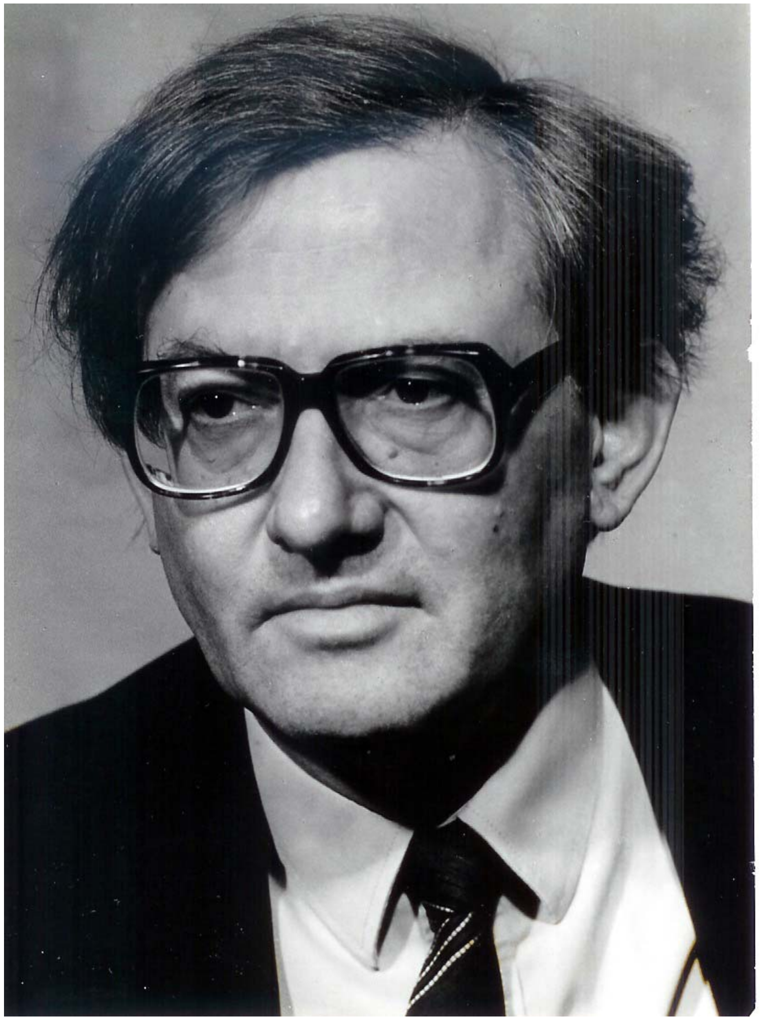
From interacting nuclear matter to strongly interacting quark matter

P. Lévai (RMKI, Budapest)

Zimányi Memorial Workshop
Budapest, 2 July 2007



József ZIMÁNYI (Jozsó)
(1931-2006)
Honorary chair of QM2005

Founder of the Hungarian relativistic heavy ion physics;

Teacher of the Budapest group;

Mastermind behind the Hungarian membership and activity at CERN;

Reformer of the Hungarian NSF;

Dreamer of the QGP for 30 years !

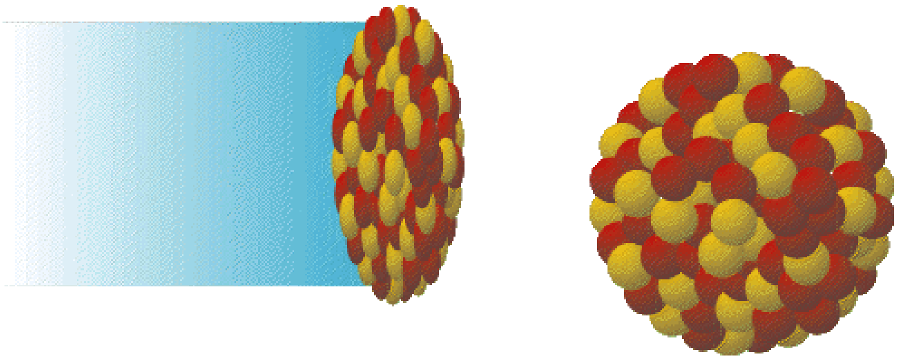
1954-74: Low energy nuclear physics (KFKI, Budapest)
γ-γ correlation; stripping reaction; optical potential; ...
1969-... : Visiting Copenhagen (Ole Hansen, NORDITA)
1974 The birth of QCD and relativistic heavy ion physics (T.D. Lee)
1979-06: ~100 theory articles and papers about HIC

- Hydrodynamical model: Bondorf-Garpman-Zimányi, '79
- Hadrochemistry: Montvay-Zimányi, '79
- Bose condensation: Zimányi-Fai-Jakobsson, '79
- Neural network: Csernai-Zimányi, '79
- Shock front: Bondorf-Ivanov-Zimányi, '81
- Three-fluid model: Lovas-Zimányi-Csernai-Greiner, '81
- Quark chemistry: Biró-Zimányi, '82
- Entropy and hadrochemistry: Biró-Barz-Lukács-Zimányi,'83
- Quark-Gluon Plasma formation: Biró-Zimányi, '85
- Relativistic Mean Field Theory: Zimányi-Bondorf-Mishustin, '85
  Zimányi-Moskowski, '90
- Pion correlation (SPACER) : Csörgő-Zimányi, '90-...
- Quark coalescence (ALCOR): Biró-Lévai-Zimányi, '95-...
- Quark mass spectra: Zimányi-Biró-Lévai-Ván, '05-...

Member of the CERN SPS NA49, RHIC PHENIX, CERN LHC ALICE !

Contents:

Relativistic heavy ion collisions: 1980-2000

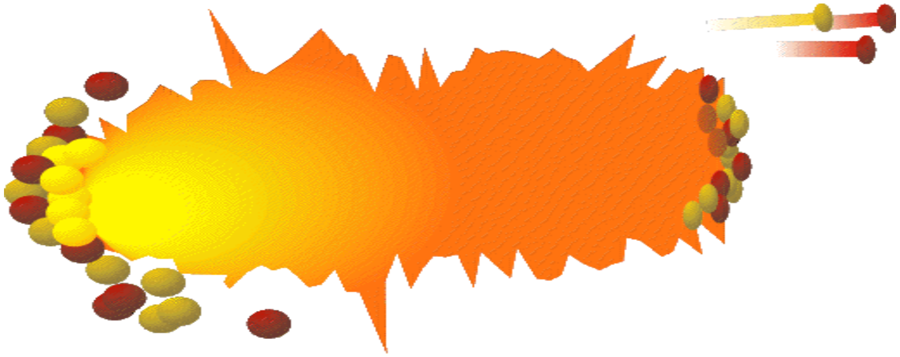


BEVALAC E(lab) = 1 GeV/A

⇩

CERN SPS E(lab) = 158 GeV/A

Q: Can we compress nuclear matter?
Will we see extreme states?



A: Strong stopping appears !!!
Many new particles will be produced!

↓

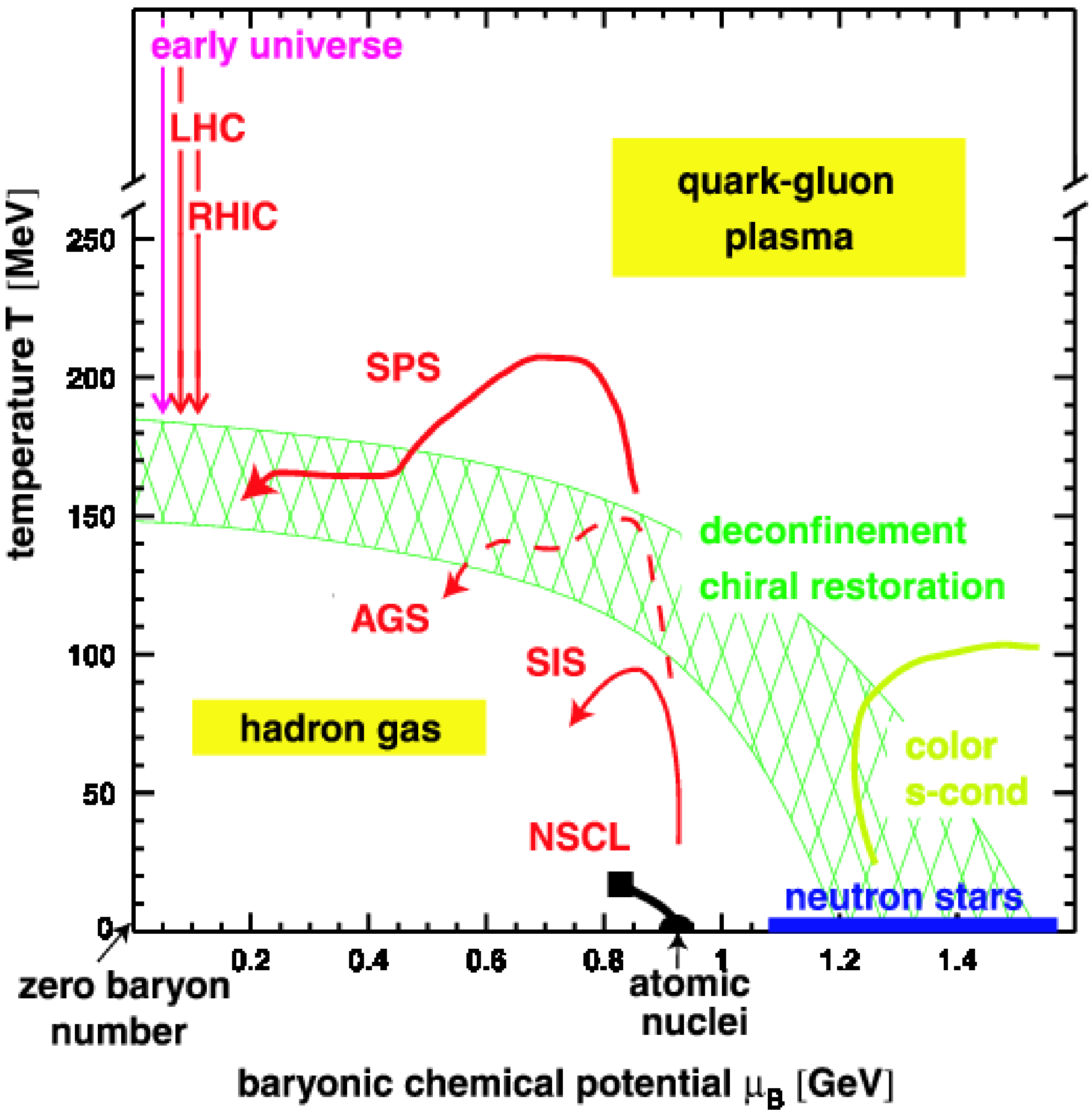
Hidrodynamical description
in thermodynamical equilibrium

↓

EOS for nuclear/hadronic matter
(EOS for neutron star)

