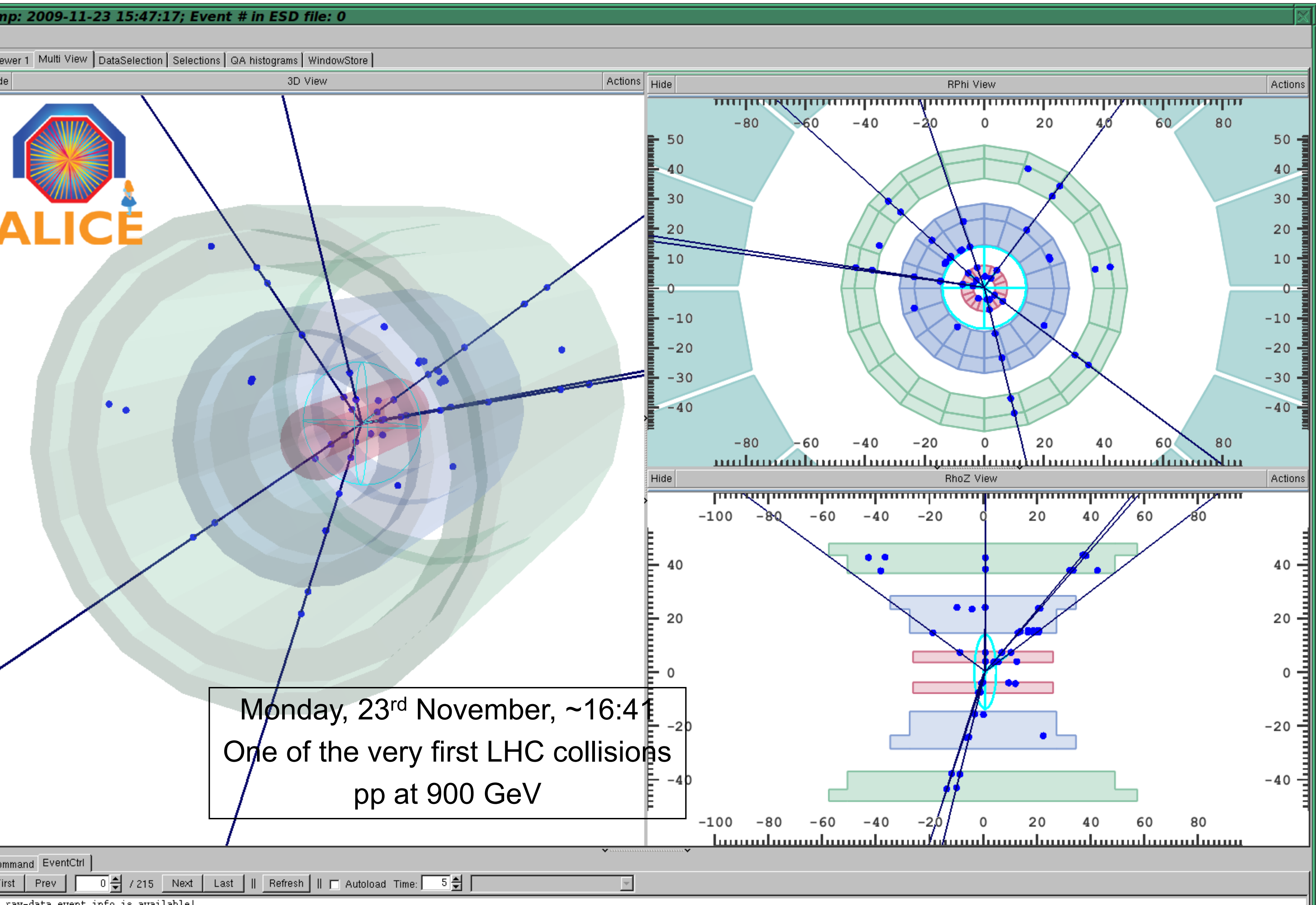
2010: Annus Mirabilis ?
The ALICE Perspective

23rd Nov 2009: The Start of LHC

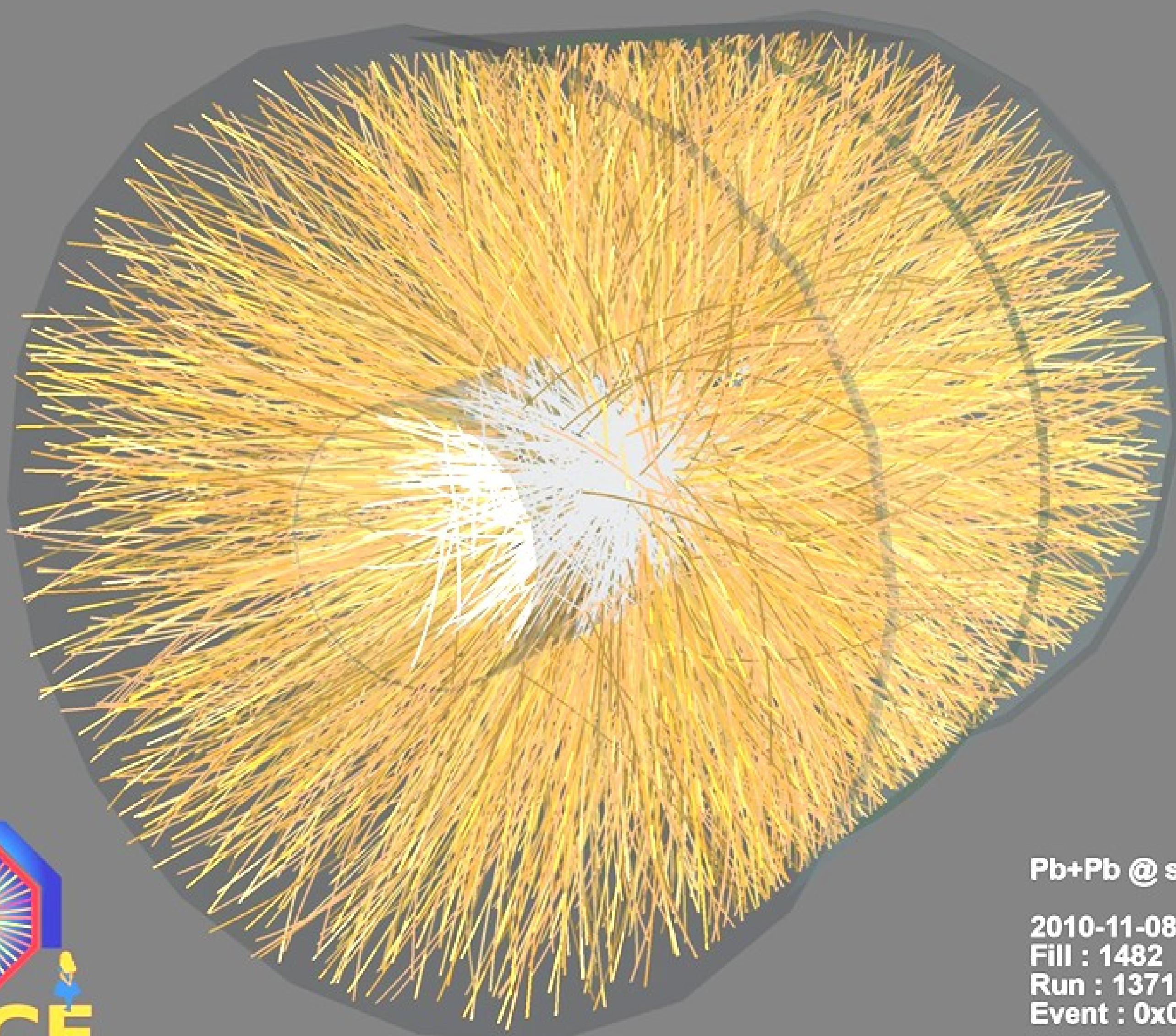


Monday, 23rd November, ~16:41

One of the very first LHC collisions

pp at 900 GeV

7 Nov 2010: First Heavy Ion Collision



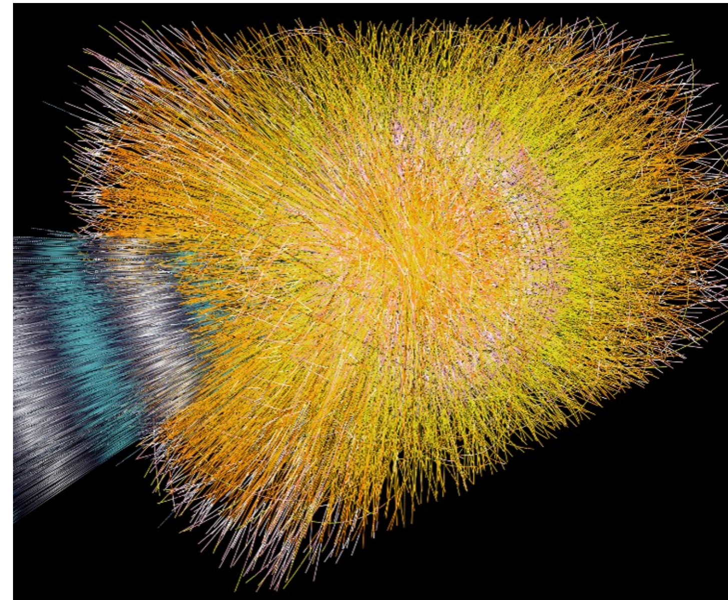
Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

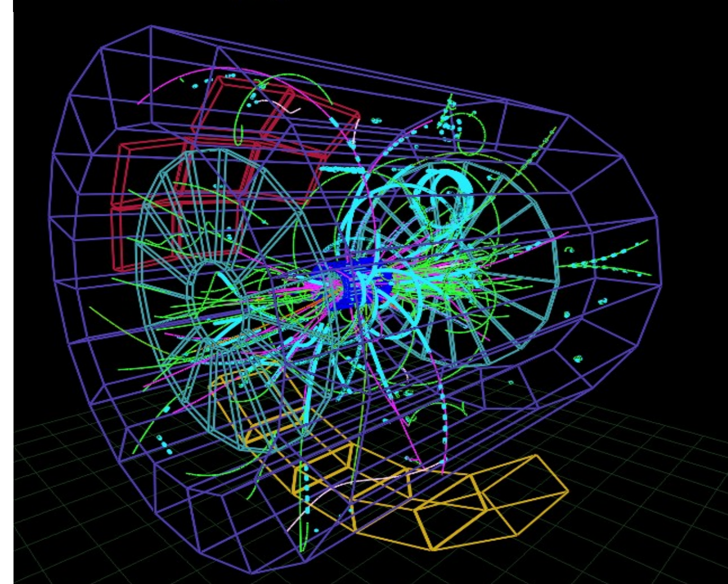
ALICE

pp physics in ALICE

- Core Business is Heavy Ions



- Physics with pp
  - ⇨ collect ‘comparison data’ for heavy ion program
    - many signals measured ‘relative’ to pp
  - ⇨ comprehensive study of MB@LHC
    - tuning of Monte Carlo (background to BSM)
  - ⇨ soft & semi-hard QCD
    - very complementary to other LHC expts
    - address specific issues of QCD

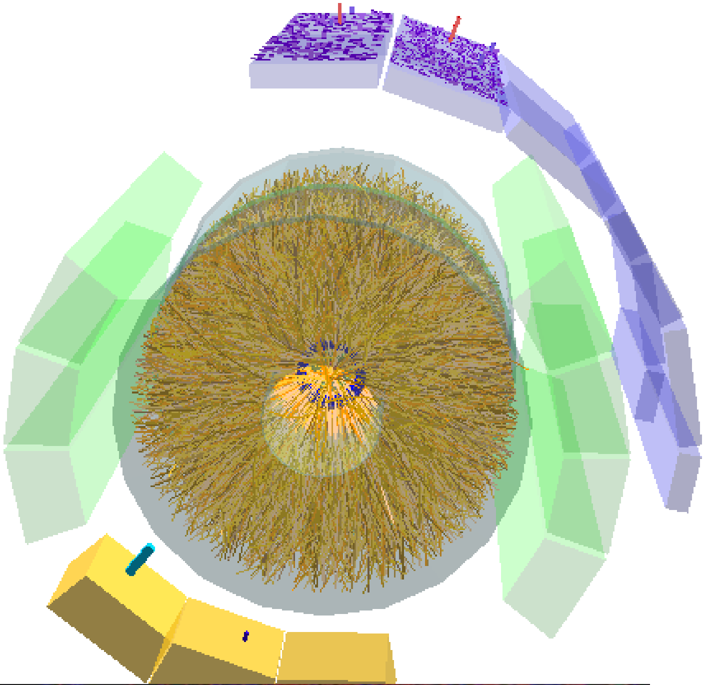


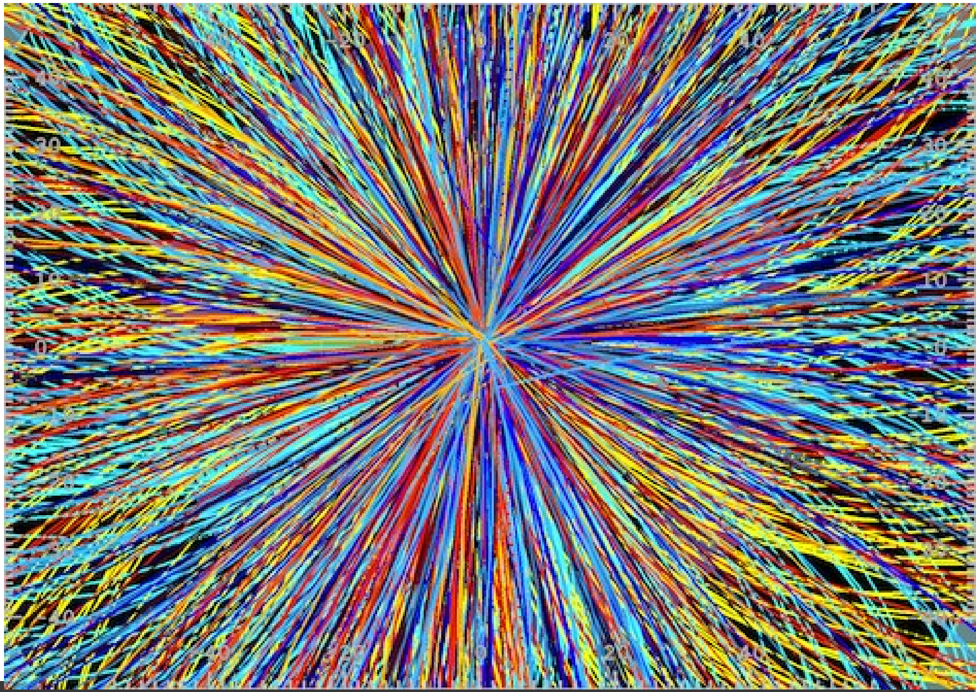
pp Results: A rich Harvest..

