# HIGH ENERGY HEAVY ION COLLISIONS AT LHC

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7th Italy-Japan Symposium on Nuclear Physics
Nov.20 – 23, 2012, Milano, ITALY

INFN
7th Italy - Japan Symposium on Nuclear Physics

筑波大学
University of Tsukuba

# Outline

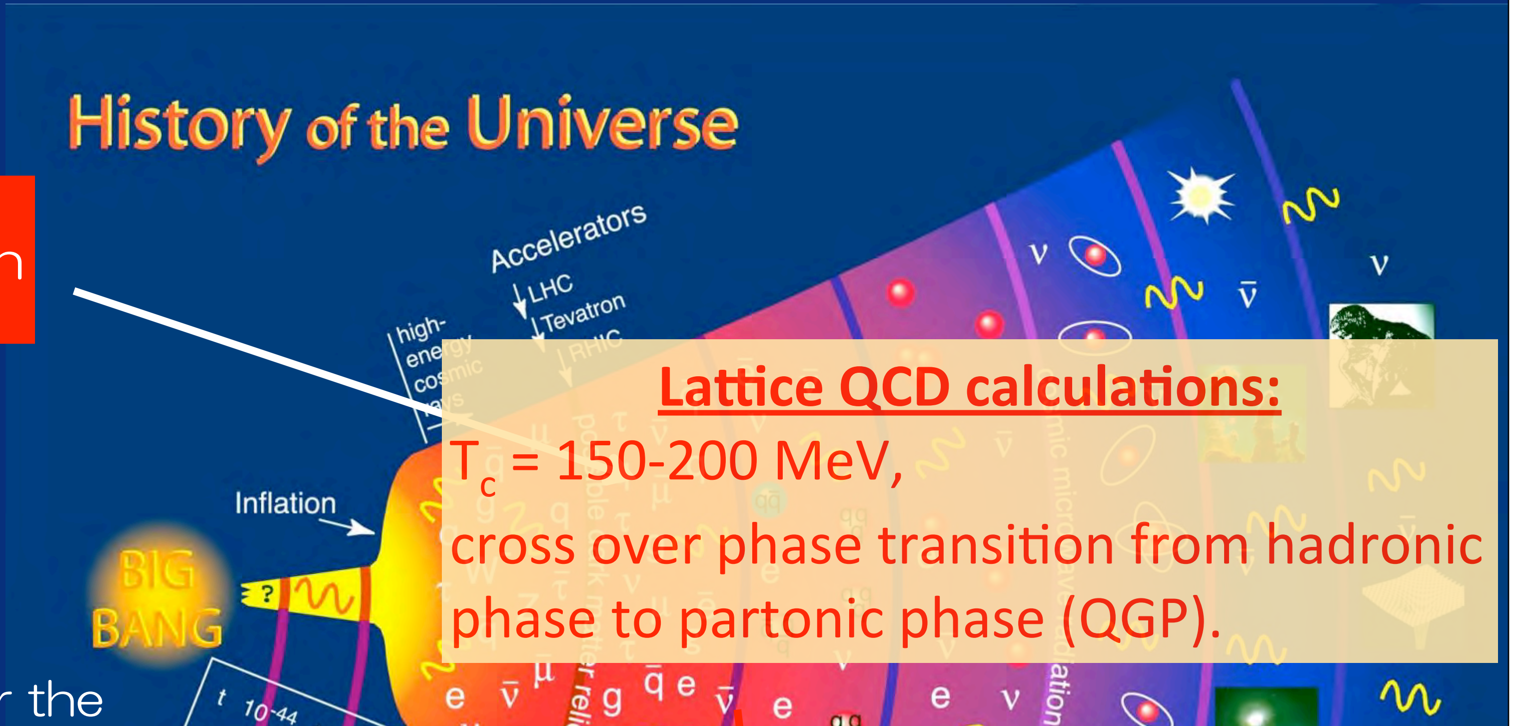
1. Introduction
2. Paton energy loss in QGP
3. QGP properties probing via hadrons
4. ALICE-DCal project (Italy-Japan collaboration)
5. Summary

QGP :
Quark Gluon Plasma

Time : after
10 μ sec after the Big Bang

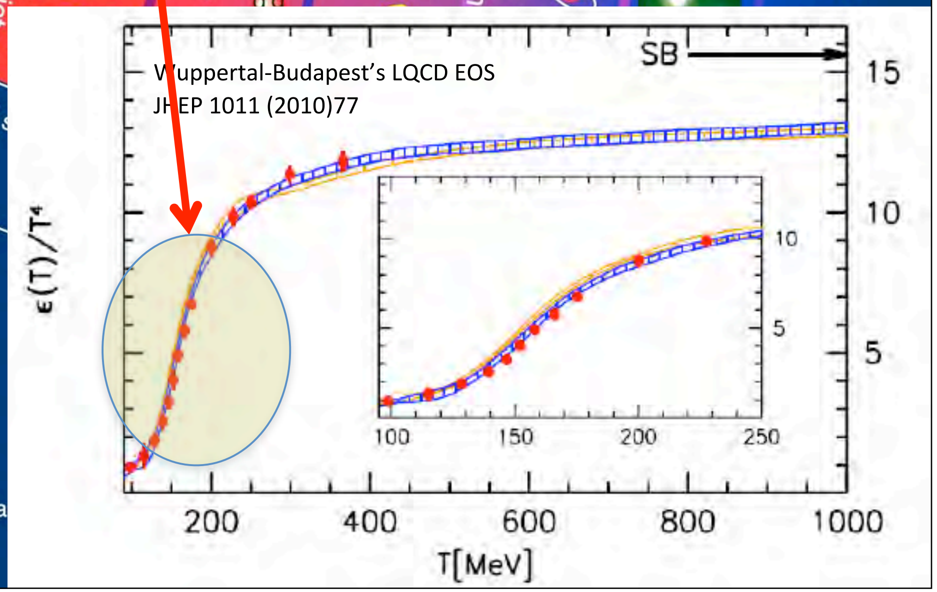
Temperature :
T = 2 x $10^{12}$ K

Energy density :
ε = 1 GeV/fm$^3$

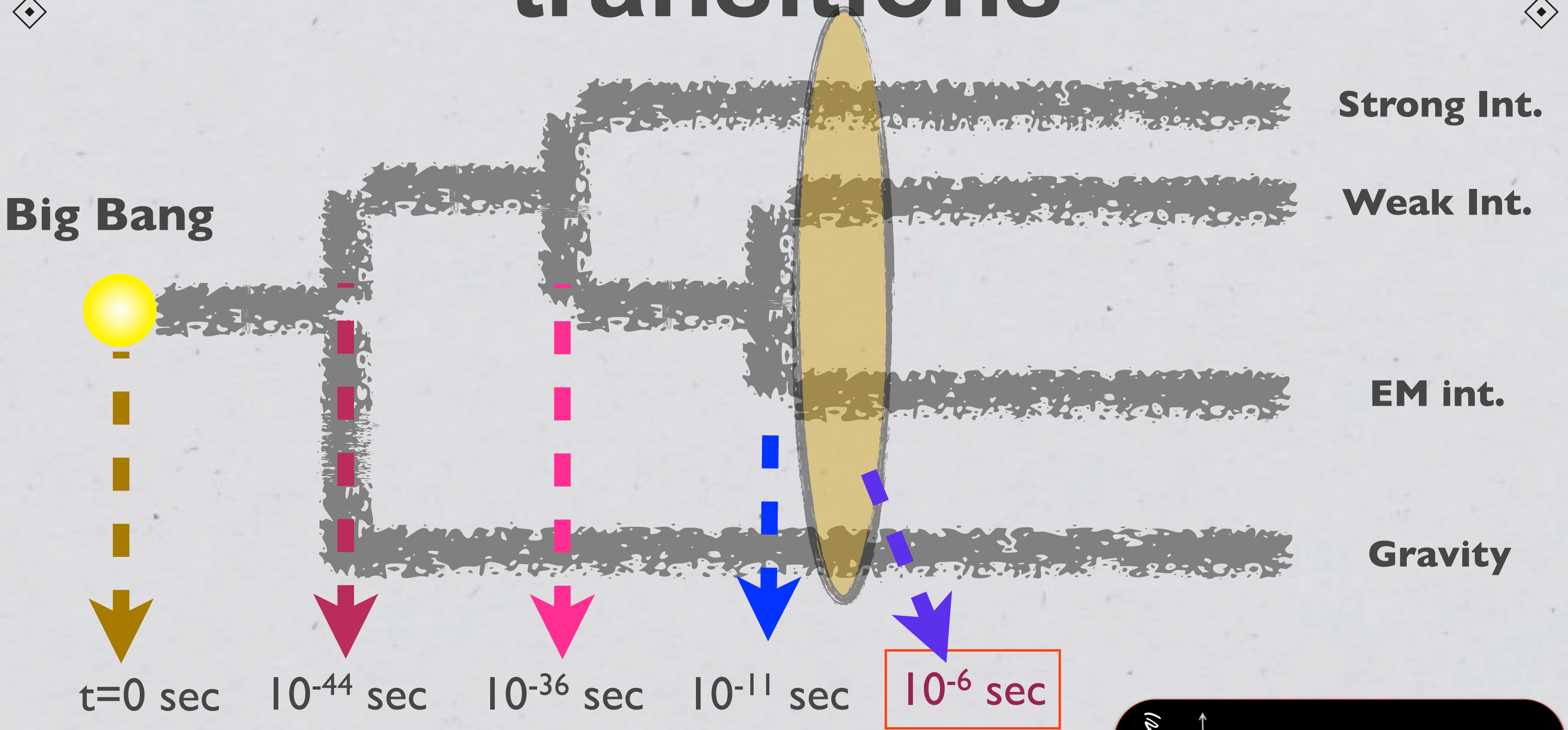



**Lattice QCD calculations:**

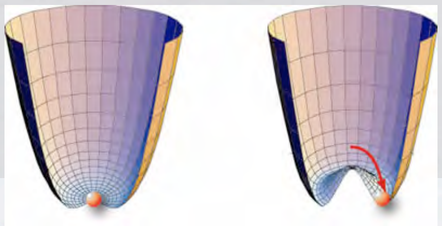
$T_c$ = 150-200 MeV,
cross over phase transition from hadronic phase to partonic phase (QGP).

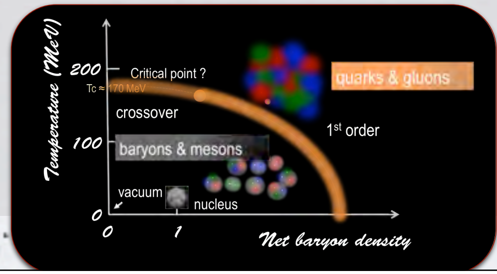


# QGP: probing phase transitions

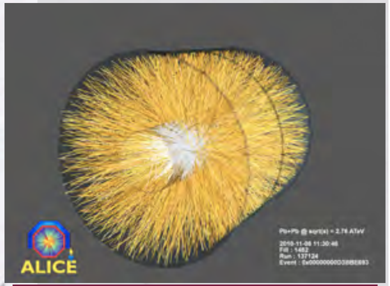



- QCD phase transition
- Chiral symmetry restoration





# Heavy ion program @ CERN-LHC

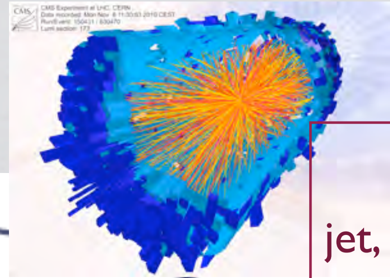



**ALICE**

Excellent PID

low $p_T$ tracking

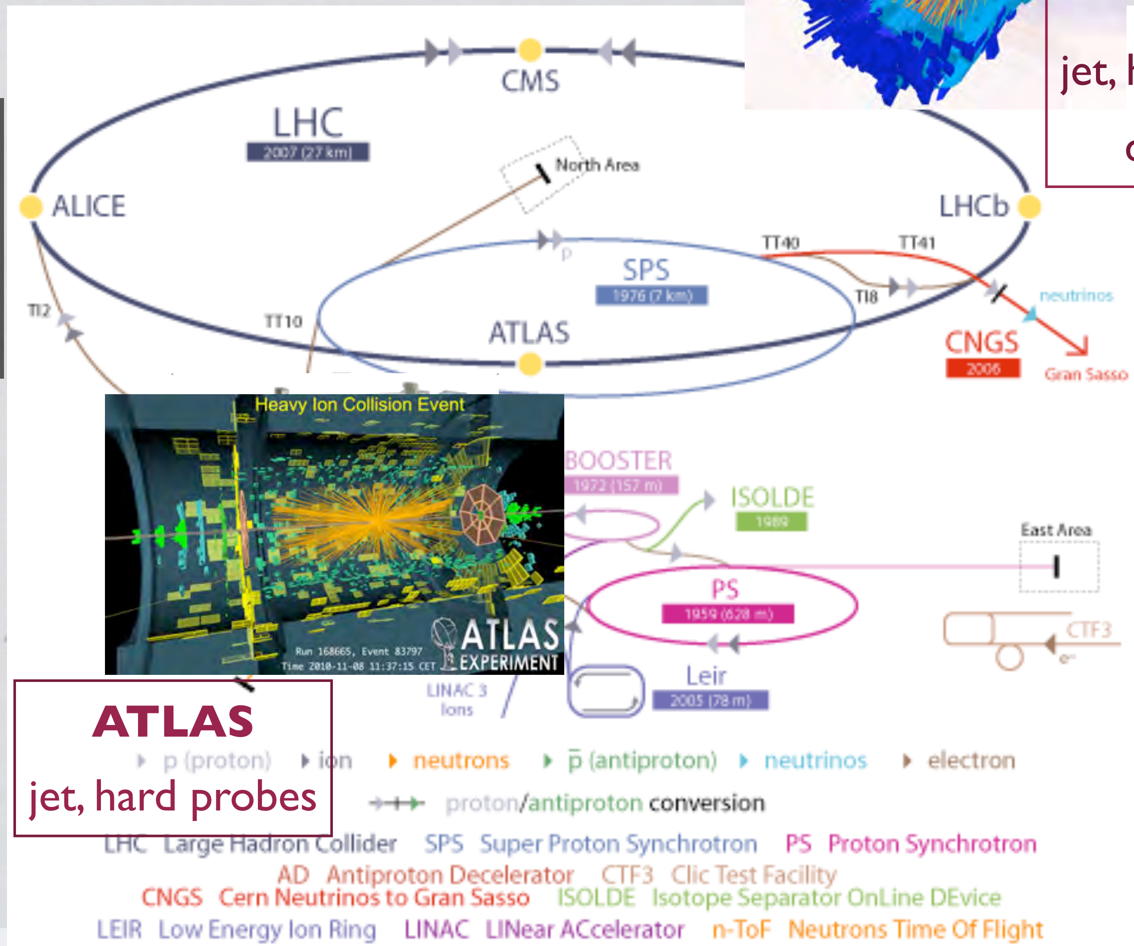
photons, e, muons



**CMS**

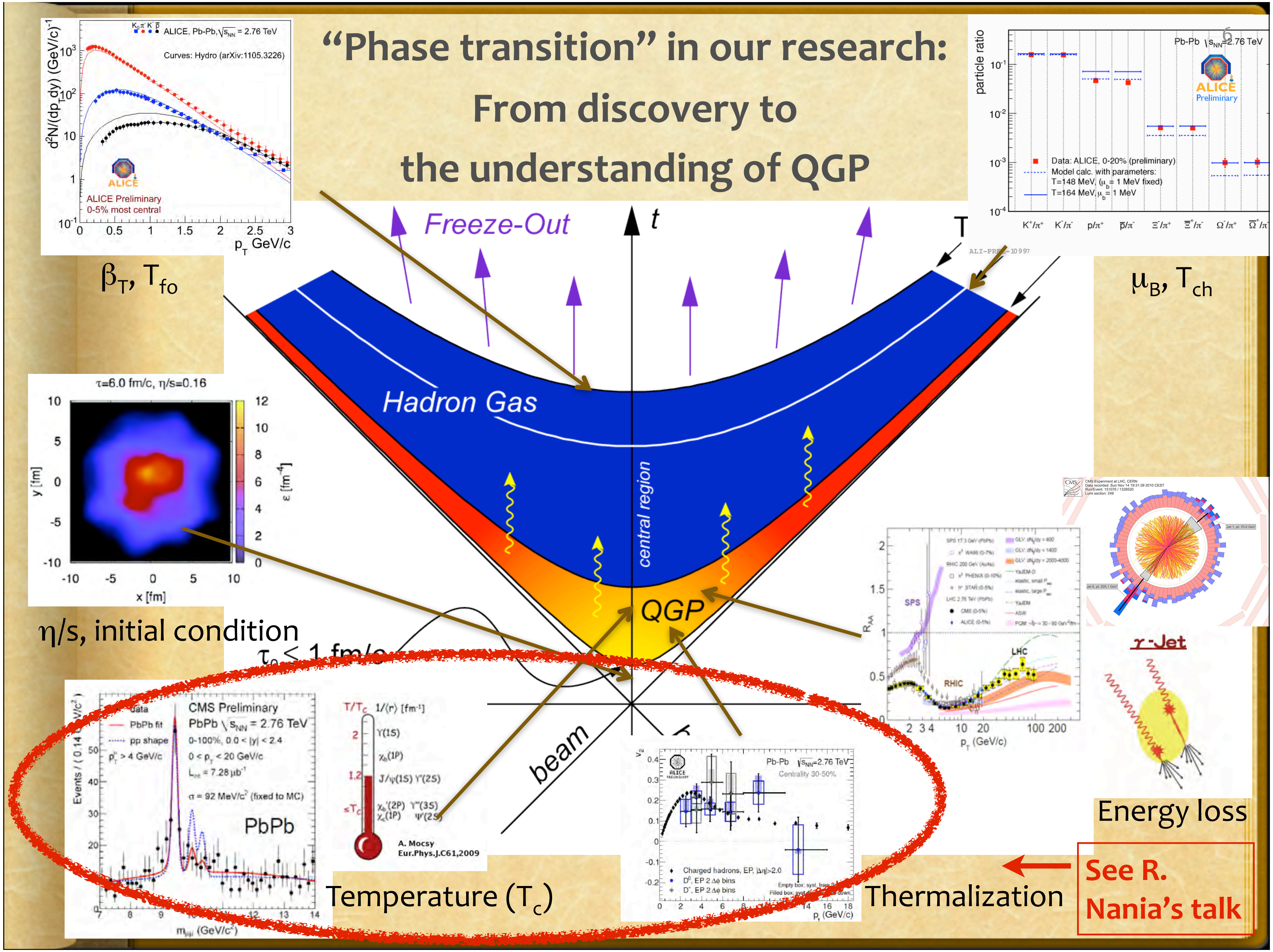
jet, hard probes,

di-muons




**ATLAS**

jet, hard probes



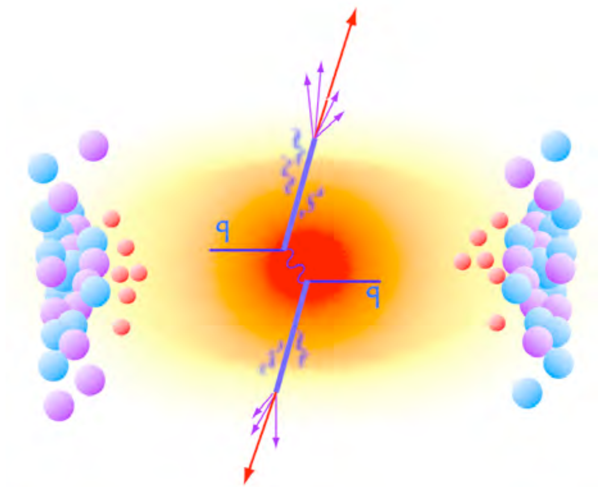
"Phase transition" in our research:
From discovery to
the understanding of QGP
Freeze-Out
t
Hadron Gas
central region
QGP
beam
$\tau_0 < 1$ fm/c
$\beta_T$, $T_{fo}$
$\mu_B$, $T_{ch}$
η/s, initial condition
Temperature ($T_c$)
Thermalization
Energy loss
γ-Jet
See R. Nania's talk
ALICE, Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
Curves: Hydro (arXiv:1105.3226)
ALICE Preliminary
0-5% most central
τ=6.0 fm/c, η/s=0.16
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
Data: ALICE, 0-20% (preliminary)
Model calc. with parameters:
T=148 MeV, ($\mu_b$ = 1 MeV fixed)
T=164 MeV, $\mu_b$ = 1 MeV
CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
PbPb
A. Mocsy
Eur.Phys.J.C61,2009
SPS
RHIC
LHC
Charged hadrons, EP, |Δη|>2.0