⇨ Interacting nuclear/hadronic matter + fireball dynamics
Collective dynamics in heavy ion collisions

EOS for the interacting nuclear/hadronic/quark matter:



Quarks and gluons are present from SPS (AGS?) energy

'Bulk' matter :

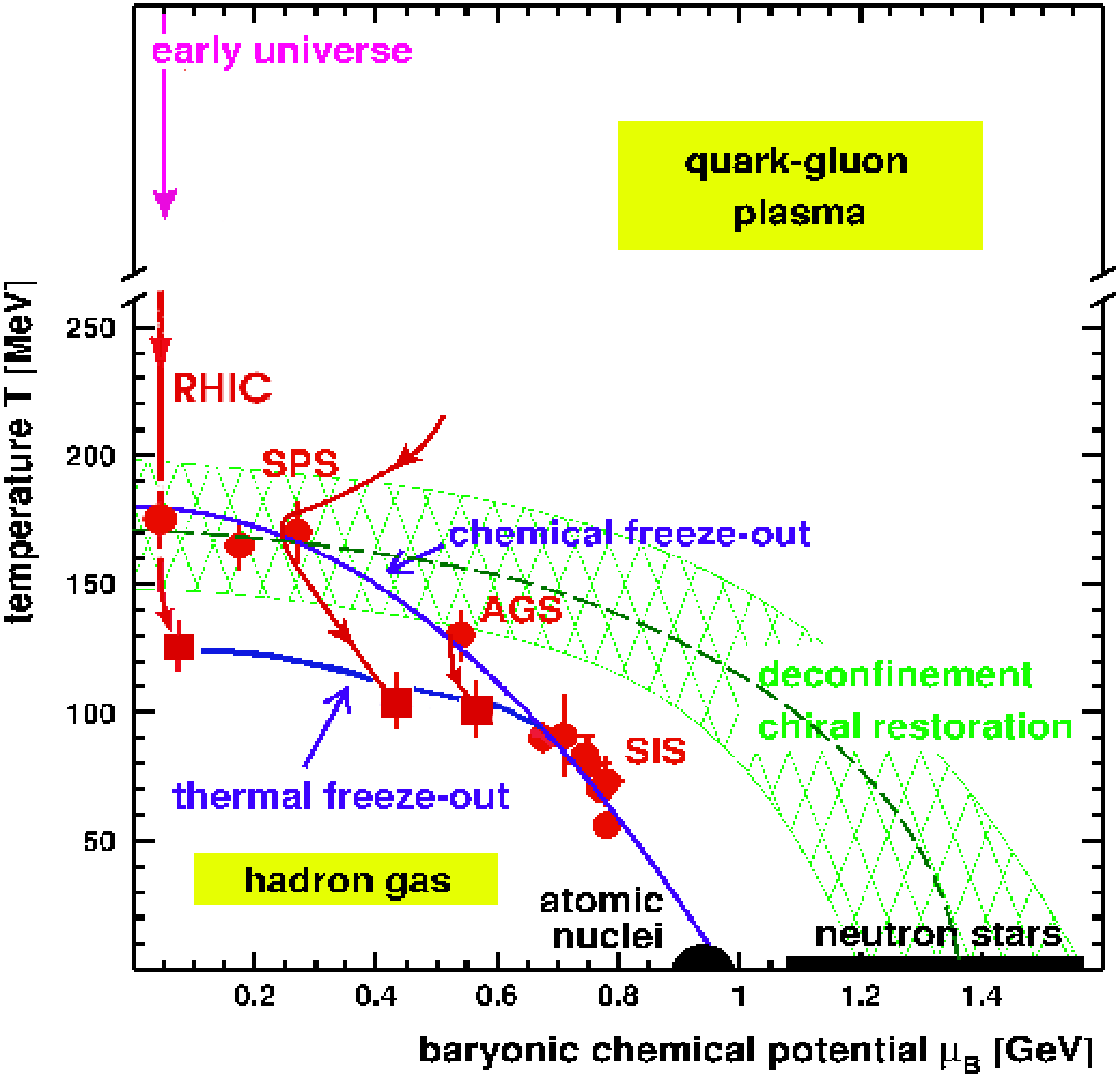
Hidrodynamical models
Thermal descriptions (T,μ)

Freeze-out conditions
in the expanding diluted
fireball

Particle production:
0 ⩽ p_T ⩽ 3 GeV

Exponential hadron distributions support thermal models

EOS for the interacting nuclear/hadronic/quark matter:



Measurement ($p_T < 3$ GeV):

Chemical and thermal freeze-out points can be determined from hadronic spectra

Questions:

Where is the quark/hadron matter phase boundary?

What are the early stages before hadronization?

Do we see any information about these early (QM) states in the hadron spectra ?

...

EOS for the interacting nuclear and hadronic matter – a la Zimányi :

1. Relativistic mean filed theory (Walecka-model, σ and ω fields)

   -- with interacting pions

   Zimányi, Bondorf, Mishustin, Theis, Bombay, 1984; NPA435,810,1985

   -- hadrochemistry in relativistic mean fields

   Biró, J. Zimányi, M. Zimányi, PLB137,271,1986

   -- mass dependent coupling constants

   $$g_{\sigma\Delta} = \left(1 + \frac{M_{\Delta} - M_{N}}{M_{N}}\right) g_{\sigma N}$$

   Lévai, Lukács, Waldhauser, Zimányi, PLB177,5,1986

   -- derivative scalar coupling ↣↣ Zimányi-Moszkowski model

   Zimányi, Moszkowski, PRC42,1416,1990

   $$M^{eff} = \frac{M}{1 + g_{s}\sigma / M}$$

   -- derivative scalar coupling + tensorial interaction

   Biró, Zimányi, PLB391,1,1997

   $$\overline{\psi}\left(\frac{\lambda}{2M^{eff}} g_{v} \sigma_{\mu\nu} F^{\mu\nu}\right)\psi$$

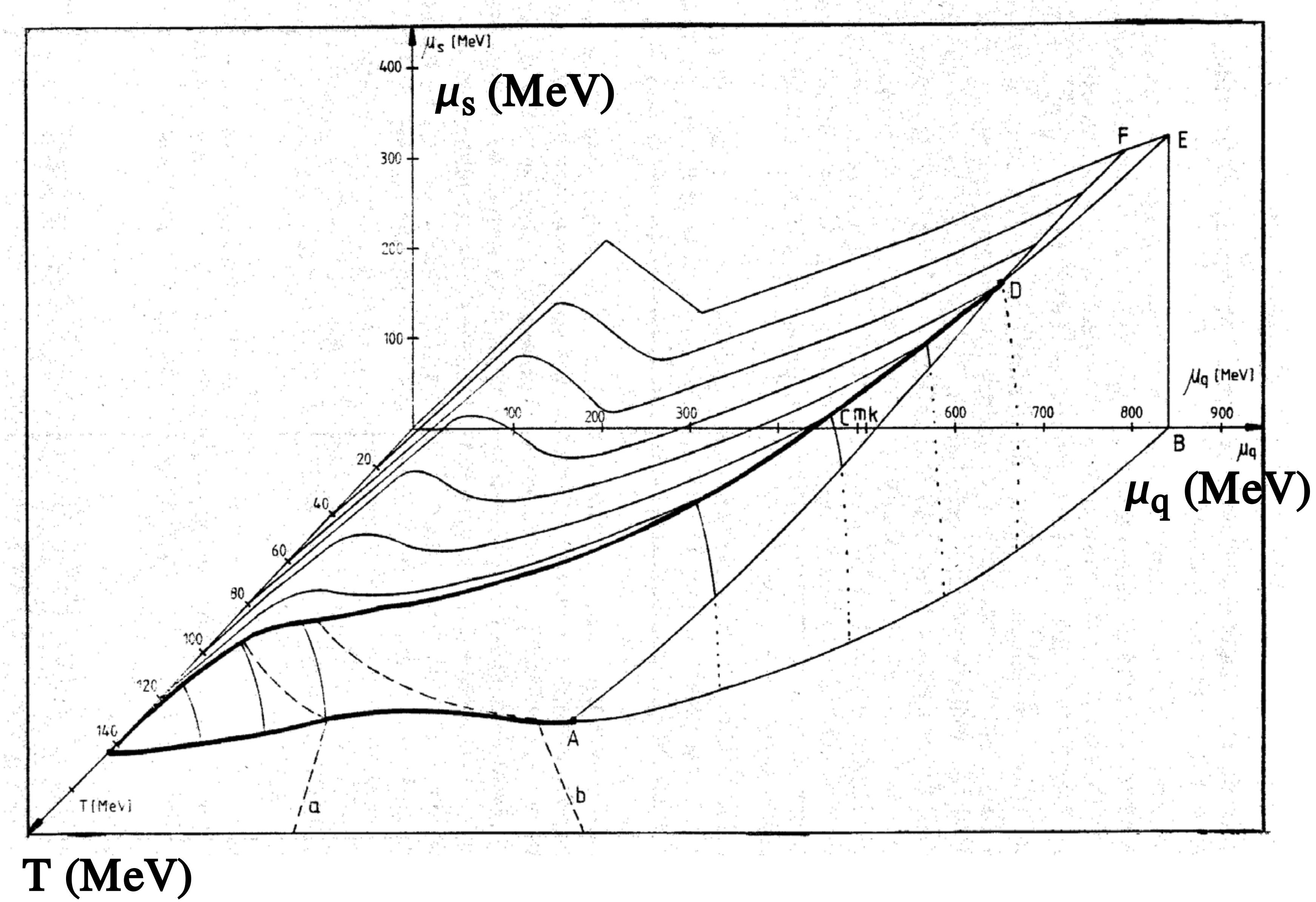
2. Density dependent equation of state [U(n)]

   Zimányi, Lukács, Lévai, Bondorf, Balázs, NPA484,647,1988

What about the QGP matter and a phase transition in equilibrium?

