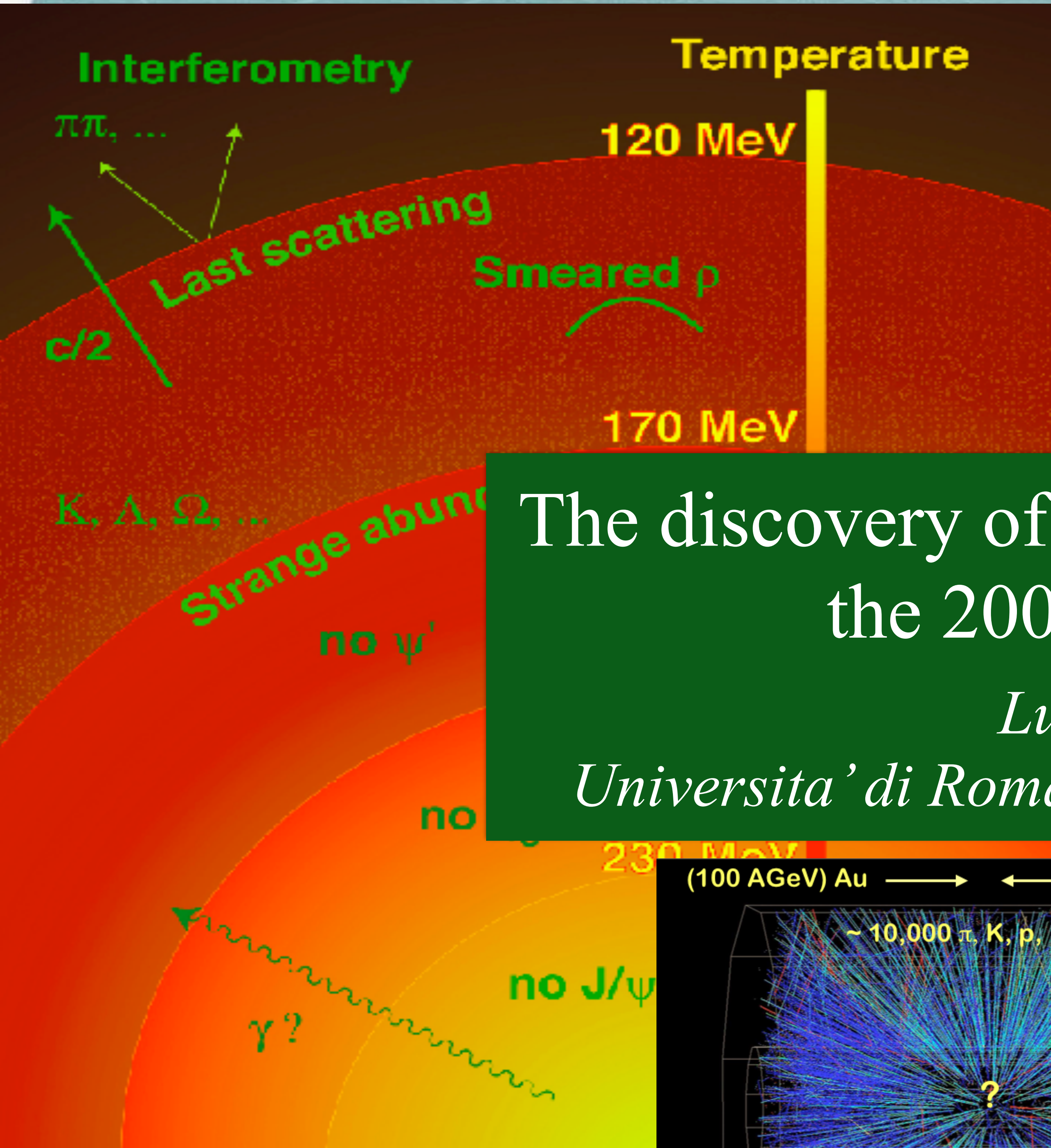
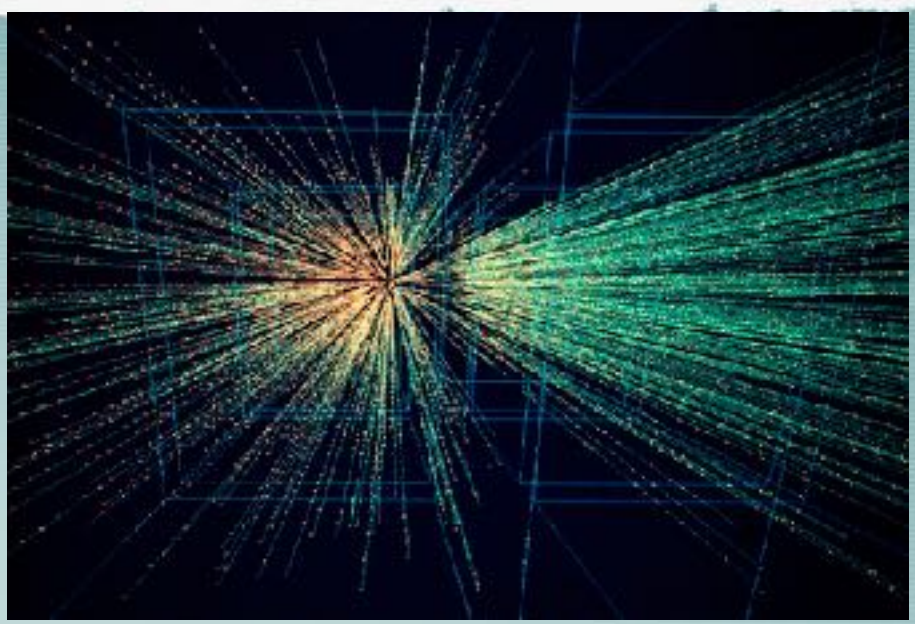
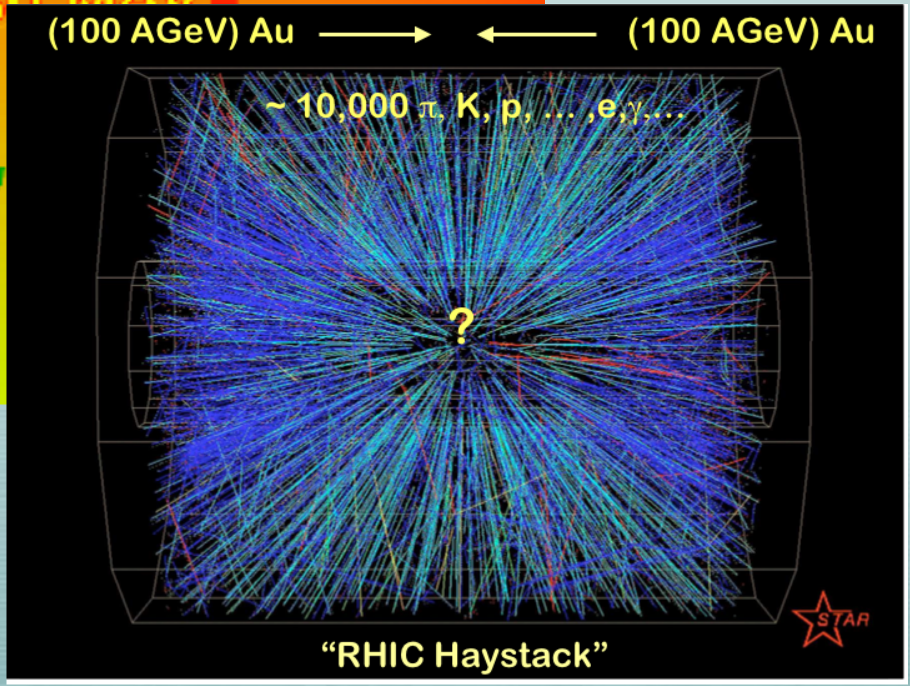


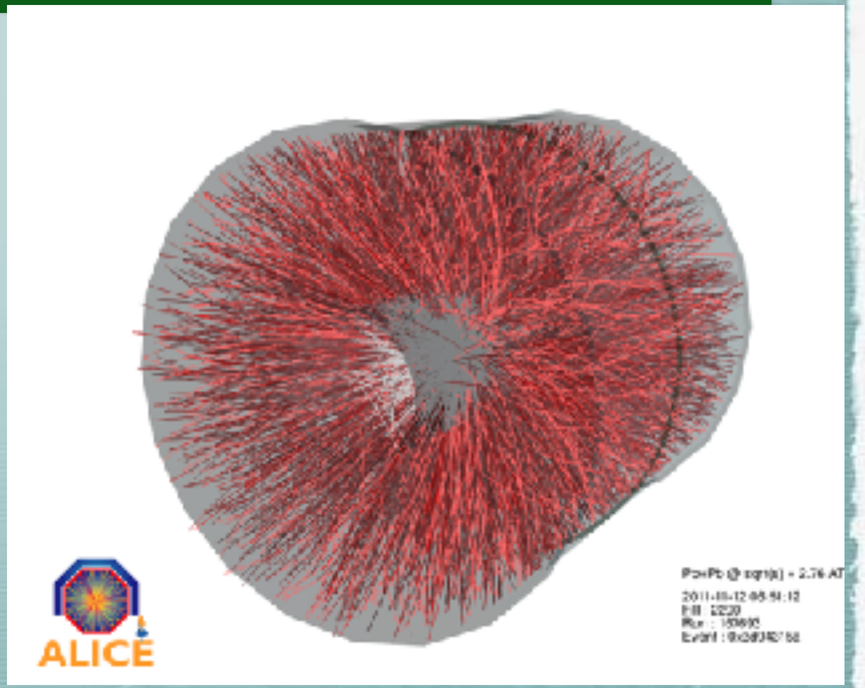


The discovery of the Quark-Gluon plasma : the 2000 announcement

Luciano Maiani
Universita' di Roma La Sapienza and INFN Roma



Au-Au @ RHIC, from STAR



Pb-Pb @ LHC, from ALICE

How did we get there? a personal recollection

C

SPECIAL SEMINAR

TITLE : A New State of Matter:
Results from the CERN Lead-Beam Programme

TIME : Thursday 10 February at 09.30 hrs

PLACE : Council Chamber, bldg 503

ABSTRACT

This special seminar aims at an assessment of the results from the heavy ion programme with lead ion beams at CERN which was started in 1994. A series of talks will cover the essential experimental findings and their interpretation in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma.

Ulrich Heinz (CERN)
Making Quark-Gluon Matter in Relativistic Nuclear Collisions

Louis Kluberg (IN^{2}P^3)
The J/ψ suppression pattern observed in Pb-Pb collisions ions: a signature for the production of a new state of matter.

Johanna Stachel (University of Heidelberg)
Virtual and real photons radiated by the cooling and hadronizing fireball.

Reinhard Stock (University of Frankfurt)
Hadron Signals of the Little Bang.

Emanuele Quercigh (CERN)
Strange signals of a new state of matter from nuclear collisions at SPS.

Luciano Maiani (Director General, CERN)
Summary.

Introduction

At the end of the sixties, two models of fundamental interactions:

- ”Bootstrap” models: all hadrons are composite of one another
- “Elementary particle” model: photons, leptons, quarks

•They predicted very different behaviour of nuclear matter at high temperature, so, it was not possible to understand the primordial Universe, before the nuclear physics age (the “first three minutes”)

•Bootstrap model predicted

$$\rho(m) = m^{\alpha}\exp(m/B)$$

- exponentially rising level spectrum, ...
- limiting temperature (Hagedorn) that can be estimated from the hadron spectrum: T=170-180 MeV

• Elementary constituents:

-a gas of free quarks and gluons, any temperature

•Then came the discovery of almost free, point-like constituents of matter, …asymptotic freedom, QCD, gluons…

A phase transition?

