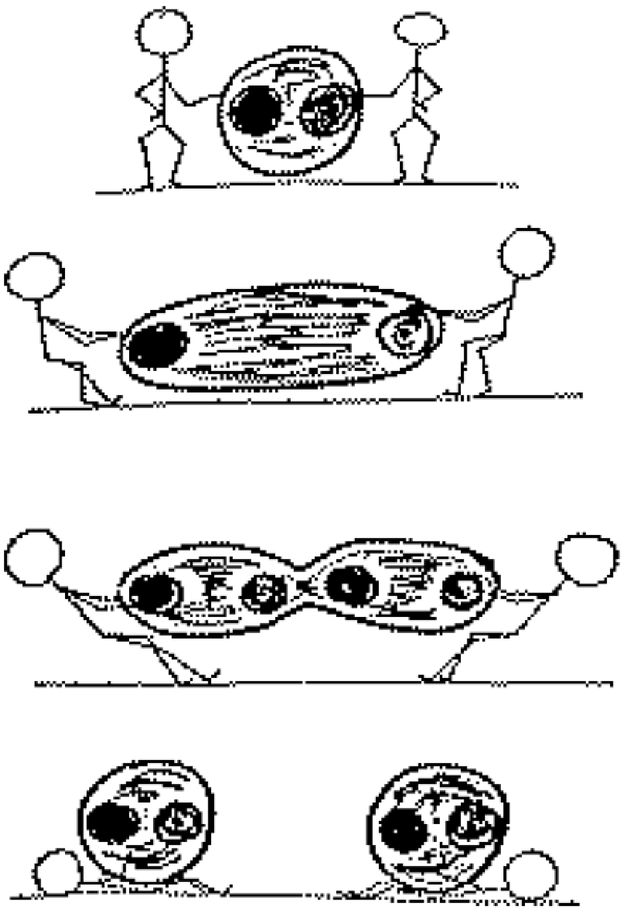


# Light flavors

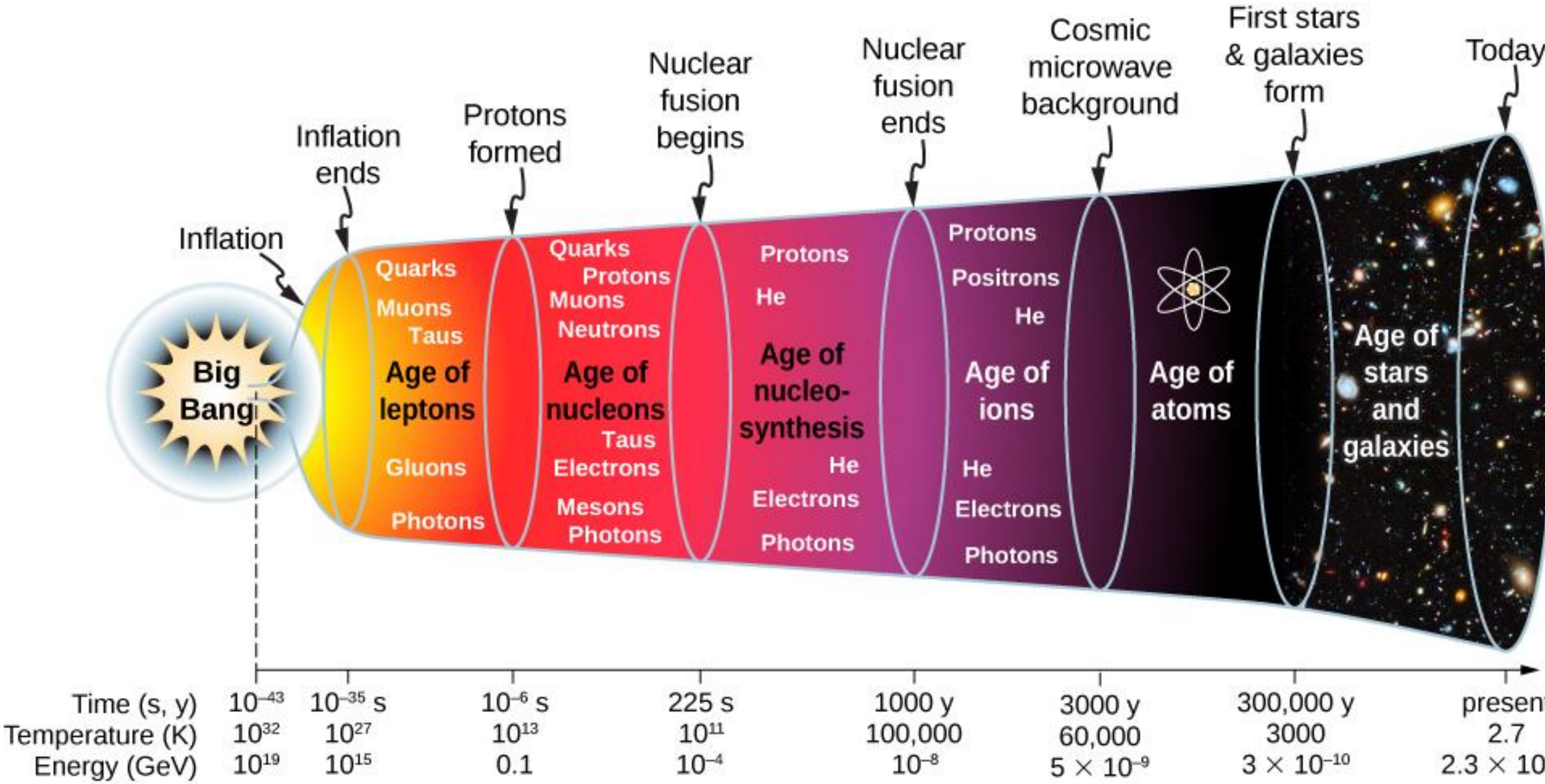
September 25$^{th}$, 2018.

Silvia Pisano

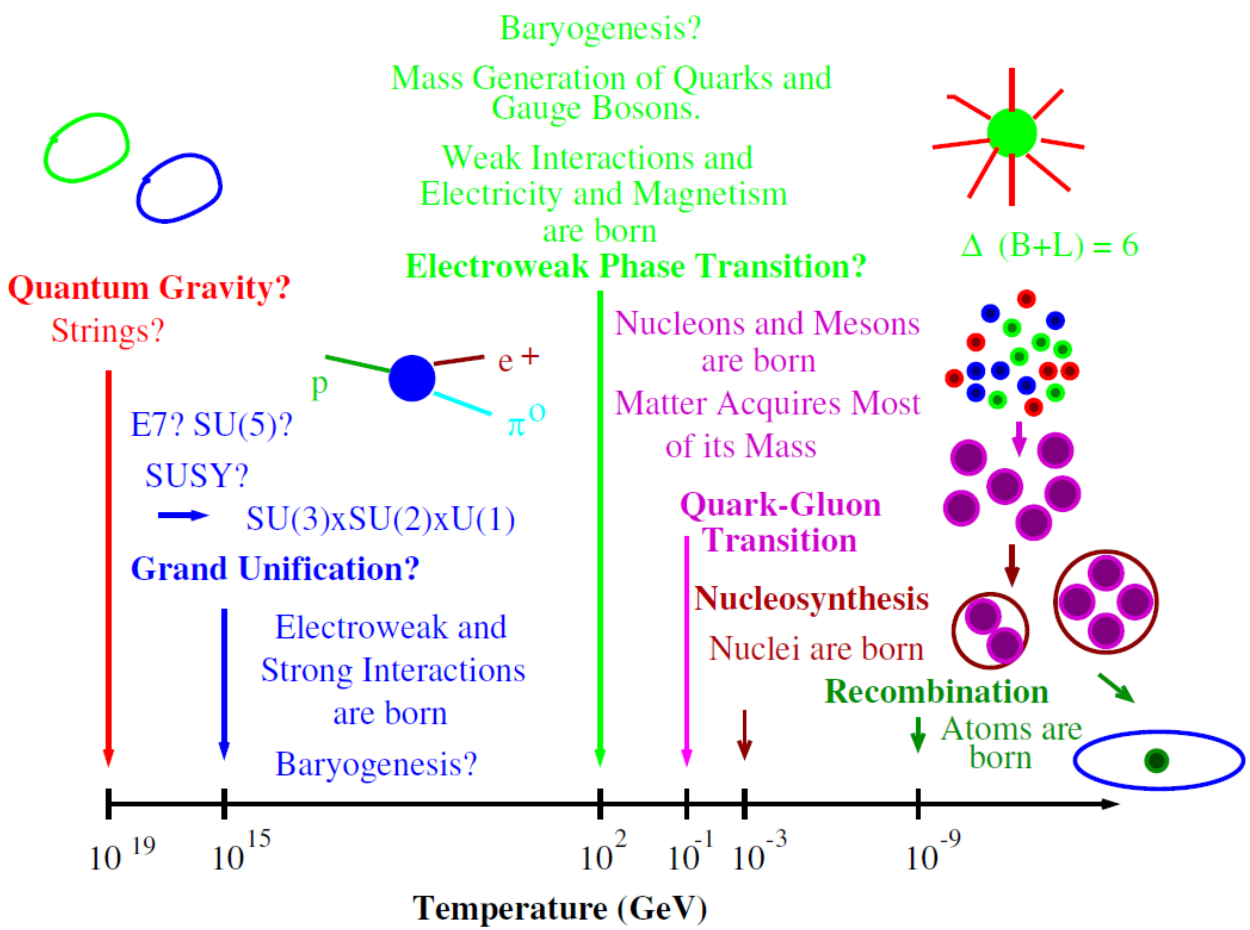
Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

Laboratori Nazionali di Frascati - INFN

# Universe «phase diagram»



# Universe «phase diagram»



# QCD phase diagram



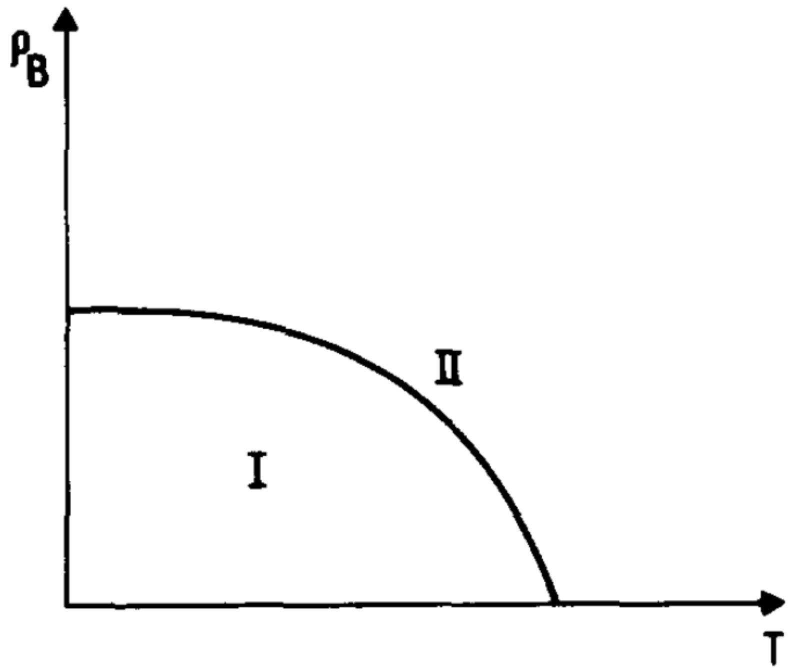
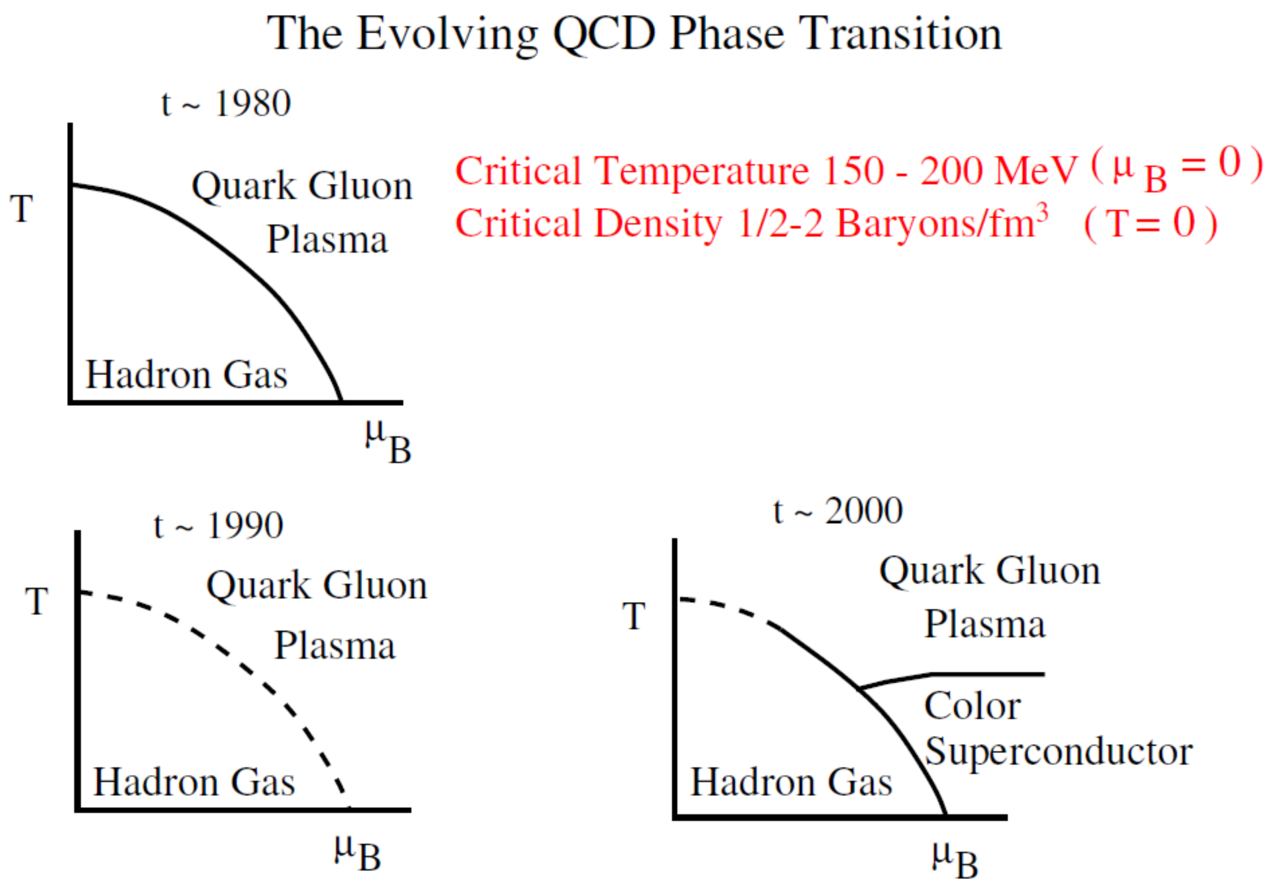



