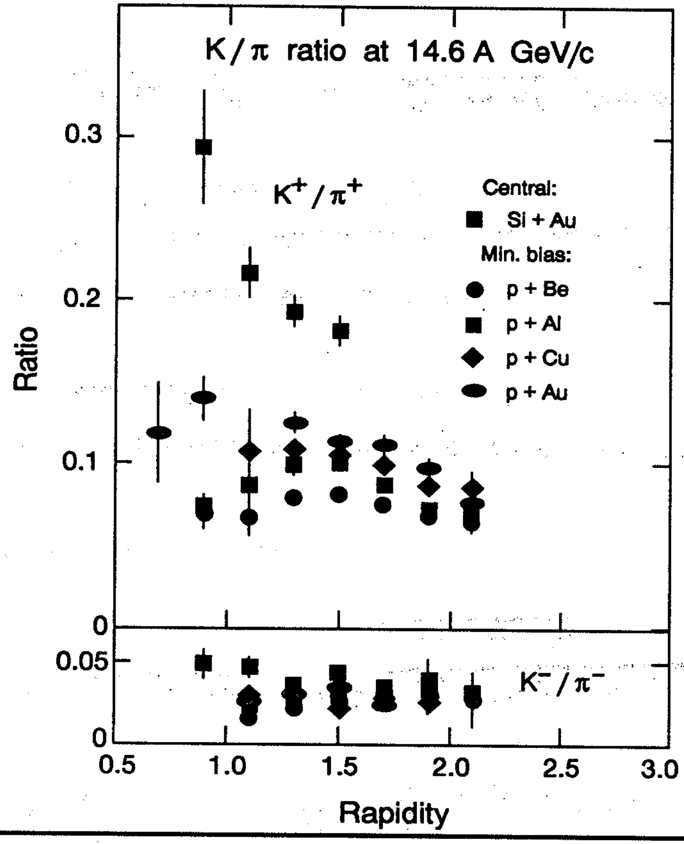
- chemical vs. thermal freeze-out

K/π -ratio (Experiment)



Kaons

E802	14.5 GeV/n Si+Au	$K^+/\pi^+ \approx 20\%$	$K^-/\pi^- \approx 3\%$
	pp	$K^+/\pi^+ \approx 6\%$	$K^-/\pi^- \approx 3\%$



NA34 200 GeV/n O+W (target fragmentation region)	$K^+/\pi^+ \approx 20\%$	$K^-/\pi^- \approx 5\%$
NA35 200 GeV/n S+S (midrapidity)	$K_0 \approx$ 2-3 times larger than in pp increasing with centrality	

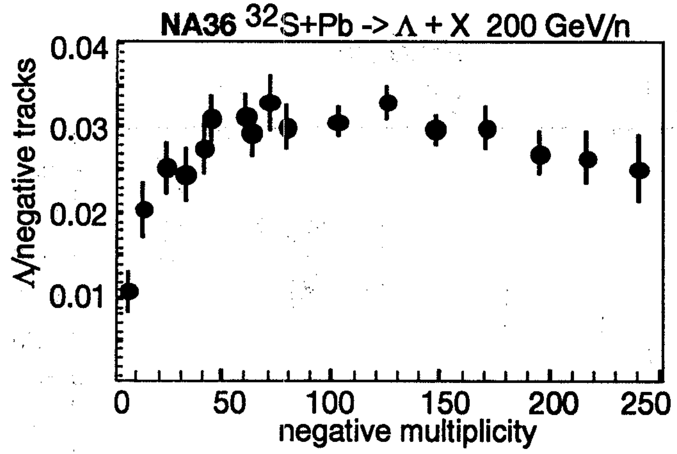
- **Strong Kaon enhancement ≈ equilibrium !**
  - ⇨ evolves gradually from p-p -> p-A -> A-A
  - ⇨ strongest in baryon dense region

