Have we seen the QGP?

Thanks to QM2018

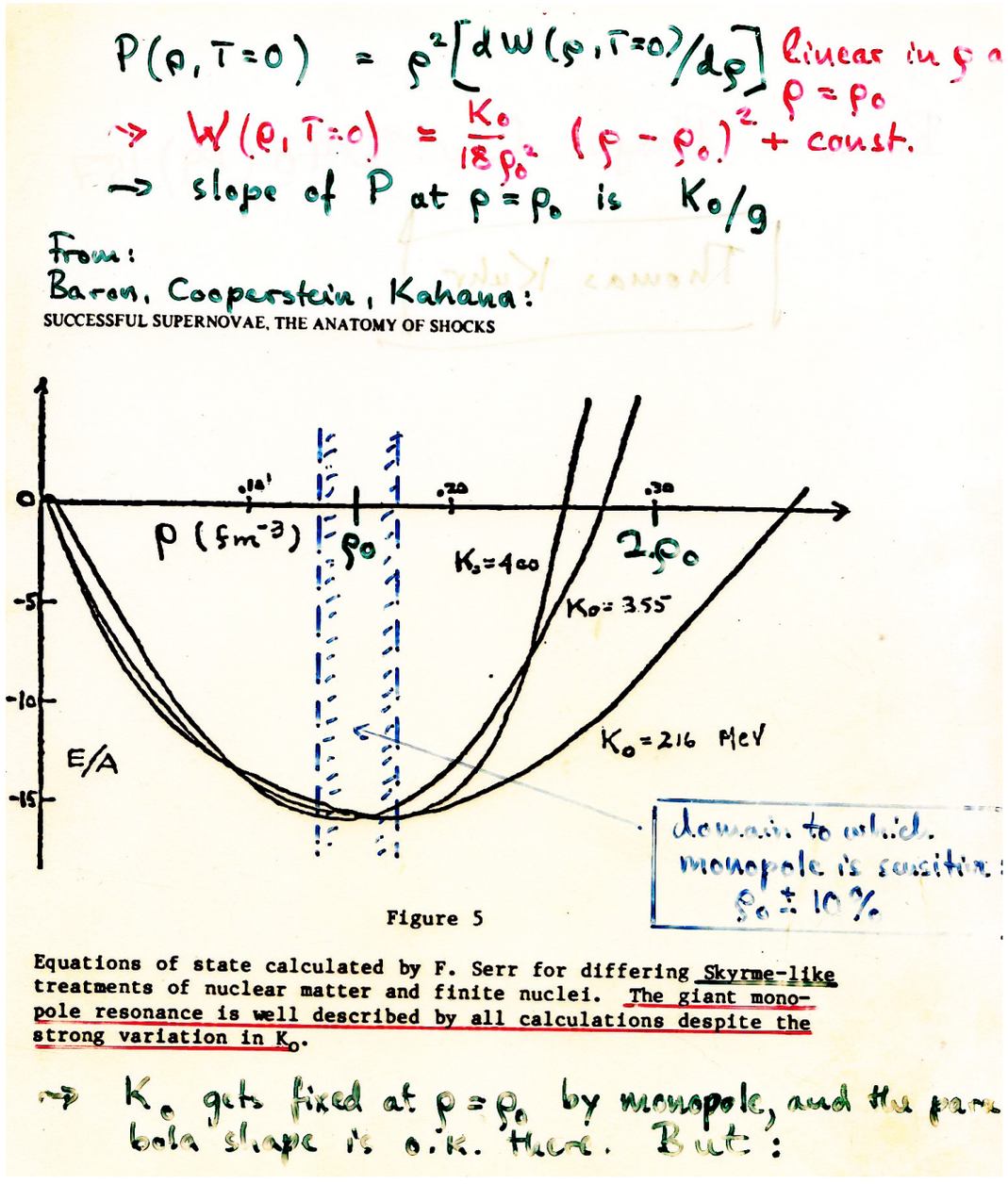
In-Kwon Yoo (Pusan Nat’l Univ.)

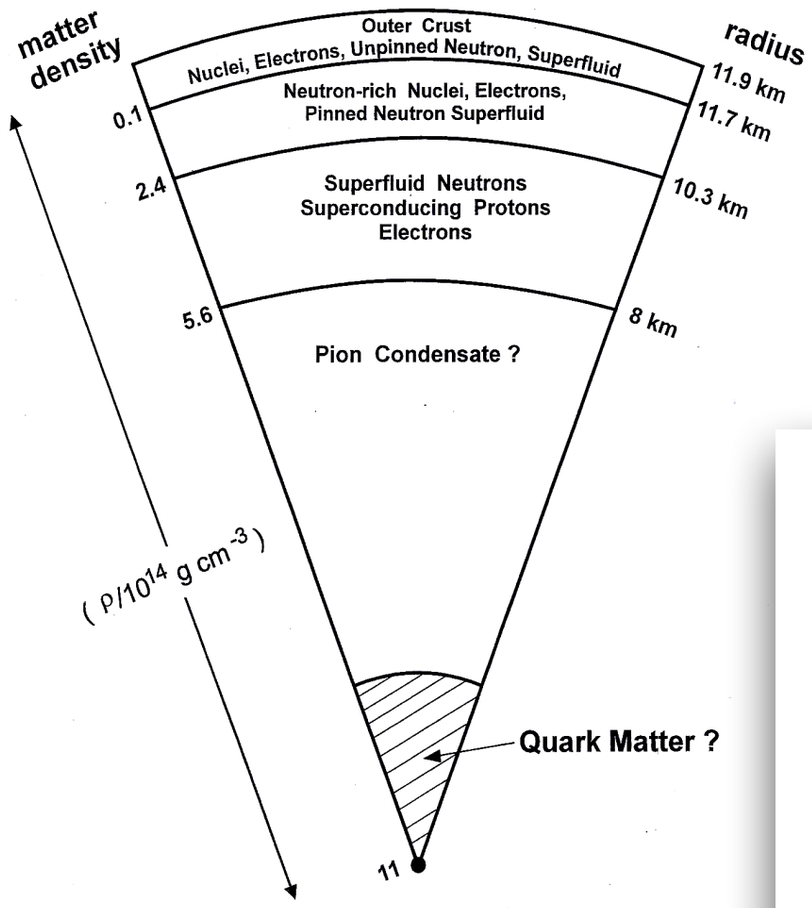
Issues

- What is QGP?
  - Historical Overview
- How can we know it?
  - Signatures of its existence
  - Its properties
- Where are we?
- Where to go?

Historical Overview

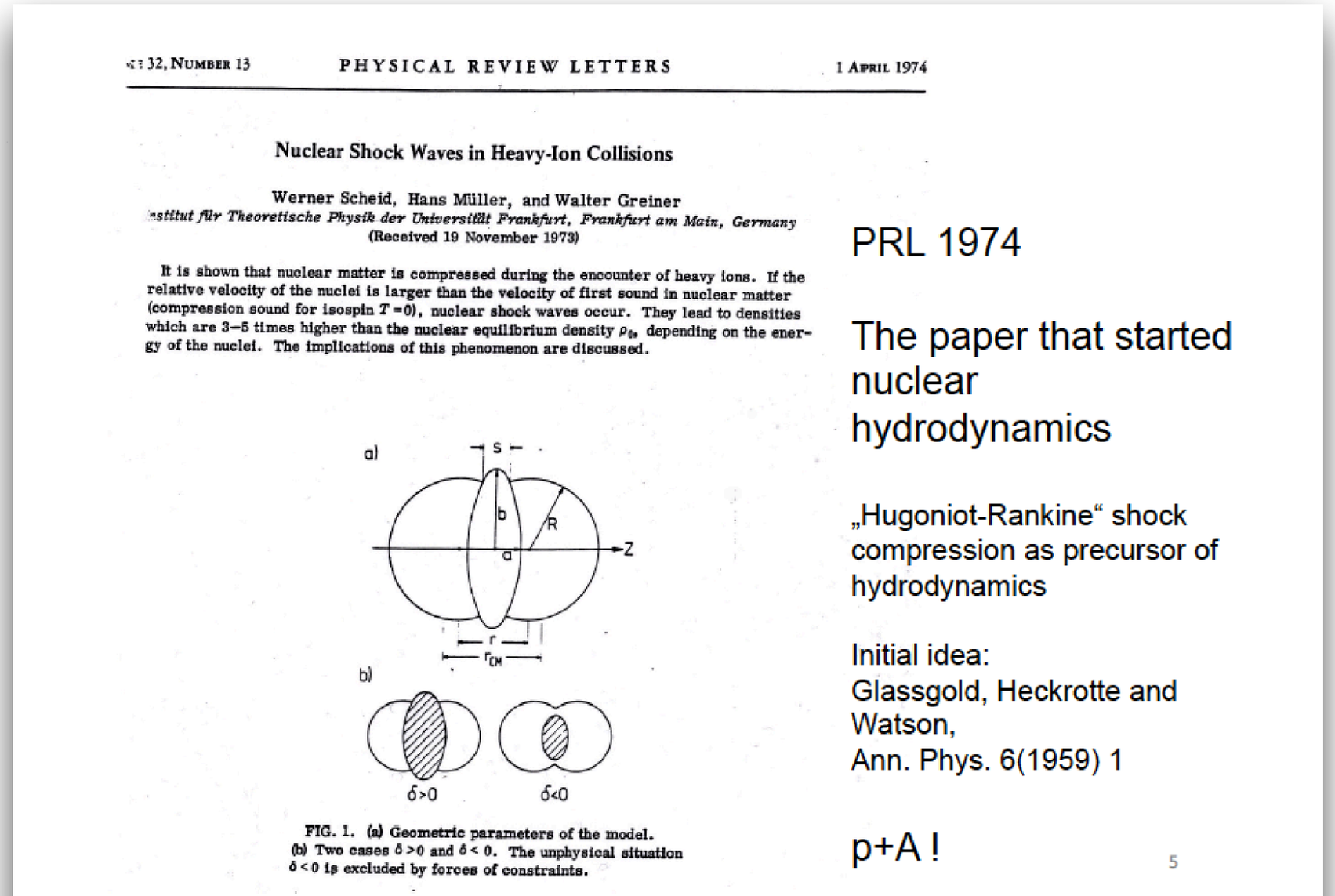
- R. Stock's lecture at QM2018
  - Nuclear/Hadronic Matter
  - EoS / Neutron Stars / Supernovae
  - Nuclear Physics Community at LBL Bevalac (1974 - 1985)
  - Advent of QCD in AA collisions





as of 1974
with later addition of
Quark Matter Core
Hypothesis

Oppenheimer Volkov
Hydro-static equilibrium 1956



VOLUME 32, NUMBER 13 PHYSICAL REVIEW LETTERS 1 APRIL 1974

Nuclear Shock Waves in Heavy-Ion Collisions

Werner Scheid, Hans Müller, and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany
(Received 19 November 1973)

It is shown that nuclear matter is compressed during the encounter of heavy ions. If the relative velocity of the nuclei is larger than the velocity of first sound in nuclear matter (compression sound for isospin $T=0$), nuclear shock waves occur. They lead to densities which are 3–5 times higher than the nuclear equilibrium density ρ_0, depending on the energy of the nuclei. The implications of this phenomenon are discussed.

FIG. 1. (a) Geometric parameters of the model. (b) Two cases $\delta > 0$ and $\delta < 0$. The unphysical situation $\delta < 0$ is excluded by forces of constraints.

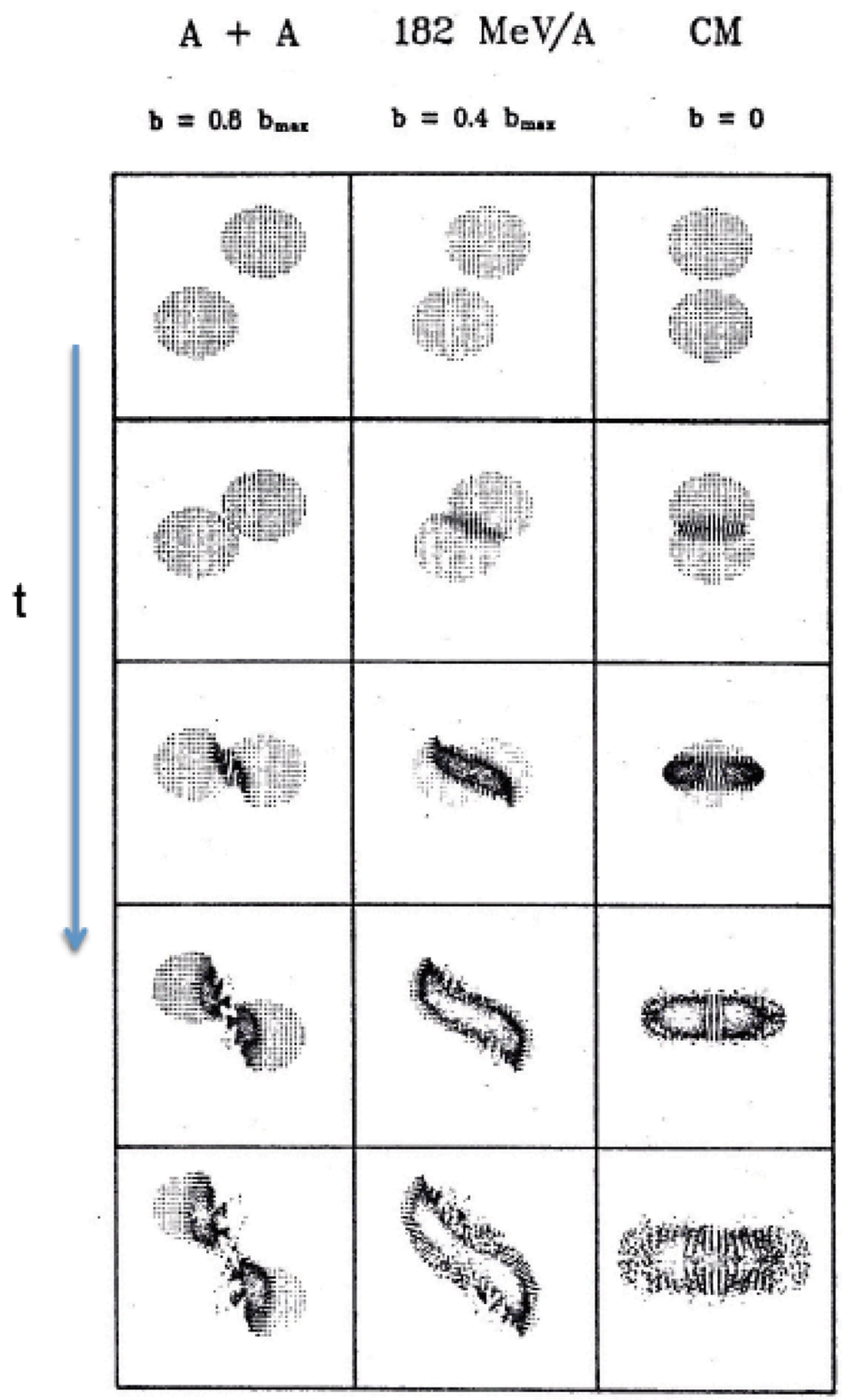
PRL 1974

The paper that started nuclear hydrodynamics

„Hugoniot-Rankine“ shock compression as precursor of hydrodynamics

Initial idea:
Glassgold, Heckrotte and Watson,
Ann. Phys. 6(1959) 1

p+A !

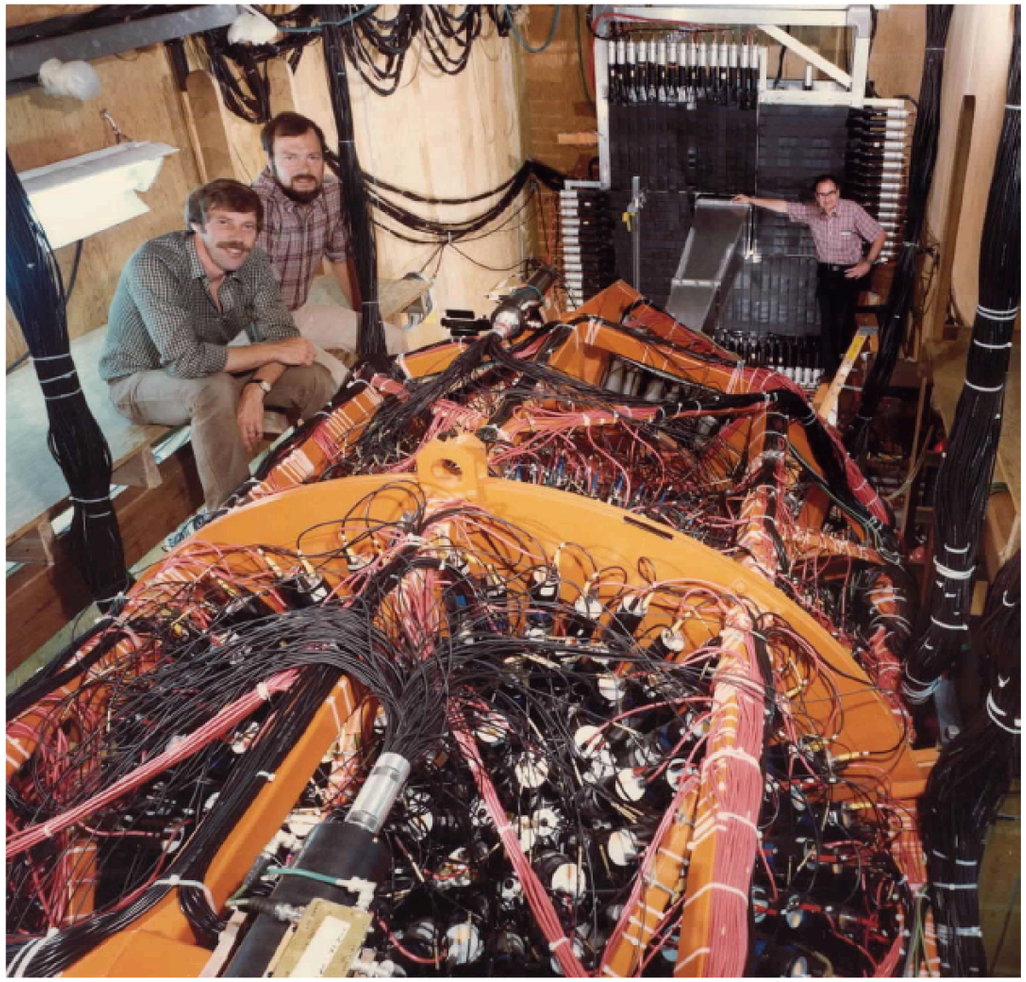


HYDRODYNAMICS!

