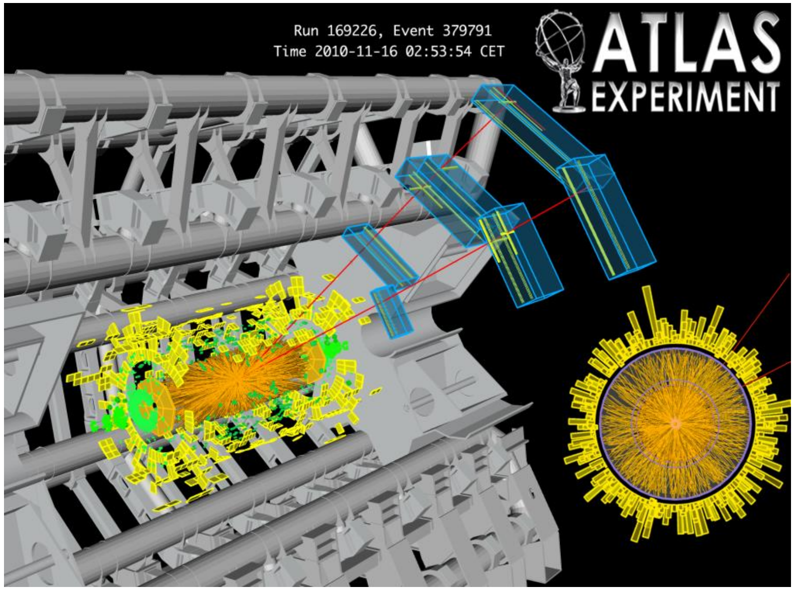
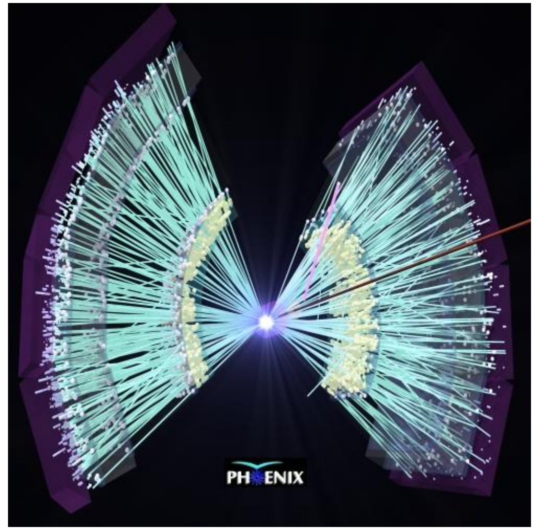
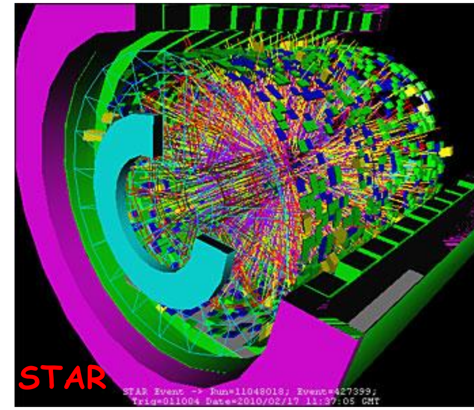
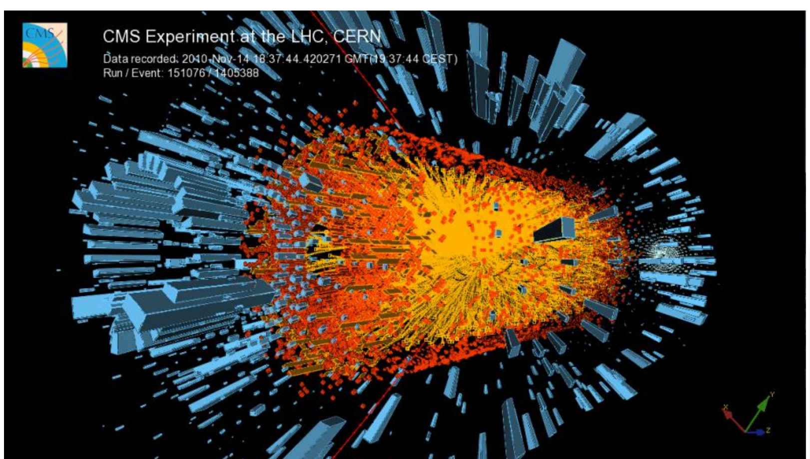
R. Nania- INFN Bologna
HASCO 2014



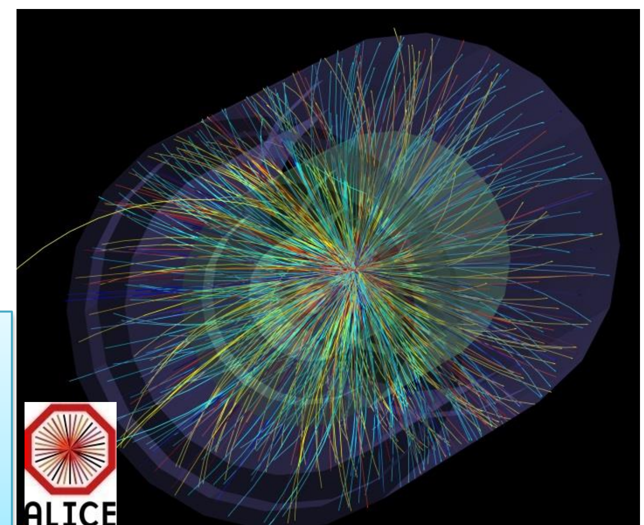



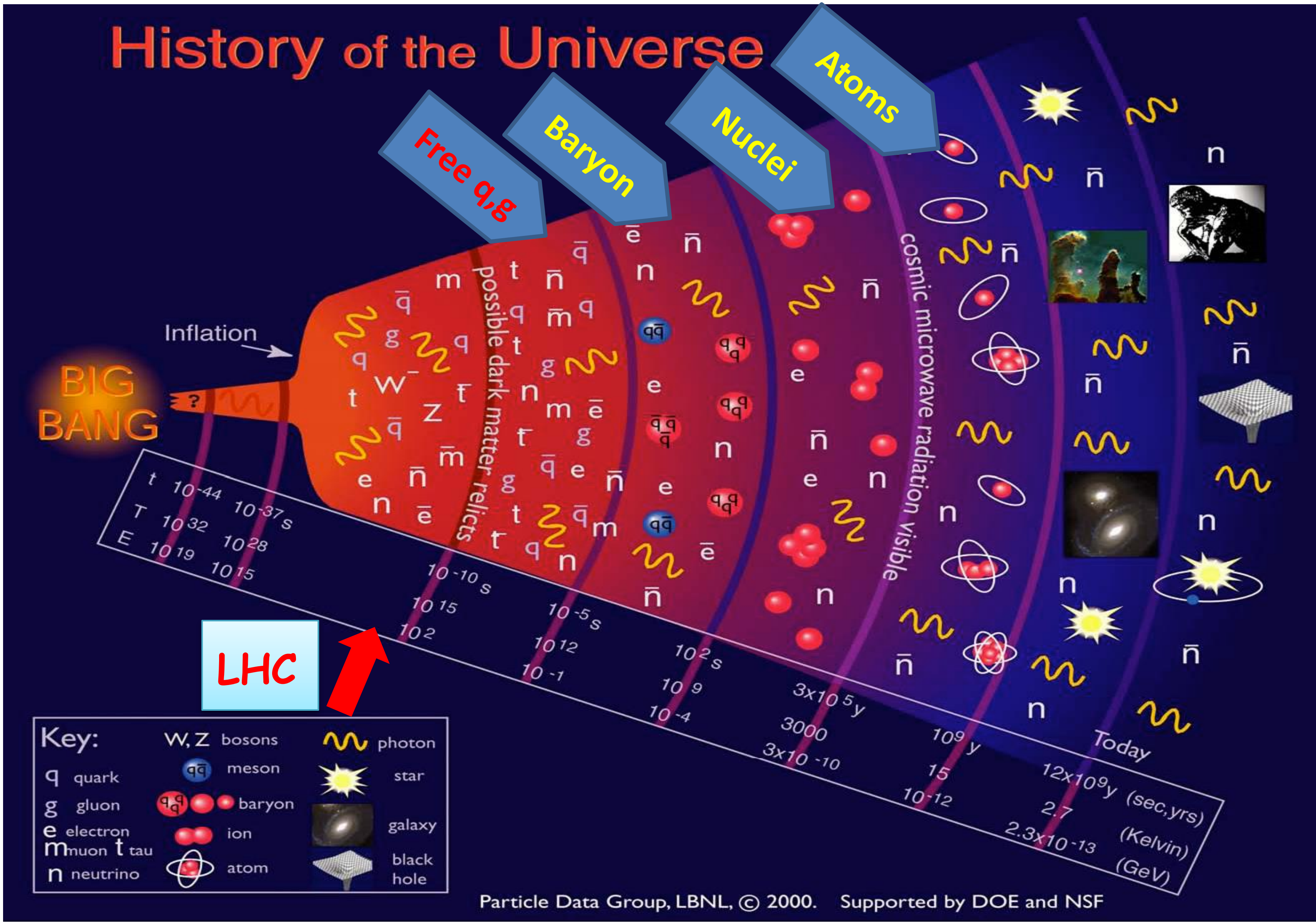




# Heavy Ions physics
# uncovering the quark-gluon plasma properties.

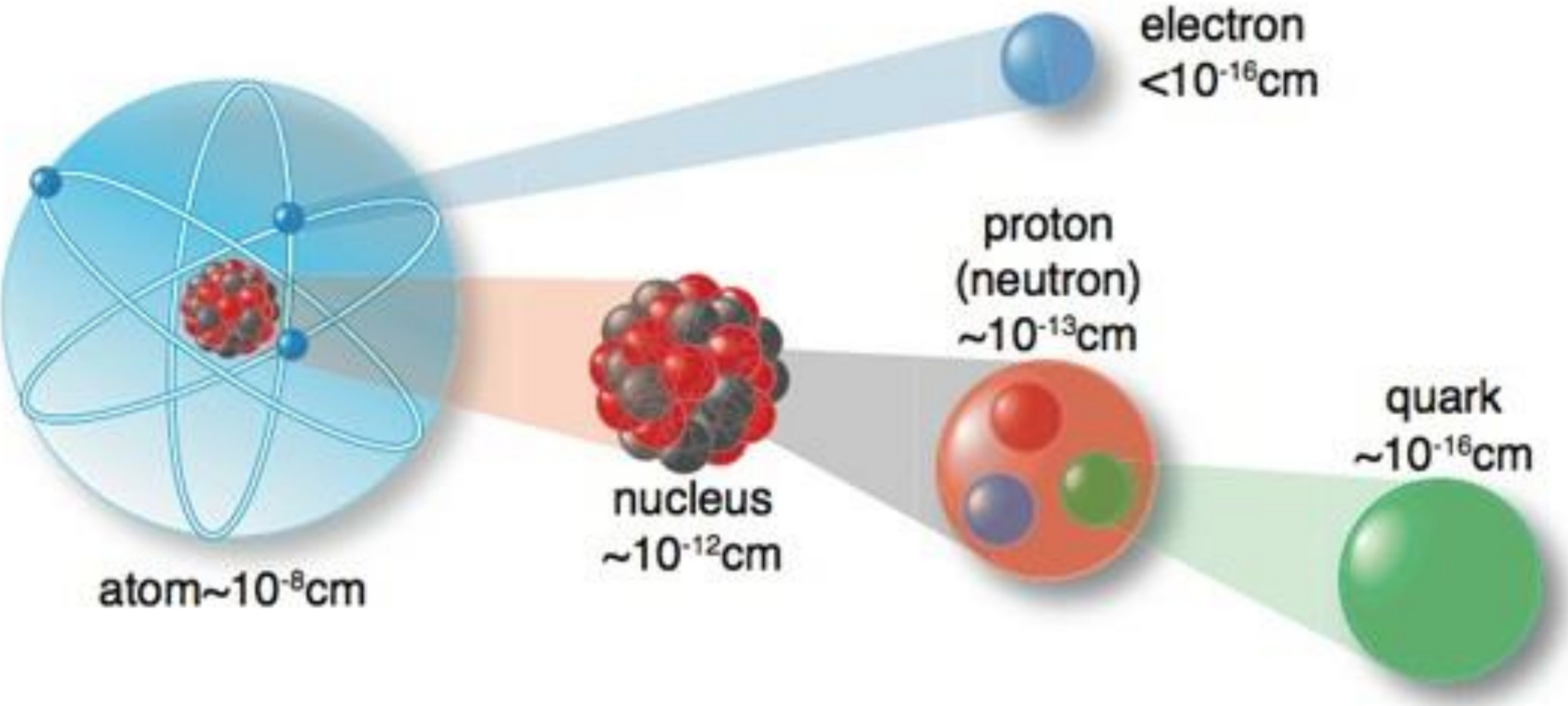



Student help
Murphy Steven
Oltmanns Jens
Sabatini Paolo
Sáez Blázquez Rocío

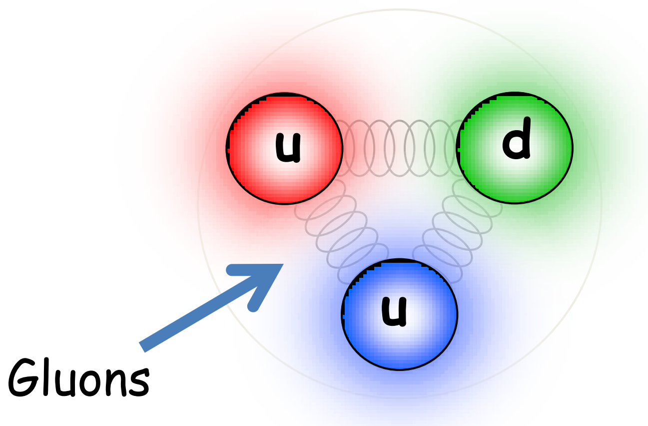



History of the Universe
Free q,g
Baryon
Nuclei
Atoms
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
LHC
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

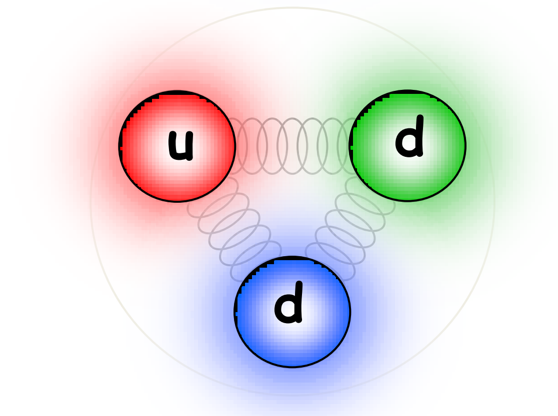
# How we understand matter



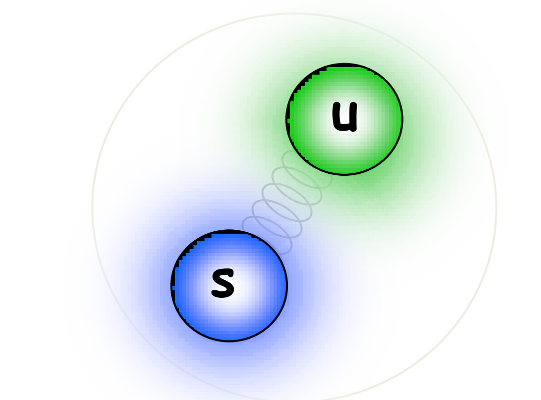
# Few examples of quark content




Proton =
uud (+2/3, +2/3, -1/3)

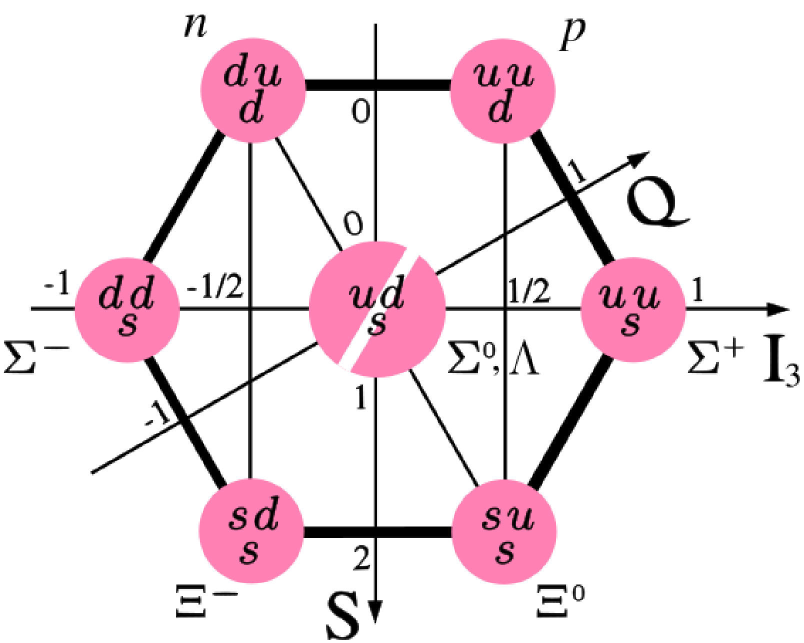


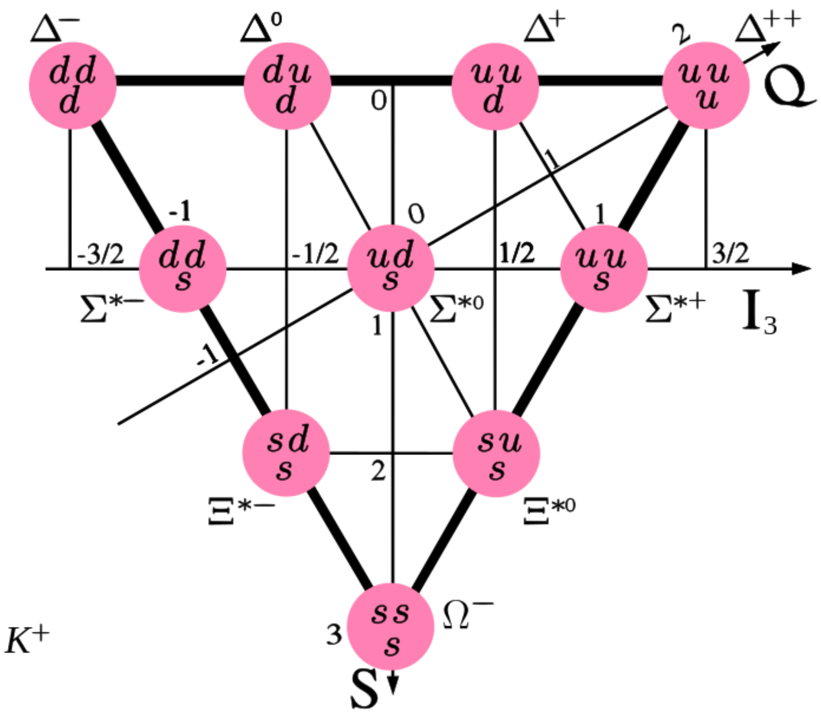

Neutron =
udd (+2/3, -1/3, -1/3)

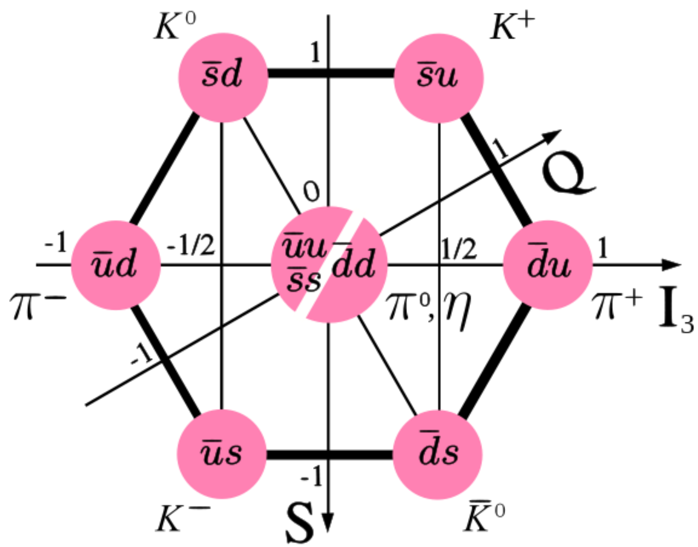



Particle K =
u anti-s (+2/3, +1/3)

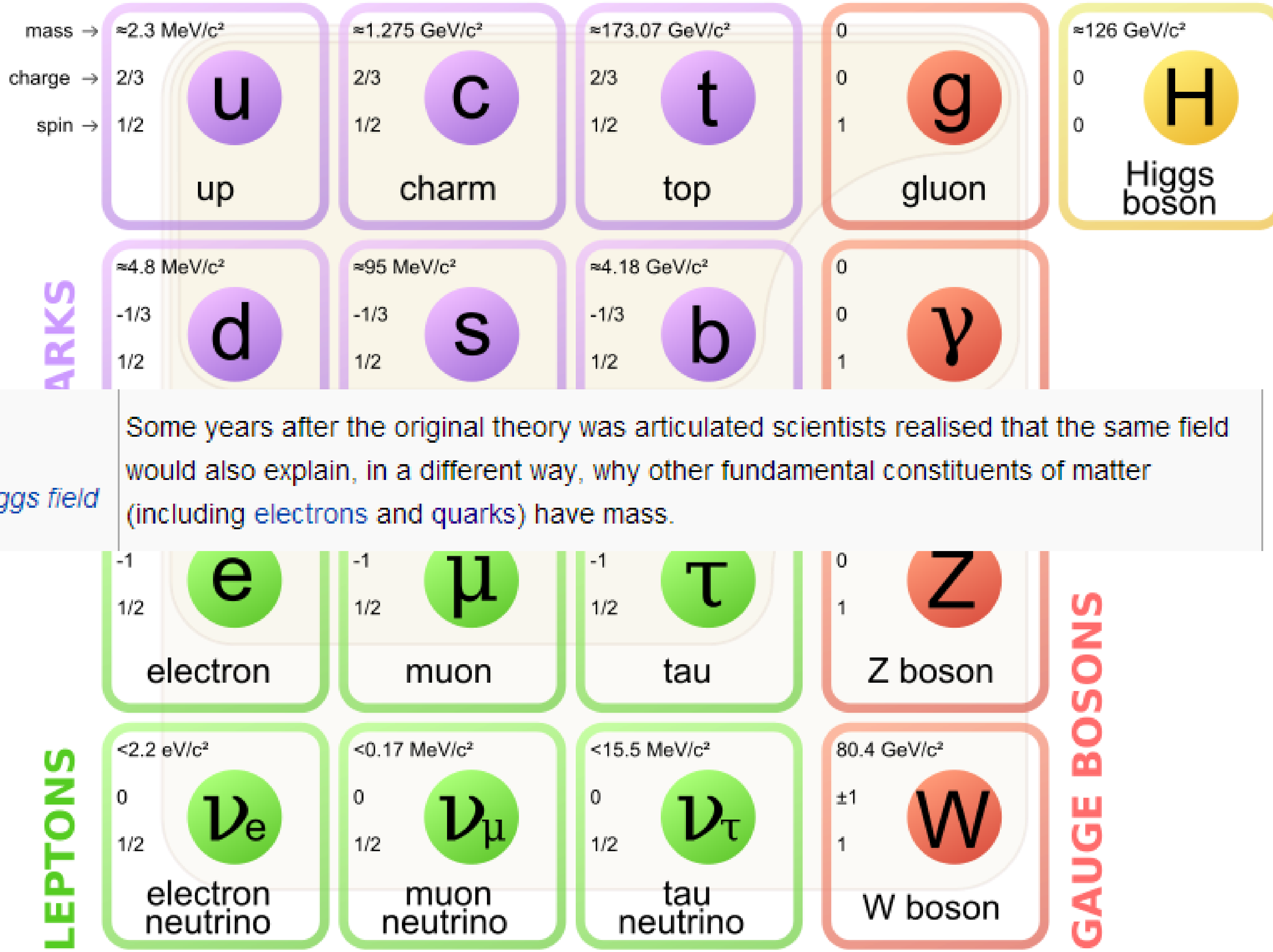
# More examples of quark content…



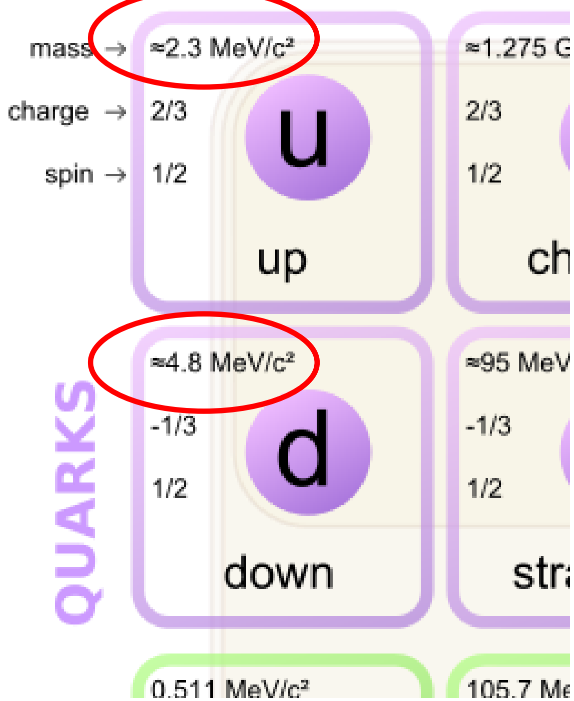



# THE STANDARD MODEL




| | |
|---|---|
| *Higgs field* | Some years after the original theory was articulated scientists realised that the same field would also explain, in a different way, why other fundamental constituents of matter (including electrons and quarks) have mass. |

## But …..




Proton = uud     Neutron = udd

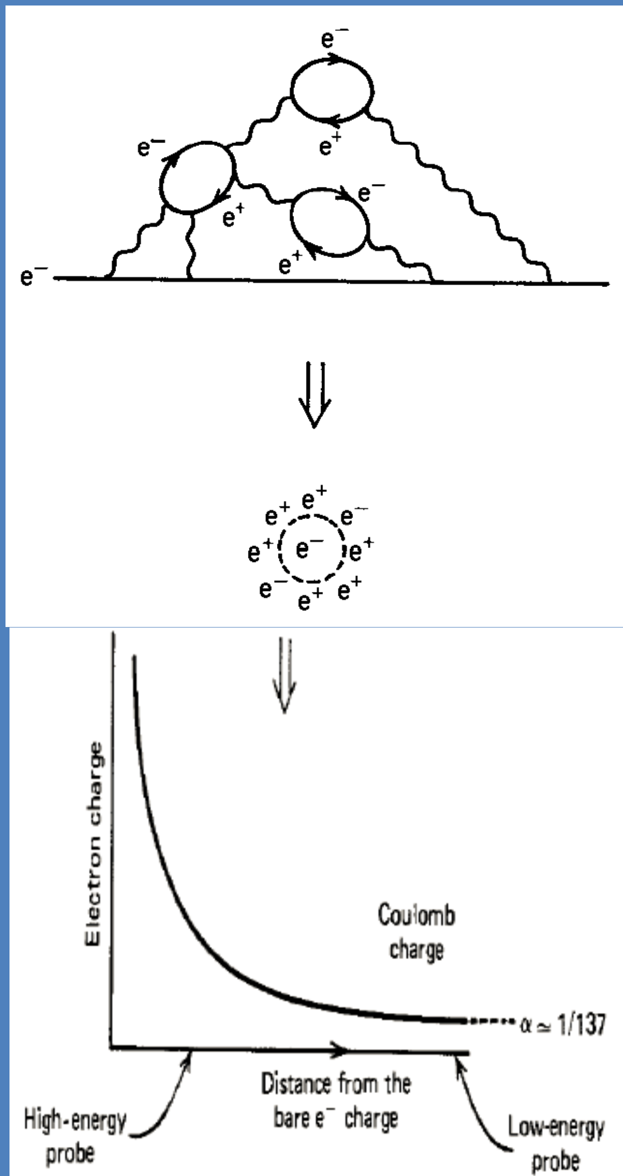
$m_p$ =2.3+2.3+4.8 MeV/c² ≠ 938 MeV/c²

$m_n$ =2.3+4,8+4.8 MeV/c² ≠ 939 MeV/c²

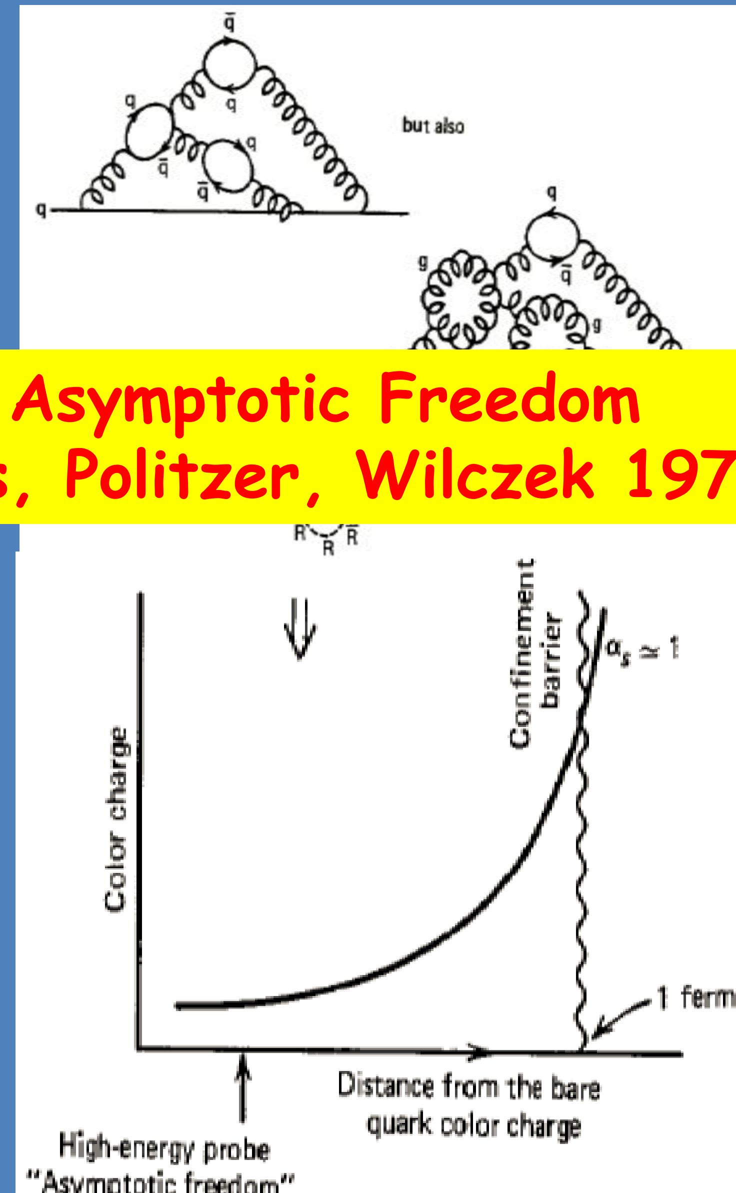
≈99% of the mass of the proton/neutron is related to the confinement energy !!!