Hyperons

NA35 O+Au
- Λ increase 2-3, no sign. effect in K_0^s, $\overline{\Lambda}$

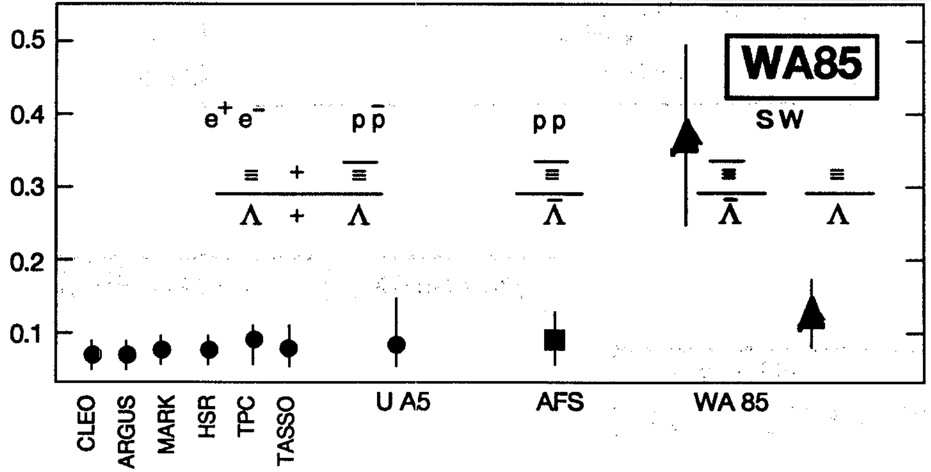
S+S
- $\Lambda,\overline{\Lambda},K_0^s$ increase ≈ 2-3 compared to pp
- y distrib: $\overline{\Lambda},K_0$central, Λ fragment. region

NA36 S+Pb
- $\Lambda,\overline{\Lambda}$ increase ≈ 2-3 compared with centrality



WA85 anti-Hyperons at $p_t > 1$ GeV, $y_{cm} \approx 0$

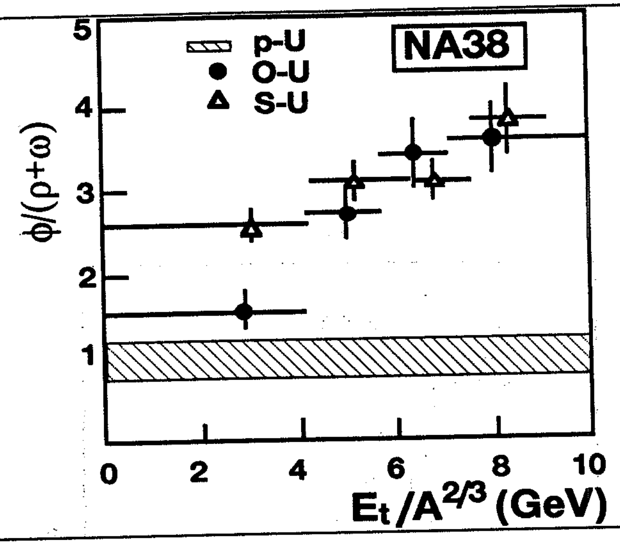
S+W/p+W
- 70% increase in Λ and $\overline{\Lambda}$
- factor >5 in $\overline{\Xi}/\overline{\Lambda}$, but low statistics



Phi Enhancement

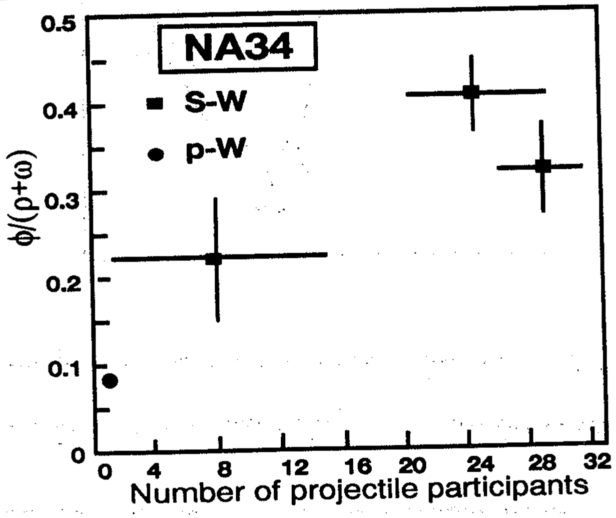
NA38 $\phi \to \mu\bar{\mu}$ high $p_t > 1.3$ GeV, $y_{cm} \approx 0.6$