Equilibrium phase boundary between hadronic matter and QGP

P. Lévai, B. Lukács, J. Zimányi, XVI. Hirschegg Workshop, 1988.

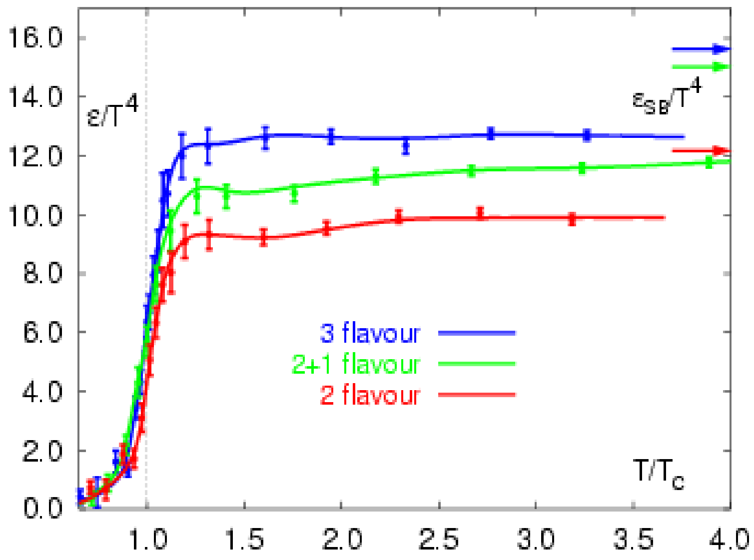


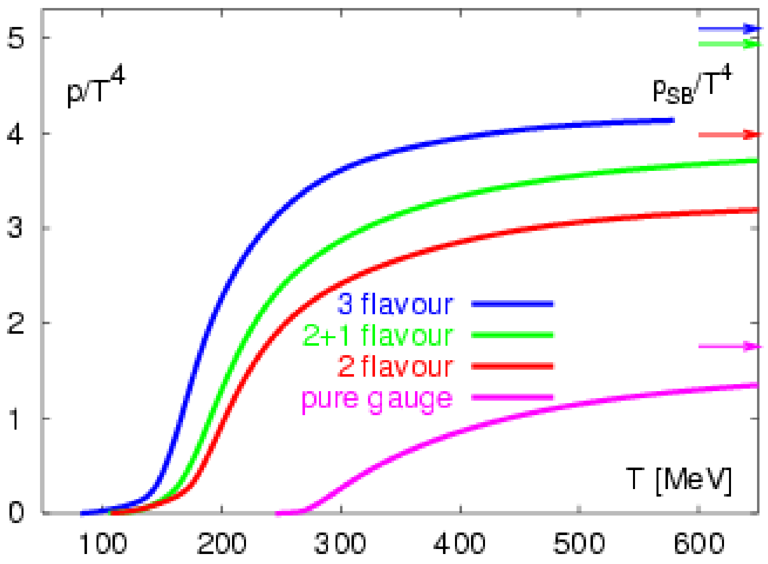
EOS for strongly interacting quark-gluon matter from lattice-QCD

zero baryon density (1990-2000)

finite baryon densities (2000 -)

➔ $\varepsilon(T, \mu)$, $P(T, \mu)$





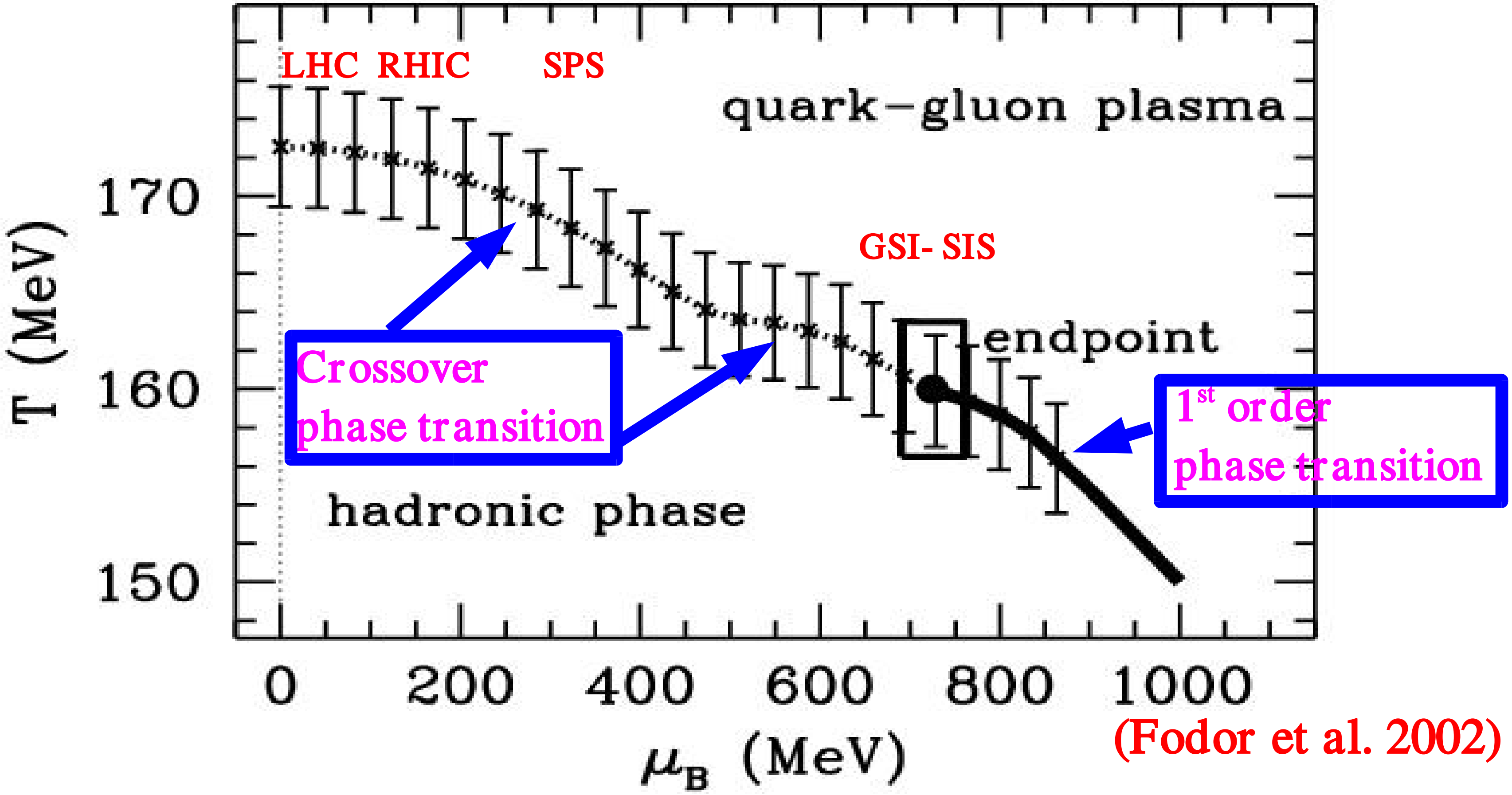
More realistic EOS for deconfined matter

Non-ideal EOS ➻ quasi-particle picture of strongly interacting QM

➤➤➤➤ Detailed microscopical picture of deconfinement is needed

Quark matter formation in heavy ion collisions

Lattice-QCD results at finite density, SU(3), $N_f=2$ $\mu>0$



LHC RHIC SPS

GSI- SIS

Crossover phase transition

1st order phase transition

(Fodor et al. 2002)

Crossover phase transition at small and intermediate baryon densities:

What is the microscopical mechanism of the hadronization ????

⇒ **QUARK COALESCENCE is one possibility**

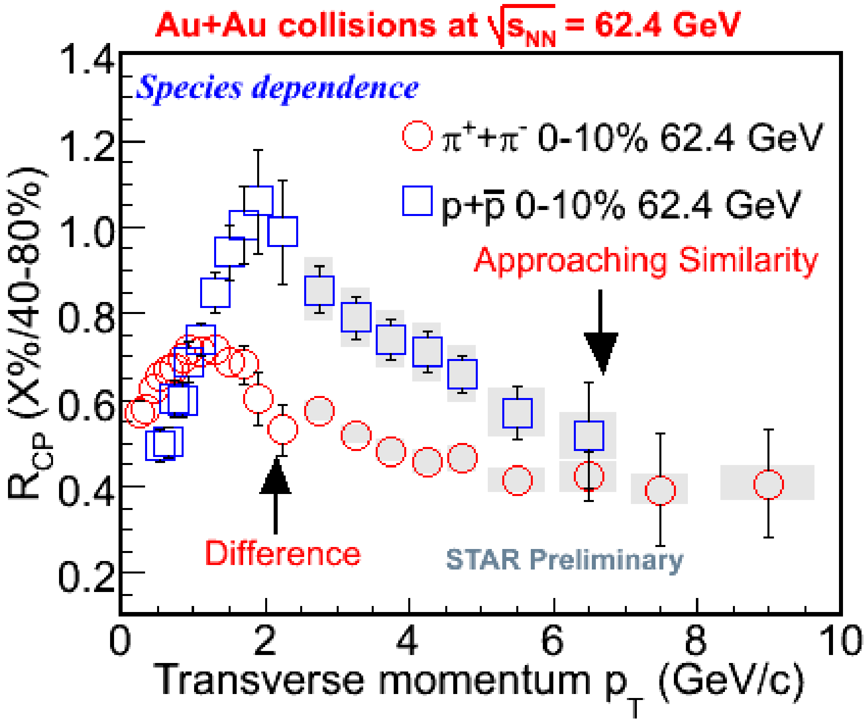
Interacting massive quarks around T_c !!

	Matter	Degrees of freedom	Hadron production	Model descr.
1983	QGP	free q,q,g (+B)	Thermal equilibrium fast thermalization (“miracles”) or parton-hadron duality	QCD pQCD
1993	wQGP	on-shell massive quasi-q,g $\Gamma_i \sim g^2 T \ln 1/g < m_i \sim g T$	Thermal equilibrium Quark-coalescence Resonance-production + decay	QCD phenom. QAP, MD
2003	sQGP	quasiparticles with mass distribution strong inter ↣ spectral func. $\Gamma_i \approx m_i \sim g T$	Quark-coalescence qq, qq – correlators	Lattice QCD QCD phenom
2006	ssQGP	no quasipartic. (geometry) [except high energy jets]	Compactification in higher (effective) dimens.	AdS/CFT
		or		
		interaction ↣ LFWF form.	Coalescence	QAP, Schröd.
		or		
		strong field dominance	Black hole phenomenology	Gen. relativity

