A Large Ion Collider Experiment

DIS 2013

ALICE

# HOT QCD MATTER CREATED AT THE LHC

***BARBARA ERAZMUS***

***FOR THE ALICE COLLABORATION***

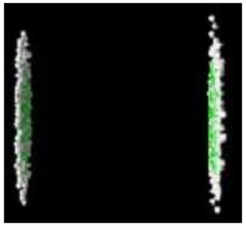
# HEAVY ION COLLISIONS AT HIGH ENERGY

***Extreme states of matter***

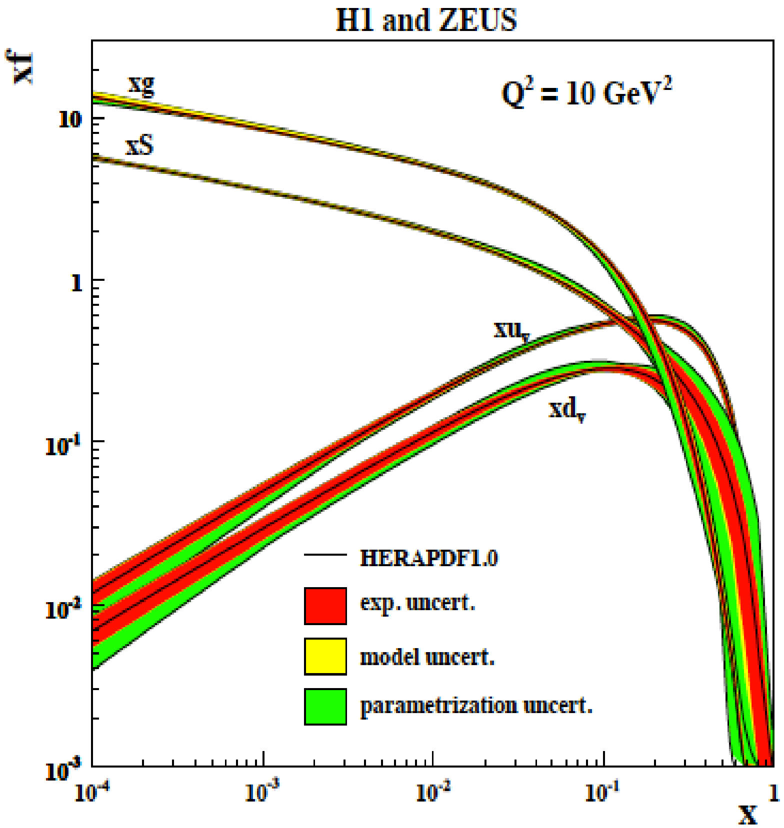
- QCD phase diagram
- Deconfinement
- Chiral symmetry restoration

***Universal character of wave functions of large nuclei***

- Dense gluonic system
- Saturation
- Color glass condensate



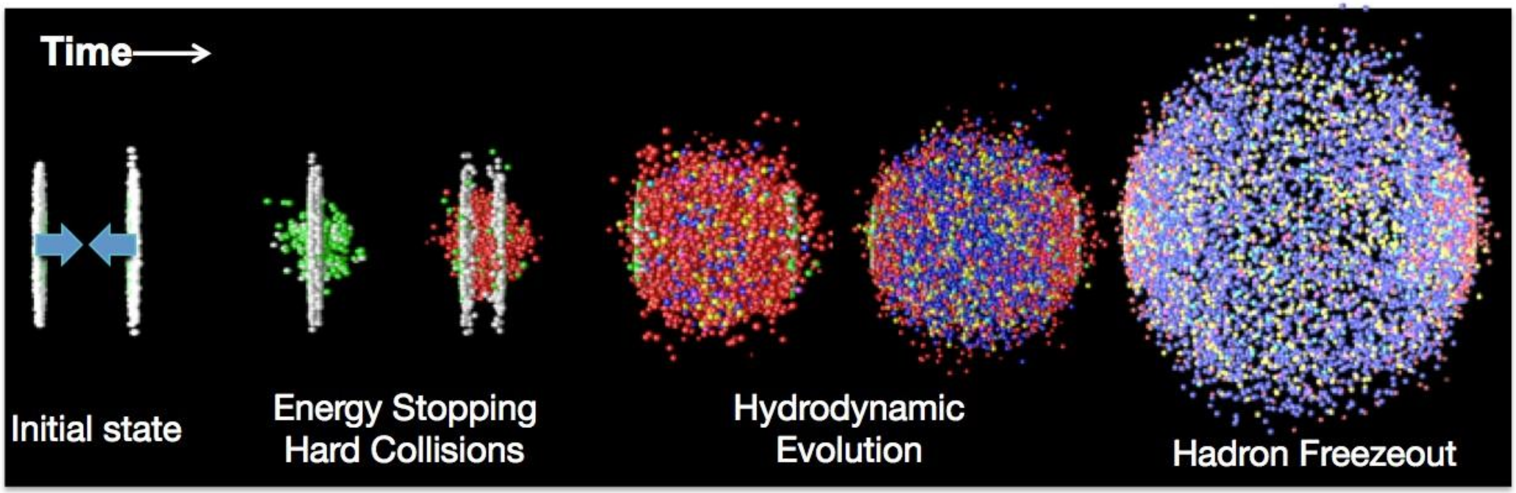
**HERA demonstrated that the gluon distribution in a proton rises very fast with decreasing x at fixed Q**

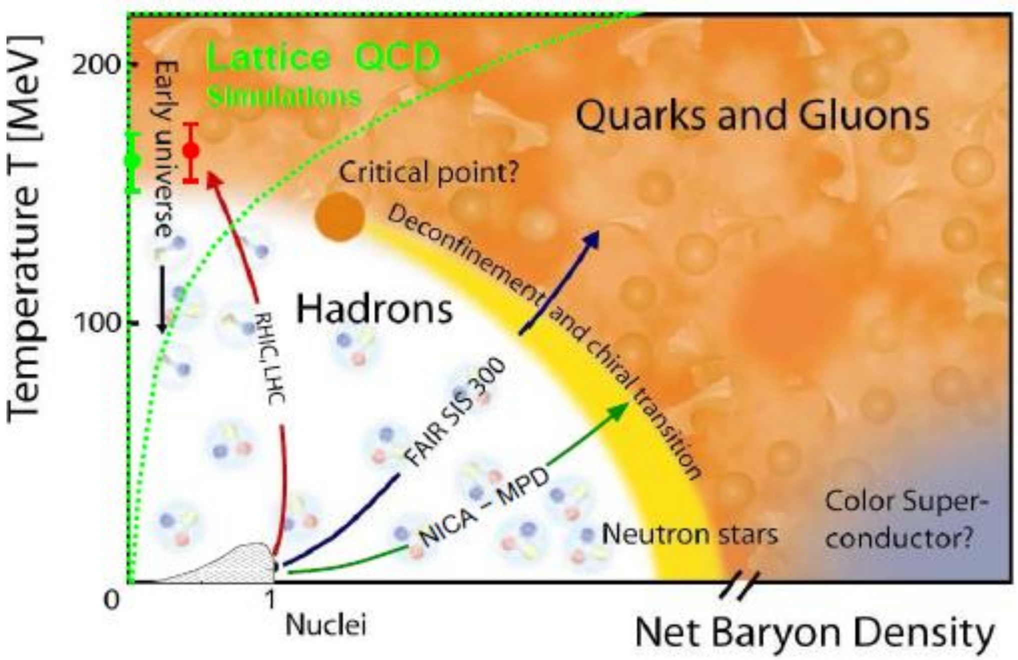



**RHIC** $(\sqrt{s} = 200\,\mathrm{GeV})$ $x \sim 10^{-2}$

**LHC** $(\sqrt{s} = 5.5\,\mathrm{TeV})$ $x \sim 4 \times 10^{-4}$

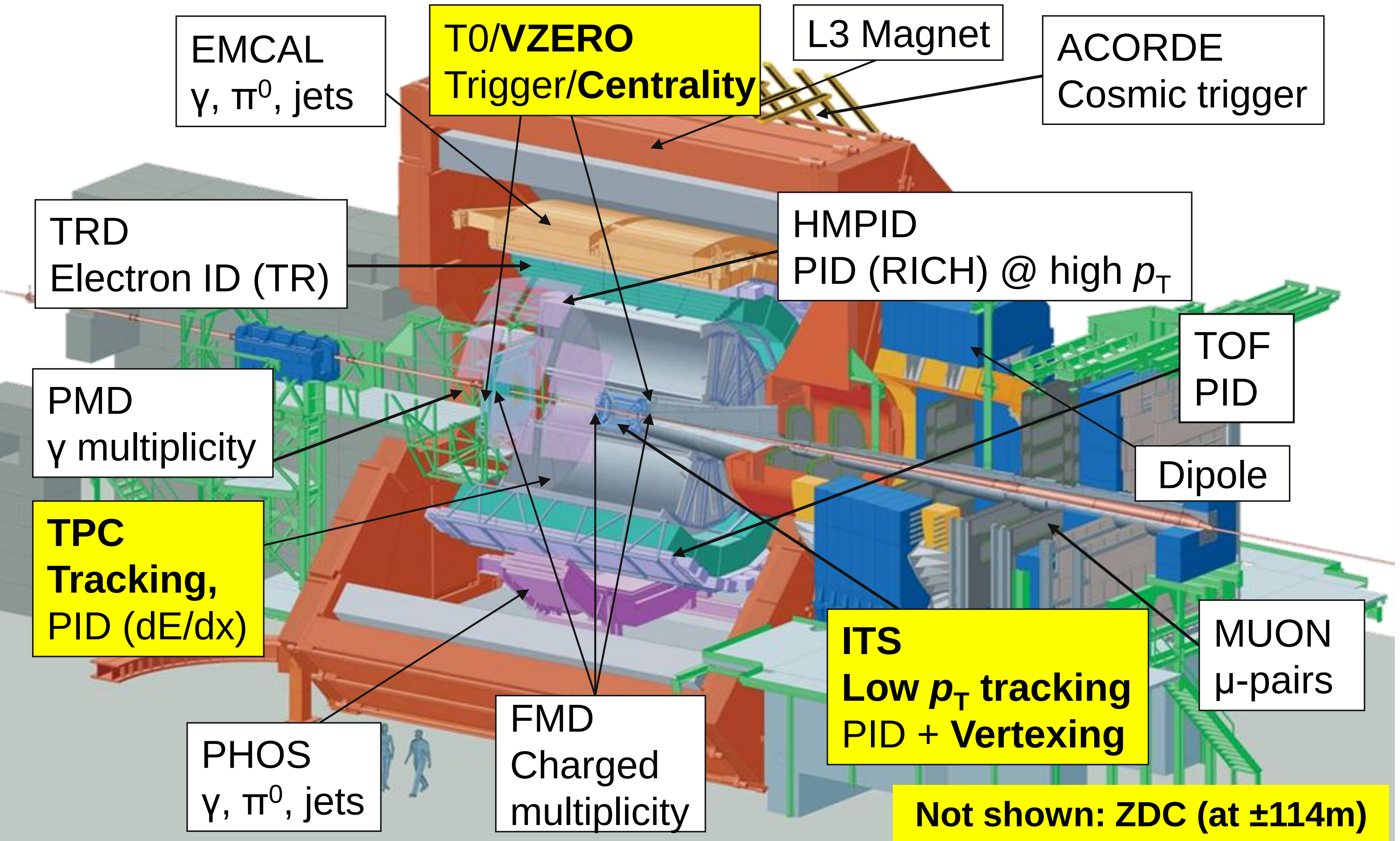
**In this range saturation of the rapidly growing gluon distribution at saturation scale Qs**