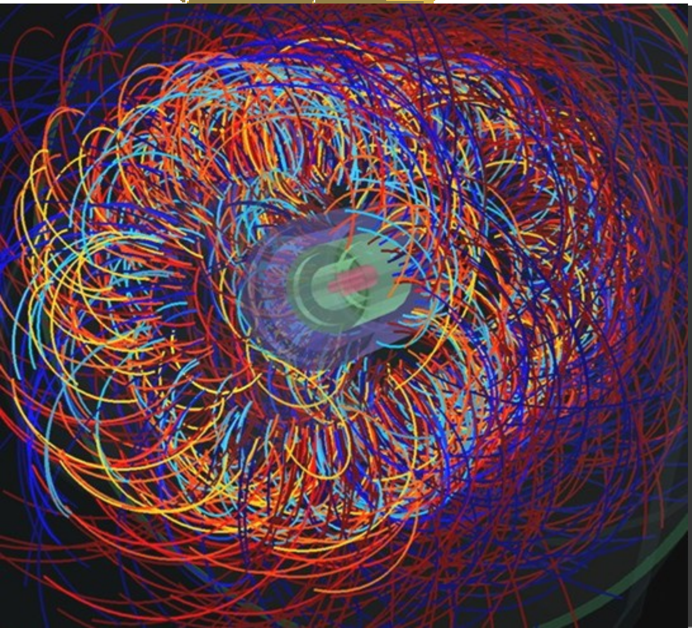
- **Published Results**
  - N_{ch} multiplicity & distributions
    - 900 GeV: **EPJC**: Vol. 65 (2010) 111
    - 900 GeV, 2.36 TeV: **EPJC**: Vol. 68 (2010) 89
    - 7 TeV: **EPJC**: Vol. 68 (2010) 345
    - } Global event properties
  - pbar/p ratio (900 GeV & 7 TeV) **PRL**: Vol. 105 (2010) 072002 → clarifies QCD issue
  - Momentum distributions (900 GeV) **PLB**: Vol. 693 (2010) 53
  - Bose-Einstein correlations (900 GeV) **PRD**: Vol. 82 (2010) 052001
  - Strangeness (K^0,Λ,Ξ,Ω,ϕ) (900 GeV) **arXiv:**1012.3257, sub. EPJC
  - Identified particles (π,K,p) (900 GeV) next week to EPJC
  - Bose-Einstein correlations (7 TeV) next week to PRD
  - } Comparison Data

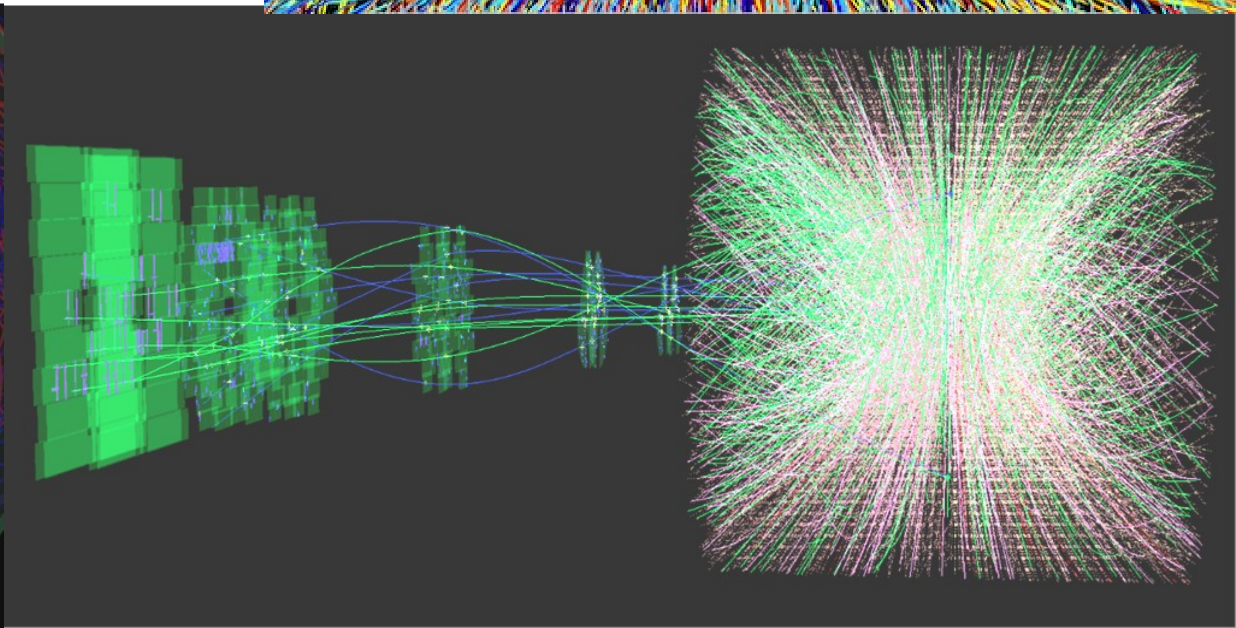
- **Many ongoing analyses/advanced paper drafts**
  - 7 TeV event properties: spectra, identified particles, strangeness, high multiplicity
  - Heavy flavour: charm (D^0,D^+, D^*), heavy quarks (c,b) –> μ, e^-
  - J/ψ –> $\mu\mu$, e^+e^-
  - pQCD: Event topology, jet fragmentation, 2-particle correlations…

Results from the Heavy Ion Run

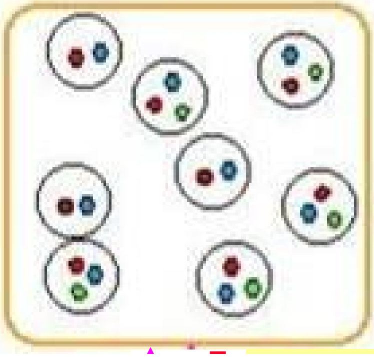








Heavy Ion Physics at the LHC



Hadronic Matter

ε(nucleus) ≈ 0.15 GeV/fm^3

ε(proton) ≈ 0.3 GeV/fm^3

q's confined

q's large effective mass

m_u,m_d ≈ 1/3 m_p ≈ 300 MeV

m_s ≈ 500 MeV

Phase Transition

composite hadrons 'melt'

Quark Gluon Plasma

ε_c > 1 - 2 GeV/fm^3

ρ_c ≈ 5 - 10 ρ(nucleus)

q's are deconfined

chiral symmetry restored

m_u ≈ m_d ≈ few MeV

m_s ≈ 150 MeV

Matter under extreme conditions

QCD prediction:

increase energy density (T, P)

→

new state of matter

QGP:

The 'primordial' state of matter
in the early Universe
(at high Temperature & energy density)

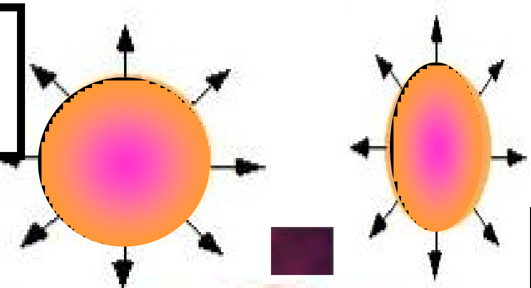
Physics is QCD:

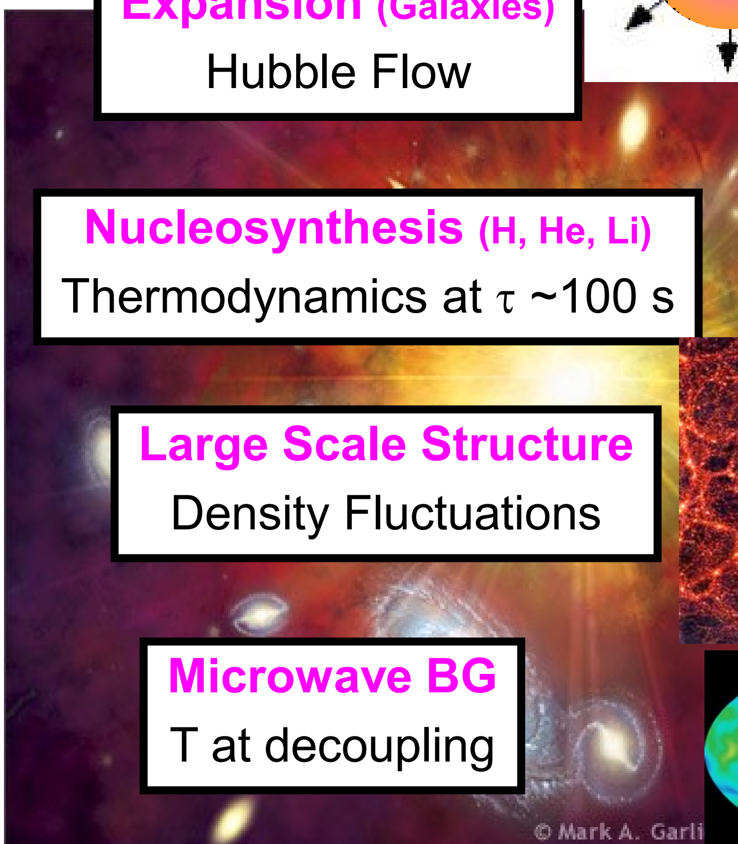
strong interaction sector of the Standard Model

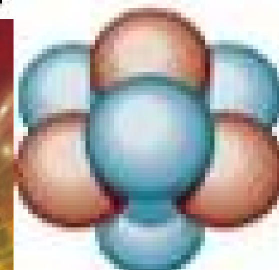
(where its very strong !)

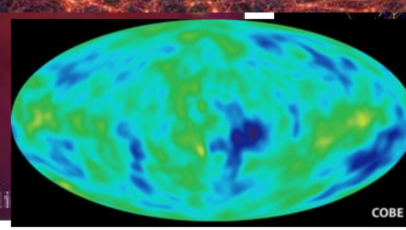
Big Bang

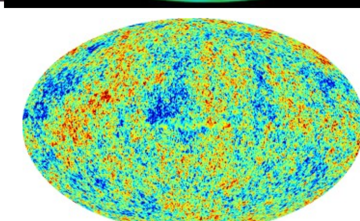
Little Bang

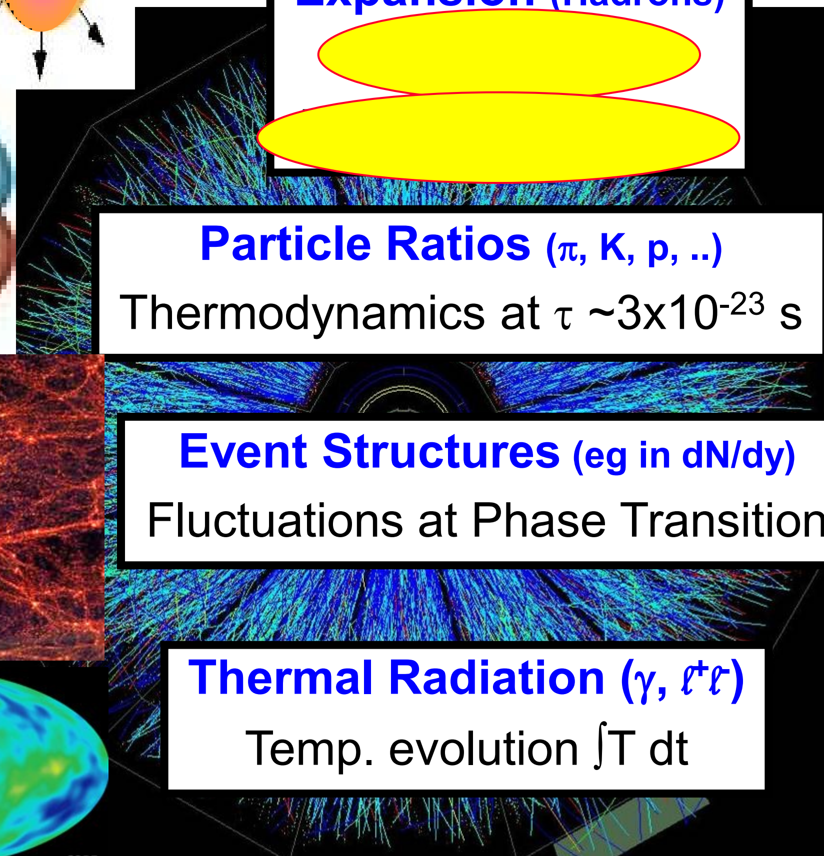












Global Characteristcs

Mass density Ω, Age

Expansion (Galaxies)

Hubble Flow

Nucleosynthesis (H, He, Li)

Thermodynamics at τ ~100 s

Large Scale Structure

Density Fluctuations

Microwave BG

T at decoupling

Temperature Fluctuations

signal from the earliest phase

Global Characteristics

Expansion (Hadrons)

Particle Ratios (π, K, p, ..)