•N. Cabibbo, G. Parisi (1975) suggested that the Hagedorn limiting temperature is just the critical temperature of a (second order) phase transition between a gas of hadrons (made of confined quarks), and a gas of deconfined quarks and gluons (quark &gluon plasma)

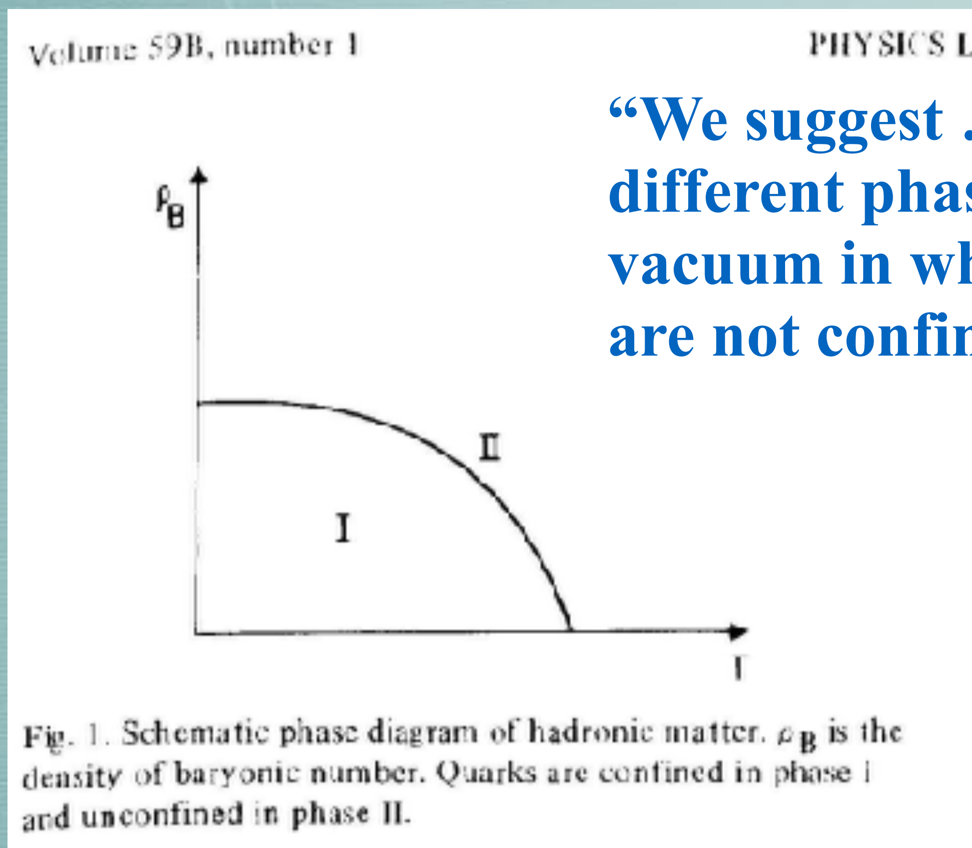

Volume 59B, number 1 PHYSICS L

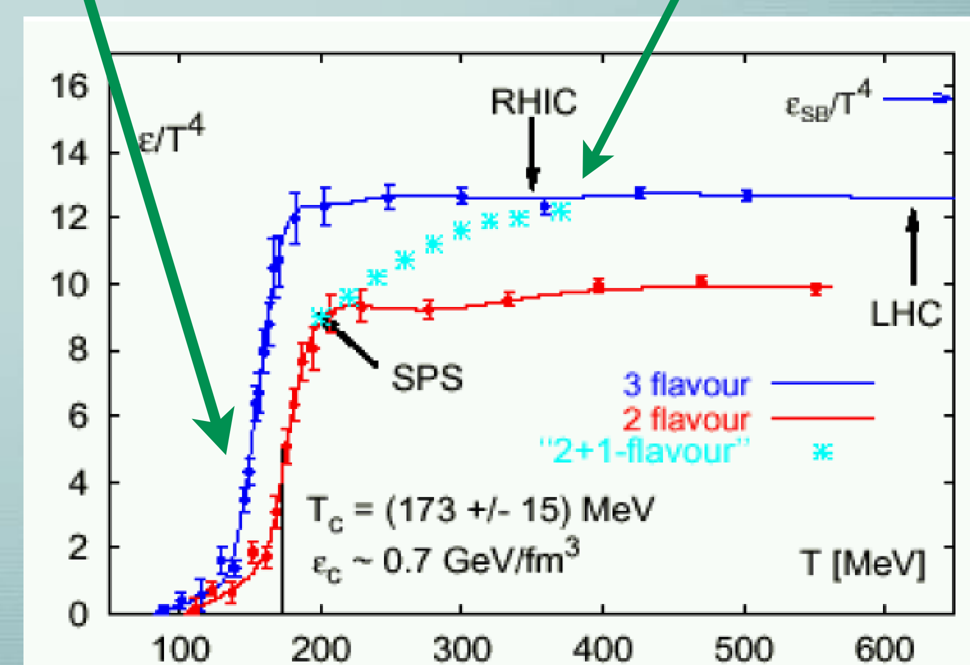
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

"We suggest … a different phase of the vacuum in which quarks are not confined"

Hadron Gas ?

QGP ?

Lattice QCD calculations of the energy density of hadronic matter vs. T (F. Karsch, Lattice QCD at High Temperature and Density, hep-lat/0106019).



a true phase transition ? cross-over only?
chiral symmetry restored ??
transition to an asymptotically free gas ??
intermediate phase of a strongly interacting Quark Gluon Plasma?
are there other phases of hadronic matter?

- A skier (quark?) is confined inside snow patches (hadrons?)

Temperature

- the skier can move further…a new phase develops

..goes up

- a skier (quark?) can move freely over long distances…

..this way

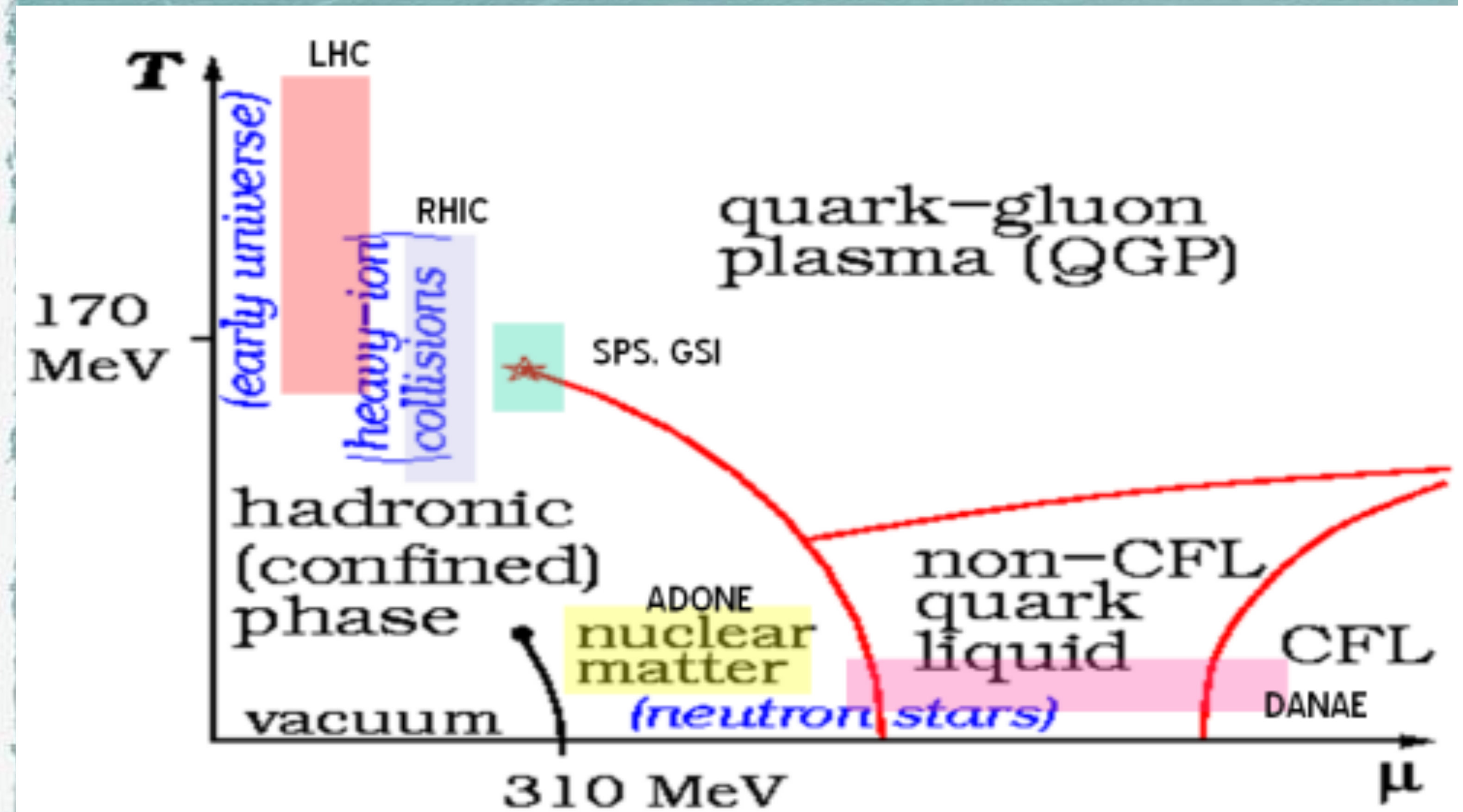
The Heavy Ion Facility

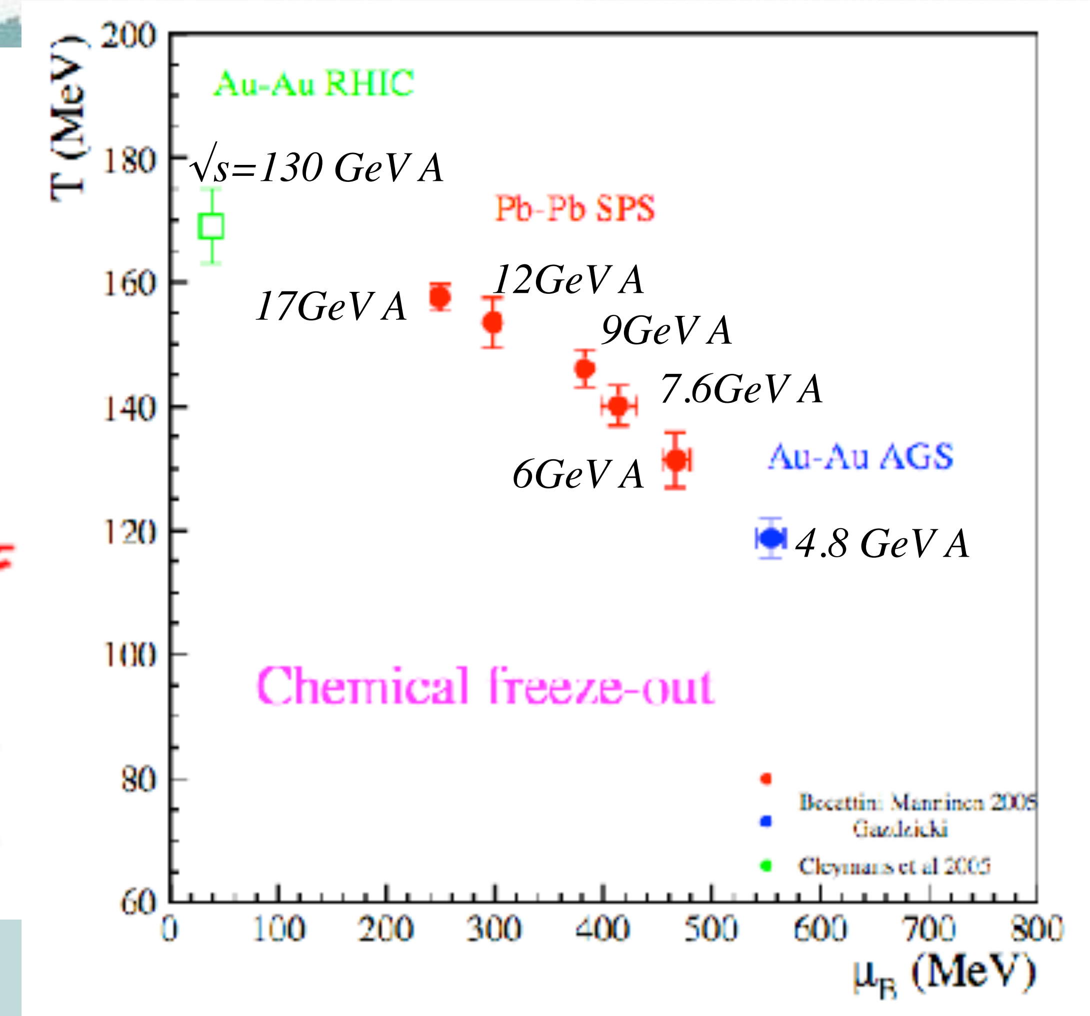
- Nuclear matter at high temperature can be studied in the collisions of Relativistic Ions
- Theory pioneered in J. Bjorken, Phys. Rev. D27, 140 (1983)
- A new branch of nuclear physics took shape in the 80's and 90's.