Fig. 1. Schematic phase diagram of hadronic matter. $\rho_B$ is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Cabibbo Parisi, Physics Letters 59B (1975) 67

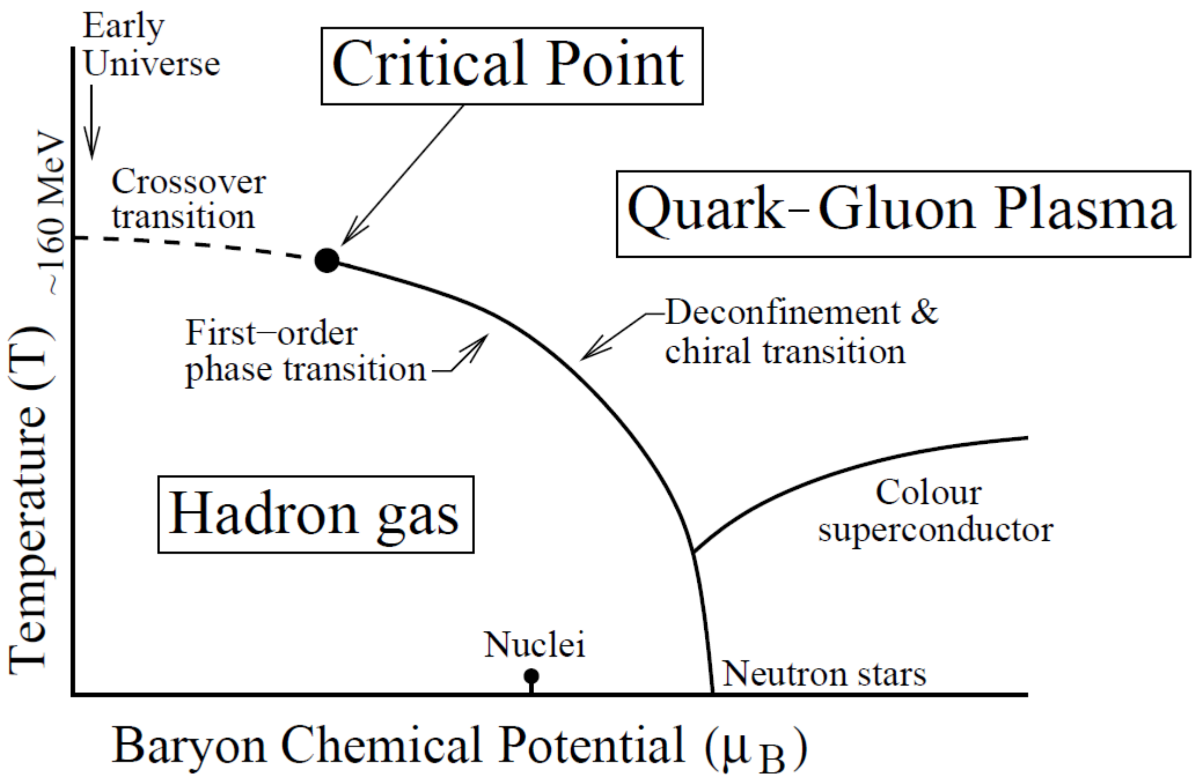
# QCD phase diagram




10.5170/CERN-2007-005.75

# QCD phase diagram

To be mapped out QUANTITATIVELY




https://arxiv.org/abs/1404.3294

# Quark-gluon plasma (QGP)

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

It is only a **transient state:**

$$\tau \sim 10^{-23} s$$

No quarks or gluons will be released!

→ no external probe can be used. A hard parton produced internally is used.

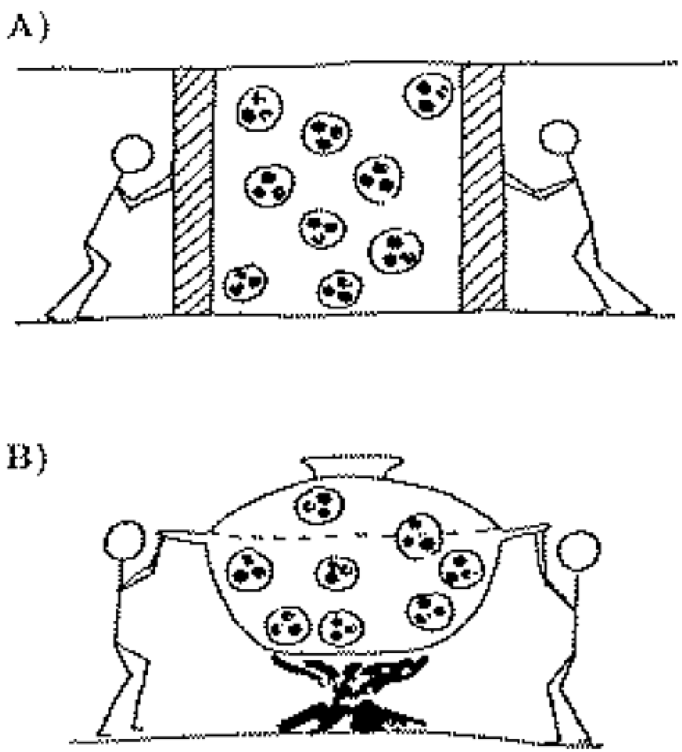
The bulk of the particles emerging from a nuclear collision are hadrons with transverse momenta of order ~ 1 GeV.

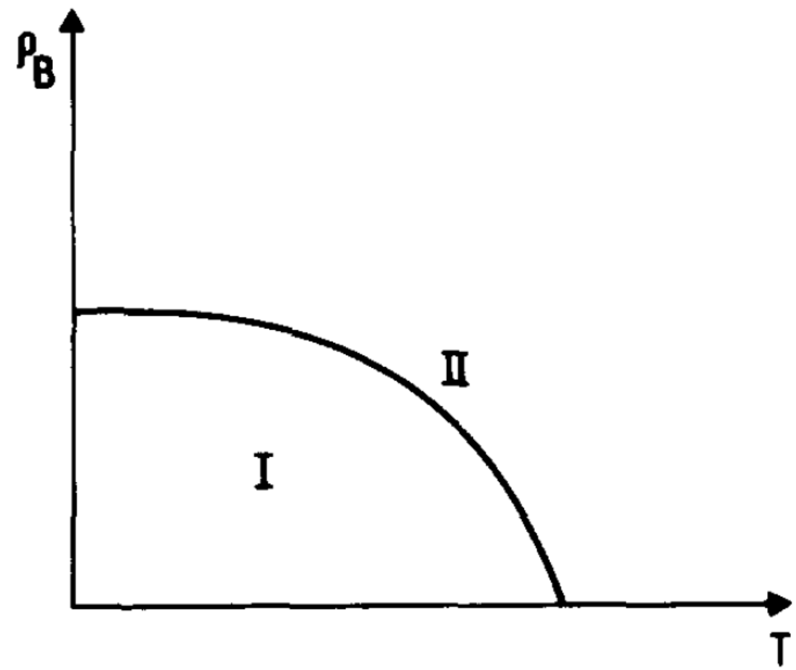
**Has QGP actually been produced?**

CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

# Two recipes for preparing dense hadronic matter

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



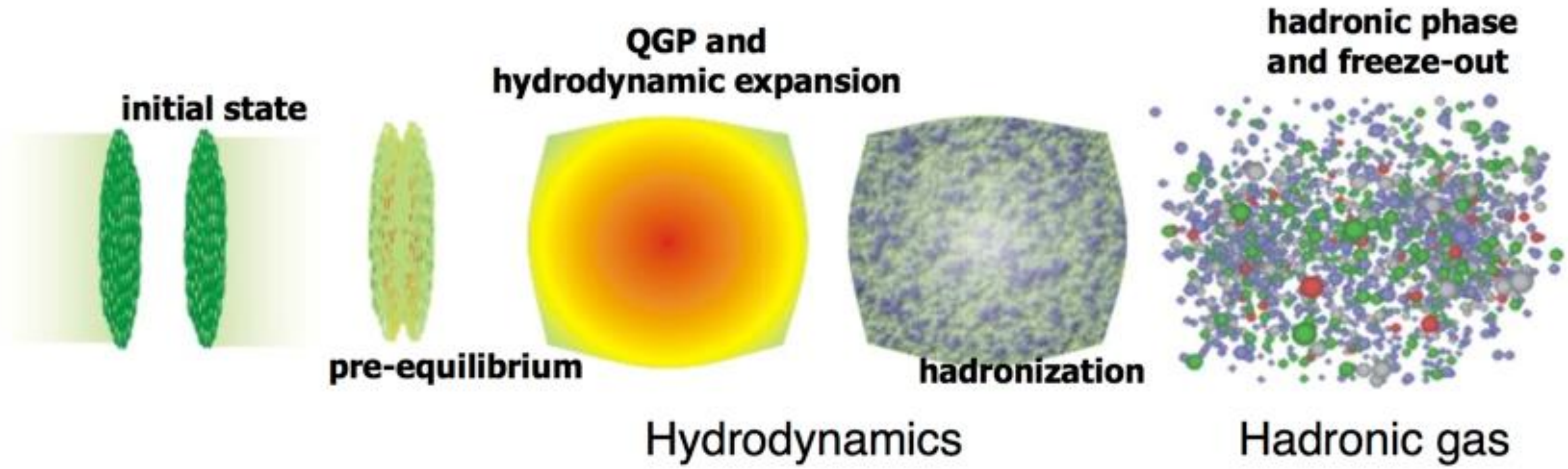




Acta Phys.Polon.B29:3711,1998
https://arxiv.org/abs/nucl-th/9905005

CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

# Relativistic Heavy-Ion Collisions

Relevant parameter is the **energy-per-nucleon**




- String decays
- Parton cascade models
- Color-glass condensate

$\tau_{therm}$?

Non-equilibrium phase: relativistic kinetic theory

At equilibrium: relativistic perfect fluid dynamics → EoS from LQCD

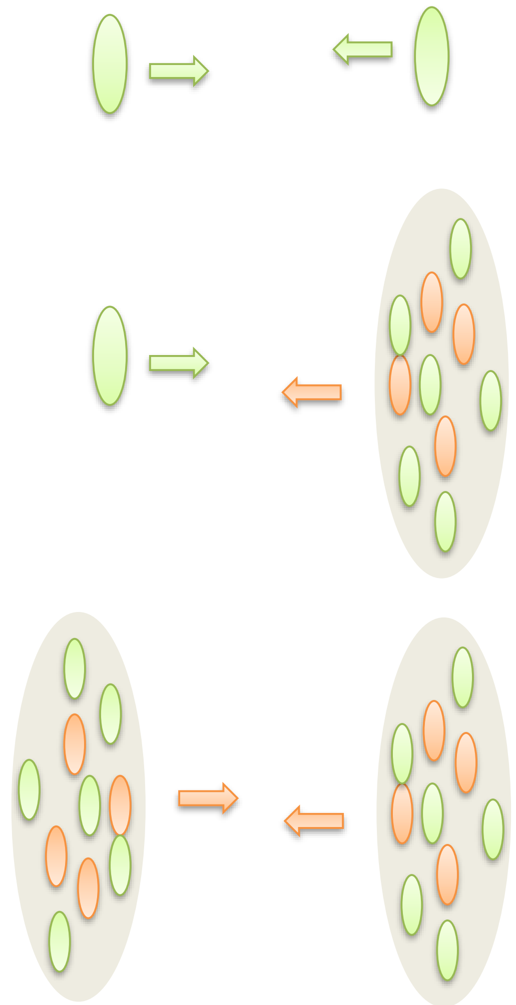
# Colliding systems

- $pp \rightarrow$ non-perturbative (low-$Q^2$) and perturbative QCD (high-$Q^2$); parton fragmentation in the *vacuum.* Reference system for other colliding systems.

- $pPb \rightarrow$ cold nuclear matter effects – might influence the particle production at low and high $p_T$; search for collective phenomena or final state effects

- $PbPb \rightarrow$ characterize the Quark-Gluon Plasma.