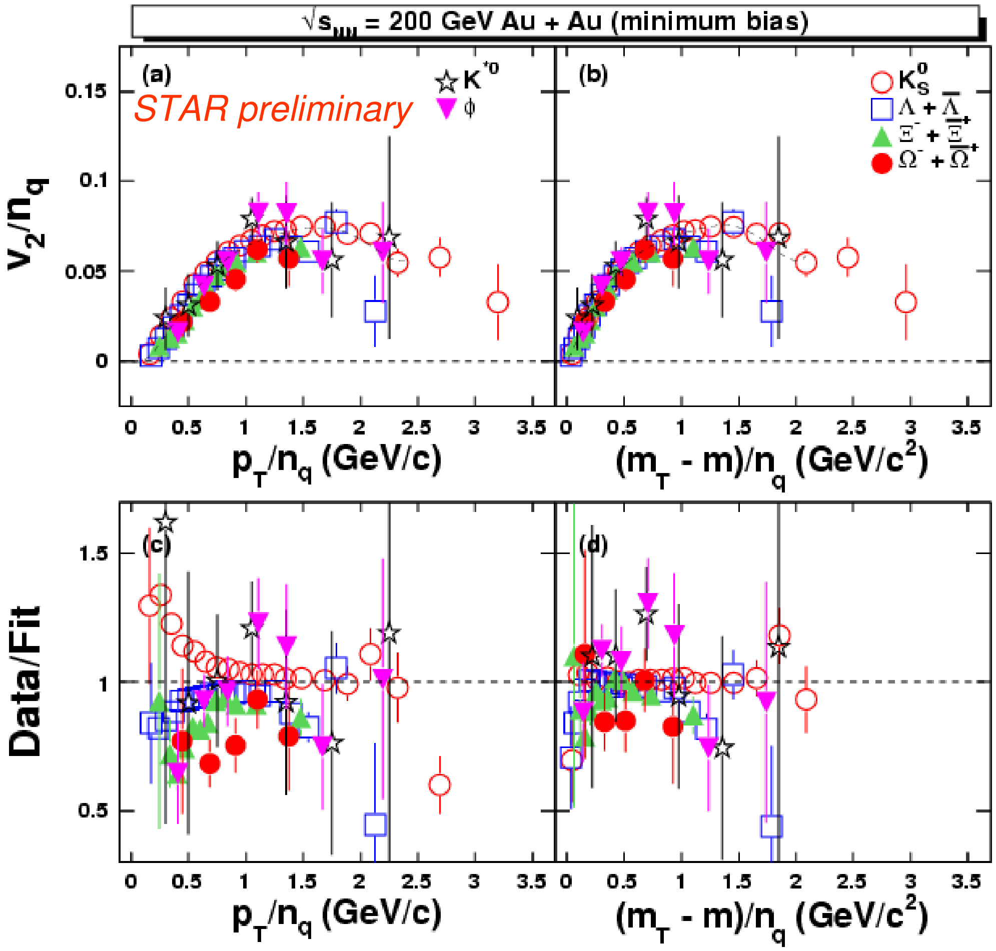
Recent RHIC results (QM06):

Meson- and baryon-suppressions are the same at high p_T!

Jet-picture incl. energy loss (pQCD)
is recovered beyond a threshold,
but anomalous B/M ratio at intermed. p_T



Constituent quark scaling can be clearly seen in v_2 !



Bulk quark-antiquark matter
around T_c phase transition,
deconfined quark-matter at $T>T_c$!

COALESCENCE: deuteron production in heavy ion collisions

Statistical quantum mechanics: [Feynman '72] ⇒ **Dover, Heinz, Zimányi PRC44(1991)1636.**

projecting the deuteron density matrix onto the two-nucleon density matrix:

[e.g. R. Scheibl, U. Heinz, PRC59(1999)1585.]

$$\frac{dN_d}{d^3P_d} \sim \frac{1}{2!}\int d^3x_1 d^3x_2 \; d^3x_1' d^3x_2' \; \phi_d^*(x_1,x_2)\phi_d(x_1',x_2') \; \langle \psi^\dagger(x_2',t_f)\psi^\dagger(x_1',t_f)\psi(x_1,t_f)\psi(x_2,t_f)\rangle$$

Deuteron wave-function: $\phi_d(x_1,x_2)=(2\pi)^{-3/2}\exp[iP_d(x_1+x_2)/2] \; \varphi_d(x_1-x_2)$

Internal wave-function: $\varphi_d(r)=(\pi d^2)^{-3/4}\exp(-r^2/2d^2)$ ⇤ **inner structure !!**

Wigner transformation: $D(r,q)=\int d^3\xi \exp[-iq\xi]\varphi_d(r+\xi/2)\varphi_d^*(r-\xi/2)$

$$\Rightarrow 8\exp(-r^2/d^2-q^2\cdot d^2)$$

Two-nucleon density matrix ↣ one-particle density matrix:

(at freeze-out the nucleons are uncorrelated)

$$\langle \psi^\dagger(x_2',t_f)\psi^\dagger(x_1',t_f)\psi(x_1,t_f)\psi(x_2,t_f)\rangle = \langle \psi^\dagger(x_2',t_f)\psi(x_2,t_f)\rangle\langle \psi^\dagger(x_1',t_f)\psi(x_1,t_f)\rangle$$

One-body Wigner function from the one-particle density matrix:

$$\langle \psi^\dagger(x',t_f)\psi(x,t_f)\rangle=\int\frac{d^3p}{(2\pi)^3}f^W(p;t_f,(x+x')/2)\exp[ip(x-x')]$$

The deuteron spectrum:

$$\frac{dN_d}{d^3P_d}=\frac{3}{(2\pi)^6}\int d^3r_d d^3q d^3r \, D(r,q) f_p^W(q_+,r_+) f_n^W(q_-,r_-)$$

Energy conservation: scattering on a third body before coalescence

QUARK COALESCENCE: meson production in bulk quark matter

Meson production: binding of a quark and an antiquark, $q + \bar{q} \Rightarrow M$

(constituent quark model, non-relativistic approx.)

--- (anti)quarks are inside a deconfined phase [QGP, QAP, CQM]

⇒ asymptotic wave functions do not exist inside deconf. phase !!!!

--- the interaction between quark and antiquark drives the meson production

⇒ non-relativistic $V(q\bar{q})$ potential (lattice-QCD results around T_c !)

--- direct calculation of coalescence matrix elements

$$M_{12} = \int d^3x_1 d^3x_2 \;\; \phi_M(|x_1 - x_2|) \;\; e^{-iPX} \;\; V_{12}(|x_1 - x_2|) \;\; \varphi_q(x_1)\varphi_{\bar{q}}(x_2)$$

⇒ $V_{12}(r)$ is an effective coalescence potential: $V_{12} = -\underline{\underline{\alpha_{eff}}} \dfrac{\langle \lambda_1 \lambda_2 \rangle}{r}$

⇒ many coalescence channels exist (π, ρ, K, K*, ϕ, ...)

--- introducing $1+2 \rightarrow 3$ coalescence cross section [e.g. ALCOR, PLB347,1995,6]:

$$\sigma_{12}(k) = \frac{m_3^2}{4\pi^2} \sqrt{\frac{2m_1 m_2}{(m_1+m_2)^2}} \;\; |M_{12}|^{12} = 16\, m_3^2 \sqrt{\pi}\, \alpha_{eff}^2\, \rho^3 \frac{a}{(1+(ka)^2)^2}$$

➡ a: Bohr radius

--- quark coalescence rate: $$\langle \sigma_{12} v_{12} \rangle = \frac{\int d^3P_1 d^3P_2 f_1(P_1) f_2(P_2) \;\; \sigma_{12} v_{12}}{\int d^3P_1 d^3P_2 f_1(P_1) f_2(P_2)}$$

Can we use such a non-relativistic approximation ??? ➣ Quark mass !?!

$m(q) \simeq 330$ MeV, $T \simeq 175$ MeV ➣ **OK**

New messages carried by strangeness and charm in AA collisions:

1. Initial strangeness/charm content of the colliding nucleons is neglected,

↣ final state strangeness/charm characterizes production dynamics !!

Newly produced strange quarks/antiquarks: $N_s = N_{\bar{s}}$

Newly produced charm quarks/antiquarks: $N_c = N_{\bar{c}}$

2. Strange and charm quark are massive and heavy:

Constituent quark masses: $M_s = M_{\bar{s}} \approx 450 - 500\ MeV$

$M_c = M_{\bar{c}} \approx 1200 - 1500\ MeV$

↣ Strange/charm hadron production is enhanced in coalescence !!

Coalescence rate is enhanced:

$$\sigma_{12}(k) = \frac{m_3^2}{4\pi^2}\sqrt{\frac{2m_1 m_2}{(m_1+m_2)^2}} \qquad |M_{12}|^{12} = 16\, m_3^2 \sqrt{\pi}\, \alpha_{eff}^2 \rho^3 \frac{a}{(1+(ka)^2)^2}$$

3. New hadron species can be measured and investigated:

↣ $K^+, K^-, \Lambda, \Xi, \Omega, \ldots; D^+, D^-, J/\psi, \Lambda_c, \Xi_c, \Omega_c, \Omega_{cc}, \Omega_{ccc}, \ldots.$

J. Zimányi et al., JPG, New J. Physics, PLB, ...

Quark matter formation in heavy ion collisions – basic assumption

ALCOR model for quark matter hadronization

Biró, Lévai, Zimányi, Phys. Lett. B347,6, 1995

Massive quarks/antiquarks are the basic d.o.f.: $u, \bar{u}, d, \bar{d}, s, \bar{s} (c, \bar{c})$

Stopping: initial quarks from colliding nucleus

$$\frac{dN(u)}{dy} = P * N_u^{(total\, u)} + \frac{dN(\langle u \bar{u} \rangle)}{dy}$$

Newly produced light quark-antiquark pairs

Newly produced strange quark-antiquark pairs $\frac{dN(s)}{dy} = \frac{dN(\langle s \bar{s} \rangle)}{dy}$

Attractive **potential** between (anti-)quarks $V_{eff}(r) = -\alpha_{eff} \frac{\langle \lambda_i \lambda_j \rangle}{r}$

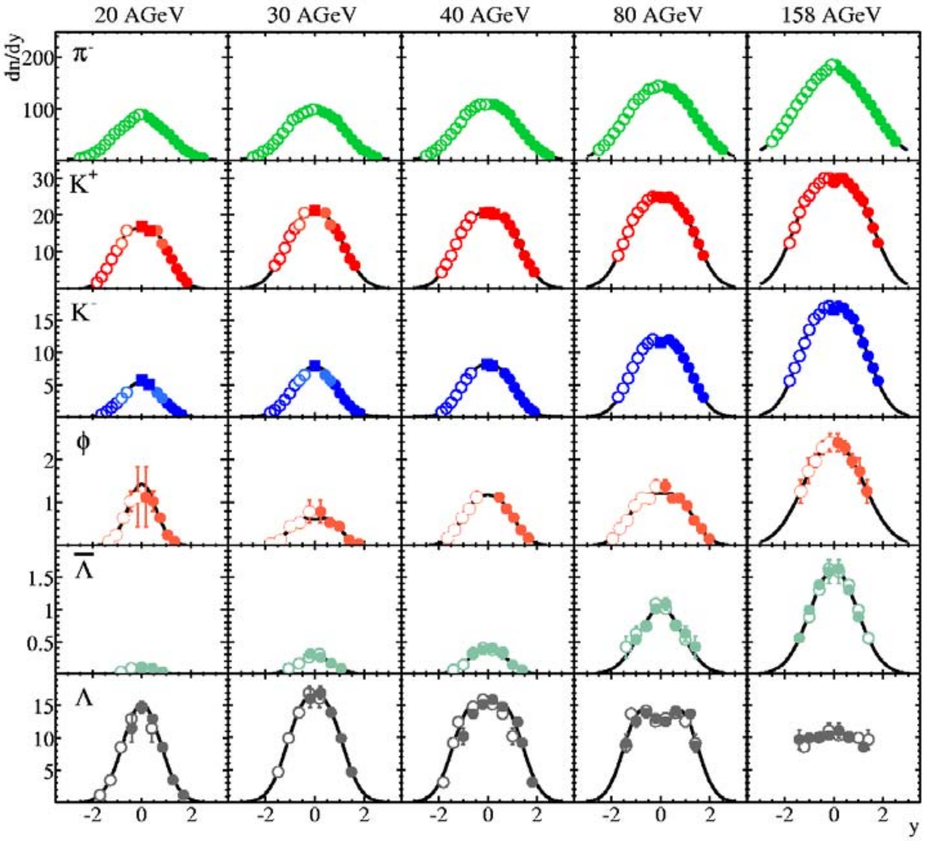
Heavy **hadron resonances** are produced -> decay

