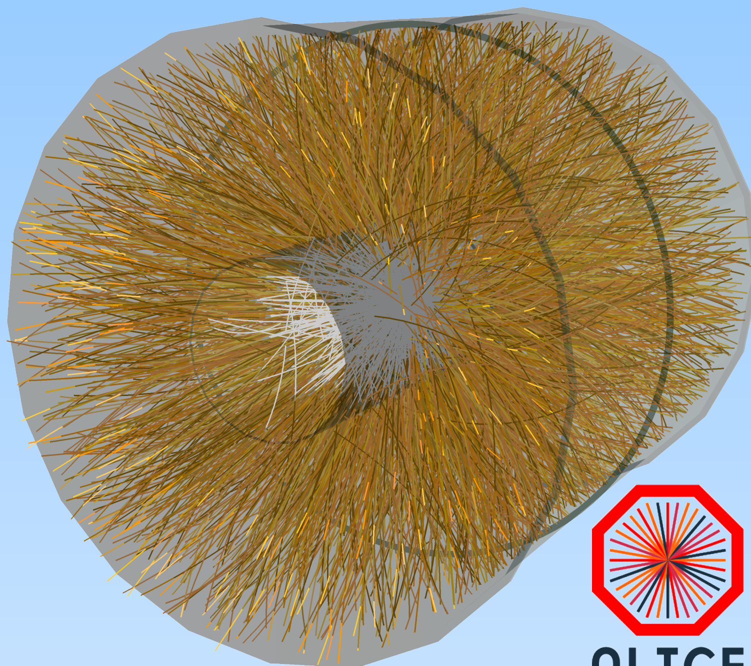
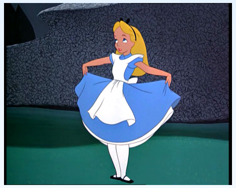


ALICE at the LHC
Highlights from run 1

Silvia Masciocchi
GSI Darmstadt

Colloquium MPP, May 7, 2013

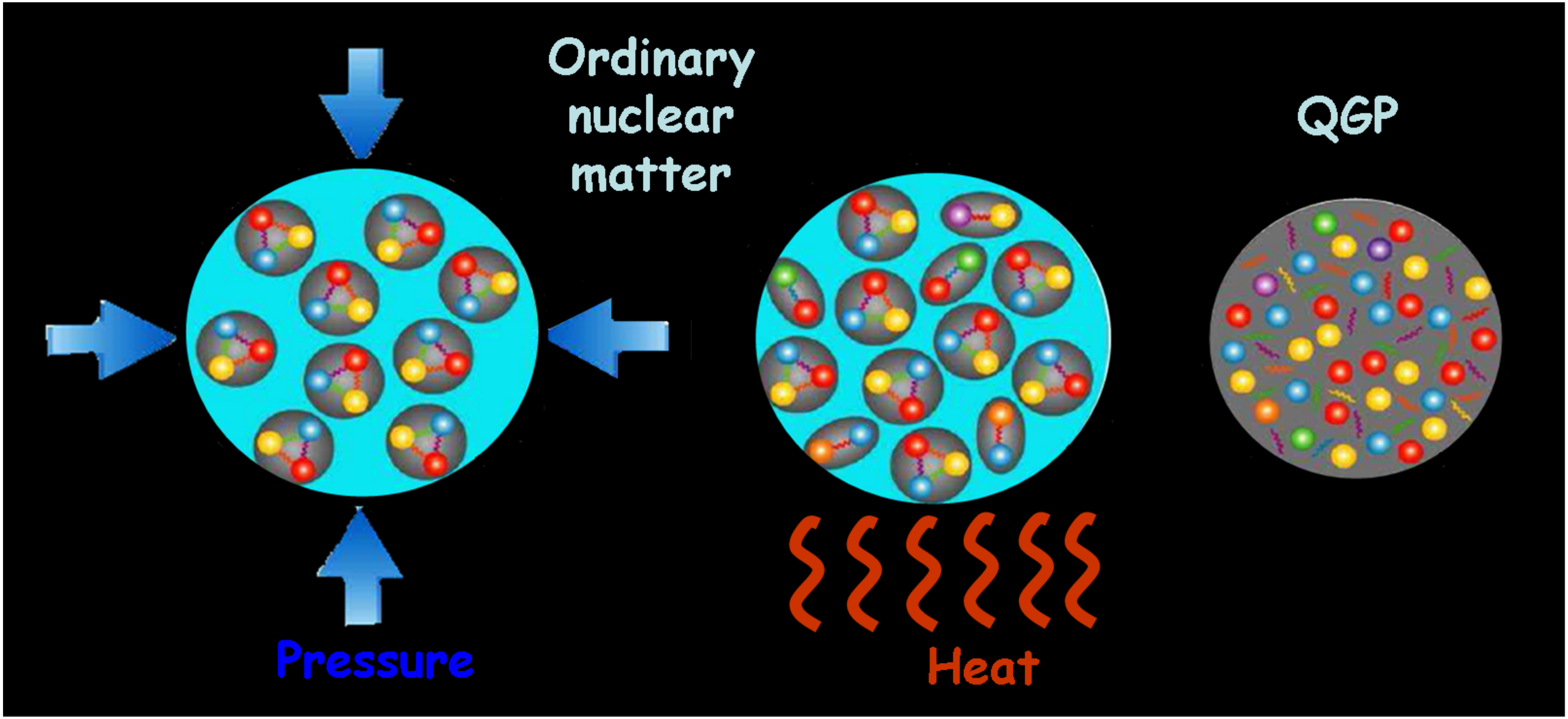


Outline

- Heavy-ion physics and the Quark-Gluon Plasma
- The Large Hadron Collider at CERN
- The ALICE experiment

- Physics results
  - QGP global properties
  - Parton energy loss
  - Heavy flavor, quarkonia
  - Nuclei, exotica
  - Proton-lead results
- Outlook

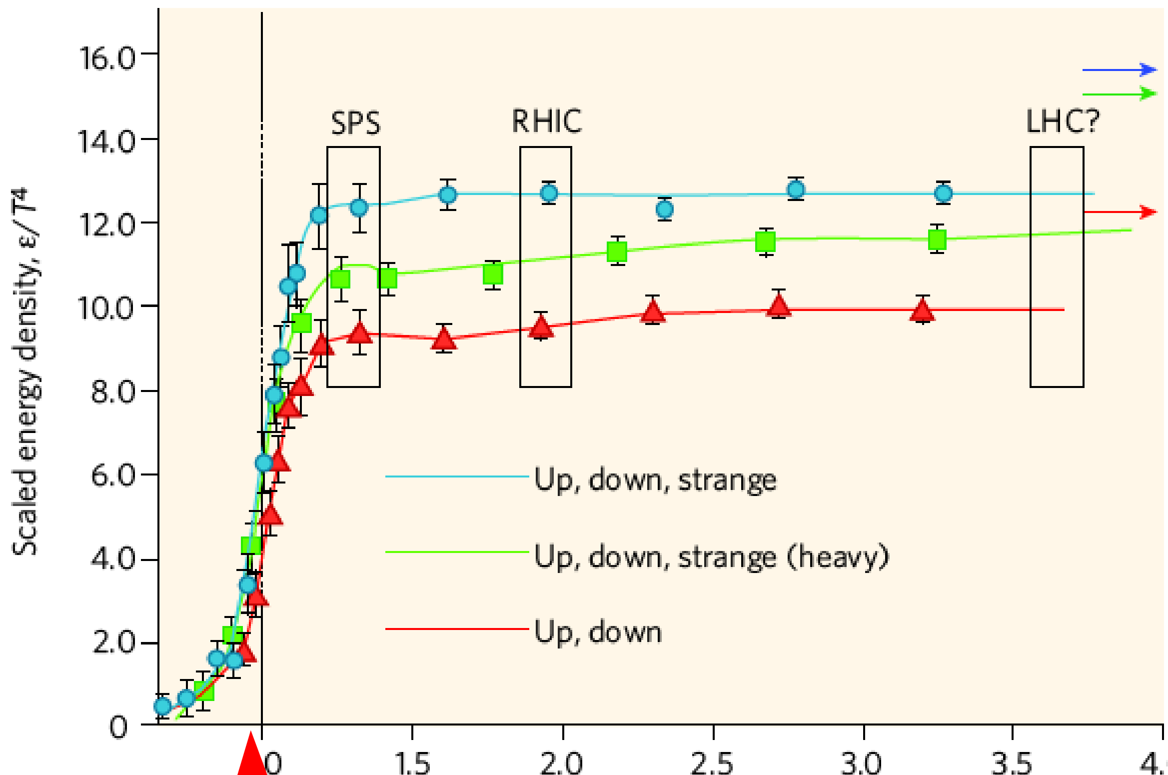
Quark-Gluon Plasma



Lattice QCD calculation

Non-perturbative problems treated by discretization on a space-time lattice

Energy density



Temperature / T_C

No details here!
Not the latest prediction!

Hadron gas to QGP

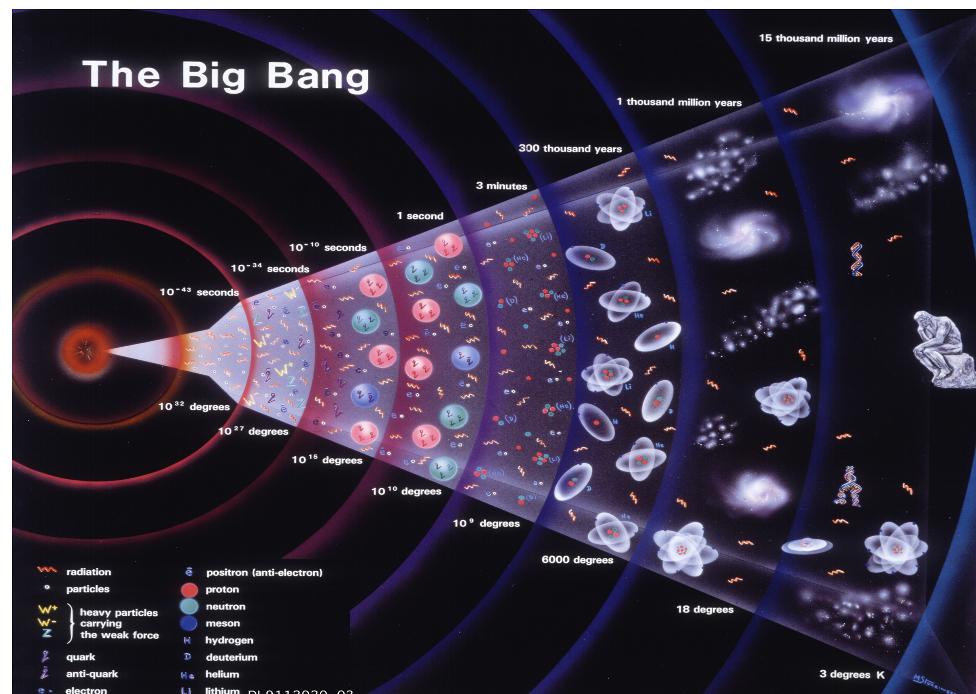
phase transition or cross over

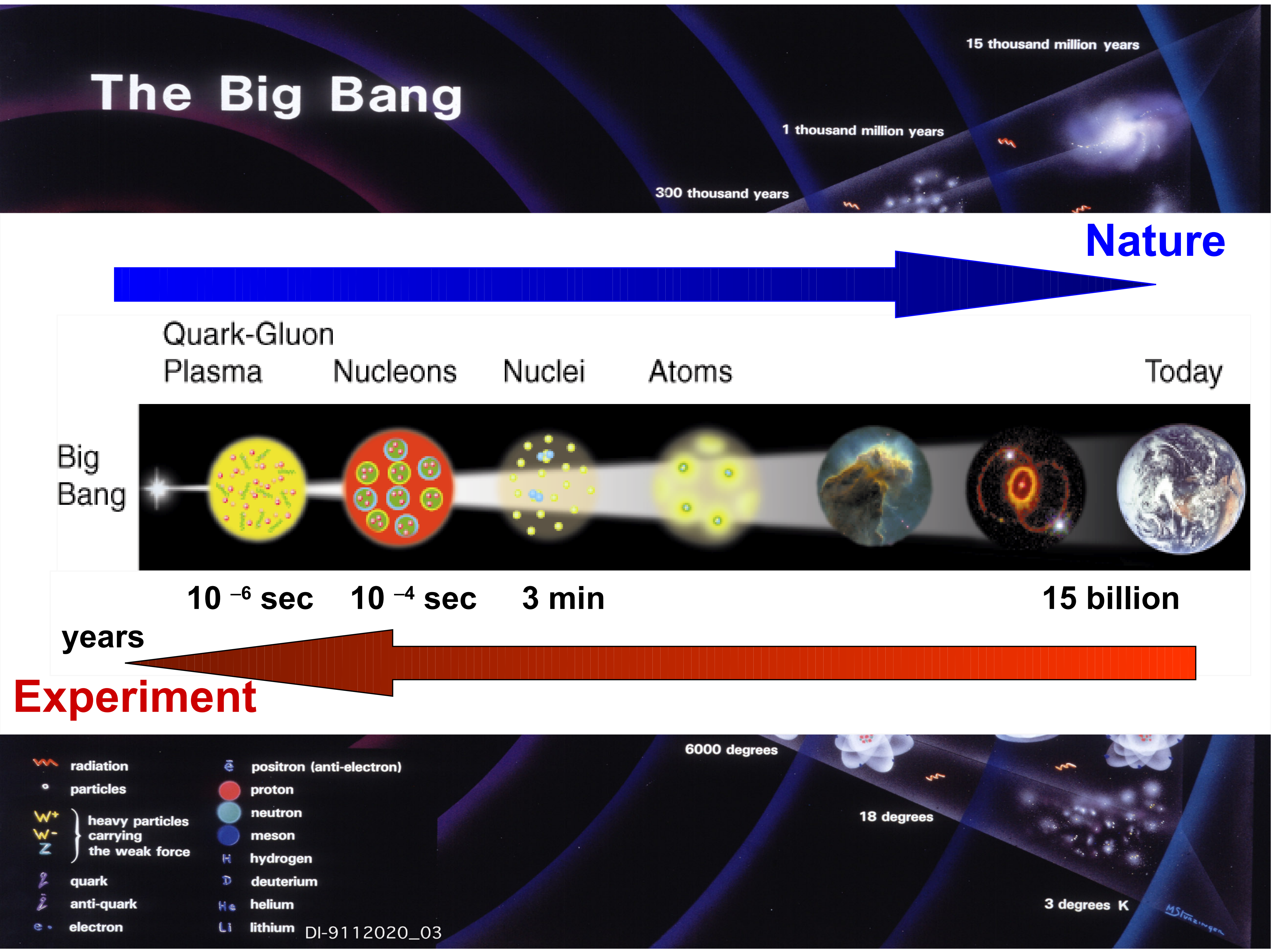
Dense and hot nuclear matter: why?

Status of matter in:

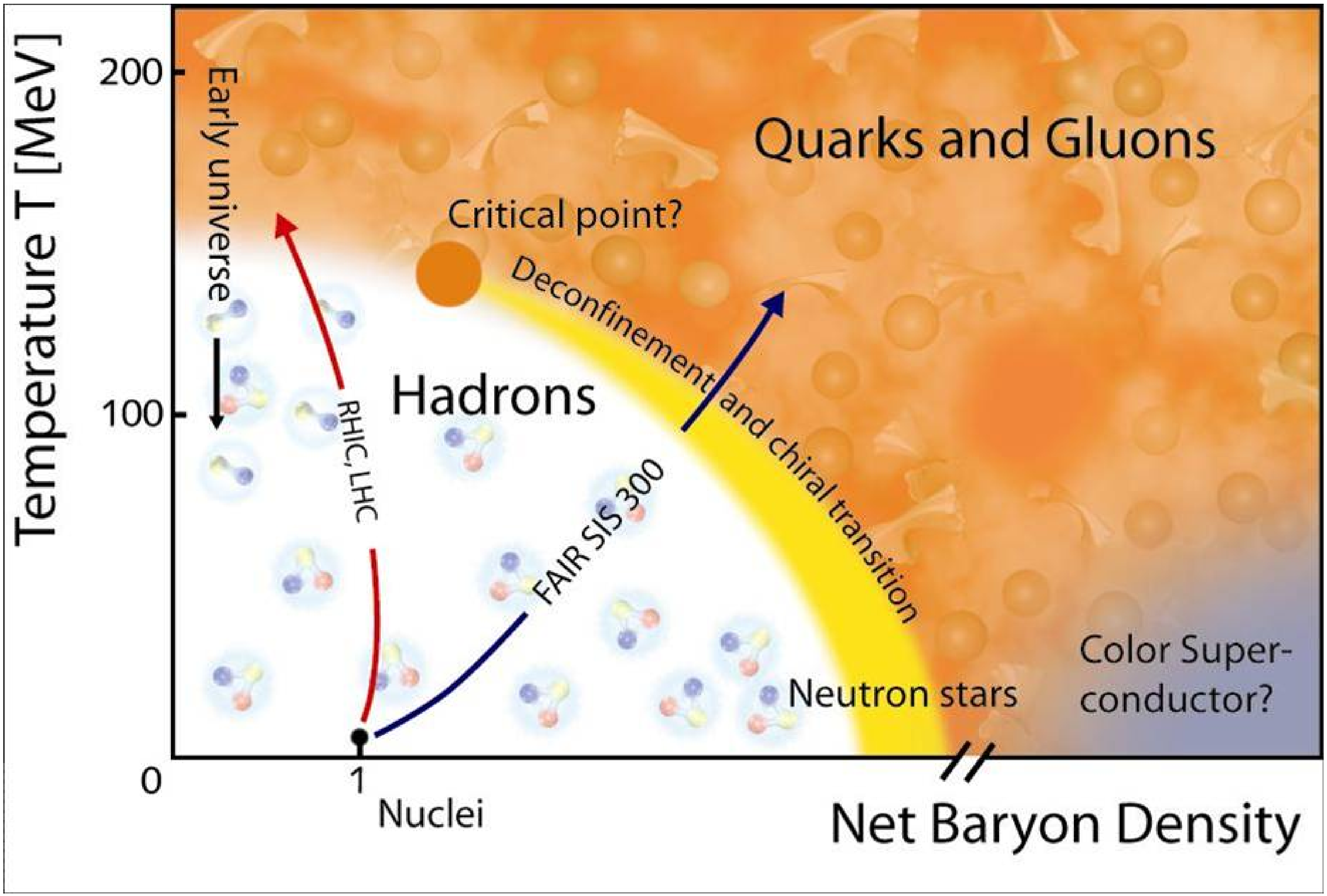
- Neutron stars and core-collapse supernovae

- First instants of our universe (10^{-6} seconds)




The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
Nature
Quark-Gluon Plasma
Nucleons
Nuclei
Atoms
Today
Big Bang
10 −6 sec
10 −4 sec
3 min
15 billion years
Experiment
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
DI-9112020_03
6000 degrees
18 degrees
3 degrees K

Phase diagram



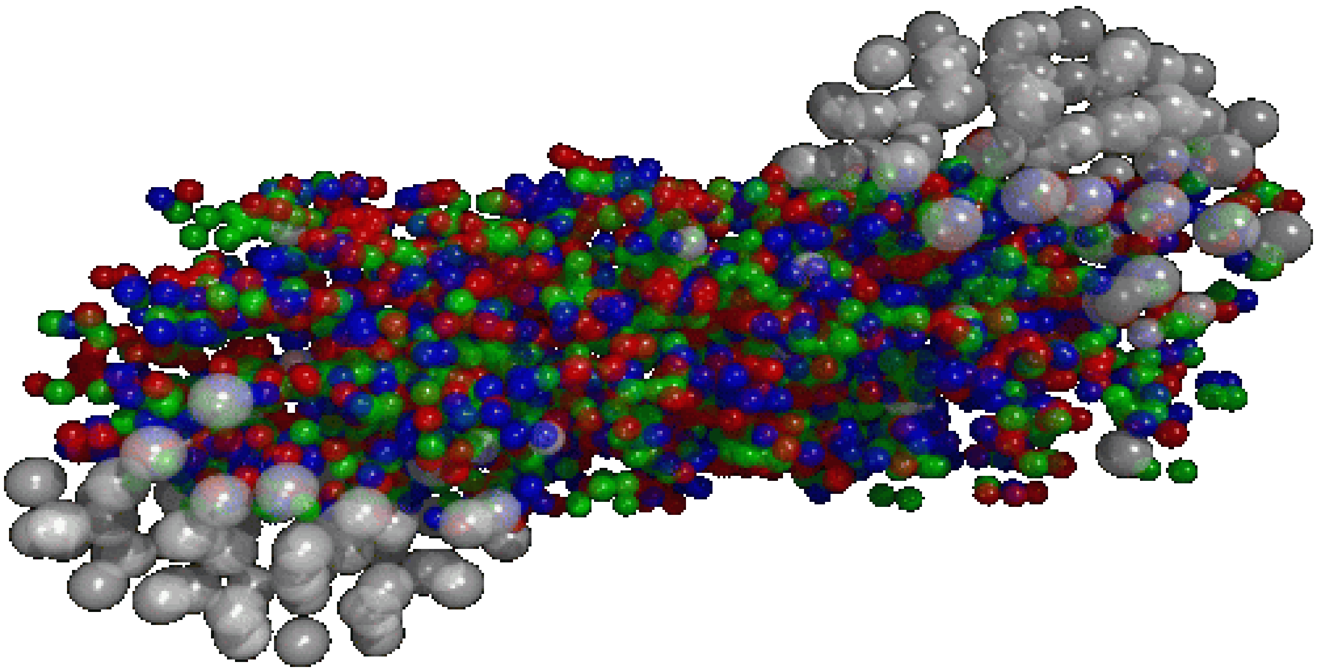
QGP in the laboratory

Produced in the collisions of **heavy ions** at **high energies**

A

A

(Au, Pb ...)



UrQMD

$\sqrt{s_{NN}}$ from few GeV at the SPS

up to 200 GeV at RHIC

up to 2.76 TeV at LHC

The Large Hadron Collider (LHC)

At CERN, Geneva, Switzerland

- 27 km length
- 4 main experiments

Colliding systems:

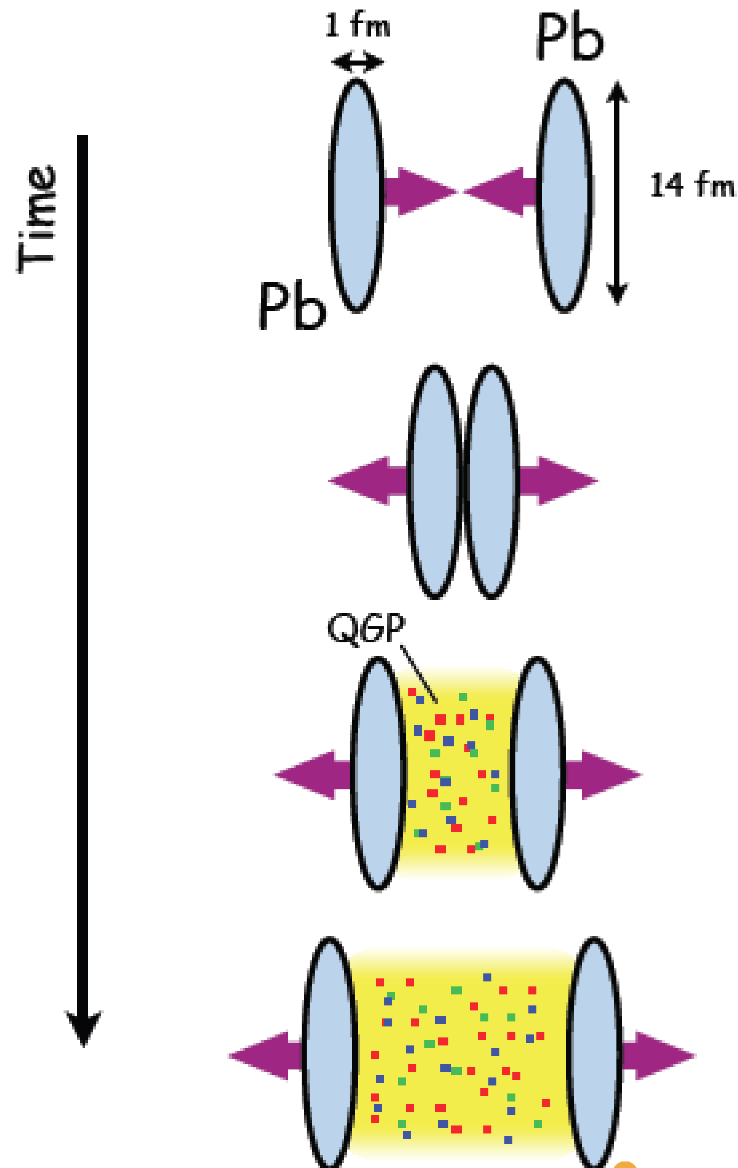
- **proton-proton**
  up to $\sqrt{s}$**=14 TeV**
  2010-2013: 7, 8 TeV
  2.76 TeV
- **Pb-Pb**
  up to $\sqrt{s_{NN}}$**=5.5 TeV**
  2010-2011: 2.76 TeV
- **p-Pb**
  2012-3: $\sqrt{s_{NN}}$**=5.02 TeV**

Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

Compress a very large amount of energy in a very small volume

→ "fireball" of hot matter

- Temperature O(10^{12} K)
  - ~10^5 x T at the center of the sun
  - ~T of the early universe (μs after Big Bang)

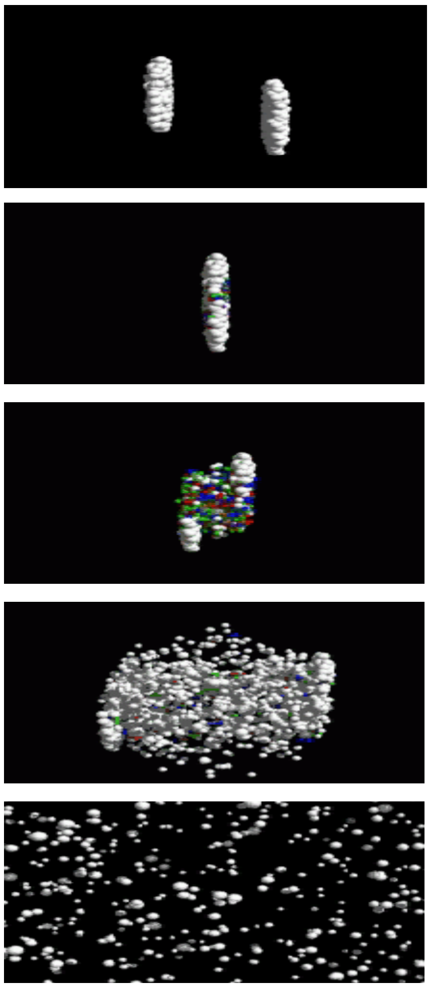


- At LHC: very high temperature
  low baryochemical potential
  (~pressure in the water phase diagram)