# 1. PARTON ENERGY LOSS

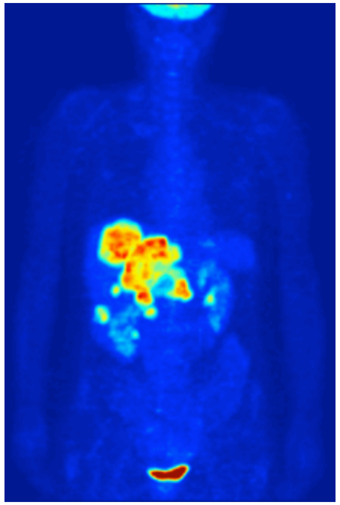
Jet quenching

# One way to measure QGP property; paton energy loss

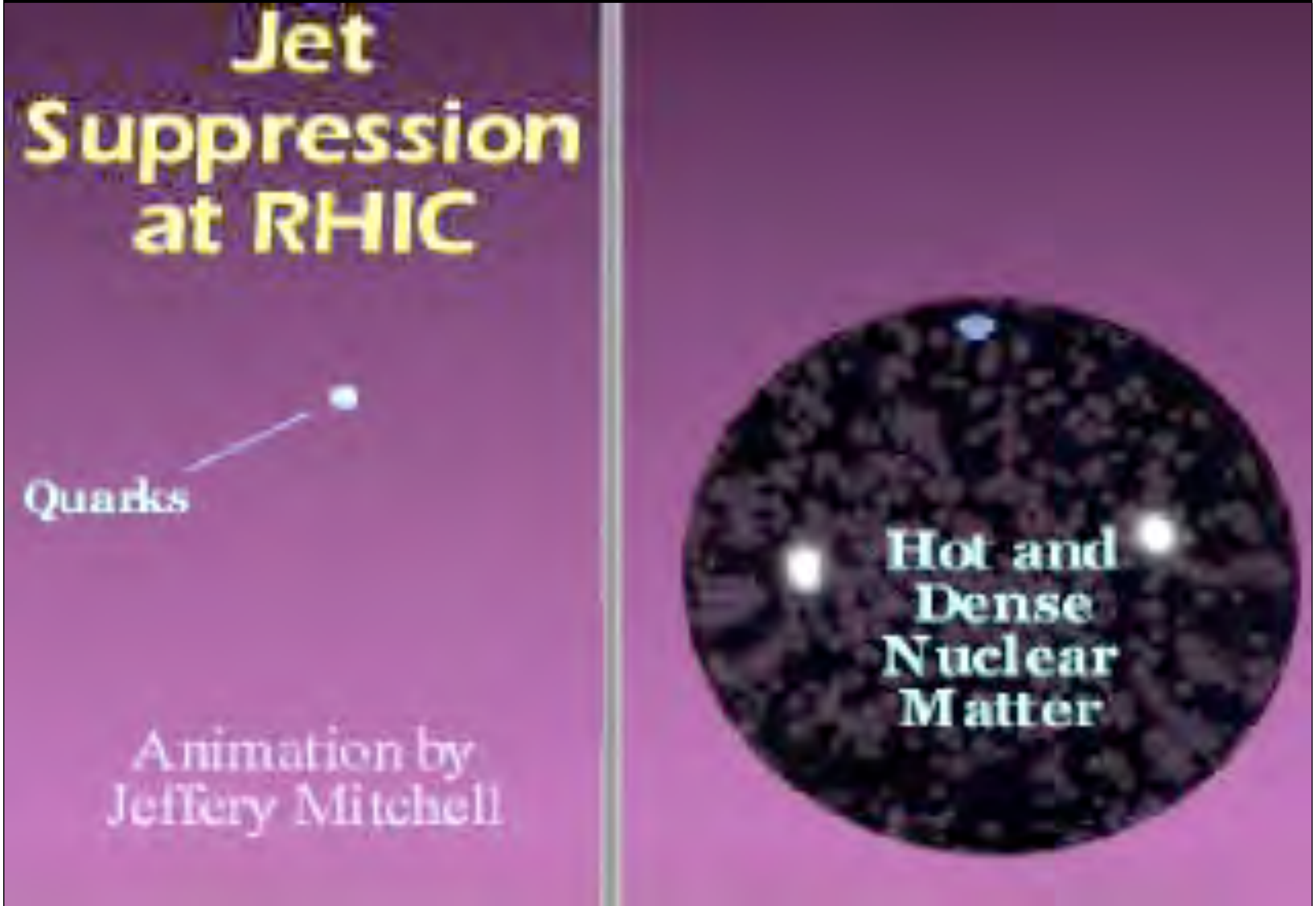
- In QGP, parton loses energy mainly due to the gluon radiation, and jet produced by the hard parton scattering is quenched (**jet quenching**).
- On the other hand, photon from hard scattering does not lose energy in QGP (EM int.)
- Using these jets and (direct) photons, one can perform:
  - **QGP tomography**
  - Study of medium response
    - low $p_T$ particle spectra, flow, HBT, etc. with jet axis.

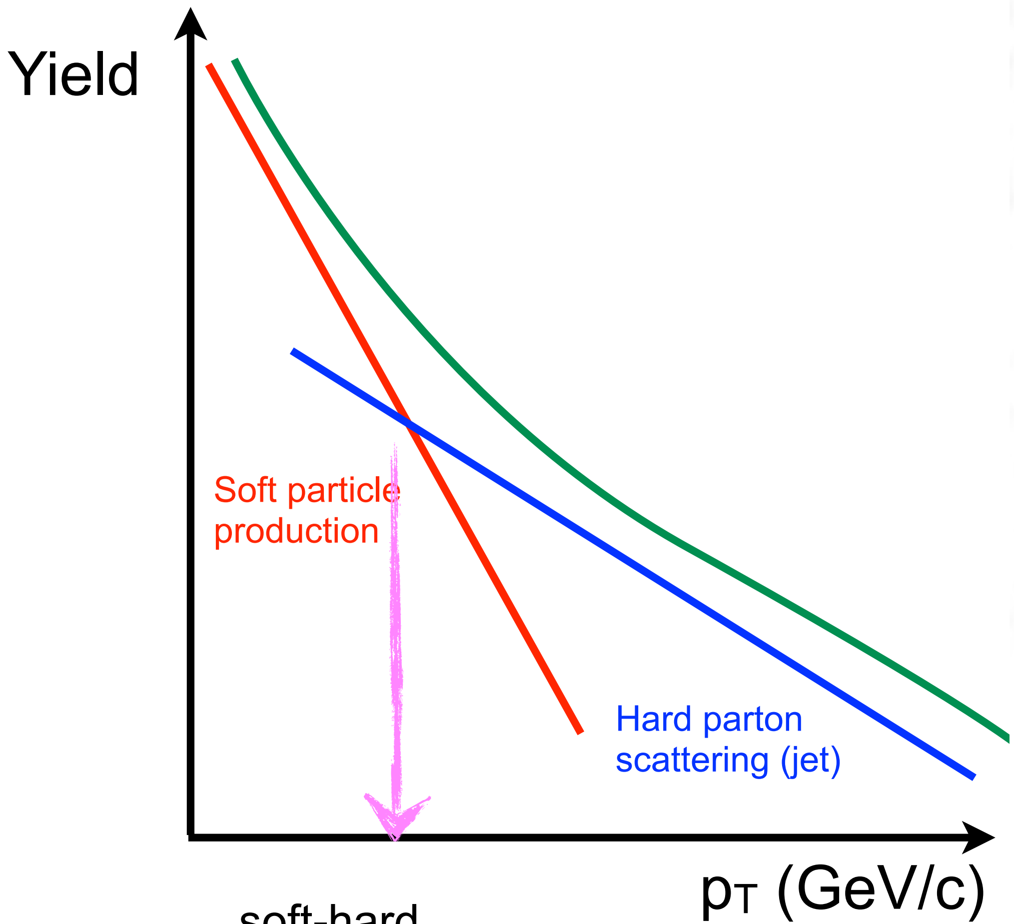



QGP jet-jet,
γ-jet tomography

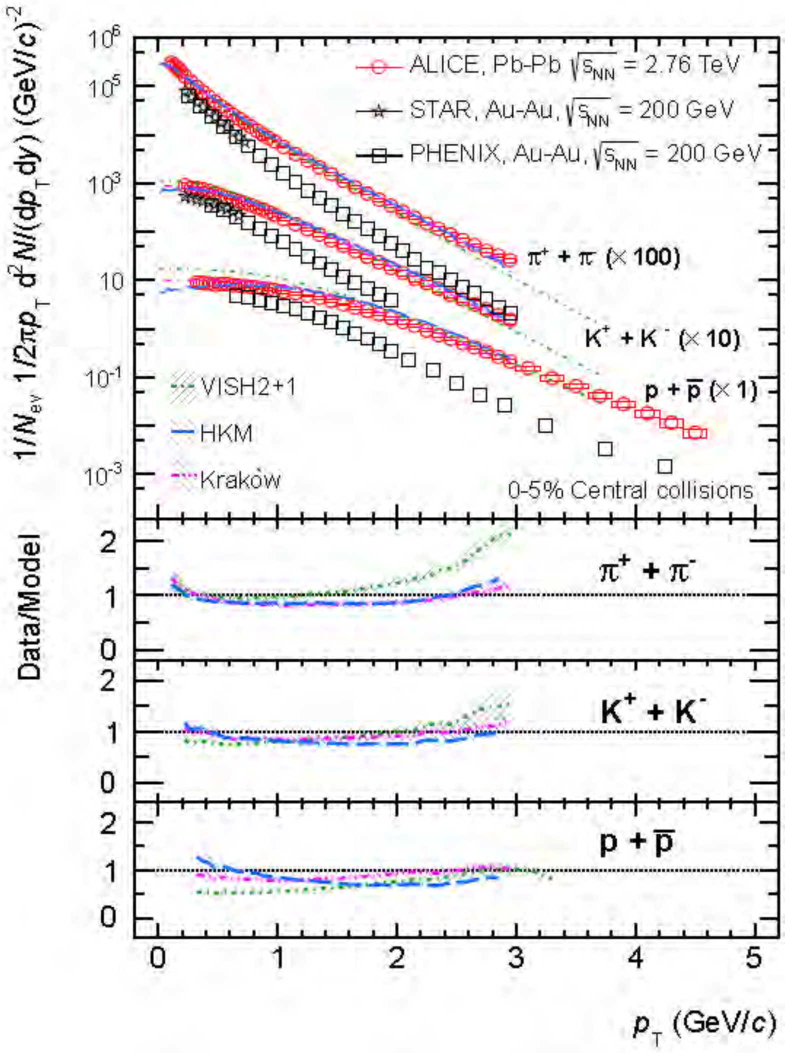


PET

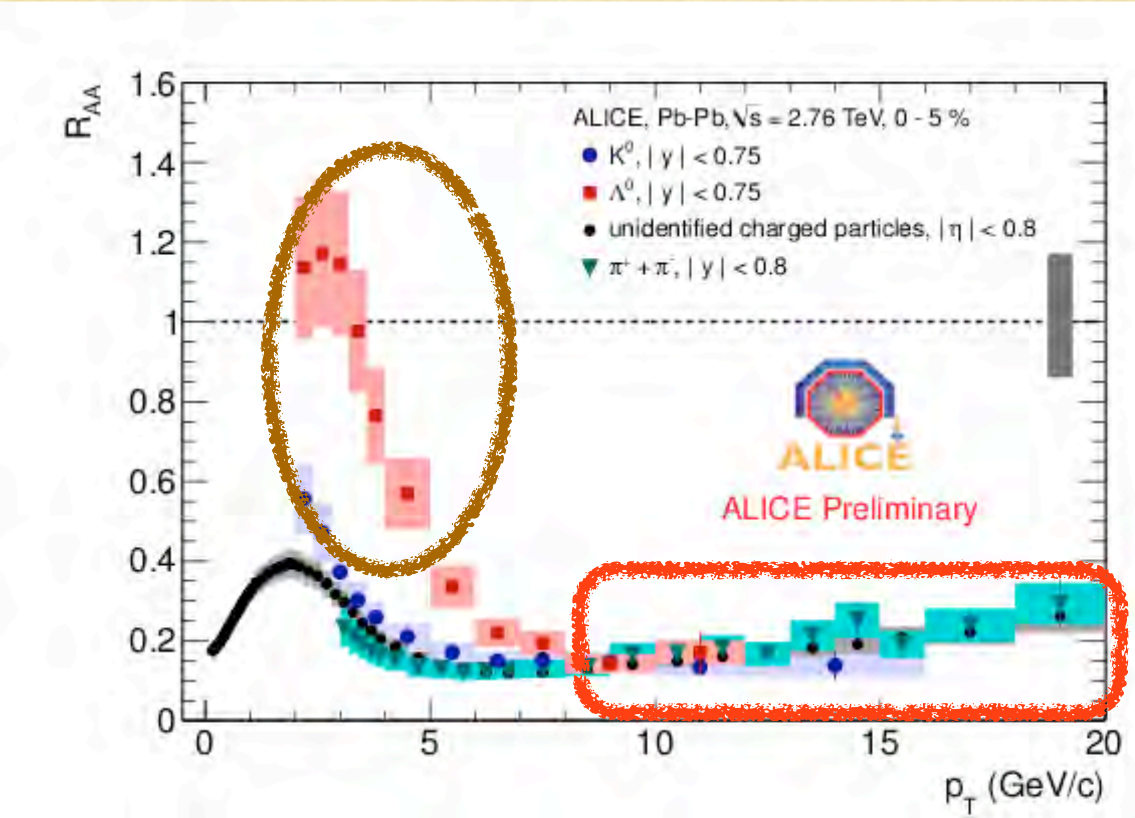

Jet
Suppression
at RHIC
Quarks
Animation by
Jeffery Mitchell
Hot and
Dense
Nuclear
Matter