R. Nix, Los Alamos Bomb Code

b ->0:
radial flow expansion

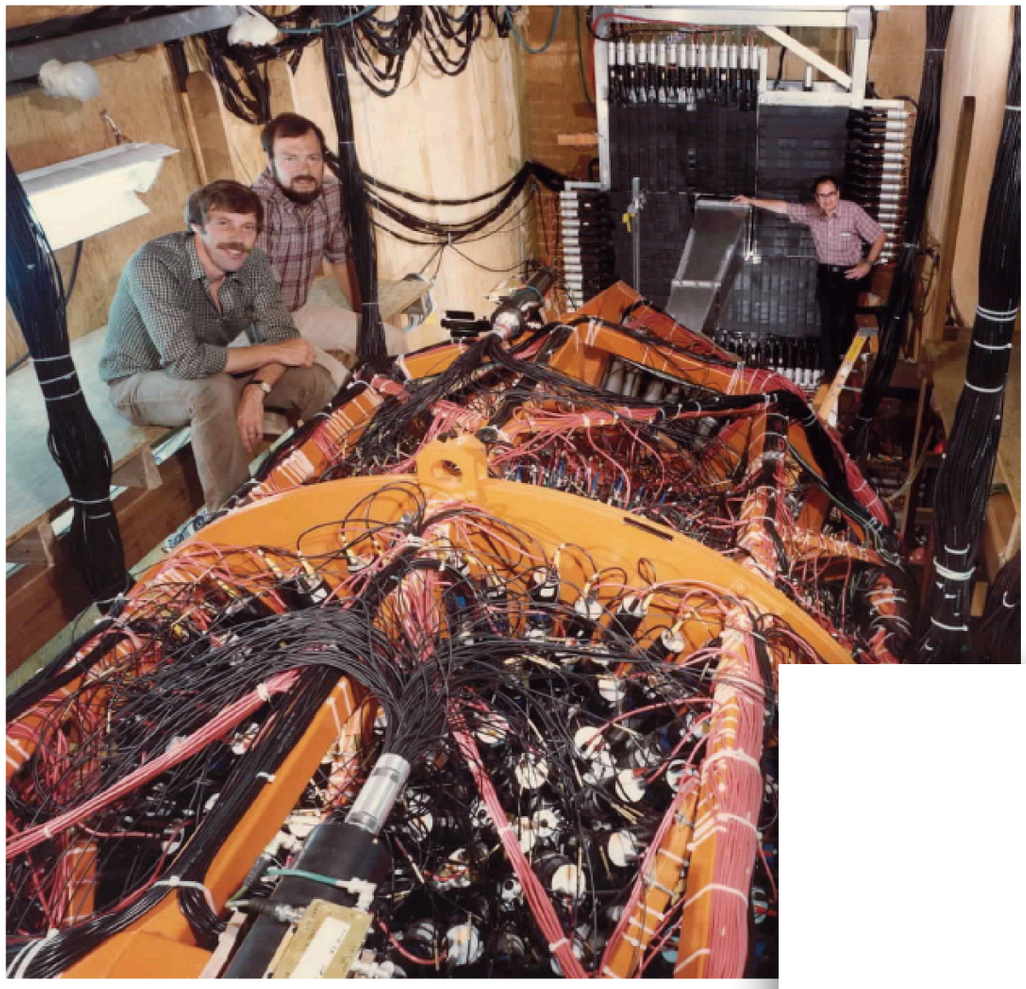
Intermediate b:
sideward flow, now v_1



Plastic Ball

850x
dE/dx-E

Gutbrod
Poskanzer
Ritter



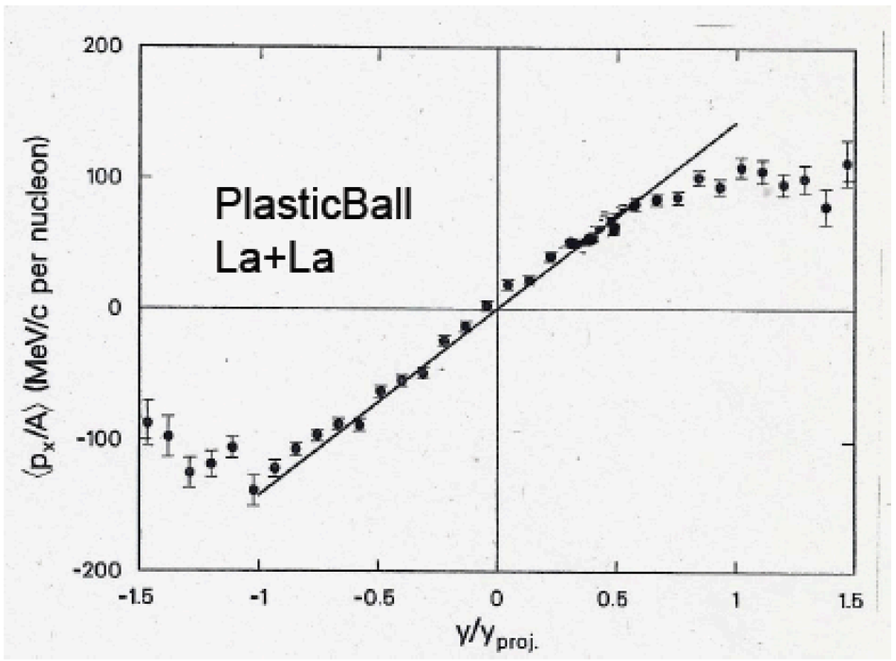
Plastic Ball

850x
dE/dx-E

Gutbrod

Deduce EoS from HYDRODYNAMICS!

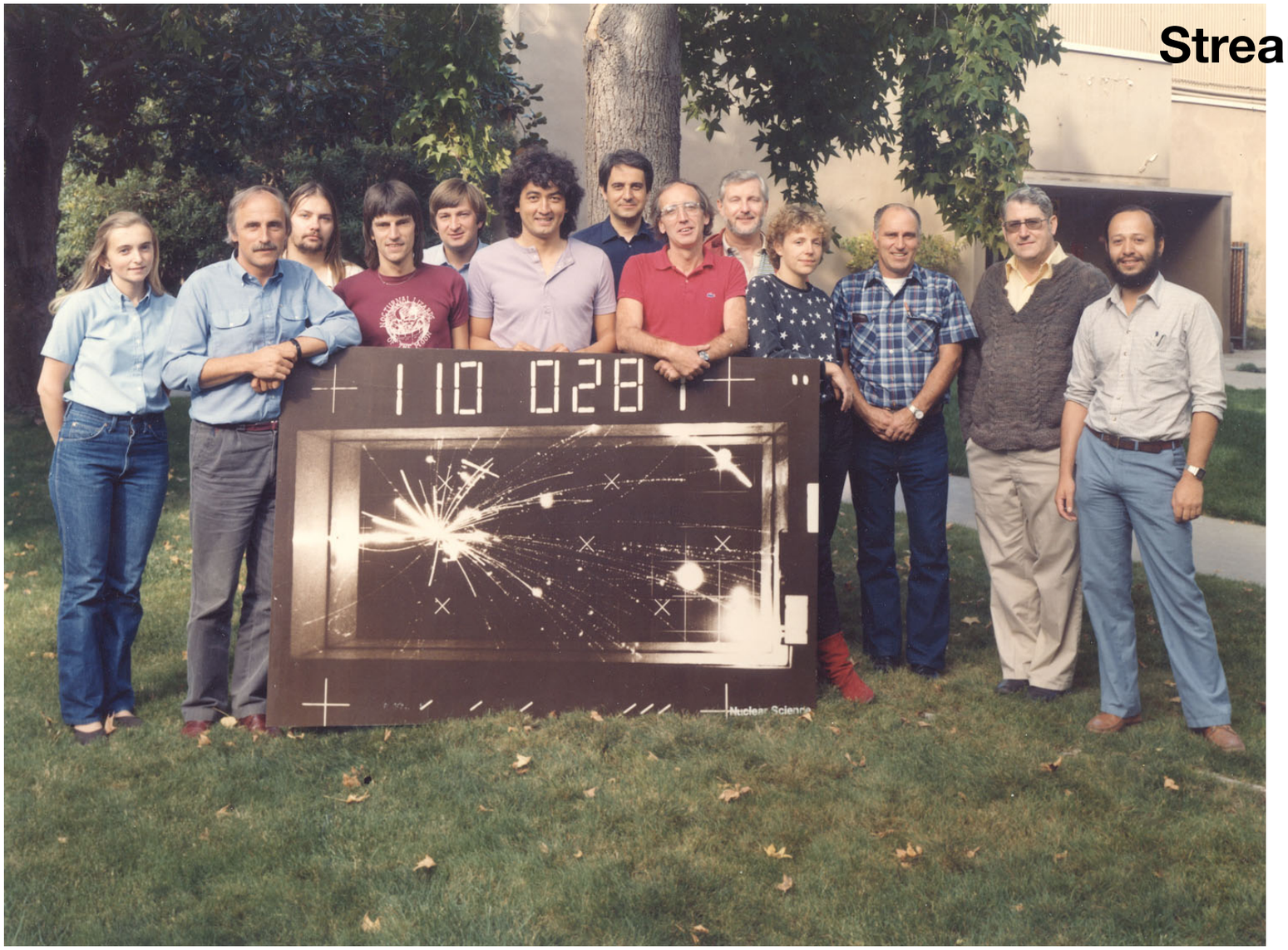
F(y) = Slope at mid-rap.



$$F(y) = P_{eff} \times S \times t_{pass}$$

EOS

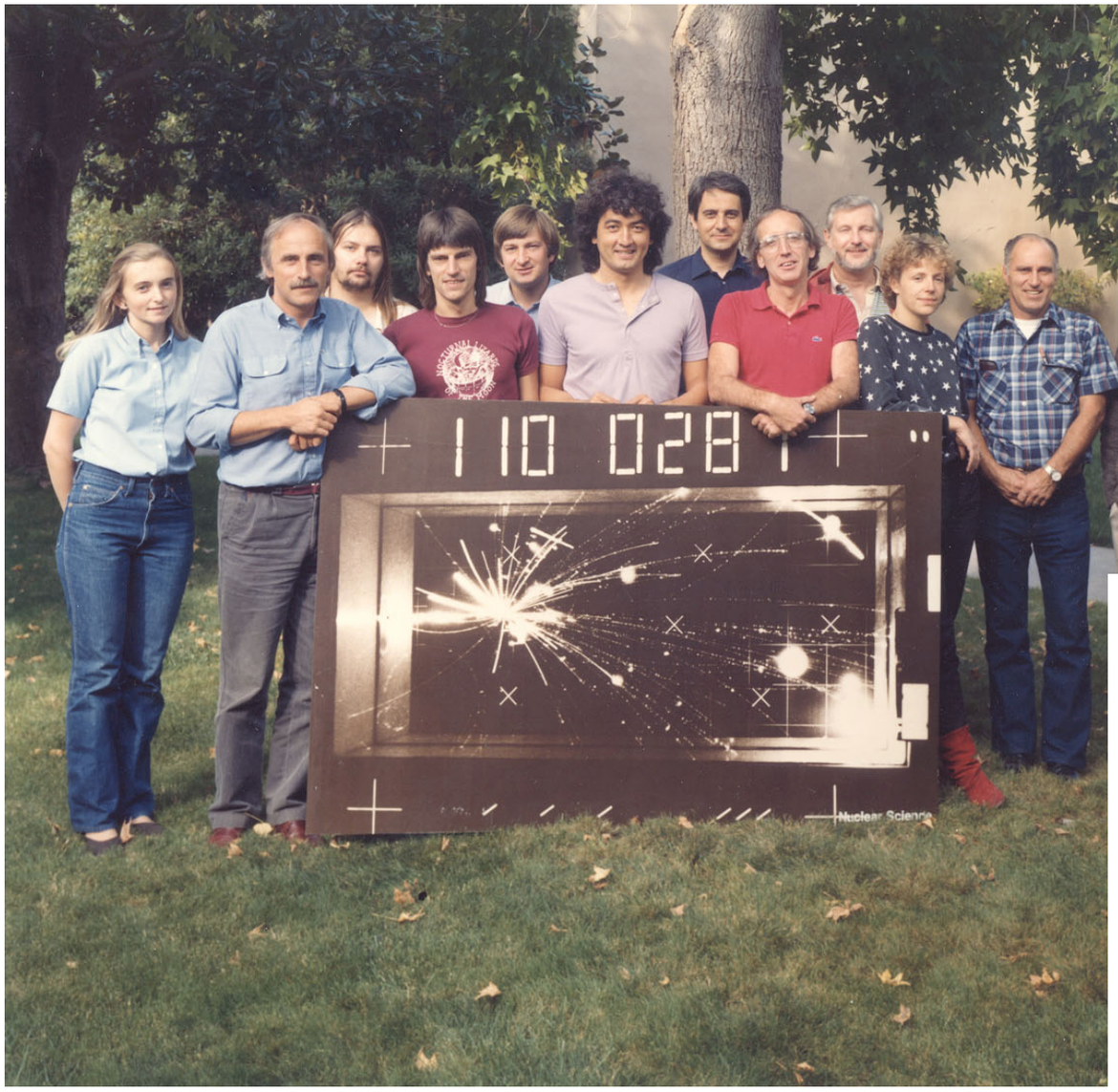
A long story since 1989!



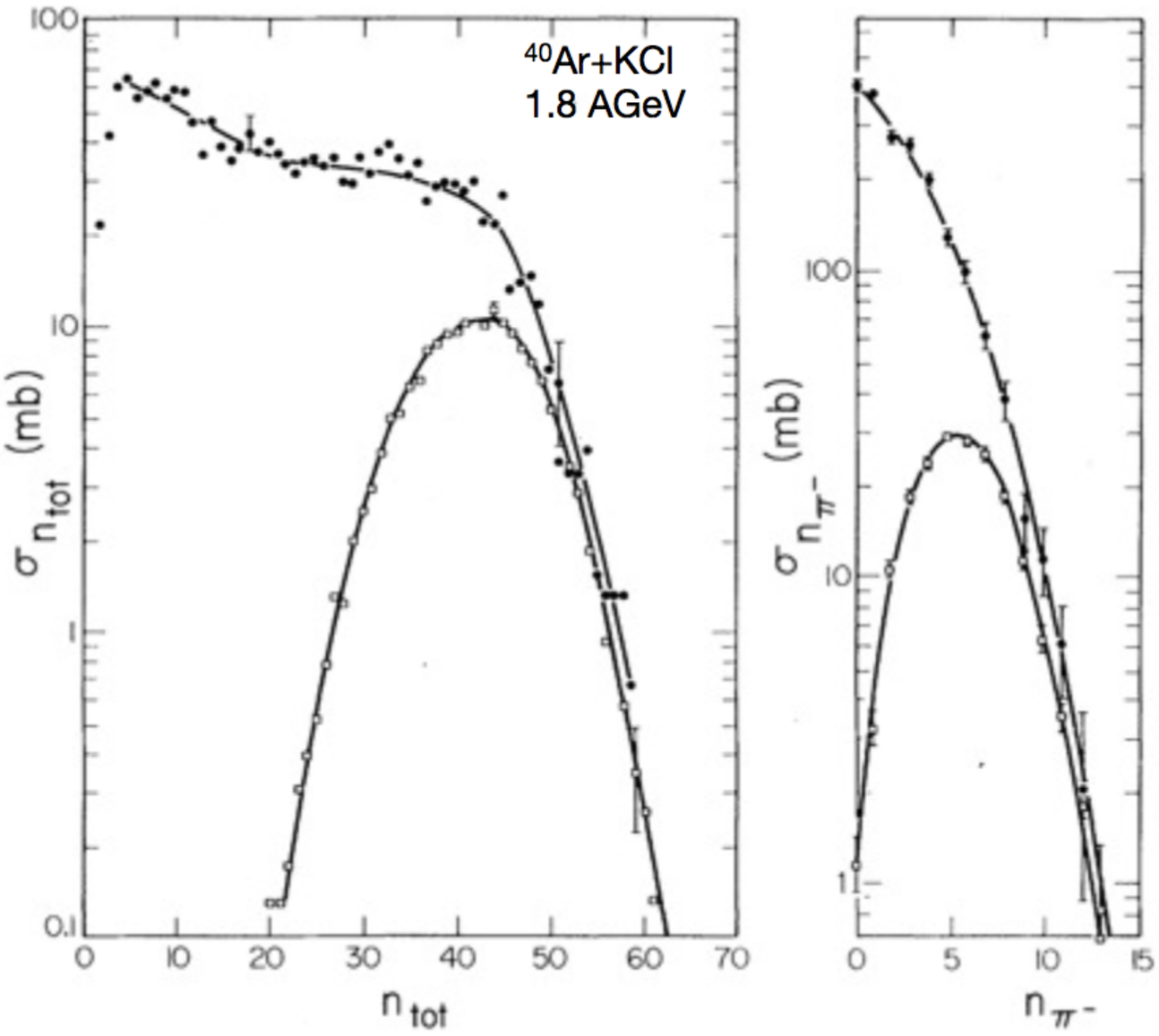
Streamer Chamber Collab. at LBL 1983

Centrality Selection and Event plane with the historical streamer chamber

Streamer Chamber Collab. at LBL 1983



Centrality Selection and Event plane with the historical streamer chamber



Phys. Rev. Lett. 45 (1980) 874

Part II:

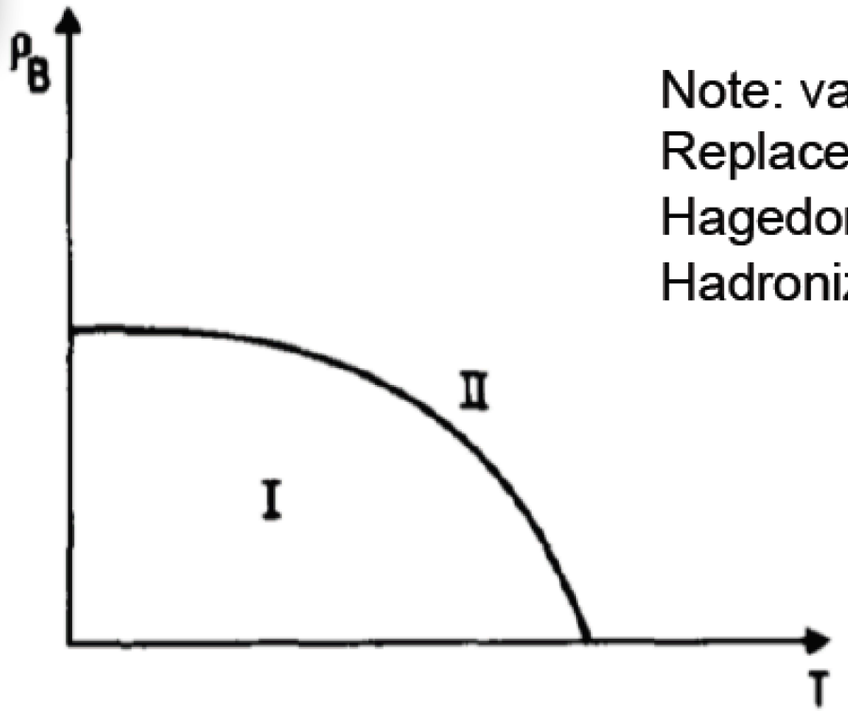
The Advent of QCD in A+A Collisions

Hagedorns limiting hadronic temperature T_H
as interpreted by Cabibbo and Parisi 1975
as indication of a second order phase transition to QGP
Phys.Lett. B59 (1975) 67

The currently accepted interpretation of the properties of hadronic matter is based on the "realistic" quark model where quarks are permanently confined in hadrons. We expect models of this kind to give rise to a phase transition at a temperature $kT \approx m_\pi$, the high temperature phase being one where quarks can move freely in space.

-> Deconfinement at T_H to a new QCD phase

The first QCD Phase Diagram



Note: variables here are (T, ρ_B).
Replaced later by (T, μ_B) in the Hagedorn-inspired Statistical Hadronization Model

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.