- At FAIR: lower temperature
  high baryochemical potential

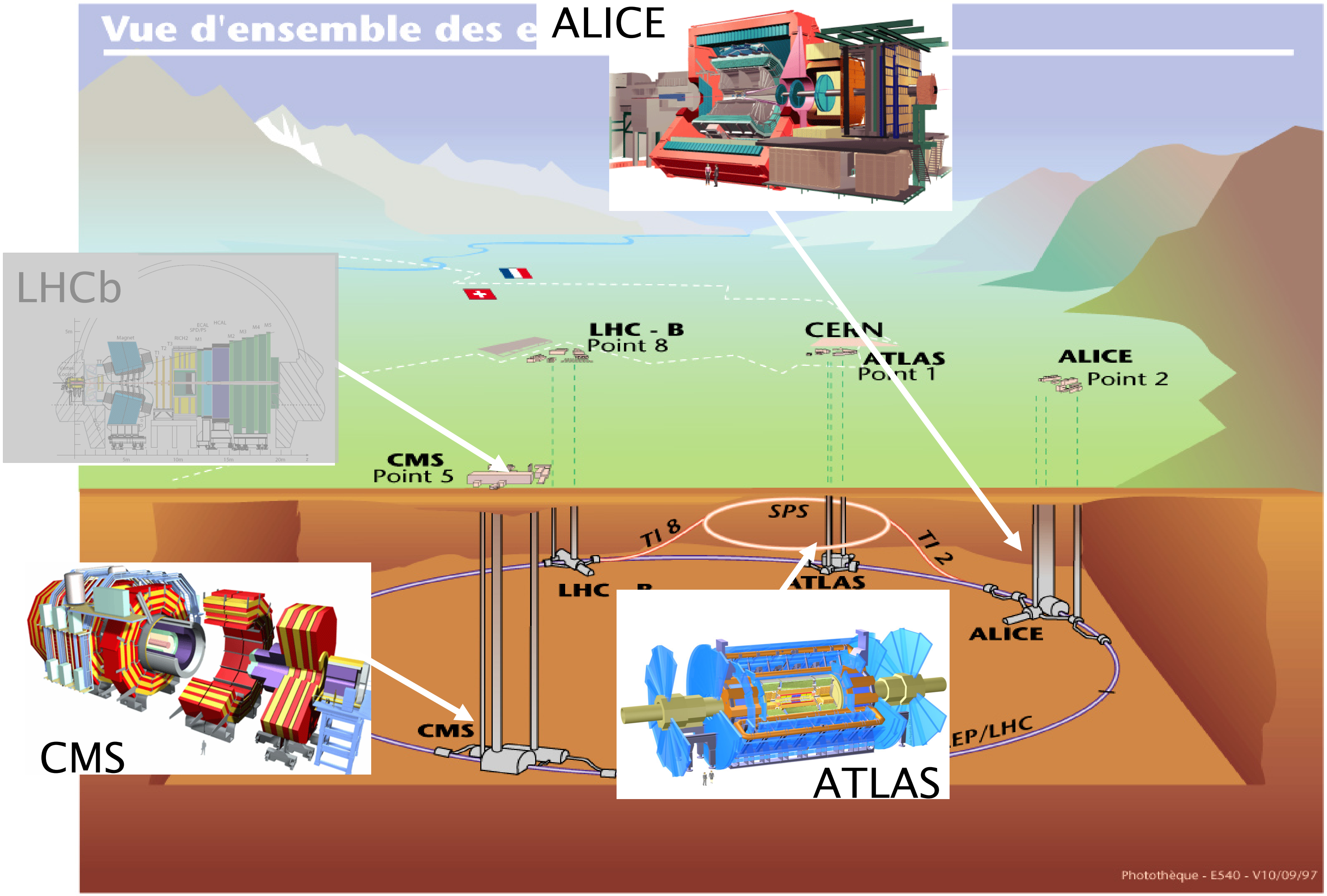
Phases of heavy ion collisions

UrQMD 160 GeV Au+Au

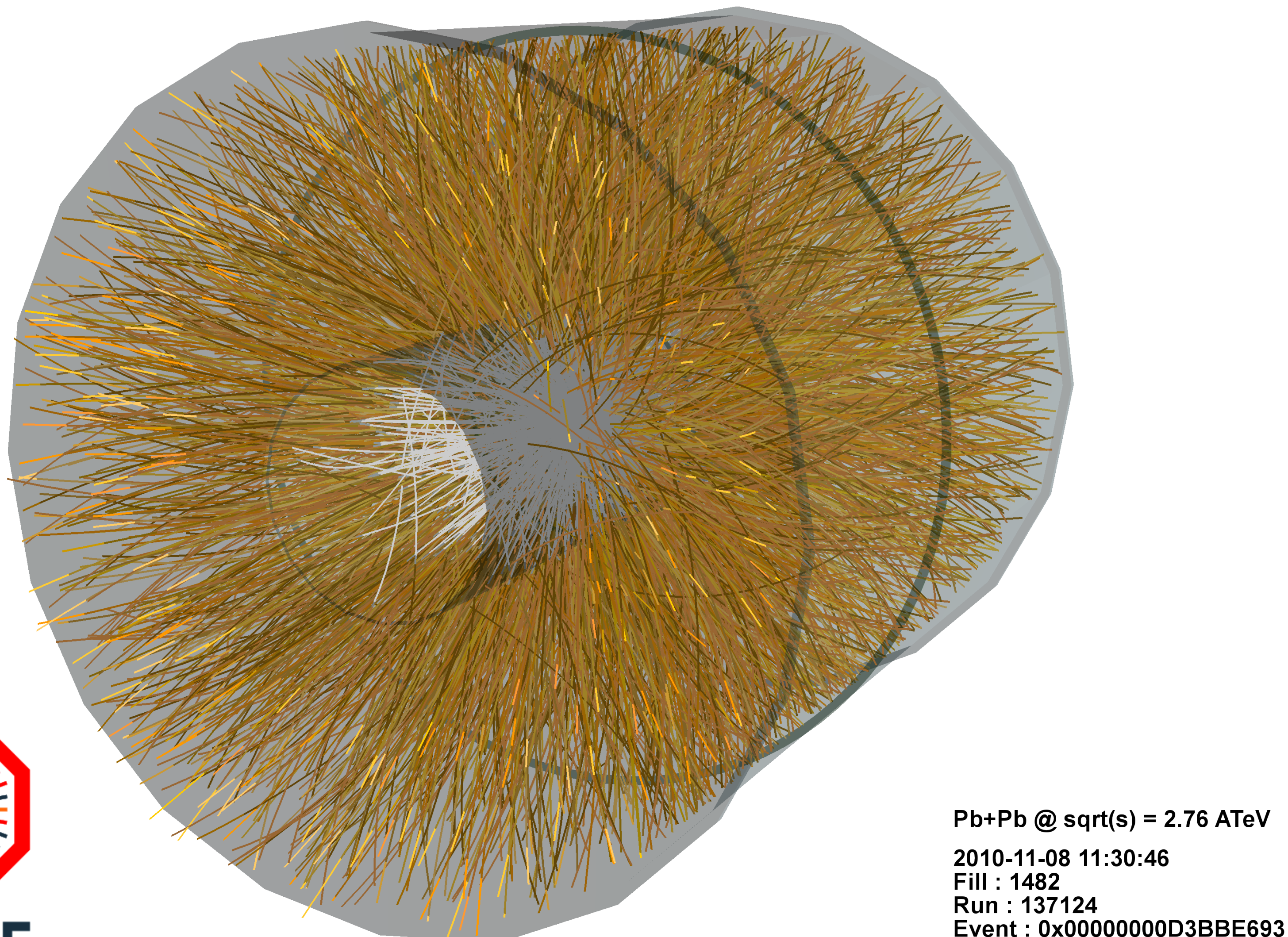


- Before collision
- Compression and heating
- **Thermalization**: equilibrium is established (t < 1 fm/c)
- Expansion and cooling (t < 10-15 fm/c)
- **Chemical freeze-out:** inelastic collisions cease (number of particles frozen)
- **Kinetic freeze-out:** elastic collisions cease (particle momenta, spectra frozen)

Experiments studying QGP



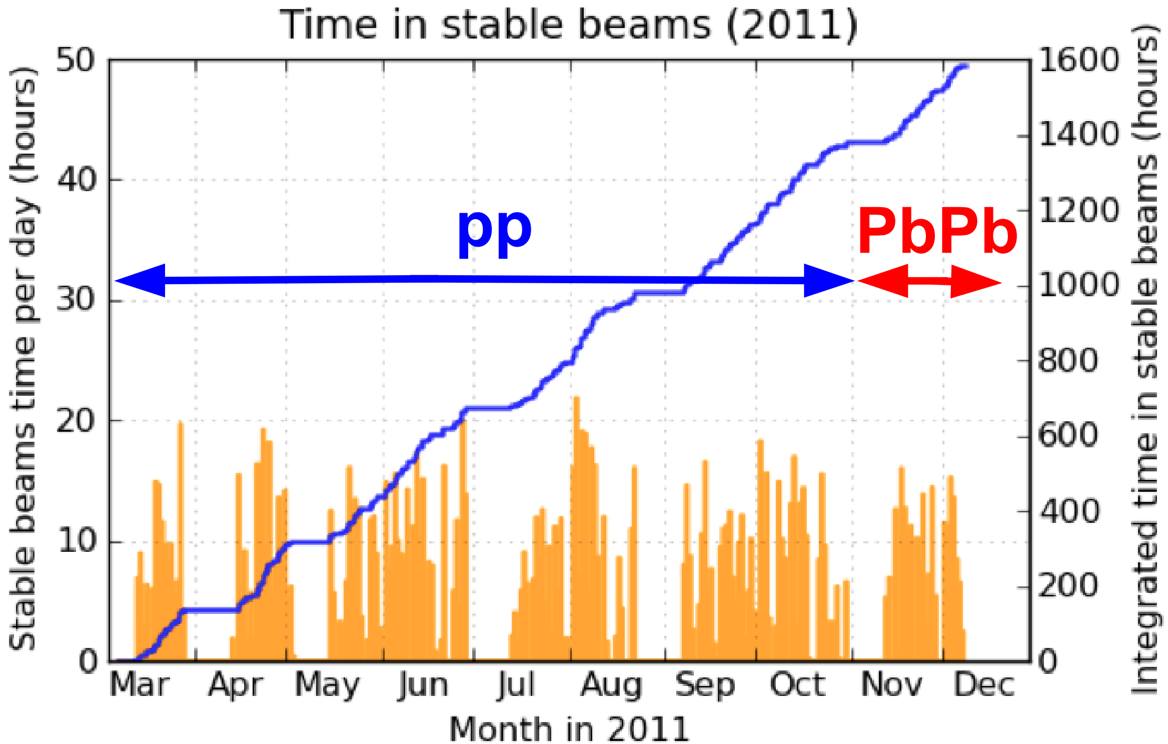
Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



LHC yearly operation

In 2010 and 2011:

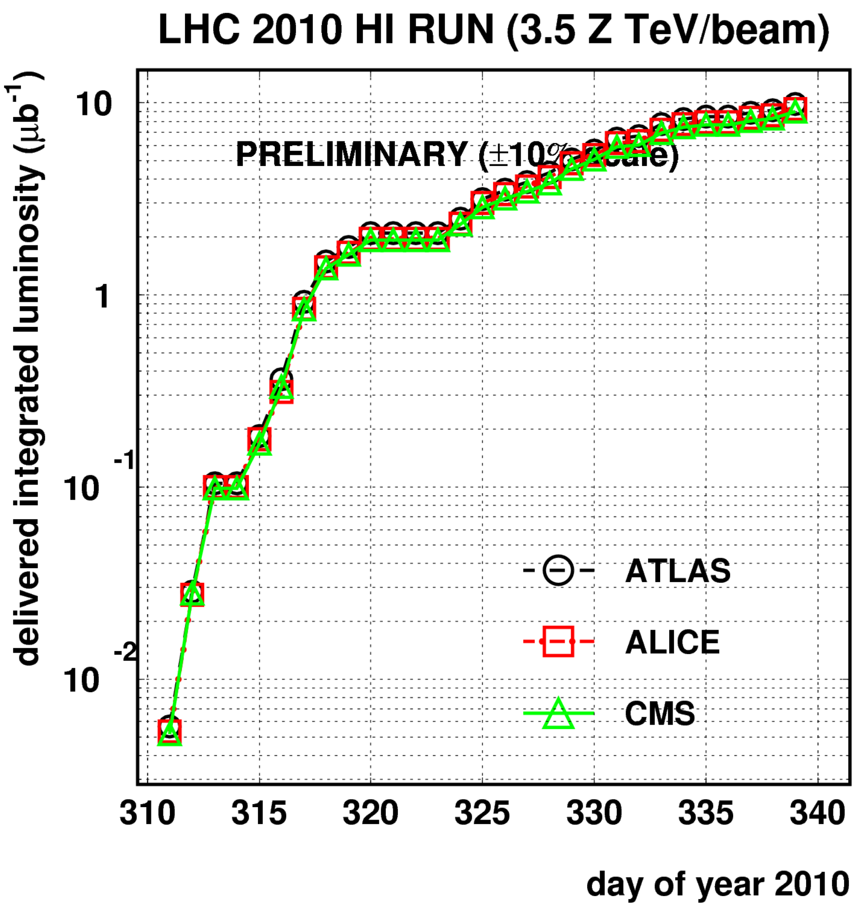
- March – October: pp collisions (~ 1400 hours of stable beams)
- November – December: 4 weeks of PbPb collisions (~ 200 hours)



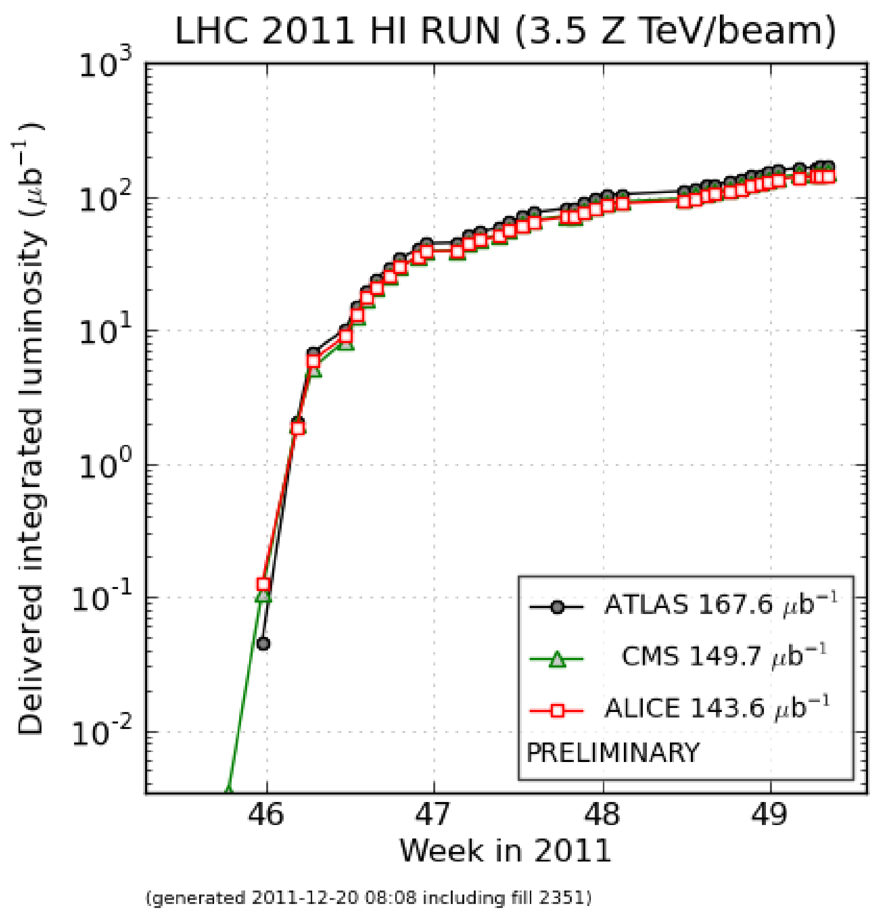
Integrated luminosities at LHC

LHC in 2011 reached amazing interaction rates,
beating its own expectations!

Pb – Pb 2010



Pb – Pb 2011

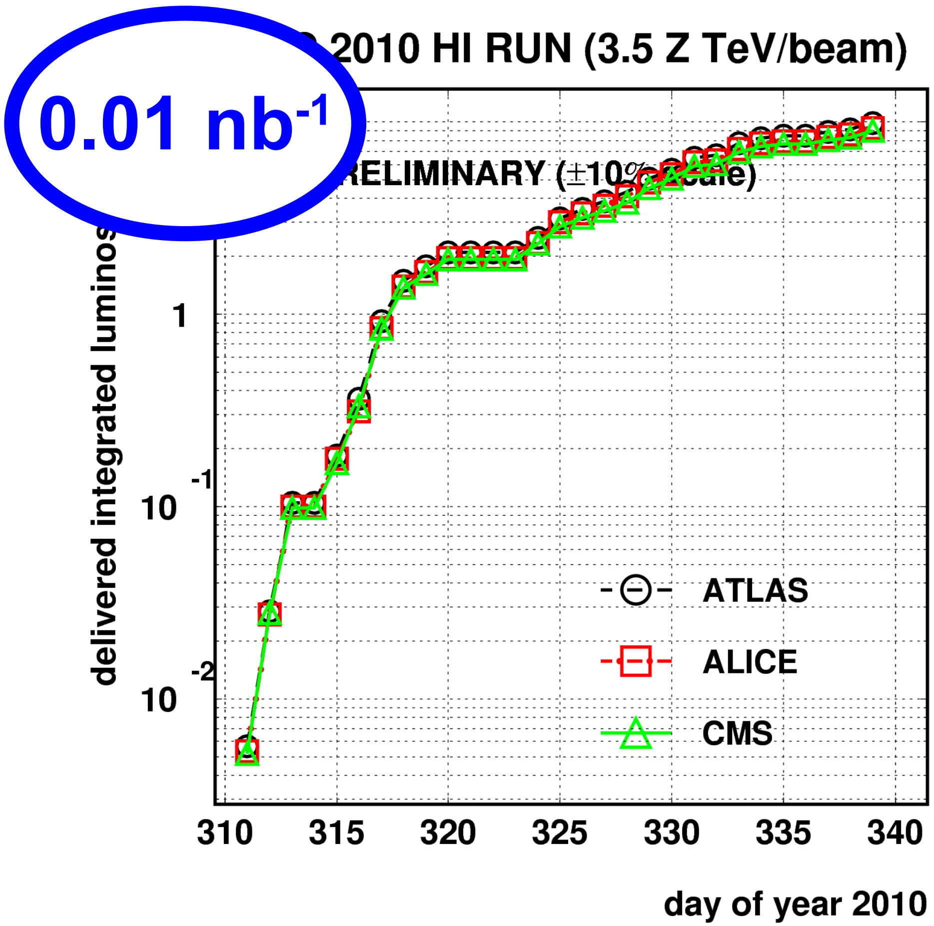


Integrated luminosities at LHC

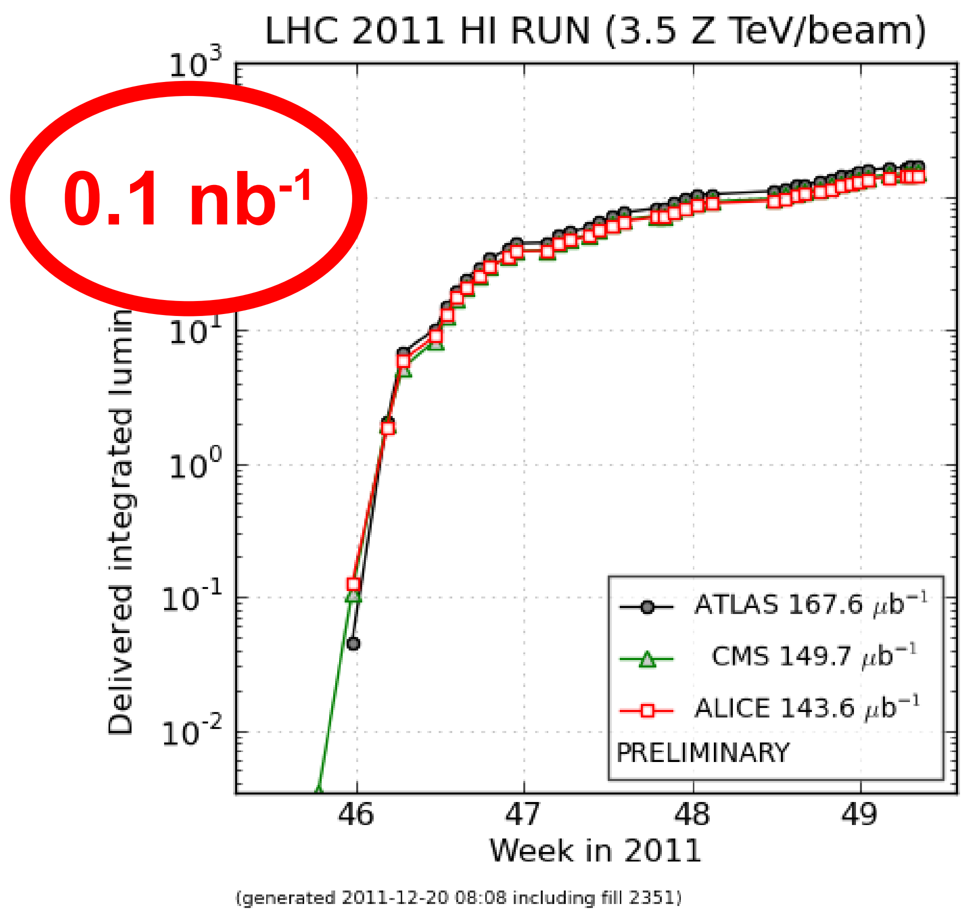
LHC in 2011 reached amazing interaction rates, beating its own expectations!

6 kHz Pb-Pb !

Pb – Pb 2010



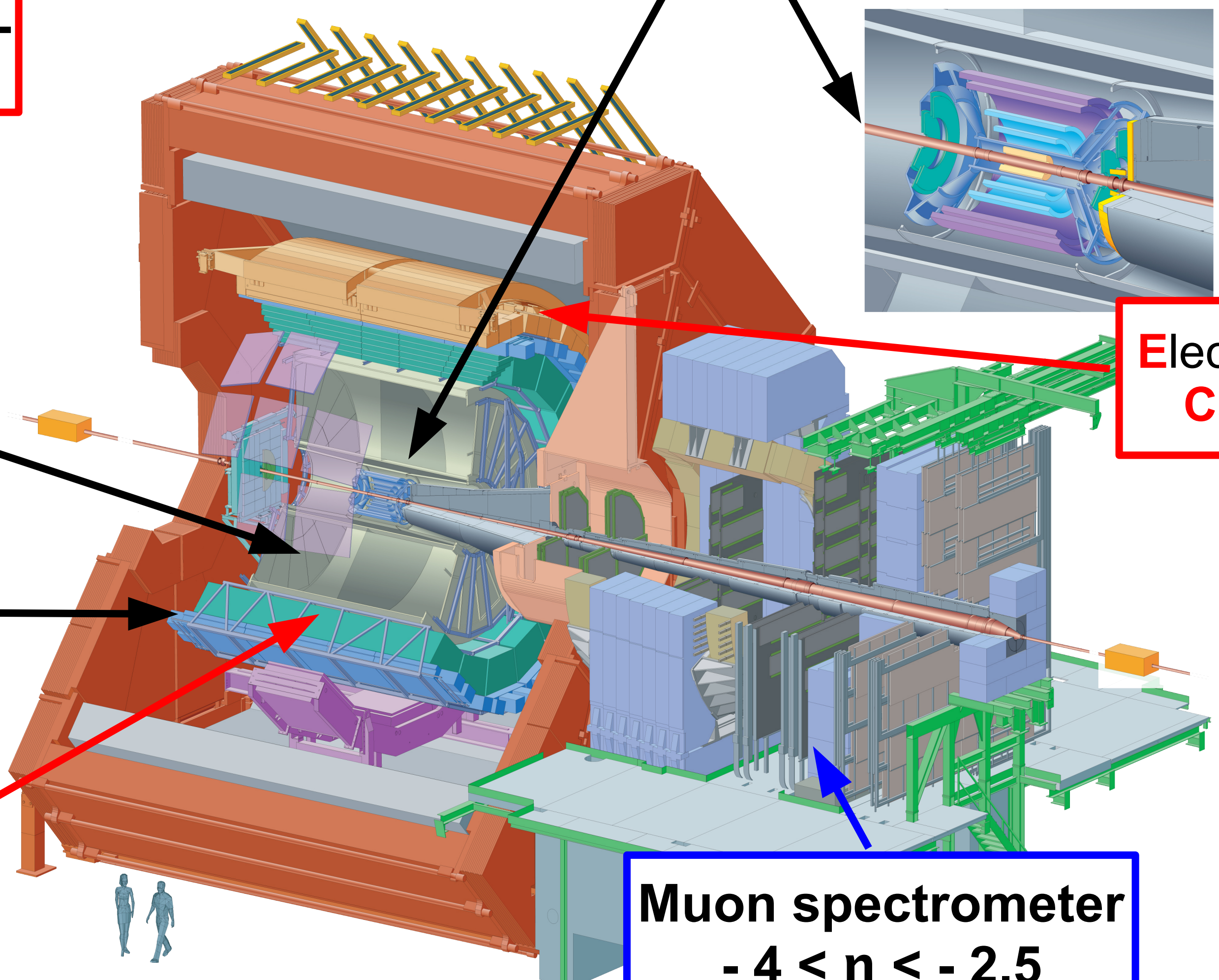
Pb – Pb 2011



ALICE: A Large Ion Collider Experiment

Total weight : 16000 T
Overall diameter : 16 m
Overall length : 26 m
Magnetic field : 0.5 Tesla

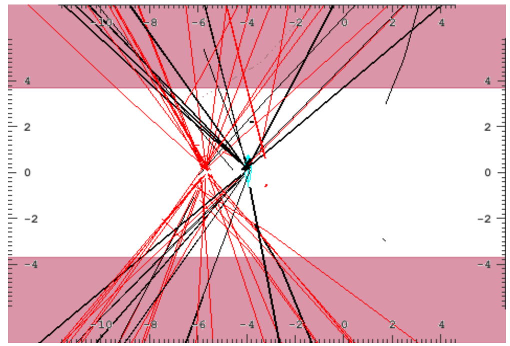
Central barrel
$|\eta| < 0.9$
L3 magnet: 0.5 T

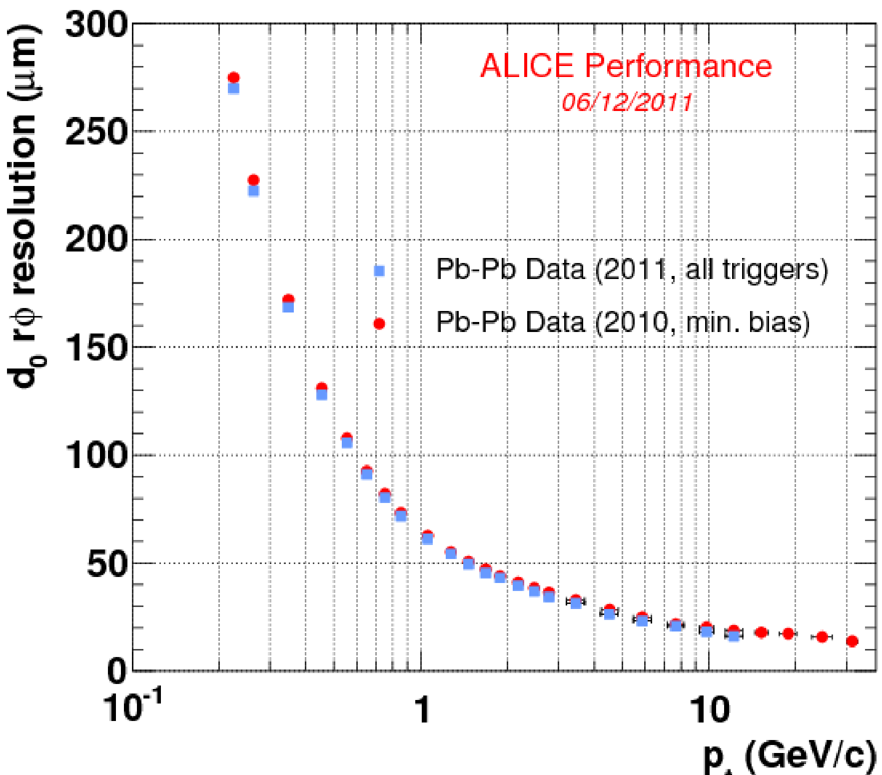


ALICE

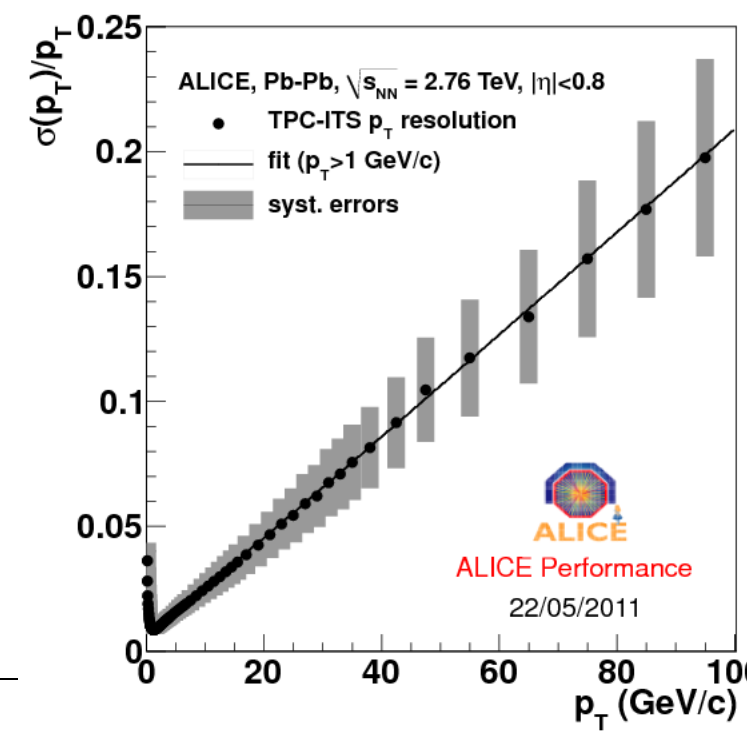
Excellent vertex reconstruction

high resolution on impact parameter



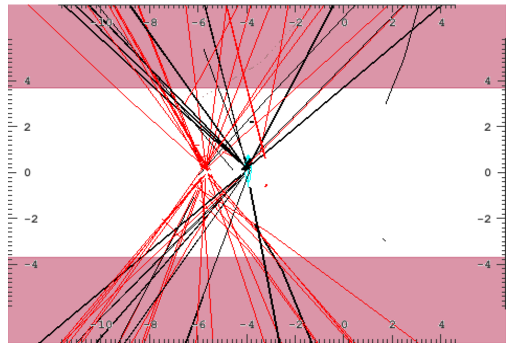


Very good resolution on transverse momentum over a wide range!



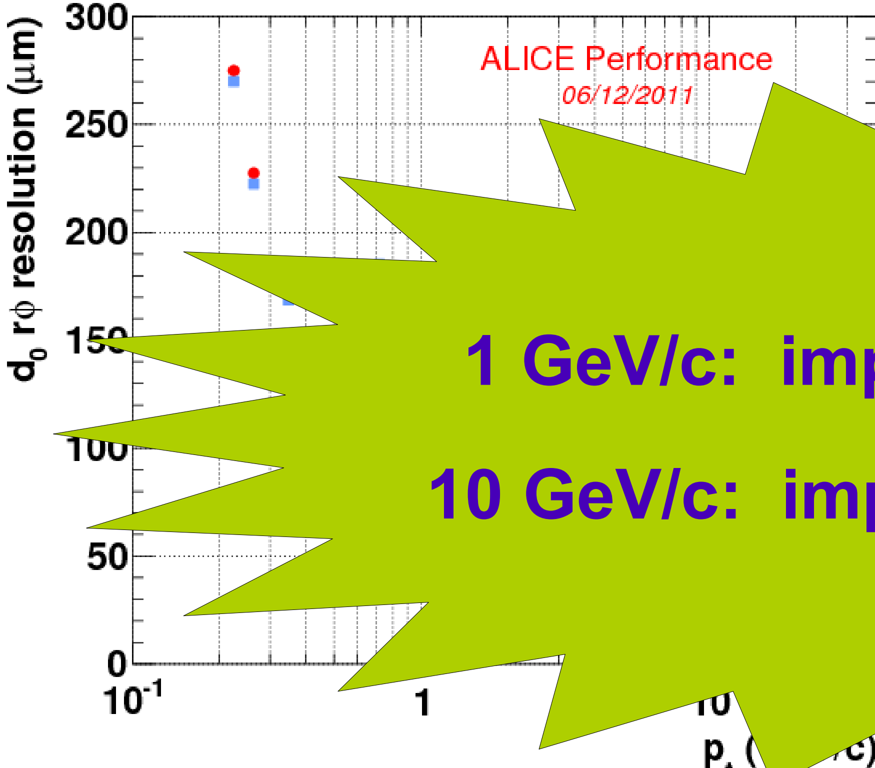
ALICE

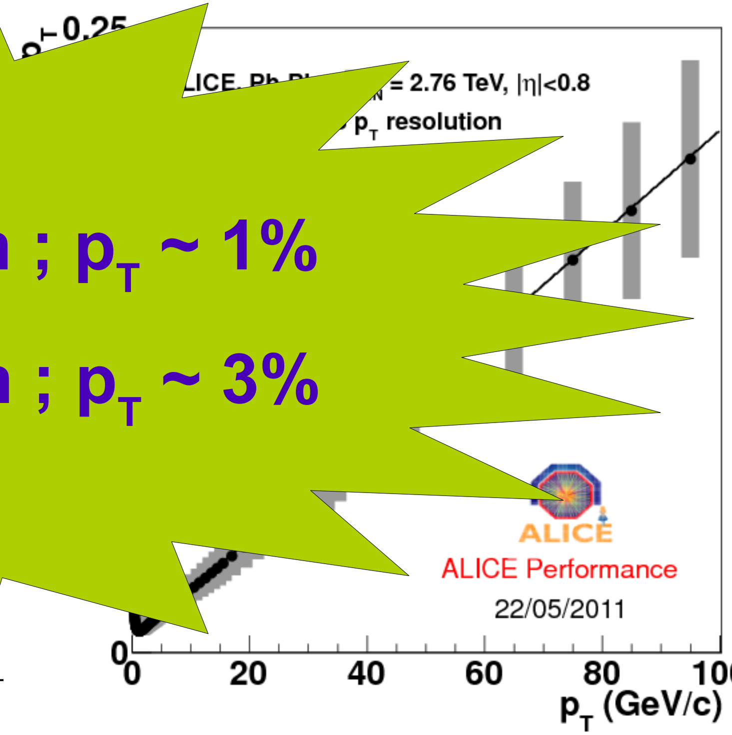
Excellent vertex reconstruction



high resolution on impact parameter

Very good resolution on transverse momentum over a wide range!