# Running coupling constants

## Electromagnetic force QED




## Strong force QCD

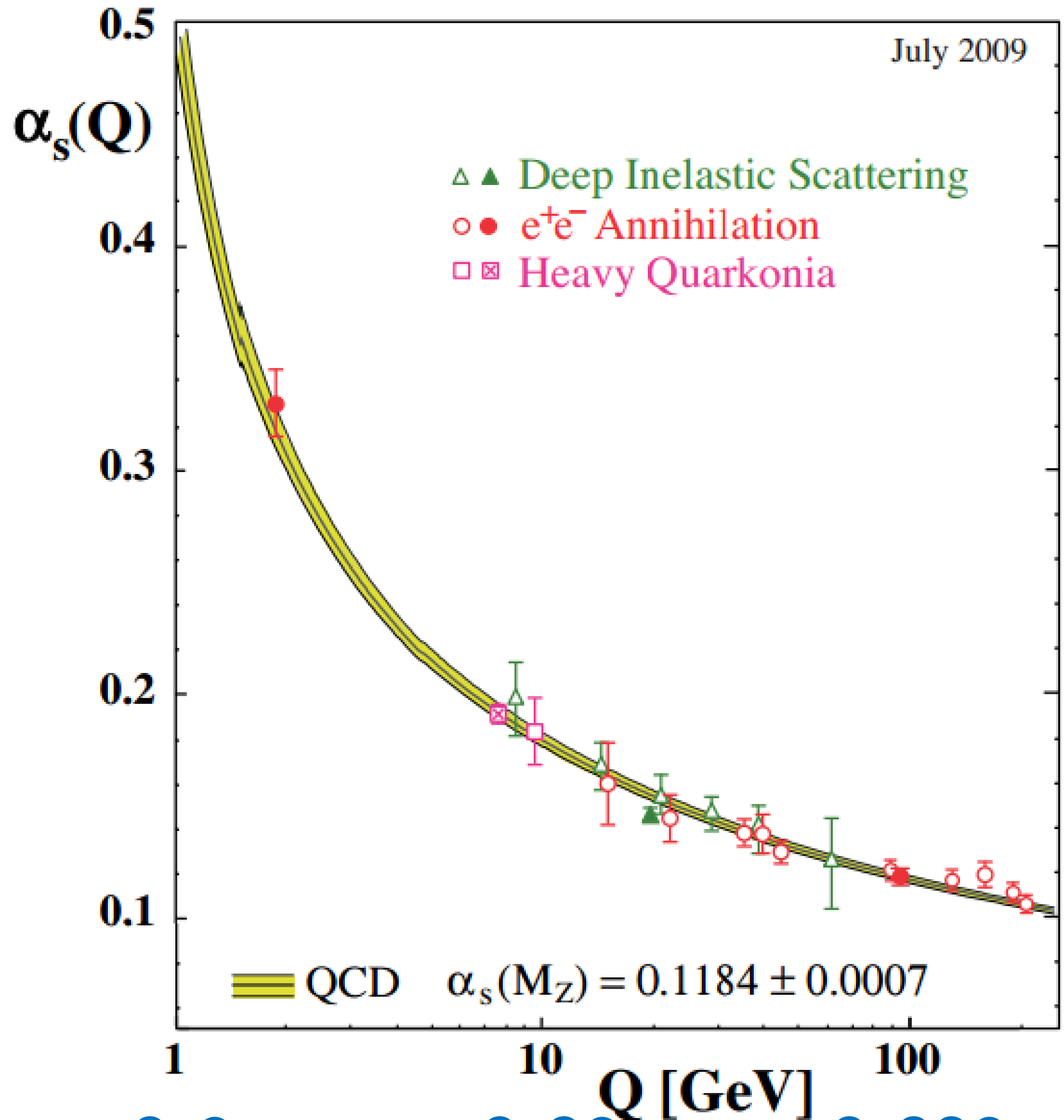



**QCD Asymptotic Freedom**
**Gross, Politzer, Wilczek 1973**

# QCD $\alpha_s$ coupling constants

$\hbar$ c ≈ 200 Mev fm

in "Natural units"
1 fm ≈ 1/ (200 MeV)

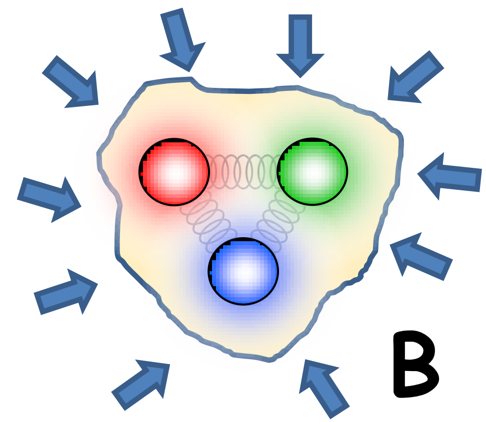



fm 0,2 0,02 0,002

# The MIT Bag model (≈ '70)
# First theorethical approach to confinement

Confinement =

bag pressure compensating quark kinetic energy




$$E = potential + kinetic =$$

$$B\,\frac{4}{3}\pi R^3 + \frac{2.04N}{R}(\hbar c)$$

$$\approx \frac{h}{\lambda} \quad for\; m_q \approx 0$$

$$\frac{dE}{dR} = -\,\frac{2.04N}{R^2}\hbar c + 4\pi R^2 B = 0$$

$$B = \frac{2.04N}{4\pi}\frac{1}{R^4}hc = 1.2\,\frac{\hbar c}{fm^4} = 1.2\,\frac{200\;MeV}{fm^3} = 240\;MeV/fm^3$$

$$\frac{\hbar c}{1fm} = 200\;MeV \qquad N = 3 \qquad r = 0.8\;fm$$

# Improving Tc evaluation
## (Stefan/Boltzmann limit)

- System of n objects ( hadrons or q and g) thermalized
- Massless and non interacting
- Zero baryonic number

**Energy density** $$\varepsilon\,(T) = \frac{\pi^2}{30} T^4$$

**Pressure** $$P\,(T) = \frac{1}{3}\varepsilon(T) = \frac{\pi^2}{90} T^4$$

**Per degree of freedom !**

Hadron gas

Ndf = 3 ($\pi^+\pi^0\pi^-$ )

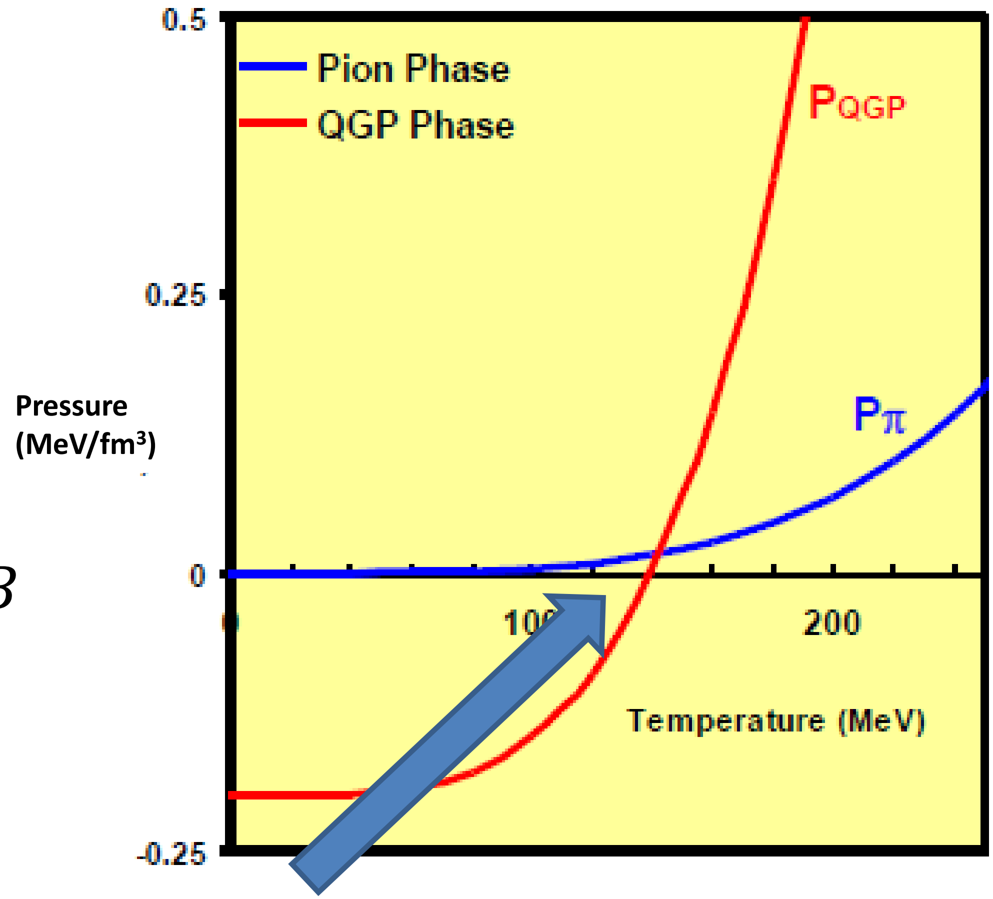
Quark gluon gas ( for 2 flavours)

Gluons : $2_s$x$8_c$ = 16
2Quarks : (7/8) x( $2_s$ x $2_f$ x $3_c$ + anti-q) = 21
Ndf = 37 *( > factor 10 w.r.t. hadron gas)*

# Deconfinement at high temperature

$$P_{had}(T) = 3\,\frac{\pi^2}{90}T^4$$

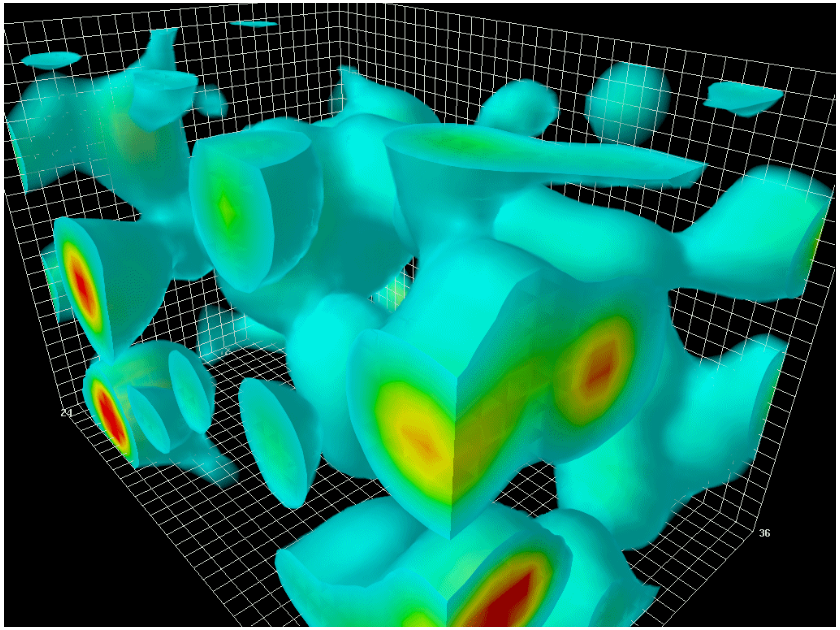
$$P_{QGP}(T) = 37\,\frac{\pi^2}{90}T^4 - B$$

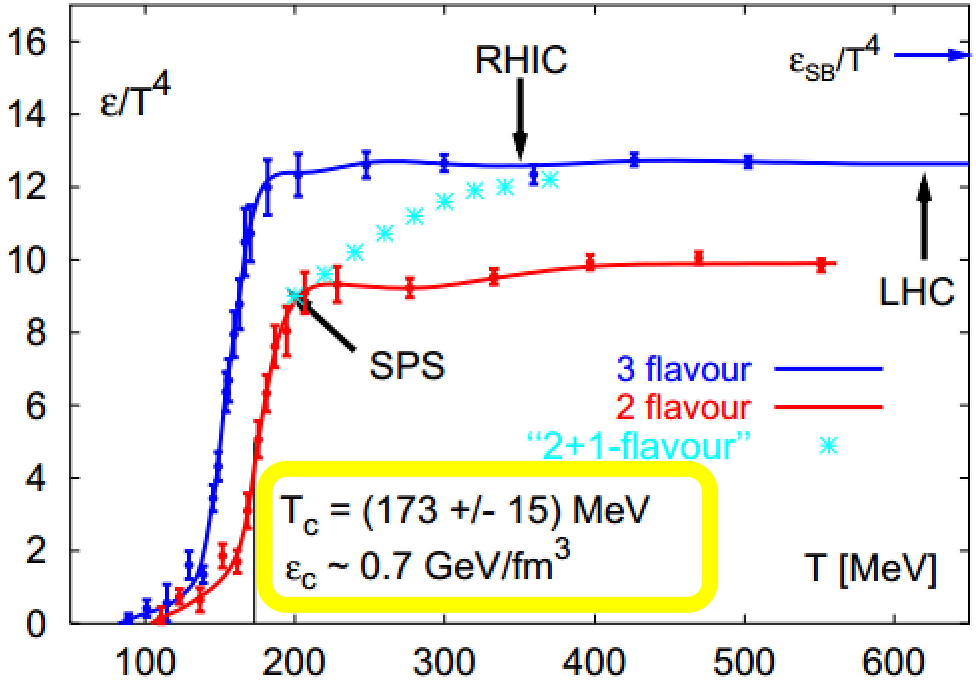



**QGP phase transition**

**at T ≈145 MeV**

# Energy density in lattice QCD: an even more precise estimate of Tc






$\varepsilon\,(T) = 46\,\frac{\pi^2}{30}T^4$

for 3 flavors

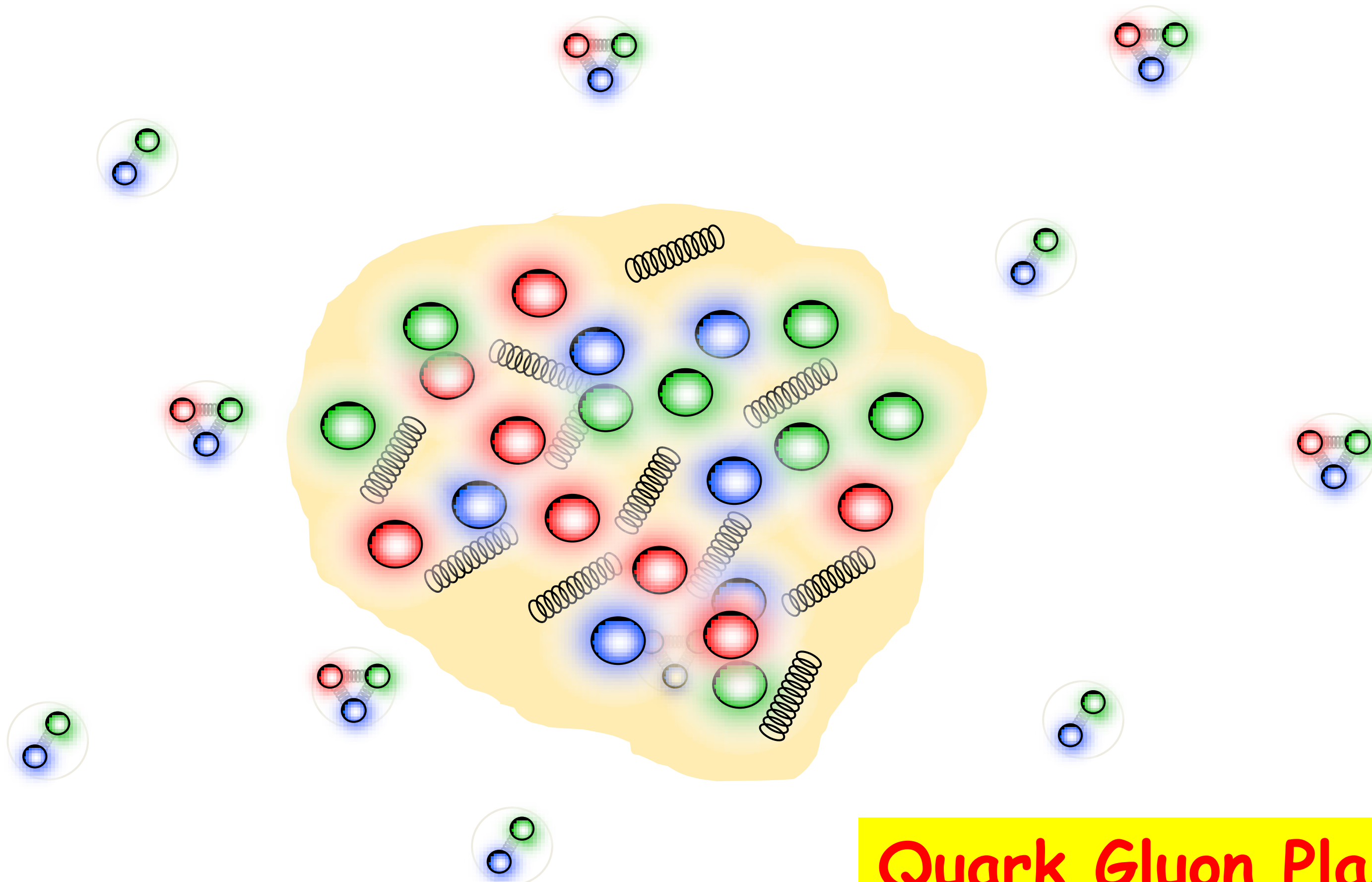
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/QCDvacuum/

NB: includes effects of masses and interactions

Light quarks $m_q$ /T= 0.4

2+1 = 2 light quarks + 1 massive $m_q$/T= 1

# Quarks and gluons are confined inside hadrons, but what happens if they collapse in a wide space region ?



**Quark Gluon Plasma**

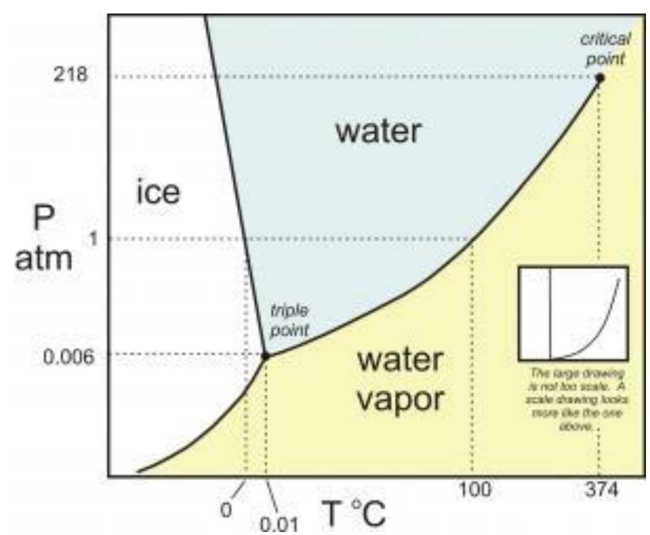
Possible answers

1. Do not care , nothing changes
2. Do care, new phenomena may appear






Temperature decreases



**Energy-temperature**

$E = K_B T$ $1/K_B = 1.16\ 10^4$ K/eV

LHC $E = 5$ TeV $= 5\ 10^{12}$ eV

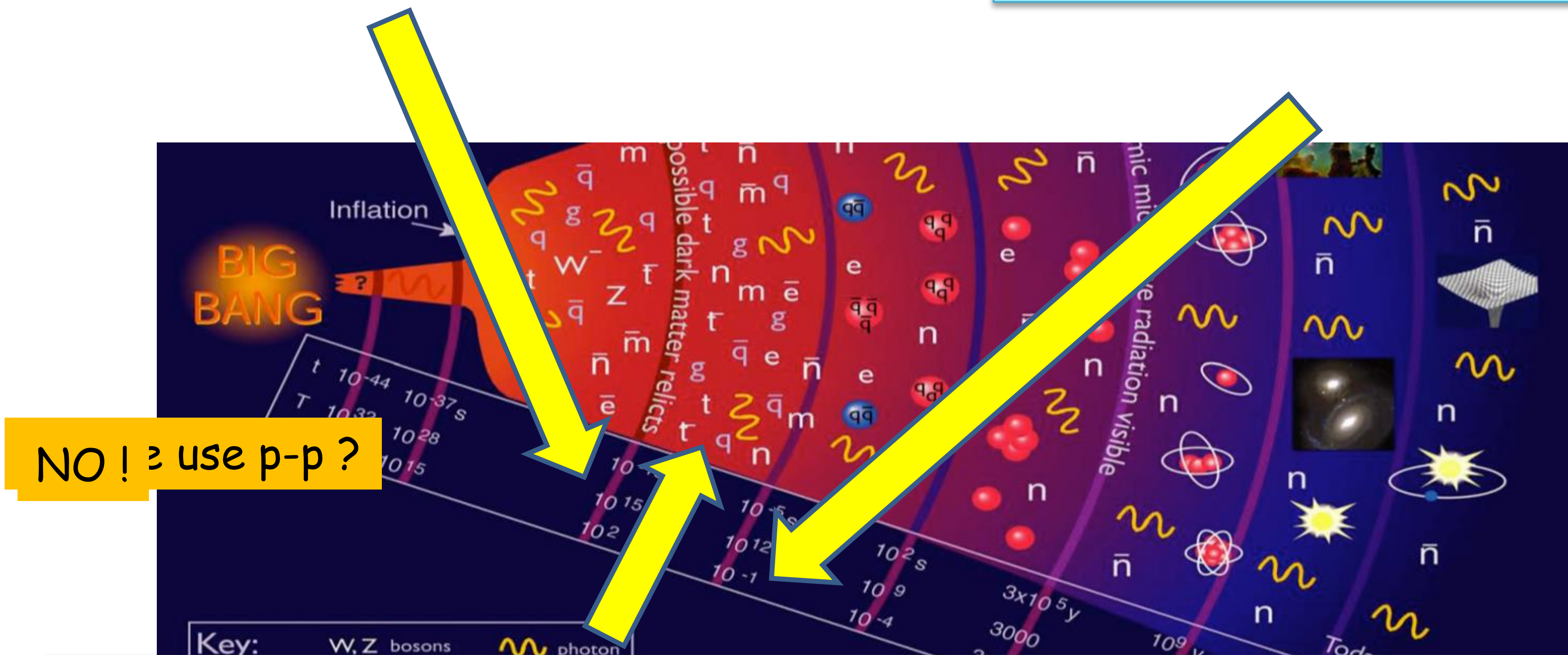
$T_{coll} = 5\ 10^{12}$ eV $\times$ $1.16\ 10^4$ K/eV $= 6.38\ 10^{16}$ K

**Energy-space**

Hadrons typically 1 fm = $10^{-15}$ m

$\hbar c \approx$ 200 MeV fm
in "Natural units"
1 fm = 1/ (200 MeV)

Energy scale hadron 200 MeV




**GOAL : probe the system at very high density and temperature**
1- system consists of many particles
2 – system in local equilibrium

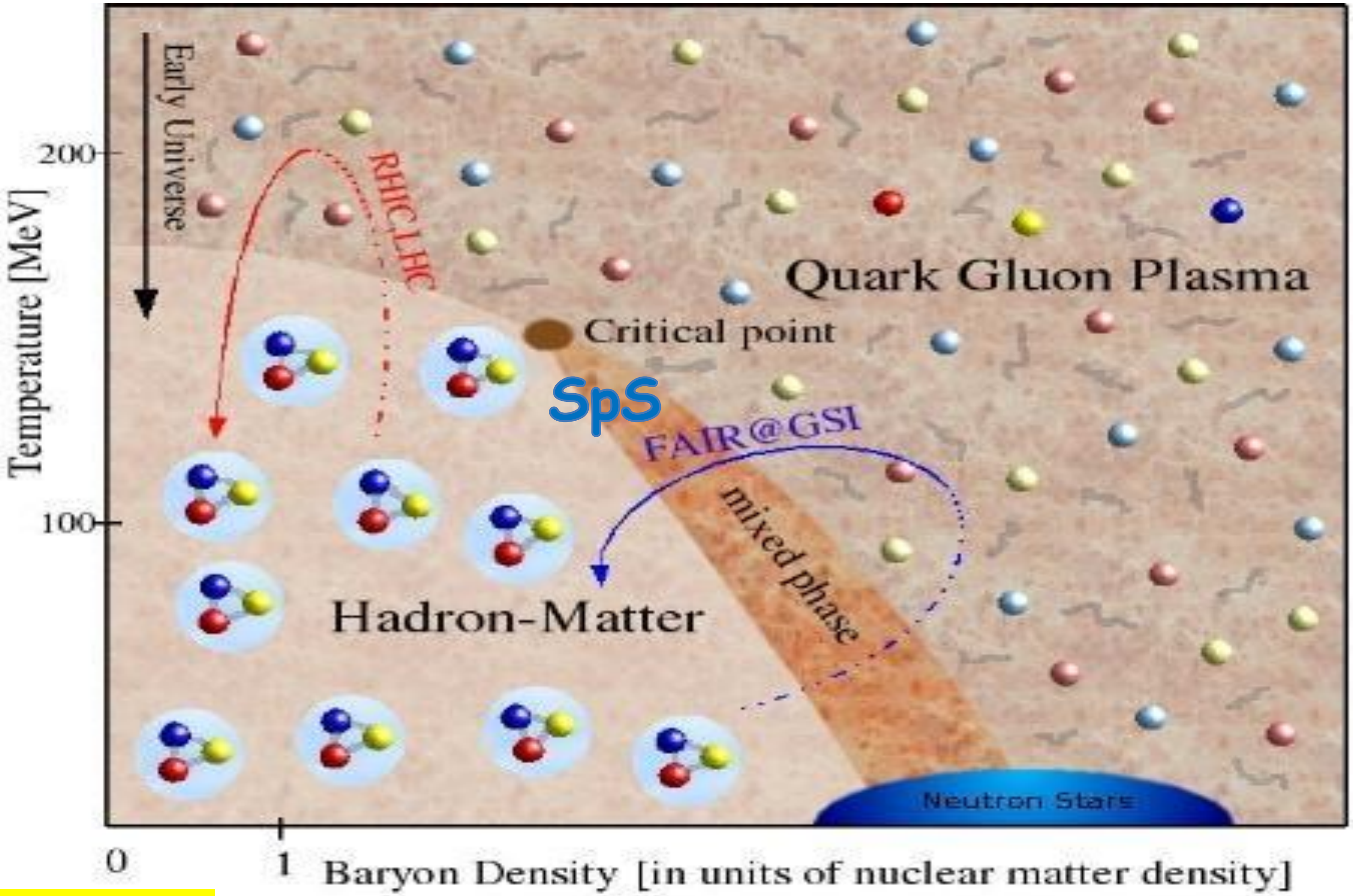
## How to study QGP in Heavy Ions Collisions
## ( low baryon densities and high temperatures)

The goal is to produce a matter with:

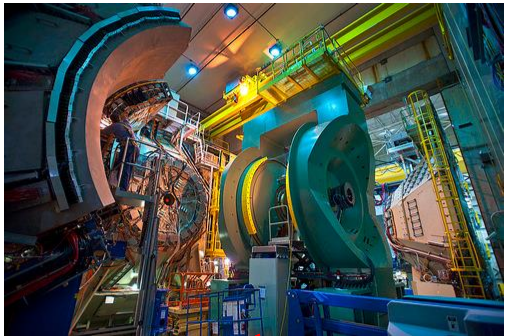
- Energy density >> 1 $GeV/fm^3$
- Lasting for > 1 fm/c
- In a volume much larger than a hadron

# Where to look for QGP : The Phase Diagram

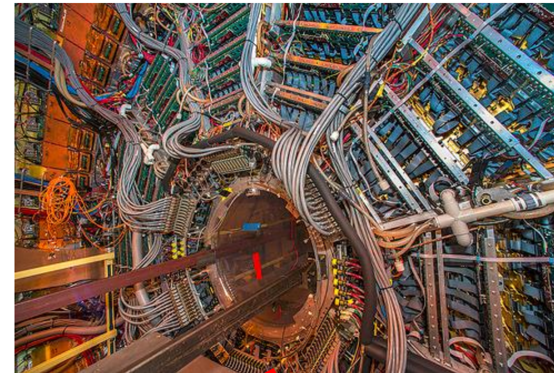
- high temperature and low baryon density (RHIC + LHC)
- Very high baryon density and low temperatures (neutron stars)
- Intermediate baryon densities and temperatures (SpS, Fair) -> Critical point