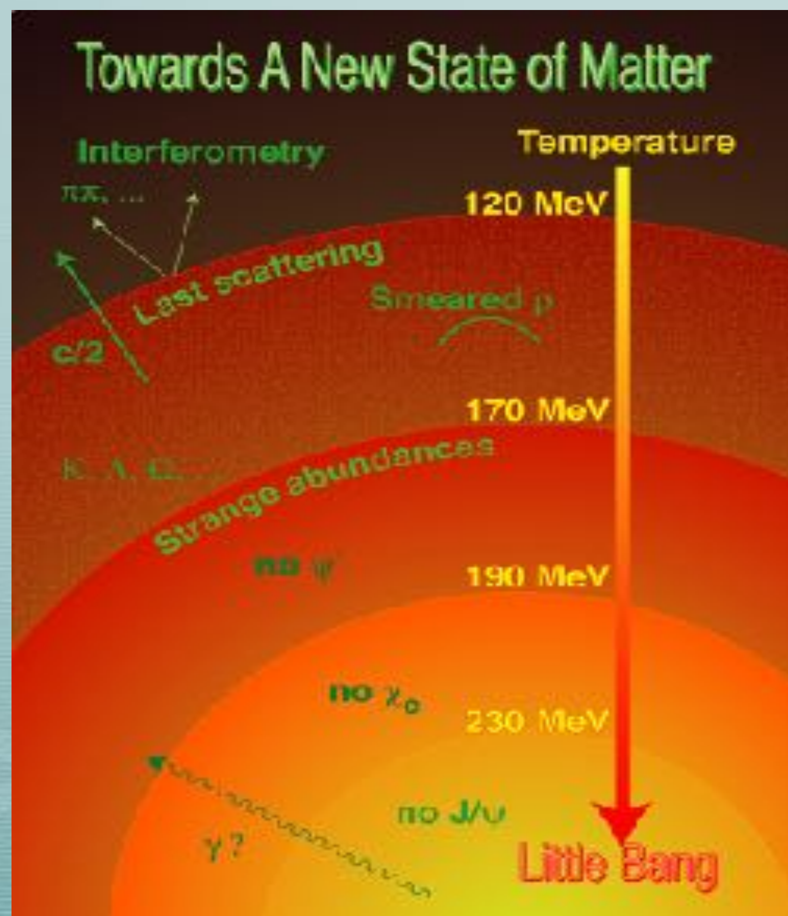
The heavy-ion facility was constructed as a collaboration between CERN and the following laboratories :

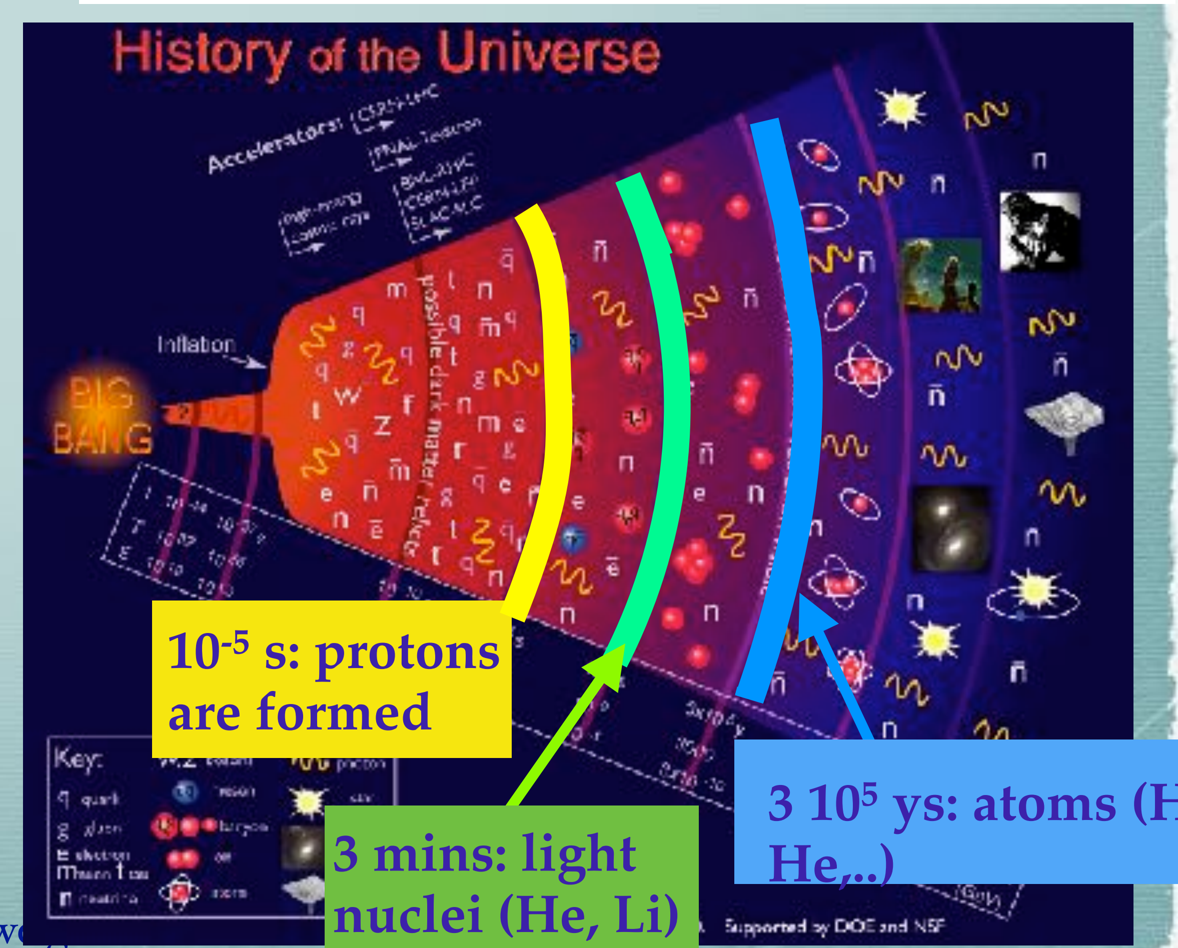
GANIL	**Caen**	**FRANCE**
INFN	**Legnaro**	**ITALY**
	Torino	**ITALY**
GSI	**Darmstadt**	**GERMANY**
Institute of Applied Physics	**Frankfurt**	**GERMANY**
Variable Energy Cyclotron (VECC)	**Calcutta**	**INDIA**
Tata Inst. of Fundamental Research (TIFR) &		
Baba Atomic Research Centre (BARC)	**Bombay**	**INDIA**
Academy of Sciences	**Prague**	**CZECH REP.**

In-cash contributions from: SWEDEN and SWITZERLAND


T
LHC
(early universe)
RHIC
(heavy-ion collisions)
170 MeV
SPS, GSI
quark–gluon plasma (QGP)
hadronic (confined) phase
ADONE
nuclear matter
non–CFL quark liquid
CFL
DANAE
vacuum
(neutron stars)
310 MeV
μ

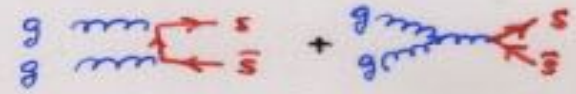

T (MeV)
Au-Au RHIC
√s=130 GeV A
Pb-Pb SPS
17GeV A
12GeV A
9GeV A
7.6GeV A
6GeV A
Au-Au AGS
4.8 GeV A
Chemical freeze-out
Becattini Manninen 2005
Gazdzicki
Cleymans et al 2005
μB (MeV)


Towards A New State of Matter
Interferometry
Temperature
120 MeV
Last scattering
Smeared ρ
170 MeV
Strange abundances
190 MeV
no ψ'
no χc
230 MeV
no J/ψ
Little Bang


History of the Universe
Inflation
BIG BANG
Key:
10⁻⁵ s: protons are formed
3 mins: light nuclei (He, Li)
3 10⁵ ys: atoms (H, He,..)

Key QGP predictions:

✓ • <u>Strangeness enhancement and chemical equilibration</u> due to shorter time scale for $s\bar{s}$ production: (Rafelski + Müller '82)



\+ higher orders

↔ gluon deconfinement + chiral symmetry restoration
(high gluon density + low mass thresholds)

<u>Hadronic background</u>: associated production + strangeness exchange

Multistrange (anti) baryon production inhibited by low densities and high mass thresholds in hadron gas.

✓ • <u>J/ψ, χ_c, ψ' suppression</u> due to color screening (Satz + Matsui '86)

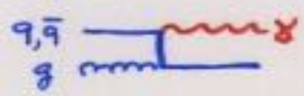
↔ color deconfinement + high gluon density

<u>Hadronic background</u>: hadronic FSI with incoming nucleons and comoving produced hadrons

Comover scattering unable to reproduce observed ψ', χ_c, J/ψ suppression pattern.