First view of deconfinement in relativistic A+A collisions

- about 1980 T.D.Lee: „Distributing enough energy density in space to melt the physical vacuum“
- „Physical Vacuum“ ≡ Color fields confined in hadrons
- after „melting“ ≡ Color fields permeate all space: QCD Plasma
- Estimate: ε(c) about 1-2 GeV/fm³ in the „fireball“

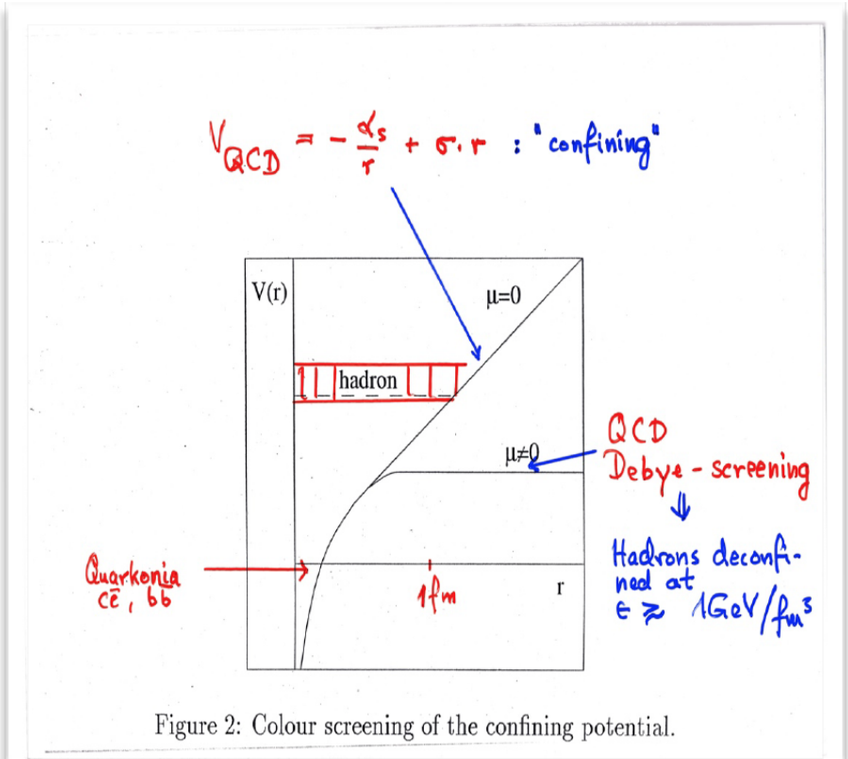
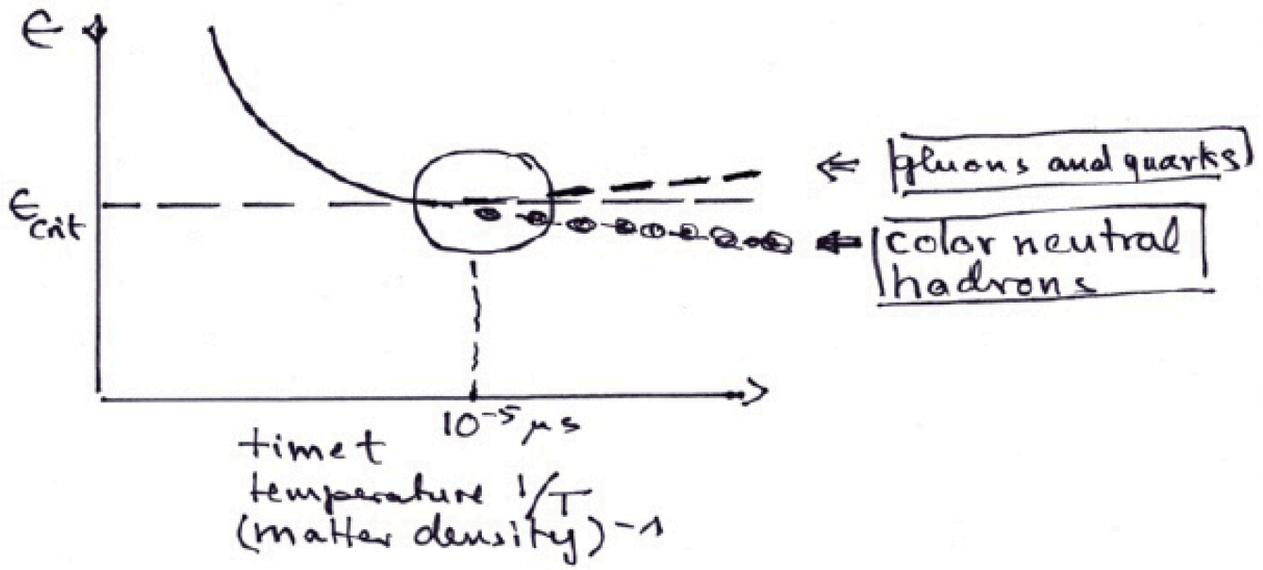


Figure 2: Colour screening of the confining potential.

Hadronization: a phase transition in the cosmic expansion

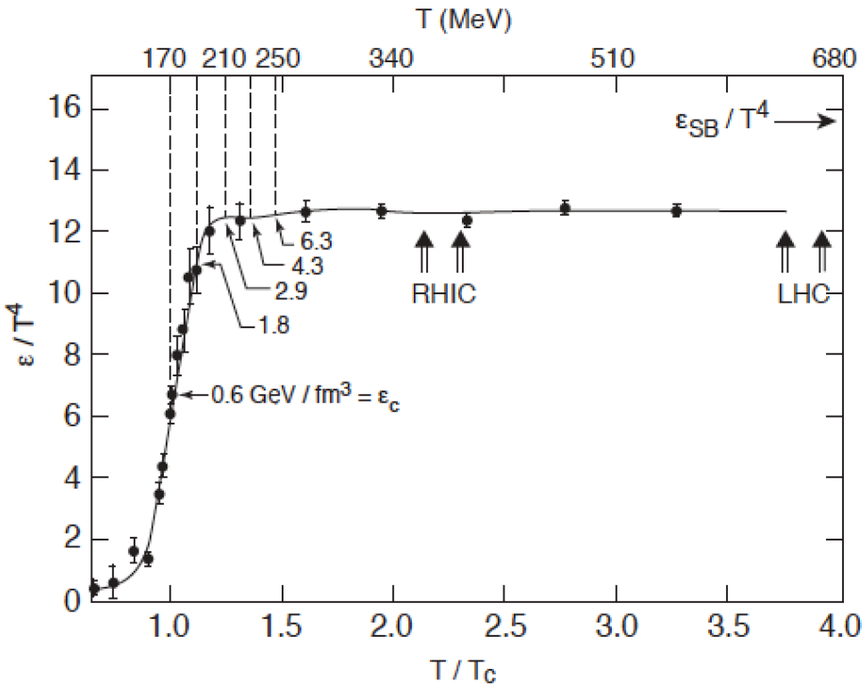
at $t \approx 10^{-5}$ s where $T \approx 2 \cdot 10^{12}$ K and $R \approx 10^{11}$ km
Matter/energy density $\epsilon = 1\,\mathrm{GeV/fm^3} \,\hat{=}\, 2 \cdot 10^{18}\,\mathrm{kg/m^3}$

The expanding {quark + gluon} matter hits a "critical point", at $\epsilon \approx 1\,\mathrm{GeV/fm^3}$, $T = 170\,\mathrm{MeV}$



Entry of Lattice QCD

Lattice QCD with three flavors(2000)



- Energy density in Lattice QCD, year 2000
- At 3 GeV/fm^3 we are at T = 210 MeV
- Note: RHIC and LHC estimates!
- Note: $\varepsilon \approx 0.6$ GeV/fm^3 at $T_c \approx 170$ MeV as it is in the Stat. Hadronization Model

Experiment Proposals!

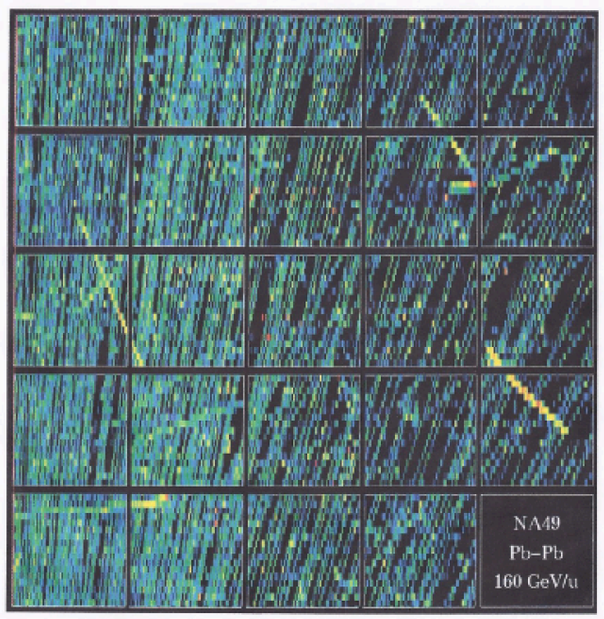
Upgrades:

- ^{4}He + ^{4}He @ CERN ISR $\sqrt{s}$ = 30 GeV
- ^{16}O, ^{32}S ... ^{208}Pb @ AGS, SPS $\sqrt{s}$ -> 20 GeV

New Constructions:

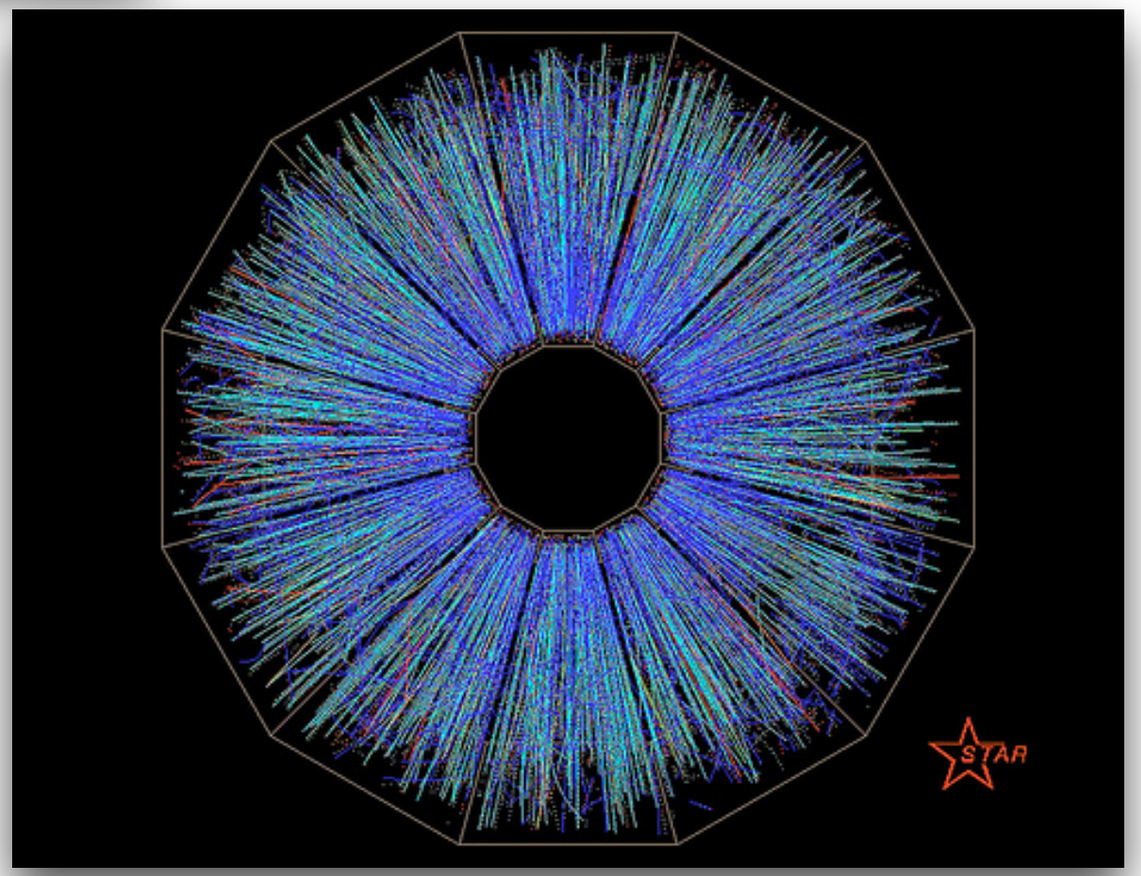
- RHIC @ BNL and LHC @ CERN

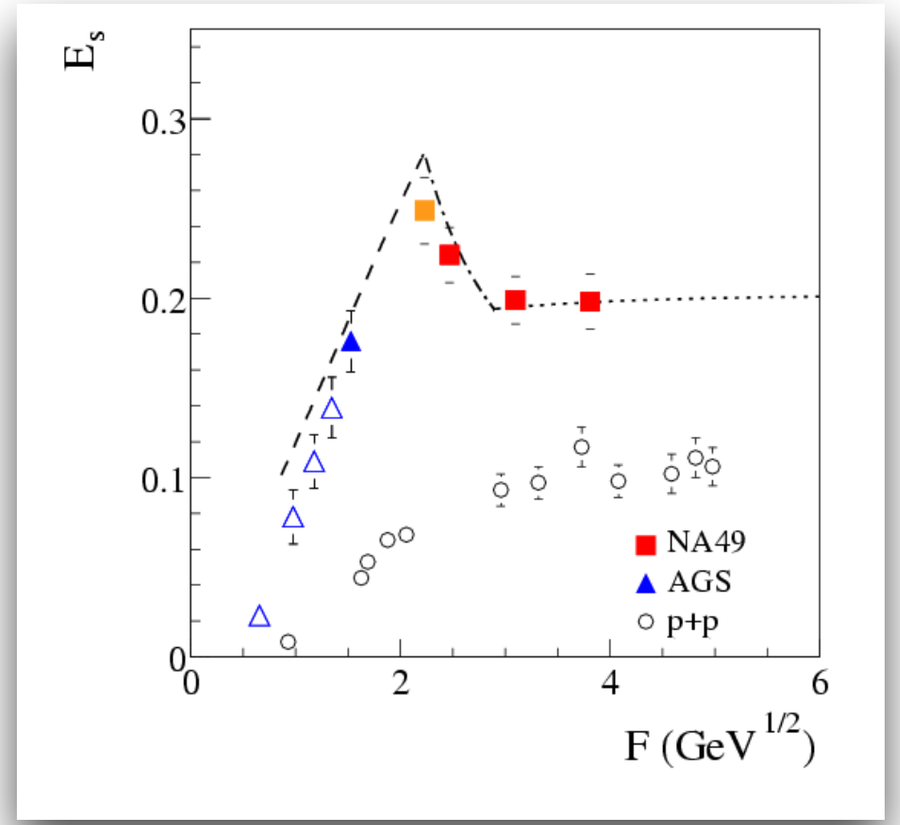
TPC Tracking 1996

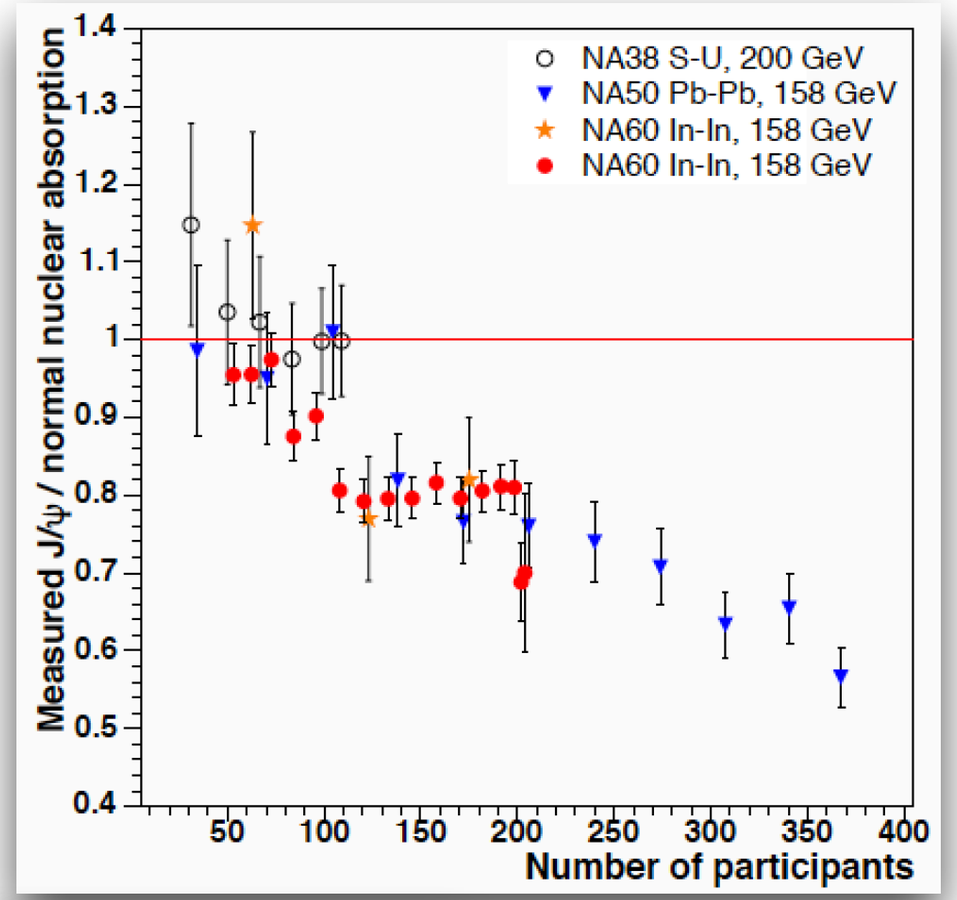


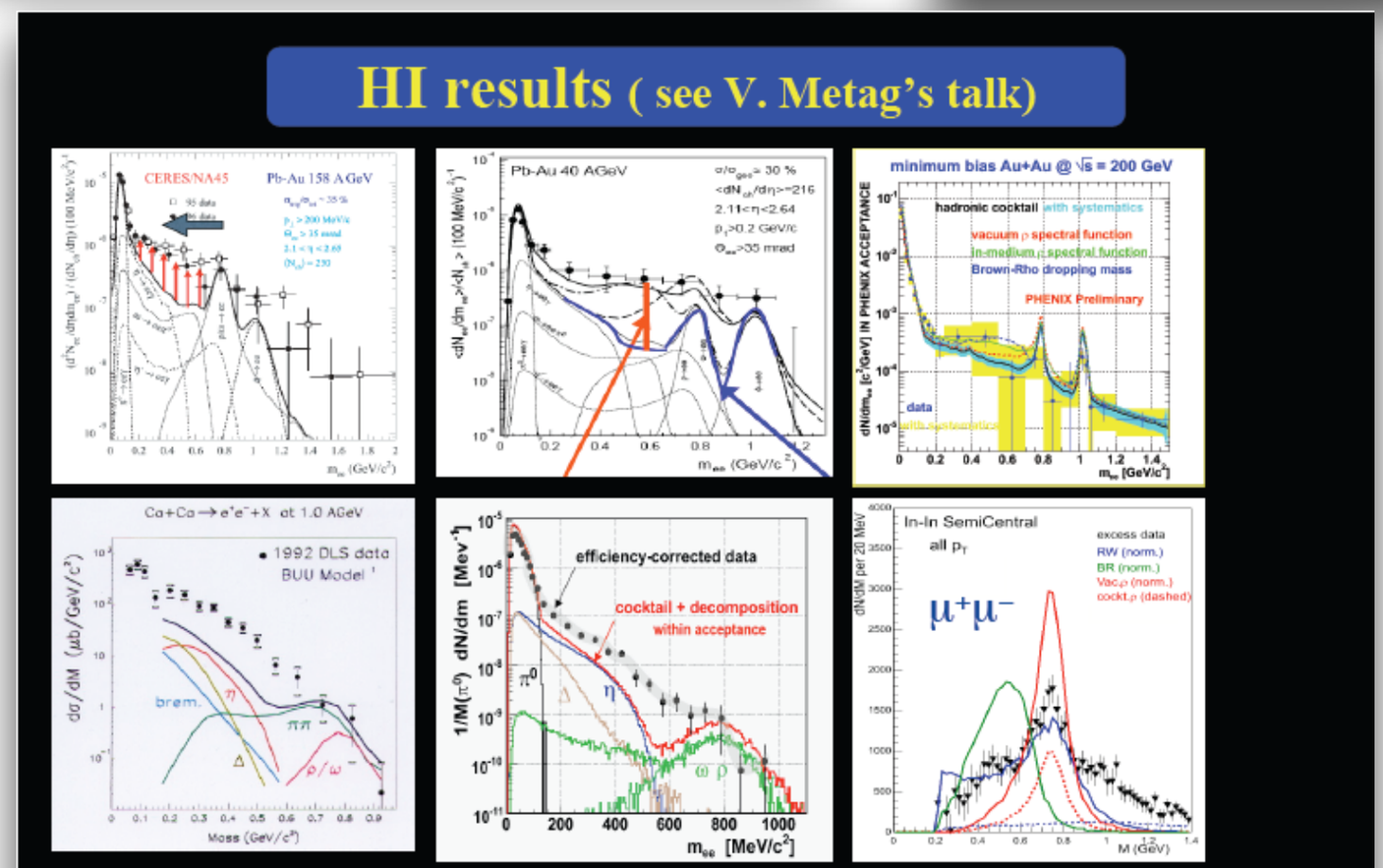
- Total charged particle multiplicity about 1000
- inner segment of TPC drift volume

Data rate from NA49 to ALICE: Factor > 1000 !