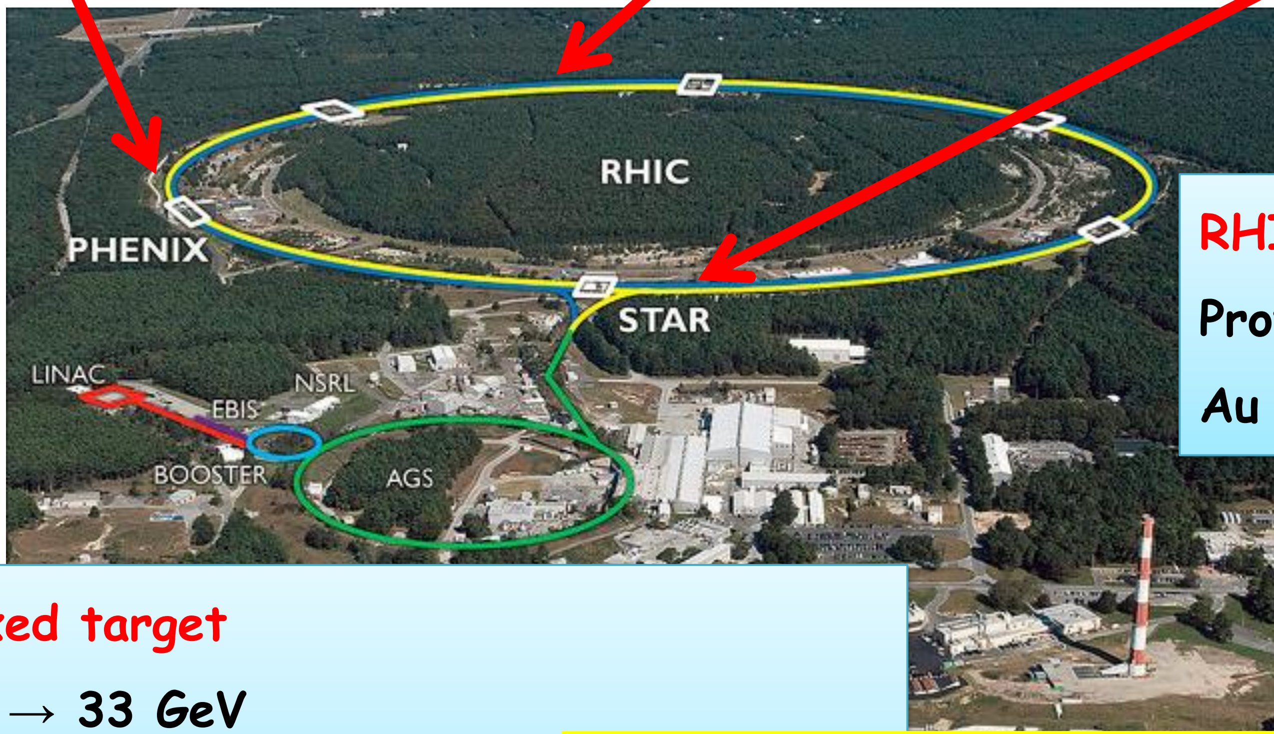

$n_p \approx n_{anti\text{-}p}$



PHENIX



STAR




**RHIC Collider**

Protons → 250 GeV

Au → 100 GeV/N

**AGS fixed target**

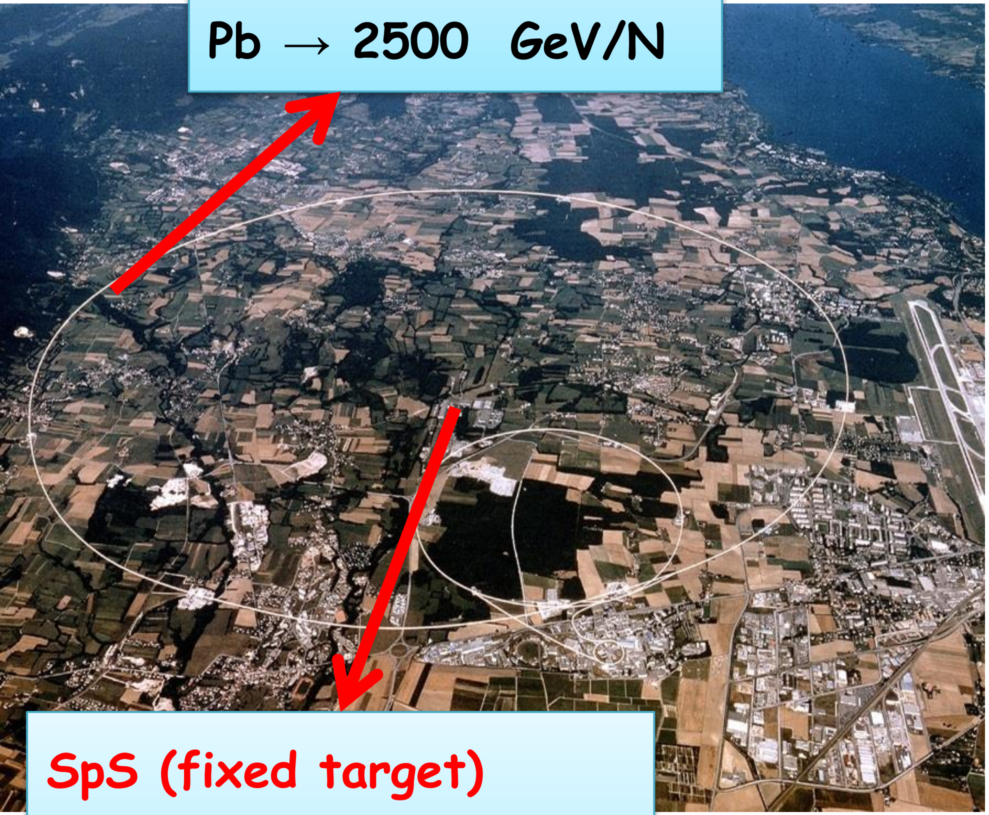
Protons → 33 GeV

Si, Au → 14,6 GeV/N

*NB: Nuclei energy scaled by Z/A w.r.t. protons*

# Brookhaven National Labs - USA

# CERN Large Hadron Collider



**LHC Collider**

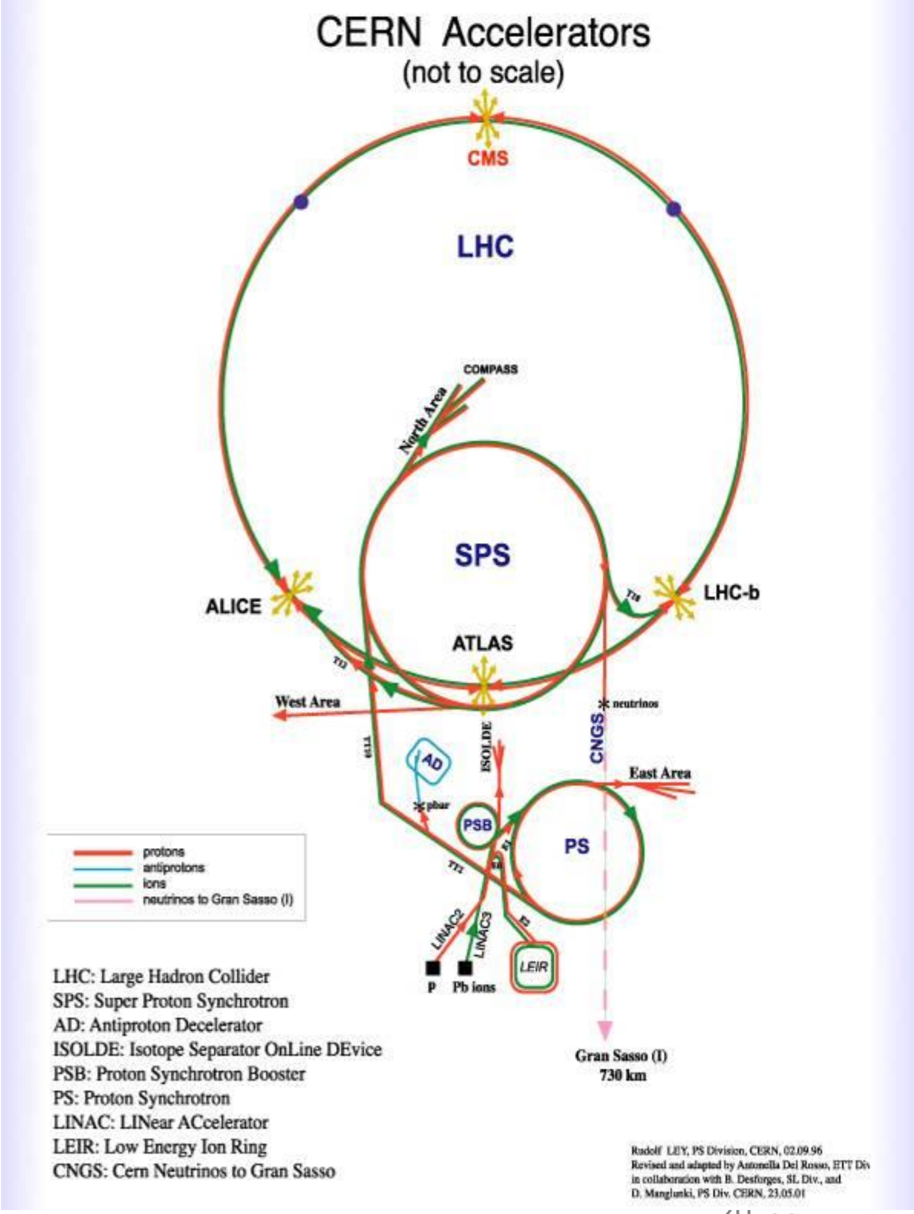
Protons → 7000 GeV

Pb → 2500 GeV/N

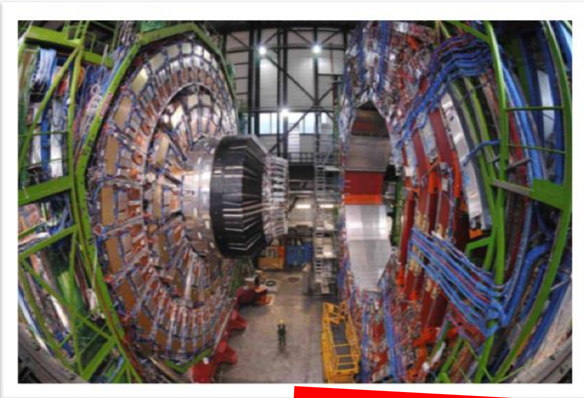
**SpS (fixed target)**

Protons → 450 GeV

O, S, Pb → 200 GeV/N



# CERN
# Large Hadron Collider

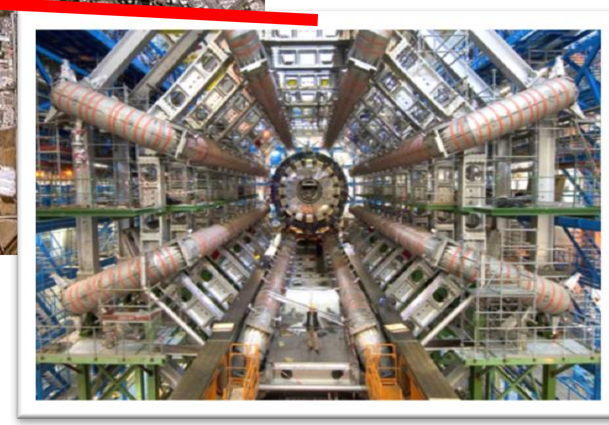


CMS

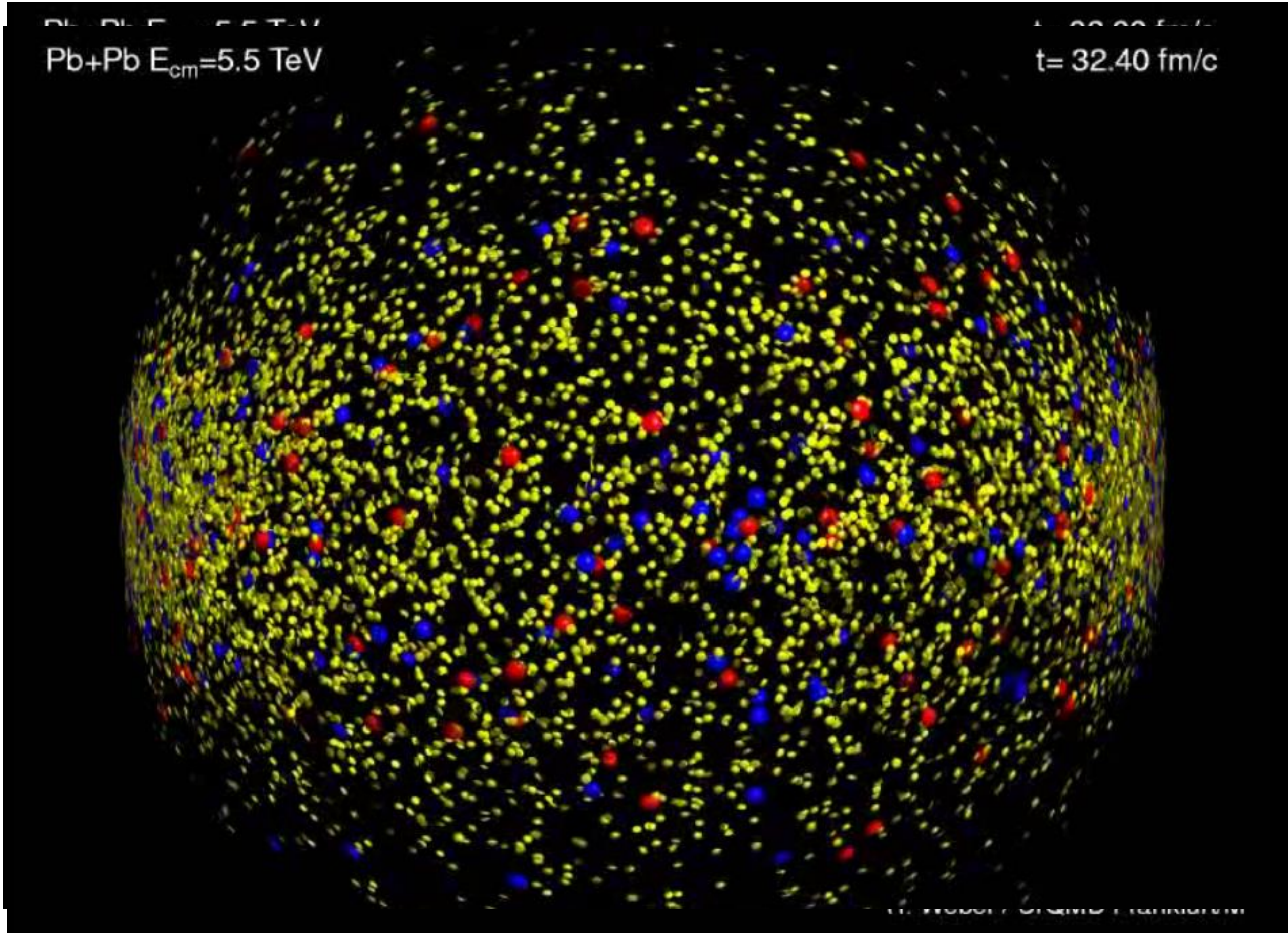
LHCB

ALICE

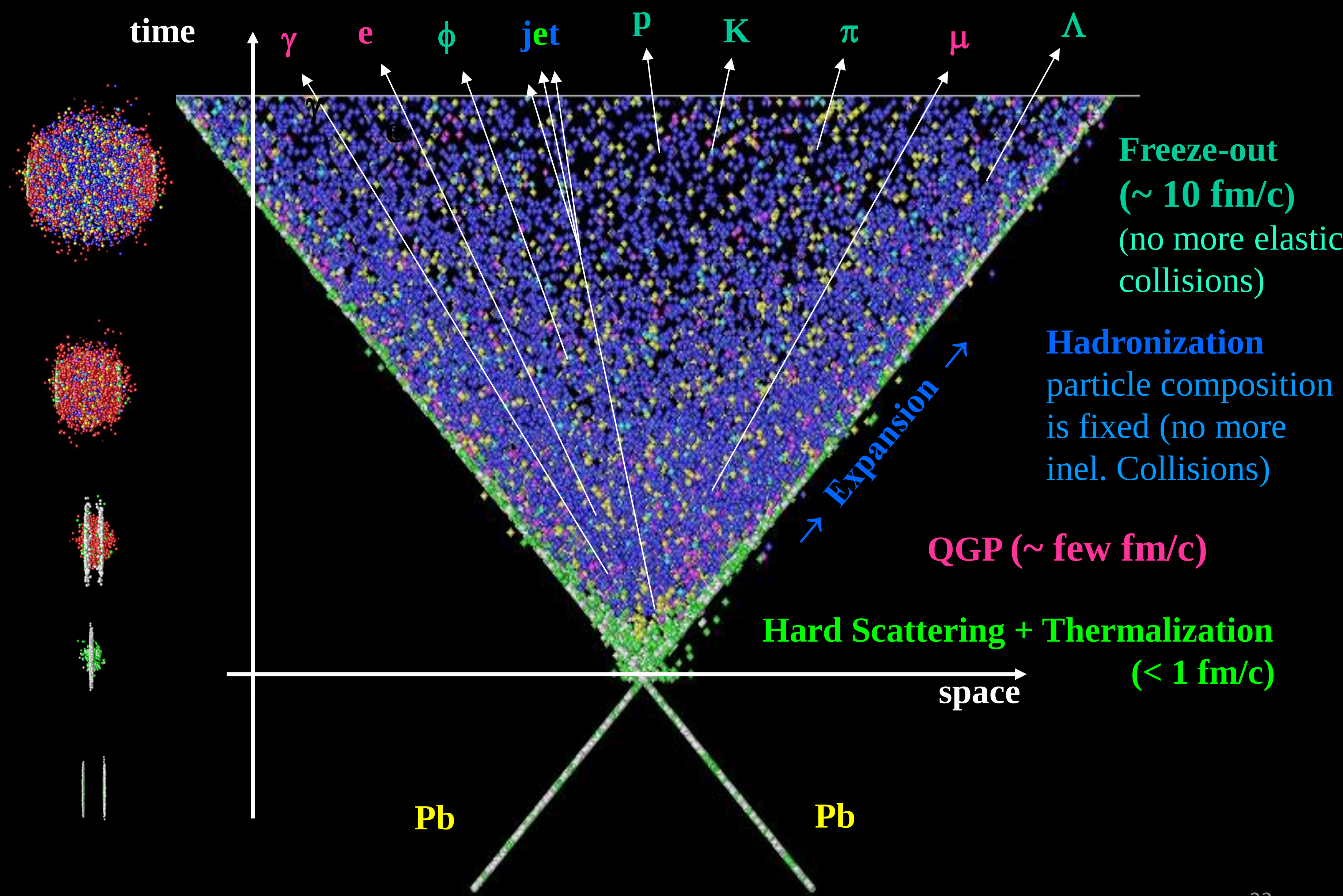
ATLAS



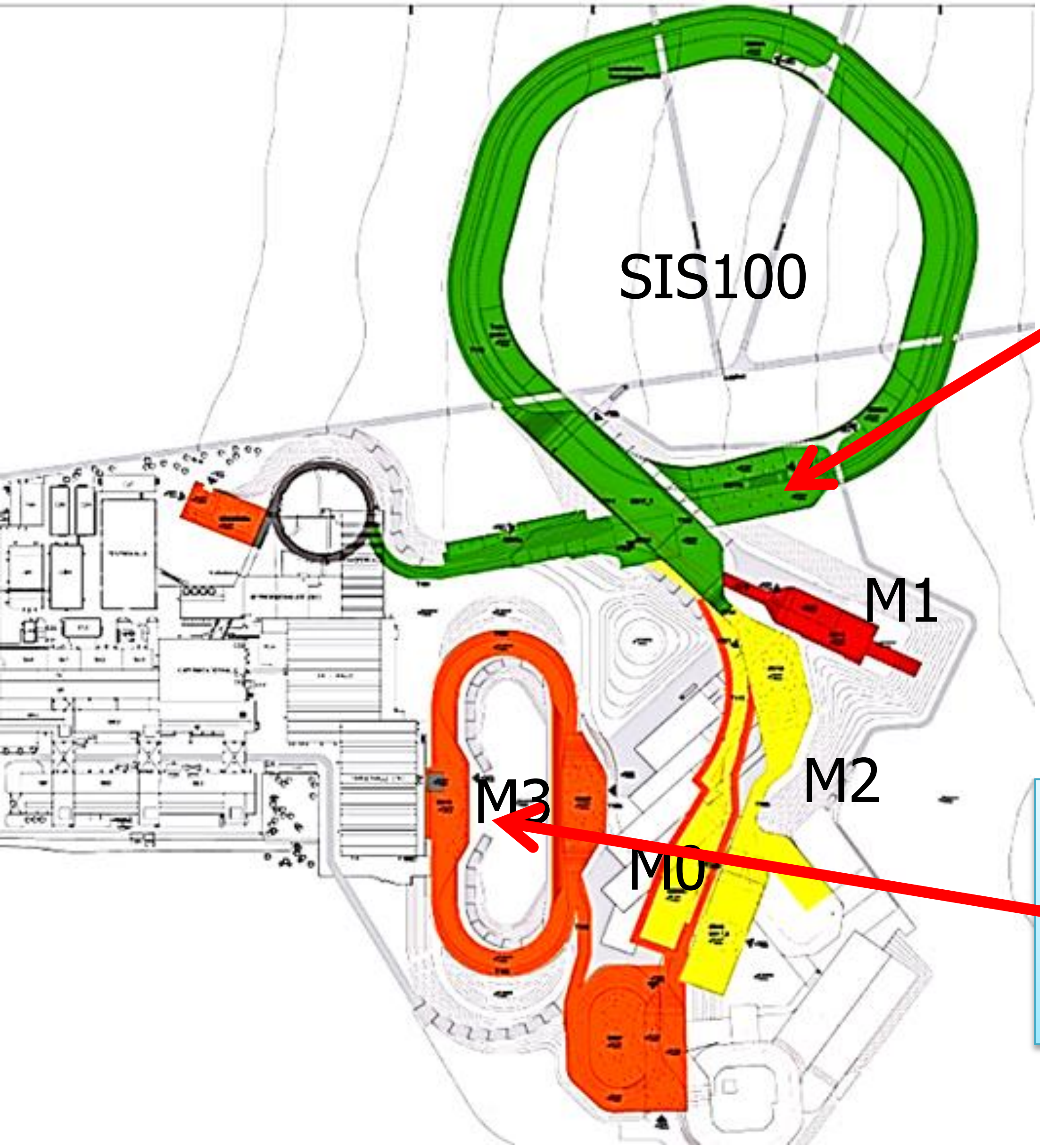
http://urqmd.org/~weber/CERNmovies/alice.mpg


Pb+Pb $E_{cm}$=5.5 TeV
t= 32.40 fm/c

What the colour mean ?



# Future HI at GSI : the FAIR project




**CBM/HADES**

Protons → 30 GeV

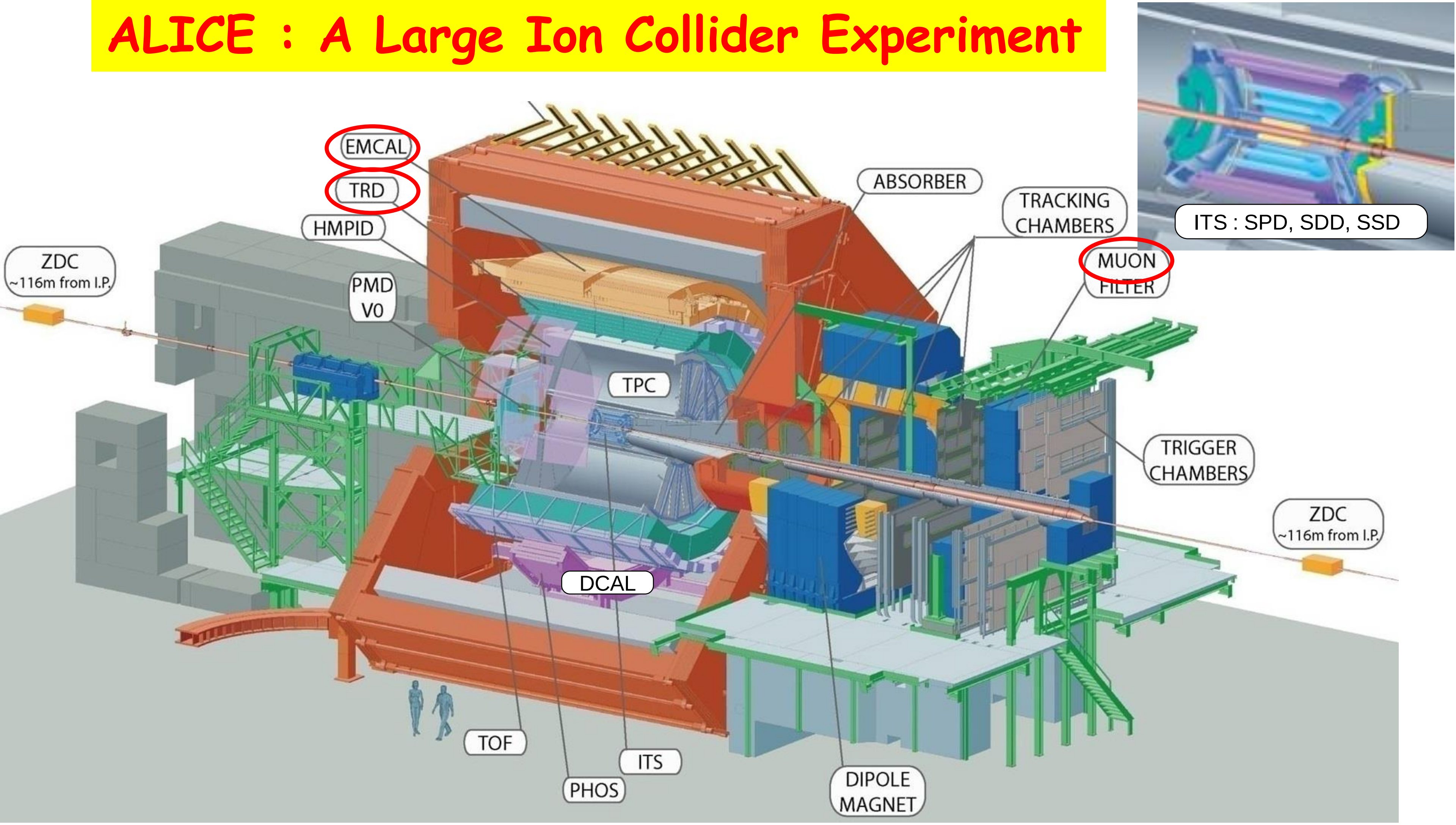
High intensity, Various targets

**PANDA**

Anti-Protons → 1.5 ÷ 15 GeV

Various target

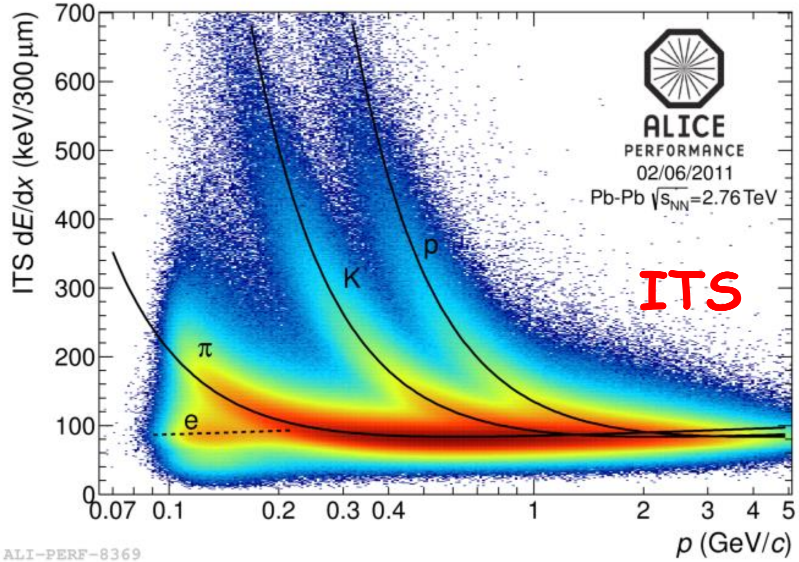
# ALICE : A Large Ion Collider Experiment

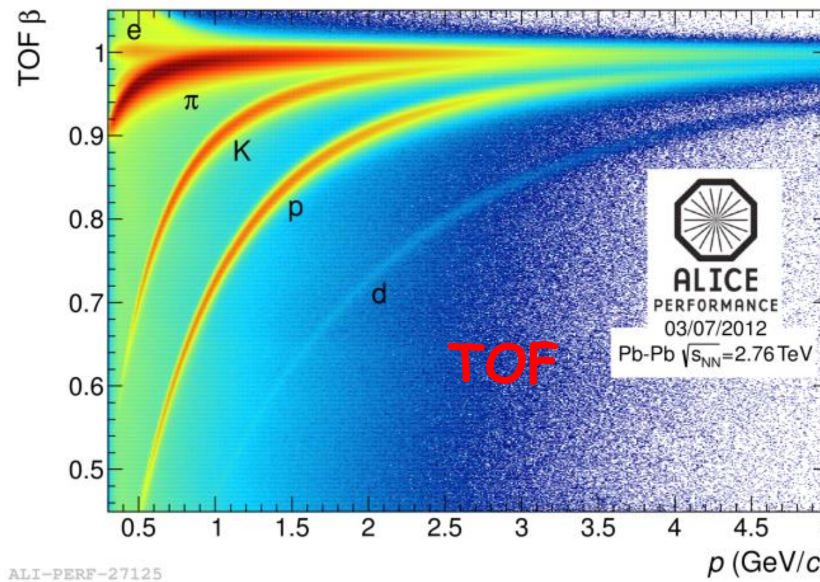


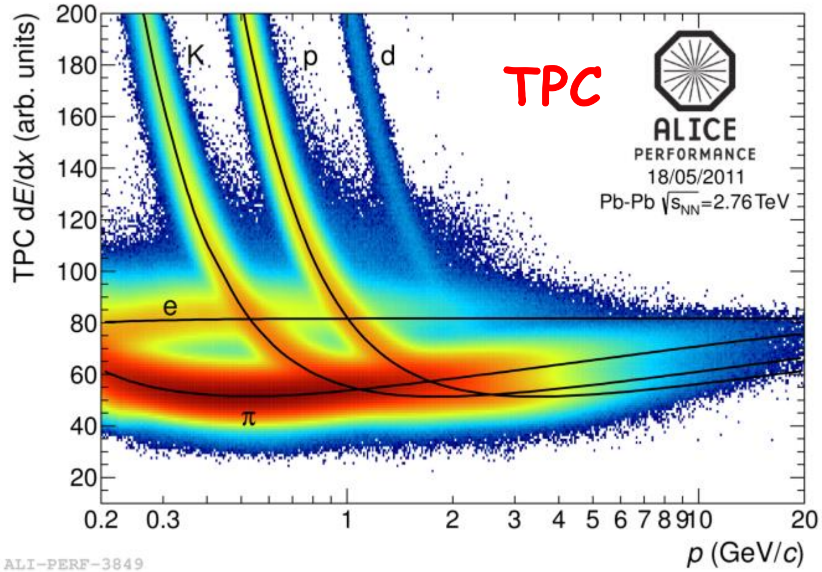

HI event

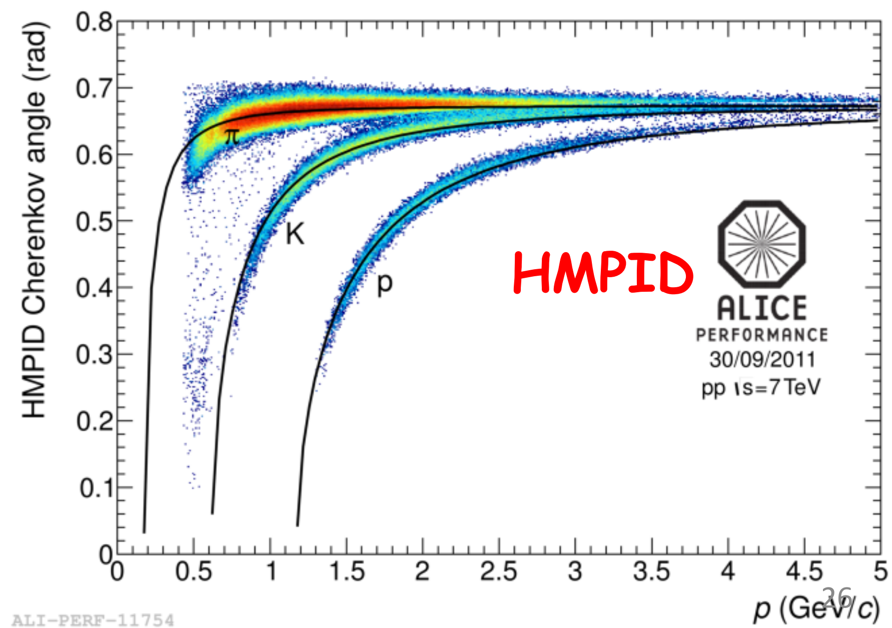
- Optimized for Heavy Ions Physics $\rightarrow$ high performances tracking and PID
- Complementary to the other LHC experiments

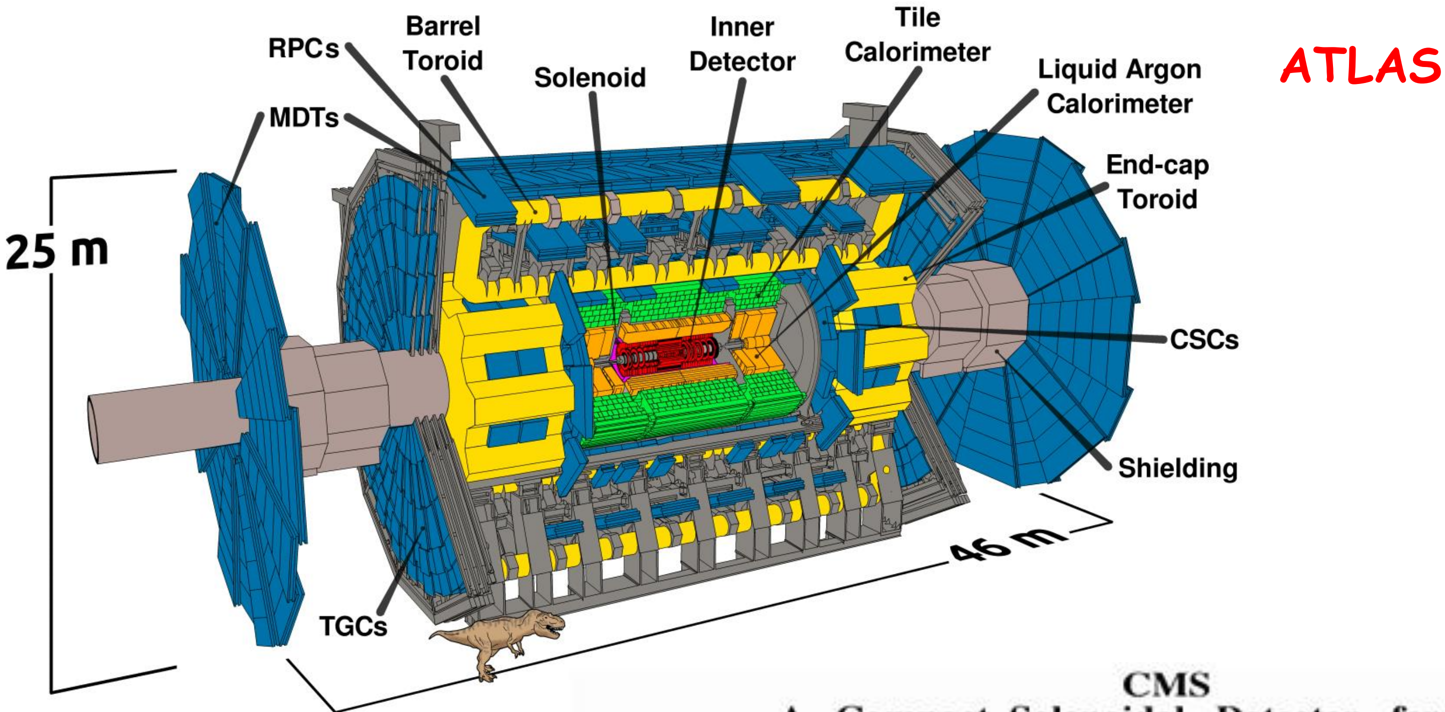
# ALICE main detector performances

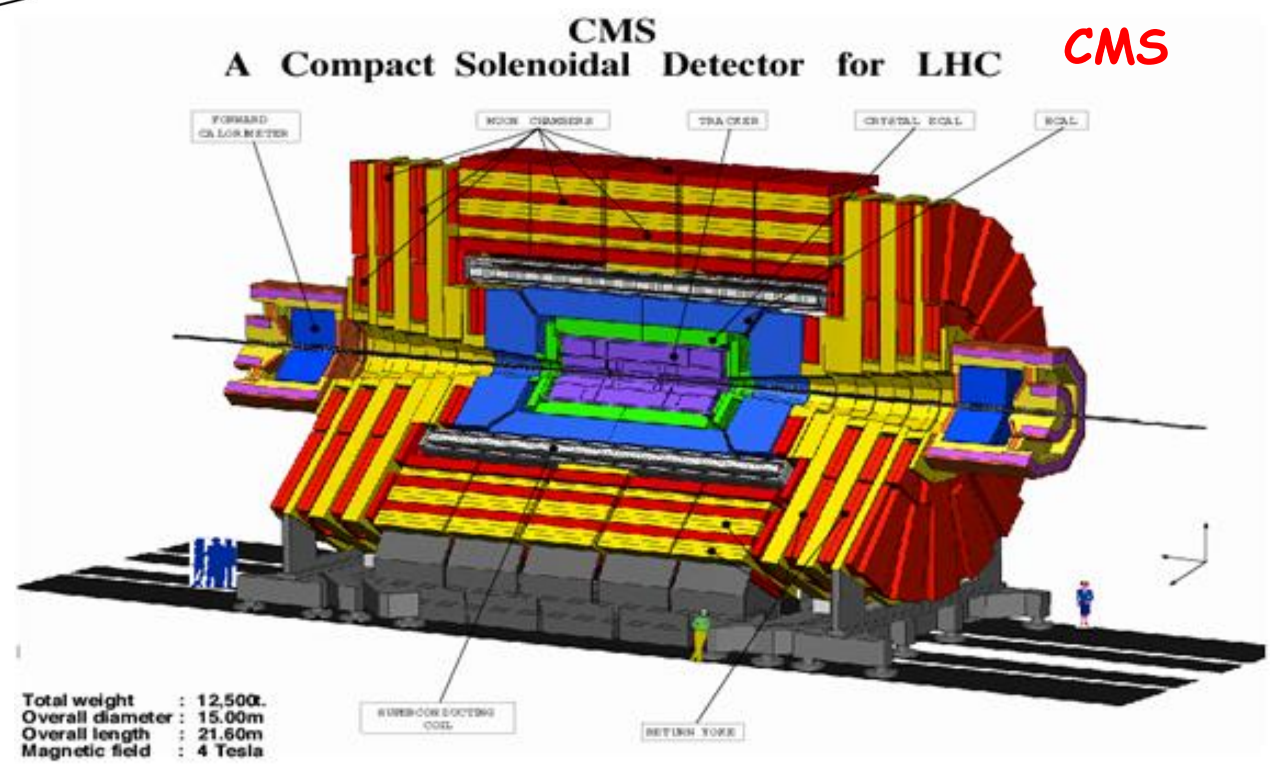


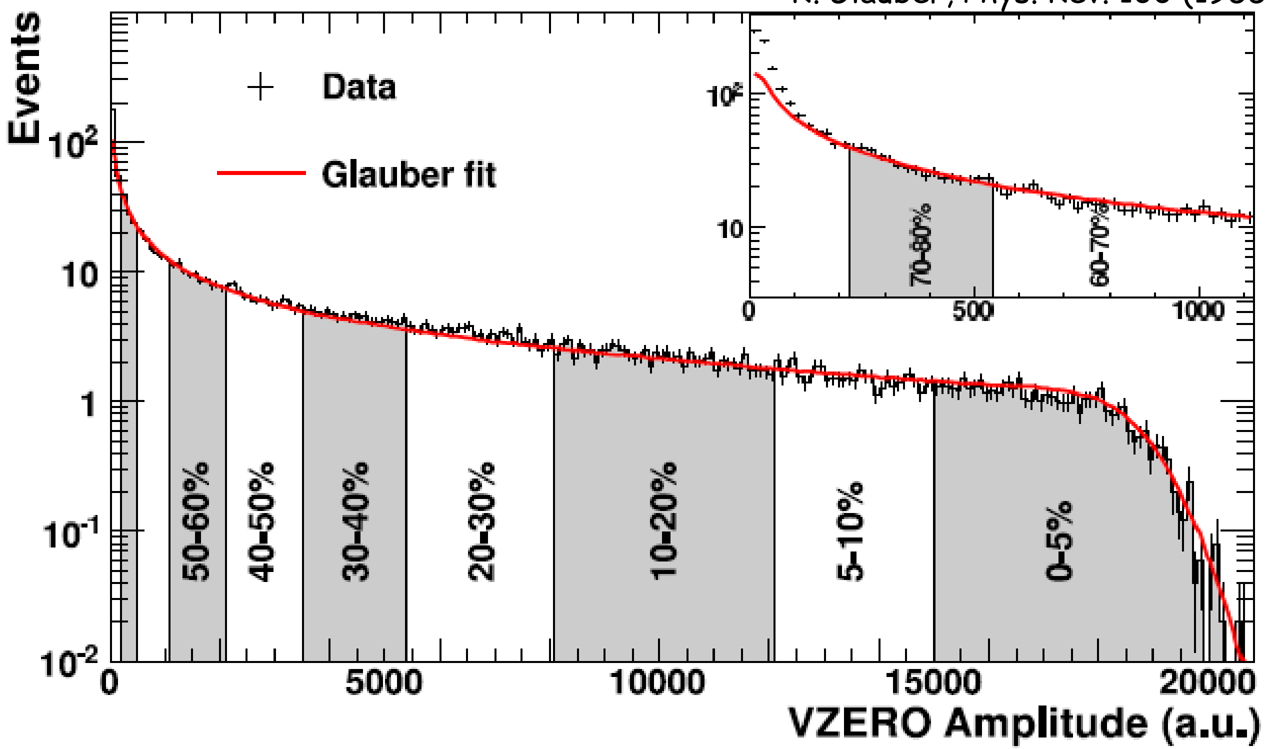

ATLAS
25 m
46 m
RPCs
Barrel
Toroid
Solenoid
Inner
Detector
Tile
Calorimeter
Liquid Argon
Calorimeter
MDTs
End-cap
Toroid
CSCs
Shielding
TGCs


CMS
CMS
A Compact Solenoidal Detector for LHC
FORWARD
CALORIMETER
MUON CHAMBERS
TRACKER
CRYSTAL ECAL
HCAL
SUPERCONDUCTING
COIL
RETURN YOKE
Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

# Variables definitions

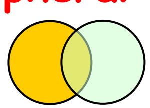
## Centrality : fraction of the total cross section