Time
Initial state
Energy Stopping
Hard Collisions
Hydrodynamic
Evolution
Hadron Freezeout

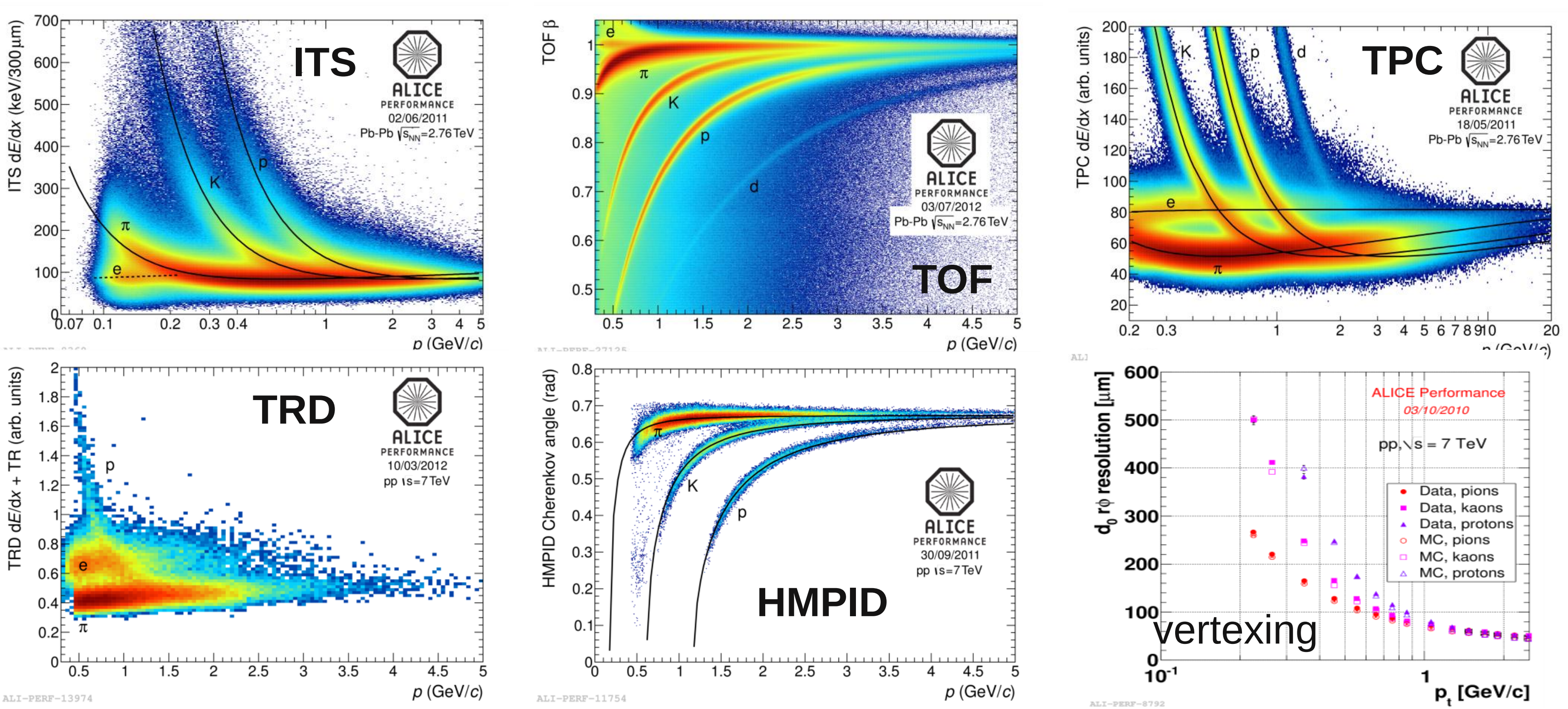

Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Lattice QCD
Simulations
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
NICA – MPD
Neutron stars
Color Super-
conductor?


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:36:37
Fill : 1482
Run : 137124
Event : 0x000000009D4C1693

# A LARGE ION COLLIDER EXPERIMENT



# ALICE – dedicated heavy-ion experiment at the LHC




- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of $X_0$
- excellent vertexing capability
- efficient low-momentum tracking down to ~ 100 MeV/*c*

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# LHC Heavy-Ion running

- Two heavy-ion runs at the LHC so far:
  - in 2010 – commissioning and the first data taking
  - in 2011 – already above nominal instant luminosity!
- p–Pb run just finished at the beginning of this year
- Followed by Long Shutdown–1 (LS1)

| year | system | energy $\sqrt{s_{NN}}$ TeV | integrated luminosity |
|---|---|---|---|
| 2010 | Pb – Pb | 2.76 | ~ 10 $\mu b^{-1}$ |
| 2011 | Pb – Pb | 2.76 | ~ 0.1 $nb^{-1}$ |
| 2013 | p – Pb | 5.02 | ~ 30 $nb^{-1}$ |

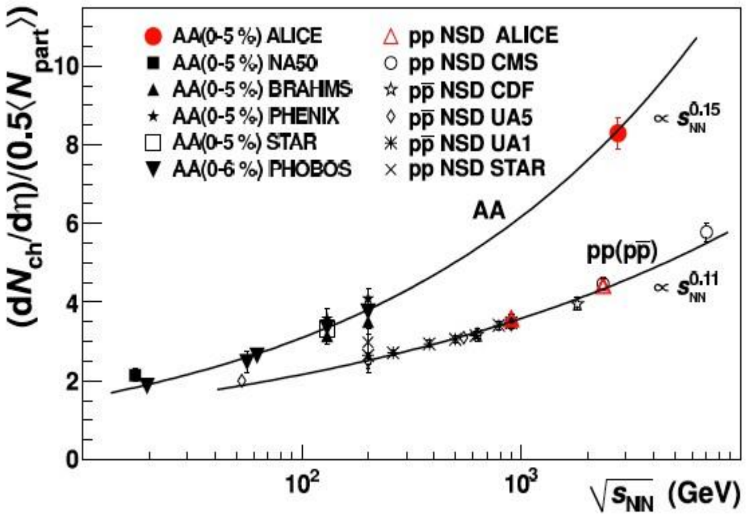
# GLOBAL EVENT PROPERTIES

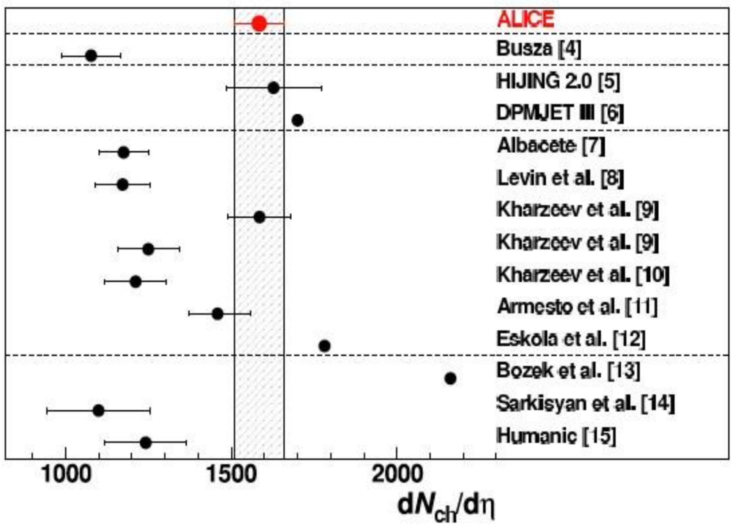
*State and dynamical evolution of the bulk matter characterized by*

*soft particles (below a few GeV/c)*

- ✓ multiplicity distributions (initial energy density)
- ✓ spectra, yields (hadronization process)
- ✓ flow (collective transport phenomena)
- ✓ correlations (space-time evolution)

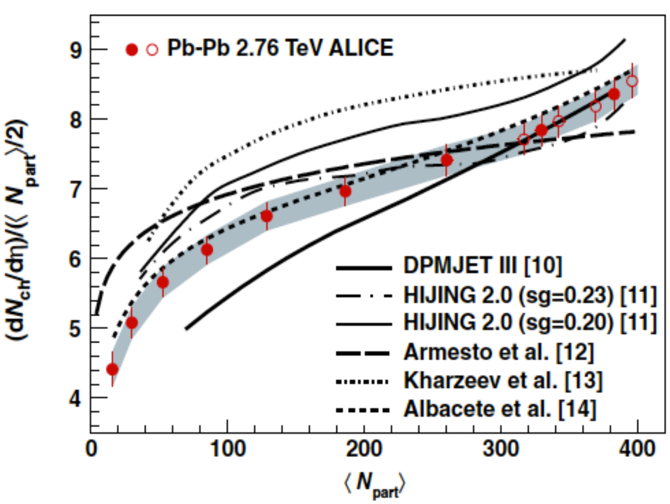
# MULTIPLICITY DISTRIBUTIONS




ALICE PRL 105 (2010)

ALICE PRL 106 (2011)




| Centrality | $dN_{ch}/d\eta$ | $\langle N_{part}\rangle$ |
|---|---|---|
| 0%–5% | $1601 \pm 60$ | $382.8 \pm 3.1$ |