soft-hard
transition ~ 4 GeV/c

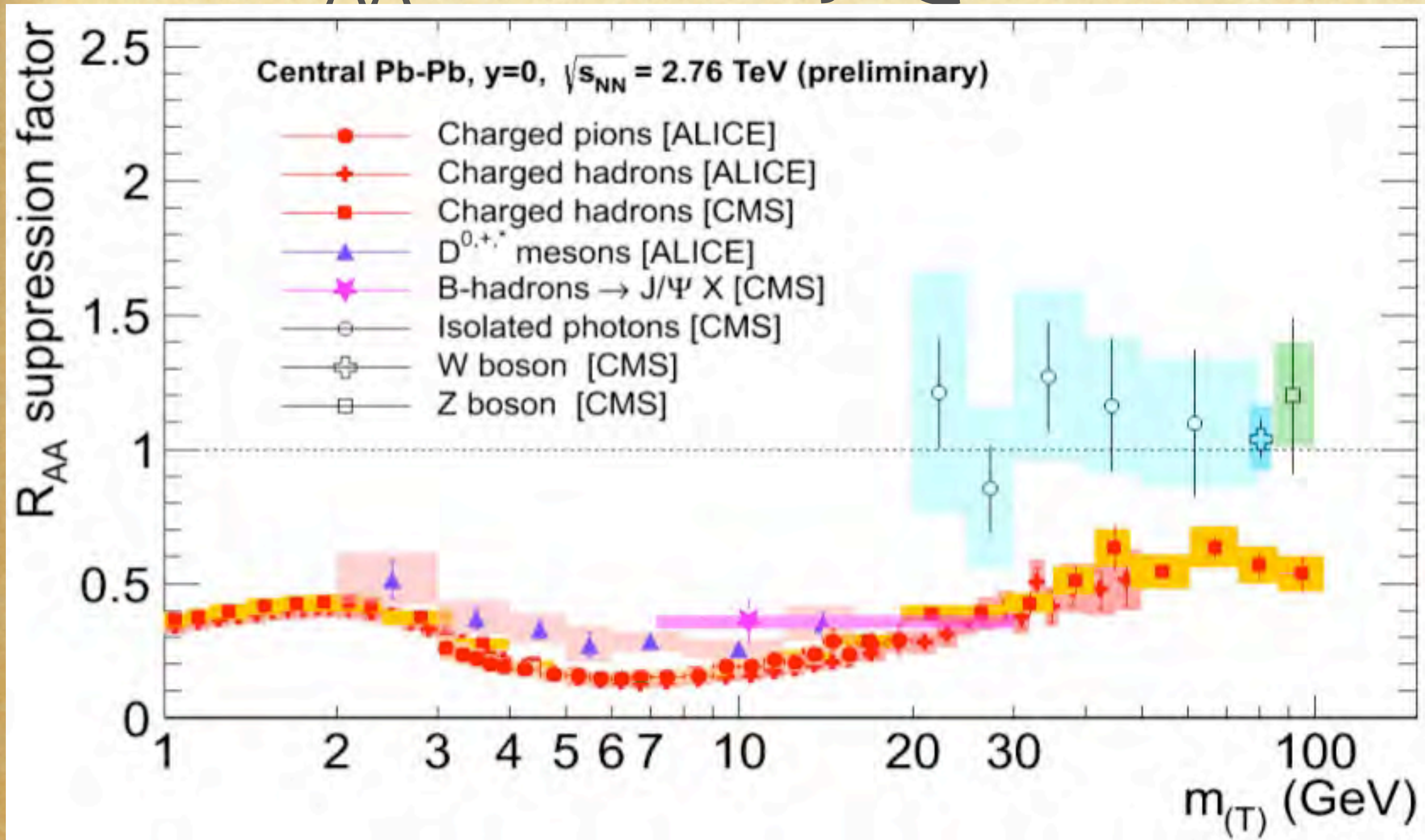


# Nuclear modification factor ($R_{AA}$)for light hadrons



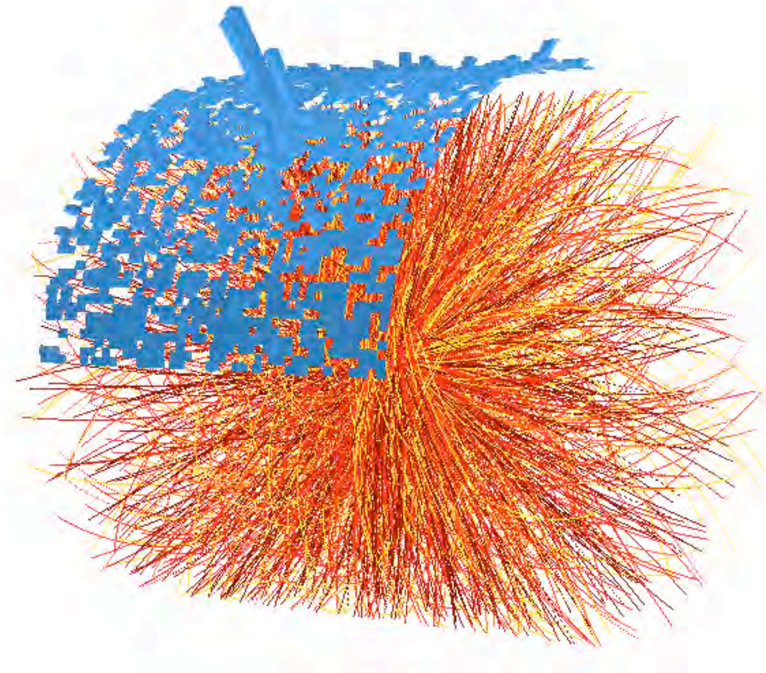

- **Hadrons with $p_T$ > 8 GeV/c are equally suppressed.**
- A Large baryon enhancement at intermediate $p_T$ (2-5 GeV/c), recombination.

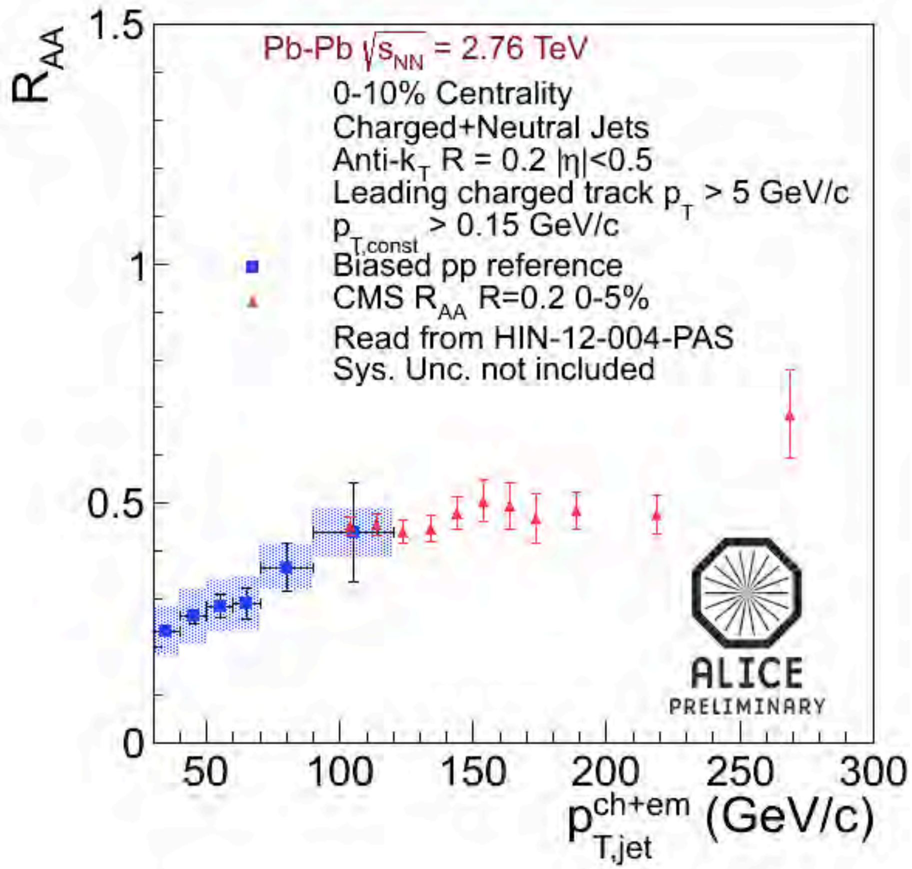
# $R_{AA}$ Summary @LHC




- **Hadron: strong yield suppression, dip at ~7 GeV.**
- **EM probes: do not suppressed.**

# jet $R_{AA}$



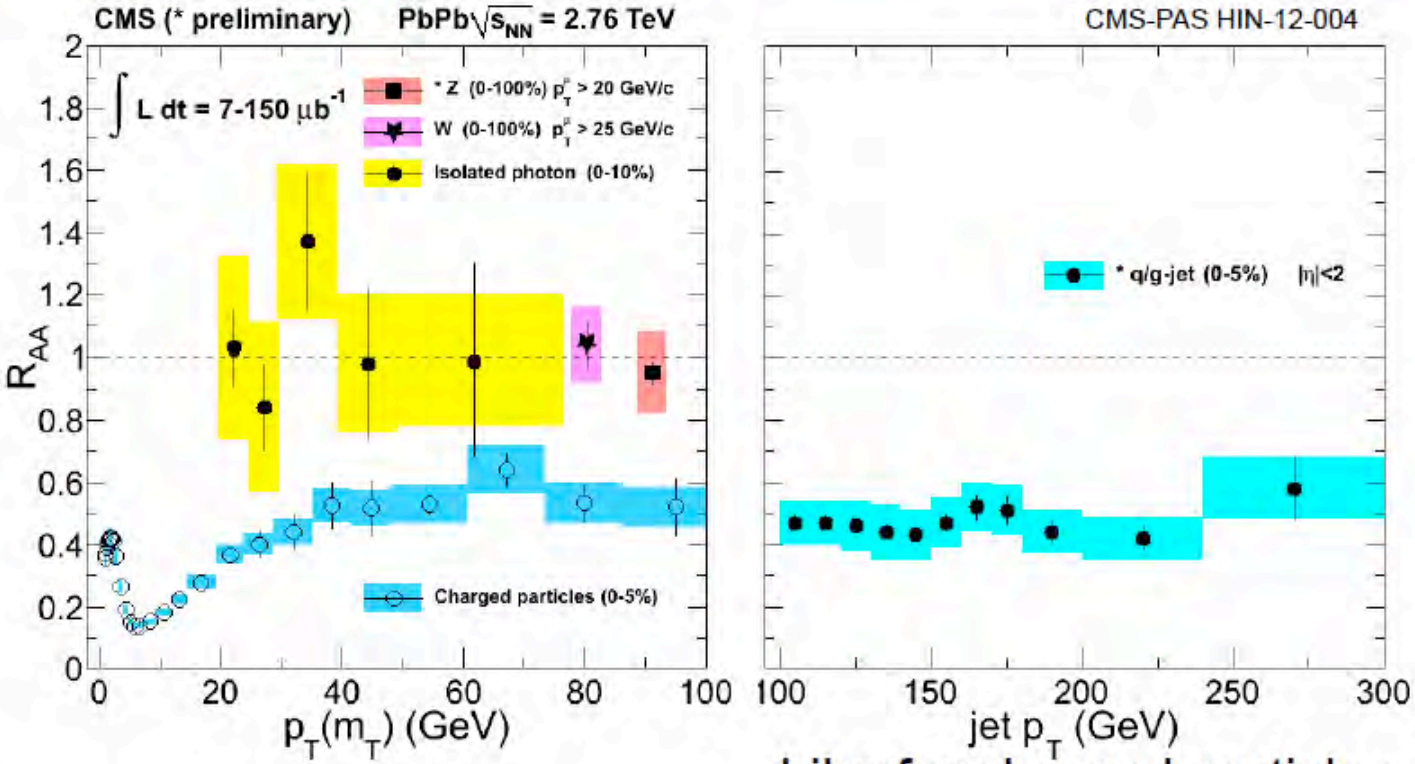



Instead of leading hadron, one can reconstruct "jet" directly.

- Strong jet suppression observed ($R_{AA}$ ~ 0.5).
- A hit of stronger suppression at lower jet $p_T$ (ALICE).

# Suppression of inclusive jets

Fully unfolded inclusive jet $R_{AA}$
pp 2.76 TeV reference



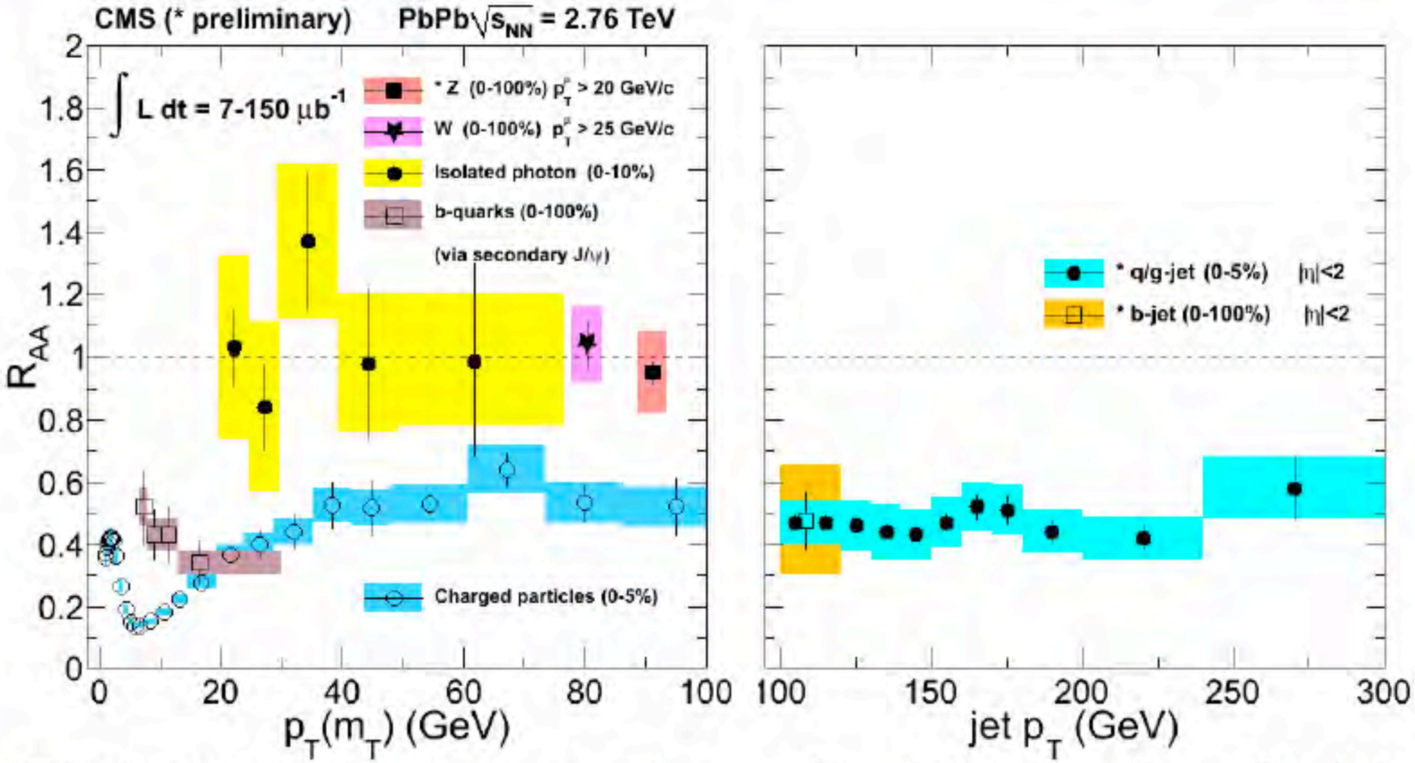

Like for charged particles,
high-$p_T$ jet $R_{AA}$ flat at ≈ 0.5

# Parton ID: b-quarks

Parallel talk
Mihee Jo (Fri)

Parallel talk
Matt Nguyen (Tue)

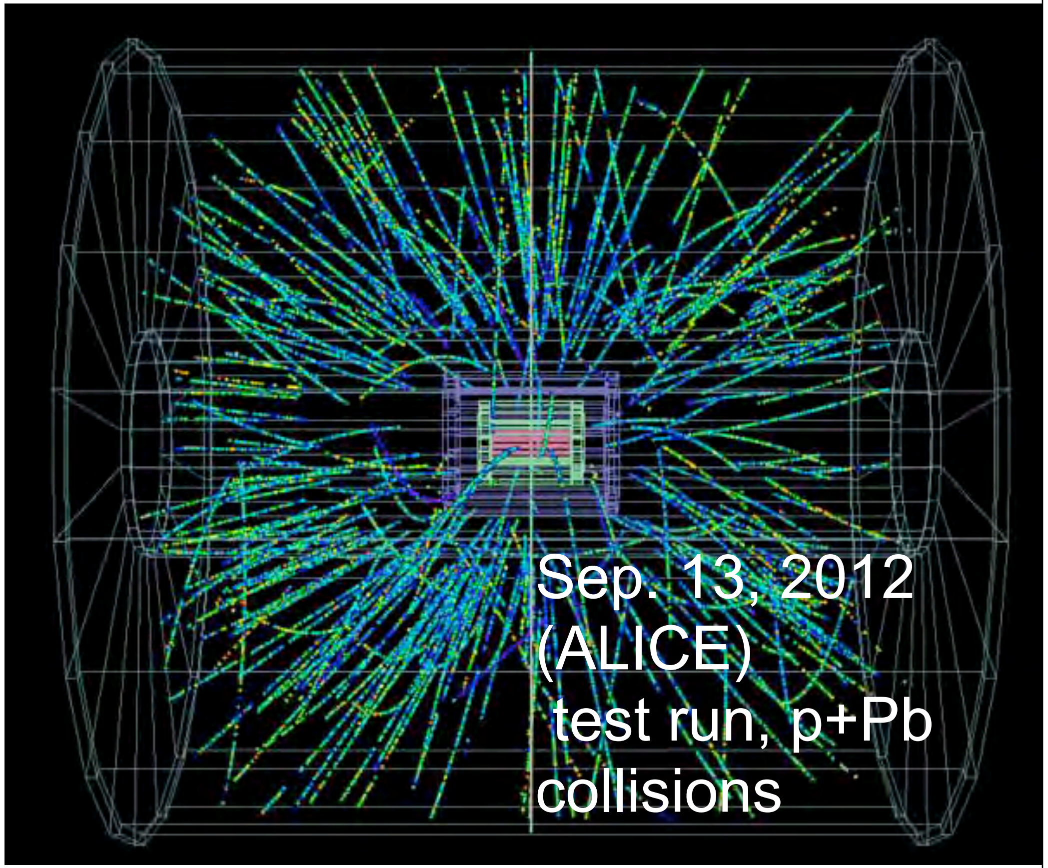
Poster
Jorge Robles




Distinct b-quark suppression pattern at low $p_T$

First observation of b-jet suppression at high $p_T$

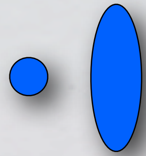
# First p+Pb data at LHC

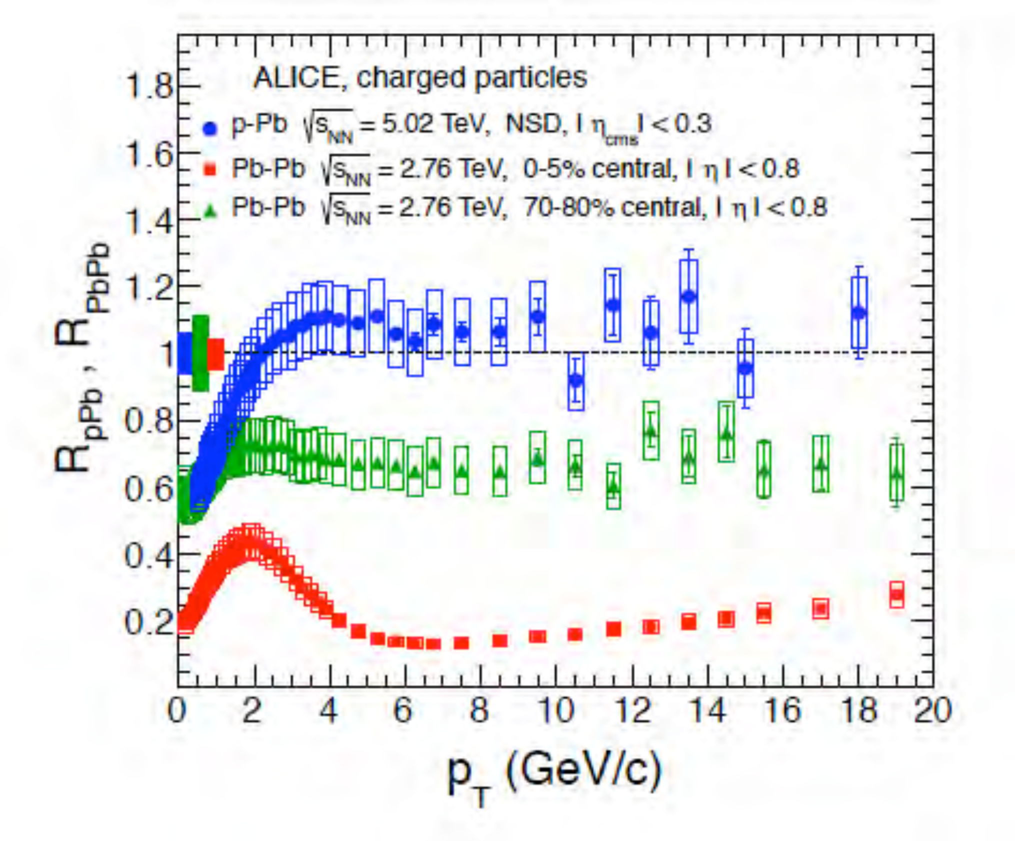



- Successful p+Pb pilot run (Sep. 13, 2012)
- p+Pb Physics run (Jan. – Feb., 2013)
  - Beam energy: $\sqrt{s_{NN}}$ = 5.02 TeV
  - Expected statistics: ~ 30 $nb^{-1}$

→ rare probe statistics equivalent to 0.15 $nb^{-1}$ of Pb-Pb.