Phys. Rev. C 88, 044909
R. Glauber, Phys. Rev. 100 (1955)

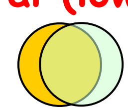



In this case with the VZERO trigger counter

Peripheral (high %)



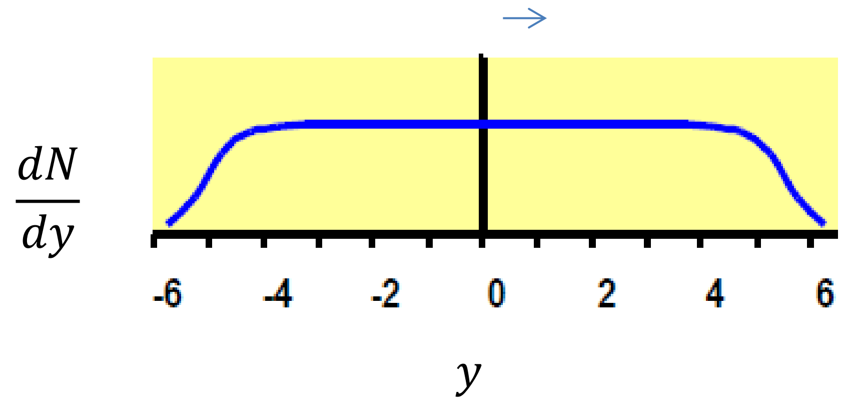
Central (low %)



# Measuring the energy density of the system - I

Rapidity differences are Boost invariant

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

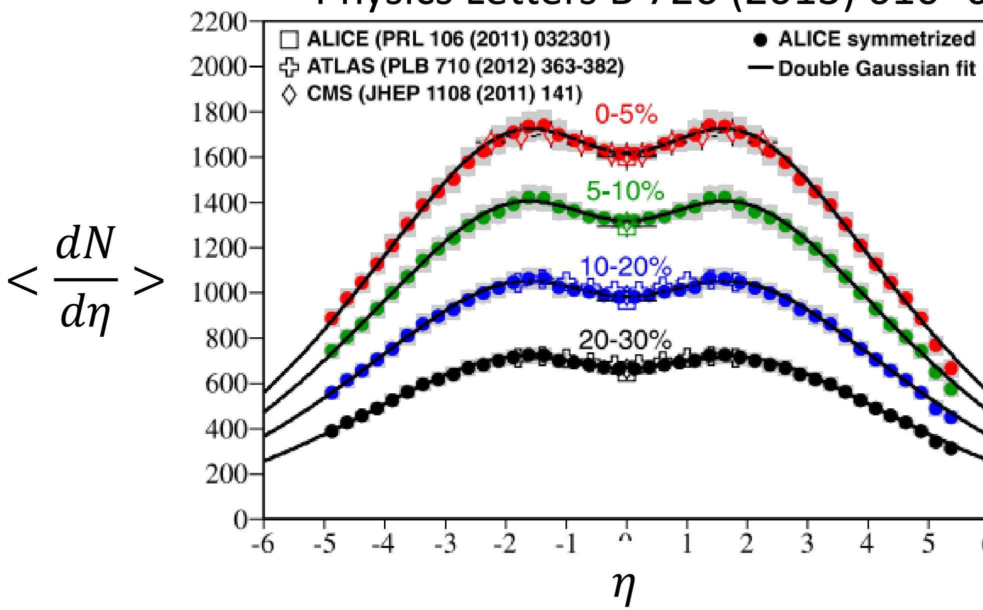



$$From\ E = \gamma m\ and\ p_z = \gamma\beta m$$
$$\rightarrow\ \beta = \tanh(y) \rightarrow for\ small\ y\ \ \rightarrow y\ \approx \beta$$

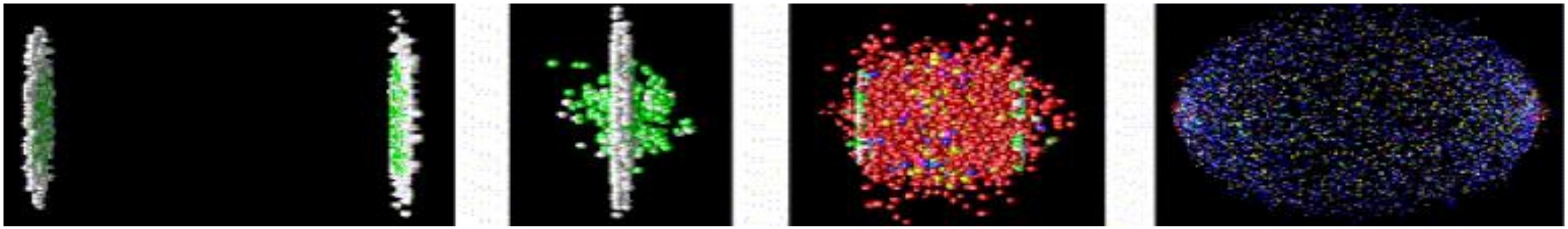
Pseudo-Rapidity

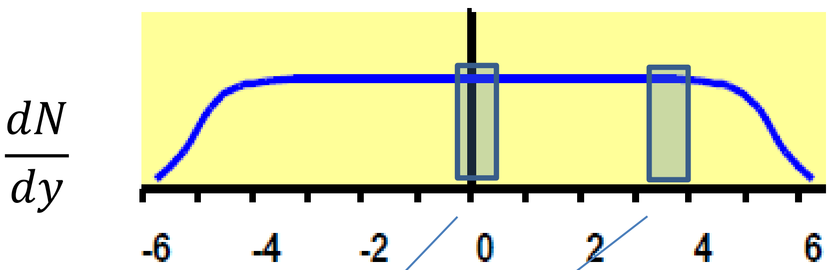
$$y\ (p \gg m) \approx \eta = -\ln\tan\frac{\theta}{2}$$

Physics Letters B 726 (2013) 610–622



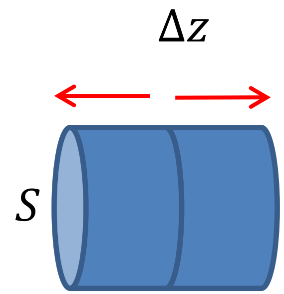
# Measuring the energy density of the system - II






$m_T^2 = m^2 + px^2 + py^2$

Same transverse energy distribution $<m_T>$




*Region filled with particles with velocity* $0 < \beta < \Delta z / c\tau$

*Around y=0*

$$\Delta N = \int_0^{\frac{d}{\tau}} \frac{dN}{d\beta} d\beta = \frac{d}{\tau}\frac{dN}{dy}$$

Total energy density as sum of all contributions

$$\varepsilon = \frac{\Delta N <m_T>}{S\Delta z} = \frac{\Delta z}{\tau}\frac{dN}{dy}\Big|_{y=0} \frac{<m_T>}{S\Delta z} = \frac{1}{\tau S}\frac{dN}{dy} < m_T > = \frac{1}{\tau S}\frac{dE_T}{dy}$$

*Bjorken* Phys. Rev. D 27, 40 (1983)

# Measuring the energy density of the system - III

Nucleon 0,13 GeV/fm³

From Bjorken we get

$$\varepsilon = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \qquad \tau \approx 1\ fm/c$$

RHIC

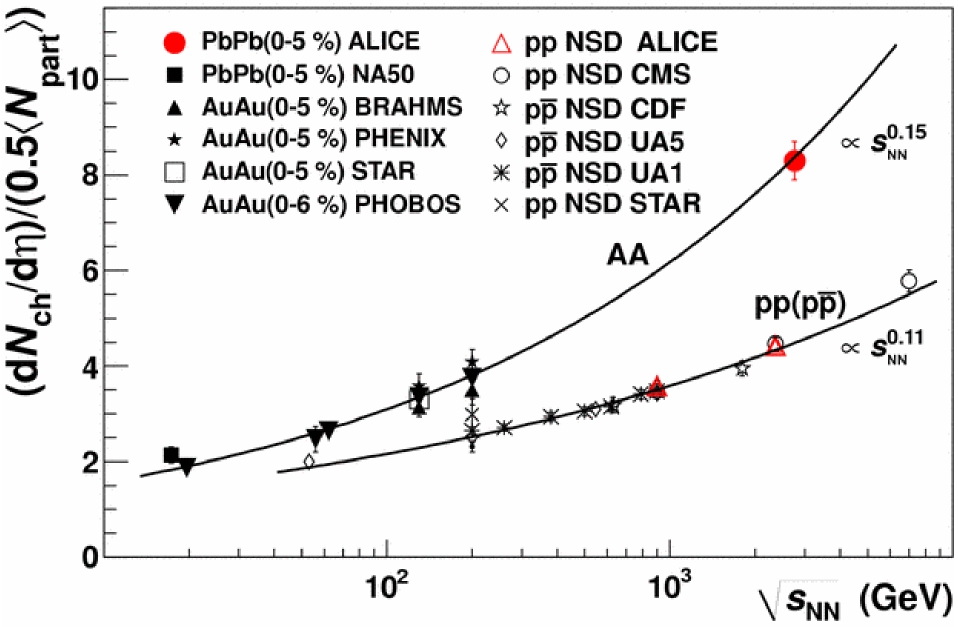
= 600 / (6.5² π) = 4.6 GeV/fm³

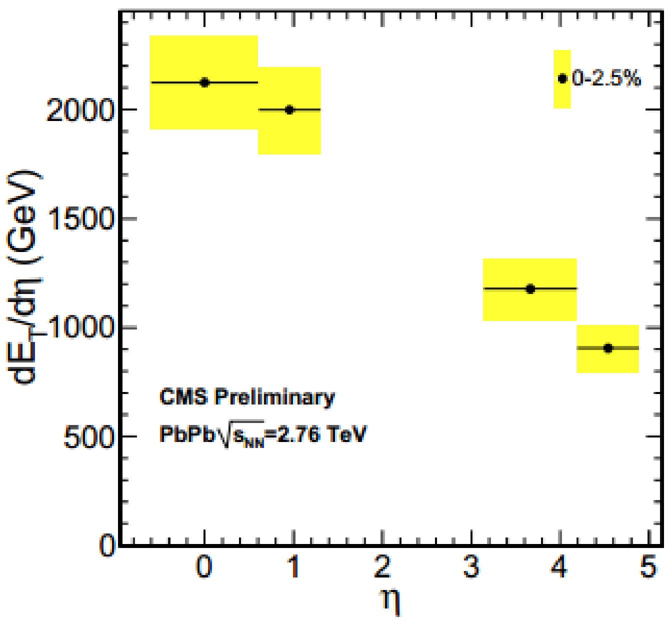
LHC

ε = 2100 / (6.5² π) = 15 GeV/fm³

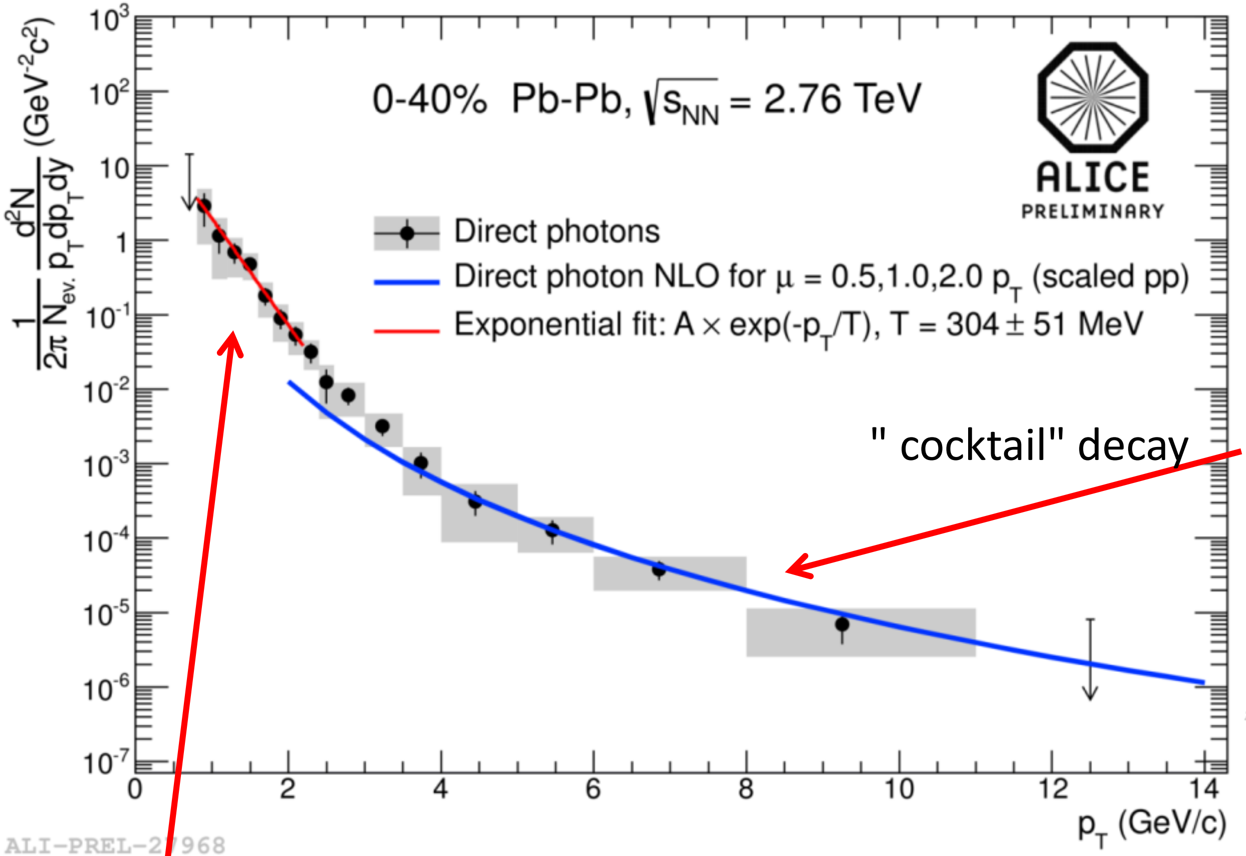
= 3 times RHIC

[J. Phys. G 38:124041]

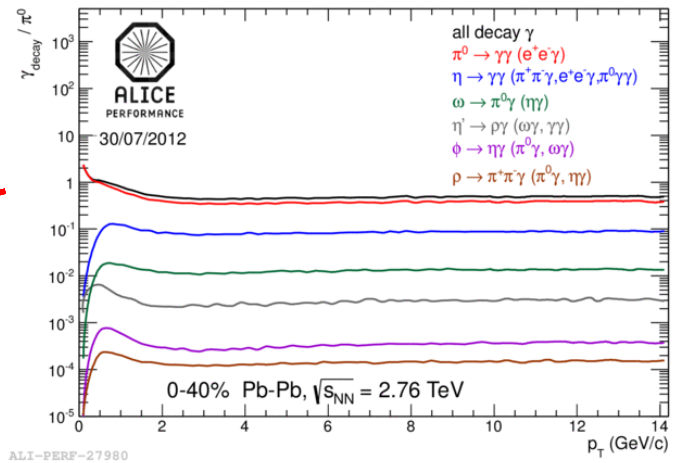


# Measuring the temperature of the system



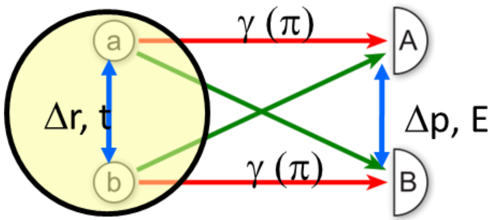

" cocktail" decay

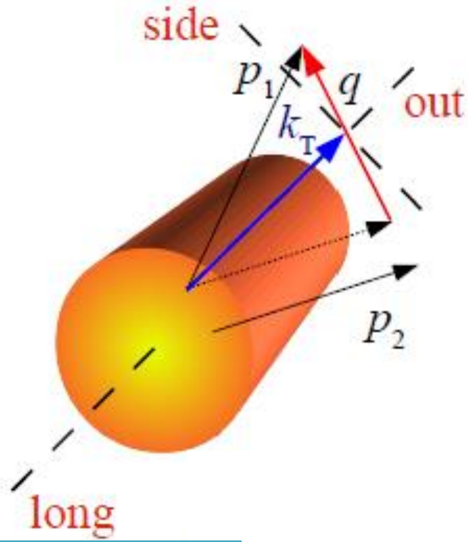



Thermal photons

**Temperature LHC-HI 304±51 MeV**
**≈1.4 x RHIC**
**≈ $10^5$ x T at Center of the Sun**

# Measuring the volume of the system




Observe (co-moving) volume via QM interferometry (Bose-Einstein)
Used also by astronomers to measure sizes of stars (Hanbury---BrownTwiss HBT)

*Define* proximity of two same-sign particles

$$q = p_1 - p_2$$

*Measure*

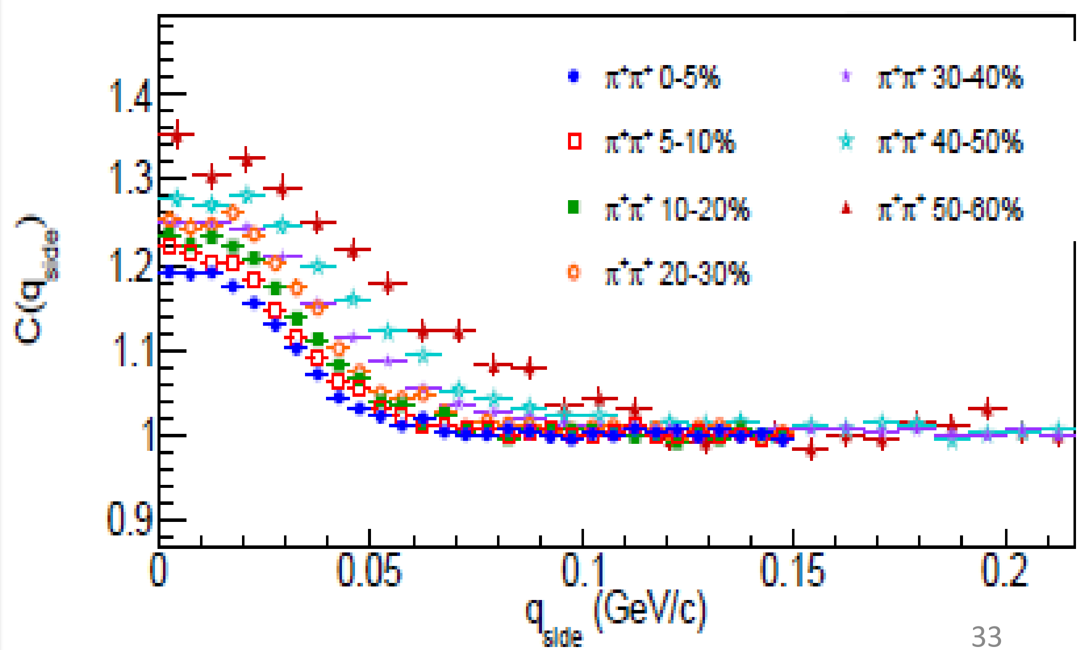
C(q) = Signal (q)/Background(q)

*Fit with*

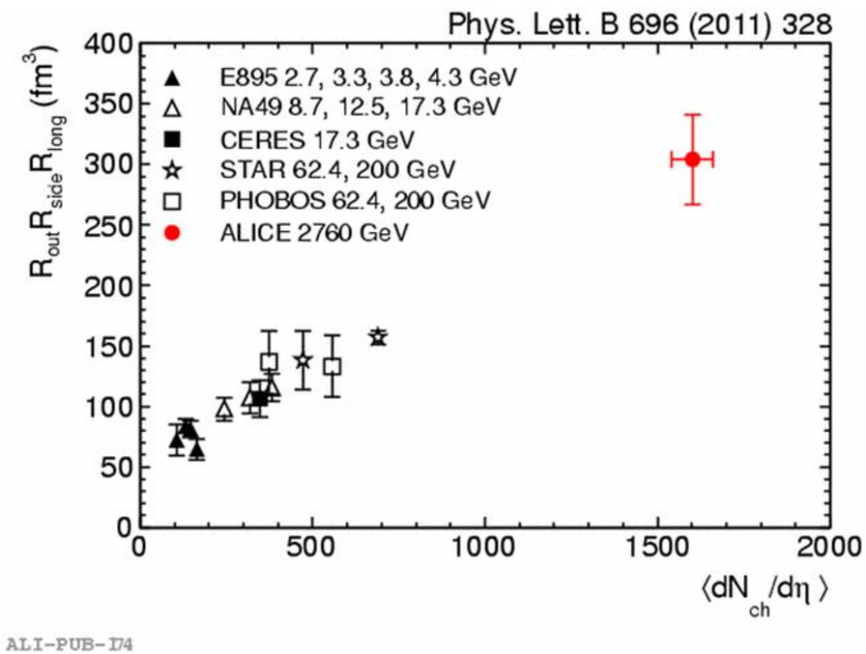
$$C(q) = \mathcal{N}[(1-\lambda) + \lambda K(q_{inv})(1+G(q))]$$

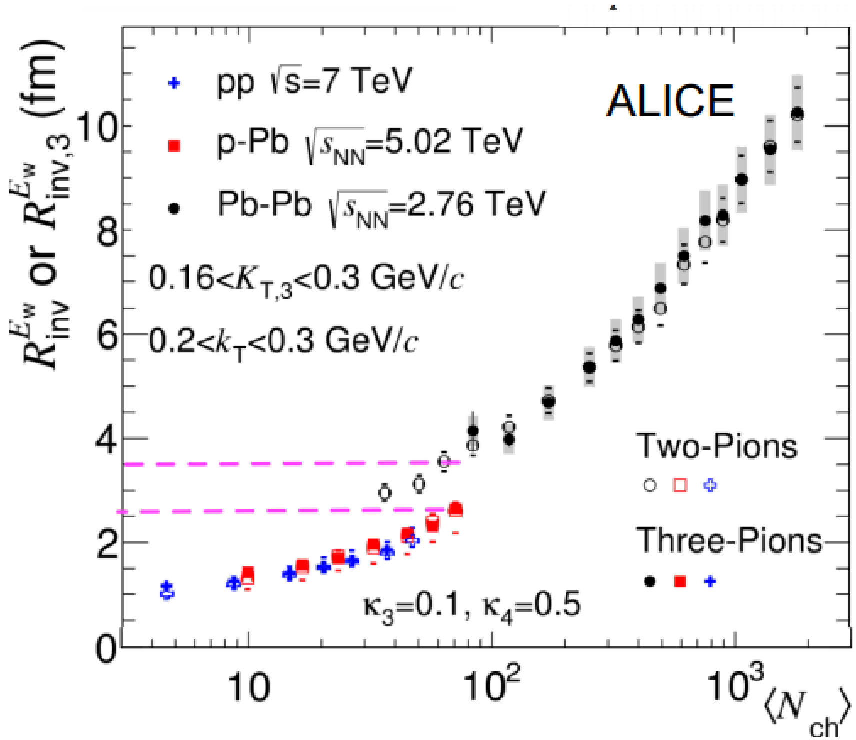
$$G(q) = e^{-(qr)^2}$$

- r effective radius source
- λ Strenght of correlation
- K Coulomb wave function
- $\mathcal{N}$ normalization factor



# Measuring the volume of the system - II




LHC ≈ 2 x RHIC ≈ up to 10 fm
Notice the comparison with p-Pb

# Thermal Model of particle production - I

A, Abdronic et al.: http://arxiv.org/pdf/hep-ph/0402291v1.pdf

Produced system in thermodynamical equilibrium.

Using the methods of (Grand Canonical) statistical mechanics, it is possible to deduce particle yields on the assumption of zero total strangeness and isospin of the system.

$$n_i = \frac{N_i}{V} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$$

$g_i$ is the spin-isospin degeneracy factor and $\mu_i \approx \mu_B$ is the baryon chemical potential (related to the baryon number conservation). Three parameters can be derived from minimization procedure: V, T and $\mu_i$

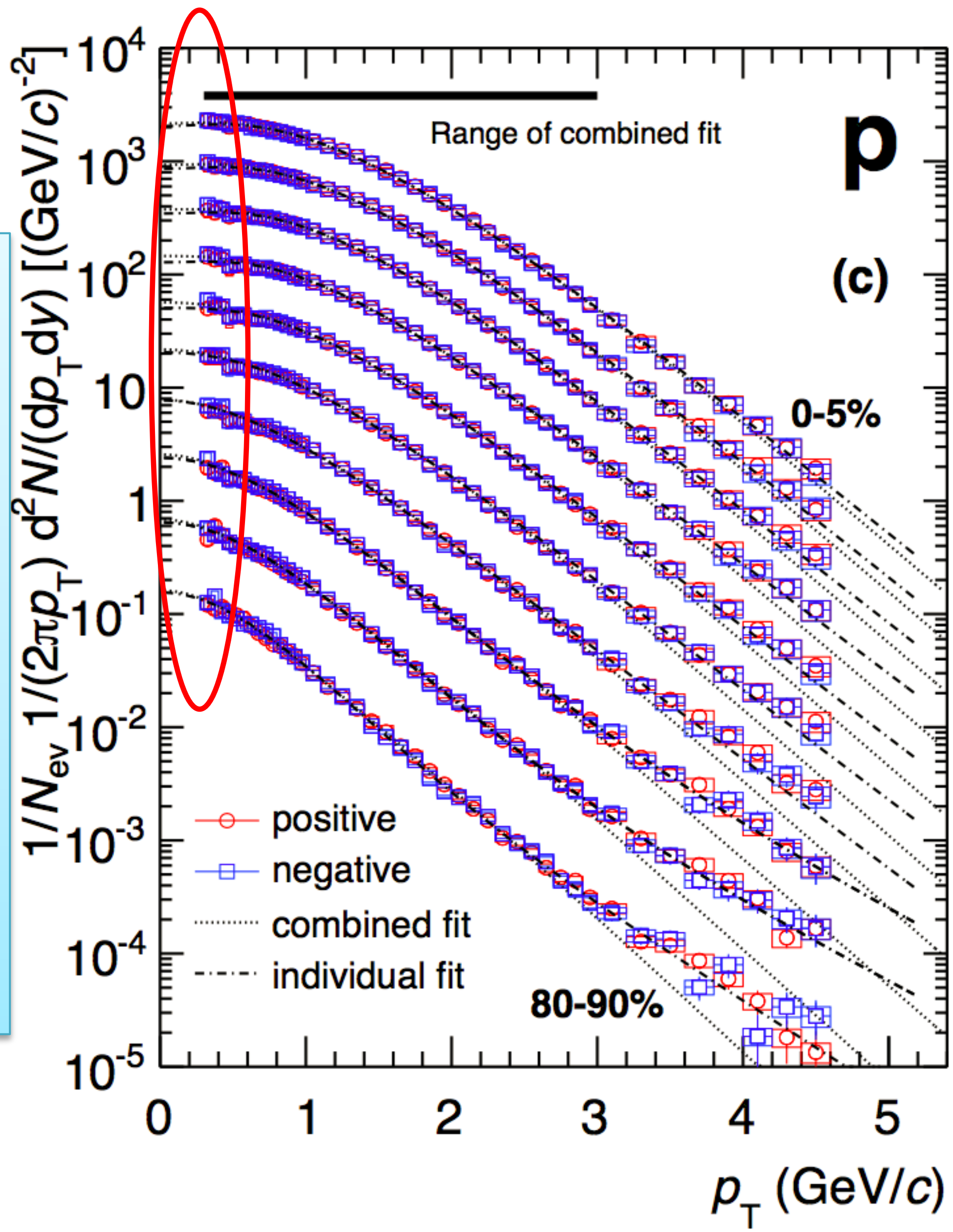
# Thermal Model of particle production - II

How to measure the particle yields ?

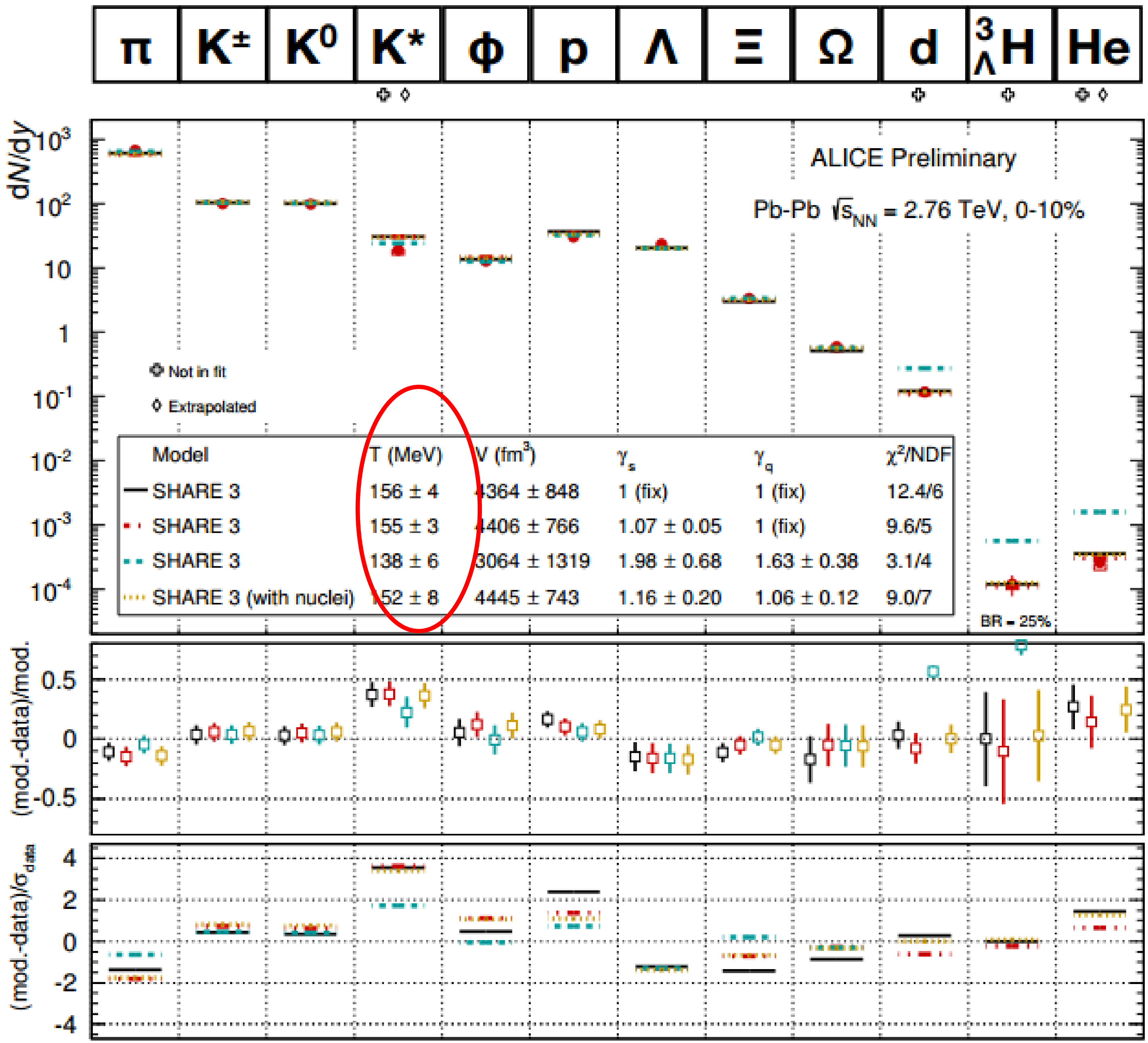
From spectra of identified particles +extrapolation to pt=0 .

Use various functional forms
<u>Blast-wave</u>
E. Schnedermannet al. Phys. Rev. C 48, 2462 (1993)

<u>Tsallis</u>
C. Tsallis, J. Stat. Phys. 52 479 (1988).