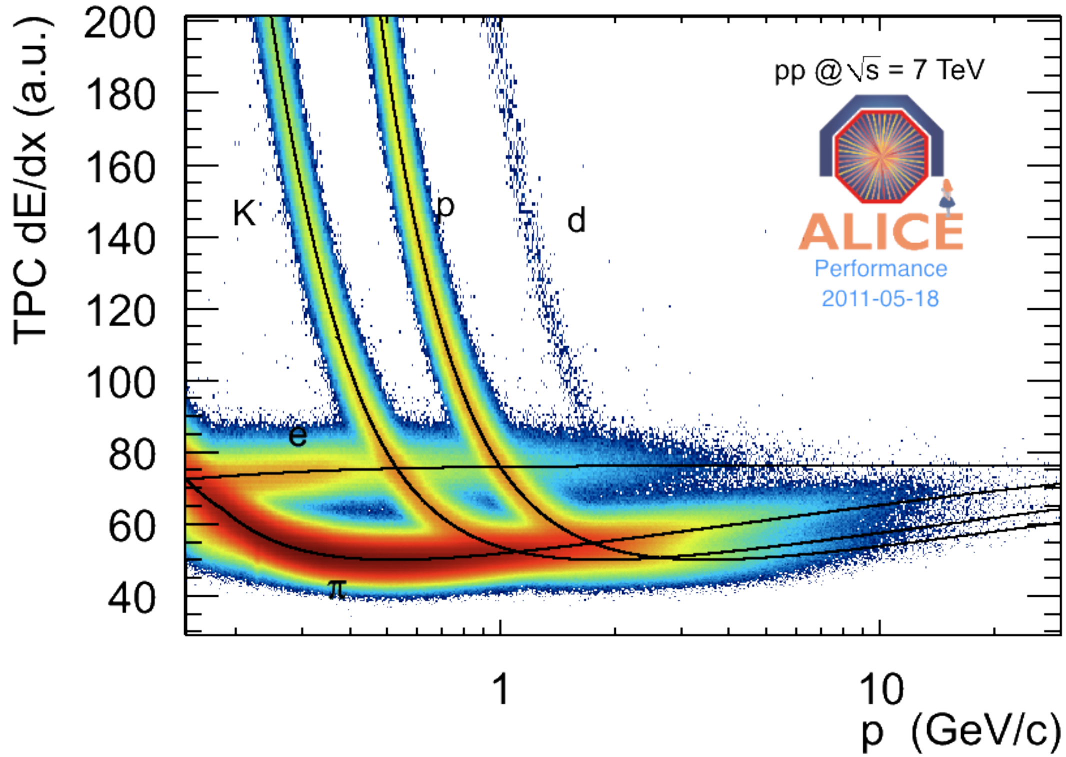


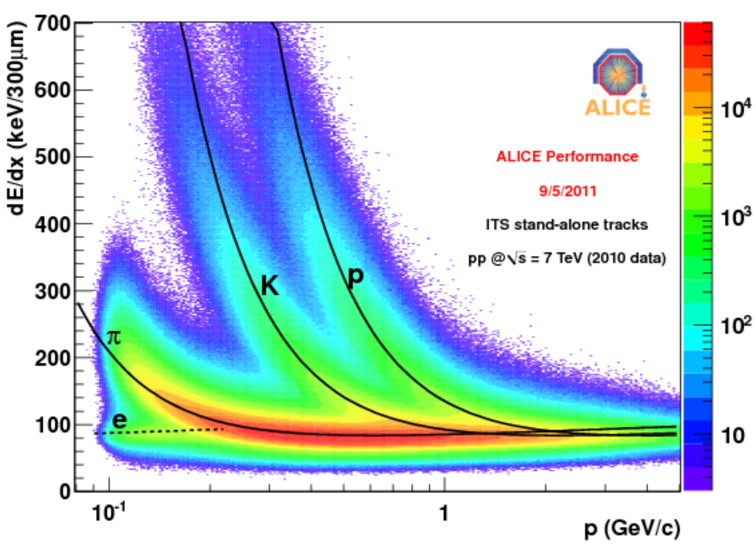
1 GeV/c: imp par ~ 65 μm ; p_T ~ 1%

10 GeV/c: imp par ~ 25 μm ; p_T ~ 3%

Wonderland: particle identification 1

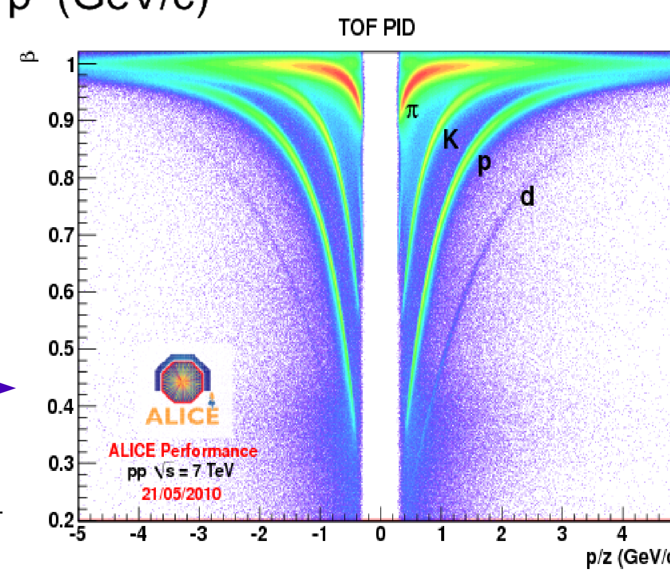
Time Projection Chamber





Inner Tracking System

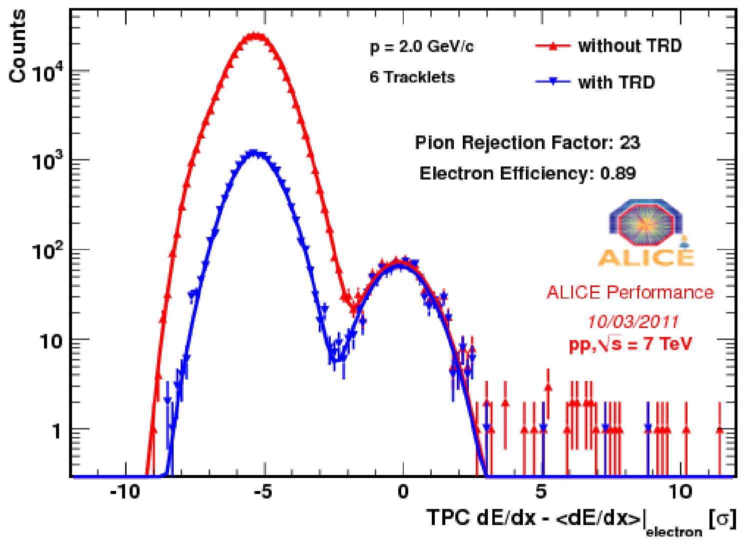
Time of Flight

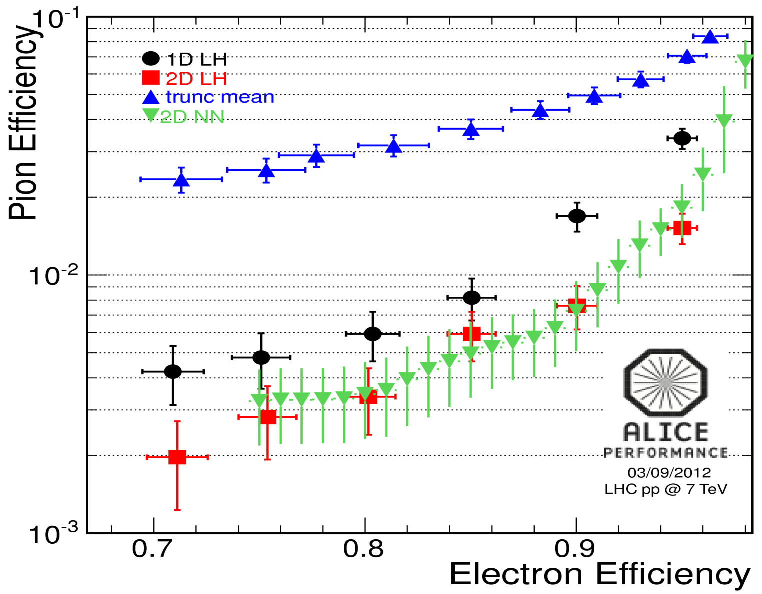


Wonderland: particle identification 2

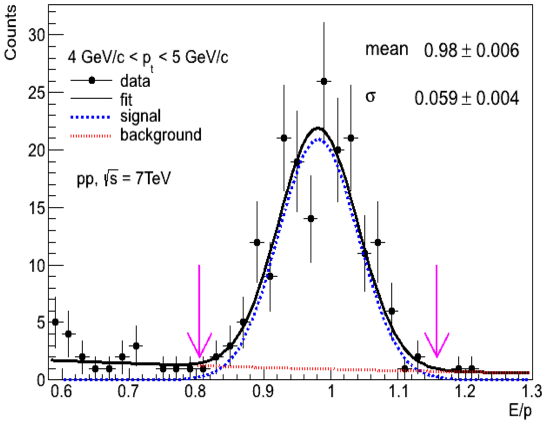
Transition Radiation Detector

e/π sep Trigger





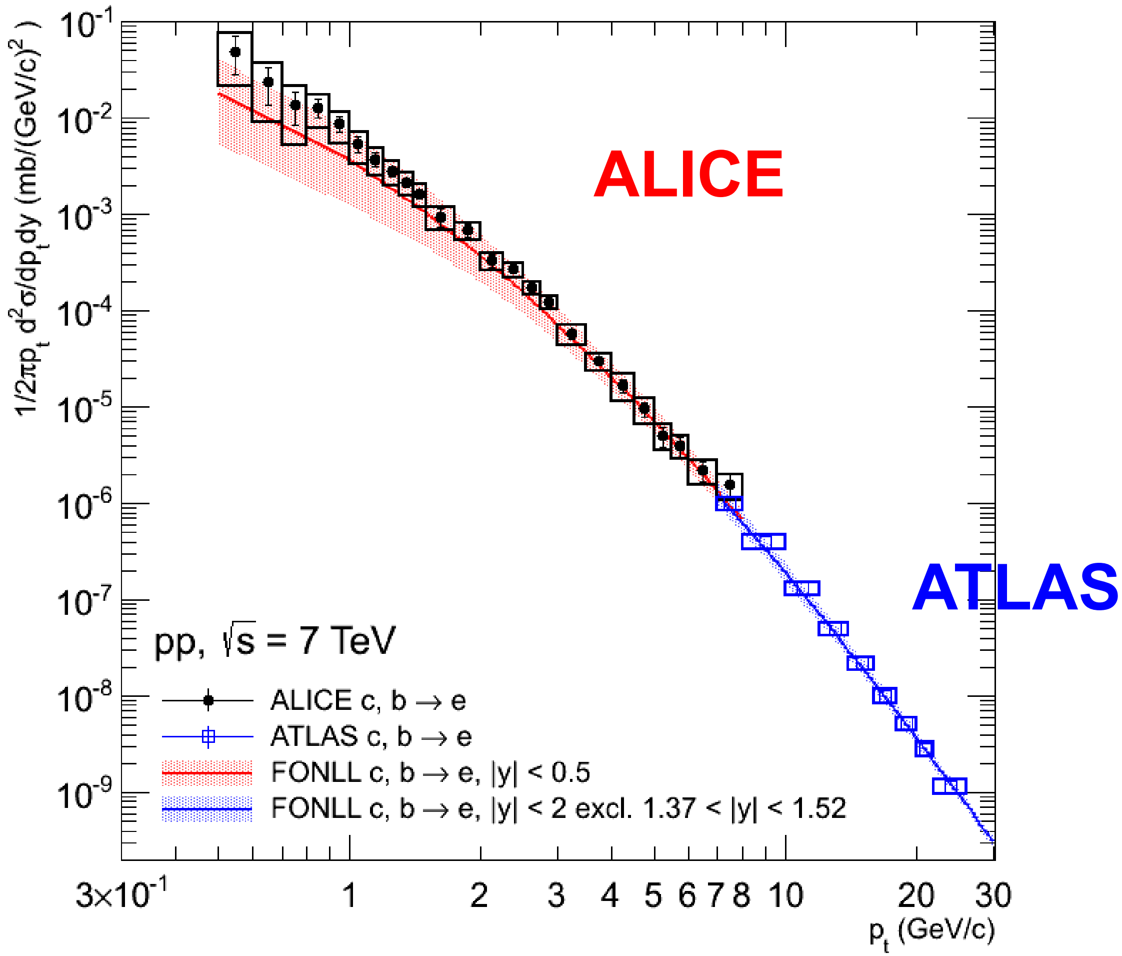
Electromagnetic Calorimeter: E/p



ALICE specialties: proton-proton

Electrons from heavy-flavour hadron decays

Production cross section of **charm + beauty → electron + X**



Test of pQCD

ATLAS: Phys.Lett., B707:438–458, 2012
ALICE: Phys.Rev. D86 (2012) 112007

ALICE specialties: proton-proton

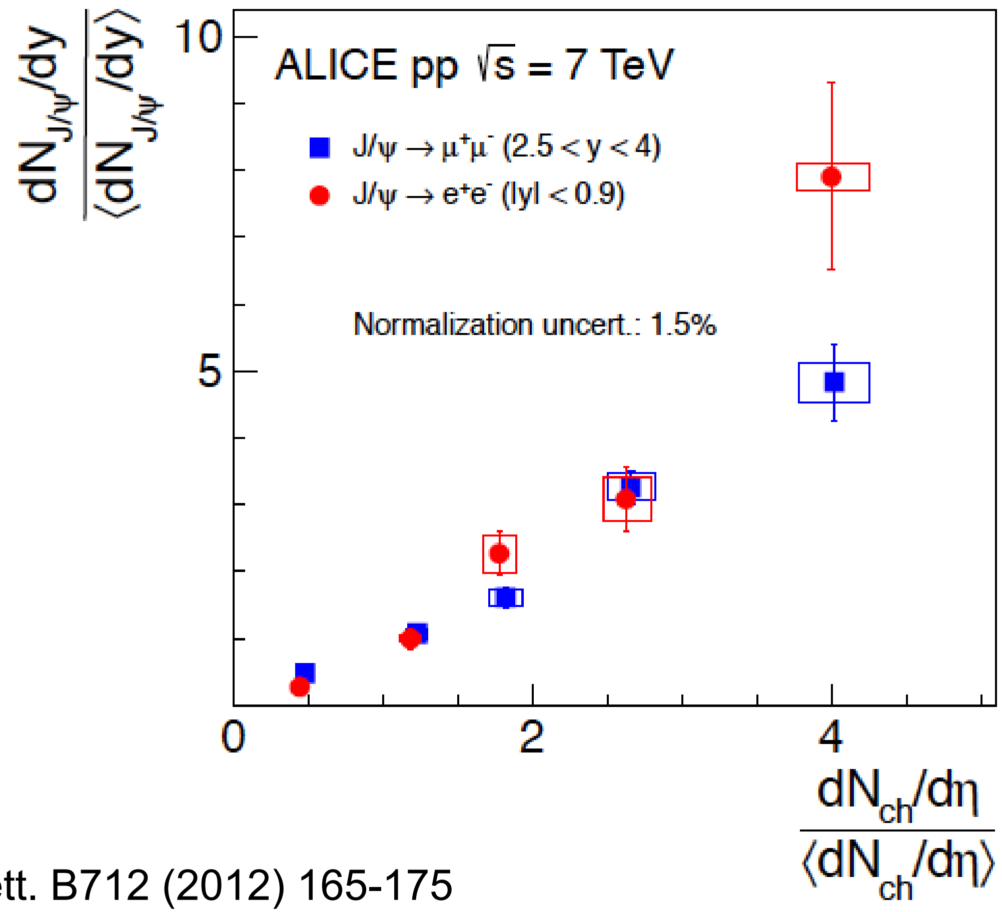
$J/\psi\ (c\bar{c}) \rightarrow e^+e^-,\ \mu^+\mu^-$

$p_T > 0$ GeV/c

Production yield as a function of charged particle multiplicity

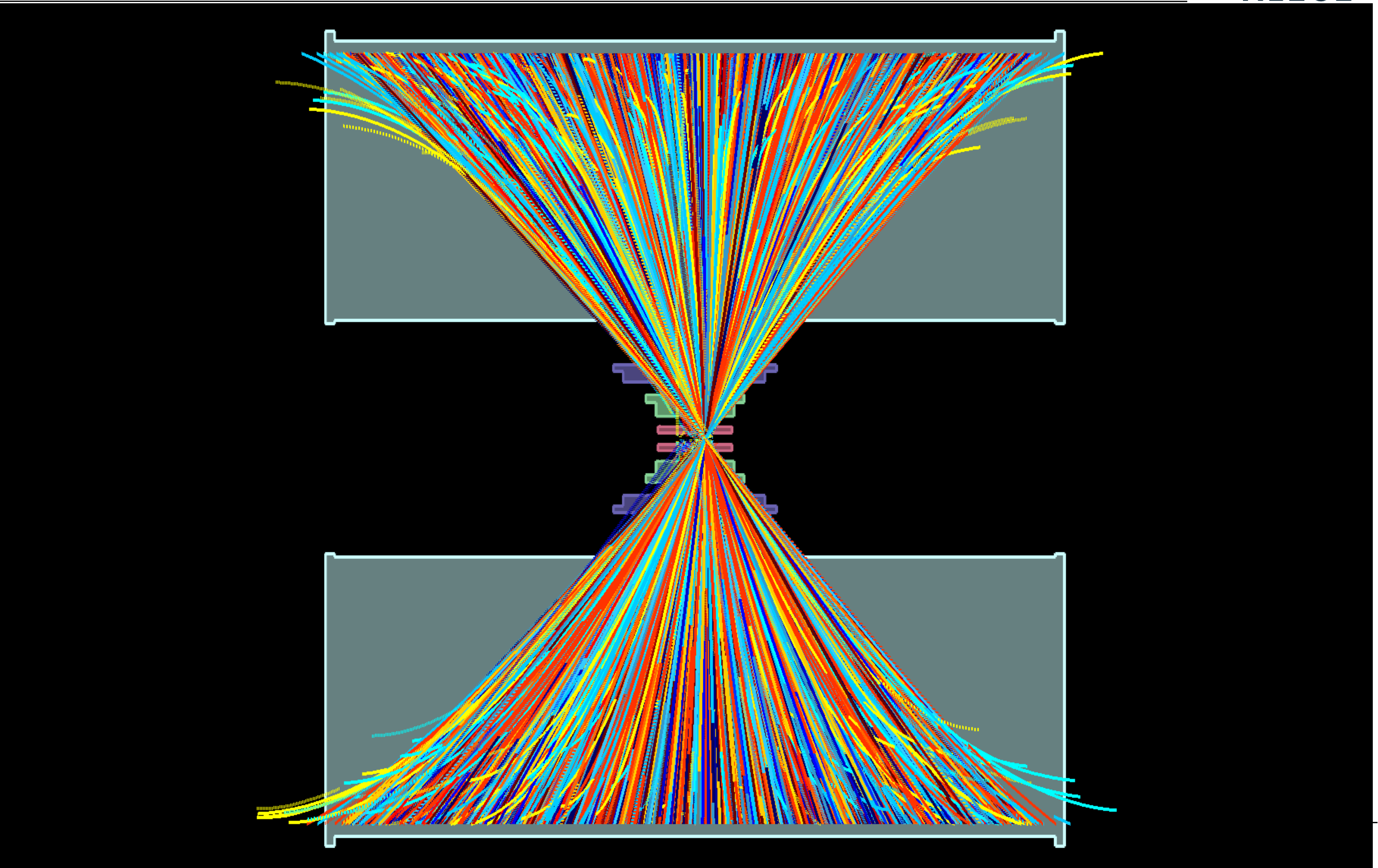
LINEAR INCREASE !

Remains a puzzle !



Phys.Lett. B712 (2012) 165-175

Pb-Pb collisions

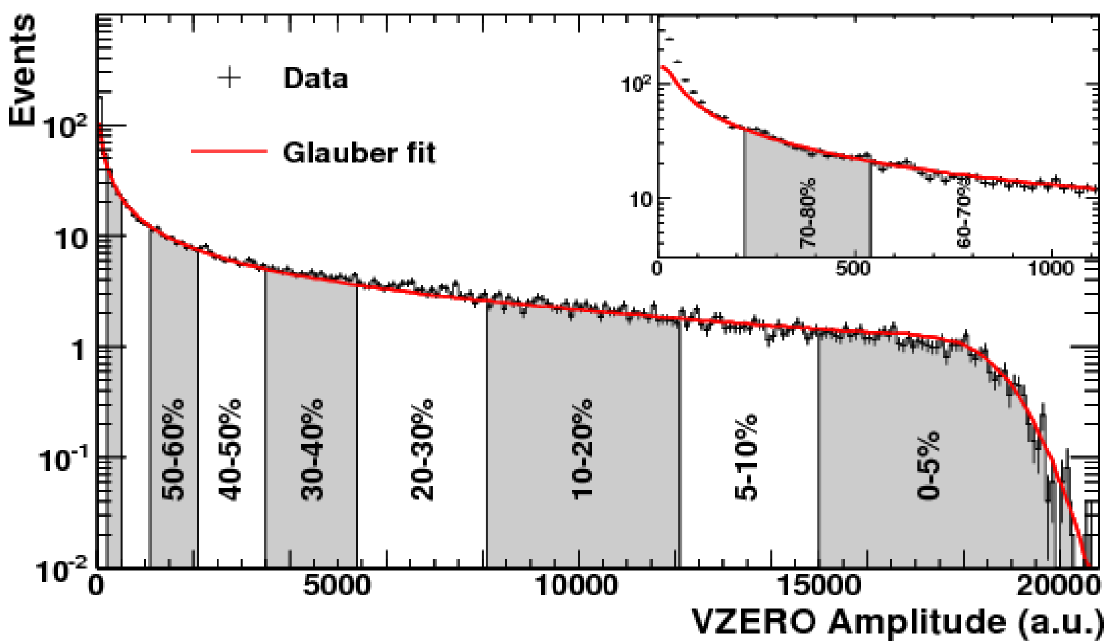


Geometry of a Pb-Pb collision

Central collisions → high number of participants → high multiplicity
Peripheral collisions → low number of participants → low multiplicity

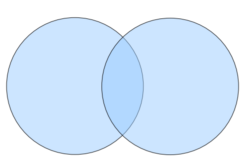
E.g. measure by VZERO scintillators + reproduced by Glauber model fit

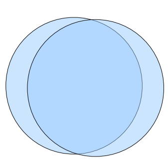
Phys. Rev. Lett. 106, 032301 (2011)



Centrality: Percentile of total hadronic cross section

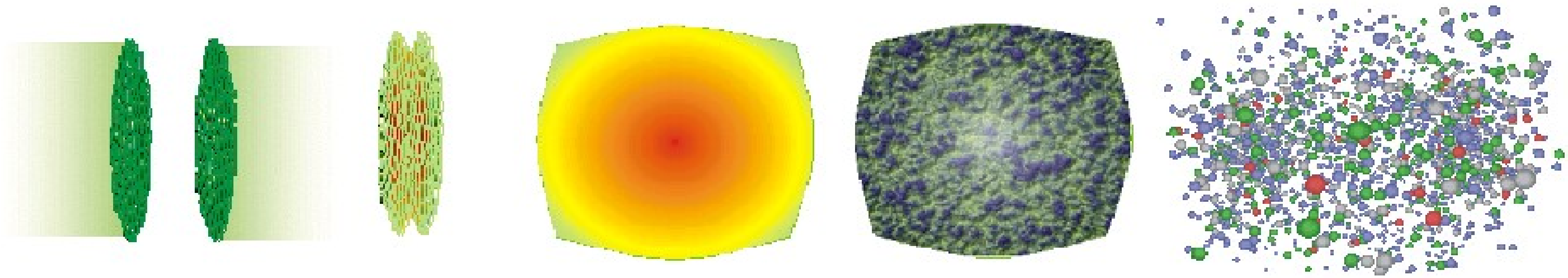
peripheral





central

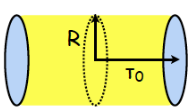
Global properties



Characterize the hot fireball produced in Pb-Pb collisions at the LHC:

- **Energy density** ↔ Multiplicity of charged particles produced
  - Bjorken estimate

$$\epsilon_{Bj} = \frac{dE_T/d\eta}{\pi R^2 \tau_0} \qquad \frac{dE_T}{d\eta} \propto \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0}$$



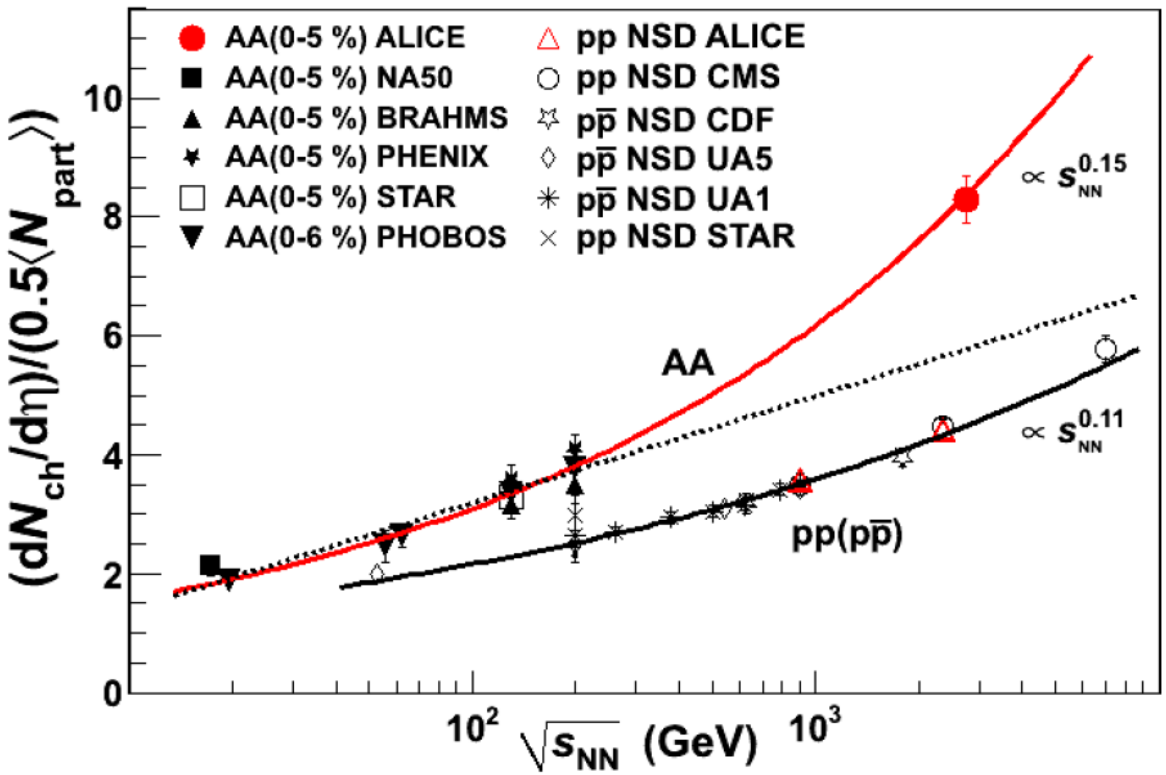
- **Size and lifetime** of the source
  - From 2-pion Bose-Einstein correlations

- **Temperature**

Multiplicity

Most central collisions (0-5%): **~1600 charged particles per unit of pseudorapidity**

$$2\frac{dN_{ch}}{d\eta}/\langle N_{part}\rangle = 8.4 \pm 0.3(sys)$$



2.2 x central Au-Au at $\sqrt{s_{NN}}$=0.2TeV

Log extrapolation fails!

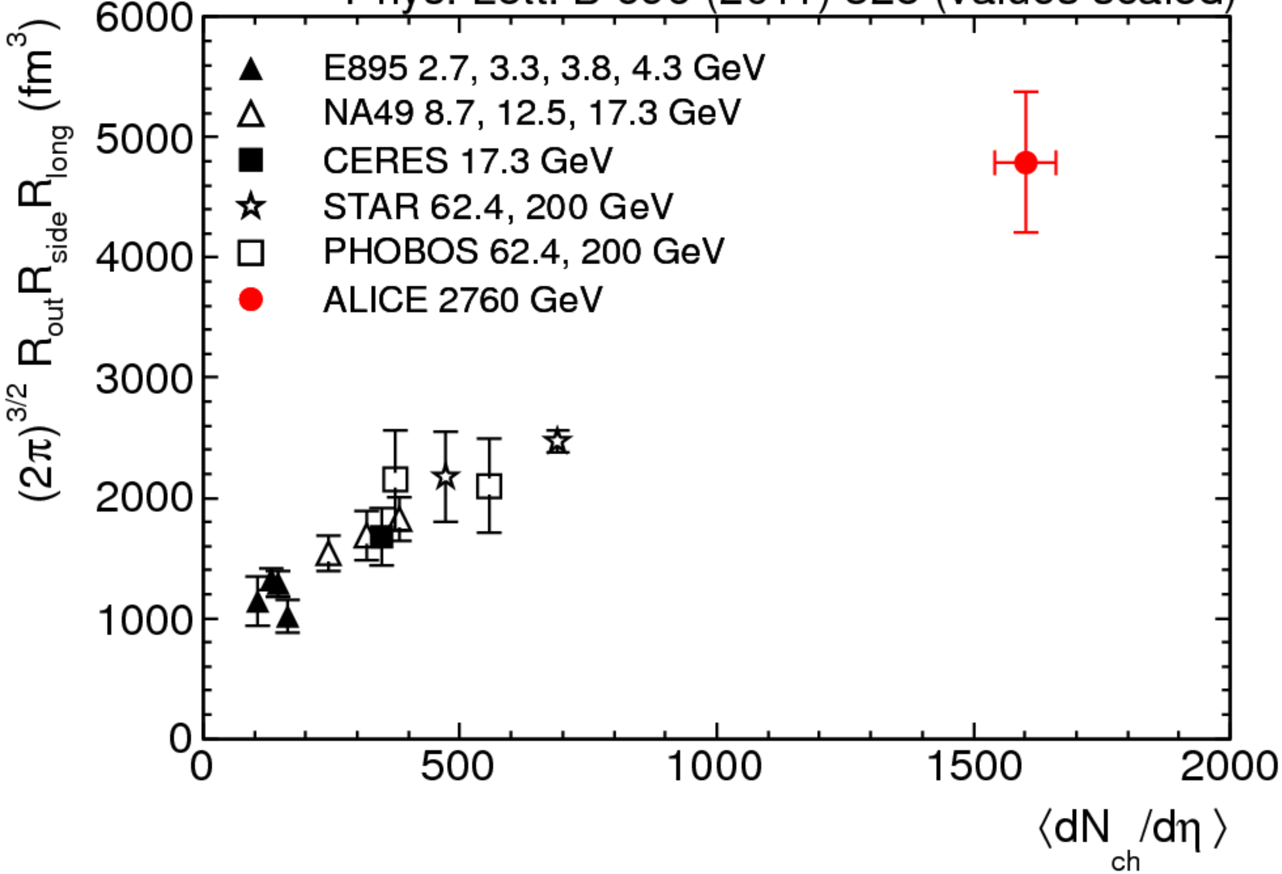
Much higher energy density !