# INITIAL DENSITY AND TEMPERATURE FROM BJORKEN FORMULA

**SEE CMS PRL 109 (2012)**

$$\varepsilon \geq \frac{dE_T/d\eta}{\tau_0 \pi R^2} = \frac{3}{2}\langle E_T/N\rangle \frac{dN_{\mathrm{ch}}/d\eta}{\tau_0 \pi R^2}$$

$$\frac{dN_{ch}}{d\eta} \simeq 1600$$

$$\epsilon\,\tau_0 \simeq 15\mathrm{GeV}/\mathrm{fm}^2$$

(2.6 times RHIC)

$$T_0 \simeq 300\,\mathrm{MeV}$$

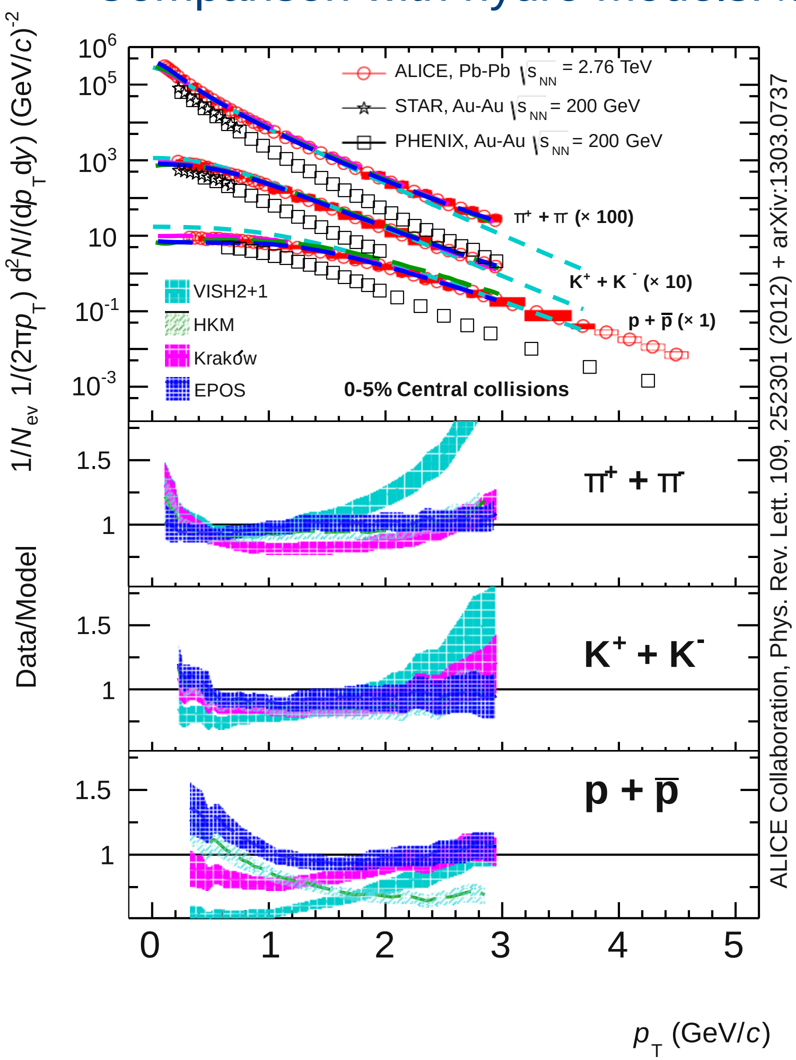
(+30% RHIC)

Lattice QCD predictions : Tc 155 MeV – 175 MeV

- The conditions of the formation of a quark gluon plasma are reached in the early stages of the collisions

# IDENTIFIED $P_T$ SPECTRA

- Comparison with hydro models: radial flow and kinetic freeze-out temperature $T_{kin}$




Large radial flow in most central events:
$<\beta_T> = 0.65 \pm 0.02$ (~10% higher w.r.t. RHIC)
increases with centrality

$T_{kin} = 95 \pm 10$ MeV
(same as RHIC within errors)

model comparisons:
- VISH2+1 (viscous hydro)
- HKM (hydro+UrQMD)
- Kraków (viscous corr., lower the effective $T_{ch}$)
- EPOS (hydro+UrQMD)

ALICE PRL 109 (2012)

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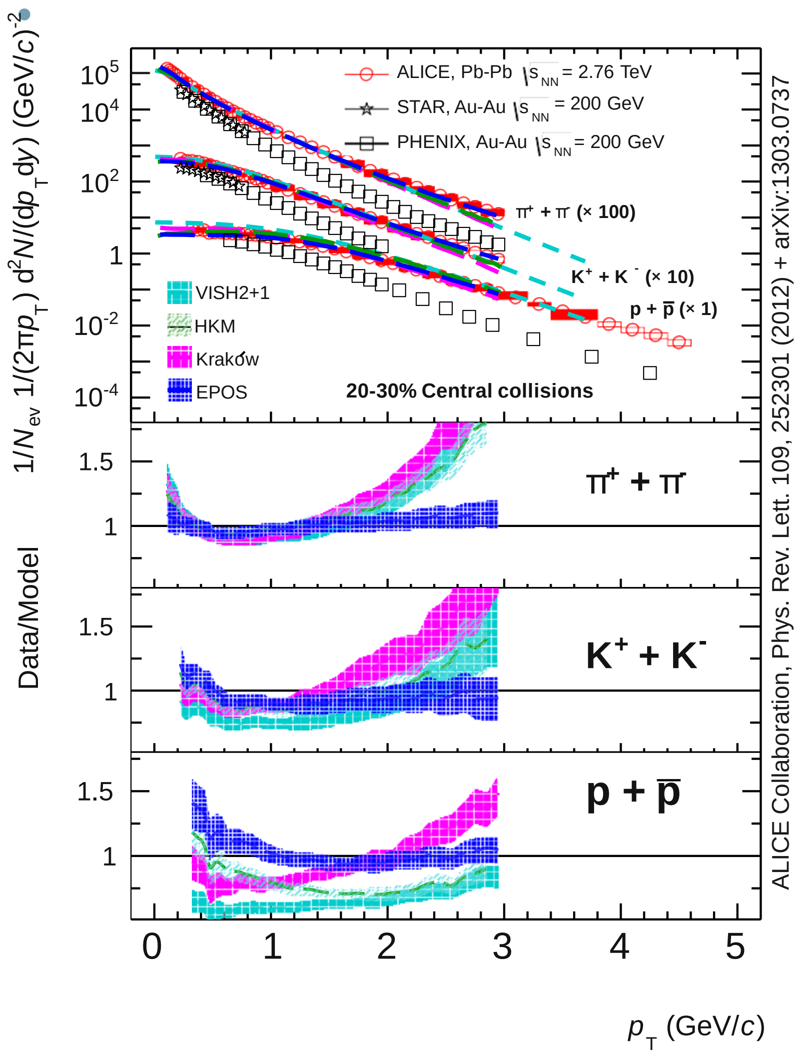


Large radial flow in top central events:
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ALICE arXiv: 1303.0737

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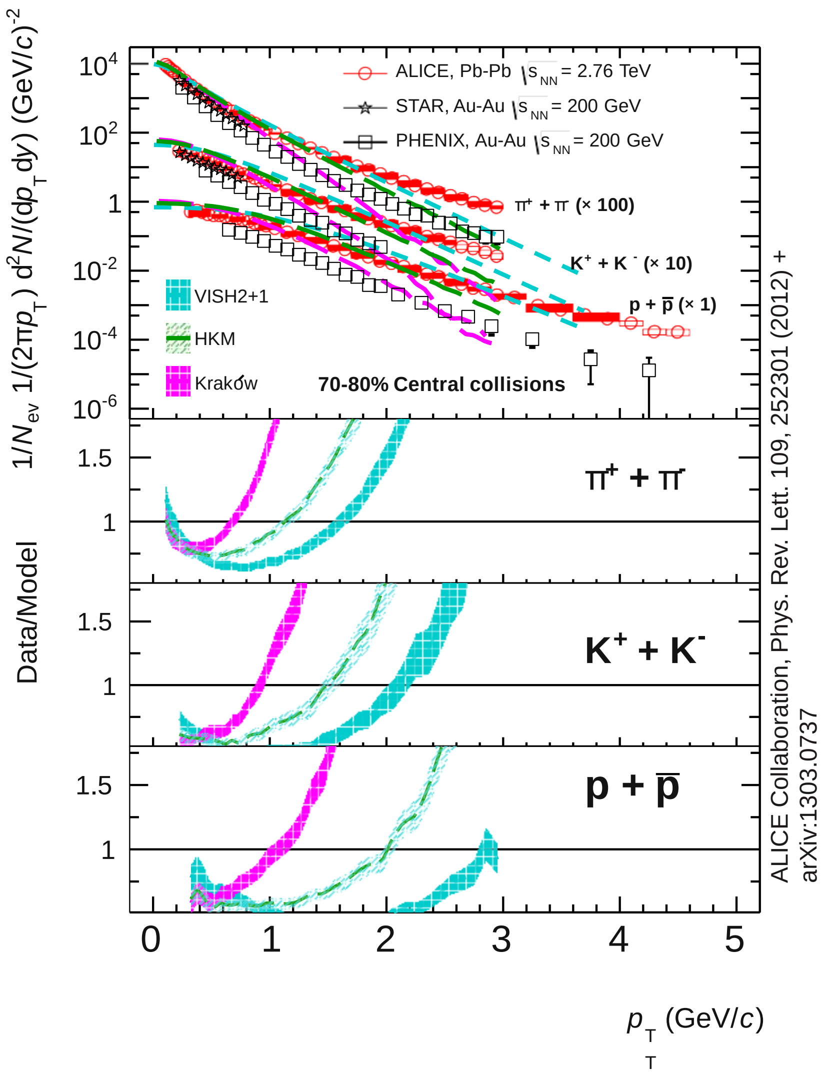


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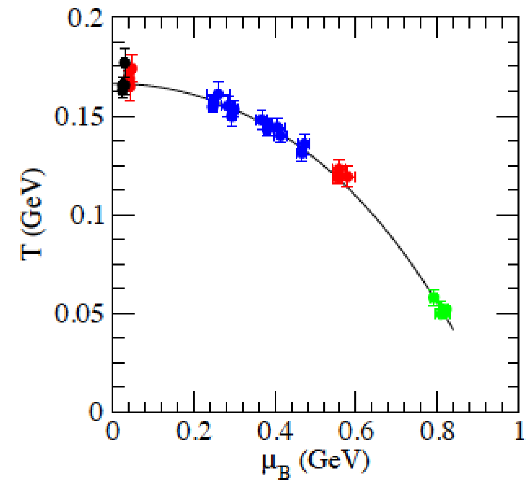
➡ more peripheral events are more challenging for the models