  Low-$p_T$: collective flow
  Intermediate-$p_T$: quark recombination (coalencence)
  High-$p_T$: jet quenching and parton fragmentation in a hot and dense medium

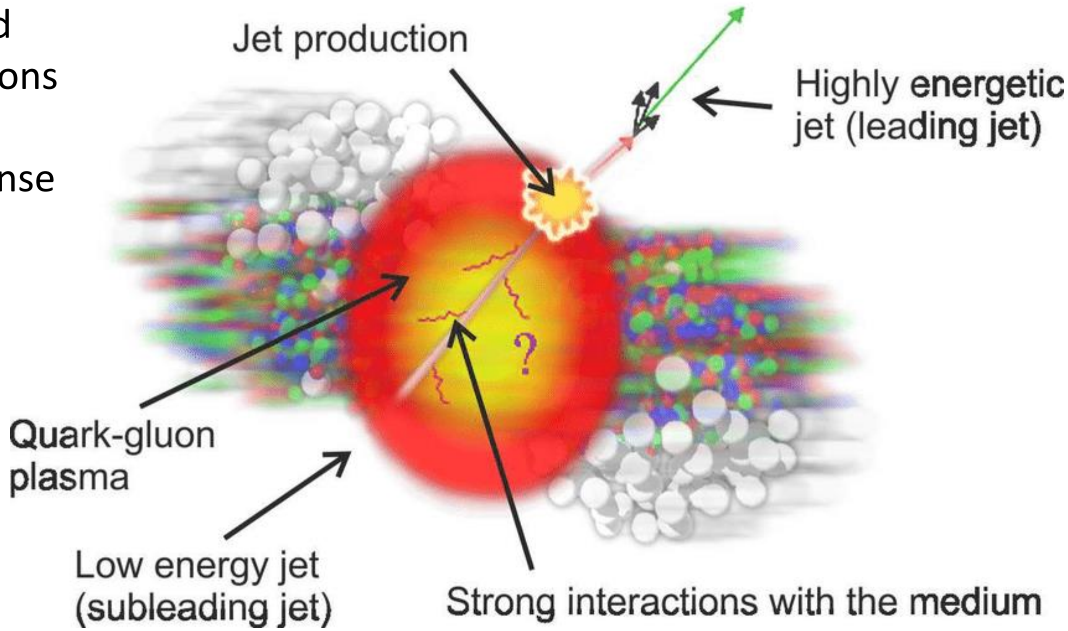


# Observables based on Light Flavors

Nuclear modification factor

- QGP can be characterized by the measurement of high-$p_T$ particles produced by the hadronization of hard scattered partons in the early stage of the collsions
- Partons lose energy in the hot and dense QCD matter
- **→ suppression of high-$p_T$ particles**

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}N^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}}\rangle \mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$




$\langle T_{AA}\rangle$ from Phys. Rev. C 97, 054910 (2018)

# $PbPb$ spectra@Alice

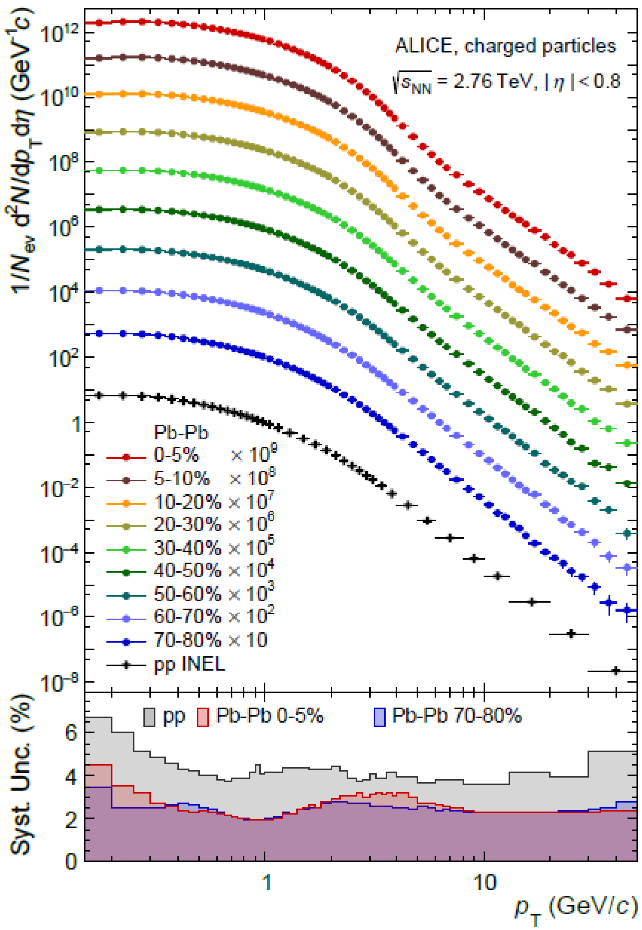
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

$p_T$ shape varies with centrality $c$

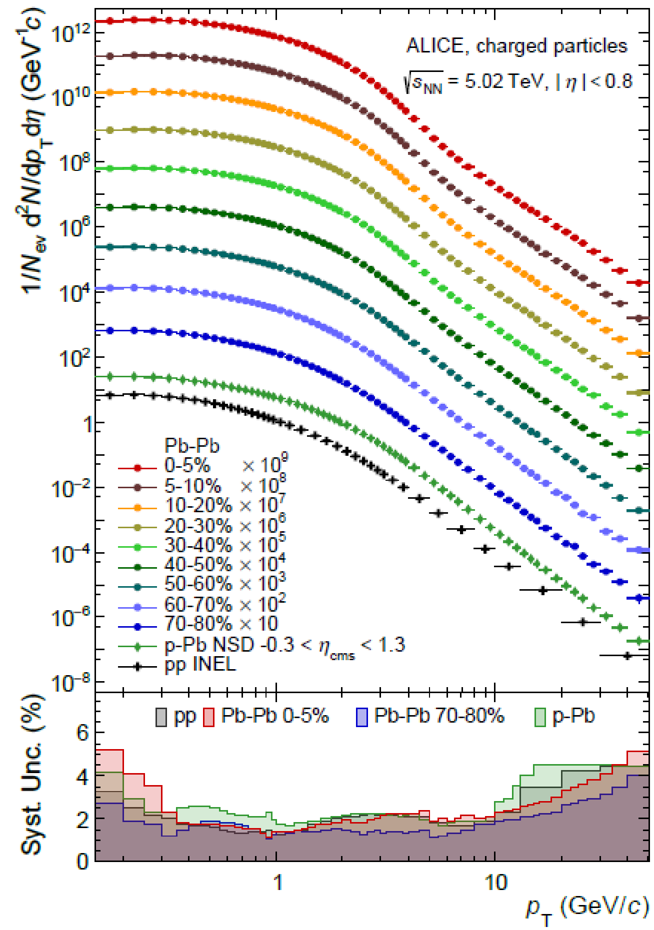
→ peripheral collisions closer to $pp$, $pPb$ shape

With increasing $c$, depletion in $PbPb$ for $p_T > 5$ GeV/c

$\sqrt{s_{NN}} = 2.76$ TeV




$\sqrt{s_{NN}} = 5.02$ TeV




Centro Fermi
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

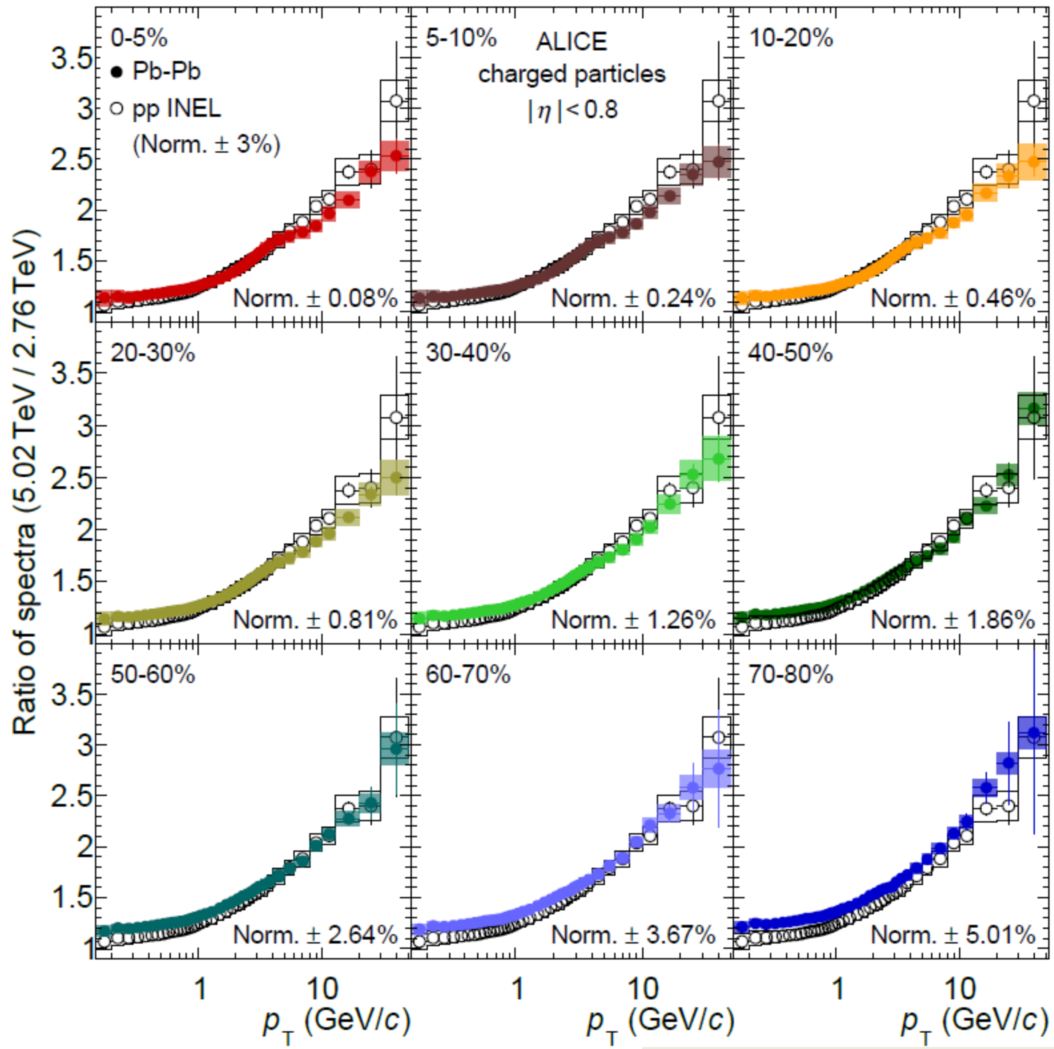


https://arxiv.org/abs/1802.09145

# Ratios at different energies

$$\frac{\sqrt{S_{NN}} = 5.02\ TeV}{\sqrt{S_{NN}} = 2.76\ TeV}$$

- 0-5% $\times 10^9$
- 5-10% $\times 10^8$
- 10-20% $\times 10^7$
- 20-30% $\times 10^6$
- 30-40% $\times 10^5$
- 40-50% $\times 10^4$
- 50-60% $\times 10^3$
- 60-70% $\times 10^2$
- 70-80% $\times 10$




Centro Fermi – Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati



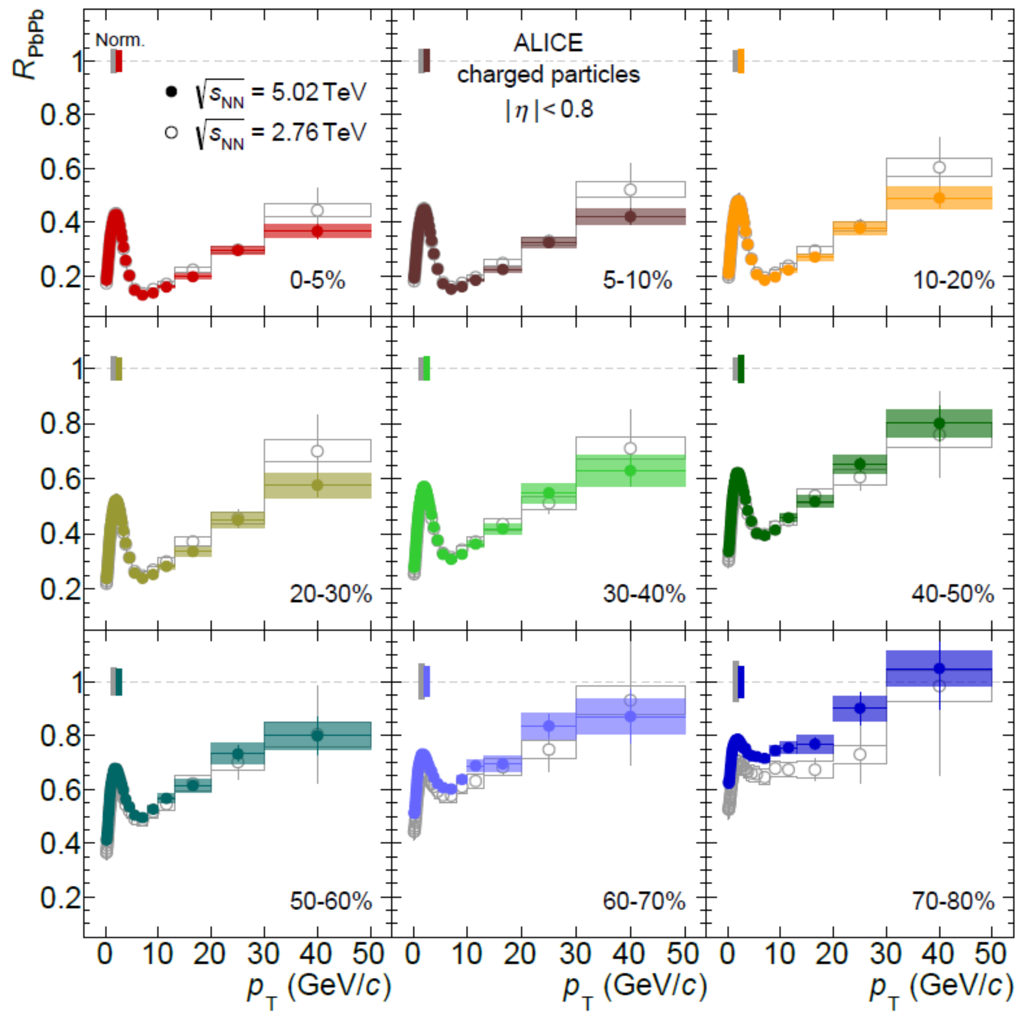
https://arxiv.org/abs/1802.09145

# Quantifying *in-medium* modifications: nuclear modification factors

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}N^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}}\rangle \mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- $\langle N_{Coll}\rangle \rightarrow$ average number of nucleon-nucleon collisions for a given centrality interval