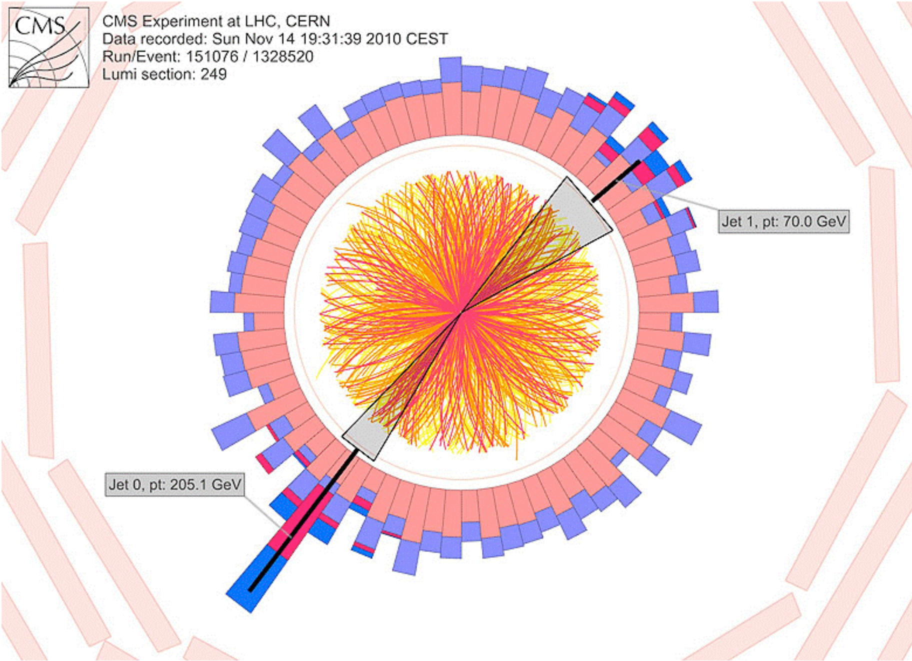
# p-Pb results (ALICE)



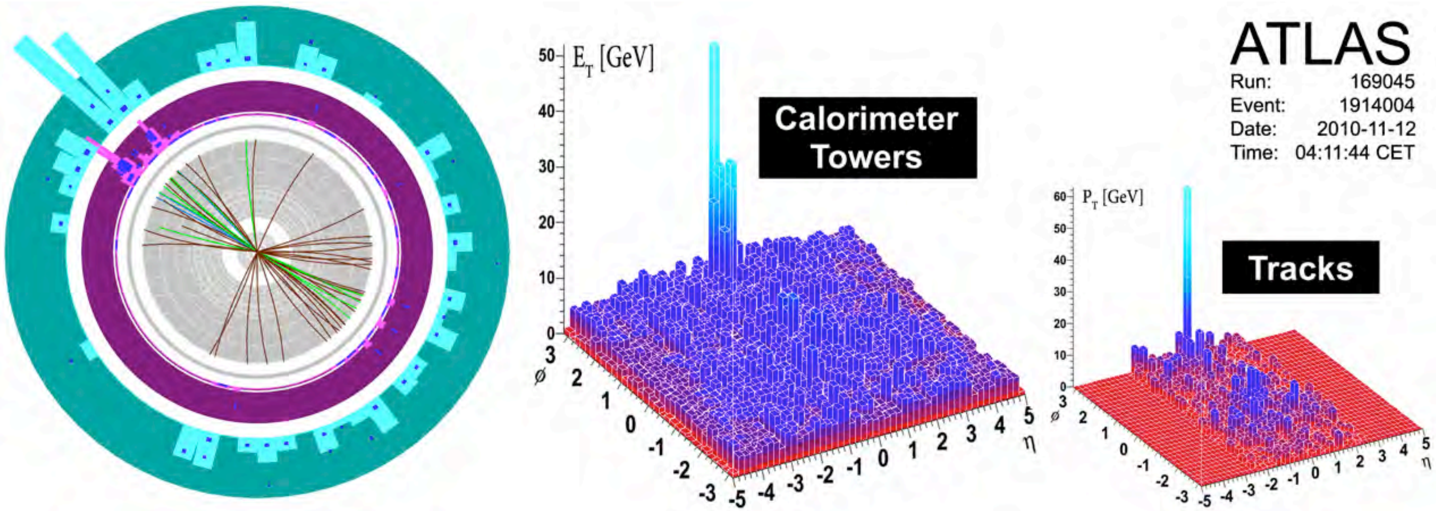



- No suppression for p-Pb collisions.
- Indicated that suppression seen in central Pb-Pb is the final state effect, not the initial state effect.

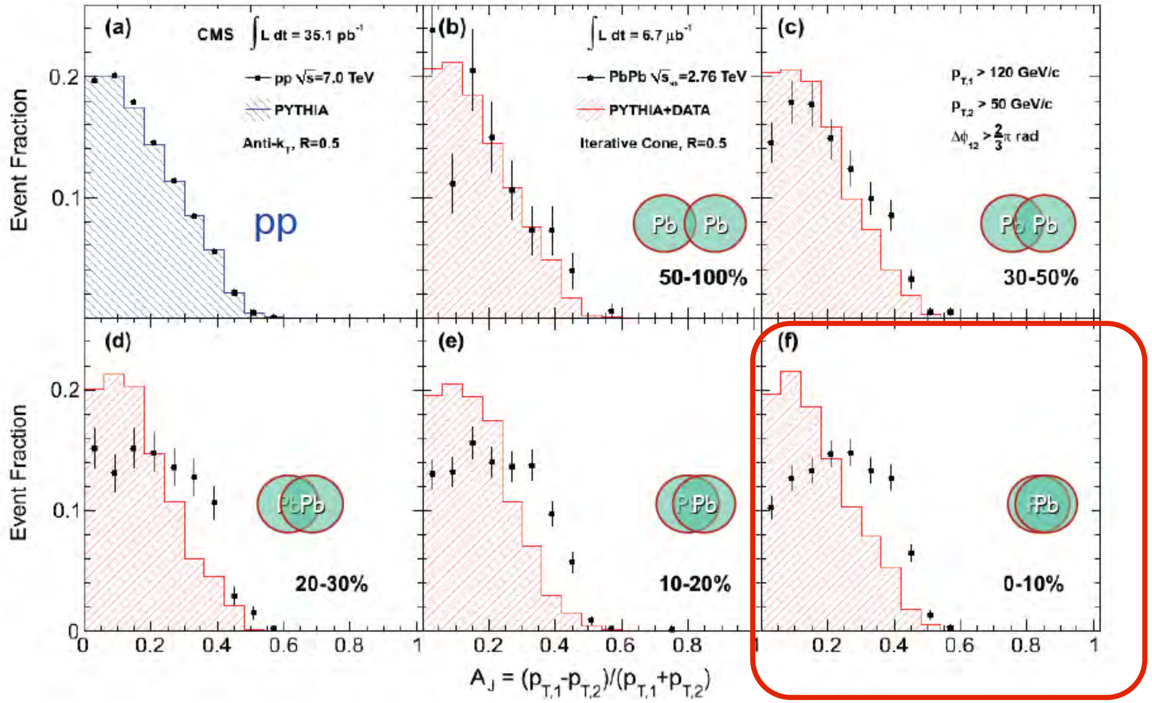
arXiv:1210.4520 (ALICE)


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

# Di-jets


ATLAS
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET
Calorimeter Towers
Tracks
E_T [GeV]
P_T [GeV]
φ
η

# $A_J$: di-jet asymmetry

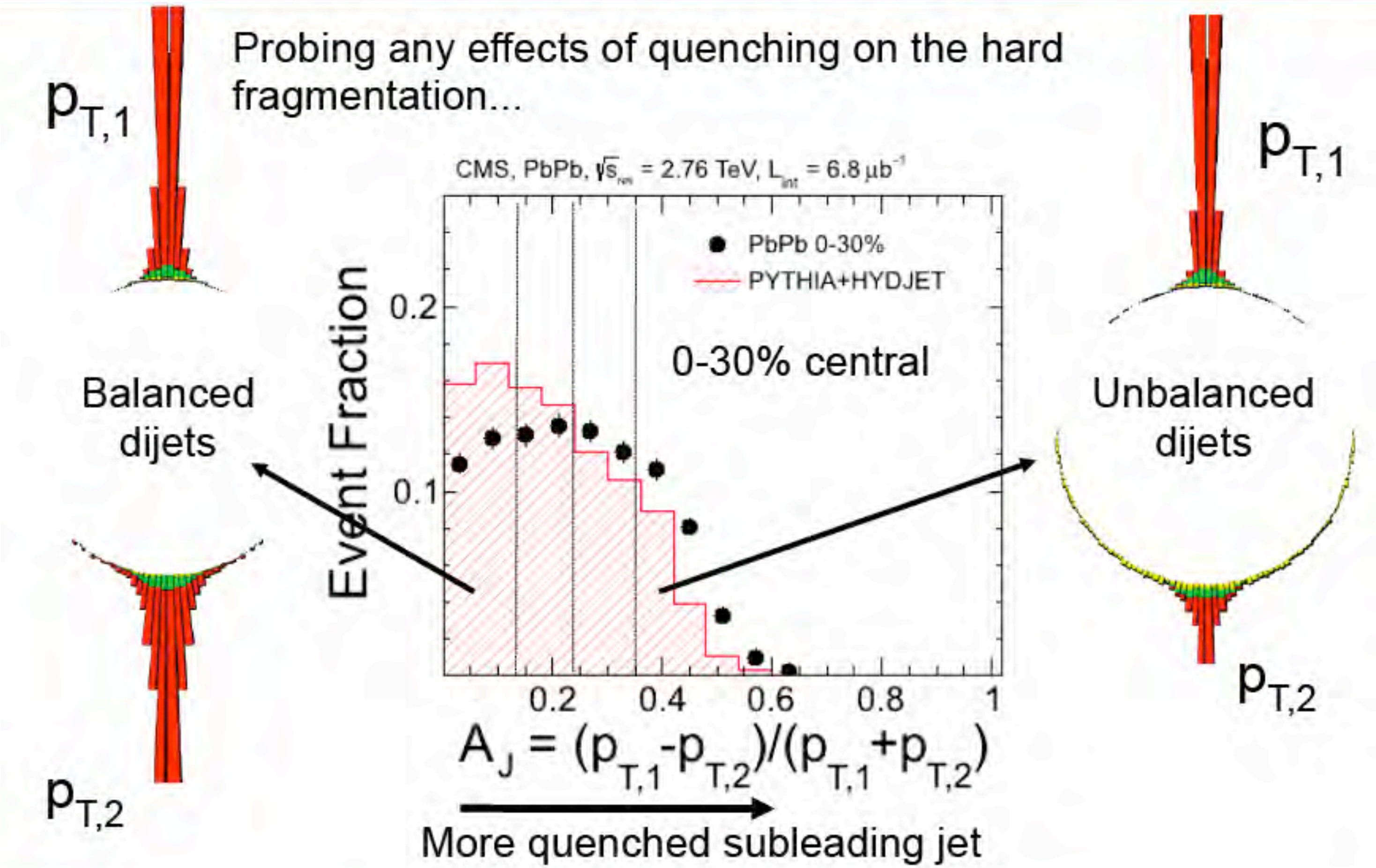



$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

CMS R=0.5

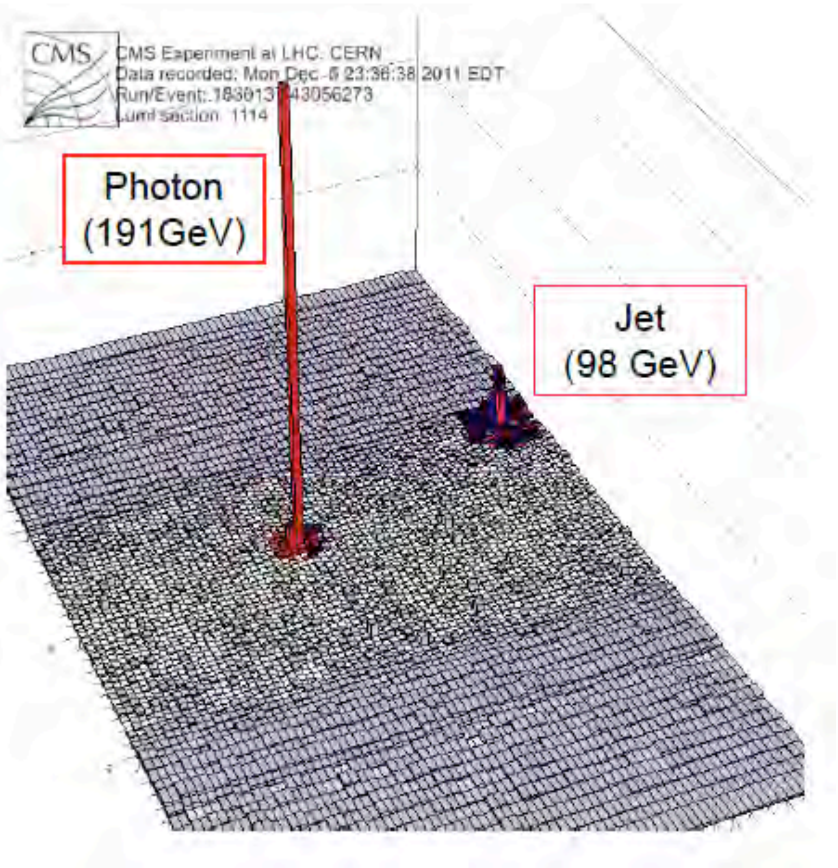
- Quantify jet energy imbalance by the asymmetry ratio.
- Large asymmetry is seen in energy imbalance in central Pb-Pb

# Differentiating in $A_J$






**Large $A_J$ : low momentum particle (< 4 GeV/c) emitted at large angle on away side.**

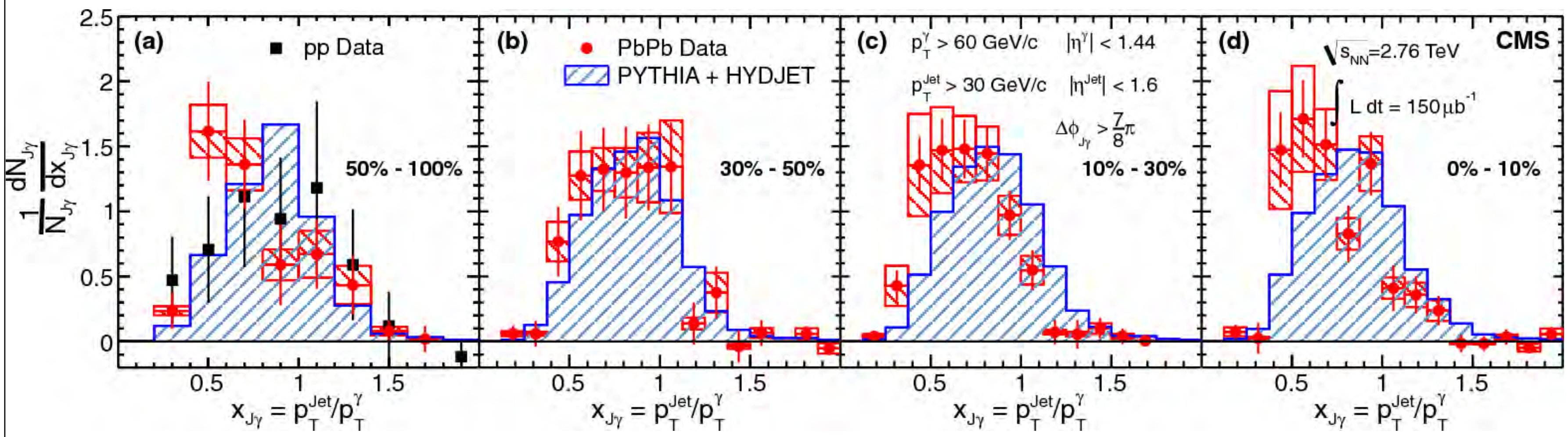


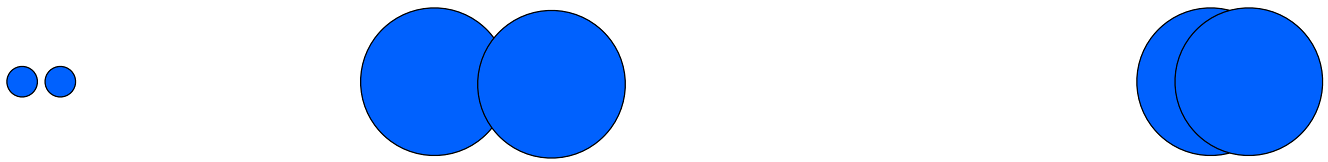

# γ-jet:

## jet quenching study with energy calibrated probes (photons)

# γ-Jet momentum balance (CMS)

arXiv:1205.0206



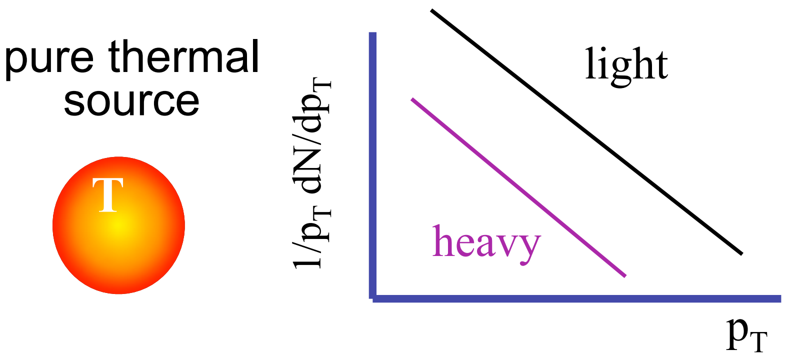
- Momentum ratio ($p_T^{\ Jet}/p_T^{\ gamma}$) shifts/decreases with collisions centrality.