ALICE arXiv: 1303.0737

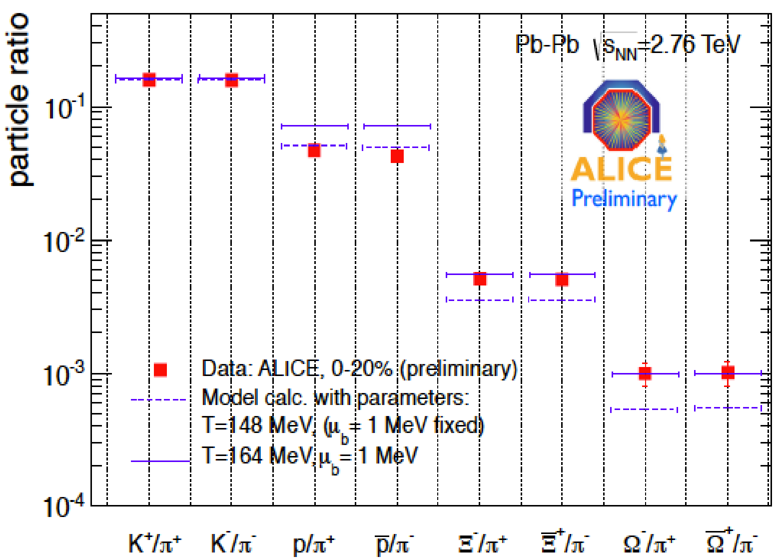
# MATTER AT CHEMICAL FREEZE-OUT

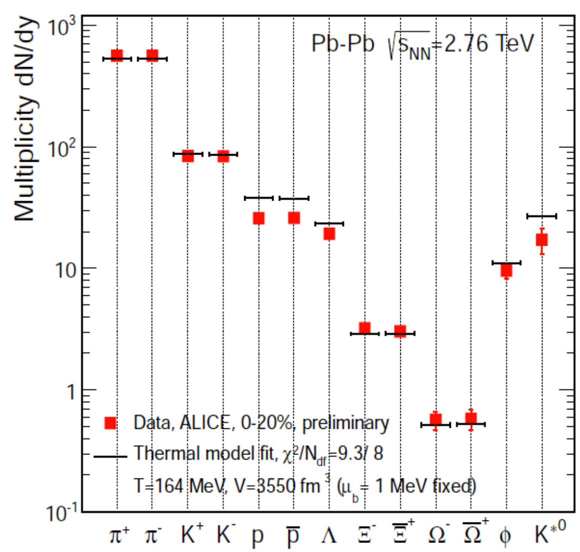
## well described by statistical models

$$n \sim \frac{1}{e^{(\varepsilon_k - \mu)/T} \pm 1}$$




**(from J. Cleymans et al, hep-ph/0511094)**



# ANNIHILATION IN BARYON-ANTIBARYON CORRELATIONS

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## Deviation of proton yields from thermal models expectations

annihilation should be taken into account while determining yields

Steinheimer, Aichelin, Bleicher; arXiv:1203.5302

Werner et al.; Phys.Rev. C85 (2012)

064907 Karpenko, Sinyukov, Werner; arXiv:1204.5351

*(...)switching BB-annihilation one suppresses baryon yields, in the same time increases pion yield, thus lowering $p/\pi$ ratio to the value 0.052, which is quite close to the one measured by ALICE(...)*

→ ***annihilation must be seen in baryon-antibaryon correlations***

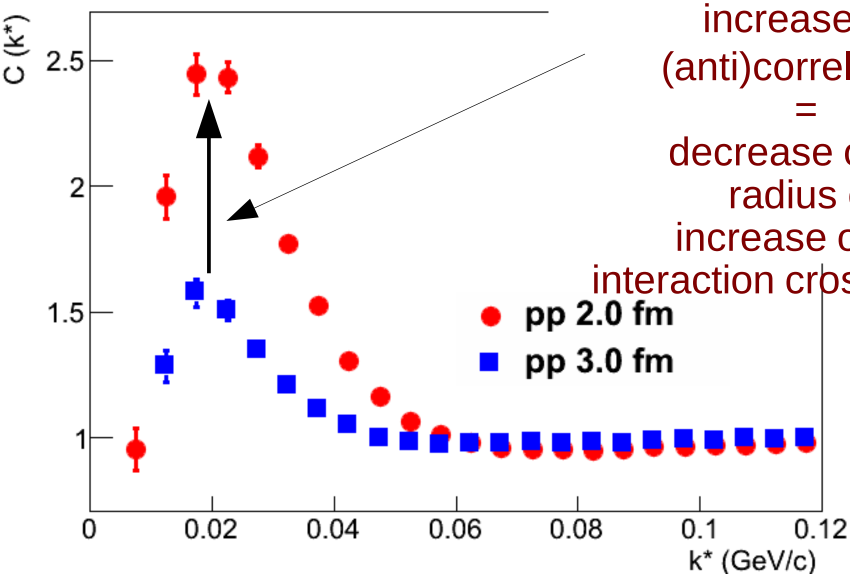
# BARYON FEMTOSCOPY

$$C(\vec{q}) = \int S(\vec{r})\,|\Psi(\vec{q},\vec{r})|^2\, d^4 r$$

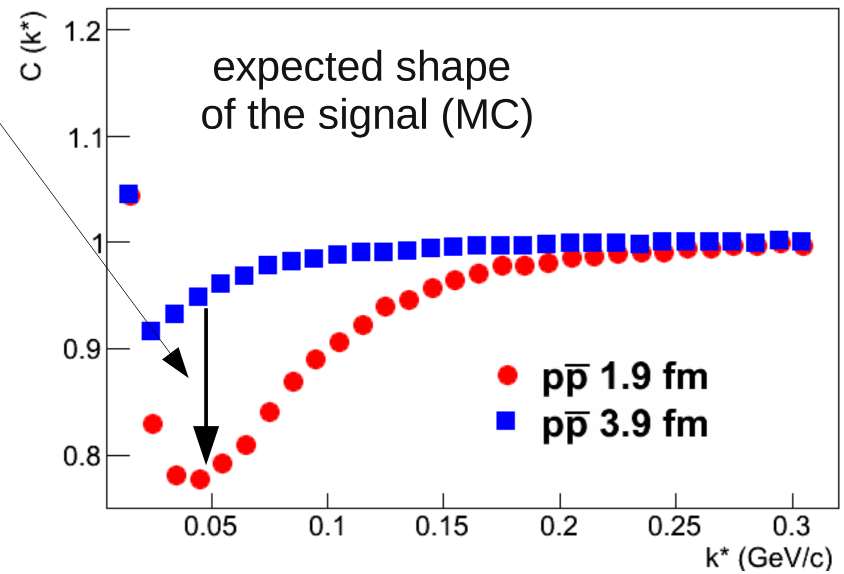
measured correlation

emission function (radius)

cross-section

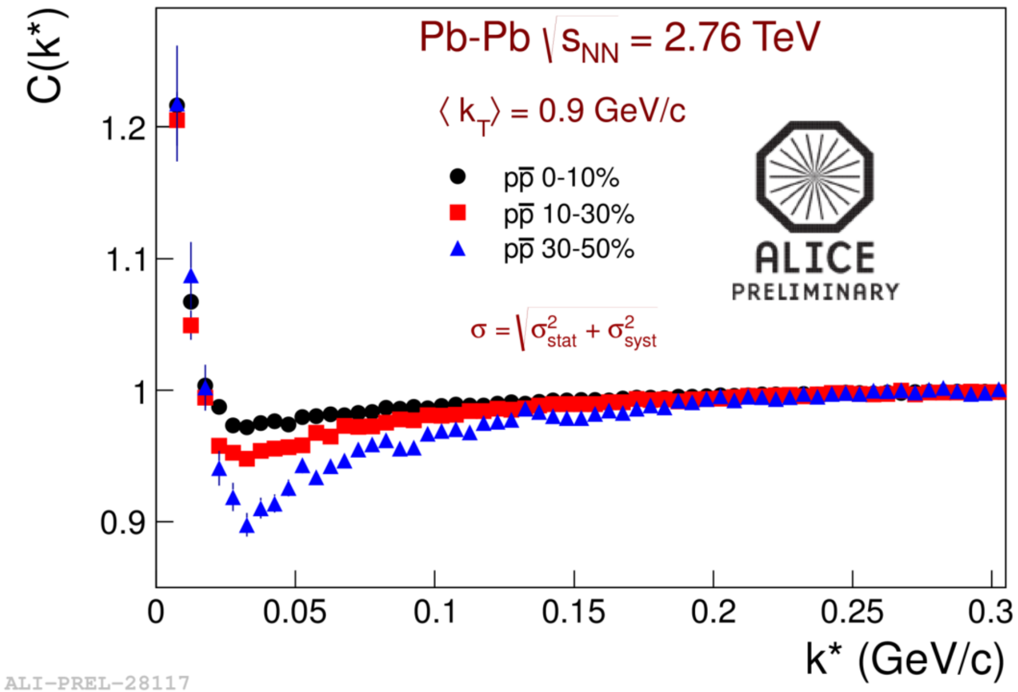



increase of
(anti)correlation
=
decrease of the
radius or
increase of the
interaction cross-section




Maciej Szymański Quark Matter 2012

# $\mathrm{p\bar{p}}$ CORRELATION FUNCTIONS




Shape dominated by Coulomb and Strong FSI

Significant annihilation (from strong FSI) expected and measured

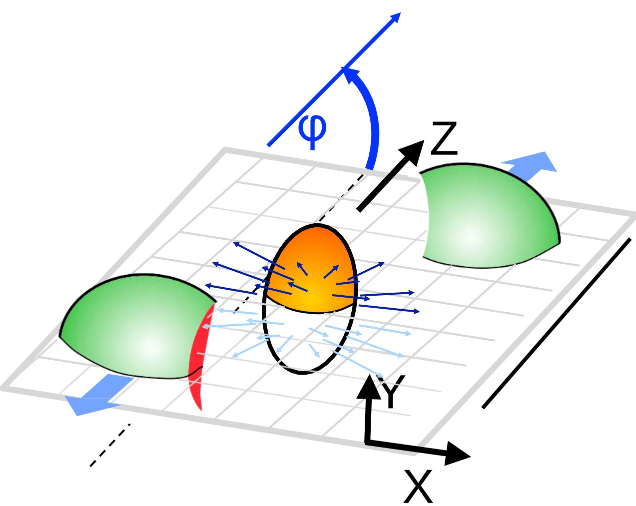
Quark Matter 2012

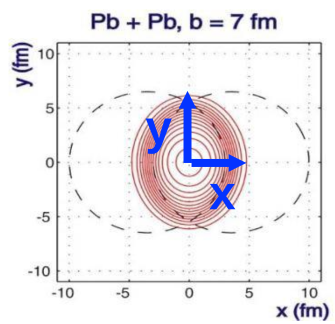
# ANISOTROPIC ELLIPTIC FLOW

## Spatial deformation

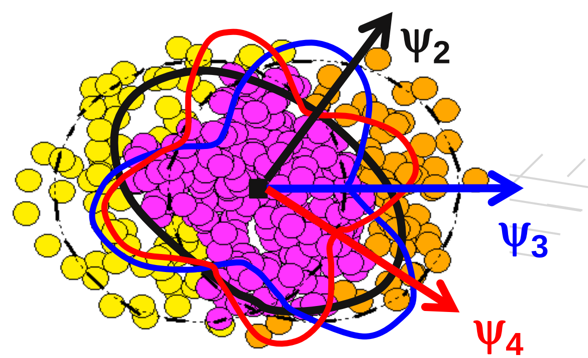
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + \,..$$

