# State of the art of HI measurements

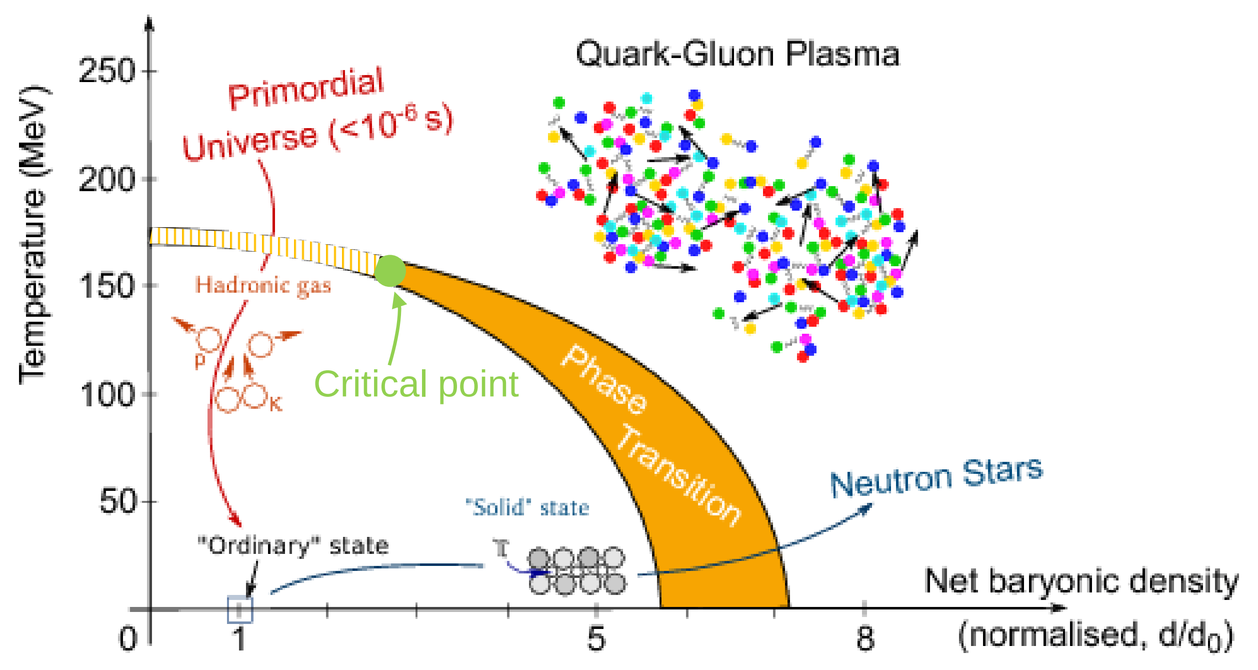
E. Scomparin
INFN Torino (Italy)

- A short introduction → Heavy ion collisions, a bit of history
- Experiments for HI collisions → Characterize the QGP
- The physics program
  - Global observables
    → The most liquid liquid that ever existed
  - Light flavors and strangeness
    → The chemistry of the QGP
  - Hard probes
    → Transport properties of the QGP
  - p-Pb vs Pb-Pb
    → a reference or more?
- Open points and prospects
  → LHC and other facilities

5th Rome Joint Workshop
Hot QCD Matters

# Experiments with heavy ions: why?

- Investigate the phase diagram of strongly interacting matter
- Currently active facilities (RHIC, LHC) access the region corresponding to **high(est) temperature** and **low(est) possible net baryon density**



- **Re-create** the first (and hottest!) liquid that ever existed and that gave rise to matter around us….
…and **study** its properties in the laboratory!

# The energy frontier

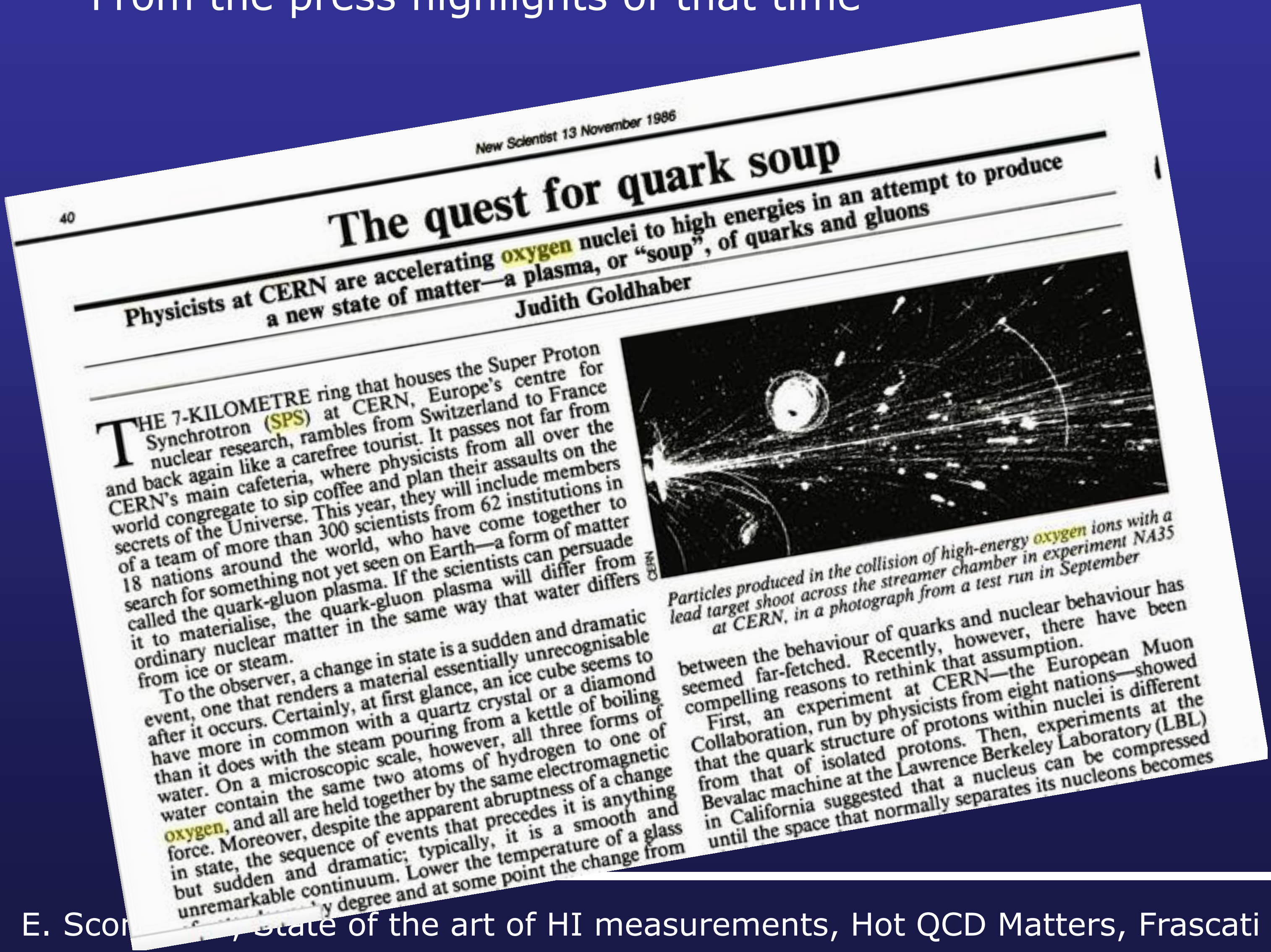
- ❑ Evolution of (some) properties of the system with the collision energy (N.B. approximate values!)

| **Central collisions** | **SPS** | **RHIC** | **LHC** |
|---|---|---|---|
| $\sqrt{s}$ (GeV) | 17 | 200 | 5000 (today) |
| $dN_{ch}/d\eta$ ($\eta=0$) | 450 | 650 | 2000 |
| Energy density (GeV/fm$^3$) | 2.2-3.2 | 5.4 | 20 |
| V (fm$^3$) (from HBT) | 120 | 160 | 300 |
| Decoupling time (fm/c) (from HBT) | 6 | 7.5 | 10.5 |
| Average QGP temperature (MeV) (photons, dileptons) | 190 | 240 | 300 |

**LHC → hotter, larger and longer lived fireball!**

# A complex (and long!) endeavor…

- (Almost) exactly 30 years ago: **first heavy-ion beams at CERN!**
  From the press highlights of that time



40 New Scientist 13 November 1986

## The quest for quark soup

**Physicists at CERN are accelerating oxygen nuclei to high energies in an attempt to produce a new state of matter—a plasma, or "soup", of quarks and gluons**

**Judith Goldhaber**

THE 7-KILOMETRE ring that houses the Super Proton Synchrotron (SPS) at CERN, Europe's centre for nuclear research, rambles from Switzerland to France and back again like a carefree tourist. It passes not far from CERN's main cafeteria, where physicists from all over the world congregate to sip coffee and plan their assaults on the secrets of the Universe. This year, they will include members of a team of more than 300 scientists from 62 institutions in 18 nations around the world, who have come together to search for something not yet seen on Earth—a form of matter called the quark-gluon plasma. If the scientists can persuade it to materialise, the quark-gluon plasma will differ from ordinary nuclear matter in the same way that water differs from ice or steam.

To the observer, a change in state is a sudden and dramatic event, one that renders a material essentially unrecognisable after it occurs. Certainly, at first glance, an ice cube seems to have more in common with a quartz crystal or a diamond than it does with the steam pouring from a kettle of boiling water. On a microscopic scale, however, all three forms of water contain the same two atoms of hydrogen to one of oxygen, and all are held together by the same electromagnetic force. Moreover, despite the apparent abruptness of a change in state, the sequence of events that precedes it is anything but sudden and dramatic; typically, it is a smooth and unremarkable continuum. Lower the temperature of a glass y degree and at some point the change from

CERN

*Particles produced in the collision of high-energy oxygen ions with a lead target shoot across the streamer chamber in experiment NA35 at CERN, in a photograph from a test run in September*

between the behaviour of quarks and nuclear behaviour has seemed far-fetched. Recently, however, there have been compelling reasons to rethink that assumption.

First, an experiment at CERN—the European Muon Collaboration, run by physicists from eight nations—showed that the quark structure of protons within nuclei is different from that of isolated protons. Then, experiments at the Bevalac machine at the Lawrence Berkeley Laboratory (LBL) in California suggested that a nucleus can be compressed until the space that normally separates its nucleons becomes

# A complex (and long!) endeavor…

- (Almost) exact **first heavy-ion beams at CERN!**
  From the press

New Scientist 19 February 1987

25

SCIENCE

## On the trail of the quark-gluon plasma

### Christine Sutton

PHYSICISTS seem to be tantalisingly close to observing the exotic state of matter known as a quark-gluon plasma, or "quagma". Theory implies that such a plasma should exist in matter where the energy density is much higher than usual. Recent experiments at CERN, the European centre for nuclear research in Geneva, suggest that high-energy collisions of oxygen nuclei with targets of large nuclei, such as lead, are approaching the appropriate energy density. High-energy cosmic-ray nuclei show similar effects.

According to current theories of particle physics, the protons and neutrons within atomic nuclei are themselves composite. They consist of quarks, which are bound together by the strong nuclear force. The force is transmitted by gluons—"messenger" particles that flit from quark to quark, and which can also interact between themselves.

At low energies, in the nuclei of the everyday world, the quarks and gluons are confined within the protons and neutrons. Moreover, even in high-energy experiments at particle accelerators, the quarks and gluons generally seem to exist only within the particles classified as hadrons. However, theories of the strong force indicate that when the energy density of matter becomes high enough, the quarks and gluons are no longer confined within hadrons, but instead form a plasma, in analogy to the way that at high energies a gas of atoms becomes a plasma of electrons and ions.

Matter in normal nuclei has an energy density of about 150 million electronvolts

transverse (sideways) to the general motion of the initial nucleus and the subsequent debris. The momentum taken sideways in these collisions is greater than might be expected by extrapolating data from lower energy experiments at accelerators (*Physical Review Letters*, vol 57, p 3249). The researchers estimate that energy densities of 1-2 $\mathrm{GeV/fm^3}$ or more existed in the collisions with the highest average values of transverse momentum.

Beyond the chamber, banks of detectors intercept the continuing paths of the particles and yield valuable information on their energies.

In this example, the streamer chamber reveals the tracks of 220 charged particles and, from other information, the researchers can estimate that some 80 or so neutral particles also emerged from the collision. From the amount of energy measured at certain angles, the team can also estimate how much of the original oxygen ion's energy has been redistributed in all direc-

CERN

*Tracks of 220 charged particles spill out from the collisions of a high-energy oxygen nucleus in a lead target to the left of this picture from the NA35 experiment at CERN*

---

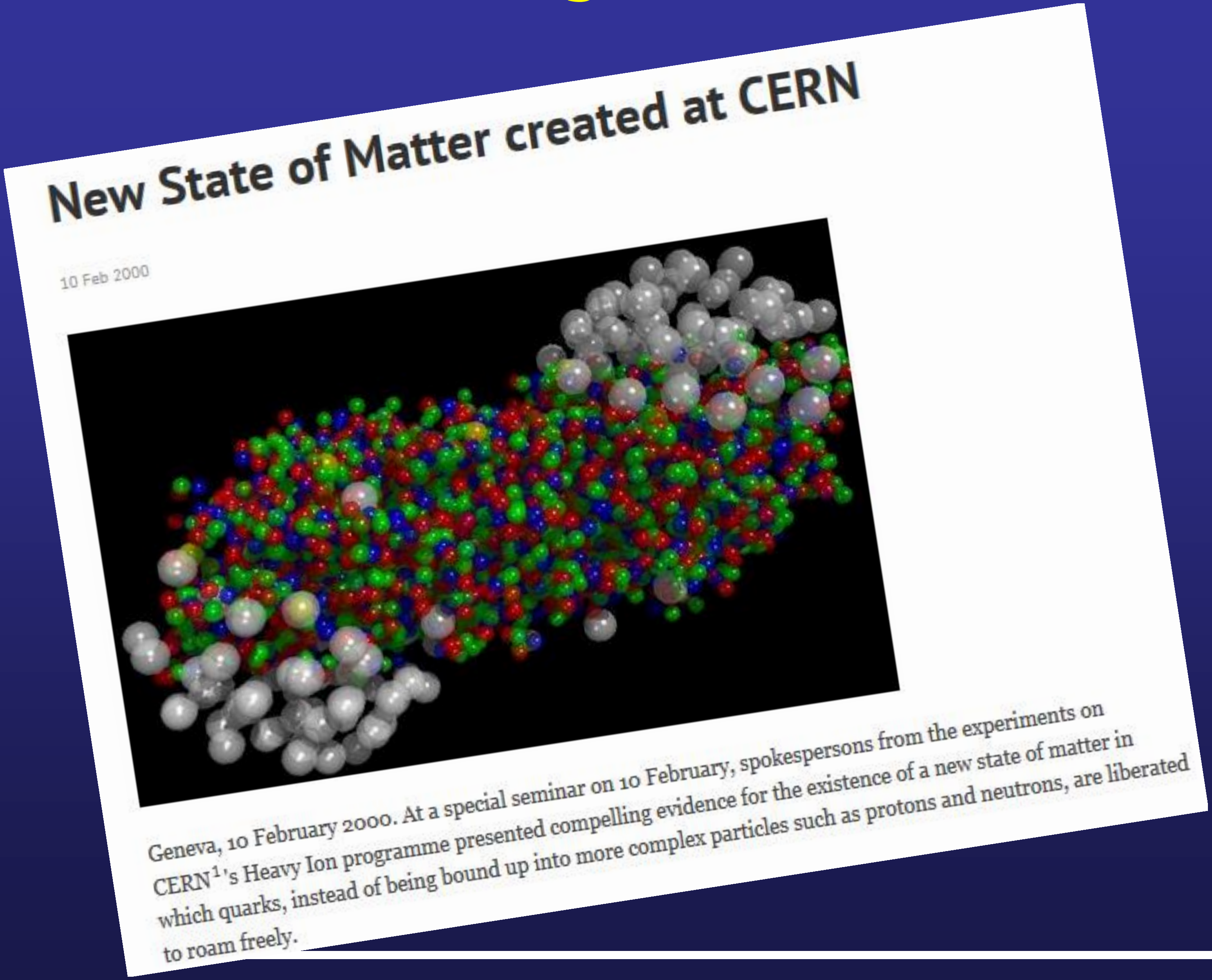
40

Physicists at CERN
a new

THE 7-KILOMETRE
Synchrotron (SPS
nuclear research,
and back again like a
CERN's main cafete
world congregate to
secrets of the Unive
of a team of more
18 nations arour
search for someth
called the quark
it to materiali
ordinary nucl
from ice or st
To the observer, a
event, one that renders a
after it occurs. Certainly, at first
have more in common with a quar
than it does with the steam pouring from
water. On a microscopic scale, however, all thr
water contain the same two atoms of hydrogen to
oxygen, and all are held together by the same electromagnetic
force. Moreover, despite the apparent abruptness of a change
in state, the sequence of events that precedes it is anything
but sudden and dramatic; typically, it is a smooth and
unremarkable continuum. Lower the temperature of a glass
y degree and at some point the change from

th
from th
Bevalac mach
in California sugg
until the space that norm

# … which brought to several discoveries

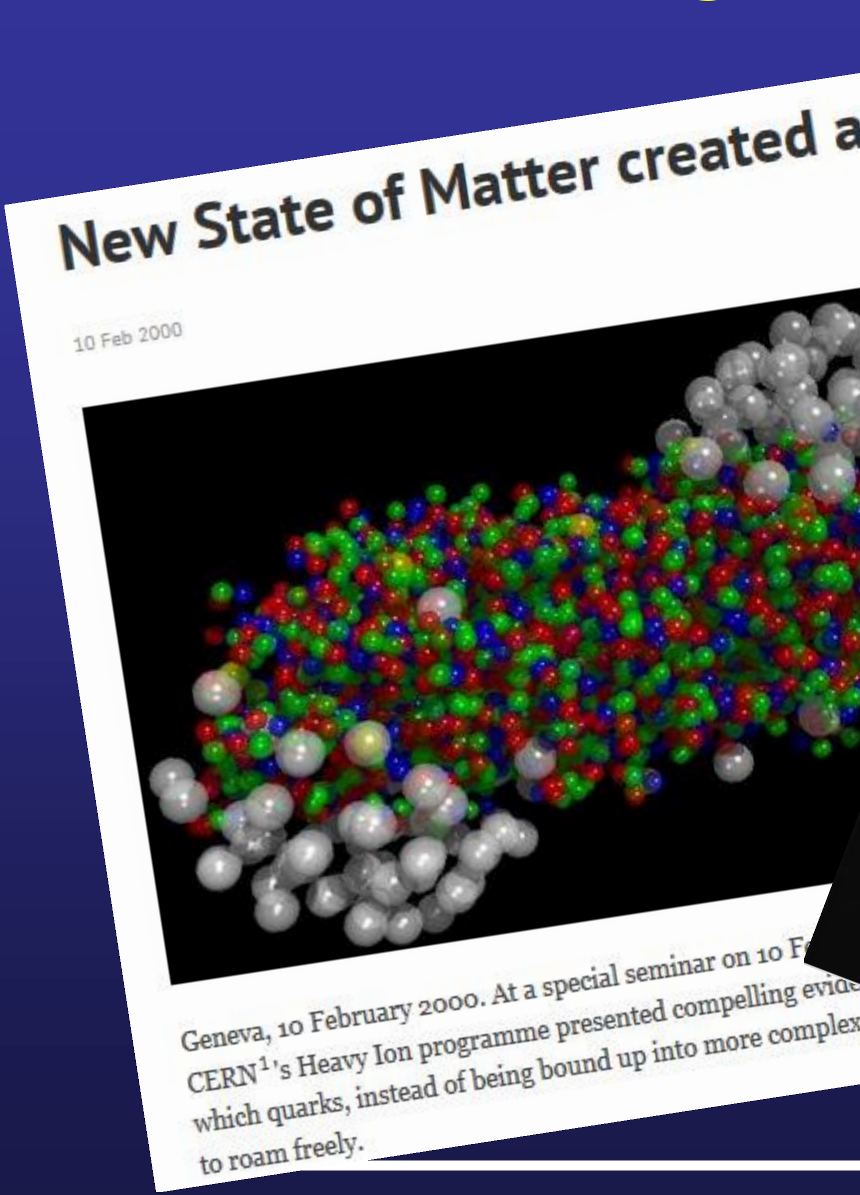


## New State of Matter created at CERN

10 Feb 2000

Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

# … which brought to several discoveries



## New State of Matter created at CERN

10 Feb 2000

Geneva, 10 February 2000. At a special seminar on 10 Fe
CERN[1]'s Heavy Ion programme presented compelling evide
which quarks, instead of being bound up into more complex partic
to roam freely.

# … which brought to several discoveries

New State of Ma

10 Feb 2000

Geneva, 10 February 2000. A
CERN[1]'s Heavy Ion progran
which quarks, instead of bei
to roam freely.

Media and Press Relations

New ALICE experiment results show novel phenomena in proton collisions

24 Apr 2017

(//cds.cern.ch/images/OPEN-PHO-EXP-2017-003-2)

As the number of particles produced in proton collisions (the blue lines) increase, the more of these so-called strange hadrons are seen (as shown by the red squares in the graph). (Image: CERN)

Geneva 24 April 2017. In a paper published today in *Nature Physics* (https://doi.org/10.1038/nphys4111), the ALICE collaboration reports that proton collisions sometimes present similar patterns to those observed in the collisions of heavy nuclei. This behaviour was spotted through observation of so-called strange hadrons in certain proton collisions in which a large number of particles are created. Strange hadrons are well-known particles with names such as Kaon, Lambda, Xi and Omega, all containing at least one so-called strange quark. The observed 'enhanced production of strange particles' is a familiar feature of quark-gluon plasma, a very hot and dense state of matter that existed just a few millionths of a second after the Big Bang, and is commonly created in collisions of heavy nuclei. But it is the first time ever that such a phenomenon is unambiguously observed in the rare proton collisions in which many particles are created. This result is likely to challenge existing theoretical models that do not predict an increase of strange particles in these events.

ANTICANCER BLOCKBUSTER? • RISE AND FALL OF THE SLIDE RULE

CIENTIFIC
MERICAN

Bringing
DNA Computers
to Life

MAY 2006
WWW.SCIAM.COM

ark Soup

REATE
F OF

MERICAN, INC.

# Was QGP born in Roma ?

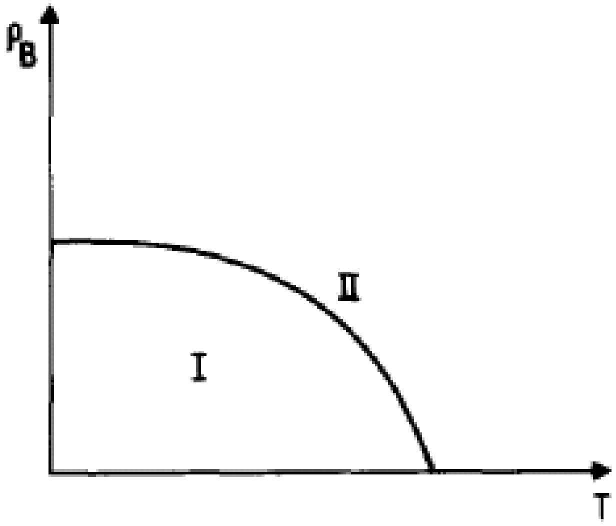
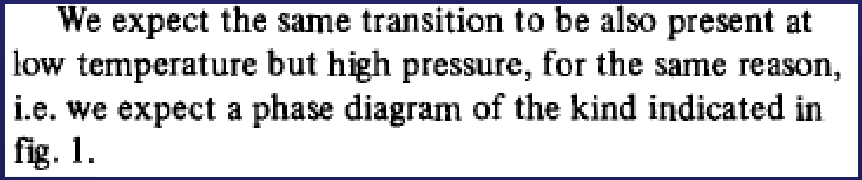


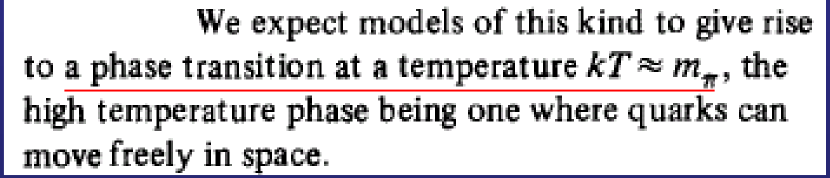
Fig. 1. Schematic phase diagram of hadronic matter. $\rho_B$ is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.



We expect the same transition to be also present at low temperature but high pressure, for the same reason, i.e. we expect a phase diagram of the kind indicated in fig. 1.

**"Experimental hadronic spectrum and quark liberation"**

Cabibbo and Parisi
*Phys. Lett*. **59B**,
67 (1975)

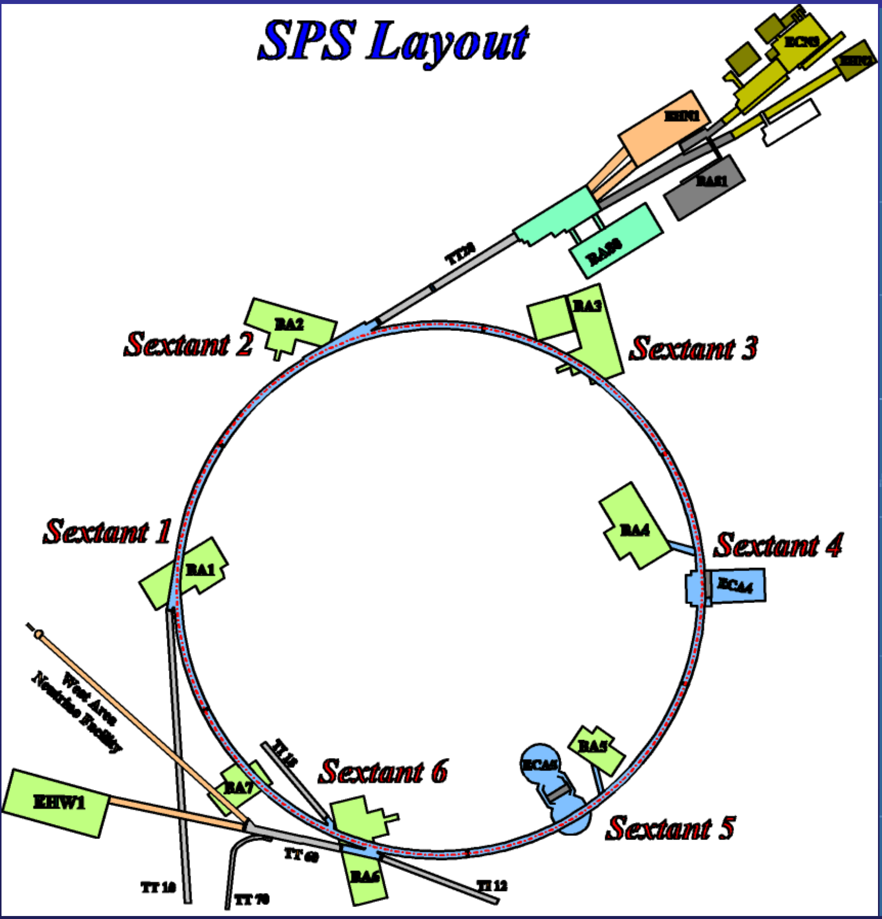


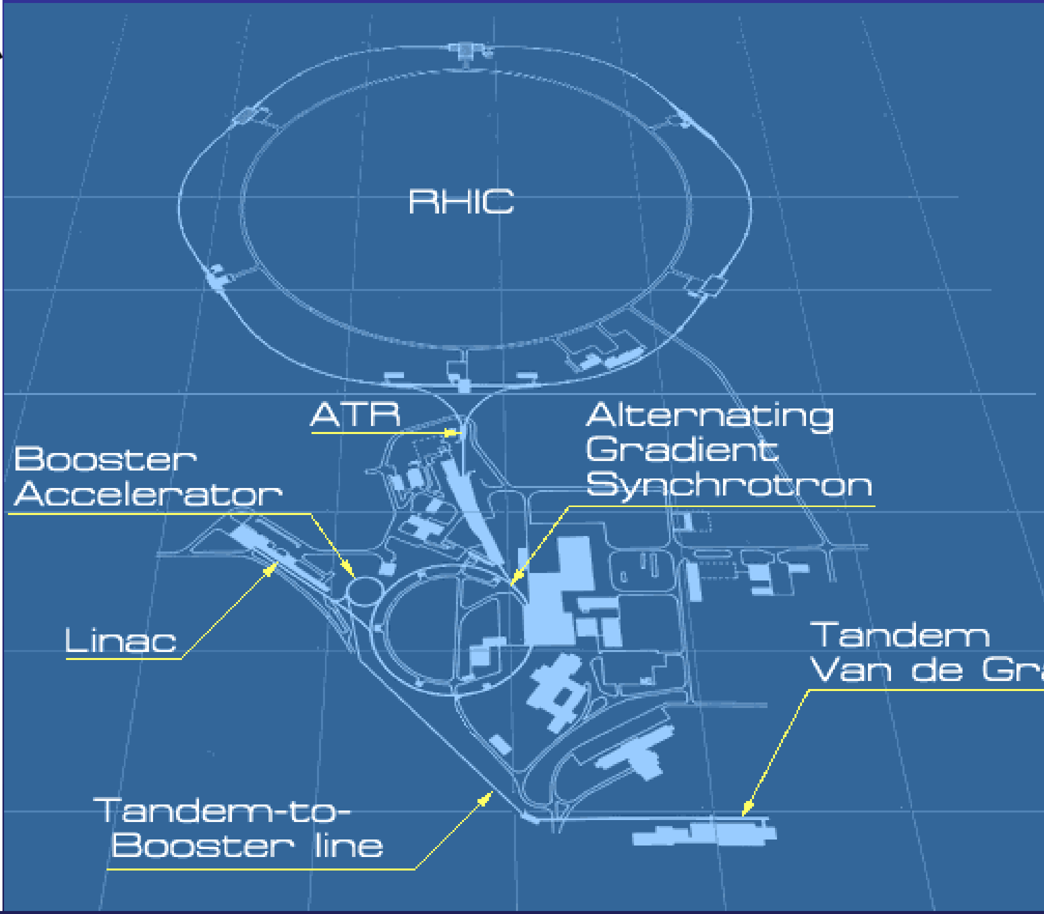
We expect models of this kind to give rise to a phase transition at a temperature $kT \approx m_\pi$, the high temperature phase being one where quarks can move freely in space.

Statement correct to ~10%!

N.B. the "word" QGP was introduced only 3 years later
E. Shuryak, "Quark-gluon plasma and hadronic production of leptons, photons and psions", Phys. Lett. 78B, 150 (1978)

# The SPS/RHIC experimental program

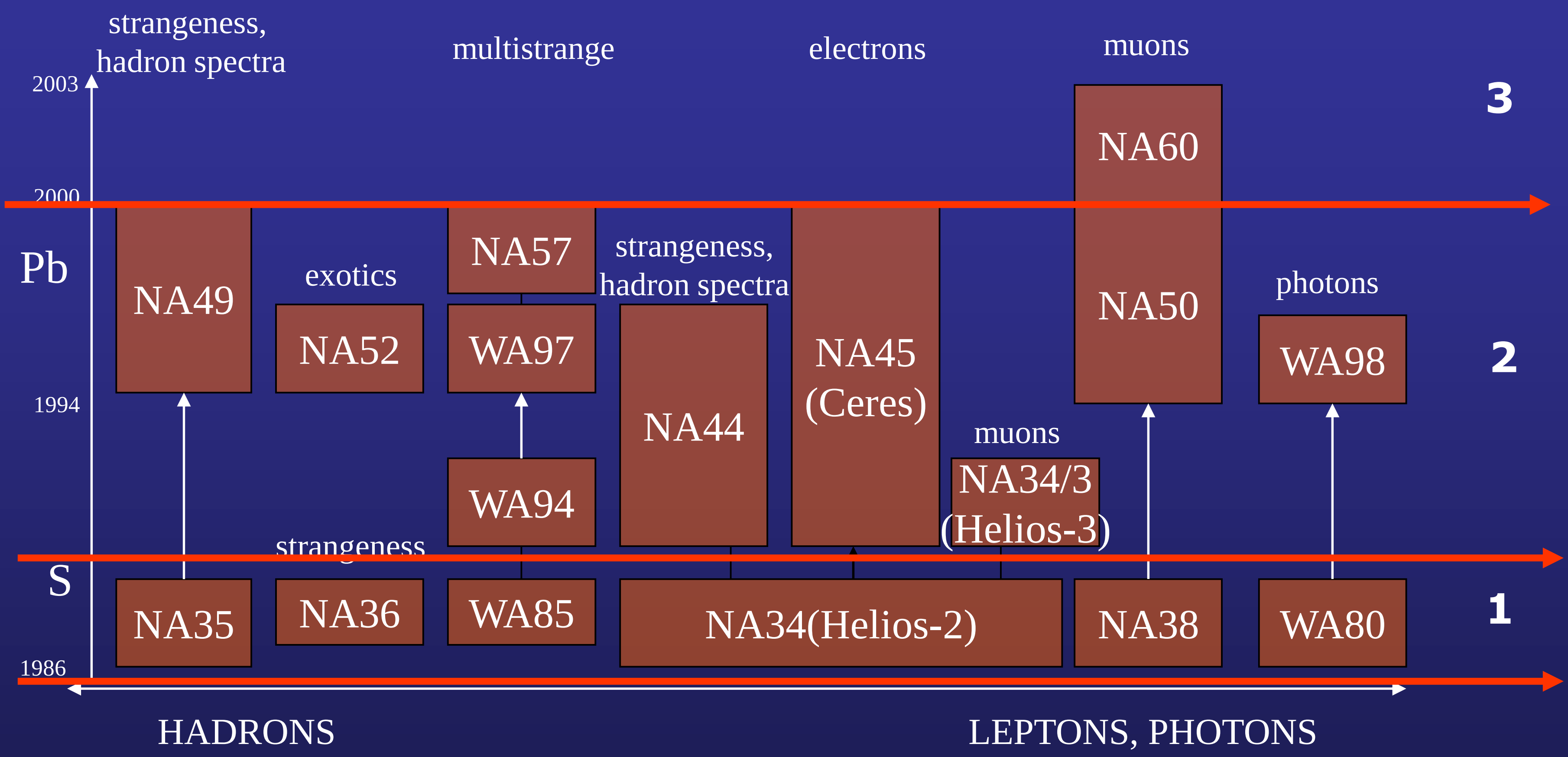




**Fixed target**
→ up to 158 A GeV Pb ions

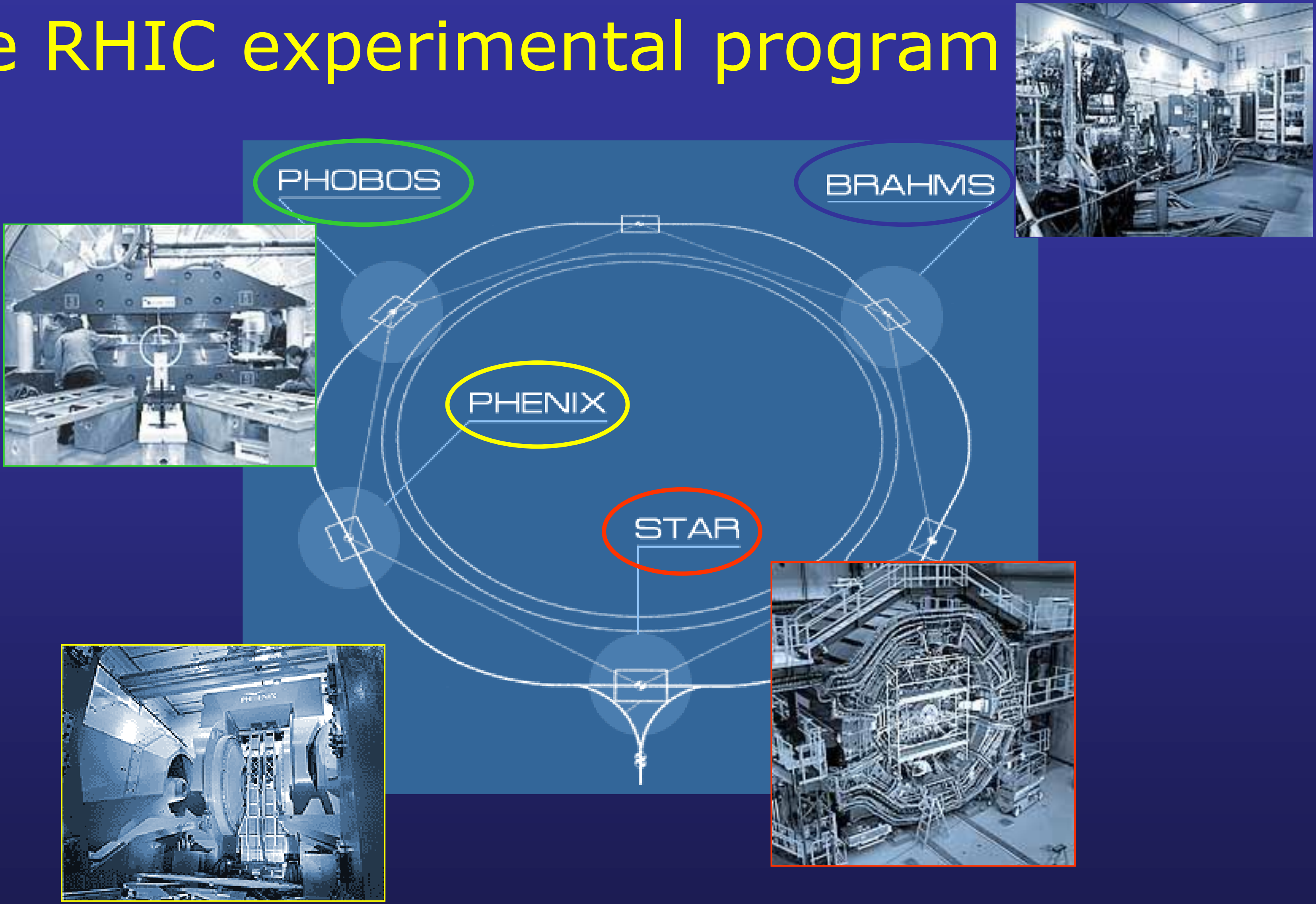
**Collider**
→ up to $\sqrt{s_{NN}}$ =200 GeV Au ions
(recently up to U)

# The SPS experimental program



From a multitude of dedicated **"small" experiments** (exploratory phase)…

# The RHIC experimental program

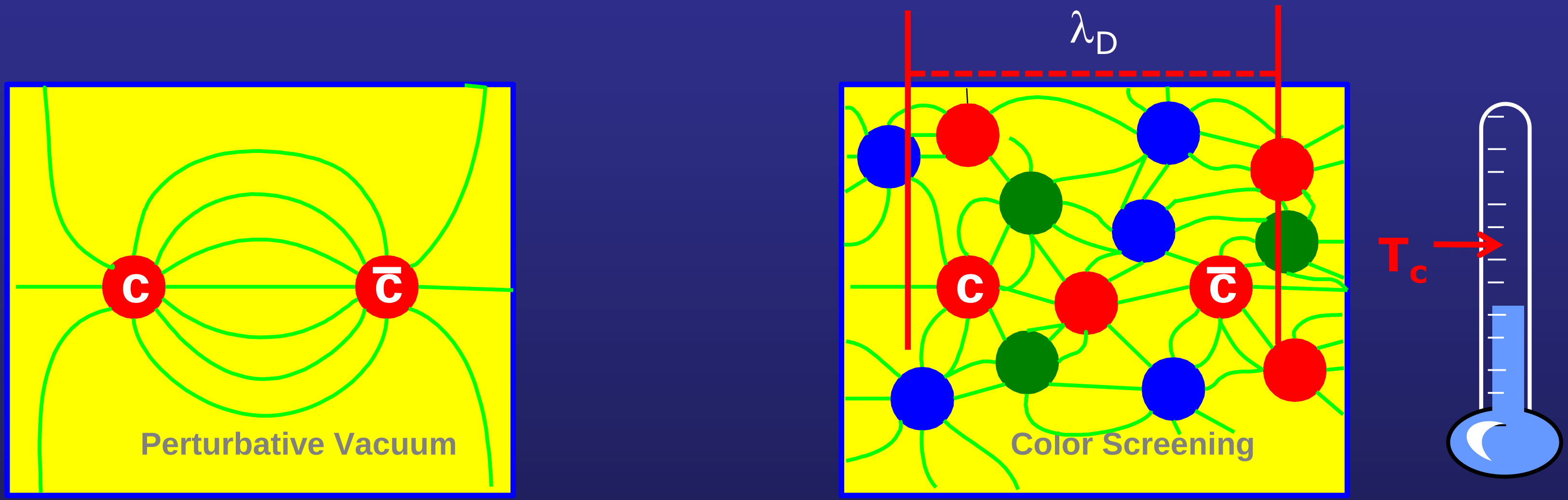


…to two **general-purpose detectors** (STAR, PHENIX), dedicated to heavy-ions (plus two small set-ups, BRAHMS and PHOBOS, now dismantled)

# The quest for QGP

- ❑ At the beginning, experiments were concentrating on the detection of the so-called **"QGP signatures"**, smoking guns for the phase transition

  - ❑ Two (famous) examples
    - ❑ The J/ψ suppression (Matsui and Satz, 1986)

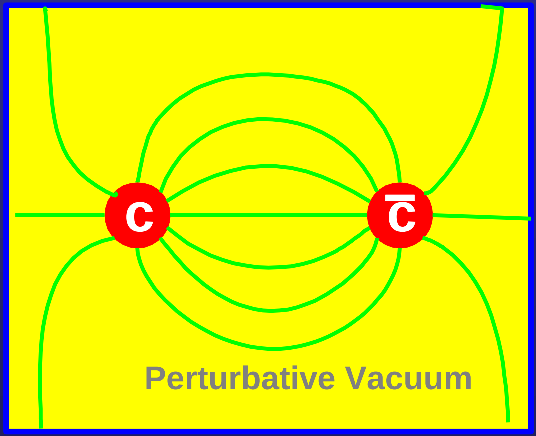


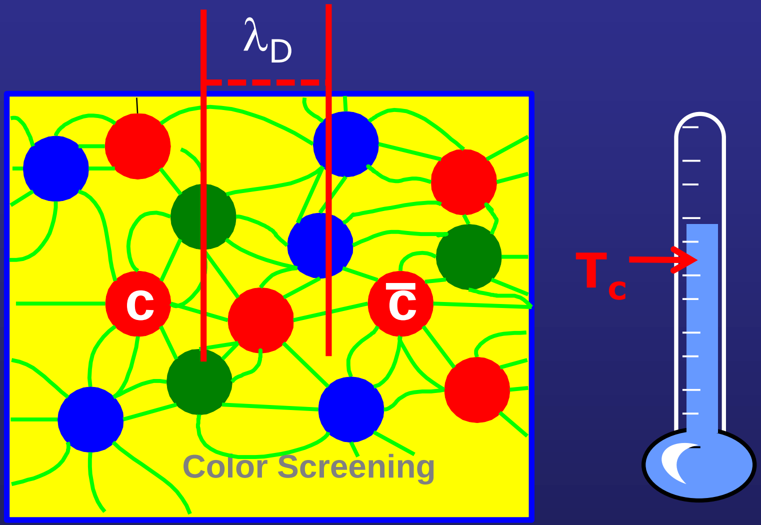
E. Scomparin, State of the art of HI measurements, Hot QCD Matters, Frascati 2017

# The quest for QGP

- At the beginning, experiments were concentrating on the detection of the so-called **“QGP signatures”**, smoking guns for the phase transition

  - Two (famous) examples
    - The J/ψ suppression (Matsui and Satz, 1986)