? • <u>Thermal electromagnetic radiation</u>: (Shuryak, Kajantie, Ruuskanen ...)

thermal dileptons



thermal photons

<u>backgrounds</u>: Drell-Yan, $D \to K\pi \to \mu^+\mu^-$, bremsstrahlung from charged hadrons; $\pi^0, \eta, \ldots \to \gamma\gamma$

Marginal S/B @ SPS, but more hope at RHIC and LHC (thermal rate ~ T^4)

Strangeness enhancement & chemical equilibration

(1) Hadron yields compatible with chemical equilibrium at

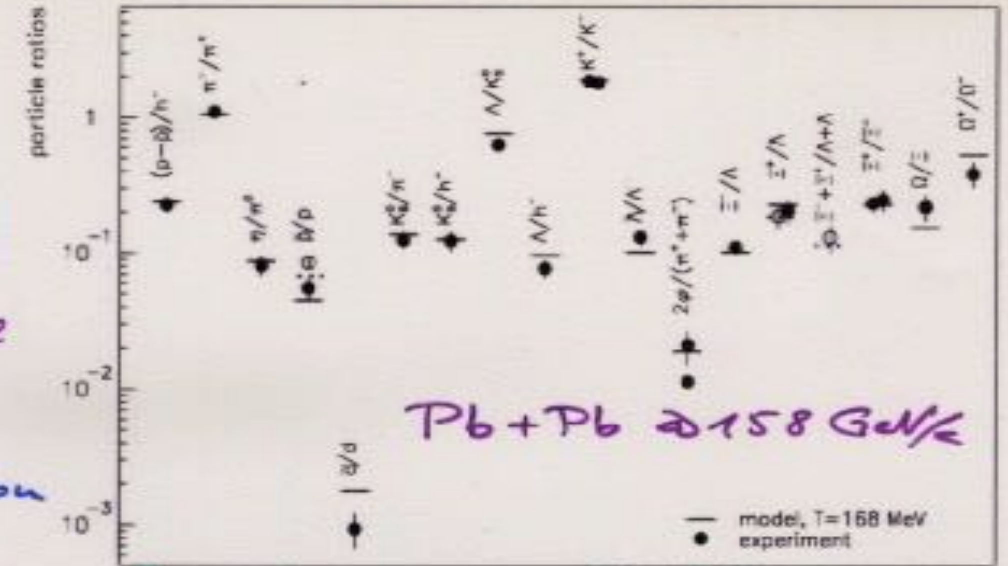
$T_{chem} = 168\,MeV \approx T_{had}$

"pre-established chemical equilibrium"

↕

statistical hadronization of quarks & gluons

(U.H., QM97; R. Stock, PLB456, 277)



Braun-Munzinger, Heppe, Stachel, PLB465(99)15

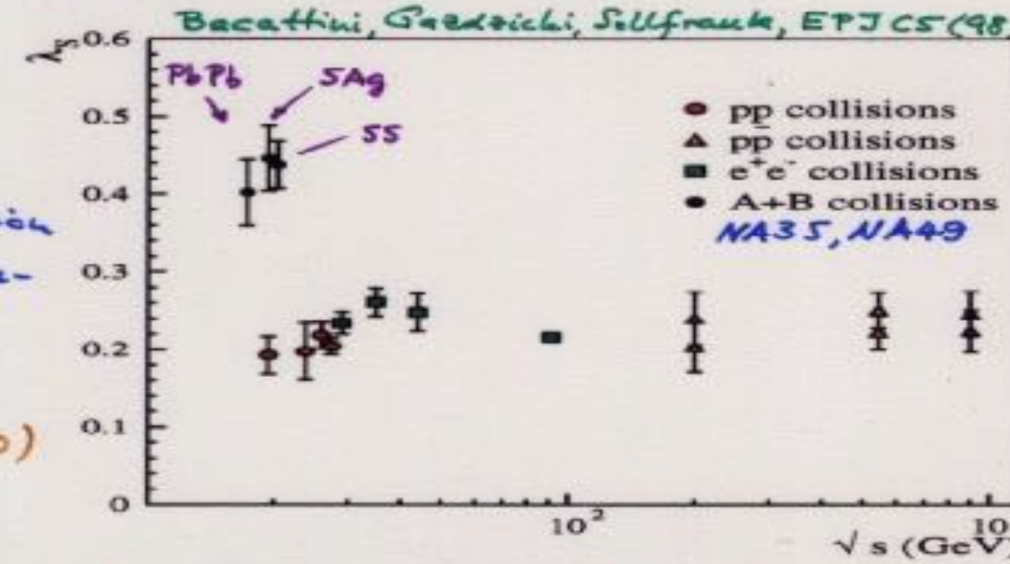
(2) Global strangeness enhancement by factor 2

↕

rapid strangeness production before or during hadronization

(Rafelski + Müller, '82
Zimanyi et al,
Friman, Knoll et al, '88–'90)

Becattini, Gazdzicki, Sollfrank, EPJ C5(98)143



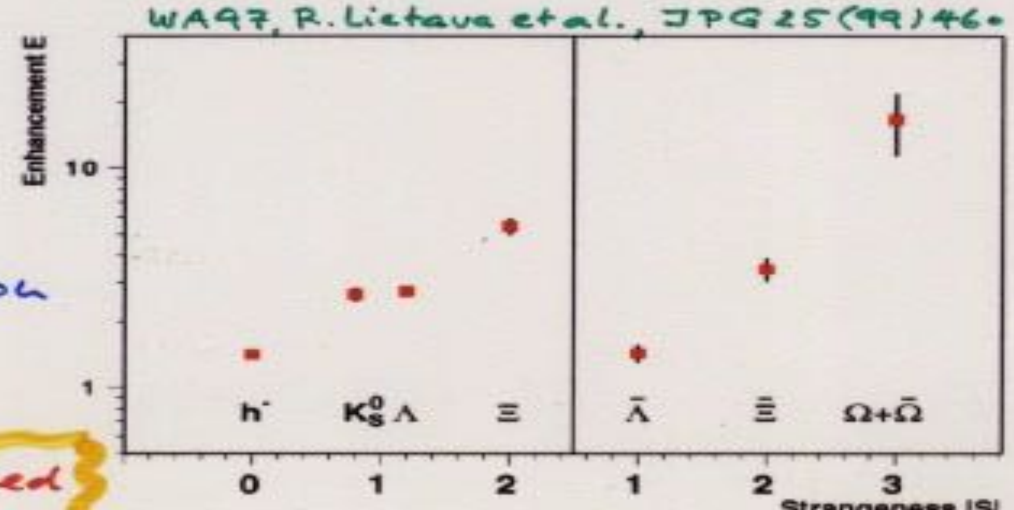
(3) Large specific enhancement factors at y_{cm} (PbPb vs. pBe) for multistrange hadrons

↕

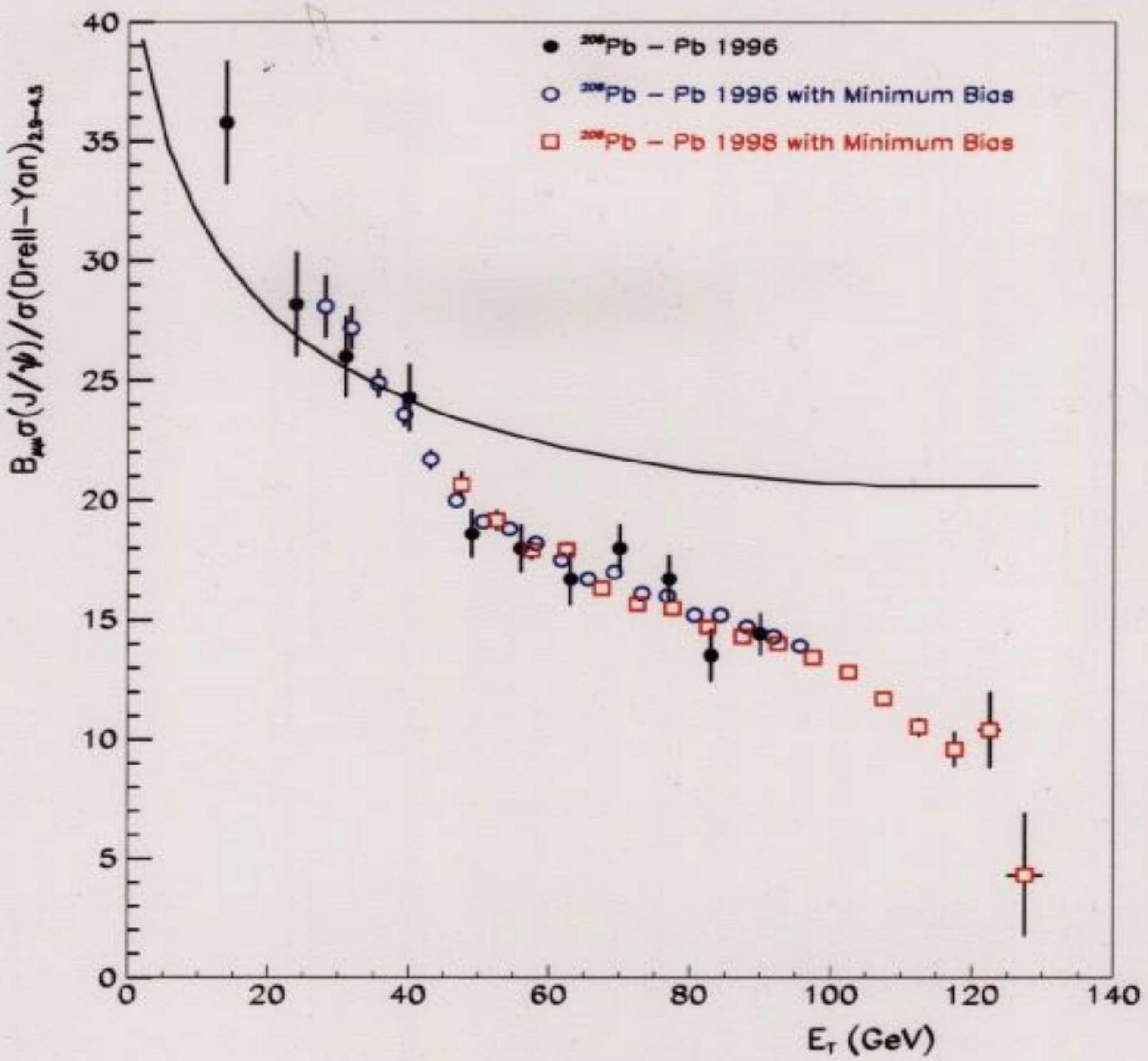
statistical hadronization

(Rafelski '91, Bialas '98)

WA97, R. Lietava et al., JPG 25(99)46.



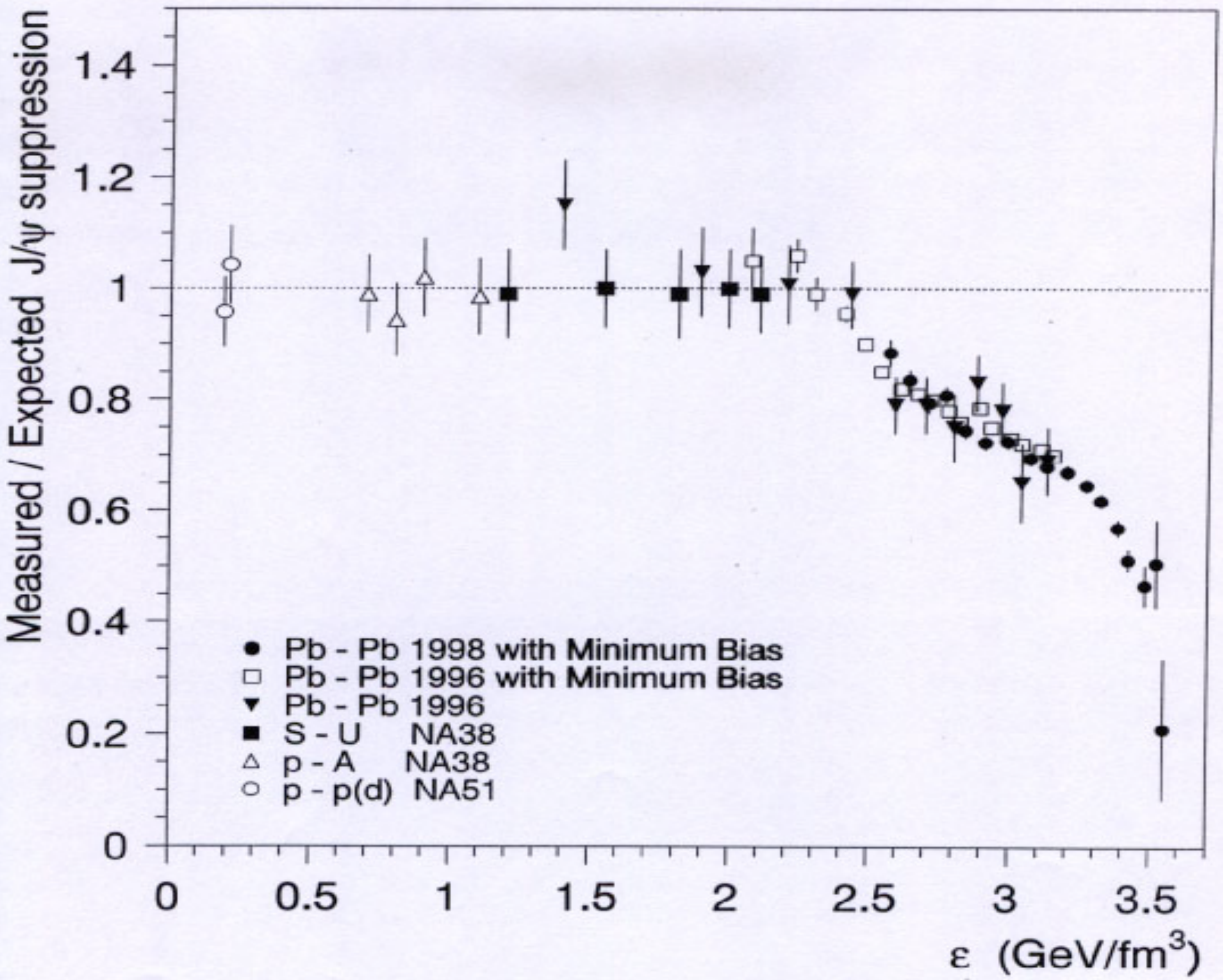
(1)–(3) cannot be explained by hadronic FSI!