Azimuthal (ϕ) pressure gradients

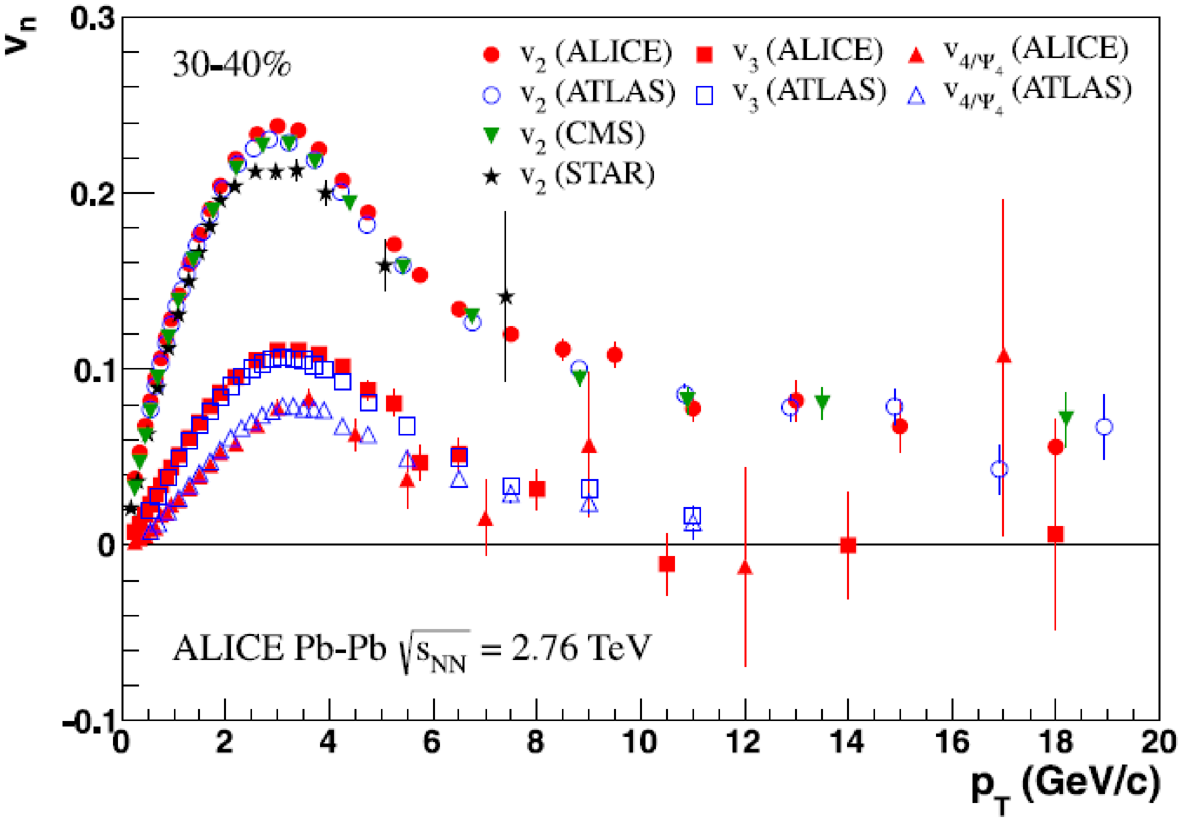



Anisotropic particle density



# ELLIPTIC FLOW COEFFICIENTS




**ALICE PLB 719 (2013)**

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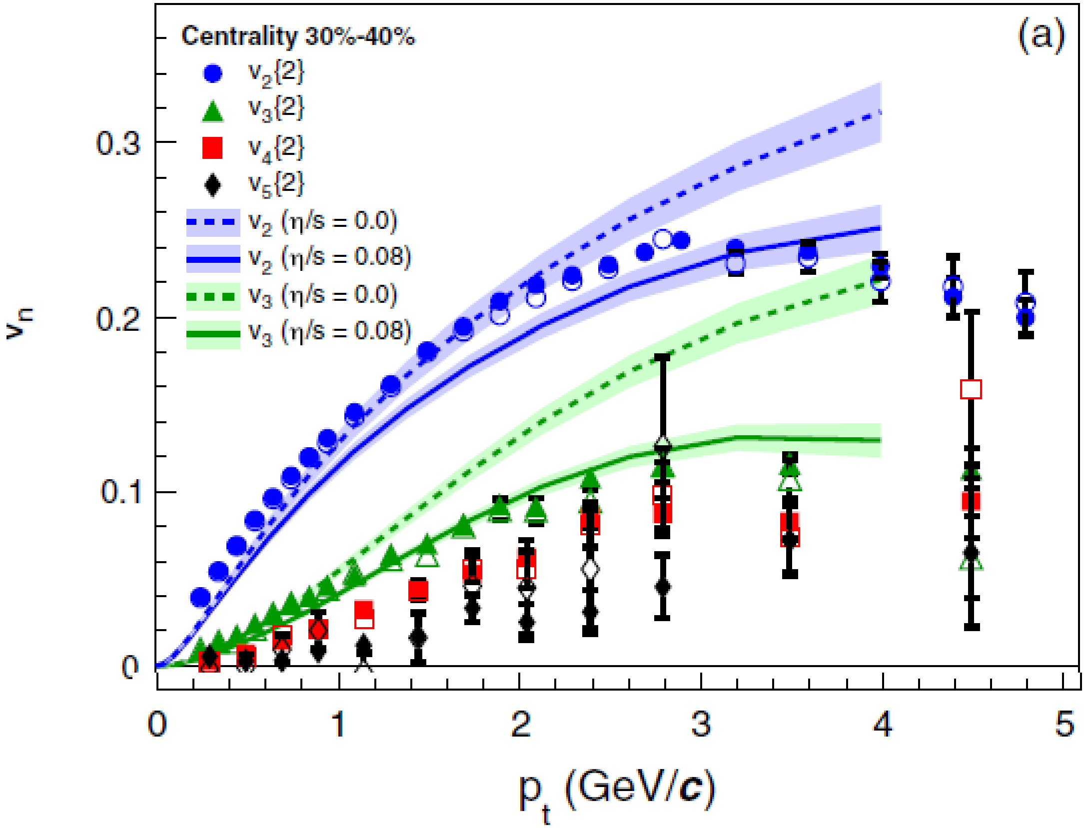



***Hydro model using Glauber initial conditions for different values of the viscosity***

Schenke, Jeon, Gale Phys.Lett. B7012 (2011)

***Further constraints on viscosity and initial conditions provided by measurements of higher harmonics very sensitive to properties of the medium***

ALICE PRL 107

# HARD PROBES AT HIGH MASS AND HIGH PT
# HEAVY QUARKS, QUARKONIA, PHOTONS, JETS…

- Created at early stages of the collisions
- Production and propagation in medium provides information about parton energy loss

# REFERENCE COLLISIONS

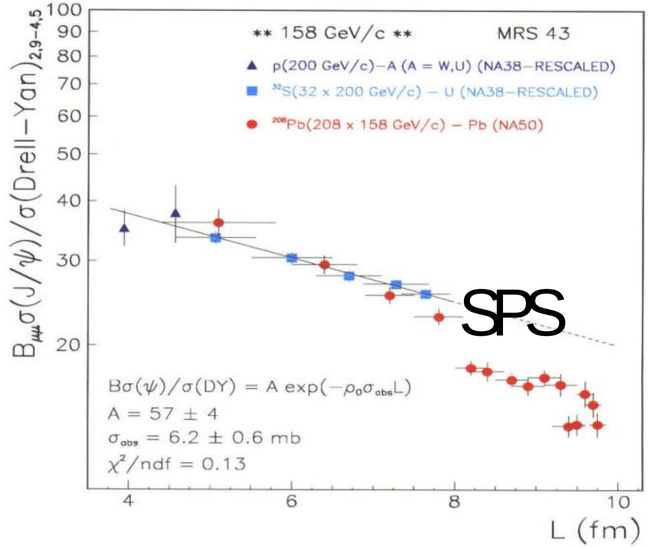
## *proton-proton*

- $R_{AA}$ – ratio of $p_T$ spectrum in AA collisions to that in pp – properly normalized by number of binary collisions

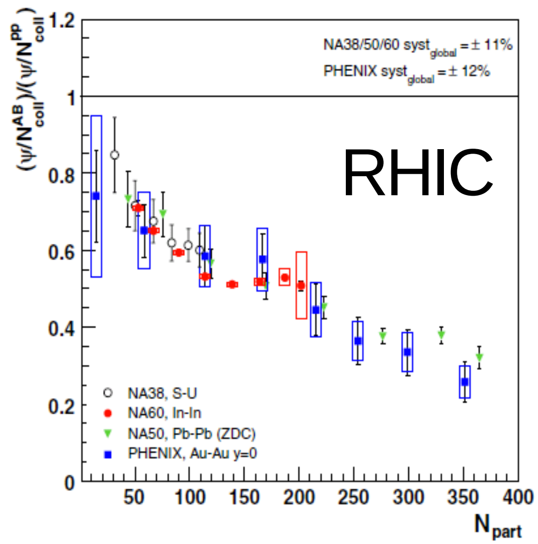
$$R_{AA} = \frac{(\mathrm{d}\sigma/\mathrm{d}p_T)_{AA}}{N_{bin}(\mathrm{d}\sigma/\mathrm{d}p_T)_{pp}} = \ ...$$

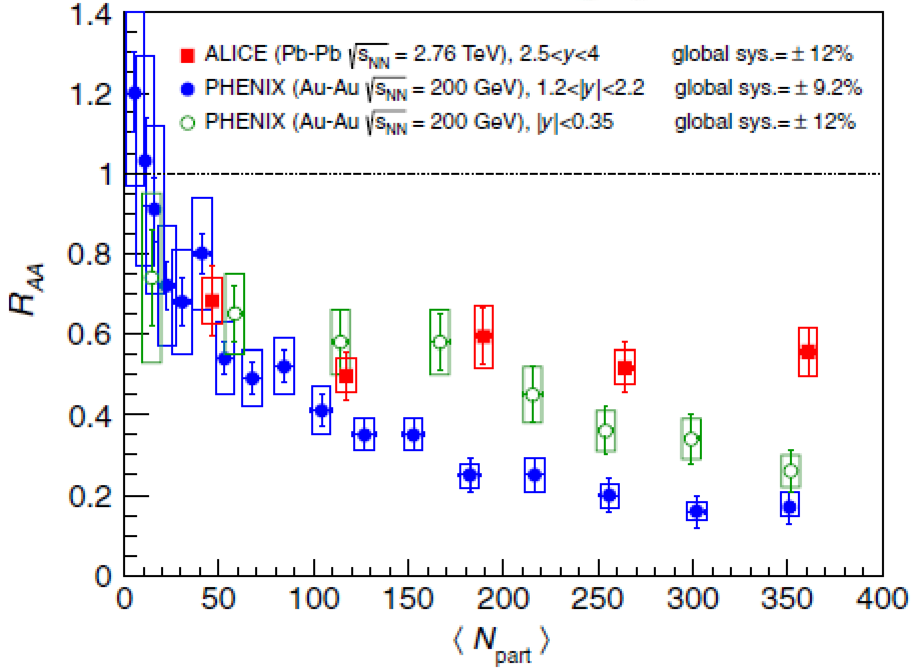
if AA would be just a superposition of pp collisions $R_{AA} = 1$