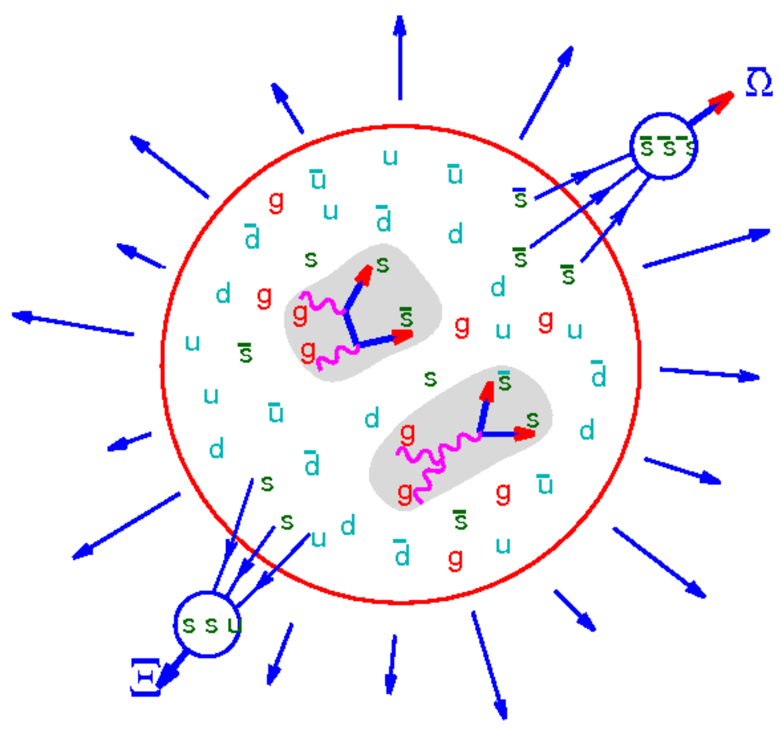




# The quest for QGP

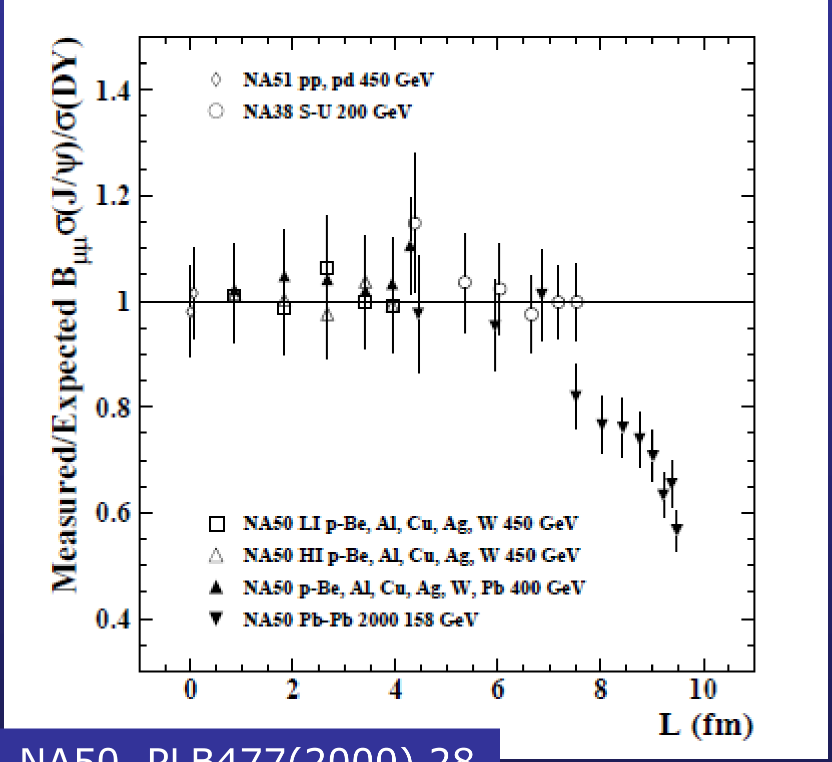
- At the beginning, experiments were concentrating on the detection of the so-called **“QGP signatures”**, smoking guns for the phase transition

  - Two (famous) examples
    - The strangeness enhancement (Hagedorn and Rafelski, 1980)



# The SPS inheritance

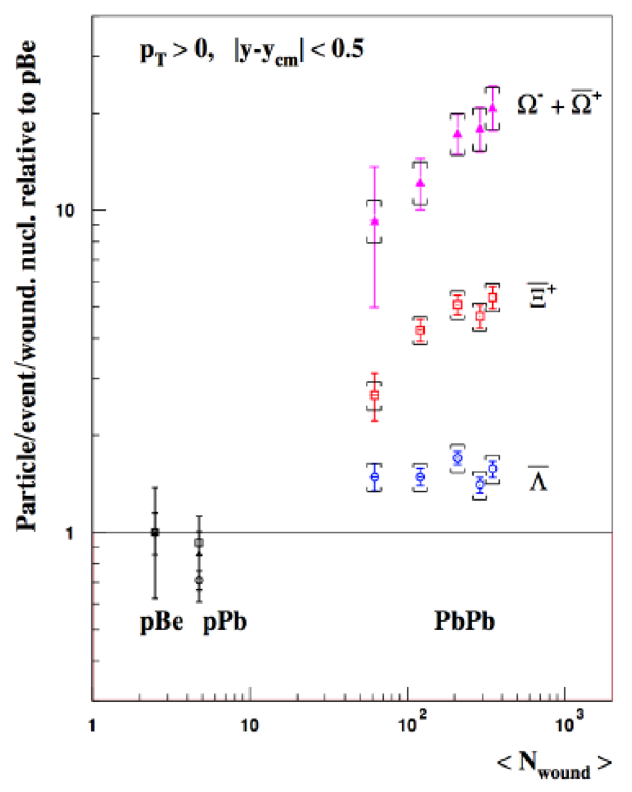
- ❑ SPS/RHIC results → crucial steps in our understanding of QGP
- ❑ **SPS → evidence for deconfinement signals**



NA50, PLB477(2000) 28

Clear signal of J/ψ suppression beyond CNM effects

NA57, J.Phys.G 32 (2006) 427



Clear enhancement of strange hyperon production

# Pinning down the QGP properties

- ❑ More recently, the approach is no more simply based on “signatures”

- ❑ Energy density needed for transition to QGP → $\varepsilon_c \sim 1$ GeV/fm$^3$
- ❑ **Energy density attained at ion colliders → $\varepsilon > 10\ \varepsilon_c$**
  **→ transition towards a deconfined state is indisputable**

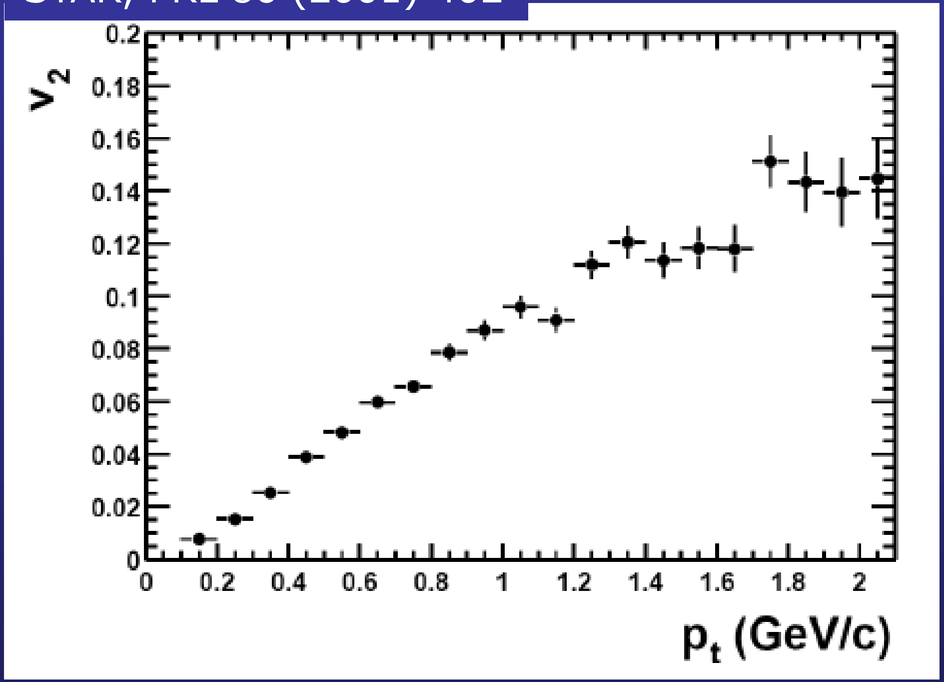
- ❑ Choose a wide set of **observables** that can have a connection, as direct as possible, with specific properties (intensive or extensive) of the system, and try to evaluate as precisely as possible those properties, starting from accurate measurements of the related observables

- ❑ Interaction between **theory and experiment** is crucial
  → data driven field, complex phenomenology

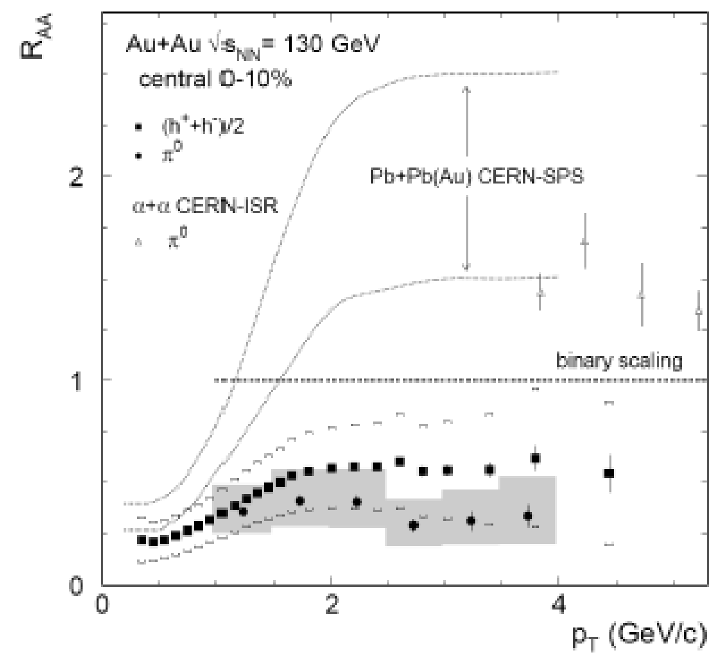
# The RHIC inheritance

- **RHIC: new observables and two major discoveries**

STAR, PRL 86 (2001) 402



PHENIX, PRL 88 (2002) 022301

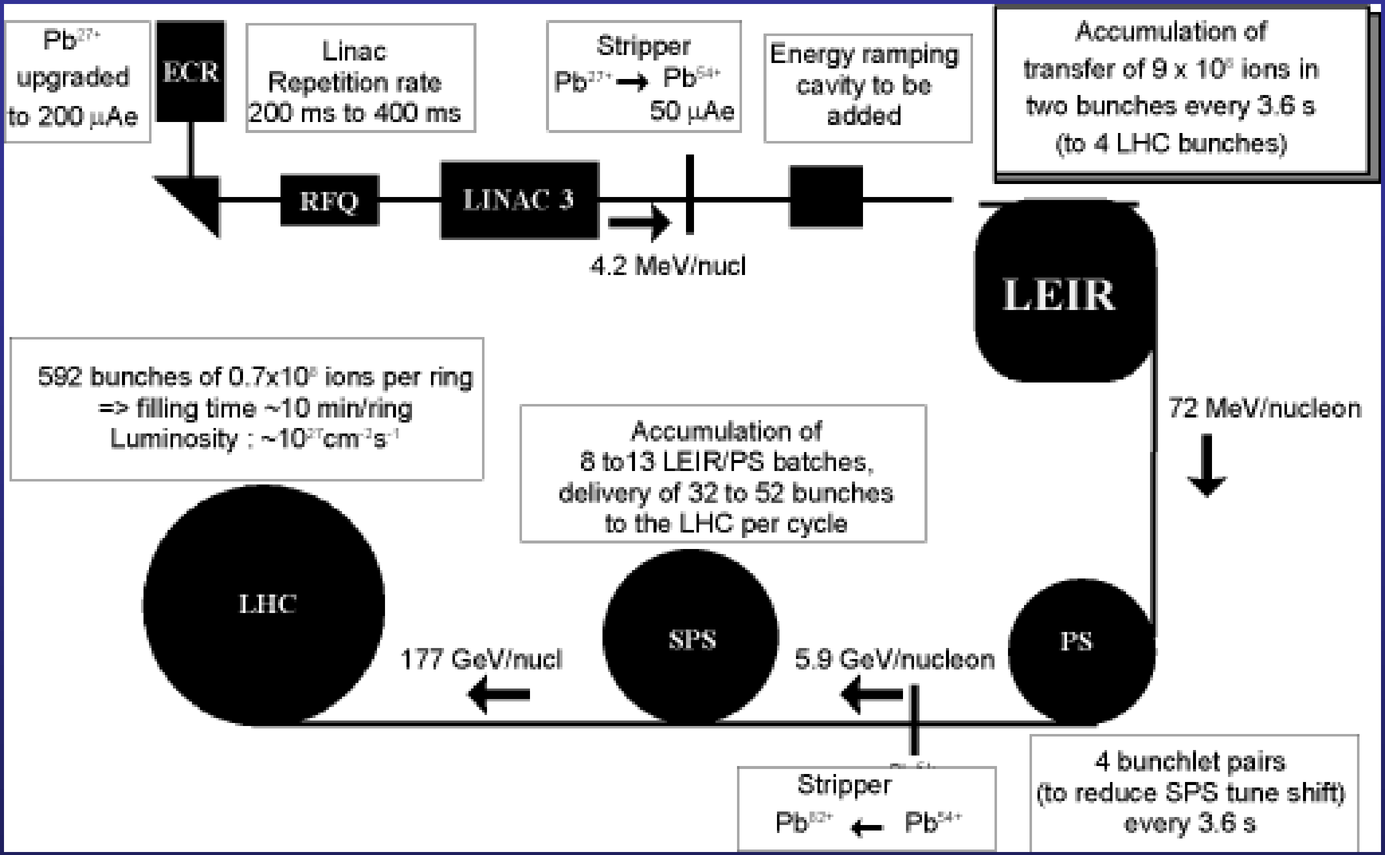


Strong elliptic flow
(close to hydro limit)

Quenching of high-$p_T$ particles in central Au-Au collisions

**QGP as a perfect liquid, opaque to hard probes traversing it**

# Heavy ions in the LHC

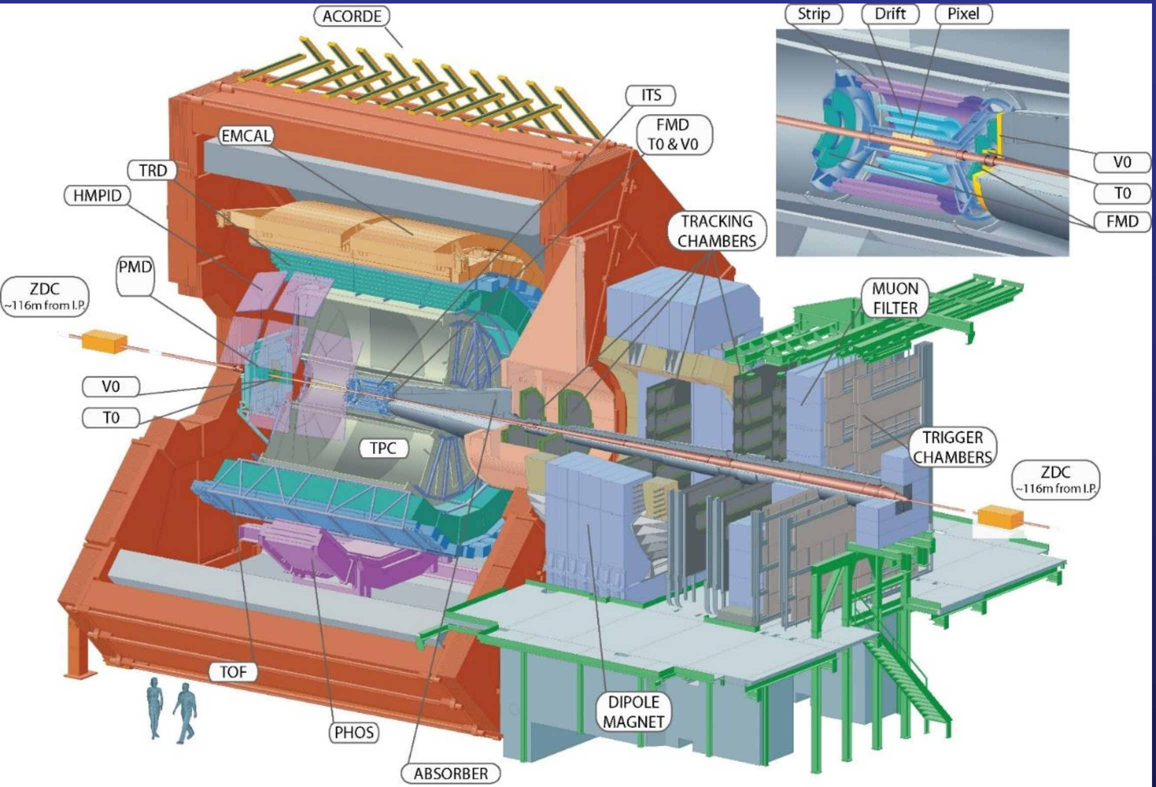


- ❑ Acceleration of ions in the LHC poses non-negligible technical problems
- ❑ Instantaneous luminosity much lower than in pp (factor $10^6$-$10^7$)

  → **limited by ions lost to e.m. dissociation and $e^-$ capture**

# LHC experiments

- **All the major LHC experiments take data with Pb-beams**
  - ALICE → dedicated experiment, from 2010
  - ATLAS, CMS → from 2010
  - LHCb → from 2013

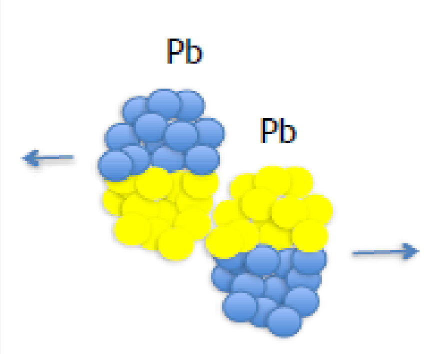


- Complete characterization of QGP observables requires

→ Powerful PID
→ Low-$p_T$ coverage (bulk of particle production)
→ Access to hard probes (jets, heavy quarks, quarkonia)

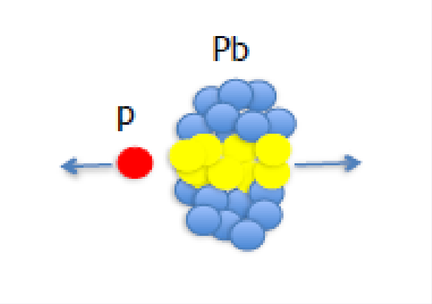
- LHC experiments are to a good extent complementary

# The collision systems

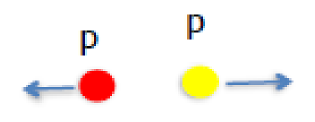


**Pb-Pb collisions**
Hot matter effects
Soft + hard probes

Three classes of collisions are needed for a complete characterization of QGP



**p-Pb collisions**
Calibrate cold nuclear matter effects (CNM)

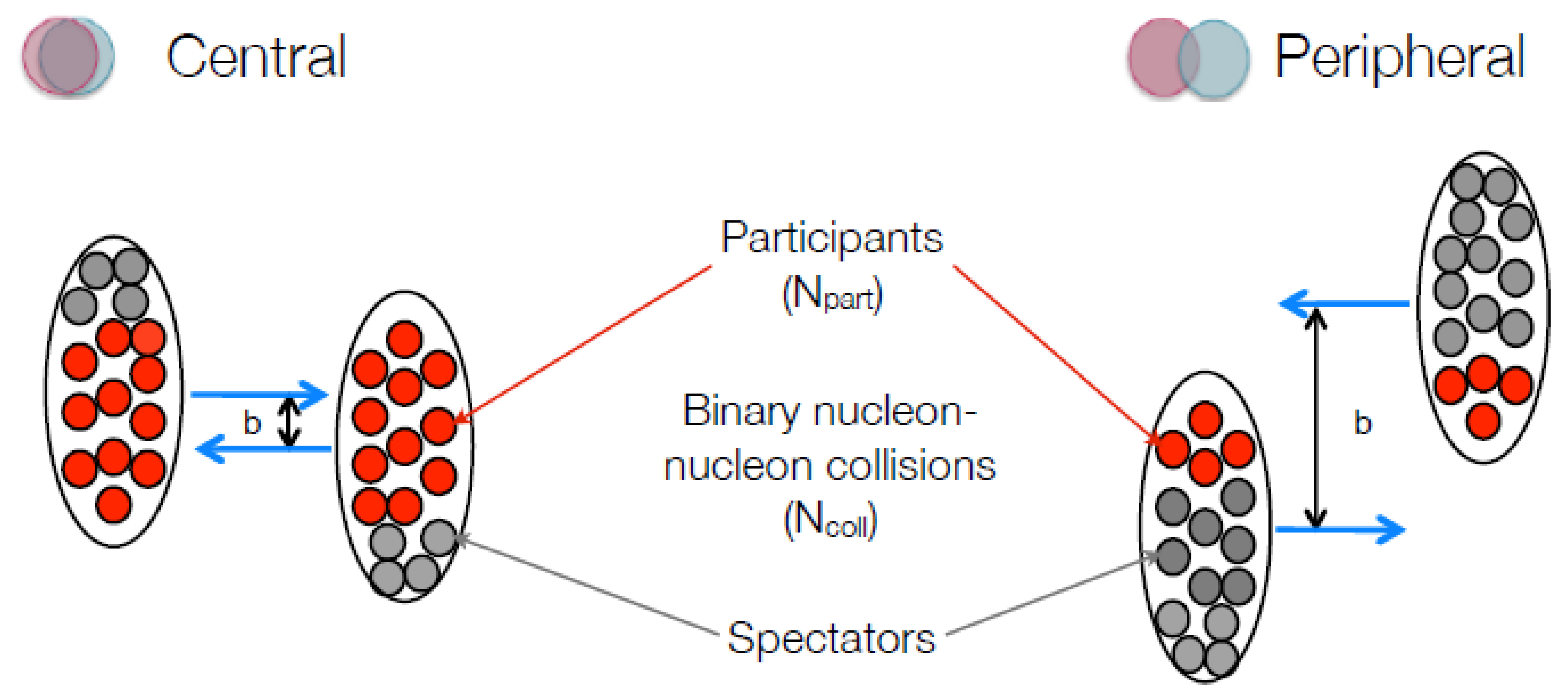


**pp collisions**
Reference for Pb-Pb studies, QCD (mainly soft)

Change of paradigm at LHC energies!
**High-multiplicity p-Pb and pp collisions show intriguing signals of QGP-like effects**

# Collision centrality

- ❑ Nuclei are extended objects
- ❑ **Geometry connected to observables via Glauber Model**
- ❑ Related to multiplicity or forward energy (spectators)



E. Scomparin, State of the art of HI measurements, Hot QCD Matters, Frascati 2017

# Data samples – run 1 (ALICE)

| **System** | **$\sqrt{s_{NN}}$ (TeV)** | **$L_{int}$** | **Year** |
|---|---|---|---|
| pp | 0.9 | 0.15 $nb^{-1}$ | 2009-2010 |
| pp | 2.76 | 1.1 $nb^{-1}$ | 2011 |
| pp | 7 | 4.8 $pb^{-1}$ | 2010-2011 |
| pp | 8 | 9.7 $pb^{-1}$ | 2012 |
| p-Pb | 5.02 | 30 $nb^{-1}$ | 2013 |
| Pb-Pb | 2.76 | 0.1 $nb^{-1}$ | 2010-2011 |

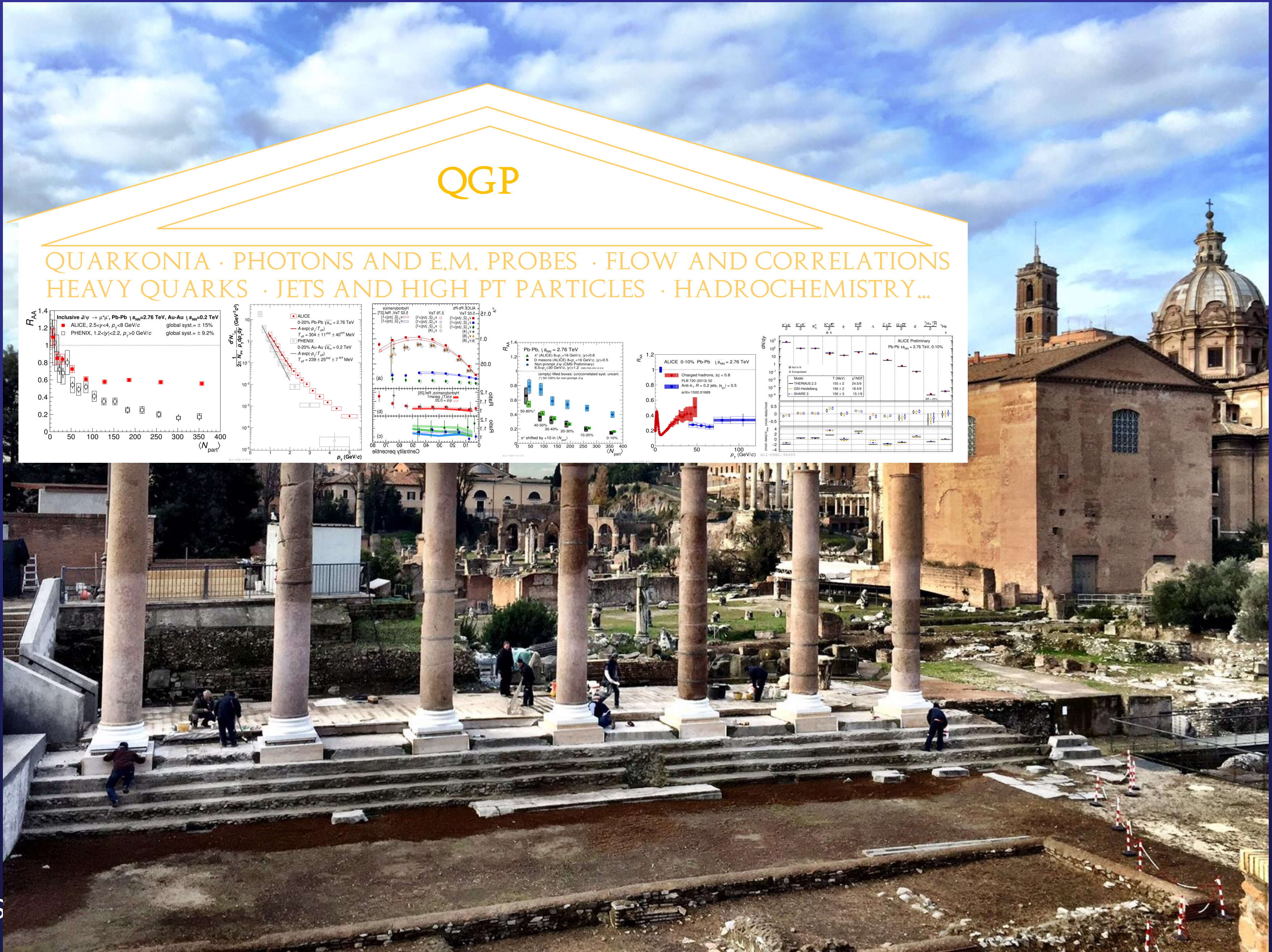
Run 1
(2009-2013)

Run 2
(2015-2018)

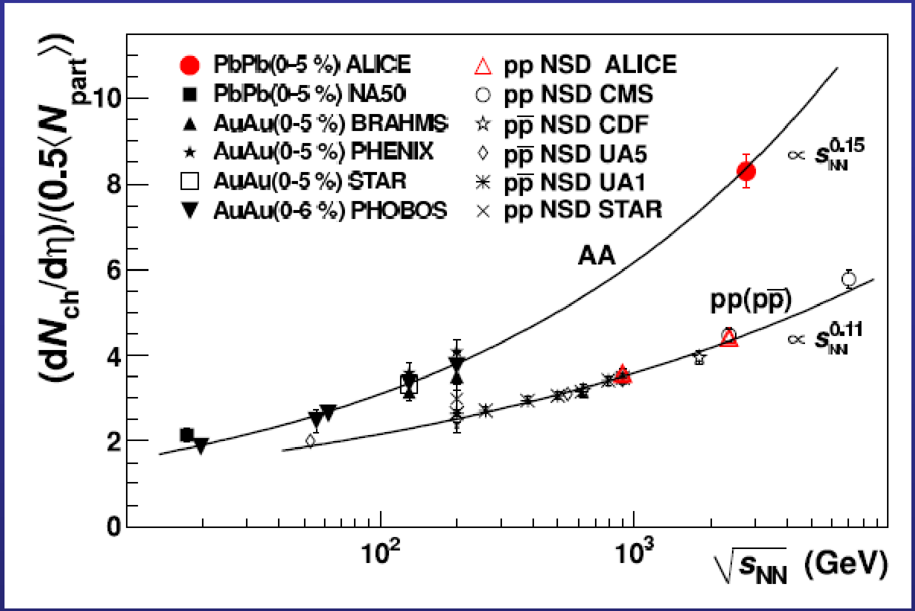
| **System** | **$\sqrt{s_{NN}}$ (TeV)** | **$L_{int}$** | **Year** |
|---|---|---|---|
| pp | 13 | 14 $pb^{-1}$ | 2015-2016 |
| Pb-Pb | 5.02 | 0.4 $nb^{-1}$ | 2015 |
| pp | 5 | 100 $nb^{-1}$ | 2015 |
| p-Pb | 5.02 | 3 $nb^{-1}$ | 2016 |
| p-Pb | 8.16 | ~20 $nb^{-1}$ | 2016 |

# Pb-Pb collisions: the columns of QGP

# Pb-Pb collisions: the columns of QGP

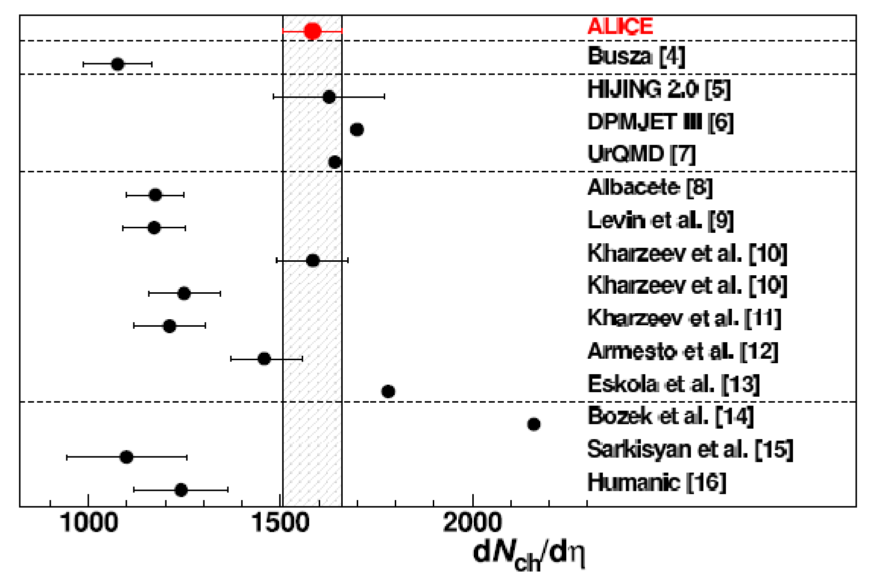


# Charged particle multiplicity



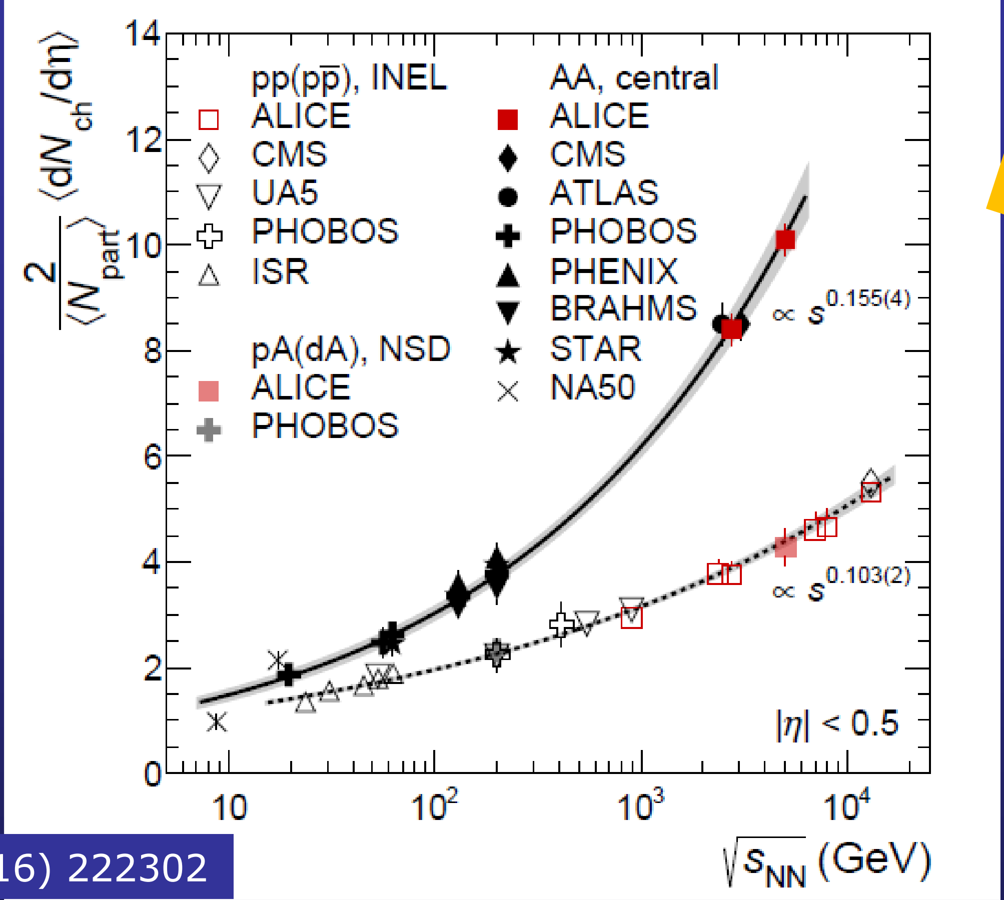
- **Steep rise in $(dN_{ch}/d\eta)/0.5\langle N_{part}\rangle$ from RHIC energy to LHC**
  (from logarithmic at low energy to power law)
  → Possibly related to the significant increase of the contribution of hard processes

- Interesting test for theoretical calculations
  → sensitive to the modelling of the initial state of the collision (gluon saturation)



ALICE, PRL 105, 252301 (2010)

# Charged particle multiplicity → run 2



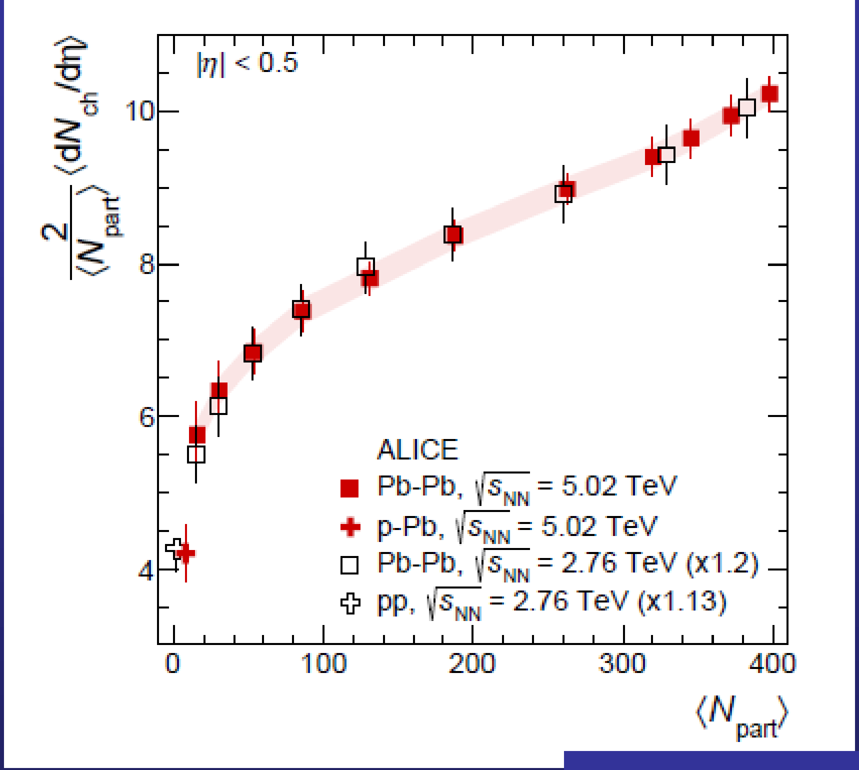
**Pb-Pb**
**$\sqrt{s_{NN}}$ =5.02 TeV**

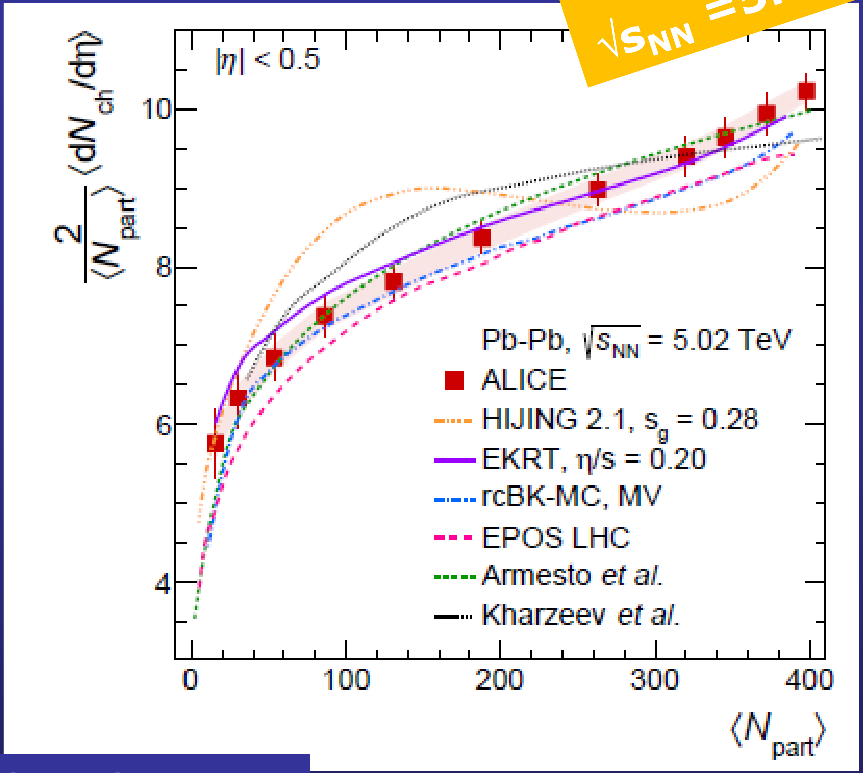
ALICE, PRL 116 (2016) 222302

- ❑ **20% increase** for the most central collisions **with respect to $\sqrt{s_{NN}}$ =2.76 TeV,** in agreement with the previously established power-law dependence
→ indicates a similar increase in the energy density reached

# Centrality dependence of ($dN_{ch}/d\eta$)

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



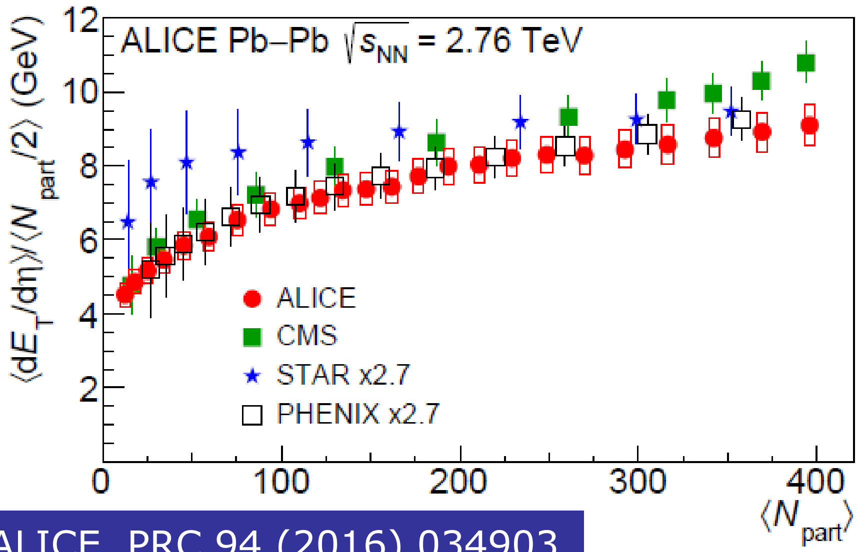


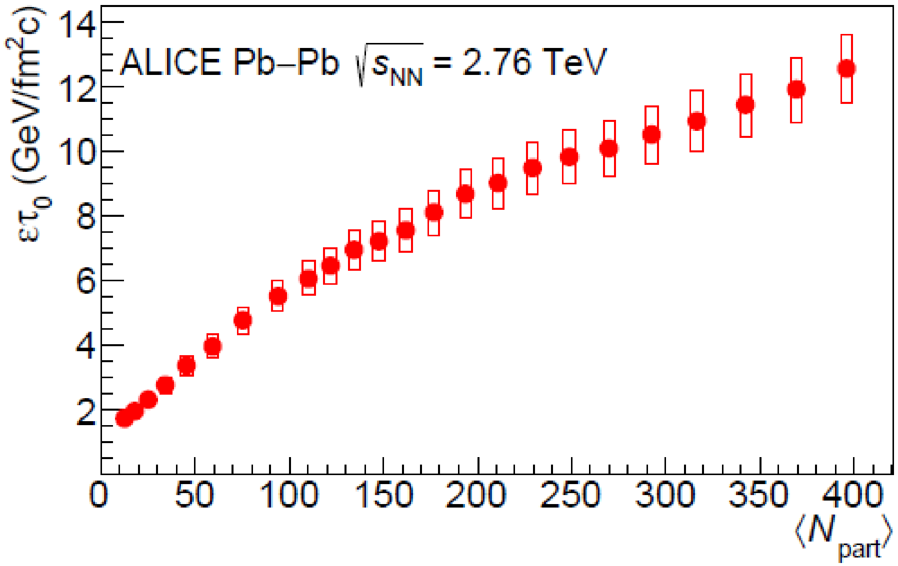
ALICE, PRL 116 (2016) 222302

- ❑ **Factor ~1.8 on charged multiplicity per participant pair, from peripheral to central collisions**
- ❑ Shape of the centrality dependence remarkably similar to RHIC
- ❑ Models tuned at $\sqrt{s_{NN}}$=2.76 TeV reasonably reproduce the 5.02 TeV data

# Transverse energy and energy density

- ❑ Use tracking detectors and PHOS/EMCAL





ALICE, PRC 94 (2016) 034903

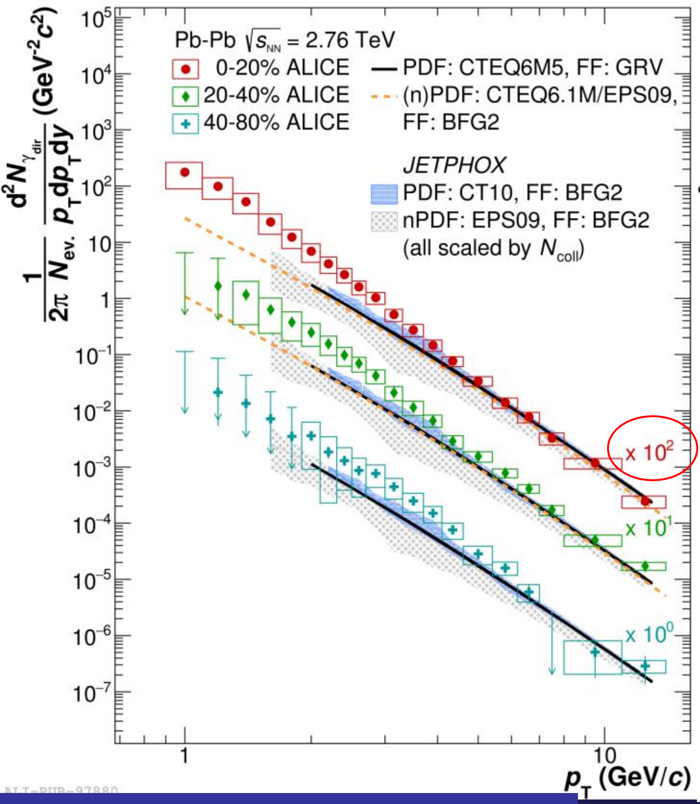
- ❑ Results consistent with CMS in 10-80%, (slightly) lower in 0-10%
- ❑ Shape of centrality dependence is similar at RHIC and LHC

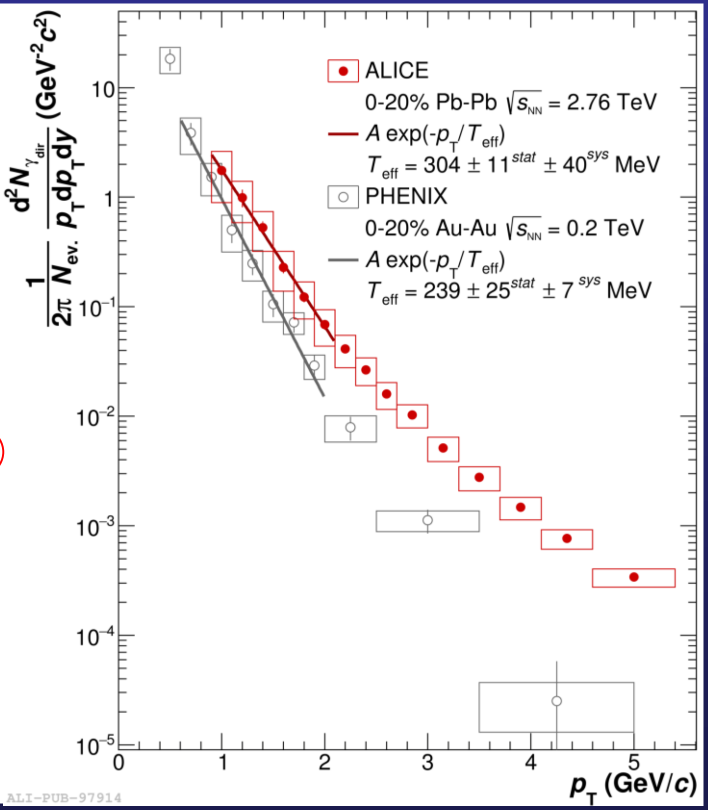
- ❑ Assuming a formation time $\tau_0$=1 fm/c
  - ❑ Energy density → $\varepsilon_{Bj}$=12.3 ± 1.0 GeV/fm$^3$ (0-5%)
  - ❑ **In the core of the reaction region → $\varepsilon_{Bj}$=21 ± 2 GeV/fm$^3$**

- ❑ To be compared with critical energy density $\varepsilon_{Bj}$~ 1 GeV/fm$^3$ !