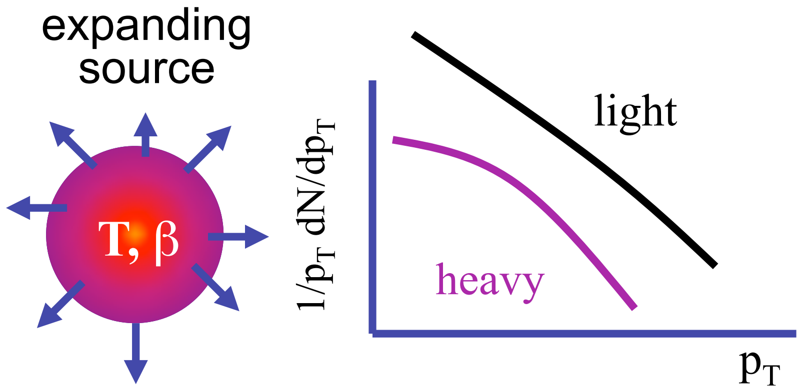
# 2. PROPERTIES OF QGP

Probing via spectra, yield, flow

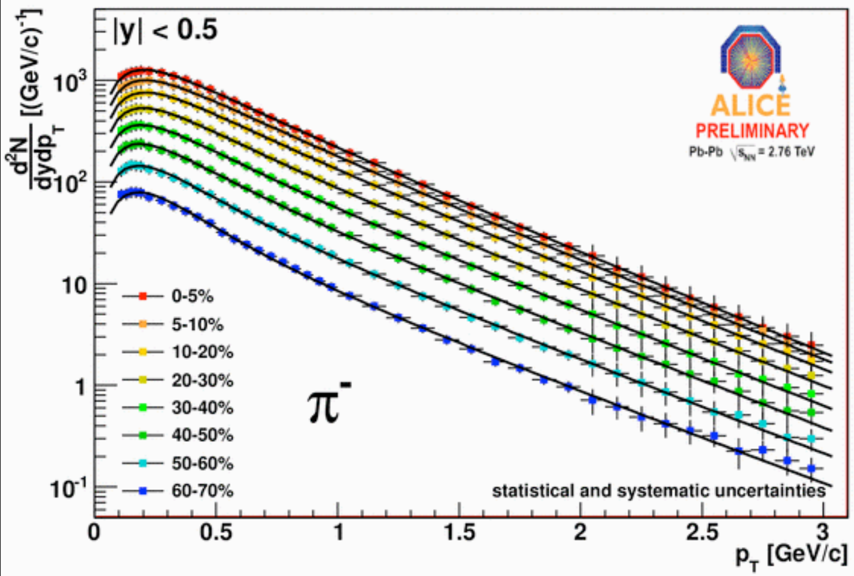
To characterize the global properties on expanding source; introduce common velocity field;

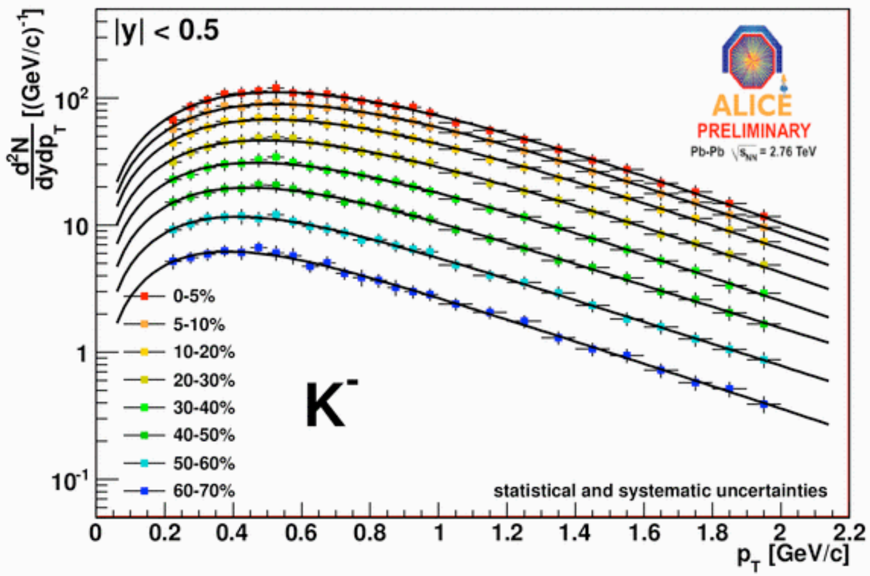
**“radial flow”**



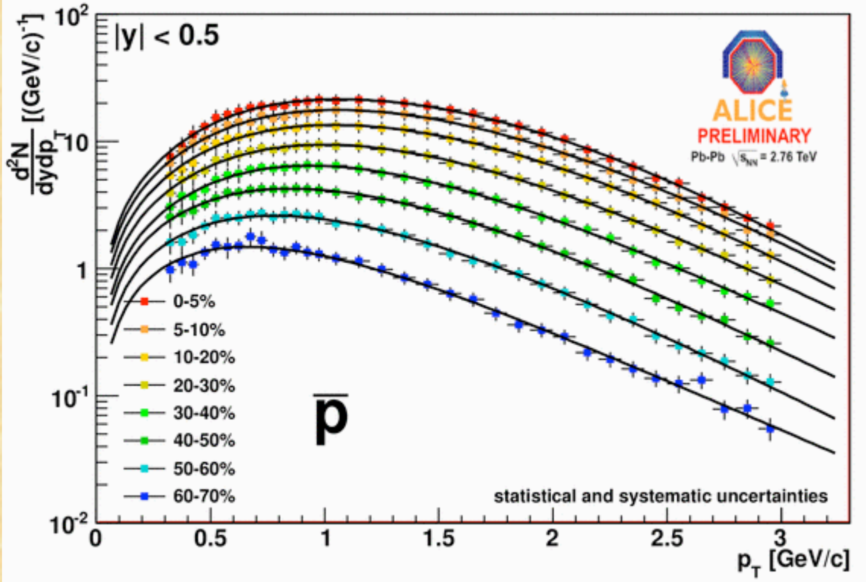



# Identified hadron spectra at LHC



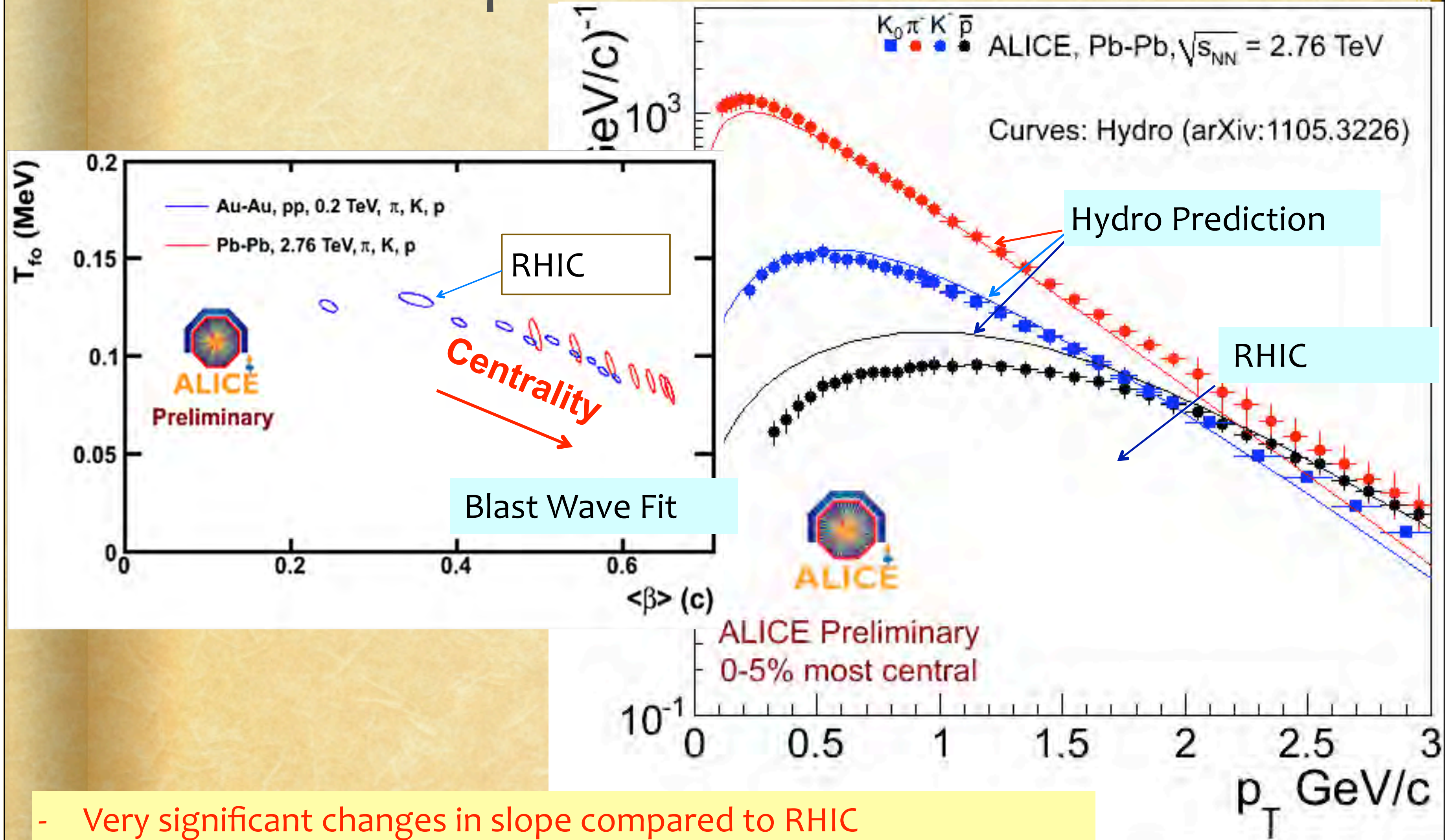




- ALICE data for pions, K, p
- Lines = blast-wave fits
  - ⇨ Parameters of the system at the kinetic freeze-out ($T_{fo}$, $\beta_T$).




ALI-PREL-2713

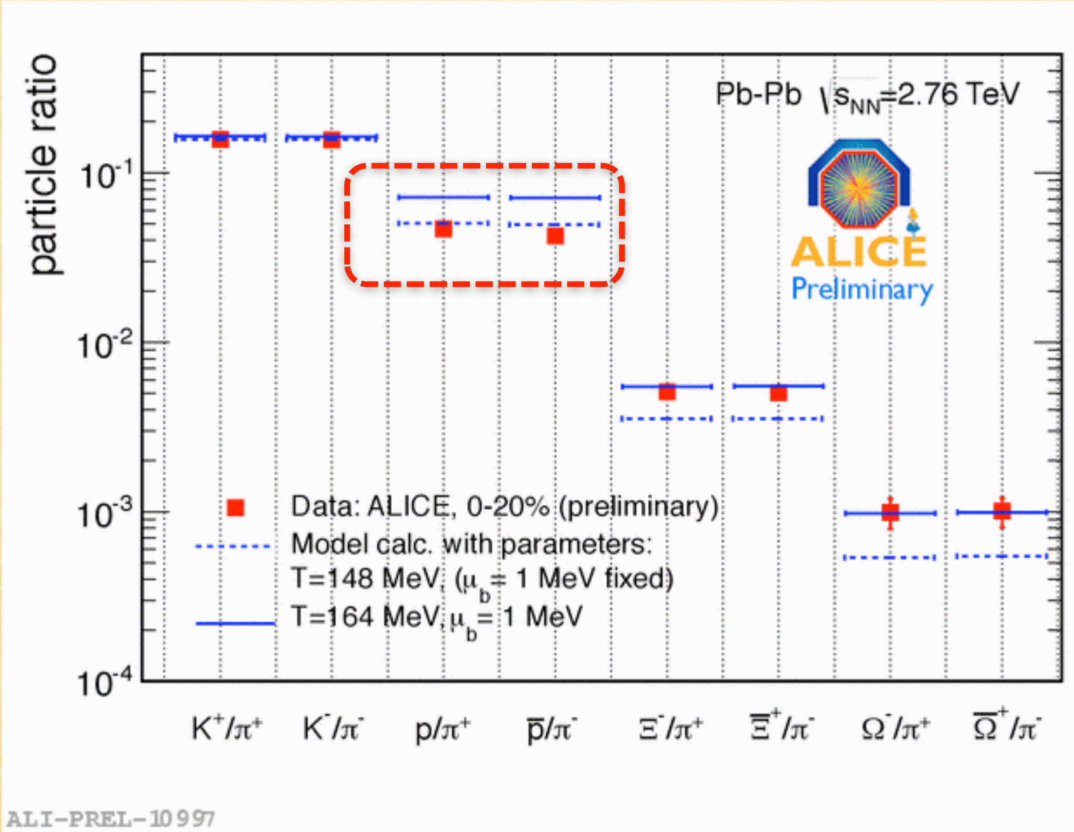
# PID spectra and radial flow



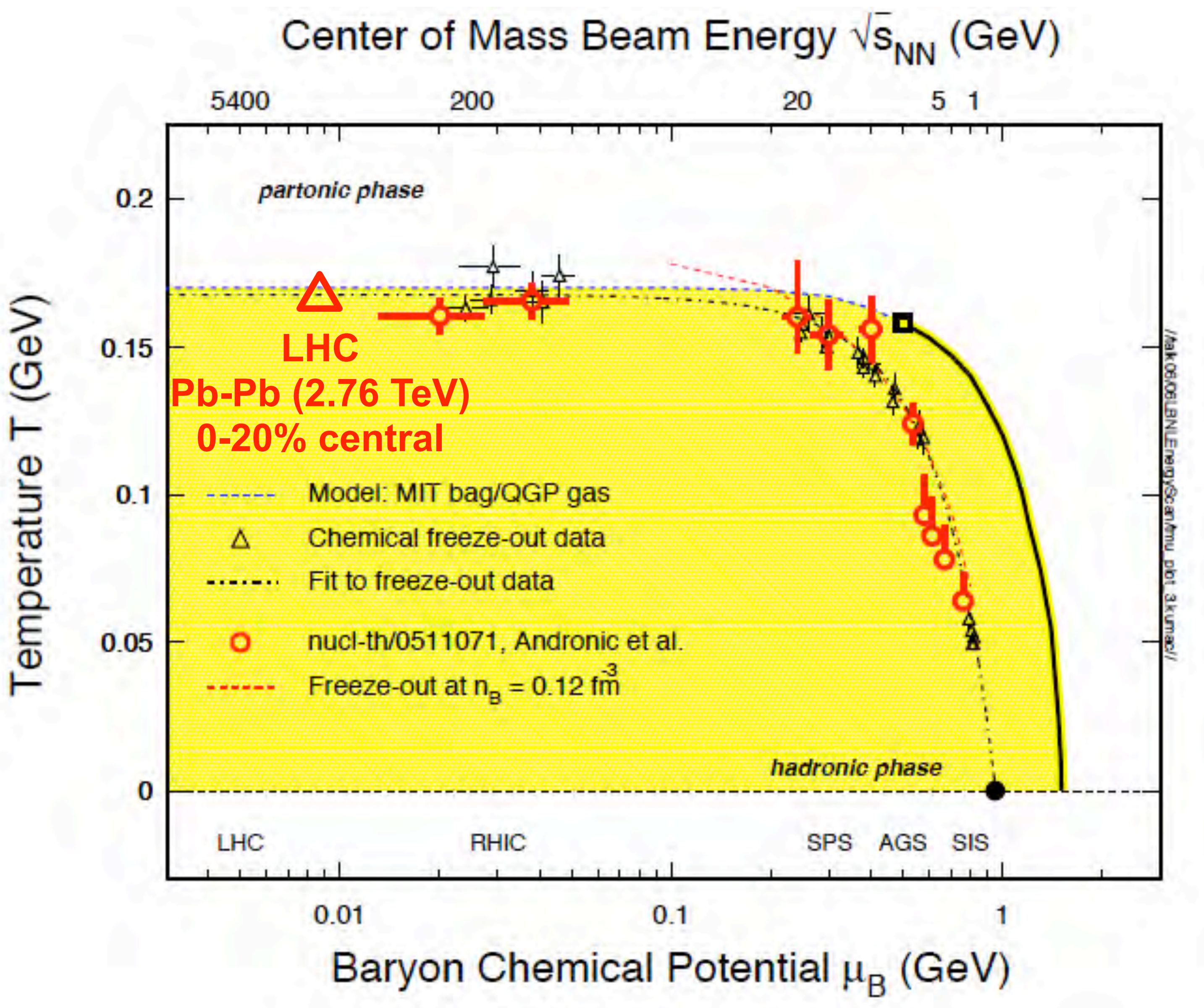

- Very significant changes in slope compared to RHIC
- Most dramatically change for protons
- Very strong radial flow, $\beta \approx 0.66$ (10% higher than RHIC)
- **Even larger than predicted by most recent hydro (e.g. protons)**

# Thermal Model Comparison

- All ratios other than p/π are predicted accurately
- **Protons: different $T_{ch}$ than strange/multi-strange,** indicating the importance of re-scattering at hadronic phase.