- factor 3 enhancement with E_t in $\phi/(\rho+\omega)$



NA34 $\phi \to \mu\mu$ $p_t \approx 0.4 - 1.2$ GeV, $y_{cm} \approx 0.6$

- $\phi/(\rho+\omega)$ enhanced also at low p_t

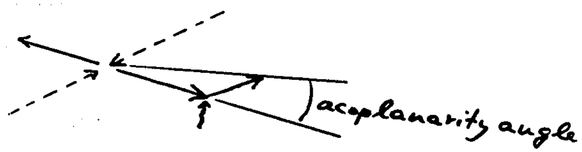


Jet quenching & Jet acoplanarity

- Jets = hard probes, which measure properties of fireball medium via their modification through soft final state interactions

Jet quenching → energy loss of leading jet partons travelling through medium (Bjorken, Thoma + Gyulassy, ...)

Jet acoplanarity → widening of out-of-plane angular distribution via rescattering (Appel, Blaizot + McLerran, Rammerstorfer + Heinz)



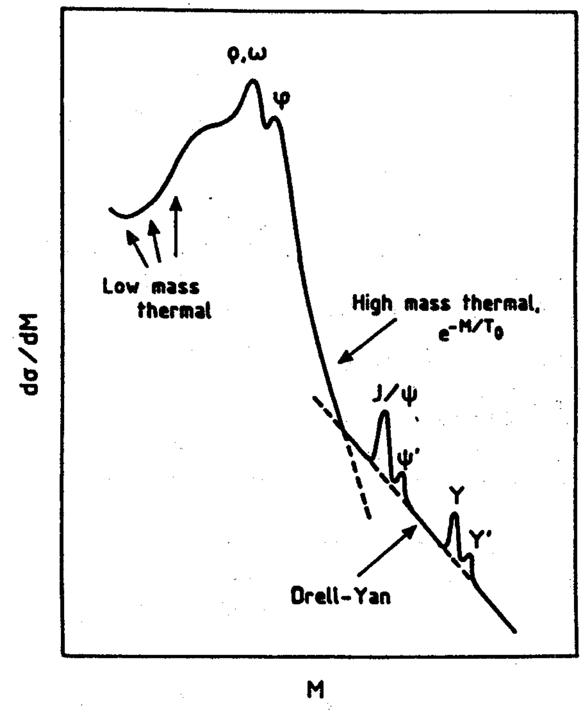
Important: Jets with $E_T \leq 40$ GeV hard to identify by calorimetry, due to enormous soft background in nucleus - nucleus collisions

→ identify by leading particles.

Use narrow correlation between direction of jet axis and of leading parton.

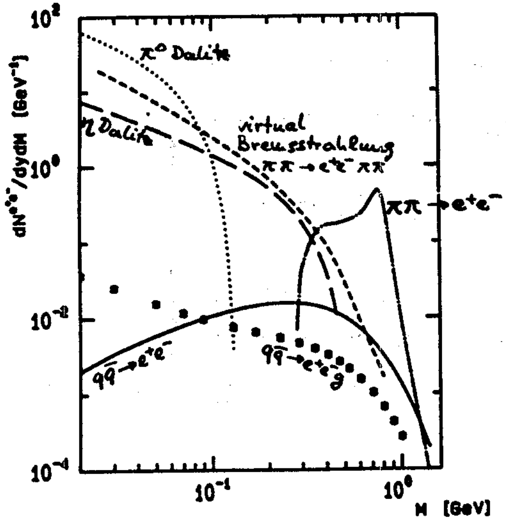
Dileptons & Photons

Decouple immediately → information on complete space-time history of collision!



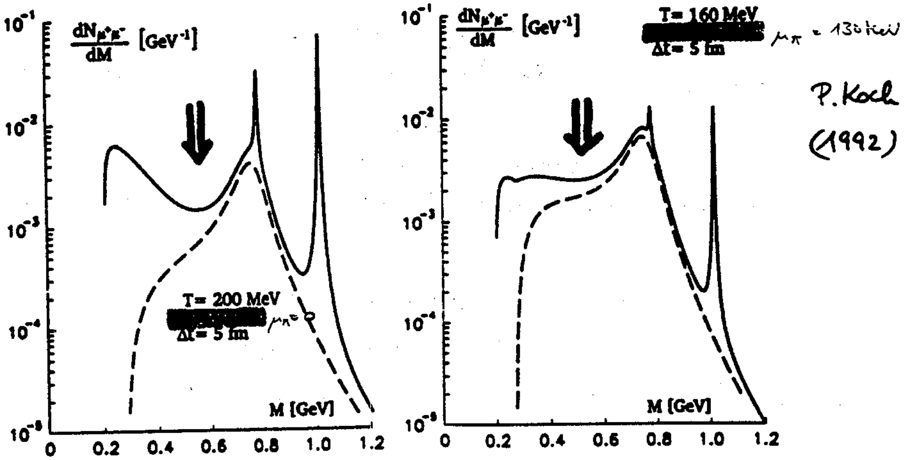
Continuum below $2m_\pi$:

Clymans, Redlich, Satz 1991



Low mass thermal dileptons from QGP → hopeless

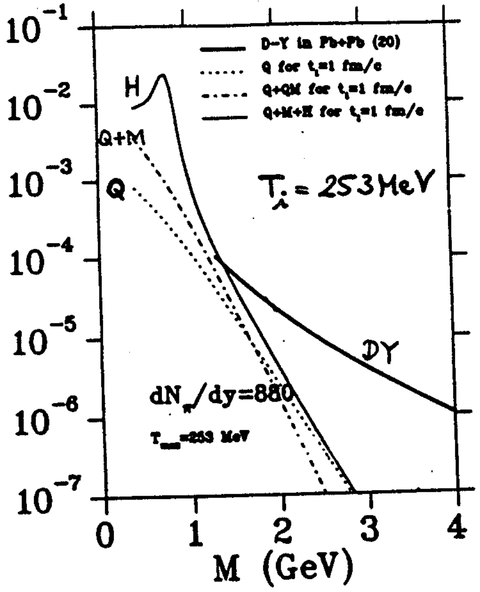
$2m_\pi < M_{\mu^+\mu^-} < m_\rho$:



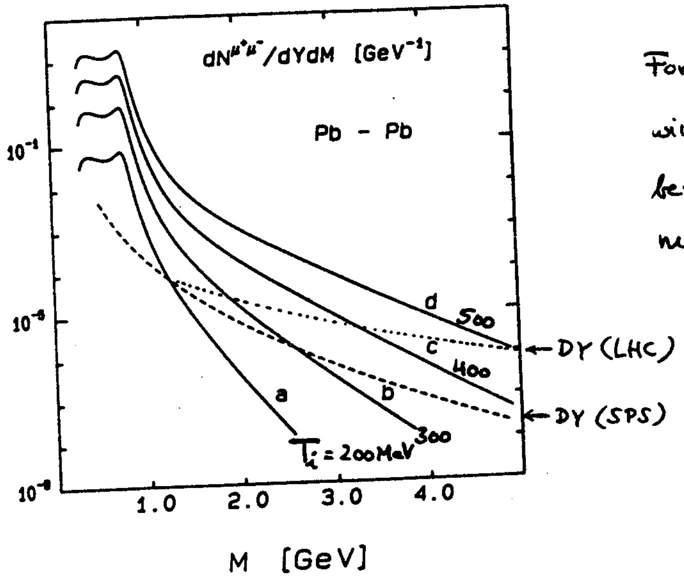
P. Koch (1992)

Region between $2m_\pi$ and m_ρ sensitive to $\mu_\pi \neq 0$!

High mass thermal dileptons:



For $T_i \leq 300$ MeV thermal QGP dileptons buried under DY and HG background.



For T_i = 350-400 MeV window for QGP between 1.5 GeV and $m_{J/\psi}$.

Difficult, but not hopeless!

