5th Berkeley School on Collective Dynamics in High Energy Collisions. June 9 – 13, 2014

Reflections on 150 years of pA & AA studies

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MIT

It is not an attempt to review who did what, when and who deserves credit for what.

- if I ever write this up, I will make sure to refer to the individual contributions.
  In a talk, it is too hard to do justice to the many who made crucial contributions to this field.

Focus of talk is on the evolution of the questions of interest and the interplay of technology, experiments, theory and sociology in the development of the field.

I

4 Periods in the development of the field of pA and AA studies

1867-1970 Evolution of nuclear, particle and cosmic ray/space physics.
Discovery of high energy pA and AA physics.

1970-1983 Period of numerous experimental opportunities and theoretical speculations.
Emergence of two communities, one primarily with a particle and one with a nuclear background. By the end of this period there are many, potentially very interesting facts that need elucidation and, more important, the "big" questions of relativistic heavy ion physics are formulated.

1983-2005 First studies of AA collisions at high energies. pp and pA are considered as a reference only.
Retreat from the "big" questions. Rich phenomenology surpasses all expectations.

2005-today Flood of data and high precision studies of the phenomenology.
Return of interest in pA collisions and drive towards a deeper understanding of pp, pA and AA phenomenology.
What are the "big" questions is the question.

Period 1: 1867-1970

Invention of:

- photographic emulsion
- ionization chamber
- Geiger-Muller counter
- Wilson cloud chamber
- coincidence circuit
- scintillation counters
- bubble chamber
- spark and wire chambers
- accelerators

Discovery of:

- radiation
- cosmic rays
- particle zoo
- foundations of nuclear and particle physics
- high energy nuclear interactions
- neutron stars

By 1970 we know that:

At very high energies multiparticle states are produced, some with extraordinary high multiplicities.

Neutron stars must have super dense nuclear matter at center

For high energy collisions Glauber model works

- σ_{pA} can be understood in terms of σ_{pp}
- can even be used to show for example that $\sigma_{\rho p} \approx \sigma_{\pi p}$ and $\neq 2\, \sigma_{\pi\pi}$

Questions in early and mid 1970's:

Mechanism of multiparticle production?

- why so little intra-nuclear cascading in pA collisions?

ie. why at very high energies pp & pA differ so little?

What is the state of matter between the instant of a pp collision and the final production of outgoing particles?

Phenomenology and mechanism of nuclear break-up during high energy collisions?

Equation of state of nuclear matter?

Properties of high density nuclear matter?

Are there any abnormal states of nuclear matter?

Nature of the vacuum?

Some interesting facts from the first period

1867: Niepce de St. Victor misses opportunity to discover radiation, cosmic rays & pA collisions!

As a result we had to wait to c1938 for first pp and pA studies.

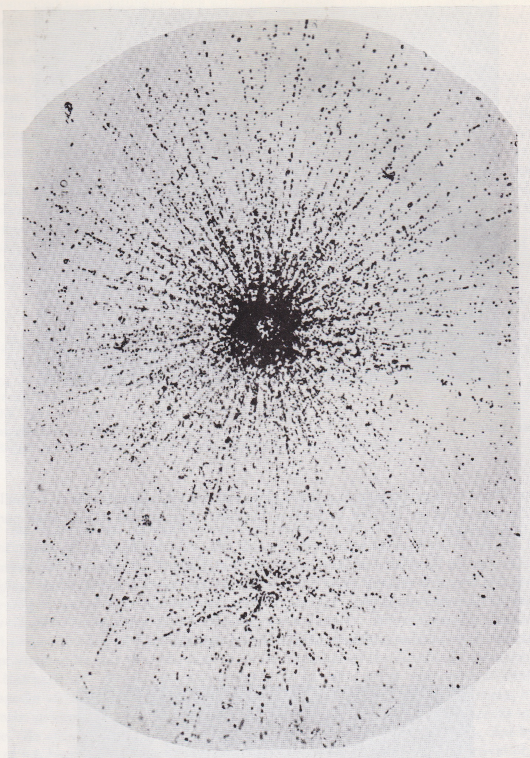


PLATE 1–5

Wratten 'Ordinary' Plate. KINOSHITA and IKEUTI (1915).

The α-particle tracks were produced by means of a sewing needle of which the point had been rubbed on a metal plate exposed to radon. The hole left by the needle point can be seen as a light patch at the centre of each pattern. Most of the tracks are due to RaC′ of range in the emulsion 54μ, the mean number of grains per track being 16. Many of the α-particles enter the emulsion from points on the needle above the level of the surface so that there is no clearly marked halo. Note the absence of large-angle scattering of the particles.

Tracks of protons and α-particles in an Agfa K-plate

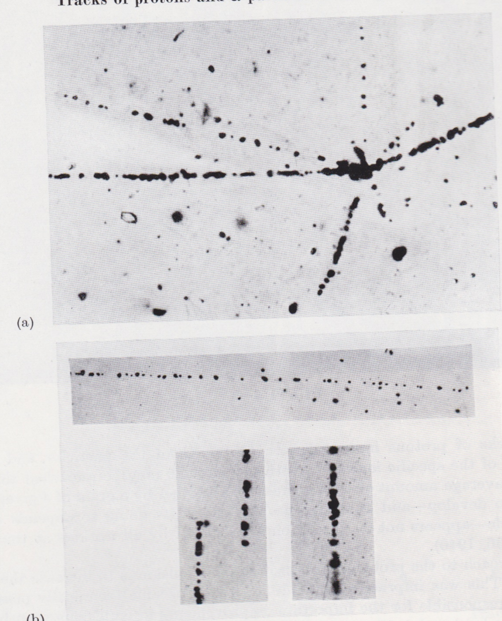


PLATE 1–10

Agfa K-plate. SCHOPPER and SCHOPPER (1939).

The upper photograph shows a nuclear disintegration produced by cosmic radiation, and displays a marked degree of discrimination between tracks of large and small specific ionisation. There is a satisfactory absence of background grains. The photograph is a mosaic of two pieces of which the outlines can just be distinguished.

The lower photographs also illustrate the 'discriminating power' of the emulsion and the absence of background, and show the tracks of a proton (horizontal) and three α-particles (vertical).

From Power, Fowler and Perkins

1912: Hess discovers cosmic rays (by taking an ionization chamber up in a balloon)

However 1912 – c1938 there are no studies of pp, pA or AA collisions!

- most important question is the source and production of cosmic rays
- prejudice that cosmic rays are "obviously" γ-rays
  (Millikan: they are the "birth cries of forming heavy nuclei")

c1930 – 1950: with the arrival of GM counters, coincidence circuit, triggered cloud chamber, better emulsions and studies at high altitude

- some cosmic rays are found which are clearly charged
- focus shifts to nature of cosmic rays
- in quick succession discovery of e^+, μ, π, K, Λ…
- beginning of HEP

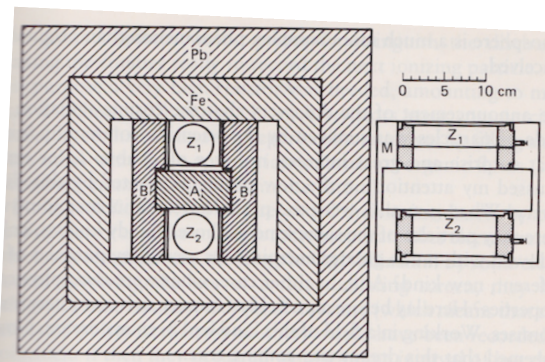


Fig. 1.1. The experiment of Bothe and Kolhörster. Coincidences between counters Z_1 and Z_2 are produced by cosmic-ray particles traversing both counters. Observations were made both with and without a 4.1 cm thick gold absorber between the counters. The coincidences observed with this absorber demonstrate the existence of cosmic-ray particles capable of traversing 4.1 cm of gold. (Gold was chosen as an absorber because of its high density.) From an article by W. Bothe and W. Kohlhörster in *Zeitschrift für Physik*, 36, 751 (1929).

From Rossi, Moments in the life of a scientist

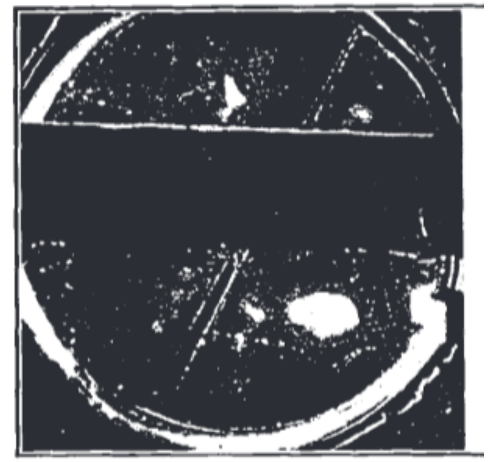
The first considerations of pp and pA multiparticle production are almost a side show

c1939 events are observed where a few minimum ionizing tracks appear to come from a single point

1939 – 1941 Heitler and Heisenberg discuss whether you can get more than one particle produced in a single collision. Heitler thinks, no!

1943 Janossy and also Wataghin observe in a cloud Chamber/Pb stack many tracks coming from a point inside the lead. Janossy concludes that intra nuclear cascades are the origin of multiparticle production.

C 1947, with the advent of high quality emulsions multiparticle production is also seen in pp collisions



Braddick et al., Nature 144,1012(1939))

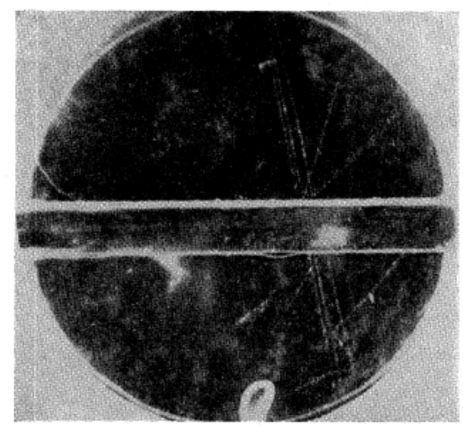


FIG. 1. Meson shower, showing three penetrating particles passing through a lead plate.

Janossy, PR 64, 345 (1943)

pPb collision

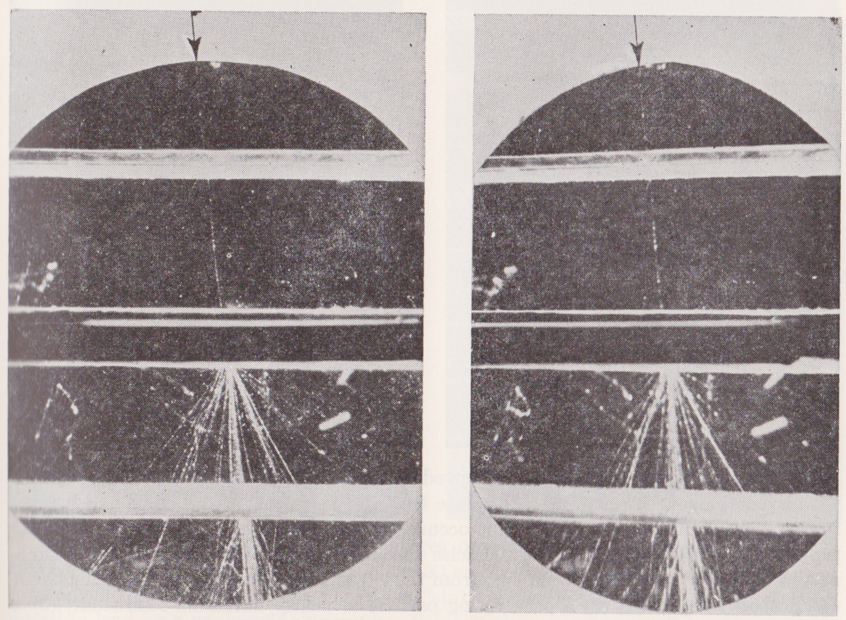
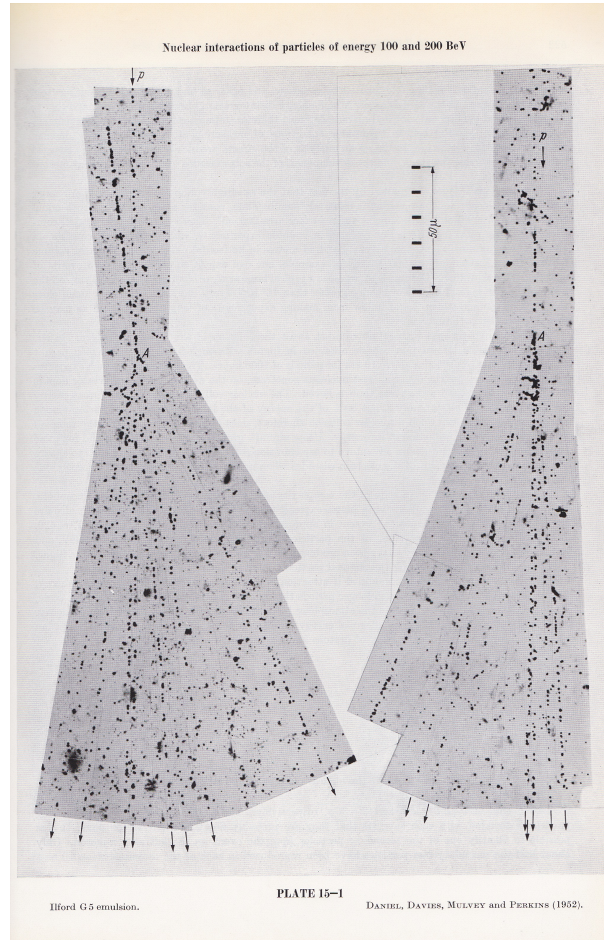


Fig. 8.1.20. Stereoscopic views of a nuclear interaction occurring in a 5-cm thick lead plate. All the visible secondary particles appear to have minimum ionization. About 11 of them traverse a 1-cm thick lead plate without undergoing secondary interactions. The event is produced by a primary particle of minimum ionization, presumably a high-energy proton. [From Shutt (SRP46).]

From Rossi, "high energy particles"

pp collision



From Powell, Fowler and Perkins

Theoretical attempts to understand multiparticle production in pp collisions

1947 Lewis, Oppenheimer and Wouthuysen	Intense fields which readjust into mesons
1949 – 1952 Heisenberg	pp produces meson field. Turbulence in the field leads to particle production. It is a slow process.
1951 Fermi	Protons stop each other and deposit all energy in a Lorentz contracted disk. Particles are produced in this hot system in thermal equilibrium and, without further interacting, escape isotropically.
1953 Landau	Similar to Fermi, however the hot system at first flows according to relativistic hydrodynamics and only later decays into the outgoing particles. Expansion is not isotropic. Pt is limited to about 0.4 GeV/c .
1952 – 1958 Takagi, Ciok, Krausharar & Marks, Cocconi etc.	Various two fireball models, ie excited nucleons which later decay into the final particles.

1950 – 1970 a 4-way split occurs driven by the availability of tools, data and interests.

1. Some continue the study of primary cosmic rays, their origins and other space science phenomena.

2. Some expand their interests in nuclear physics to include nuclear matter – the EOS, the properties of the inner core of the recently discovered neutron stars (1967) and nuclear break-up (evaporation) in high energy collisions.