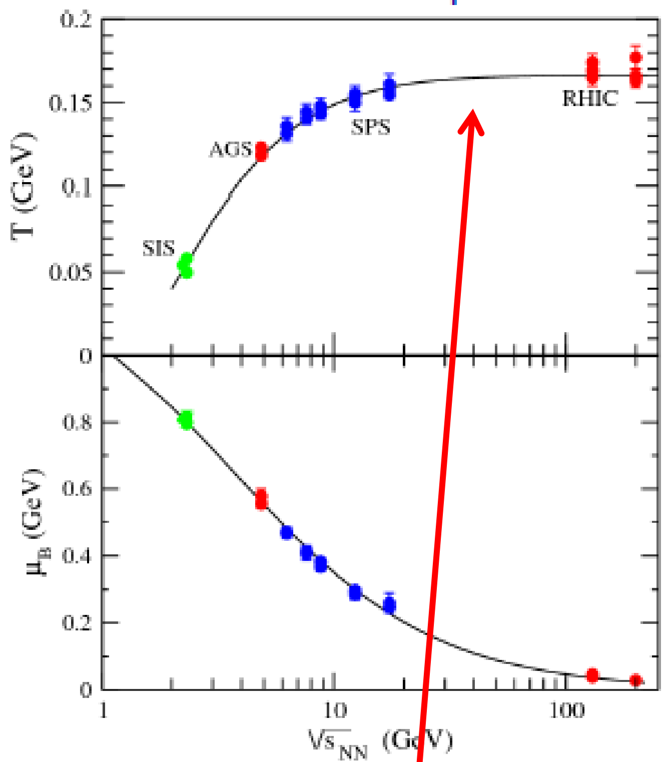
# Thermal Model of particle production - III



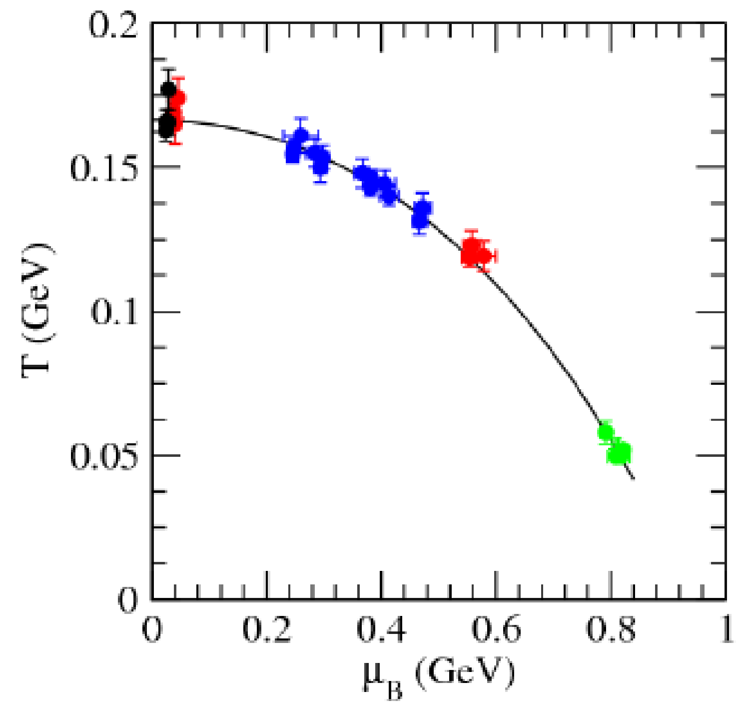
# Thermal Model and Phase diagram

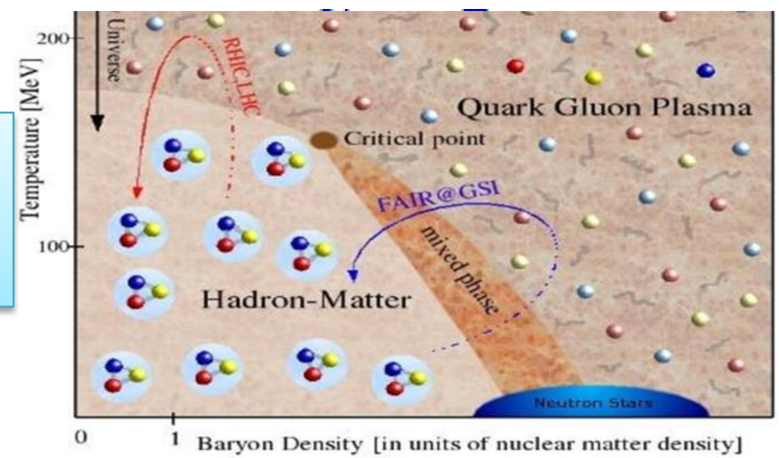
From these fits to particle yields it is possible to fill the Phase diagram changing the different energies

Hadron Gas Model parameters




Freeze-out curve




NB : Additional energy goes into heating of QGP which cools down again to the critical temperature

J. Cleymans et al. Hep-hp/0511094

# Modelling High Energy Heavy Ion collisions

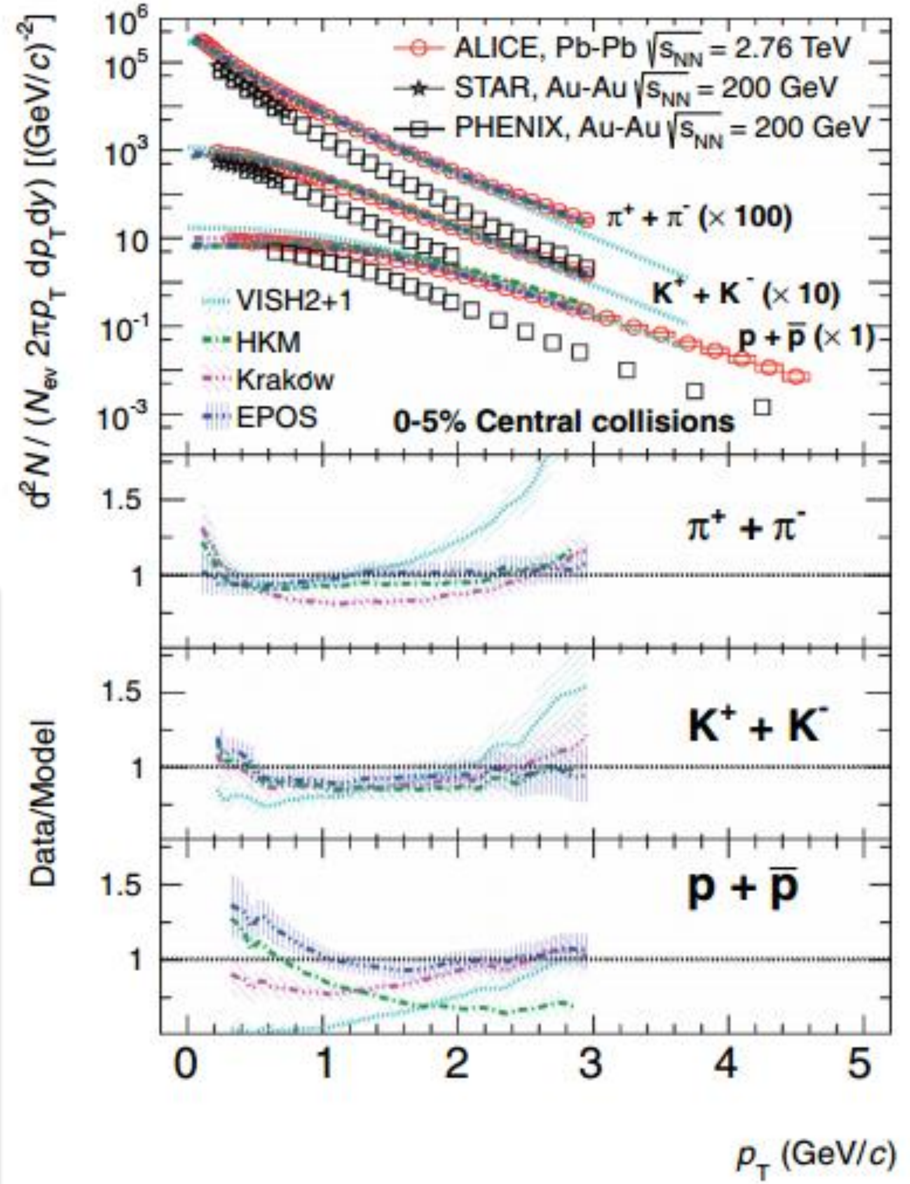
Relativistic hydrodynamical models describe reasonably well particle production validating the assumption of a matter which has reached thermal equilibrium after the collisions

VISH2+1 is a viscous hydrodynamic model where the yields are thermal ( but bad protons).

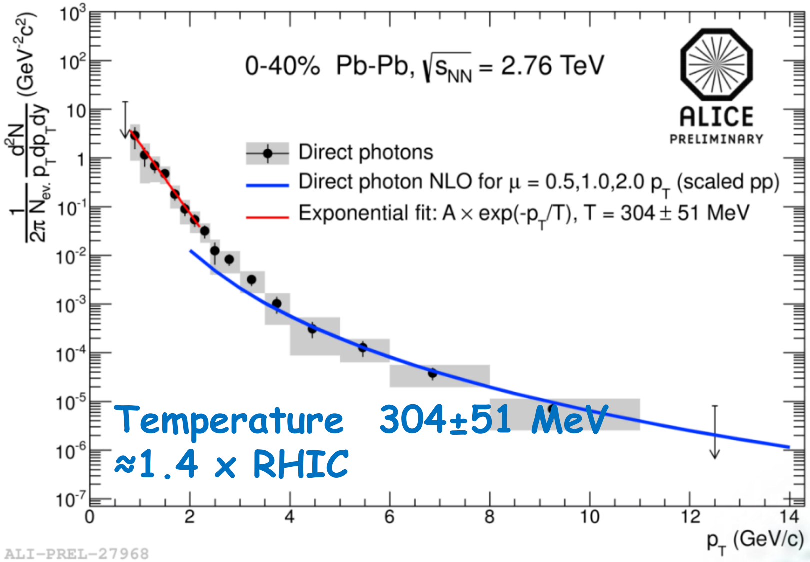
HKM is an ideal hydrodynamics model, in which after the hydrodynamic phase particles are injected into a hadronic cascade model (UrQMD), Antibaryon-baryon annihilation is an important ingredient for the description of particle yields .

Krakow model uses an ansatz to describe deviation from equilibrium due to bulk viscosity corrections at freeze-out.

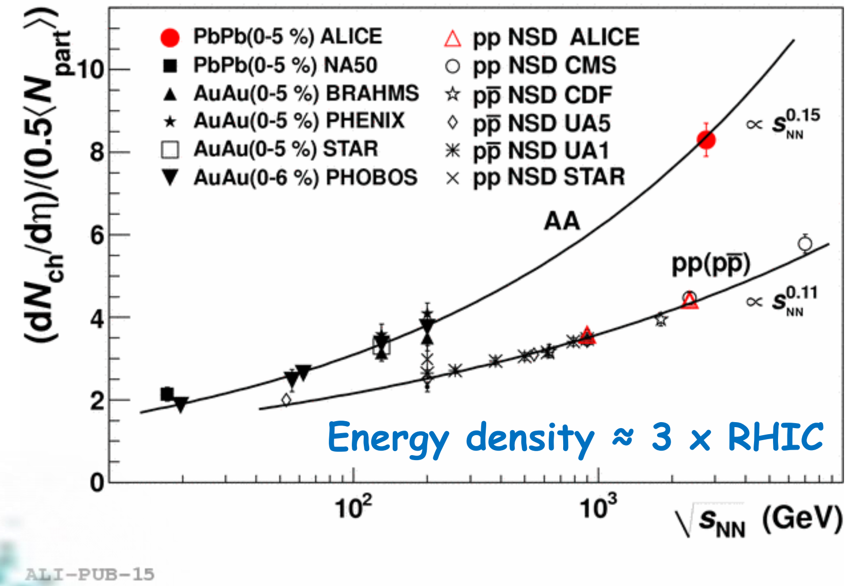
EPOS (2.17v3) model, the initial hard scattering creates "flux tubes" which either escape the medium and hadronize as jets or contribute to the bulk matter (includes UrQMD)



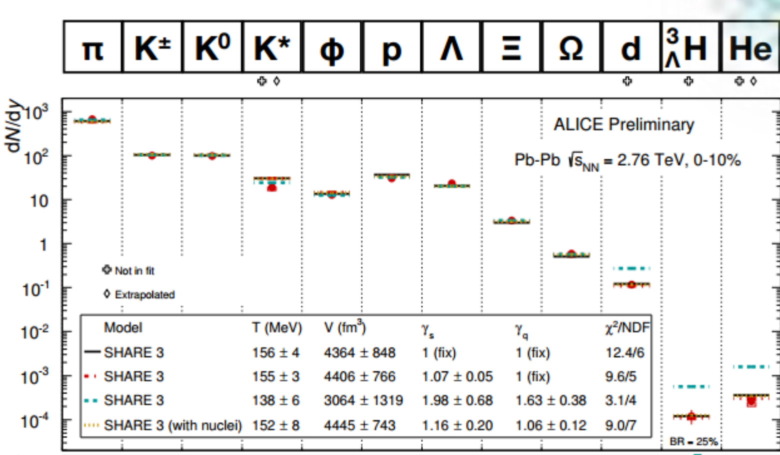
# Global characterization of the medium




Temperature 304±51 MeV
≈1.4 x RHIC

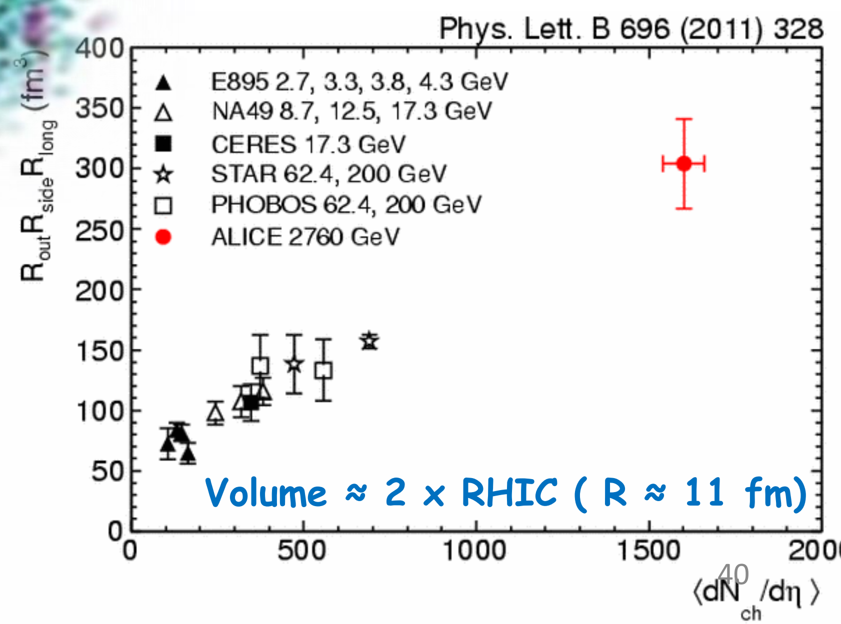



Energy density ≈ 3 x RHIC




| Model | T (MeV) | V (fm³) | $\gamma_s$ | $\gamma_q$ | $\chi^2$/NDF |
|---|---|---|---|---|---|
| SHARE 3 | 156 ± 4 | 4364 ± 848 | 1 (fix) | 1 (fix) | 12.4/6 |
| SHARE 3 | 155 ± 3 | 4406 ± 766 | 1.07 ± 0.05 | 1 (fix) | 9.6/5 |
| SHARE 3 | 138 ± 6 | 3064 ± 1319 | 1.98 ± 0.68 | 1.63 ± 0.38 | 3.1/4 |
| SHARE 3 (with nuclei) | 152 ± 8 | 4445 ± 743 | 1.16 ± 0.20 | 1.06 ± 0.12 | 9.0/7 |

Temperature deconfinemnt ≈ 155-160 MeV




Volume ≈ 2 x RHIC ( R ≈ 11 fm)

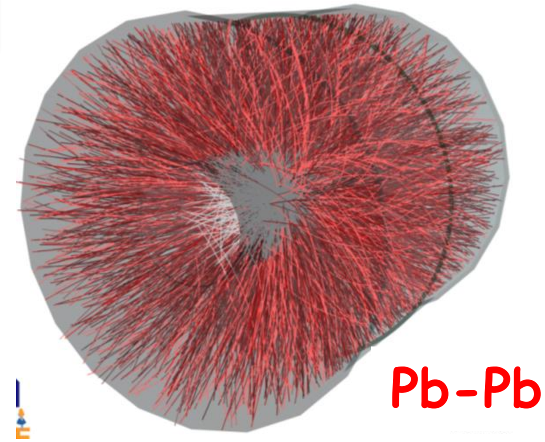
# Conclusions I

- Heavy Ions collisions allow to study the matter (Quark Gluon Plasma) as of few tens of microsecond after Big Bang
- The critical temperature for deconfinement of matter is around 150-170 MeV from lattice QCD.
- Experiments at AGS, SpS, RHIC and LHC ( and in the future at FAIR) allow to study QGP formation in several points of the phase diagram.
- The study of the global parameters of the matter in Heavy Ions collisions allow to set for LHC an energy density of 15 Gev/fm$^3$ , temperature above 300 MeV and radii up to 11 fm
- Thermal models reasonably describe particle yields and spectra with a temperature around 155 MeV.
- Relativistic Hydrodynamical models reasonably describe the global properties of the final states indicating a thermalization of the hot , dense matter created.

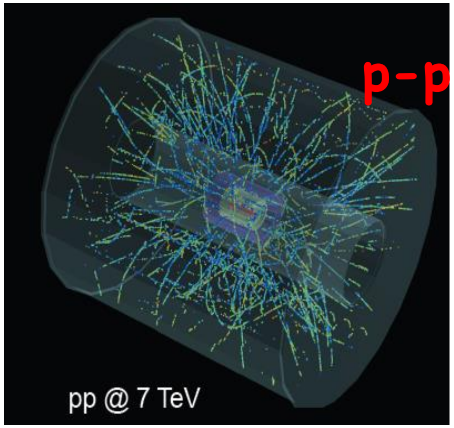
# Part II

# Not only Heavy Ions …

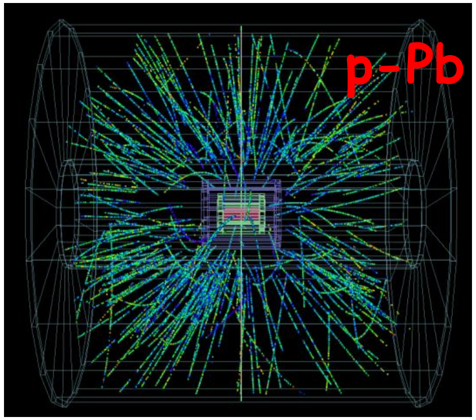
A complete analysis of HI collisions should go beyond global statistical/thermal analysis.



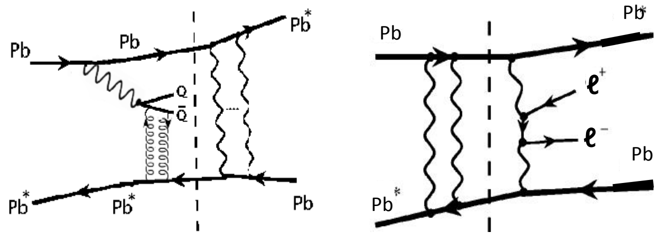

p-p collisions are required to compare Pb-Pb with $N_{coll} \times$ p-p




Pb-p collisions are required to understand the effects of the cold nuclear matter



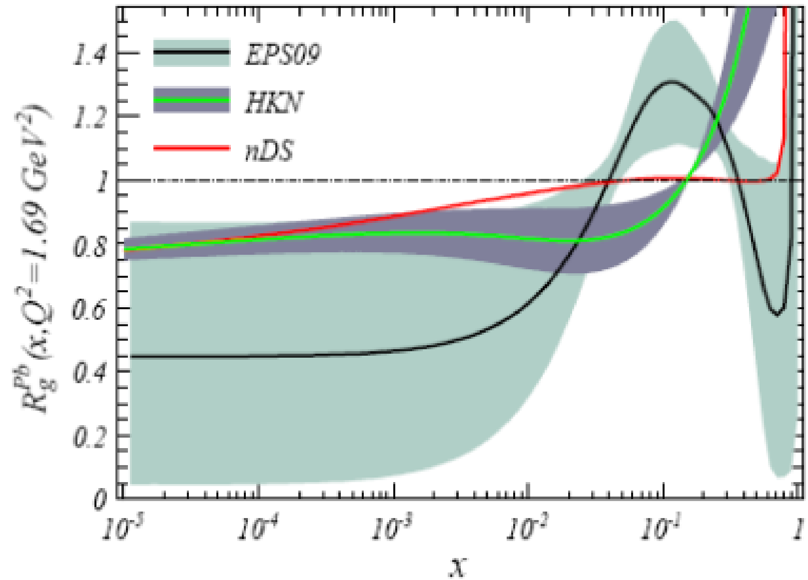
# Not only HI !
# J/ψ production
# in untraperipheral collisions

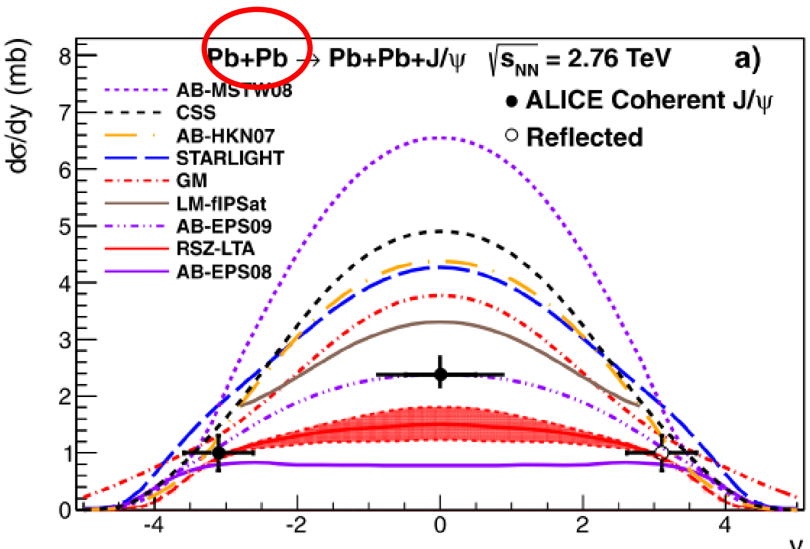


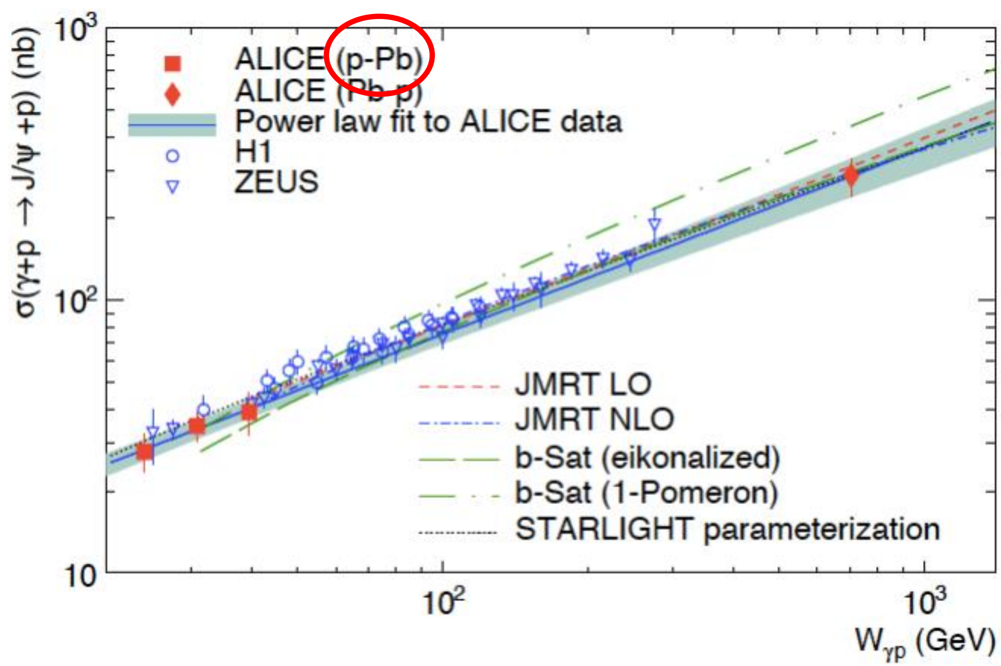

γA → J/ψ   γ γ → J/ψ

**Cross section sensitive to $G_{Pb}^{2}$ at low-x**

Nuclear gluon shadowing factor vs x



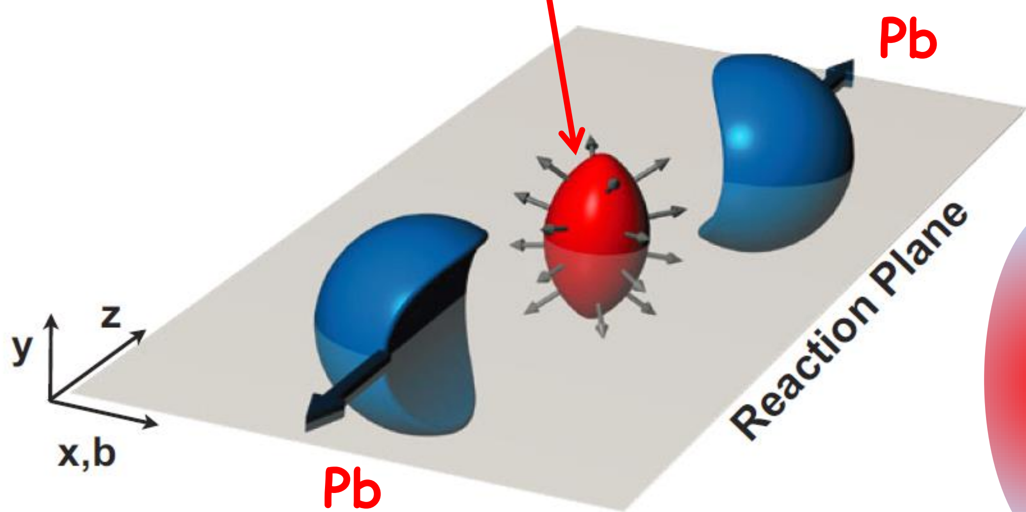



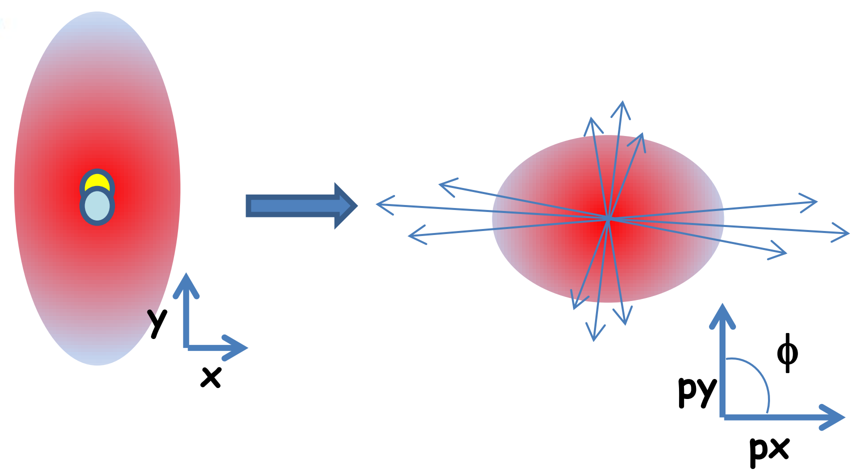

**Preference of Lo-pQCD models with gluons shadowing**

# Elliptic flow v2 / I

Hot medium with thermal equilibrium reached in very short time, not to modify the geometry. Very high pressure gradients.



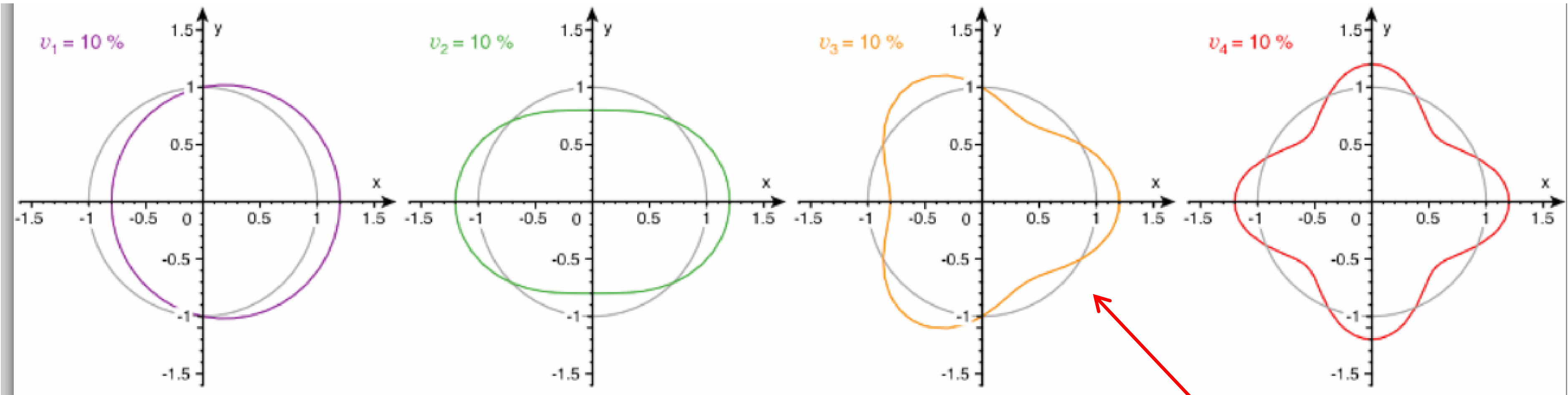

Very important to compare the two regions




Momentum space

Define the reaction plane from tracks and measure $\phi$ with respect to this plane

# Elliptic flow v2 / II

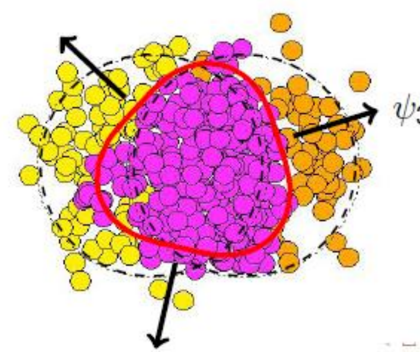



$$\frac{d^2N}{dp_t d\phi} = \frac{dN}{dp_t}\left[1 + 2\upsilon_2 \cos(2\phi) + 2\upsilon_4 \cos(4\phi) + .....\right]$$

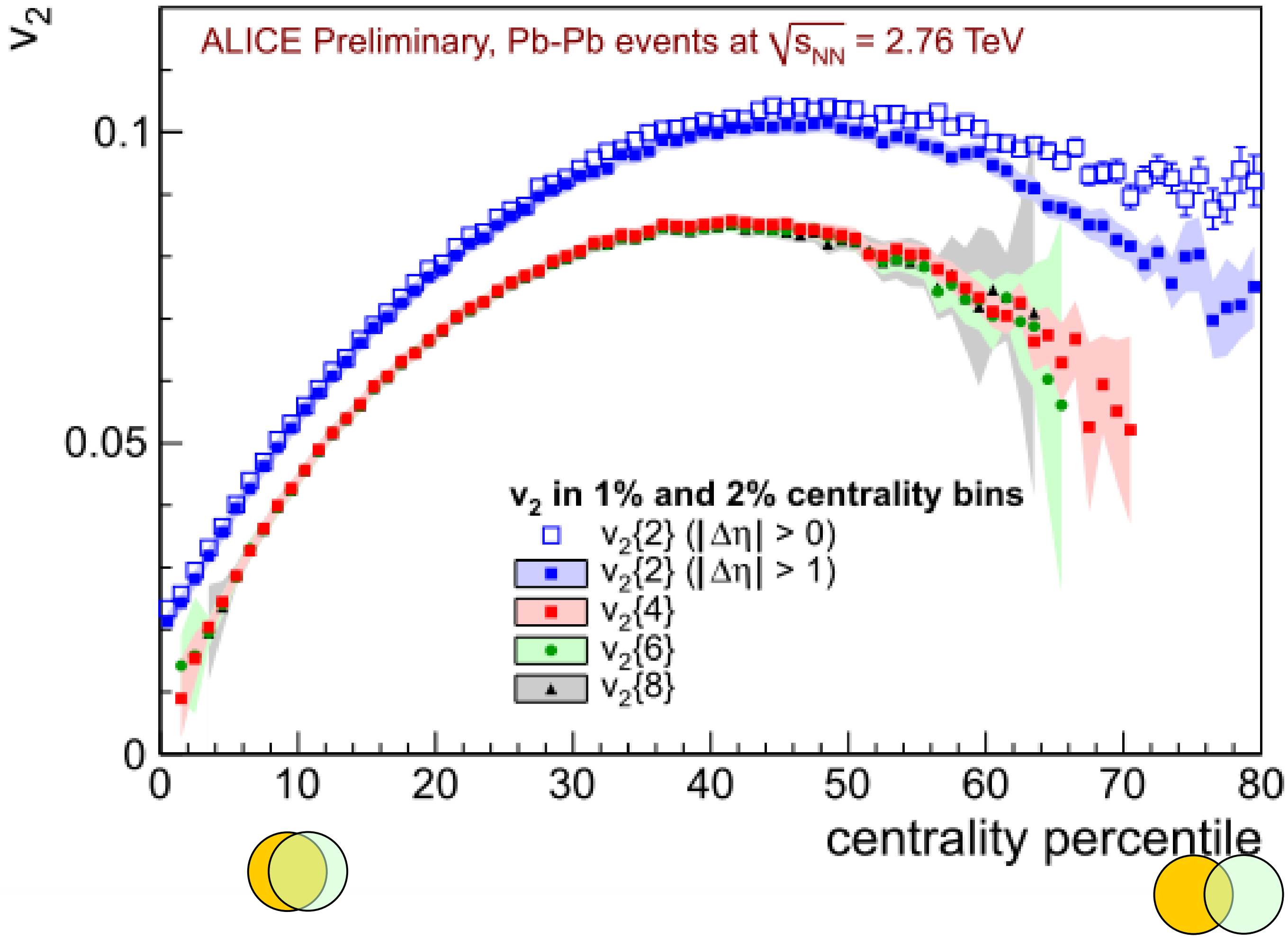
$\nu_i$ will depend on

$p_t$ : the higher the pt the less important the anisotropy observed

Centrality : the overlapping region changes



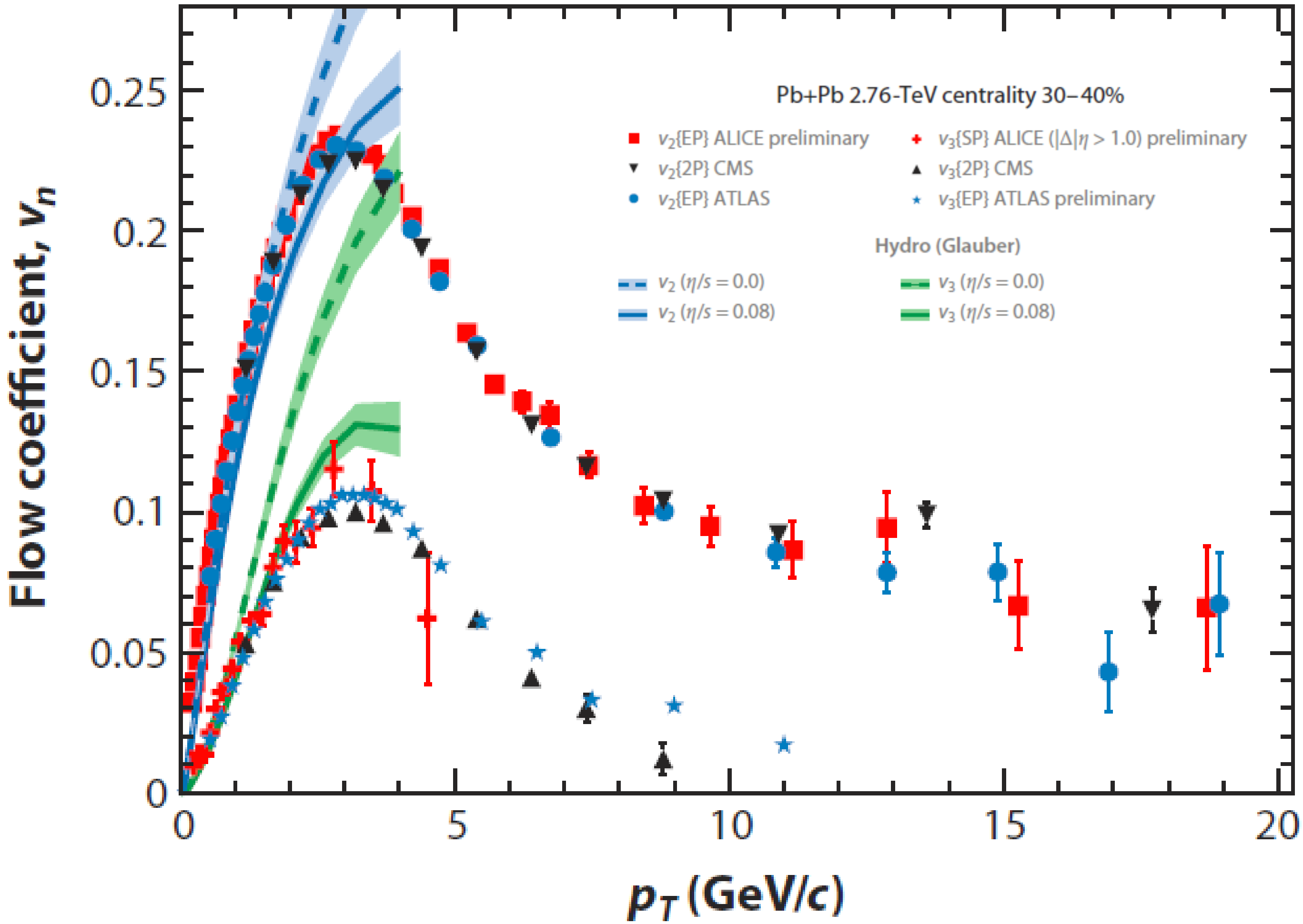
# Elliptic flow v2 / IV




$\nu_i$ will depend on centrality : the lower the centrality the less important is the anisotropy observed. Maximum around 50-60%.