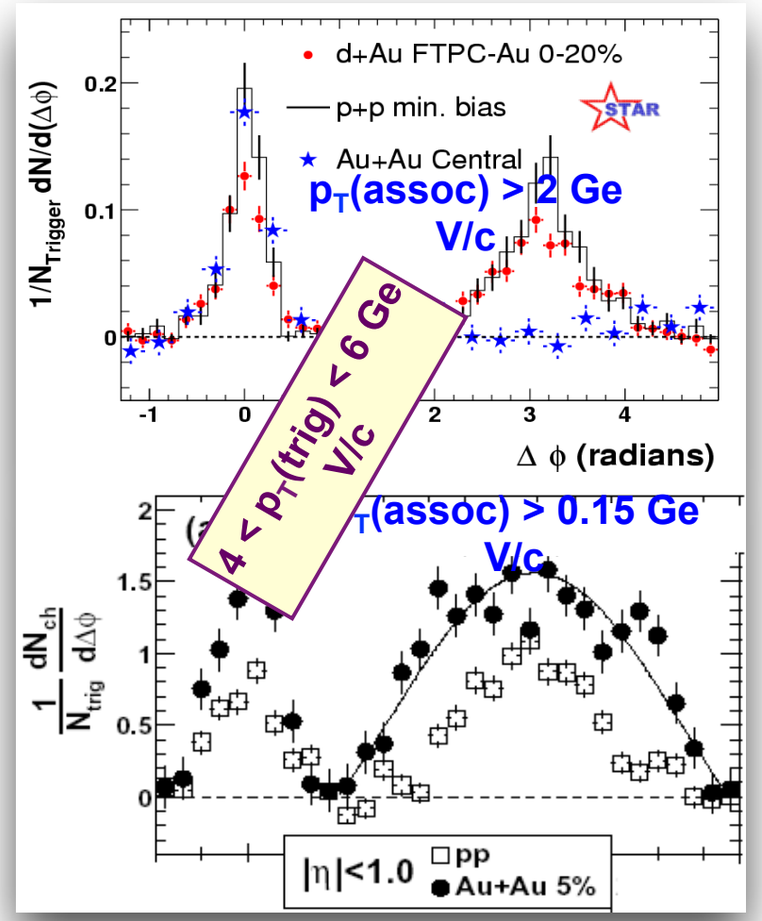


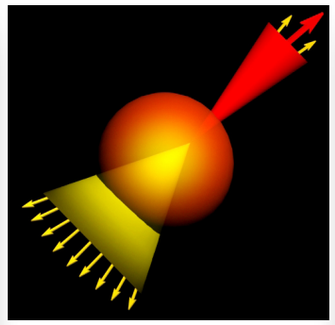

E_s
0.3
0.2
0.1
0
0
2
4
6
F (GeV^1/2)
NA49
AGS
p+p

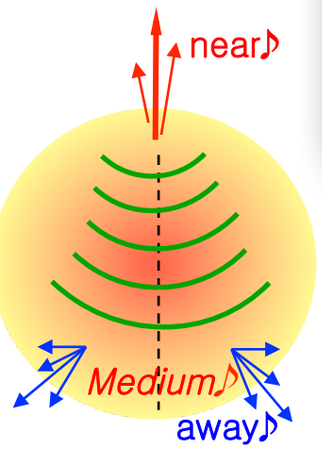

NA38 S-U, 200 GeV
NA50 Pb-Pb, 158 GeV
NA60 In-In, 158 GeV
NA60 In-In, 158 GeV
Measured J/ψ / normal nuclear absorption
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
50
100
150
200
250
300
350
400
Number of participants


HI results (see V. Metag's talk)
CERES/NA45
Pb-Au 158 A GeV
Pb-Au 40 AGeV
minimum bias Au+Au @ √s = 200 GeV
hadronic cocktail with systematics
vacuum ρ spectral function
in-medium ρ spectral function
Brown-Rho dropping mass
PHENIX Preliminary
data
Ca+Ca→e+e−+X at 1.0 AGeV
1992 DLS data
BUU Model
brem.
efficiency-corrected data
cocktail + decomposition
within acceptance
In-In SemiCentral
all p_T
excess data
RW (norm.)
BR (norm.)
Vac.ρ (norm.)
cockt.ρ (dashed)
μ+μ−
Clear excess of dileptons observed. NA60: Γ ↗ , no ΔM
Chaden Djalali
QM2006 Shanghai
5

SPS-Era







mach cone

The RHIC Revolution

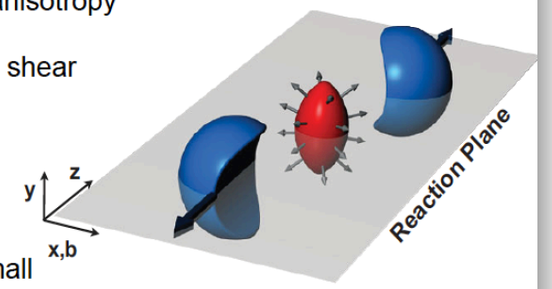
Elliptic Flow v_2 generated by primordial source anisotropy

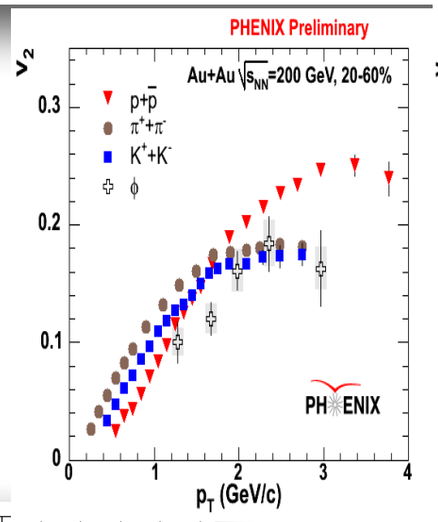
Sensitive to scaled shear viscosity η/s

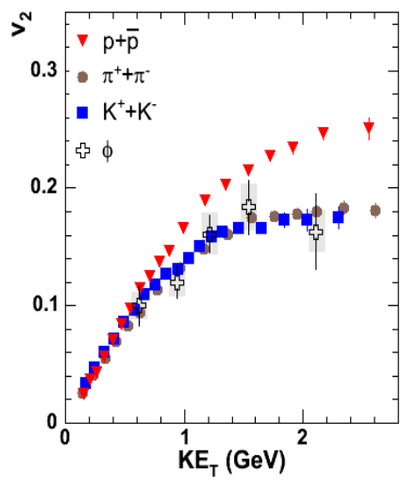
Viscous relativistic hydrodynamics

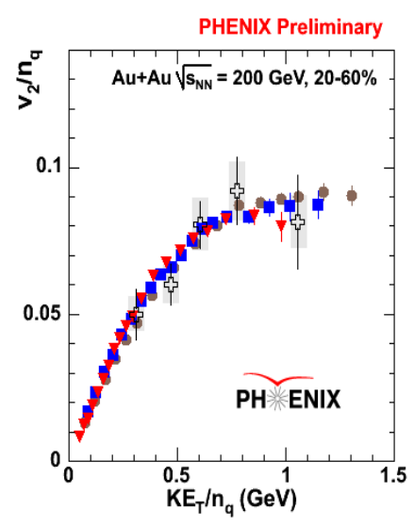
BUT: η/s is very small

QGP is a nearly ideal fluid

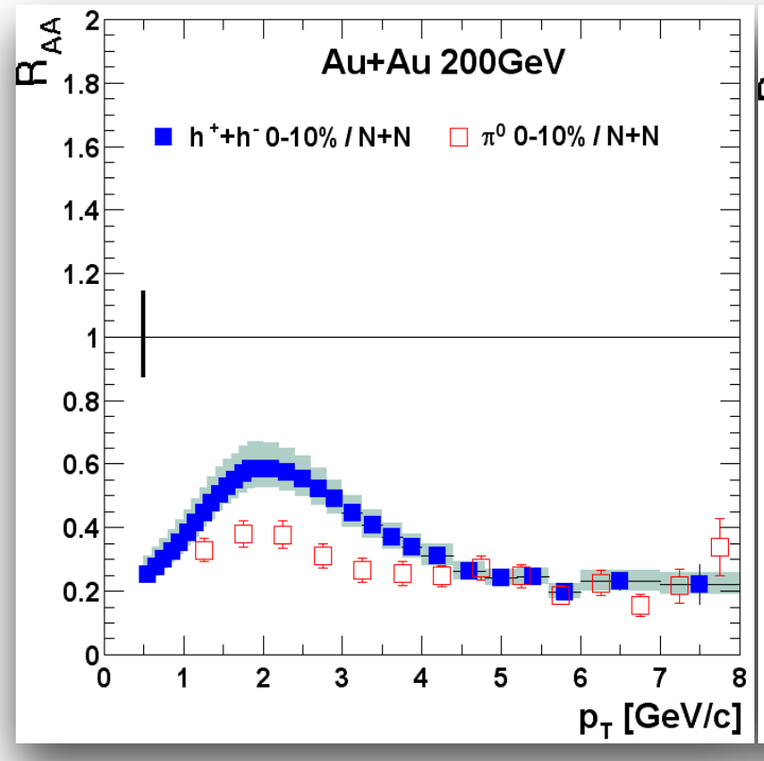


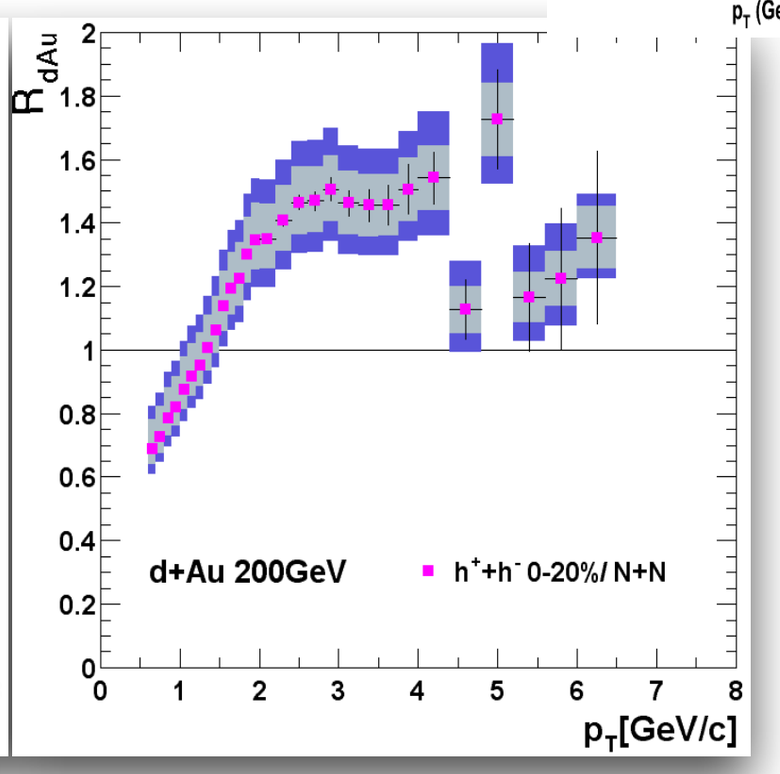


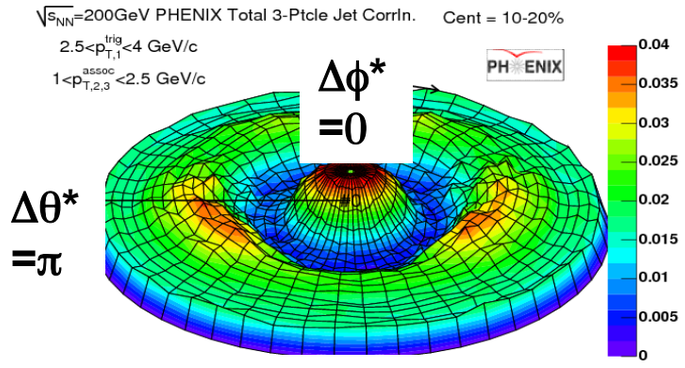




RHIC-Era

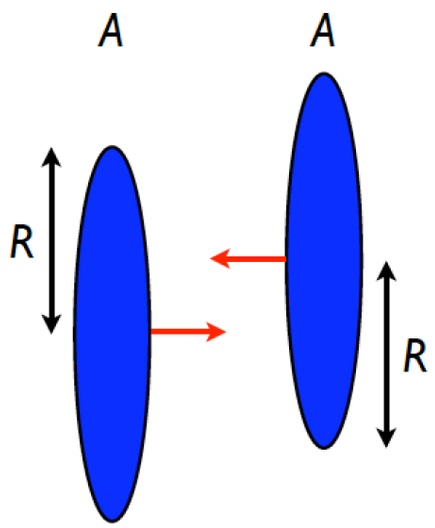






PHENIX Preliminary

Early time resolution as a consequence of short interpenetration time



$\tau = 2R/\gamma$
= 1.5 fm/c at top SPS energy
= 0.14 fm/c at top RHIC energy

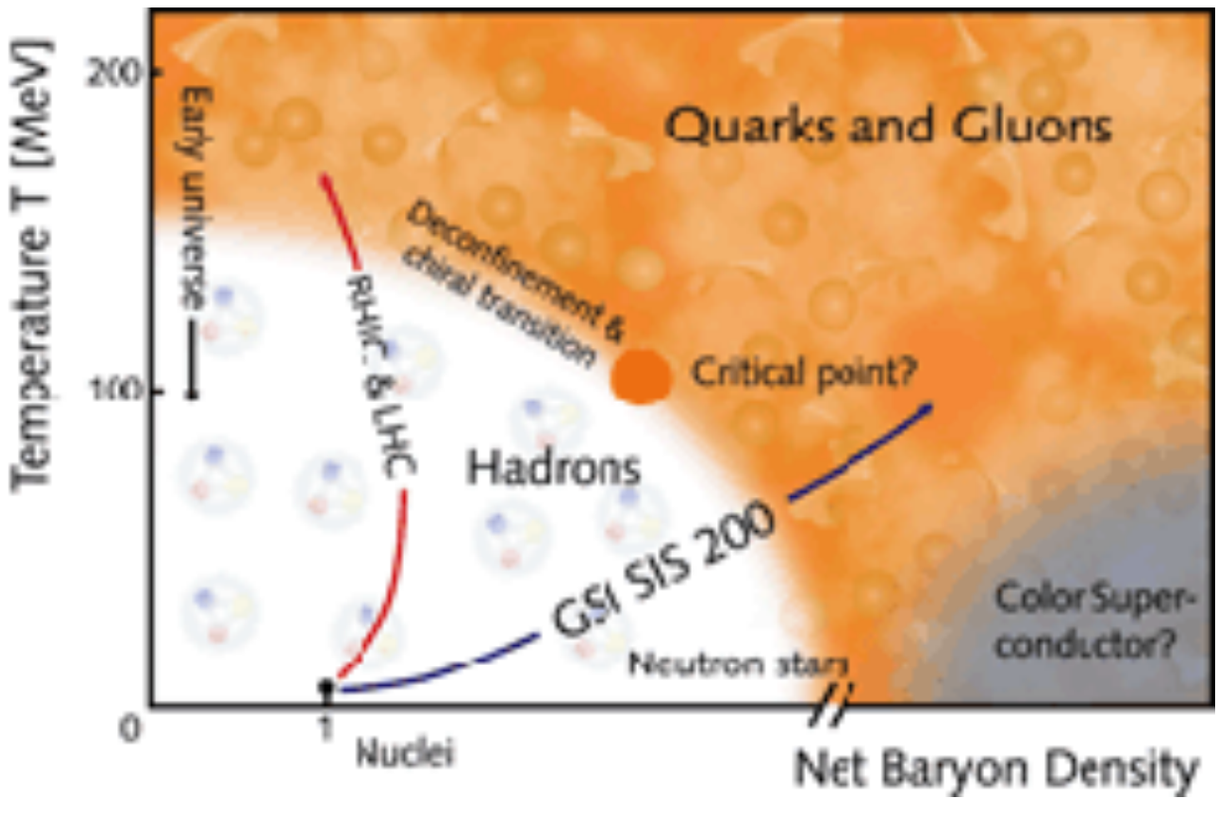
= 0.06 fm/c at LHC

Hot matter study

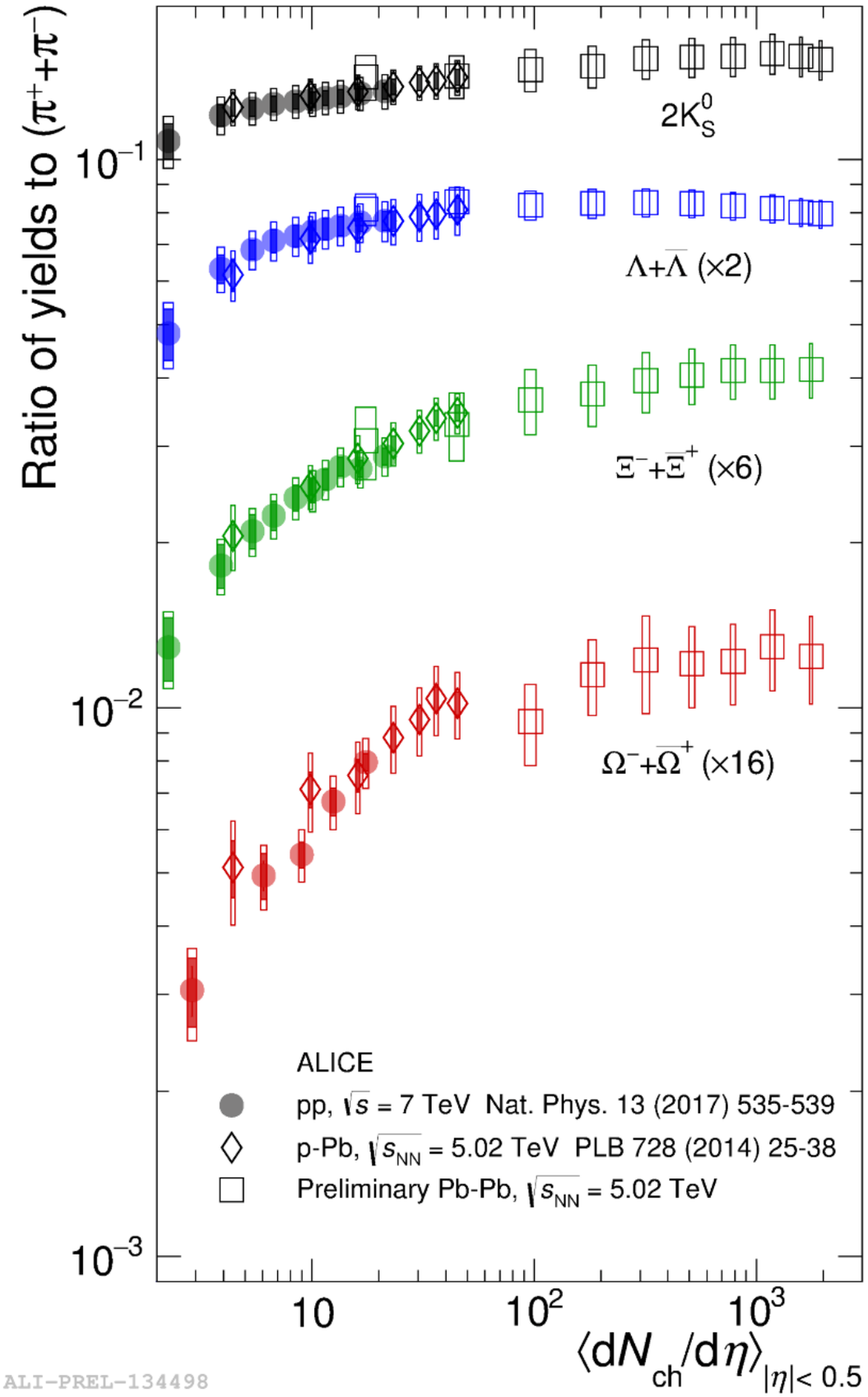
- **strongly interacting hot matter**
- **Properties: viscosity**
- **how opaque?**
- **is it QGP?**