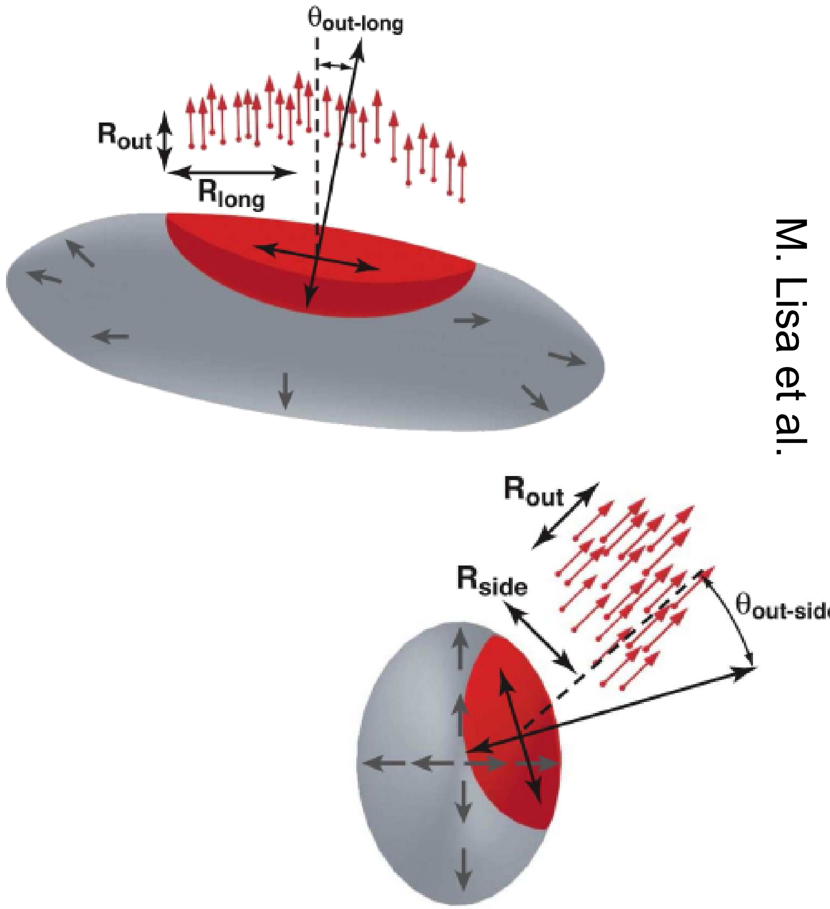
PRL 105, 252301 (2010)

Source size

Source size for hadron emission determined by Hanbury-Brown Twiss (HBT) methods: two-pion correlations

Phys. Lett. B 696 (2011) 328 (values scaled)





M. Lisa et al.

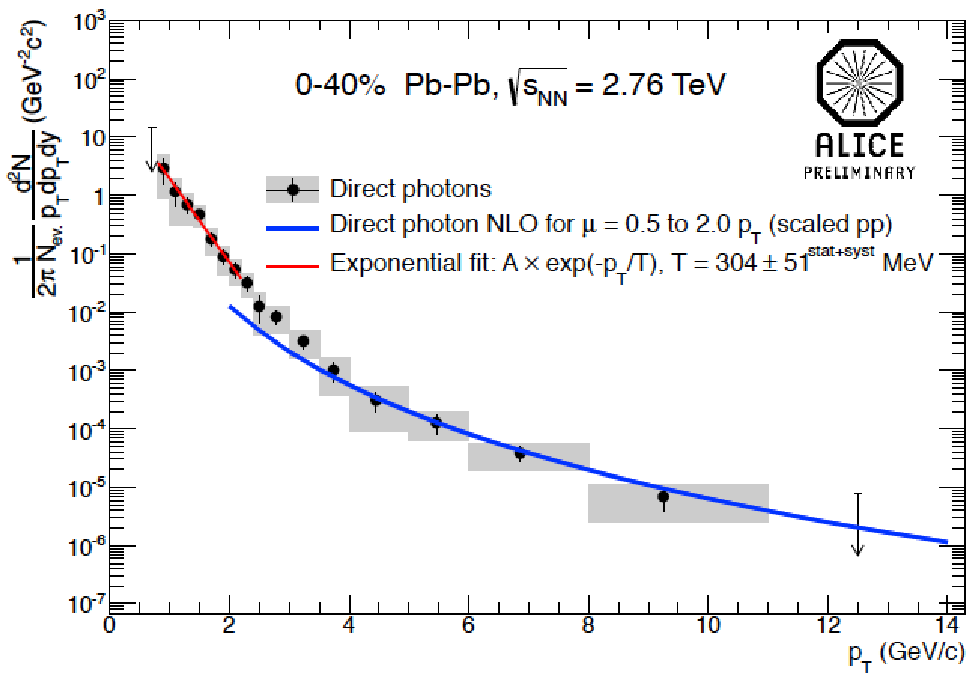
Volume
2 times larger
than at RHIC !

Direct photons

Photons that are not produced by particle decays.

Include thermal photons, from scattering of thermalized particles:

- QGP: $q\bar{q} \rightarrow g\gamma, qg \rightarrow q\gamma (+\mathrm{NLO})$
- HHG (hot hadronic gas): hadronic interactions (e.g. $\pi^+ \pi^- \rightarrow \gamma \rho_0$)



Excess at low p_T interpreted as thermal signal

At low p_T (<2.2 GeV/c) spectrum fitted with an exponential →

Slope parameter: T_{ALICE} = 304 ± 51$^{stat+syst}$ MeV (0-40%)

T_{PHENIX} = 221 ± 19^{stat} ± 19^{syst} MeV (0-20%)

Hottest temperature: in the news

http://www.space.com/17084-quark-gluon-plasma-big-bang-conditions.html

Hottest Particle Soup May Reveal Secrets of Primordial Universe

Clara Moskowitz, LiveScience Senior Writer

Date: 13 August 2012 Time: 04:59 PM ET

In Cooperation with LIVE SCIENCE.

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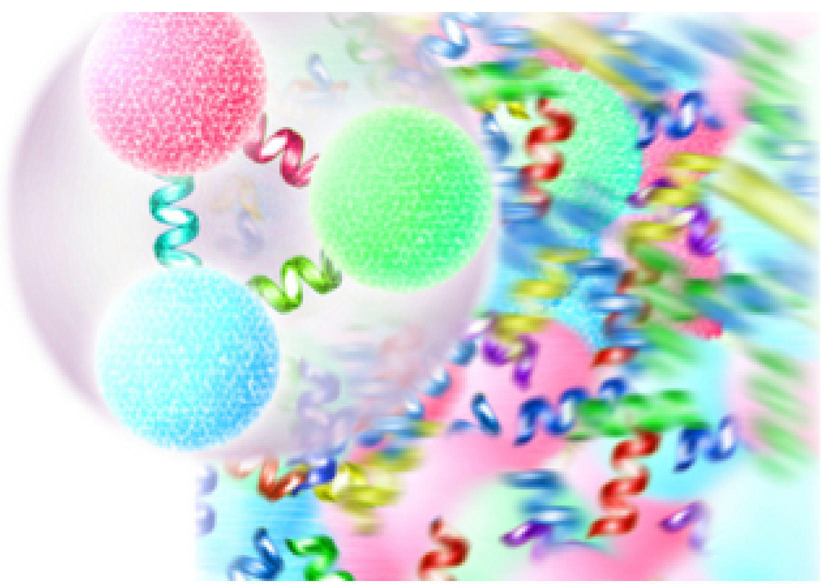


A soup of ultra-hot elementary particles could be the key to understanding what the universe was like just after its formation, scientists say.

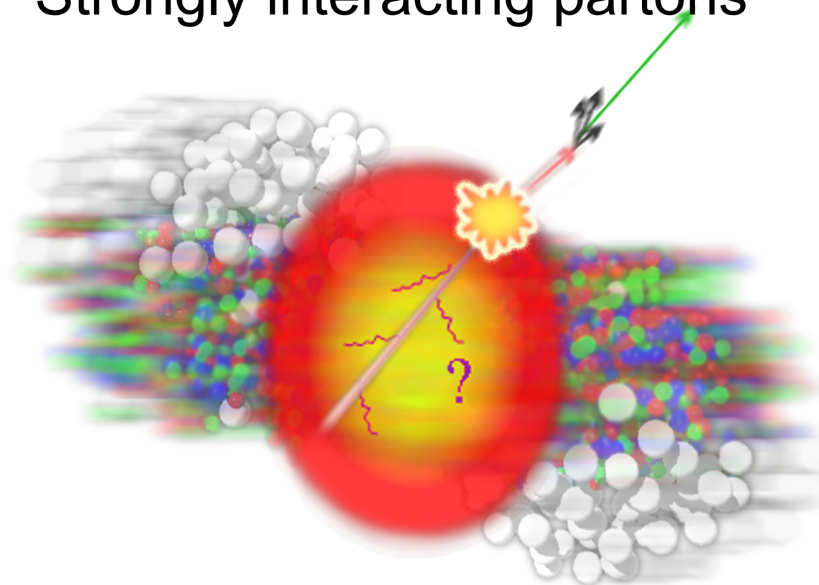
Over the past few years, physicists have created this soup inside two of the world's most powerful particle accelerators — the Large Hadron Collider (LHC) in Switzerland and the Relativistic Heavy Ion Collider (RHIC) in New York — by smashing

Energy loss

Understand internal structure from the absorption and attenuation of radiation

Probes for the QGP?

Strongly interacting partons



Interaction of gluons, light and heavy quarks inside the medium

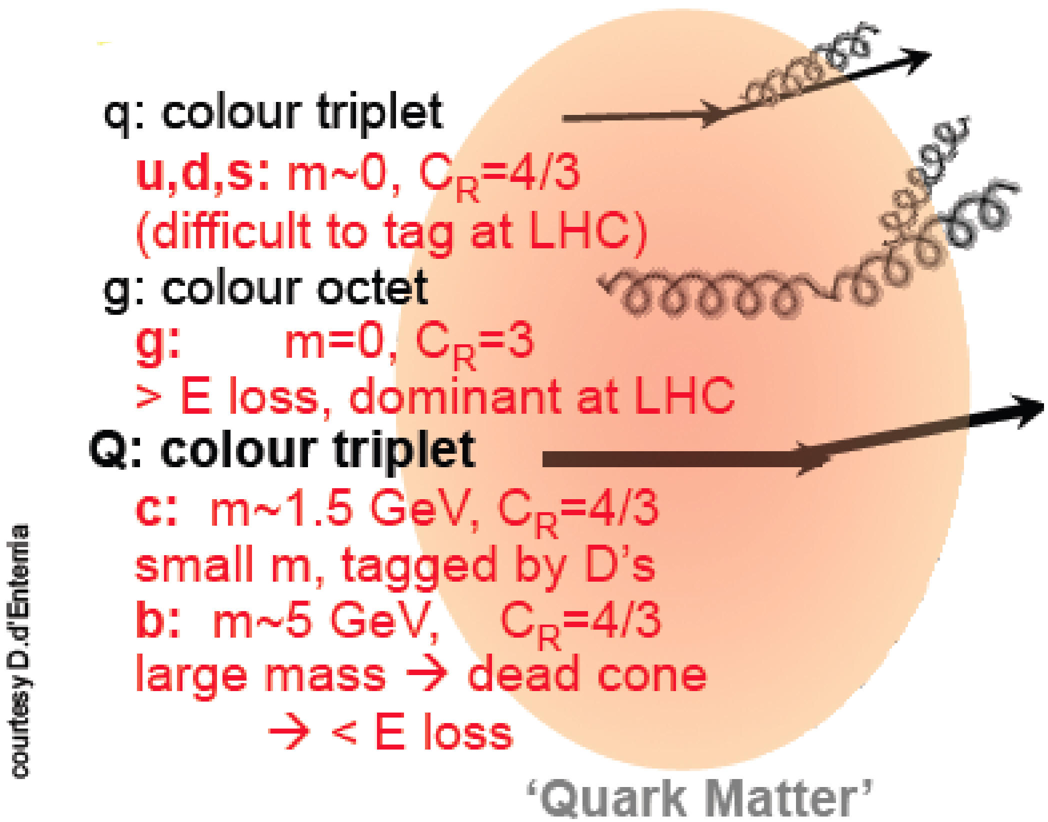
→ energy loss, suppression

In-medium parton energy loss

- Energy loss by:
  - Medium-induced gluon radiation
  - Collisions with medium partons
- Depends on:
  - Colour coupling factor C_R (g>q)
  - Parton mass
- Predicted energy loss:

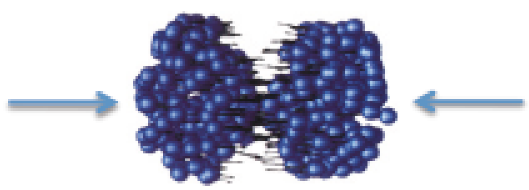
$\Delta E_{gluon} > \Delta E_{q \approx c} > \Delta E_b$

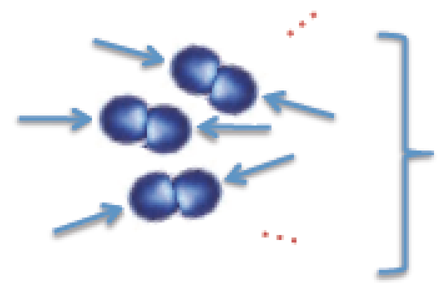
"suppression": $\pi > D > B$



Nuclear modification factor

Is Pb-Pb different from N * (nucleon – nucleon) ?





$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{coll}}$$

← Scaling by number of binary collisions (Glauber)

No medium effect → $R_{AA} \approx 1$

Medium effect → medium "slows" down particles → $R_{AA} < 1$

Nuclear modification factor

$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{coll}}$$

pp reference:

- Proton-proton data sample recorded at $\sqrt{s}$ = 2.76 TeV
- If statistically limited → scaled from results at $\sqrt{s}$ = 7 TeV (NLO, FONLL,...)

Results about:

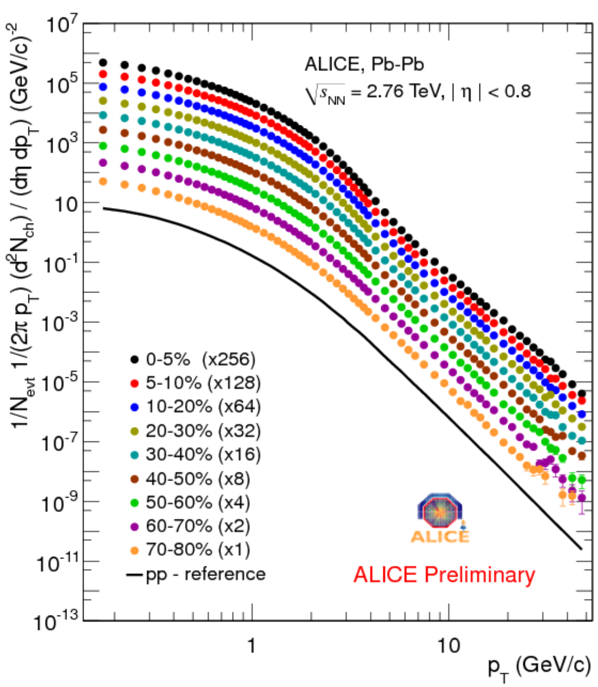
- **Charged particles**
- **Identified particles: pions, K^0_S, Λ**
- **Heavy-flavour hadrons**
- **Quarkonia**

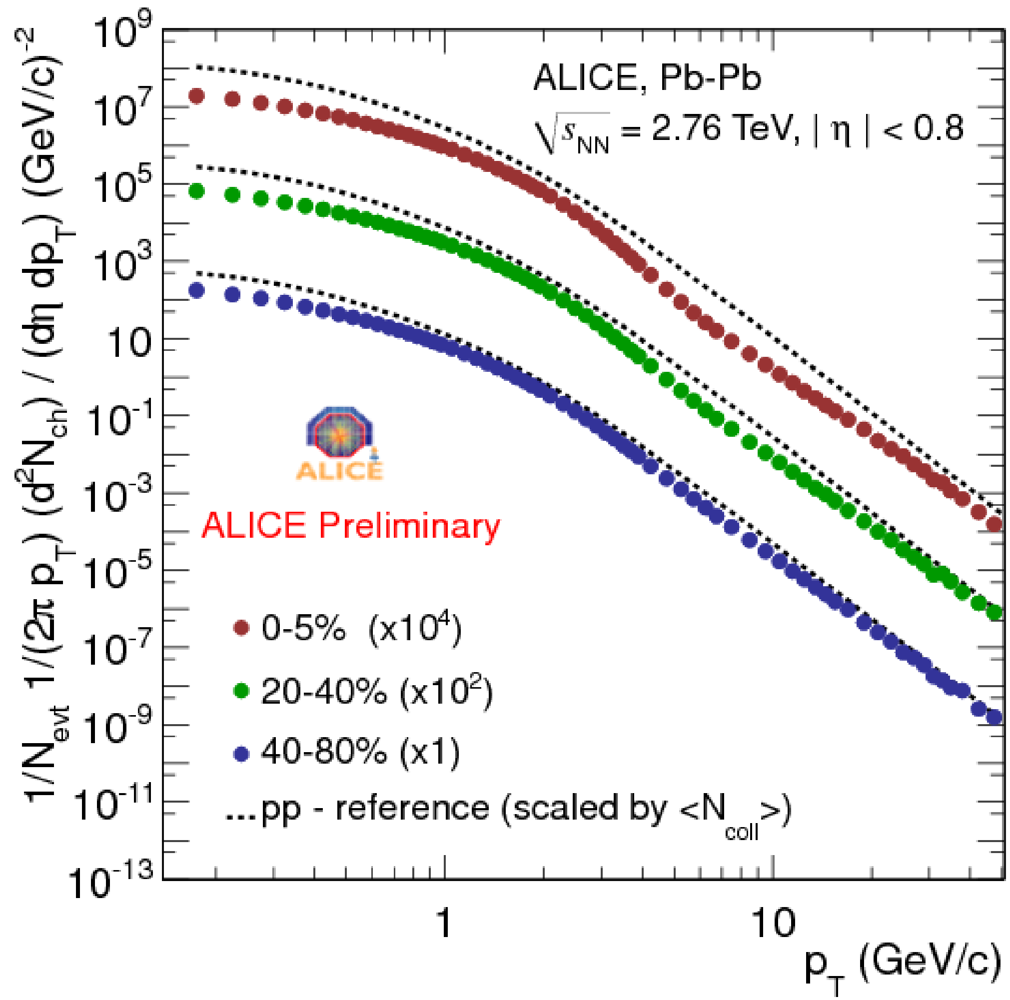
Exclusive !!
Reconstructed charm mesons
Separation charm / beauty

Charged particle spectra

Clear modification of the p_T spectrum shape !

Effect stronger with increasing centrality !





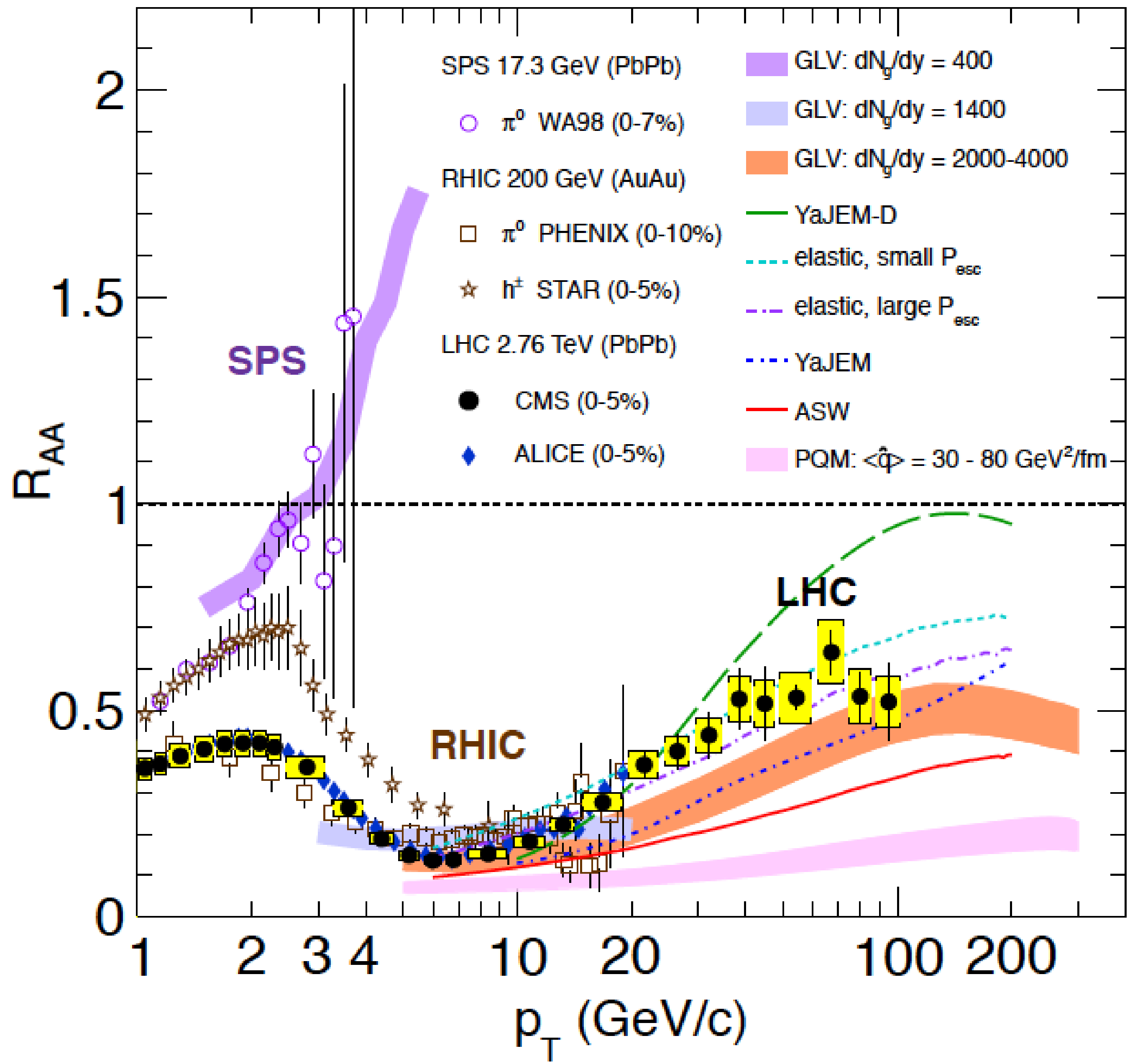
Charged particle R_{AA}

0-5% most central coll.

- Minimum at p_T ~ 6-7 GeV/c
- Then a slow increase for higher p_T
- Still a significant suppression at 100 GeV/c !!

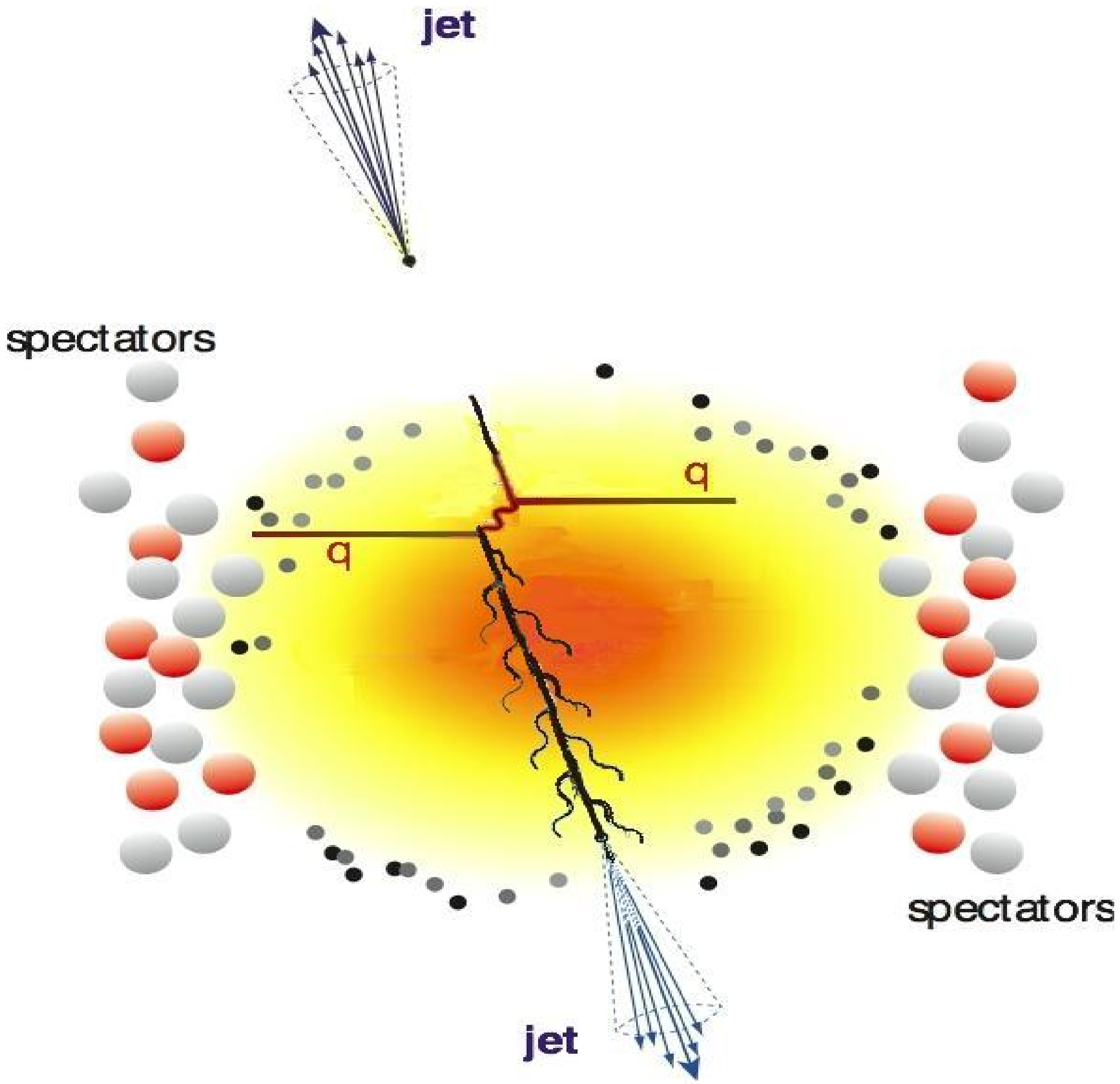
Medium so dense that pQCD still not restored around 100 GeV/c !!