3. Many, encouraged by the availability of higher and higher energy accelerators, become HE physicists. They do not concentrate on multiparticle phenomena – they find simple reactions of more fundamental interest. Furthermore neither the energy (except for rare cosmic ray events) nor detector technology and computing power are adequate for multiparticle studies.

4. Finally, a substantial international community emerges, whose bread and butter, are the exposure of nuclear emulsions to cosmic rays at high altitudes and, when available, to accelerator beams. They produce the first characterization of multiparticle states produced in high energy pp, pA and AA collisions. They observe that pp and pA collisions are not very different from each other (except, of course, for the products which result from the disintegration of the nuclei). The "emulsion" community is the first example of truly large international collaboration (eg JACEE collaboration (1986)).

At the end of period 1 (1867-1970), the questions of interest related to future pp and pA physics are:

Mechanism of multiparticle production?

- why so little intra-nuclear cascading in pA collisions?
  ie. why at very high energies pp & pA differ so little?

What is the state of matter between the instant of a pp collision and the final production of outgoing particles?

Phenomenology and mechanism of nuclear break-up during high energy collisions?

Equation of state of nuclear matter?

Properties of high density nuclear matter?

Are there any abnormal states of nuclear matter?

Nature of the vacuum?

Period 2: 1970 – 1983

This is the period of numerous experimental opportunities and theoretical speculations and emergence of two communities, one primarily with a particle and one with a nuclear background.

1971 ISR at CERN: p, d, α collider with cms energy $\sqrt{s_{nn}}$ 23 – 63 GeV
(shut down in 1984 to make resources available for LEP. Could have been a valuable (?) AA collider)

1972 National Accelerator at NAL (later called Fermilab). 200 GeV/c proton beams and secondary beams of π, K, μ & ν. Beams were made available for some fixed target nuclear studies.

Observation of interesting and unexpected facts (mostly ahead of their time!).

- participant scaling (does not explain lack of cascading but quantifies it)
- extended longitudinal scaling
- universal quenching of forward going particles in cold nuclear matter
- baryon stopping is sufficient to produce in AA colliders interesting high energy and baryon density
- Cronin Effect (large nuclear enhancement of particles at $P_t \approx$ 1-4 GeV/c)
- surprising transparency of cold nuclear matter to coherently produced hadronic systems.

From c1976 onwards the energy of the external beams at fermilab gradually increases to 900 GeV.

- over 50 emulsion exposures
- several fixed target programs to study phenomena such as Drell-Yan production of di-muons, including J/ψ
- μA scattering to study differences in parton distributions in protons and nuclei and propagation of partons in cold nuclear matter.

1976 SPS at CERN 400 GeV proton beam and various secondary beams used for HEP studies. As a by-product: big surprise – EMC Effect (nucleon parton distribution functions modified inside nuclei)

c1974 Influenced by the discovery of neutron stars(1967), of asymptotic freedom(1973), the MIT bag model(1974), Hagedorn limiting temperature(c1968) etc., a new field is born. It profoundly influences research at Berkeley (significantly enhanced by influx of physicists from Germany). Studies move to EOS of nuclear matter, metastable phases of nuclear matter (eg. Lee-Wick matter), nuclei far from stability, nuclear dissociation at high energies, nuclear hydrodynamics etc.

1974 Bear Mountain Workshop " BEV/NUCLEON COLLISIONS OF HEAVY IONS – HOW AND WHY"

- this was a highly influential gathering which had a huge impact on the launching of relativistic heavy ion physics.

1974 BEVALAC at LBL: up to Argon beams, 0.25 – 2.1 GeV/nucleon on fixed nuclear targets.

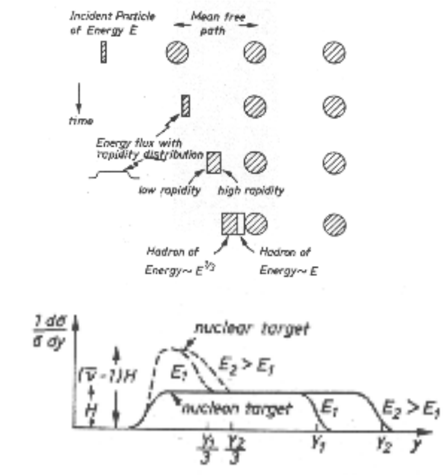
- The BEVALAC observes phenomena which indicate that nuclear matter is being compressed and flows. They do not find any new forms of baryonic matter or highly abnormal effects. However it has a profound influence on the development of the relativistic heavy ion field. In particular it breeds leaders of the field and develops detectors and analysis techniques that prove later to be very important.

C1979 First discussions of QGP

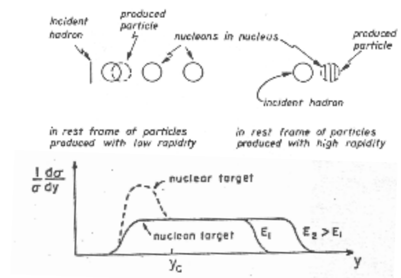
The two communities have very different views of pA and AA collisions

pA community view:
(influenced by the parton model)

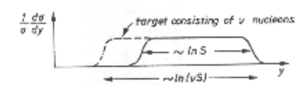
Godfried's energy cascade model



Parton and single chain multiperipheral type models



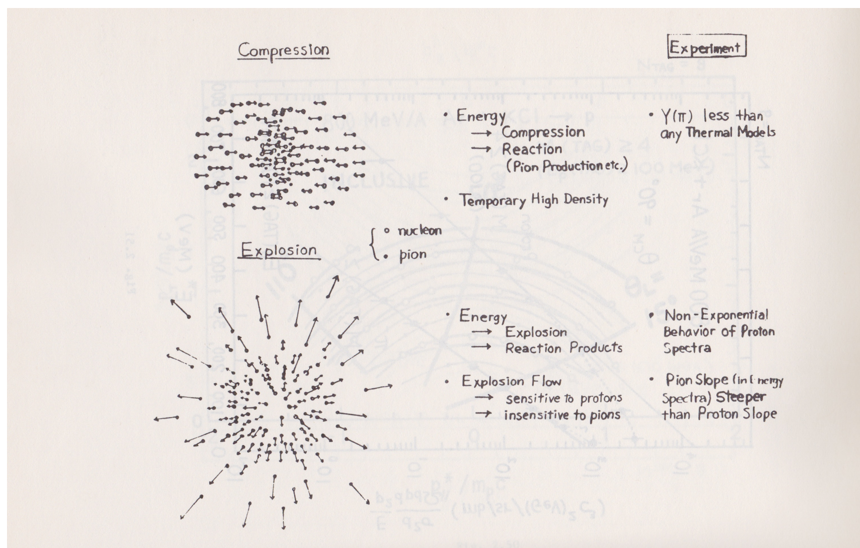
pA = pp at higher energy (cumulative tube model)



$$R_A \sim \frac{\ln(\nu S)}{\ln S} \sim 1 + \frac{\ln \nu}{\ln S} \to 1 \text{ as } E \to \infty.$$

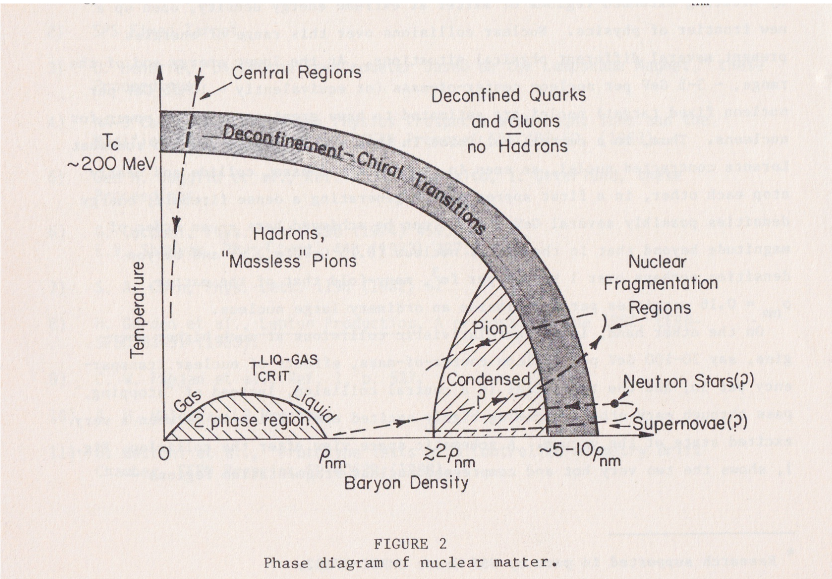
From WB review,
Acta Phys. Pol. B8(1977)

AA community view:
(influenced by low energy nuclear collisions)



From S.Nagamiya. 4th HE HI Summer Study, LBL 1978

"Big" questions c1983:



From G.Baym, QM 1983

- What is the nature of the QCD vacuum?
- Is it possible to create and study Disoriented Chiral Condensates?
- Is it possible to observe the deconfinement phase transition?
- is it possible to observe the chiral restoration phase transition?

Everyone wants to discover the "QGP"
At this time, pA and the question of how particles are produced takes a back seat!

Practical questions:

- Are nuclei large enough so that the system produced in high energy collisions is in chemical and thermal equilibrium? (Note: It was already shown that stopping is adequate)

How did I get involved in this physics?

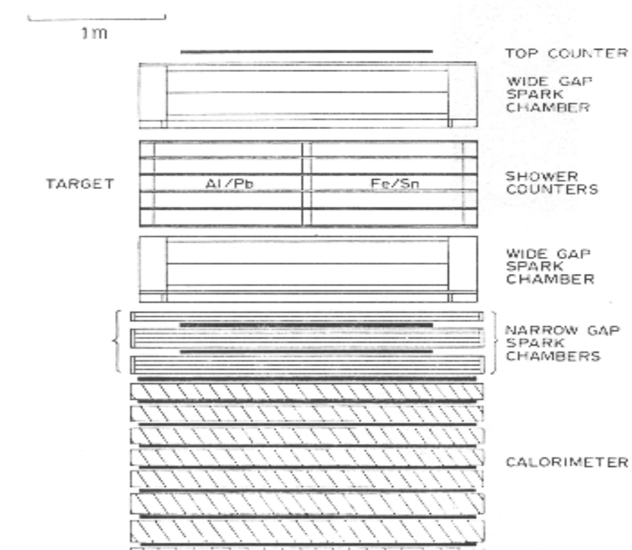
1967 – 1969 $\gamma A \rightarrow \rho A$

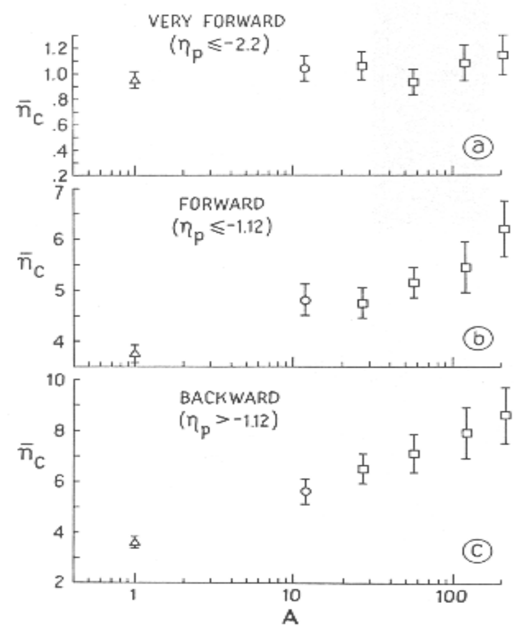
$\sigma_{\rho p} \approx \sigma_{\pi p}$ therefore $\rho \neq 2\pi$'s

1972 at MIT seminar given by Larry Jones (Michigan)

Echo Lake Calorimeter-Spark Chamber $\sqrt{s_{NN}} = 13 - 31 GeV$

(L.Jones et al. Preprint UM HE 74-23)



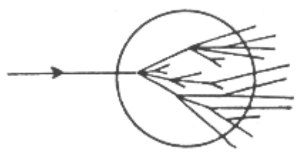


I got interested in the following questions:

- mechanism of particle production in pp collisions?
- space-time evolutin of the production process?

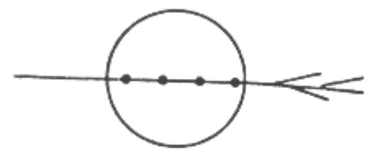
From Fermilab E178 proposal (1972):

Proposed by W.Busza, J.Friedman, H.Kendall, L.Rosenson



$\langle n \rangle_A \sim \langle n \rangle_p A^{1/3}$

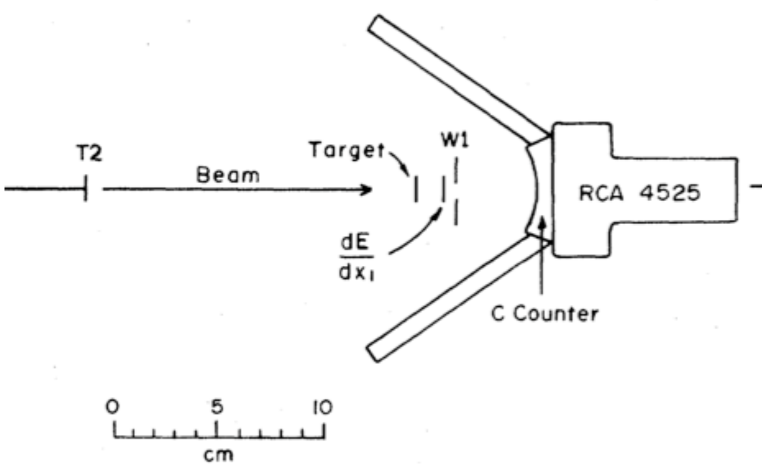
or



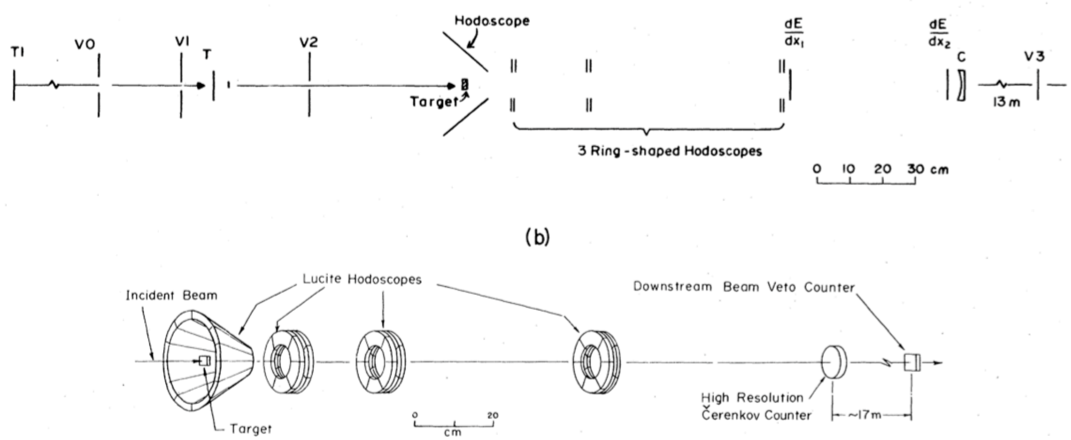
$\langle n \rangle_A \sim \langle n \rangle_p$ or