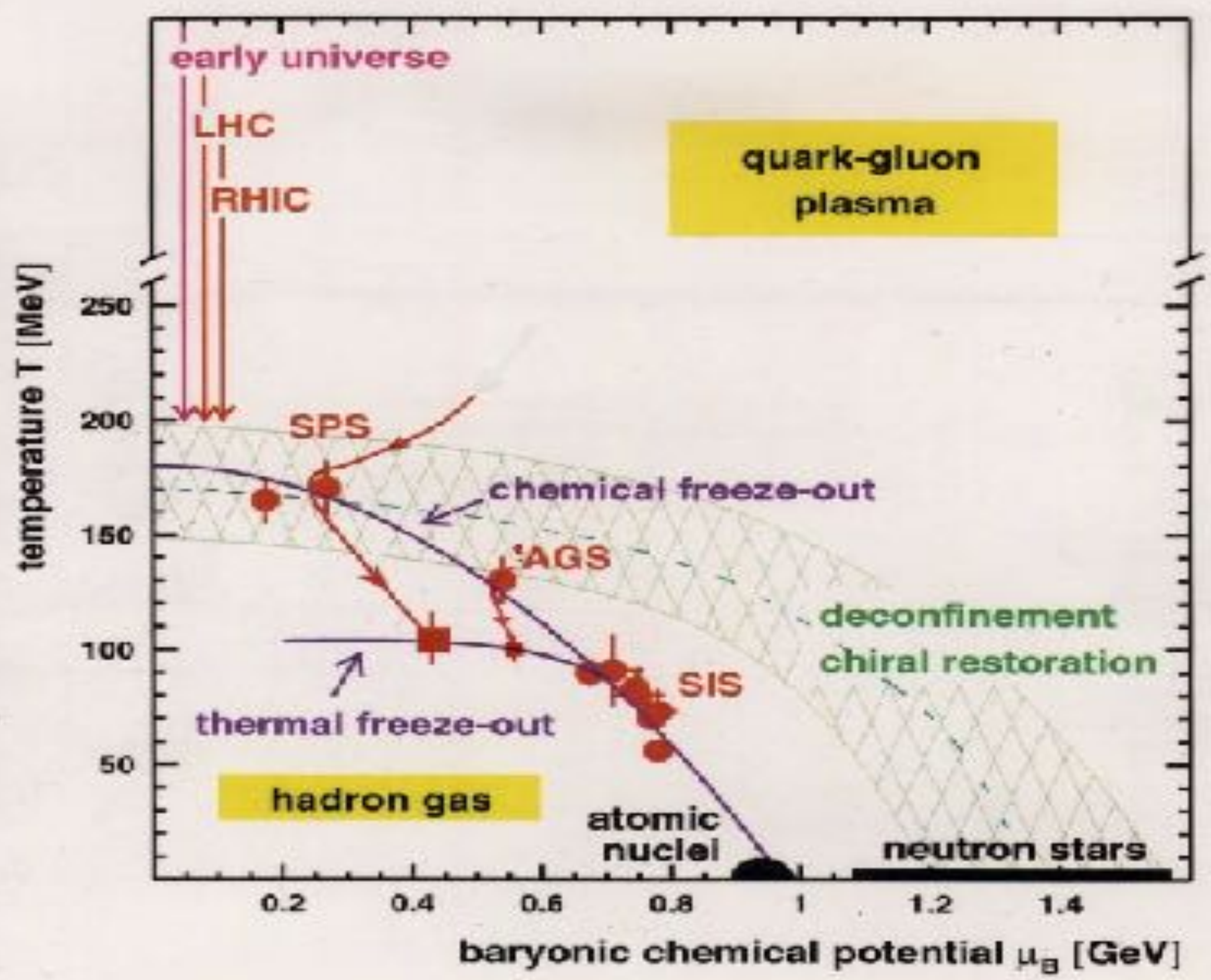


NA50 @ QM99

QM99

Understanding the stepwise suppression pattern





Feb 10, 2000:

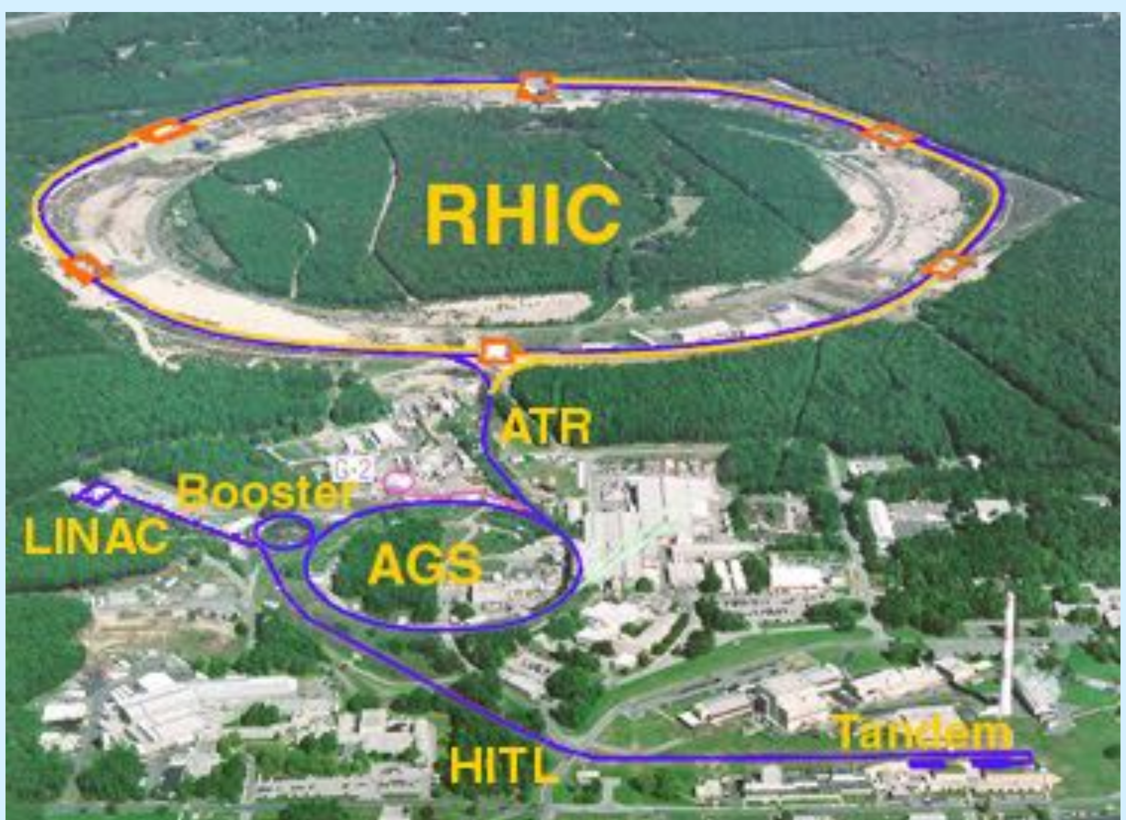
"...The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma."

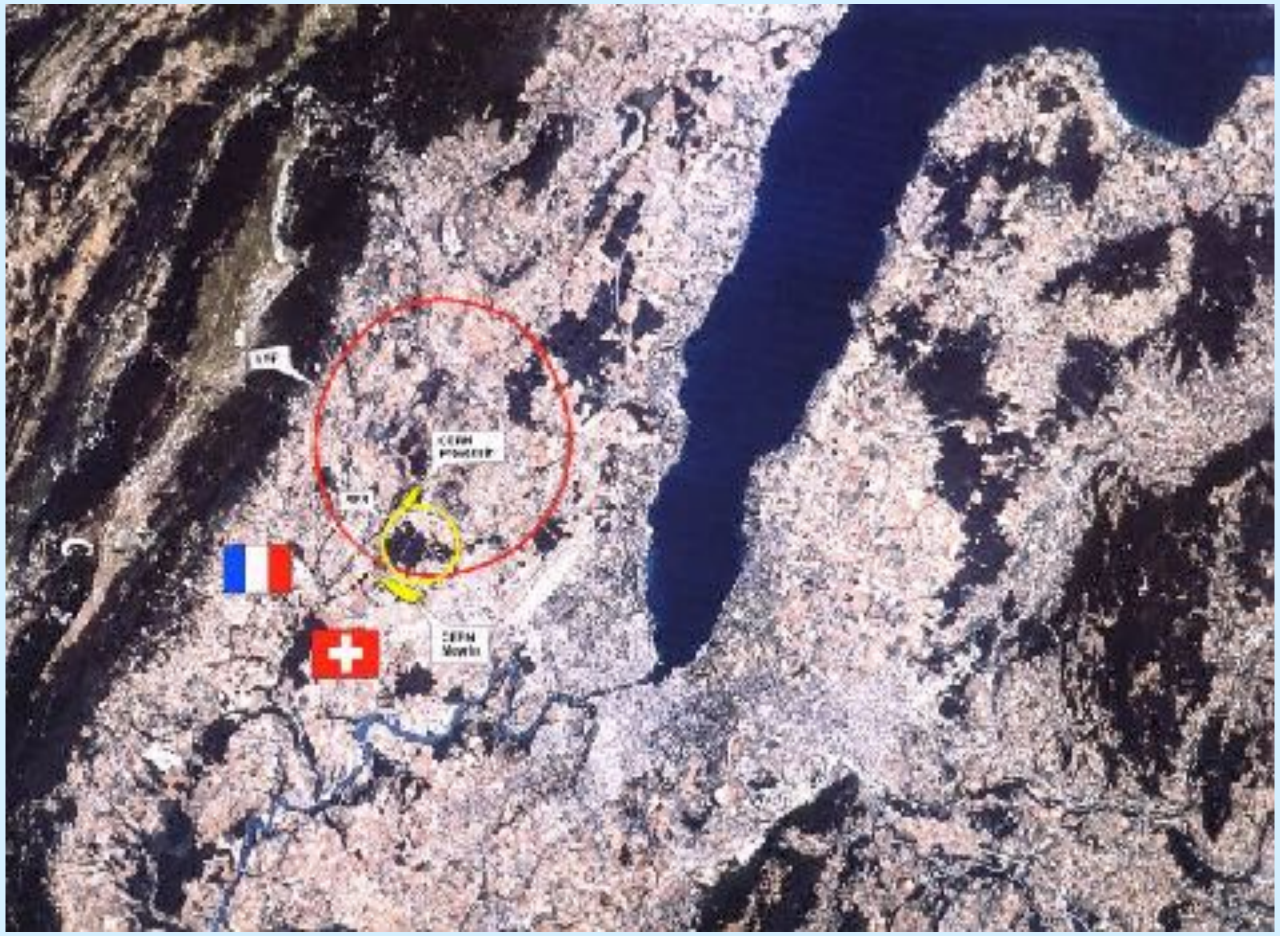
…..