Thermodynamics at τ ~3x10^{-23} s

Event Structures (eg in dN/dy)

Fluctuations at Phase Transition

Thermal Radiation (γ, $\ell^+\ell^-$)

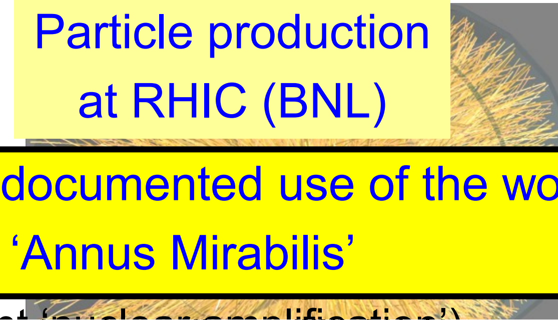
Temp. evolution ∫T dt

Colour Screening (J/Ψ, Y)

Characterizing the Little Bang (1)

- **Particle Production and Energy density ε:**
  - ⇨ Produced Particles: **$dN_{ch}/d\eta$ ~ 1600 ± 76 (syst)**
    - ~ 30,000 particles in total, ~ 400 times p
    - somewhat on high side of expectations
    - growth with energy faster in AA than pp (√s dependent 'nuclear amplification')
  - ⇨ **Energy density ε > 3 x RHIC** (fixed τ_0)
  - ⇨ **Temperature + 30%**
    - lower limit, likely τ_0(

Particle production at RHIC (BNL)



1666: First documented use of the word 'Annus Mirabilis'

Matter under extreme conditions:

ε > 15 GeV/fm^3

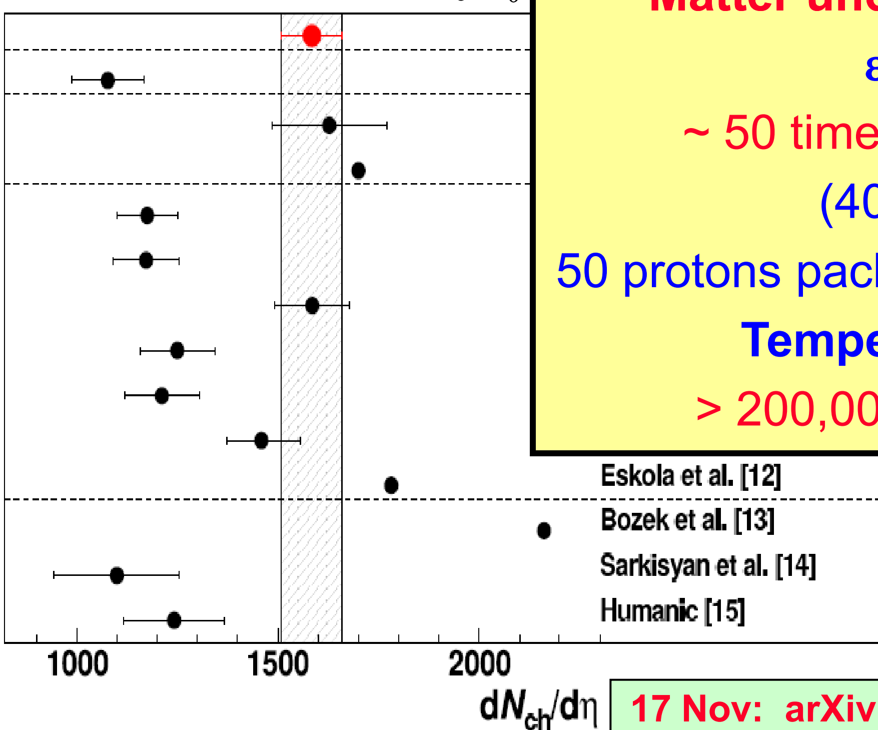
~ 50 times core of a neutron star

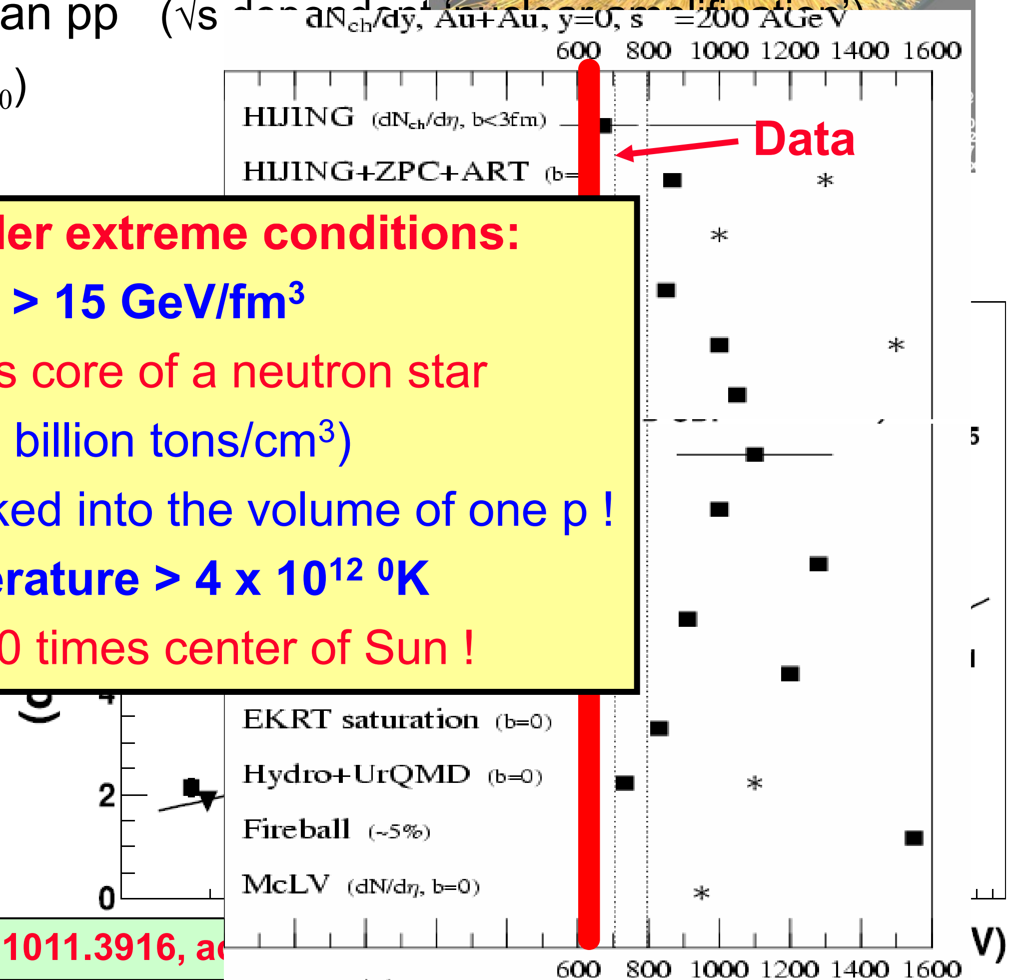
(40 billion tons/cm^3)

50 protons packed into the volume of one p !

Temperature > 4 x 10^{12} ^{0}K

> 200,000 times center of Sun !





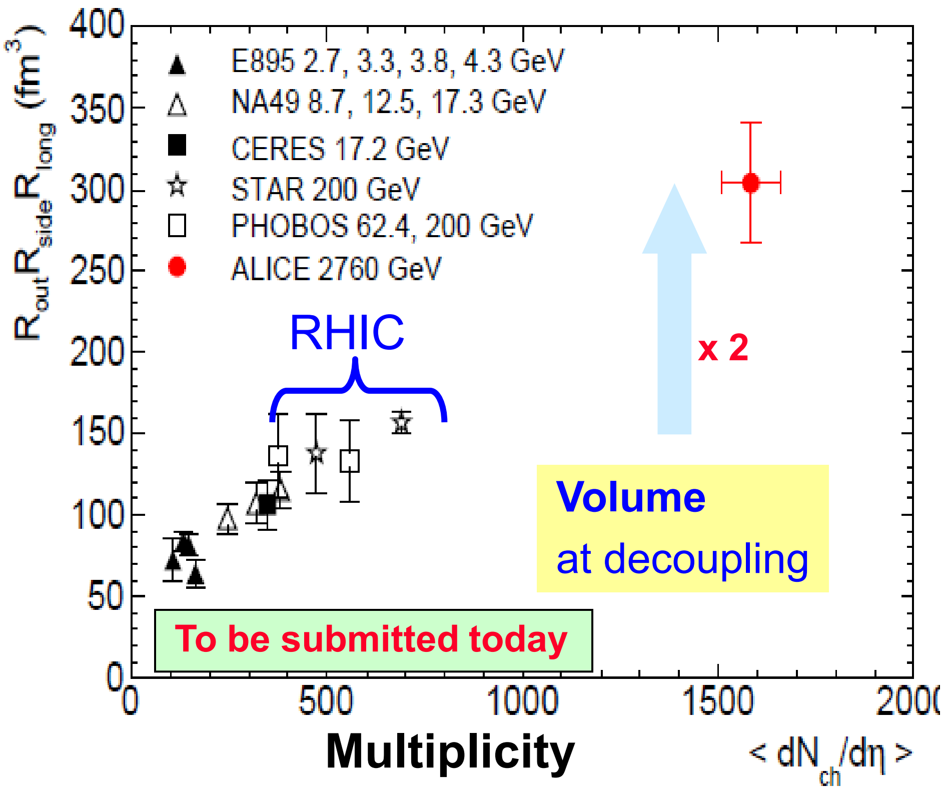
17 Nov: arXiv:1011.3916, ac

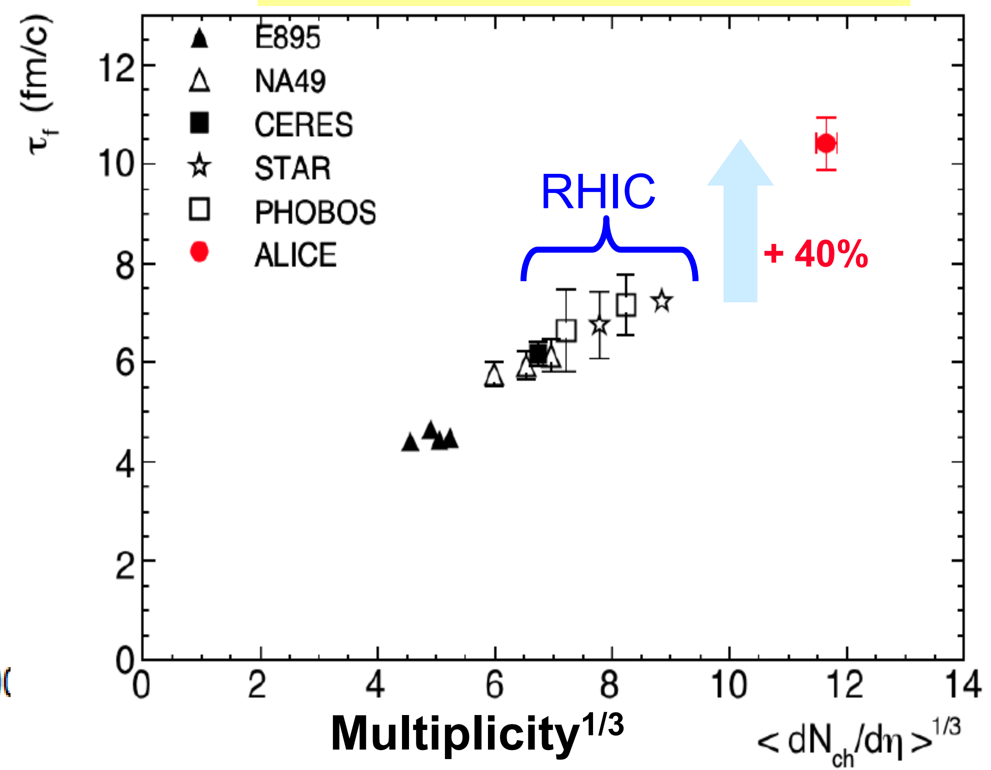
Characterizing the Little Bang (2)

- Volume and Lifetime:
  - ⇨ Identical particle interferometry
    - ✪ Quantum effect, leading to Bose Einstein Condensate at zero temperature
  - ⇨ **Volume ≈ 2 x RHIC** **(≈ 300 fm^3)**
    - ✪ observable 'comoving' volume !
  - ⇨ **Lifetime ≈ +30-40%** **(> 10 fm/c ~ 3×10^{-23} s)**

'Little Bang' lives some 10^{40} less than current age of Universe..