$\langle n(A,s) \rangle \sim \langle n(p,\bar{\nu}s) \rangle$

E178A



E178B or PHOBOS 1

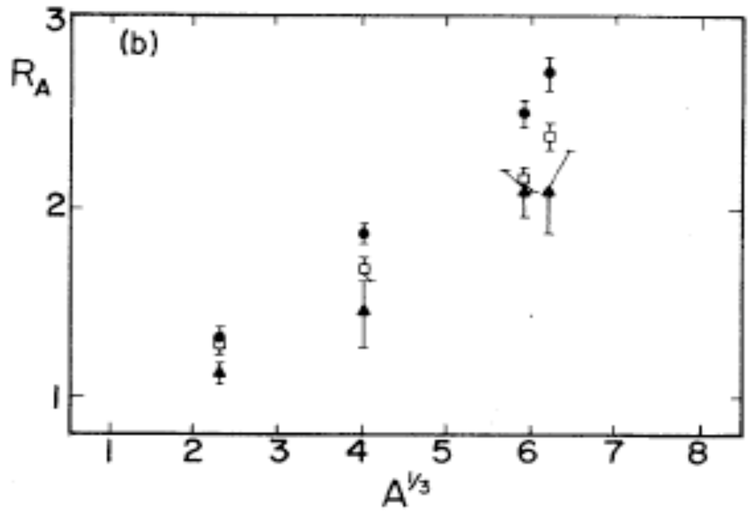


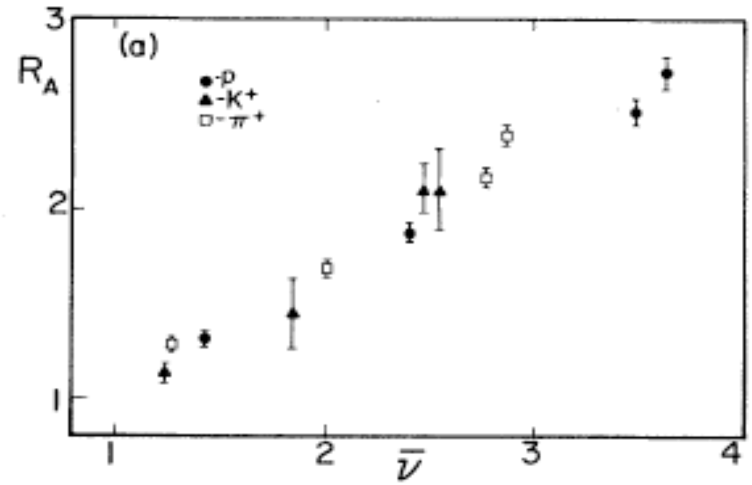
W. B and C. Young, Meeting on the HE collisions involving nuclei, Trieste 1974

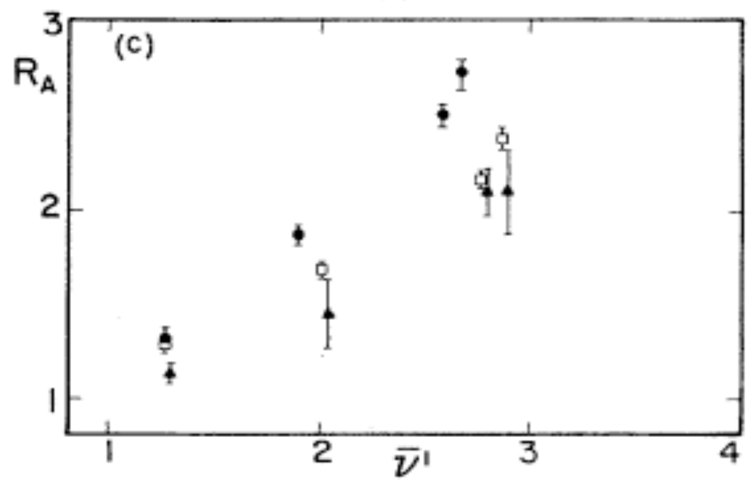
J.E. Elias et al., PR D22 (1980) 13

Surprise: discovery of participant scaling

$R_A = N_{pA} / N_{pp} = \frac{1}{2} + \frac{1}{2}\bar{\nu} = \frac{1}{2} + \frac{1}{2} N_{coll} = \frac{1}{2}$ wounded nucleons $= \frac{1}{2} N_{part}$







Different cross-section after the first collision

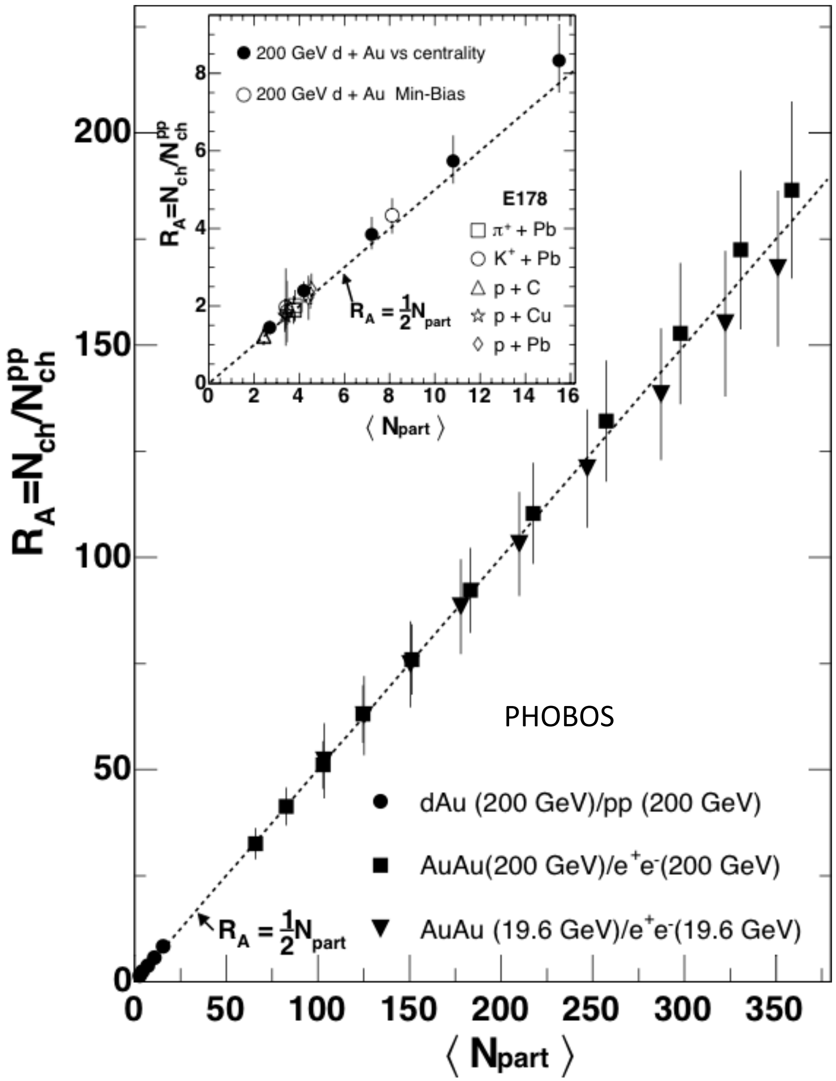
$\bar{\nu} = N_{coll} = N_{part} - 1 = A\sigma_{pp} / \sigma_{pA}$

π, *k*, *p* Data $\sqrt{S_{NN}}$ 10 to 20 GeV

W.Busza et al. (E178) PRL34 (1975) 836

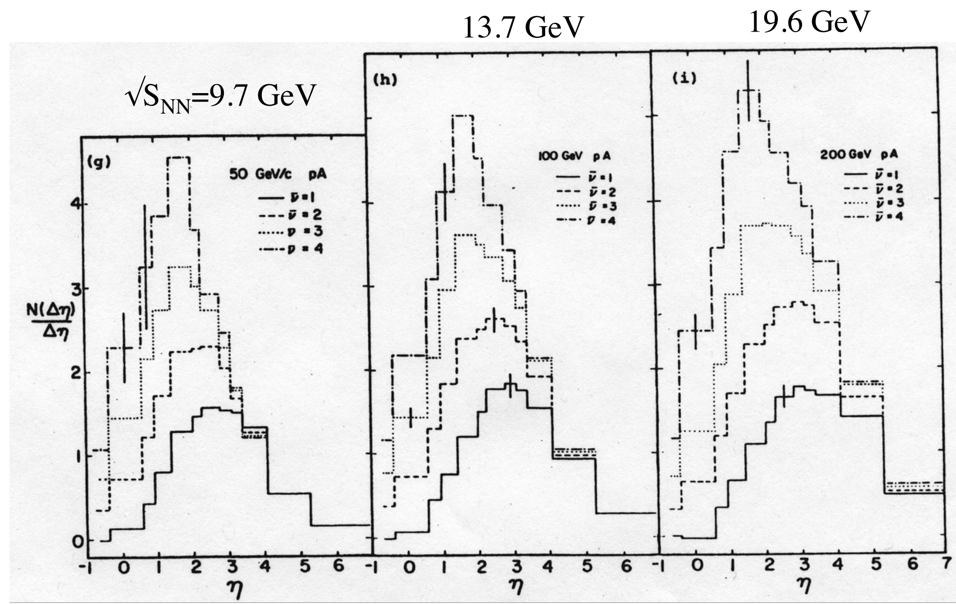
J. E. Elias et al., (E178) PRL 41 (1978) 285

Note: to date no deviation seen of N_{part} scaling of total charged multiplicity.



or wounded nucleons

E178: pA data

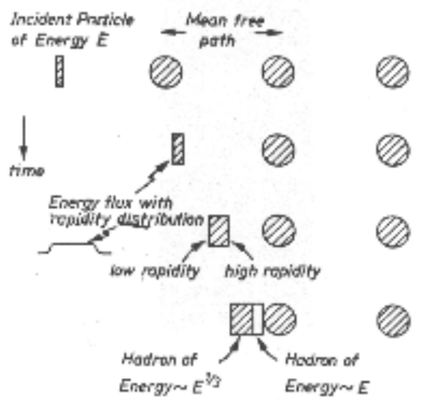


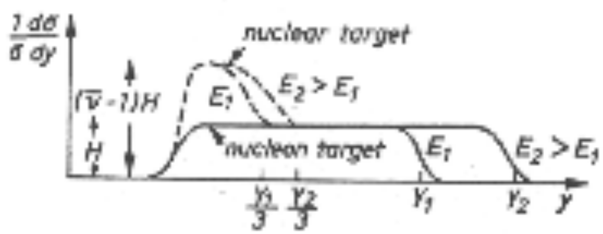
Data for different $\bar{\nu}$ (=N_{part}-1)

PHOBOS: W. Busza, Acta Phys. Pol. B35 (2004)2873
E178: W.Busza et al. PRL34 (1975) 836 and J.Elias et al., PR D22 (1980) 13

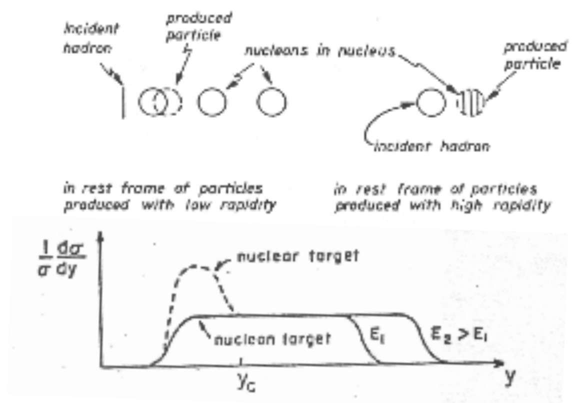
Examples of the variety of models proposed in the 1970's

Godfried's energy cascade model

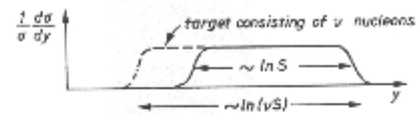




Parton and single chain multiperipheral type models



pA = pp at higher energy

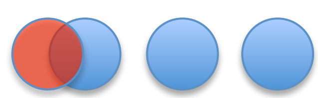


$$R_A \sim \frac{\ln(\nu S)}{\ln S} \sim 1 + \frac{\ln \nu}{\ln S} \to 1 \text{ as } E \to \infty.$$

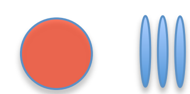
From WB review,
Acta Phys. Pol. B8(1977)

None of the above lead to the observed rapidity distributions, energy dependence, or long range correlations

c1976 realization that special relativity plays a crucial role and the importance of "formation time":



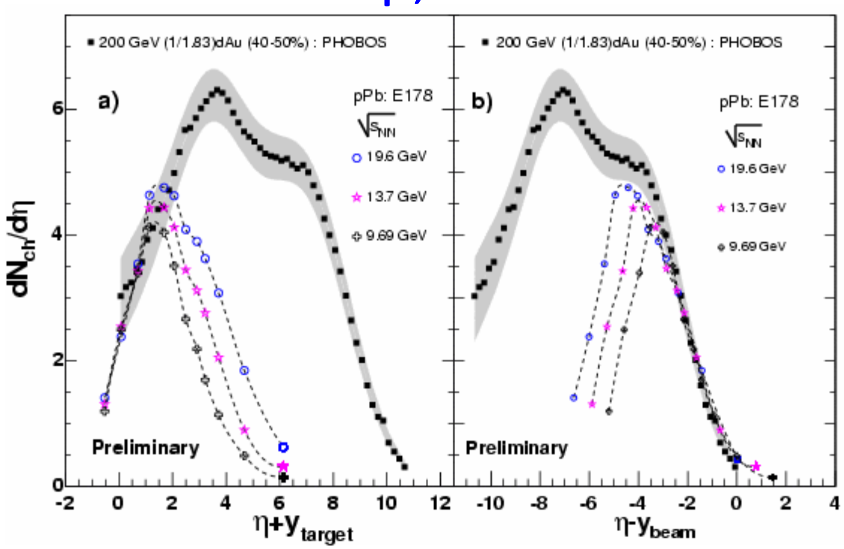
In rest frame of particles produced with rapidity close to that of the nucleus



In rest frame of particles produced with rapidity close to that of the incident proton

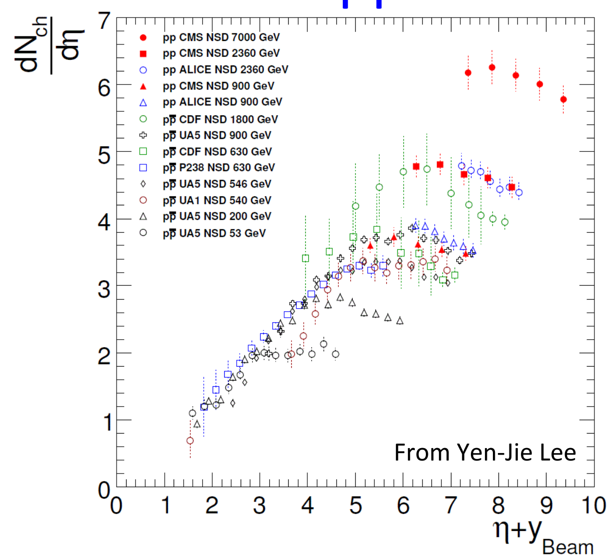
Universality of extended longitudinal scaling : direct evidence of saturation, e.g. CGC

p,d-A

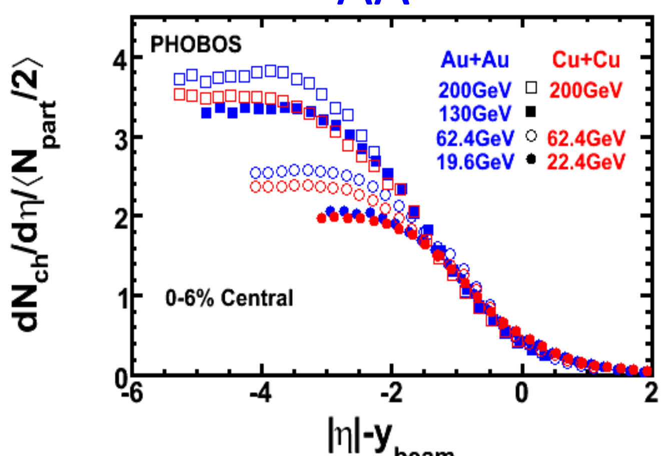


PHOBOS, Nucl. Phys. A 757 (2005) 28.
E178: PRD 22 (1980) 13

pp

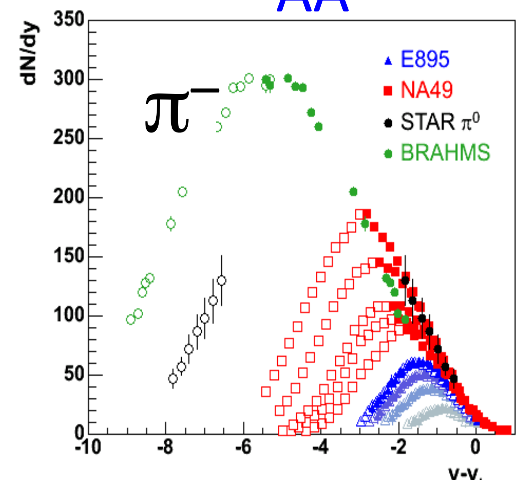


AA



arXiv: 0709.4008 [nucl-ex]

AA



Veres, QM2005

E178 led me to:

Fermilab E451: study of the leading particles in pi, K, p – A at 100 GeV/c , using the single arm spectrometer at Fermilab.