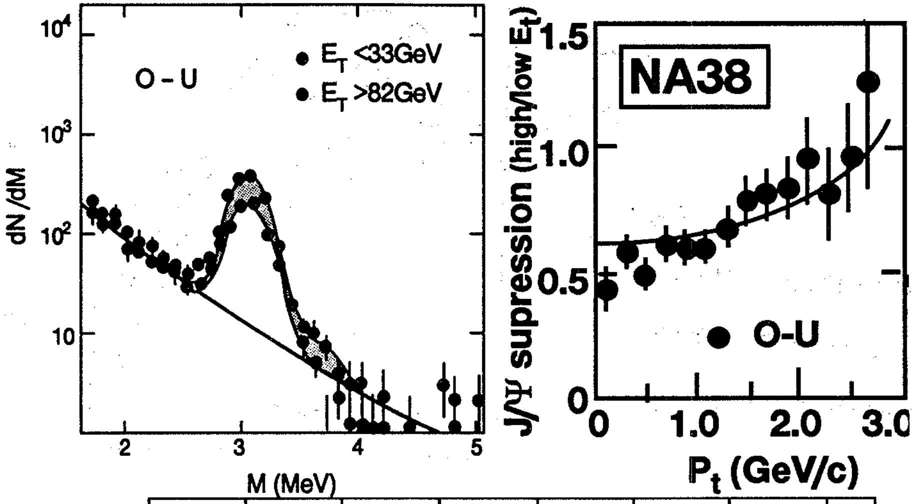
Vector Mesons:

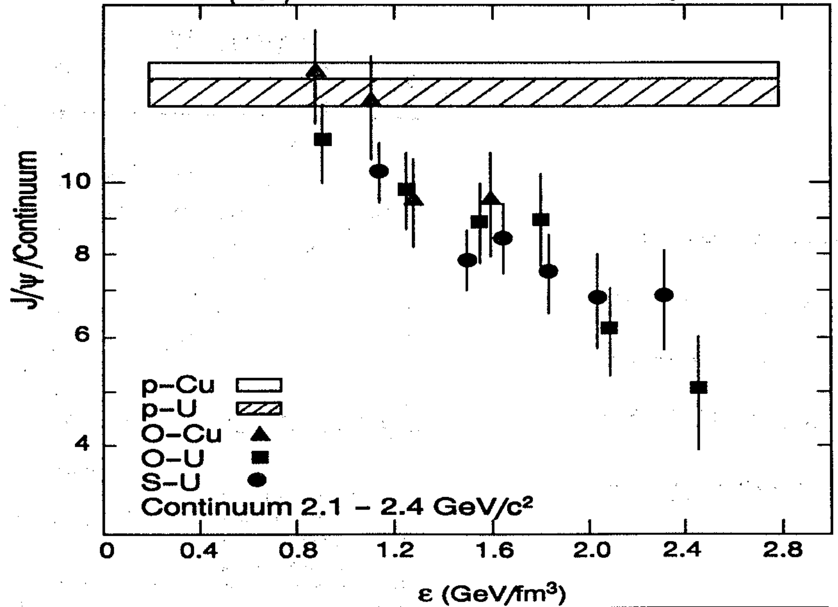
A: Heavy Quarkonia $J/\psi, \psi', \ldots, \Upsilon, \Upsilon', \Upsilon'' \ldots$

- Early production by hard parton-parton scattering
  - → sensitive to nuclear modifications of structure functions (EMC, shadowing...)
  - → simultaneous study of DY necessary to separate initial state from final state effects
    Study A-dependence (<u>pp</u>, SS, PbPb!)
- Multiple initial state scattering before parton fusion into $c\bar{c}$, $b\bar{b}$
  - → changes $p_\perp$-spectrum of initial $c\bar{c}$, $b\bar{b}$ pair
  - → study $p_\perp$-dependence of Quarkonium and DY production
  - → Need good acceptance at $\boxed{\text{low } p_\perp \approx 0}$, where these effects are strongest, but also at large $p_\perp$
    Note: at large $p_\perp$ problematic background from B decays expected
- Final state absorption effects by soft processes in dense medium:
  - "melting" of bound states by color screening
  - collision dissociation by scattering with partons or hadrons in dense medium
  - → study systematics in $\underline{E_T}$, $\underline{p_\perp}$, need separation of $\underline{J/\psi, \psi', \ldots, \Upsilon, \Upsilon', \Upsilon''}$ to study dependence on binding energy and system size → need good mass resolution $\lesssim 100-150$ MeV!