Lifetime: from collision to 'freeze-out' (hadron decoupling)

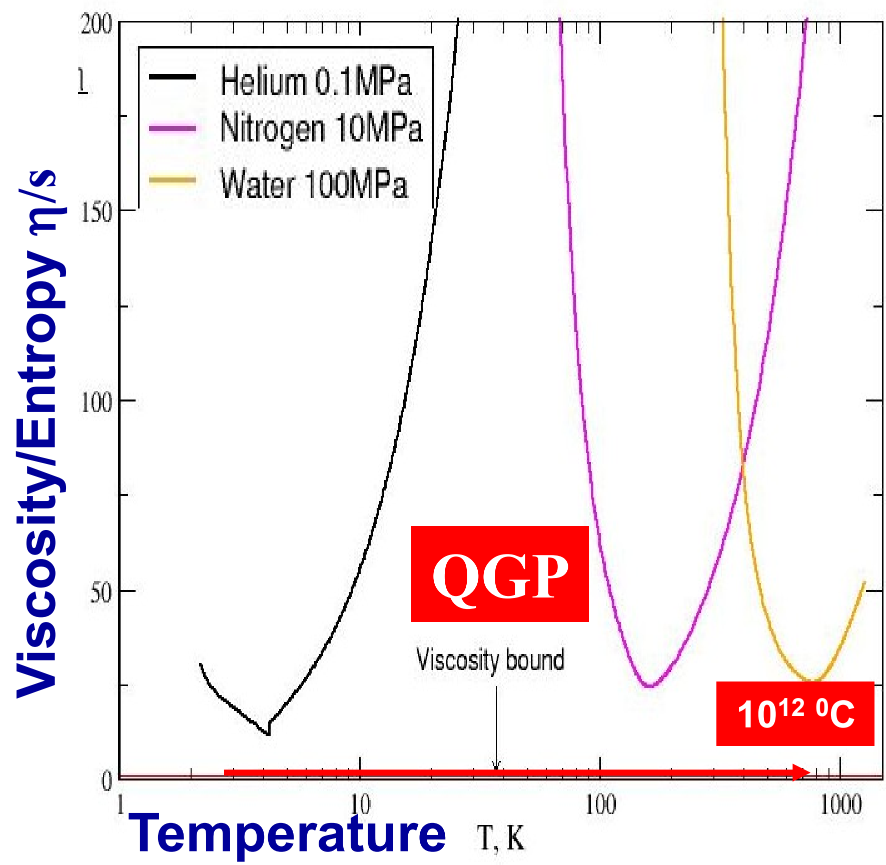




Characterizing the Matter (1)

- RHIC discovery in 2005: The QGP is a (almost) perfect liquid
  - ⇨ **perfect liquid → Viscosity** $\eta \approx 0$ ('response to pressure gradients')
    (→ strong interactions in the liquid)
  - ⇨ QGP almost **ideal fluid**, η/S < 0.2 - 0.5
    - ✪ usually use Viscosity/Entropy (η/S dimensionless number)
- unexpected result
  - ⇨ QGP though to behave like a gas (weakly interacting)
  - ⇨ closest Theory prediction $\eta/S > 1/4\pi \approx 0.08$
    - ✪ AdS/CFT:

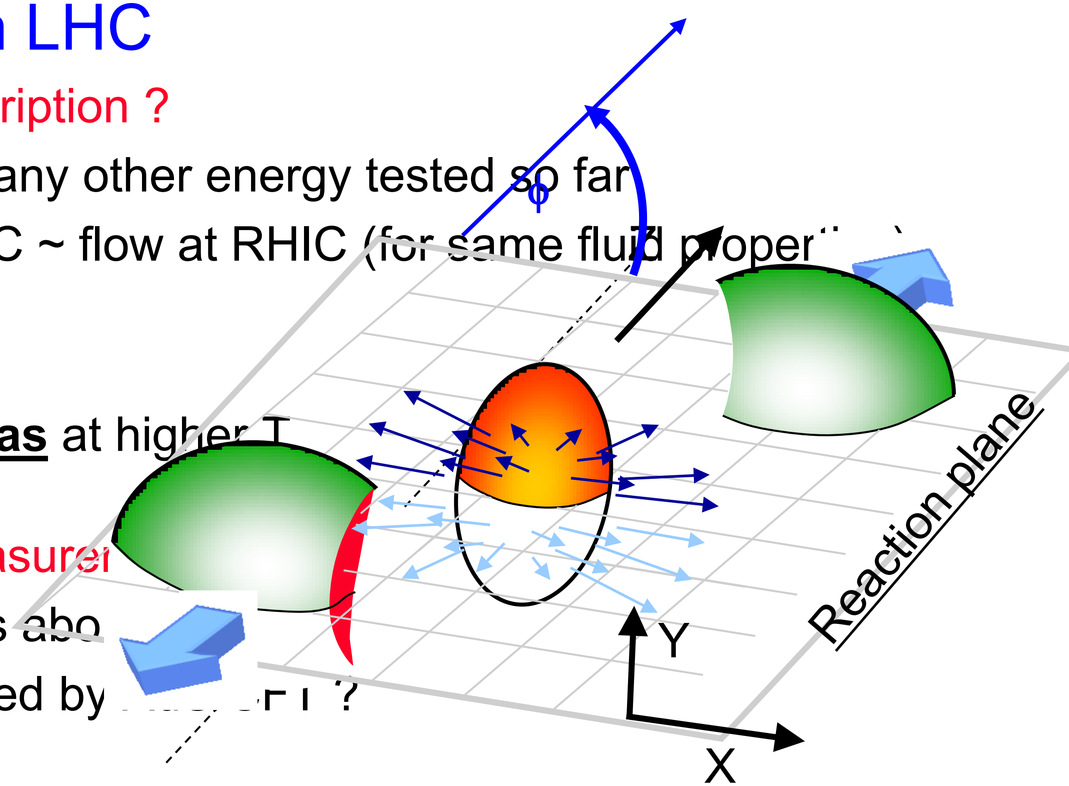
SUSY string theory in 5 dimensions !



BNL Press release, April 18, 2005:
QGP = "Perfect" Liquid
New state of matter more remarkable than predicted – raising many new questions

Does the QGP 'flow' at LHC ?

- 'Elliptic Flow'
  - ⇨ Pressure gradients & the nuclear collision geometry lead to a characteristic **'sideway splash'** of the produced particles
- Hydrodynamics
  - ⇨ predicts flow pattern as function of geometry & fluid properties (e.g. η/S)
- Answers anticipated from LHC
  - ⇨ is Hydro actually the correct description ?
    - 1 ✪ only successful at RHIC, not at any other energy tested so far
    - ✪ **testable prediction**: flow at LHC ~ flow at RHIC (for same fluid proper
  - ⇨ is the matter still a fluid ?
    - 2 ✪ or does it become more like a **gas** at higher T
  - ⇨ how perfect a fluid: precision measure
    - 3 ✪ current uncertainty from RHIC is abo
    - ✪ is it at the quantum limit stipulated by ?



First Elliptic Flow Measurement at LHC

- Elliptic Flow as function of momentum.

practically no change with energy !

1 ⇨ **1)** Hydro prediction confirmed !

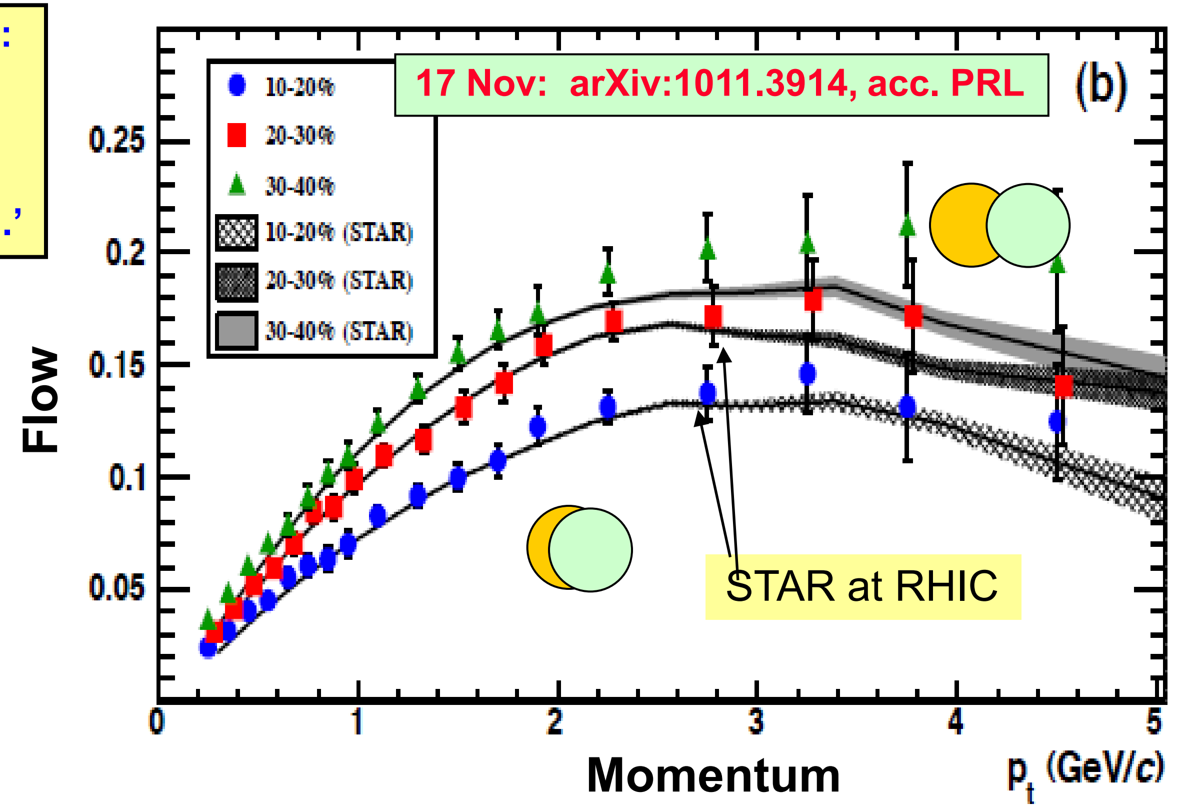
2 ⇨ **2)** QGP still behaves like a liquid even at Temperature of LHC

⇨ some small differences, to be investigated further

- extends towards more distant collisons/higher p_t ?

CERN Press release, November 26, 2010:

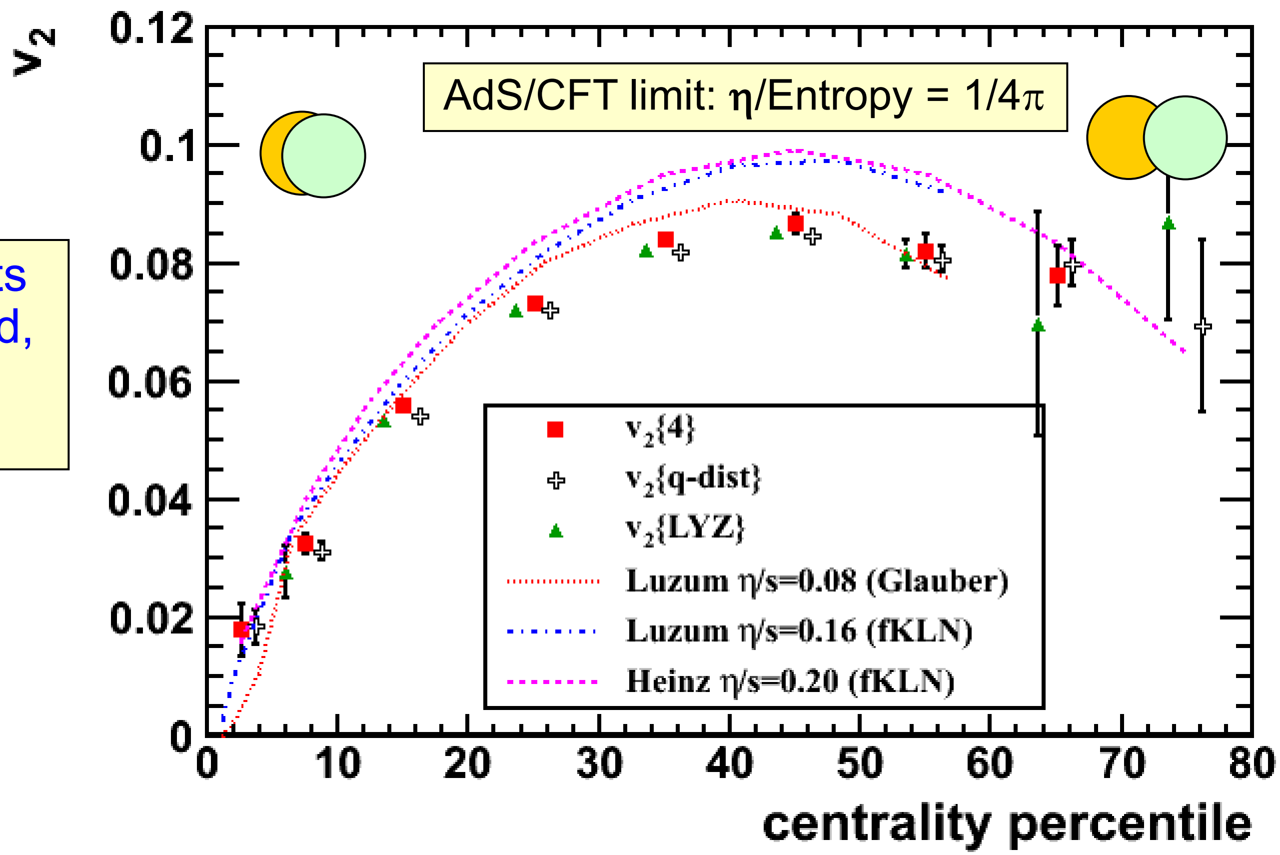
'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'



Towards Precision Measurements

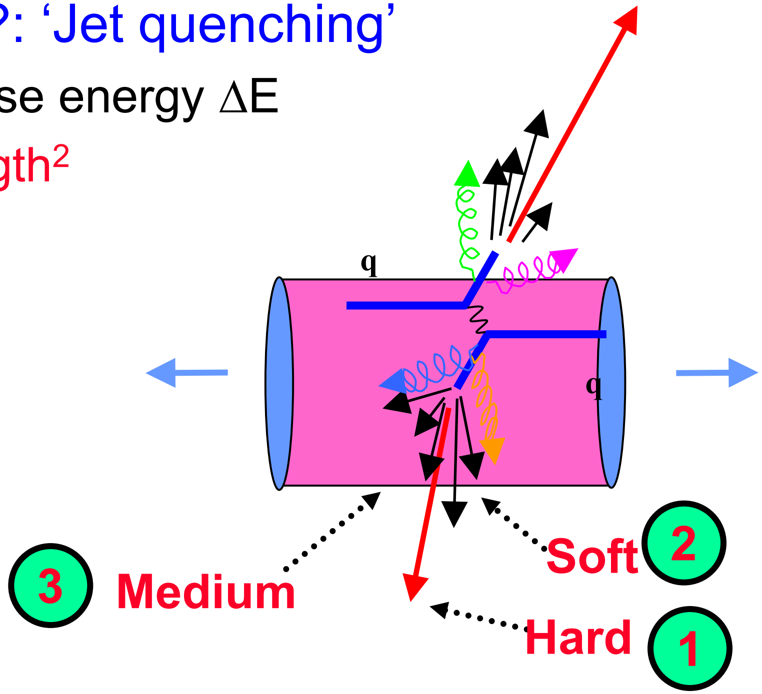
- Sensitivity to fluid viscosity η
  - ⇨ Quantitative results will need much more time and more experimental input …
  - 3 ✪ elliptic flow with identified particles, radial flow ('radial expansion'), better determination of initial geometry, ……

Precision measurements are still some way ahead, but it looks like we can get there !