➡ **Hard probes: HF**

➡ **How about LF?**



Nat. Phys. 13 (2017)535-539



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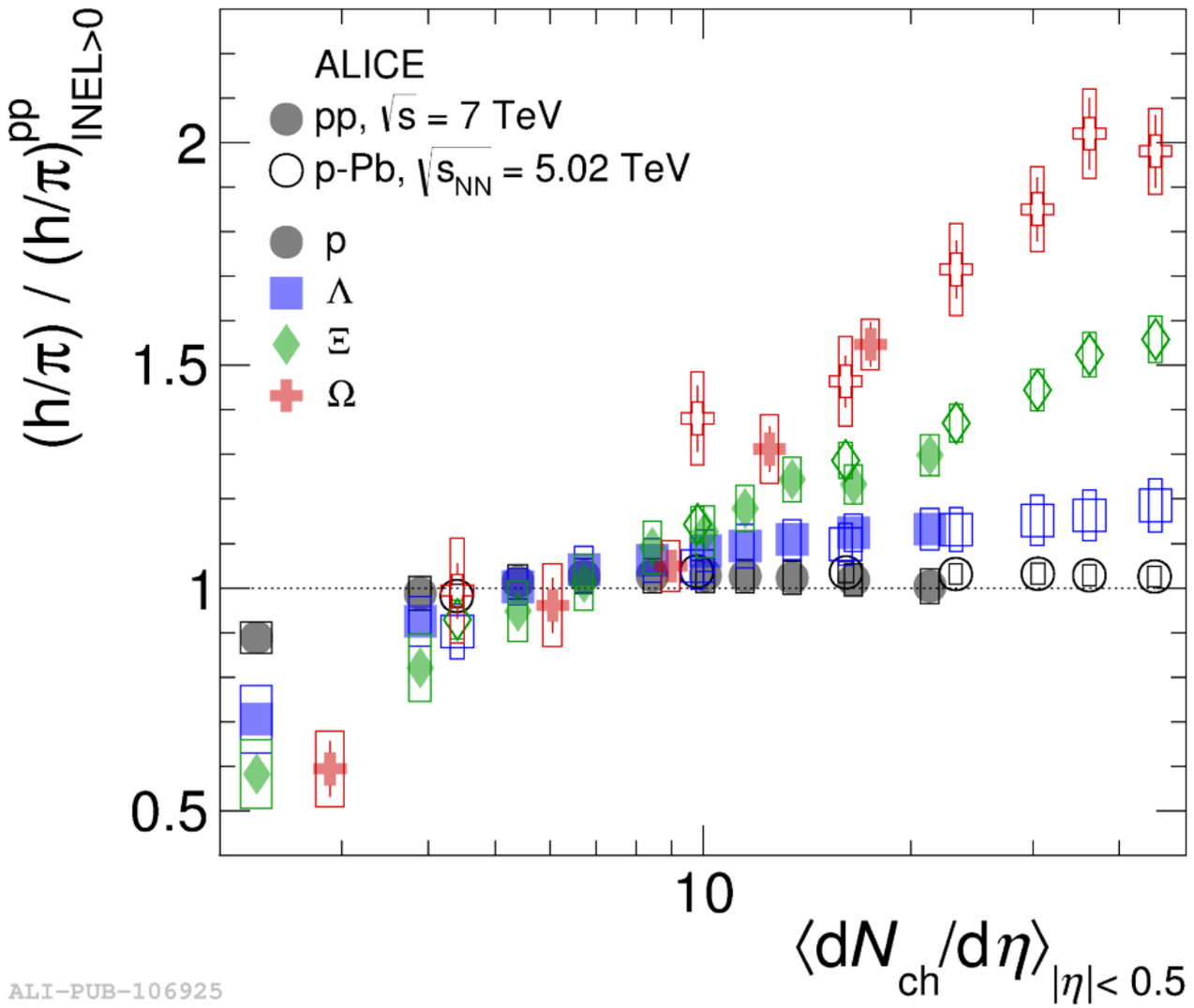

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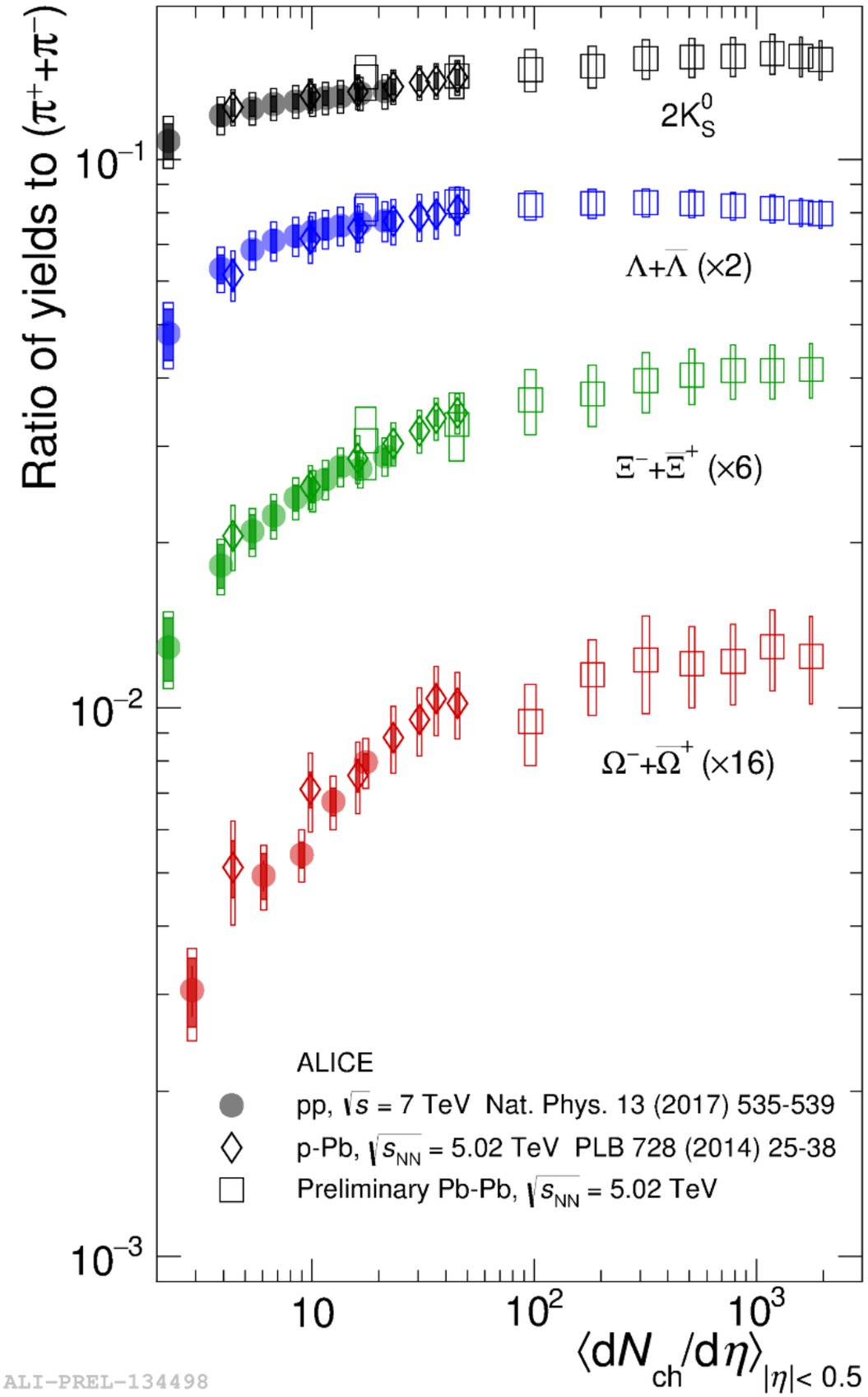
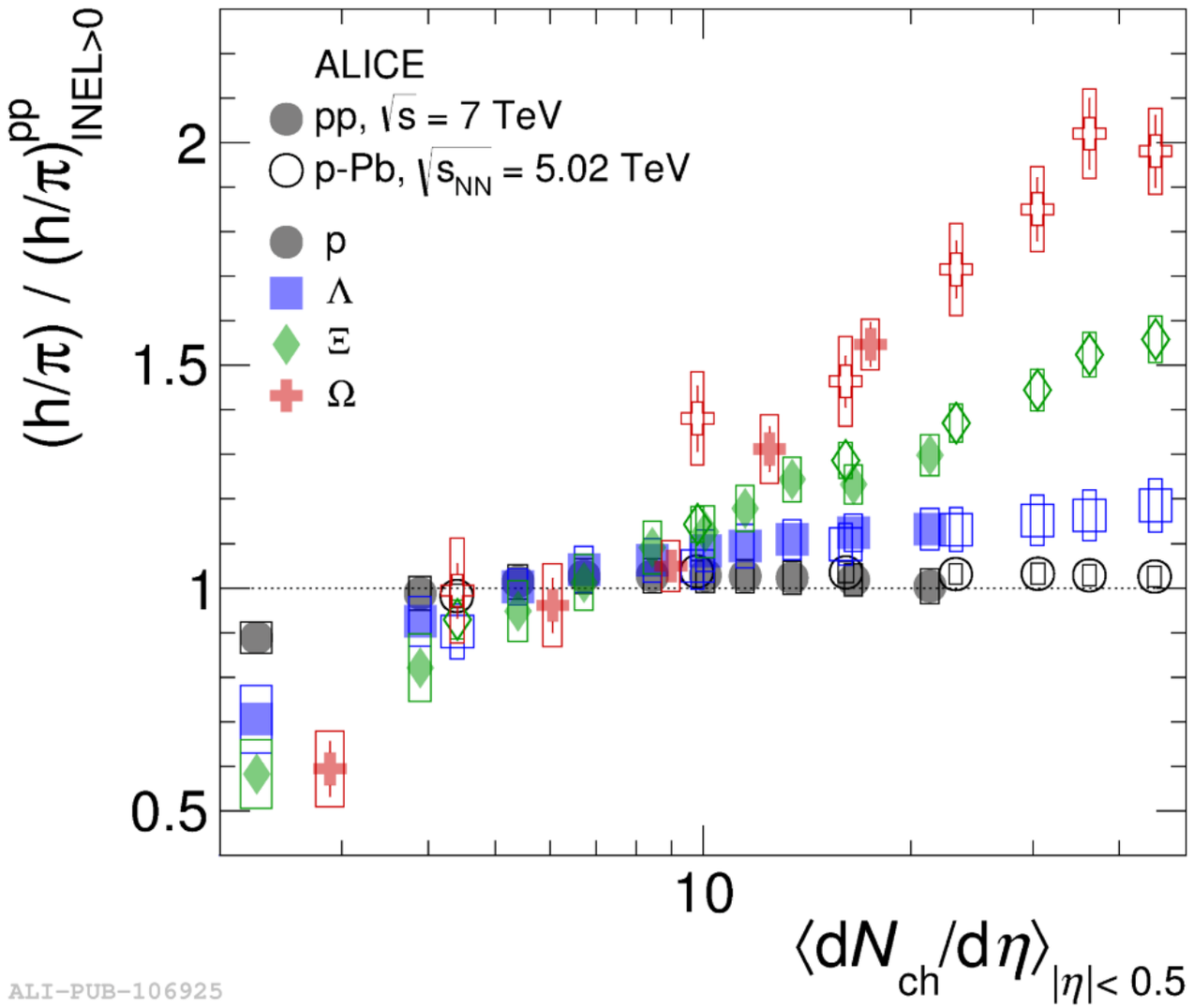


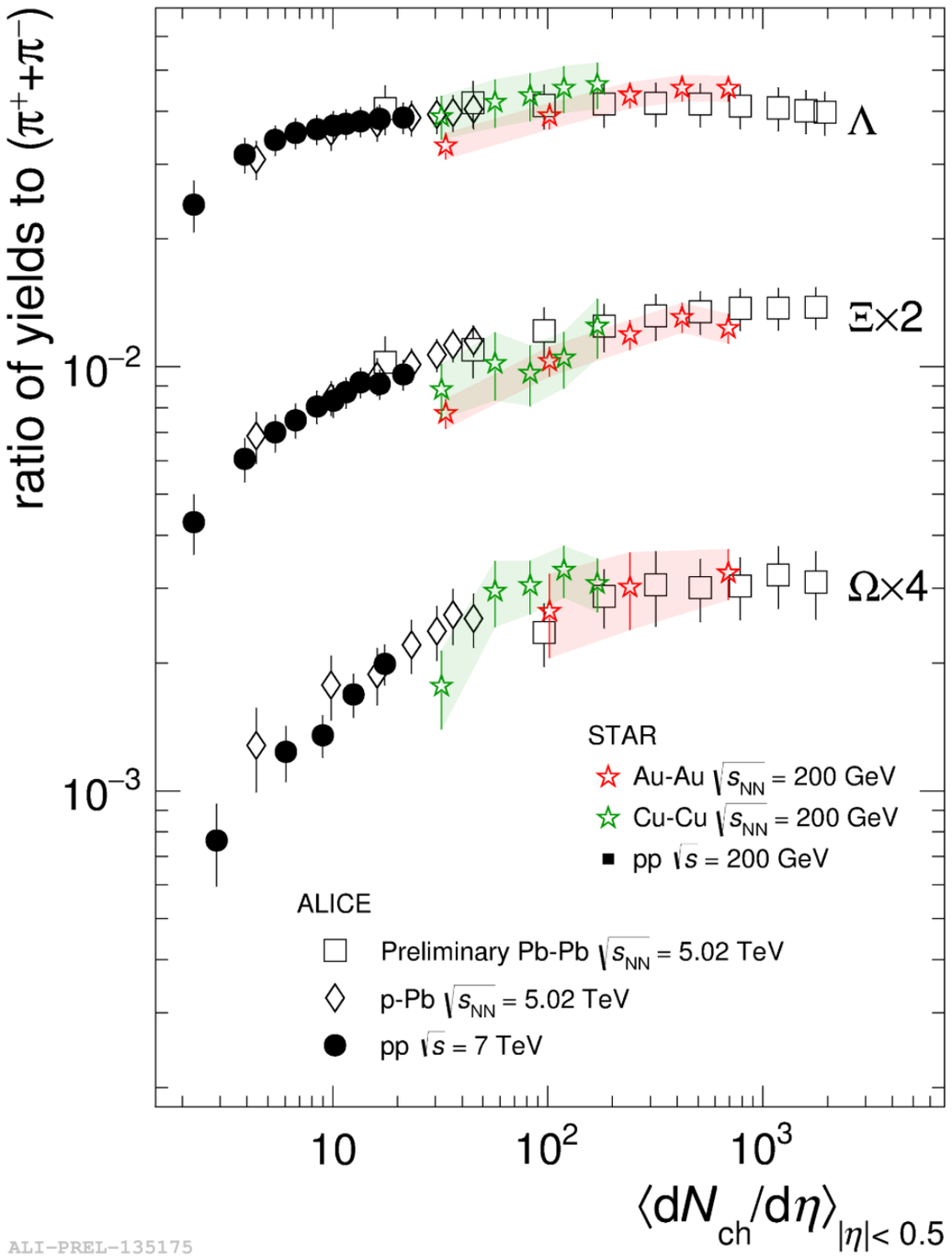
Nat. Phys. 13 (2017)535-539



Multiplicity = Universal Variable for the collisions

- Energy, System don't matter!

➡Attention to the small system!



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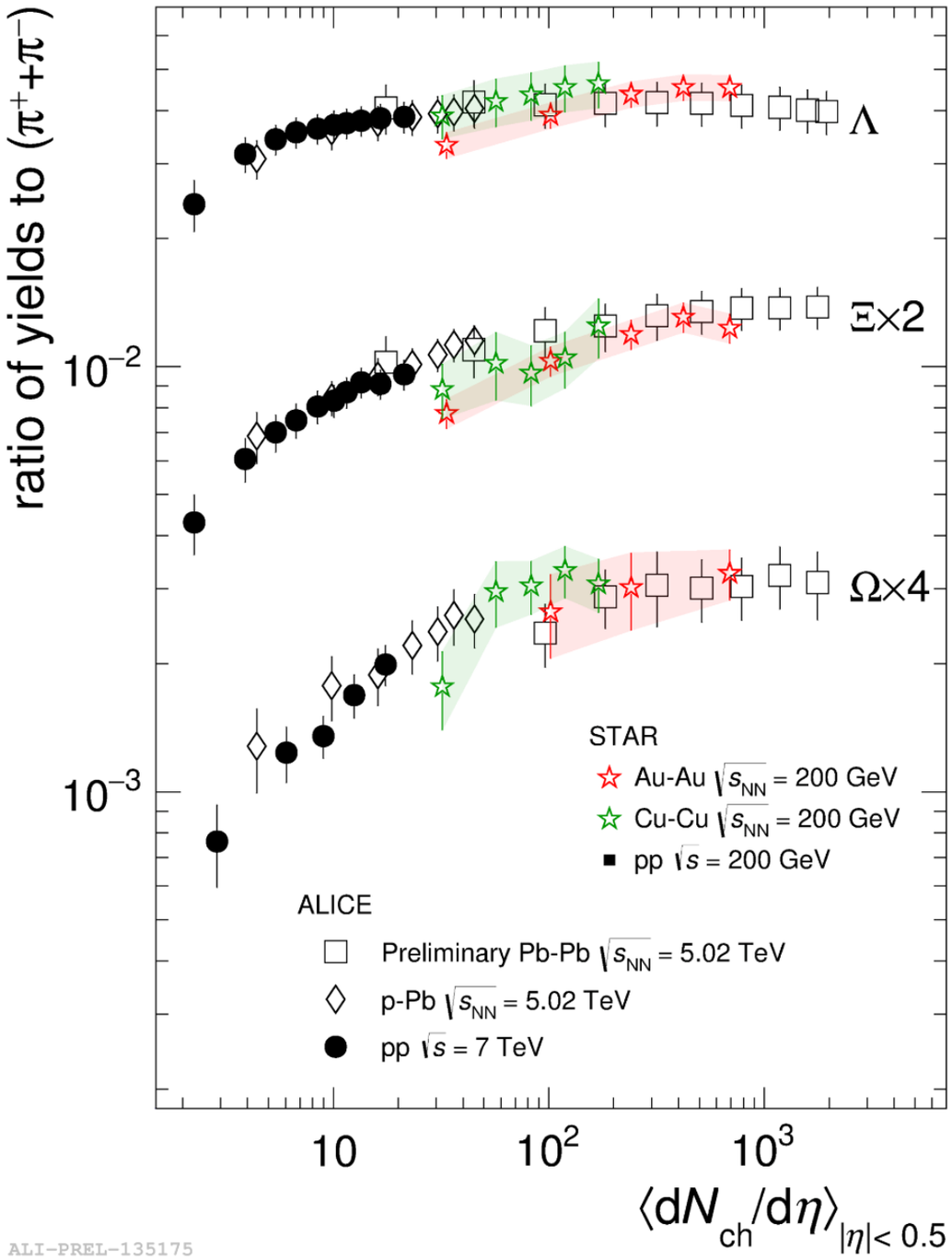
Even also for RHIC data!