Models!



arXiv: 1202.2554v1 [nucl-ex]

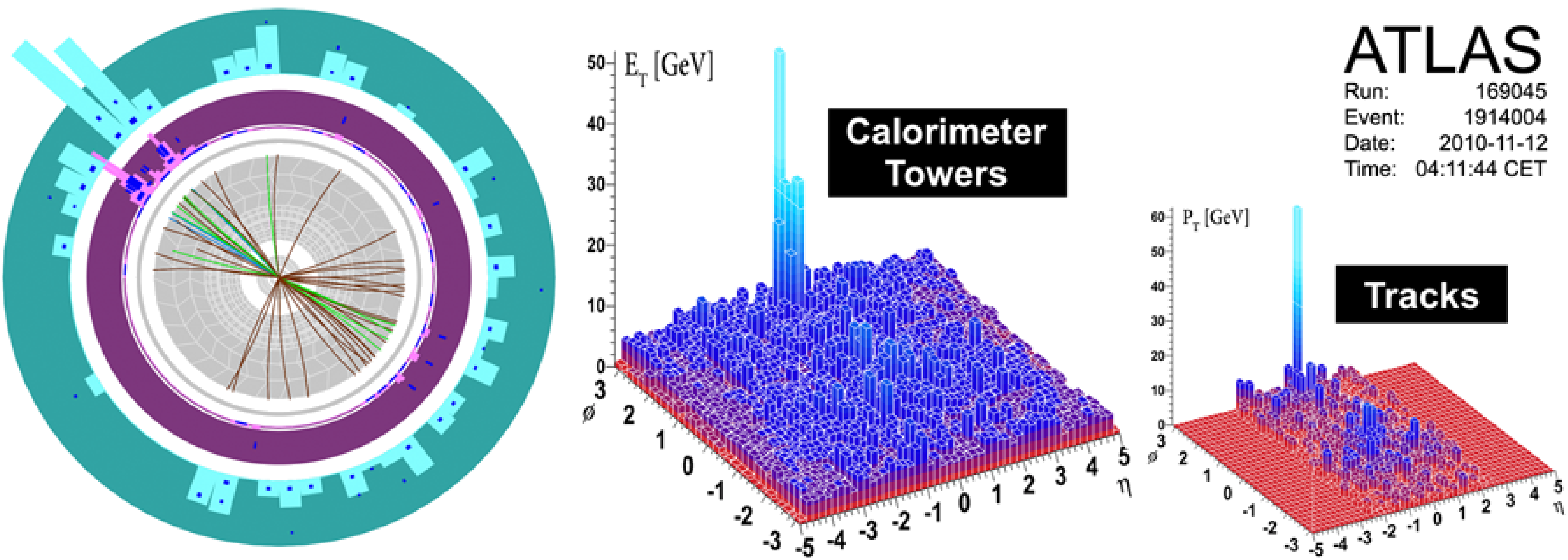
Even higher energies: jets



Di-jet asymmetry

Jet measurements specialty of ATLAS and CMS

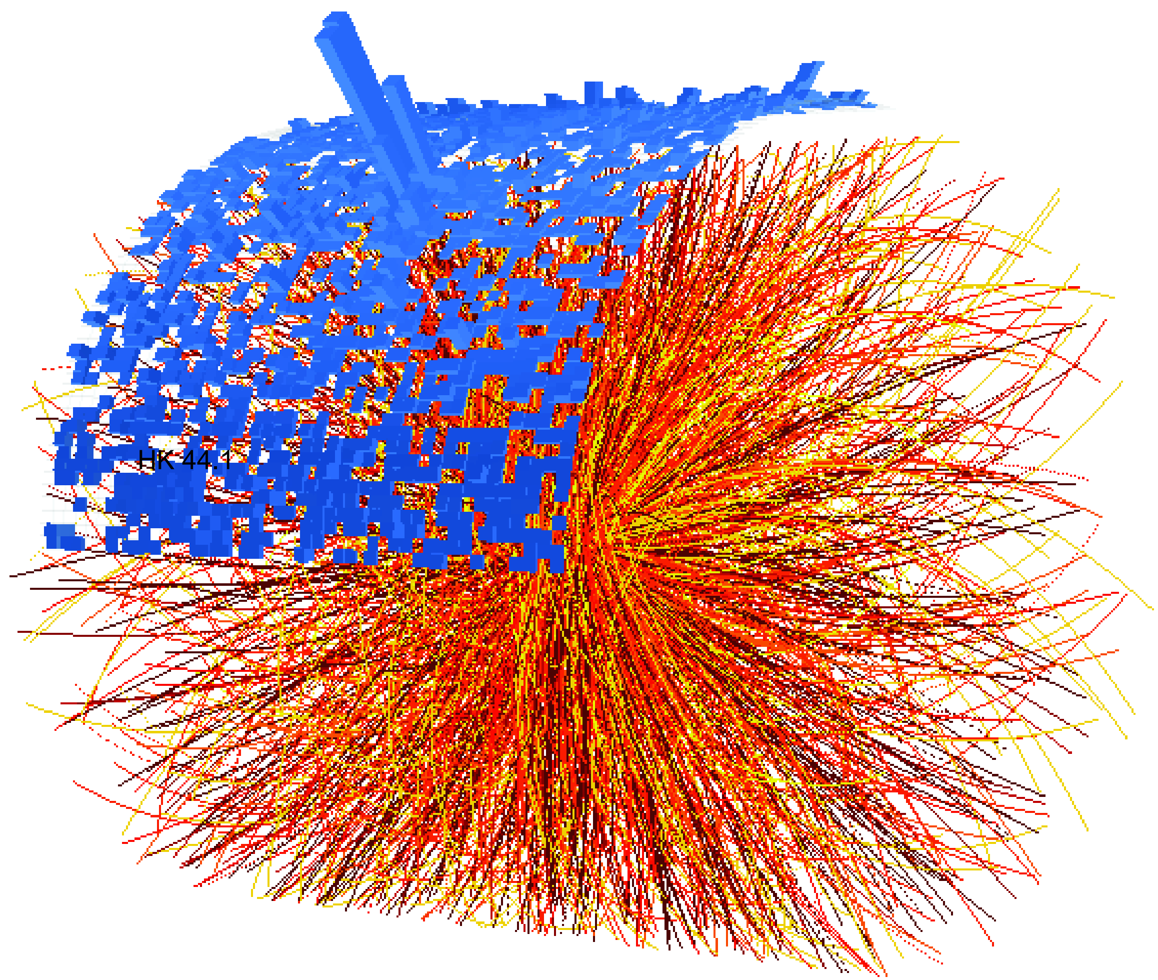
Large di-jet imbalance observed



PRL 105 (2010) 252303

Jets in ALICE

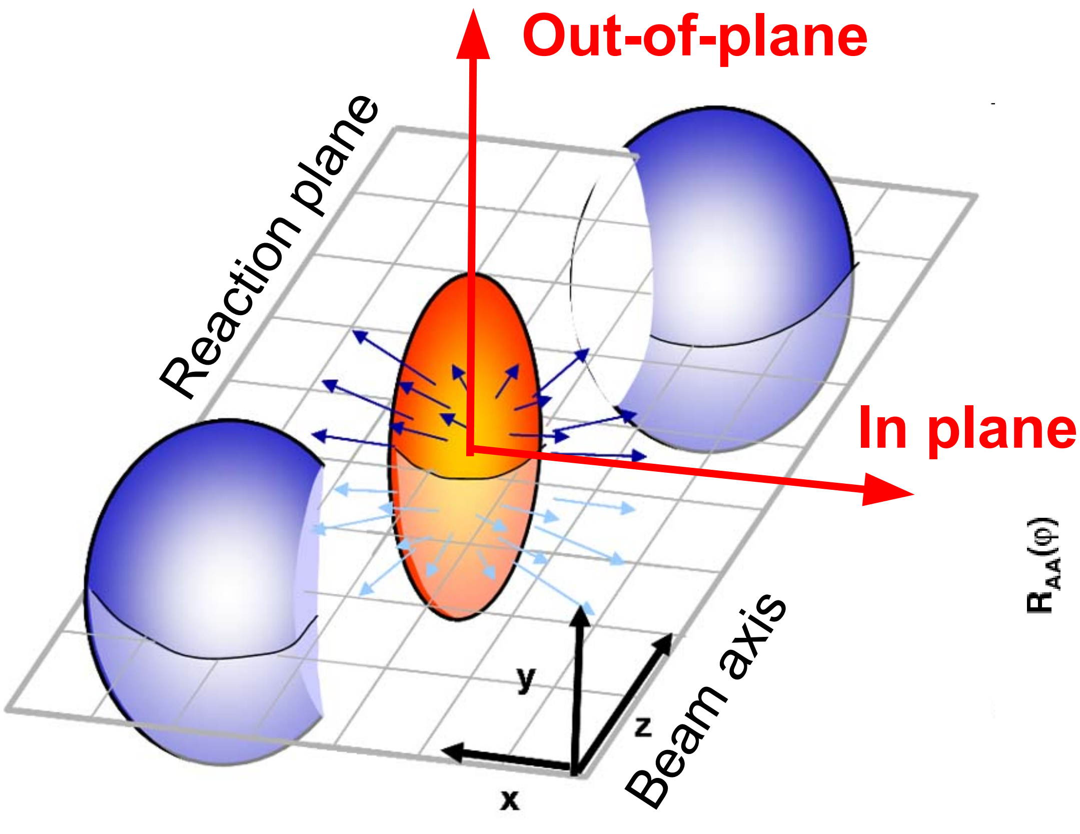
- EMCal trigger
  (limited acceptance,
  later completion)
- Has behind the ALICE TPC for charged track reconstruction and particle identification



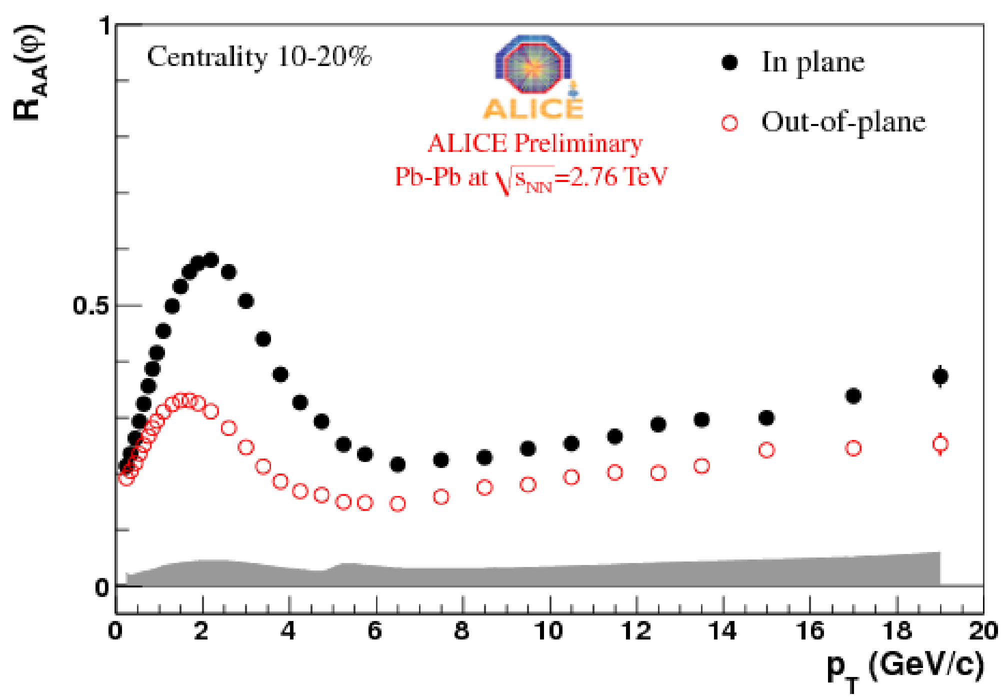
→ results coming soon!

→ **jet chemistry!**
(with particle identification)

Charged particle R_{AA} vs reaction plane

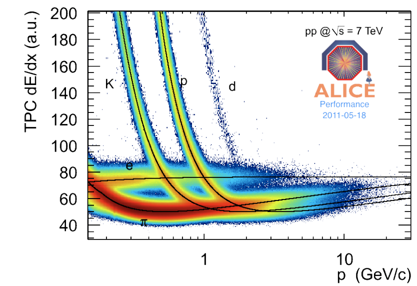


Further details into the fireball shape and path-length dependence of the energy loss



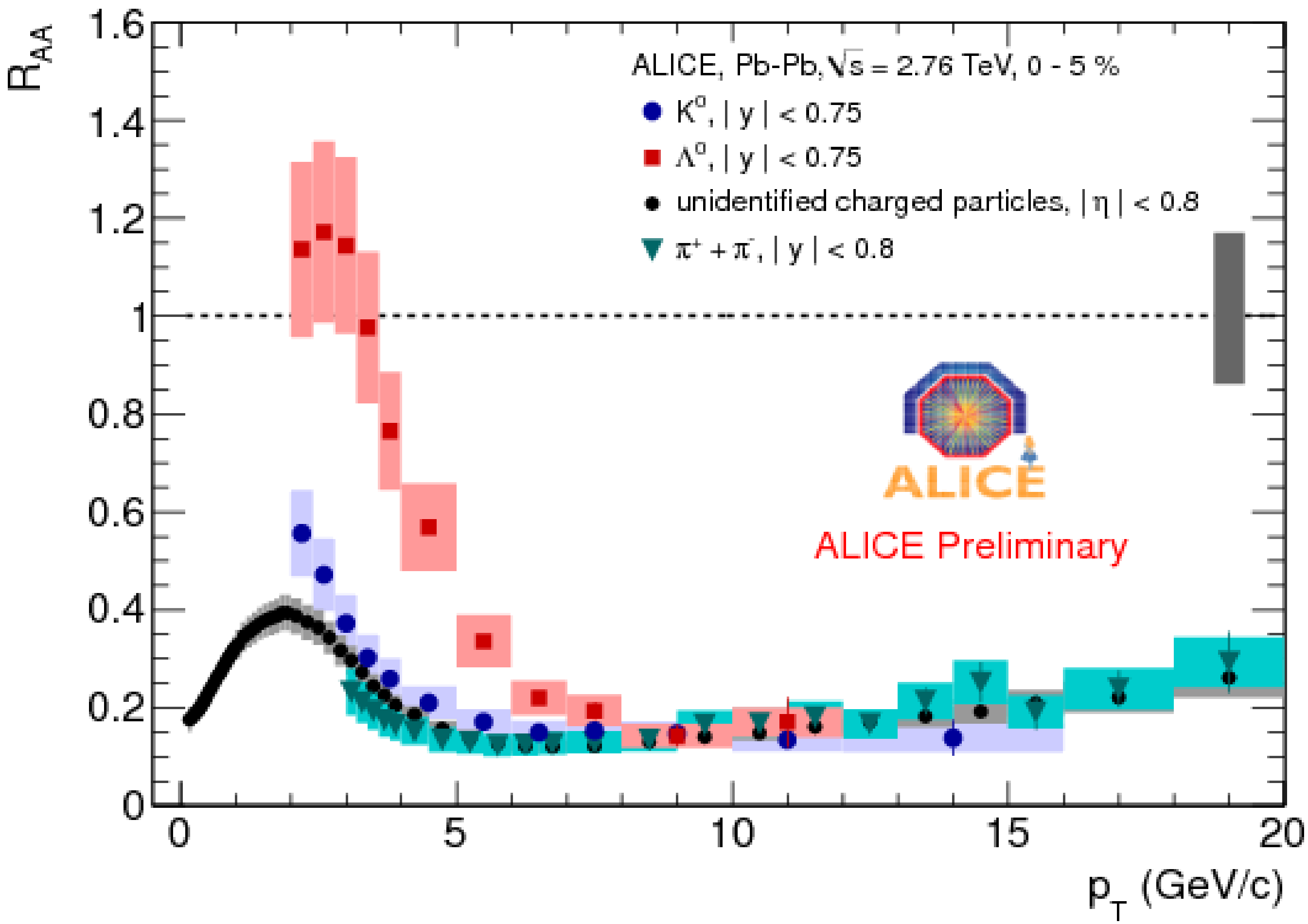
Stronger suppression
out-of-plane
→ longer path

R_{AA}: identified particles



Thanks to the excellent particle identification (TPC):

Identified π, $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$



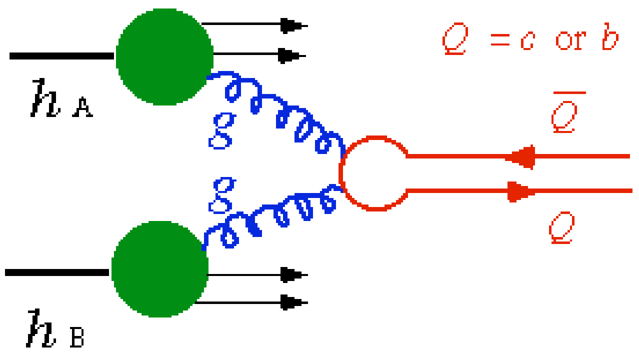
Suppression similar for all light hadrons for p_T>8 GeV/c

No suppression of Λ at low p_T

Λ/K enhancement

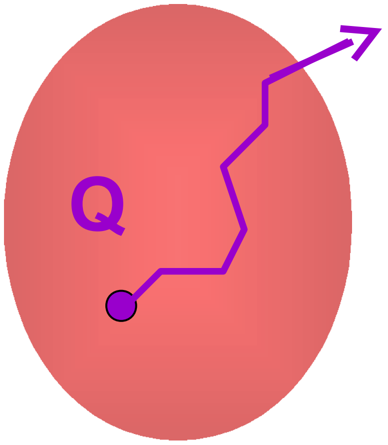
Heavy flavours: probes of the medium

- Heavy flavors are produced mostly by gluon-gluon fusion ...



- … in the **INITIAL** partonic collisions $\rightarrow$ present from the **early time** of the medium, in the **HIGHEST DENSITY** phase

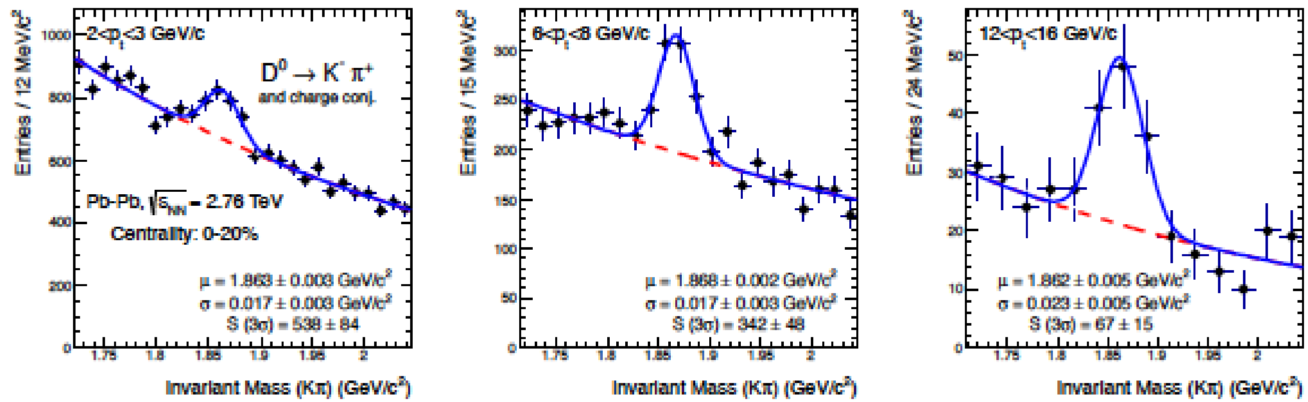
- Travel and interact in the medium $\rightarrow$ **FULL collision history**



Large production cross sections at LHC energies !!

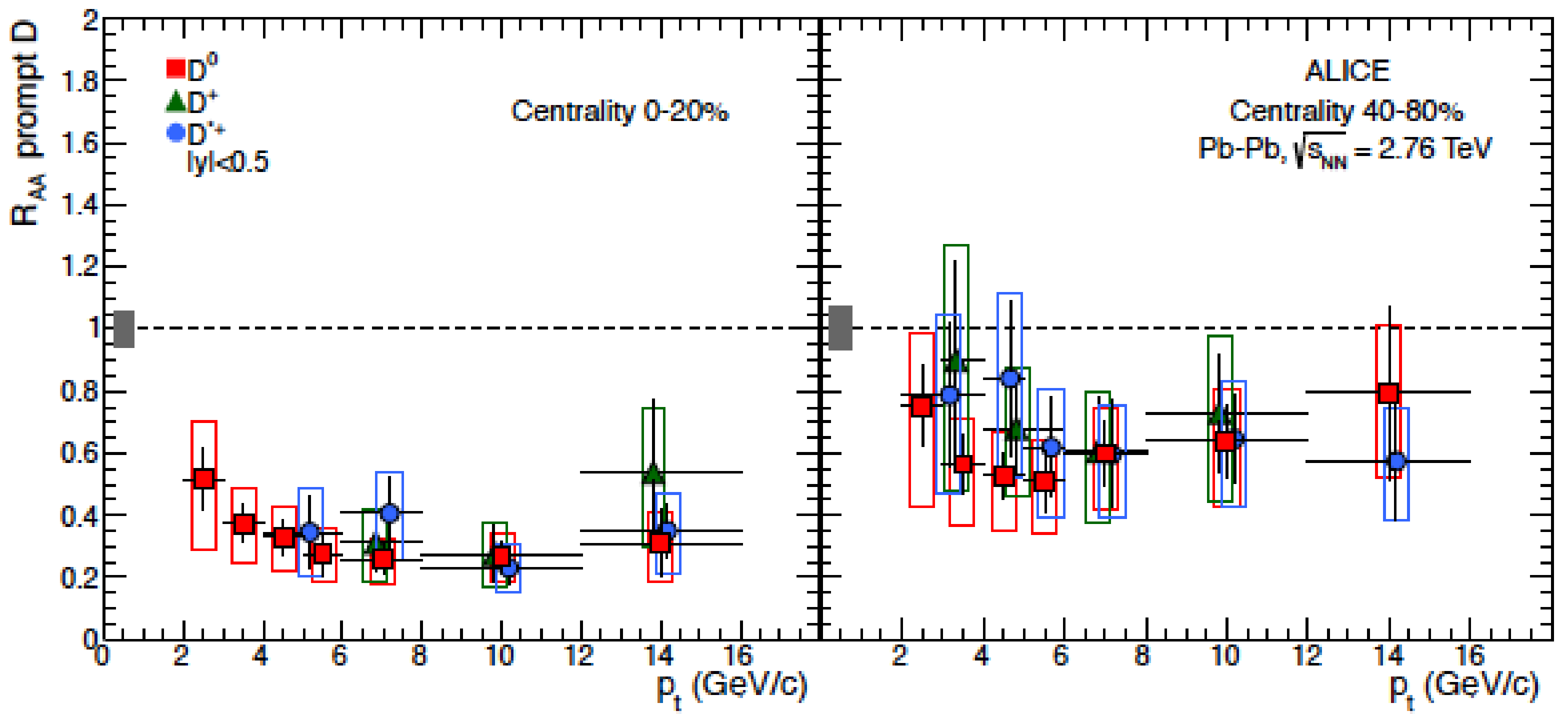
Charm: D mesons

$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
$D^{*+} \rightarrow D^0 \pi^+$



R_{AA}

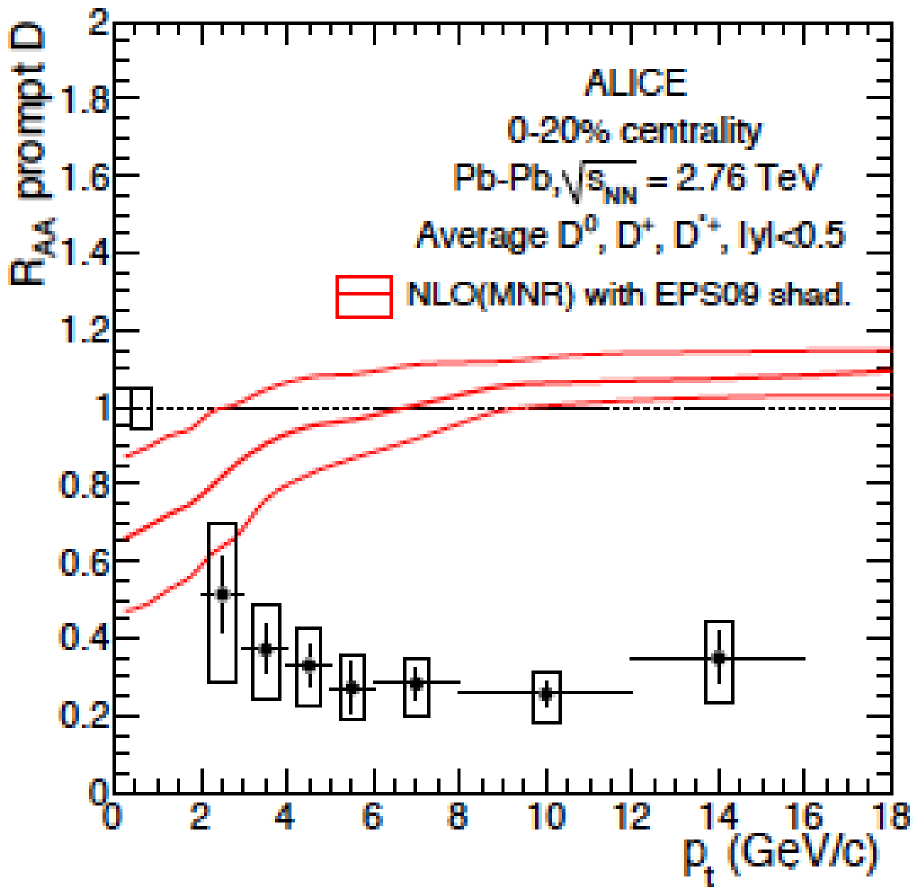
Strong suppression



JHEP 1209 (2012) 112

Charm: D mesons and theory (1)

Initial state effects: nuclear shadowing (reducing the parton distribution functions) cannot explain suppression above 6 GeV/c

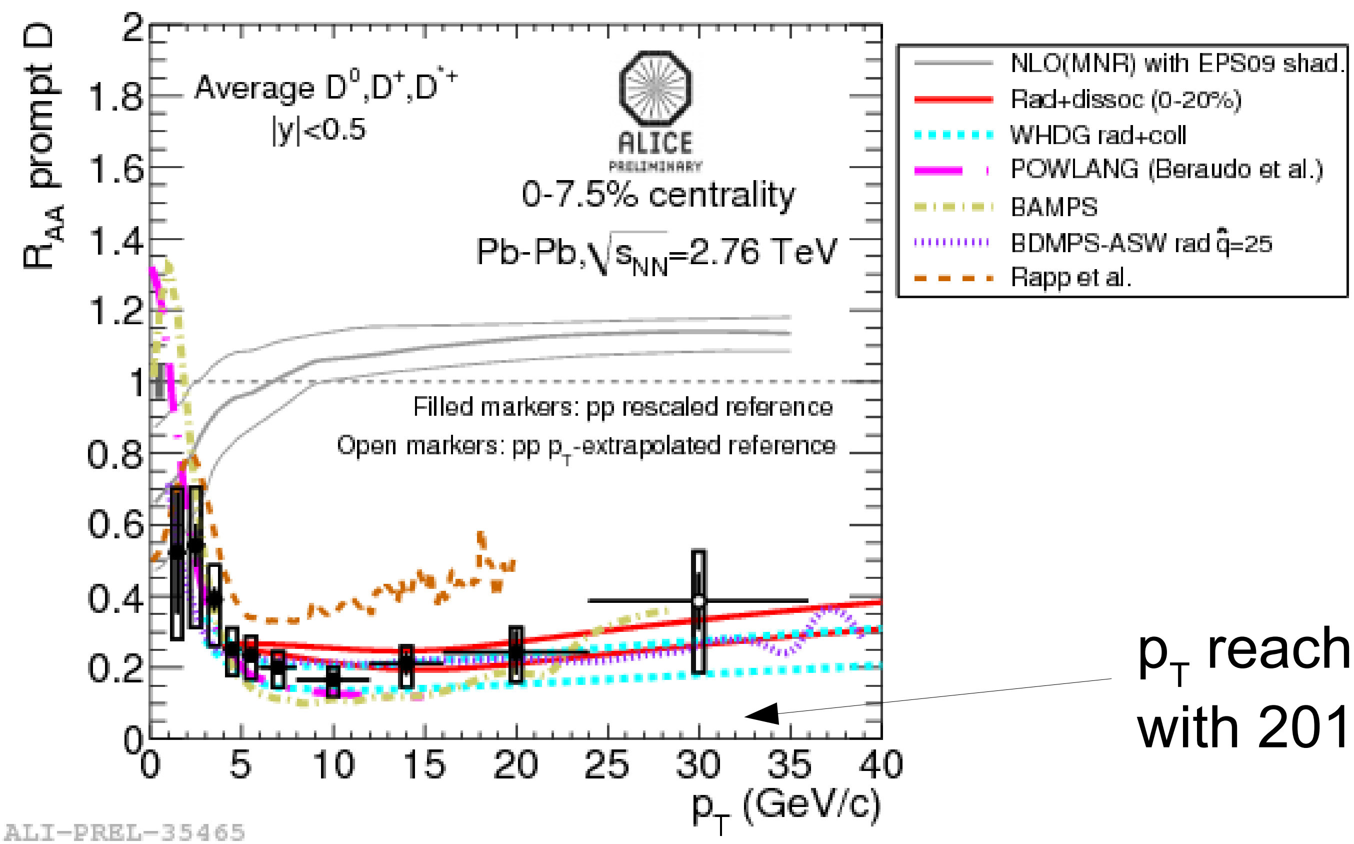


Charm: D mesons and theory (2)

Parton energy loss models:

1) radiative + collisional (inelastic + elastic)