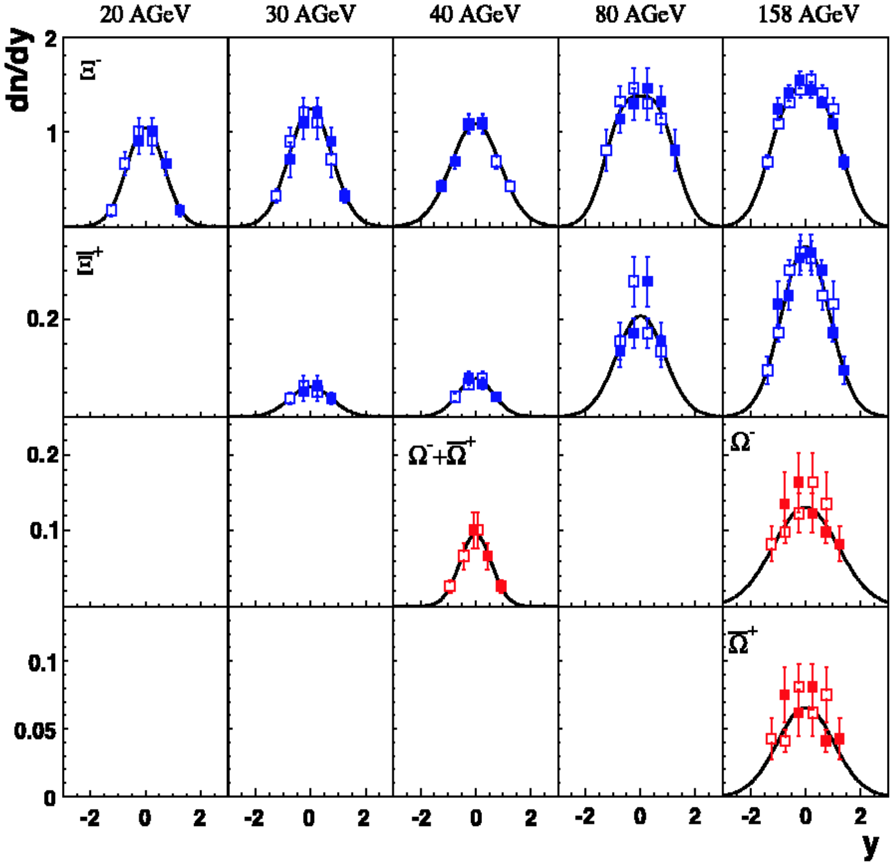
4 input parameters: $\underline{P}; \underline{\langle u \bar{u} \rangle} = \langle d \bar{d} \rangle; \langle s \bar{s} \rangle = \underline{f_s} * (\langle u \bar{u} \rangle + \langle d \bar{d} \rangle); \underline{\alpha_{eff}}$

Quark matter formation at SPS energies between 20-158 GeV/nucl

Detailed NA49 results on hadron production:

Rapidity distributions ↣ rapidity dependent analyzis





Baryon asymmetry (stopping) is very much rapidity dependent !!!

"Total" particle numbers ↣↣↣ rapidity densities, dN/dy

ALCOR results at SPS energies in the mid-rapidity:

Input parameters:

dN/dy (y=0)	20 GeV/n	30 GeV/n	40 GeV/n	80 GeV/n	158 GeV/n
π^-	90±5	95±5	110±5	145±5	182±5
K^-	5.5±0.5	8±0.5	8±0.5	12±0.5	17.5±0.5
K^+/K^-	3±0.2	2.6±0.2	2.55±0.2	2.1±0.2	1.7±0.2
Ξ^+	---	0.05±0.02	0.07±0.02	0.2±0.05	0.34±0.04
[Ξ^-	1±0.2	1.2±0.2	1.1±0.1	1.4±0.2	1.5±0.2]

ALCOR parameters:

New uu-pairs (± 2)	45	50	62	88	123
f_s (± 0.01)	0.40	0.35	0.30	0.28	0.24
α_s (± 0.02)	0.80	0.80	0.80	0.80	0.72
$\text{Stopping}_{y=0}$ (± 1%)	20 %	20%	20%	20%	15 %

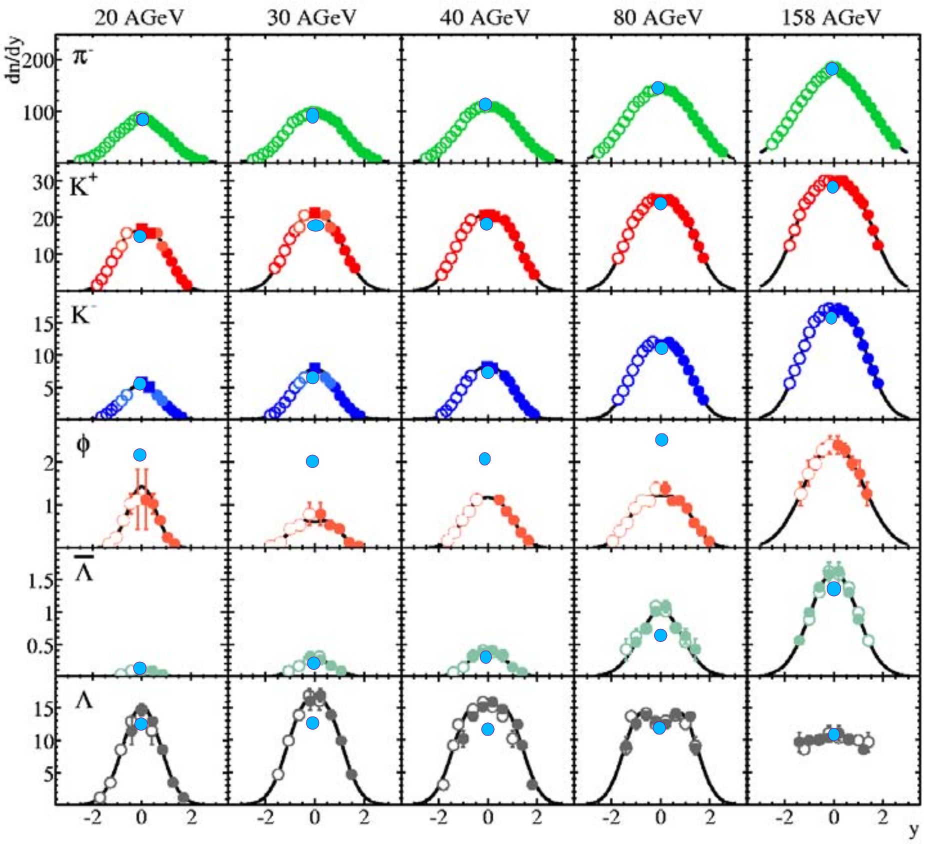
ALCOR result (examples):

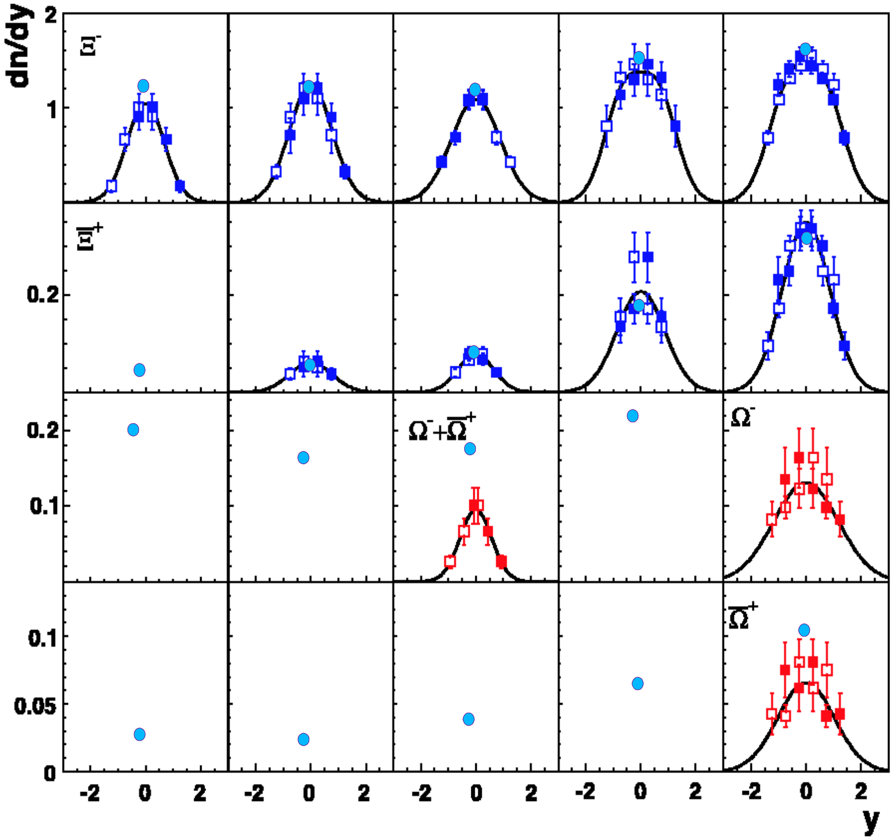
K^+/π^+	0.213	0.192	0.173	0.171	0.158
Λ^0/p^-	1.36	1.16	1.0	0.93	0.80
ϕ / K^-	0.42	0.385	0.34	0.32	0.28
$(\Omega^-+\Omega^+)/\pi^-$ x 100	0.268	0.217	0.189	0.233	0.244

Quark matter formation at SPS energies between 20-158 GeV/nucl

ALCOR results in the mid-rapidities:

(Maybe this is the time for a full, rapidity dependent analysis.)