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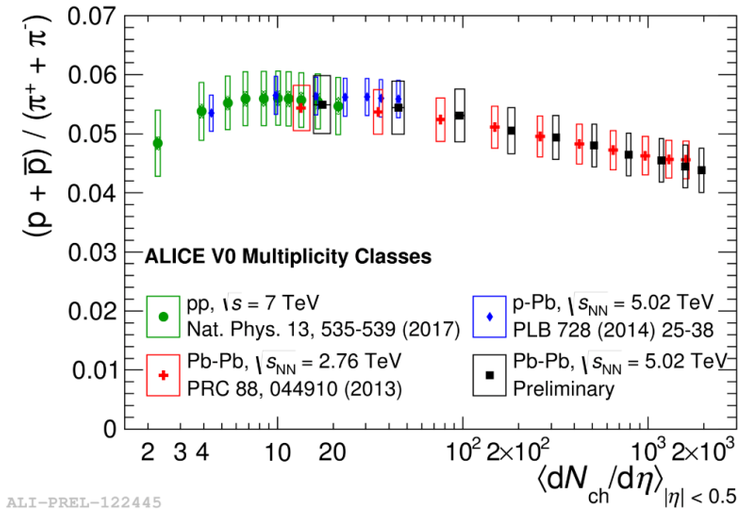
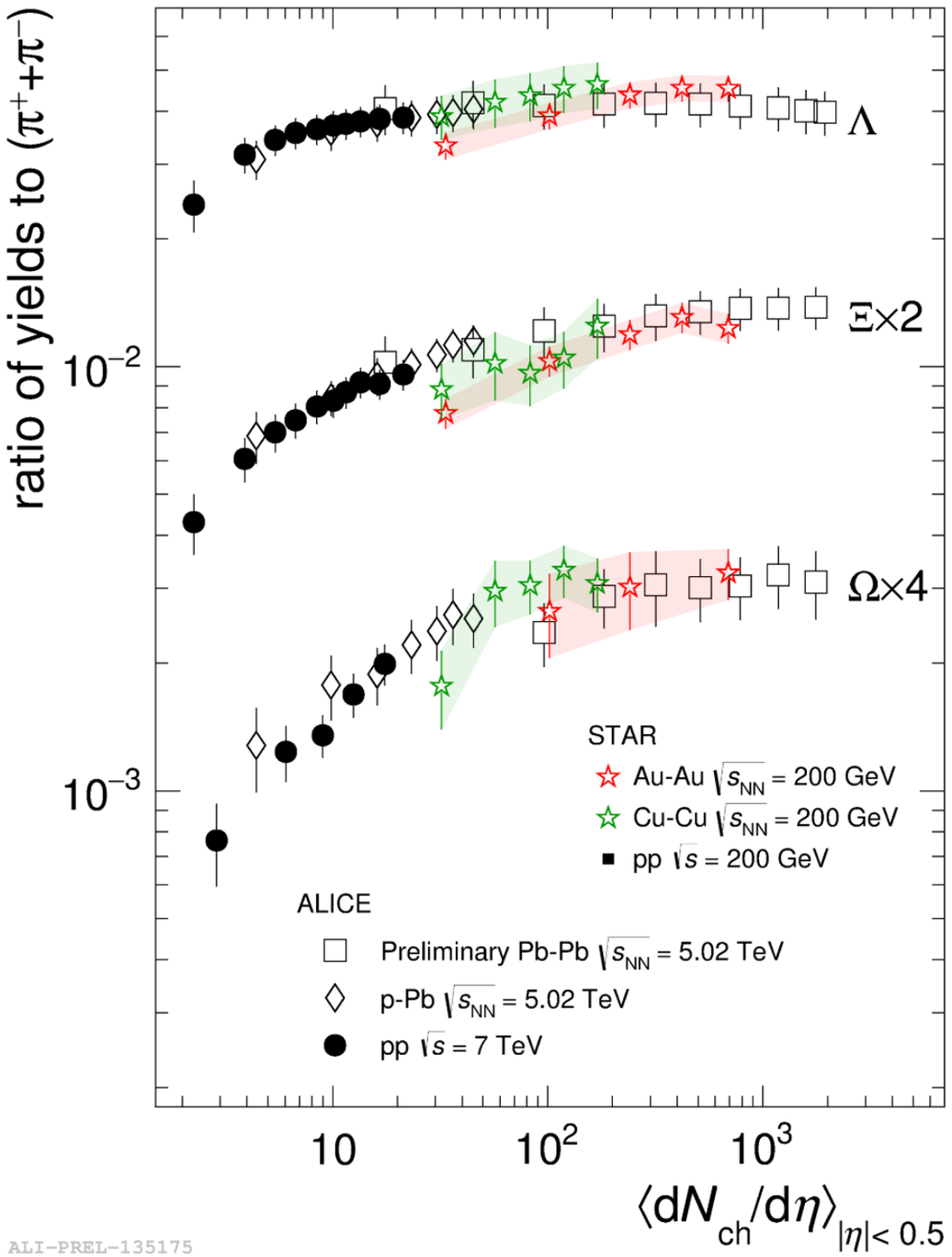


ALI-PREL-122445

Even also for RHIC data!



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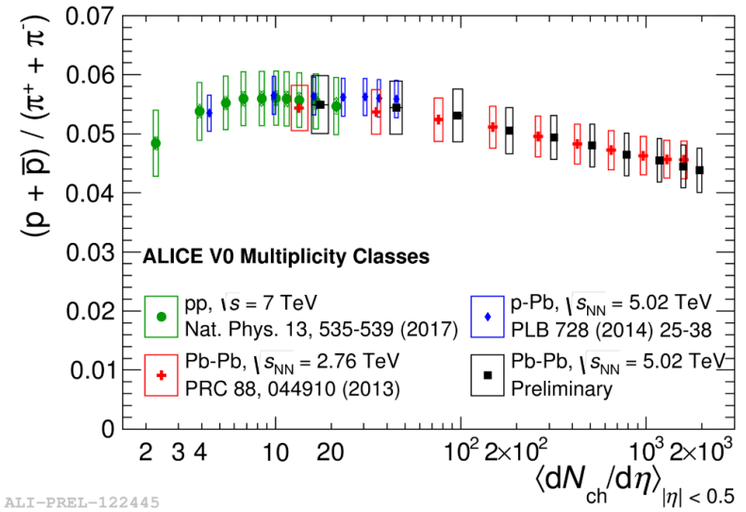

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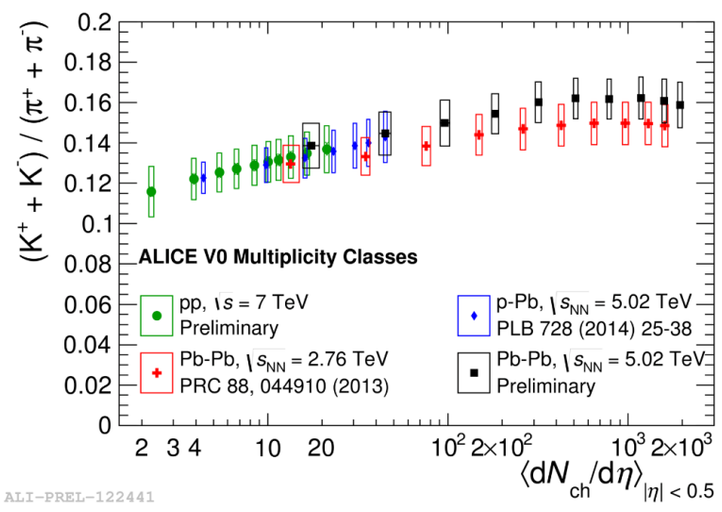
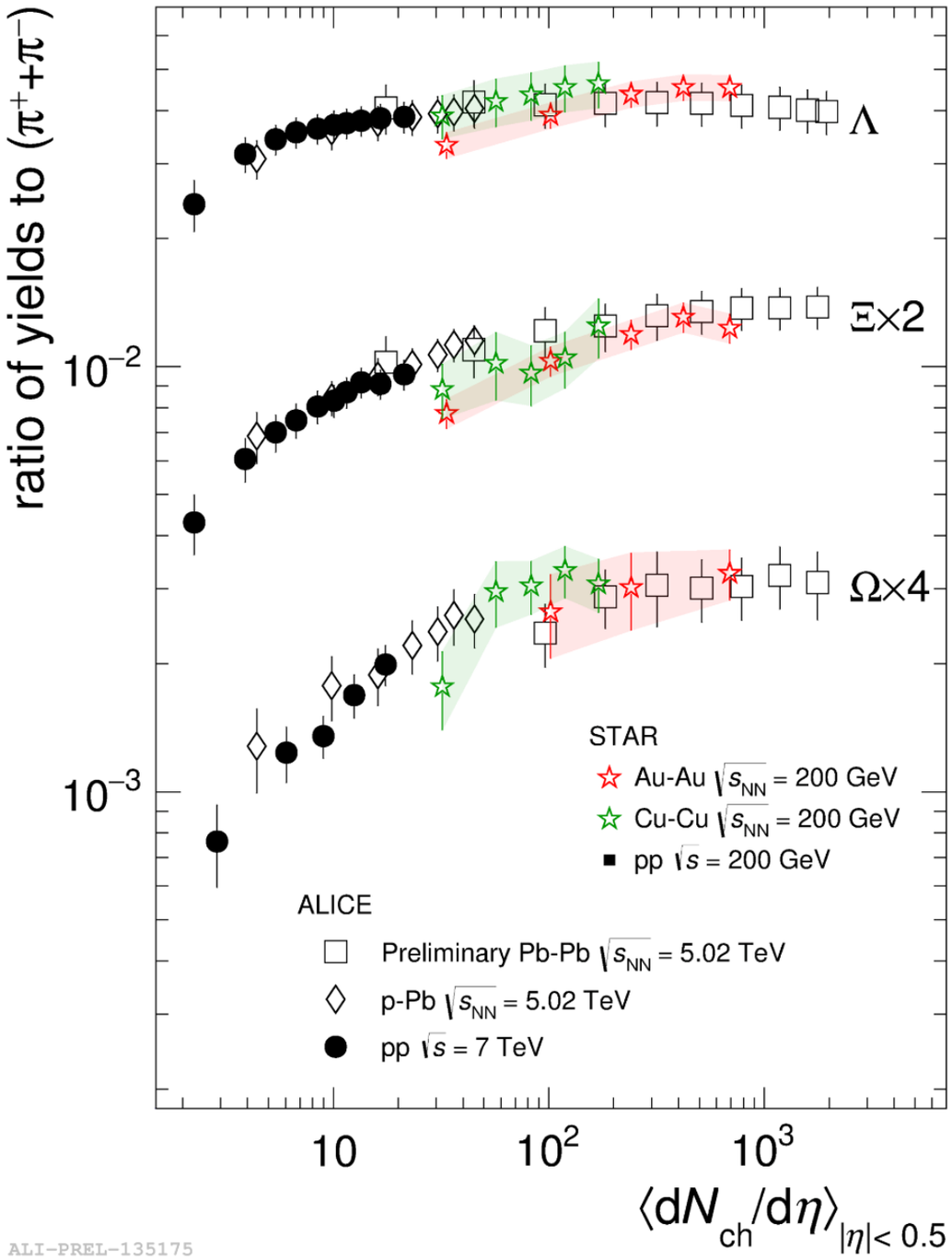


ALI-PREL-122441

Even also for RHIC data!



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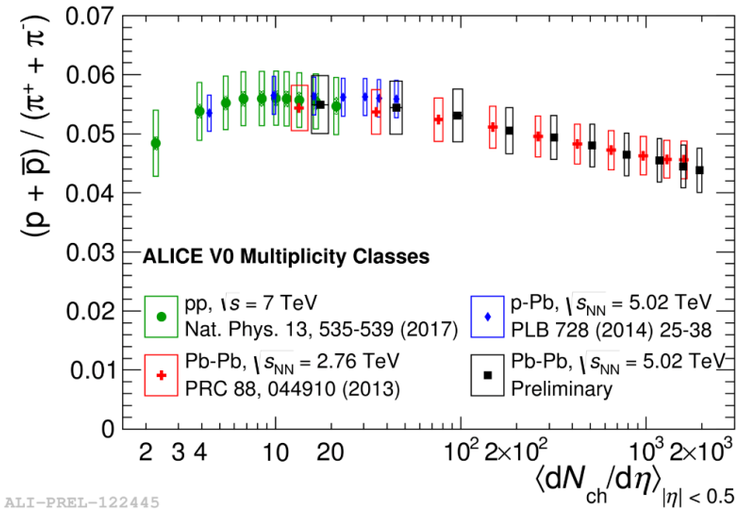

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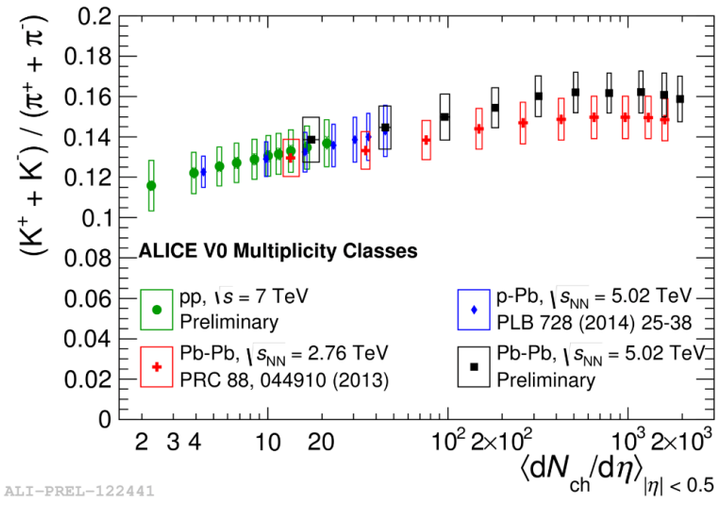

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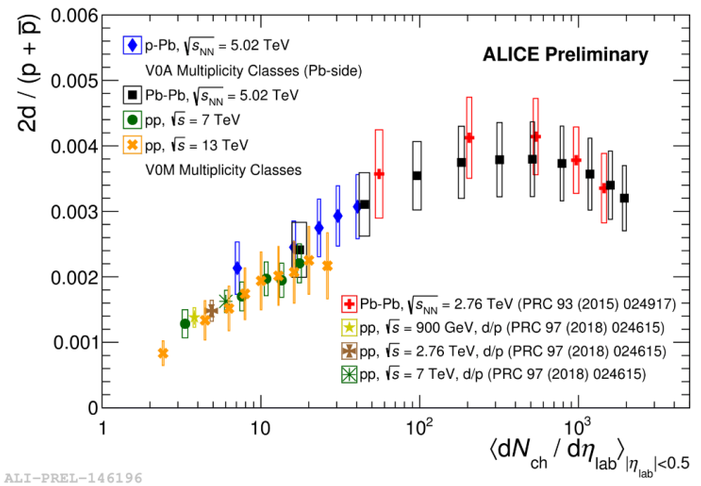
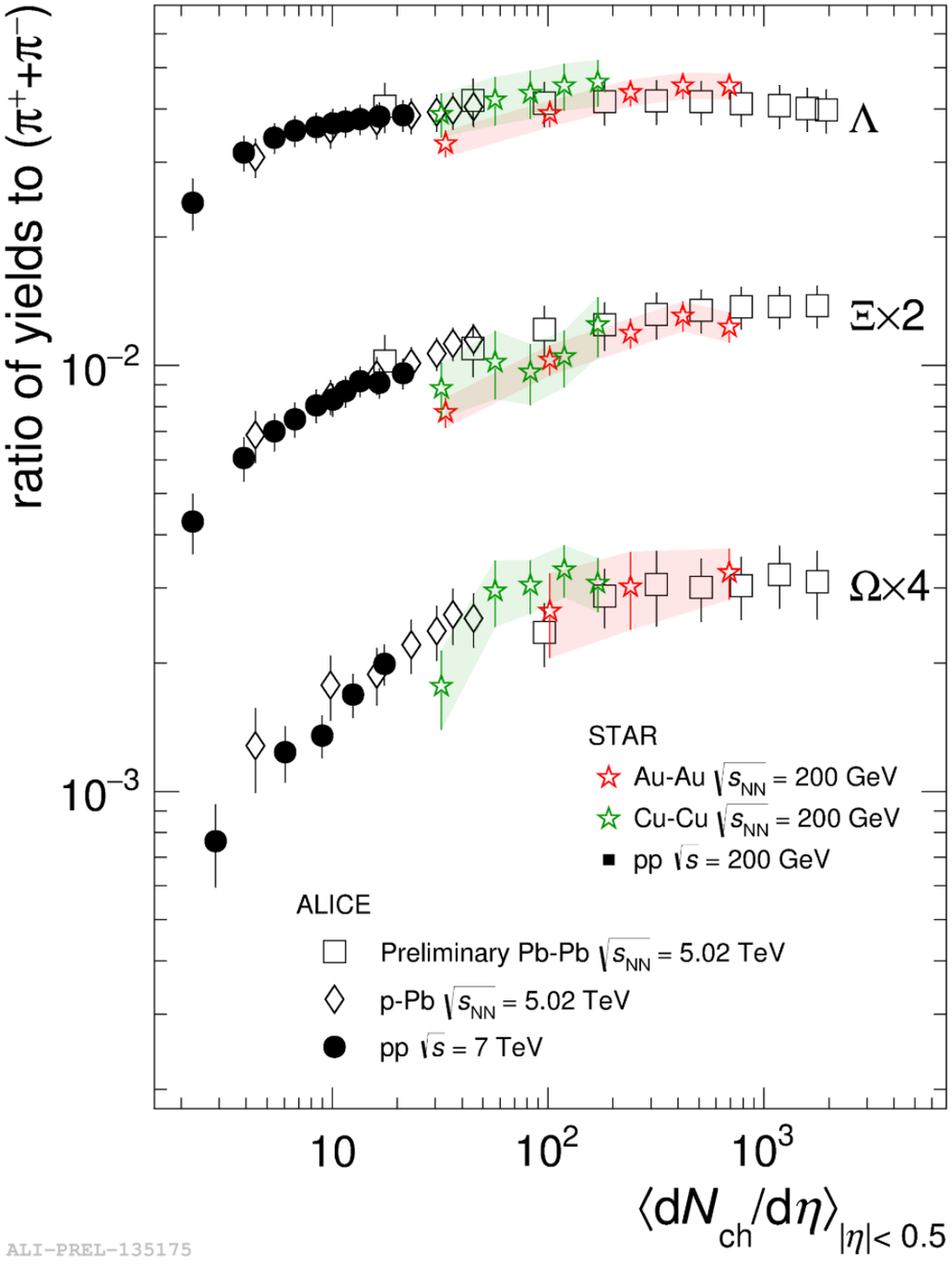


ALI-PREL-146196

Even also for RHIC data!



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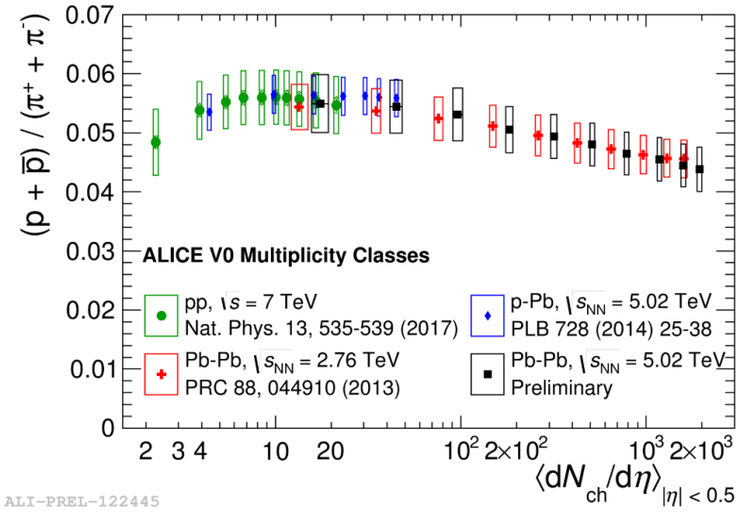

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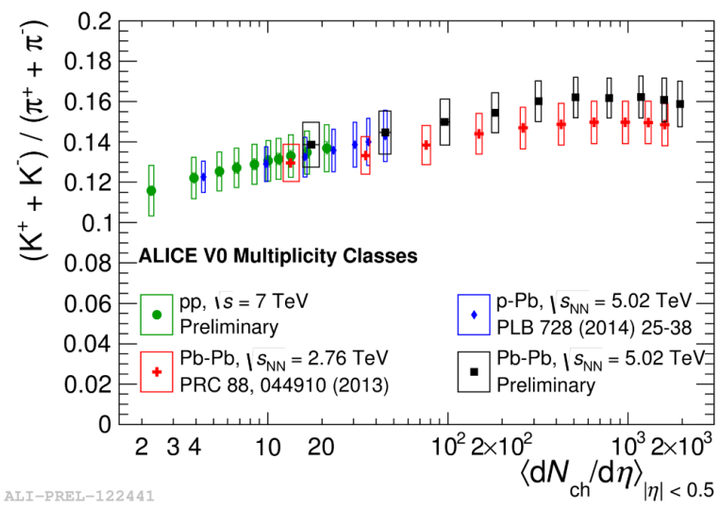

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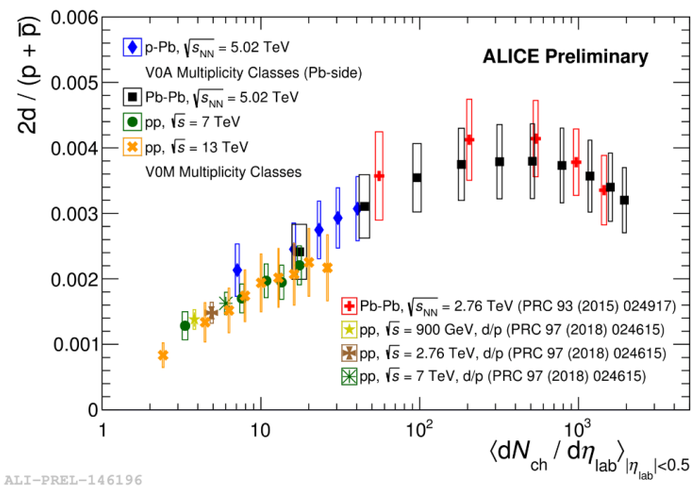