# Elliptic flow v2 / III

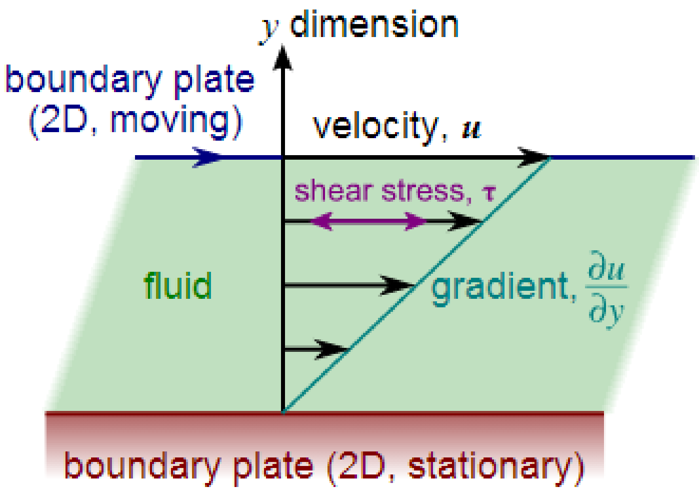
Muller et al Annu. Rev. Nucl. Part. Sci. 2012.62:361-386.




Pb+Pb 2.76-TeV centrality 30–40%

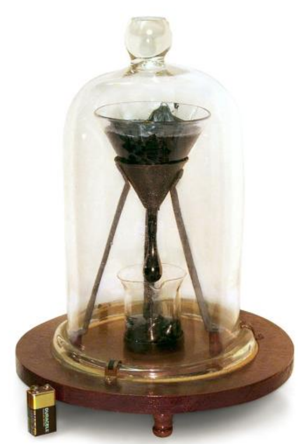
# Why Elliptic flow is important

## Viscosity




*Wikipedia*: Laminar shear of fluid between two plates. Friction between the fluid and the moving boundaries causes the fluid to shear. The force required for this action is a measure of the fluid's viscosity

| Date | Event | Duration (months) | Duration (years) |
|---|---|---|---|
| 1927 | Hot pitch poured | - | - |
| October 1930 | Stem cut | 0 | 0.0 |
| December 1938 | 1st drop fell | 98 | 8.1 |
| February 1947 | 2nd drop fell | 99 | 8.2 |
| April 1954 | 3rd drop fell | 86 | 7.2 |
| May 1962 | 4th drop fell | 97 | 8.1 |
| August 1970 | 5th drop fell | 99 | 8.3 |
| April 1979 | 6th drop fell | 104 | 8.7 |
| July 1988 | 7th drop fell | 111 | 9.2 |
| November 2000 | 8th drop fell | 148 | 12.3 |
| 17 April 2014 | 9th drop touched 8th drop | (156) | (13.4) |
| 24 April 2014 | 9th drop separated from funnel during beaker change | 156 | 13.4 |

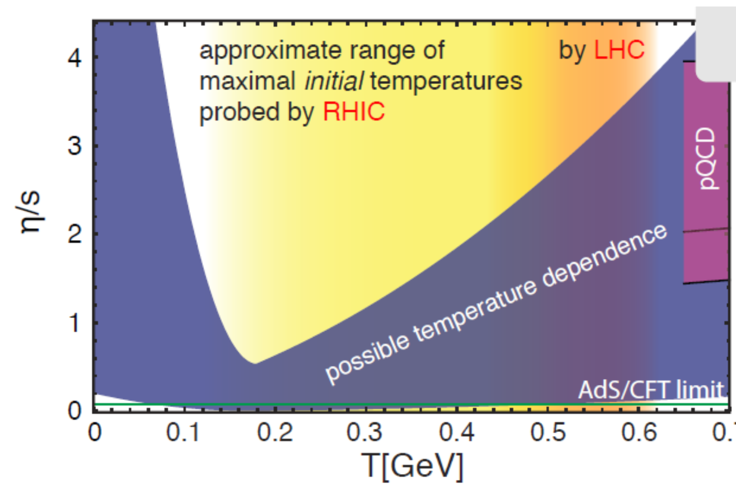


http://en.wikipedia.org/wiki/Pitch_drop_experiment

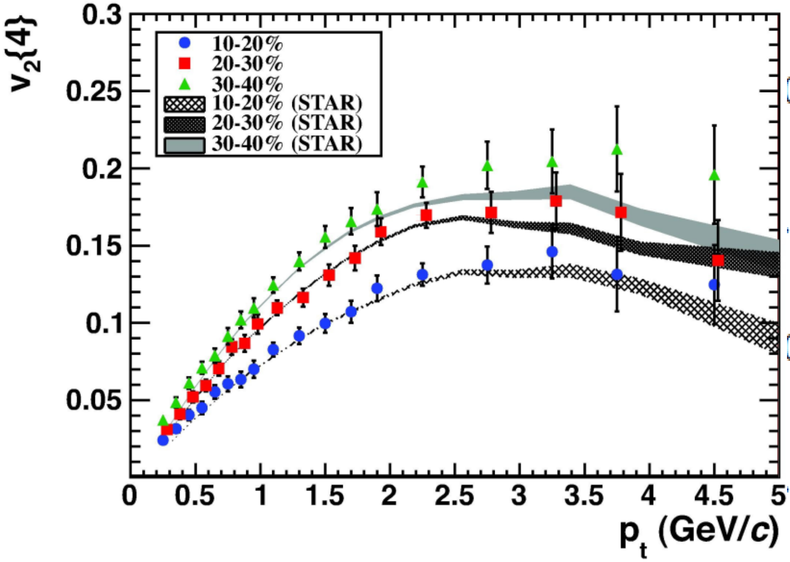
# Why Elliptic flow is important

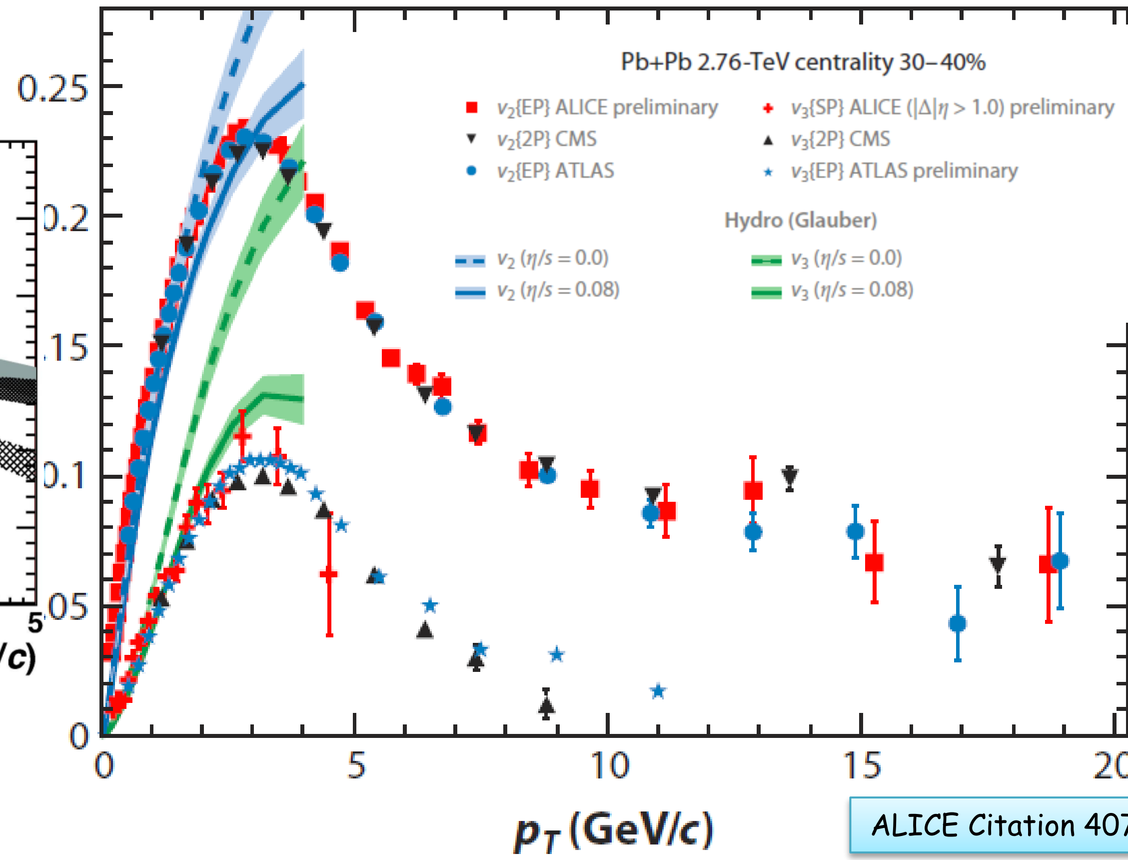
Data can be compared with relativistic hydrodynamic models and allow extraction of the medium viscosity

Fluids : viscosity decrease with temperature
Gas : viscosity increase with temperature



# Why Elliptic flow is important



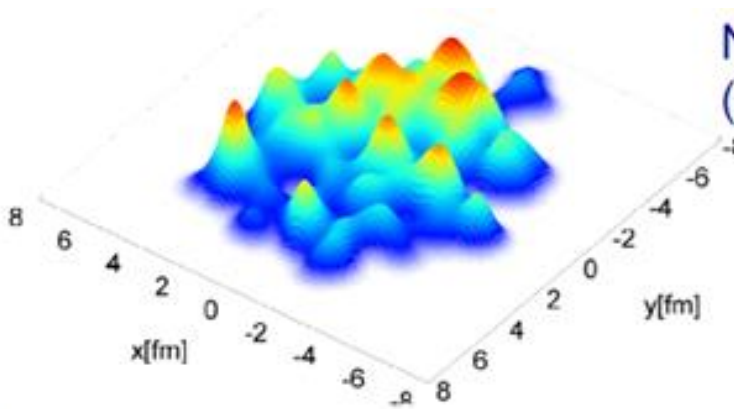

ALICE Citation 407

Results consistent with

- No change w.r.t. RHIC
- Presence of a perfect liquid ( η/s small ), NOT a gas of free quarks and gluons

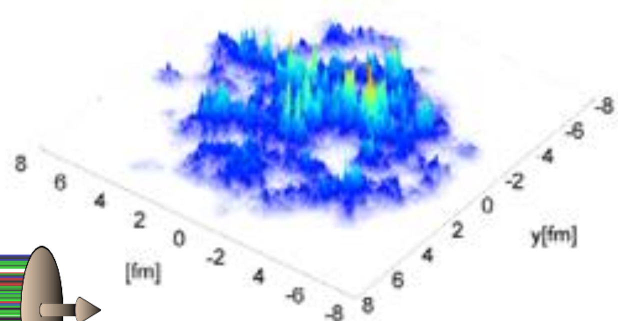
**Now available precise modelling initial state fluctuations to compare with flow measurements**

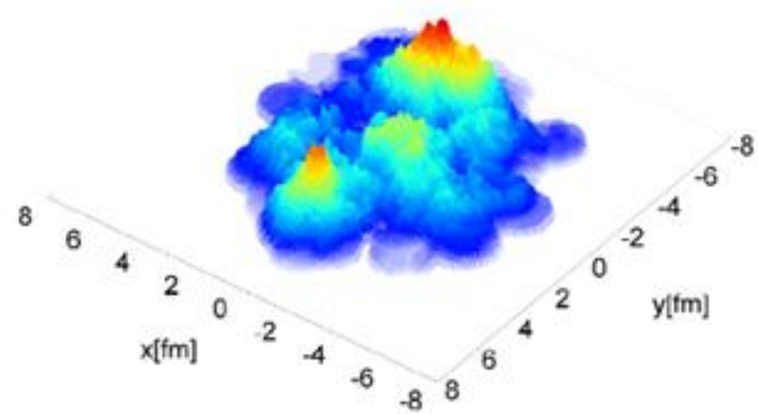
Nucleons
(std Glauber Model)

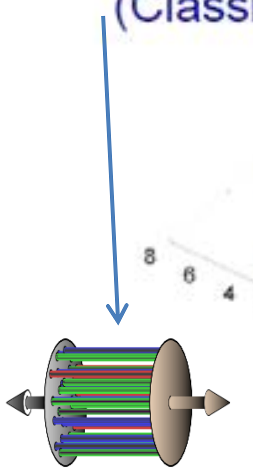



‘MC-KLN’
(CGC Color fields)

Glasma
(Classical color fields)



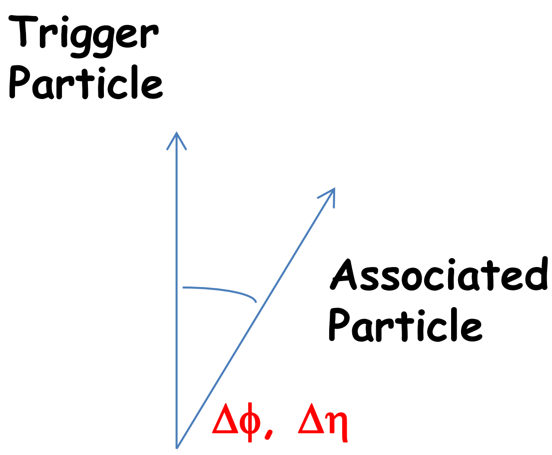



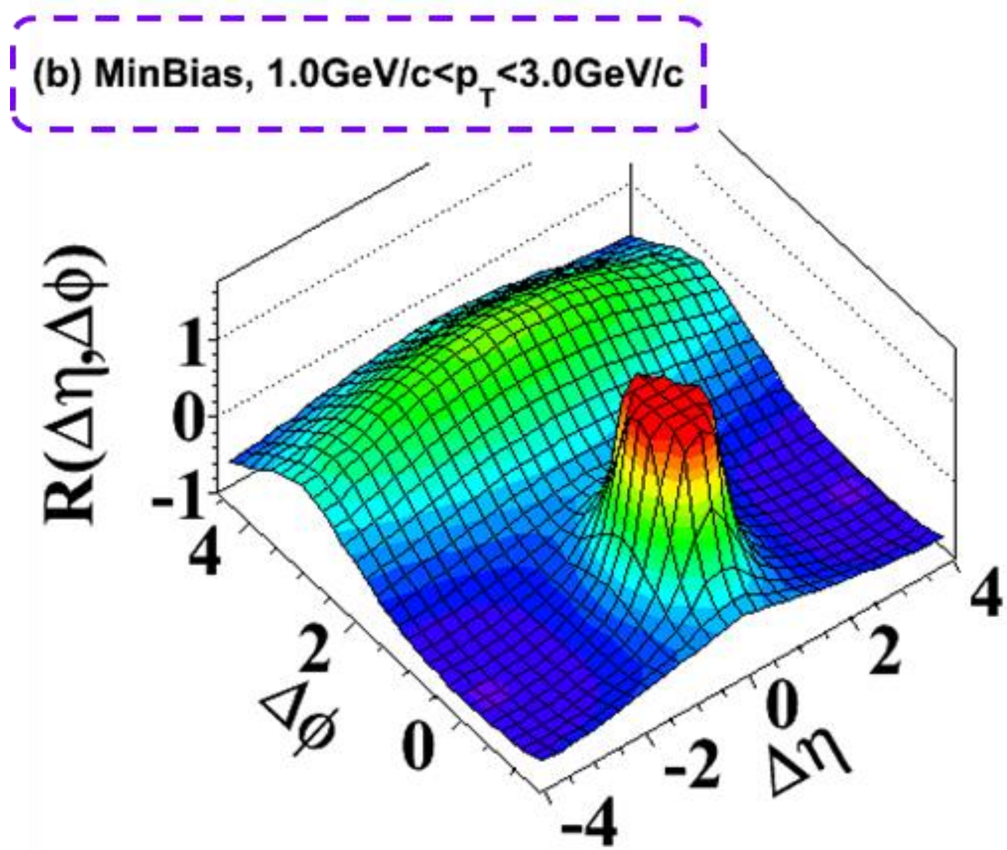



The initial chromo-~*E* and ~*B* fields form longitudinal “flux tubes” extending between the projectiles.

Schenke et al PRL 108 , 2523901
http://quark.phy.bnl.gov/~bschenke/

# Flow and correlations

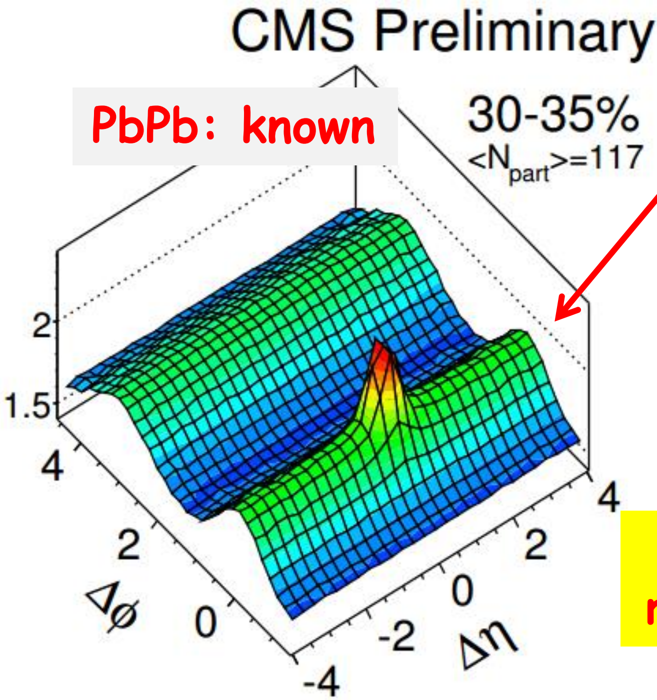


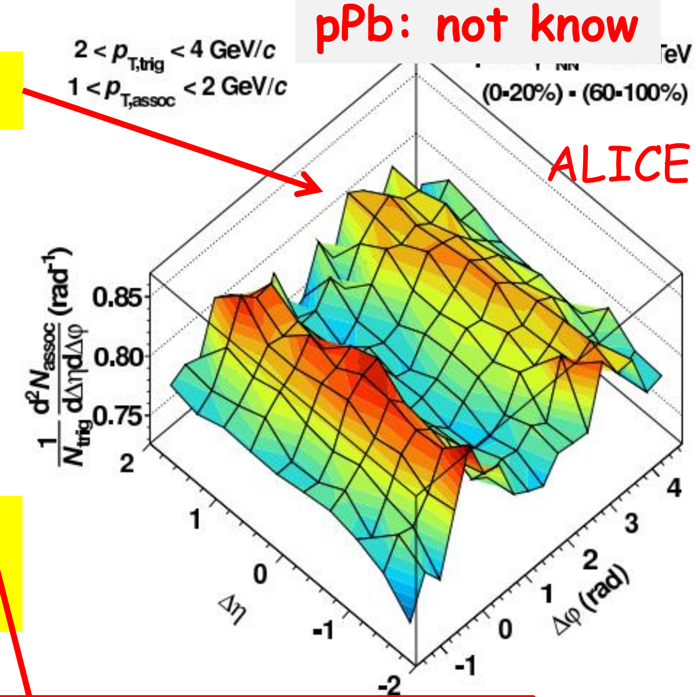



PbPb: known

The "double ridge"

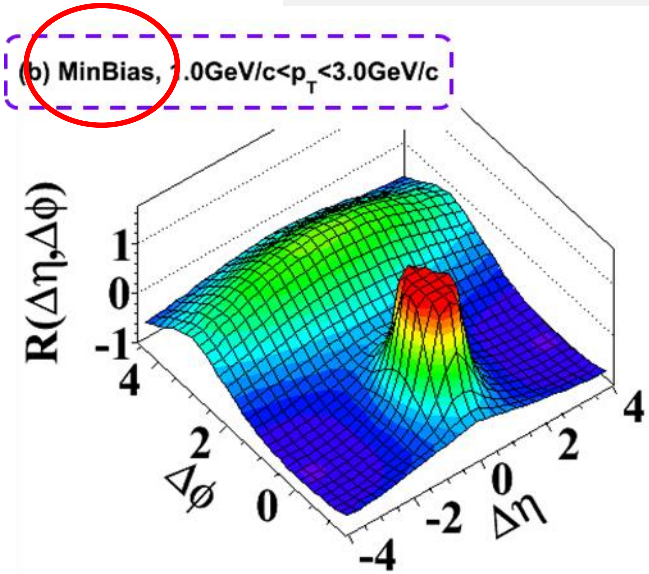
pPb: not know

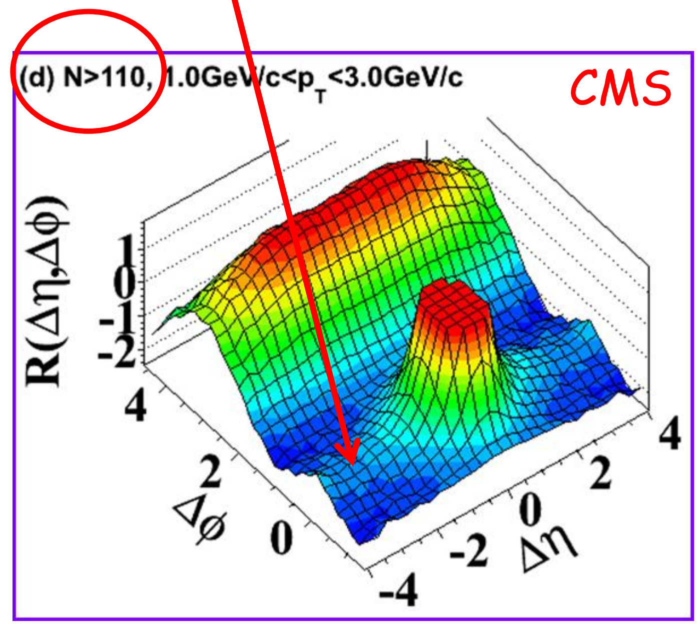


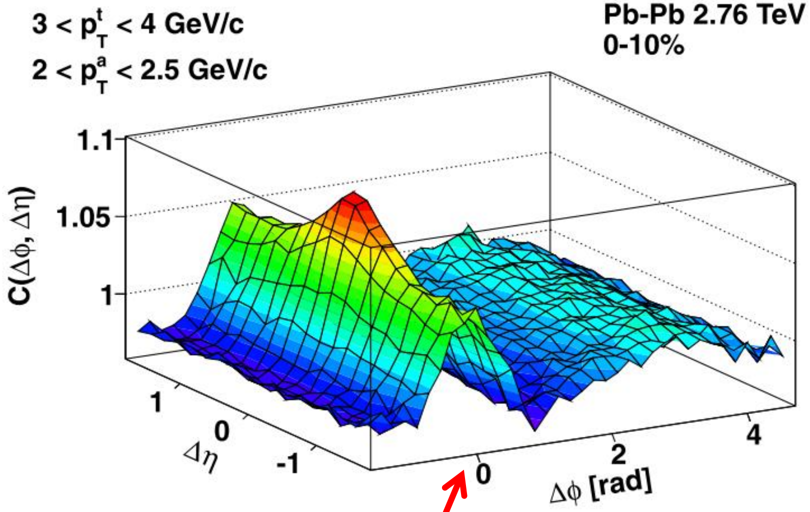

Collective phenomena related to multiplicity

pp – unexpected !



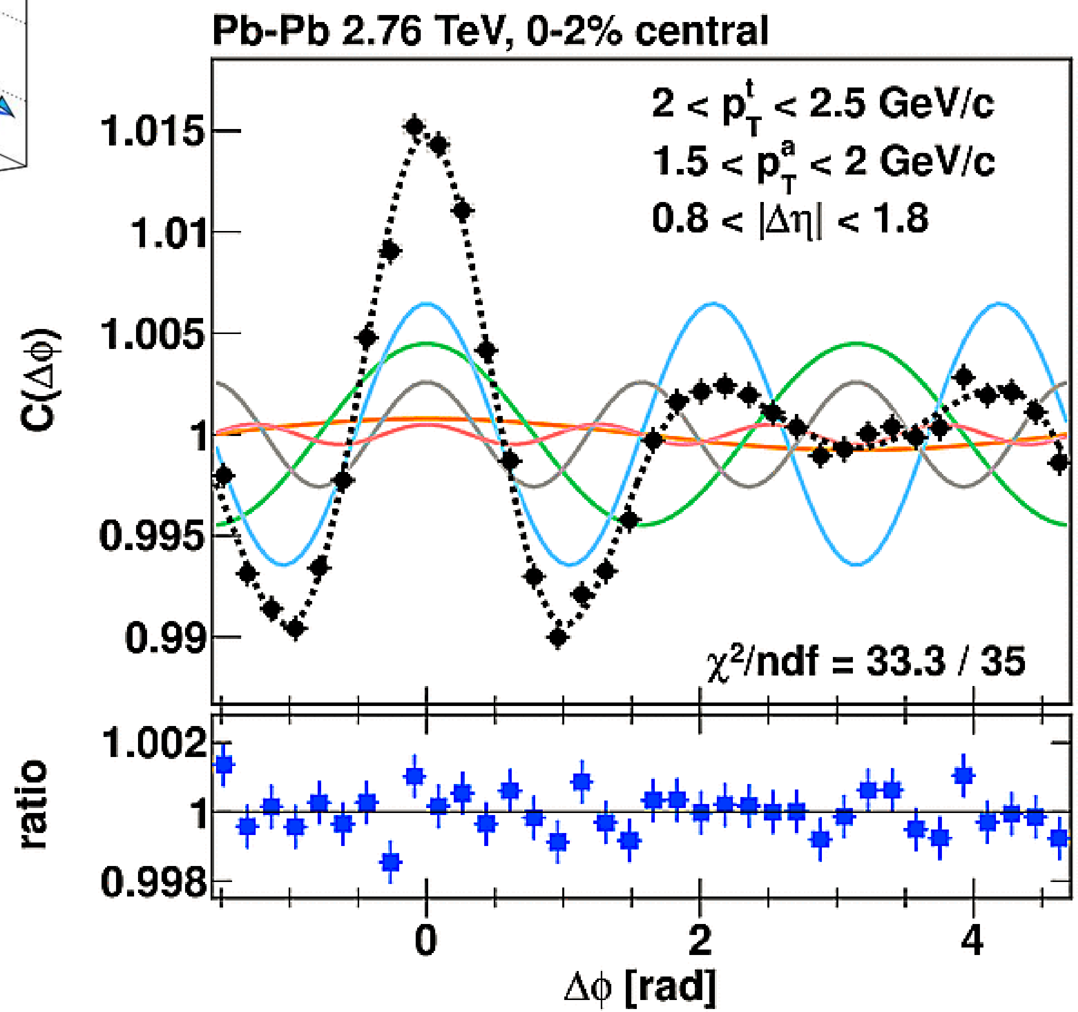



# Flow and correlations

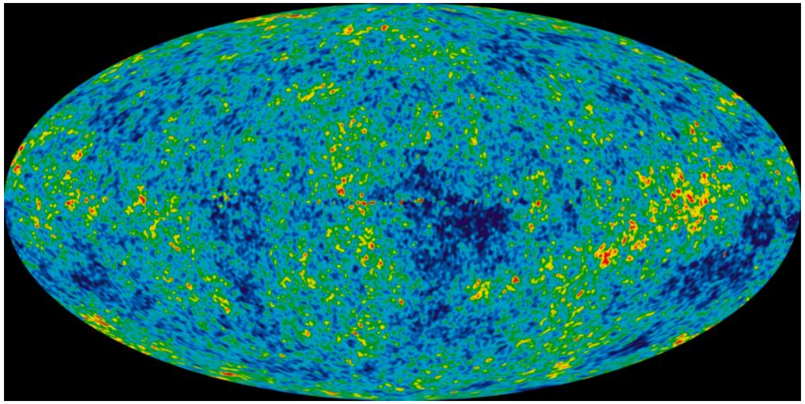


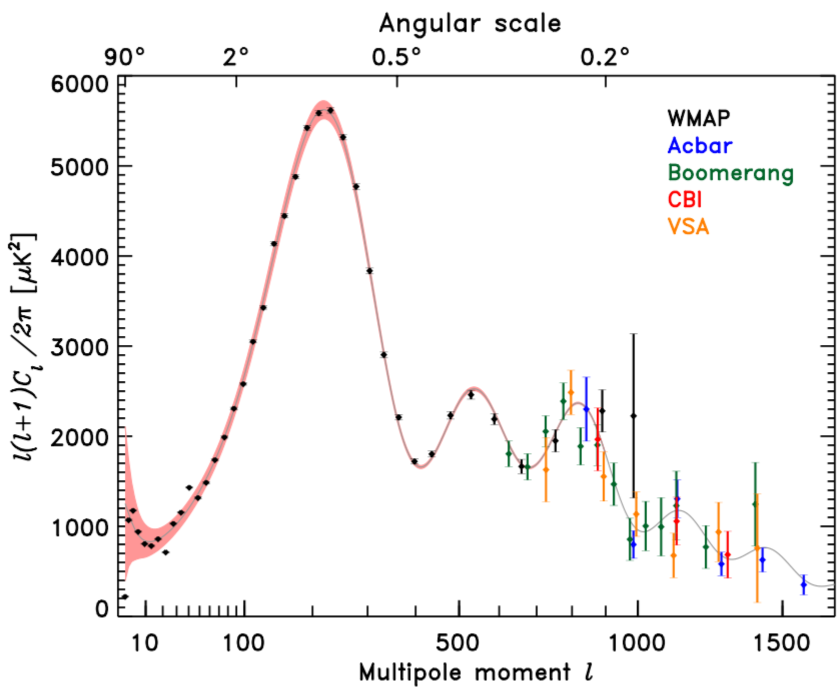

Two particle correlations in the 0-2% central collisions are fitted with Fourier analysis. First five harmonics describe shape at $10^{-3}$ level

Physics Letters B 708 (2012) 249–264



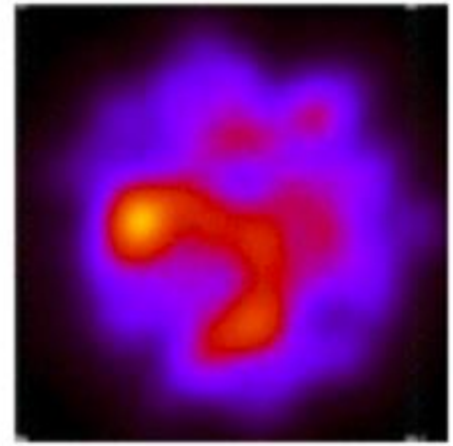
## WMAP Cosmic Microwave Background

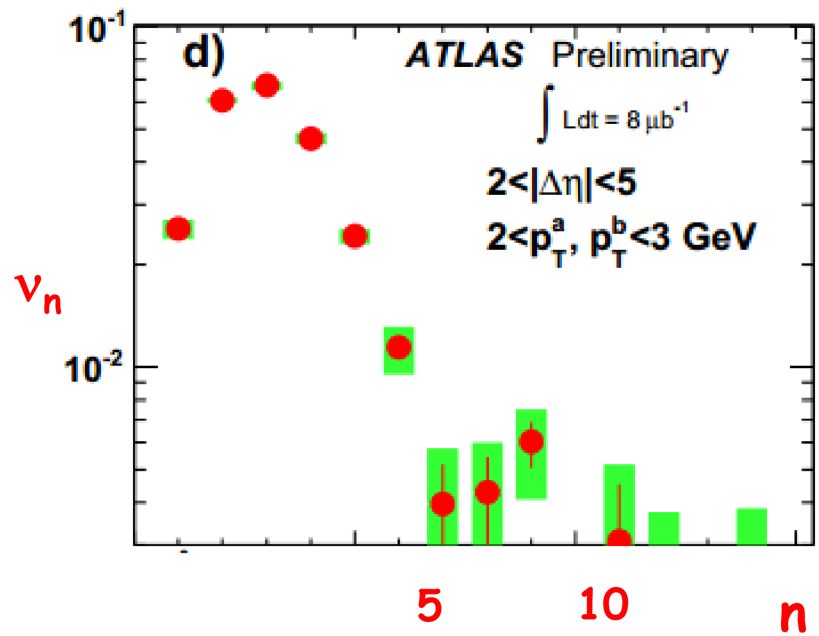




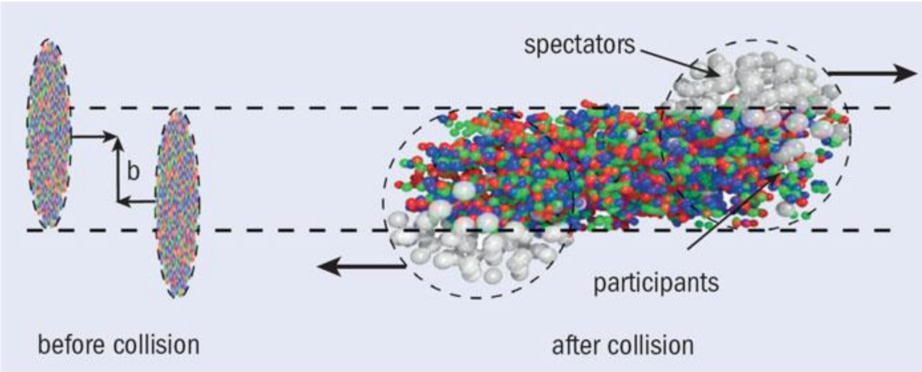

Understanding universe structure

## HI collisions QGP






Understanding initial QGP conditions and transport theory



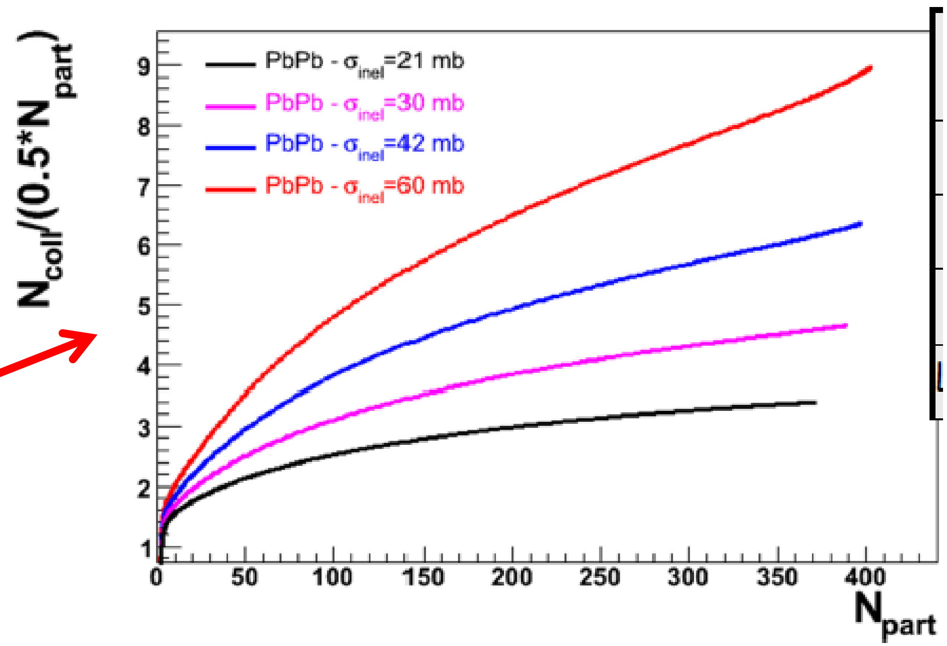

# Variables definitions

If Ncoll so high why not search for Higgs in Pb-Pb?