" The higher energies of RHIC and LHC are needed to complete the picture and provide a full characterisation of the Quark-Gluon Plasma."

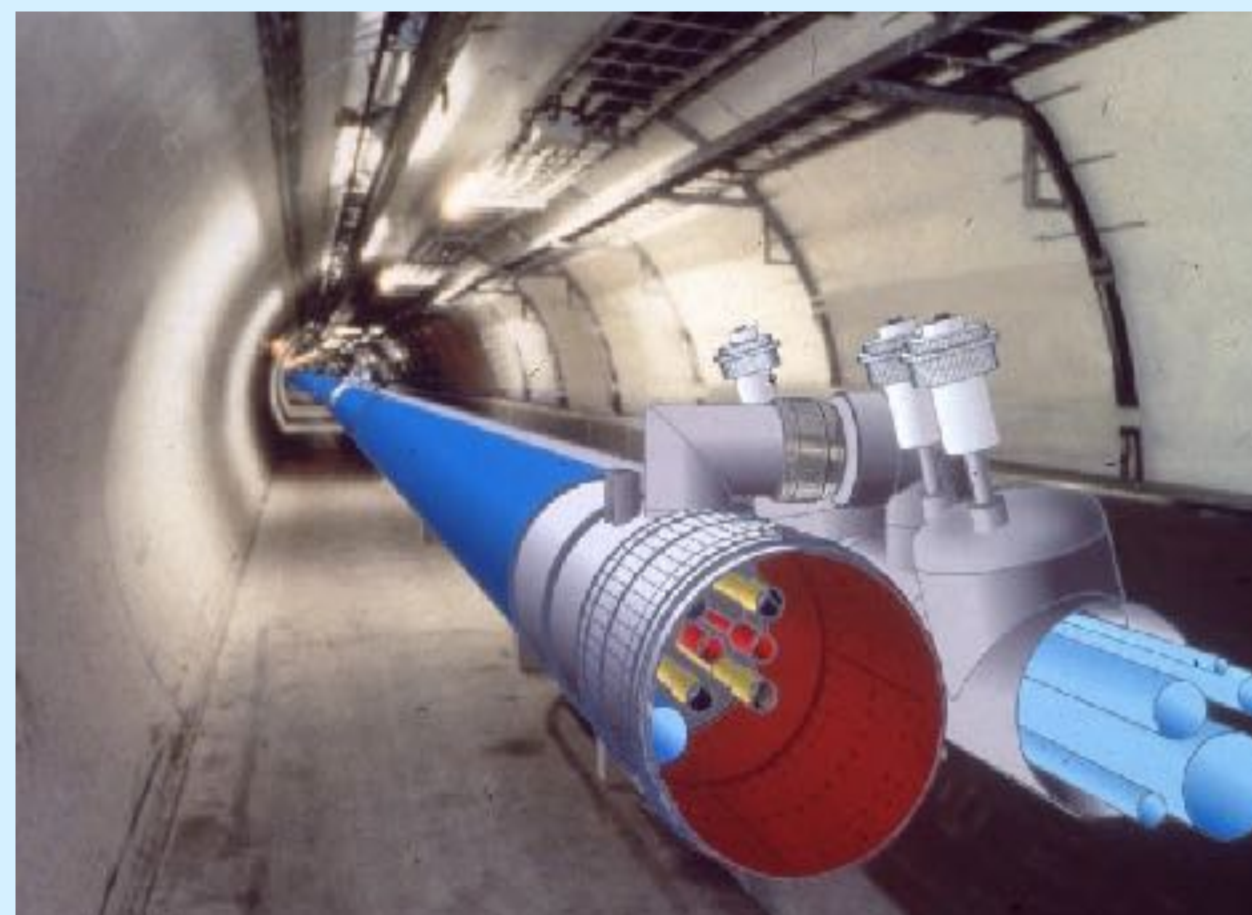
Next Rounds in Quark Gluon Plasm
Hunting:

1. The Relativistic Heavy Ion Collide
Brookhaven, summer 2000 to ...





2. The Large Hadron Collider CERN, 2005 to ...

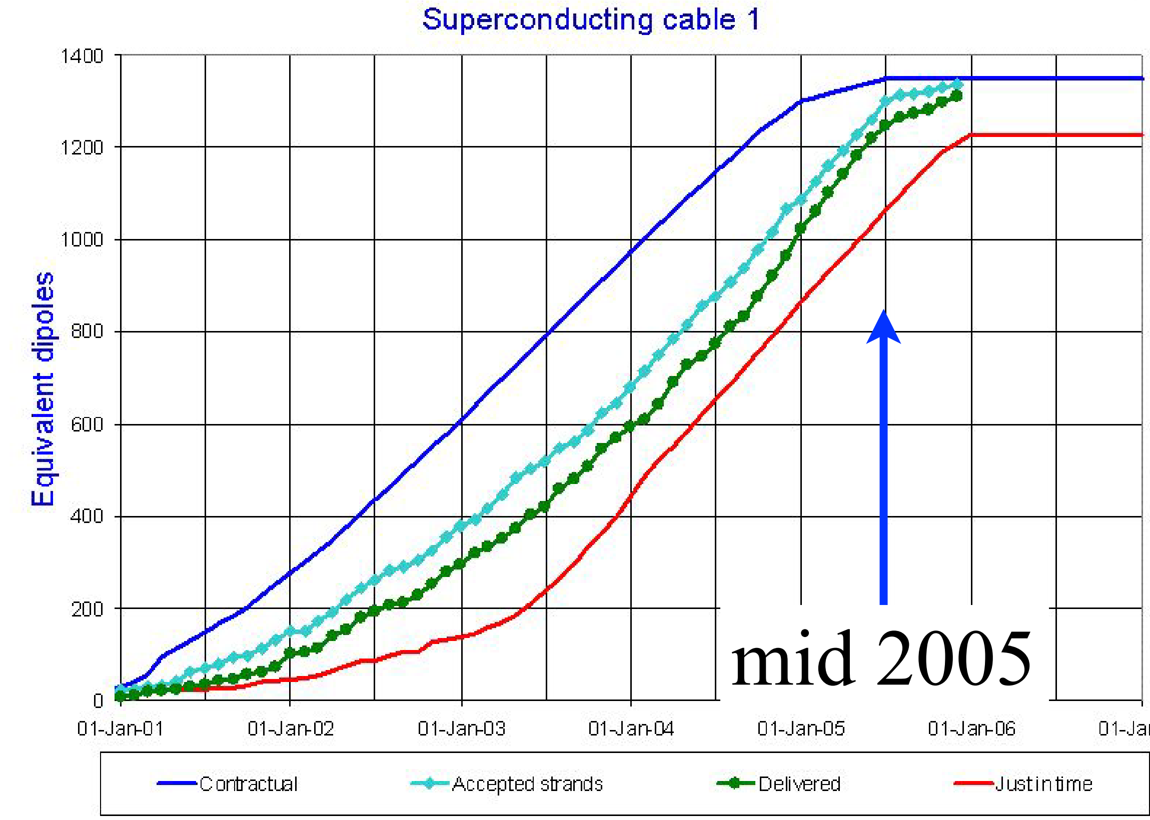


1.1. LHC Schedule

- Contracts for dipole cold mass assembly are being signed; CERN has a double role: supplier of SC cables, end-customer of the dipoles. We must be prudent in defining the dipole delivery schedule, hence the LHC schedule.
- SC cable production to end mid 2005;
- last dipole delivered July 1st, 2006;
- Machine closed and cold: Oct. 2006;
- First beam: April 2007;
- First physics: mid 2007;
- Very solid foundation of the LHC confirmed by SC cable panel and Machine Advisory Committee.

L. Maiani. March 21, 2002 Committee of Council 8

LHC Progress Dashboard



Updated 30 Nov 2005 Data provided by A. Verweij AT-MAS

- 1.5 year delay due to problems with QRL
- another 1.5 year for the accident
- later resolved by Steve Myers

Sept. 10th 2008: first beams

Lyn Evans and Lucio Rossi receive at CERN the last dipole

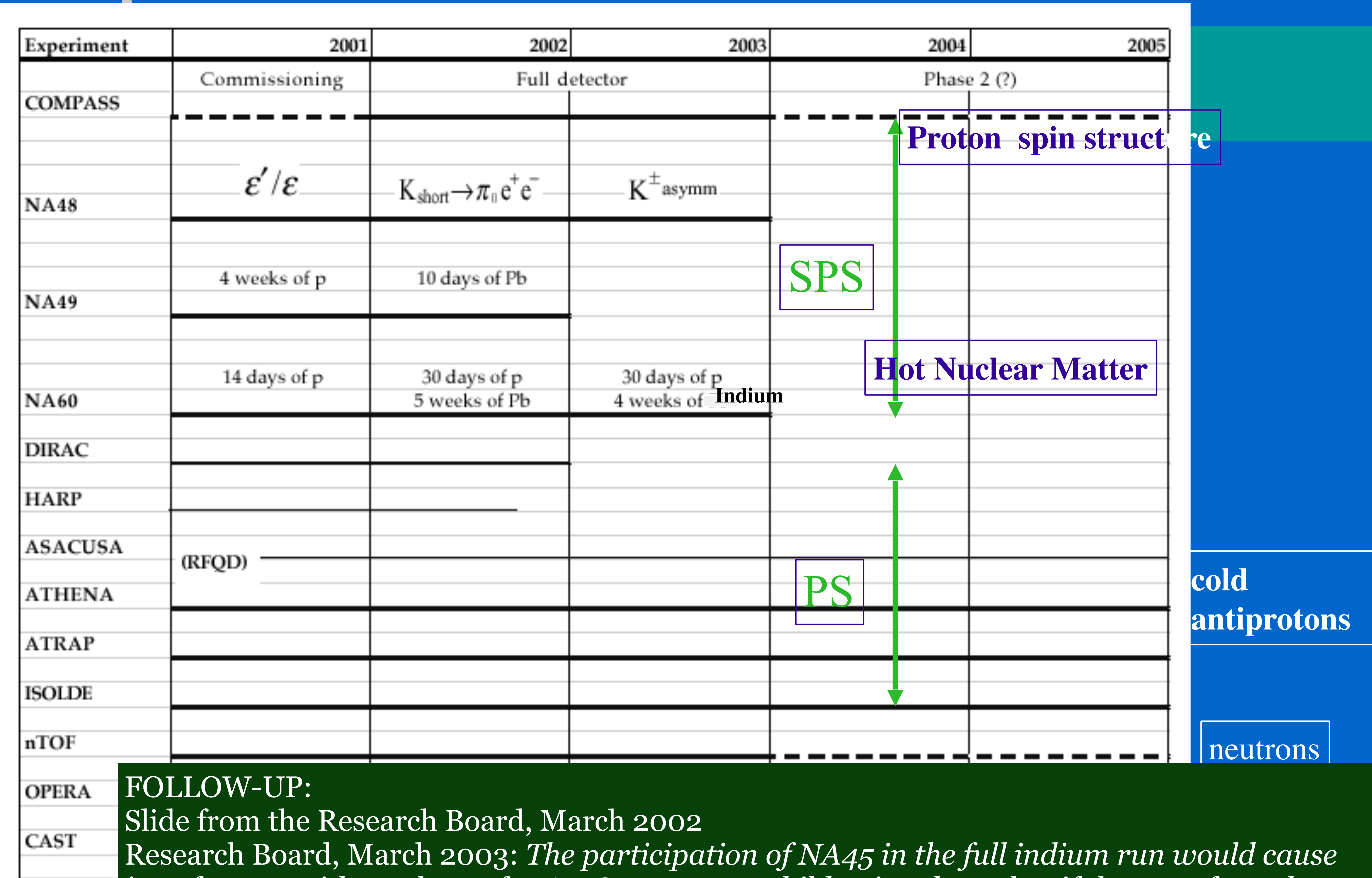
- useful beams: 2010
- useful physics: 2011