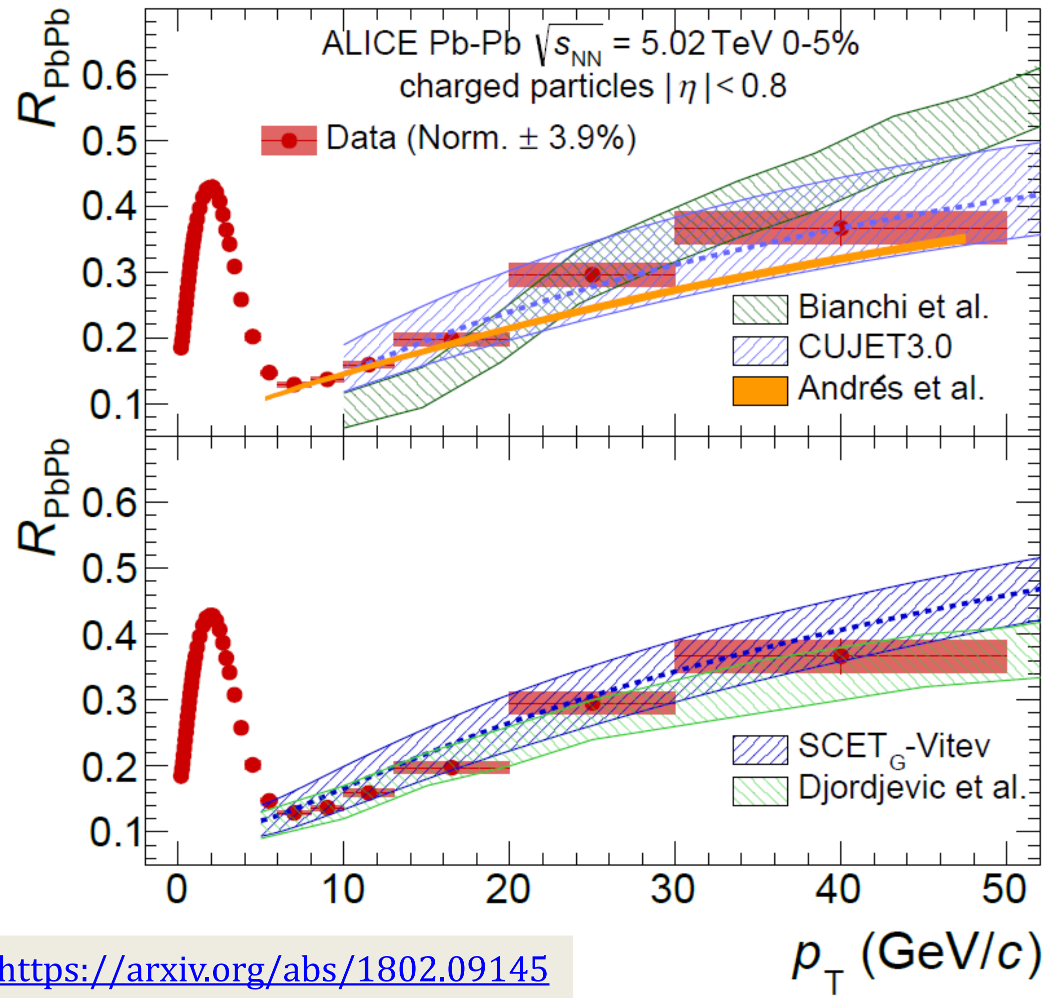
Less suppression for peripheral collisions



# Quantifying *in-medium* modifications: nuclear modification factors

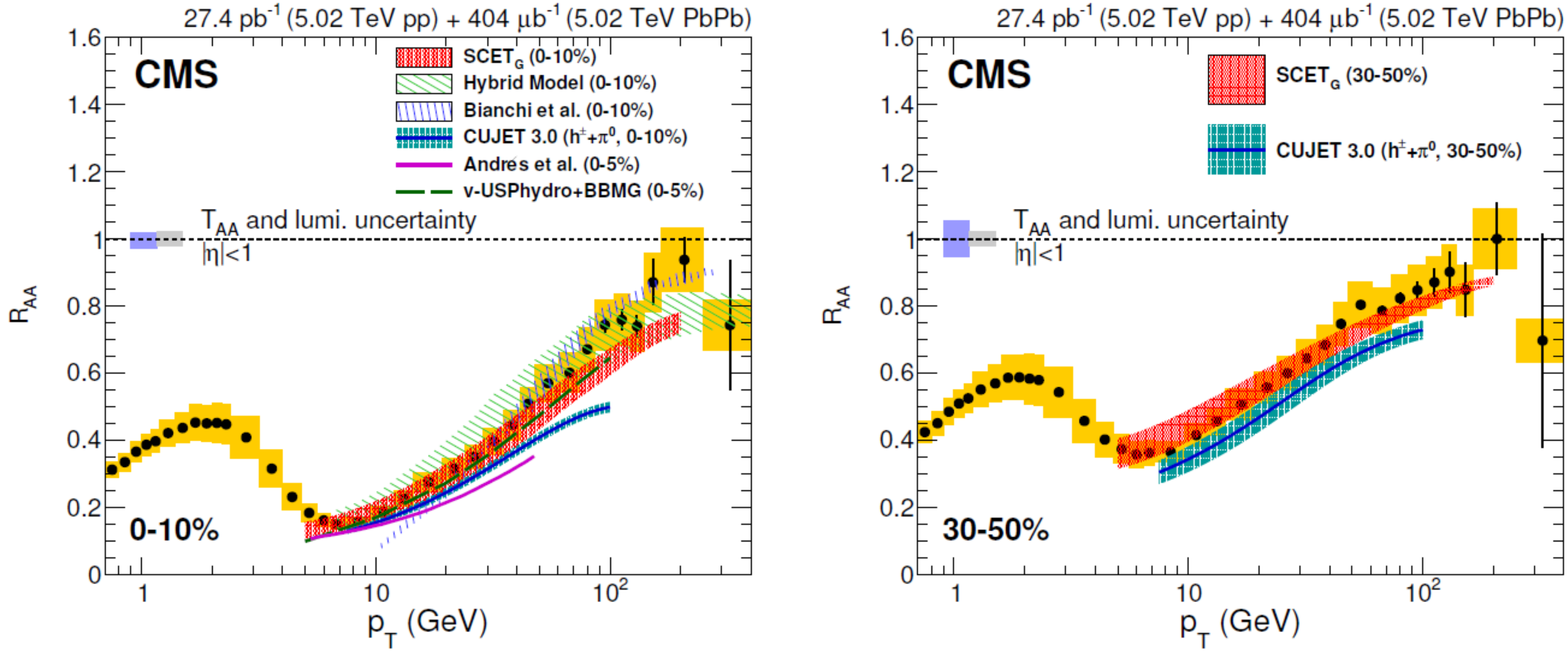
$SCET_G$ → extended soft-collinear effective theory for inclusive particle production and suppression in QGP: $pQCD$-based hard cross-sections and QGP medium evolved FF + CNM effects

Bianchi *et al.* → pQCD + hydrodynamical expansion, trasport coefficient



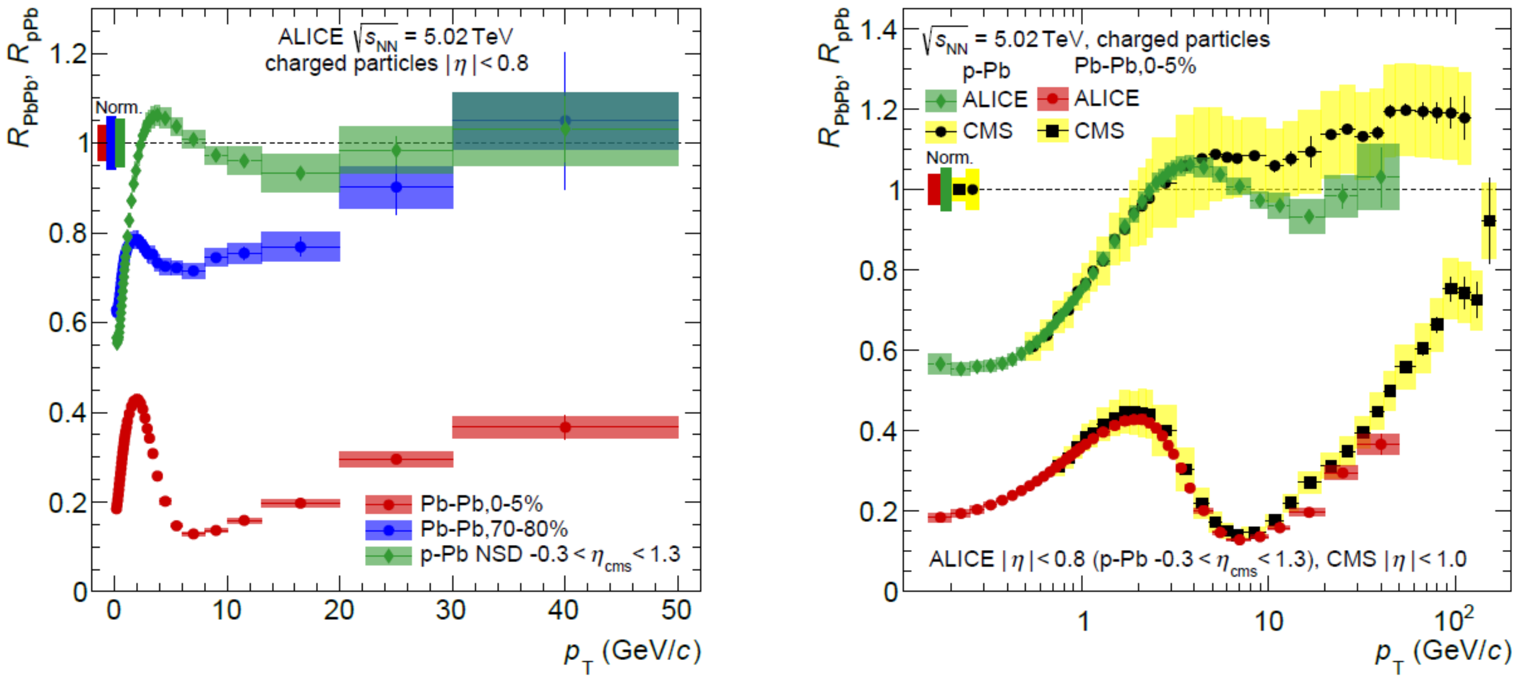

https://arxiv.org/abs/1802.09145

# $PbPb\ R_{AA}$@CMS




JHEP 04 (2017) 039

# Disentangle possible *cold-nuclear-matter* effects




$$R_{p\mathrm{Pb}}(p_T) = \frac{d^2N_{\mathrm{ch}}^{p\mathrm{Pb}}/d\eta dp_T}{\langle T_{p\mathrm{Pb}}\rangle d^2\sigma_{\mathrm{ch}}^{pp}/d\eta dp_T}$$

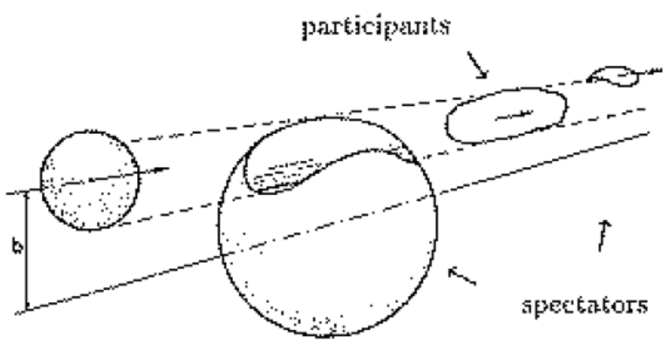
https://arxiv.org/abs/1802.09145
Physics Letters B 728 (2014) 25–38