# Direct photons and temperature

- ❑ Direct photon spectra at $p_T$>5GeV/*c* are in agreement with pQCD pp calculations scaled by $N_{coll}$
- ❑ Central Pb-Pb collisions (0-20%): 2.6σ excess for 0.9< $p_T$<2.1 GeV/*c*
- ❑ Low $p_T$ dominated by thermal photons
  **→ $T_{eff}$ = 304±11±40 MeV (~30% higher than RHIC)**



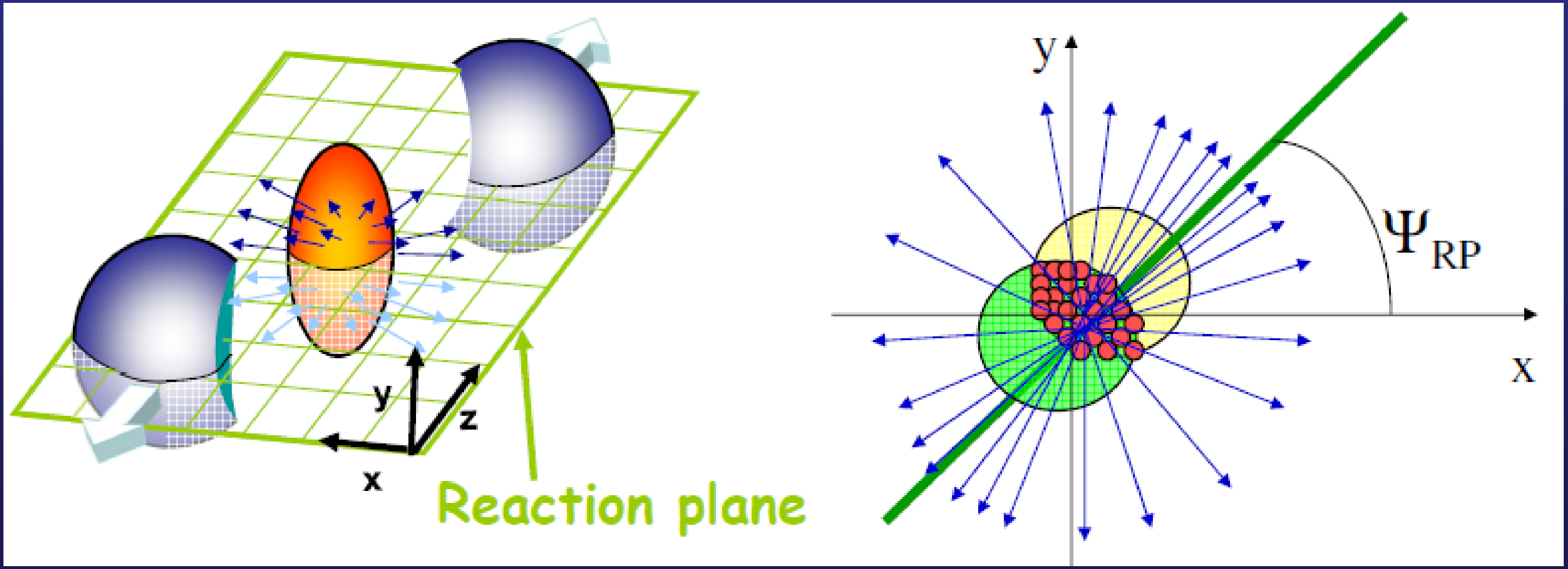


- ❑ Interpretation of the inverse slope parameter not trivial
  → A correlation with the initial temperature exists
- ❑ Two contributions
  → blue-shifted photons from the late stages (high radial flow)
  → high-T photons from early stages

ALICE, PLB 754 (2016) 235

# Azimuthal anisotropy

- ☐ Impact parameter + beam direction → reaction plane
- ☐ Correlation between azimuthal emission angles and reaction plane
  - → Evidence for collective behaviour
- ☐ Non-central heavy-ion collisions
  - → geometrical anisotropy of the fireball
- ☐ In a hydro-dynamic scenario
  - → **Azimuthal anisotropy mainly related to different pressure gradients in the collectively expanding medium**



E. Scomparin, State of the art of HI measurements, Hot QCD Matters, Frascati 2017

# Azimuthal anisotropy

- ❑ Fourier expansion of the azimuthal distributions

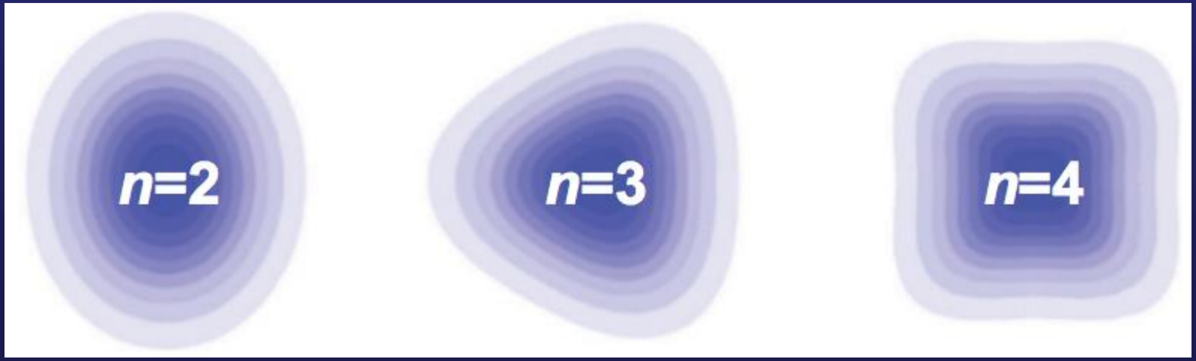
$$\frac{dN}{d(\varphi-\Psi_{RP})}=\frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos(2(\varphi-\Psi_{RP}))+\ldots\right)$$

$$v_n=\left\langle\cos\left[n(\varphi-\Psi_{RP})\right]\right\rangle$$

**$v_2$: elliptic flow: strongly related to the thermalisation of the medium**

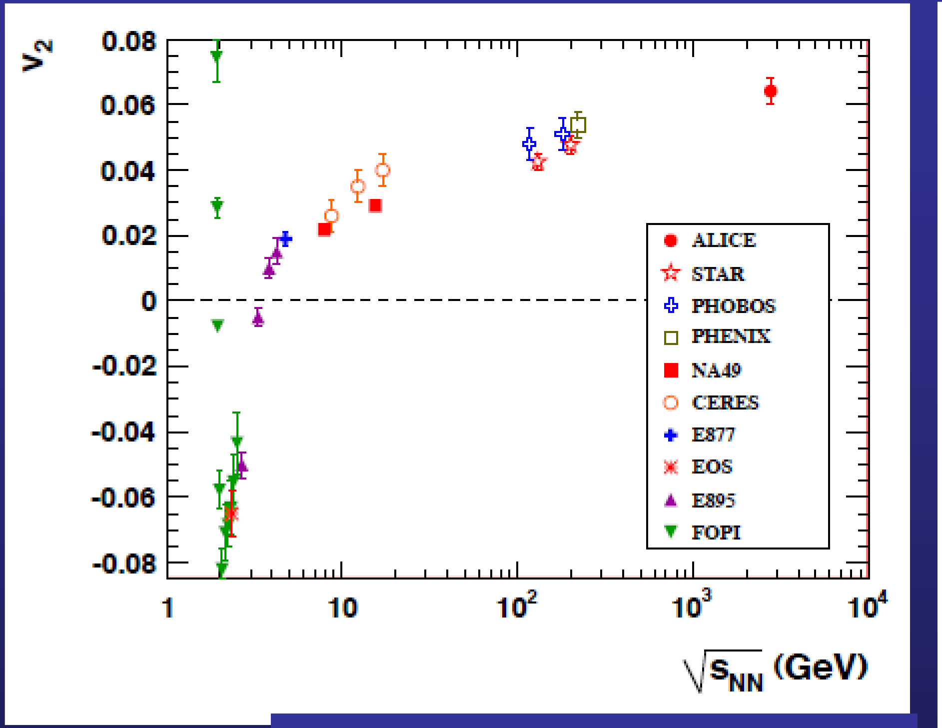
**$v_3$, $v_4$, … : information on the geometric fluctuations of the initial state**

(odd harmonics should be zero w/o fluctuations)

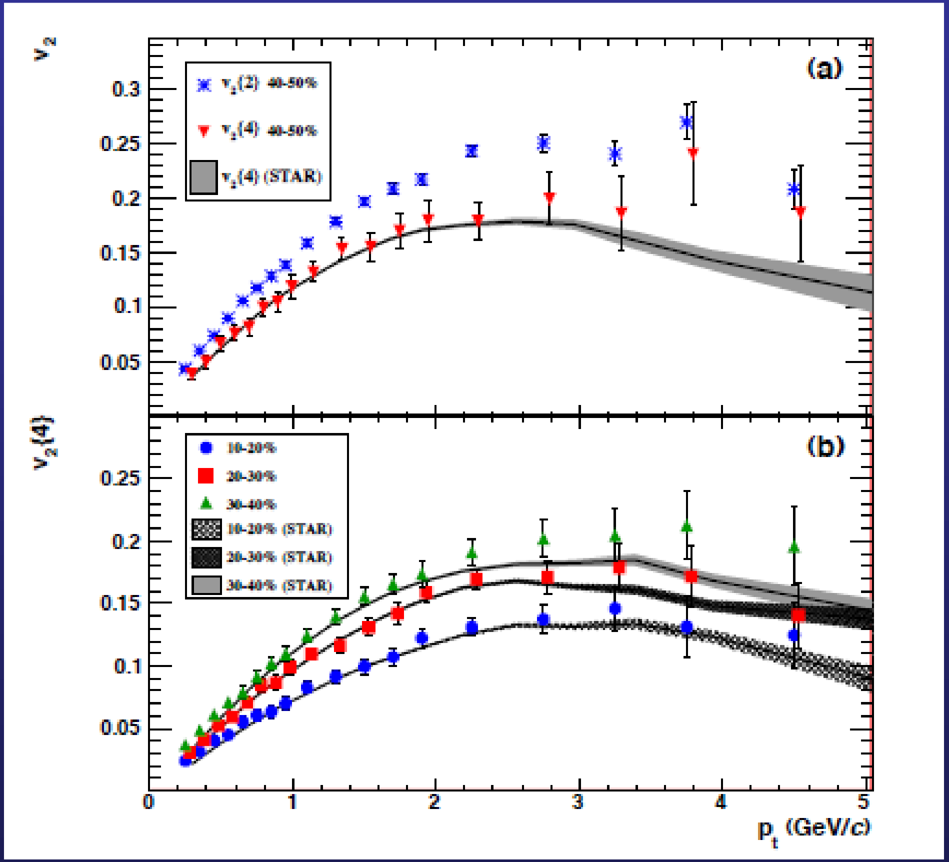


# Elliptic flow – run 1 results

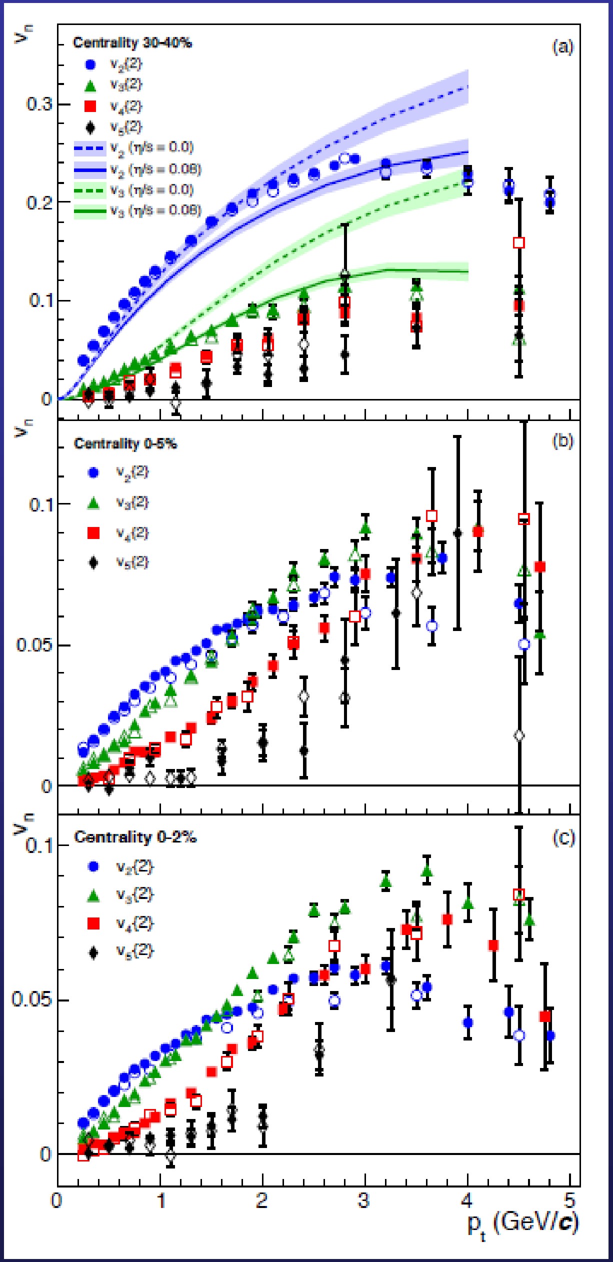
- **Integrated $v_2$ is >0, increases by ~30% from RHIC to LHC energy**



ALICE, PRL 105, 252302 (2010)



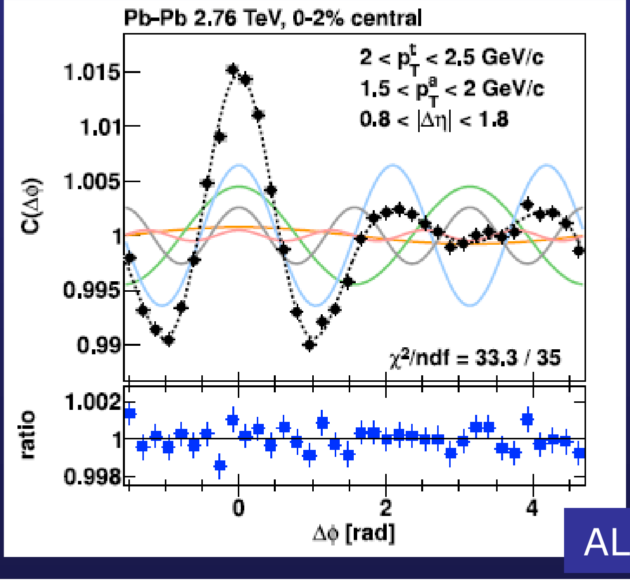
- At fixed $p_T$, the elliptic flow values are very similar at RHIC and LHC energies
  → higher integrated $v_2$ at LHC related to the $\langle p_T \rangle$ increase



# Higher flow harmonics

- Comparisons with hydro models: **$v_2$ and $v_3$ values consistent with values of the viscosity to entropy density ratio close to the ideal fluid limit → $\eta/s = 1/4\pi$**

- (Ultra) central events: $v_2$ strongly decreases, reaction region has a nearly spherical symmetry. Higher harmonics, dominated by fluctuations, are sizeable

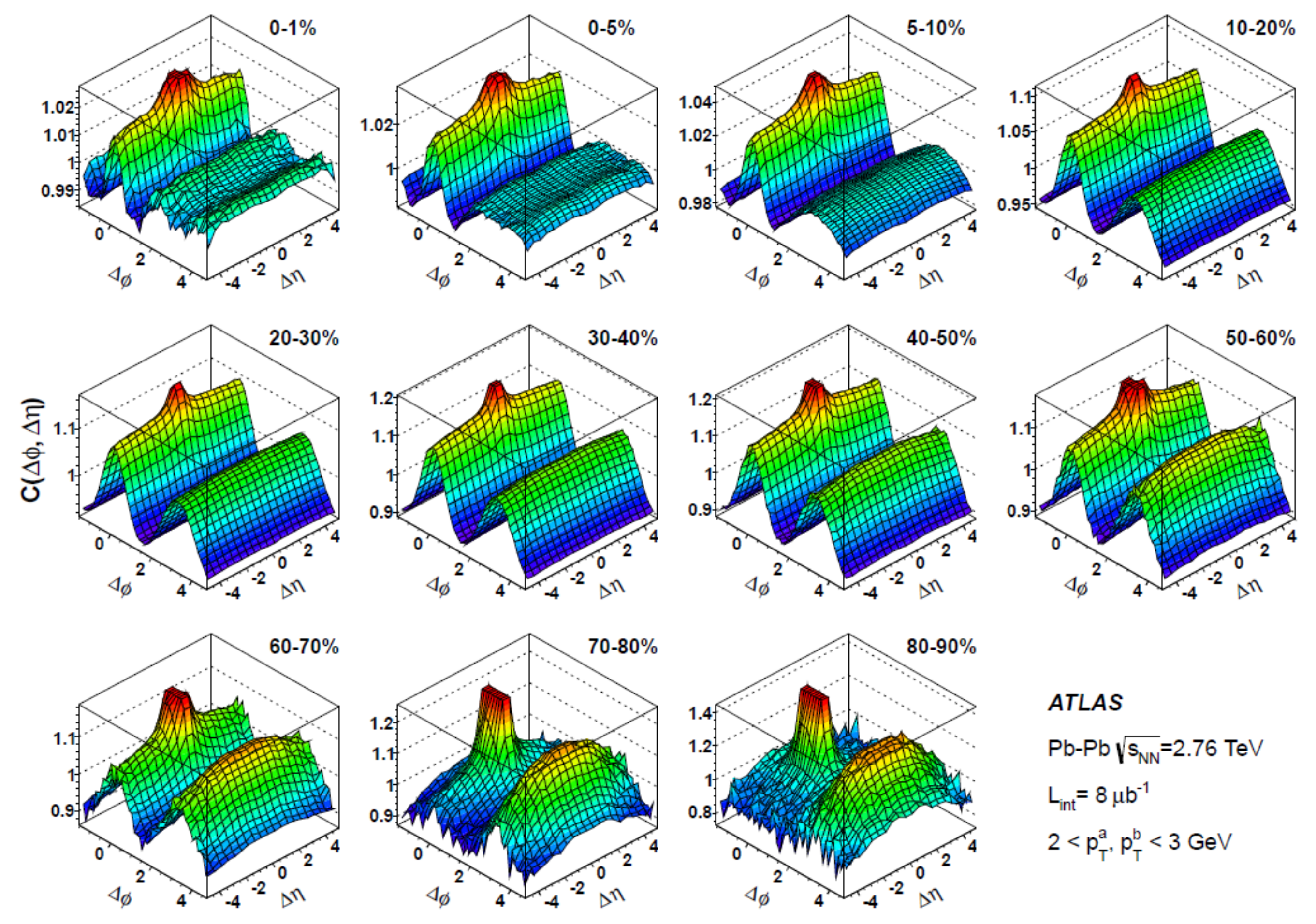


- Also 2-particle correlations studies show evidence for anisotropies up to the 5th harmonics

ALICE, PRL 107 (2011) 032301

# Flow harmonics from 2-particle correlations

ATLAS, PRC 86(2012) 014907



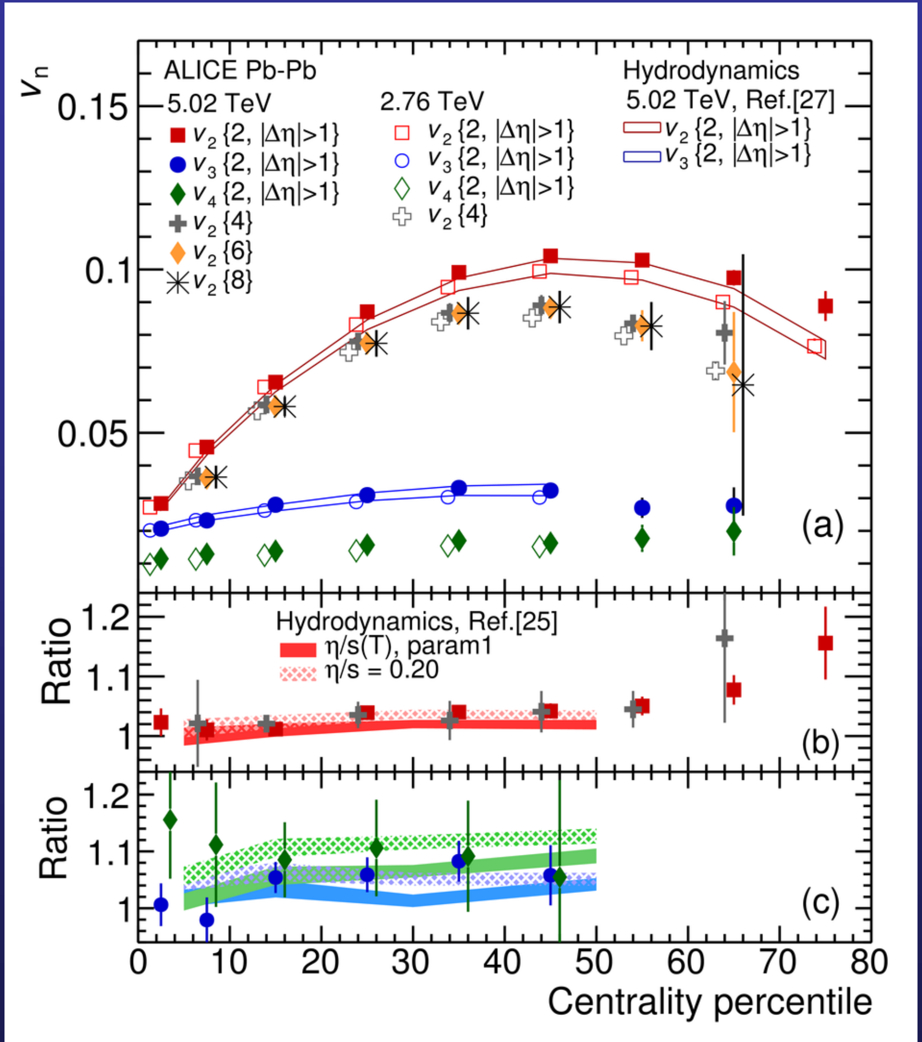
**“Ridge” extending to large $\Delta\eta$ in the region $\Delta\phi \approx 0$** (long-range structure)

Related to the presence of non-zero Fourier harmonics (plus contribution from jet production, concentrated at small $\Delta\eta$)

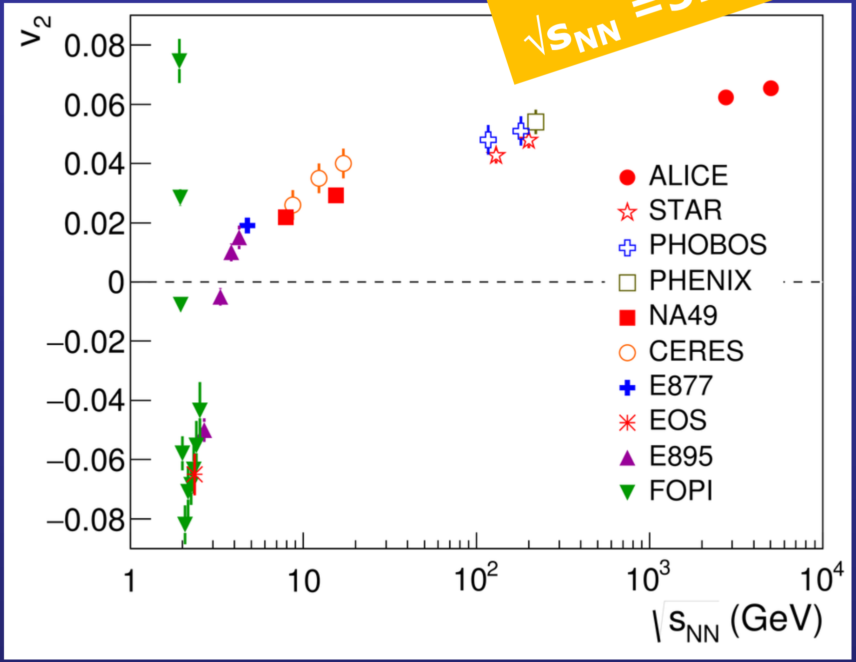
Thought to be typical of Pb-Pb collisions → **evidence for collective effects**

# Elliptic flow – run 2 results

**Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV**



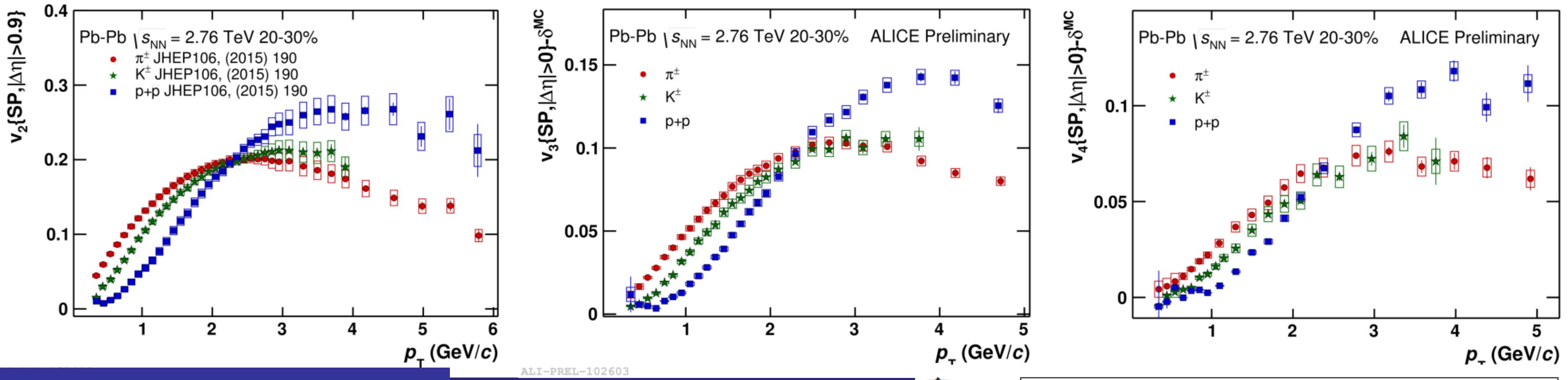
ALICE, PRL 116 (2016) 132302



- $v_n$ for the $p_T$ range $0.2<p_T<5.0$ GeV/$c$ vs centrality (ratios are between 5.02 TeV and 2.76 TeV results)
- **Average increase of (3.0±0.6)% for $v_2$, (4.3±1.4)% for $v_3$ and (10.2±3.8)% for $v_4$ from 2.76 to 5.02 TeV, for 0-50% centrality**
- Results compatible with predictions from hydrodynamic models

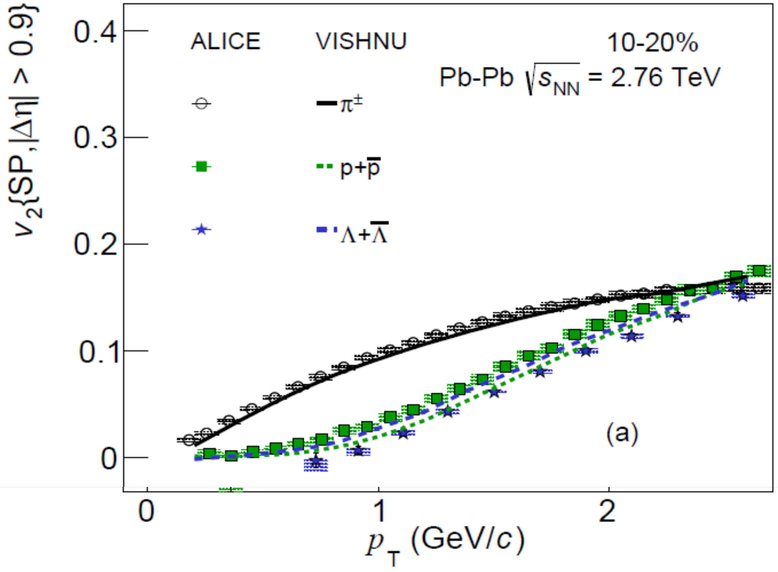
# Identified particles: flow

- Studies of flow harmonics for various particle species show **significant dependence on particle mass**



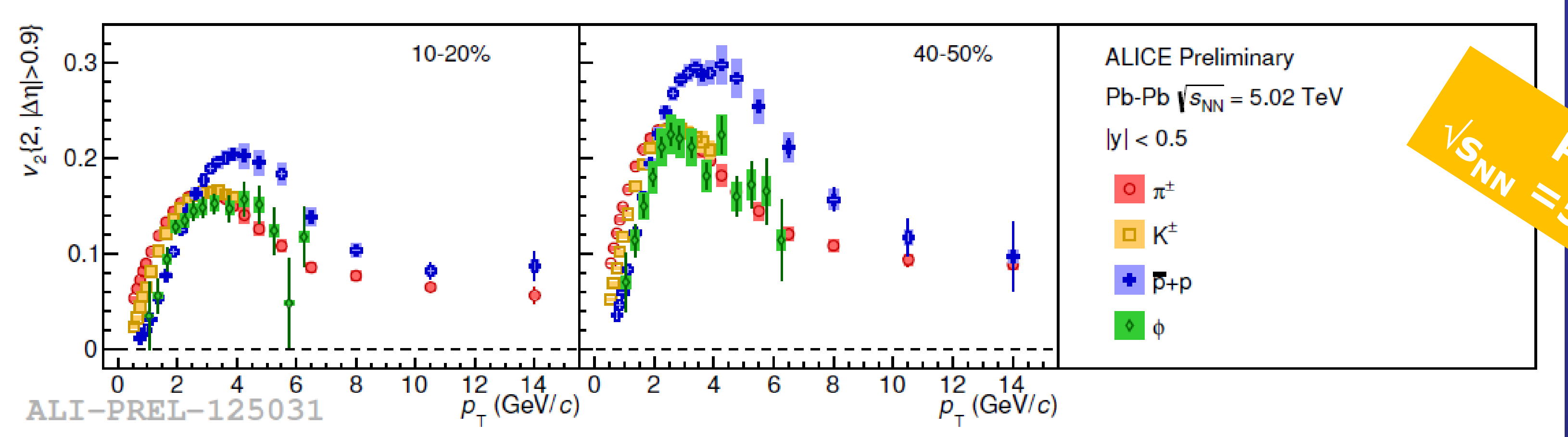
ALICE, JHEP 06 (2015) 190

- **Mass ordering** can be interpreted in terms of an **interplay between collective radial expansion and anisotropic flow**
- At high $p_T$, particles tend to group according to mesons vs baryons (but no precise $n_q$ scaling visible)
- Effects well reproduced by QGP+hadronic cascade models (VISHNU)

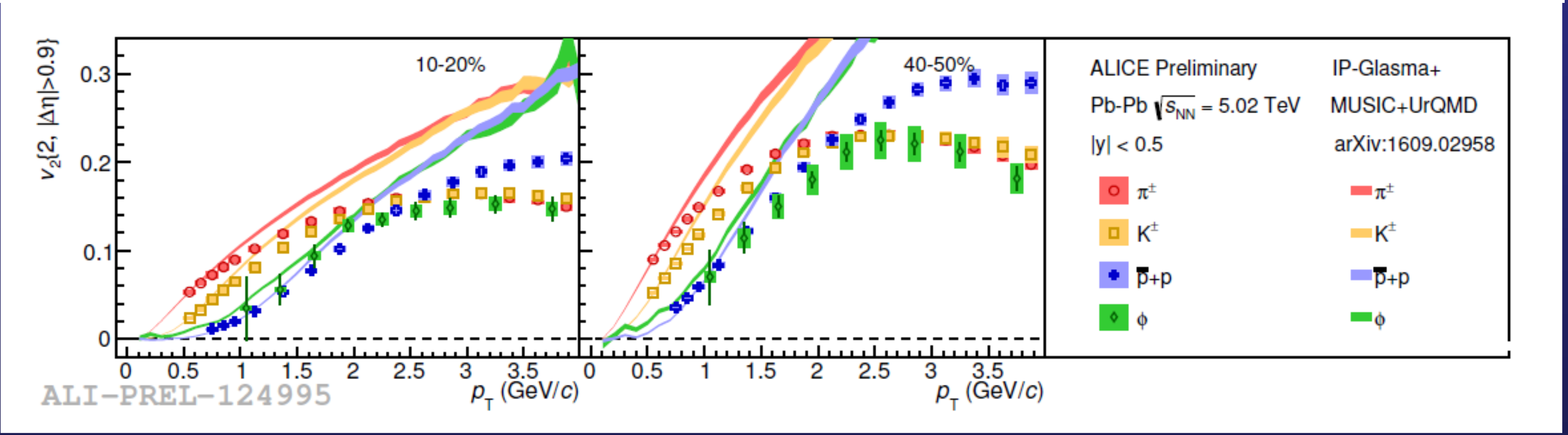


# Recent run-2 results

- Include **$\phi$-meson $v_2$** (mass similar to proton, baryon vs meson effects?)

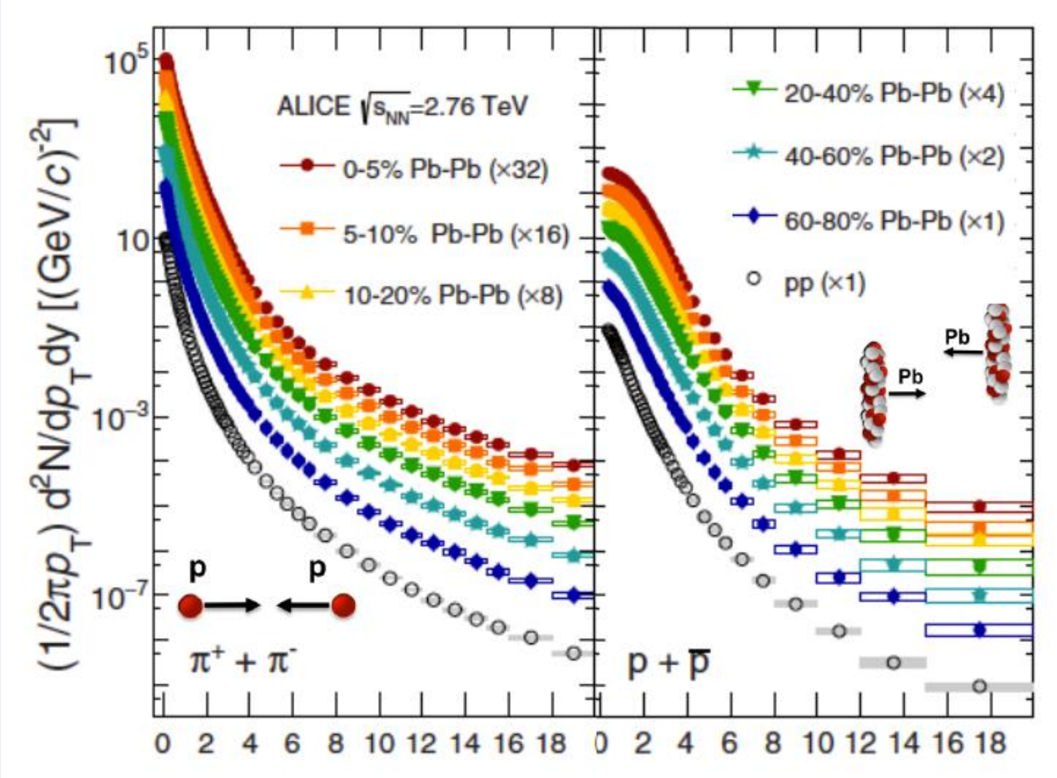


Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV



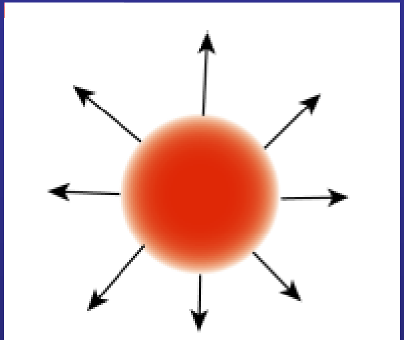
- **Low-$p_T$ $v_2$ as test for hydrodynamic expansion**
- Good agreement at low $p_T$ for central collisions, less good for peripheral

# Identified particles: spectra

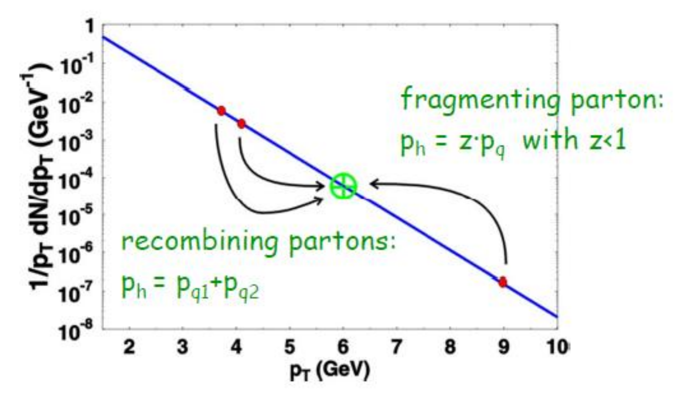


- ❑ Wide $p_T$ range accessible
- ❑ Sensitive to various physics mechanisms

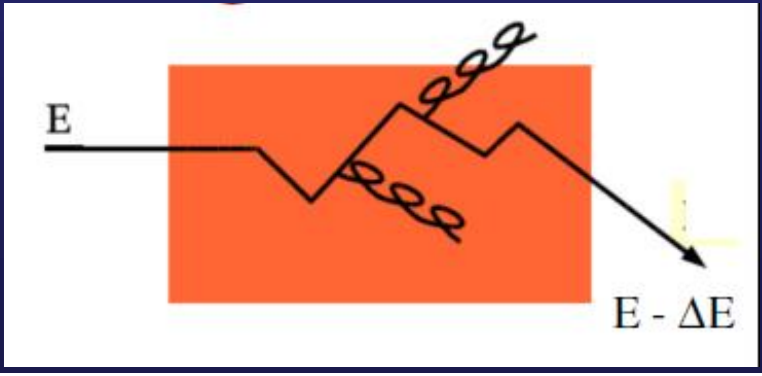
**1) Low $p_T$: collective effects** (radial flow)



**2) Intermediate $p_T$: fragmentation vs recombination**



**3) High $p_T$: parton energy loss**

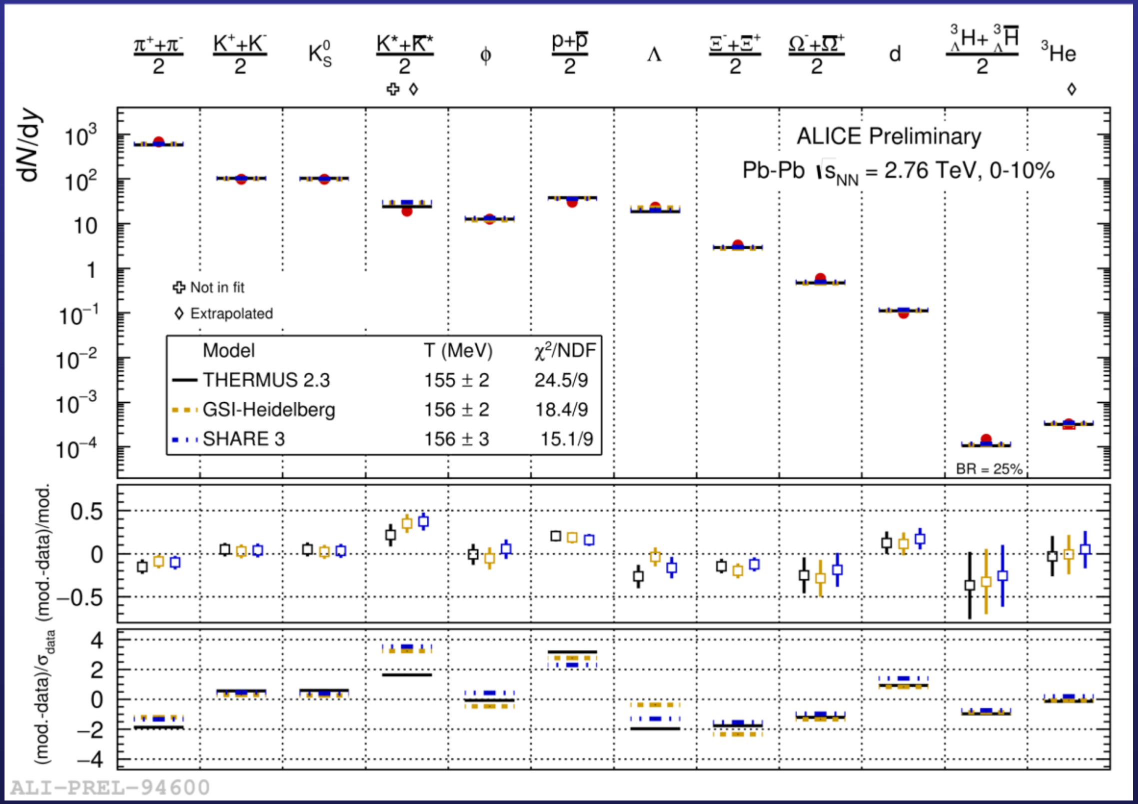


# Identified particles: integrated yields

- ☐ Particle yields of light flavour hadrons described by thermal model fits
- ☐ Fit parameters
  $T_{ch}$ → chemical freeze-out temperature
  $\mu_B$ → baryochemical potential