# $J/\psi$ SUPPRESSION




'anomalous' suppression

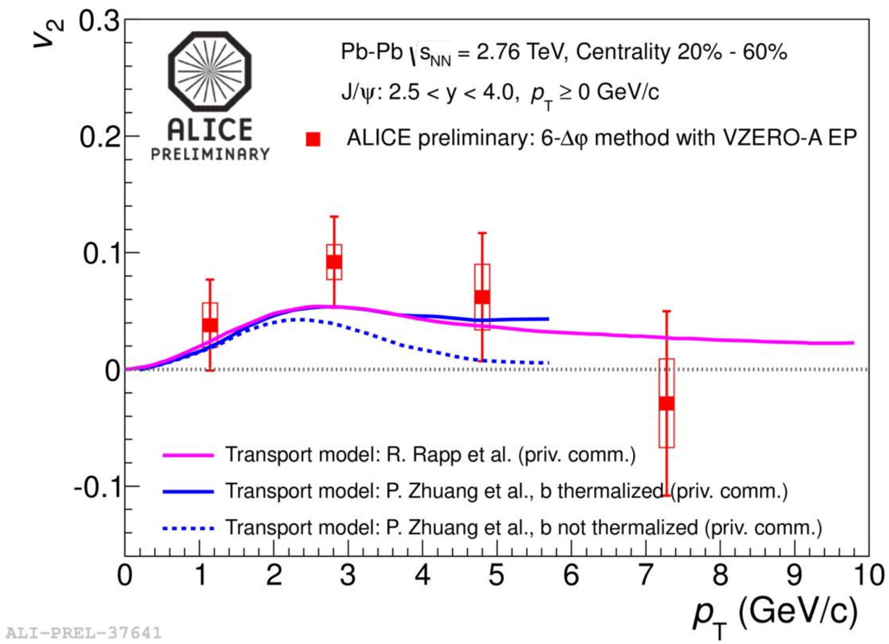


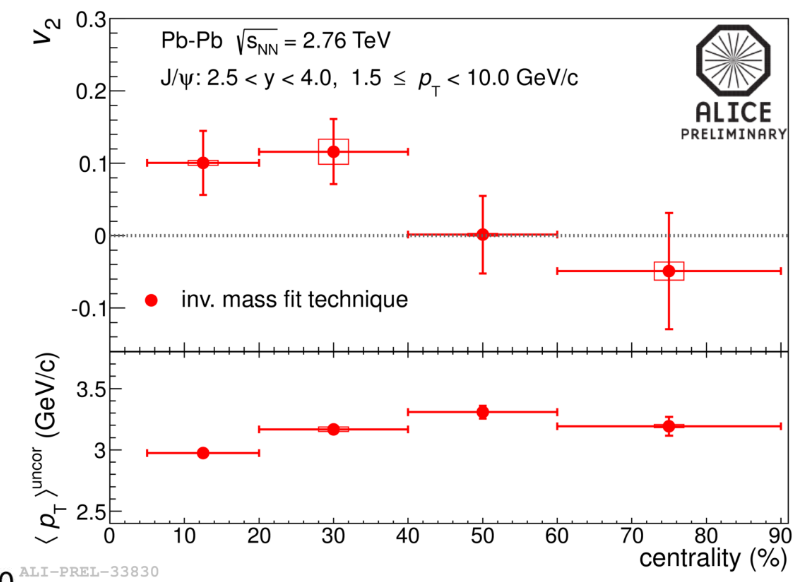




suppression / regeneration

ALICE PRL 109 (2013)

# J/ψ elliptic flow




arXiv: 1303.5880

J/ψ produced by recombination of thermalized c-quarks should have non-zero elliptic flow

– measurements give a hint for non-zero $v_2$

– qualitative agreement with transport models, including regeneration

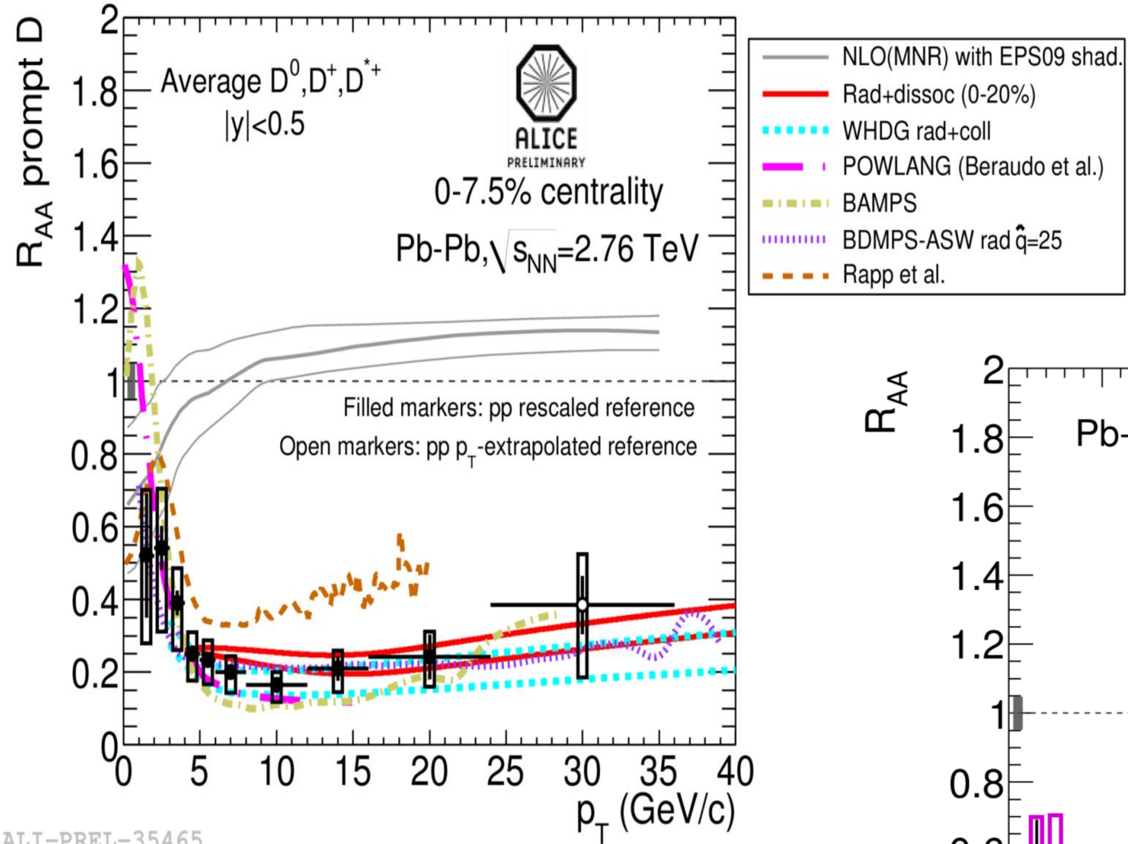
– complementary to indications obtained from J/ψ $R_{AA}$ studies