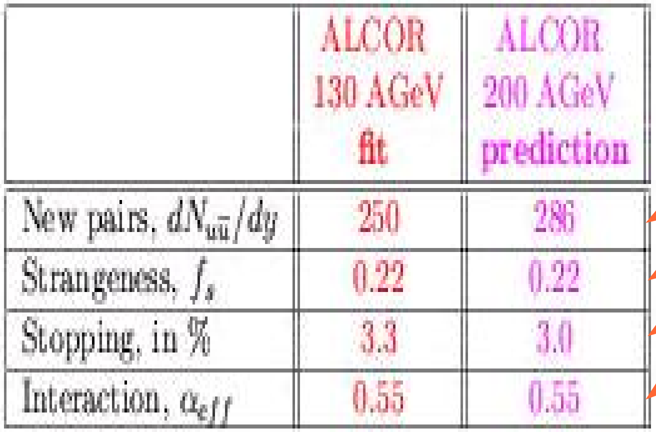


Further improvements on wave functions ↣↣↣ **G. Hamar's talk**

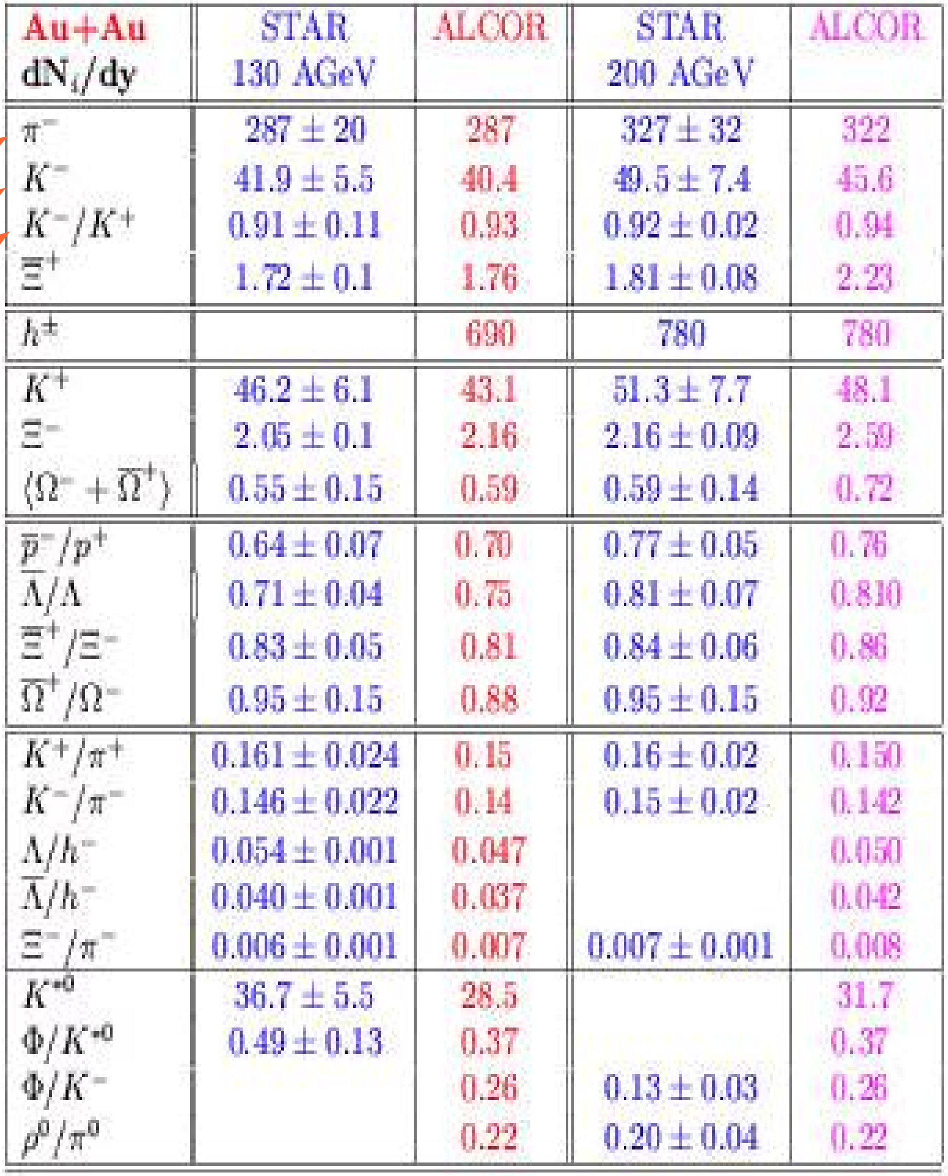
on quark mass distributions ↣↣↣ **T.S. Biro's talk**

Quark matter formation at RHIC at √s = 130 & 200 A GeV

ALCOR model for quark matter hadronization



	ALCOR 130 AGeV fit	ALCOR 200 AGeV prediction
New pairs, $dN_{u\bar{u}}/dy$	250	286
Strangeness, f_s	0.22	0.22
Stopping, in %	3.3	3.0
Interaction, α_{eff}	0.55	0.55

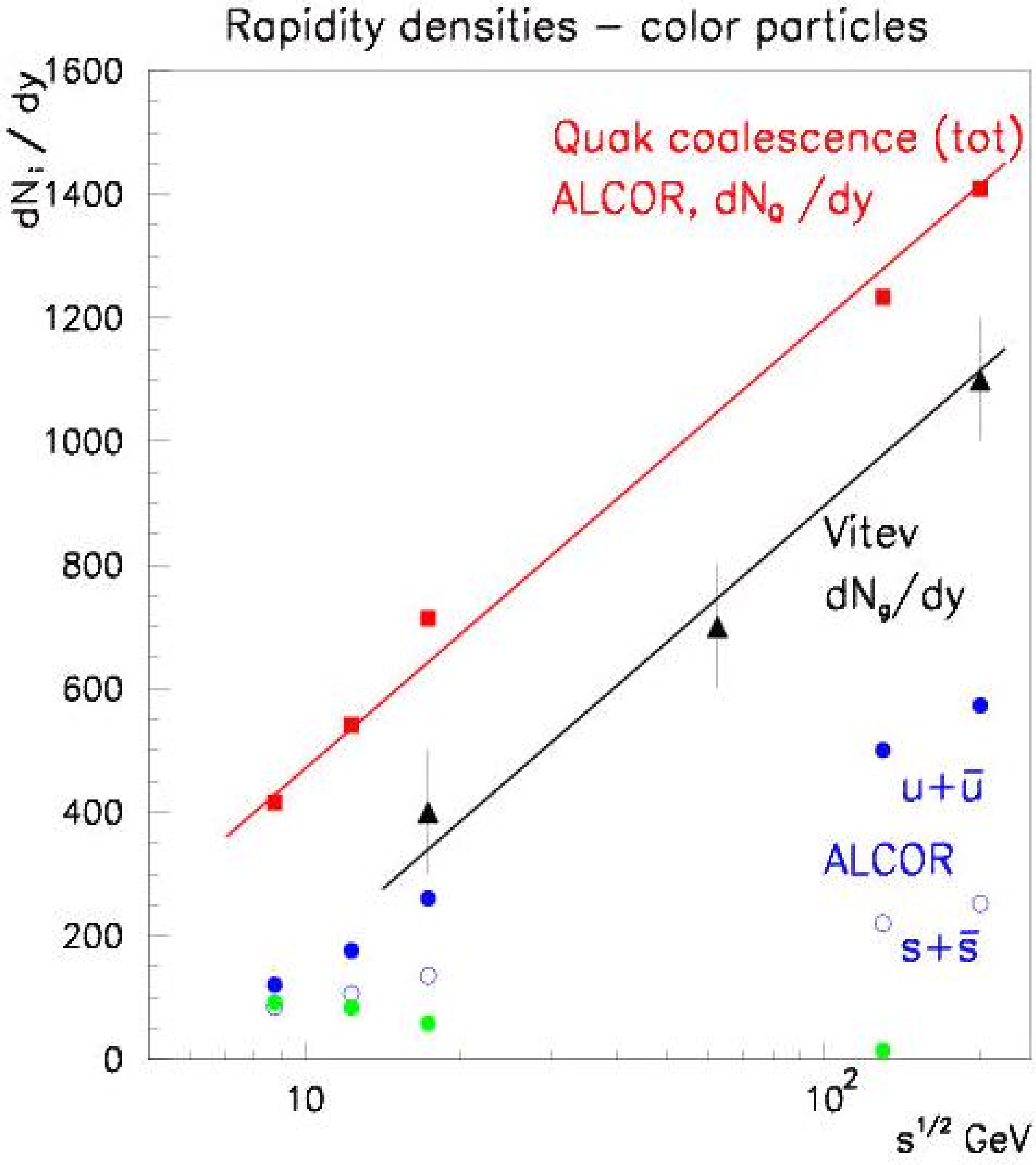


Au+Au dN$_i$/dy	STAR 130 AGeV	ALCOR	STAR 200 AGeV	ALCOR
π^-	287 ± 20	287	327 ± 32	322
K^-	41.9 ± 5.5	40.4	49.5 ± 7.4	45.6
K^-/K^+	0.91 ± 0.11	0.93	0.92 ± 0.02	0.94
Ξ^+	1.72 ± 0.1	1.76	1.81 ± 0.08	2.23
$h^\pm$		690	780	780
K^+	46.2 ± 6.1	43.1	51.3 ± 7.7	48.1
Ξ^-	2.05 ± 0.1	2.16	2.16 ± 0.09	2.59
$\langle\Omega^- + \overline{\Omega}^+\rangle$	0.55 ± 0.15	0.59	0.59 ± 0.14	0.72
$\overline{p}^-/p^+$	0.64 ± 0.07	0.70	0.77 ± 0.05	0.76
$\overline{\Lambda}/\Lambda$	0.71 ± 0.04	0.75	0.81 ± 0.07	0.810
Ξ^+/Ξ^-	0.83 ± 0.05	0.81	0.84 ± 0.06	0.86
$\overline{\Omega}^+/\Omega^-$	0.95 ± 0.15	0.88	0.95 ± 0.15	0.92
K^+/π^+	0.161 ± 0.024	0.15	0.16 ± 0.02	0.150
K^-/π^-	0.146 ± 0.022	0.14	0.15 ± 0.02	0.142
Λ/h^-	0.054 ± 0.001	0.047		0.050
$\overline{\Lambda}/h^-$	0.040 ± 0.001	0.037		0.042
Ξ^-/π^-	0.006 ± 0.001	0.007	0.007 ± 0.001	0.008
K^{*0}	36.7 ± 5.5	28.5		31.7
Φ/K^{*0}	0.49 ± 0.13	0.37		0.37
Φ/K^-		0.26	0.13 ± 0.03	0.26
ρ^0/π^0		0.22	0.20 ± 0.04	0.22

Quark-coalescence:

reproduces most of the
bulk properties at RHIC energies
(particle numbers, ratios,
their energy dependence)

Color particle densities --- quarks or gluons ???