- 1.5 year delay due to problems with QRL

1.3. The LHC experimental programme

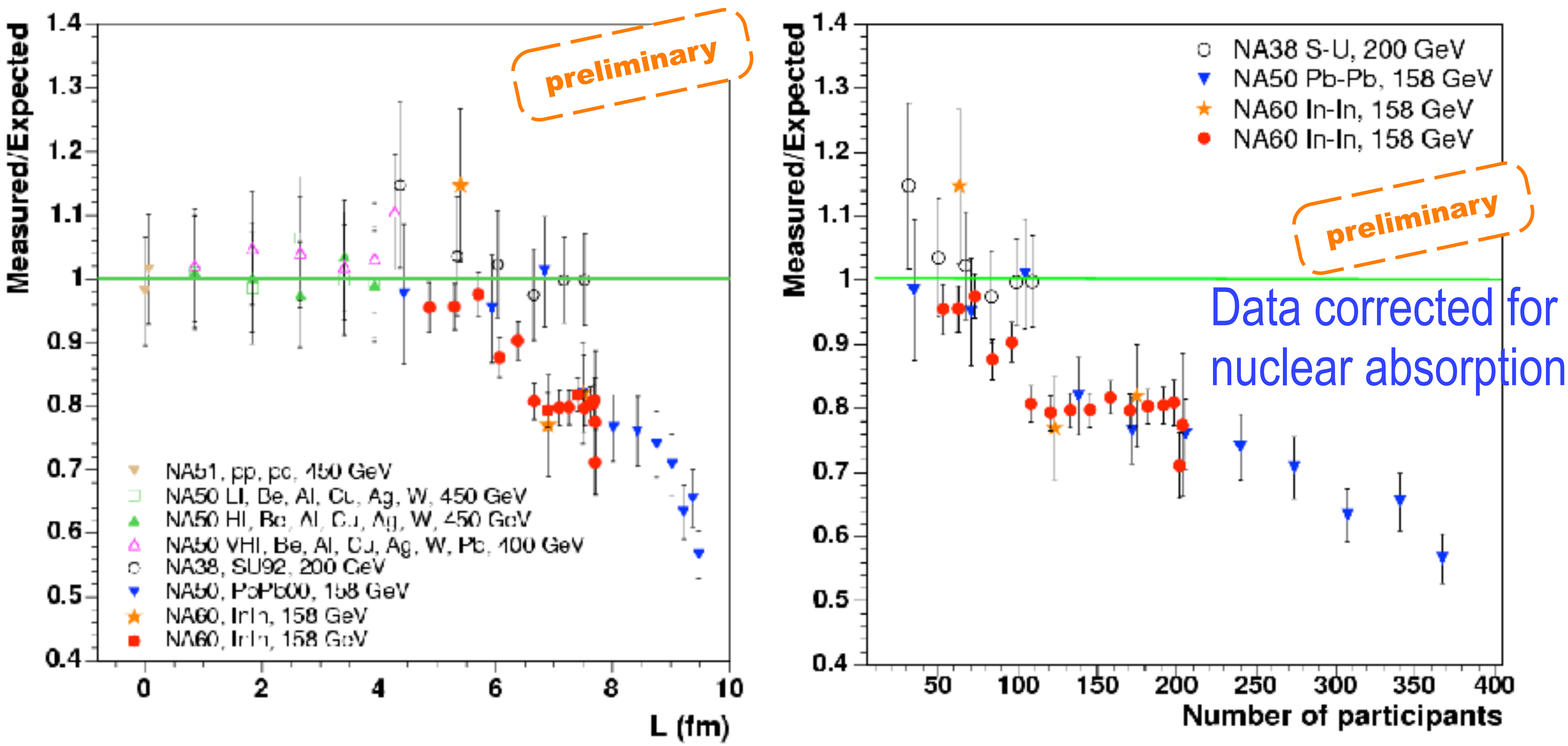
- We **do not** plan to delay further or suppress either ALICE or LHCb
  - Heavy ion collisions were a fundamental factor in LHC approval in 1996.
  - LHCb extends studies of CP violation in the B system. Precision far beyond current B factories, entirely new decay channels.
  - Expts promoted by more than 1500 scientists, approved and funded in their own countries.
  - Cancellation would cause havoc and embarrassment in MS and to our partners in non-MS.

The Fixed Target Experimental Programme at CERN, 2001- 2005



FOLLOW-UP:
Slide from the Research Board, March 2002
Research Board, March 2003: *The participation of NA45 in the full indium run would cause interference with test beam for ALICE. M. Hauschild pointed out that if they ran for only 30 days the conflict with ALICE could be avoided.*

C. Lourenco for NA60, EPS Conference, Lisbon 2005



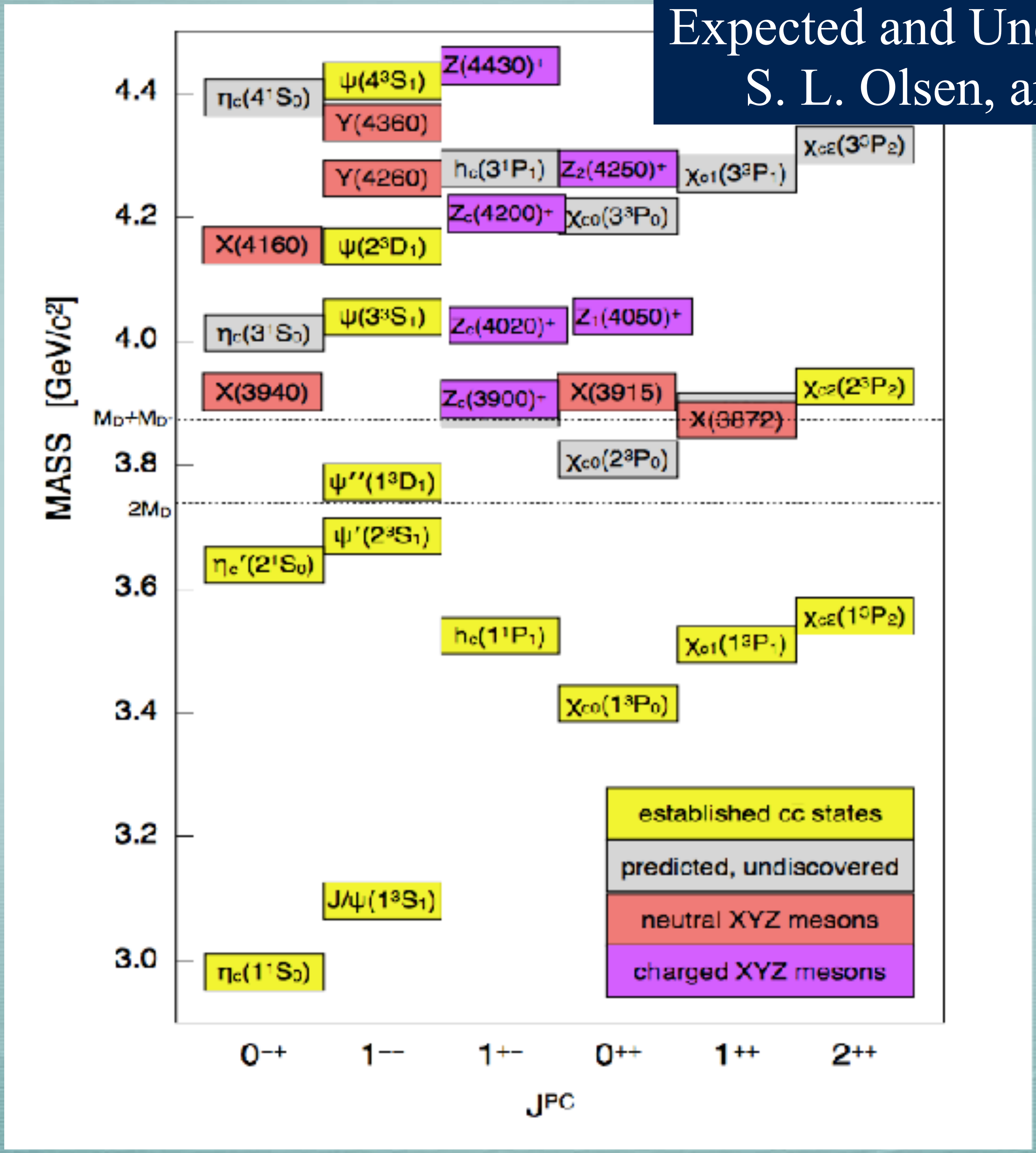
As a function of the number of participants, the J/ψ suppression pattern measured in In-In collisions by NA60 is in good agreement with the Pb-Pb pattern recently published by NA50

A more significant comparison requires Pb-Pb points with reduced error bars

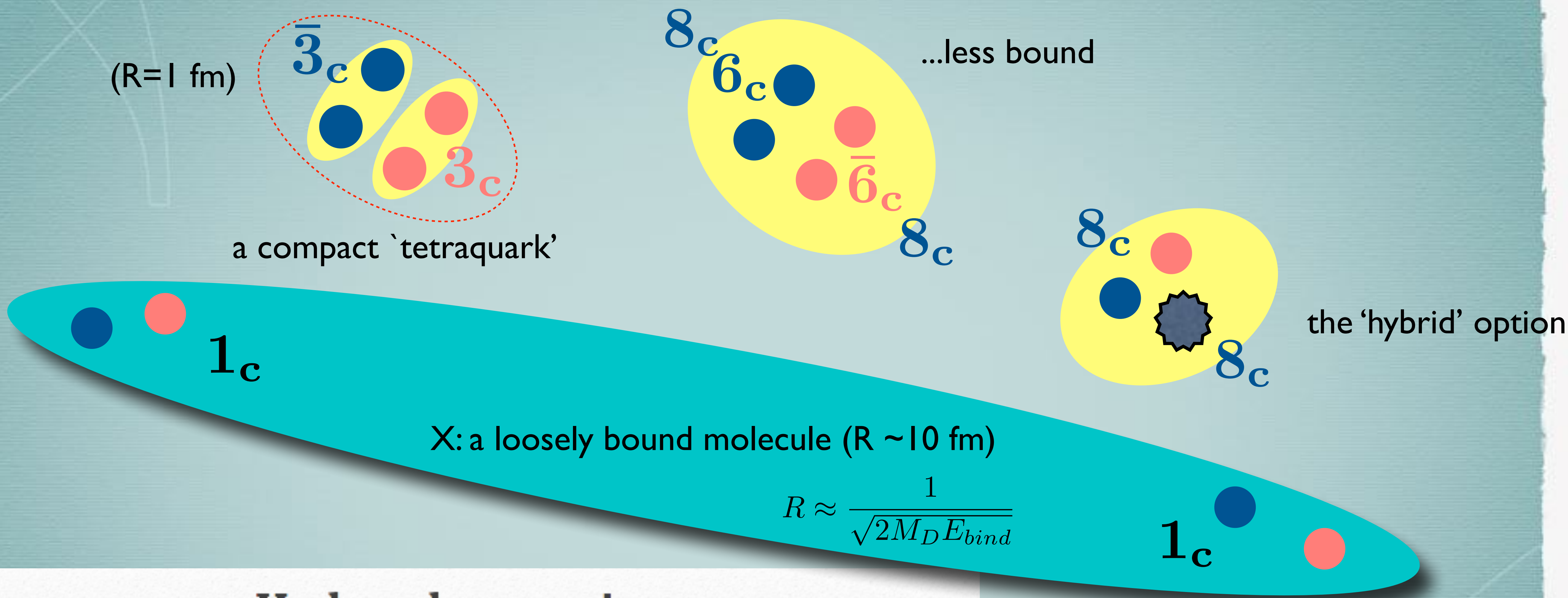
(NA50 is working on an analysis method which does not use the DY yield as normalization)