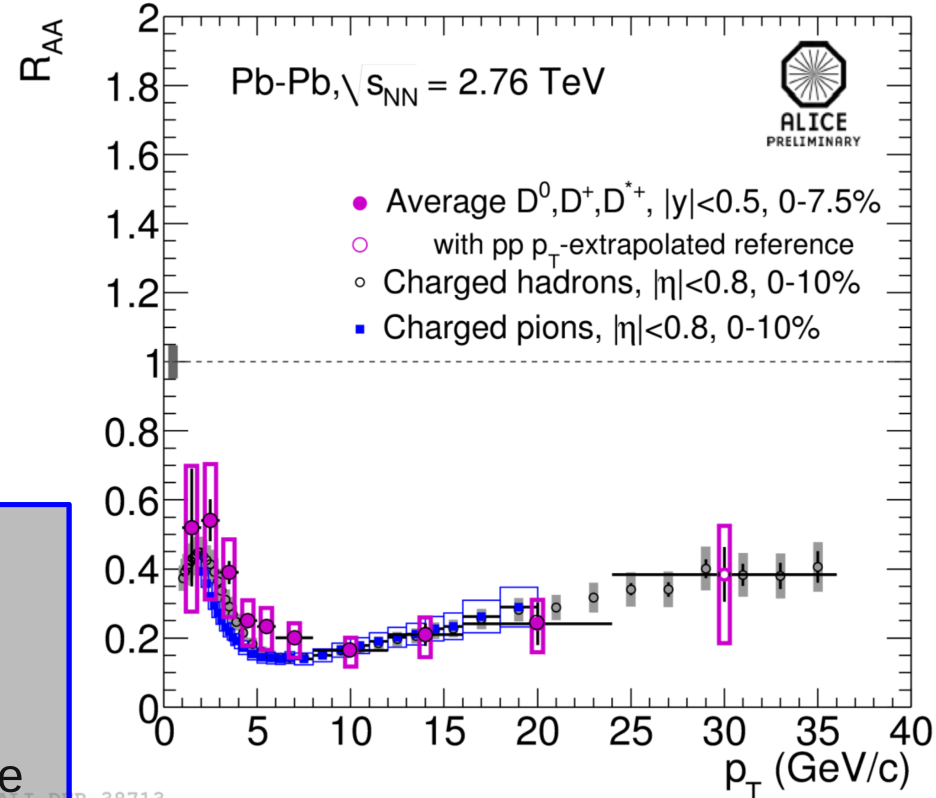
# *SEE THE PRESENTATION*

***Charmonium and e+e- pair photoproduction in ultra peripheral Pb-Pb collisions 2.76 TeV***

*(Eugenio Scapparone)*

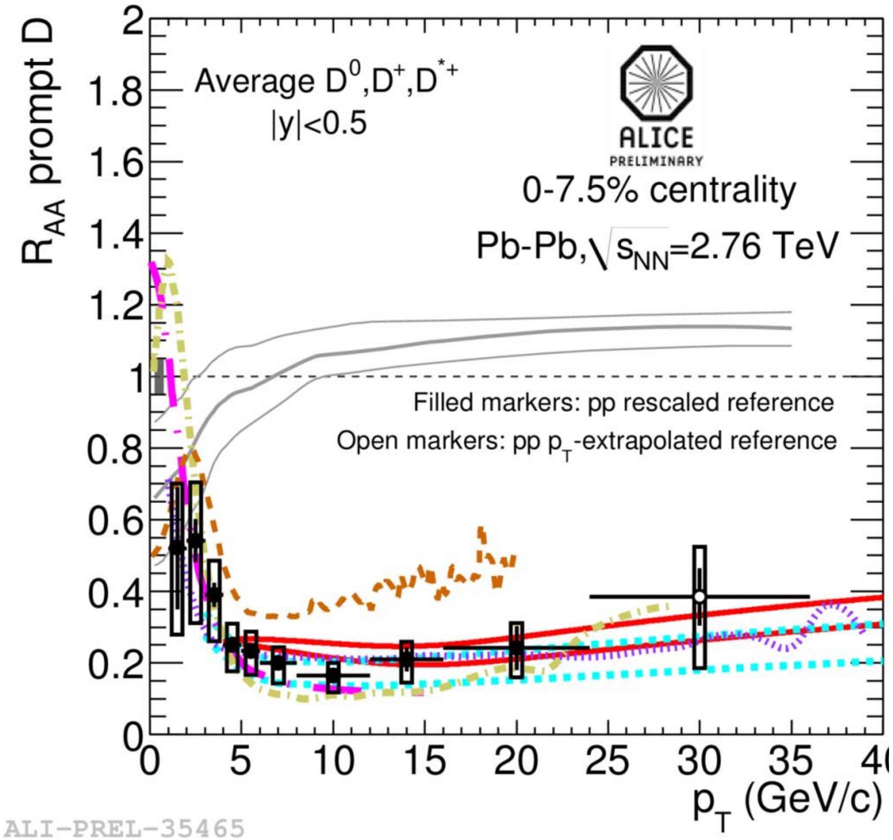
# D MESONS RAA

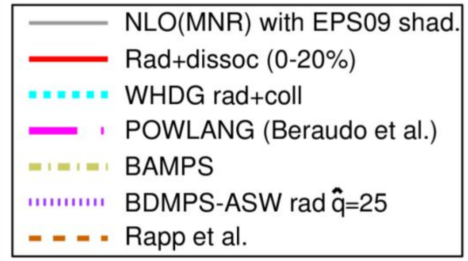


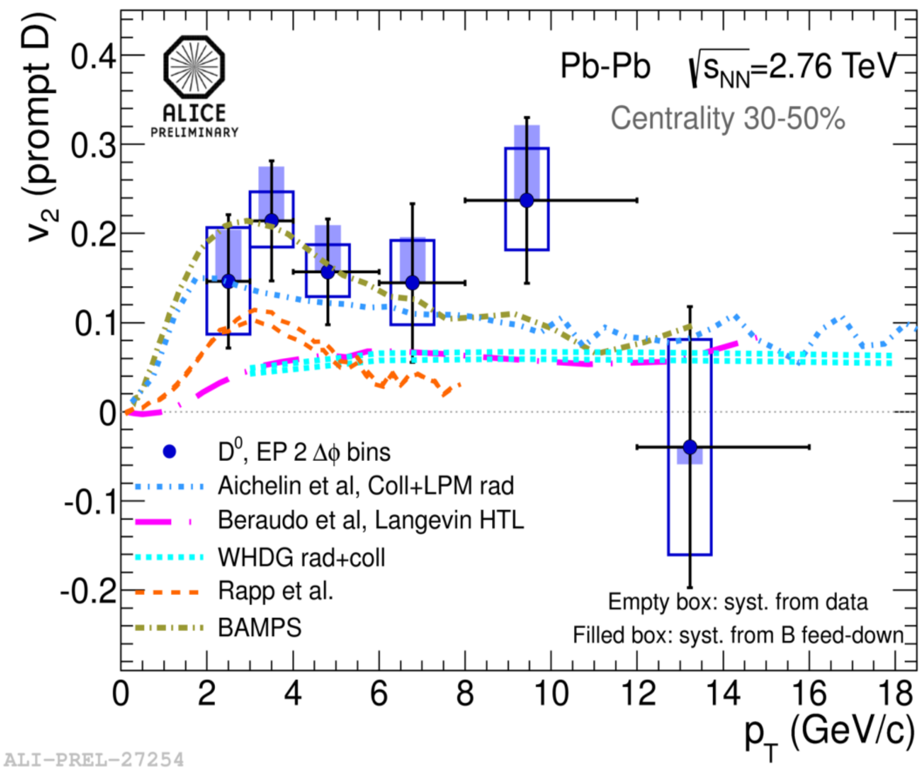




Average D-meson $R_{AA}$:
– $p_T$ < 8 GeV/$c$ hint of slightly less suppression than for light hadrons
– $p_T$ > 8 GeV/$c$ both (all) very similar
no indication of colour charge dependence

# D MESONS $v_2$



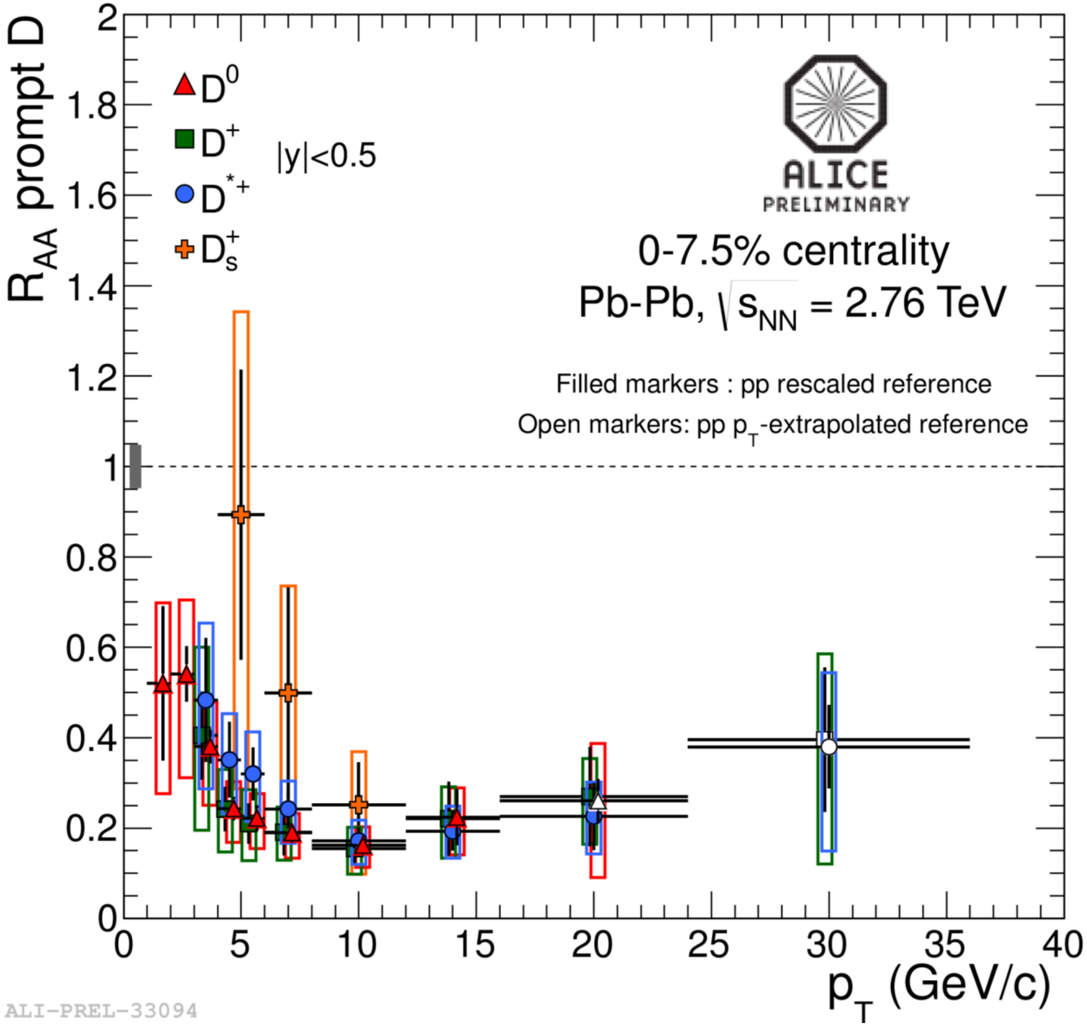



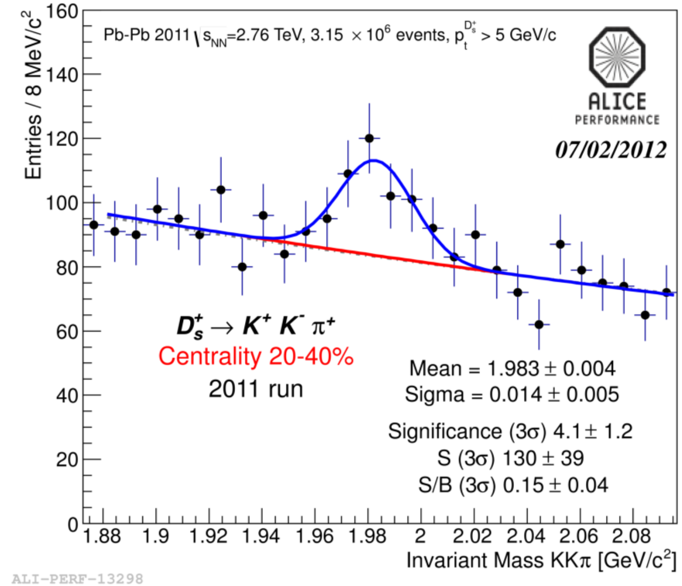




Non-zero D meson $v_2$ observed
Comparable to that of light hadrons

Simultaneous description of $R_{AA}$ and $v_2$
c-quark transport coefficient in medium