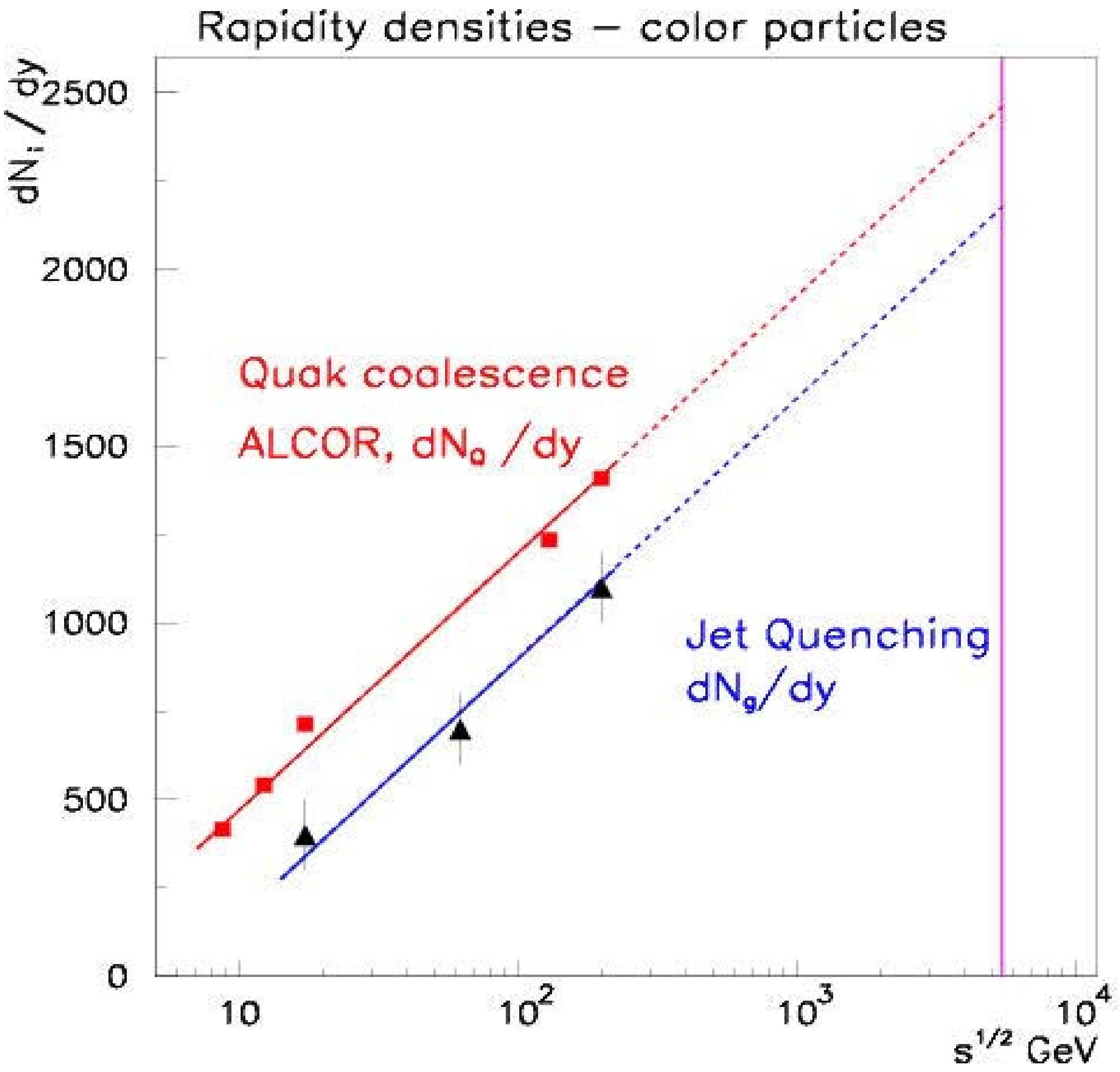
S^1/2 (GeV)	Quark-coalesc dNq/dy	Jet-quench dNg/dy	L/λ
17.3	710±100	400±100	1.5± 0.5
62.4	1000±100	700±100	2.5± 0.5
200.0	1400±100	1100±100	3.5± 0.5
	ALCOR	I. Vitev	P. Levai

Quench: earlier stage

Quark coalescence: later stage

Entropy is OK

Estimate for rapidity density at y=0 at LHC energy:



2 times RHIC
soft multiplicity
(maybe a little bit more)

2 times RHIC opacity:
L/λ = 8 at RHIC
(maybe a little bit more)

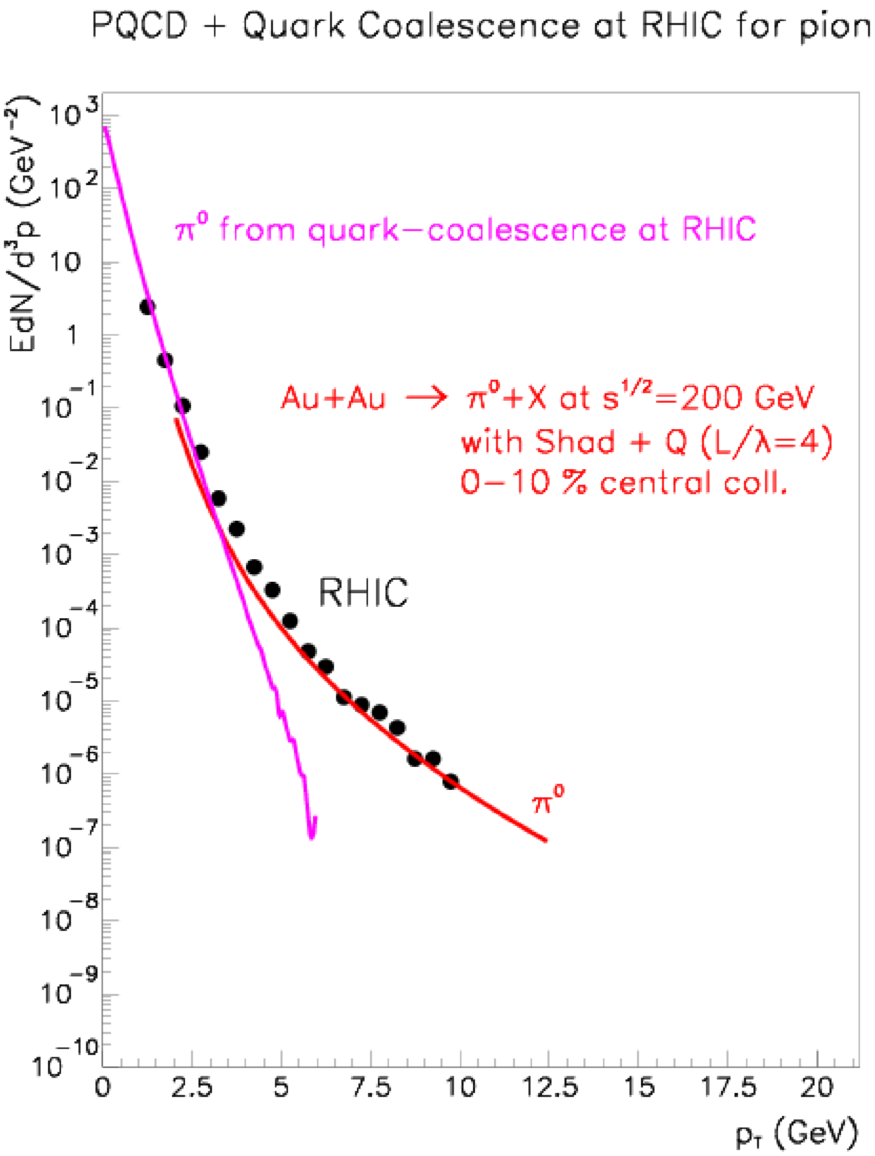
Linear increase is solid
Saturation gives similar res.
Multiparticle production:
larger yield

ALCOR results (RHIC) and predictions (LHC) in the mid-rapidity:

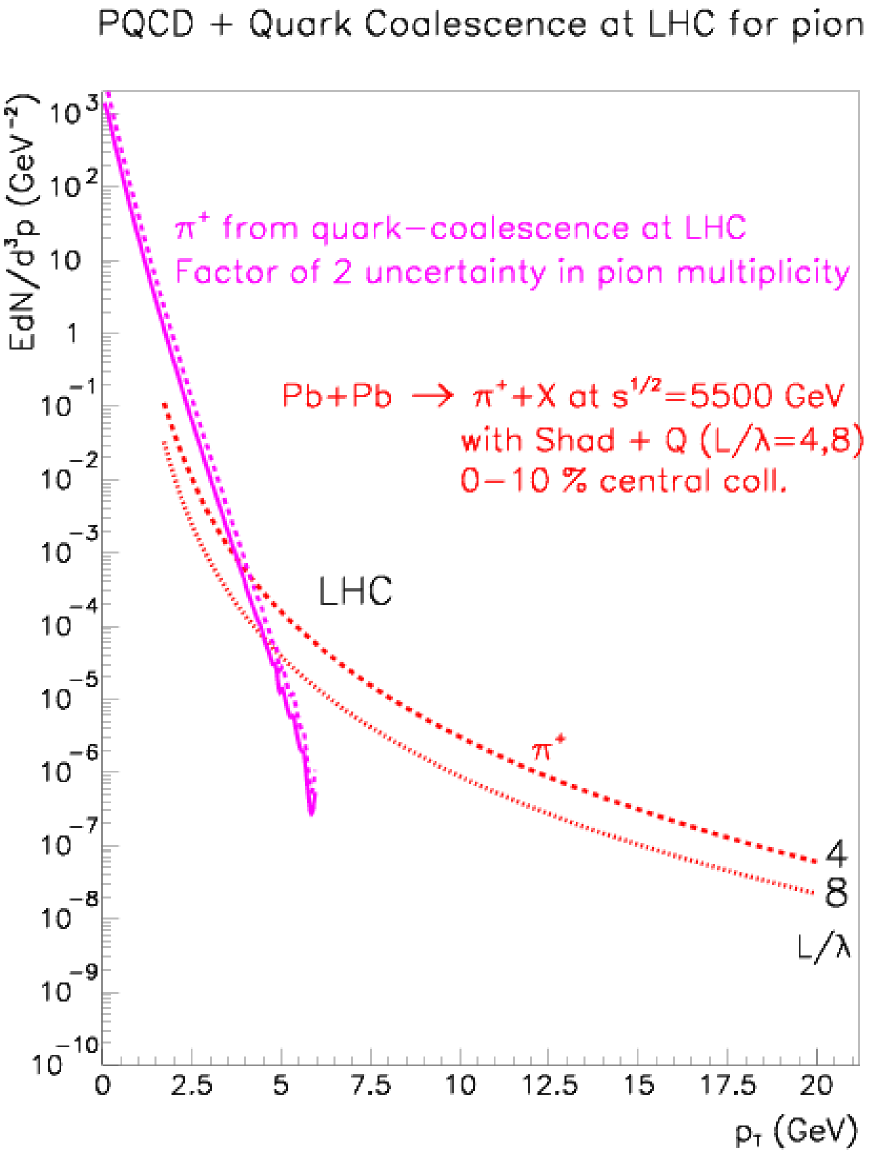
dN/dy (y=0)	200 GeV	RHIC.data	LHC-I: 5500 AGeV	LHC-II: 5500 AGeV
New uu-pairs	286		500	750
f_s (strangeness)	0.22		0.22	0.22
α_s (eff. coupling)	0.55		0.55	0.55
Stopping in y=0	3 %		1 %	1 %
Total (u+d+s+anti)	1396		2440	3660
$h^{\pm}$	780	780±40	1252	1830
π^-	322	327±32	500	724
K^+	48	51.3± 7.7	70	99
p^+	19		37	62
Ξ^-	2.59	2.16±0.09	6.42	10.7
K^+/π^+	0.15	0.16±0.02	0.14	0.14
Ξ^-/π^-	0.008	0.007±0.001	0.013	0.015
ρ^0/π^0	0.22	0.20±0.04	0.21	0.20
ϕ / K^-	0.26	0.15±0.03	0.25	0.25

Pions at RHIC and LHC from the ALCOR/MICOR + pQCD

(Coalescence results at v_T=0.6.)