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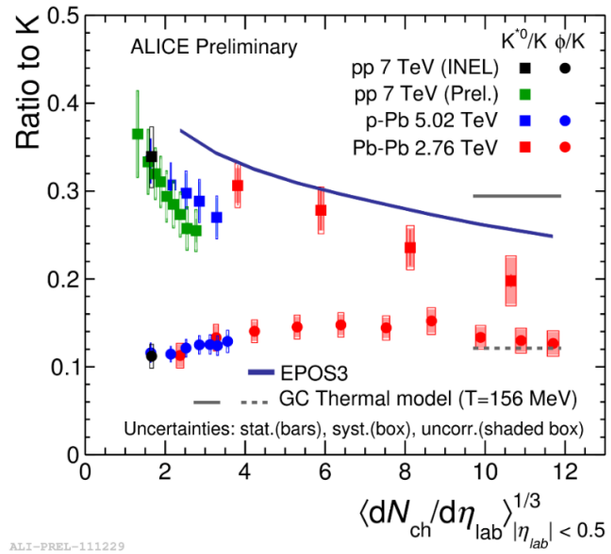
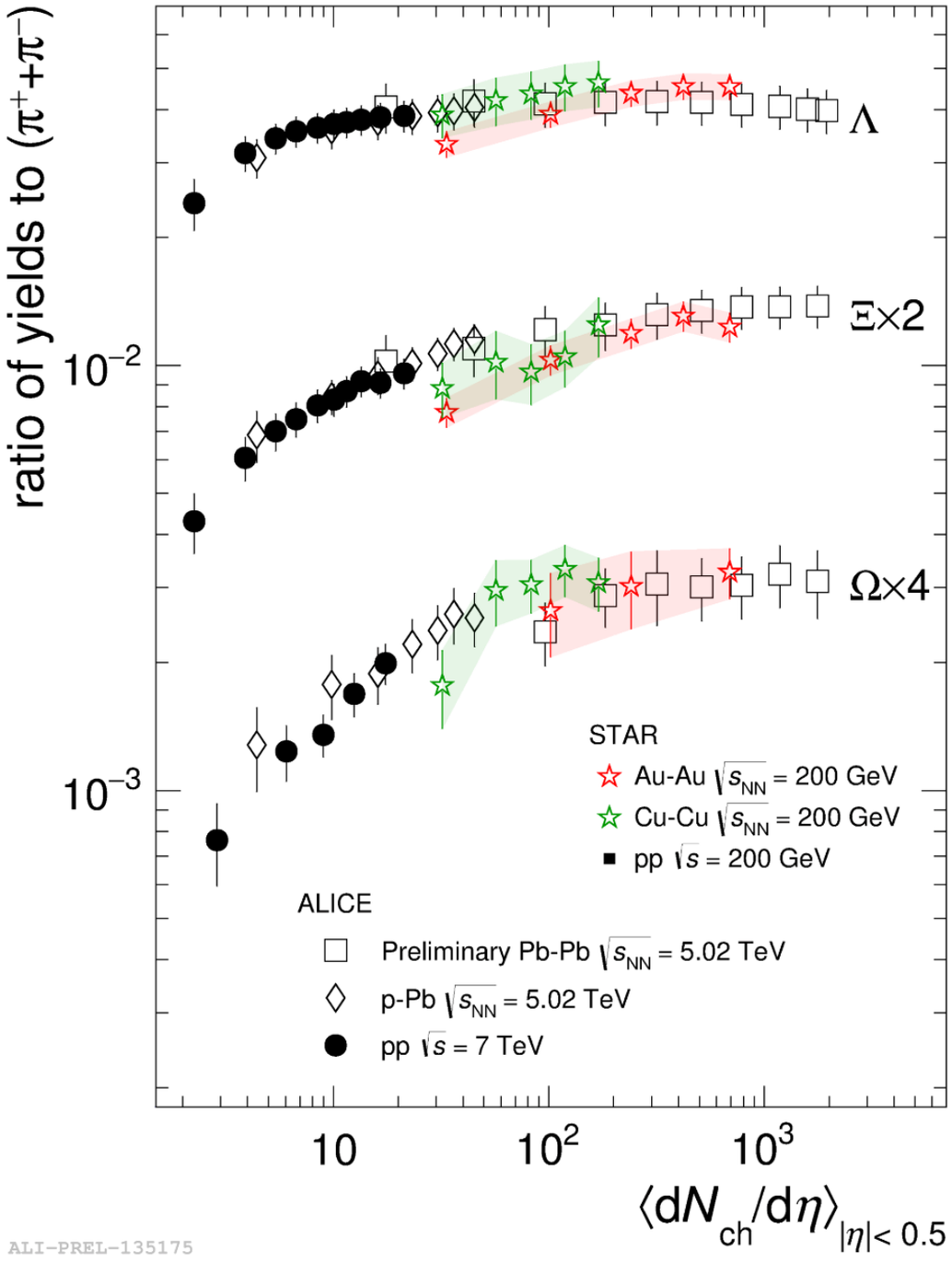
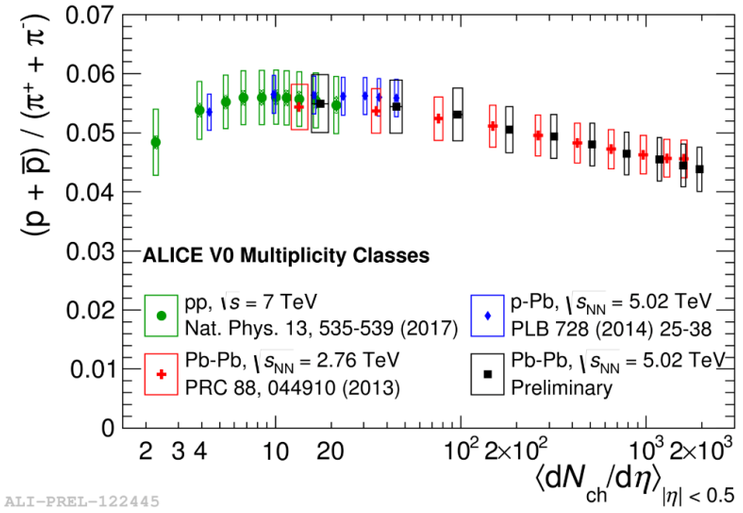
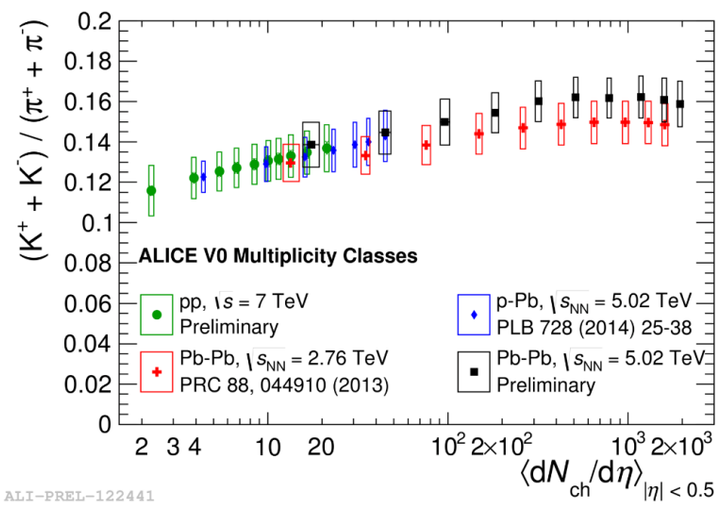


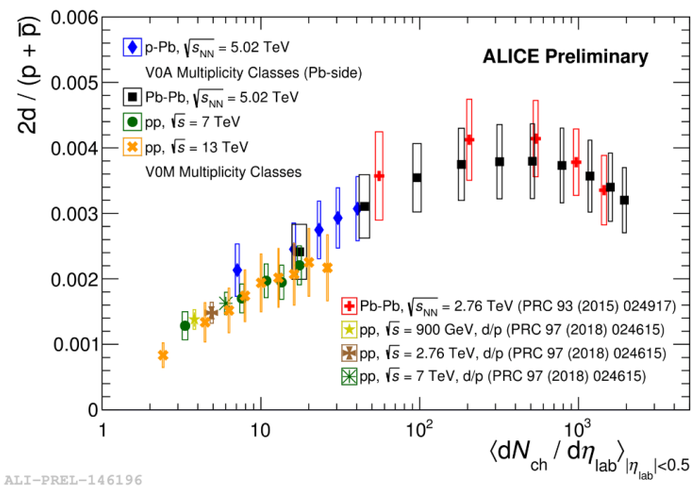
ALI-PREL-111229

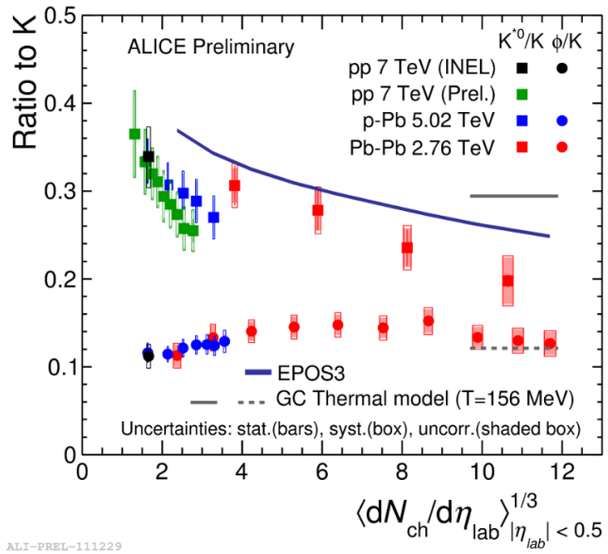
Even also for RHIC data!









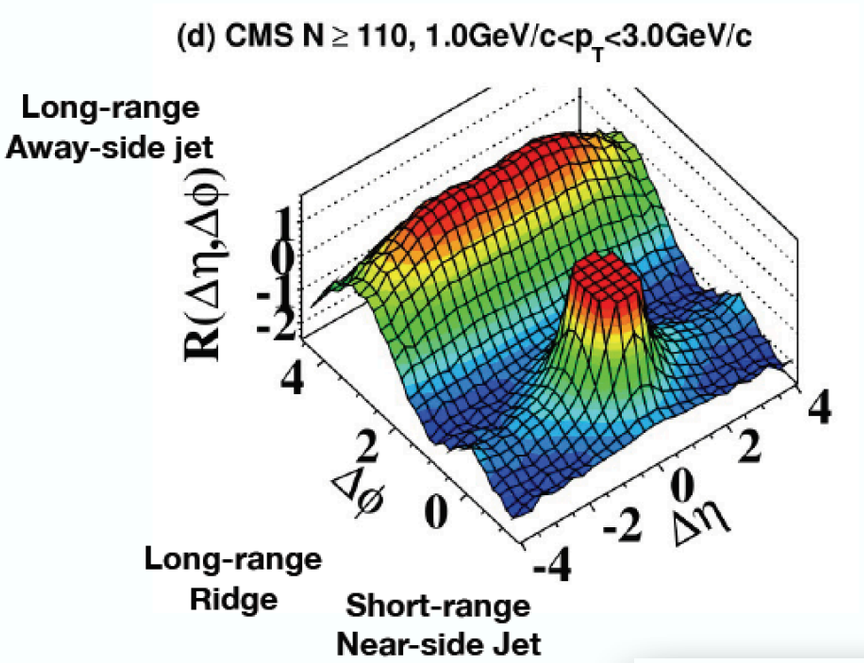


Even also for RHIC data!

Even for all LFs, not only for Strangeness

Ridge in High Multiplicity pp

CMS, JHEP 09 (2010) 091



Collectivity in small systems

~ year 2005: sQGP signature
~ year 2010: sQGP in pp as well?

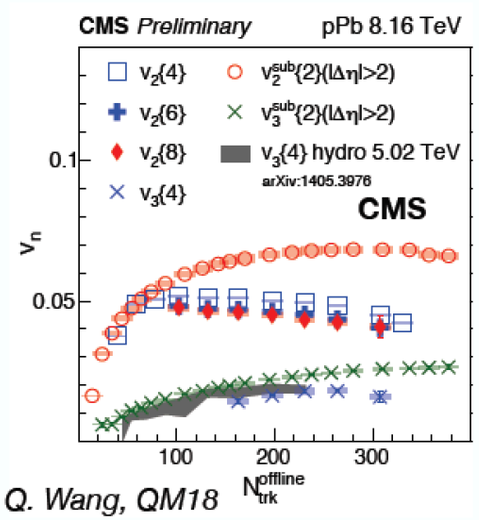
ridge includes v_2 + higher orders

Li Yi's talk at QM2018

Bounty Evidence of Collectivity at LHC

Selected few QM results

Multi-particle v_n

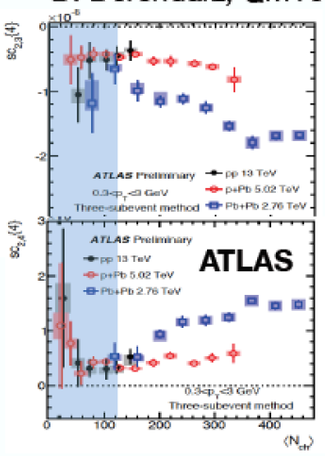


Q. Wang, QM18

$v_3\{4\}\neq 0$

Sub-event cumulants

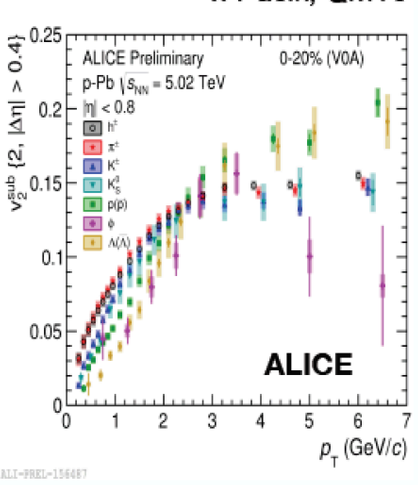
D. Derendarz, QM18



Overlap multiplicity range: system independent

PID v_2

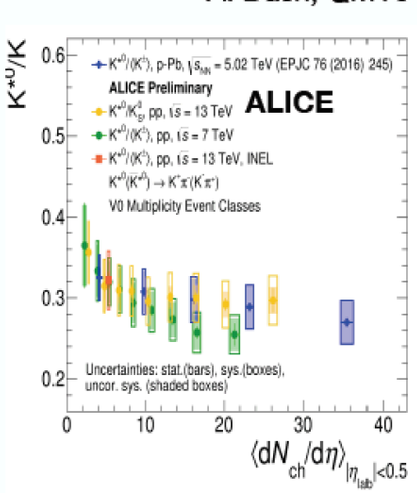
V. Pacík, QM18



Mass ordering

Resonance

A. Dash, QM18

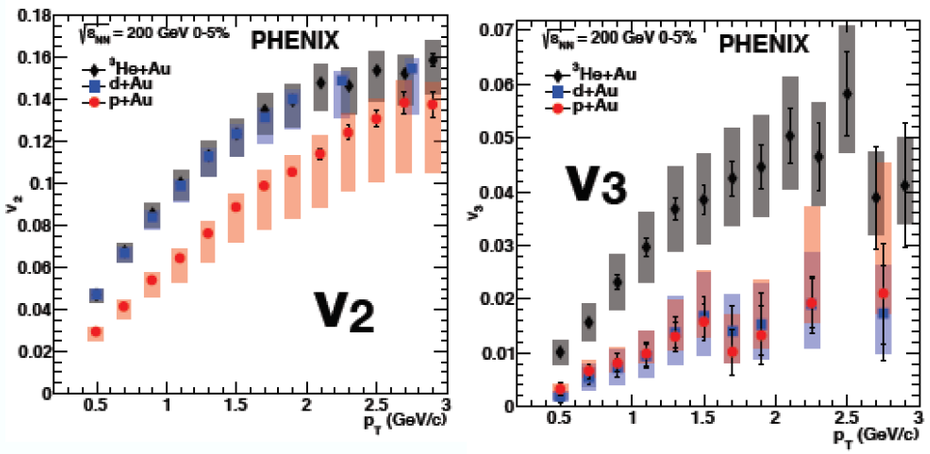


Re-scattering

Evidences of Collectivity at RHIC

Selected few QM results

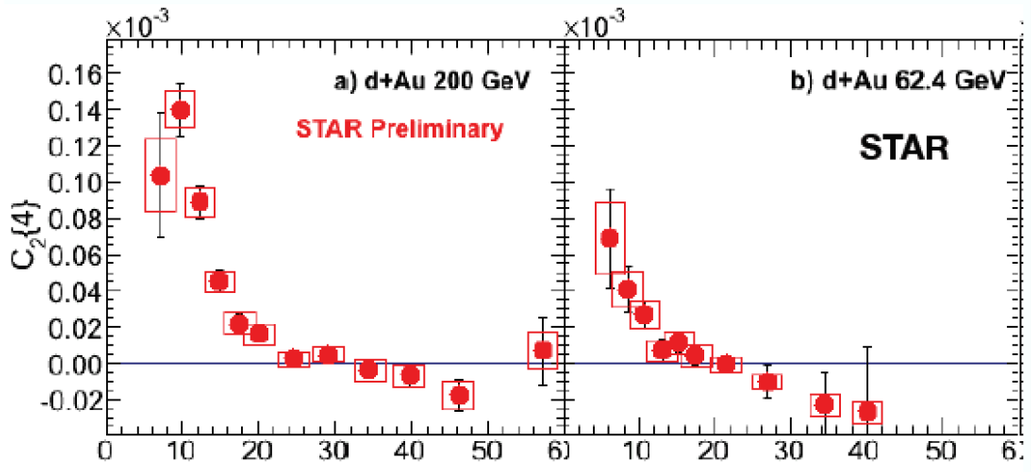
System shape scan



S. Morrow, QM18

v_n ordering, sensitive to initial geometry
Small QGP droplet?

4-particle cumulants



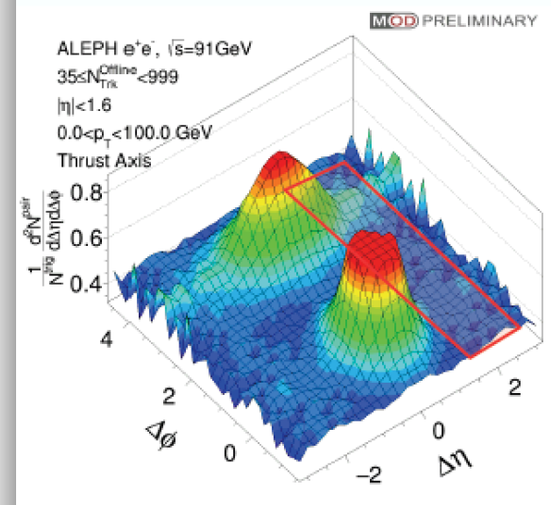
S. Huang, QM18

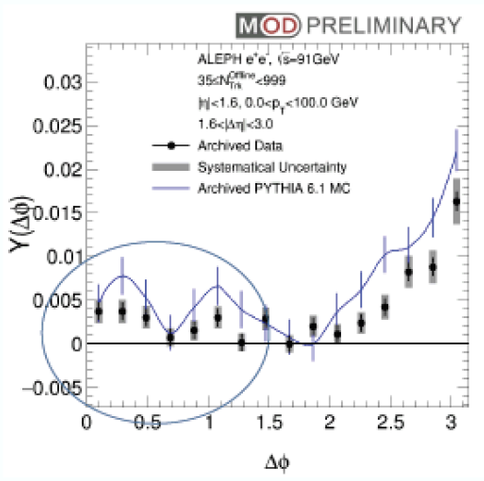
Negative $c_2\{4\}$

Even Smaller System

e^+e^-

Y. Lee, QM18





Long-range correlation in e^+e^-

PYTHIA seems to be able to describe it

Where does Collectivity Come from?

Next talk! M.Strickland

Hydro High density system evolution

Smallest QGP droplet?

Initial spatial anisotropy, driven by pressure gradient

Low density AMPT, "escape model"; Kinetic transport; ..

L. He, et al, PLB 753, 506
A, Kurkela, QM18
…

Initial spatial anisotropy

CGC Initial momentum anisotropy

C. Bierlich, QM18
B. Blok, QM18
…

MPI + CR, ..