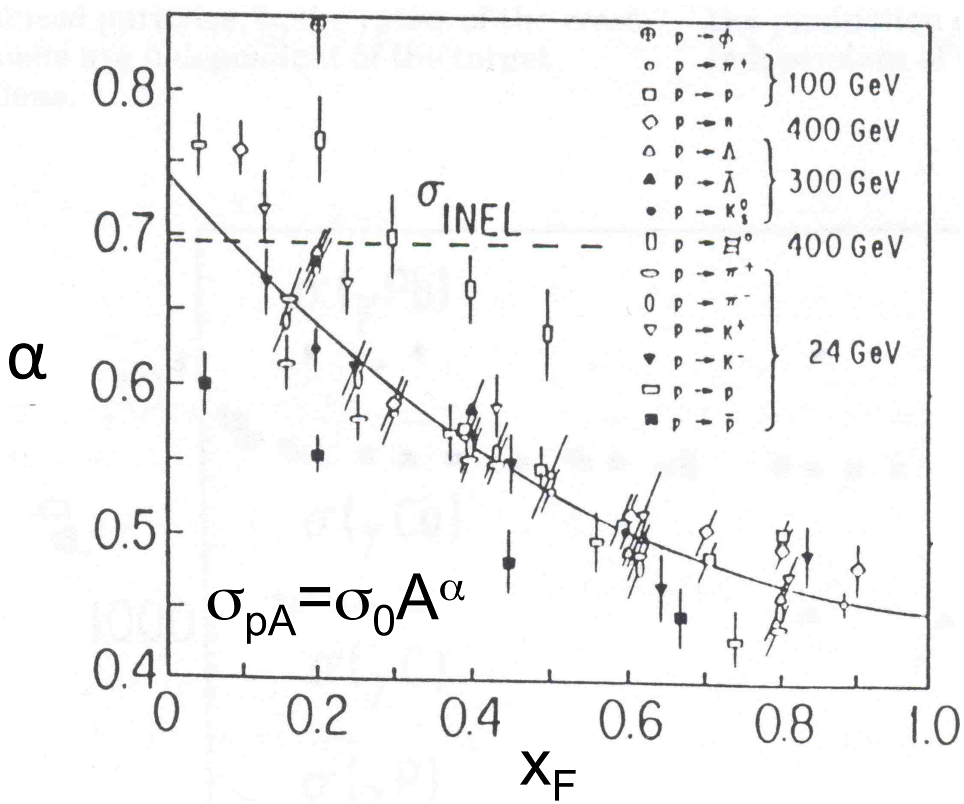
Fermilab E565: hybrid hydrogen bubble chamber with nuclear plates and forward spectrometer to study multiparticle production and leading particles in pA at 200 GeV/c

Fermilab E665: Study of muon-nucleus multiparticle production, in particular shadowing and propagation of quarks in cold nuclear matter

Universal quenching of particles produced in the very forward direction

pA collisions

Various beam energies: 24, 100, 300, 400 GeV
Various final states: ϕ, π^+, π^-,p ,p,n,Λ,K^0,Ξ,K^+,K^-



D.Barton et al PRD27 (1983) 2580 E451)
W. Busza, Nucl. Phys. A544:49 (1992)

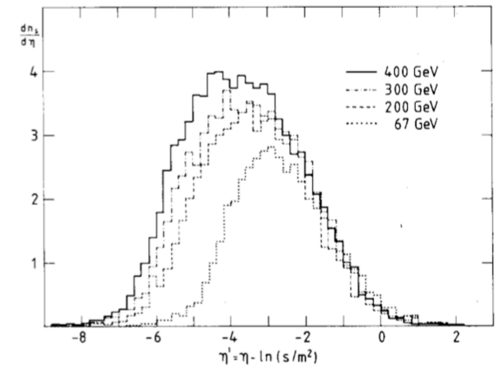
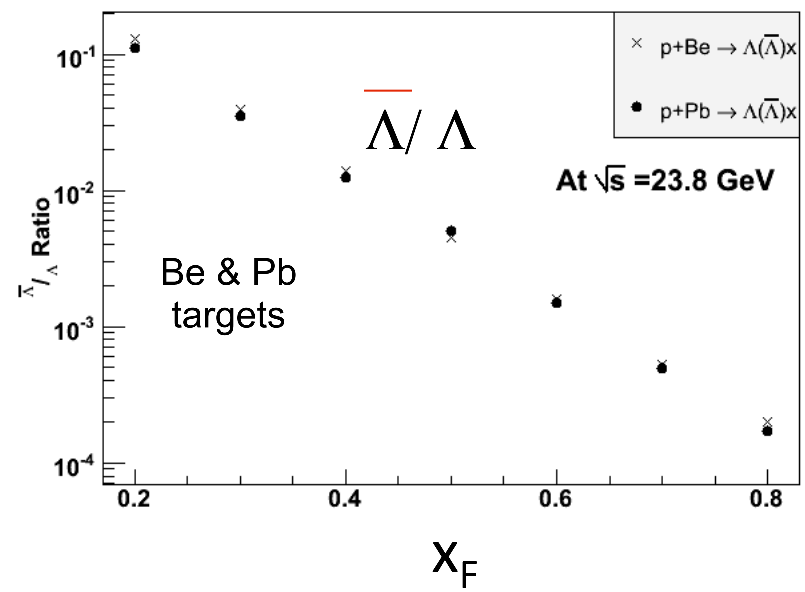


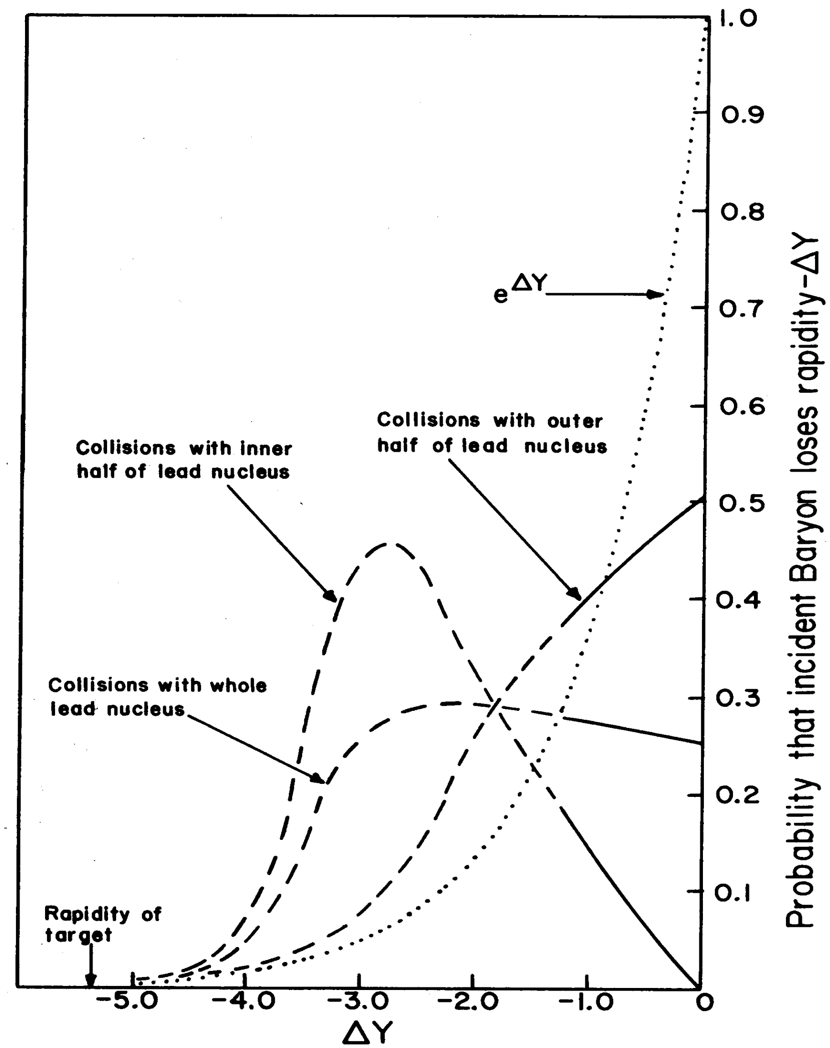
Fig. 13. The total inclusive shower-particle distribution in the projectile rest frame.

pEmulsion data (Otterlund et al., compilation NPB142 (1978) 445)



Skupic et al., PRD 18 (1978) 3115

Baryon stopping



WB and A.S. Goldhaber,
Phys.Lett. 139B (1984) 235

There is a rapidity loss $\Delta y \geq 2.0$ when a relativistic baryon passes through a large nucleus i.e the baryon deposits 85% of its energy (independent of energy)!

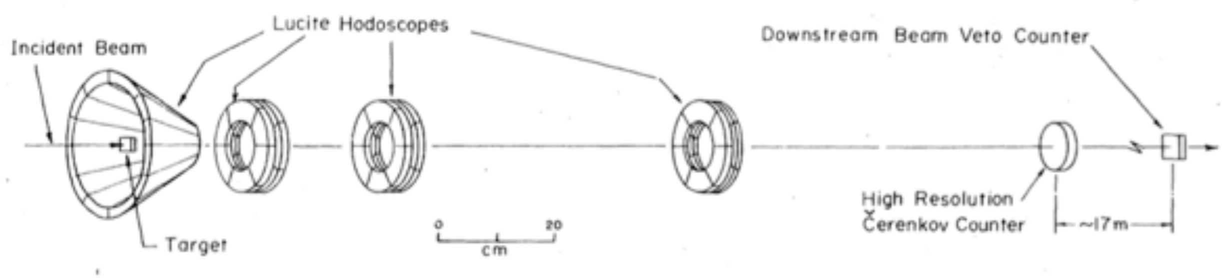
Conclusions:

RHIC will not be a bust!

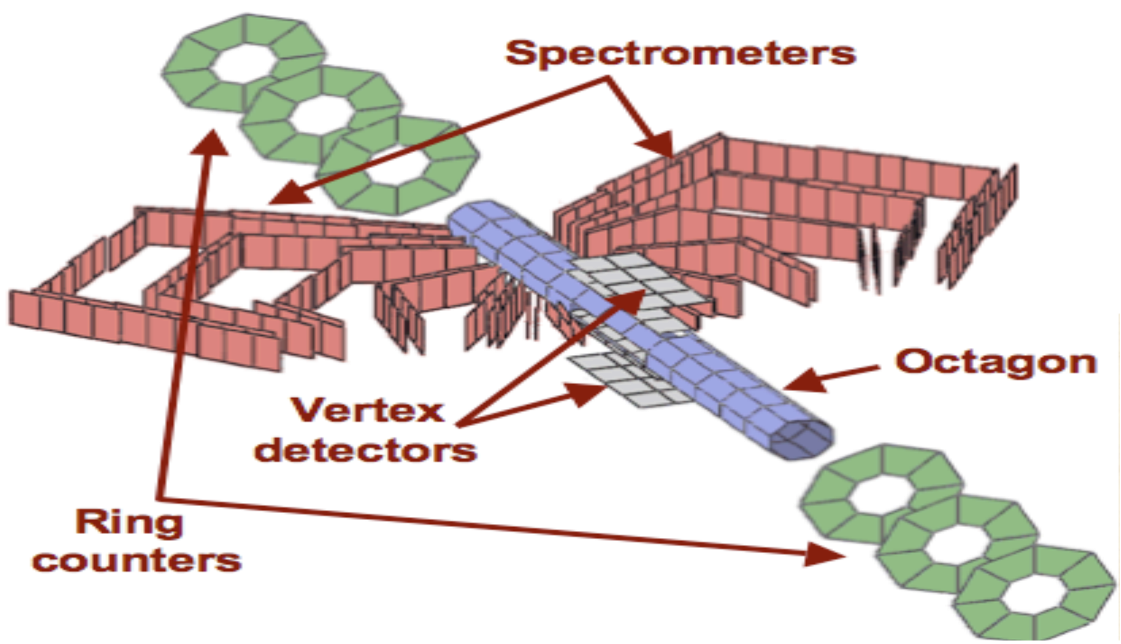
In AA collisions the maximum baryon density will be produced for $\sqrt{s_{NN}} \approx 7$ GeV/nucleon pair
or in a fixed target experiment, for incident nucleus energy of ≈ 25 GeV per nucleon.

PHOBOS @RHIC:

1972 Fermilab E178 (PHOBOS - 1)



1991 PHOBOS



"Big" questions c1983:

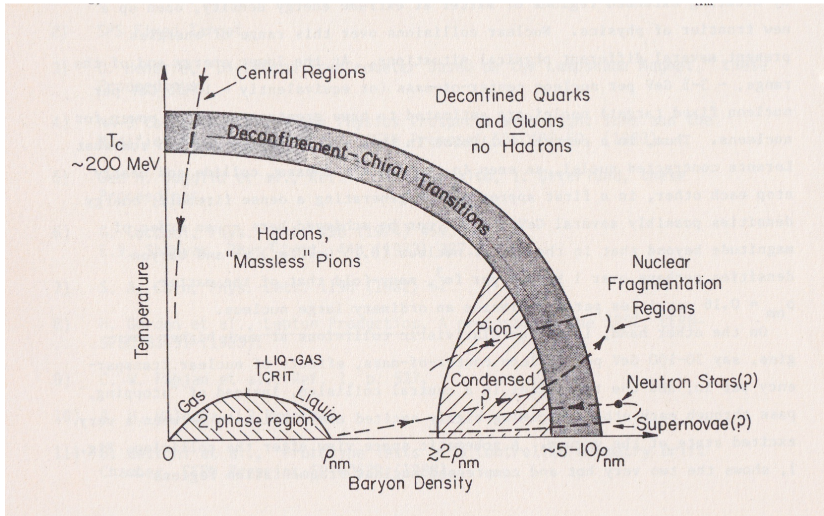


FIGURE 2
Phase diagram of nuclear matter.