Characterizing the Matter (2)

- How strongly interacting is the matter ?: 'Jet quenching'
  - ⇨ quarks/gluons traveling through QGP loose energy ΔE
    - ✪ some unusual properties, e.g. ΔE ~ Length^2 (not ΔE ~ L, as in normal matter !)

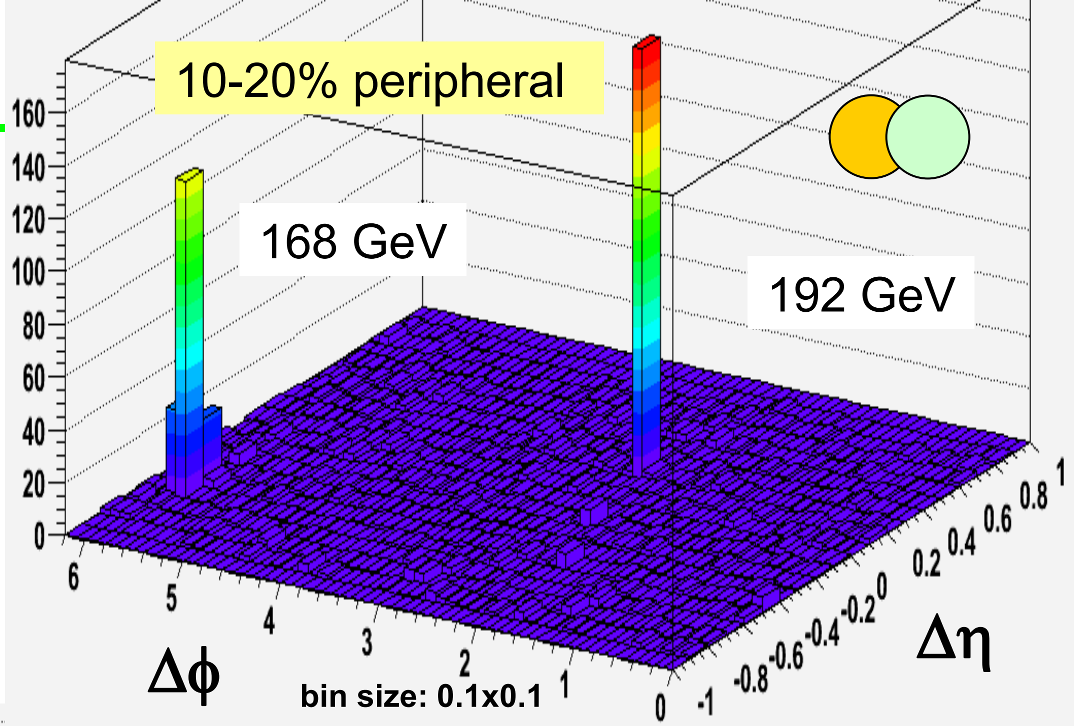


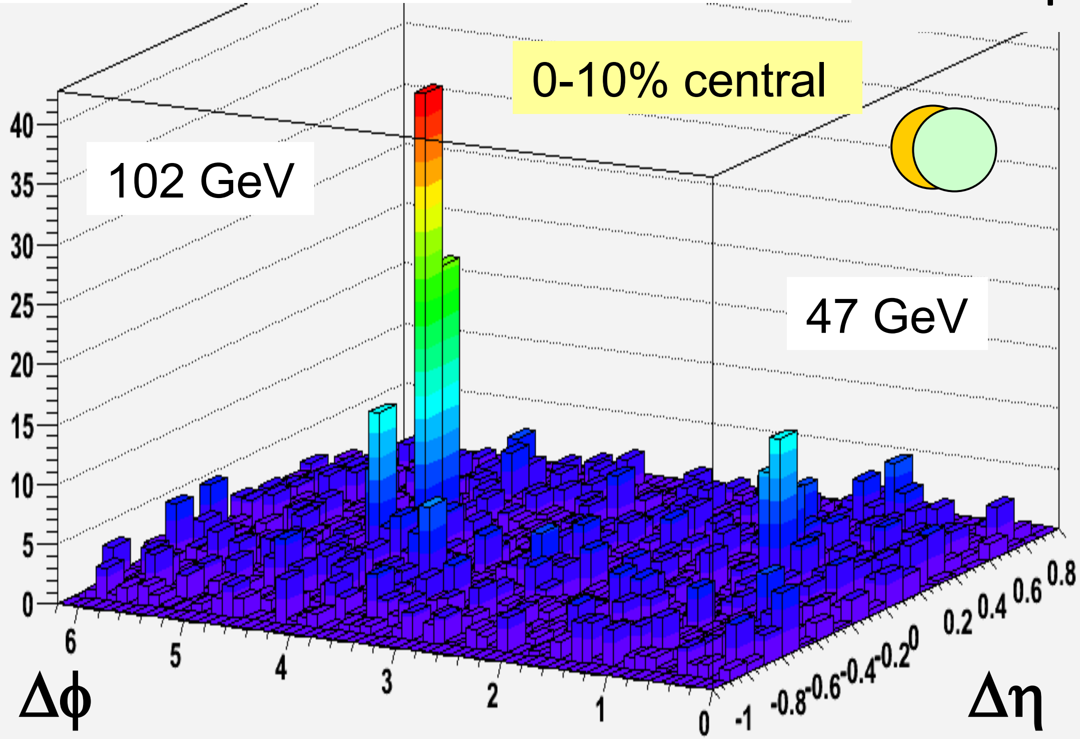
  - ⇨ how much energy is lost ? (measures 'interaction strength' of QGP)
    - ✪ look at high momentum ('hard') part of jets
  - ⇨ how is it lost ?
    - ✪ many **soft** or few **hard** scatterings
    - ✪ look at low momentum ('soft') part
  - ⇨ 'response of QGP'
    - ✪ shock waves, Mach cones ??
    - ✪ look at average ('very soft') particles of the medium

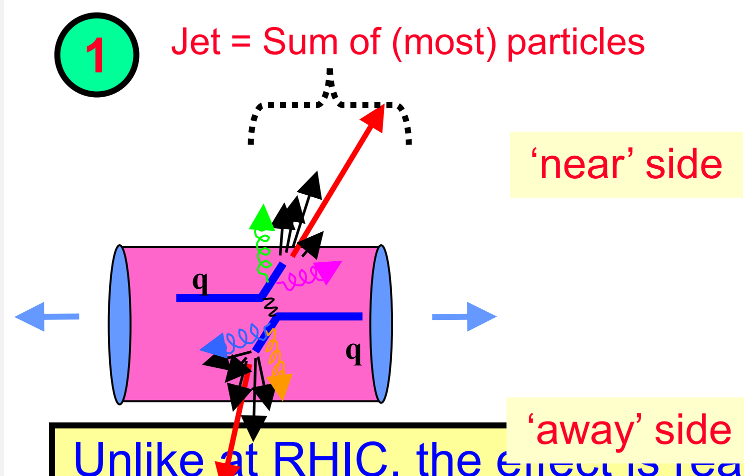
'Jet' breaking the sound barrier

Charged Jets

- Jets in ALICE (TPC)
  - ⇨ we see qualitatively a similar effect to Atlas/CMS





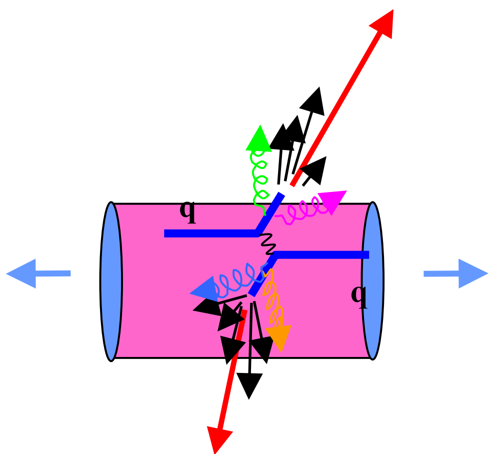


Unlike at RHIC, the effect is readily and directly visible at LHC.

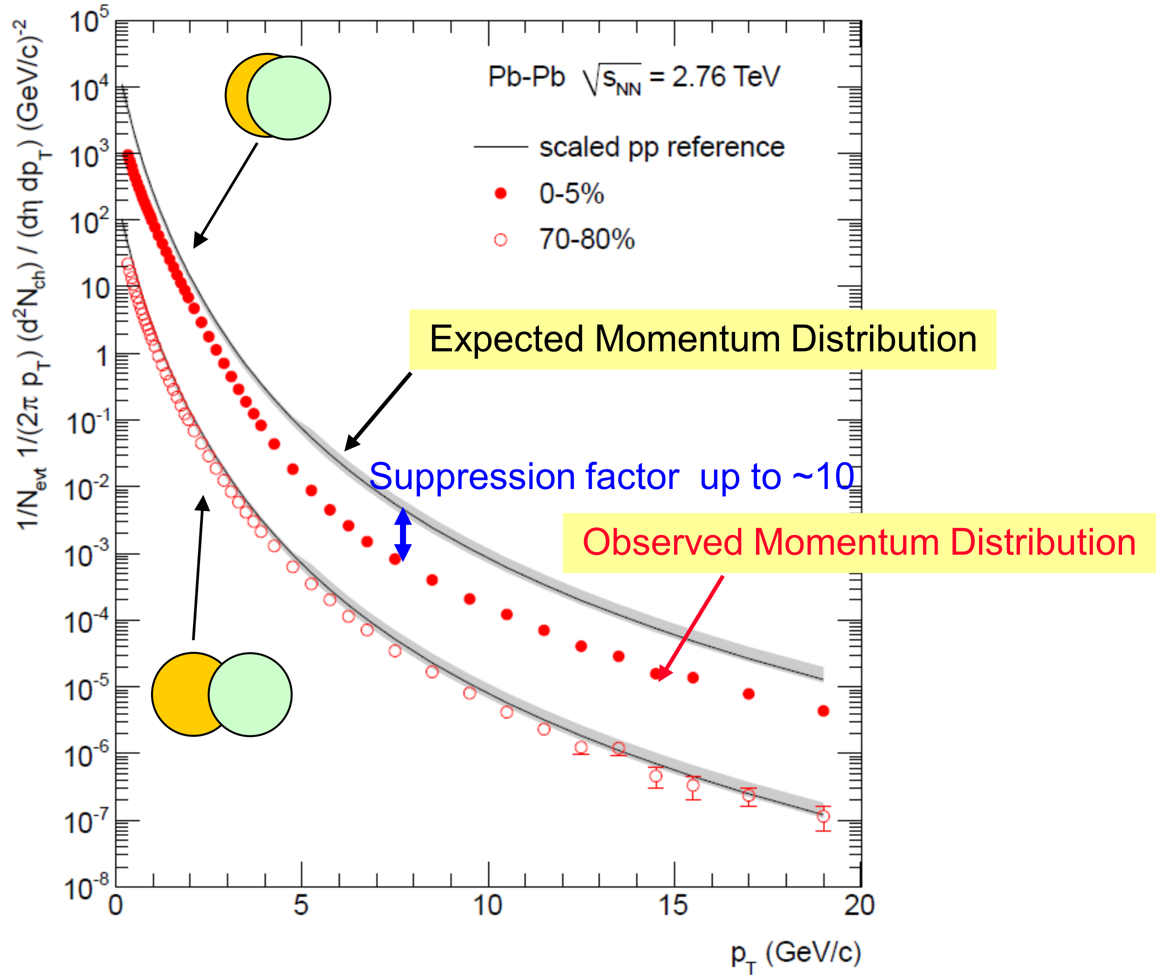
Quantifying energy loss needs further analysys

'Jet Quenching' seen in single high p_t particles

- Strong suppression of high momentum particles (~ jet fragments)
  - ⇨ on first sight, **seems stronger** than at RHIC
  - ⇨ distinct (and very interesting) **dependence on momentum**



Most energetic ('leading') jet particle

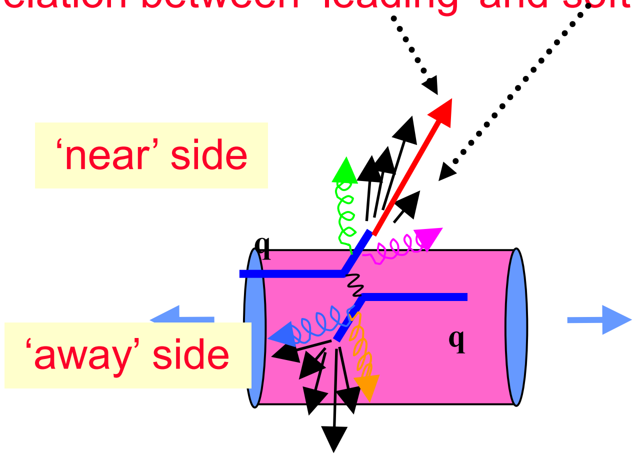


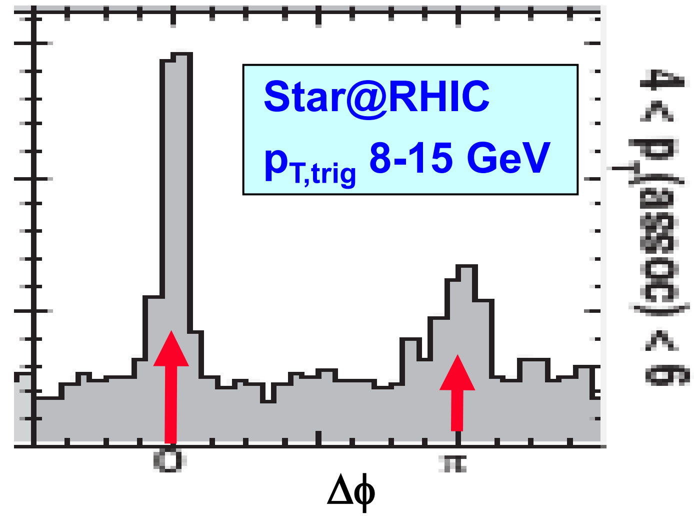
2 Dec: arXiv:1012.1004, acc. PLB

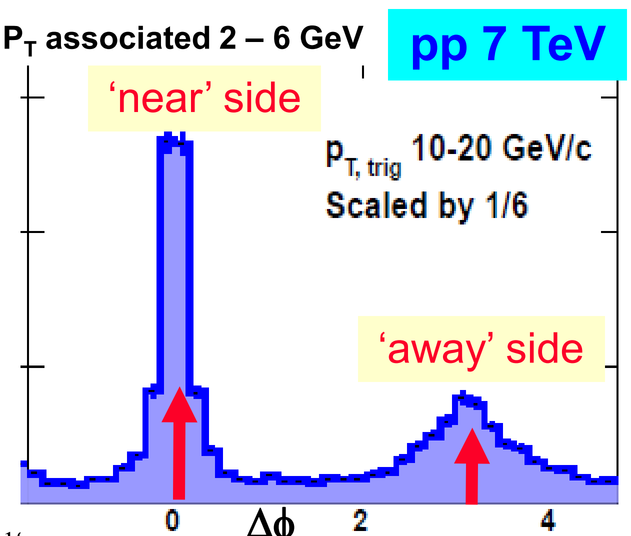
Jet Quenching seen by high p_T Correlations