# $D_s$ MESONS $R_{AA}$




Strong suppression (~ 4–5 )
at $p_T$ above 8 GeV/$c$

Uncertainty will improve with
future pp and Pb–Pb data taking

# SEE THE PRESENTATION

***Open heavy flavour production with the ALICE experiment***

*(Diego Stocco)*

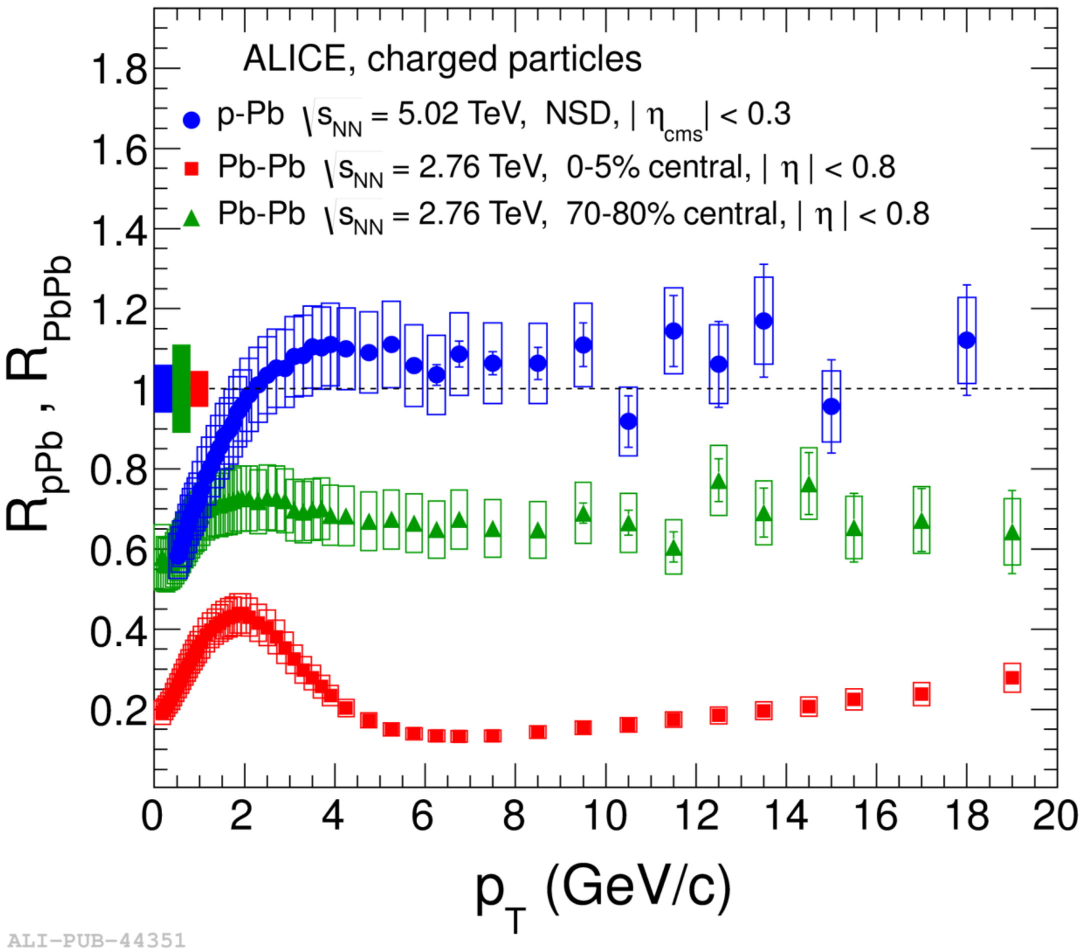
# REFERENCE COLLISIONS

## *p - Pb*

- Reference for Pb-Pb collisions ?
- Cold nuclear matter ?
- Unexpected collective effects ?

# COLD NUCLEAR MATTER EFFECTS VS. JET QUENCHING IN PB-PB…

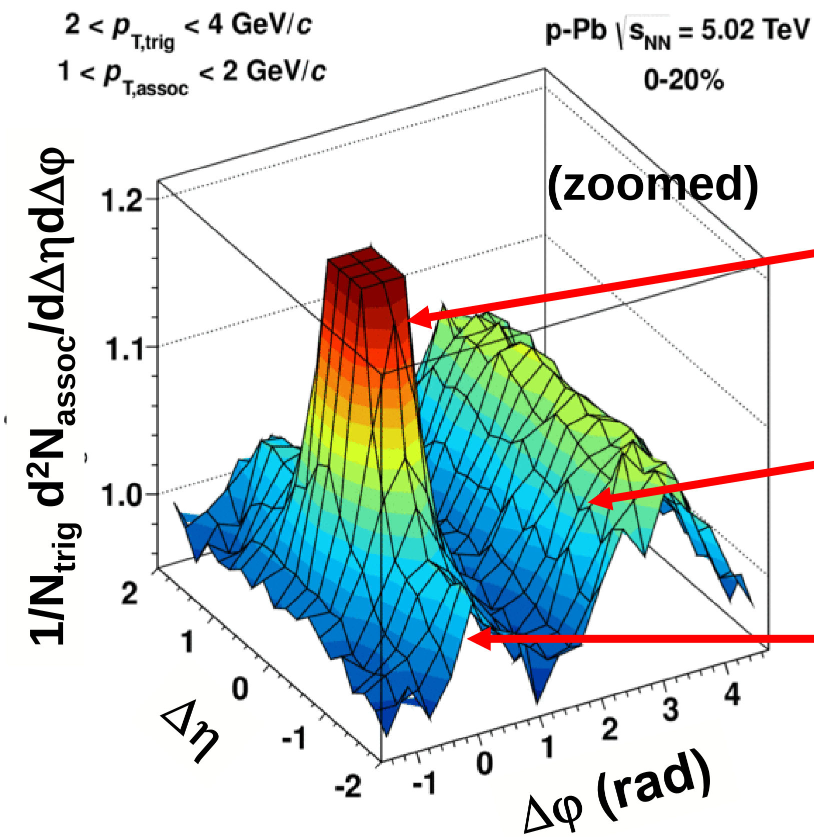
Phys. Rev. Lett. 110, 082302 (2013)




Compatible with unity above 2-3 GeV/c

Jet quenching in Pb-Pb collisions is a final state effect <=> QGP opaque to energetic partons

# THE RIDGE




**2 < $p_{T,trig}$ < 4 GeV/c**
**1 < $p_{T,assoc}$ < 2 GeV/c**
**20% highest multiplicity**

**Near-side jet**
**(Δφ ~ 0, Δη ~ 0)**

**Away-side jet**
**(Δφ ~ π, elongated in Δη)**

**Near-side ridge**
**(Δφ ~ 0, elongated in Δη)**

- The near-side long-range ridge observed by CMS in pp and p-Pb double ridge seen by ALICE and ATLAS in p-Pb
  [JHEP 09 (2010) 091, PLB718 (2013) 795]

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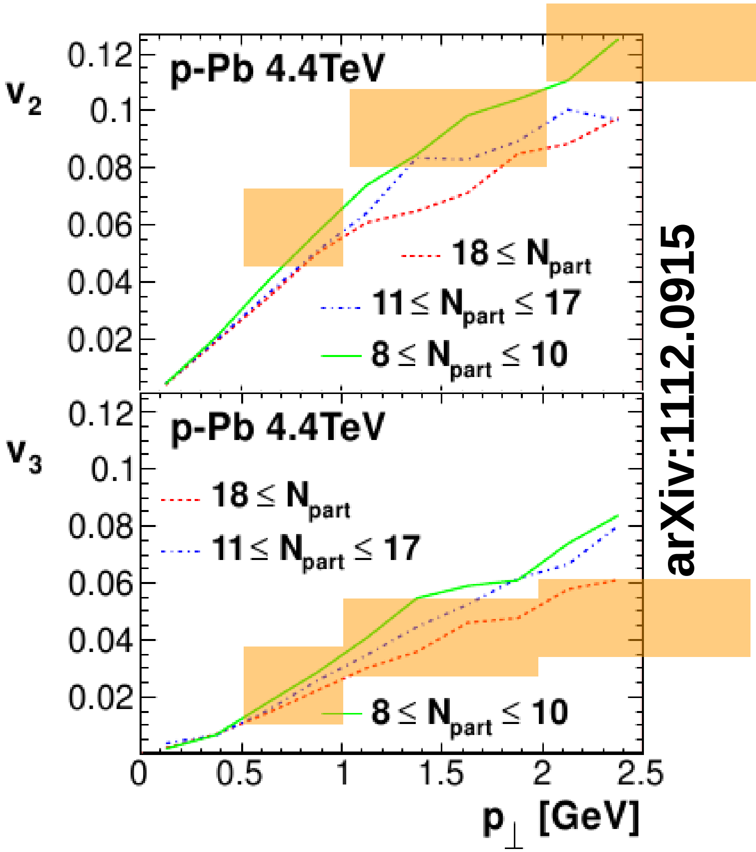
# INTERPRETATION

Flow?

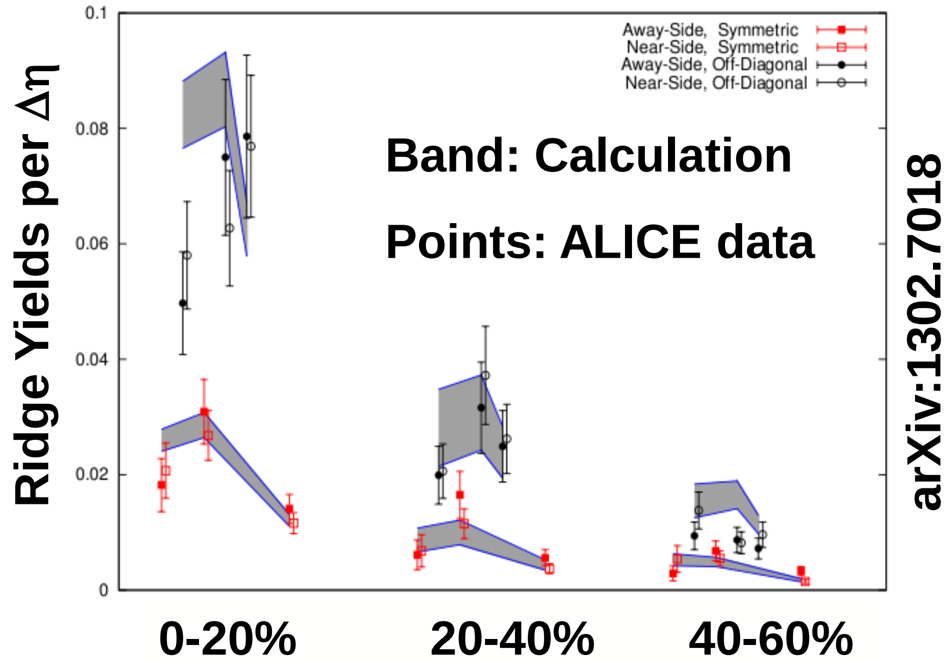
3+1 viscous hydro (arXiv:1112.0915)




Saturation?

Color glass condensate

(arXiv:1302.7018)



# CONCLUSIONS

- Hot and dense matter created at the LHC behaves as a liquid with low viscosity well described by hydrodynamical approaches

- New precise hard probes allow to study the QGP

- Recent measurements of proton-lead collisions reveal surprising (collective ?) behaviour

# SEE THE PRESENTATION

***Upgrade and physics prospects of the ALICE experiment***

*(Levente Molnar)*