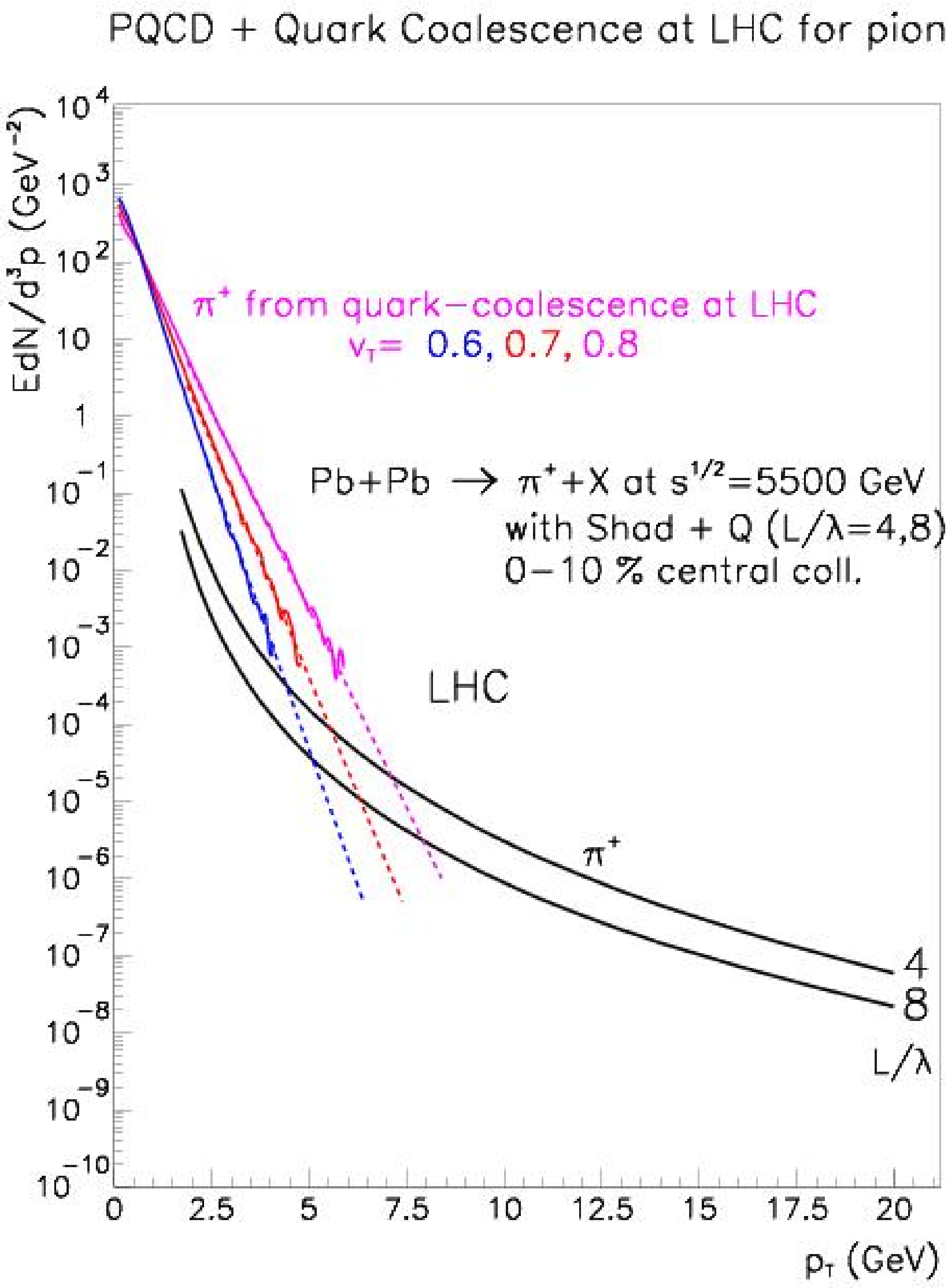


PQCD + Quark Coalescence at RHIC for pion



PQCD + Quark Coalescence at LHC for pion

Overlap at p_T = 2.5 - 3 GeV (RHIC) **at 4 ± 1 GeV at LHC**



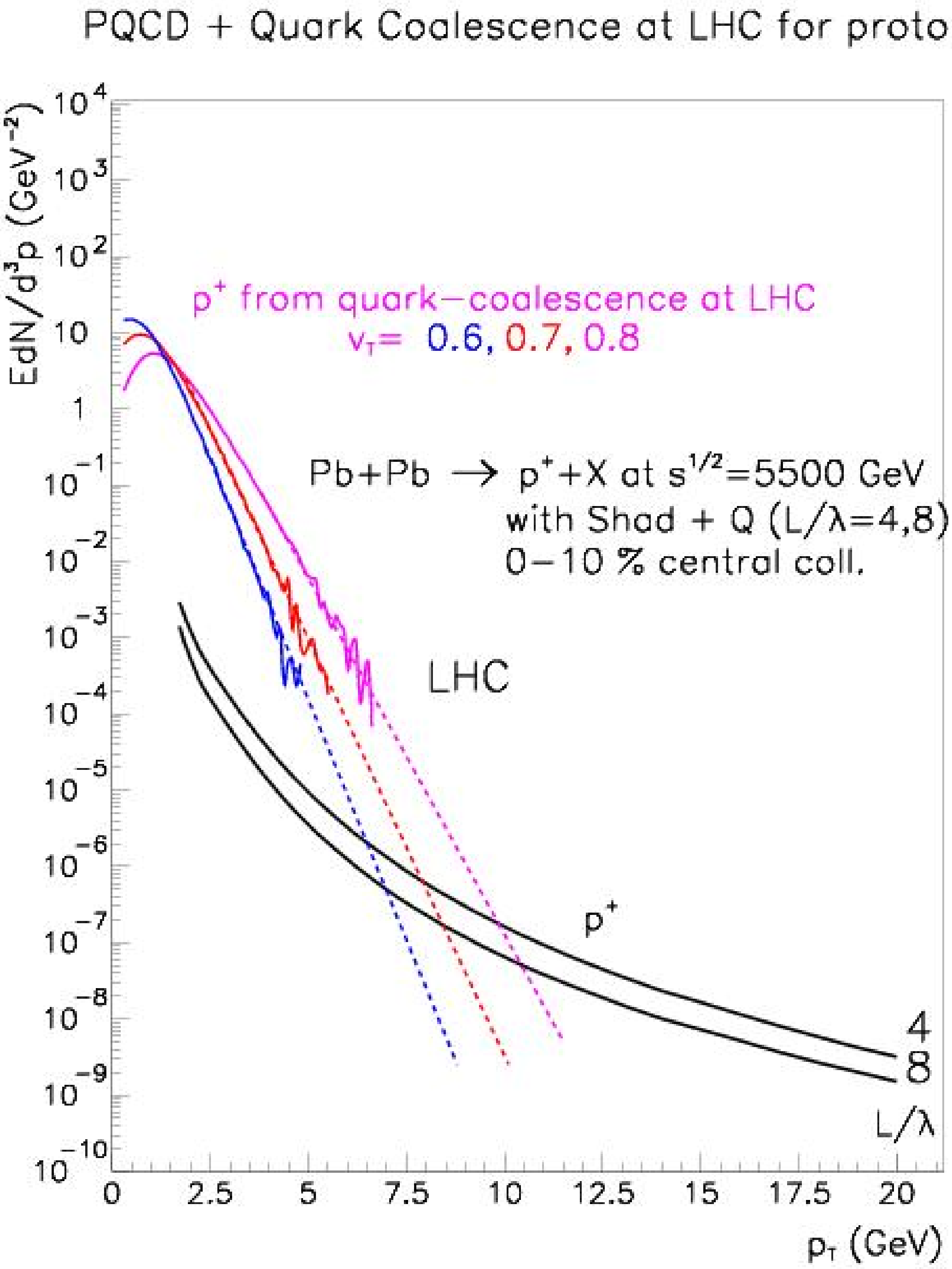
Pions at LHC:
(latest calculation)

$dN/dy\ (\pi^+, y=0) = 500$

$dN/dy\ (h^-, y=0) = 625$

$v_T=0.6, 0.7, 0.8$

Uncertainty from the transverse flow.



Protons at LHC:
(latest calculation)

dN/dy (p^+, y=0) = 70

dN/dy (h^-, y=0) = 625

v_T=0.6, 0.7, 0.8

Uncertainty from the transverse flow.

Lambdas at LHC:

dN/dy (Λ, y=0) = 45

dN/dy ($\overline{\Lambda}$, y=0) = 44

Charm hadron production at RHIC and LHC energies

Absolute numbers: early speculations at RHIC, 6-6 Λ_c, $(D^0+\bar{D}^0)$

(P. Levai, T.S. Biró, P. Csizmadia, T. Csörgő, J. Zimányi, SQ01, J. Phys. G27 (2001) 703.)

let us wait a little bit ↣↣↣ $ALCOR_4$

How large is f_c ? $\langle c\bar{c}\rangle = f_c * (\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)$

Ratios, namely special combinations for quark coalescence.

Meson ratios: D_s / D

$$\frac{M(c\bar{s})}{M(c\bar{u})} = \frac{N_{\bar{s}}}{N_{\bar{u}}} \cdot \frac{\sigma v(c\bar{s})}{\sigma v(c\bar{u})}$$

Baryon ratios: Ξ_c / Λ_c , Ω_c / Ξ_c , ...

$$\frac{B(cus)}{B(cuu)} = \frac{N_s}{N_u} \cdot \frac{\sigma v(cus)}{\sigma v(cuu)}$$

Coalescence dynamics can be studied from these ratios,

especially in the very heavy quark mass limit

↣↣ testing different wave function models (G. Hamar, PL)

Chapters from József Zimányi's scientific heritage:

1. Interacting nuclear/hadronic matter ⇐ challenging task

2. Strongly interacting quark matter ⇐ even larger challenge

3. Hadronization descriptions are very "phenomenological"
   it is essential to understand ⇔ confinement

4. The success of the coalescence models at SPS and RHIC energies
   quark number counting rule ⇐ why does it work ?

Message for the future:

5. Further input on identified hadron numbers and spectra
   - LHC ALICE can measure light, strange and charm hadrons
     (low and high-pT windows: TPC+TOF, HMPID, VHMPID)
   - CERN NA49/NA61 (GSI/FAIR): the end point of the
     nuclear/quark phase transition