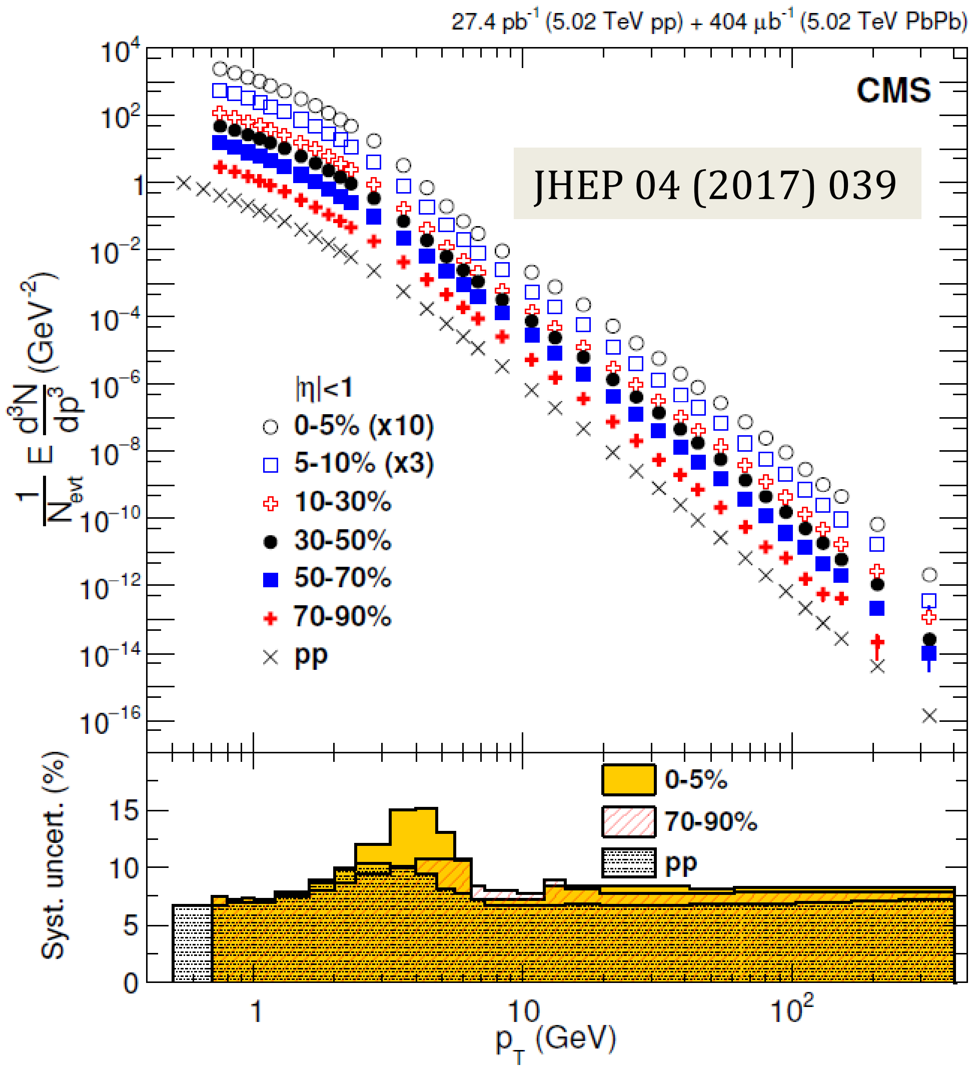
# $PbPb$ spectra@CMS

Power-low behaviour in $pp$

Different centrality classes shown for $PbPb$

$p_T$-dependent structures in $PbPb$



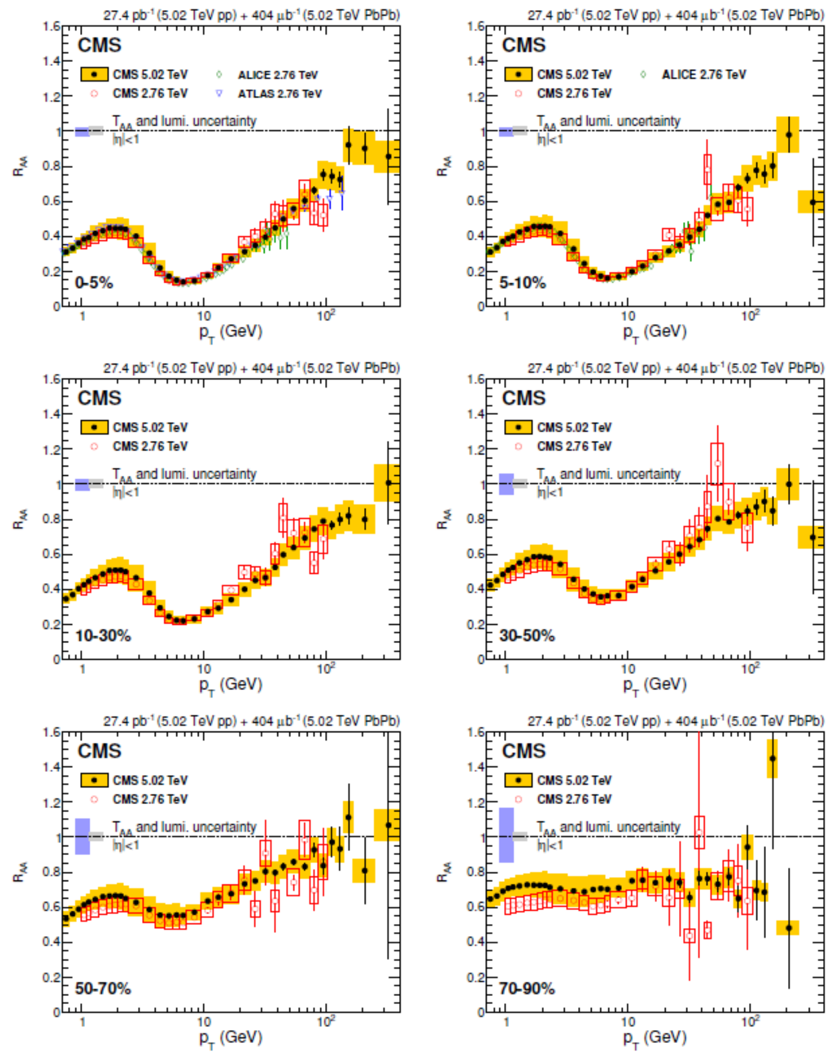



# $PbPb\ R_{AA}$@CMS

Characteristic pattern with local maxima ($p_T \sim 2$ GeV) and minima ($p_T \sim 7$ GeV)

Features stronger in central collisions → competition between nuclear parton distribution function effects, radial flow, parton energy loss, Cronin

JHEP 04 (2017) 039




Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

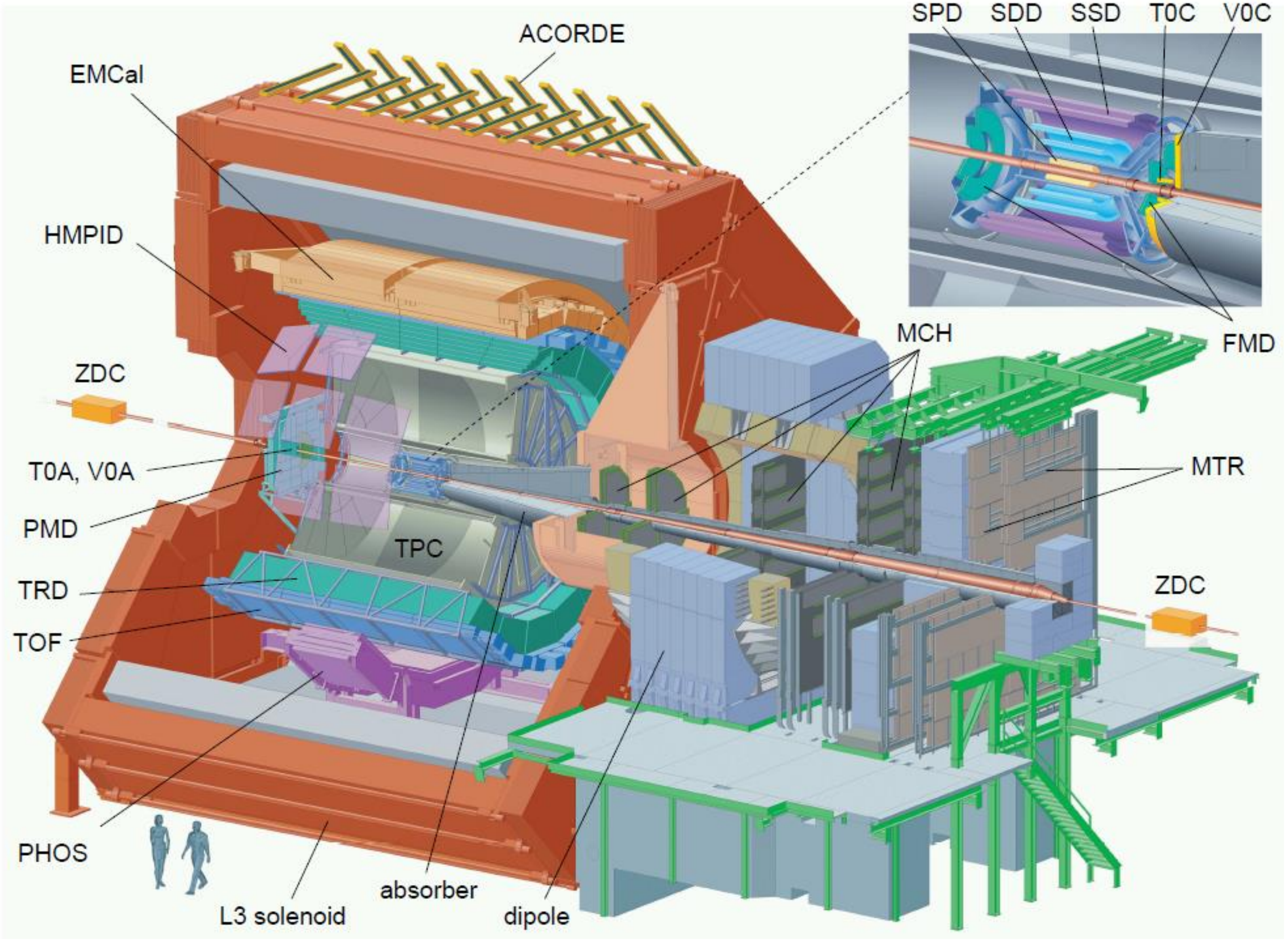
Centro Fermi
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

# Conclusions

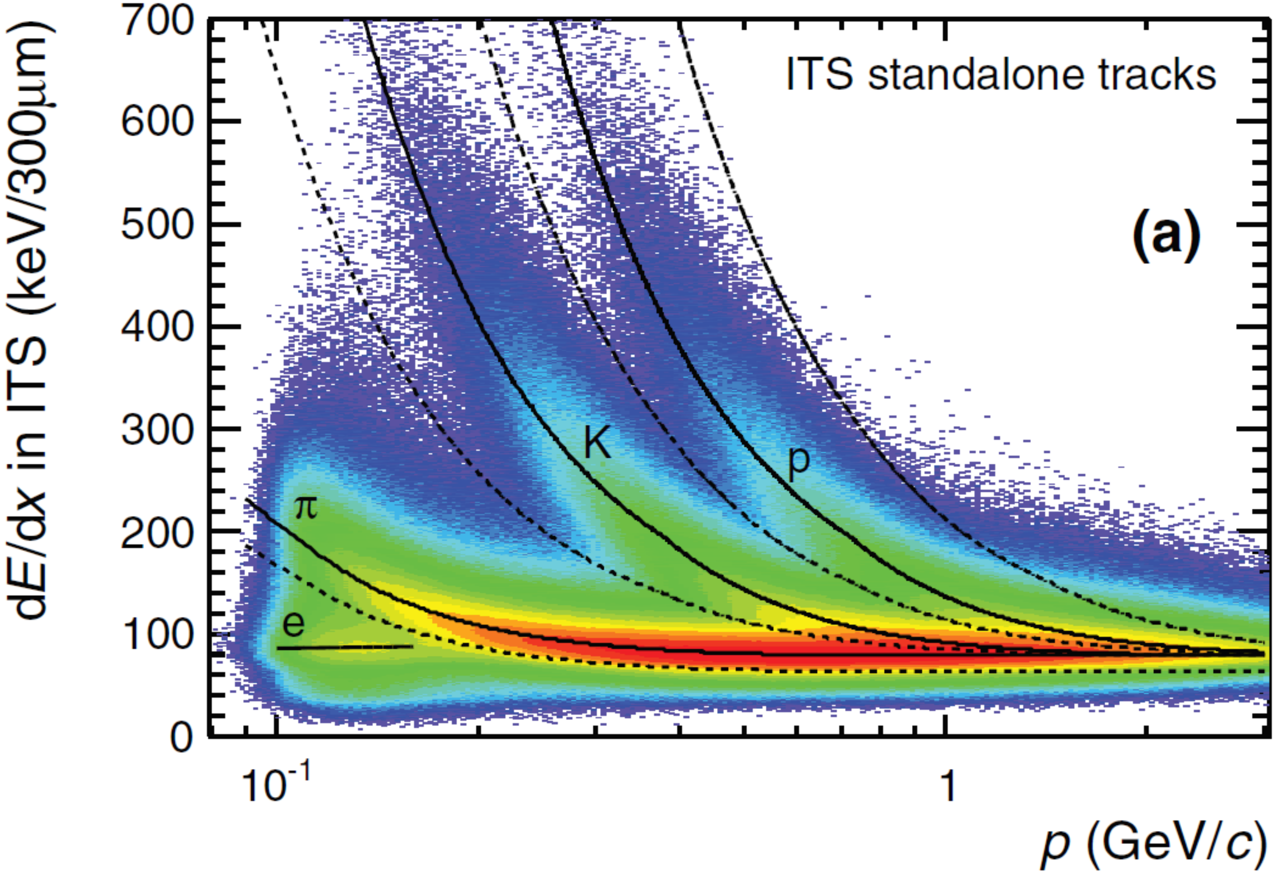
- Light flavor based observables represent a strategic tool also in high-energy physics
- Many hints on the hadron formation can be guessed by their properties
- Comparing different collision system allows to disentangle pure QGP-related effects to the cold nuclear matter induced ones
- Light flavour measurements give the possibility to test and tune thermal and hydro models and to study the particles production and energy loss mechanisms