Yields span 7 orders of magnitude

Agreement within 20% (exception $K^{*0}$ and p )



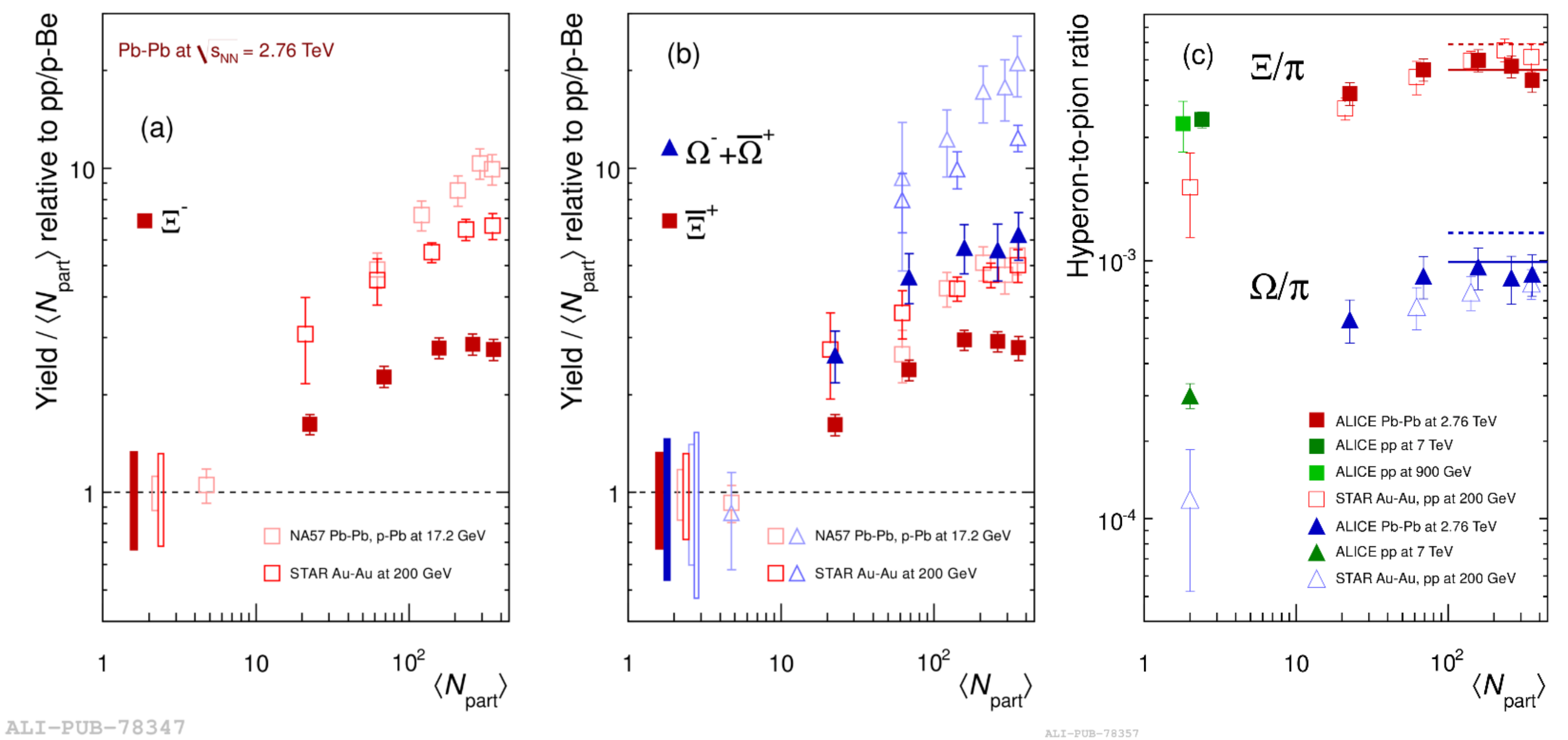
Chemical freeze-out temperature
→ $T_{ch}$ ~ 156 MeV

- ☐ **Hadrons are produced in chemical equilibrium in Pb-Pb collisions at the LHC, as at the SPS and RHIC**

# Back to strangeness enhancement

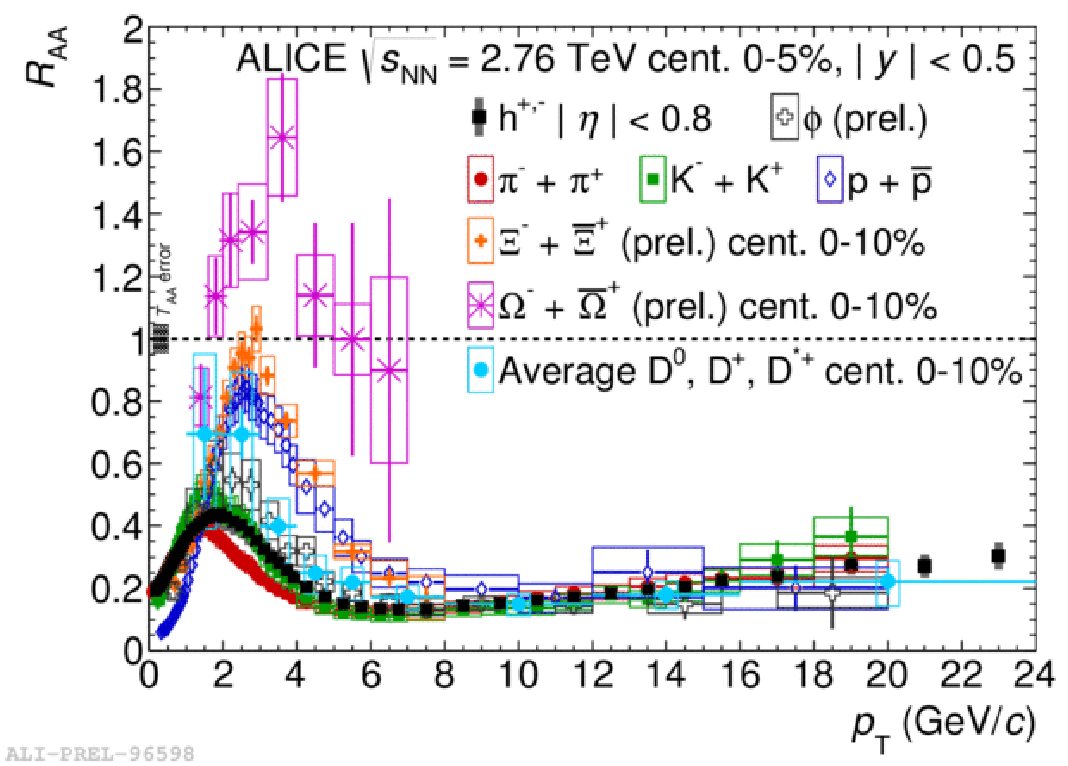
- ❑ **Strangeness enhancement** in A-A observed from SPS up to LHC.
- ❑ More important for **lower energy experiments!** Why?

PLB 728 (2014) 216–227



- ❑ Possible explanation → strangeness enhancement in A-A actually comes from **canonical suppression in pp**, more important for lower energies

# Moving towards high $p_T$ (hard probes)



Particle ID available
up to $p_T$ ~20 GeV/c !

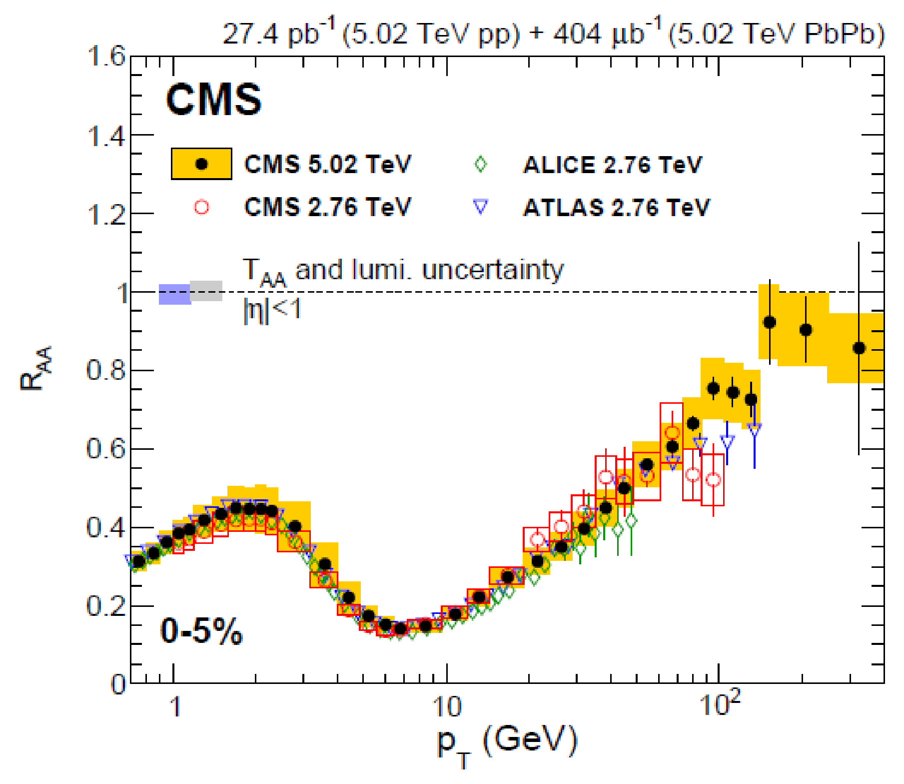
$$R_{AA} = \frac{dN^P_{AA}}{\langle N_{Coll} \rangle \, dN^P_{pp}}$$

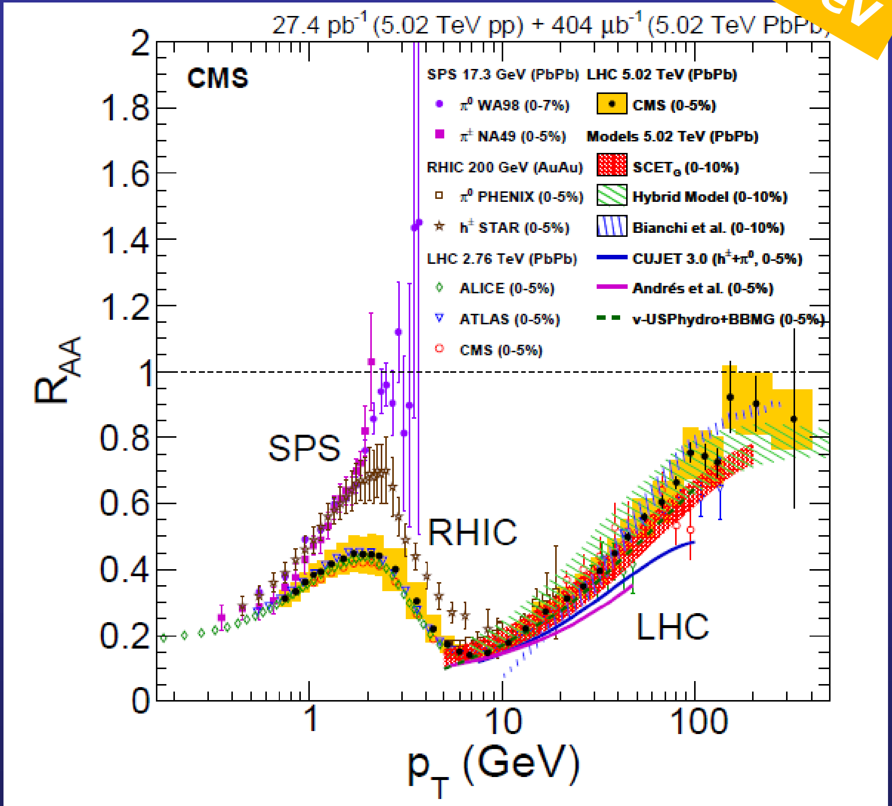
**$R_{AA}$<1 suppression**
**$R_{AA}$>1 enhancement**

- ❑ High $p_T$ → strong suppression with respect to $N_{coll}$ scaling
- ❑ NO sizeable difference vs particle species
  → hadronization is not affected by the medium, **the effect is due to parton energy loss in hot matter**

# Extending up to $p_T$=400 GeV/c!

**Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV**

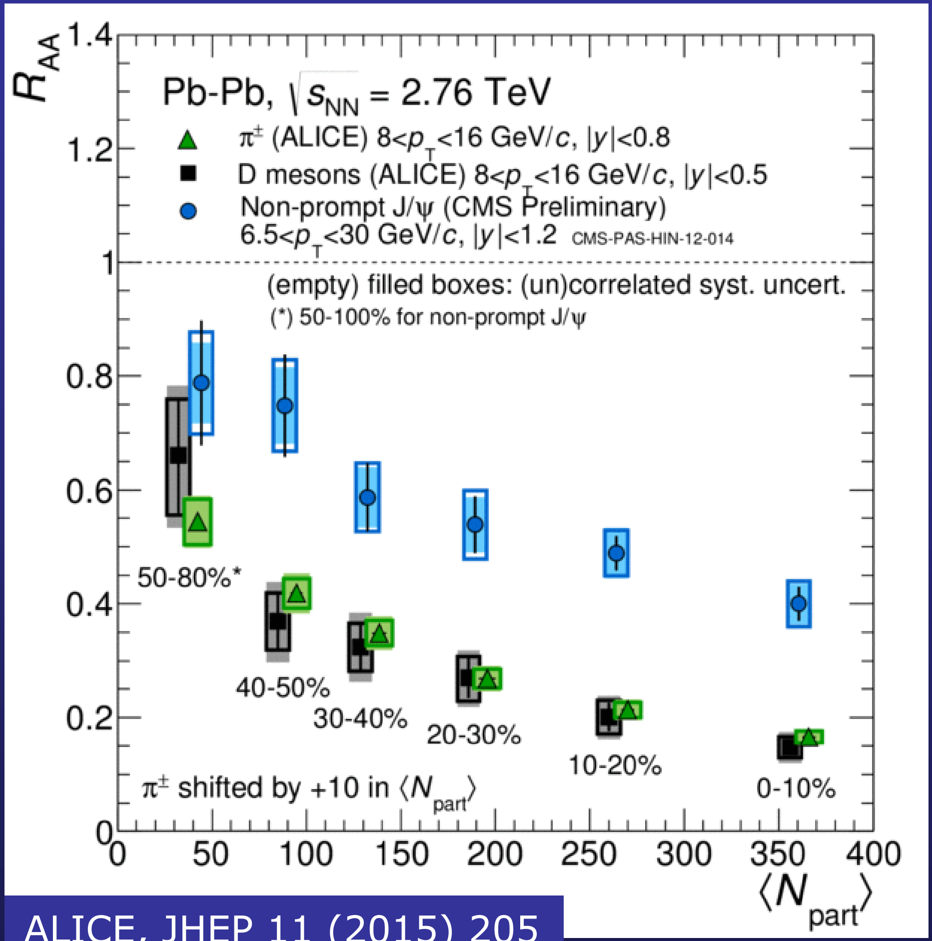




CMS, JHEP 04(2017) 039

- ❑ New CMS results reach unprecedented $p_T$ coverage
- ❑ Remarkably, the **$R_{AA}$ approaches 1 for $p_T$>200 GeV/c (?!)**
- ❑ No significant differences between $\sqrt{s_{NN}}$=2.76 and 5.02 TeV results

# Moving to a detailed understanding Heavy quark $R_{AA}$



ALICE, JHEP 11 (2015) 205
CMS-PAS-HIN-12-014

- ❑ Energy loss expected to depend
  - → On parton color charge (g vs q)
  - → On parton mass (heavy vs light q)

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

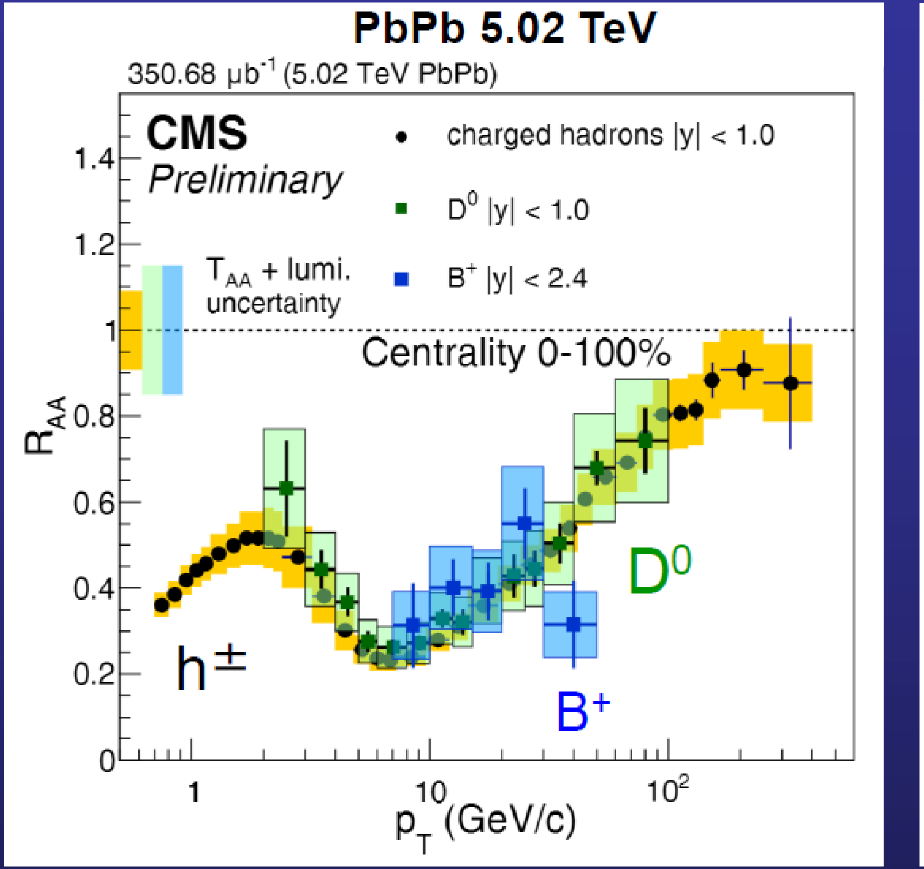
leading to an $R_{AA}$ hierarchy

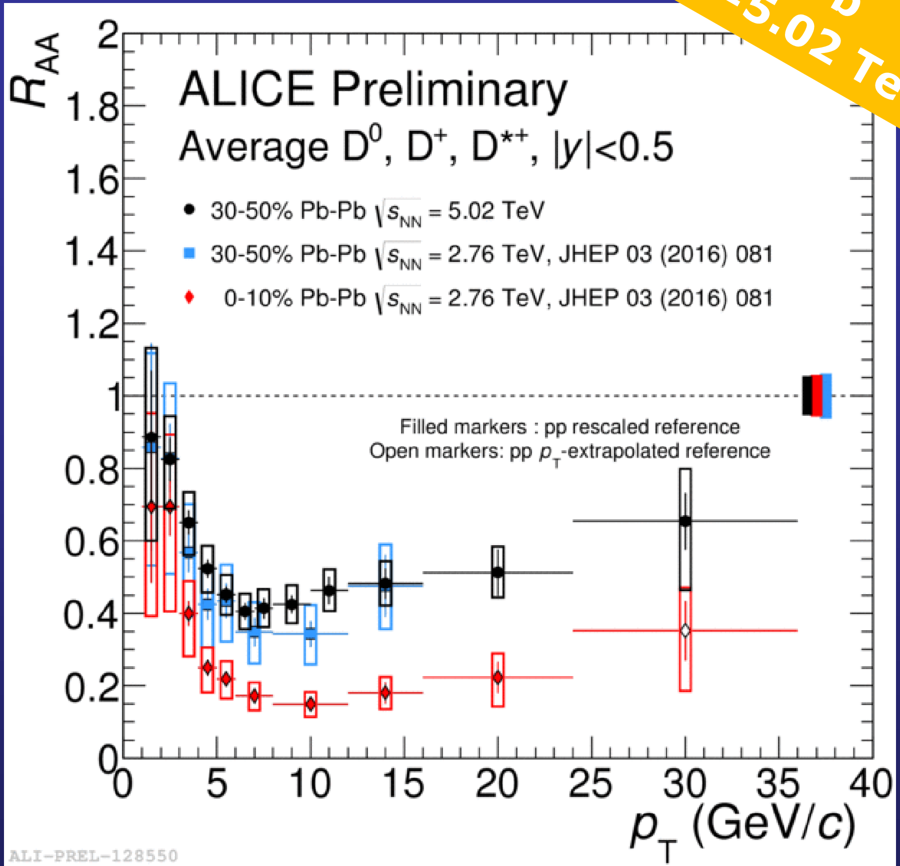
**$R_{AA}$(B) > $R_{AA}$(D) clearly observed (at "low" $p_T$)**

- ❑ $R_{AA}$ (D) ~ $R_{AA}$ ($\pi$) → color charge dependency of energy loss compensated by the softer fragmentation and $p_T$ spectrum of gluons

# More insights from run-2

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

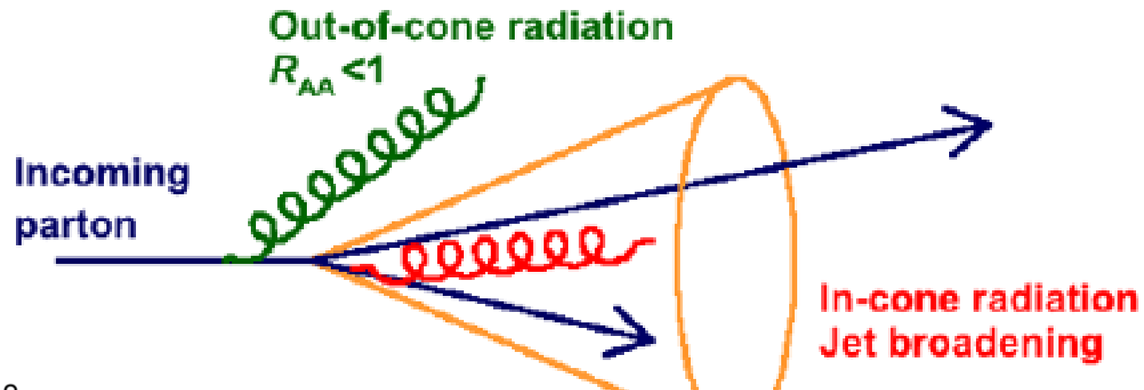


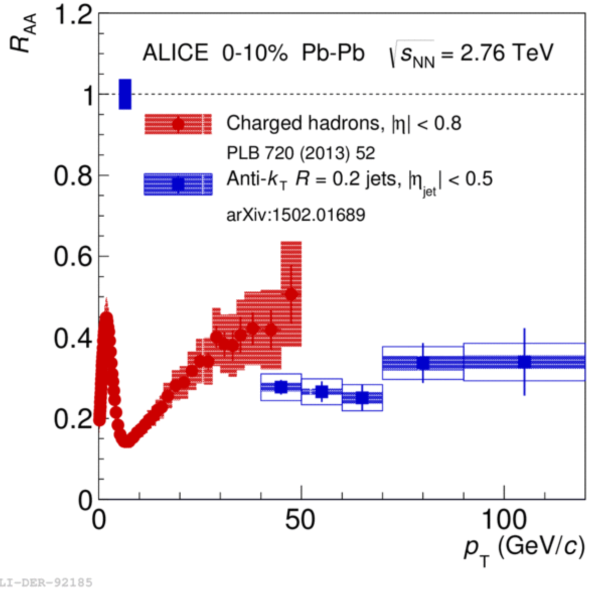


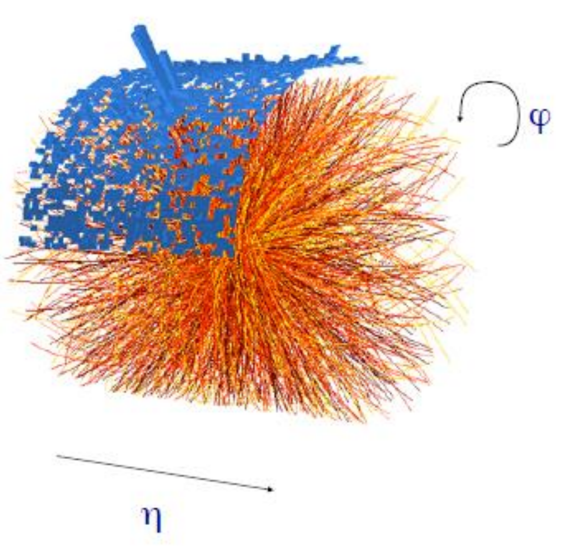
- ❑ ALICE: precise measurement of D-meson $R_{AA}$ up to $p_T$=36 GeV/c
- ❑ CMS: **first direct measurement of B-meson $R_{AA}$**
  - ❑ High $p_T$ → no appreciable flavor dependence is seen
  - ❑ Tension with non-prompt J/ψ measurement at the low-$p_T$ edge?

# Jets: more info on energy loss

Measure energy loss distributions {
Longitudinal → fragm. functions
Transverse → Jet profiles







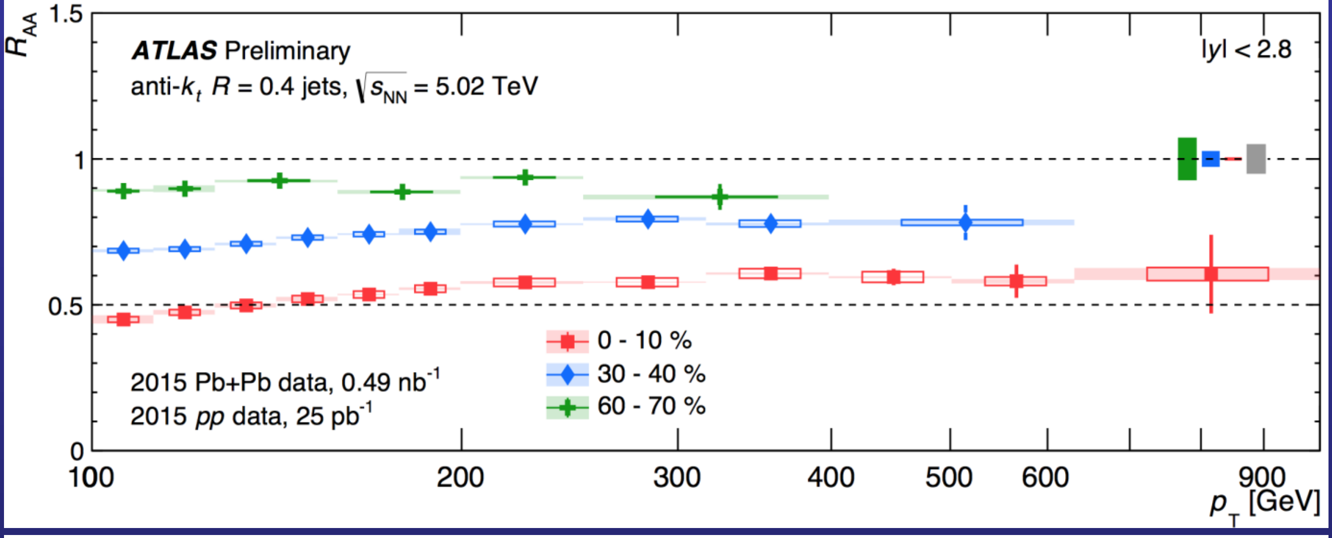
- ☐ **Strong jet suppression observed**
- ☐ Evidence for significant out-of-cone radiation

- ☐ Similar $R_{AA}$ as in high-$p_T$ hadrons (caution on the comparison of the $p_T$ scale!)

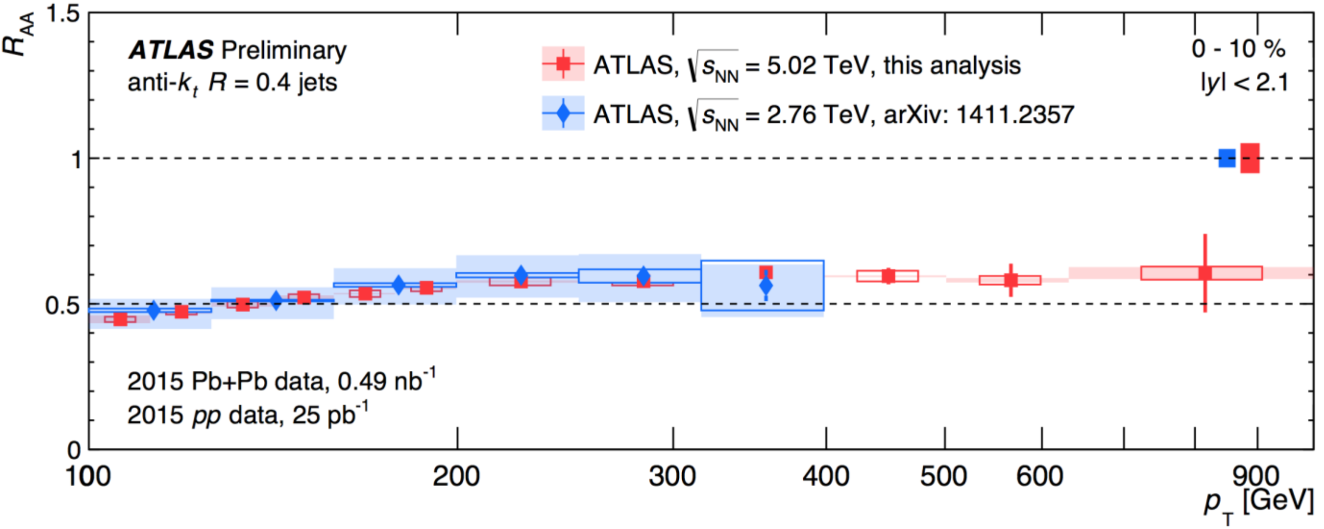
# Very high $p_T$ jets

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

- Extend **$p_T$ coverage up to 1 TeV!**



Contrary to (no) suppression of high $p_T$ hadrons, **jets are strongly suppressed** up to maximum $p_T$



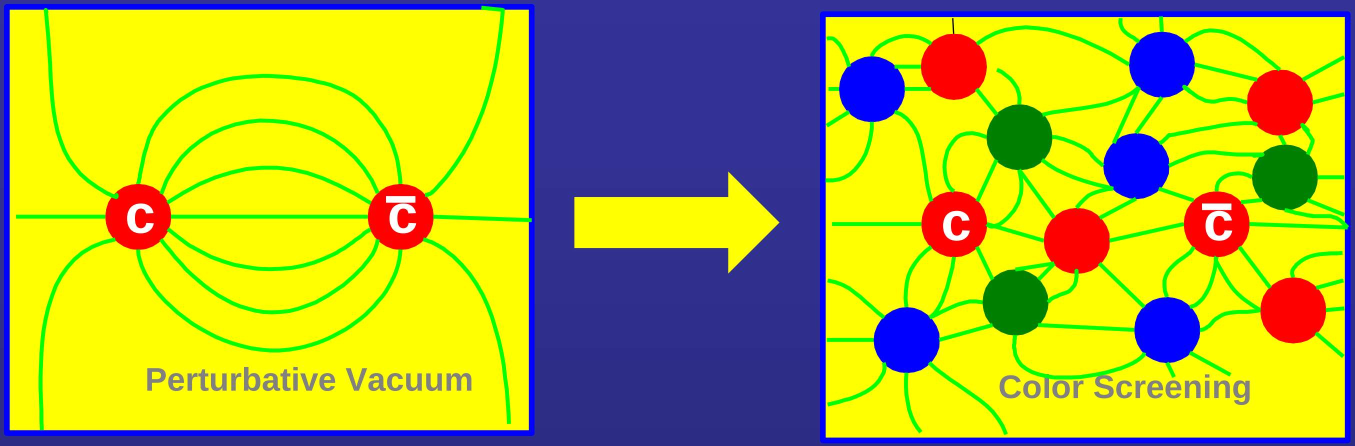
No significant $\sqrt{s_{NN}}$ dependence of jet $R_{AA}$

# Heavy quarkonium

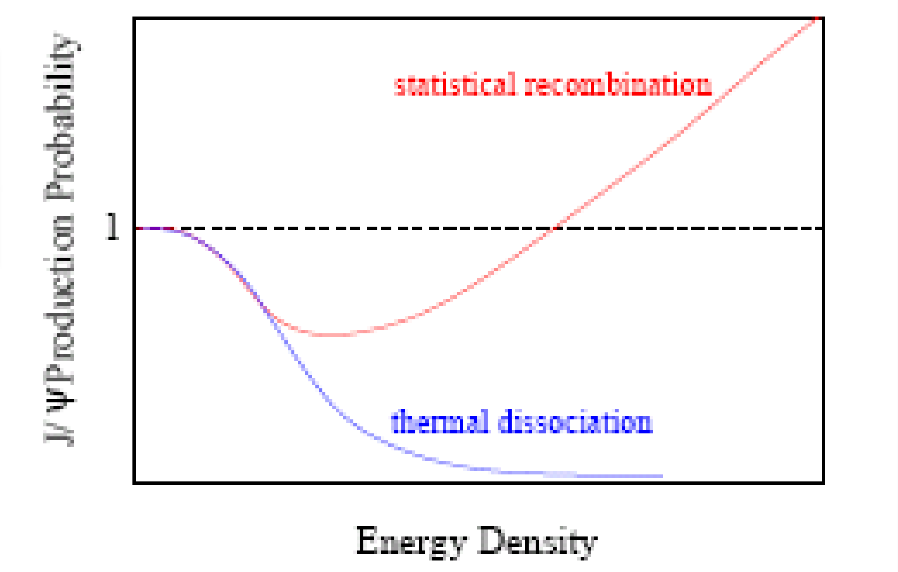
Screening of
strong interactions
in a QGP

→ **Charmonium supppression**

T. Matsui and H. Satz,
PLB178 (1986) 416



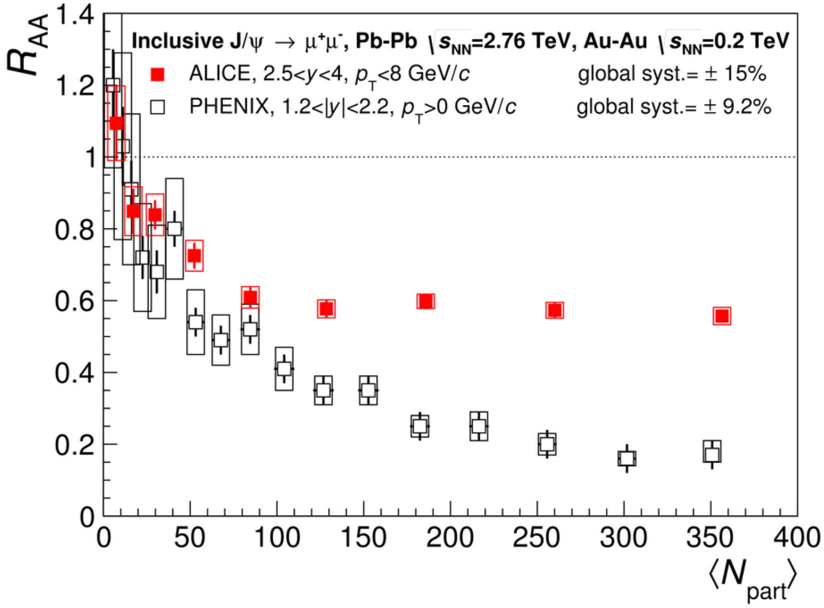
| **Central AA collisions** | **SPS 20 GeV** | **RHIC 200 GeV** | **LHC 2.76 TeV** | **LHC 5 TeV** |
|---|---|---|---|---|
| $N_{ccbar}$/event | ~0.2 | ~10 | ~85 | ~115 |

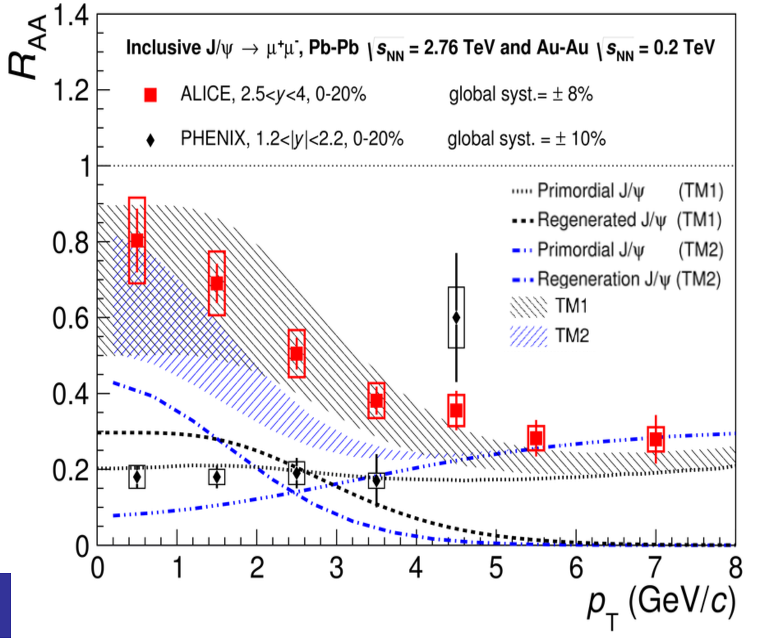


Large charm quark multiplicity at LHC energy may lead to a **recombination mechanism** which enhances charmonium production

# Charmonium suppression

- ☐ J/ψ is strongly suppressed in Pb-Pb collisions, as expected in case of color screening, but less at the LHC than at RHIC
- ☐ $R_{AA}$ does not vary with centrality for $N_{part}$>100





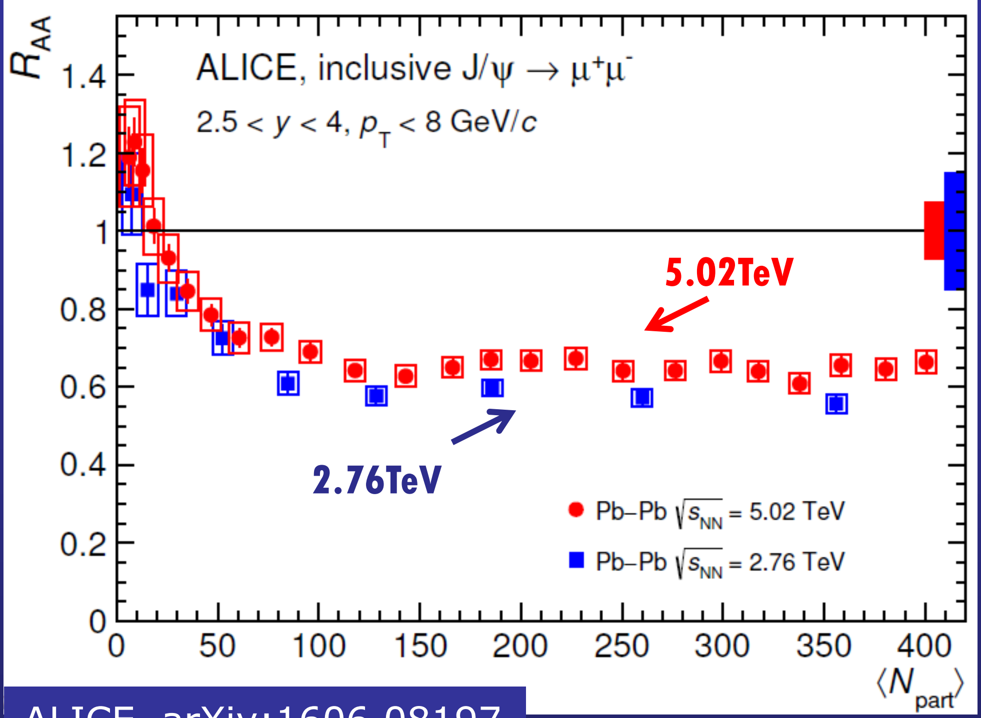
- ☐ Less suppression at low $p_T$, contrary to RHIC

- **☐ Re-generation mechanisms are needed to describe data**

ALICE, JHEP 05 (2016) 179

# Recent results on J/$\psi$

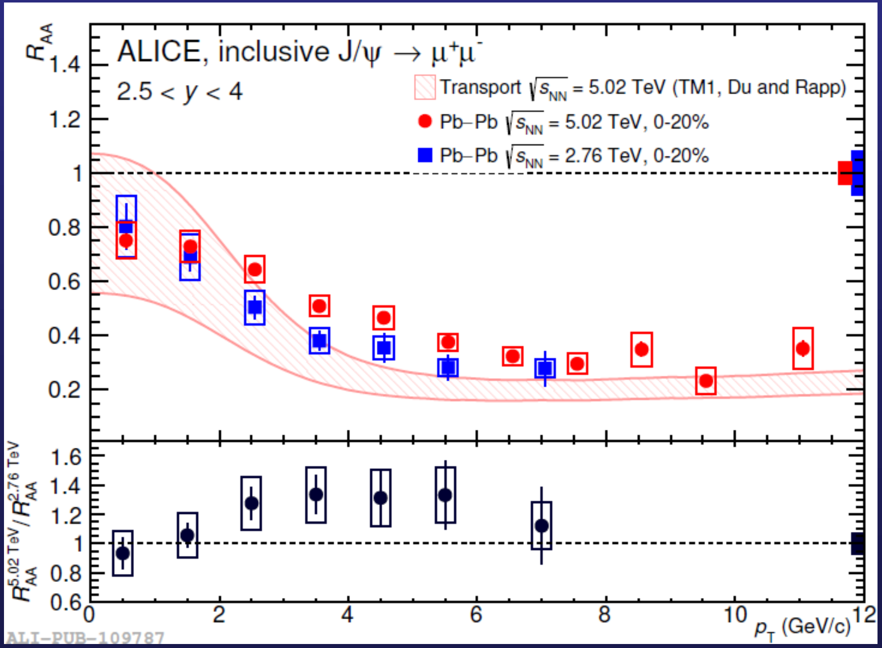
**Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV**