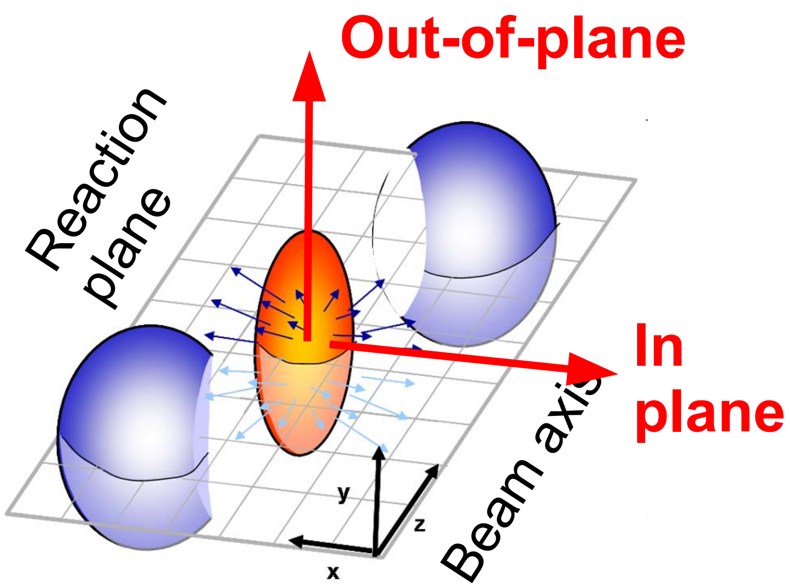
2) radiative + D dissociation

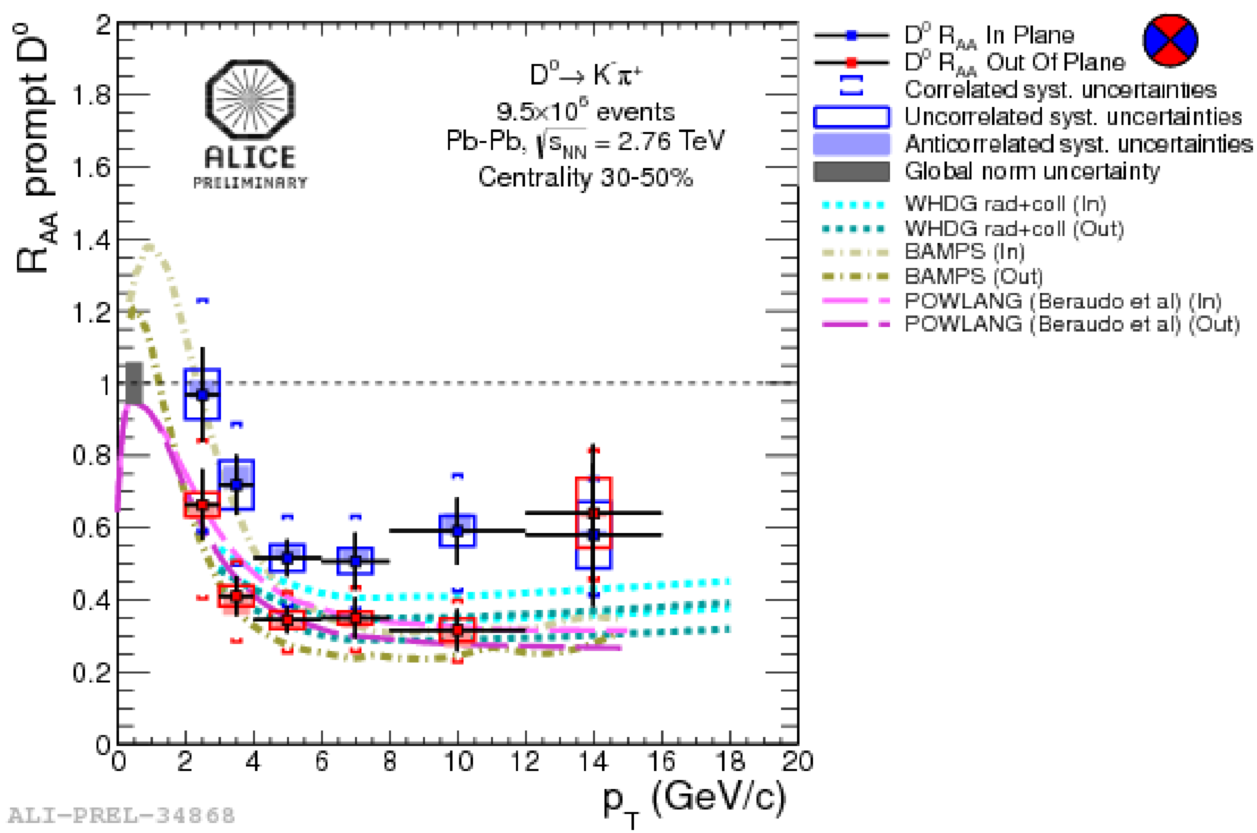


p_T reach extended with 2011 statistics

Charm: D mesons

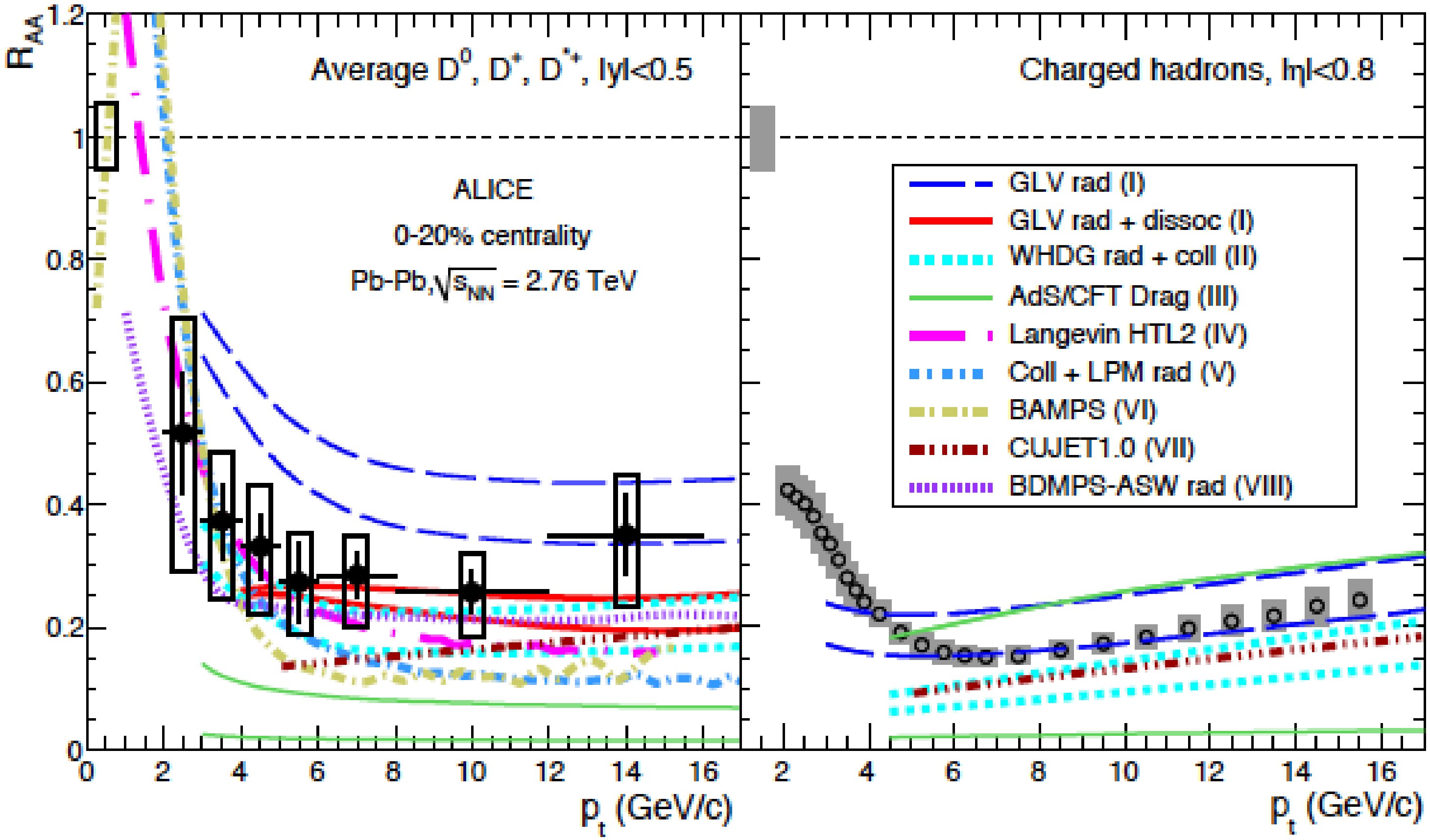
Also for charm compare in and out of plane:



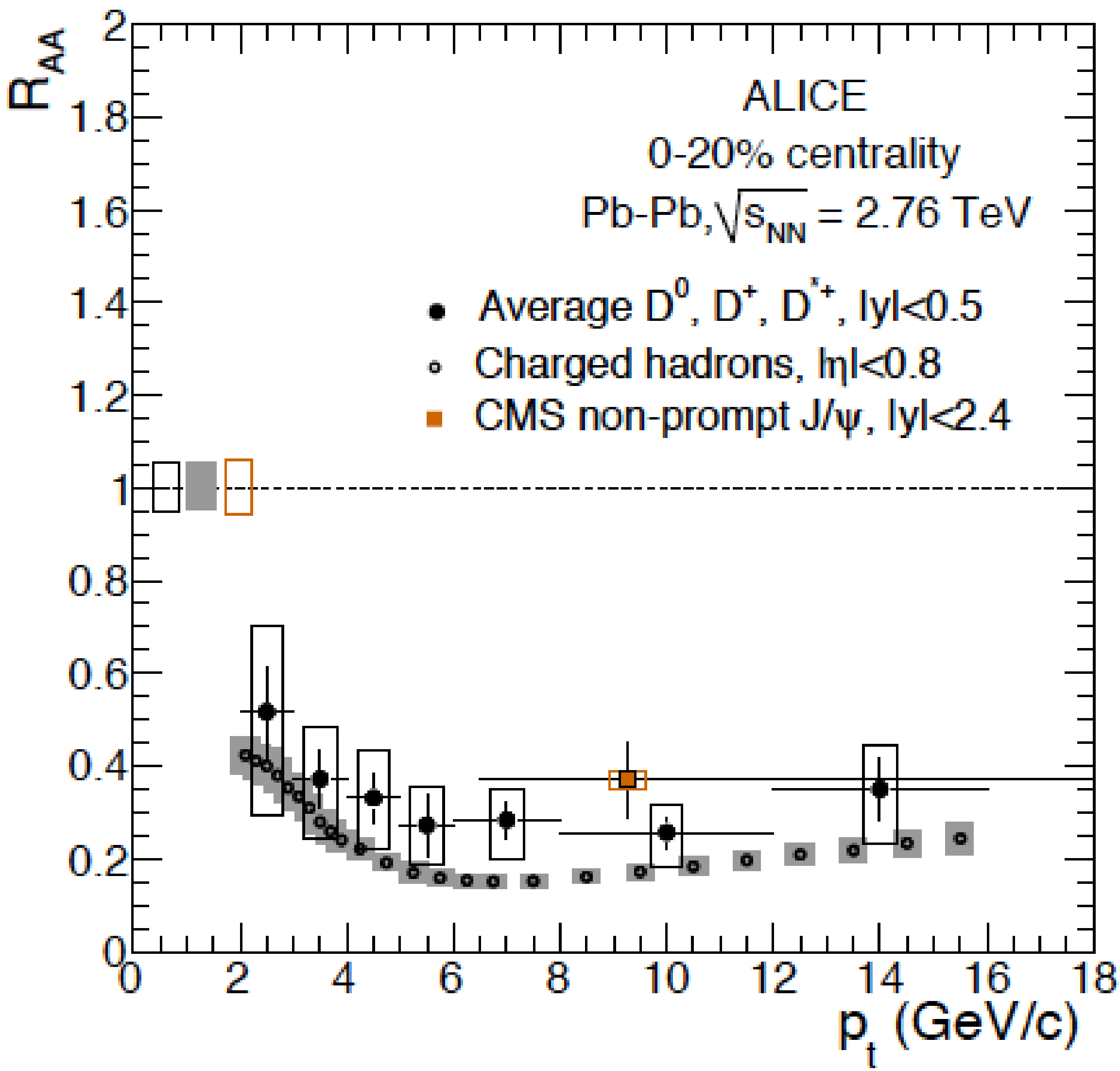


D mesons, pions, theory

Parton energy loss models have to give a coherent description of the suppression of heavy and light quark hadrons



Charged, charm, and beauty



Strong suppression observed for

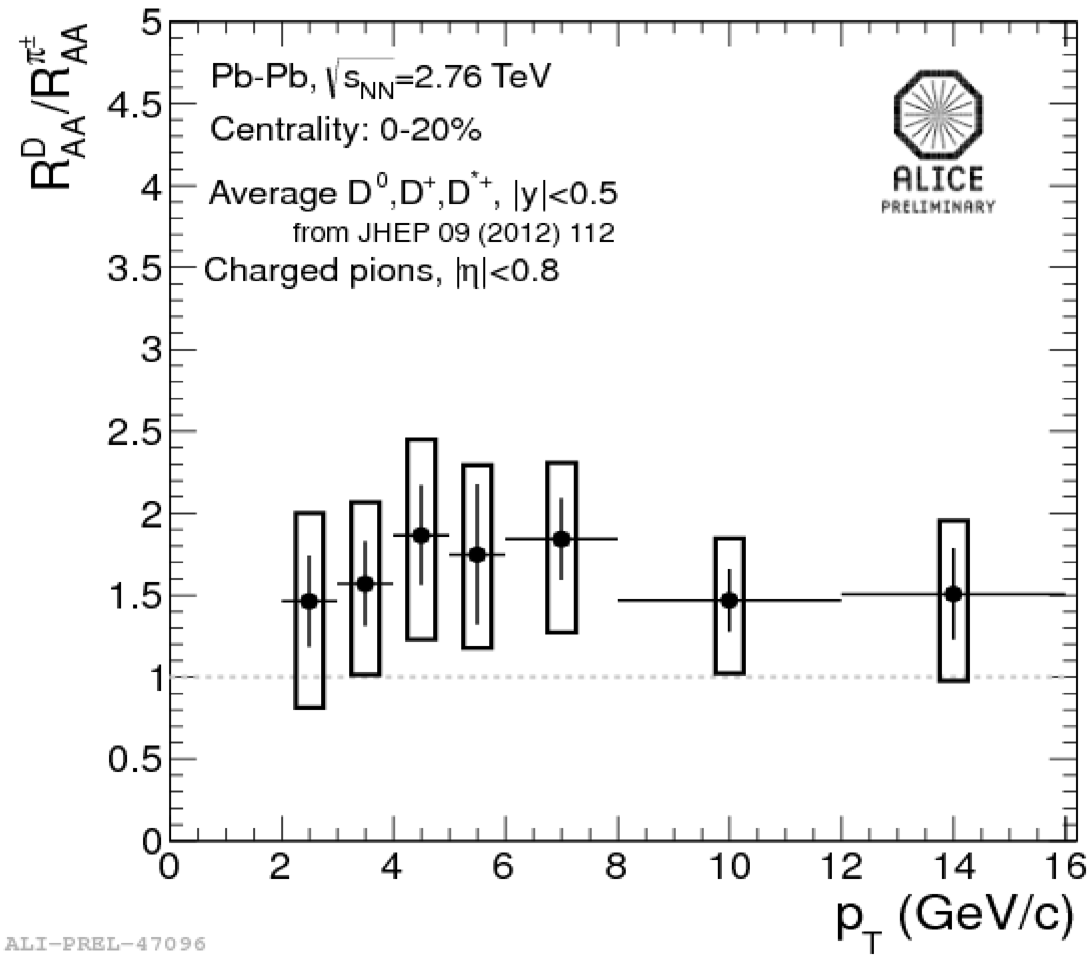
- Light hadrons
- Charm
- Beauty

CMS JHEP 1205, 063 (2012)

Maybe a mild ordering

Not yet conclusive!

D mesons and pions



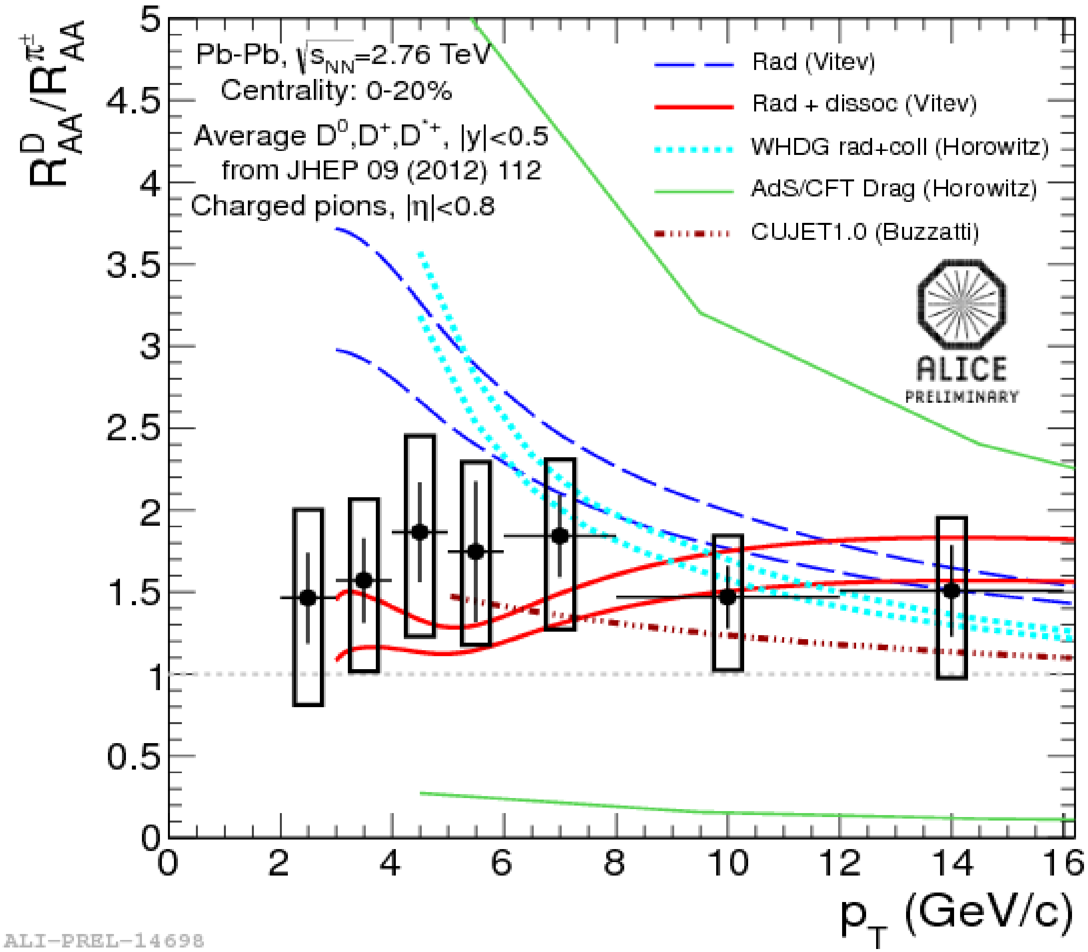
Ratio of nuclear modification factor for D mesons (charm) and for pions

Maybe a mild ordering

Not yet conclusive!

More statistics and higher precision measurements needed

D mesons and pions



Ratio of nuclear modification factor for D mesons (charm) and for pions

Maybe a mild ordering

Not yet conclusive!

More statistics and higher precision measurements needed

Theory effort needed

Charm and beauty with electrons

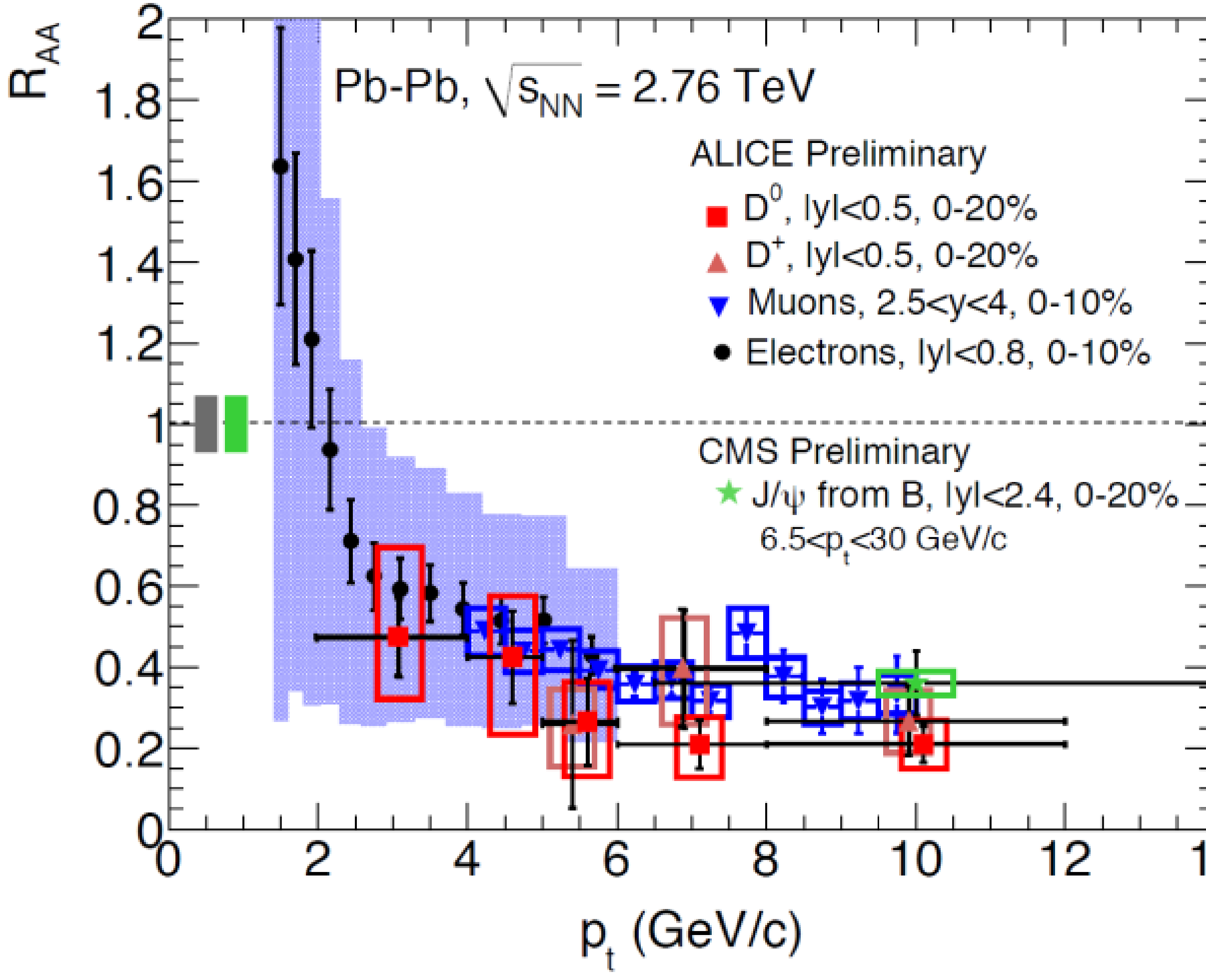
Inclusive spectrum:

$c, b \rightarrow e$

$c, b \rightarrow \mu$

Still large systematics, being improved.

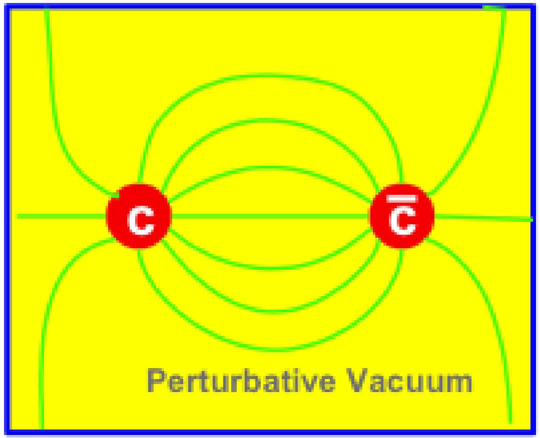
Potential for pure beauty with an impact parameter analysis



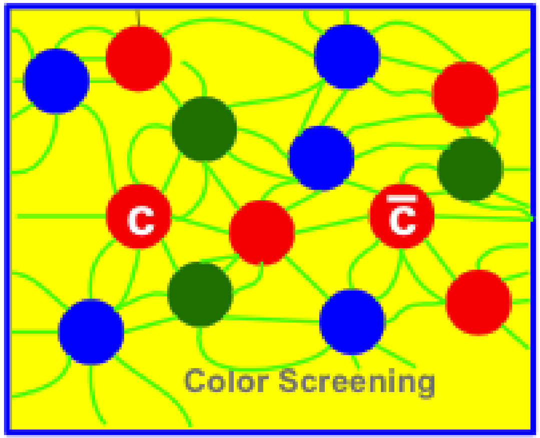
Quarkonium

$Q\bar{Q}$ states
- $c\bar{c}$: J/ψ, ψ', χ_c
- $b\bar{b}$: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b

Probes of the medium by excellence!



Screening of the strong interactions in the QGP!



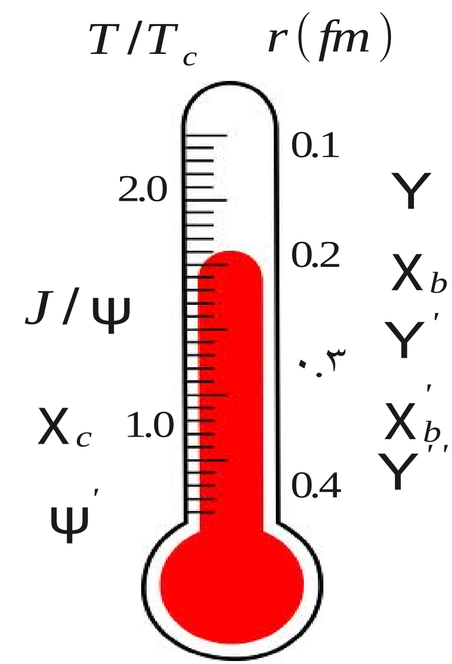
Screening stronger at higher temperatures!

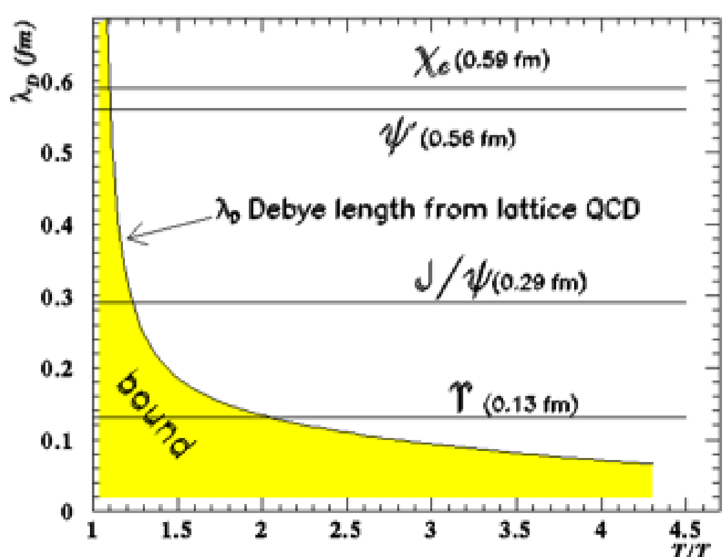
Quarkonium: sequential melting

- The color-screening is stronger at higher temperatures
- λ_D is the maximum size of a bound state to survive in the medium
  - It decreases when the temperature increases
- Different quarkonium states have different sizes

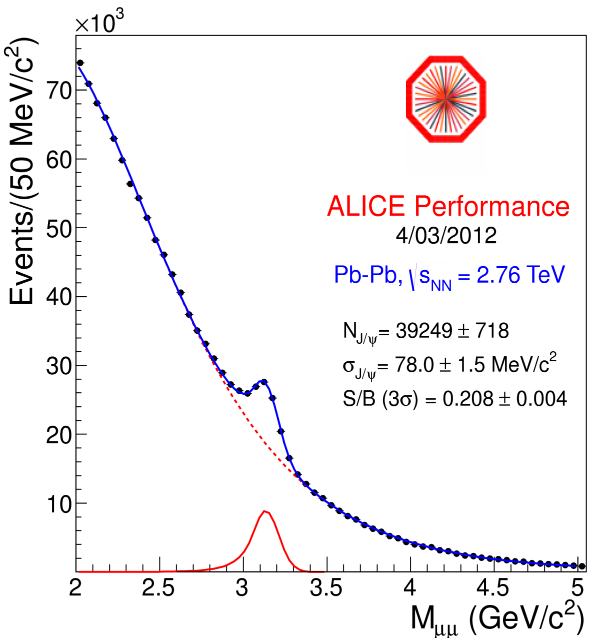
→ the melting of the resonances should follow a sequence defined by their size

→ thermometer of the QGP !



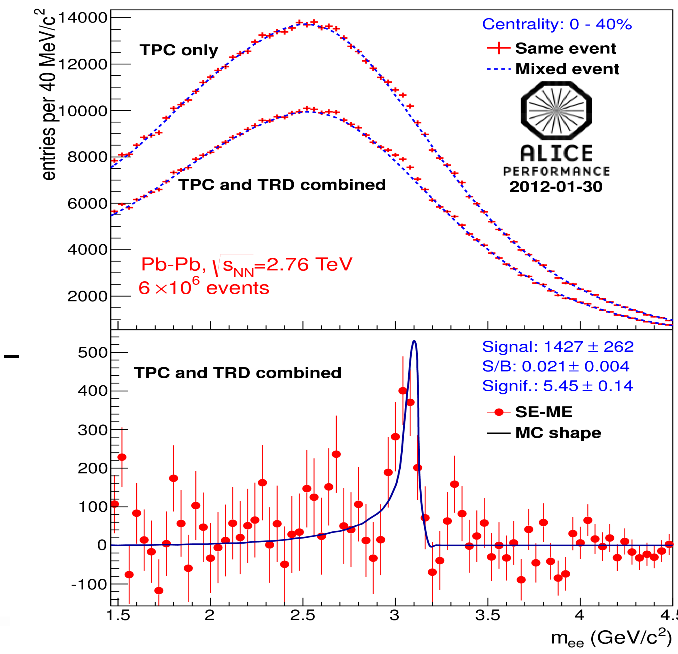


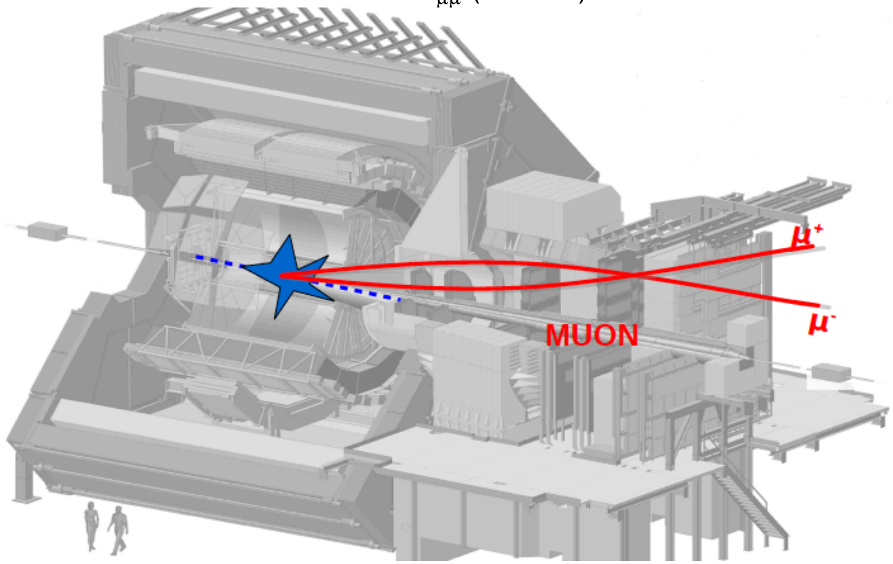
J/ψ in ALICE

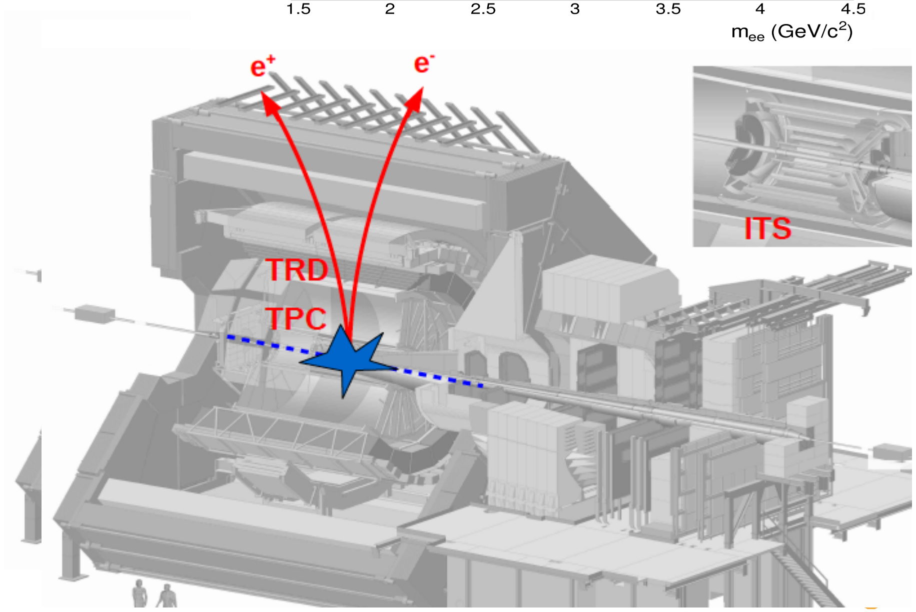


J/ψ

$\mu^+\mu^-$ e^+e^-

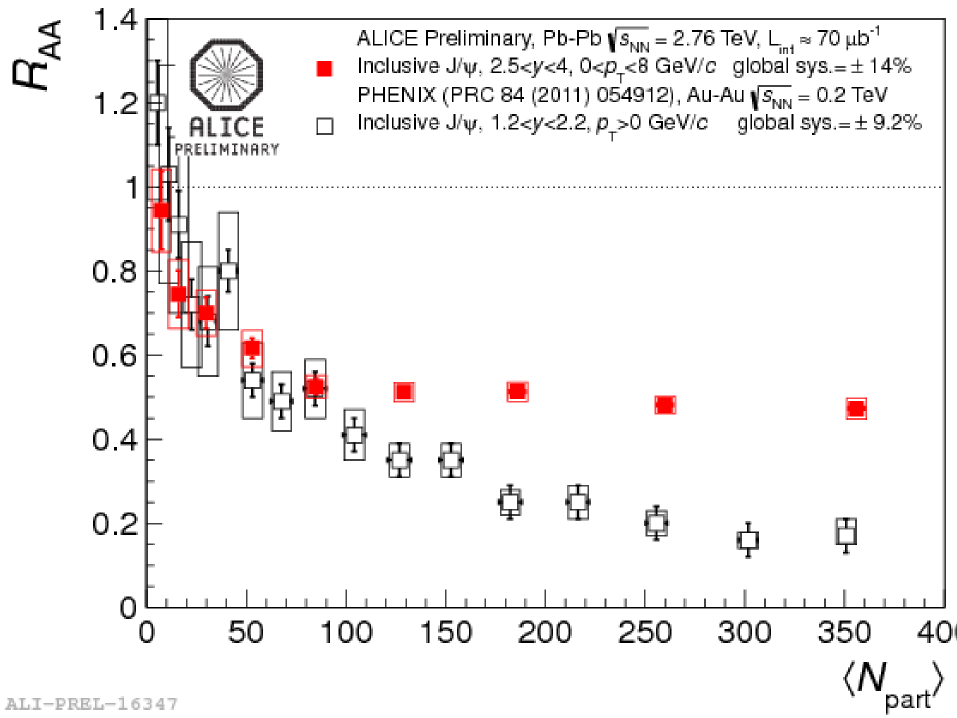


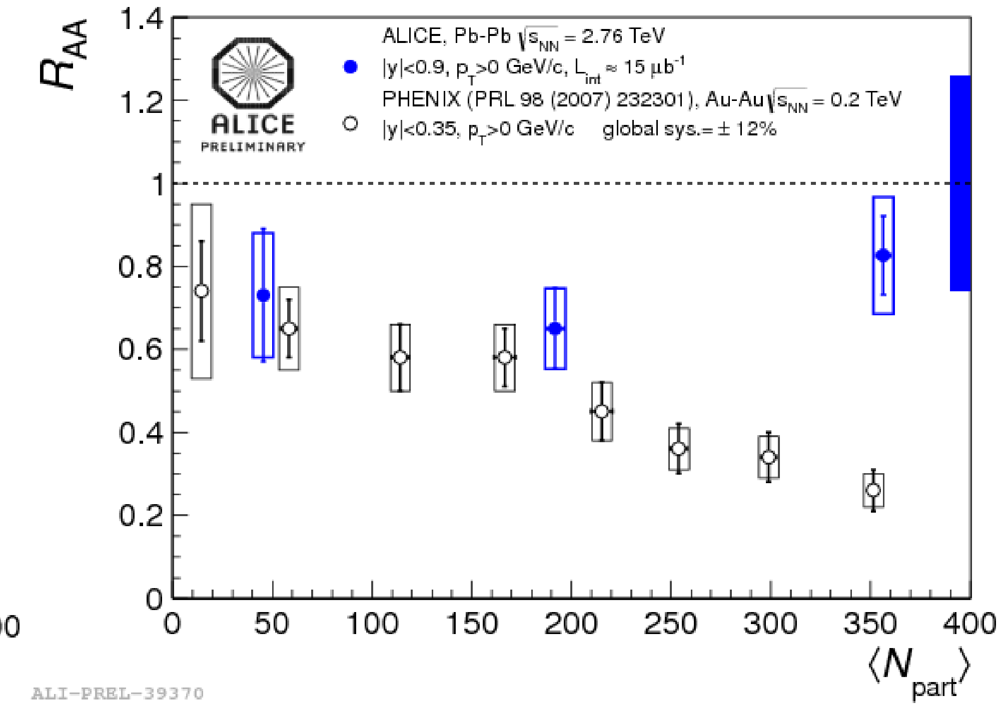




J/ψ production: results

Forward rapidity ($\mu^+\mu^-$) $p_T>0$ Mid rapidity (e^+e^-)