NO ! $N_{ev} = L\,\sigma$

Number of nucleons participating to the collision $N_{part}$

Average number of binary collisions between nucleons $N_{coll}$
*NB: usually independent collisions*




NB
Soft physics related to $N_{part}$
Hard physics related to $N_{coll}$

Example:
Centrality 0-1%
Npar = 403
Ncoll = 1681

# Variables definitions

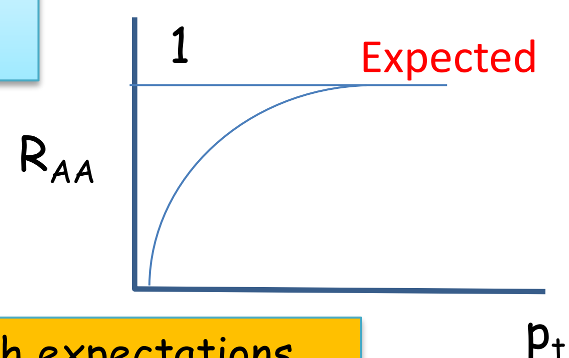
## Nuclear modification factor

$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{COLL} \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

$R_{AA}$ =1 simple scaling
Expected at high $p_t$

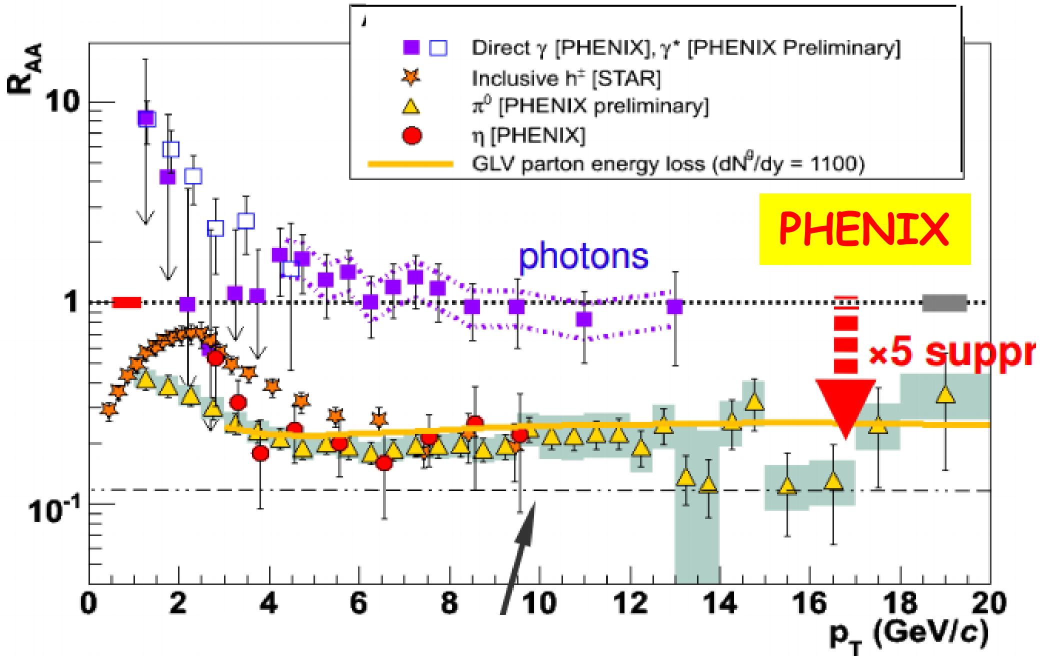
$R_{AA}$ <1 absorption by medium
Expected at low $p_t$

Indicates if in HI collisions the yield of particles, compared with pp yield , scales with the number of collisions or not




Which expectations for $\gamma$ , Z , W ?

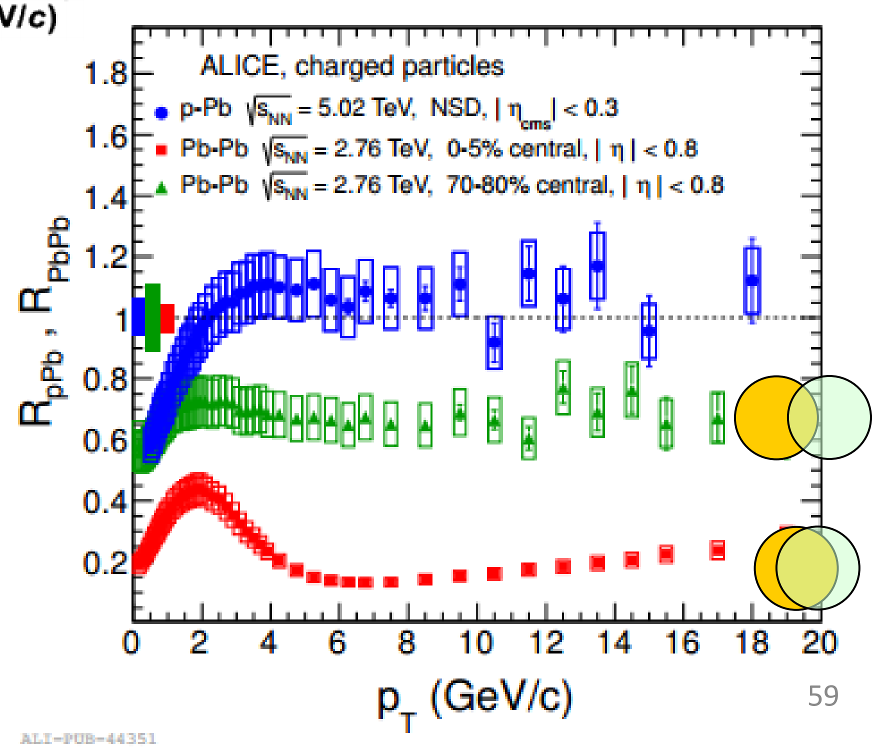
# Nuclear modification factor



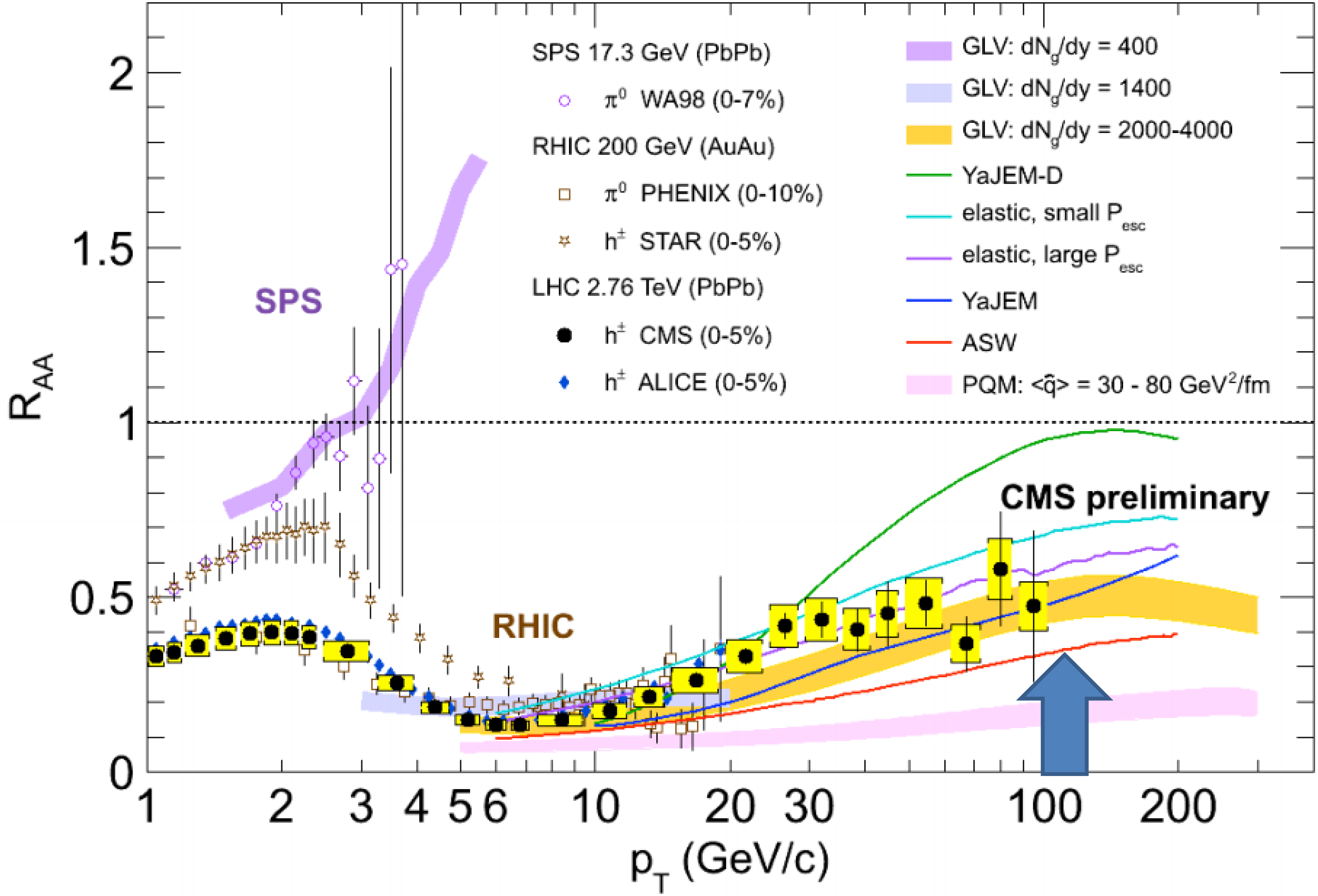

Photons do not show suppression since they do not participate in the strong forces

p-Pb collisions do not show suppression in cold matter

Peripheral collisions show a smaller suppression

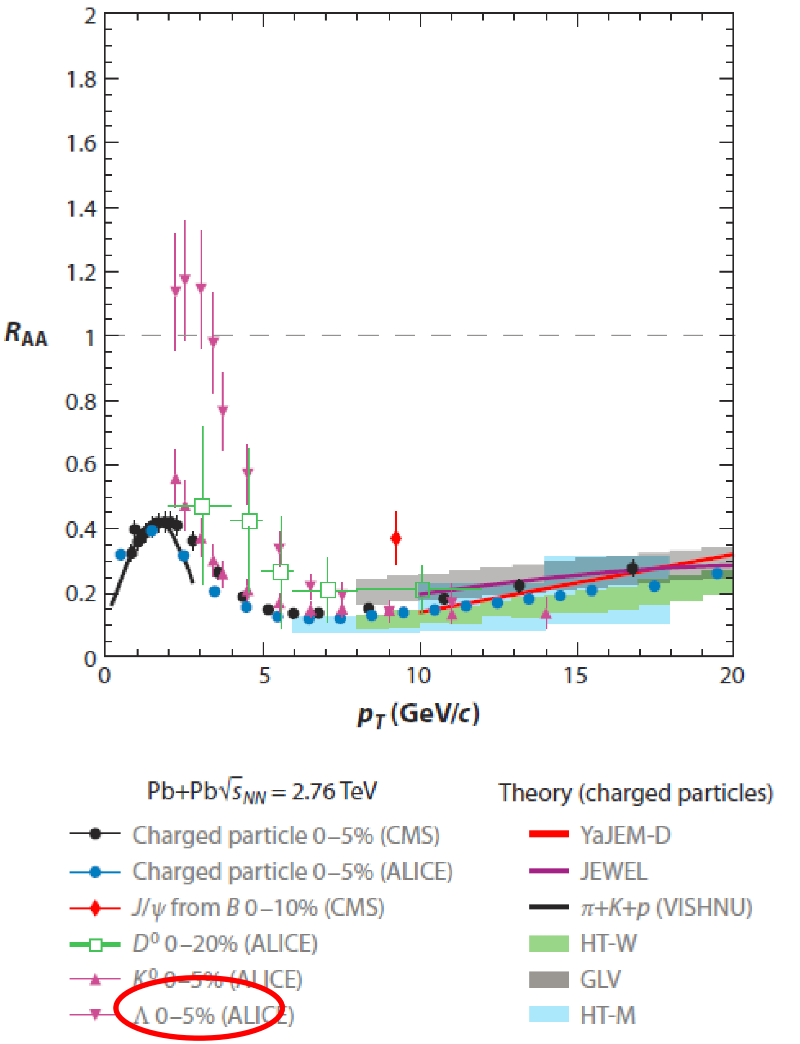


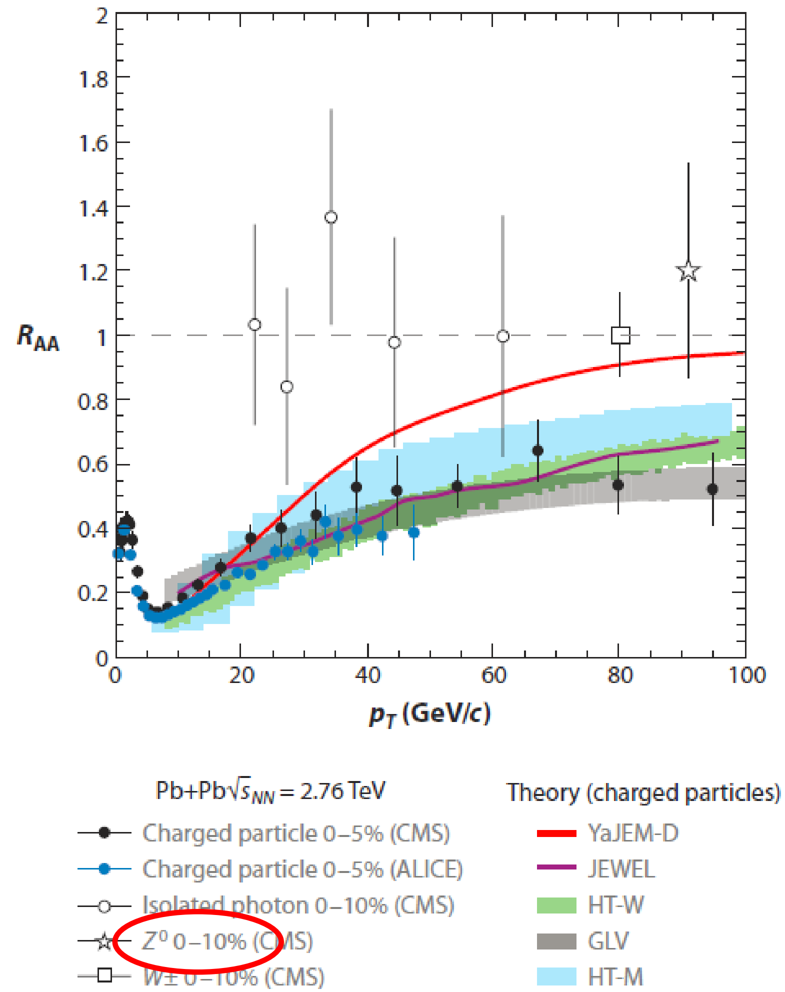
# Nuclear modification factor : LHC vs RHIC



# Nuclear modification factor: a compilation

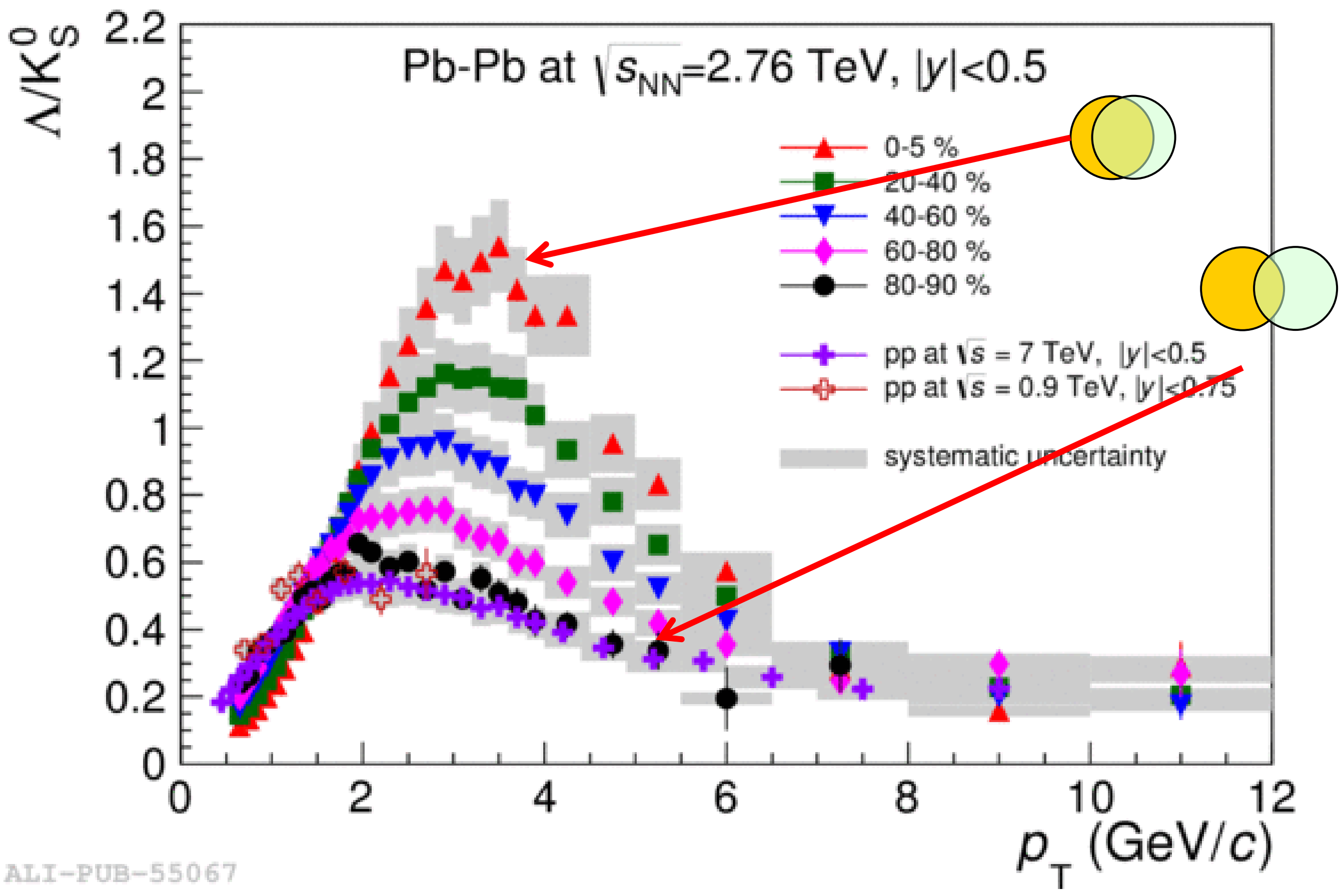
Muller et al Annu. Rev. Nucl. Part. Sci. 2012.62:361-386.



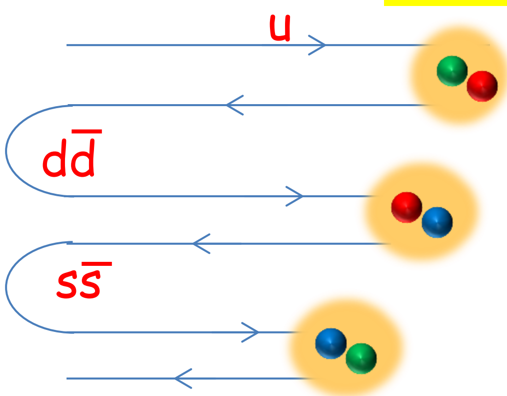



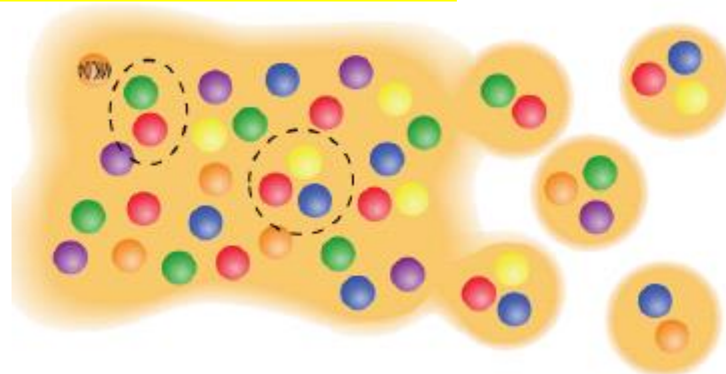

Parton traversing a hot and dense medium loose substantially more energy than in cold nuclear reaction, both via gluon radiation and elastic scattering

# Baryon enhancement in PbPb collisions



# Hadronization models in medium



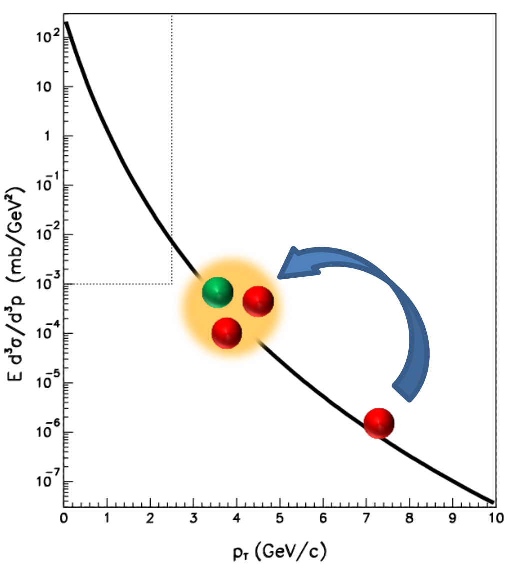



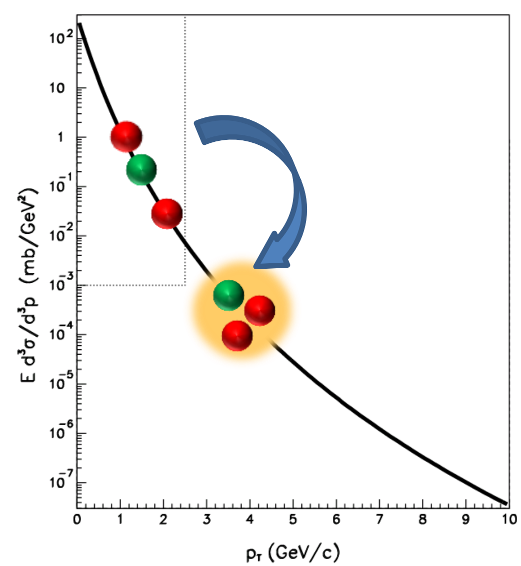
**Lund fragmentation**

- Small baryon/meson ratio
- $p^{\text{final hadron}} < p^{\text{fragmenting parton}}$

**Coalescence**

- higher baryon/meson ratio
- $p^{\text{final hadron}} > p^{\text{fragmenting parton}}$



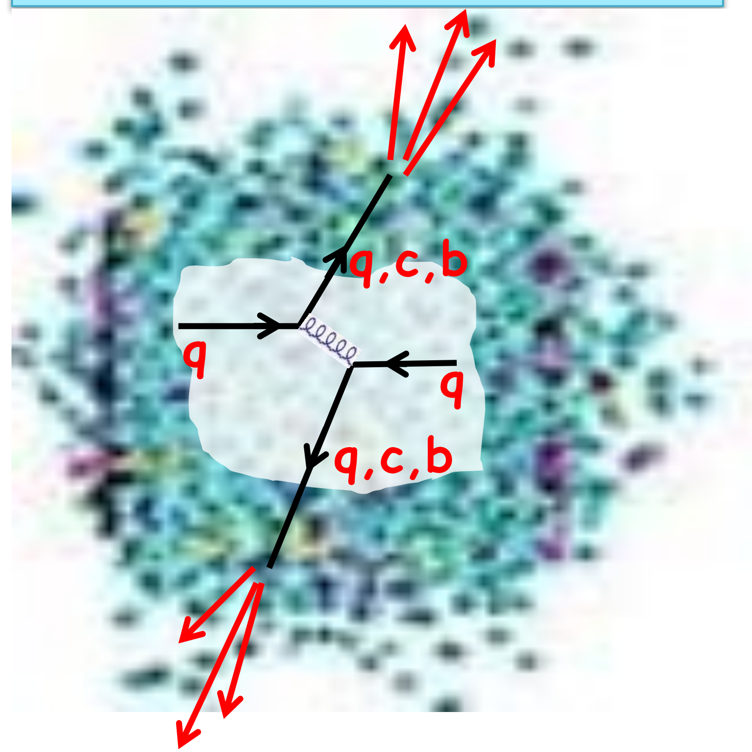



# How to characterize the hot medium from inside

A: Via measurements of the bulk properties of the particles produced: Spectra , hadrochemistry

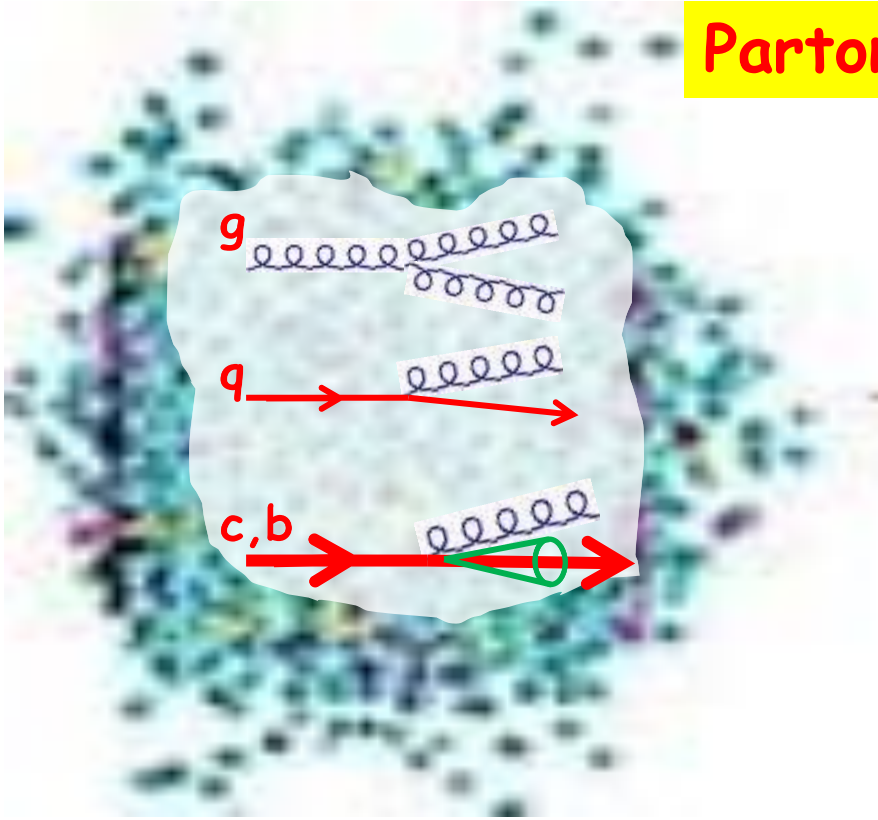
B: elliptic flow , particle correlations …

C: Hot medium tomography using hard probes produced in the collision




Heavy Flavours ,Jets , high pt particles: we can calculate how many

# Partons energy loss in medium




Depends on:

Casimir factors related to flavour

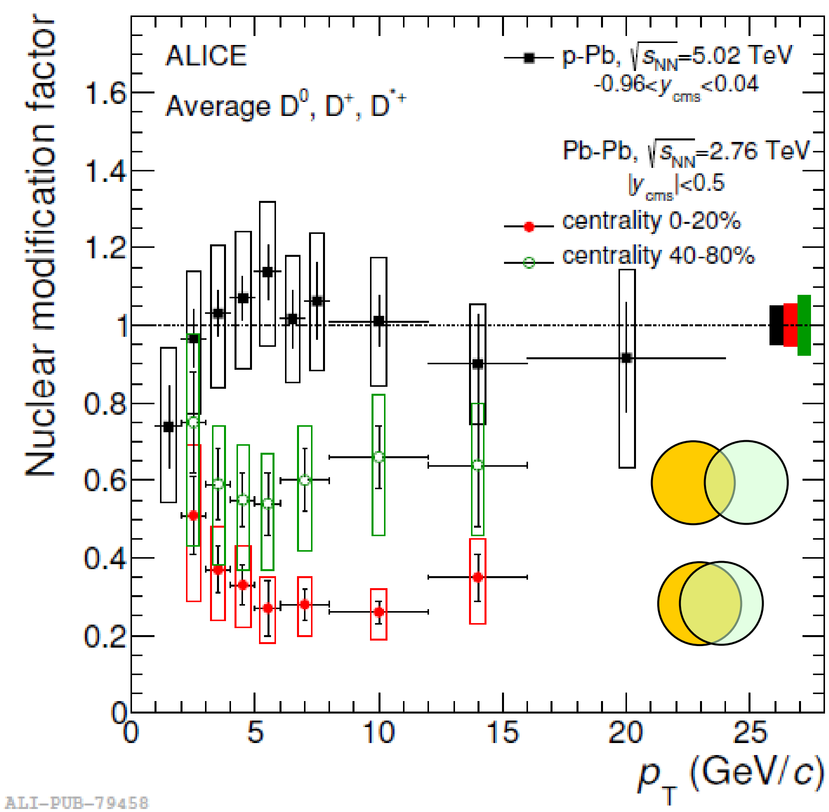
$C_R^{\ g} = 3 \qquad C_R^{\ q,c,b} = 4/3$

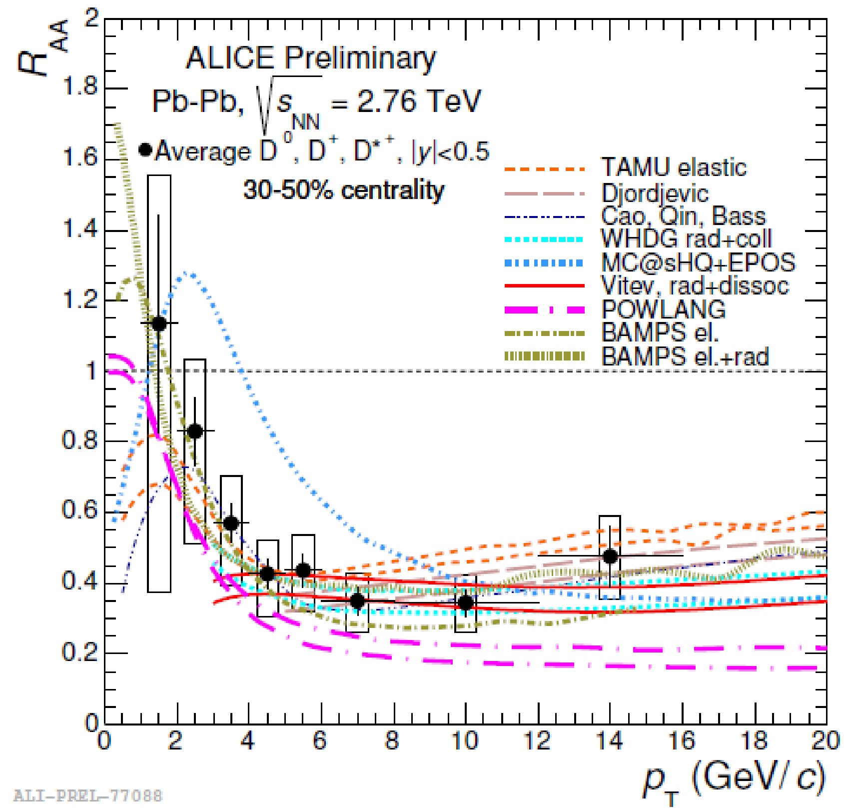
Mass ( dead cone effect) → lower gluon radiation for c and b