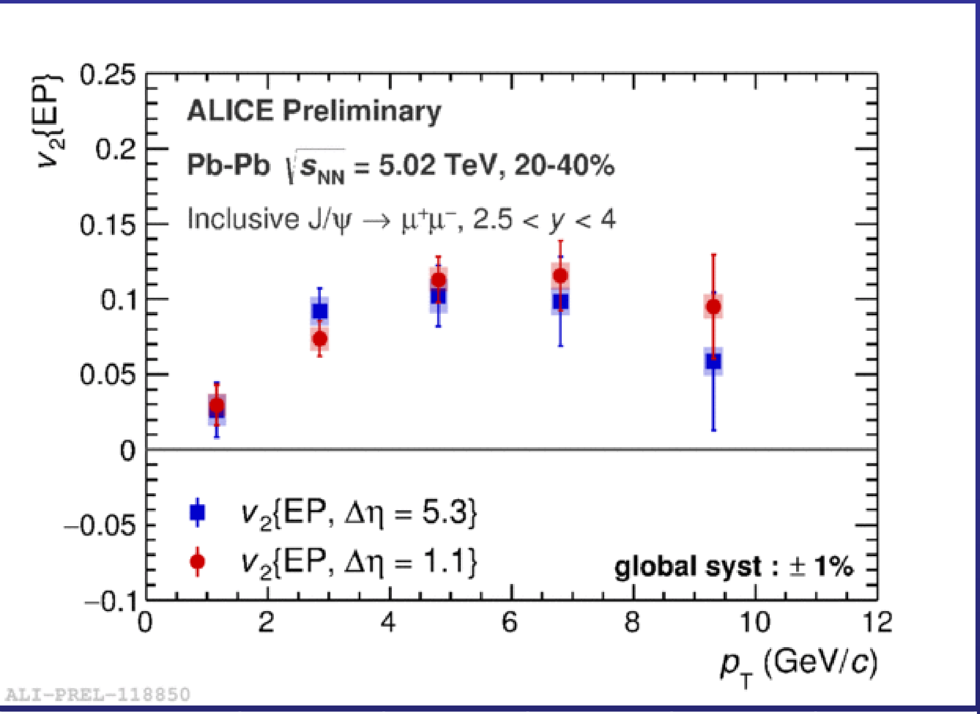
ALICE, arXiv:1606.08197

- Similar suppression at $\sqrt{s_{NN}}$ =2.76 and 5.02 TeV
- More accurate recent data confirm the remarkably flat behavior of $R_{AA}$ vs $N_{part}$

- **$R_{AA}$ increases at low $p_T$, at both energies, as expected in a regeneration scenario**
- Hint for an increase of $R_{AA}$, at 5.02TeV, in $2<p_T<6$ GeV/c



# New J/$\psi$ $v_2$ results



| $p_T$ (GeV/c) | 0-2 | 2-4 | 4-6 | 6-8 | 8-12 |
|---|---|---|---|---|---|
| $\Delta\eta$=1.1 | 2.2$\sigma$ | 6.3$\sigma$ | 7.4$\sigma$ | 5.0$\sigma$ | 2.8$\sigma$ |
| $\Delta\eta$=5.3 | 1.4$\sigma$ | 6.2$\sigma$ | 5.0$\sigma$ | 3.3$\sigma$ | 1.3$\sigma$ |

- ❑ The contribution of J/$\psi$ from (re)combination could lead to an **elliptic flow** signal at LHC energy → hints observed in run-1 results

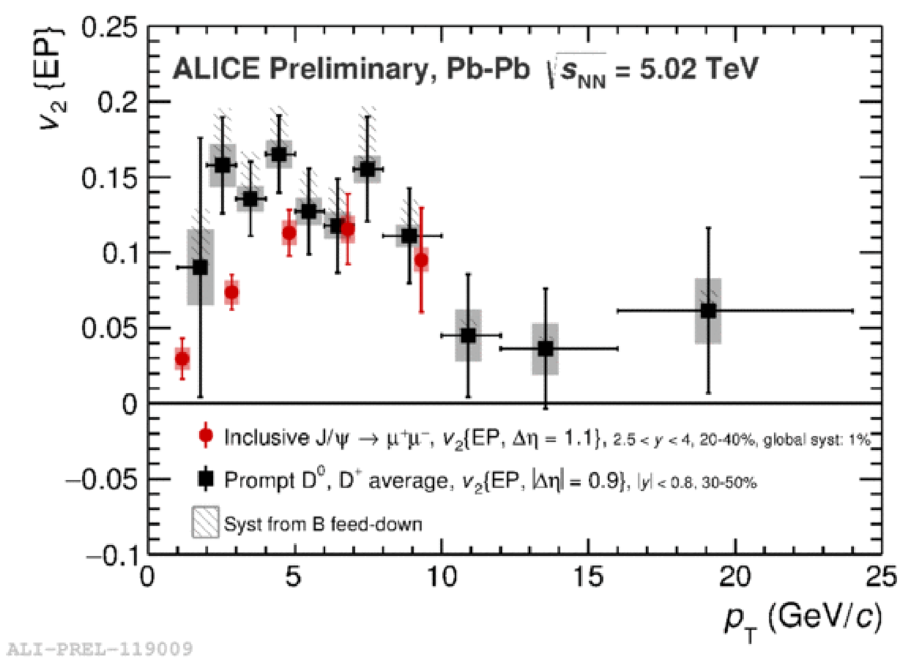
- ❑ **From hint to evidence for a non-zero $v_2$ signal**, maximum for 4<$p_T$<6 GeV/c, 20-40% centrality

- ❑ Agreement, within uncertainties, with run-1 results

- ❑ Comparison closed vs open charm → Learn about **light vs heavy quark flow**

- ❑ A significant fraction of observed J/$\psi$ comes from charm quarks which thermalized in the QGP

# New J/ψ $v_2$ results



| $p_T$ (GeV/c) | 0-2 | 2-4 | 4-6 | 6-8 | 8-12 |
|---|---|---|---|---|---|
| Δη=1.1 | 2.2σ | 6.3σ | 7.4σ | 5.0σ | 2.8σ |
| Δη=5.3 | 1.4σ | 6.2σ | 5.0σ | 3.3σ | 1.3σ |

❑ The contribution of J/ψ from (re)combination could lead to an **elliptic flow** signal at LHC energy → hints observed in run-1 results

❑ **From hint to evidence for a non-zero $v_2$ signal**, maximum for $4<p_T<6$ GeV/c, 20-40% centrality

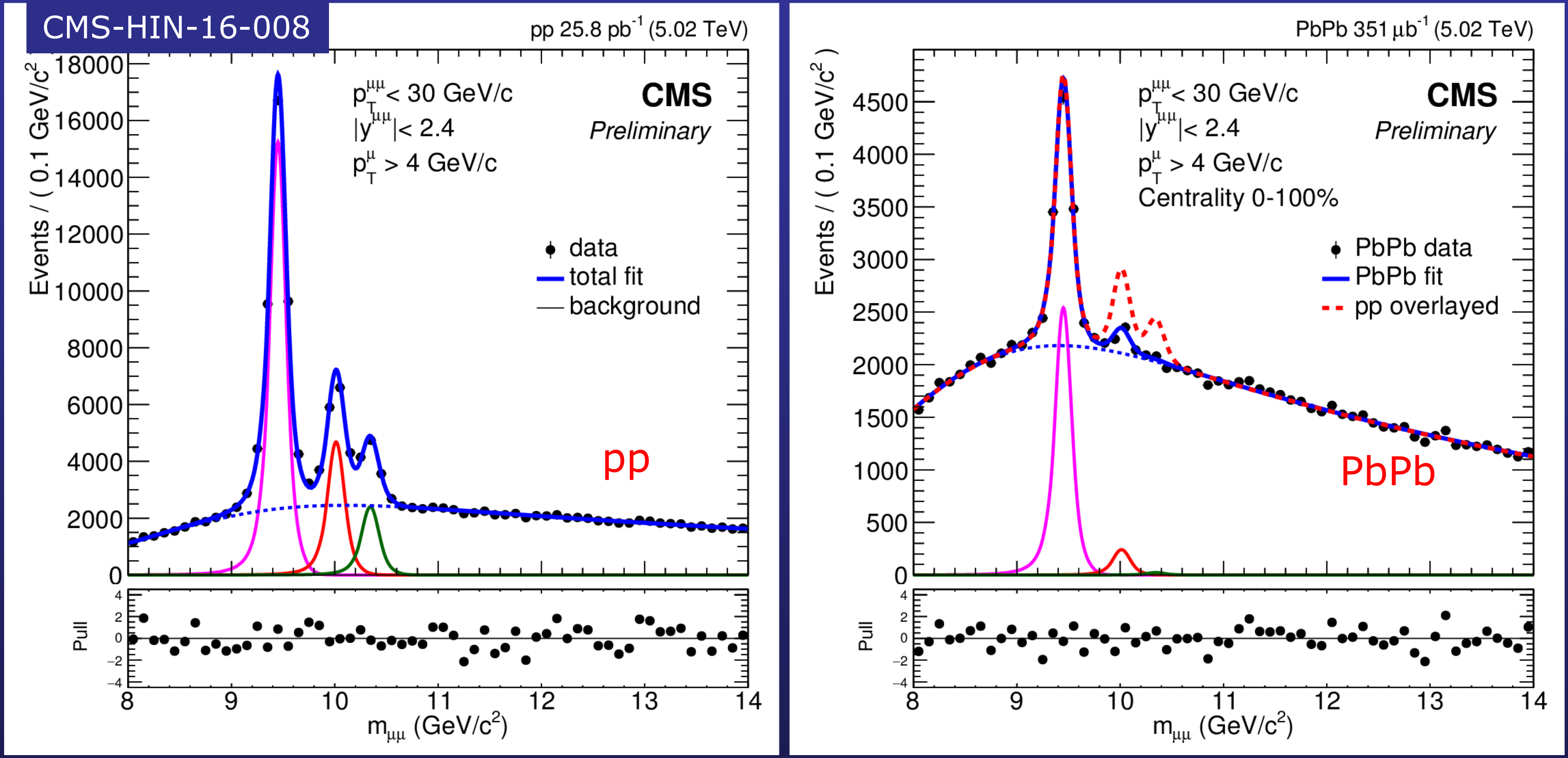
❑ Agreement, within uncertainties, with run-1 results

❑ Comparison closed vs open charm
→ Learn about **light vs heavy quark flow**

❑ A significant fraction of observed J/ψ comes from charm quarks which thermalized in the QGP

# Bottomonium (sequential) suppression

- Probably the **most spectacular result** from quarkonia in HI at the LHC

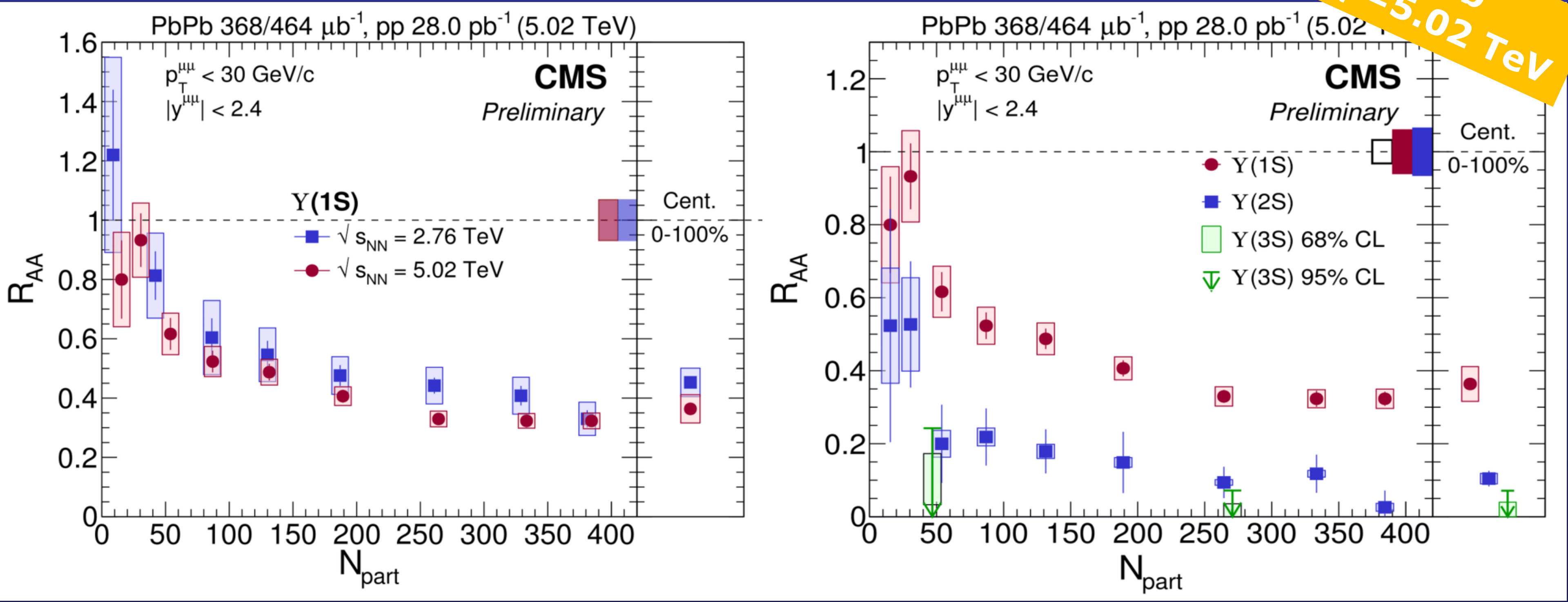

CMS-HIN-16-008

- Recent **CMS results at √s=5.02** TeV confirm the ϒ(2S,3S) suppression relative to the strongly bound ϒ(1S)!

# New $R_{AA}$ results

- $\sqrt{s_{NN}}$=2.76 TeV, strong centrality dependence, **up to factor ~2 and ~8 suppression for ϒ(1S) and ϒ(2S), respectively**

**Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV**

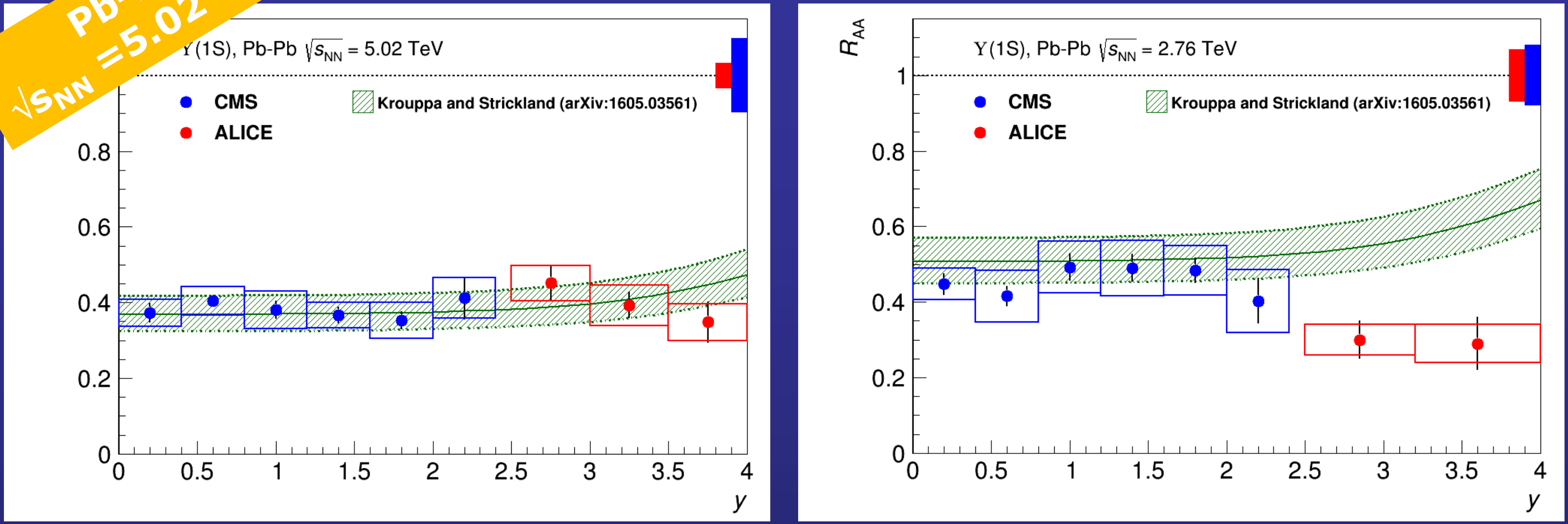


V. Khachatryan et al.,CMS
arXiv:1611.01510

- **New CMS results at $\sqrt{s_{NN}}$=5.02 TeV**
- Indications for slightly stronger suppression

**Pb-Pb**
**$\sqrt{s_{NN}}$ =5.02 TeV**

# $R_{AA}$ vs y: ALICE and CMS Υ(1S)



- Suppression **increases** with y at **$\sqrt{s_{NN}}$=2.76 TeV**
- Suppression **constant** vs y at **$\sqrt{s_{NN}}$=5.02 TeV**

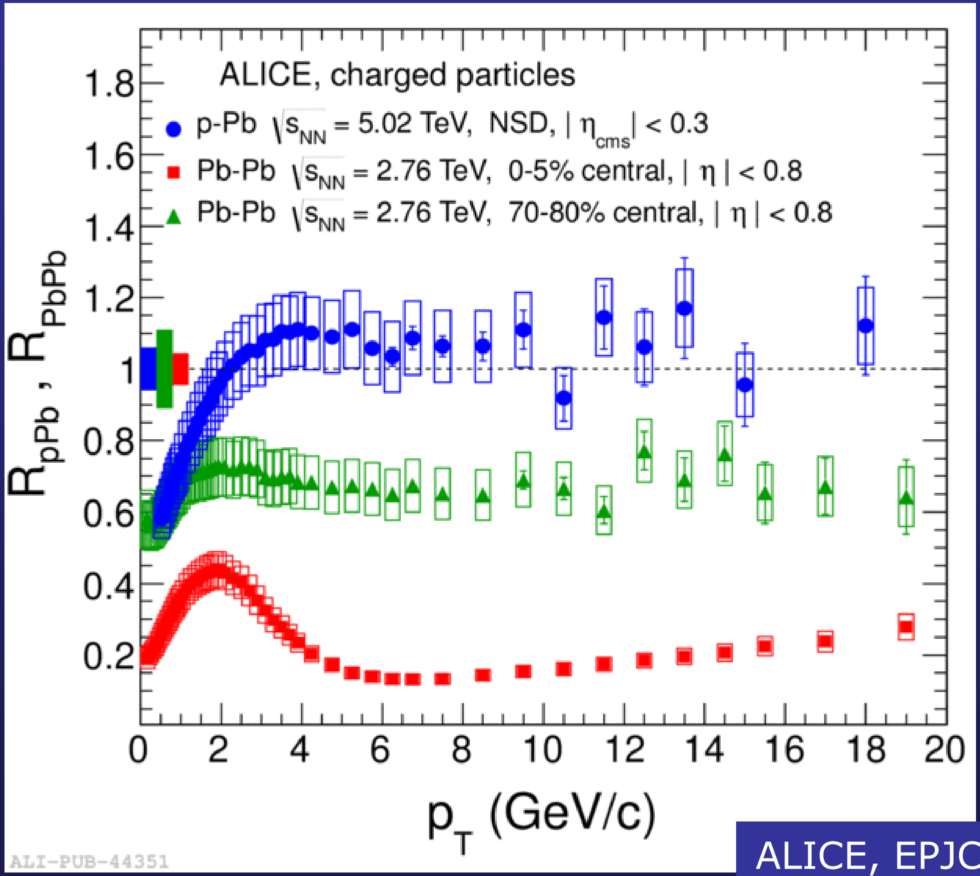
- $\sqrt{s_{NN}}$=2.76 TeV: typical features of a **(re)generation pattern,** which seems to vanish at $\sqrt{s_{NN}}$=5.02 TeV

- Can the y-dependence of **CNM effects vs y** play a role? Not likely
- Systematic uncertainties not negligible
- Model (Strickland) agrees well with $\sqrt{s_{NN}}$=5.02 TeV results

# p-Pb and pp collisions

# Moving to smaller systems: p-Pb

- ☐ Common wisdom → use pA collisions to calibrate the size of cold nuclear matter effects and isolate QGP-related signals
- ☐ Example: $R_{AA}$ vs $R_{pA}$ for charged hadrons

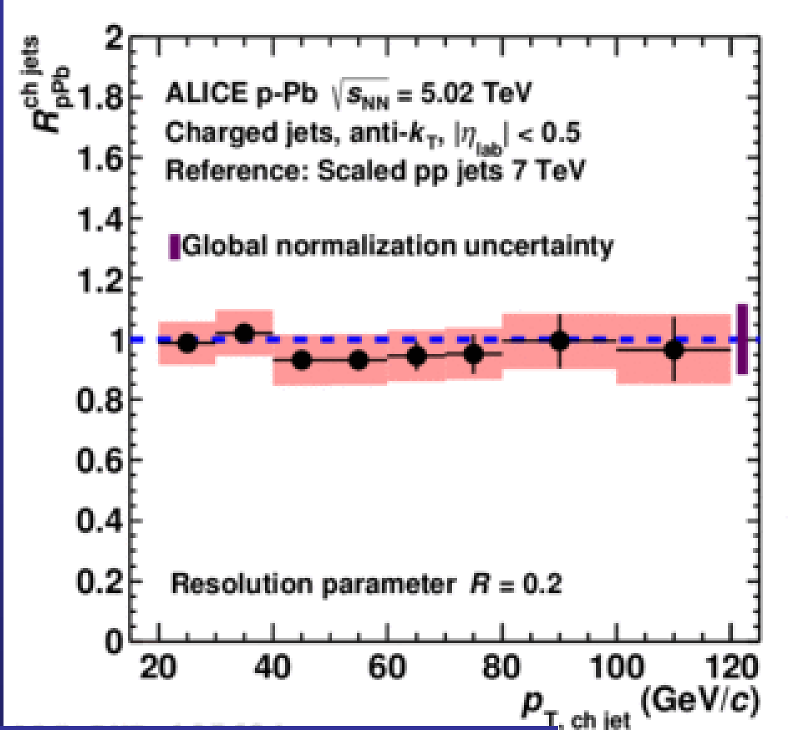


ALICE, EPJC 74 (2014) 3054

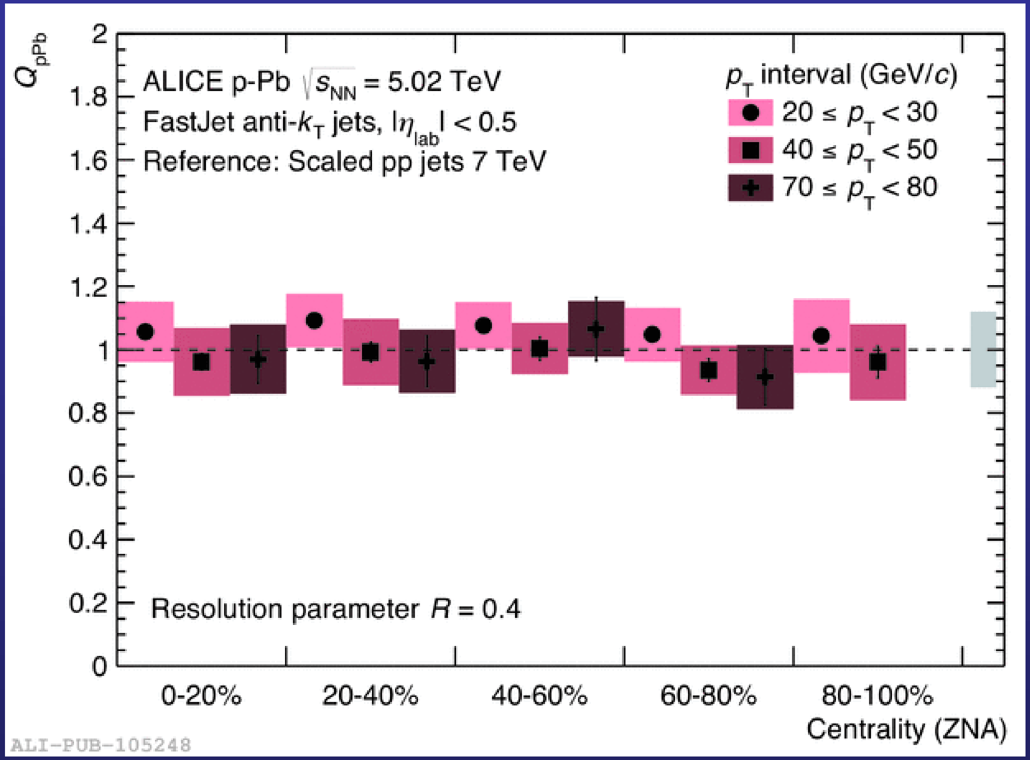
- ☐ **Demonstrates that the suppression signal observed at high $p_T$ in Pb-Pb collisions is NOT related to cold nuclear matter effects**

What about other hard probes ?

# pA results: jets

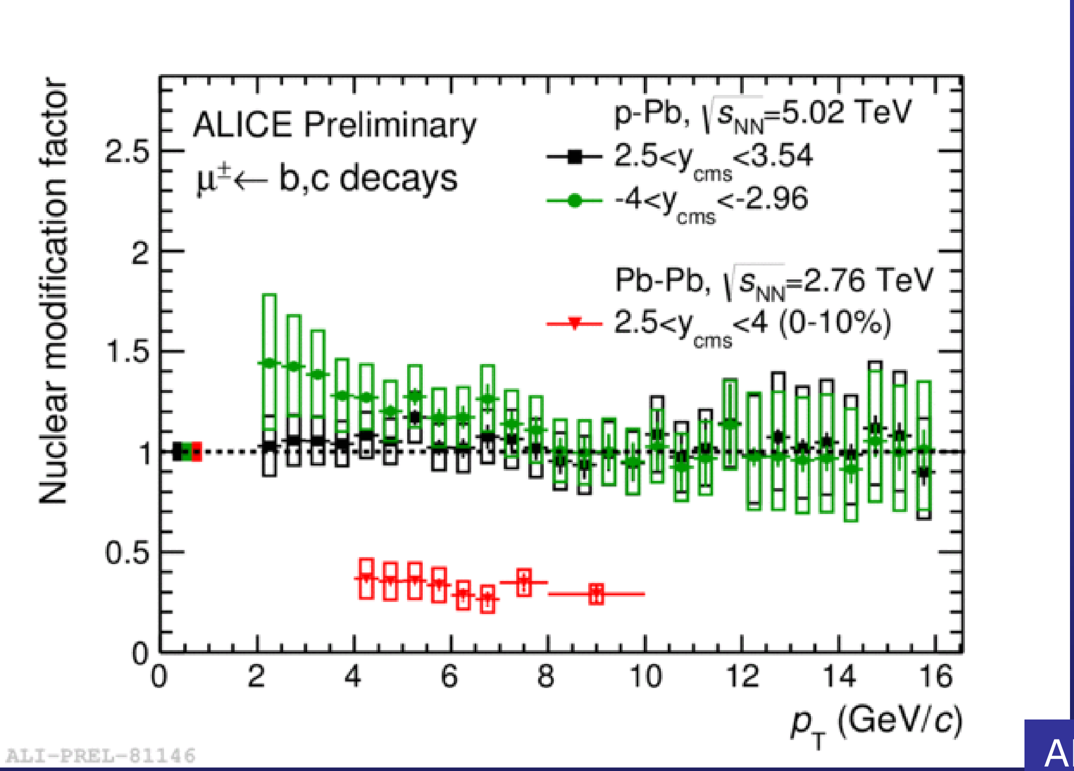


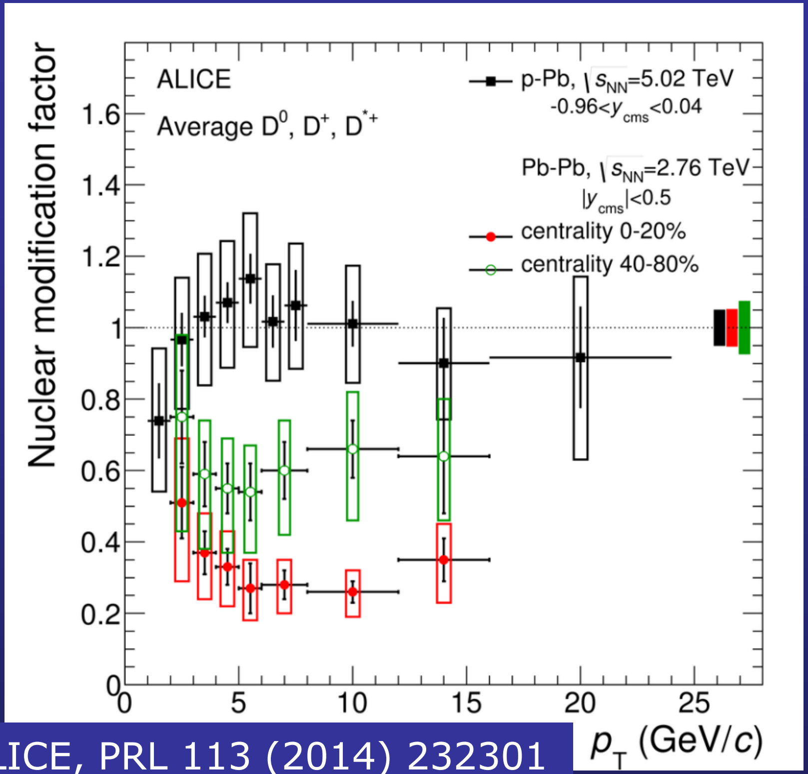
ALICE, EPJC 76 (2016) 271



- **No effects on jets from CNM**, even as a function of the centrality of the p-Pb collision → the suppression effect seen in Pb-Pb is due to hot matter effects

# pA results: heavy quark production



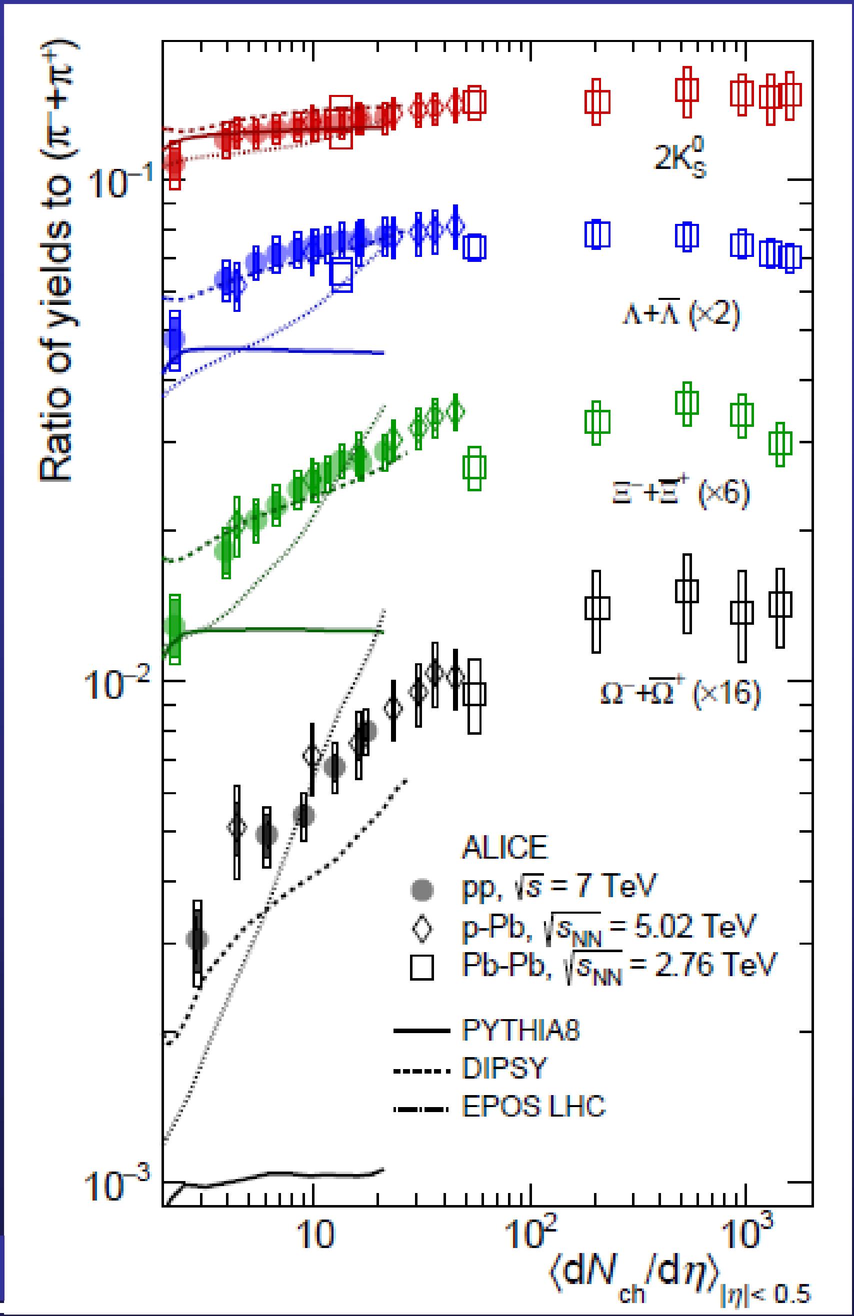


ALICE, PRL 113 (2014) 232301

- ☐ At both forward-y (muons from semileptonic heavy quark decays) and central-y (D-meson hadronic decays) **no significant CNM effects**
- ☐ What about soft/global observables ?

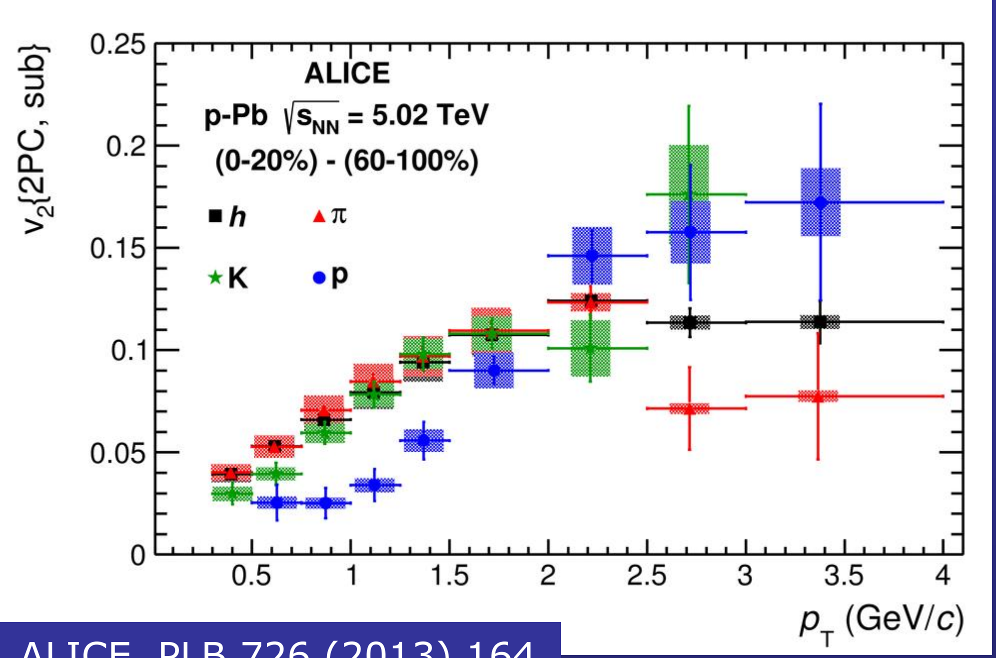
# pA/pp: strangeness

- ☐ Saturation of strangeness production observed in Pb-Pb collisions for kaons and hyperons
- ☐ p-Pb yields (normalized to pions) gradually reach the Pb-Pb value when increasing the event centrality
- ☐ Even in pp collisions, a similar increasing trend can be seen considering increasing charged particle multiplicities
- ☐ Contrary to hard probes, **these results show typical hot matter effects also for small collision systems!**

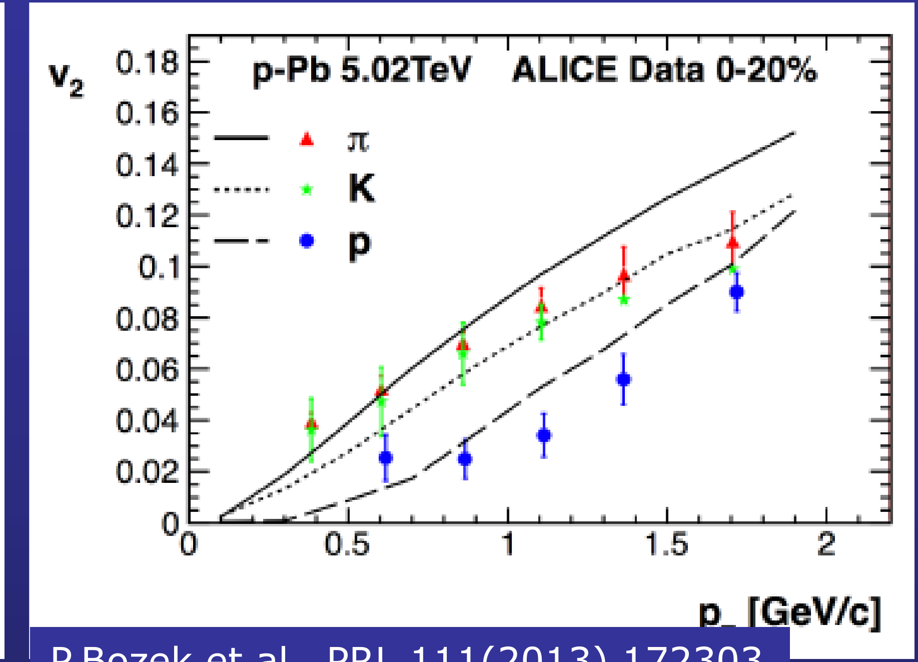


ALICE, NATURE Physics 2017, DOI:10.1038

# pA results: $v_2$



ALICE, PLB 726 (2013) 164

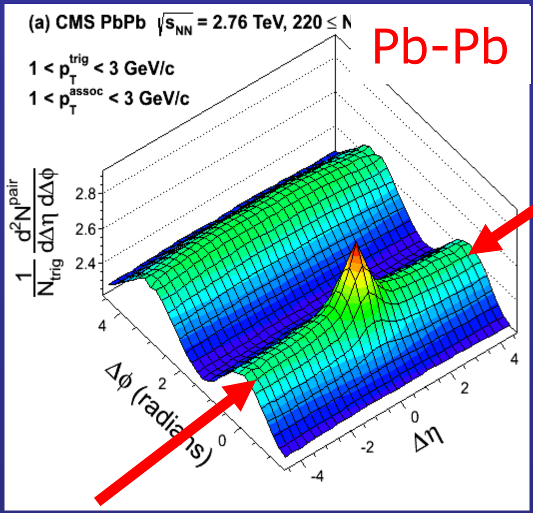


P.Bozek et al., PRL 111(2013) 172303

- Similar 'mass ordering' observed for $v_2$ from two-particle correlations in p-Pb
- Hydrodynamic models can describe the data
- Very surprising result!
  - p-Pb was supposed to be the reference system
  - Applicability of hydrodynamics questionable

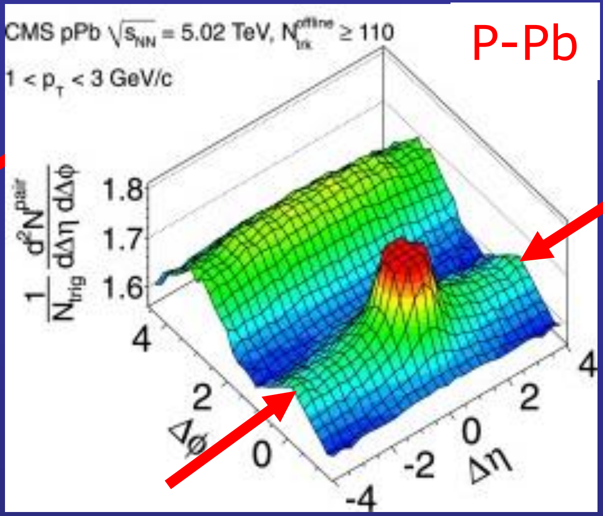
**Are we observing a 'pressure driven' effect ?**

# Smooth evolution from pp to Pb-Pb?



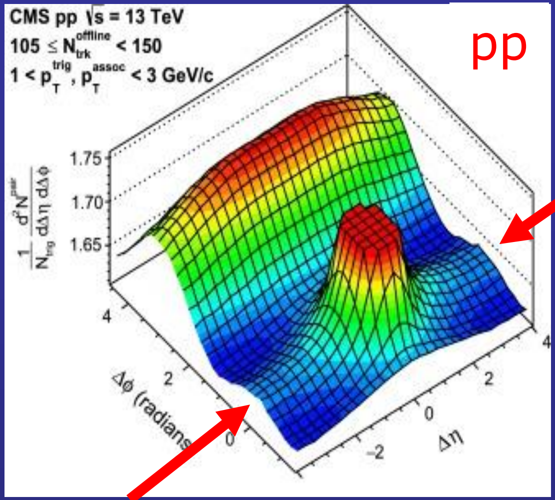
Pb-Pb

JHEP 07 (2011) 076



P-Pb

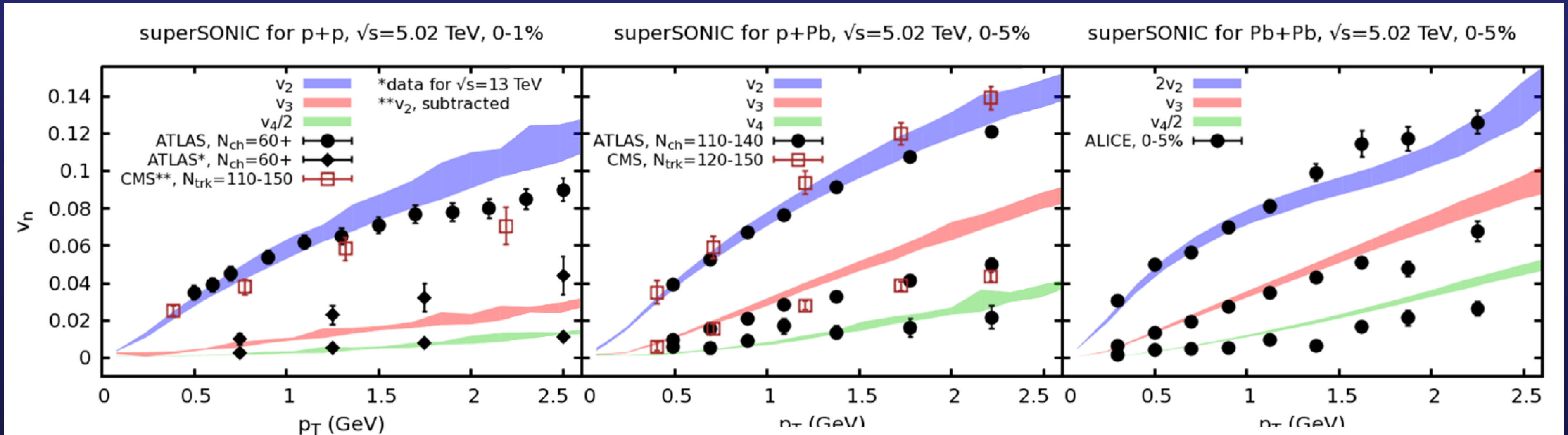
PLB 718 (2013) 795



pp

PLB 765 (2017) 193

- ☐ 2-particles correlation → Ridge at $\Delta\phi=0$ (large $\Delta\eta$) in Pb-Pb attributed to **collective flow of an expanding QGP**
- ☐ What about p-Pb and pp ? Gluon correlations in the initial state? QGP??