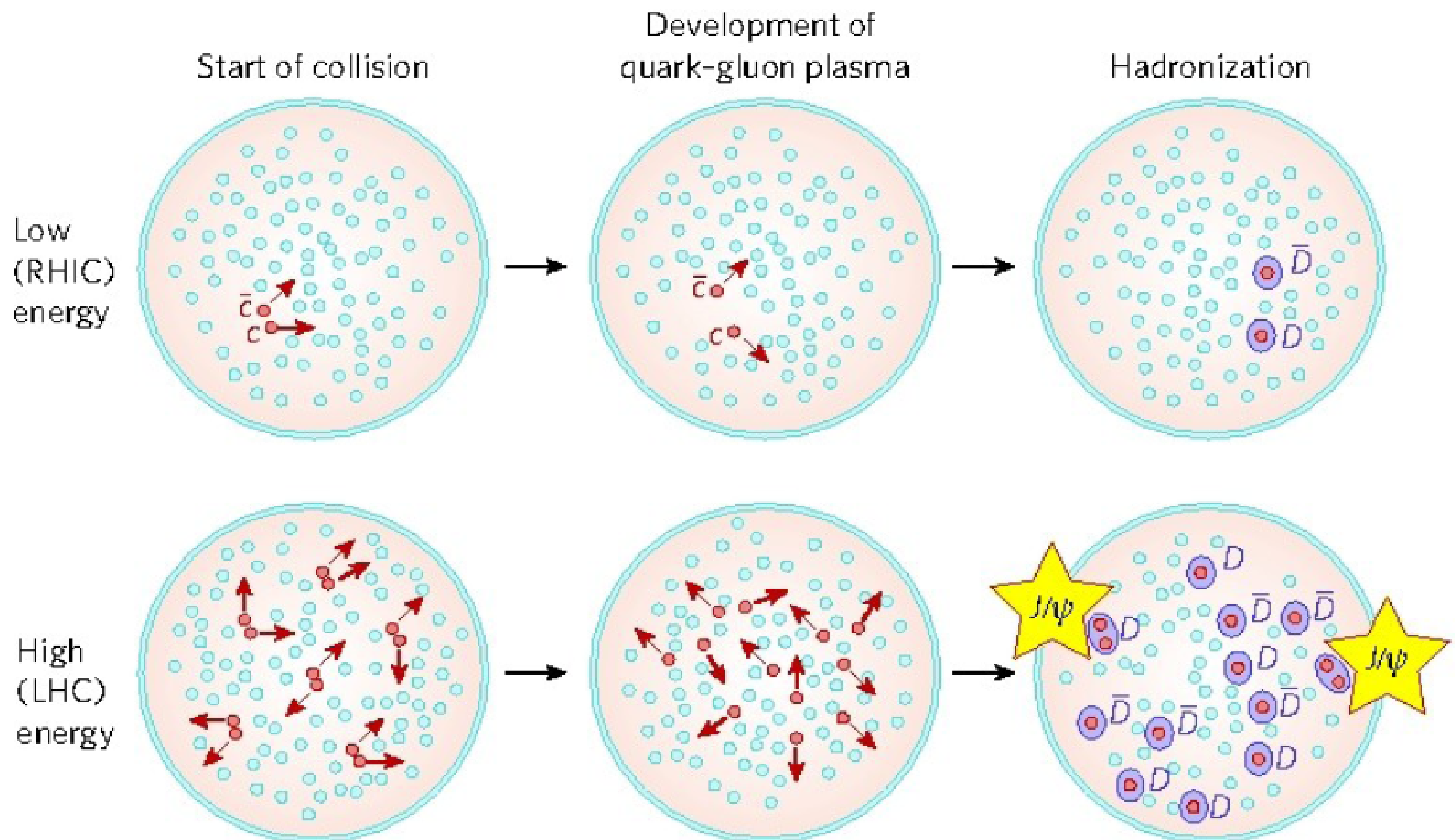




- Shown as function of collision centrality
- ALICE compared to RHIC, PHENIX result (lower energy density)
- Higher yield at the LHC !! Lower suppression? … unlikely!

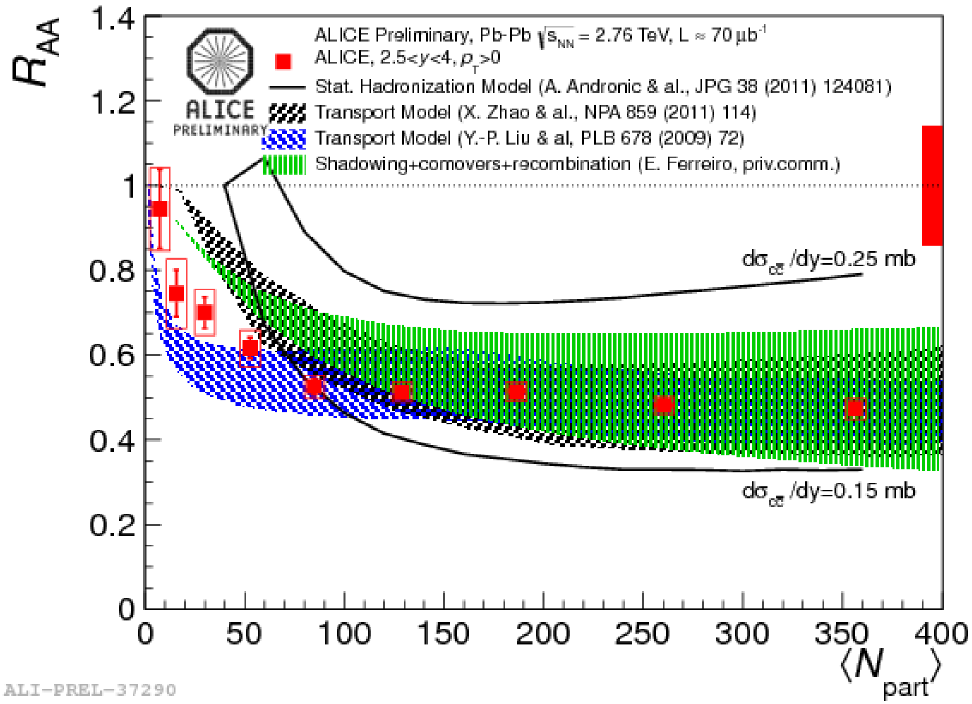
J/ψ production: models

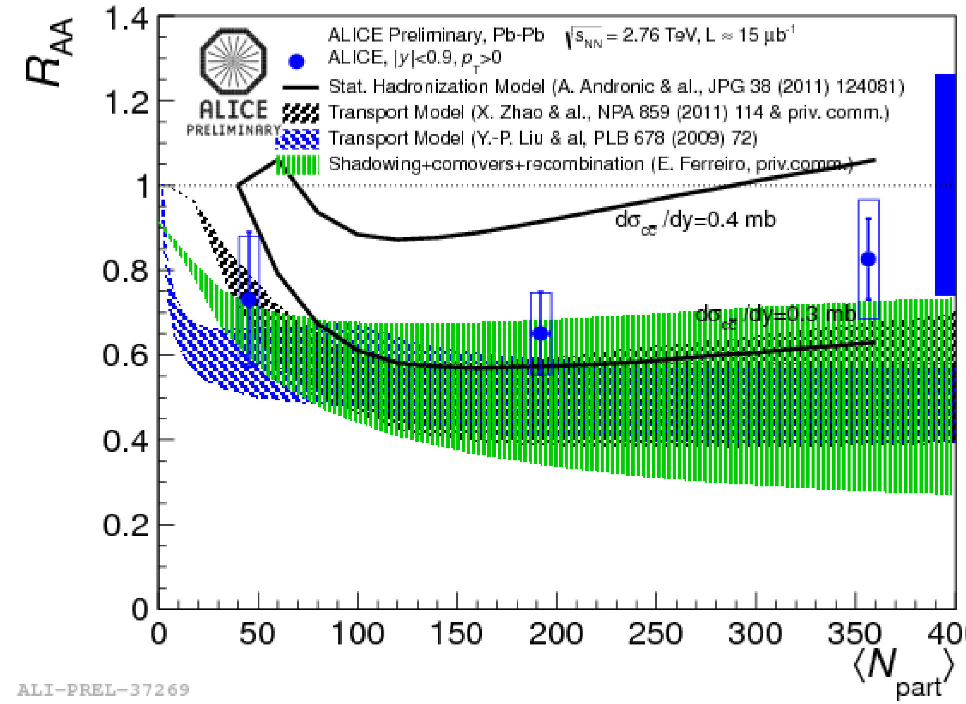
can be explained by regeneration in the QGP or by statistical hadronization
→ signature of deconfinement



J/ψ production: models

(Re-)generation of J/ψ from deconfined charm quarks in the medium





Still missing ingredients to estimate quantitatively the final state effects:

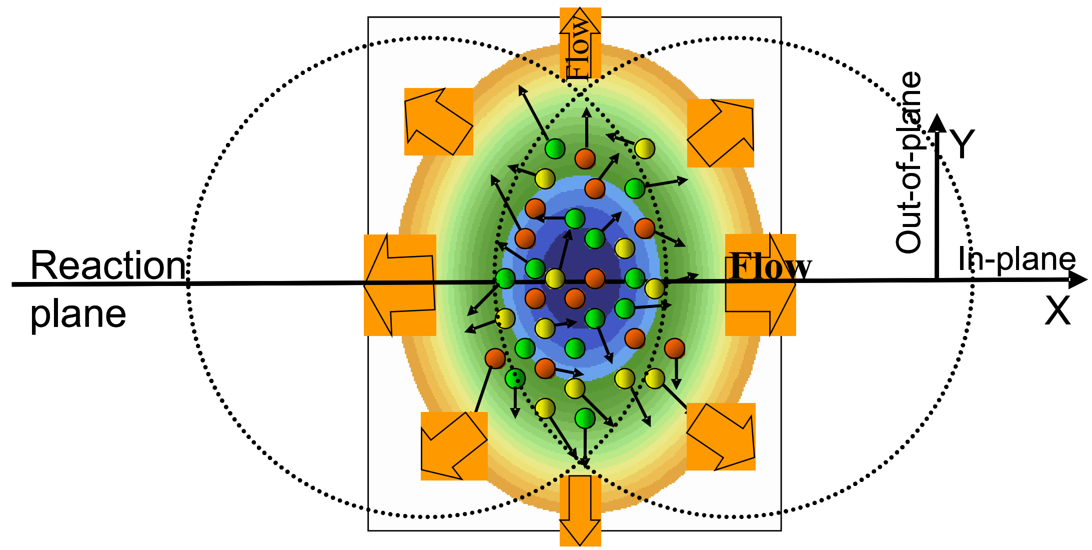
- Cold Nuclear Matter effects: nuclear absorption likely to be negligible
- Shadowing

} **pPb run!!**

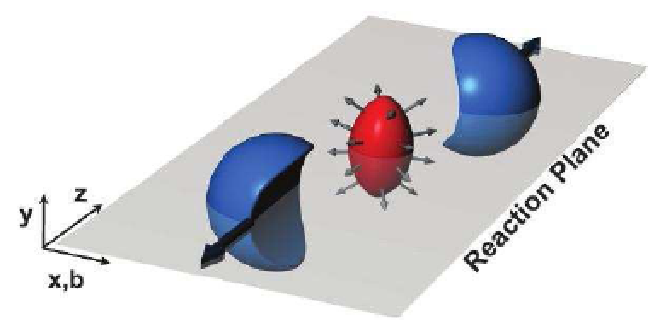
- Charm production cross section
- Beauty feed-down (order of ~ 10%)

Azimuthal asymmetry

Non-central collisions are asymmetric in azimuth
(plane of the screen)



A transfer of this asymmetry to the momentum space provides a measure of the strength of the collective phenomena



Large mean free path

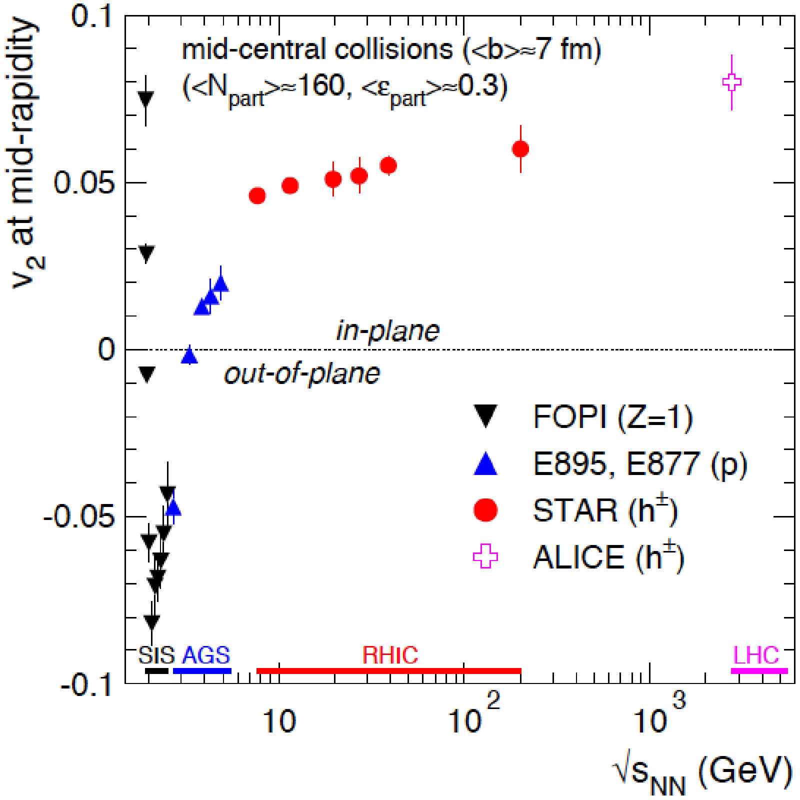
- particles stream out isotropically, no memory of the asymmetry
- extreme: ideal gas (infinite mean free path)

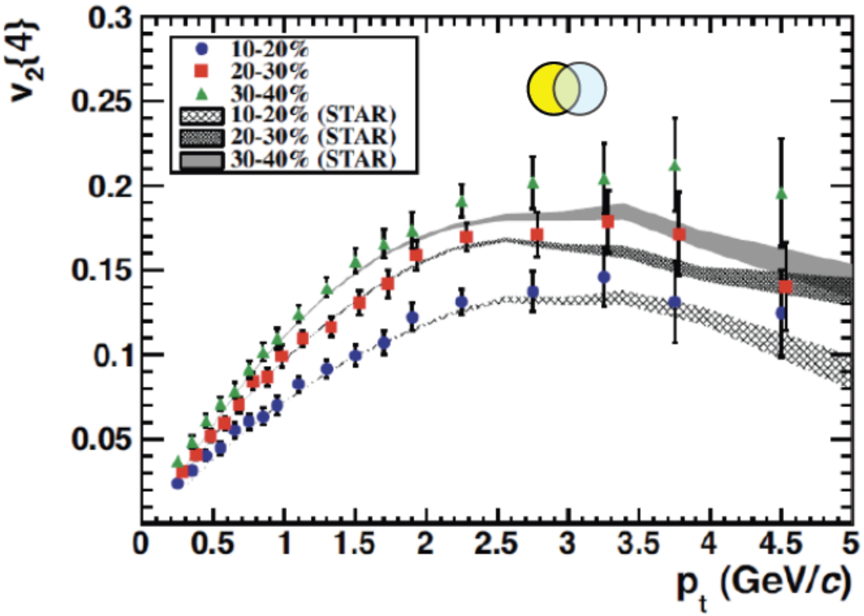
Small mean free path

- larger density gradient -> larger pressure gradient -> larger momentum
- extreme: ideal liquid (zero mean free path, hydrodynamic limit)

Anisotropic flow

Azimuthal asymmetry is quantified by second coefficient (v_2) of Fourier expansion of azimuthal distribution



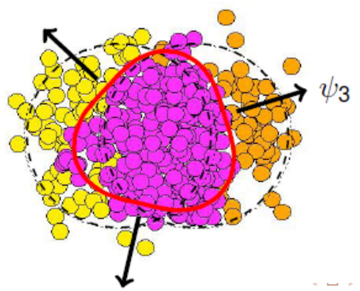


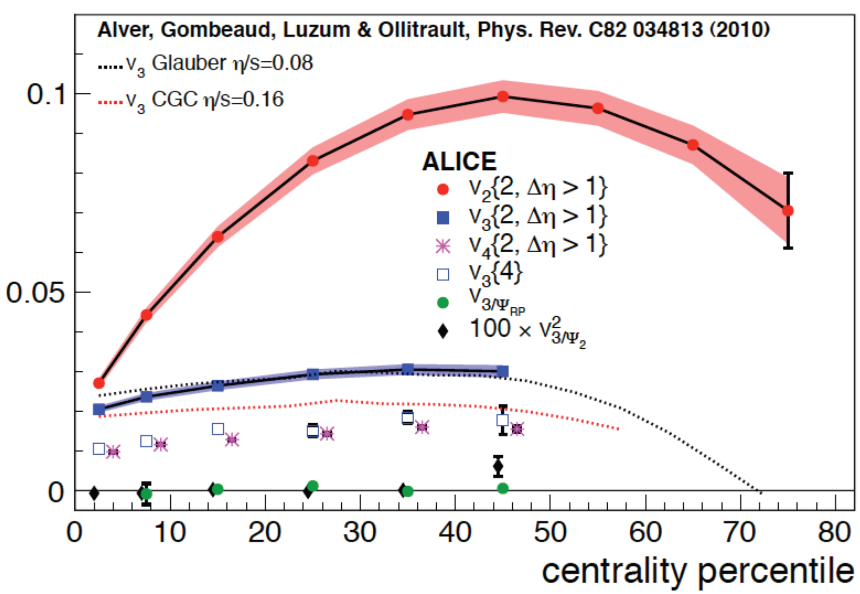
PRL 105 (2010) 252302

v_2 large at the LHC! The system still behaves very close to an ideal liquid

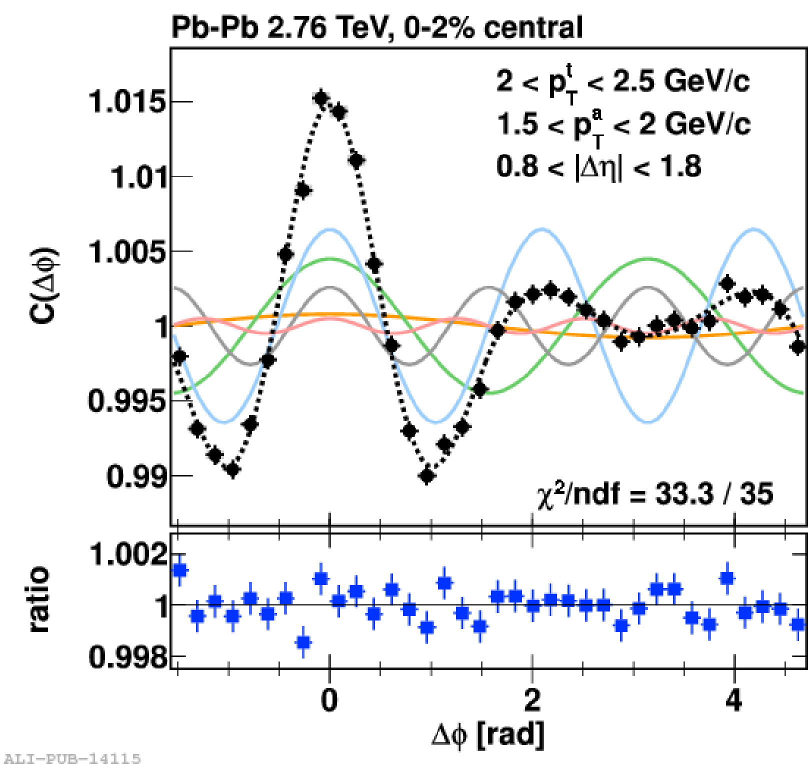
Higher harmonics

v_3 (triangular flow) sensitive to initial fluctuations → non zero!





Long-η-range correlations

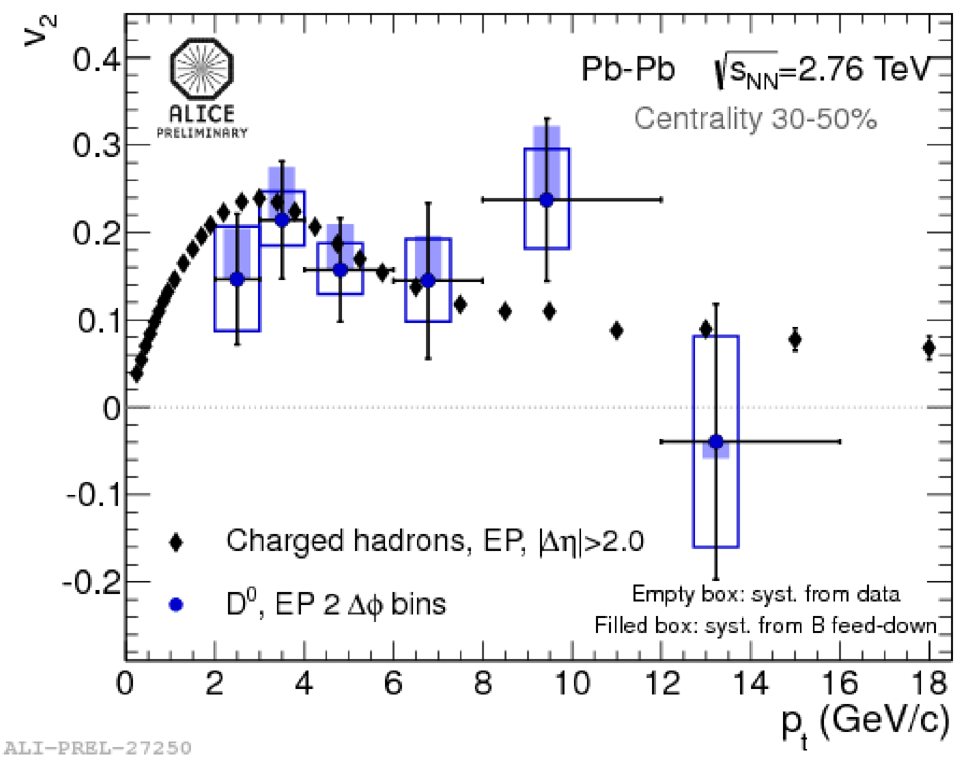


Sum of 5 order harmonics explains "ridge" and "Mach cone" structures.

Phys. Lett. B708 (2012) 249-264

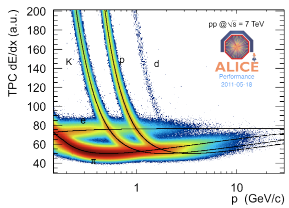
Charm flow

Elliptic flow of D mesons compatible with that of charged hadrons



→ indication of charm **thermalization** in the medium !