A. Andronic et al, PLB 673: 142-145 (2009)



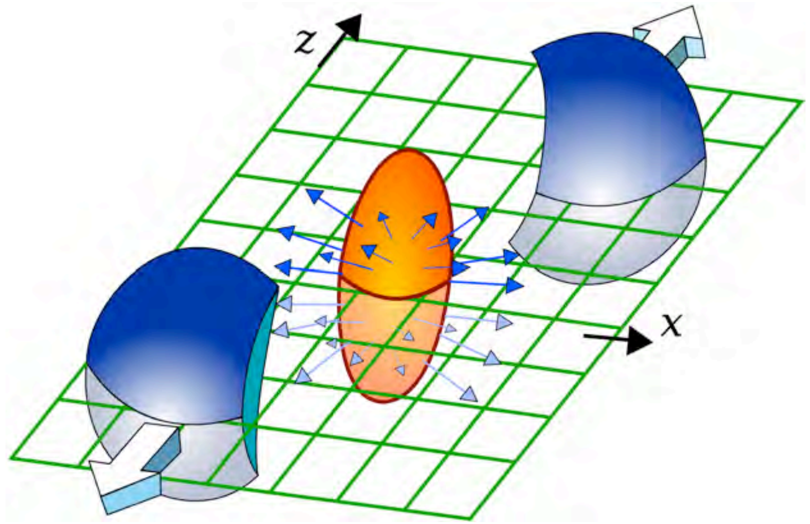

Braz. J. Phys. vol.37 no.2c São Paulo June 2007

**http://dx.doi.org/10.1590/S0103-97332007000500024**

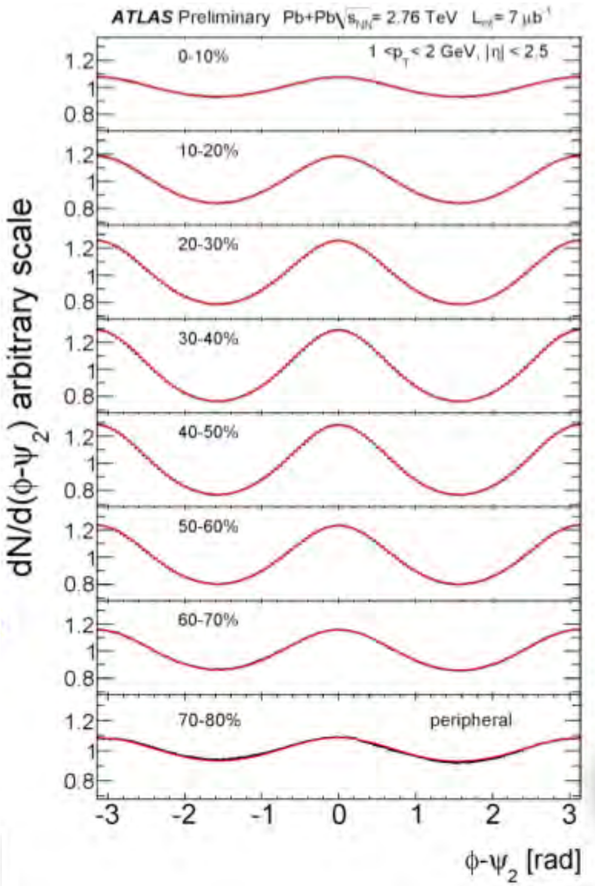
N. Xu

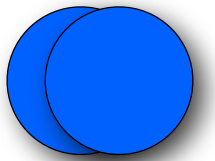
# **Anisotropic flow;**

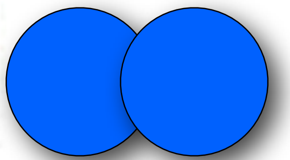
sensitive to the early time of
collisions, pressure gradients, EOS.

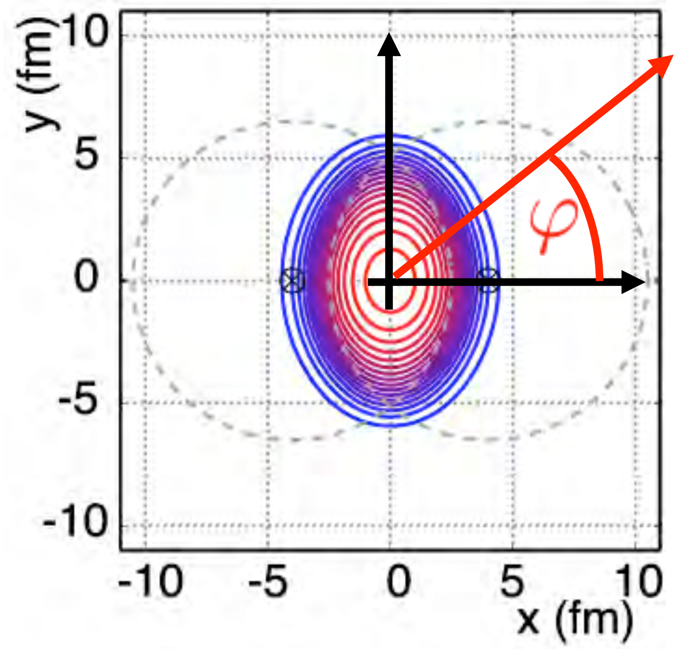


# Elliptic flow; $v_2$



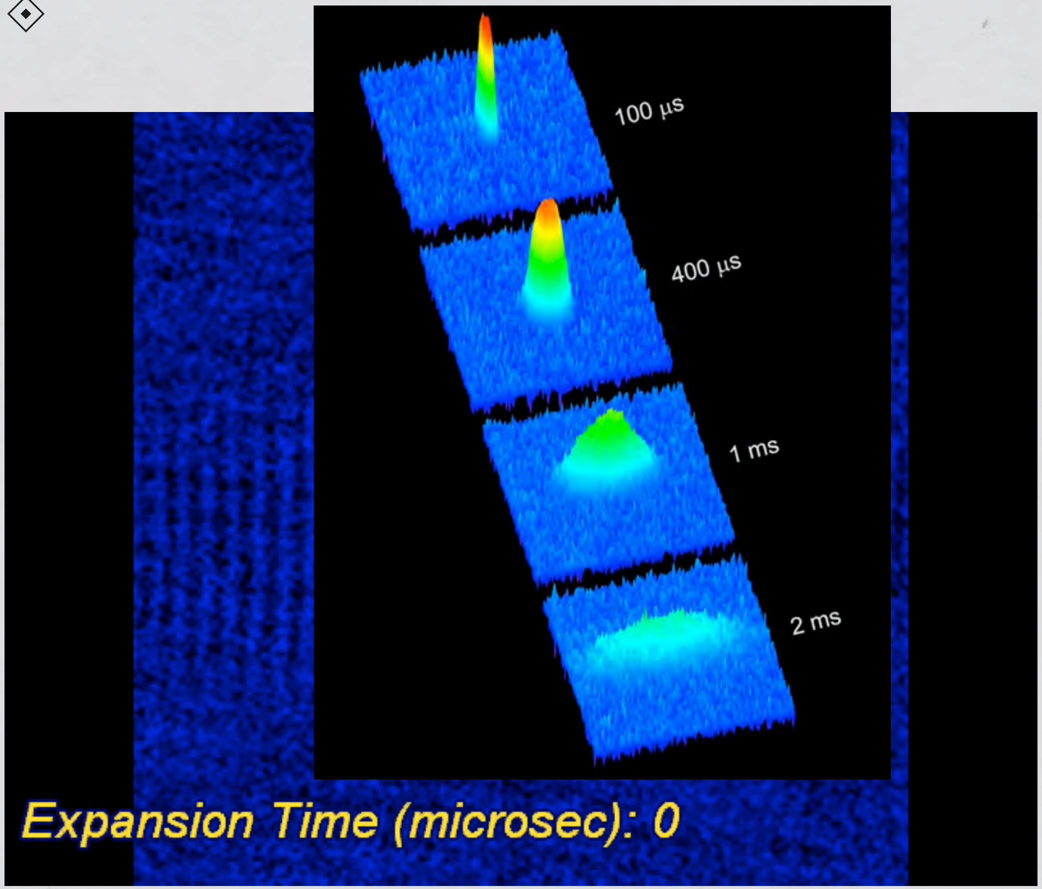








$$\frac{dN}{p_T dp_T dy d\varphi}(p_T,\varphi;b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2v_2(p_T;b)\cos(2\varphi) + \ldots\right)$$

# strongly coupled system at $10^{-6}$ K




**World at $10^{-6}$ K**

$^6$Li (optical laser cooling)

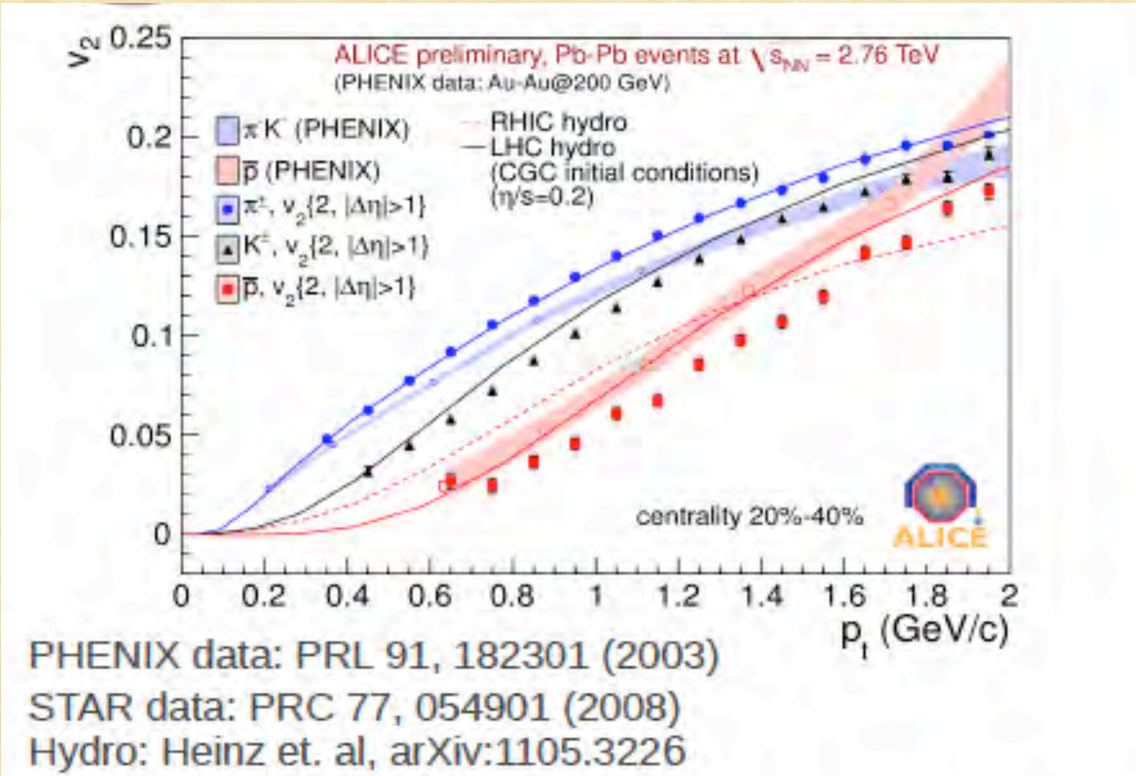
Fermi gas system

= strongly coupled system

**Very similar at $10^{12}$ K**

**= strongly coupled QGP (sQGP)**

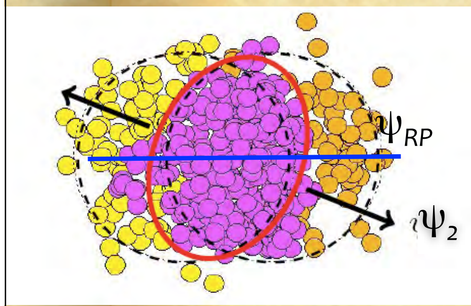
# Identified particle $v_2$

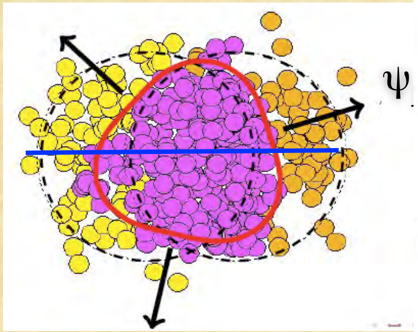


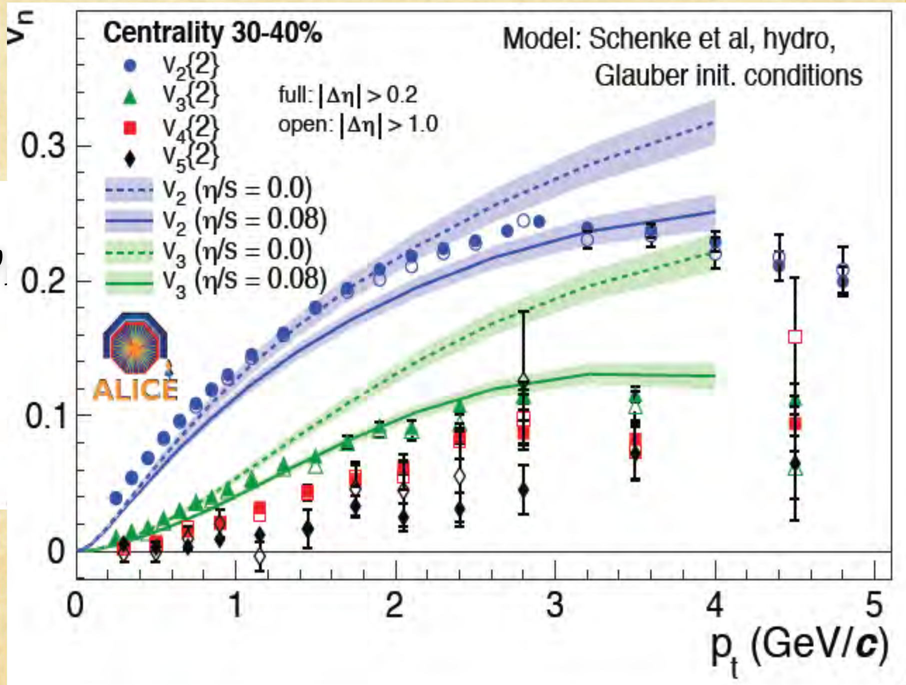

- **Large mass splitting at LHC compared to RHIC as predicted by hydrodynamics models.**
- Pion $v_2$: described well by hydro. predictions with MC-KNL CGC initial conditions and $\eta/s = 0.2$.
- (K and ) Anti-protons: overestimated by the same calc. for central collisions.

# Higher order harmonics; $v_n$

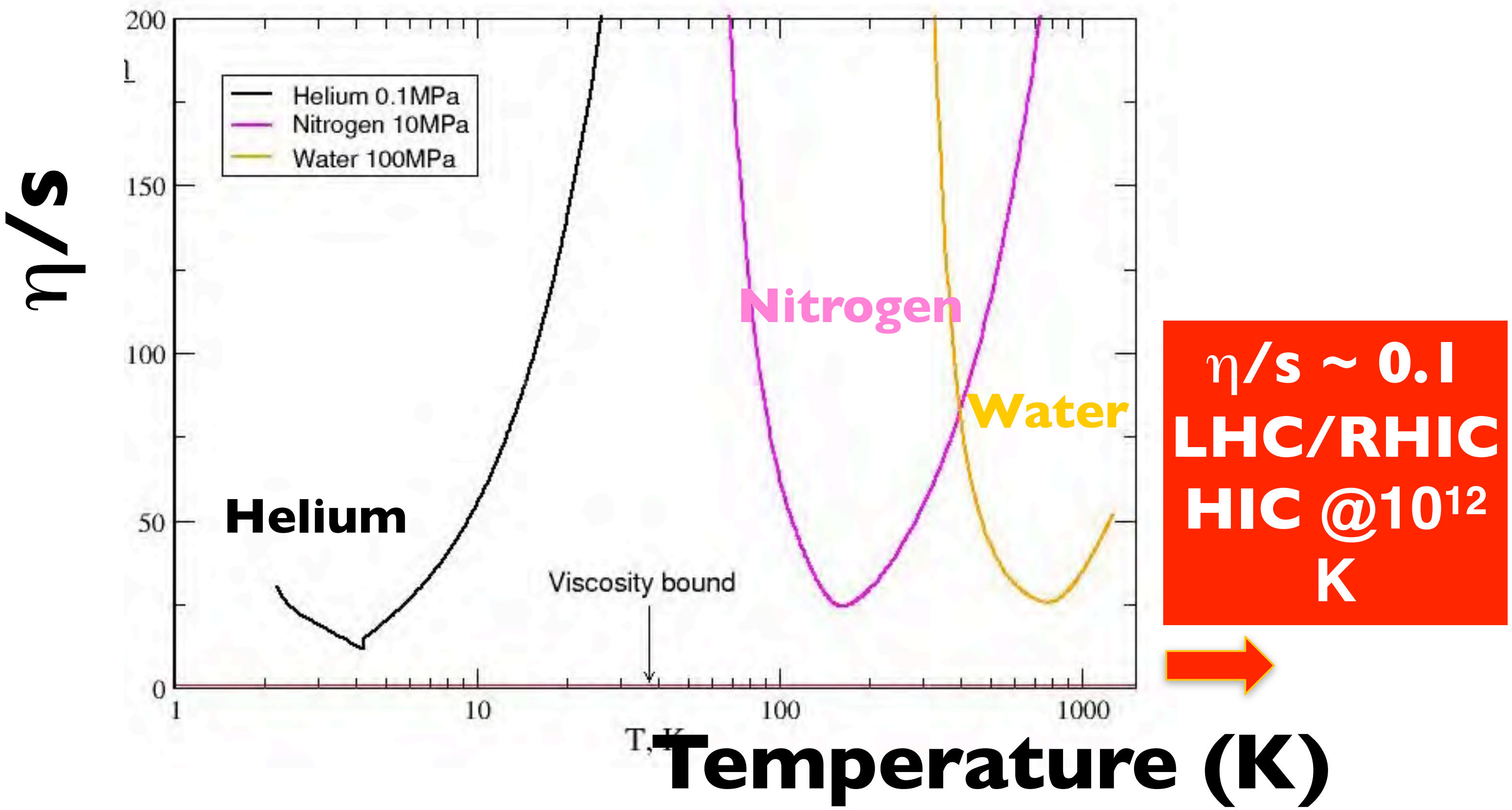
PRL 107, 032301 (2011), ALICE



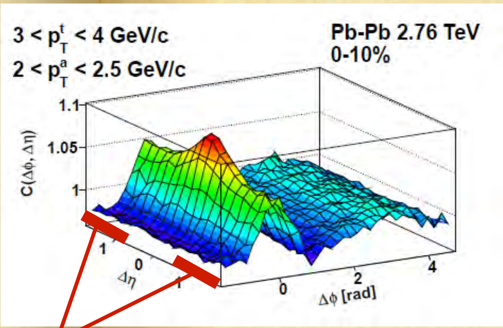

- **$v_3$ sensitive to shear viscosity $\eta/s$ and to initial conditions (Glauber, CGC) .**
- No simultaneous description of $v_2$ and $v_3$ with the same $\eta/s$.




RHIC $v_2$ data : $\eta/s \sim 0.1$.