**One fluid to rule them all** … ” arXiv:1701.07145

# Future prospects

☐ Existing colliders

**LHC**
Run 2 to end in 2018
Heavy-ion program approved for run 3
and run 4 (end in 2029)

**Energy frontier**

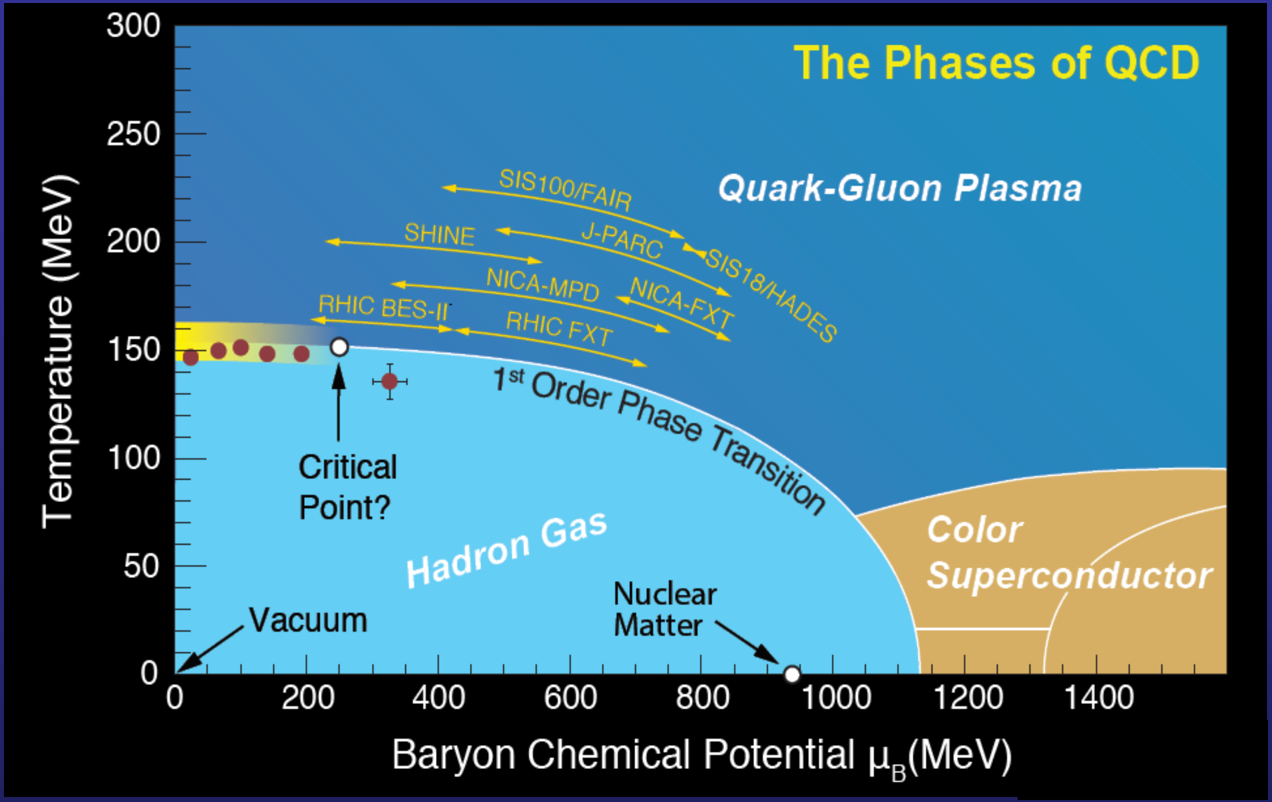
**RHIC**
2018: lighter ions (Zr-Zr, Ru-Ru) at $\sqrt{s_{NN}}$ =200 GeV (STAR)
2022-2025: Au-Au 100 · $10^9$ events (sPHENIX)
Beam Energy Scan (BES), 2019-2020 (STAR)

☐ Other facilities

**FAIR @ GSI**
Fixed target Phase 1 : up to $10^{10}$ /s $^{238}$U at 11 A · GeV
**NICA @ JINR**
Collider, up to $10^{27}$ cm$^{-2}$s$^{-1}$ Au-Au at $\sqrt{s_{NN}}$=4-11 GeV
**SPS @ CERN**
Fixed target, > $10^6$/s $^{208}$Pb at 13 – 158 A· GeV

**Study of the QCD phase diagram**

# Detailed studies of the phase diagram

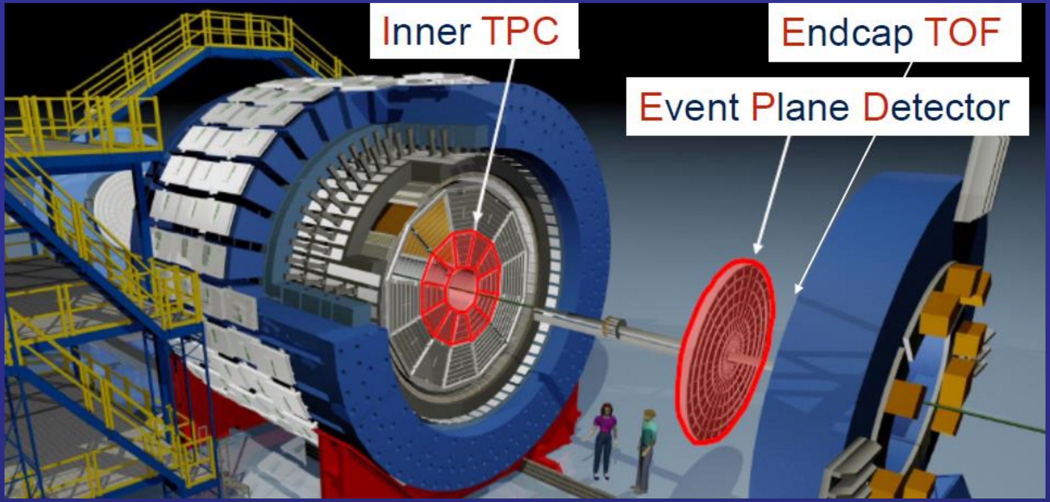


Mapping of the phase diagram at the foreseen facilities

- ☐ Experimental info related to the study of the phase diagram is scarce
- ☐ **Existence of the critical point of QCD ?**
- ☐ Evidence for 1st order phase transition at large $\mu_B$ ?
- ☐ Study the onset of deconfinement via energy scans

→ Quickly becoming **among the hottest topics** in our field

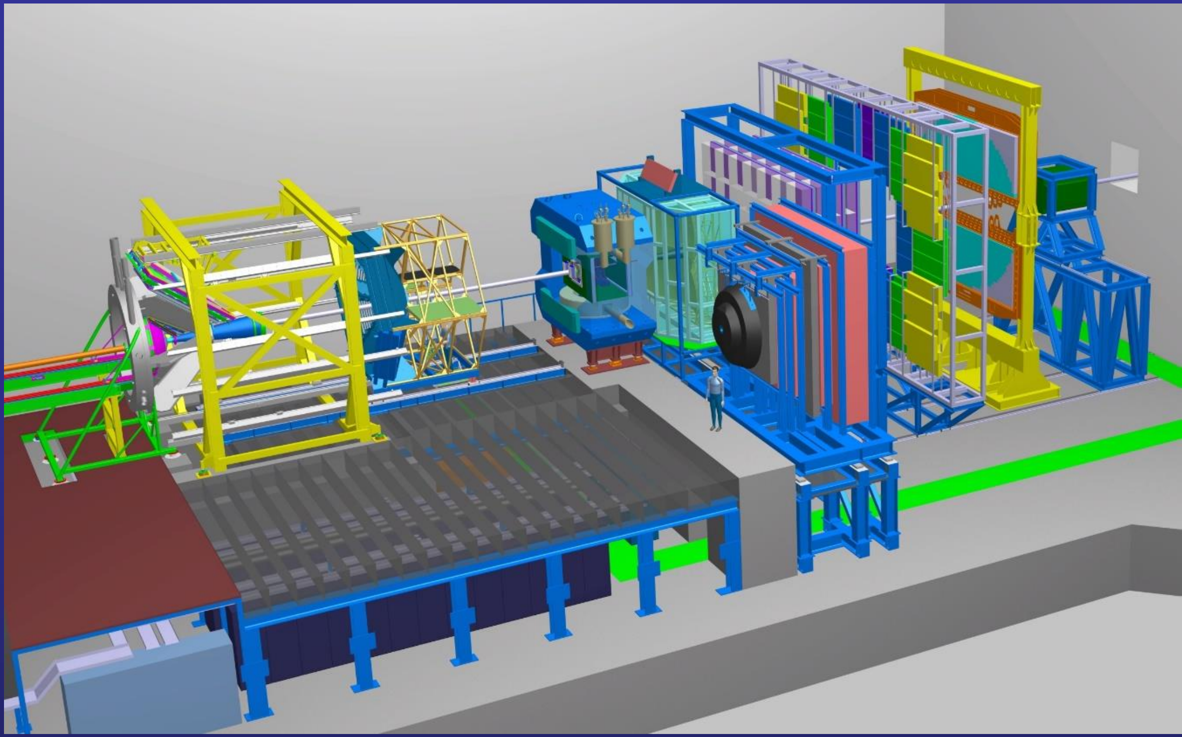
# STAR and BES-II



- ❑ 10-25 times more statistics with respect to BES-I
- ❑ **$\sqrt{s_{NN}}$ = 3 - 19.6 GeV**
- ❑ Fixed target mode to cover $\sqrt{s_{NN}}<7.7$ GeV

- ❑ Main physics topics
- ❑ Threshold of deconfinement
  - "high-$p_T$" suppression disappears
  - No more baryon vs meson effects in $v_2$
  - $v_3$ goes to zero
- ❑ Indications for critical point
  → Look for **critical phenomena**
  - "Extra" **fluctuations of conserved quantities** (baryon number, charge, strangeness)
  - Discontinuities of the higher moments of particle number distributions

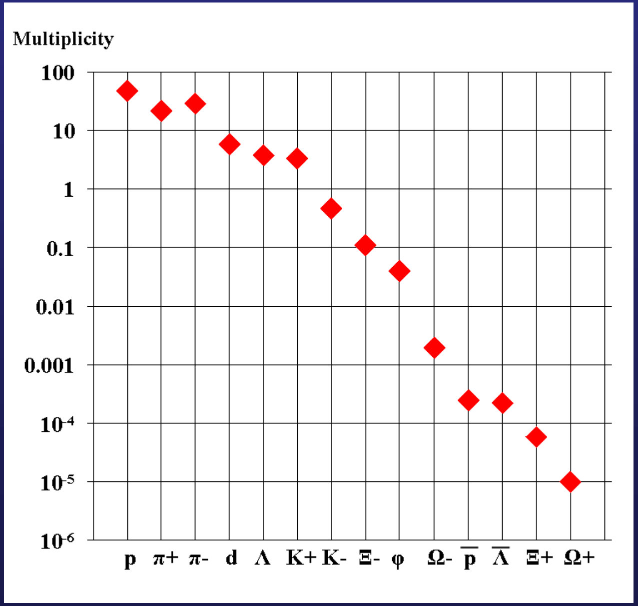
# The CBM experiment



❑ Focus on the study of (very) high $\mu_B$ region

❑ Existing HADES setup coupled to
  - Muon detection system
  - Electron detection system

**Central Au-Au, 4 A GeV**

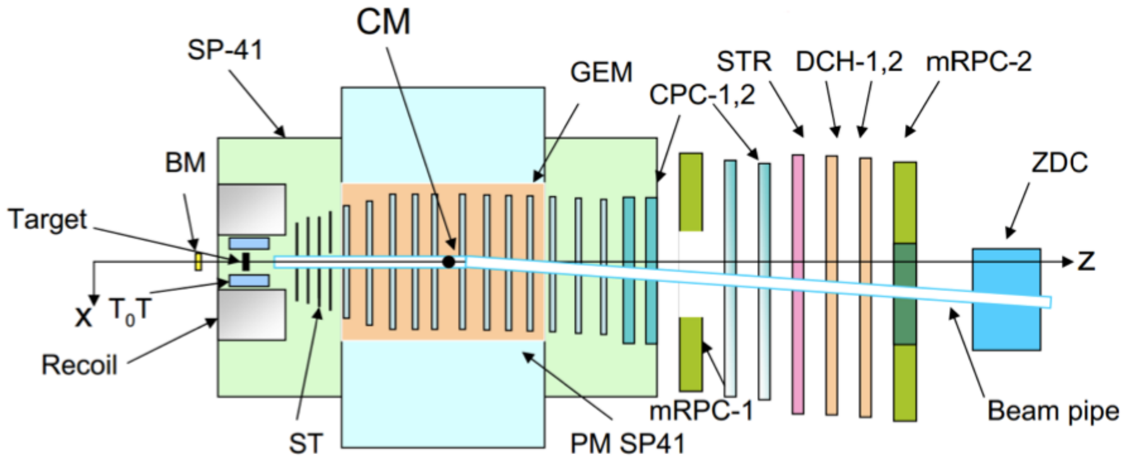


❑ Study of matter chemistry, including strangeness production, requires **very high interaction rates up to 10 MHz !**

❑ Study charm production close to pp threshold and sub-threshold in A-A

# NICA @ JINR

- Both **fixed-target and collider** experiments



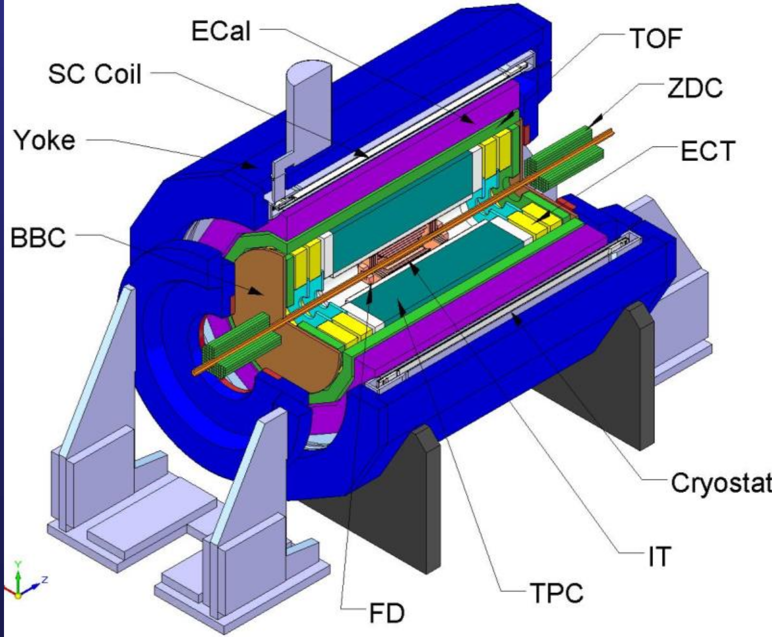
## BM@N

- Nuclotron extracted beams
- Interaction rate: ~5 $10^4$ $s^{-1}$
- Energy: 3.5 – 4.5 A GeV
- From November 2017

- 2021-2023: energy ($\sqrt{s_{NN}}$=4-11 GeV) and system scan → (mainly) hadronic observables
- Phase II → photons, dileptons, open charm

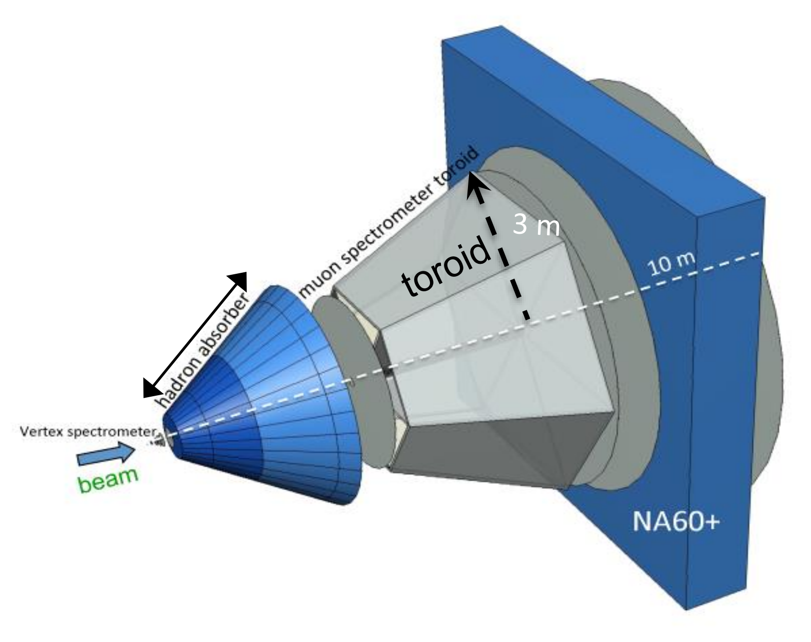
| Particle | Mult. | Decay | ε | N/week |
|---|---|---|---|---|
| Λ | ~35 | $p+\pi^-$ | ~10% | ~1 · $10^7$ |
| $\Xi^-$ | ~2 | $\Lambda+\pi^-$ | 1.6% | 1.0 · $10^5$ |
| ρ | 31 | e+e- | 35% | 2.5 · $10^3$ |
| Ω | 0.14 | Λ+K | 2% | 9.5 · $10^3$ |

## MPD

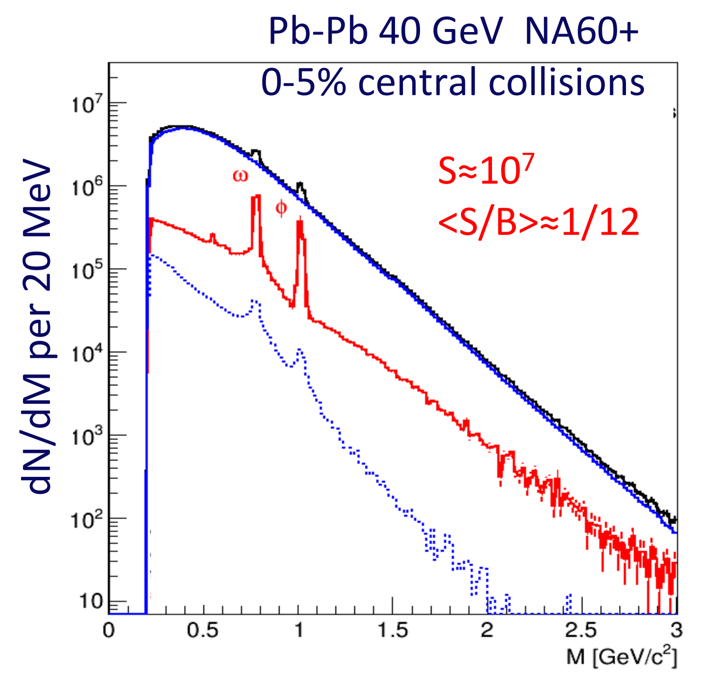


E. Scomparin, State of the art of HI measurements, Hot QCD Matters, Frascati 2017

# NA60+ at CERN SPS



- Study of **dilepton and charmonium production** with Pb beams from 20 to 158 AGeV (beam energy scan)
- Muon + vertex spectrometer, toroidal + dipole B fields



- Main physics topics
  - T (from dilepton spectrum) vs $\varepsilon$
    → **1st order phase transition**
  - Mixing $\rho$ - $a_1$ (intermediate mass continuum)
    → **chiral symmetry restoration**

# Conclusions…

- LHC experiments have collected a wealth of data through LHC run 1 and are now enriching their data sample in run 2
- Very large set of observables investigated, from global variables to identified particle spectra, electromagnetic and hard probes (jets, high-$p_T$ hadrons, open heavy quark production, quarkonia,…)
- From the study of the hottest lump of matter created up to now at particle accelerators
  - **Confirm effects seen at SPS/RHIC** extending them to a new energy scale
  - **Bring new discoveries,** and among them
    - → **Jets** are strongly affected by the medium
    - → Mass-dependence of **heavy quark** energy loss
    - → Evidence for **charmonium** production through re-combination of deconfined charm quarks
    - → Strong **bottomonium** suppression
    - → Hydrodynamic description holds not only for large QGP volumes, but also for the **medium created in smaller systems**

# …and open questions (1)

- ❑ Even if a lot has been learnt at th LHC, many important points still need clarification. A few examples:

- ❑ **Thermal description of hadronic yields**
  - ❑ Common to ALL lighter systems, including $e^+e^-$
  - ❑ LHC: discrepancy for protons (too few!), light nuclei correctly described (not destroyed in the final state due weak binding energy ?!)

- ❑ **Quarkonium**
  - ❑ Success of suppression + regeneration model at LHC
  - ❑ Magic compensation of the effect moving from $\sqrt{s_{NN}}$ = 2.76 to 5.02 TeV

- ❑ **High-$p_T$ hadron suppression**
  - ❑ Again, compensation of the effect moving from $\sqrt{s_{NN}}$ = 2.76 to 5.02 TeV

- ❑ **Mass and color charge dependence of parton energy loss**
  - ❑ b-quark energy loss smaller (but check direct B vs non-prompt J/ψ
  - ❑ Not really seen in c vs u,d vs g (some explanations proposed, though)
  - ❑ Even J/ψ $R_{AA}$ is remarkably similar to that of open charm !

# …and open questions (2)

- **What are we observing in small systems at the LHC ?**

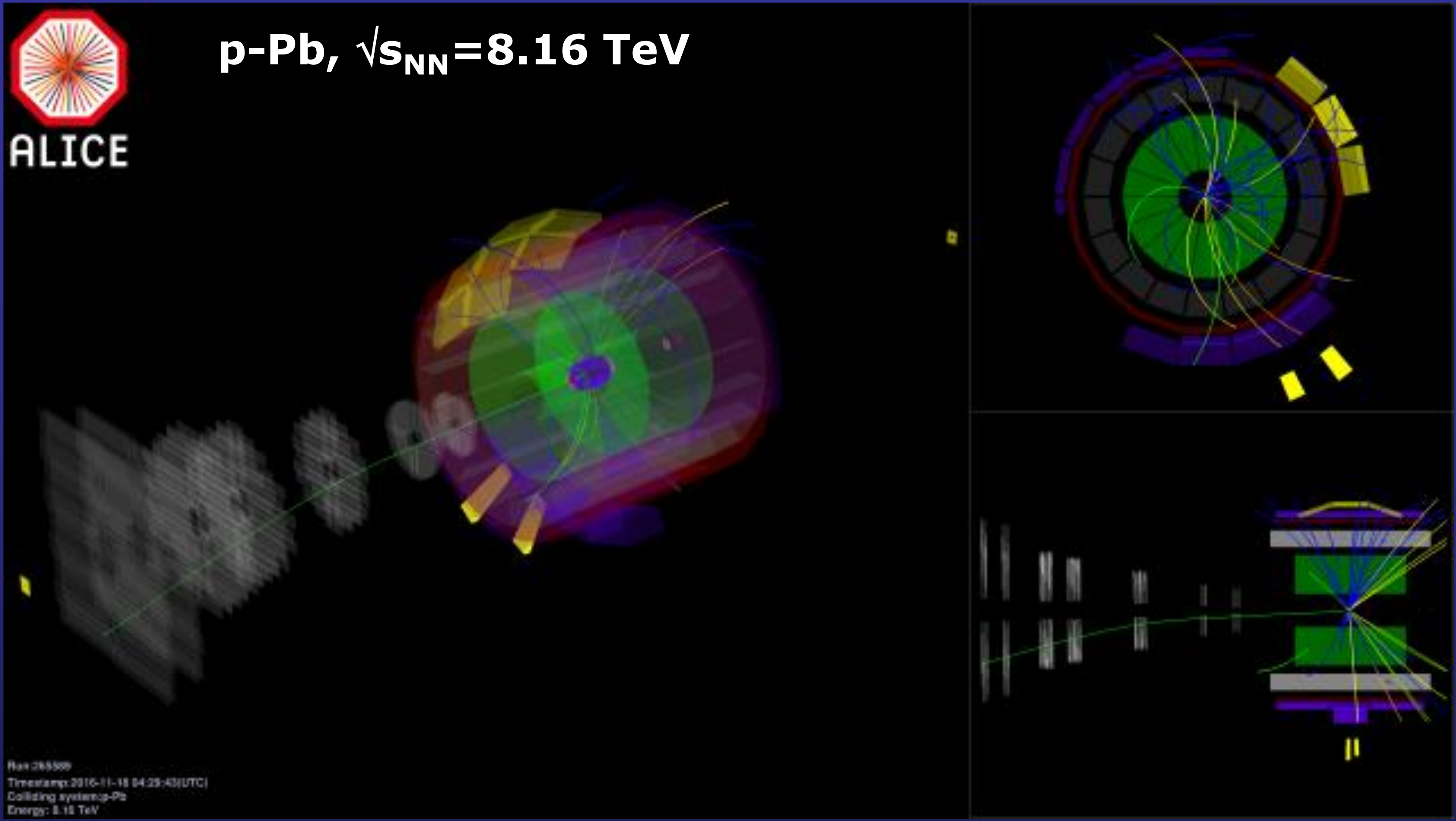
- Collective effects seen already in pp collisions (ridge, etc.)
  - Related to hydrodynamic flow or to initial state quantum correlations?
- Strangeness enhancement smoothly increases from pp to Pb-Pb AND from low- to high-multiplicity pp
  - Still largely unexplained
- No clear effects seen when moving to hard(er) probes

**→ which matter are we creating in small systems ? Where is the difference with respect to Pb-Pb collisions ?**

- **What will we observe at low(er) energy facilities?**

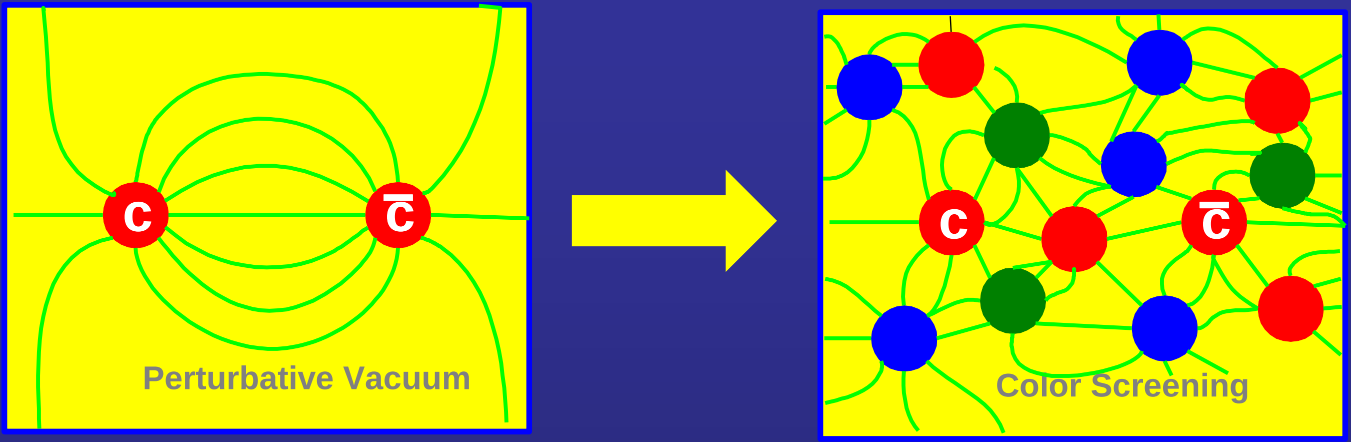
- Can the onset of deconfinement be precisely pinpointed, seen the smooth evolution of most measured quantities?
- Will the interpretation of near-threshold observables define a clear picture ?

# Other stuff


ALICE
p-Pb, $\sqrt{s_{NN}}$=8.16 TeV
Timestamp:2016-11-18 04:28:43(UTC)
Colliding system:p-Pb
Energy: 8.16 TeV

# Thank you!

# Quarkonia in 2016: from color screening…



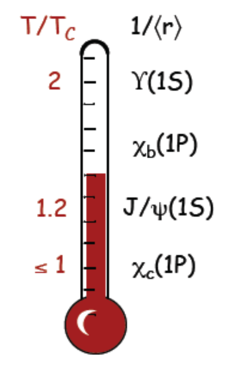
Screening of
strong interactions
in a QGP

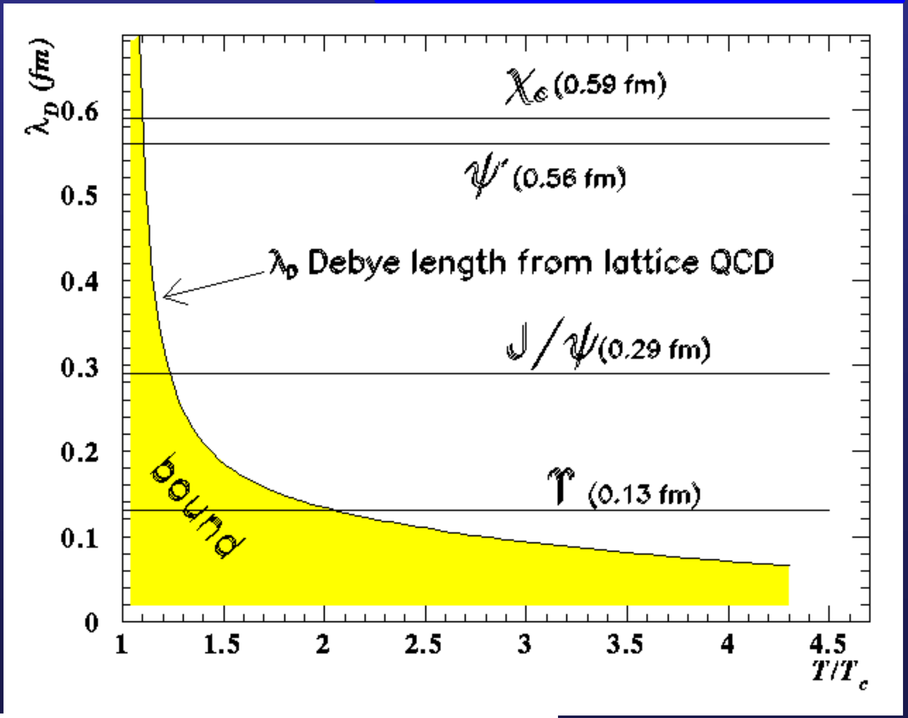
T. Matsui and H. Satz,
PLB178 (1986) 416

- Screening stronger at high T
- $\lambda_D$ → maximum size of a bound state, decreases when T increases
- Different states, different sizes

Resonance melting

QGP
thermometer

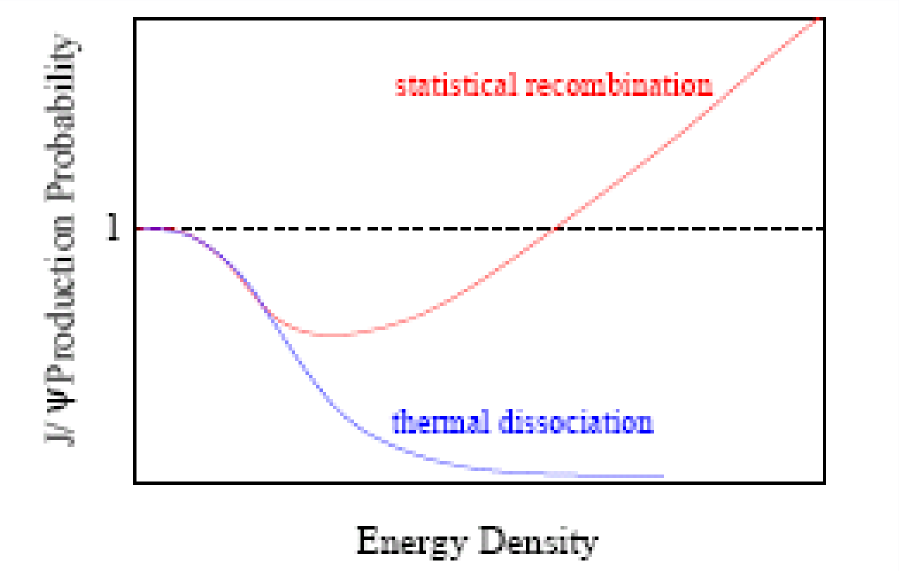




# …to regeneration

At sufficiently high energy, the cc pair multiplicity becomes large

| Central AA collisions | SPS 20 GeV | RHIC 200 GeV | LHC 2.76TeV |
|---|---|---|---|
| $N_{ccbar}$/event | ~0.2 | ~10 | ~85 |



P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196
Thews, Schroedter and Rafelski, PRC63 054905 (2001)

Statistical approach:

- Charmonium fully melted in QGP
- Charmonium produced, together with all other hadrons, at chemical freeze-out, according to statistical weights

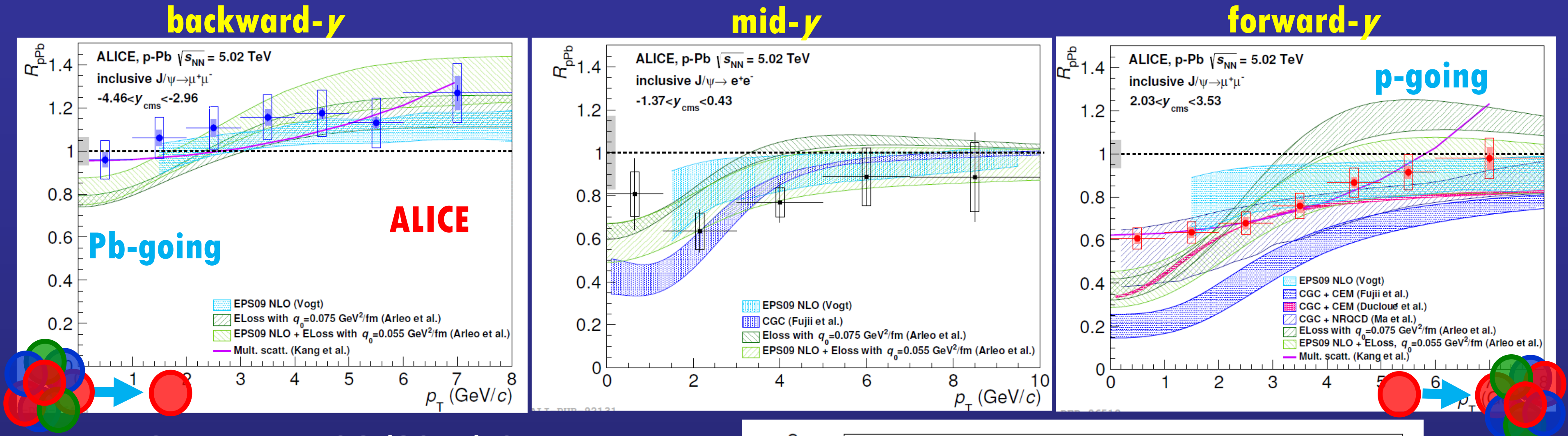
Kinetic recombination:

- Continuous dissociation/regeneration over QGP lifetime

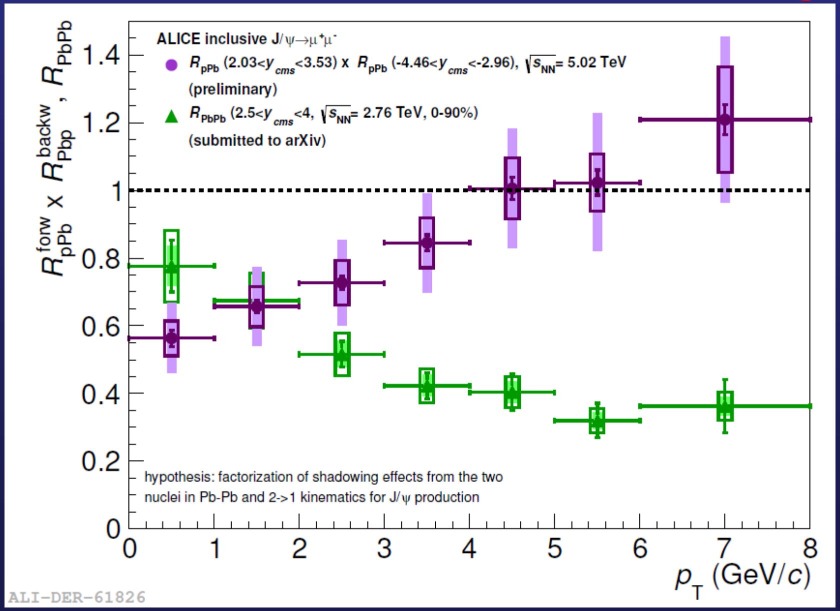
Contrary to the color screening scenario this mechanism can lead to a charmonium enhancement

# CNM effects are not negligible!

- p-Pb collisions, $\sqrt{s_{NN}}$=5.02 TeV, $R_{pPb}$ vs $p_T$



ALICE, JHEP 1506 (2015) 055



- Fair agreement with models (shadowing/CGC + energy loss)

- (Rough) extrapolation of CNM effects to Pb-Pb $R_{PbPb}^{cold}=R_{pPb}\times R_{Pbp}$

→ Evidence for hot matter effects!

# ψ(2S) in p-Pb collisions

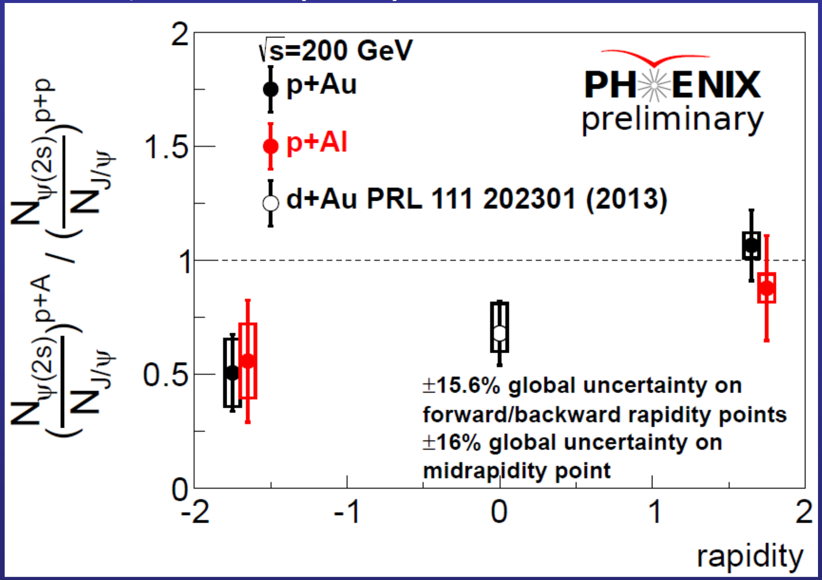
❑ ψ(2S) suppression is stronger than the J/ψ one at RHIC and LHC

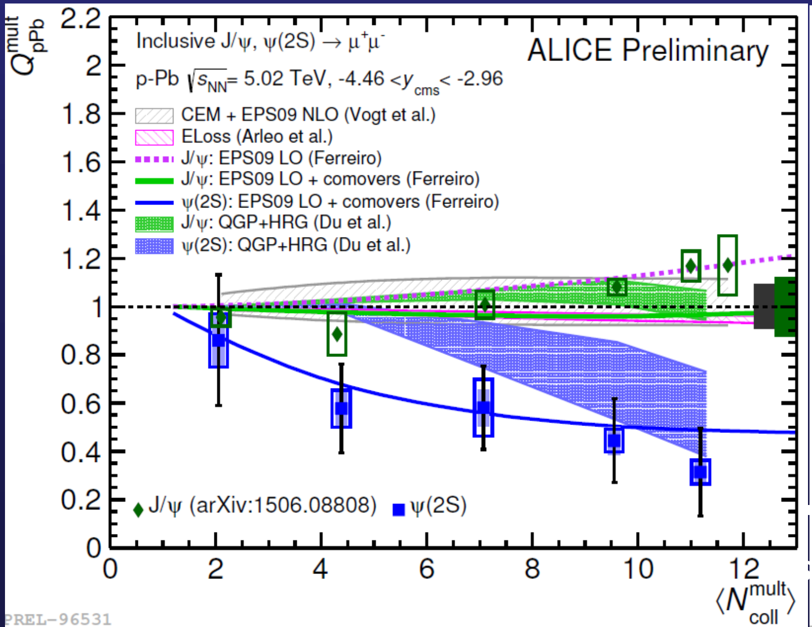
→ shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression

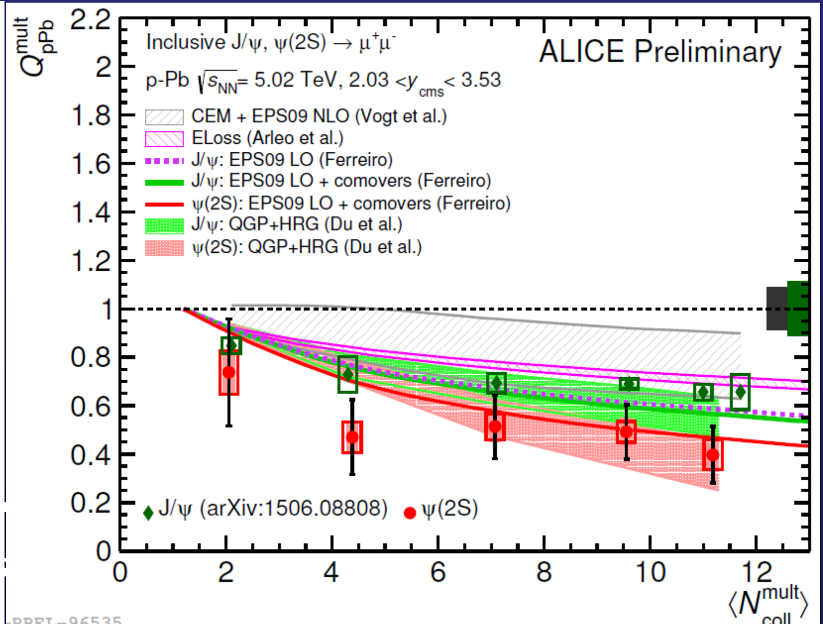
→ Only QGP+hadron resonance gas (Rapp) or comovers (Ferreiro) models describe the strong ψ(2S) suppression at LHC

❑ Accurate Pb-Pb results still missing!