From G.Baym, QM 1983

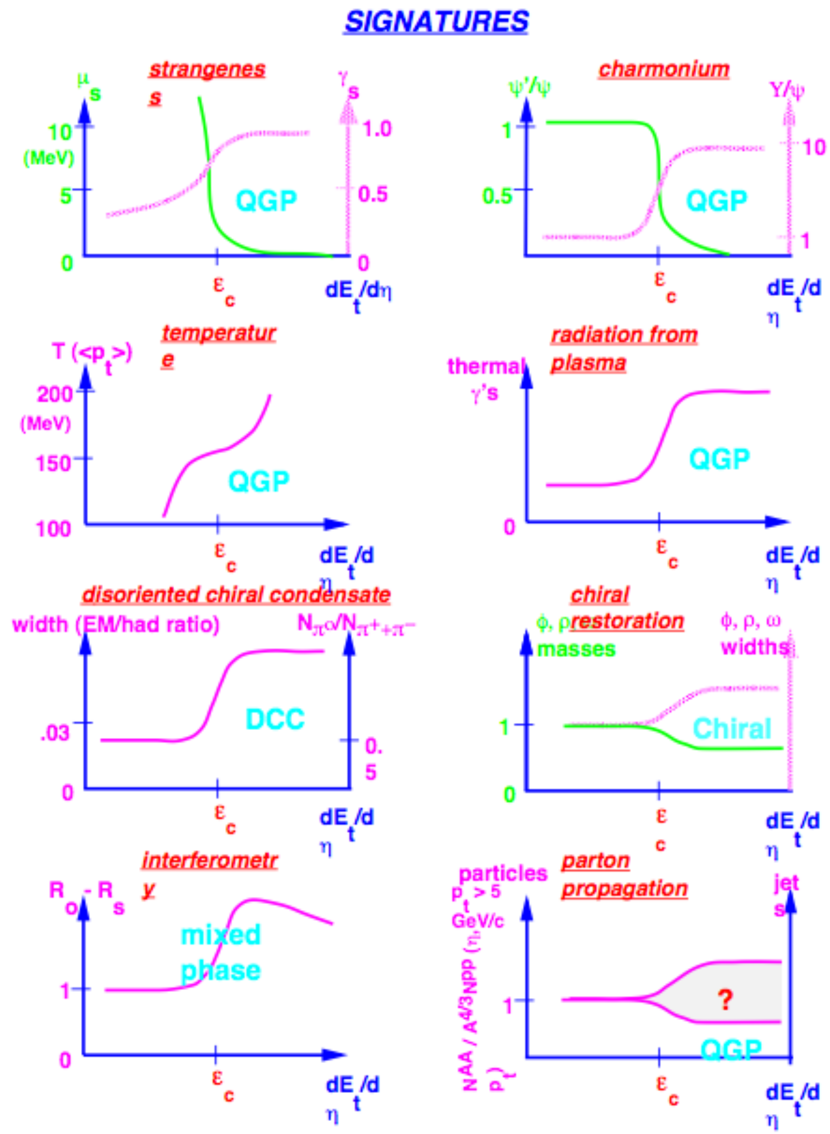
- What is the nature of the QCD vacuum?
- Is it possible to create and study Disoriented Chiral Condensates?
- Is it possible to observe the deconfinement phase transition?
- is it possible to observe the chiral restoration phase transition?

Everyone wants to discover the "QGP"
At this time, pA and the question of how particles are produced take a back seat!

Practical questions:

- Are nuclei large enough so that the system produced in high energy collisions is in chemical and thermal equilibrium? (Note: It was already shown that stopping is adequate)

In the 1980's 1990's the expectations were too good to be true!



From Harris and Mueller
Ann. Rev. Nucl. Sci. 1996

Period 3: 1983-2005 First systematic, high quality data and quantitative theoretical studies of high energy AA collisions. pp and pA are studied only as a reference

1986 – 1995 AGS at BNL

E802/E859/E866/E917, E810, E814/E877, E858/E878, E815, E864, E895, E896, E910, E941 detectors measuring energy, spectra, particle types (strangeness) and correlations in various regions of rapidity

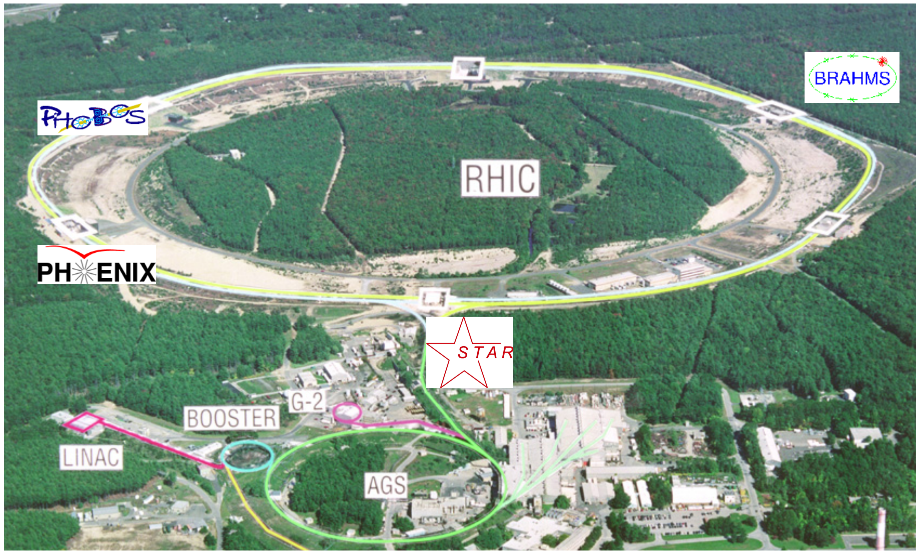
at first O and Si beams at 10 and 14.6 GeV/nucleon on nuclear targets, later also p & Au beams & lower energies

1986 – 1999 SPS at CERN

NA34, NA35/NA49/NA61, NA36, NA38/NA50/NA60, NA44, NA45, NA52, WA 80/98, WA85, WA94, WA97/NA57 and emulsion detectors measuring energy, spectra, particle types (strangeness), J/ψ, direct photons and correlations in various regions of rapidity

at first O and S beams at 60 and 200 GeV/nucleon on nuclear targets, later Pb beams at 40, 80, 158 GeV/nucleon
& pA measurements for reference

2000 RHIC at BNL



pp at $\sqrt{s_{nn}}$ = 200, 500, 510 GeV

dAu at $\sqrt{s_{nn}}$ = 200 GeV

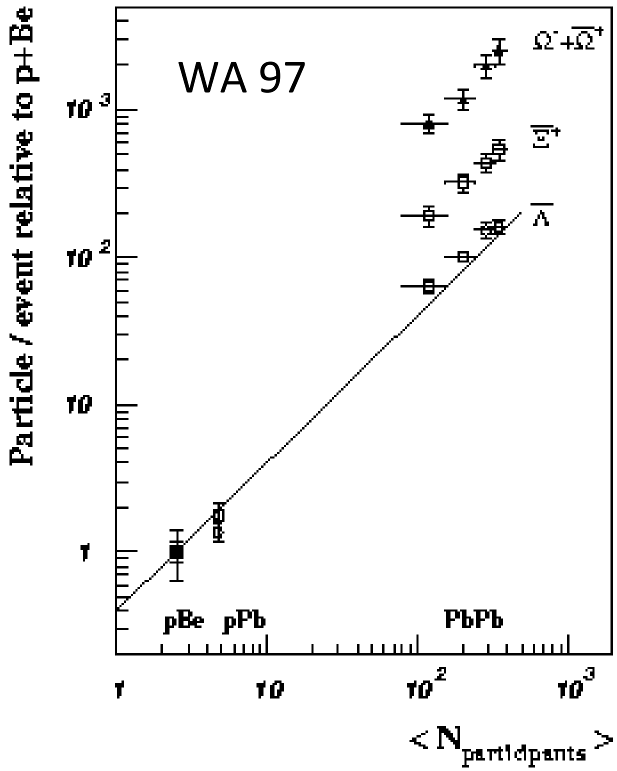
CuCu at $\sqrt{s_{nn}}$ = 22.4, 62.4, 200 GeV

CuAu at $\sqrt{s_{nn}}$ = 200 GeV

AuAu at $\sqrt{s_{nn}}$ = 7.7, 9.2, 15, 19, 19.6, 27, 39, 62.4, 130, 200 GeV

UU at $\sqrt{s_{nn}}$ = 192.8 GeV

Strangeness:



Chemical equilibrium:

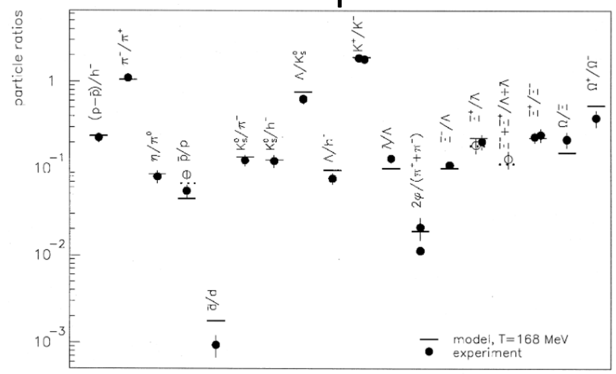
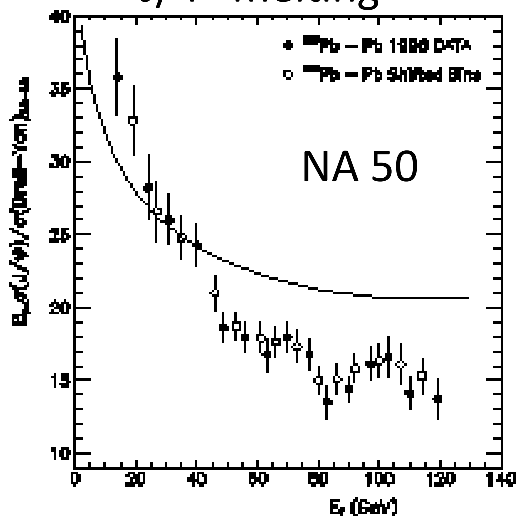
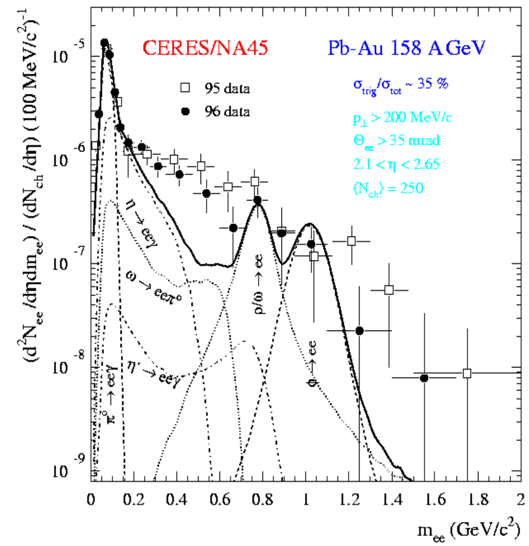


Fig. 3. Comparison between model and experimental particle ratios. For experimental data, errors and information about feeding corrections, see Table 1 and references therein.

J/Ψ melting



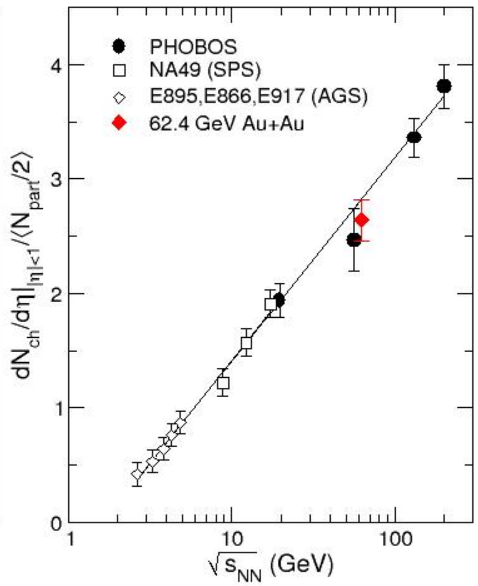
Thermal radiation and modification of resonances:



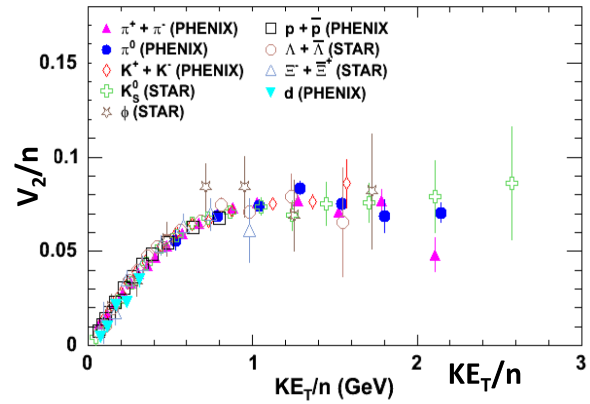
10 Feb. 2000 at CERN Press release: New State of Matter created at CERN

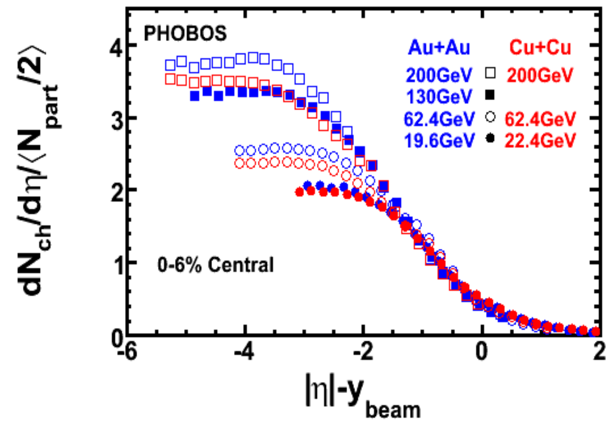
Professor Luciano Maiani, CERN Director General, said "*The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider.*"

Crucial observations:

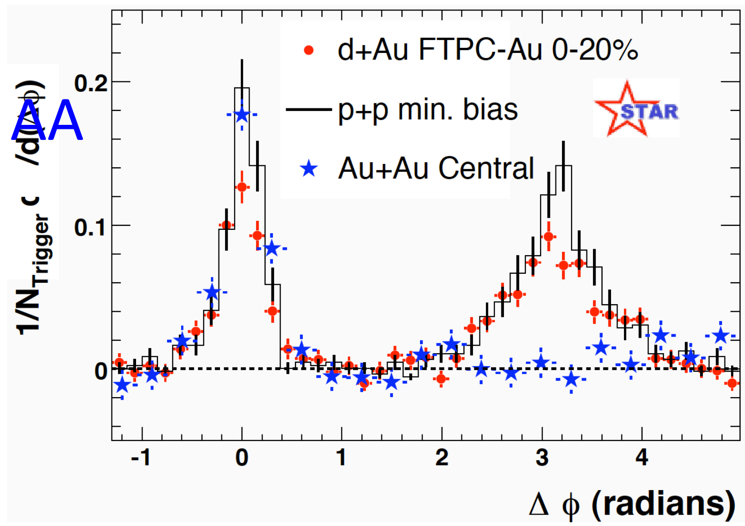


Sufficiently high energy density is accessible





Evidence of saturation in the initial state - CGC

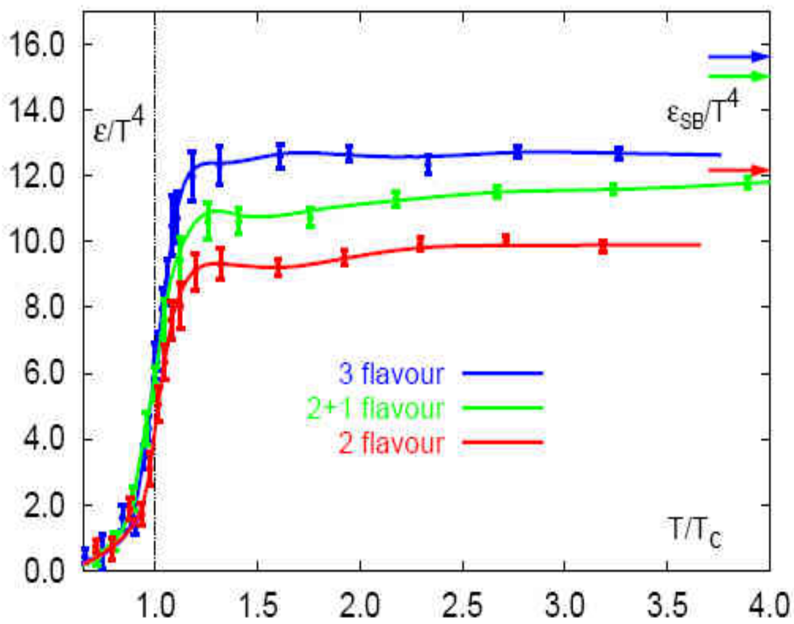


PHOBOS, Hofman, QM2006

The system produced is very strongly interacting

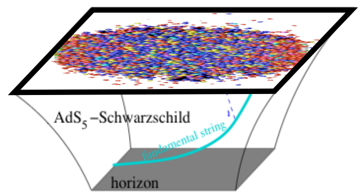
Crucial theoretical observations:

Calculations on the lattice:



F. Karsch, Nucl. Phys. A698, 199c (2002).

Calculations based on string theory:



N=4SYM in strong coupling limit (using gauge gravity duality)

$\eta/s \gtrsim 1/(4\pi)$

By 2005 Realization that there is:

- No sign of the creation of a DCC.

- The phase transition is a cross-over.

- Lattice calculations and data suggest that the weakly interacting QGP is out of experimental reach

However there is lots of good news:

- stopping, as expected, is adequate to create an interesting high energy density system at mid rapidity, and possibly produces an interesting high baryon density at the lower energies or higher rapidities.

- Technology and detectors are up to the challenges of the field.

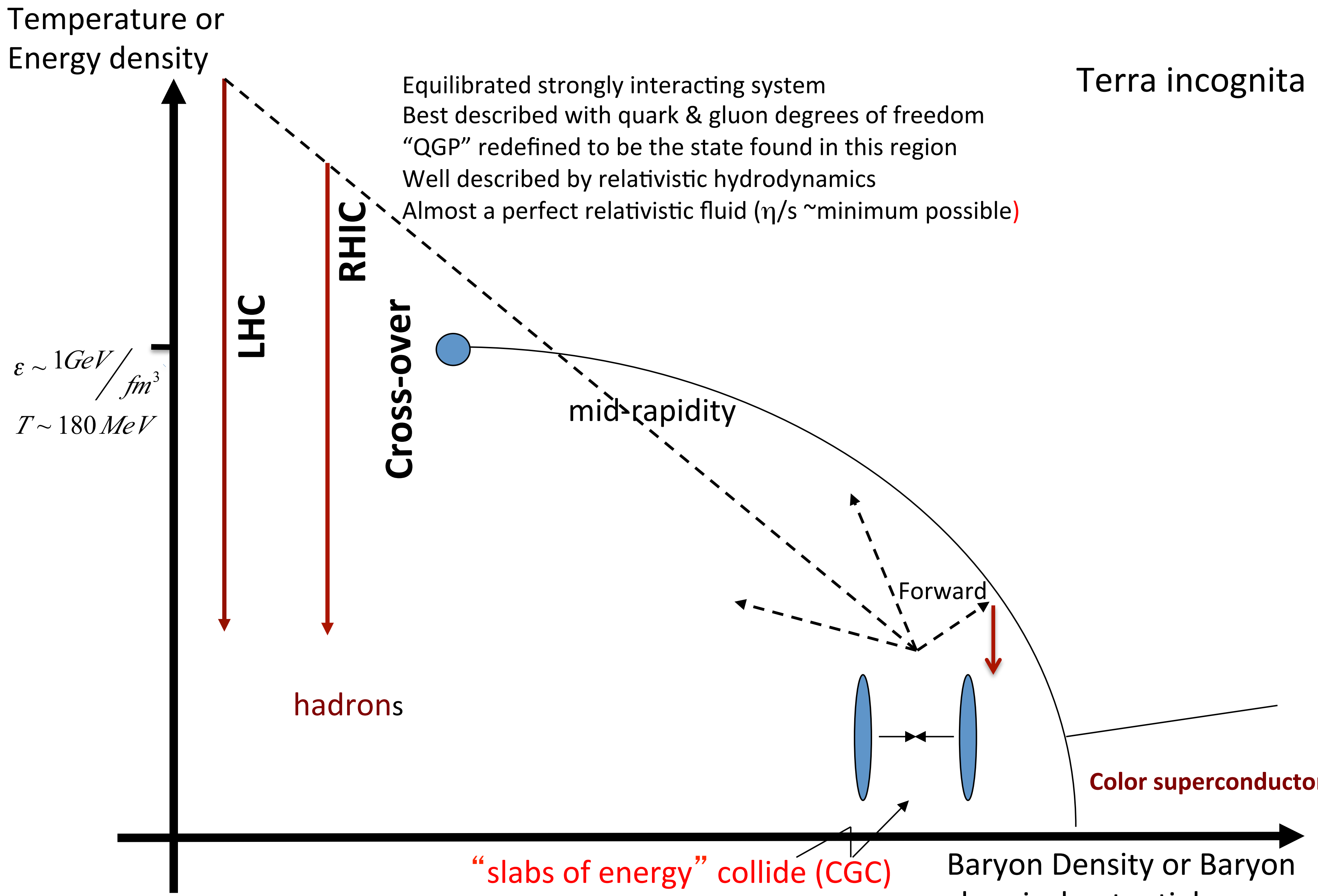
- Unexpected exciting phenomenology surpasses all expectations. A strongly interacting system of quarks and gluons is produced which is even more interesting than the searched for QGP. The system is first named “sQGP” and/or “perfect liquid”. It is then gradually redefined as the “QGP”.

April 18, 2005: Press release in Tampa
RHIC Scientists serve up "perfect" liquid

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

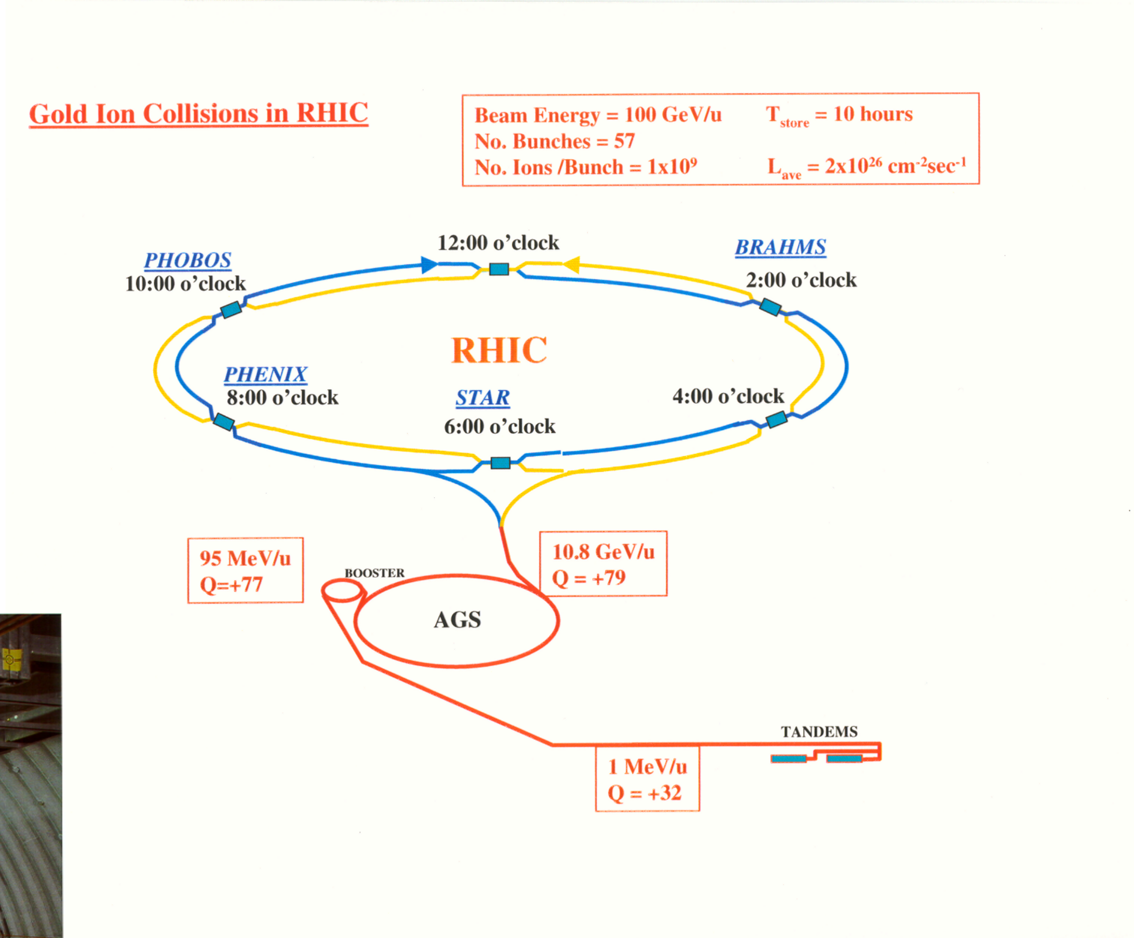
The standard picture of heavy ion collisions at end of period 3 (1983 – 2005)

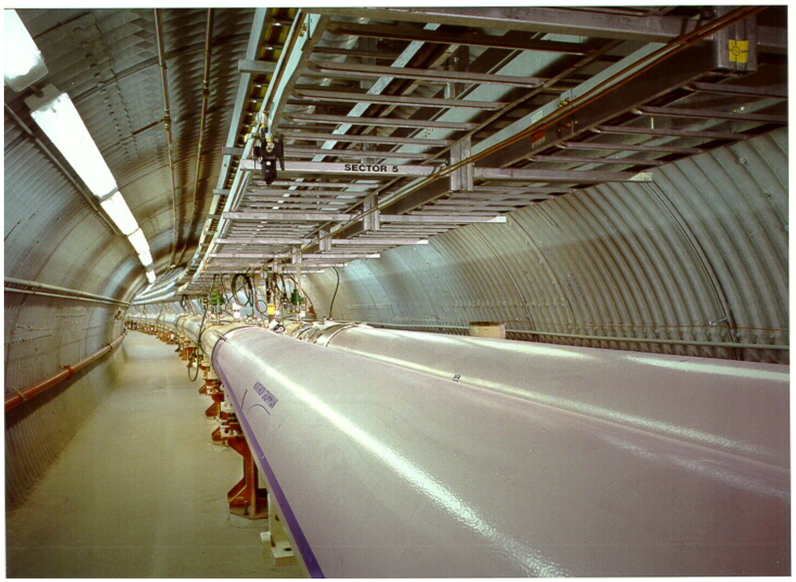



MIT Heavy Ion Event Display: Au+Au 200 GeV
Heavy Ion Group @ MIT
Yen-Jie Lee, Sungho Yoon and Wit Busza
T= 0.00 fm/c

Considering how relatively little interest there was for pA and AA physics in the 1970's from the general physics community, how did we get to where we are today?

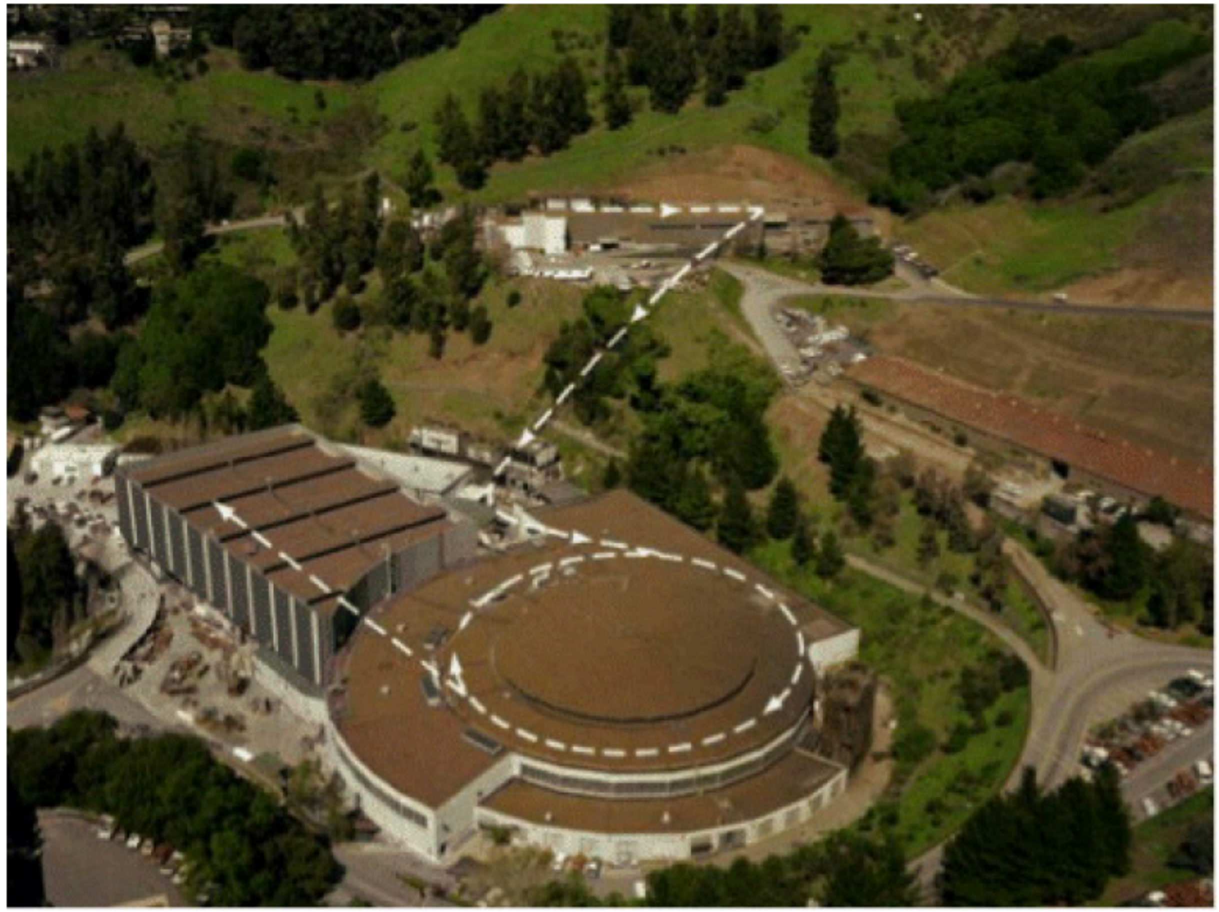
The RHIC story





1974 Tandem completed, Isabelle launched
1983 Woods Hole meeting: Isabelle/CBA cancelled
1984 RHIC proposal
1986 AGS heavy ion program starts