How can we distinguish the models?

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- **How can we be sure for QGP?**
- **Why no quenching? Not observed, yet?**

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- collectivity of matter
- But NOT equillibriated
- How to confirm? E-by-E multiplicity fluctuation must be able to be explained by Poisson with just One parameter
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- SJeon: ChWPark - looked at a quenching effect with putting 'hot' qgp droplets produced in Hi-Mul pp (also M.Strickland)
- Important is T_init produced in the collision
- Stat. Model fit for pp? Any T-chem?
- Low pT

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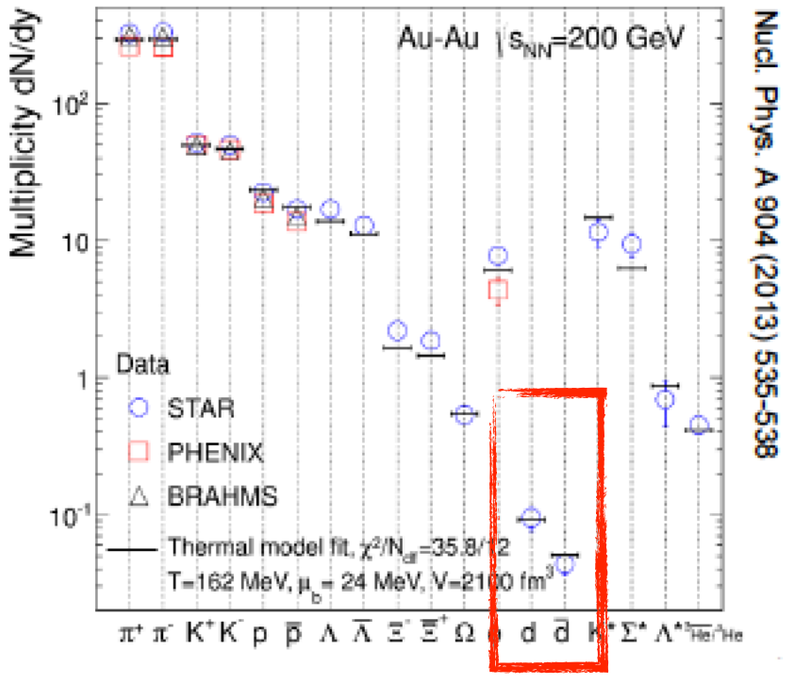
Always-on-switch

Yesterday is history, tomorrow is mystery and today is a present

Yesterday's mystery



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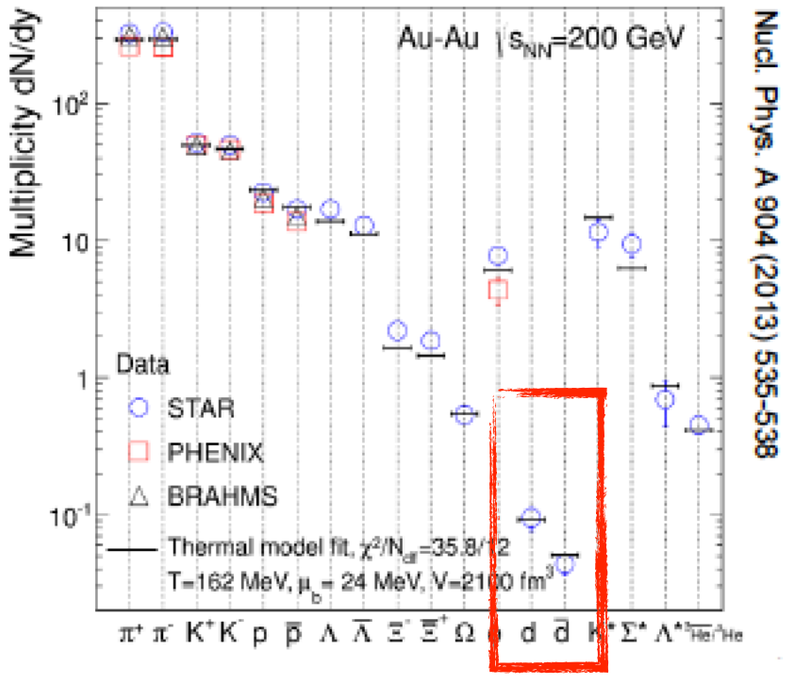
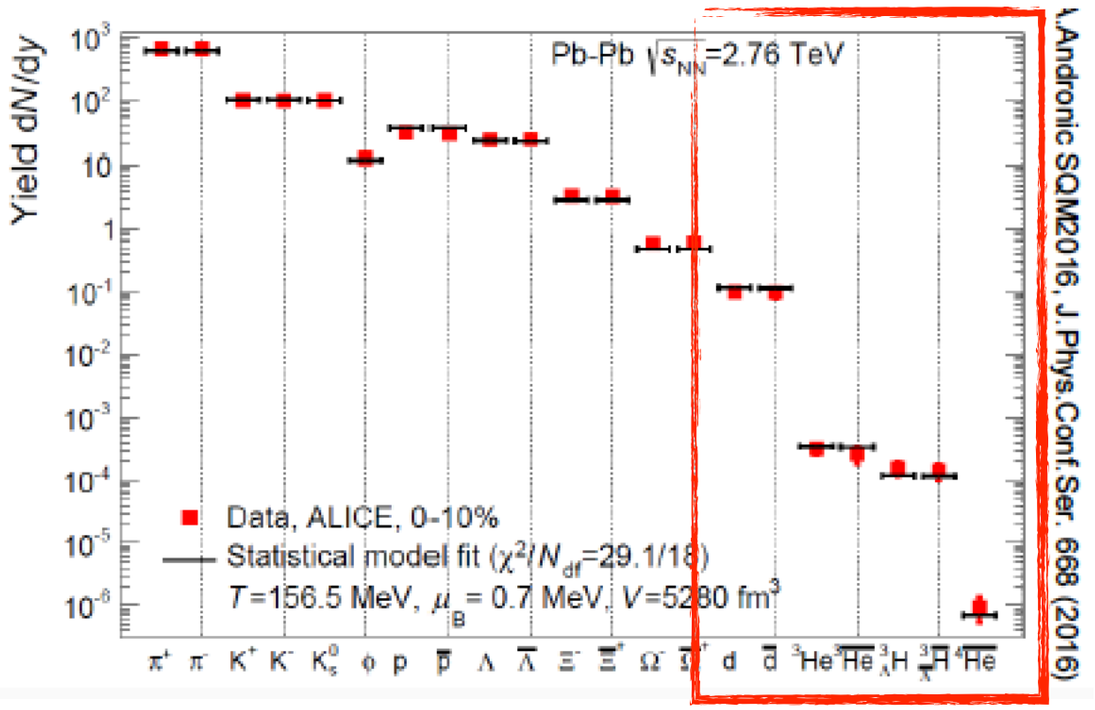


today's mystery, as well!



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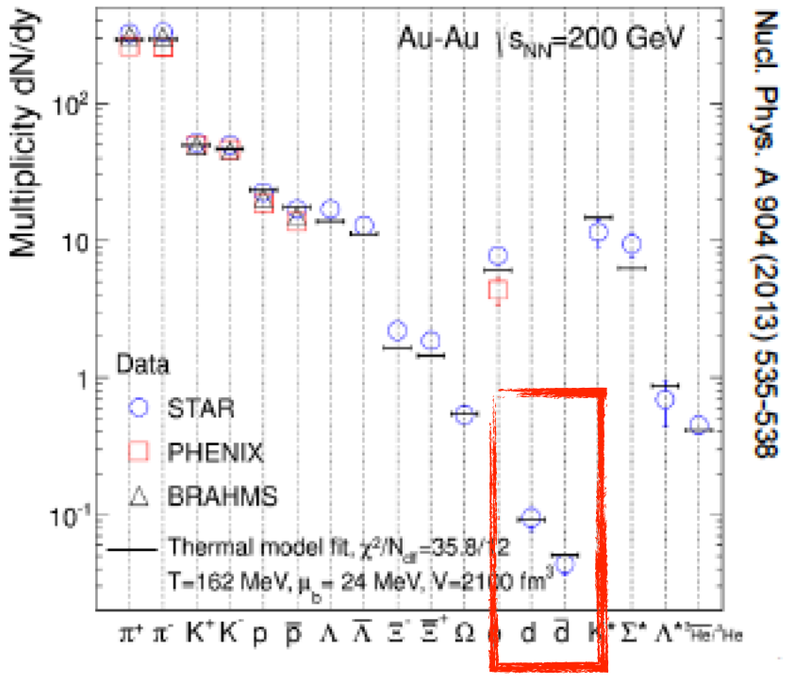

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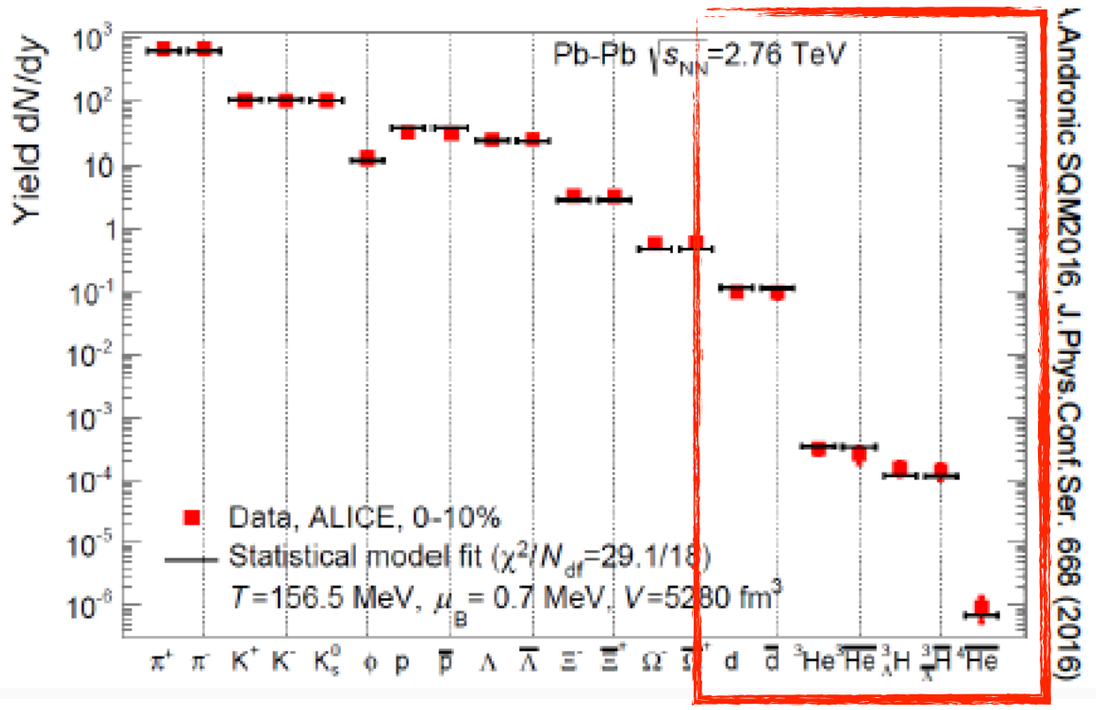
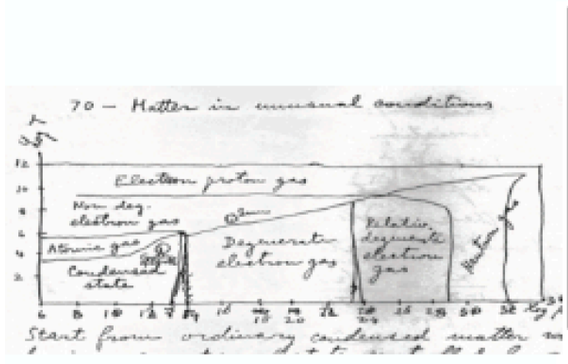
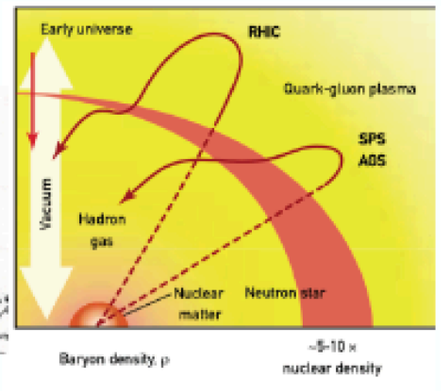
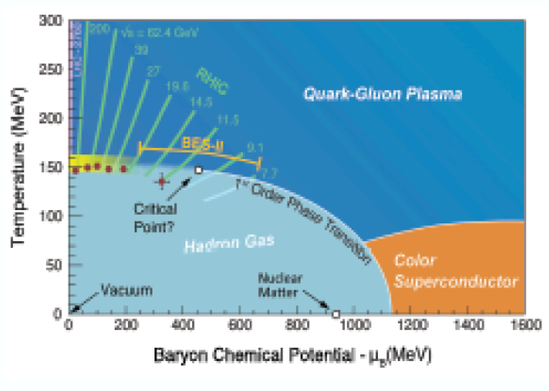




Fermi (1952)



2002



2015

EIC
sPHENIX
FCC
?

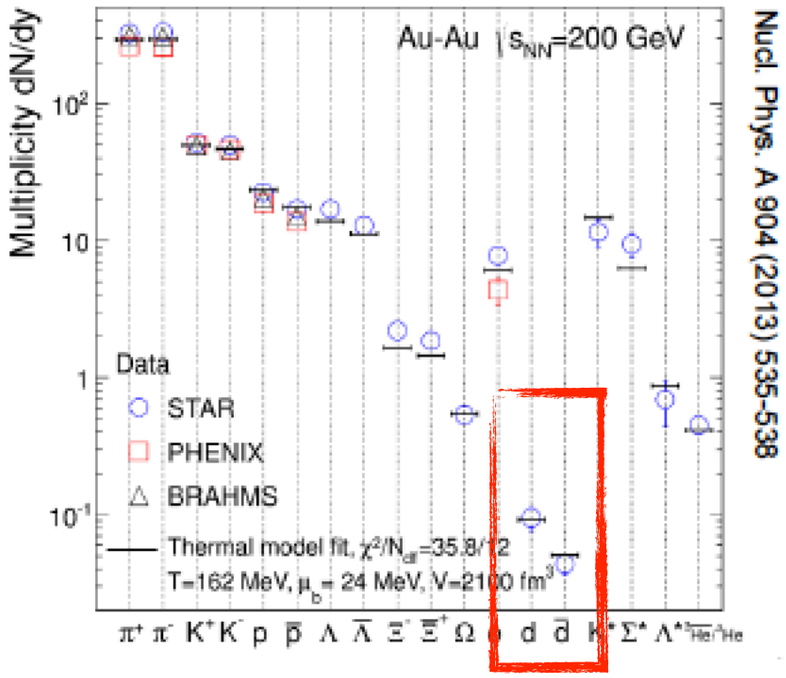
2020+

RHIC starts running

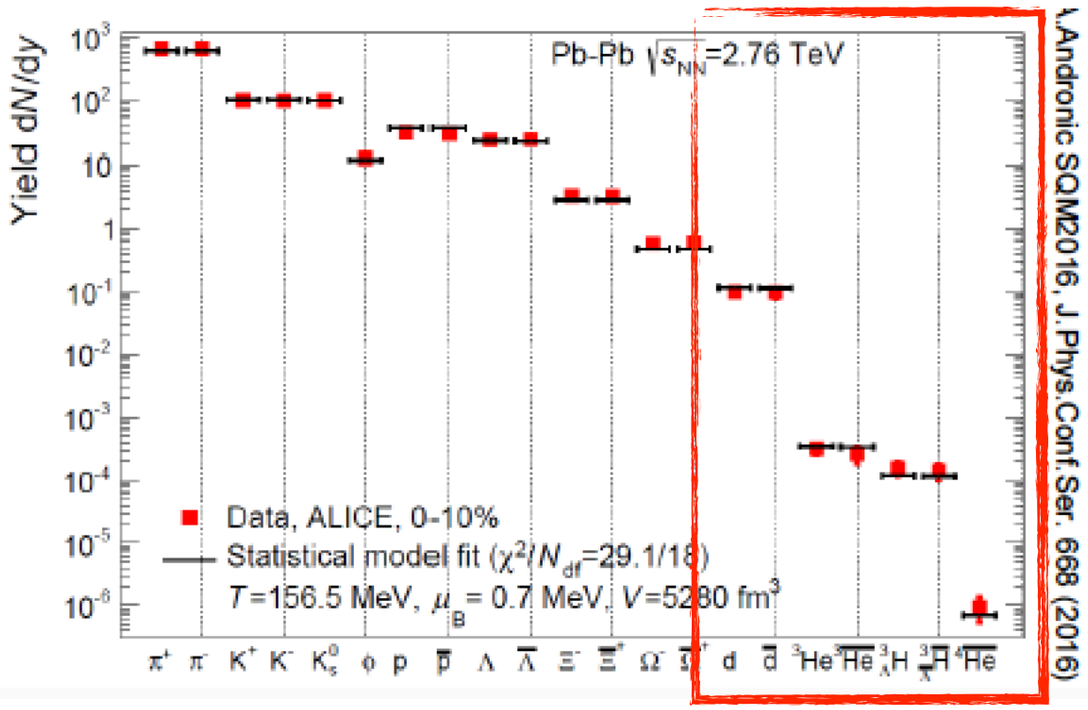
BESII

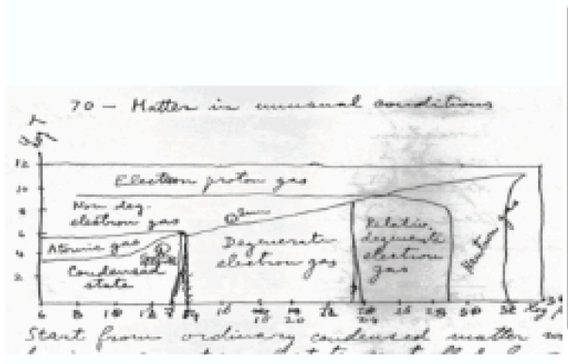
Yesterday is history, tomorrow is mystery and today is a present

Yesterday's mystery



today's mystery, as well!





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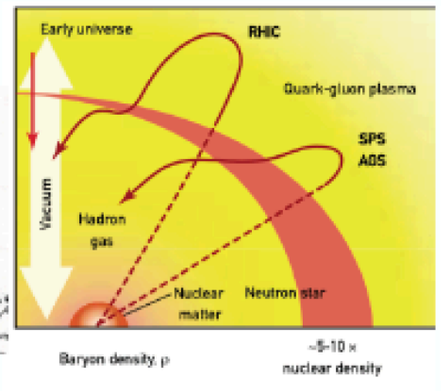

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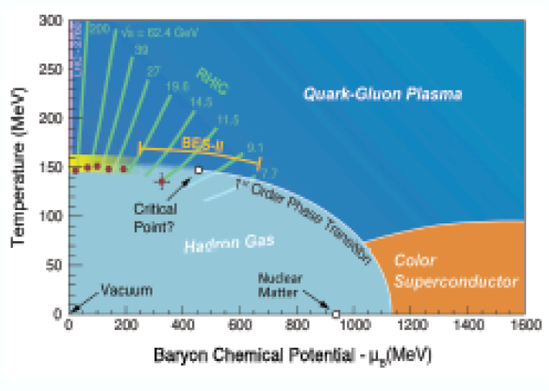

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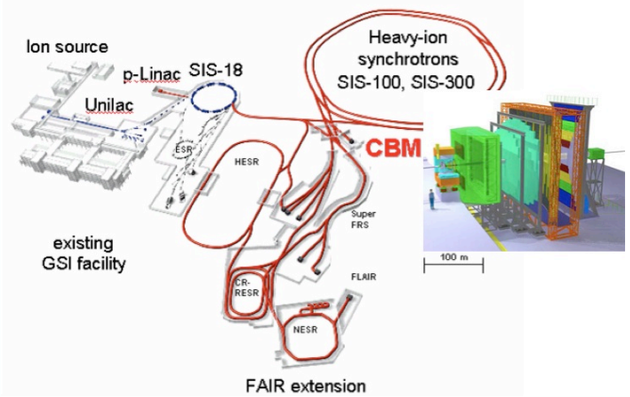

RHIC starts running

BESII

The Compressed Baryonic Matter experiment