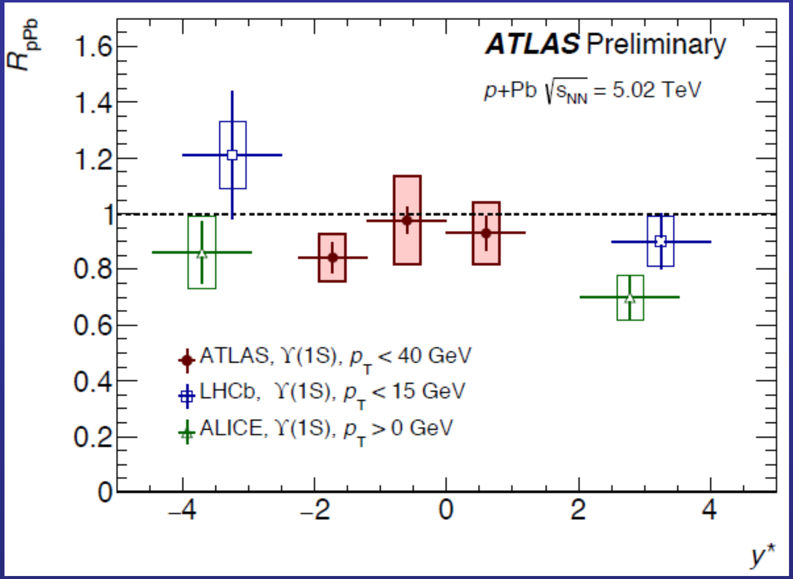
ALICE, JHEP 1412(2014)073, LHCb-CONF-2015-005
PHENIX, PRL 111 (2013) 202301

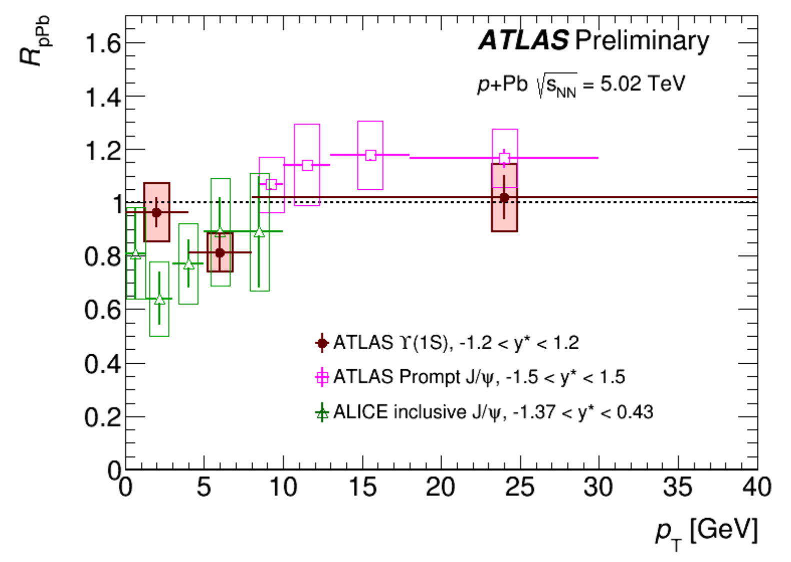


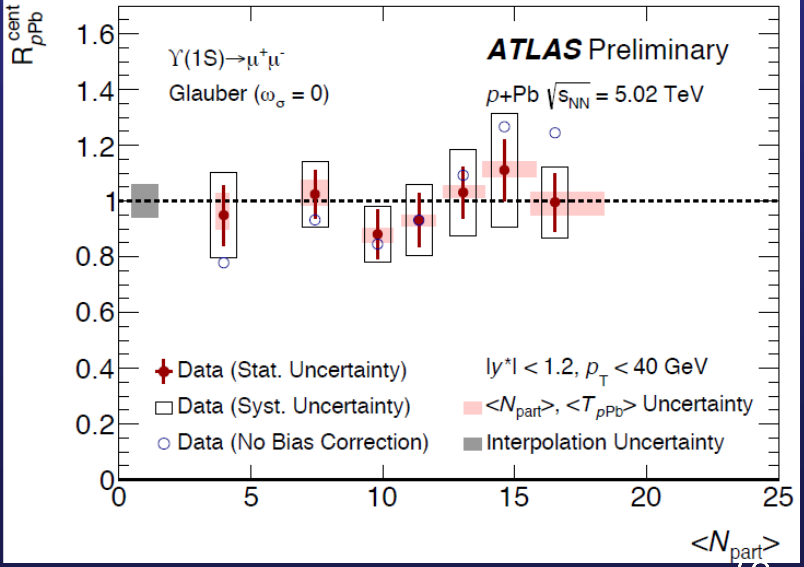




# Weak CNM effects for bottomonium







- $R_{pPb}$ close to 1 and with no significant dependence on y, $p_T$ and centrality

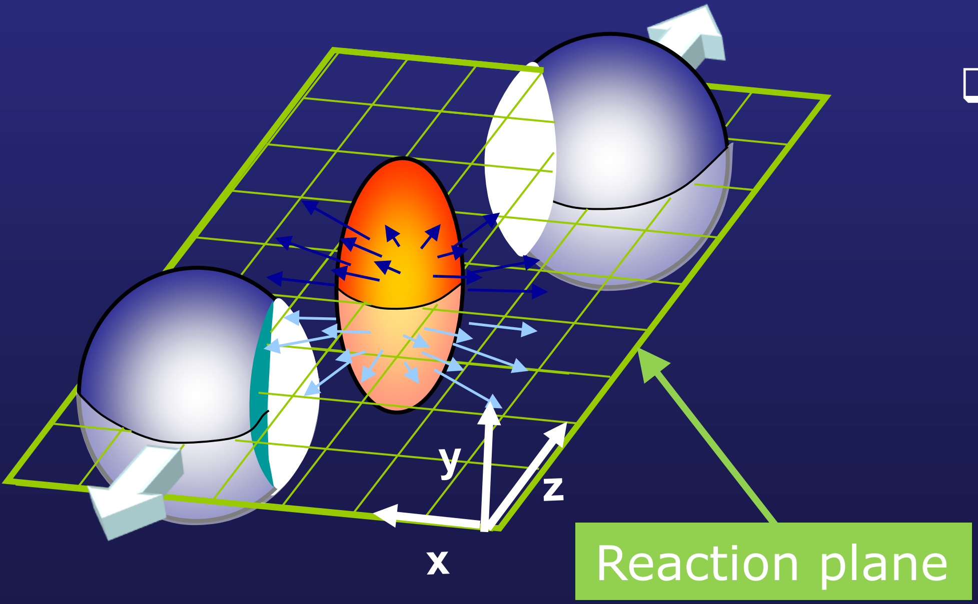
- Fair agreement ALICE vs LHCb (within large uncertainties)

ALICE, PLB 740 (2015) 105
ATLAS-CONF-2015-050
LHCb, JHEP 07(2014)094

# Anisotropic transverse flow

- ☐ In collisions with $b \neq 0$ (non central) the fireball has a geometric anisotropy, with the overlap region being an ellipsoid

- ☐ Macroscopically (hydrodynamic description)
  - ☐ The pressure gradients, i.e. the forces "pushing" the particles are anisotropic ($\varphi$-dependent), and larger in the x-z plane
  - ☐ $\varphi$-dependent velocity → anisotropic azimuthal distribution of particles



- ☐ Microscopically
  - ☐ Interactions between produced particles (if strong enough!) can convert the initial geometric anisotropy in an anisotropy in the momentum distributions of particles, which can be measured

# Anisotropic transverse flow

- ❑ Starting from the azimuthal distributions of the produced particles with respect to the reaction plane $\Psi_{RP}$, one can use a Fourier decomposition and write

$$\frac{dN}{d(\varphi-\Psi_{RP})} = \frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos\left(2\left(\varphi-\Psi_{RP}\right)\right)+....\right)$$

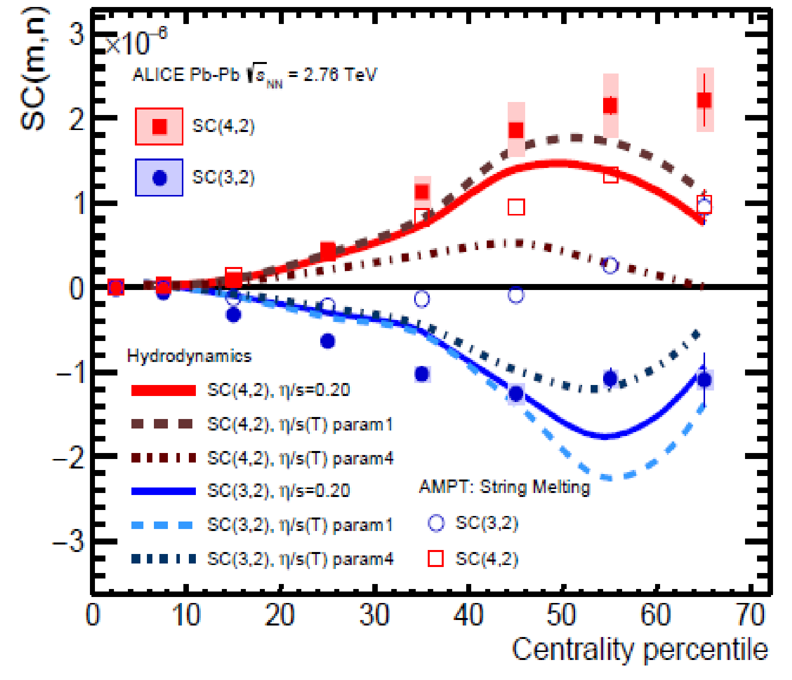
- ❑ The terms in $\sin(\varphi-\Psi_{RP})$ are not present since the particle distributions need to be symmetric with respect to $\Psi_{RP}$
- ❑ The coefficients of the various harmonics describe the deviations with respect to an isotropic distribution
- ❑ From the properties of Fourier's series one has

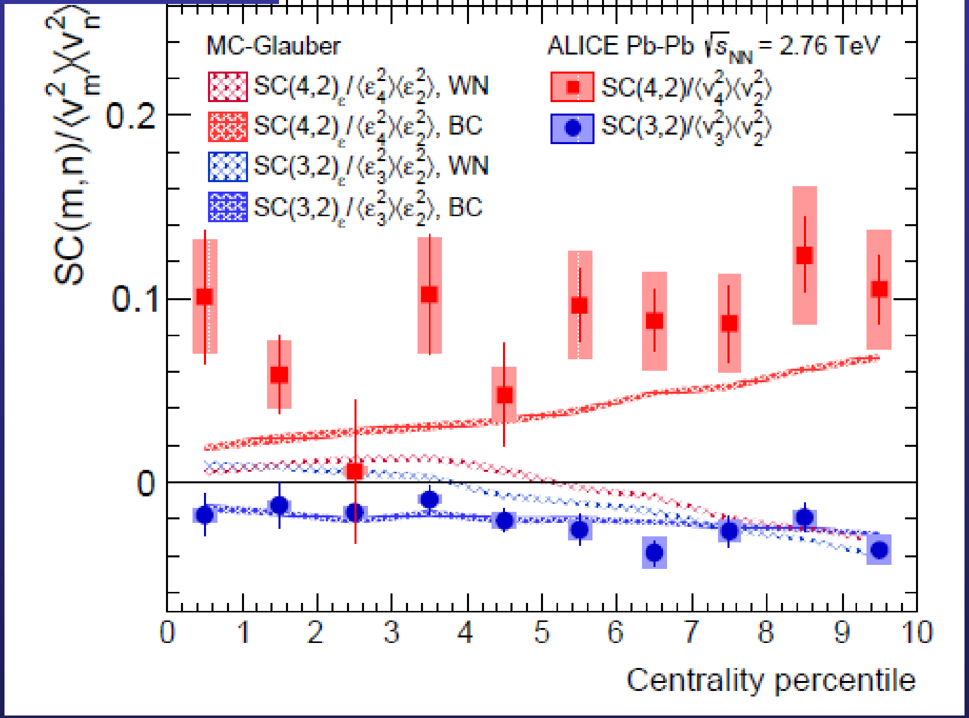
$$v_n = \left\langle \cos\left[n\left(\varphi-\Psi_{RP}\right)\right]\right\rangle$$

# Other recent results on anisotropies

- ☐ More complex observables can be defined, which are more robust against systematic biases originating from non-flow effect
→ **E-by-E fluctuations of amplitudes of anisotropic flow harmonics**

ALICE, PRL 117 (2016) 182301





No single centrality where a single parametrization of η/s describes BOTH correlations

Central collisions very sensitive to various parameterizations of the MC-Glauber initial conditions

# E-by-E fluctuations of amplitudes of anisotropic flow harmonics

Symmetric 2-harmonic 4-particle Cumulant → SC(m,n) with m≠n

$$\begin{aligned}\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c &= \langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle\\ &\quad-\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle\\ &= \langle v_m^2 v_n^2\rangle-\langle v_m^2\rangle\,\langle v_n^2\rangle\,,\end{aligned}$$

$\langle\langle\ \rangle\rangle$ indicates averaging in two steps

a) Over all distinct particle quadruplets in the events

b) Single event averages weighted with `number of combinations’

SC(m,n) is zero if no flow fluctuations or if magnitudes of $v_m$ and $v_n$ are uncorrelated

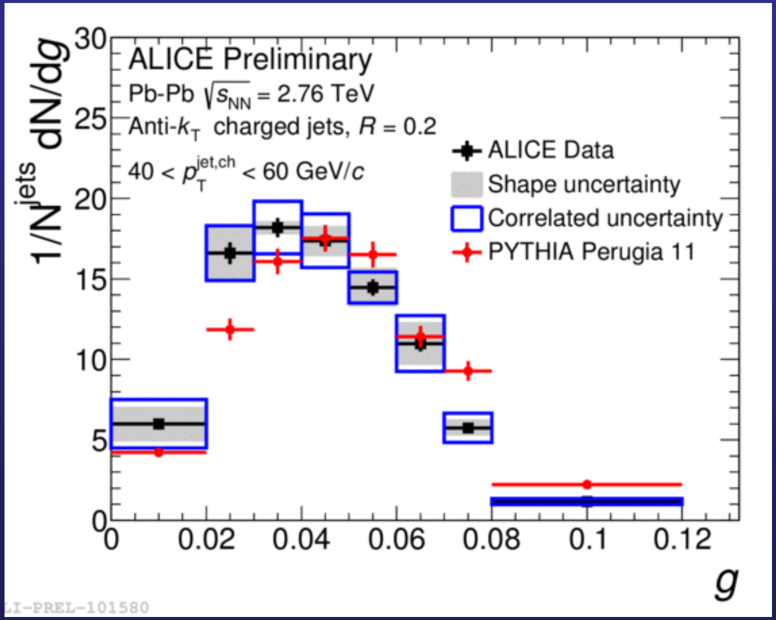
# Analyzing jet shapes

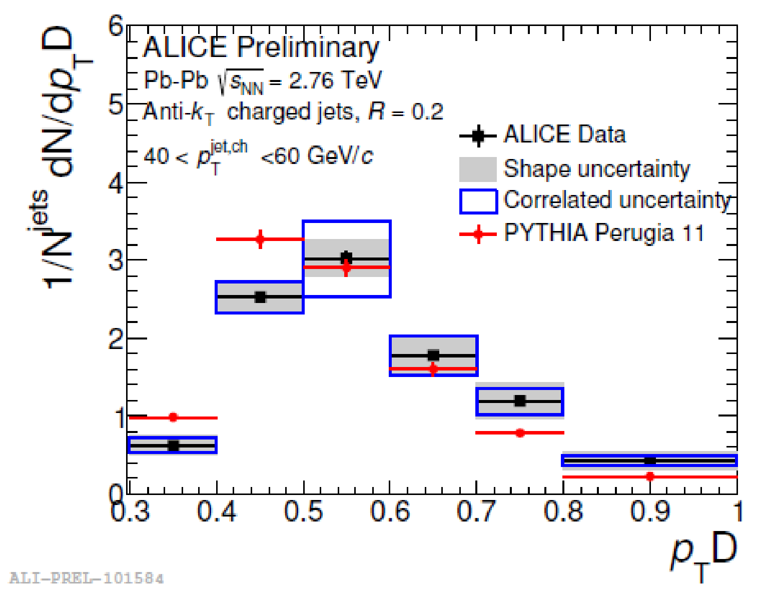
$$g = \sum_{i \in \mathrm{jet}} \frac{p_T^i}{p_T^{jet}} |r_i|$$

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

$p_T$-weighted width of the jet
(low g for collimated jets)

Dispersion of constituents in jets
Fewer constituents → higher $p_T D$





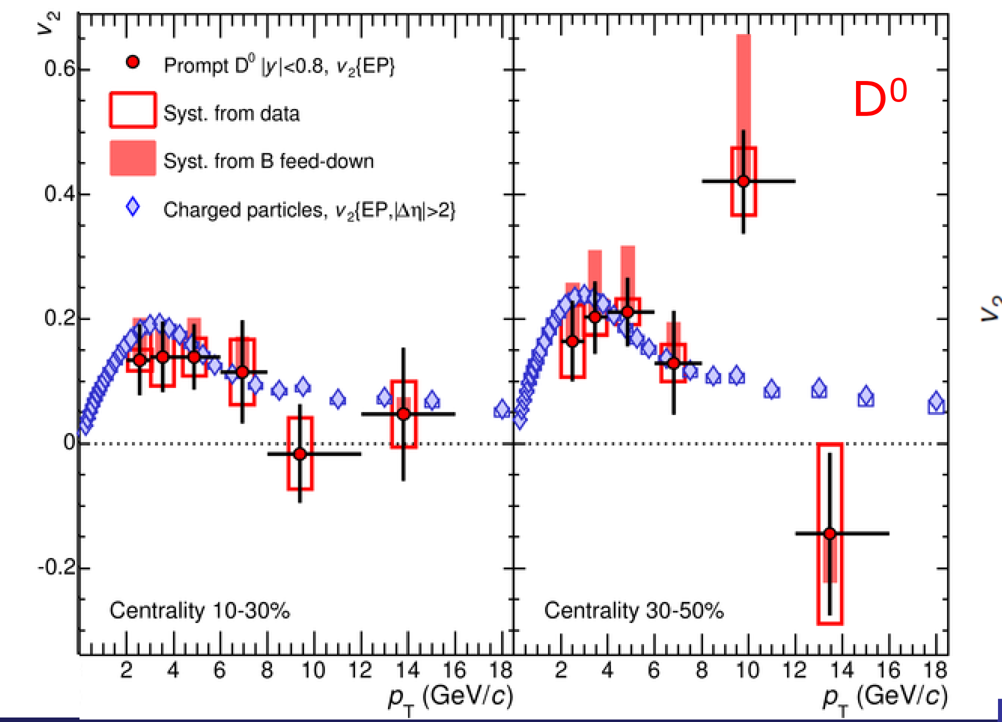
**Core of jets in Pb-Pb appears to be more collimated than in pp**

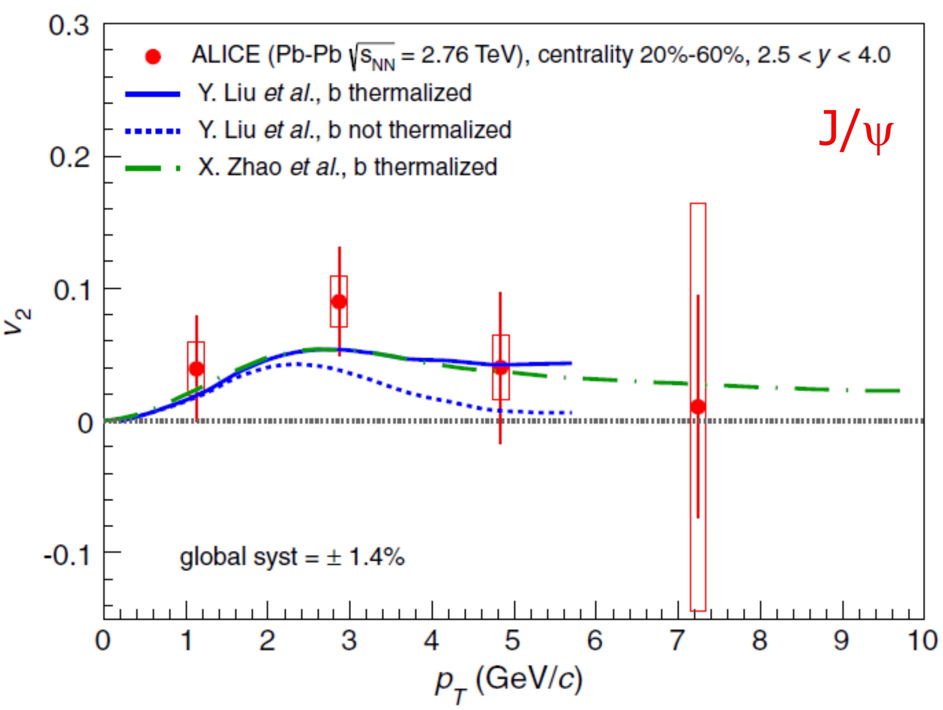
Shift to higher $p_T D$ in Pb-Pb
→ fewer jet constituents and
larger $p_T$ dispersion

# Heavy quark/quarkonium $v_2$

- ❑ ALICE results show evidence for D-meson elliptic flow and strong indications for $J/\psi$ $v_2$ in Pb-Pb collisions

ALICE, PRC 90 (2014) 034904





ALICE, PRL 111 (2013) 162301

- ❑ Low (intermediate) $p_T$ non-zero $v_2$ → **indication for c-quark thermalization and further confirmation for $J/\psi$ production by recombination**

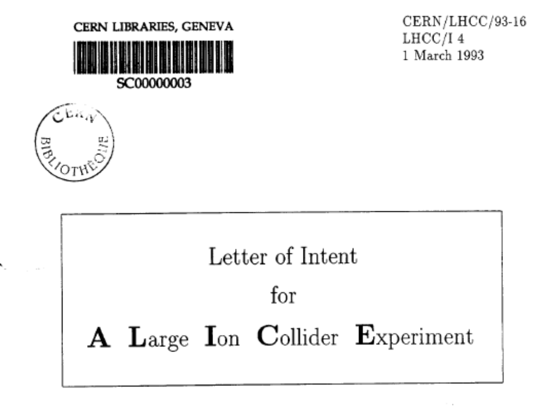
# ALICE: a complex (and long!) project

March 1992 → Evian meeting "Towards the LHC Experimental Programme"

**March 1993 → The ALICE Letter of Intent**

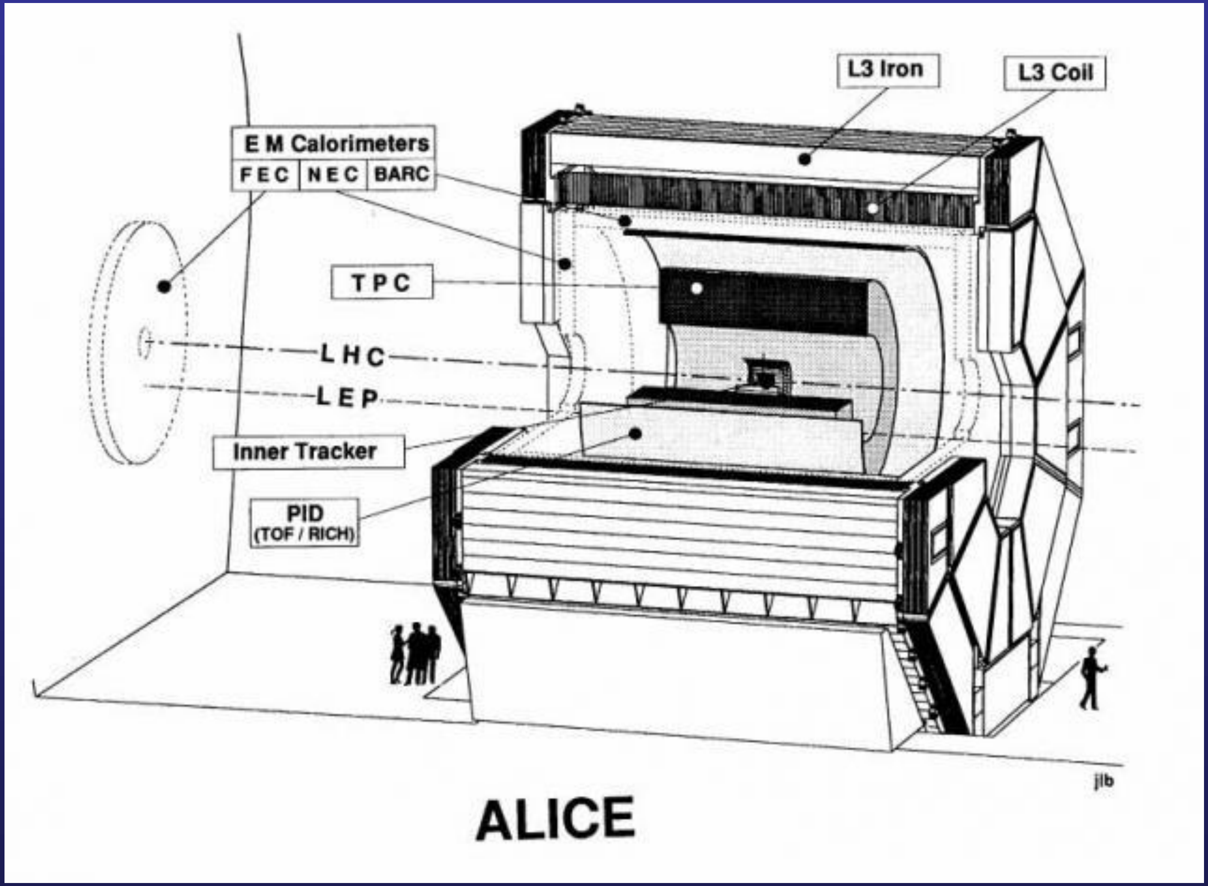
→ Use L3 magnet
→ TPC-based tracking
→ Emphasis on PID

At that time
→ Only y~0
→ No muon-dedicated detectors



CERN/LHCC/93-16
LHCC/I 4
1 March 1993

Letter of Intent
for
A Large Ion Collider Experiment



42 institutes, 230 people

# ALICE nowadays

**42 countries, 174 institutes, 1800 members**

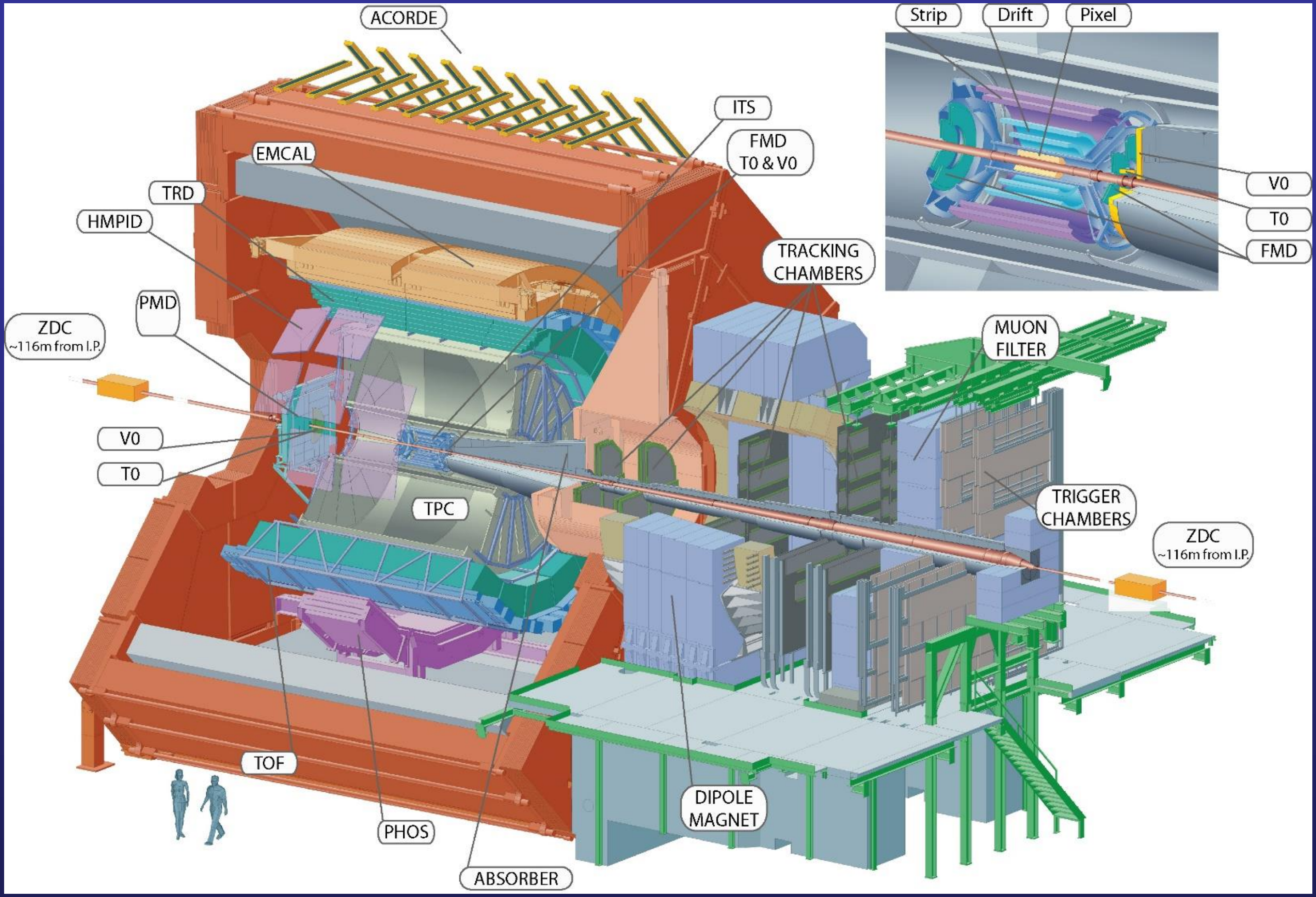
A Large Ion Collider Experiment

**ALICE COLLABORATION**

**AS NOVEMBER 2016**

- ❑ A world-wide Collaboration
- ❑ Goal → **exploit the unique physics potential of nucleus-nucleus interactions at LHC energies**

# The ALICE detector

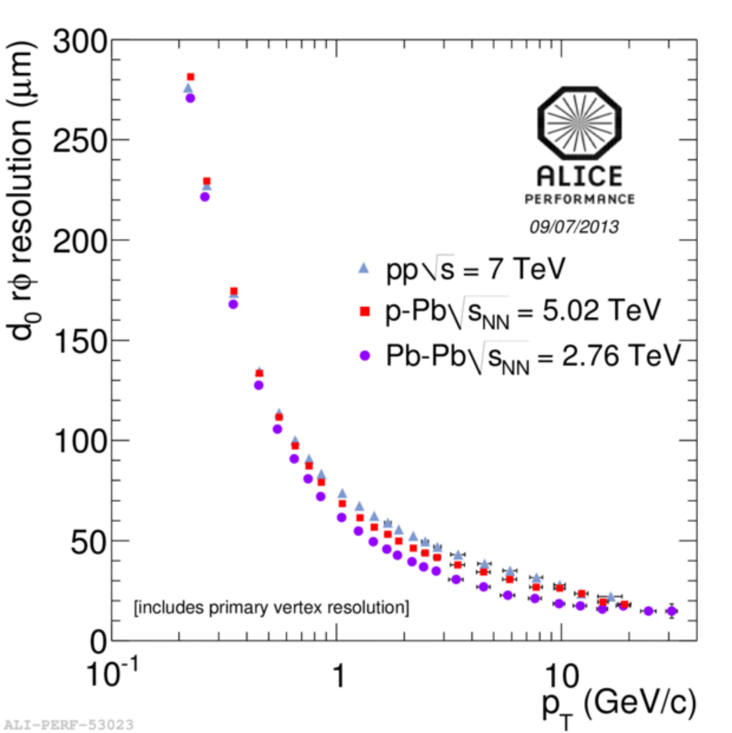


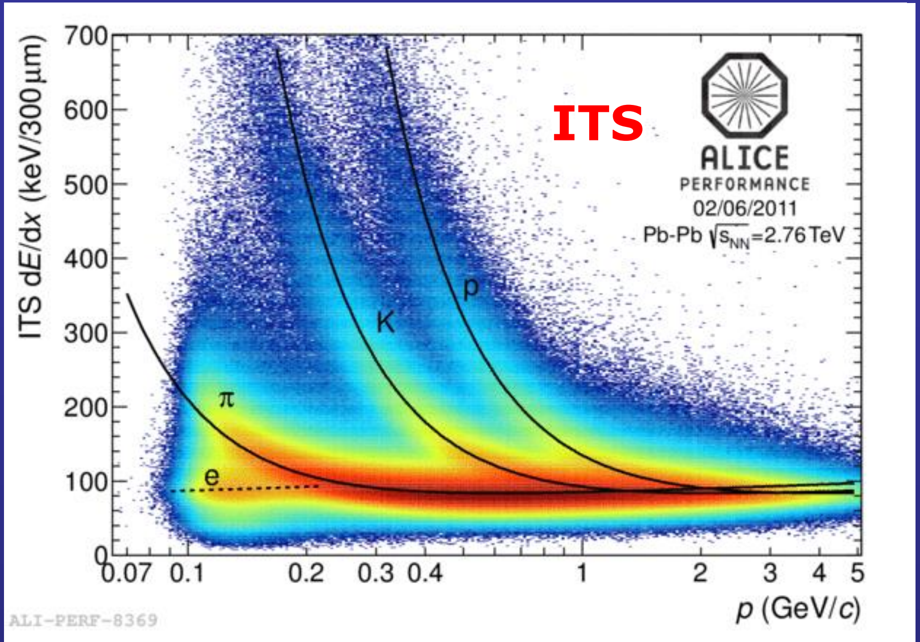
- ☐ General-purpose detector for the **study of QGP-related signals at the LHC,** with several unique features (see next slides)

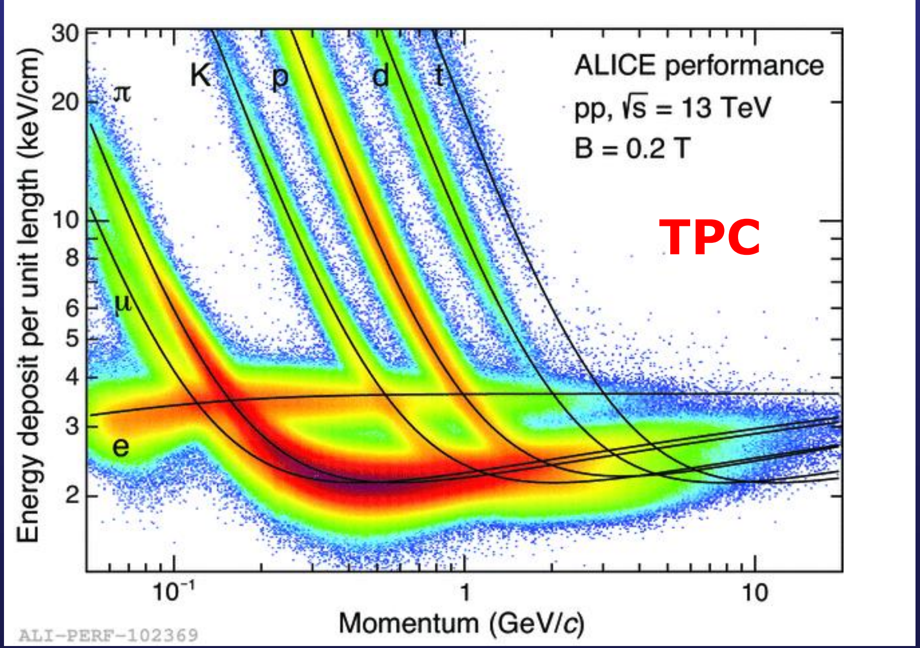
# ALICE performance

- **Excellent PID capabilities** down to very low p ~ 100 MeV/c

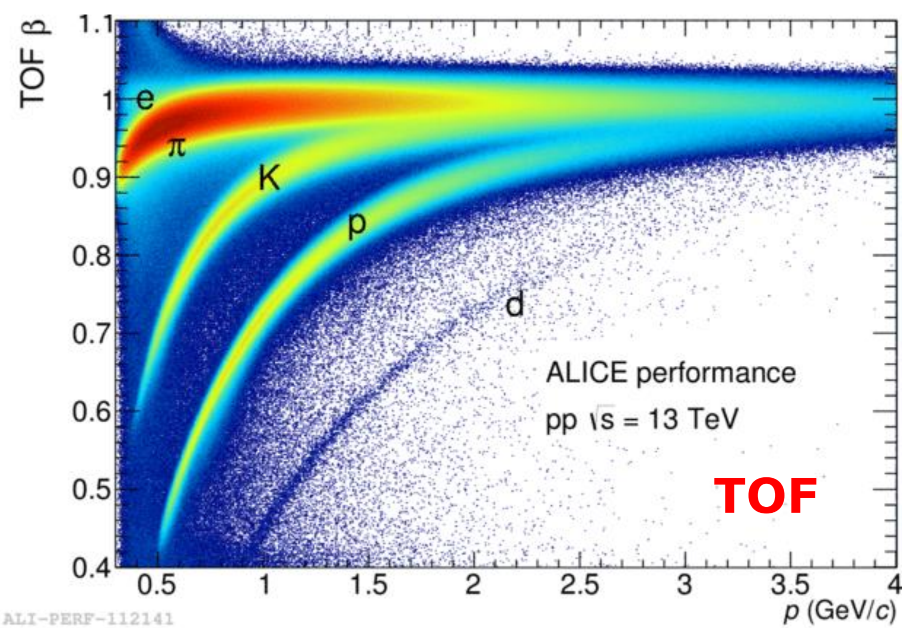
- Track impact parameter resolution allows for reconstruction of secondary vertices from D decays



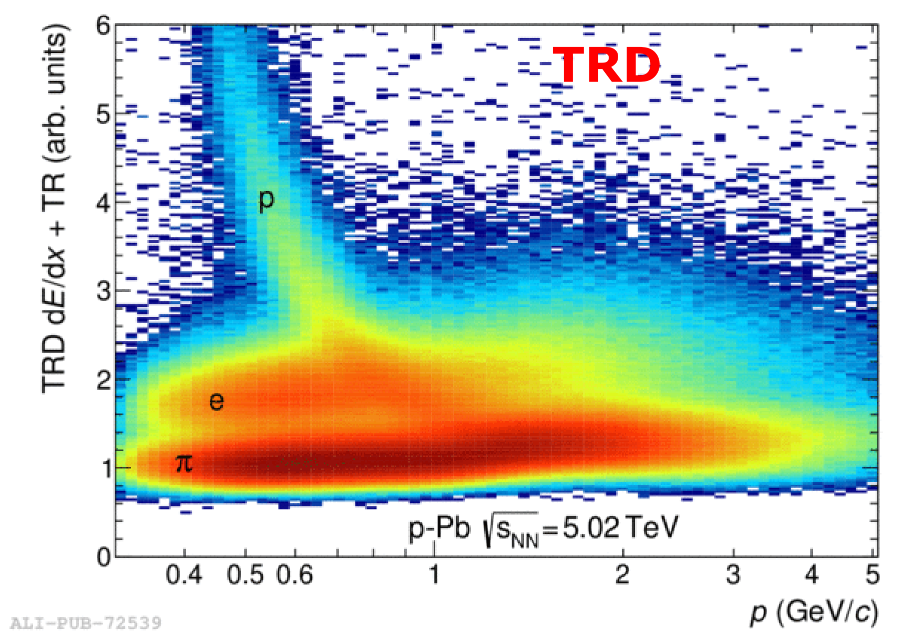




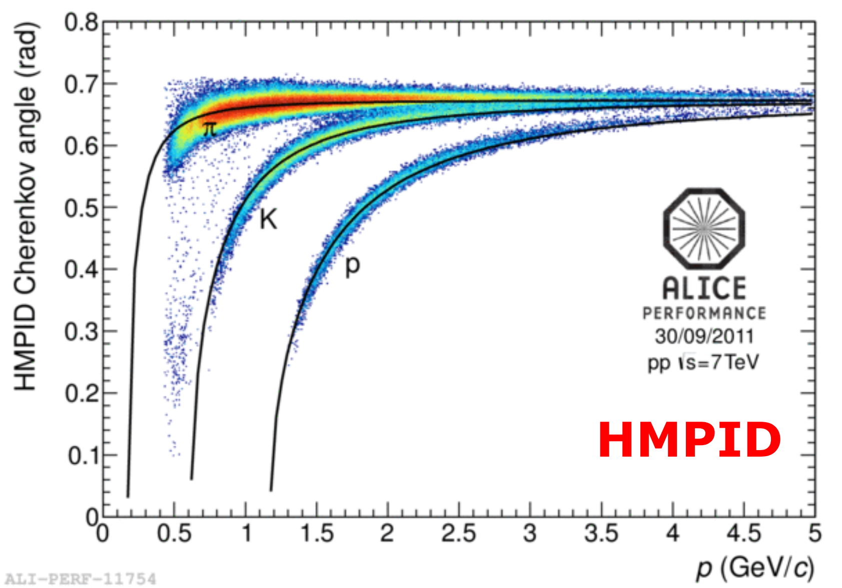
# ALICE performance



ALI-PERF-112141



ALI-PUB-72539



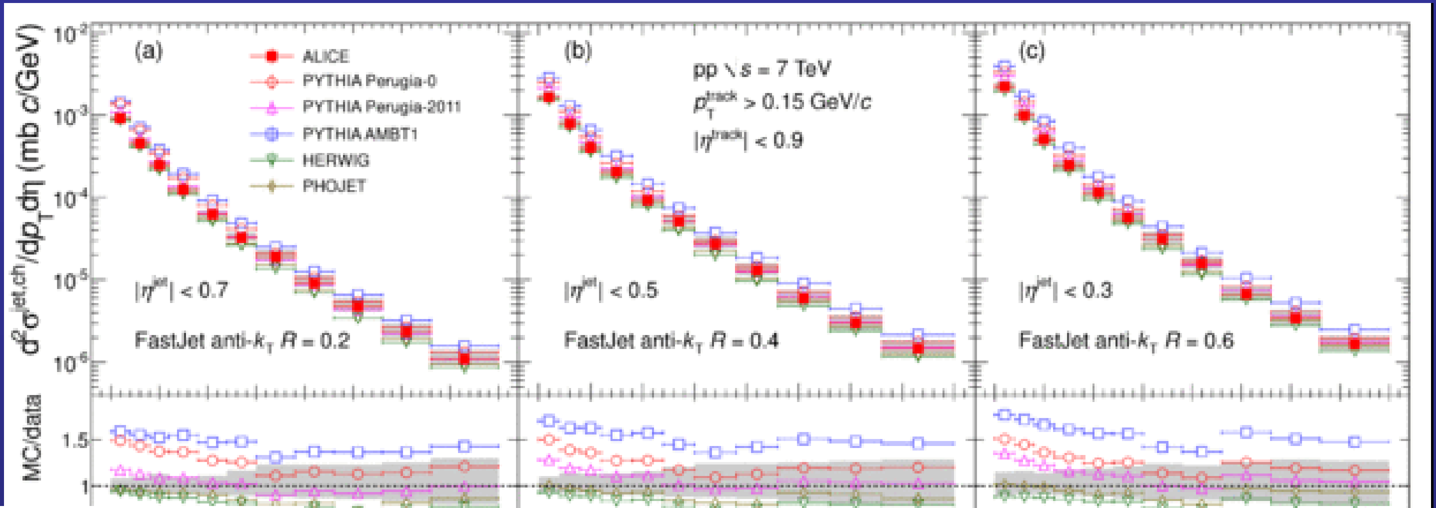
ALI-PERF-11754

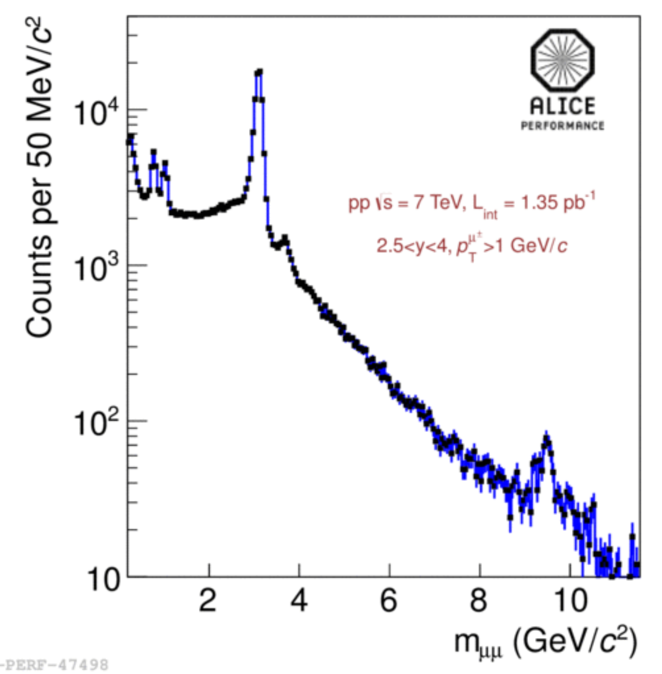
- TOF, HMPID significantly **extend PID capabilities**

- TRD allows triggering **on electrons** in the central barrel

# ALICE performance (hard probes)

**Jet physics**
via
EMCAL
(trigger)

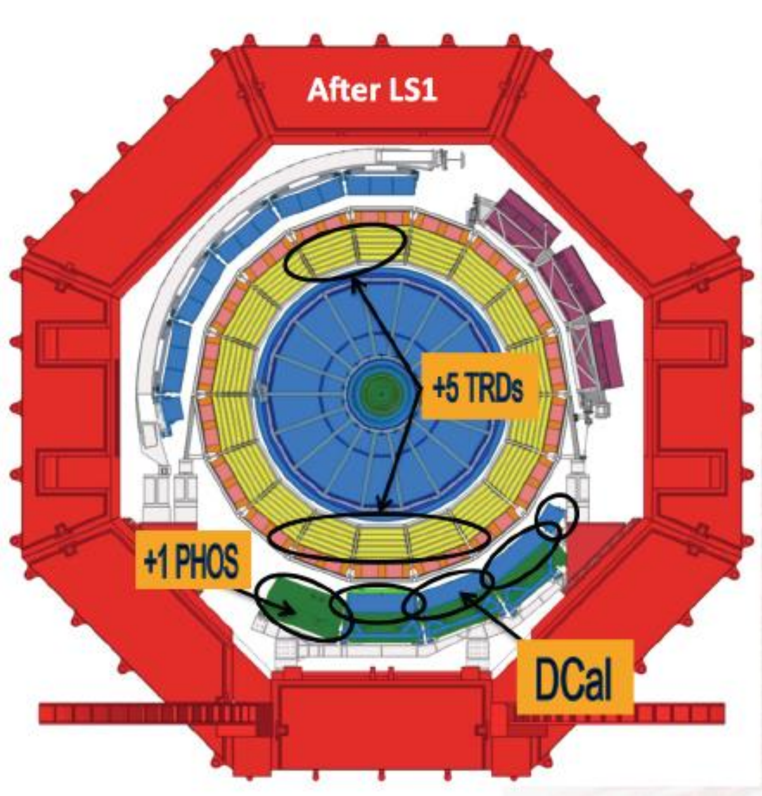




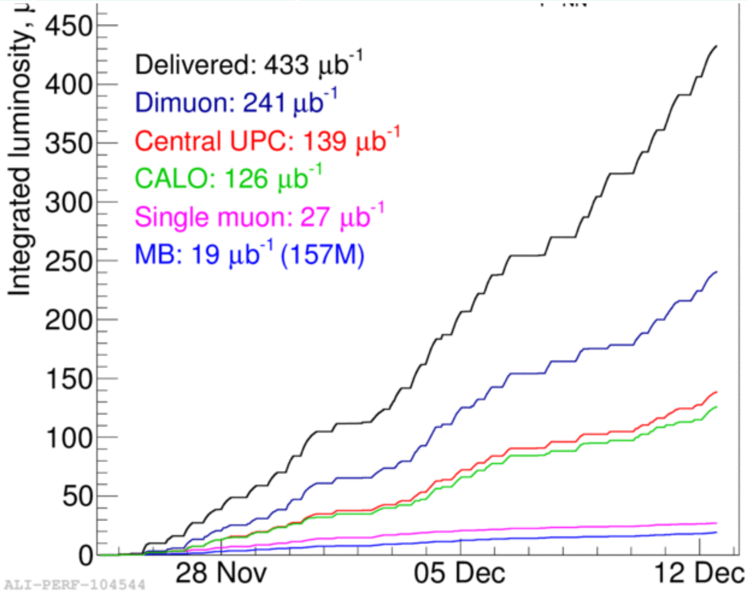
**Muon triggering** (forward-y) allows for detection of heavy quarkonia ($J/\psi$, $\psi$(2S), $\Upsilon$(1S,2S,..))