**Mass ordering expectations:**

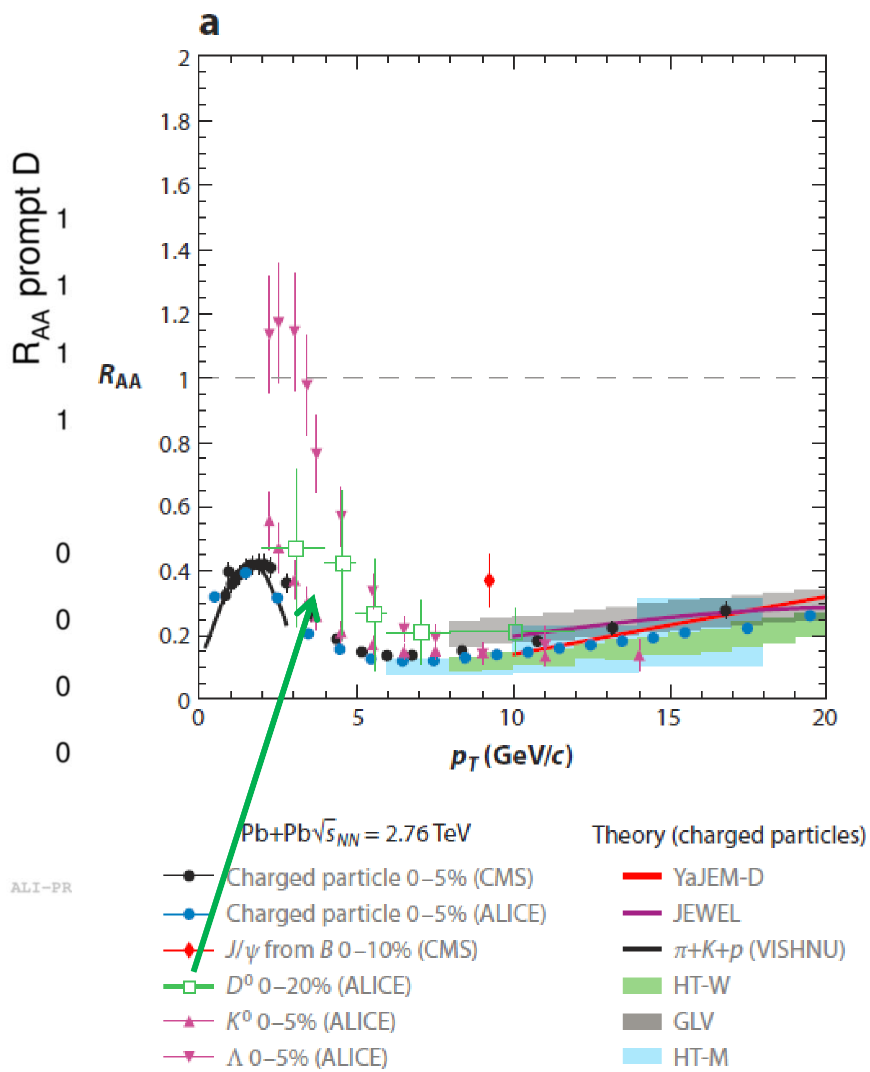
$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

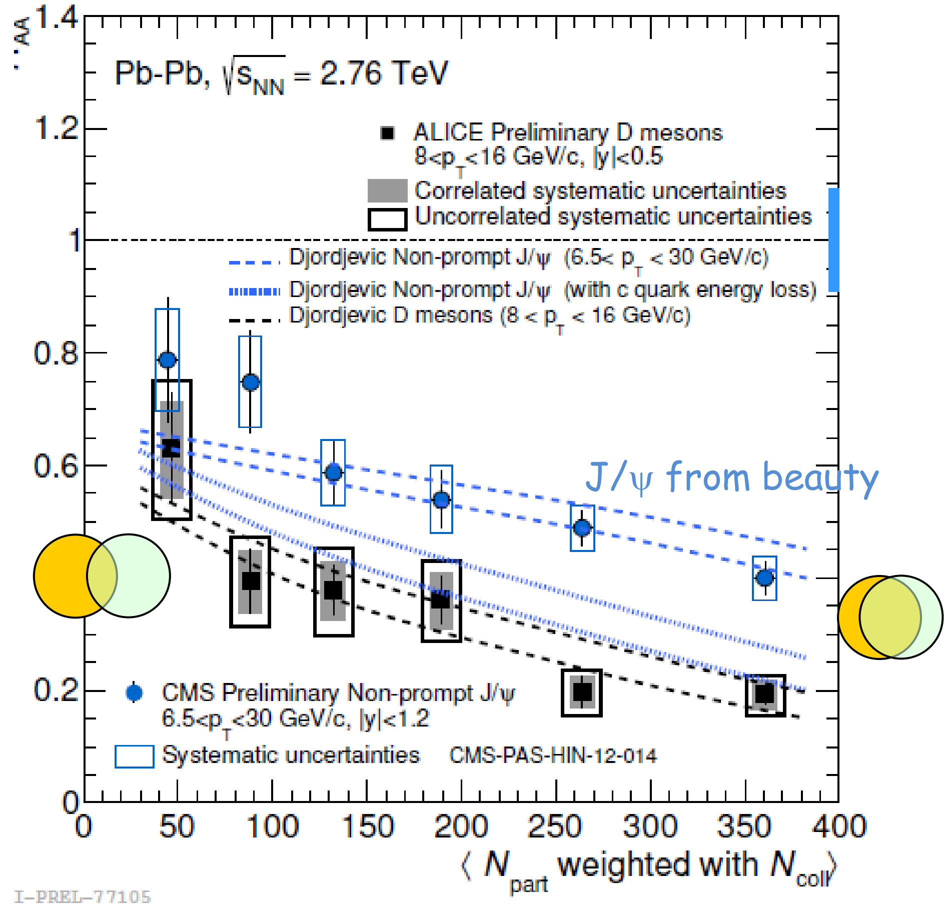
# ALICE D production



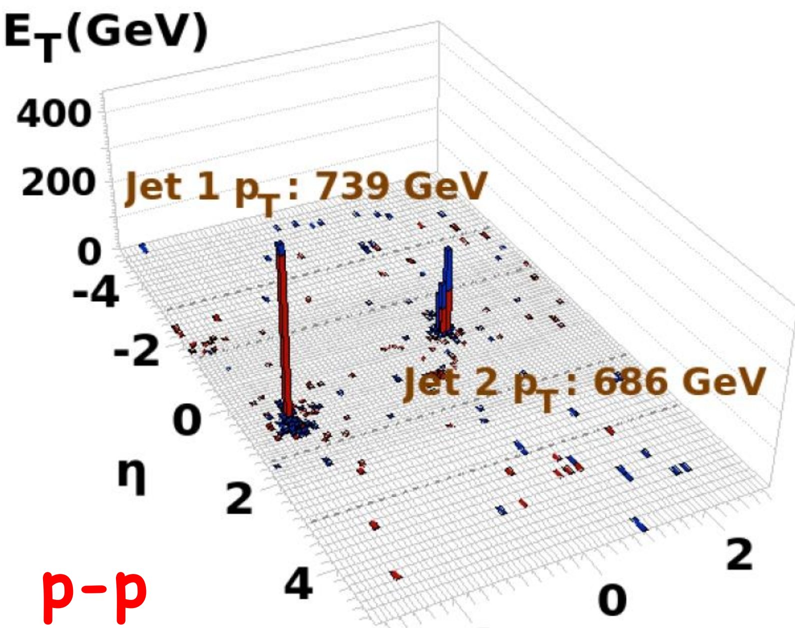
# HF production : indications for mass ordering

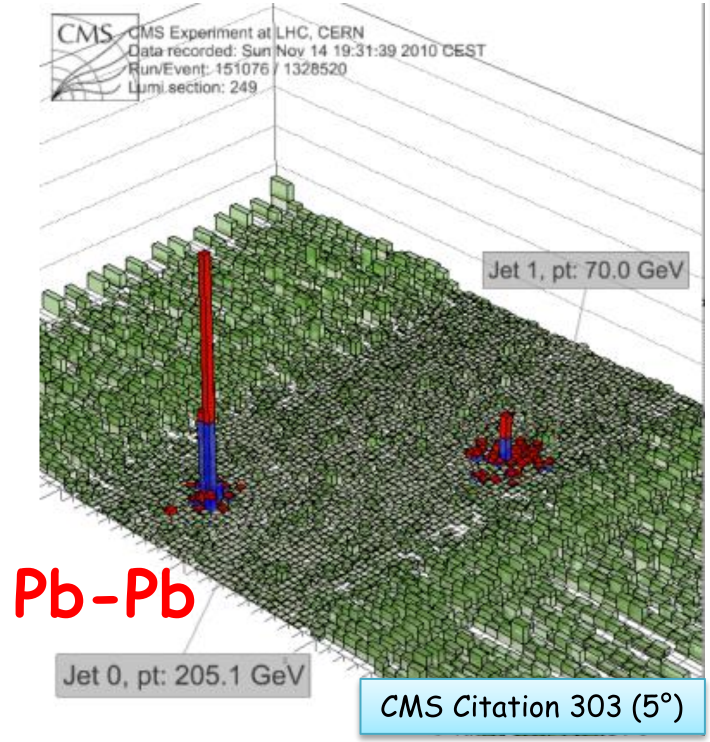


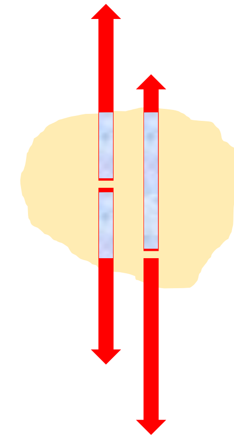

Hints for an energy loss in medium with mass gerarchy $R^{\pi}_{AA} < R^{c}_{AA} < R^{b}_{AA}$

# Jets quenching in PbPb



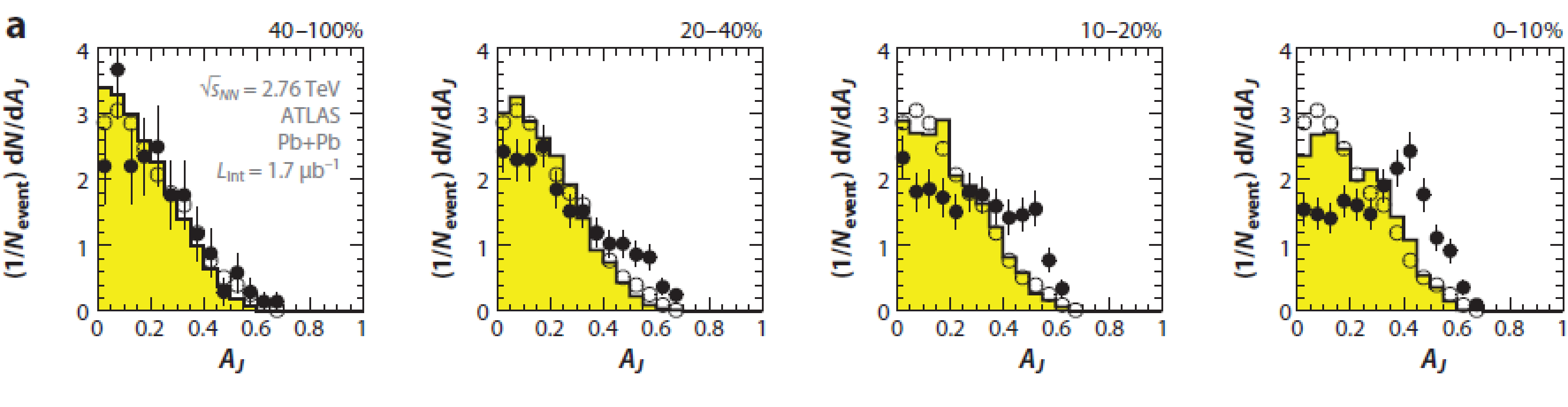

Always?



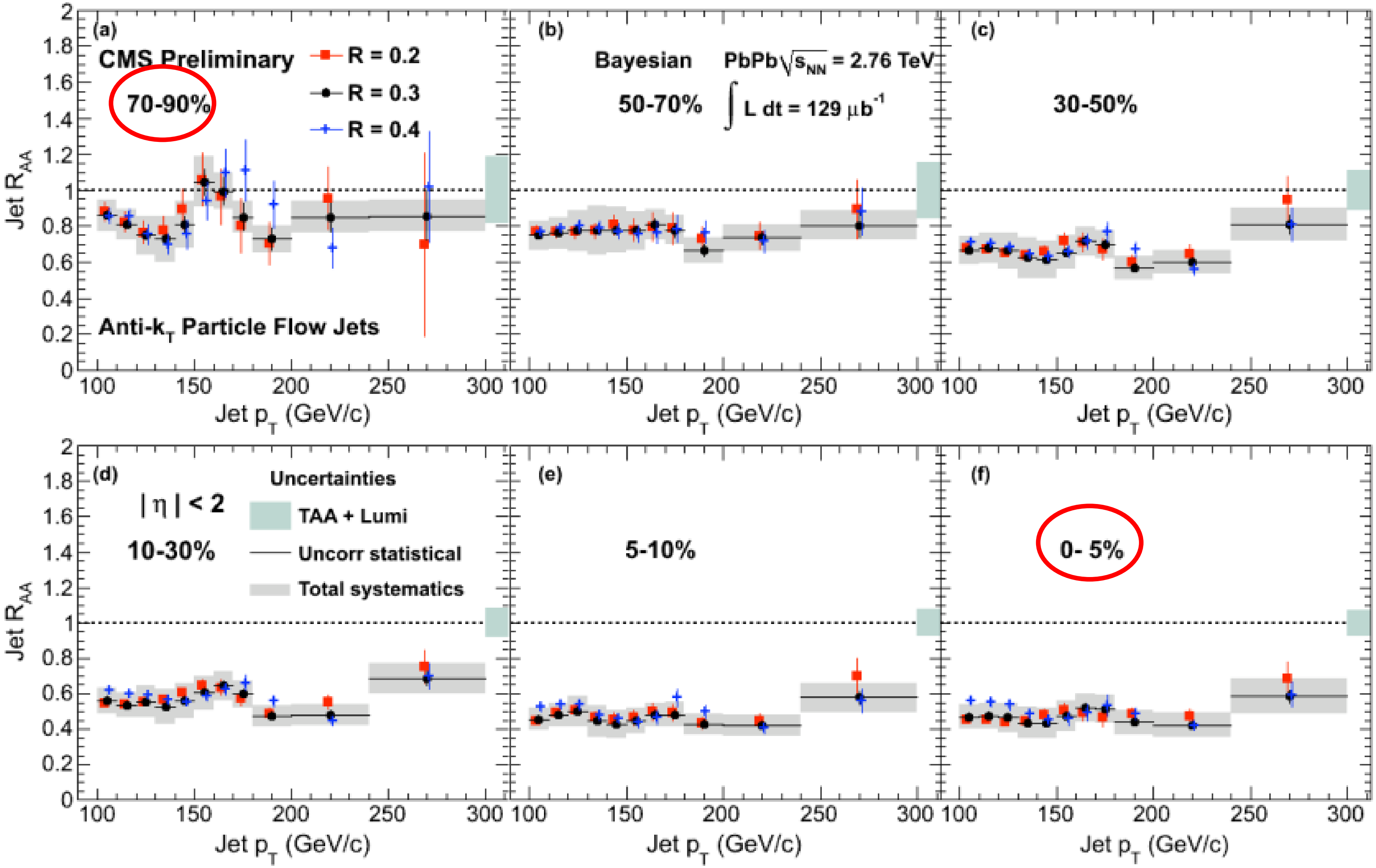
$$A_j = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

= 0 if jets almost equal

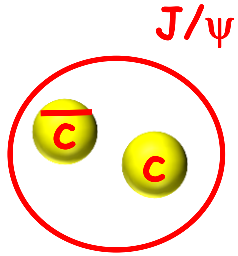
> 0 if jets have different pT



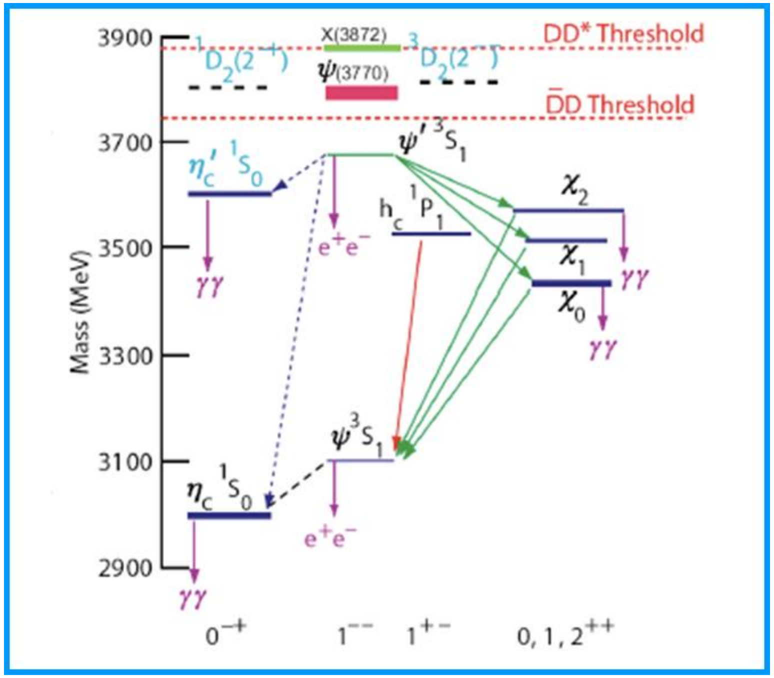
# Jets quenching in PbPb



# Quarkonia in QGP

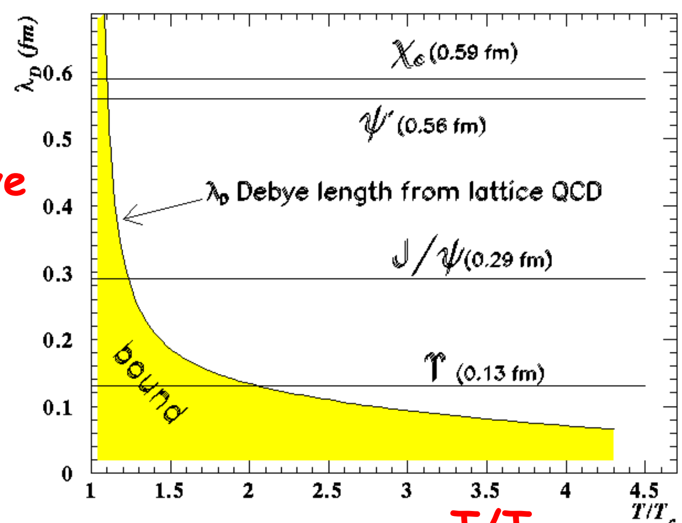



$$V(r) = -\frac{\alpha}{r} + kr$$

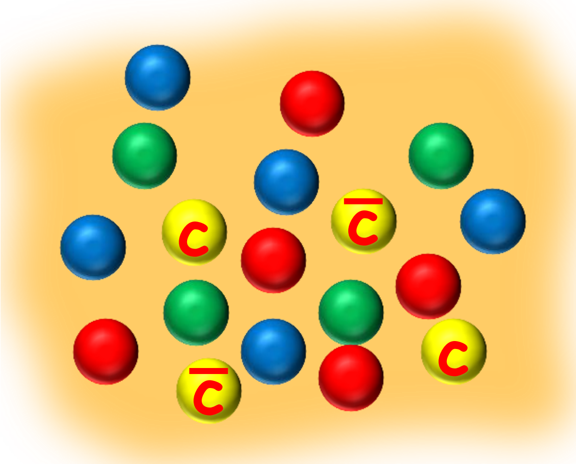



$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_d}$$

λ Debye




$T/T_c$



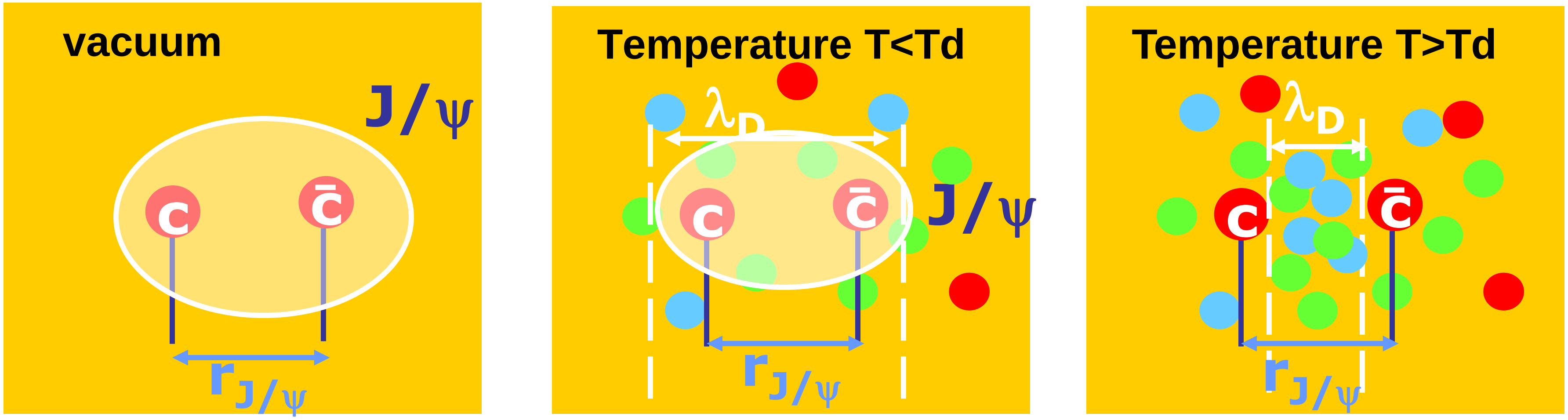

Color Screening → Charmonium production suppressed

Matsui T, Satz H (1986)
PHYSICS LETTERS B 178(4): 416-422.

# Debye screening

R. Arnaldi

➡ The screening radius $\lambda_D(T)$ (i.e. the maximum distance which allows the formation of a bound QQ pair) decreases with the temperature T




At a given T:

if resonance radius < $\lambda_D(T)$
→ resonance can be formed

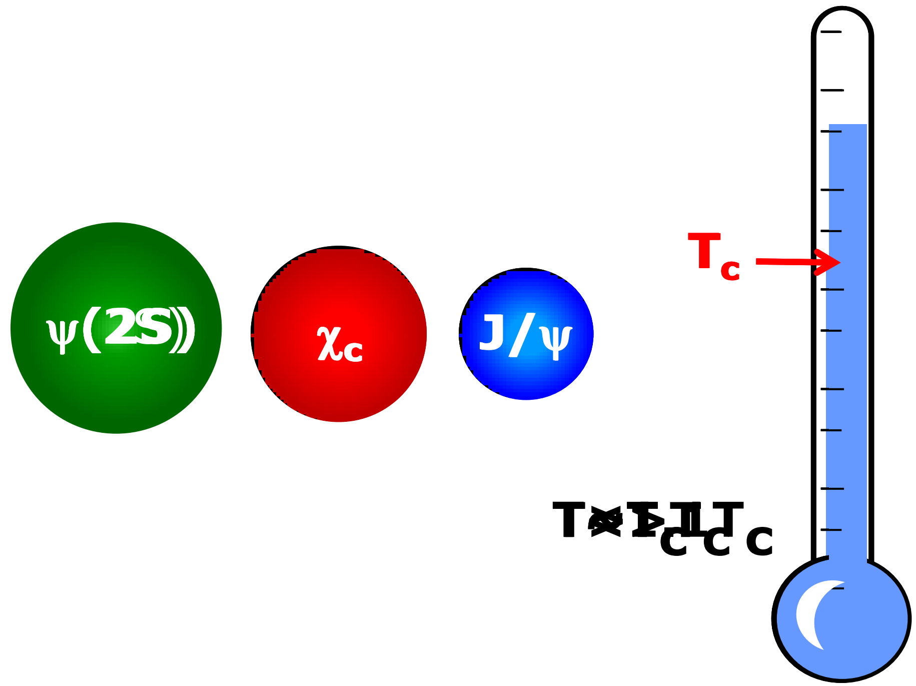
if resonance radius > $\lambda_D(T)$
→ no resonance can be formed

# Production of J/psi :
# a thermometer of the initial QGP temperature

R. Arnaldi

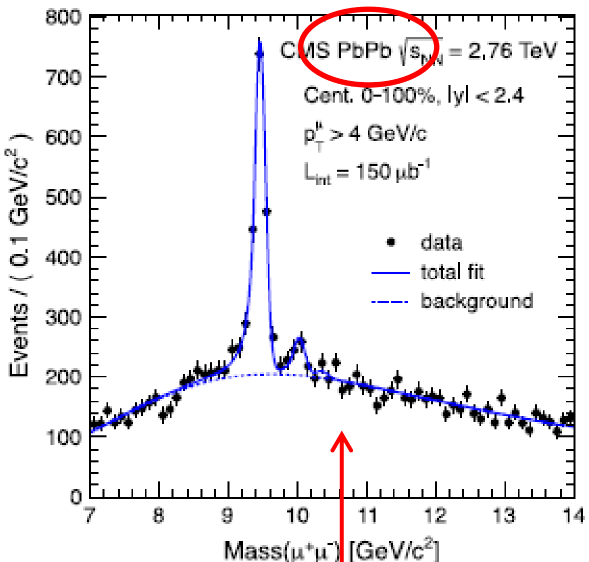
| state | $J/\psi$ | $\chi_c$ | $\psi(2S)$ |
|---|---|---|---|
| Mass(GeV) | 3.10 | 3.51 | 3.69 |
| $\Delta E$ (GeV) | 0.64 | 0.22 | 0.05 |
| $r_o$(fm) | 0.50 | 0.72 | 0.90 |

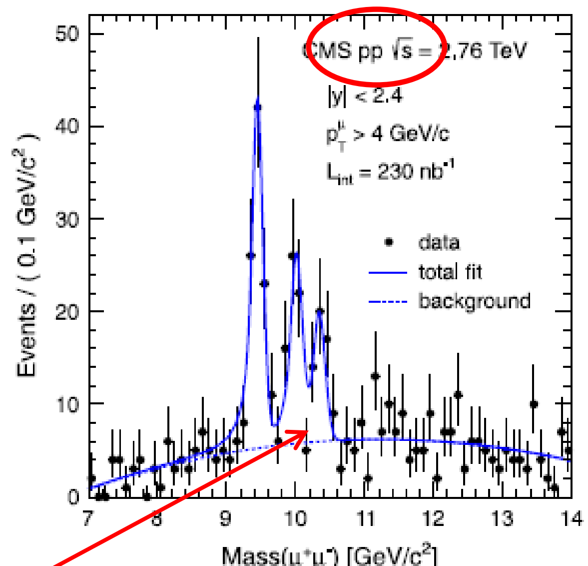
| state | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ |
|---|---|---|---|
| Mass(GeV) | 9.46 | 10.0 | 10.36 |
| $\Delta E$ (GeV) | 1.10 | 0.54 | 0.20 |
| $r_o$(fm) | 0.28 | 0.56 | 0.78 |



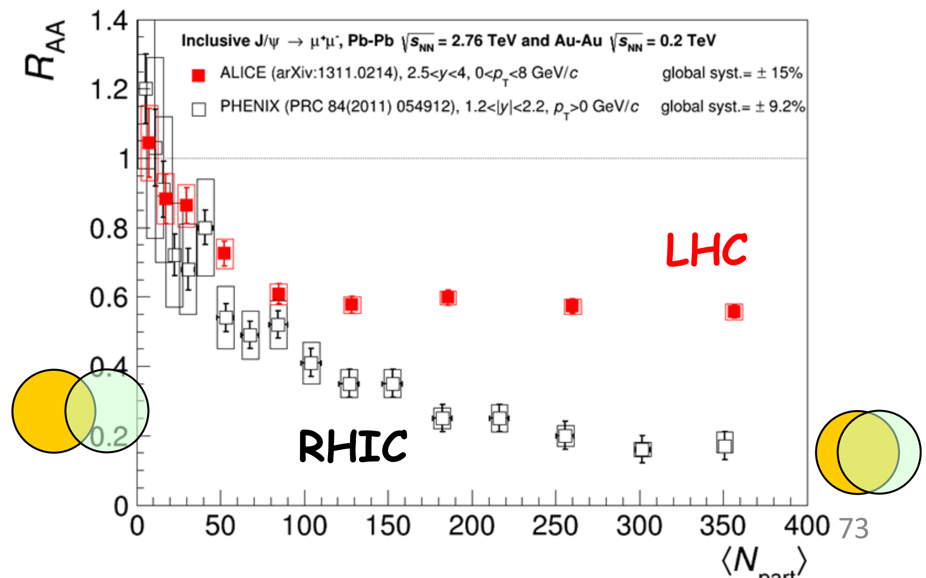

(Digal,Petrecki,Satz PRD 64(2001) 0940150)

# Production of J/psi :
# a thermometer of the initial QGP temperature



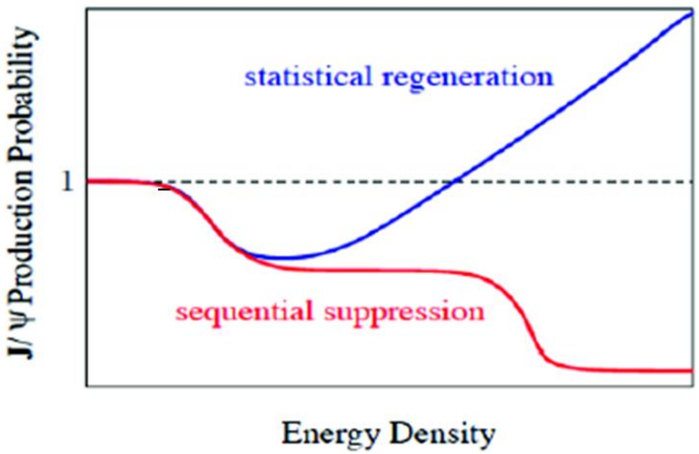



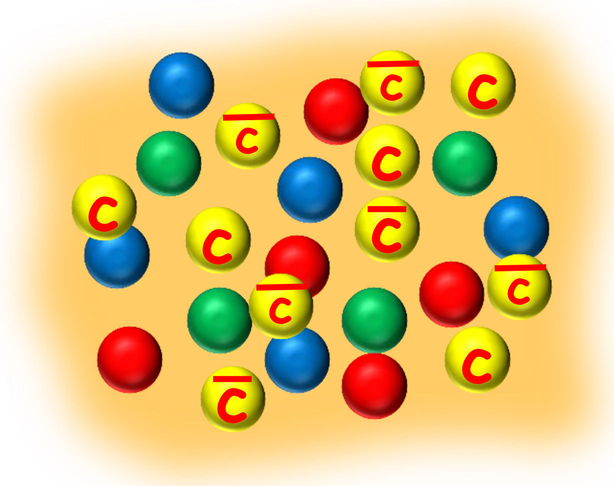

ψ(2S)



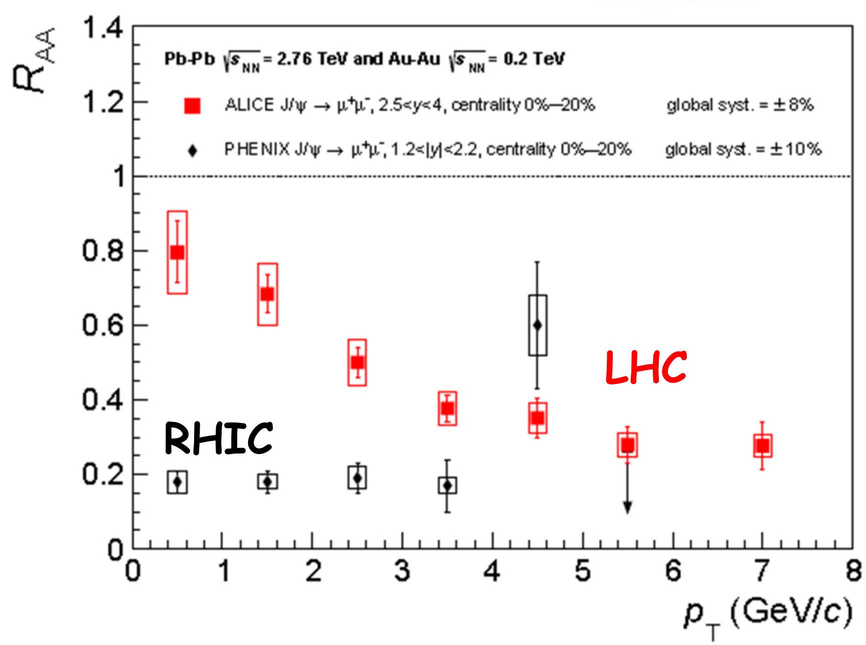

Anything strange ?

# Production of J/psi :
# a thermometer of the initial QGP temperature



At higher densities (LHC) higher probability of regeneration



# Conclusions - II

- More specific analyisis have been performed to understand the QCD properties of the matter produced in HI
- Elliptic flow indicates that the matter produced looks more like a perfect fluid than a free gas of quarks and gluons
- Two particles correlations indicates the presence of collective phenomena (ridge) not only in Pb-Pb collisions but also, unexpectedly, in p-Pb and high multiplicity p-p events indicating possible universal properties in particle formations
- The nuclear modification factor RAA is < 1 , indicating a suppression for particle production due to energy loss inside the QGP whose properties can then be studied by hydrodynamical models.
- Hard probes ( jets and Heavy Flavour) are like projectiles crossing the QGP and thus allowing a careful check of the QCD energy loss mechanisms
- Production of quarkonia is a thermometer for the initial QGP tmperature.

- LHC and RHIC Heavy Ions programs have plans through the end of 2020ies.
- High luminosity will allow more detailed studies using hard probes (charm, beauty, jets) and low mass leptons pairs. An e-Pb collider will improve our knowledge of the Nuclei PDF.

Further reading:


M. Riordan and W.A. Zajc , Scientific American , May 2006

P.B. Munzinger and J. Stachel , NATURE Vol 448 19 July 2007

B. Muller et al. Annu. Rev. Nucl. Part. Sci. 2012.62:361-386.

G. Roland et al., Progress in Particle and Nuclear Physics 77 (2014) 70–127

U. Heinz , Xiv:hep-ph/0407360v1 30 Jul 2004