A novel application? Exotic hadrons in Heavy Ion Collisions @LHC

Expected and Unexpected Charmonia
S. L. Olsen, arXiv:1511.01589

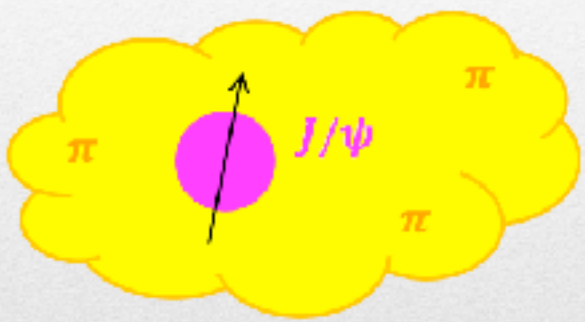


Models for X Y Z mesons



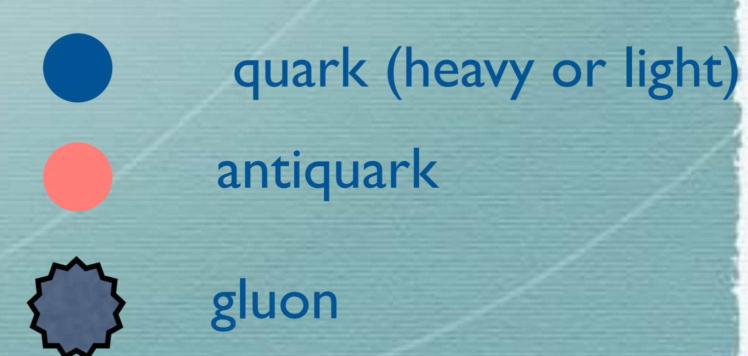
Hadro-charmonium

Voloshin arXiv:1304.0380



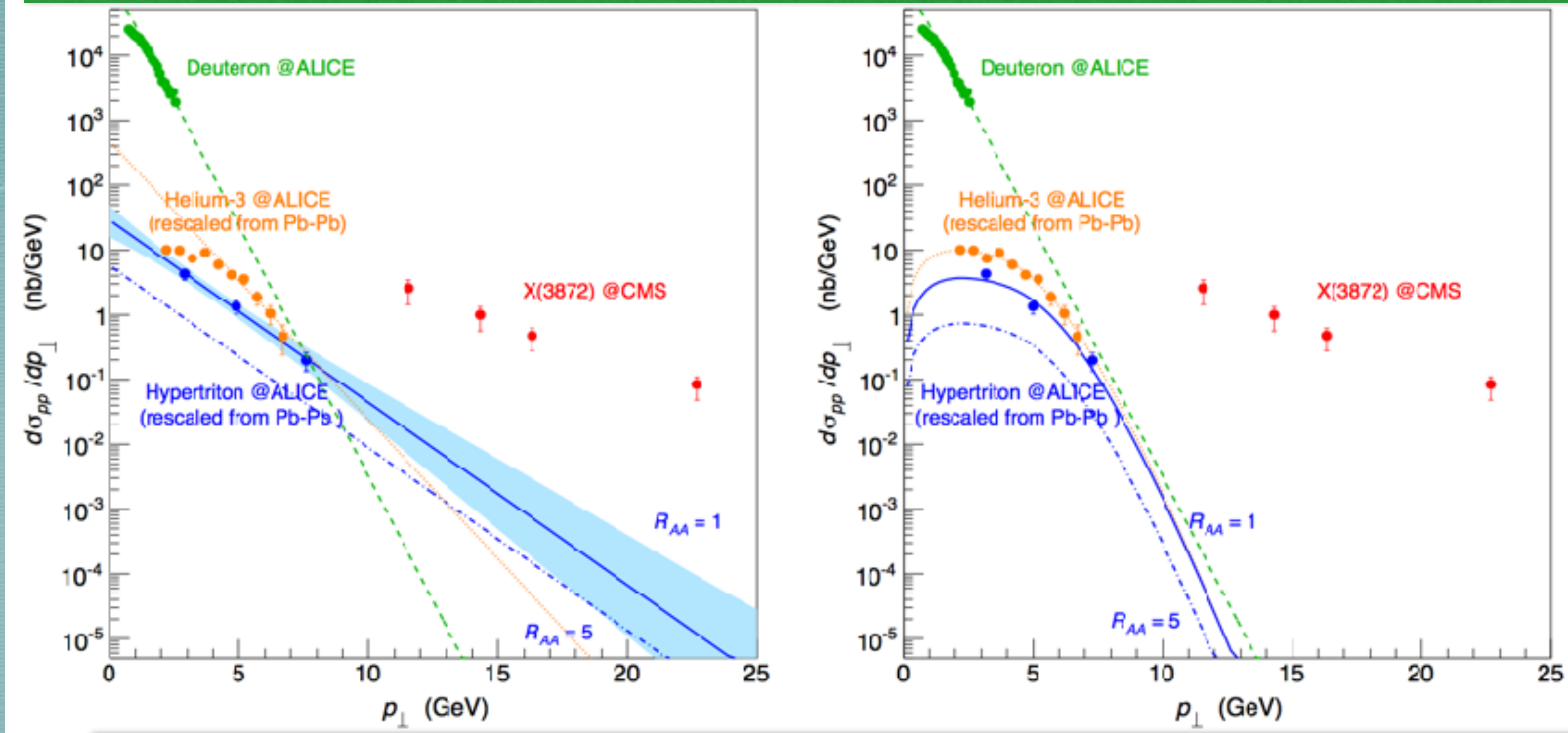
A $c\bar{c}$ state surrounded by light matter

Decay into $\eta_c\ \rho$ forbidden by HQSS



A. Esposito *et al.*, Phys. Rev. D **92** (2015) 3, 034028

Rescaling from Pb-Pb ALICE cross sections to p-p CMS cross section is done with: Glauber model (**left panel**) and blast-wave function (**right panel**}) (R_{AA} or R_{CP} =1)



Collective effects in Pb-Pb (e.g.quark-gluon plasma) **enhance nuclear cross sections** and therefore **reduce the cross section rescaled to p-p**.

- There is a vast difference in the probability of producing X(3872) and that of producing light nuclei, true "hadronic molecules", in high energy collisions
- high energy production of suspected exotic hadrons from quark-gluon plasma in HI collisions at colliders can be very effective tool to discriminate different models
- a long list of suspects: $f_0(980)$, X(3872), $Z^{\pm}(3900)$, $Z^{\pm}(4020)$, $Z^{\pm}(4430)$, X(4140)….

P. Giubellino, talk in *Ninety Years of Fermions*, Roma, Accademia dei Lincei, October 2016

The exploration of the phase diagram of strongly interacting matter: a world wide enterprise

CERN, about 1500 scientists in ALICE, CMS, ATLAS and LHCb (2010-2028…)

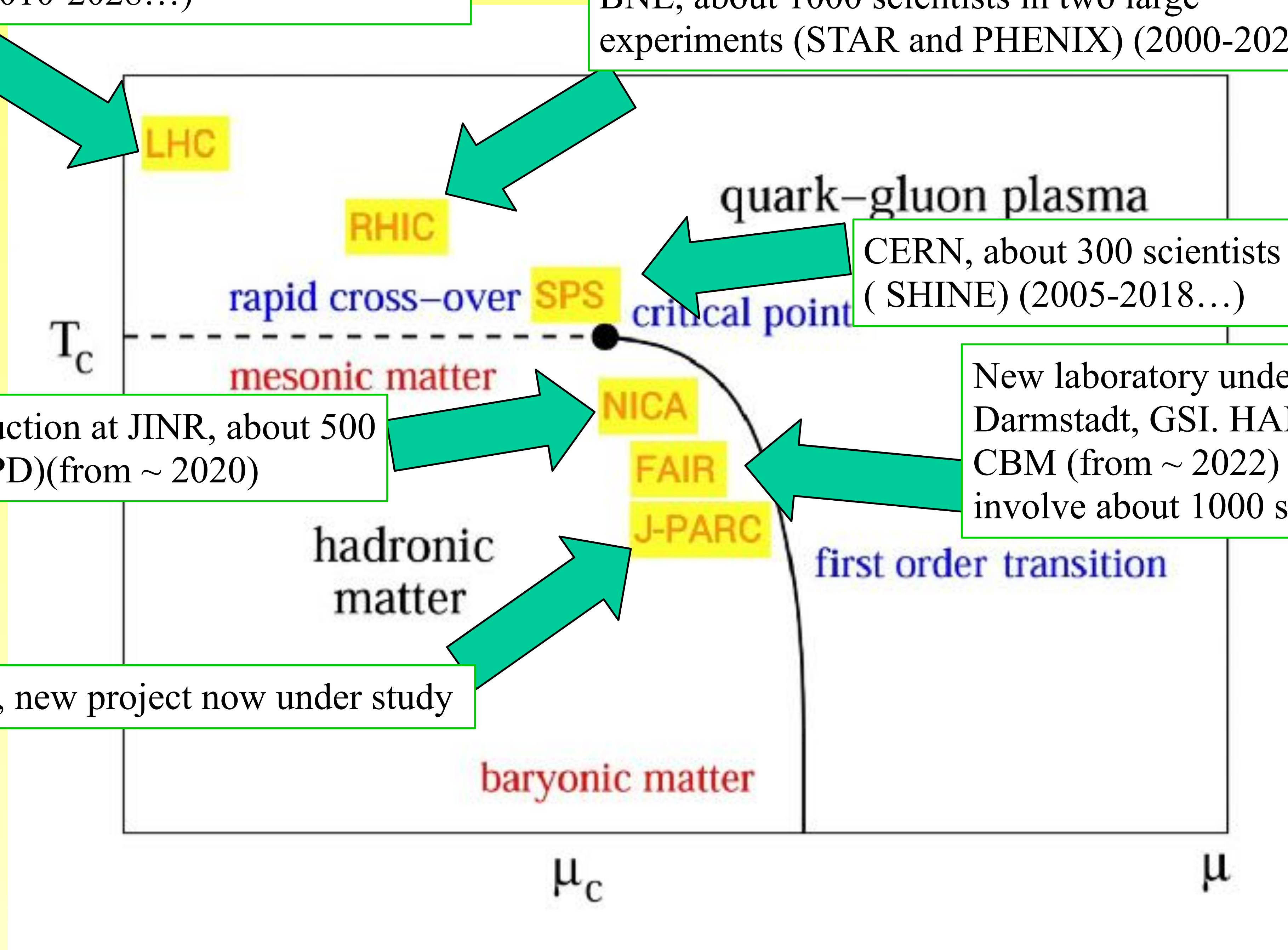
BNL, about 1000 scientists in two large experiments (STAR and PHENIX) (2000-2024…)

CERN, about 300 scientists (SHINE) (2005-2018…)

Under construction at JINR, about 500 scientists (MPD)(from ~ 2020)

New laboratory under construction in Darmstadt, GSI. HADES (active) and CBM (from ~ 2022) experiments involve about 1000 scientists.

Japan, new project now under study



Summing up

- The february 2000 announcement was based on circumstantial but solid evidence
- Critics notwithstanding, it was full justified
- Subsequent investigations showed that the situation was the one envisaged in the CERN announcement

SPS COLLISIONS HAD PRODUCED A NEW PHASE OF HADRONIC MATTER IN GREAT PART THE ONE ENVISAGED BY THEORETICAL INVESTIGATIONS CARRIED OUT AFTER DISCOVERY OF QCD

THE STORY IS NOT FINISHED
FURTHER SURPRISES ARE TO BE EXPECTED