Full coverage of QGP-related signals from low to high-$p_T$, at both central and forward-y

# Data samples – run 2 (ALICE)



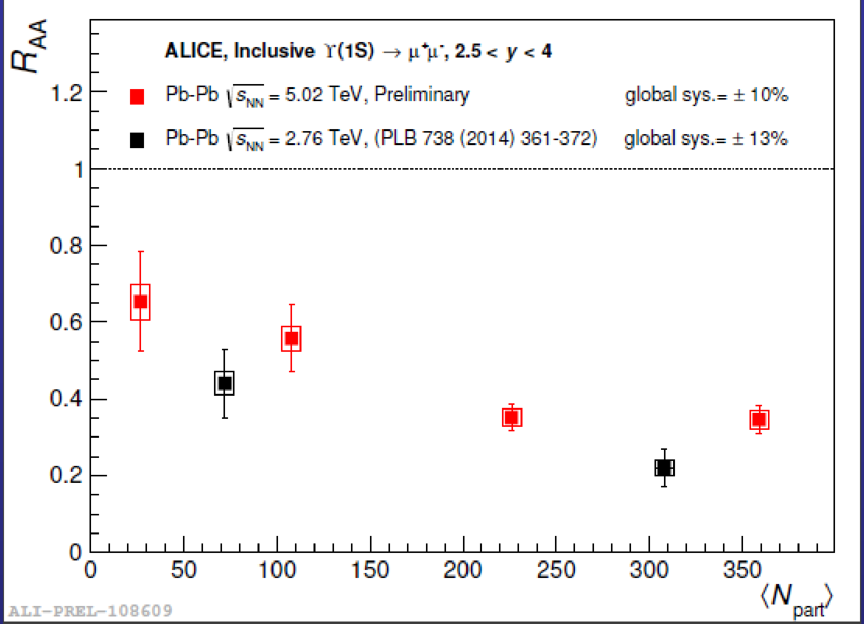
| **System** | **$\sqrt{s_{NN}}$ (TeV)** | **$L_{int}$** | **Year** |
|---|---|---|---|
| pp | 13 | 14 $pb^{-1}$ | 2015-2016 |
| Pb-Pb | 5.02 | 0.4 $nb^{-1}$ | 2015 |
| pp | 5 | 100 $nb^{-1}$ | 2015 |
| p-Pb | 5.02 | 3 $nb^{-1}$ | 2016 |
| p-Pb | 8.16 | ~20 $nb^{-1}$ | 2016 |

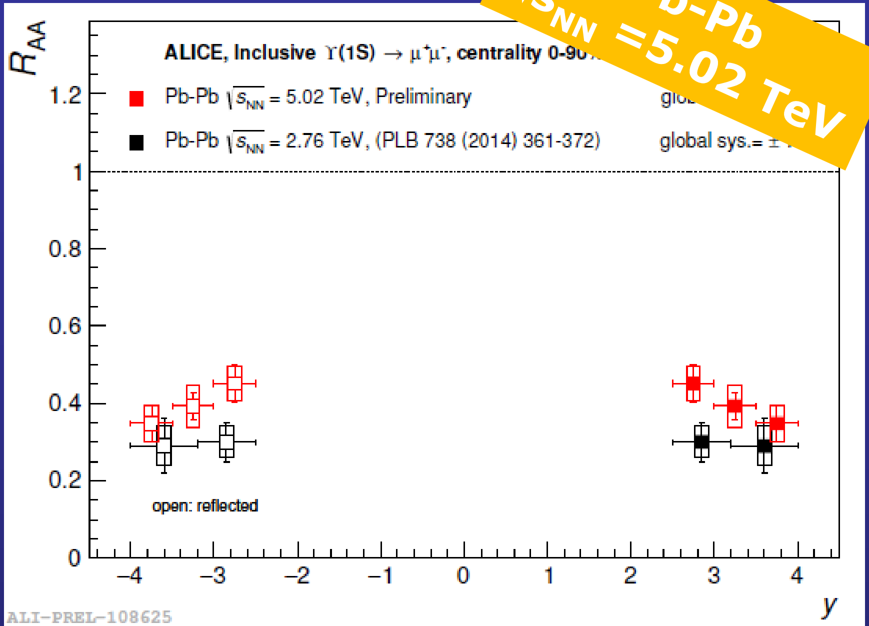


- **New detectors installed**
  - Complete TRD
  - Install DCal
  - Extended PHOS
  - Install CPV in front of PHOS

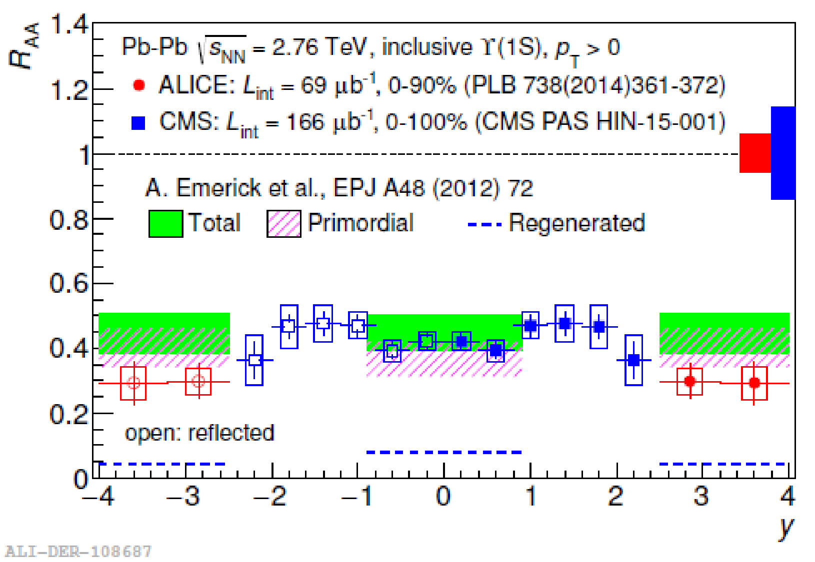
# Recent bottomonium results

**Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV**





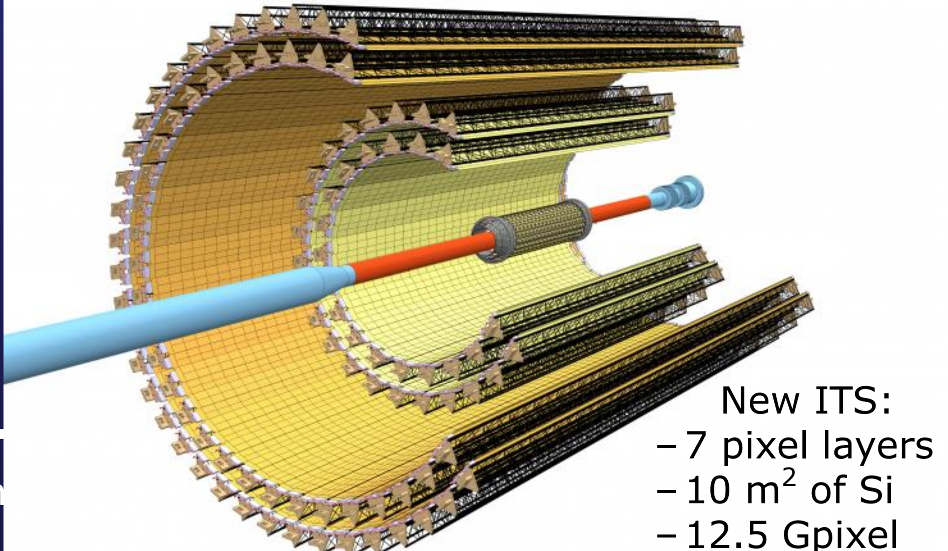
- Tendency to LESS suppression for the ϒ(1S) when increasing energy ?
- $R_{AA}$ at $\sqrt{s_{NN}}$=2.76 and 5 TeV compatible, but also the y-shape **but reminds recombination patterns** (unexpected because of the relatively low b-quark cross section)
- Possible tension in the comparison with theoretical models



# ALICE upgrade

- Conditions expected for LHC run 3 (2021-2023)
  - Pb-Pb peak interaction rate: 50 kHz (now 8 kHz)
- Present ALICE readout rate ≤ 1 kHz
- **Physics goal for run 3:**
  - **High precision measurements of rare signals (focus on low $p_T$), to be reached through**
    - **Increase of the readout rate to 50 kHz**
    - **Improvement of the pointing resolution at central (new ITS) and forward y (Muon Forward Tracker)**

- The ALICE upgrade requires major improvements for the TPC and other detectors → higher R/O rate
- Online reduction of the data volume, $L_{int}>10$ nb$^{-1}$ (100 times run 1)
- Technical Design Reports approved → Moving to construction phase



New ITS:
- 7 pixel layers
- 10 m$^2$ of Si
- 12.5 Gpixel

# Conclusions (2)

- ❑ **LHC run 2** goes on at full speed
- ❑ No qualitatively different effects are expected moving from $\sqrt{s_{NN}}$=2.76 to 5.02 TeV, but **the quality of the results is improved,** thanks to higher luminosities and better understanding of the apparatus

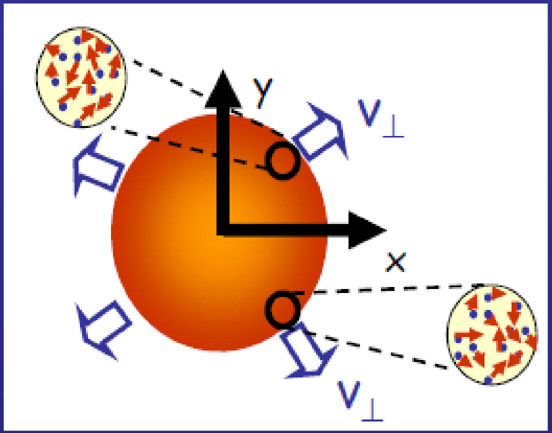
- ❑ Recent ALICE run 2 results include
  - ❑ **Study of hadron multiplicity**
  - ❑ **Elliptic flow**
  - ❑ **Suppression of high-$p_T$ particles**
  - ❑ **Charmonium and bottomonium**

- ❑ Many more to come…**stay tuned!**

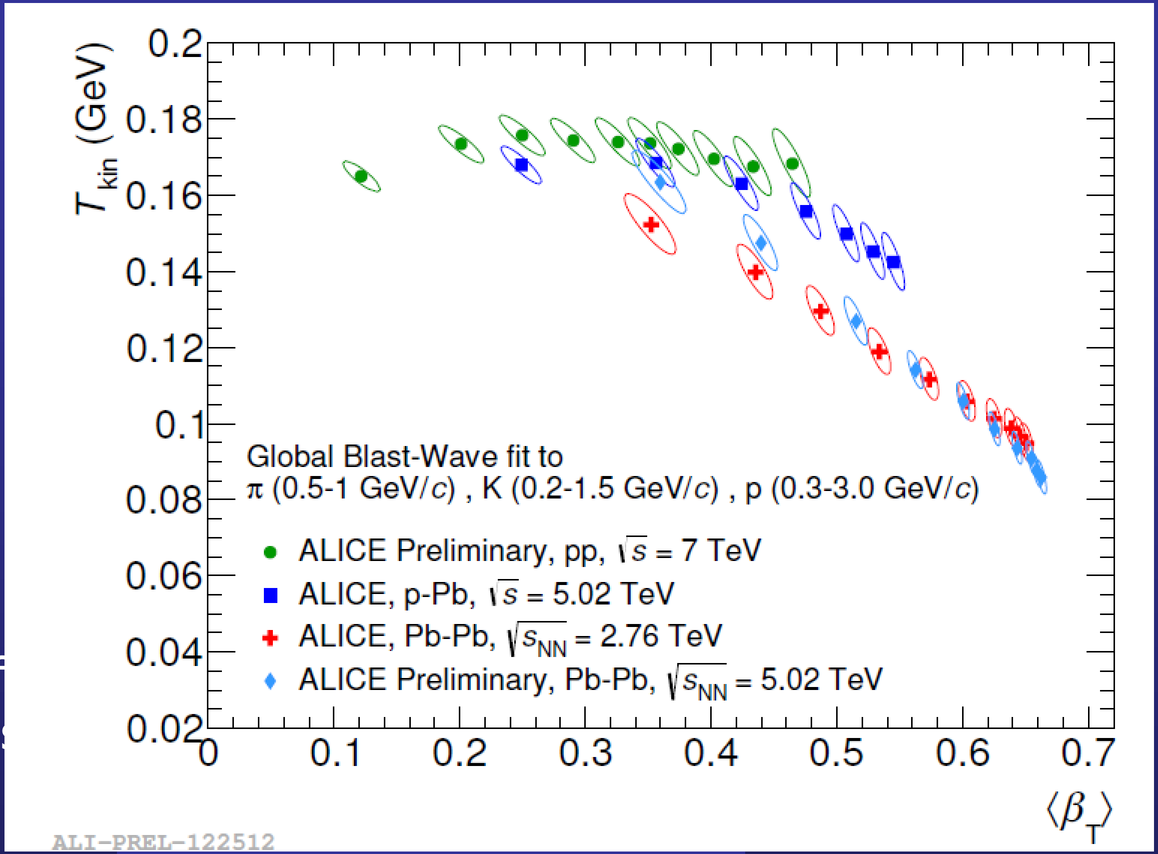
- ❑ Physics program extending into run 3 and run 4 thanks to the **substantial upgrades** foreseen for LS2

# Low $p_T$: radial flow parameters

- ☐ Collective radial flow modifies $p_T$ spectra



- ☐ ($\text{Low-}p_T$) slopes are modif according to the particle ma and expansion velocity



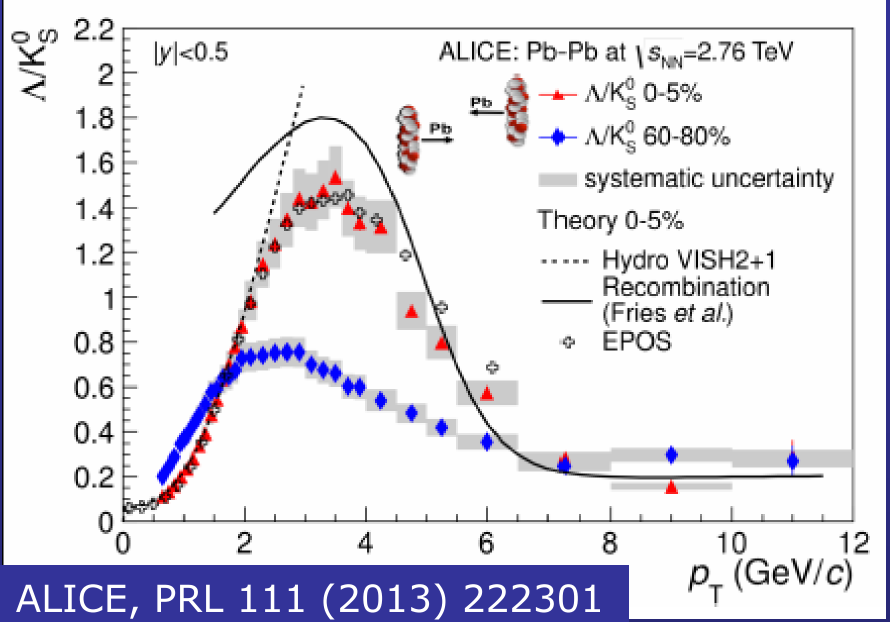
ALICE, PRC 88, 044910 (2013)
ALICE, PLB 728 (2014) 25-38

Blast-wave fits
→ Extract $T_{kin}$ and $\beta_T$

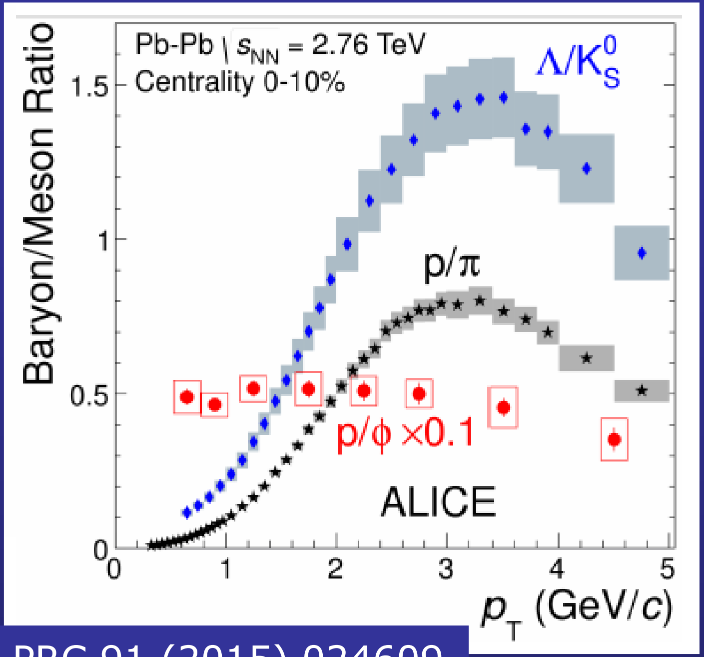
Central Pb-Pb collisions

**Kinetic freeze-out $T_{kin}$<100 MeV**
**Expansion velocity ~ 0.65c**

# Intermediate $p_T$: baryon/meson ratio



ALICE, PRL 111 (2013) 222301



ALICE, PRC 91 (2015) 024609

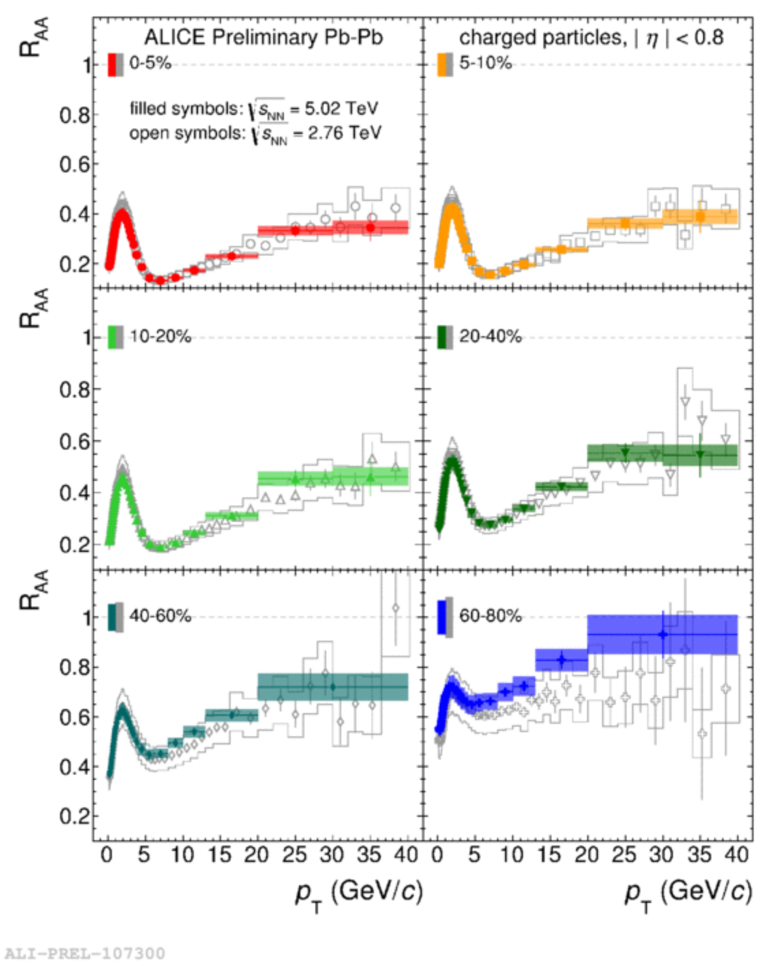
- ❑ Enhancement at intermediate $p_T$
  - → Hydrodynamics describes only the rise at < 2 GeV/*c*
  - → Recombination (pushes baryons to higher $p_T$) reproduces effect but overestimates
  - → EPOS gives good description of the data (with flow)

- ❑ p and $\phi$ have similar masses
- ❑ $p/\phi$ flat vs $p_T$ in central Pb-Pb

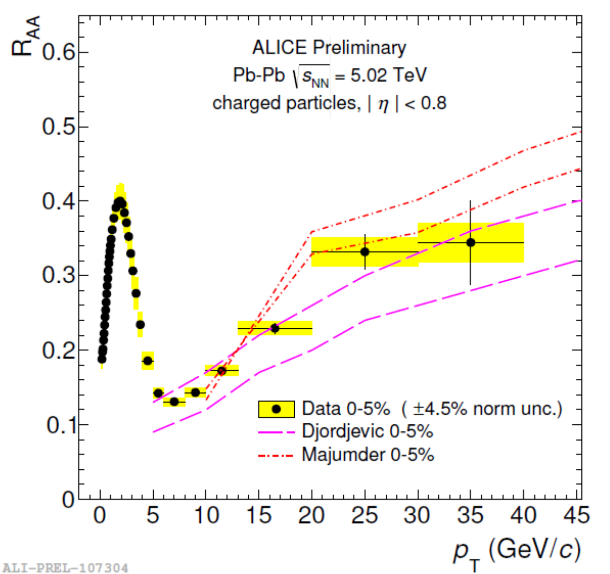
**→ Mass determines the spectral shapes (as in hydrodynamics)**

# Hard probes of the QGP
# Recent results on high $p_T$ hadrons

**Pb-Pb $\sqrt{s_{NN}}$ =5.02 TeV**



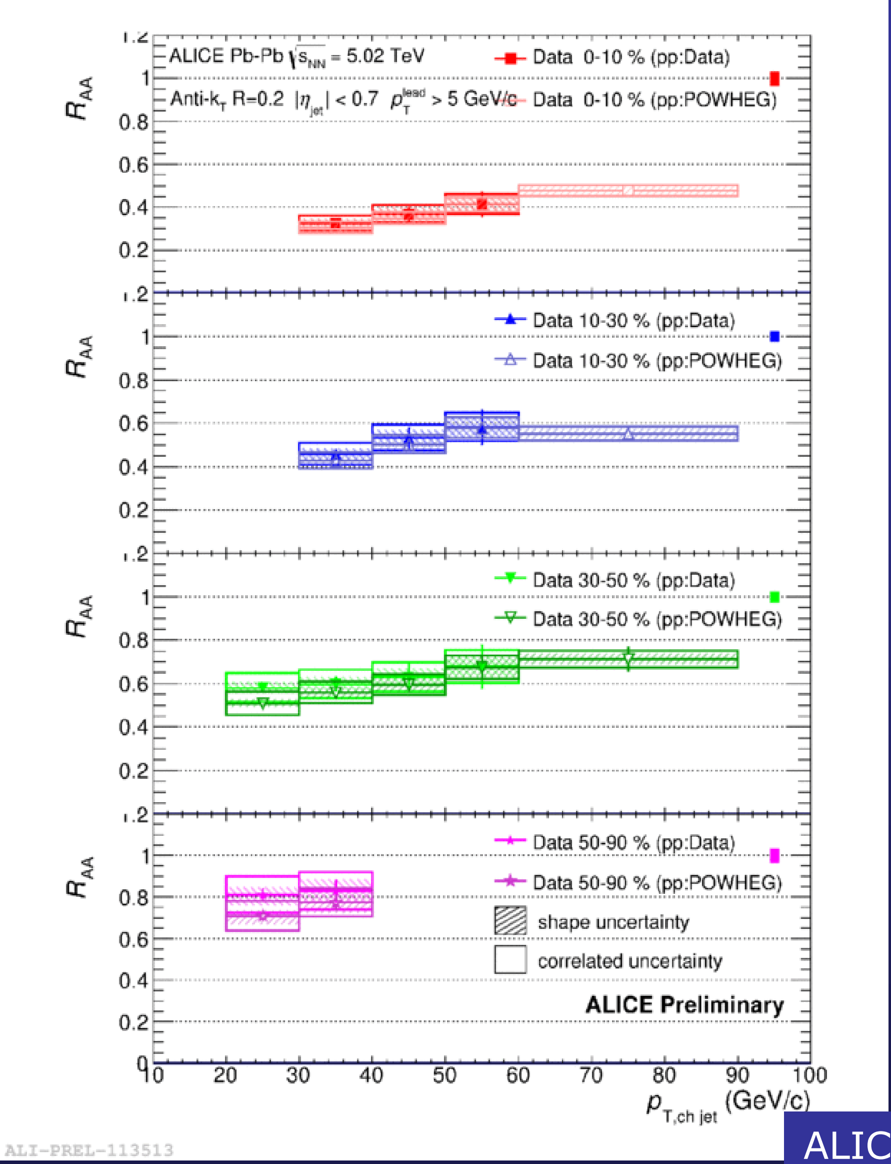
- ☐ Strong suppression up to $p_T$=40 GeV/c
- ☐ **Remarkable similarity between results at $\sqrt{s_{NN}}$=2.76 and 5 TeV**
- ☐ "Compensation" between increasing suppression and modification of the shape of $p_T$ spectra ?



(Further) constraints to energy loss models

# Recent results on jet $R_{AA}$

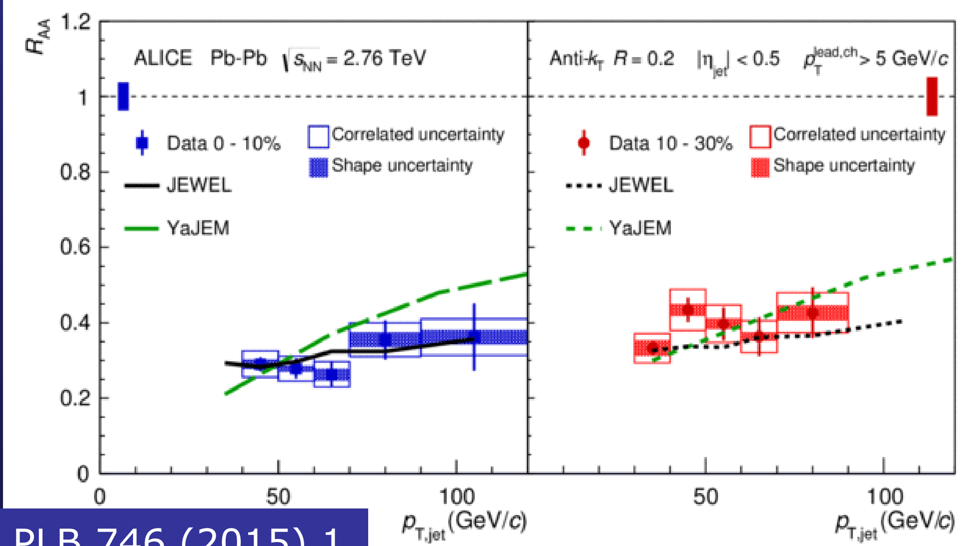
**Pb-Pb**
**$\sqrt{s_{NN}}$ =5.02 TeV**



- Strong out-of-cone jet radiation

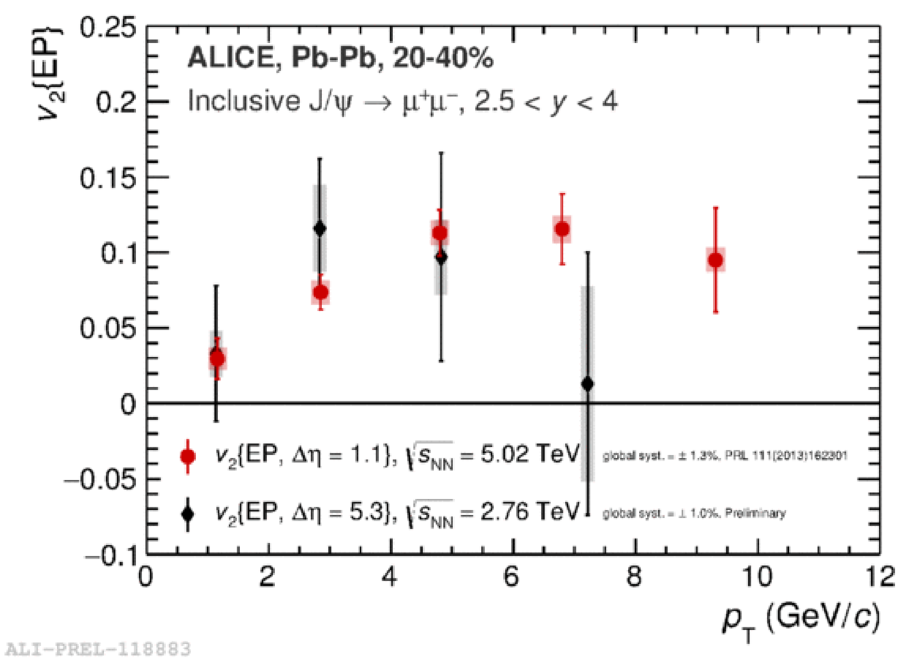
- **Similar effect at $\sqrt{s_{NN}}$=5.02 and 2.76 TeV**
  - Denser medium → smaller $R_{AA}$
  - Harder collisions → larger $R_{AA}$
    → Compensation of the two effects

- Jet suppression reasonably well reproduced by energy loss MC models



ALICE, PLB 746 (2015) 1

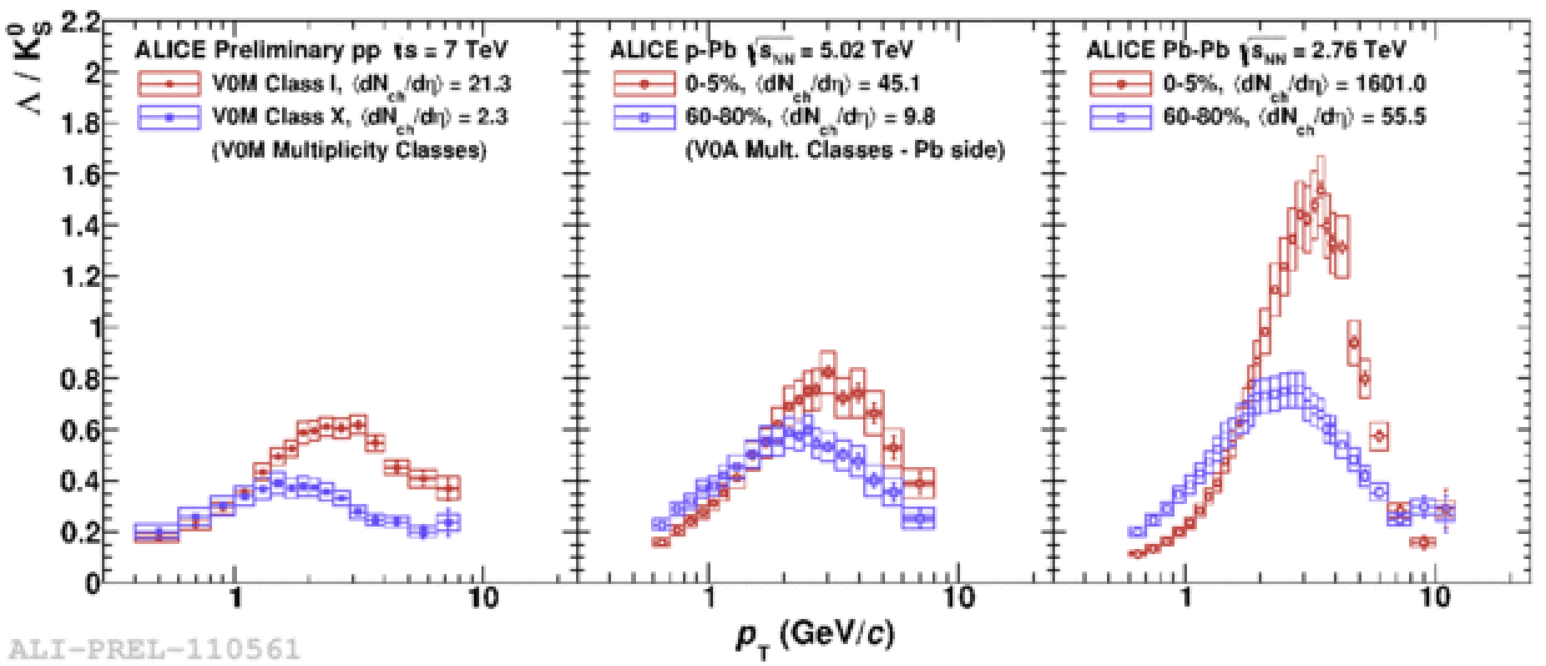
# New J/ψ $v_2$ results



| $p_T$ (GeV/c) | 0-2 | 2-4 | 4-6 | 6-8 | 8-12 |
|---|---|---|---|---|---|
| Δη=1.1 | 2.2σ | 6.3σ | 7.4σ | 5.0σ | 2.8σ |
| Δη=5.3 | 1.4σ | 6.2σ | 5.0σ | 3.3σ | 1.3σ |

- ❑ The contribution of J/ψ from (re)combination could lead to an **elliptic flow** signal at LHC energy
  → hints observed in run-1 results
- ❑ **From hint to evidence for a non-zero $v_2$ signal**, maximum for 4<$p_T$<6 GeV/c, 20-40% centrality
- ❑ Agreement, within uncertainties, with run-1 results
- ❑ Comparison closed vs open charm
  → Learn about **light vs heavy quark flow**
- ❑ A significant fraction of observed J/ψ comes from charm quarks which thermalized in the QGP

# pA/pp results: baryon/meson



- Clear evolution with multiplicity
  - Mid-$p_T$: ratio increases
  - Low-$p_T$: corresponding depletion

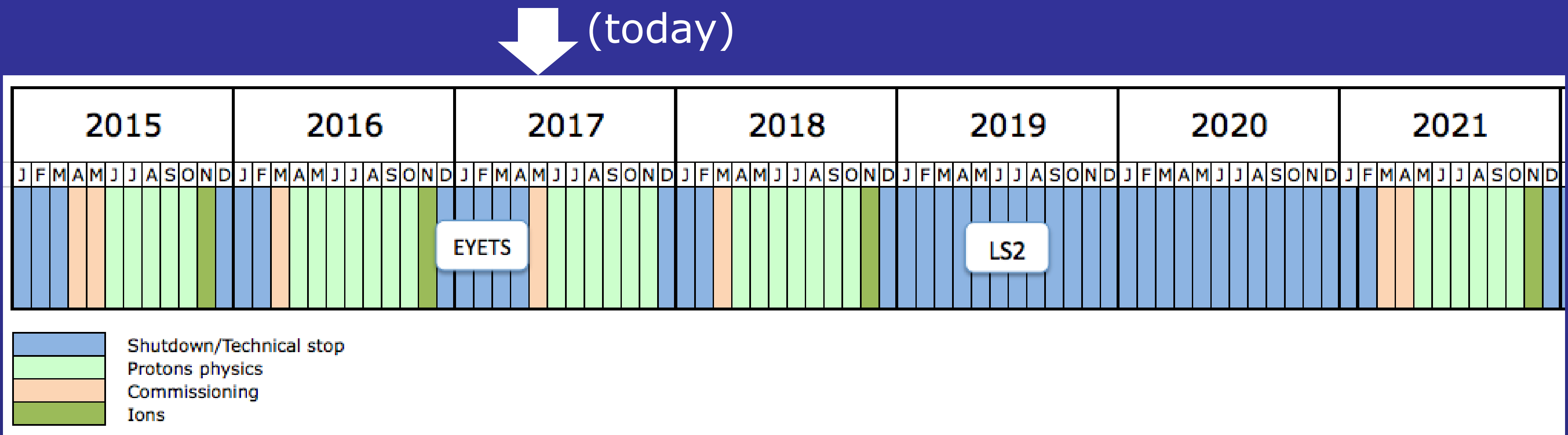
**Reminiscent of Pb-Pb phenomenology**

...generally understood (for Pb-Pb!) in terms of

  - collective flow
  - recombination

- Quantitatively similar when comparing event classes with similar $N_{ch}$

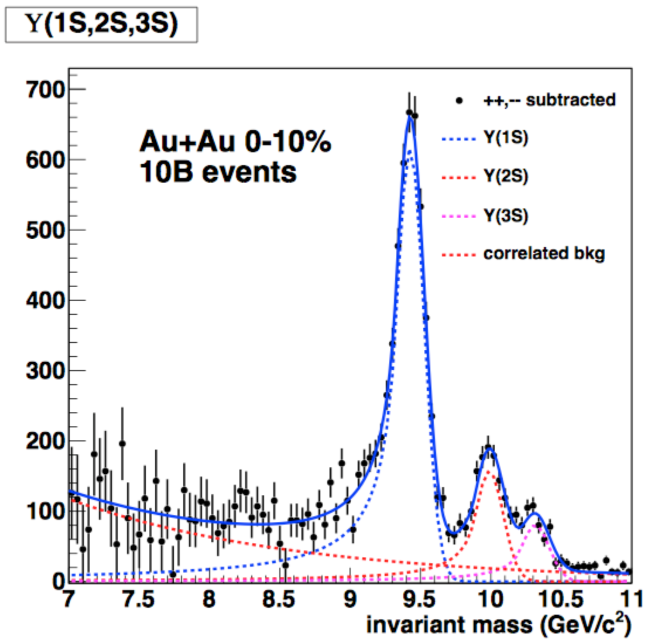
# Future of LHC heavy-ion program

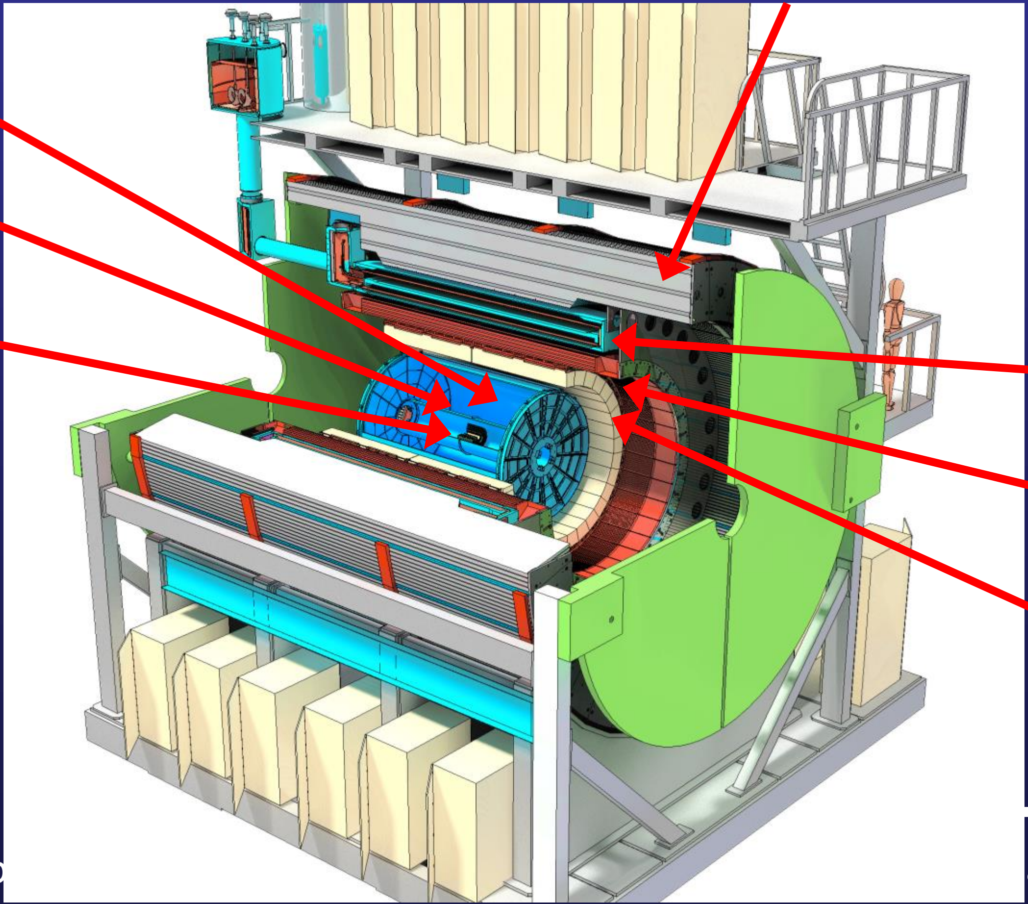


- 2018: Pb-Pb run, maximum available energy, L= $10^{27}$ cm$^{-2}$ s$^{-1}$
- LS2: ALICE upgrades apparatus (TPC, ITS, MFT) → stand 50 kHz event rate expected for run-3 and improve tracking
  LHCb upgrades tracker → higher granularity, push towards central collisions
  ATLAS new muon small wheel → reduce fake trigger
  CMS muon upgrade → add GEM for $p_T$ resolution, RPC for reducing background (better time resolution), extend coverage to $\eta>2.4$
- 2021-2023: LHC run-3, experiments require $L_{int}>10$ nb$^{-1}$ for Pb-Pb
  (compared to $L_{int} \sim 1$ nb$^{-1}$ for run-2)
  Possibility of accelerating lighter ions under discussion
- 2026-2029: LHC run-4

# The sPHENIX experiment

- ☐ Focus on
  - ☐ Spectroscopy of Υ states →
  - ☐ Jet structure
  - ☐ b-tagged jets





Outer HCal

TPC

INTT

MAPS

Solenoid Magnet

Inner HCal

EMCal