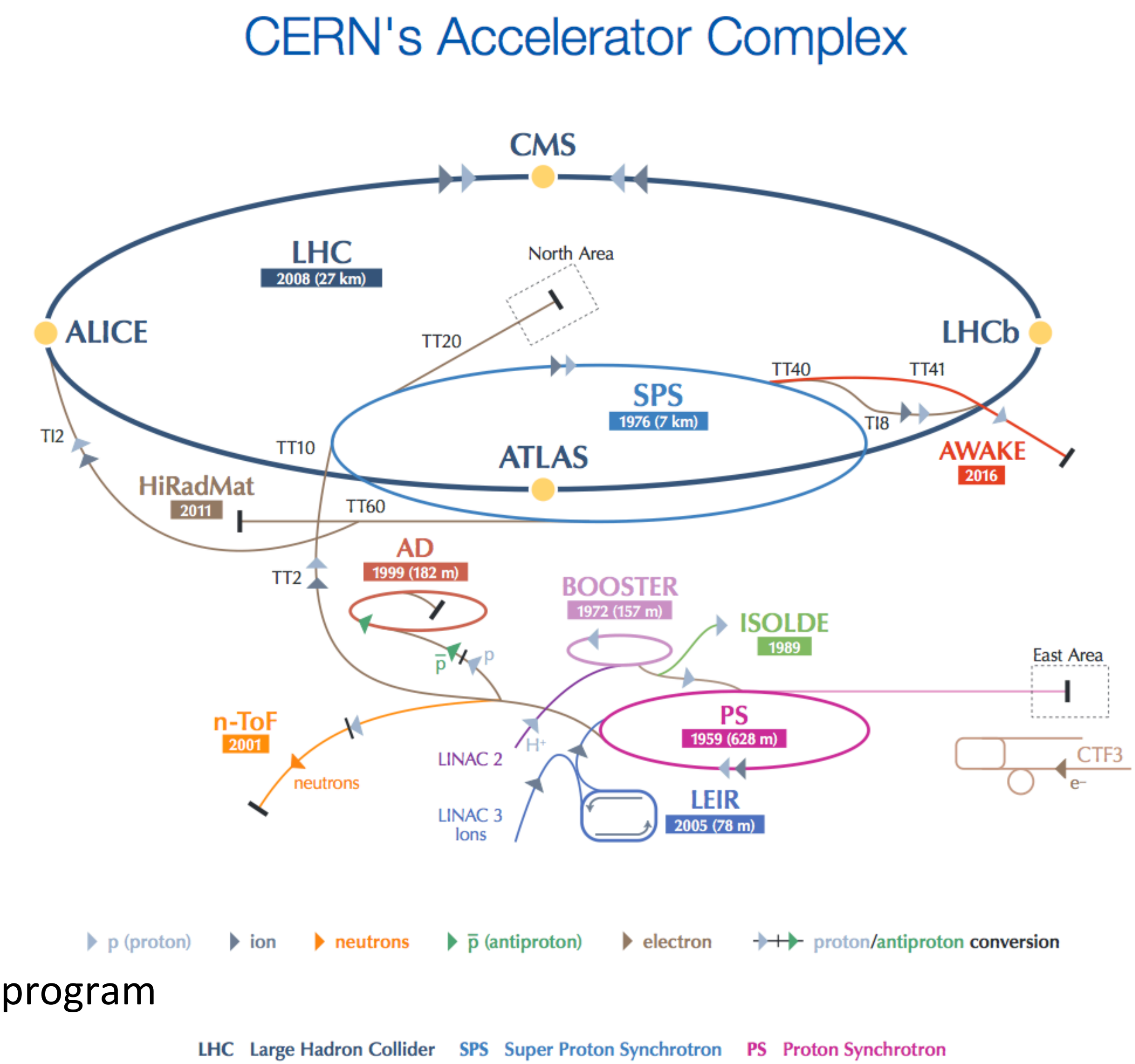
The Bevalac story



Photograph of the HILAC and BEVALAC in Berkeley [Blum2013]

1974 SuperHilac + Bevatron = Bevalac
C1984 end of AA program

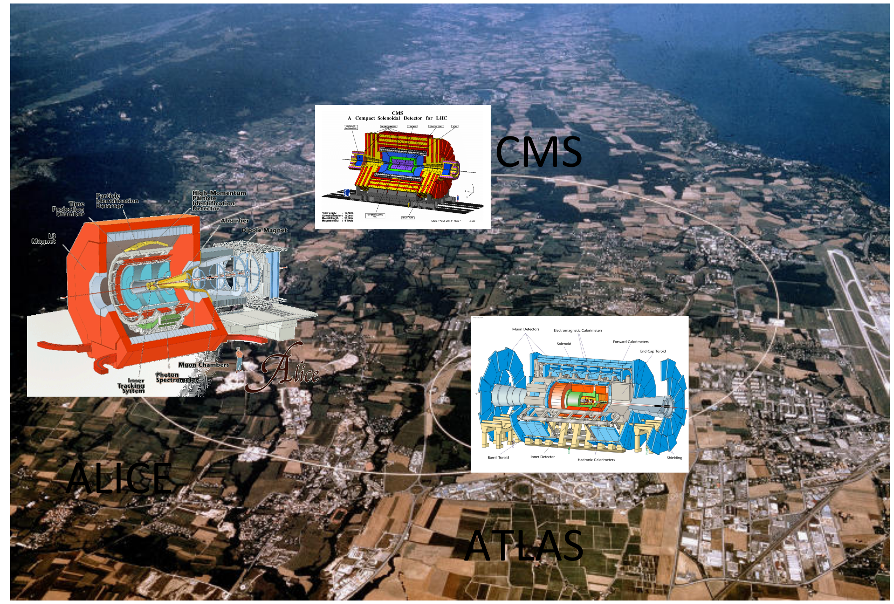
The SPS story



1986 start of SPS heavy ion program

Period 4 The present era

LHC



RHIC

PHOBOS

STAR  BRAHMS

PHENIX

First Au beams in 2000

Top energy $\sqrt{s_{NN}}$ = 0.2TeV

First Pb beams in 2010

Top energy $\sqrt{s_{NN}}$ = 2.8TeV

From Gunther Roland

Period 4: 2005 – present. High precision study of the extensive phenomenology of pp, pA and AA collisions

Superb RHIC performance, ability to operate at low energies and upgrades of the STAR and PHENIX detectors open a big window at the lower energy landscape – search for critical point.

Unbelievably successful operation of the LHC and the three detectors ALICE, ATLAS and CMS yield more data than the community can reasonably absorb.

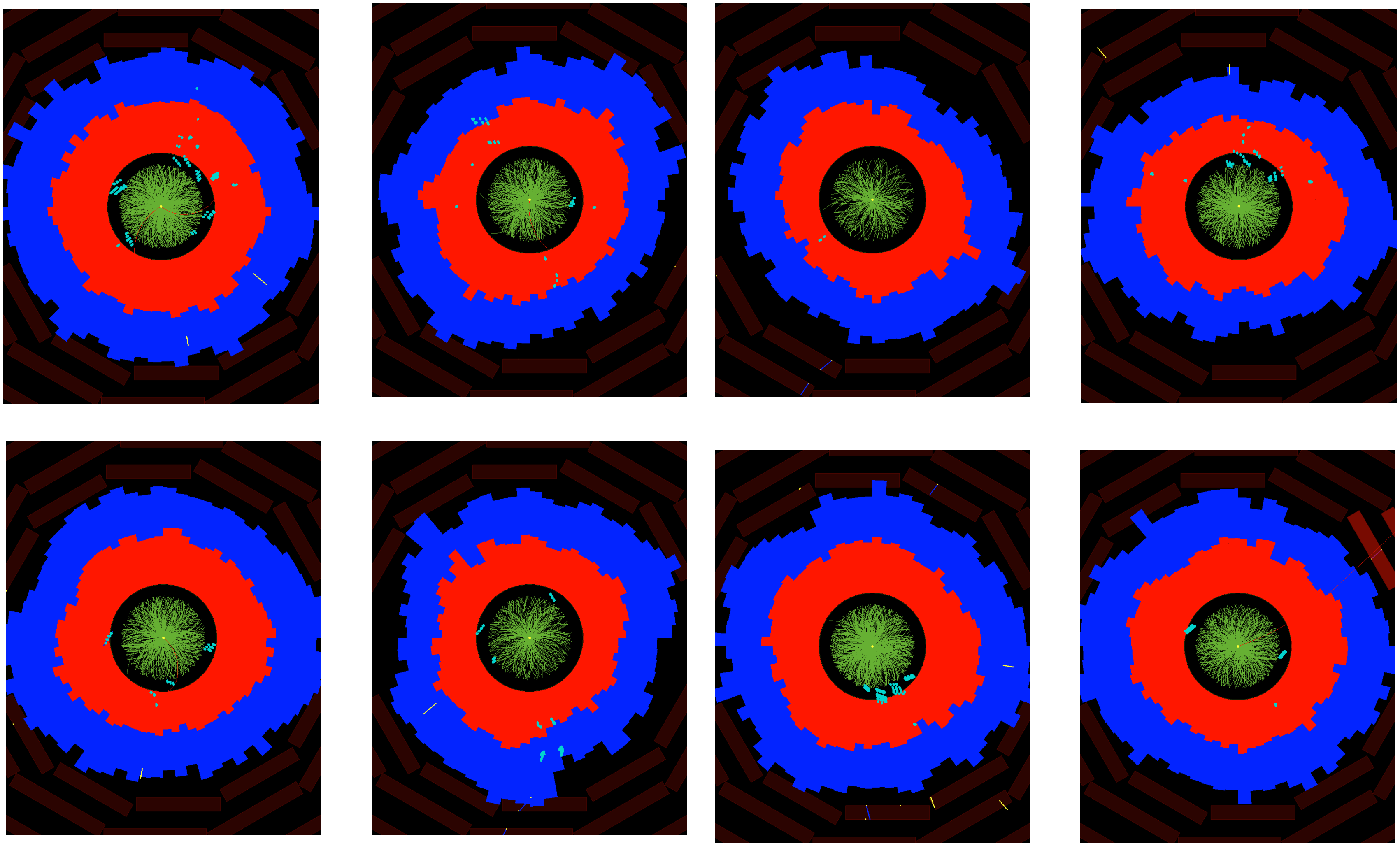
Fortunately progress in and availability of computing power makes the task of data handling, analysis of data and theoretical analysis almost manageable.

There are indications that we are close to the understanding, in the full sense of the word, many of the facts.

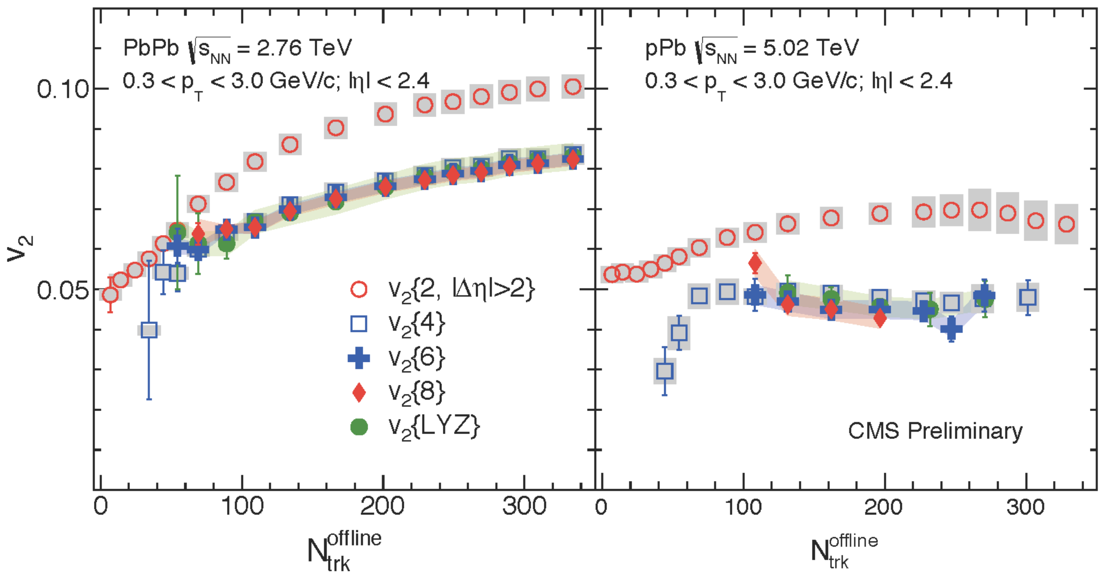
The challenge is to sort out which phenomena are really of fundamental importance and come up with the next "Big" questions.