# backup

# Alice

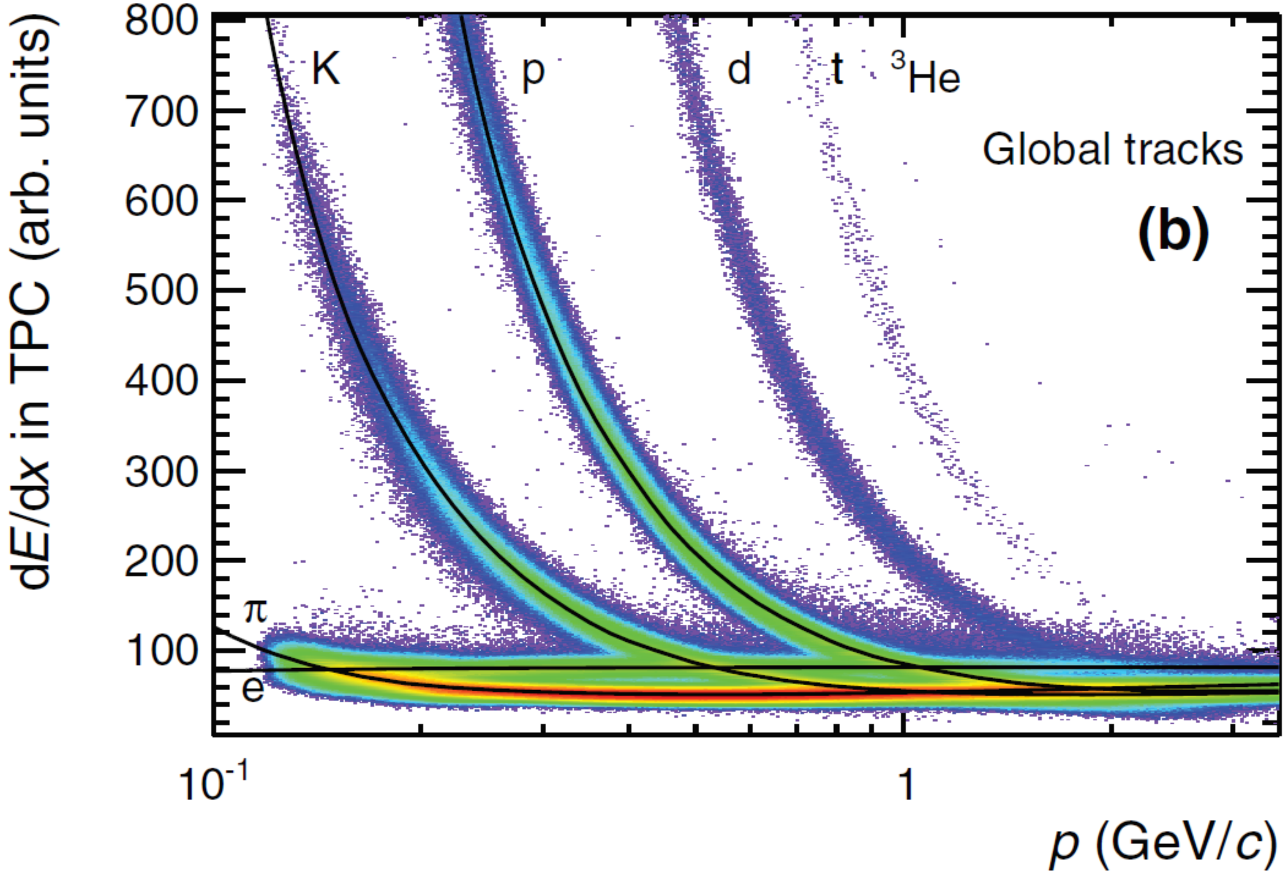

ACORDE
EMCal
HMPID
ZDC
T0A, V0A
PMD
TPC
TRD
TOF
PHOS
L3 solenoid
absorber
dipole
SPD
SDD
SSD
T0C
V0C
FMD
MCH
MTR
ZDC

# Alice Inner-Tracking System (ITS)




| Analysis | $\pi$ | $K$ | $p$ |
|---|---|---|---|
| ITS stand-alone | 0.10–0.60 | 0.20–0.50 | 0.30–0.60 |
| TPC/TOF | 0.20–1.20 | 0.25–1.20 | 0.45–1.80 |
| TOF fits | 0.50–3.00 | 0.45–3.00 | 0.50–4.60 |

# Alice Time-Projection Chamber

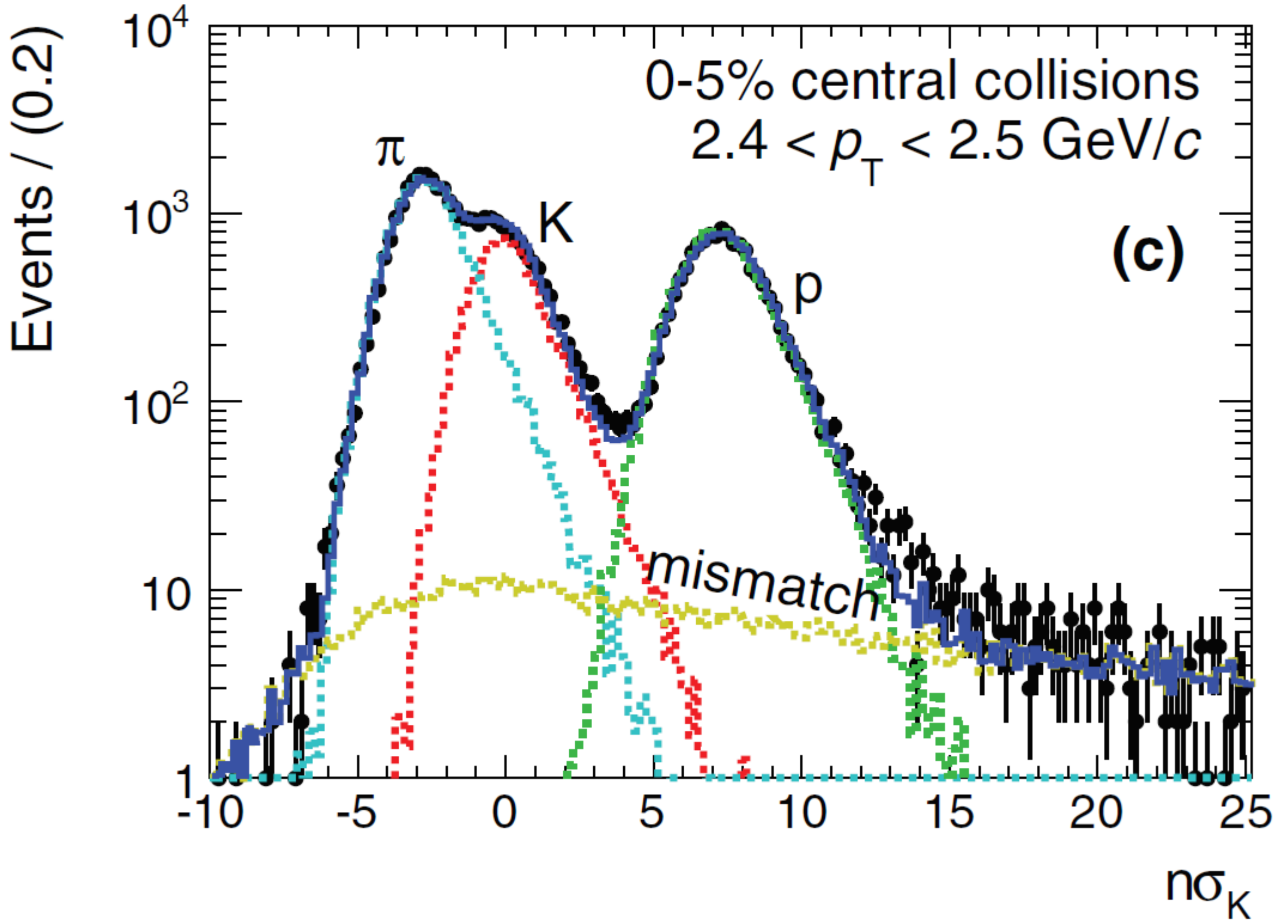



| Analysis | $\pi$ | $K$ | $p$ |
|---|---|---|---|
| ITS stand-alone | 0.10–0.60 | 0.20–0.50 | 0.30–0.60 |
| TPC/TOF | 0.20–1.20 | 0.25–1.20 | 0.45–1.80 |
| TOF fits | 0.50–3.00 | 0.45–3.00 | 0.50–4.60 |

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

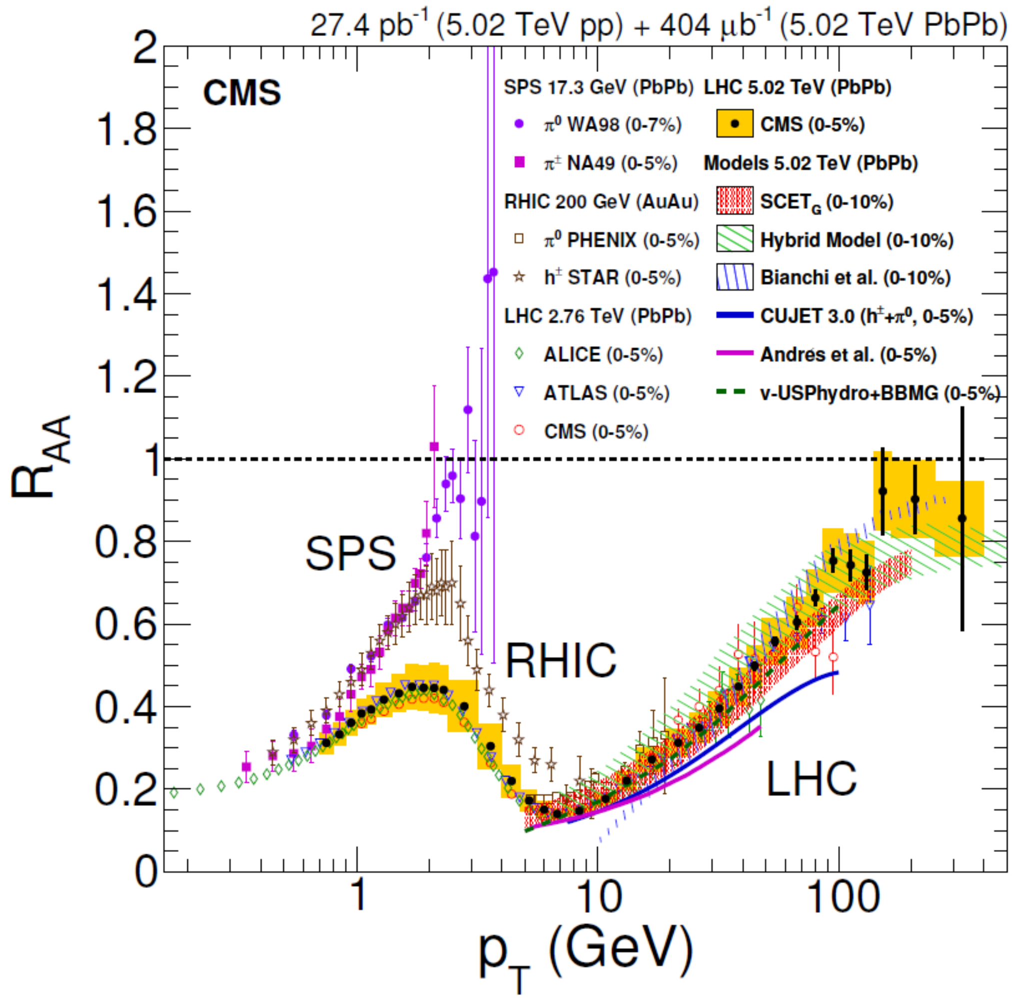
Centro Fermi
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

# Alice Time-Of-Flight




| Analysis | $\pi$ | $K$ | $p$ |
|---|---|---|---|
| ITS stand-alone | 0.10–0.60 | 0.20–0.50 | 0.30–0.60 |
| TPC/TOF | 0.20–1.20 | 0.25–1.20 | 0.45–1.80 |
| TOF fits | 0.50–3.00 | 0.45–3.00 | 0.50–4.60 |

# Comparisons



# Evolution of a heavy-ion collision

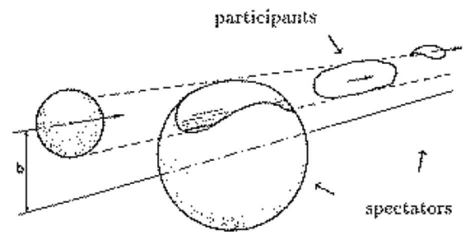
1. Colliding nuclei: coherent could of partons (color-glass condensate plate)

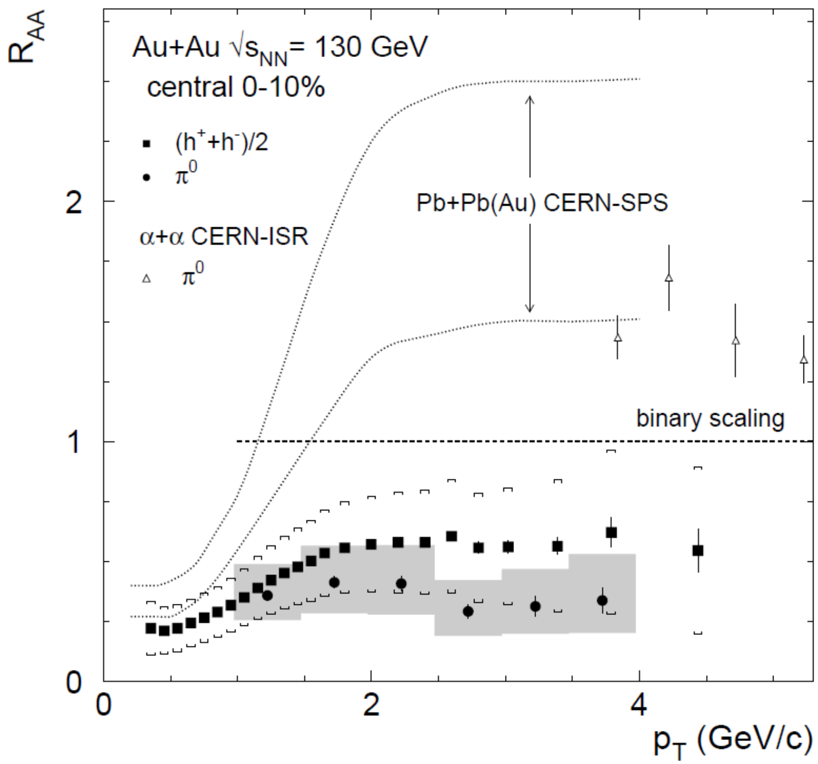
2. A significant fraction of $E_{kin}$ deposited in the central region→ high-energy-density fireball (Glasma, non-equilibrium state) – still a coherent state