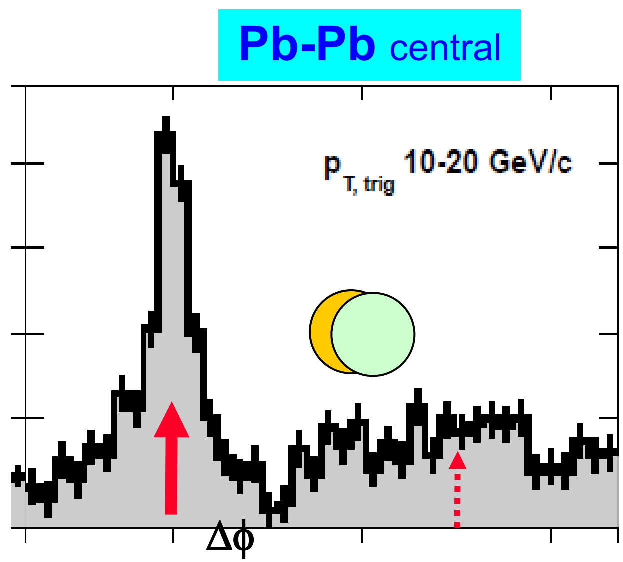
- classic 'jet quenching signal'
  - ⇨ away side correlation in central Pb-Pb disappears
  - ⇨ seems stronger than at RHIC

(2) Correlation between 'leading' and soft jet particles



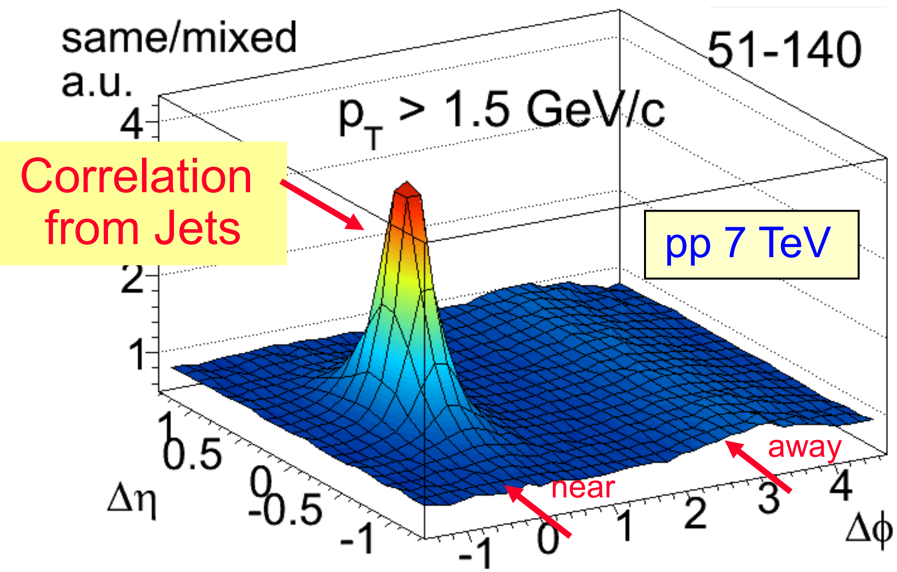


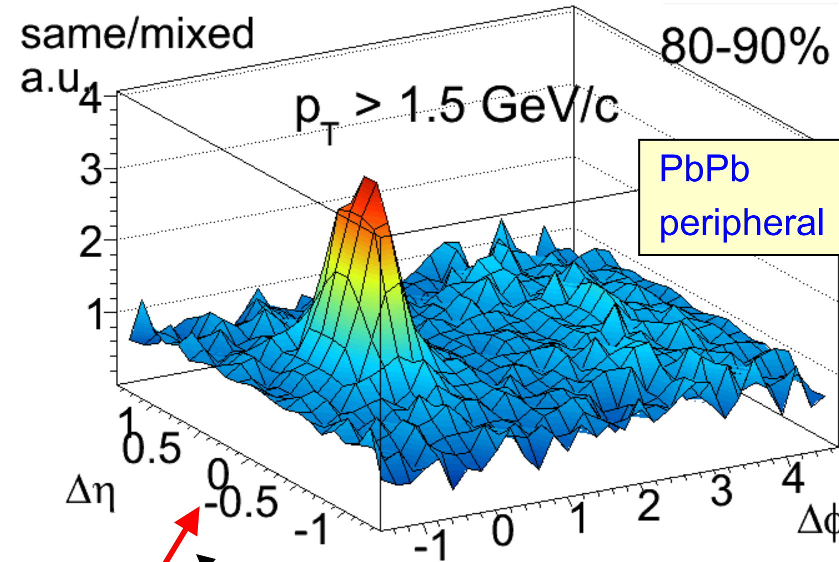


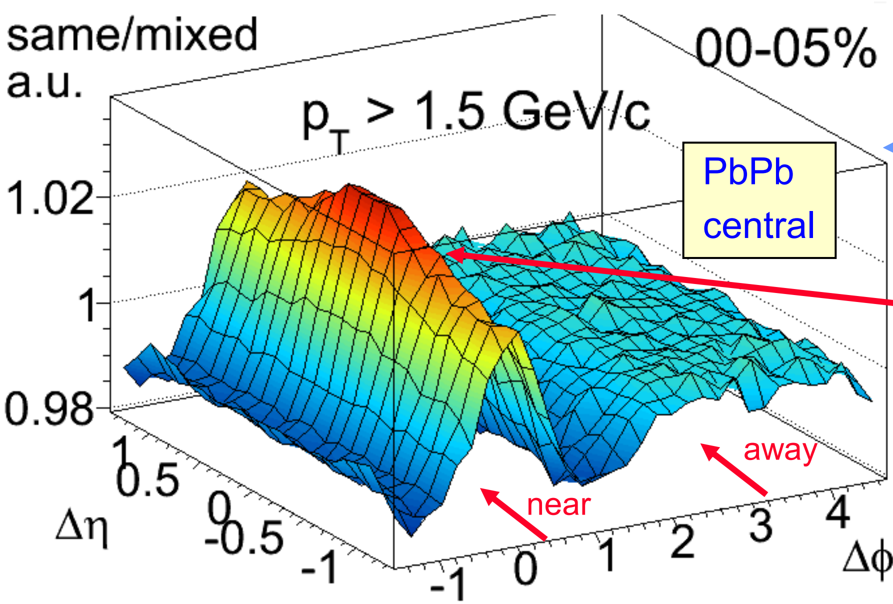


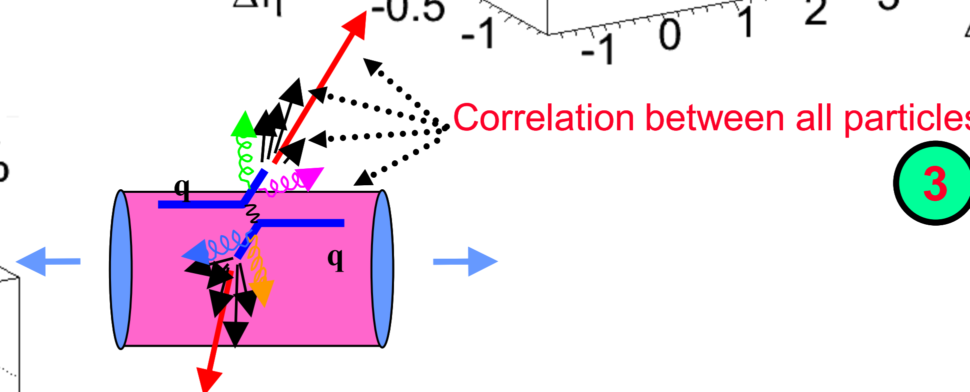
Jet Quenching (?) seen via Multiparticle Correlations

- 'Autocorrelation':





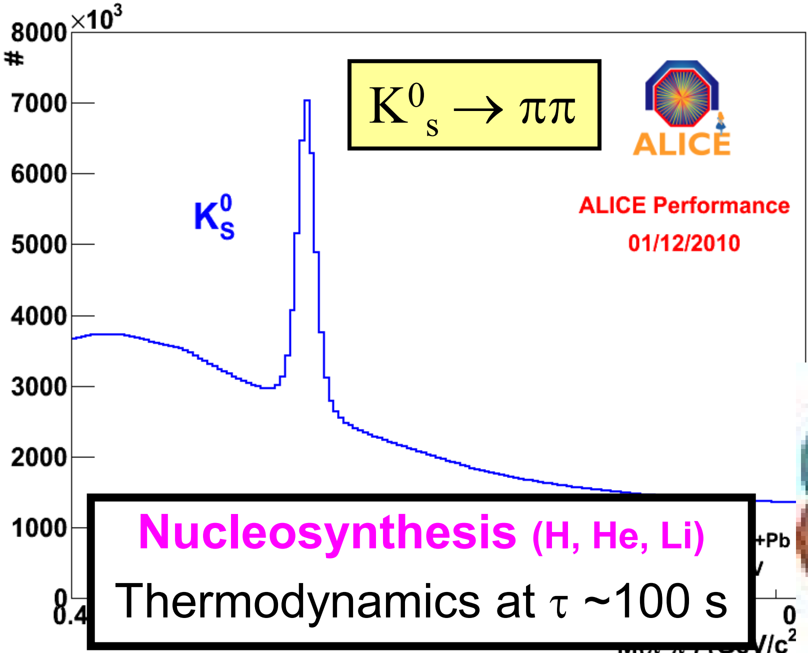


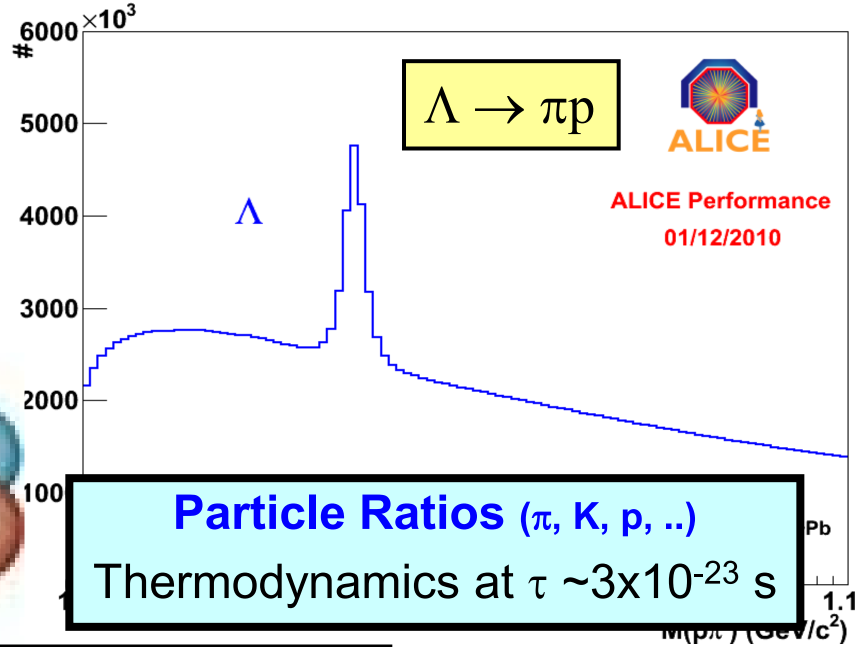


'near side ridge':

- striking effect, not really understood
- response of QGP to jet quenching ?
- initial state gluon radiation ?
- ???