At LHC you have to be blind not to see collective behavior

On-line displays of CMS events.
EM and hadronic energy in the transverse plane at mid-rapidity is shown

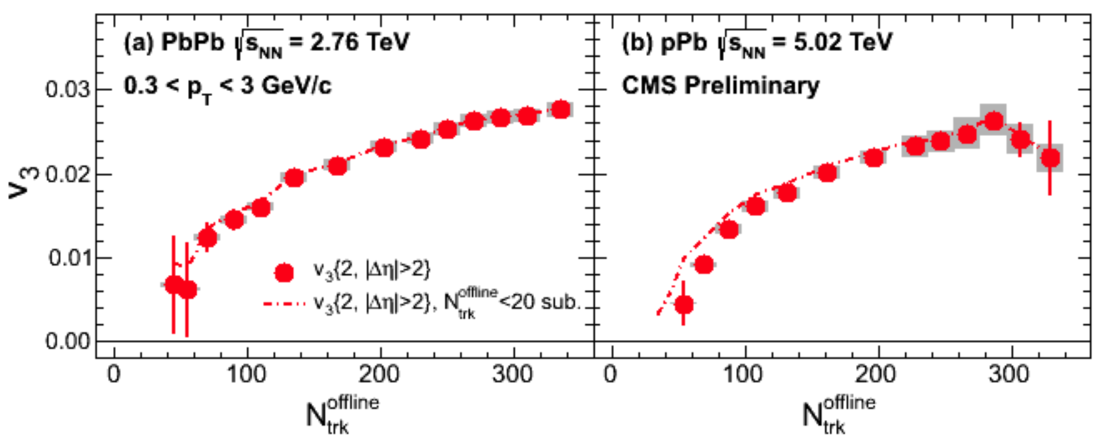


Flow measurements are clearly related to many particle collective effects



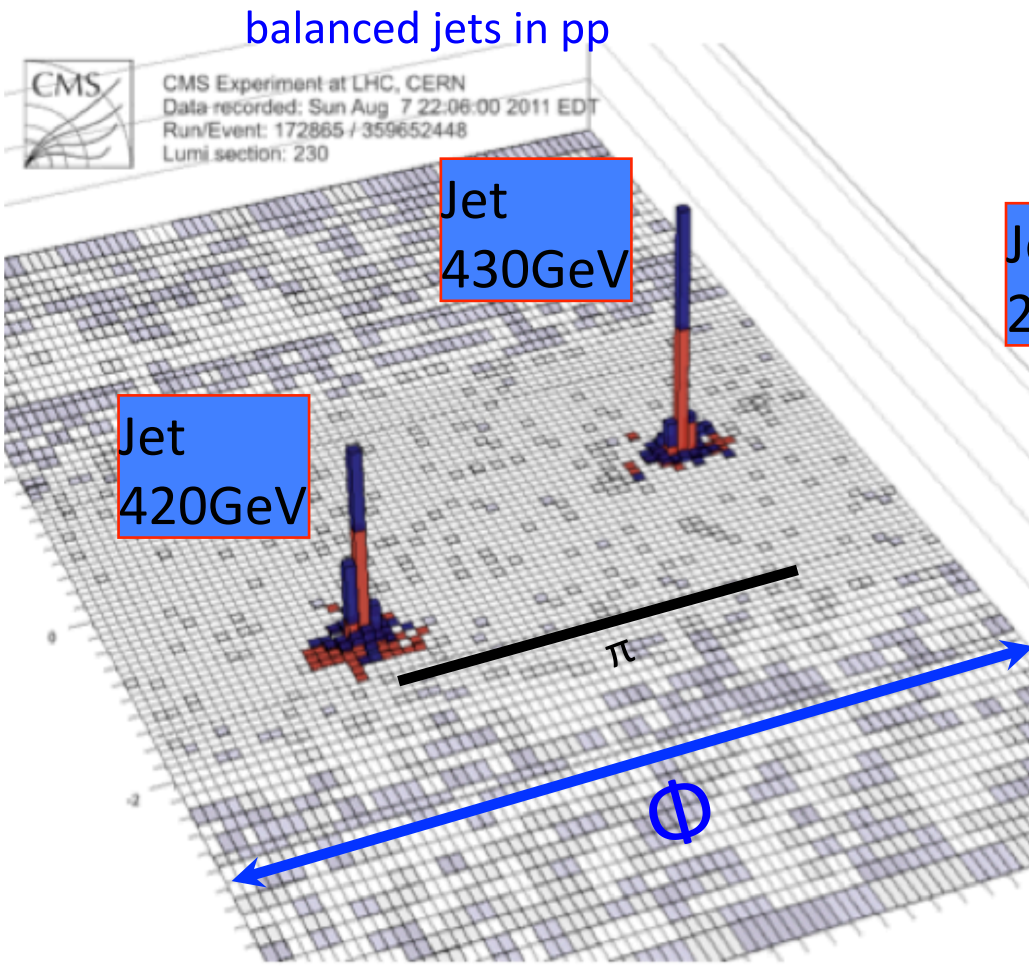
R. Granier de Cassagnac, QM2014

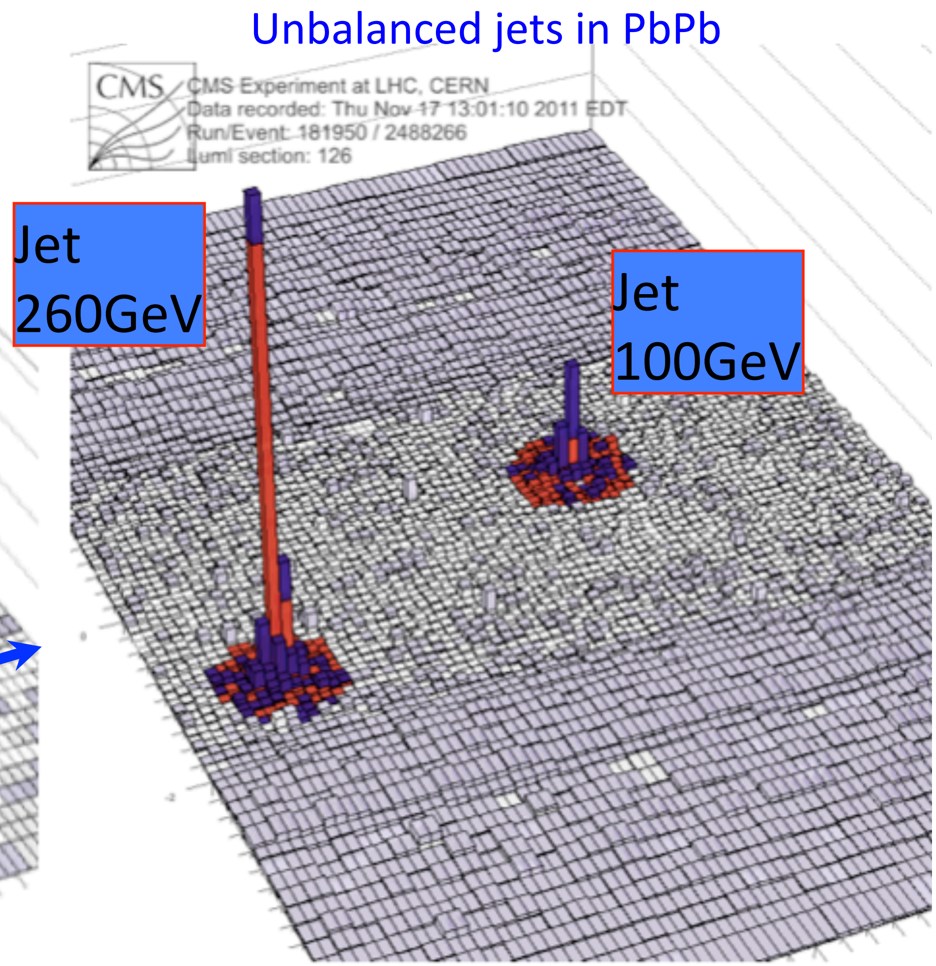
And fluctuations are important! But who ordered the incredible similarity of AA and pA?



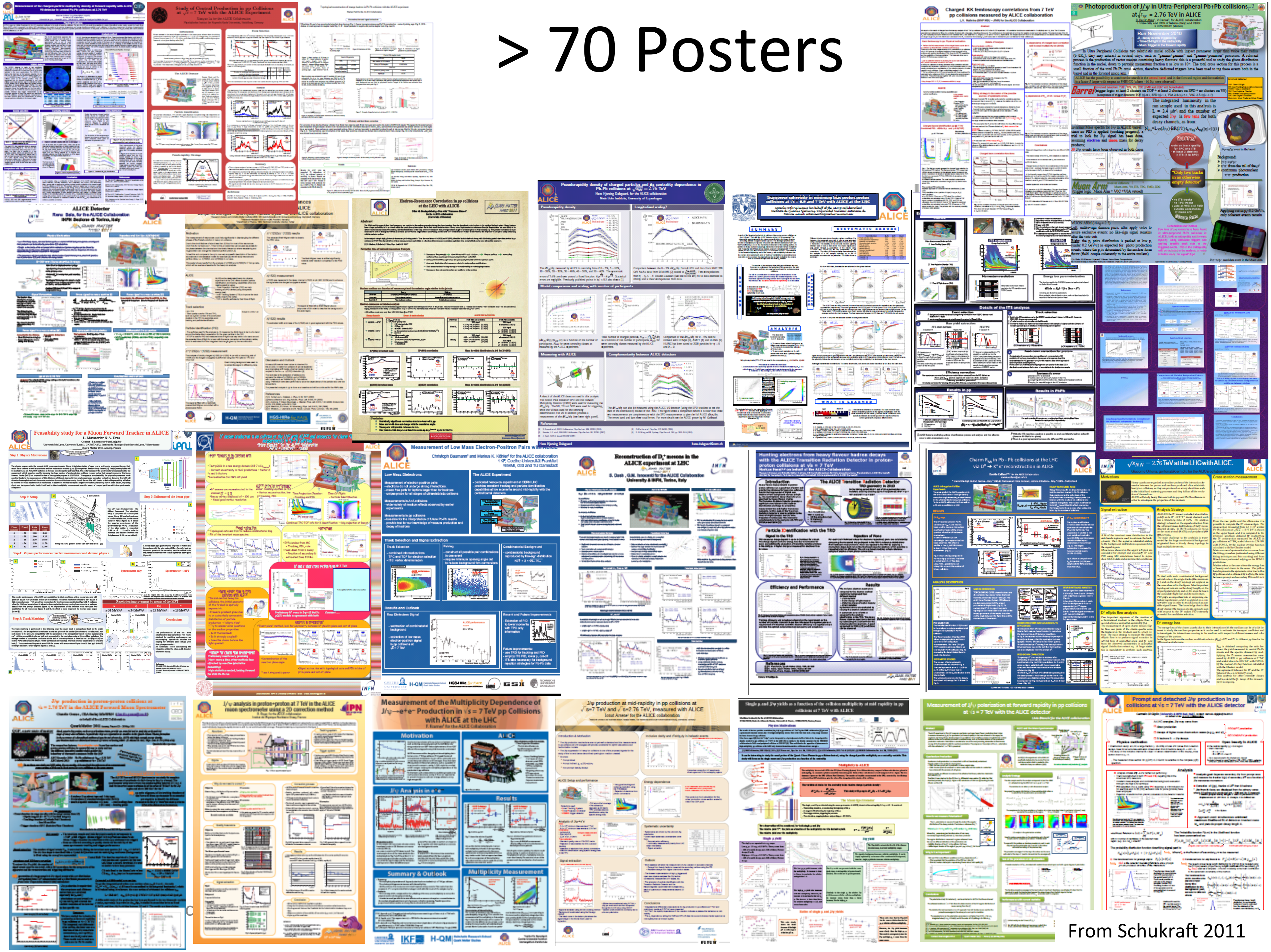
From Gunther Roland

Jet quenching – again you have to be blind not to see it!



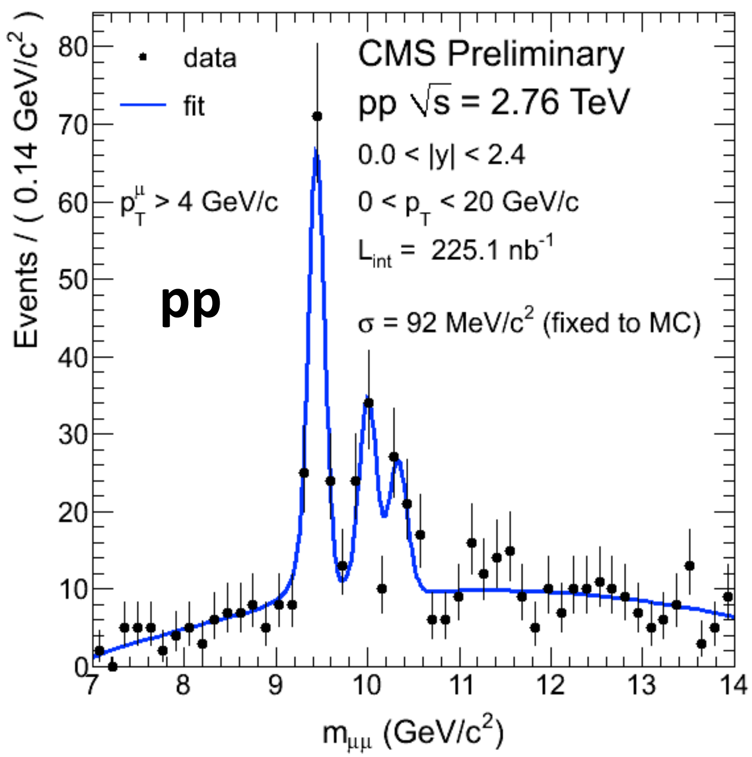


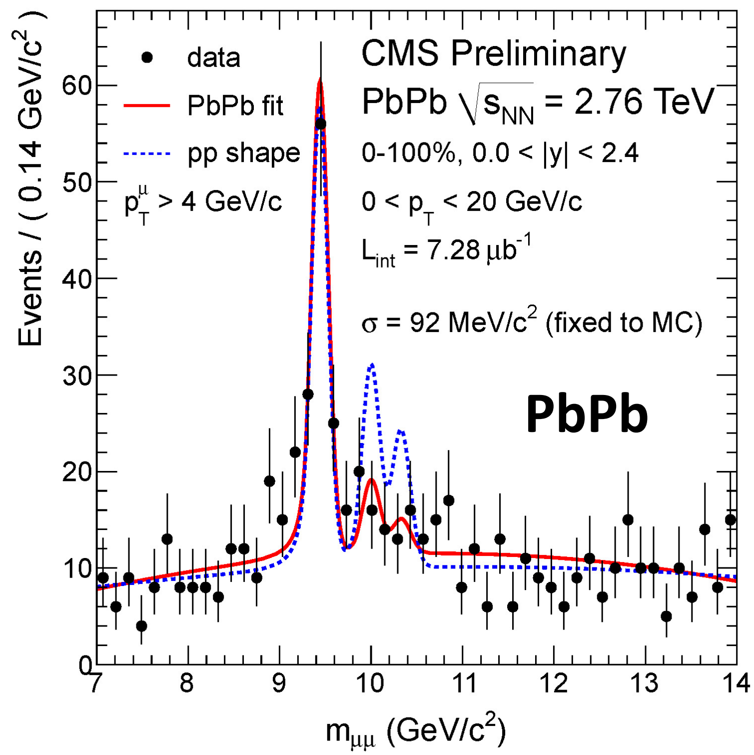
> 70 Posters



From Schukraft 2011

There are striking effects, eg. The larger Y states seem to dissolve in this new QCD medium





So where are we today?

We have a vast amount of high class data and most of it seems to make sense in terms of reasonable models.

Big questions:

- phase diagram of QCD?
  - including EOS of the various phases
  - critical point
  - transition from sQGP to wQGP
  - high baryon potential region
- are there any abnormal states of the vacuum or nuclear matter?

Almost as big questions:

- how are particles produced in pp, pA and AA, starting from the initial state of the incoming particles to the final production of the asymptotic state of the outgoing particles.
- is the system produced in pp, pA and AA large enough and lasts for long enough to be in thermal and chemical equilibrium. If not, is this relevant?

We also owe it to the tax payer to understand all the observed phenomena, such as jet-quenching, flow, melting, similarity of pp, pA and AA etc.

Finally some nasty thoughts: if spectra measured in the late 1880's had much better resolution, what would have happened to the Bohr model? Phlogiston was a fluid that lasted from 1667 until the end of the 18th century!

I conclude that today the opportunities in our field are almost endless.

Now it is up to you, the students, to develop the "Standard Model of the Condensed Matter of QCD". It seems that we are almost there!

I wish to thank everyone who provided me with information, in particular, G.Baym, P.Braun-Munzinger, M.Gyulassy, R.Holynski, A.Kerman, T.Matsui, N.Samios, S.Steadman, R.Stock and W.Zajc