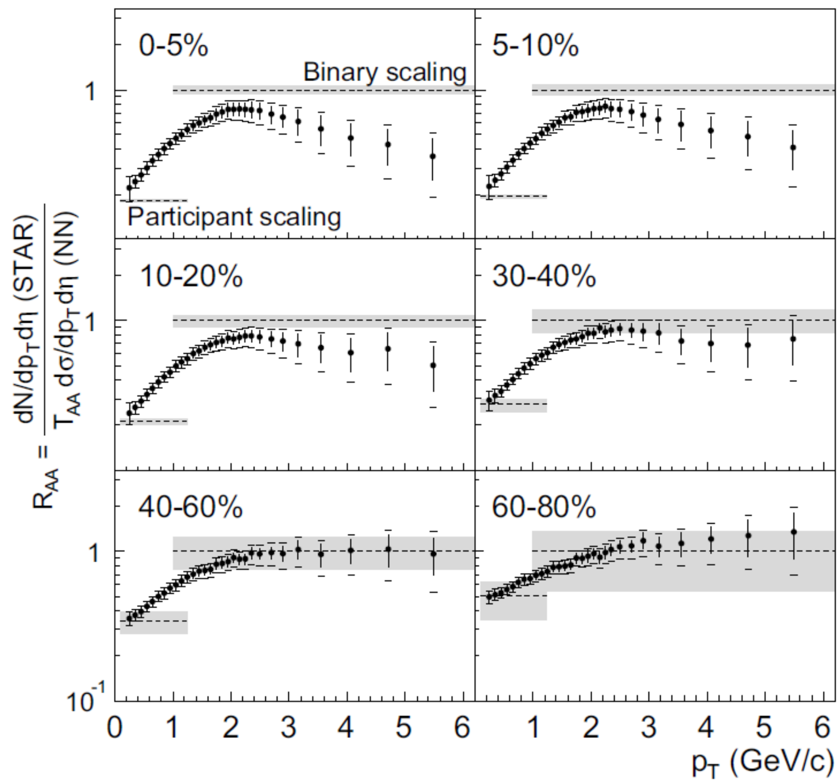
3. Subsequent collisions among partons leads to thermalized QGP. It happens at $1 fm/c$