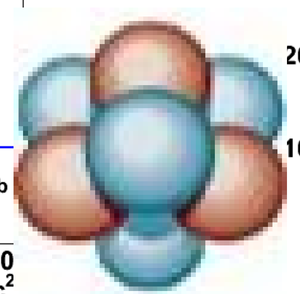
Particle Production in Pb-Pb





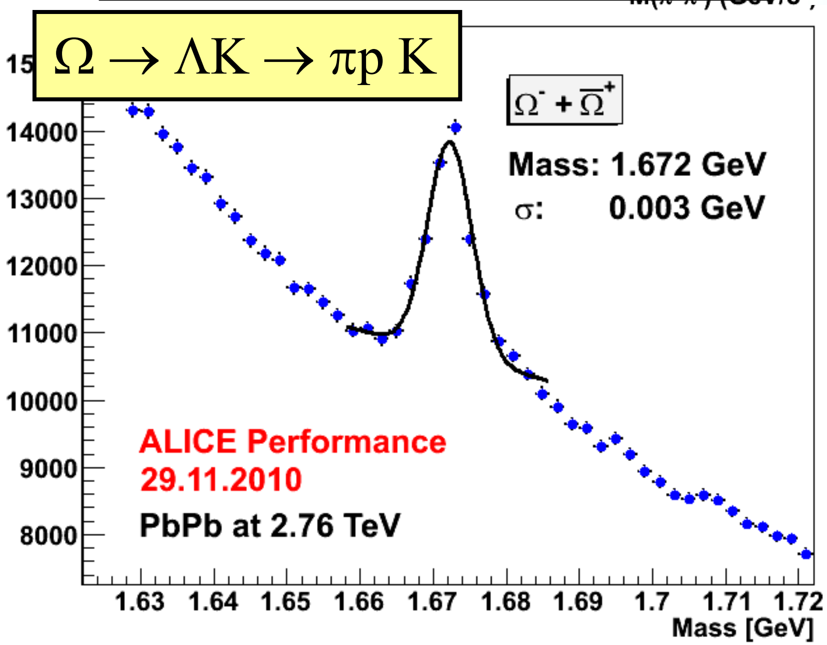
Nucleosynthesis (H, He, Li)

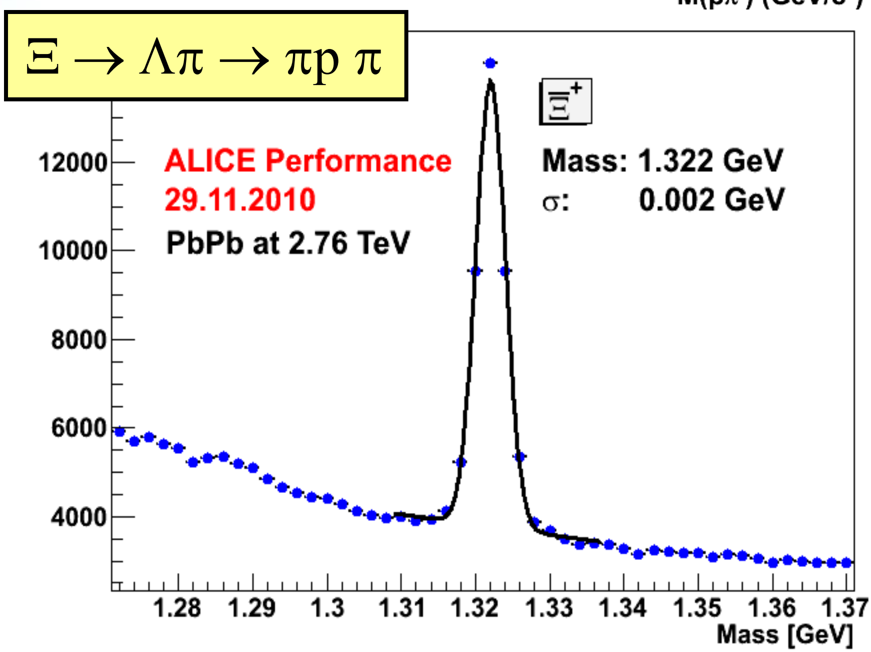
Thermodynamics at τ ~100 s



Particle Ratios (π, K, p, ..)

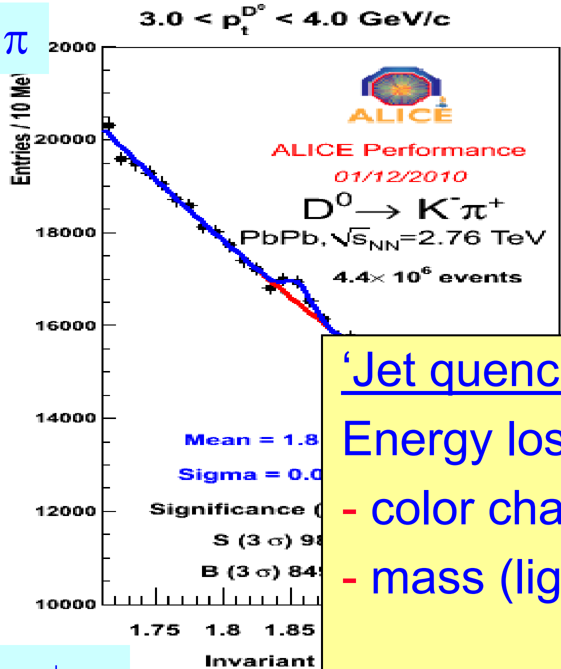
Thermodynamics at τ ~$3x10^{-23}$ s

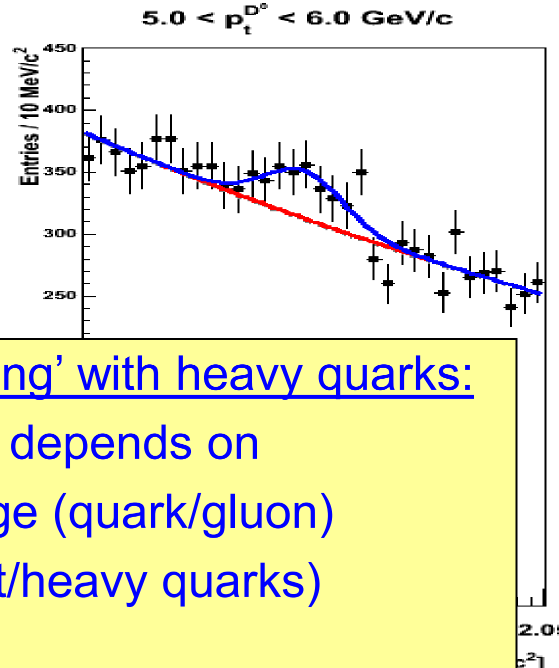


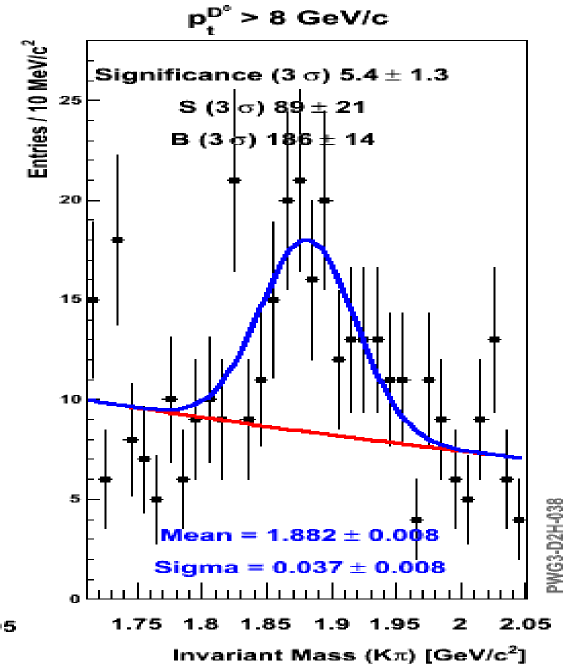


Charm in Pb-Pb

$D^0 \to K\,\pi$







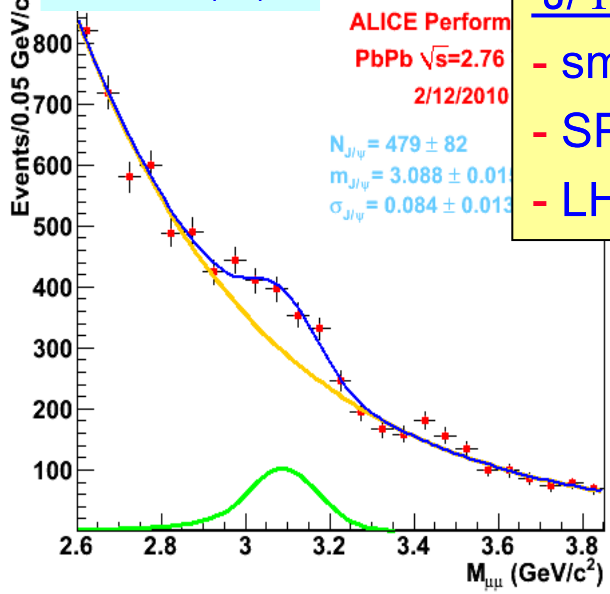
'Jet quenching' with heavy quarks:

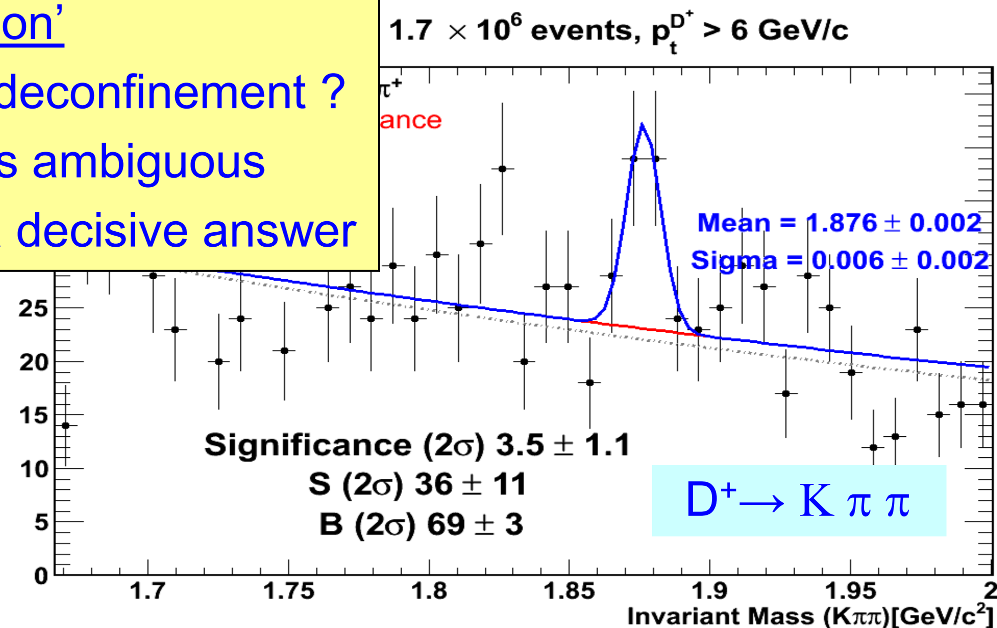
Energy loss depends on
- color charge (quark/gluon)
- mass (light/heavy quarks)

'J/Ψ & Y suppression'

- smoking gun for deconfinement ?
- SPS/RHIC results ambiguous
- LHC could give a decisive answer

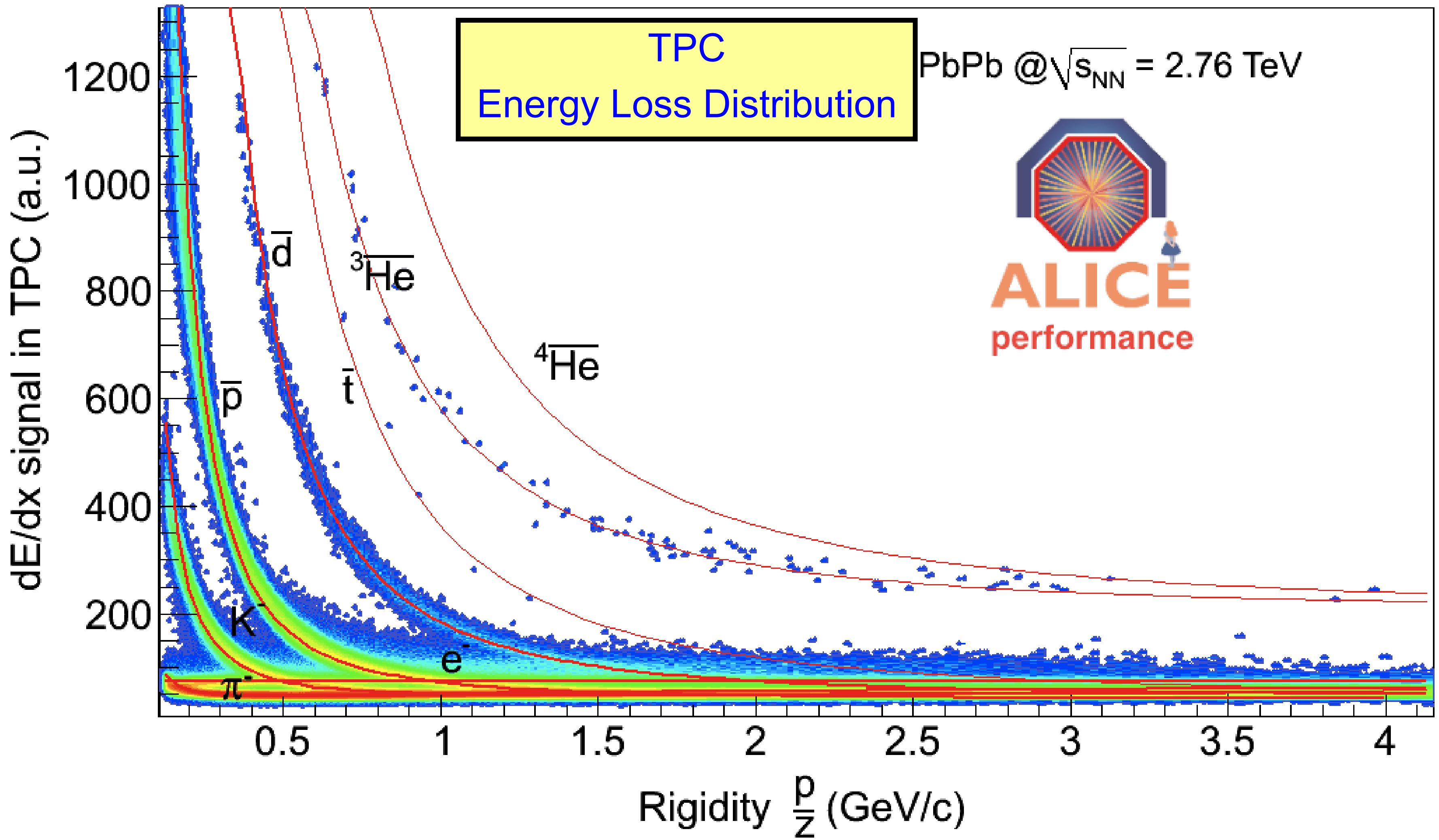
$J/\Psi \to \mu^+\mu^-$





$D^+ \to K\,\pi\,\pi$

Anti-Nuclei



~ 2 M Pb-Pb Min Bias events

Near (and medium) Term Future

- We have barely scratched the surface, 3 weeks into a 10 year program
  - ⇨ need factor ~ 100 in integrated luminosity for rare signals
    - **next year** we should approach **design luminosity** (~20 x higher than 2010)
    - Quarkonia suppression (J/Ψ, Ψ', Y, Y',Y'), heavy Quarks (b,c), γ-jet, ….
  - ⇨ running at full LHC energy
    - gain of 10-15% in **energy density**, larger **cross section** for rare probes
  - ⇨ p – Nucleus comparison data
    - to distinguish **QGP** effects from **nuclear** effects ('shadowing')
    - study of **Color Glass Condensate**
      (yet another <u>exotic dense matter at 'zero temperature'</u>)
  - ⇨ running with lower mass ions (Ar-Ar ?)
    - study **volume** effects
    - LHC can achieve much **higher luminosity** with lighter ions

Plenty of work (and exciting physics) ahead !