J/Ψ Suppression

NA38 J/Ψ ->μμ relative to continuum (DY)

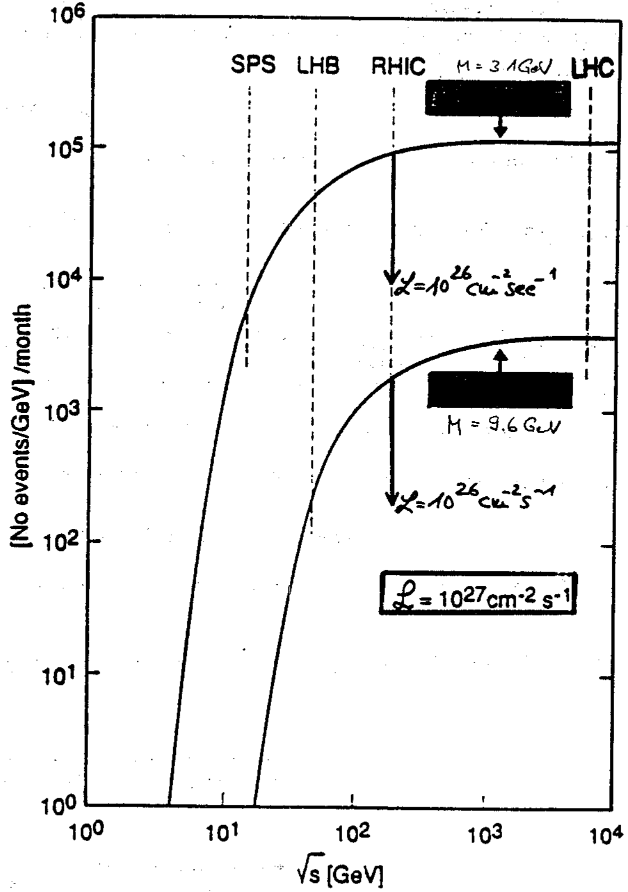




Strong E_t & p_t dependent suppression !

Important: Good statistics on DY spectrum between $c\bar{c}$ and $b\bar{b}$ resonance region to separate initial state from final state affects.

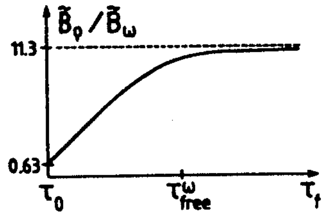
Drell-Yan rates at M_ψ and M_Υ

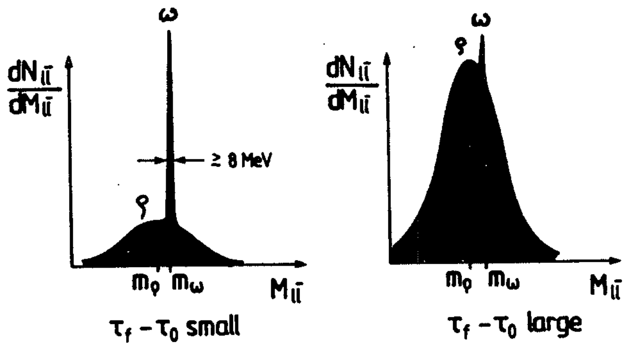


B: Low-Mass Vector Mesons ρ^0, ω, ϕ

- → information on space-time history of *hadronic stage* of collision (after hadronization)

- "*ρ-clock*":





$\tau_f - \tau_0$ small

$\tau_f - \tau_0$ large

- medium modifications of V-meson masses and widths (Shuryak...) → need $\tau(\text{hadronic phase}) \gtrsim \tau_V$

  e.g. $\frac{\phi \to l\bar{l}}{\phi \to K\bar{K}}$ as function of E_T (or ε)

- ϕ/ρ^0 or ϕ/ω → strangeness enhancement.

Important: $p_\perp$-spectrum, $0 \le p_\perp^{Vector} \lesssim 1\text{-}2$ GeV

SUMMARY

What LHC can do better than RHIC:

- Higher initial energy density

  $$\varepsilon_0 \gtrsim 10\,\varepsilon_c$$

- Higher initial temperature

  $$T_i \gtrsim 2\,T_c$$

  } Only here QGP ≈ ideal plasma

- Higher specific entropy

  $S/A \gtrsim 10^3$ → closer to Early Universe

- Larger lifetimes and freeze-out volumes
  - → better thermalization and equilibration
  - → collective flow more prominent
  - → only here QGP begins to dominate space-time evolution

- Thermal dileptons from QGP (only possible if $T_i \gtrsim 350-400$ MeV)

- DY up to m_Υ
- Full study of $c\bar{c}$ and $b\bar{b}$ spectrum
- Effects of dense matter on jets

  } if $\mathcal{L} \gtrsim 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$