# *AuAu* spectra@RHIC

First indication of strong medium effects



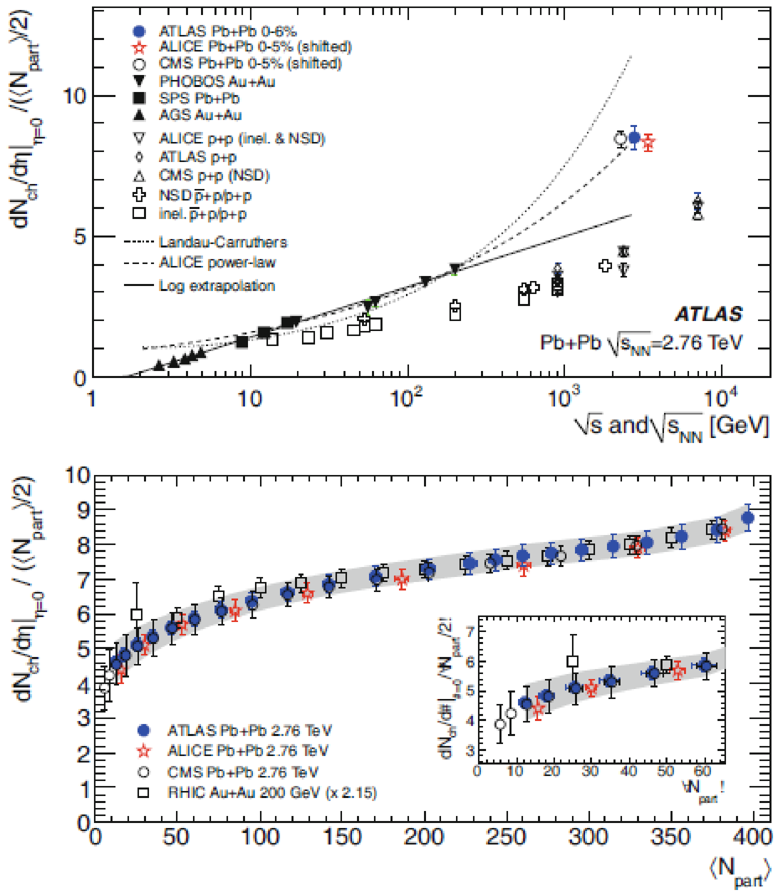



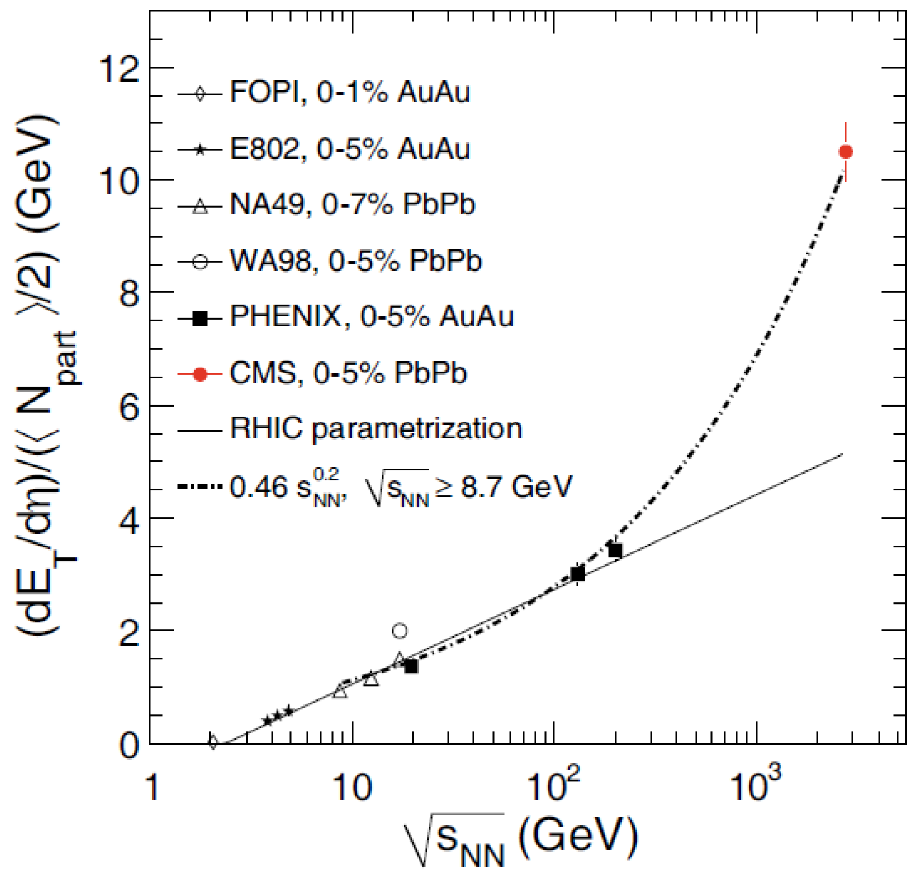

PHENIX:
Phys.Rev.Lett.88:022301,2002

STAR:
Phys.Rev.Lett.89:202301,2002

# Soft probes

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

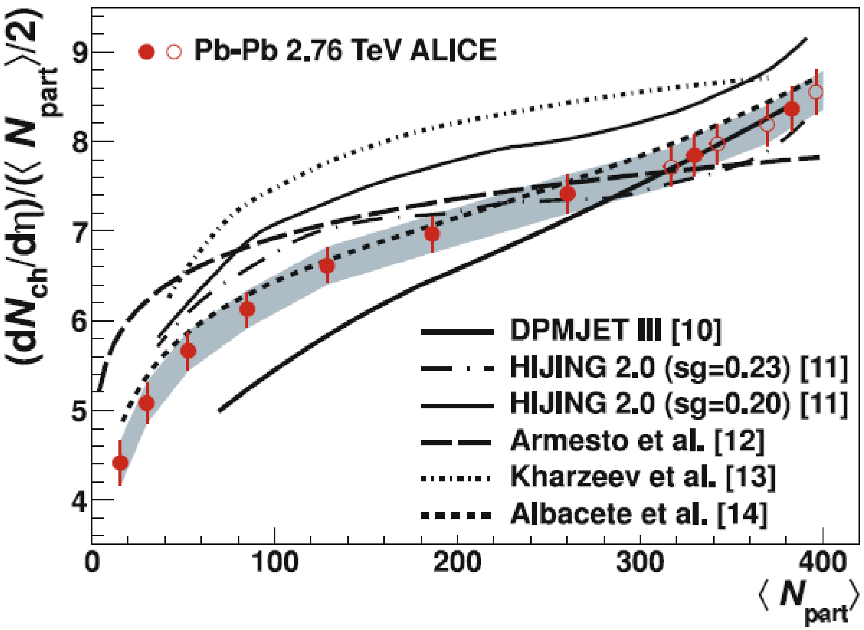


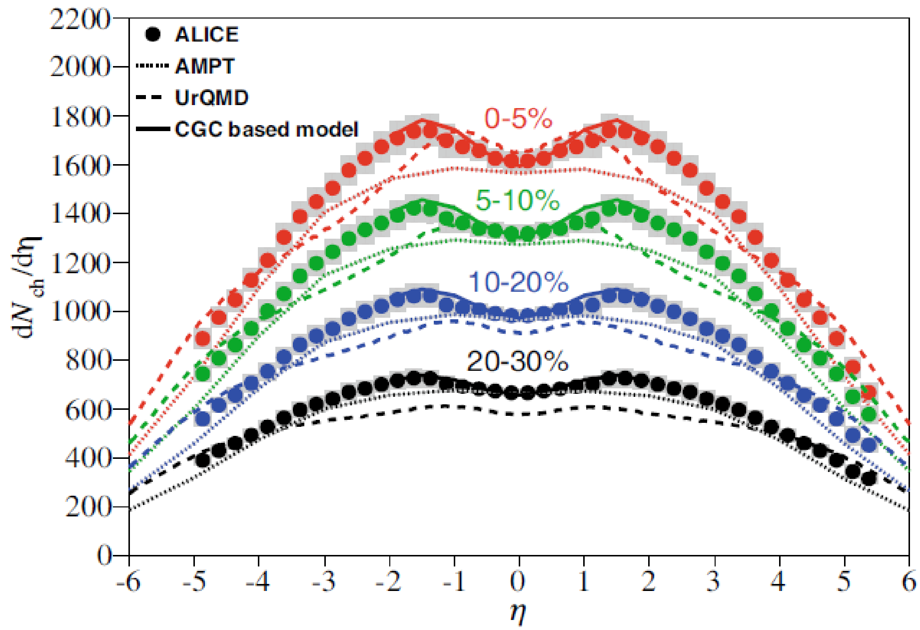




Eur. Phys. J. Plus (2016) 131: 52

CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

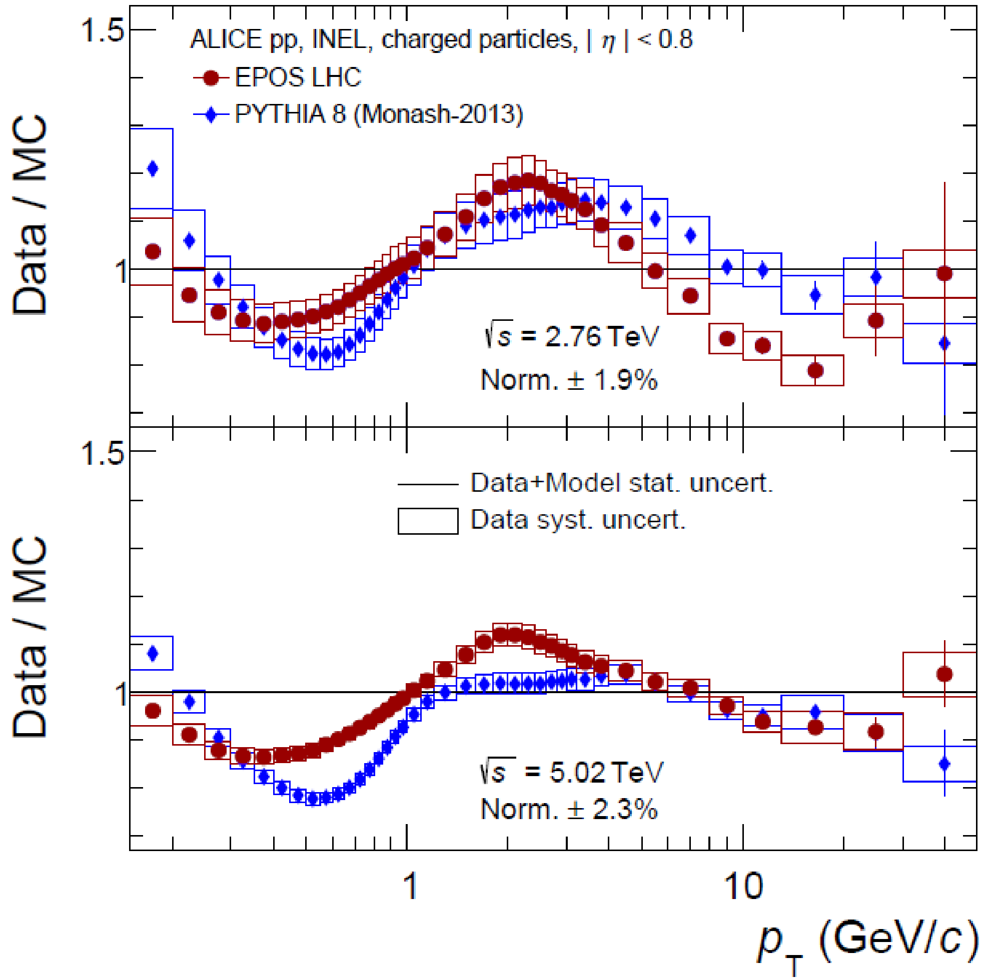
# Soft probes




Eur. Phys. J. Plus (2016) 131: 52

# Testing generation models in $pp$



# Strangeness enhancement

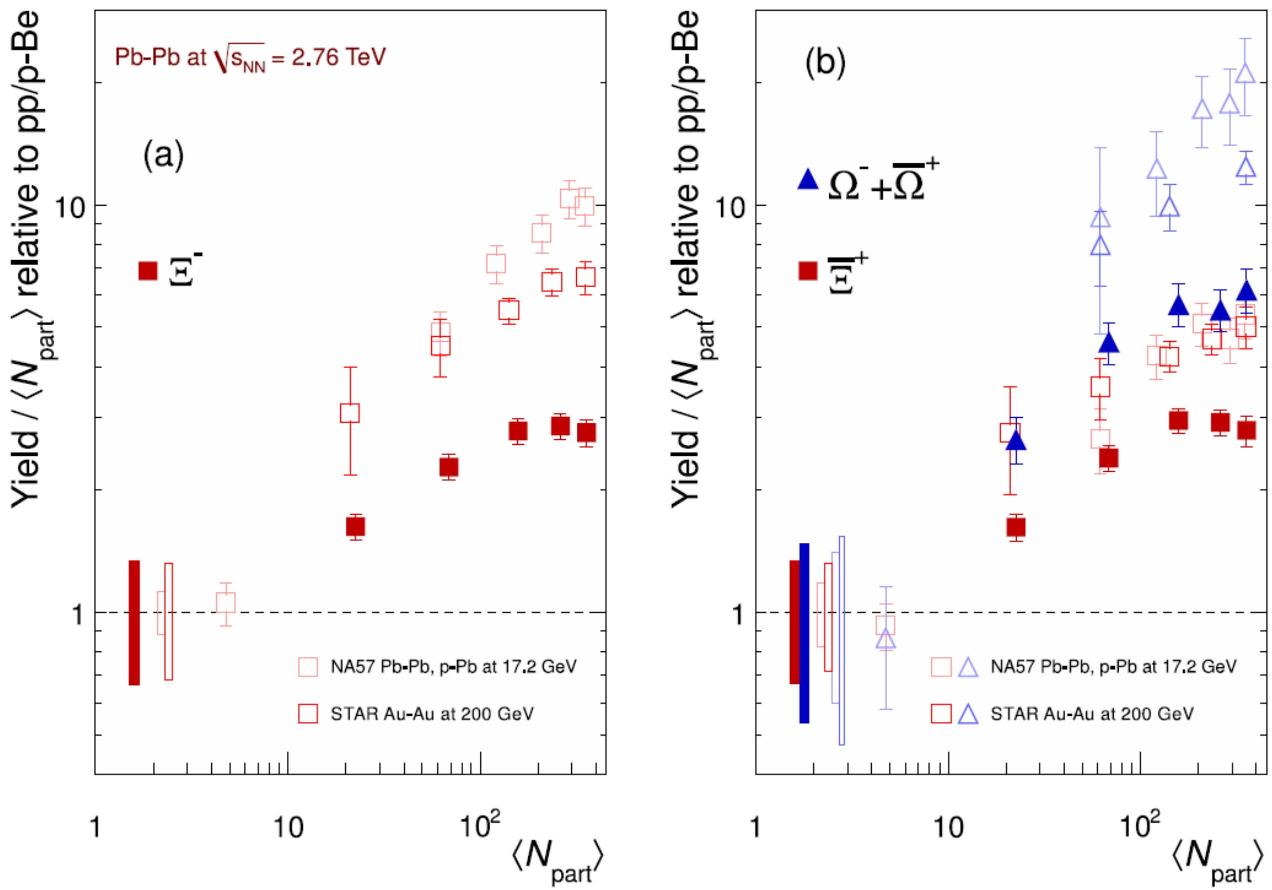
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Among the first signature for QGP production Phys. Rev. Lett. 48. 1066 (1982)

→ **easier to produce strangeness at the quark-gluon than hadron level**

Effect seen at SPS, RHIC, LHC

Increase with strangeness content and with centrality, the latter up to saturation → hadron resonance gas in thermal equilibrium




Phys. Lett. B 728 (2014) 216

CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

# Strangeness enhancement

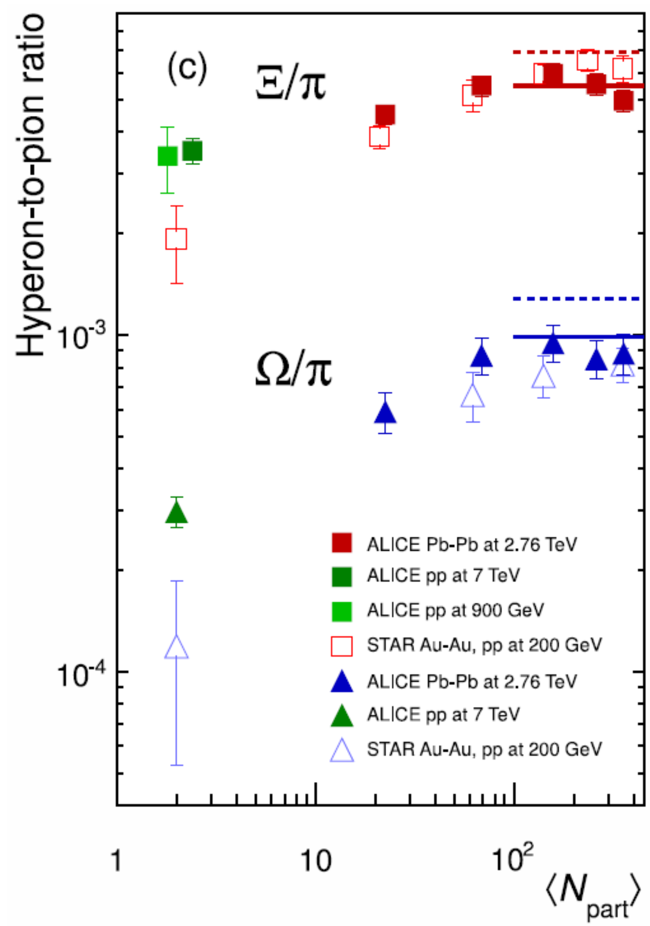


Among the first signature for QGP production Phys. Rev. Lett. 48. 1066 (1982)

→ **easier to produce strangeness at the quark-gluon than hadron level**

Effect seen at SPS, RHIC, LHC

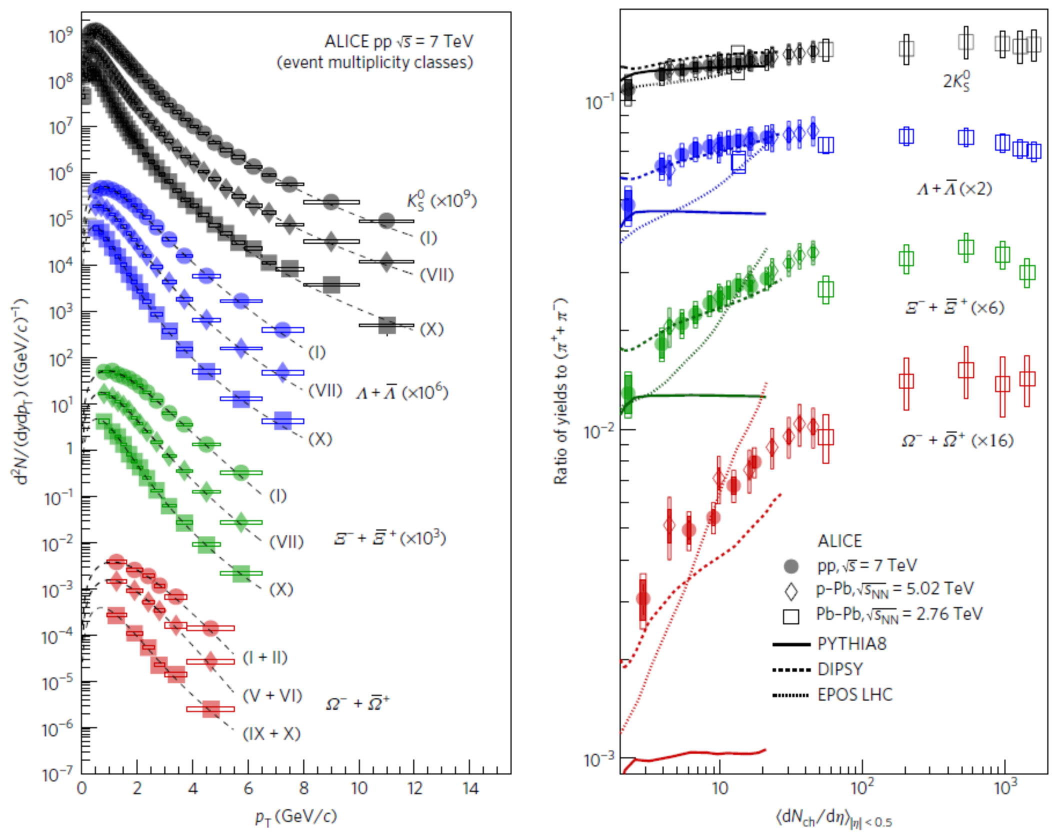
Decrease with $\sqrt{s_{NN}}$ → strangeness production increase in $pp$ with $\sqrt{s_{NN}}$, while appears to be saturated in $PbPb$




Phys. Lett. B 728 (2014) 216

# Strangeness enhancement

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati




Nature Physics 13 (2017) 535

**Strange-to-non-strange ratio in $pp, pPb, PbPb$**

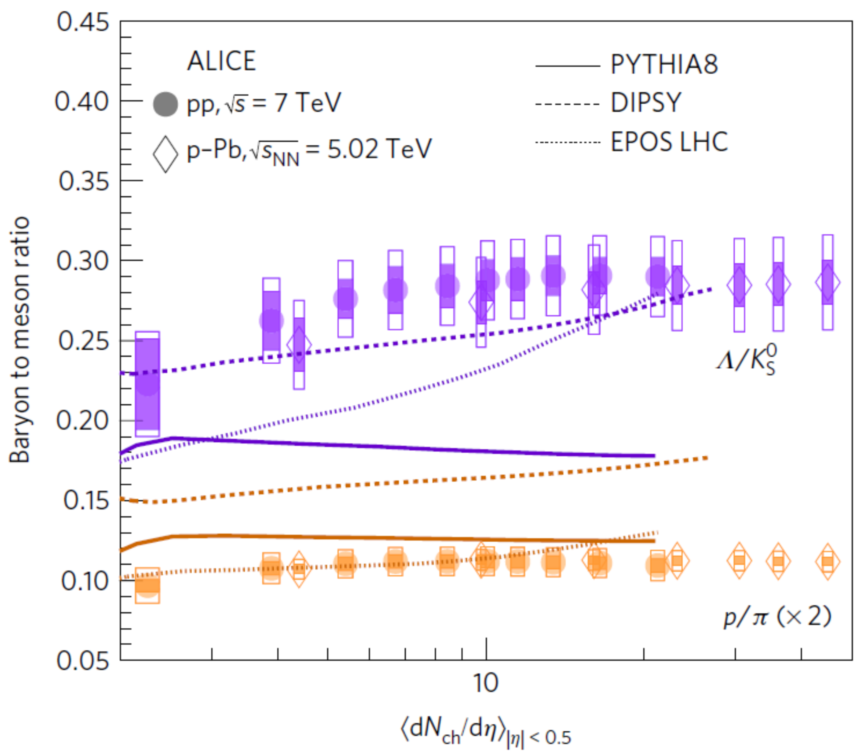
1. Ratio is enhanced from $pp$ to central $PbPb$ collisions
2. Saturated in central $PbPb$ for all the particles

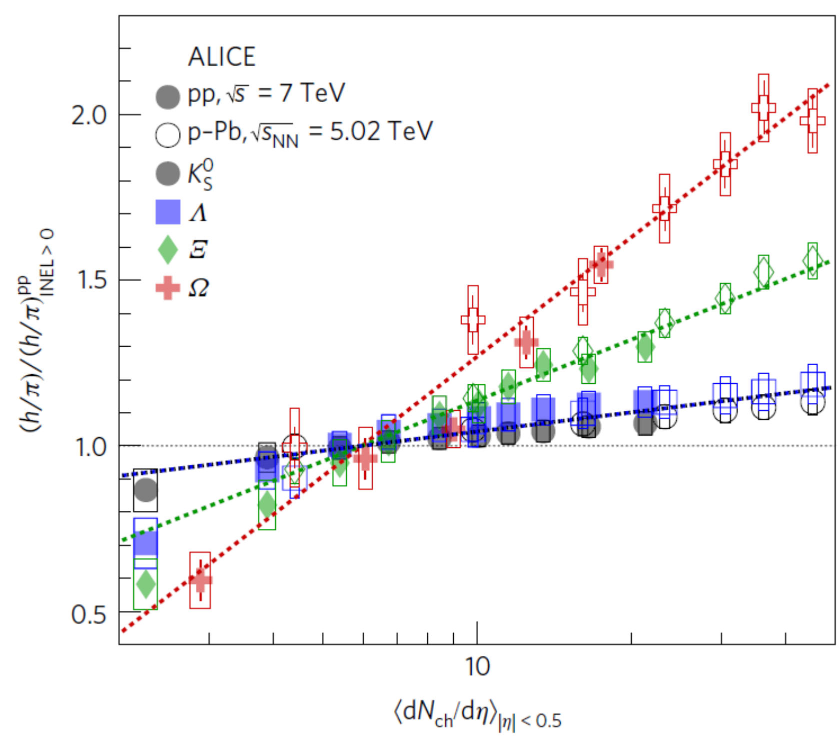
- PYTHIA8 (color reconnection) underestimates the effect
- DIPSY (color ropes) qualitatively good; underestimates $\Omega/\pi$ and overestimates $p/\pi$
- EPOS LHC (core-corona approach) only quantitatively describes the trend

CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

# Strangeness enhancement

- text




Nature Physics 13 (2017) 535

# Why light flavor spectra

Primary charged particles produced in the collisions and their decay products (except for particles from weak decays of strange hadrons)

- Spectra are the earlier observable that can be addressed
- Light flavors containing $u, d, s$ quarks represent the main constituents of the particles produced
- Mandatory for a detailed understanding of the collision mechanism
- $pPb$ data ⇒ important chance to test the emergence of possible initial state effects
- Spectra to be compared to previous $pp$ and $Pb-Pb$ data in a wide transverse momentum range

# title

- text