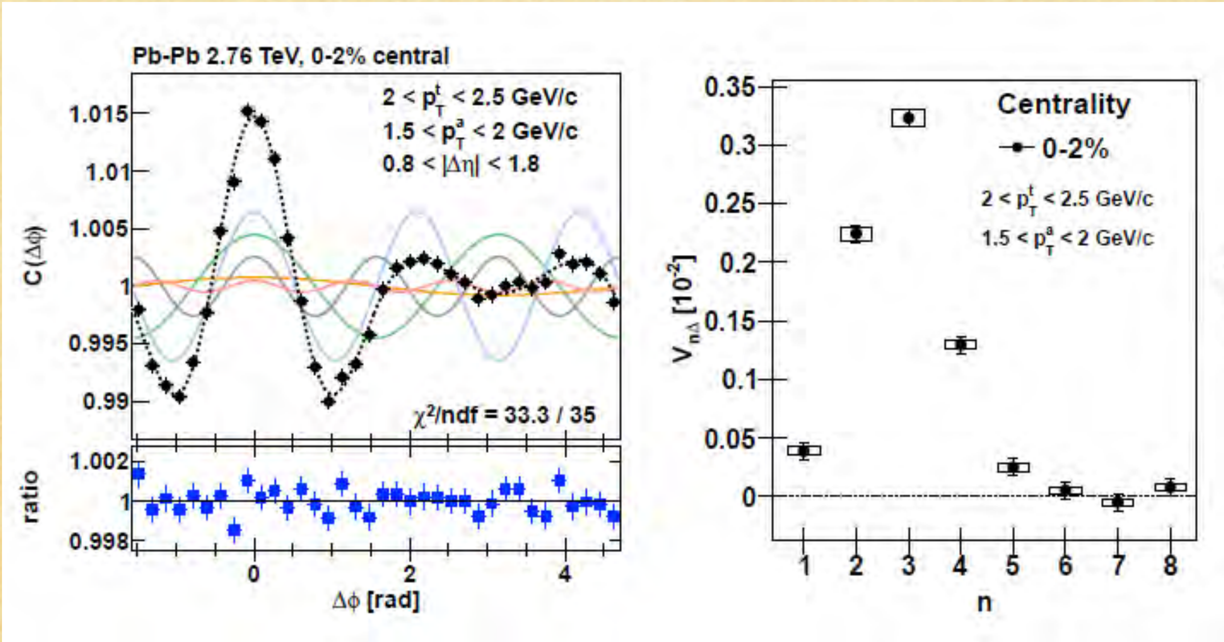
Smallest $\eta/s$ in the world, approaching the quantum viscosity bound (1/4pi)

# Fourier decomposition in di-hadron corr.




- Extract 1D $\Delta\varphi$ correlations by integrating the $C(\Delta\eta,\Delta\varphi)$ in $0.8<|\Delta\eta|<1.8$ range and do a Fourier decomposition

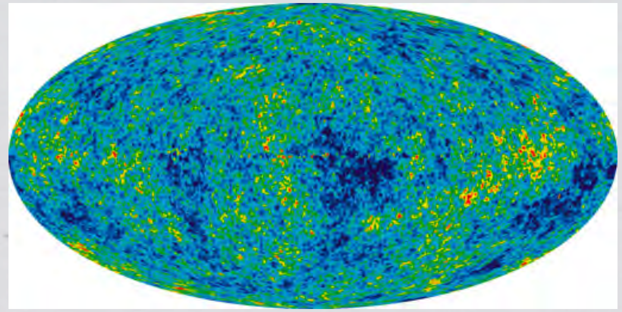
$$C(\Delta\varphi) = \frac{1}{\Delta\eta_{max} - \Delta\eta_{min}} \int_{\Delta\eta_{min}}^{\Delta\eta_{max}} C(\Delta\eta, \Delta\varphi) \propto 1 + 2\sum_{n=1} v_{n\Delta} \cos(n\Delta\varphi)$$

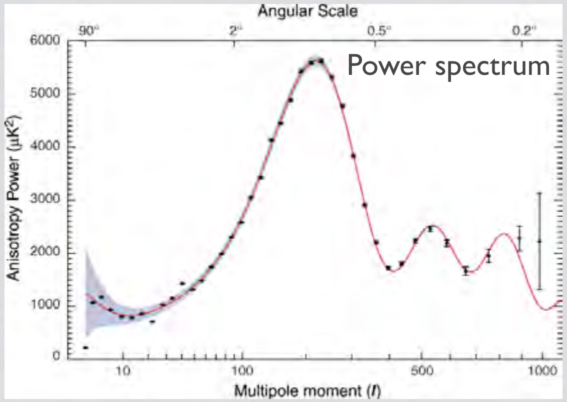


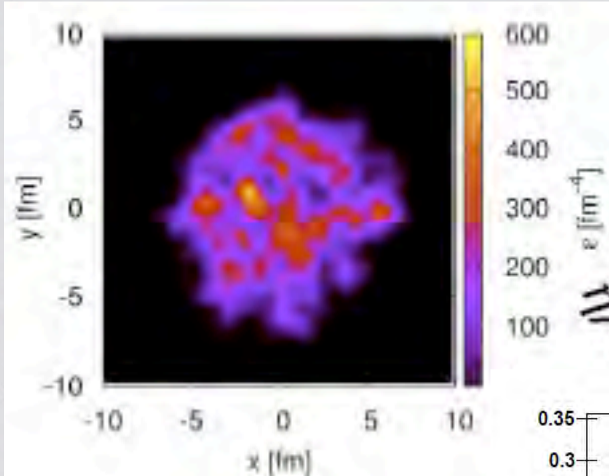

- **5 components describe completely the correlations at large $\Delta\eta$ and low $p_T$**

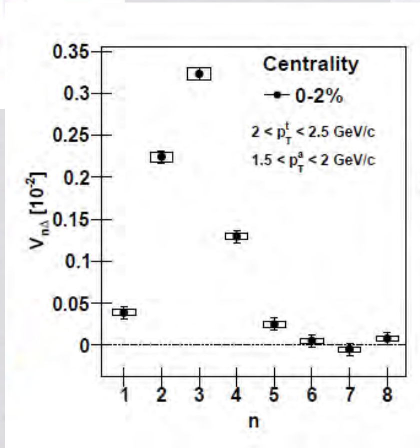
arXiv:1109.2501

# WMAP vs. Heavy Ion Collisions





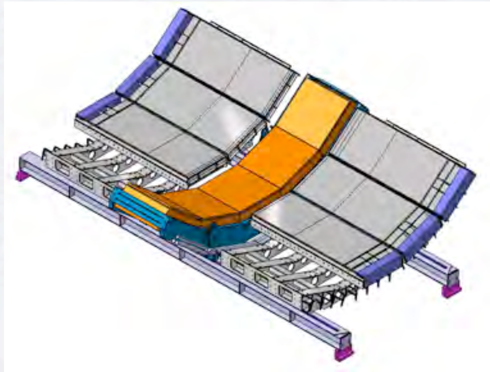




**WMAP**

Cosmological parameters

**Heavy ion collisions**

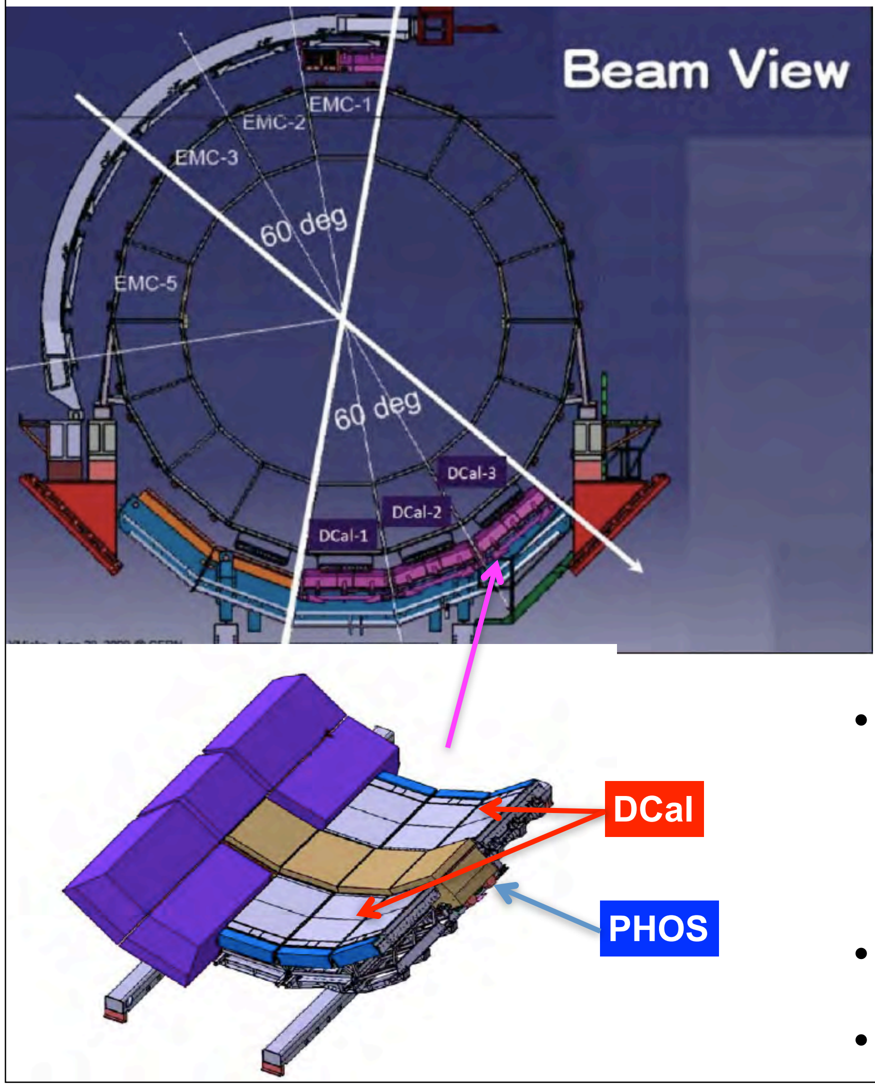
initial condition, QGP properties (e.g. eta/s)



# 3. ALICE-DCAL

From view point of Italy-Japan collaboration

# ALICE Dijet Calorimeter (DCal)



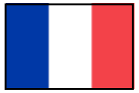

- Extension of the acceptance of EMCal .

  Lead-scintillator sampling type EMC with APD readout.
  - EMCal: $\Delta\phi$ = 110°
  - DCal: $\Delta\phi$ = 60° (on opposite side of EMCal→good uniformity, less sys. uncertainty)
  - $\Delta\eta$ = 0.7 for both EMCal and DCal + PHOS
  - Energy resolution: ~10%/√E
- Allow back-to-back hadron-jet, di-jet measurements in ALICE, with R = 0.4 jet cone radius, up to $p_T$ ~ 150 GeV/c.
- Enhance jet, $\gamma$ trigger capability.
- Full energy scale for $\gamma$: 250 GeV.

# ALICE-DCal Collaboration

China
Huazhong Normal University (CCNU), Wuhan

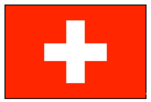
Finland
University of Jyvaskyla



France
LPSC Grenoble, Subatech Nantes, IPHC Strasbourg

Italy
INFN Catania (Armando Palmeri, Angela Badala), LNF Frascati (Alessandra Fantoni)

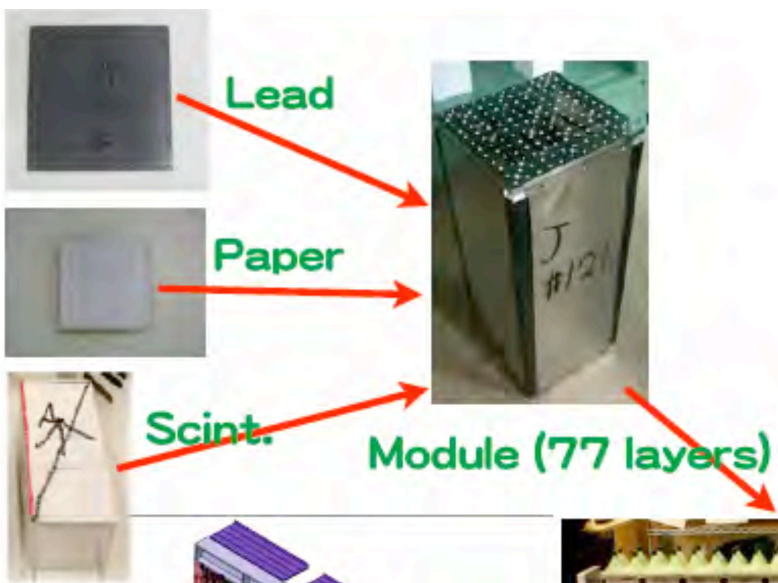
Japan
Hiroshima University, University of Tokyo, University of Tsukuba

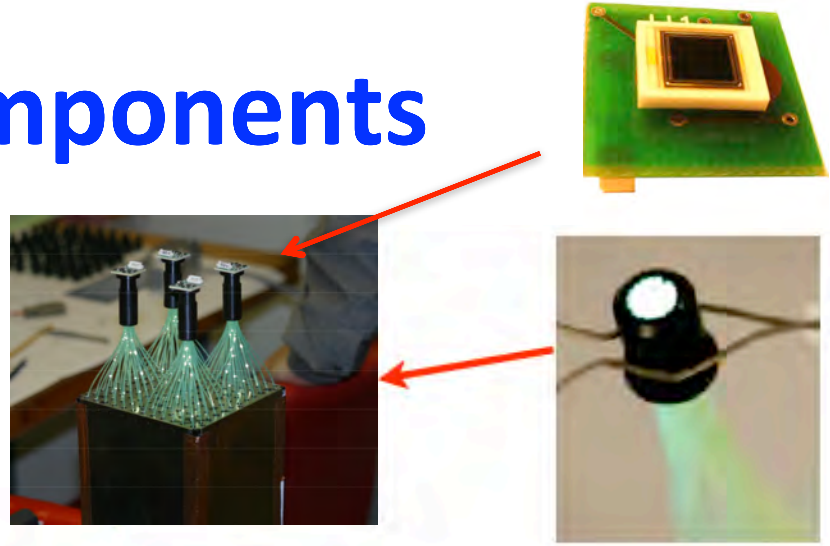


Switzerland
CERN

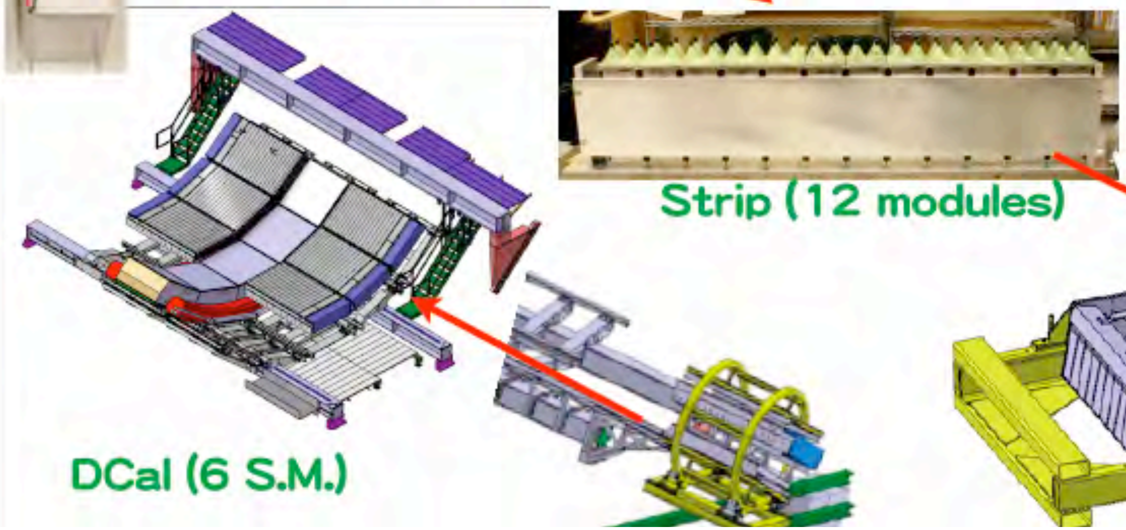
USA
Lawrence Berkeley National Laboratory, Wayne State University, University of Houston, University of Tennessee, Lawrence Livermore National Laboratory, Yale University, Oak Ridge National Laboratory, Creighton University, Cal Poly San Luis Obispo, Purdue University

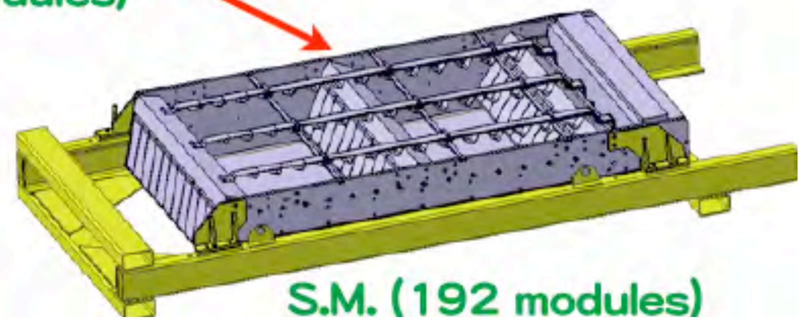
# DCal components



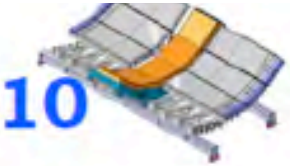




| Quantity | Value |
|---|---|
| Tower Size (at $\eta$=0) | ~6.0 × ~6.0 × 24.6 cm$^3$ (active) |
| Tower Size | $\Delta\phi$ x $\Delta\eta$ = 0.0143 x 0.0143 |
| Sampling Ratio | 1.44 mm Pb / 1.76 mm Scintillator |
| Number of Layers | 77 |
| Effective Radiation Length $X_0$ | 12.3 mm |
| Effective Moliere Radius $R_M$ | 3.20 cm |
| Effective Density | 5.68 g/cm$^3$ |
| Sampling Fraction | 10.5 |
| Number of Radiation Lengths | 20.1 |



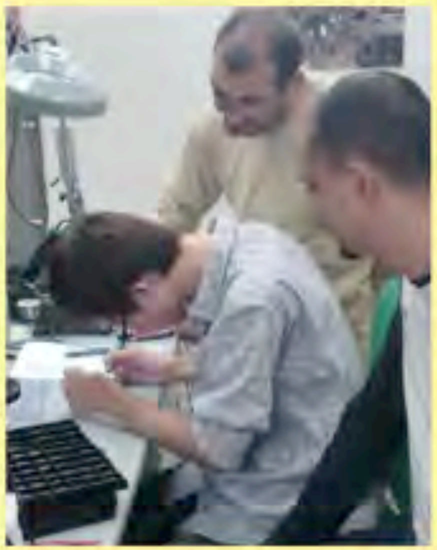



# Tsukuba team at Catania in Oct.-Dec,2010

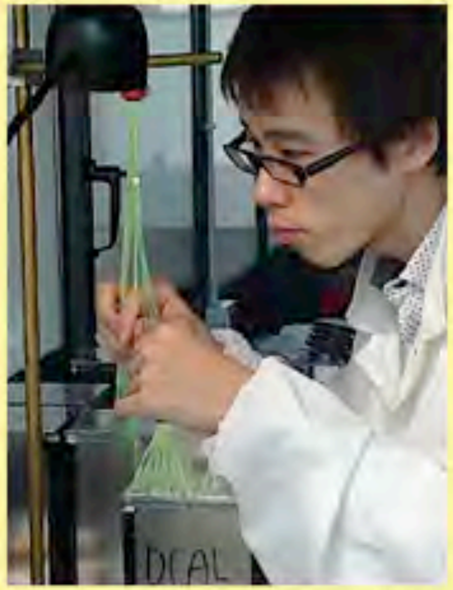


- Module Assembly & APD assembly/calibration at Catania
  - Assembly of modules (96 modules, 1/2 S.M.)
  - APD assembly & calibration (2400)