A pretty efficient start …

Selected for a Viewpoint in *Physics*
PRL **105**, 252302 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

K. Aamodt *et al.**
(ALICE Collaboration)

(Received 18 November 2010; published 13 December 2010)

We report the first measurement of charged particle elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.2 < p_t < 5.0$ GeV/c. The elliptic flow signal v_2, measured using the 4-particle correlation method, averaged over transverse momentum and pseudorapidity is $0.087 \pm 0.002(\text{stat}) \pm 0.003(\text{syst})$ in the 40%–50% centrality class. The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.2 near $p_t = 3$ GeV/c. Compared to RHIC Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the elliptic flow increases by about 30%. Some hydrodynamic model predictions which include viscous corrections are in agreement with the observed increase.

DOI: 10.1103/PhysRevLett.105.252302 PACS numbers: 25.75.Ld, 25.75.Gz, 25.75.Nq

The goal of ultrarelativistic nuclear collisions is the creation and study of the quark-gluon plasma (QGP), a state of matter whose existence at high energy density is predicted by quantum chromodynamics. One of the experimental observables that is sensitive to the properties of this matter is the azimuthal distribution of particles in the plane perpendicular to the beam direction. When nuclei collide at finite impact parameter (noncentral collisions), the geometrical overlap region and therefore the initial matter …

scribe flow at RHIC predict an increase of the elliptic flow at the LHC ranging from 10% to 30%, with the largest increase predicted by models which account for viscous corrections [15–18] at RHIC energies. In models with viscous corrections, v_2 at RHIC is below the ideal hydrodynamic limit [12,17] and therefore can show a stronger increase with energy. In hydrodynamic models the charged particle elliptic flow as a function of transverse momentum does not change significantly [7,14] while the …

… rapidity, and Ψ_R the reaction plane angle. The reaction plane is the plane defined by the beam axis z and the impact parameter direction. In general the coefficients $v_n = \langle\cos[n(\phi - \Psi_R)]\rangle$ are p_t and y dependent—therefore we

PRL **105**, 252301 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Charged-Particle Multiplicity Density at Midrapidity in Central Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

K. Aamodt *et al.**
(ALICE Collaboration)

(Received 19 November 2010; published 13 December 2010)

The first measurement of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV is presented. For an event sample corresponding to the most central 5% of the hadronic cross section, the pseudorapidity density of primary charged particles at midrapidity is $1584 \pm 4(\text{stat}) \pm 76(\text{syst})$, which corresponds to $8.3 \pm 0.4(\text{syst})$ per participating nucleon pair. This represents an increase of about a factor 1.9 relative to pp collisions at similar collision energies, and about a factor 2.2 to central Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV. This measurement provides the first experimental constraint for models of nucleus-nucleus collisions at LHC energies.

DOI: 10.1103/PhysRevLett.105.252301 PACS numbers: 25.75.Ag

The theory of strong interactions, quantum chromodynamics (QCD), predicts a phase transition at high temperature between hadronic matter, where quarks and gluons are confined inside hadrons, and a deconfined state of matter, the quark-gluon plasma. A new frontier in the study of QCD matter opened with the first collisions of ^{208}Pb ions in November 2010, at the Large Hadron Collider (LHC) at …

the collision, including decay products, except those from weak decays of strange particles.

The present measurement extends the study of particle densities in nucleus-nucleus collisions into the TeV regime. We make comparisons to model predictions [4–16] and to previous measurements in nucleus-nucleus collisions at lower energies at the SPS and RHIC [17–25], as …

*Full author list given at the end of the article.

and $-3.7 < \eta < -1.7$ (VZERO-C). Both the amplitude and the time signal in each scintillator are recorded. The VZERO time resolution is better than 1 ns, allowing discrimination of beam-beam collisions from background events produced upstream of the experiment. The

- **Published Pb-Pb Results**
  - ⇨ Elliptic Flow — Phys. Rev. Lett. **105**, 252302 (2010)
  - ⇨ Charged particle density — Phys. Rev. Lett. **105**, 252301 (2010).
  - ⇨ High p_t suppression — **arXiv:**1012.1004. , acc. by PLB
  - ⇨ Centrality dependence of N_{ch} — **arXiv:**1012.1657. , subm. to PRL
  - ⇨ Bose-Einstein correlations — to be submitted today to PLB

Physics 3, 105 (2010)

In the late 1970s he introduced the term "quark-gluon plasma."

Phys. Rev. Let. 'Viewpoint'

A "Little Bang" arrives at the LHC

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Published December 13, 2010

The first experiments to study the quark-gluon plasma at the LHC reveal that even at the hottest temperatures ever produced at a particle accelerator, this extreme state of matter remains the best example of an ideal liquid.

I just want to note that this is the **first Viewpoint on an LHC paper**

Note that **of the 18,000 papers** the Physical Review publishes every year, **only about 100** receive Viewpoints.

Cheers,
Robert Garisto
Associate Editor
Physical Review Letters

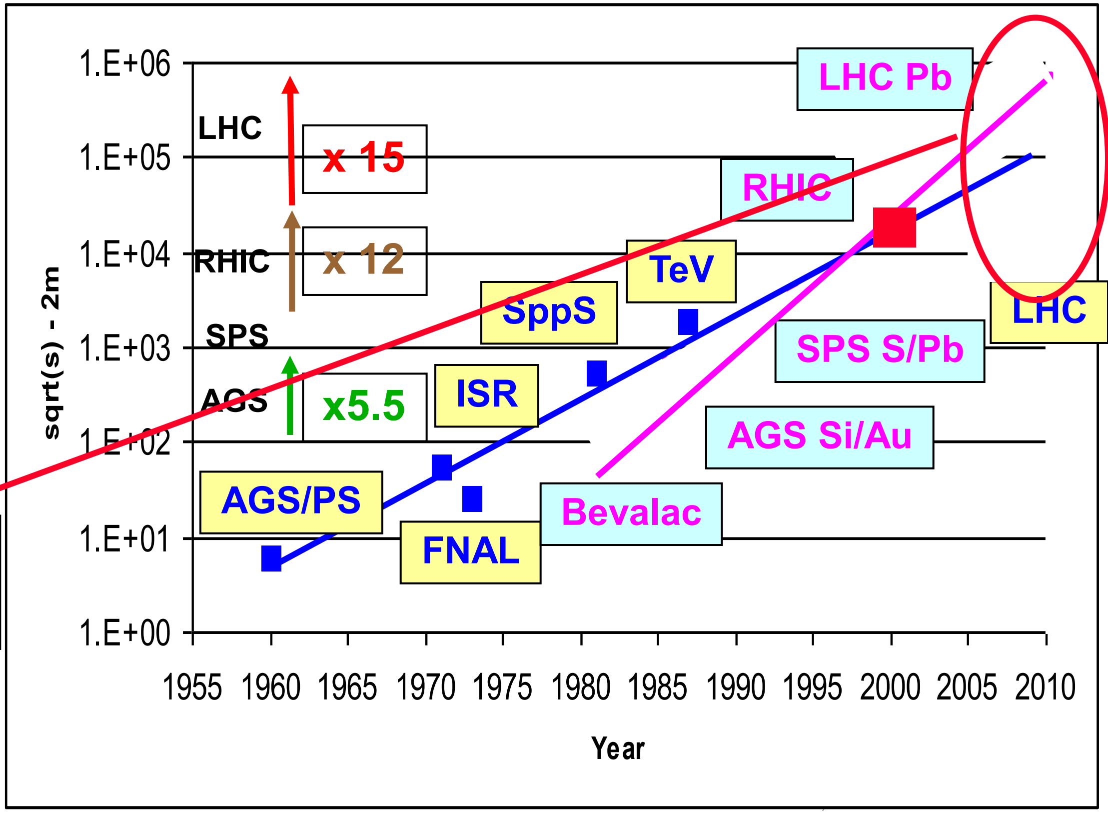
The LHC and Heavy Ions

- **Particle Physics: energy doubling time ~ 4 years**
- **Heavy Ion Physics: doubling time ~ 2 years**
  - ⇨ energy increase by factor 10^4 in ~ 30 years
  - ⇨ starting 70'- to early 80's at Bevalac
    - ✪ field started by a few dozen physicists from a handful of countries
    - ✪ > 2000 physicists active worldwide today

Field went from the periphery into a **central activity** of contemporary **Nuclear Physics**
(and now gets even some HEP guys excited !)

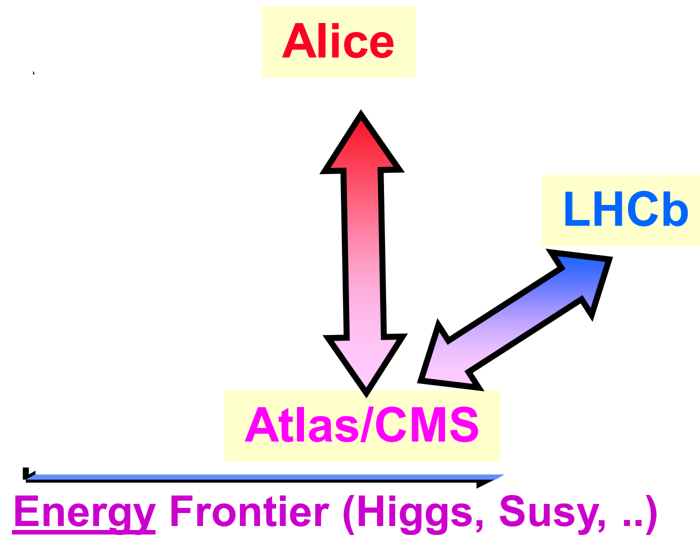
LHC: At the Energy Frontier of both Nuclear and High Energy Physics

Total center-of-mass energy versus time



Versatility of LHC & Complementarily of Experiments
make the whole of LHC larger than the sum of its parts

- Common Questions
  - ⇨ generation of mass
    - **elementary** particles => Higgs => **Atlas/CMS**
    - **composite** particles => QGP => **Alice**
  - ⇨ broken symmetries
    - **SuperSymmetry**: matter <=> forces => **Atlas/CMS**
    - **ChiralSymmetry**: matter <=> QCD vacuum => **Alice**
    - **CP Symmetry:** matter <=> antimatter => **LHCb**



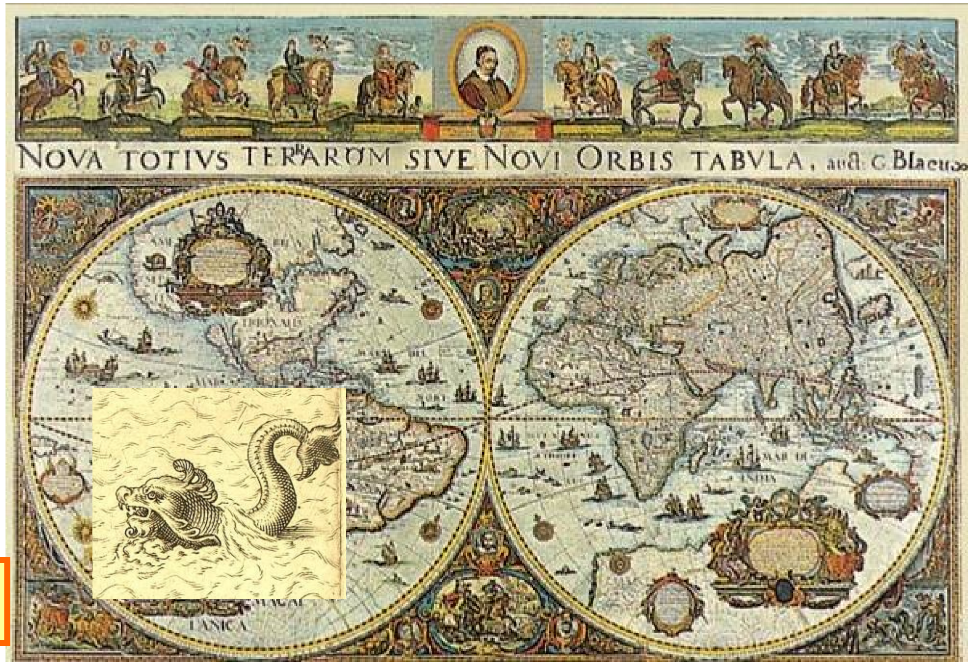
- Different Approaches
  - ⇨ **'Concentrated Energy'** **=> Atlas/CM**
    => new high mass particles
  - ⇨ **'Distributed Energy'** => **Alice**
    => heat and melt matter
  - ⇨ **'Borrowed Energy'** => **LHCb**
    => indirect effects of virtual high mass particles

2010: A ‘wonderful’ Year, indeed

- LHC is a fantastic ‘Big Bang’ machine
  - ⇨ even for LHC standards, quality and efficiency of first ion run was outstanding
    - ✪ **Thanks** and **Congratulations** to the CERN accelerator teams
  - ⇨ Heavy Ion collisions look even more interesting than anticipated

> There is plenty of exciting physics (and fun)
> at the LHC
> exploring QCD in a new domain,
> where the strong interaction is really strong !

- Looking forward to continue the journey further into the ‘terra incognita’ of HI at LHC



Hic sunt Leones !