Hiroki & Maya at Catania fir APD & module assembly

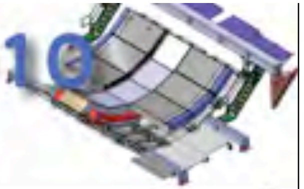


Maya Shimura



Hiroki Yokoyama

# Tsukuba team at Catania in Oct.-Dec.2010

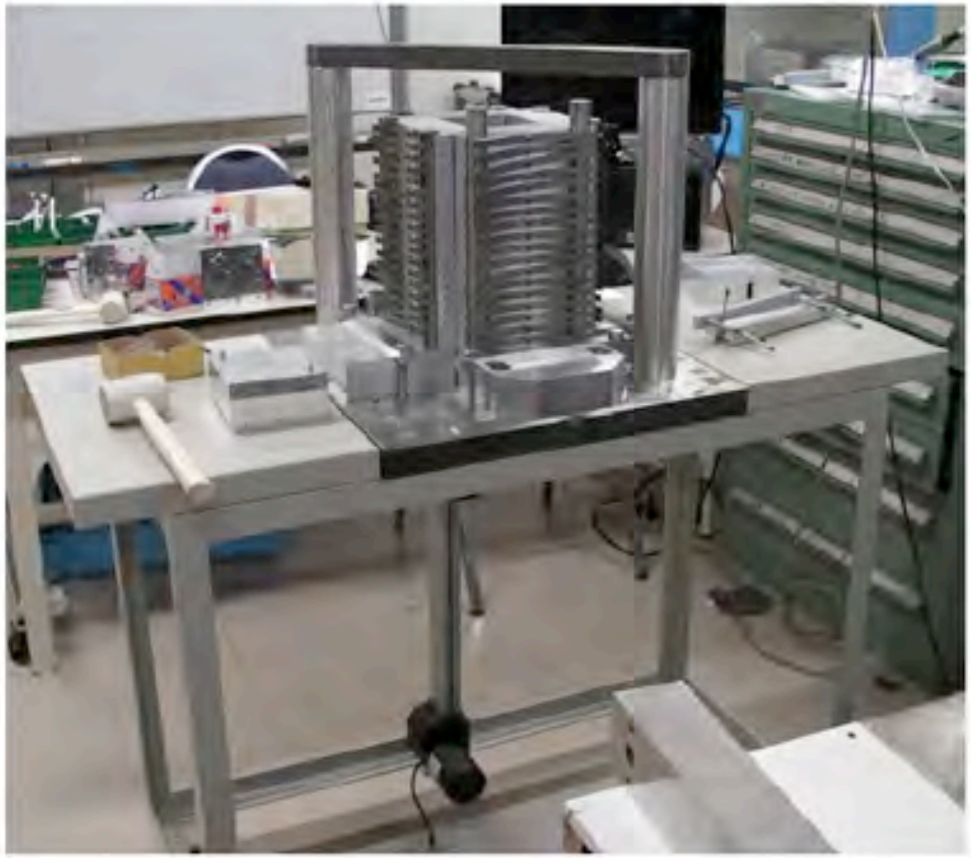


- ✓Completed 96 modules production with Catania's help.
- ✓APD assembly/calibration for 2,400 APDs with Angela B.'s team

Hiroki & Maya at Catania

Strip assembly also done at Catania, then ship to France.

# Francesco N. & Maurizio S. from Catania, visited Tsukuba (Nov. 11-18, 2010)

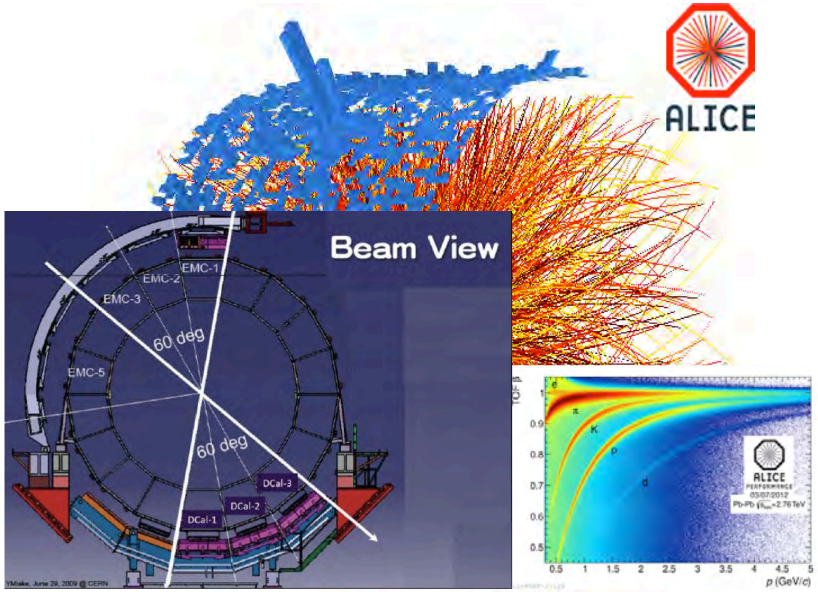


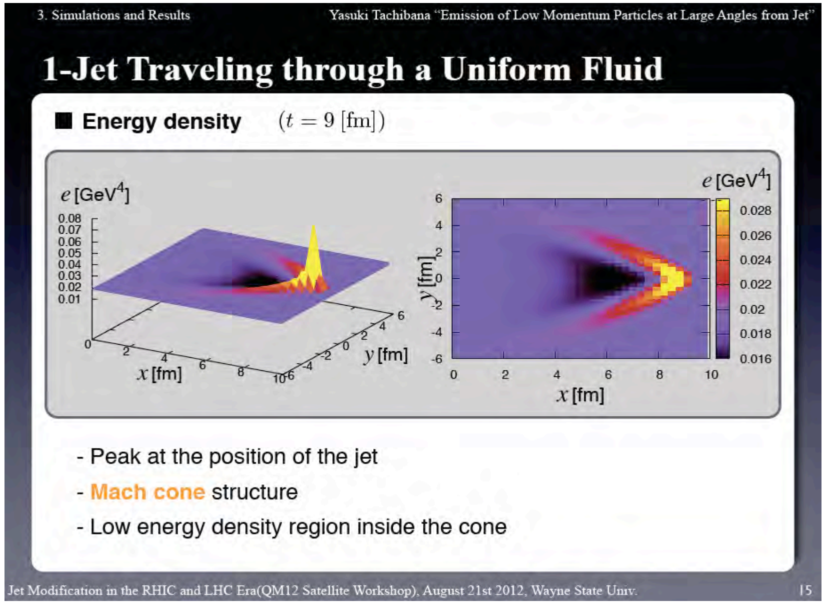
- Francesco & Maurizio visited Tsukuba in Nov. 9-17, 2010
- Second assemble station becomes operational

## All modules are in Subatech / Grenoble, will install in LHC long shutdown (2013-2014), physics in 2015.

March 3, 2011

# Perspective of physics with DCal: Medium response with jets




3+1 hydro + jet (Tachibana, Hirano) QM2012

- Excellent hadron PID (0.15 – 20 GeV/c), suitable detector to measure the medium response with PID, jet ID and trigger by EMCal.
- Bulk properties (PID spectra, $v_2$, HBT, etc.) with a large jet energy imbalance.
- Key to access $c_s$, EOS?

# SUMMARY

- Rich harvest of LHC new HI data by the complimentary measurements by ALICE, ATLAS, CMS.
- Hottest, small eta/s, strongly coupled QGP produced at LHC heavy ion collisions.
- A lot of progress towards the precession measurements of QGP properties for next decade.

# BACK UP SLIDES

# Jet suppression

arXiv:1208.1967 [hep-ex] Submitted to Phys. Lett.B

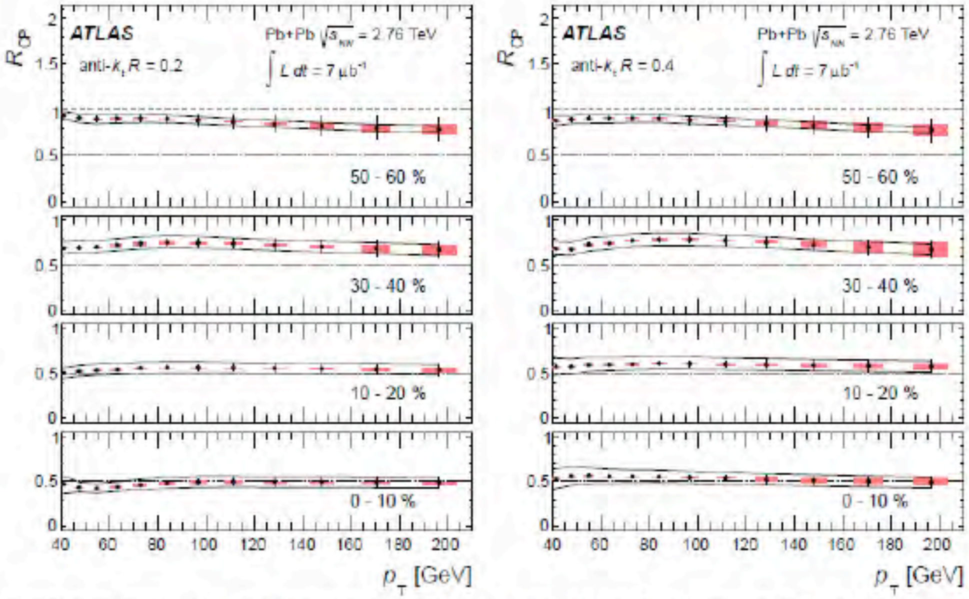
$$R_{cp} = \frac{\frac{1}{N_{coll}^{cent}} E \frac{d^3N^{cent}}{dp^3}}{\frac{1}{N_{coll}^{periph}} E \frac{d^3N^{periph}}{dp^3}}$$

peripheral reference: 60-80%

## First LHC result on jet suppression

**Unfolded $p_T$ spectra**

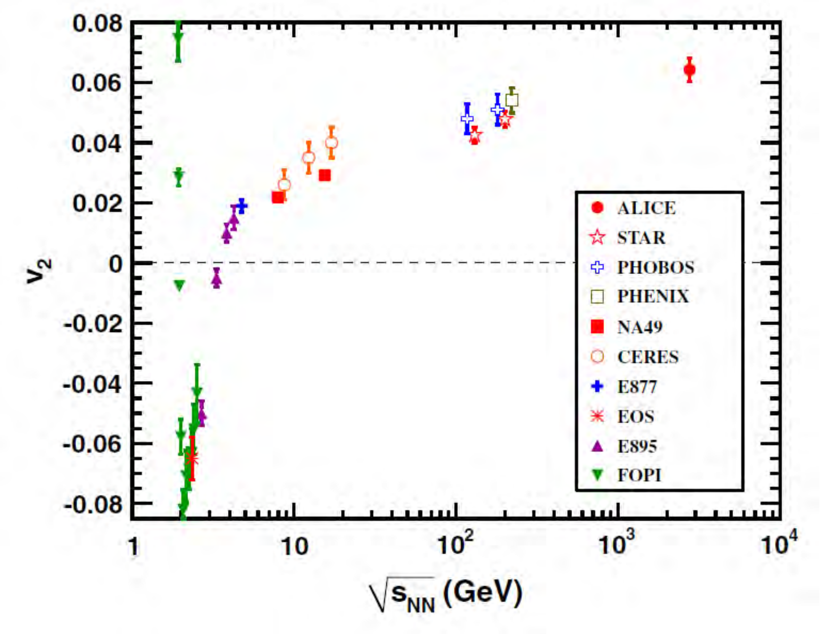
**For jet sizes R=0.2, 0.3, 0.4 and 0.5**

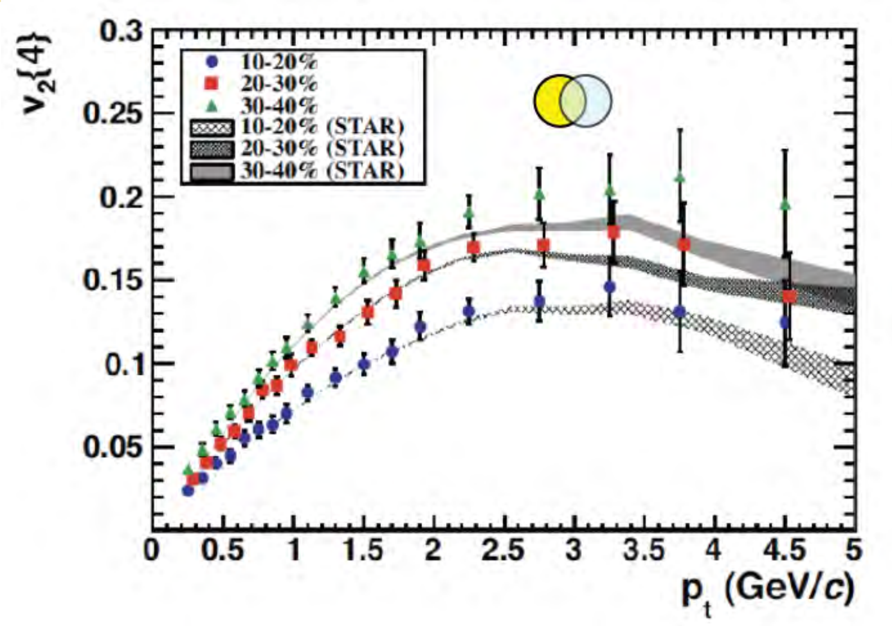
**R=0.2**  **R=0.4**



- A factor of ~2 suppression in 0-10% most central collisions
- Suppression independent of jet $p_T$

# Very similar $v_2$ at RHIC and LHC

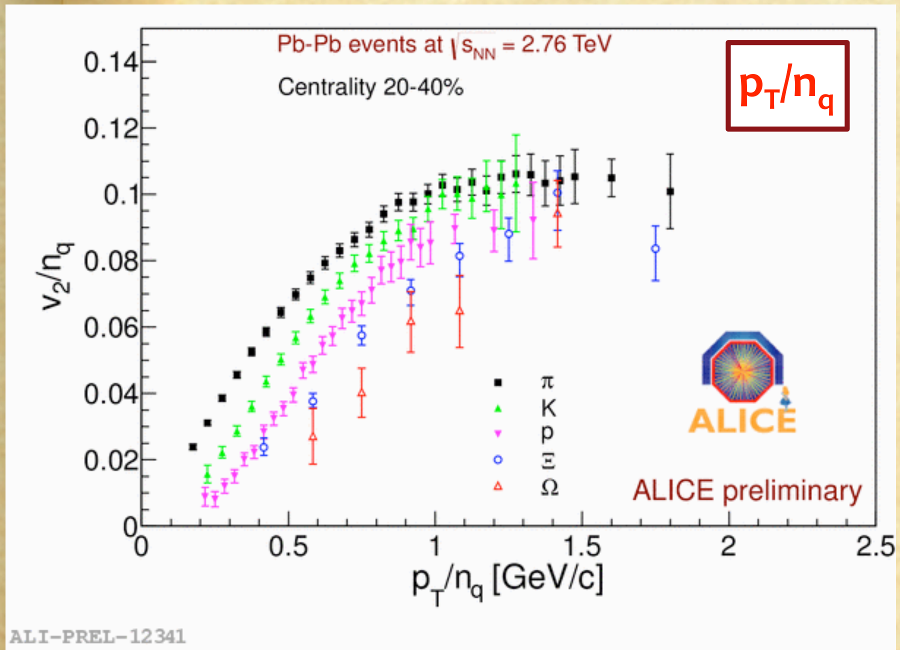


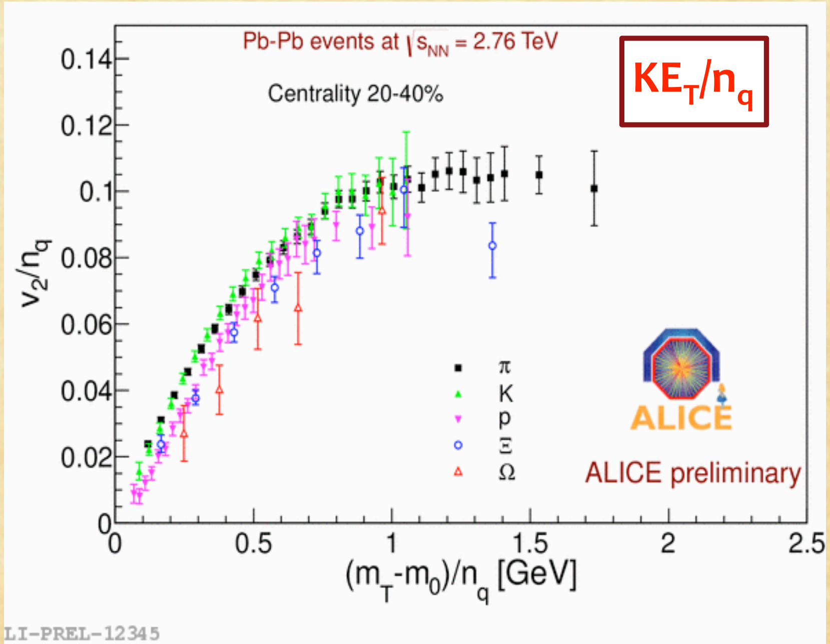




PRL 105 (2010) 252302

- At LHC, $p_T$ integrated $v_2$ increases by 30% compared to RHIC data at $\sqrt{s_{NN}}$=200 GeV.
- $v_2$ vs. $p_T$ does not change within uncertainties between $\sqrt{s_{NN}}$=200 GeV and 2.76 TeV

# Quark number scaling of $v_2$




- Just simple $p_T/n_q$ scaling does not work at LHC.
- Scaling works better as a function of transverse energy, but not perfect.