Nuclei and exotica in ALICE

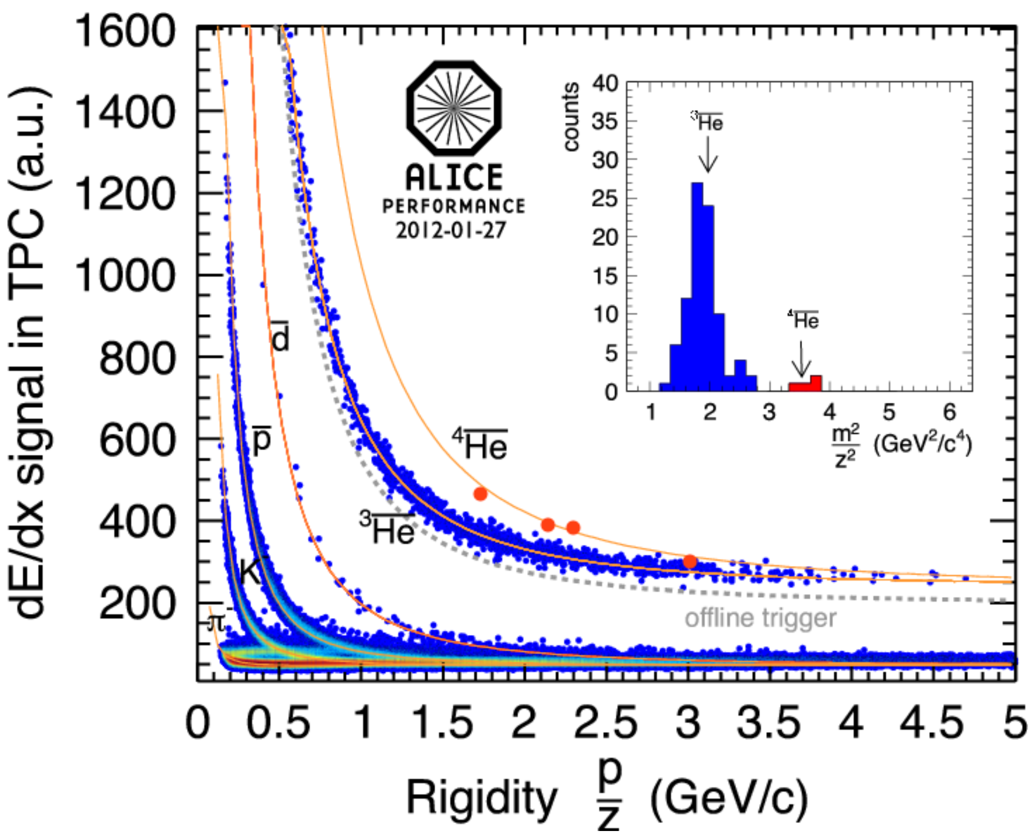


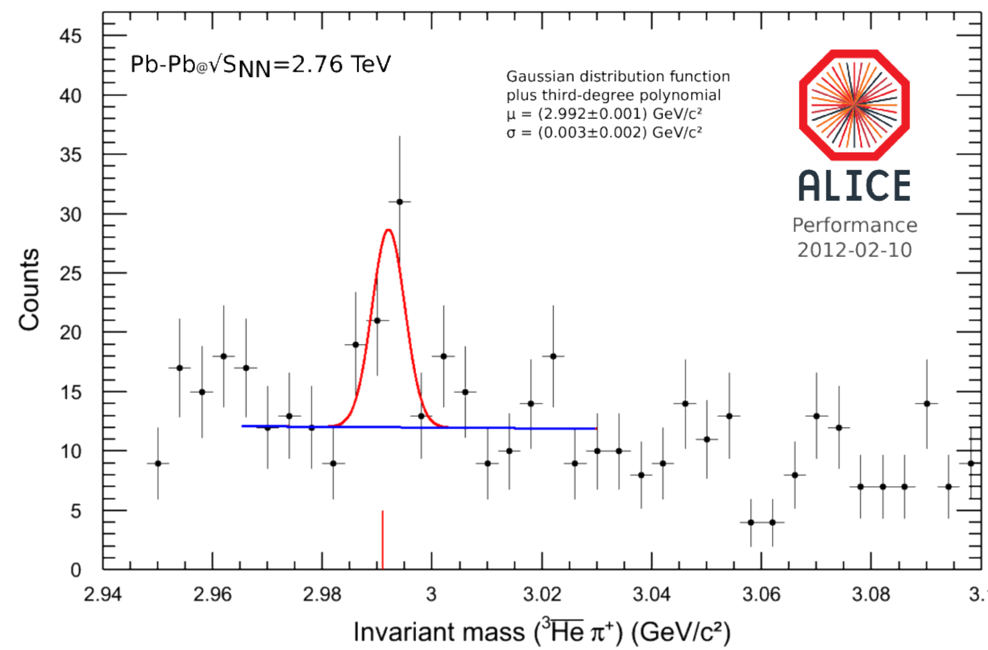
Using the excellent particle identification in the TPC

Heaviest anti-matter: $^{4}\overline{He}$

Anti-hypertriton observation

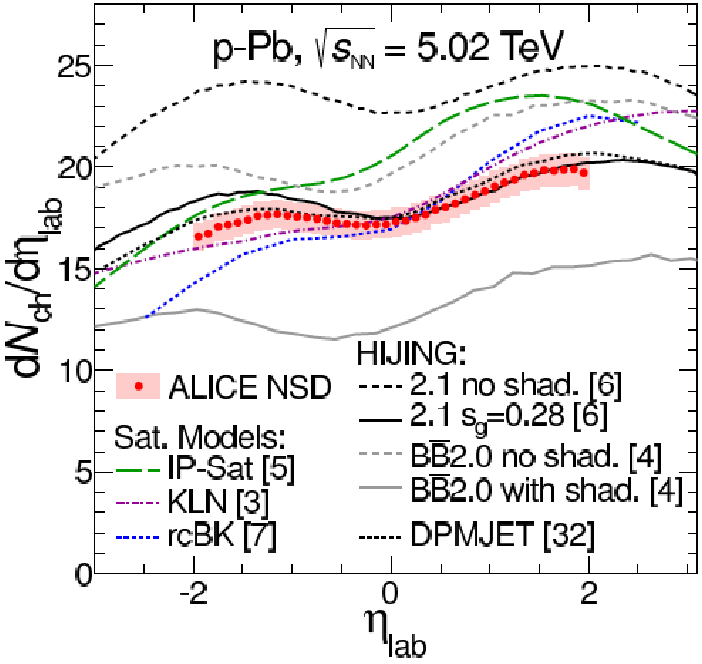
$^{3}_{\overline{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$





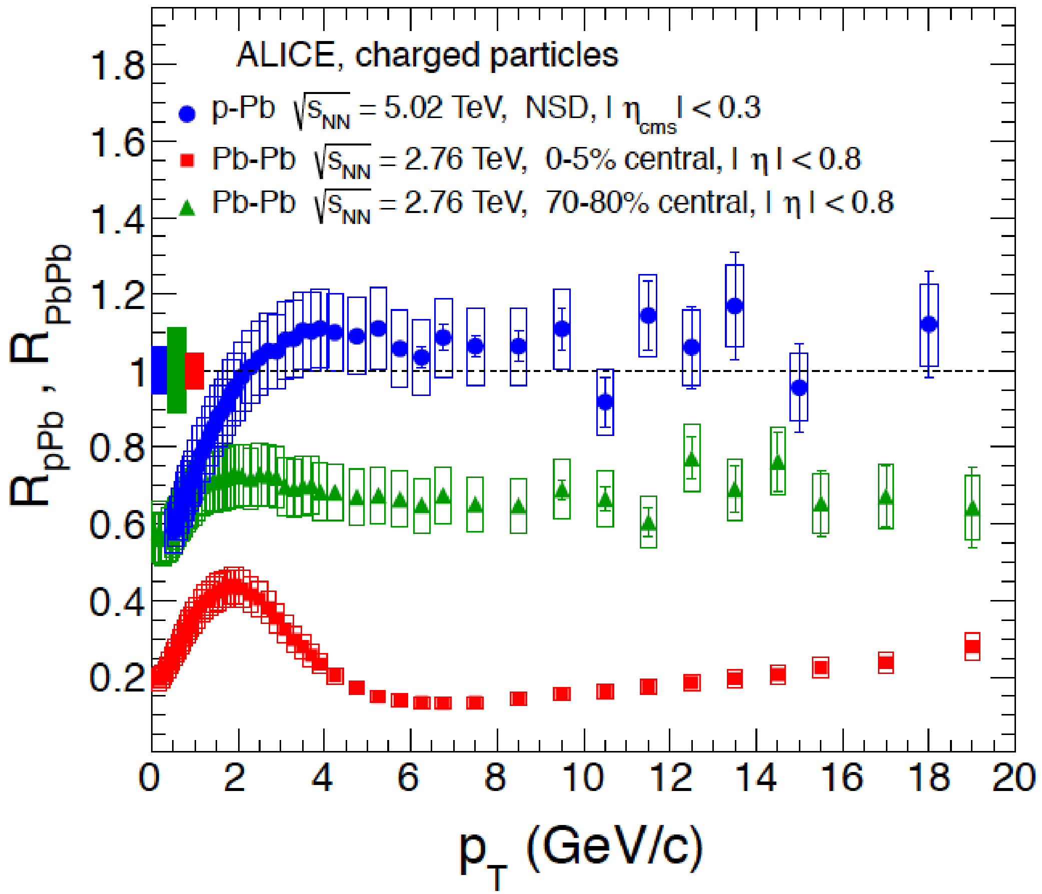
proton-Pb collisions

- Important control experiment to disentangle **INITIAL STATE** effects due to the nuclear structure of the projectiles:
  Shadowing (reduction of the parton distribution functions at low x), nuclear absorption, from the **FINAL STATE** effects
- Pilot run in Sept 2012, 4 week run in Jan-Feb 2013



proton-Pb collisions

Nuclear modification factor R_{pPb} for charged tracks compared to peripheral and central Pb-Pb collisions



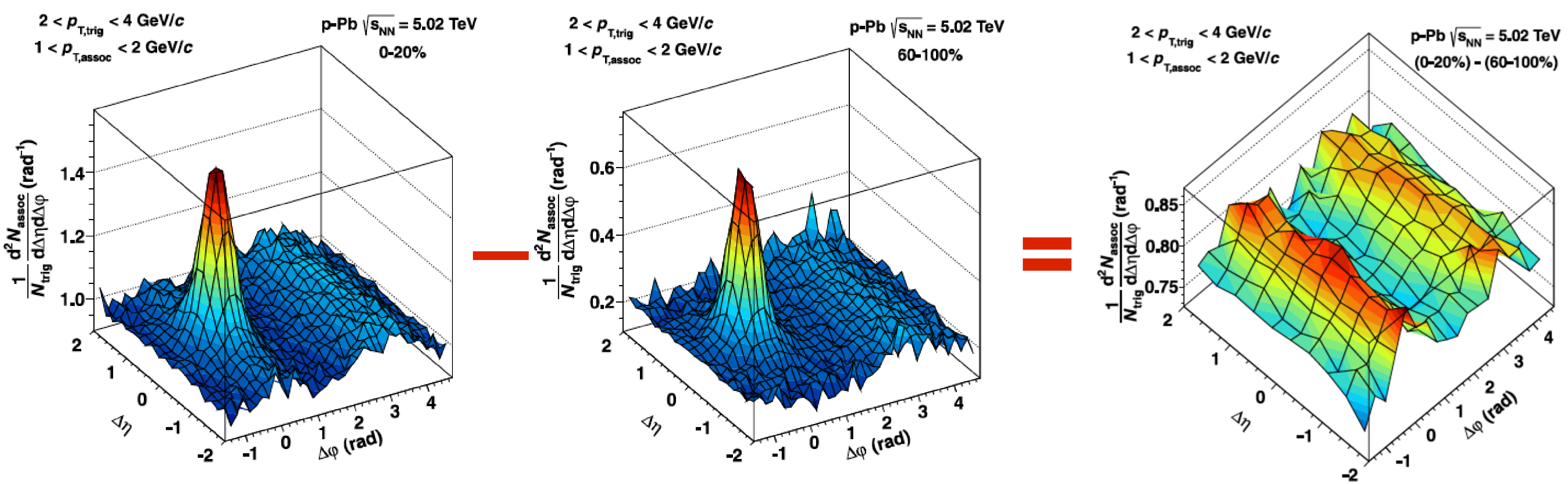
The large suppression up to high p_T is a pure final state effect

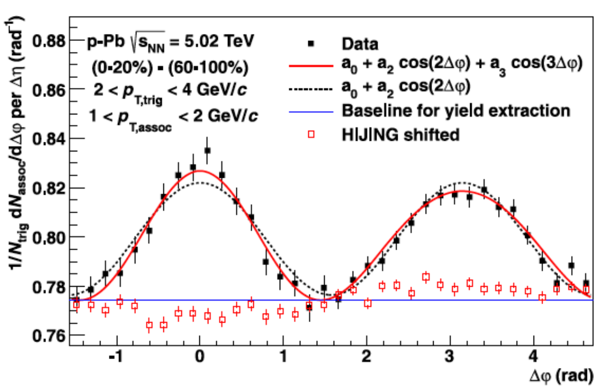
→ parton energy loss in the medium

Phys.Lett. B696 (2011) 30-39
Phys. Rev. Lett. 110, 082302 (2013)

The double ridge in p-Pb

Two-particle correlations, in different event-multiplicity bins:





Intriguing!

Azimuthal distribution consistent with flow parameter fits. Hydro-model interpretation? Or Color Glass Condensate?

Phys. Lett. B 719 (2013) 29-41

The future

- 2013-14: LHC long shutdown 1
  Detector consolidation in preparation for ...
- 2015-17: RUN 2 **FULL ENERGY !!**
  pp @ 14 TeV, Pb-Pb @ $\sqrt{s_{NN}}$ = 5.5 TeV ← **20 kHz !!!**
- 2018: LHC long shutdown 2
- ≥ 2019: **HIGH LUMINOSITY → 50 kHz Pb-Pb collisions**
  LHC experiment upgrades to cope with the higher rates!!
  New vertex detectors
  Faster readout, pipelining, continuous readout, TPC with GEM ...

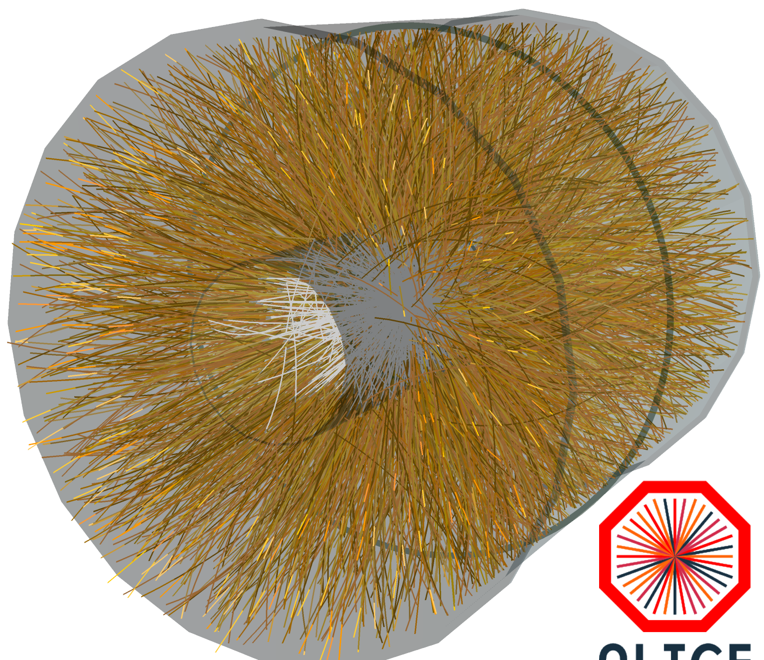
Summary

- Pb-Pb collisions at the LHC at $\sqrt{s_{NN}}$ = 2.76 TeV produce droplets of Quark-Gluon Plasma at **unprecedented conditions**
  - Energy density, fireball size and lifetime > 2 times RHIC
  - Correlations tell us about collectivity, fluctuations, ...
- Many probes give insights on the hot medium produced
  - From light to **heavy quark hadrons, to jets, to quarkonia** (cross section!)
  - Energy loss, up to very high momenta
- Quarkonia show the validity of (re-)combination models in a deconfined medium
- The excellent performance of the LHC gives the experiments **high statistics** of excellent quality data (luminosity!)

Summary

Hot physics at extreme conditions of matter

Fascinating perspectives to further explore new regimes



THANK YOU !

ALICE Germany

- Uni Münster
- FH Köln
- Uni Frankfurt
- GSI Darmstadt
- Uni Darmstadt
- Uni Heidelberg
- FH Worms
- Uni Tübingen

Time Projection Chamber

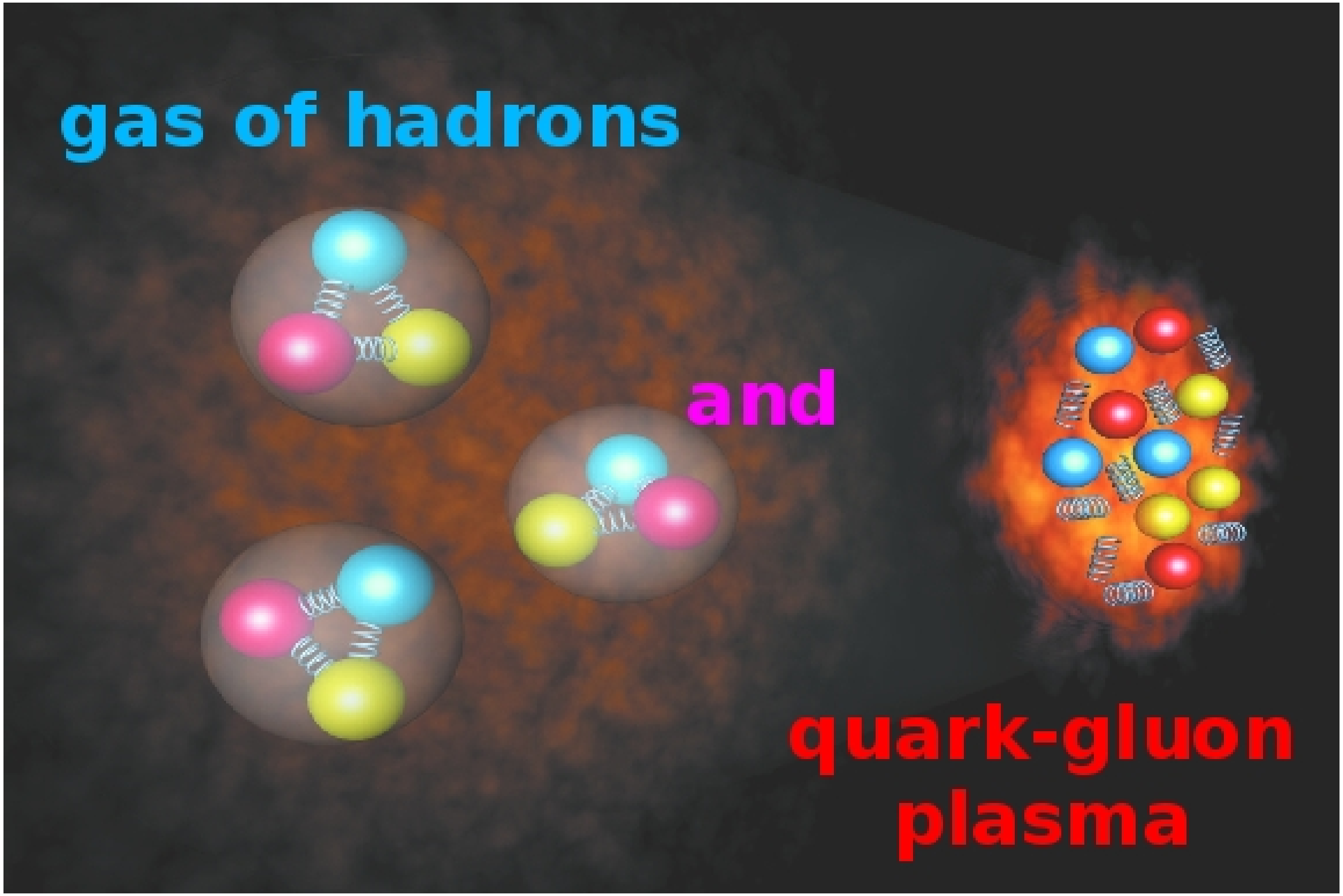
Transition Radiation Detector

High Level Trigger

SPARES

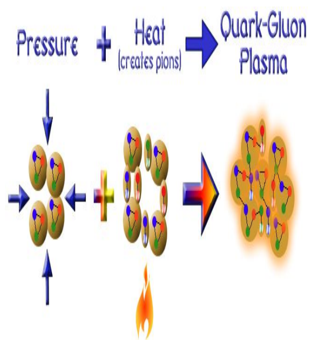
Quark-Gluon Plasma

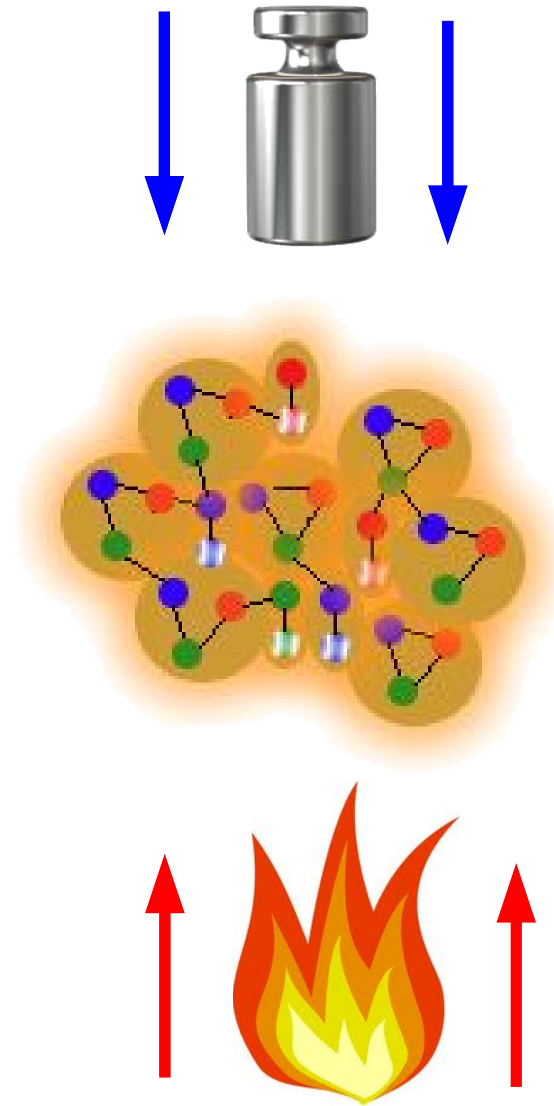
State of strongly interacting matter no longer confined in a hadron



Quark-Gluon Plasma

Confined hadronic matter

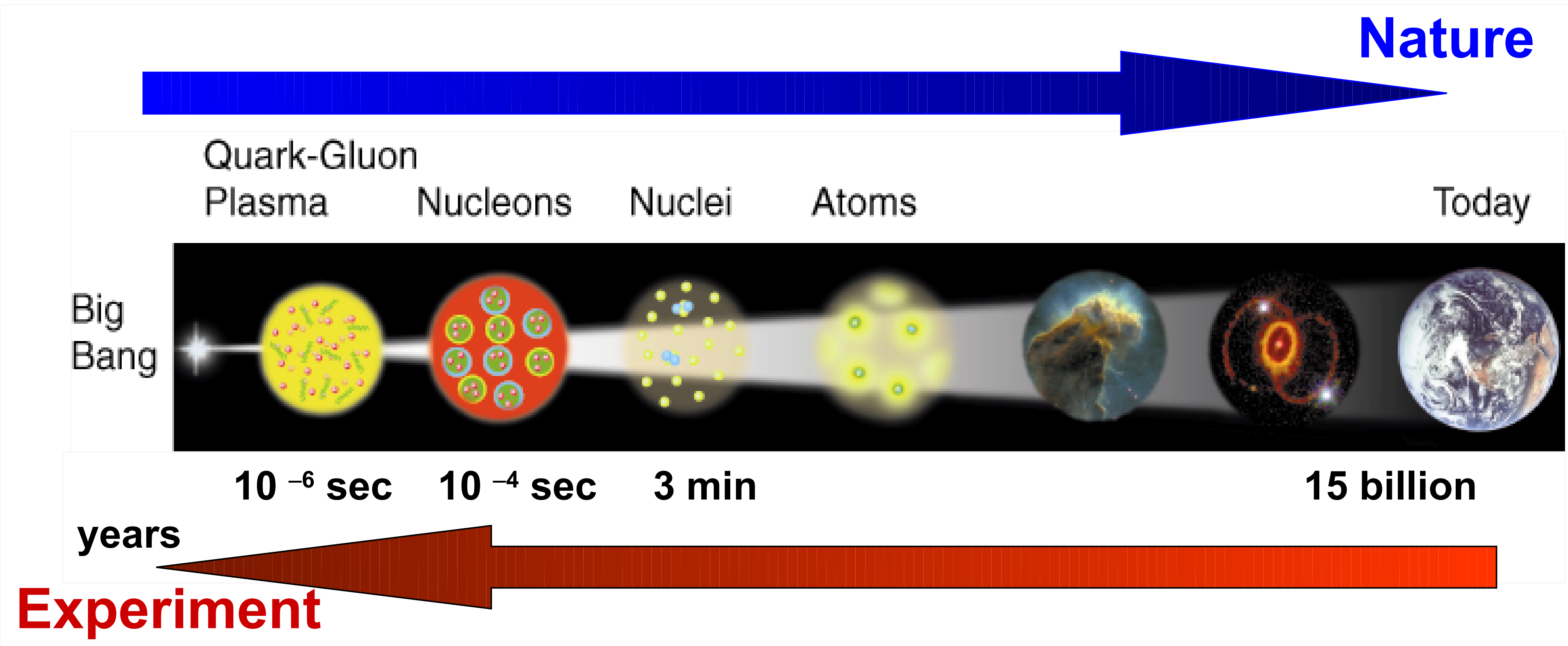




Under conditions of high **energy density** and/or **high temperature**

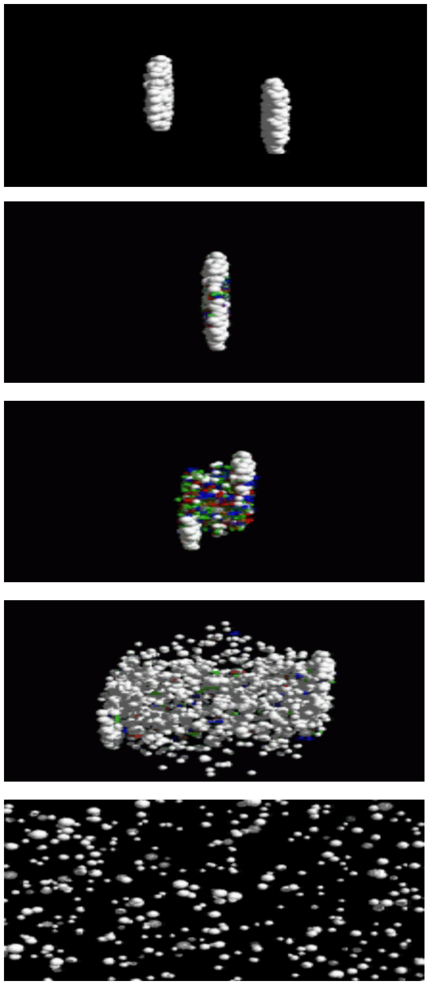
→ deconfined plasma of quarks and gluons

Go back in the universe history



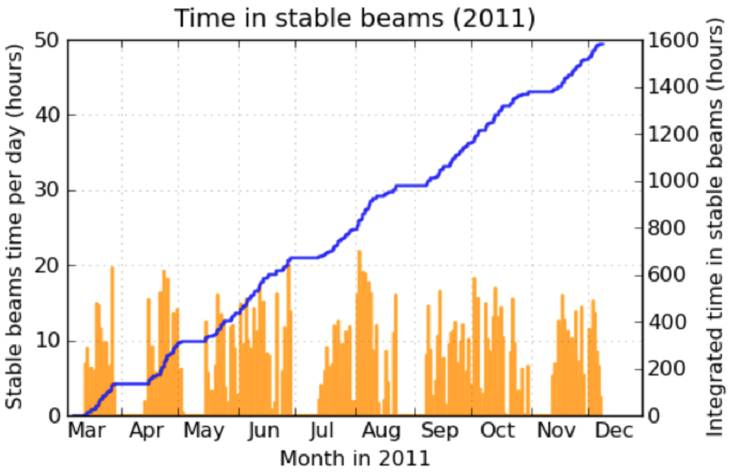
Phases of heavy ion collisions

UrQMD 160 GeV Au+Au



- Before collision
- Compression and heating
- Thermalization: equilibrium is established (t < 1 fm/c)
- Expansion and cooling (t < 10-15 fm/c)
- Chemical freeze-out: inelastic collisions cease (number of particles frozen)
- Kinetic freeze-out: elastic collisions cease (particle momenta, spectra frozen)

Data taking and triggers



What does ALICE do with all those LHC fills?

2010: **minimum bias** trigger (*) + muon

2011: from mostly minimum bias + muon (spring)

to mostly **trigger**ed data (autumn)

pp: EMCal, muon ...

PbPb: EMCal, muon, centrality, ultra-peripheral ...

(*) see spares

With triggers we **inspect** a much higher fraction of the interaction rate.

But careful !!!!

More ingredients: data sets

Main samples of real data collected by ALICE so far:
Rough size estimator: "good" ESD sample (very approximately!!)

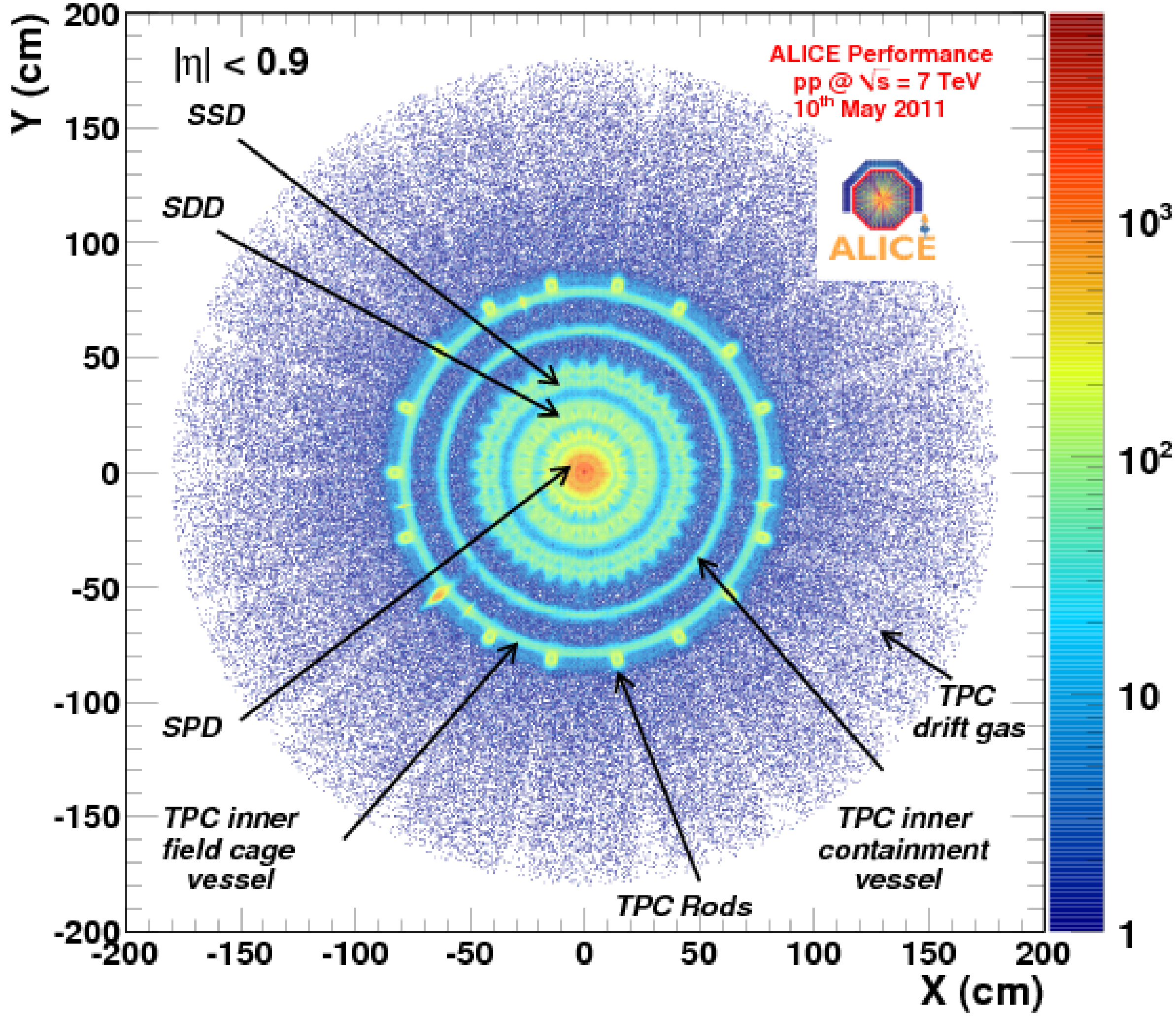
- **pp 2010**: min bias large statistics 450x10^6 events, ~100 TBytes
- **PbPb 2010**: minimum bias, first sample 20x10^6 events, ~60 TBytes
- **pp 2011**: from minimum bias to triggers
  interaction rate increasing significantly, pile up
  2 energies: reference sample (2.76 TeV), 7 TeV
- **PbPb 2011:** triggers, high statistics ~ 120x10^6 events, ~**600 TBytes**

Plus the matching MC !!!

(all numbers are just a rough approximation, order of magnitude)

ALICE material budget

Via the reconstruction of photon conversion in the detector material

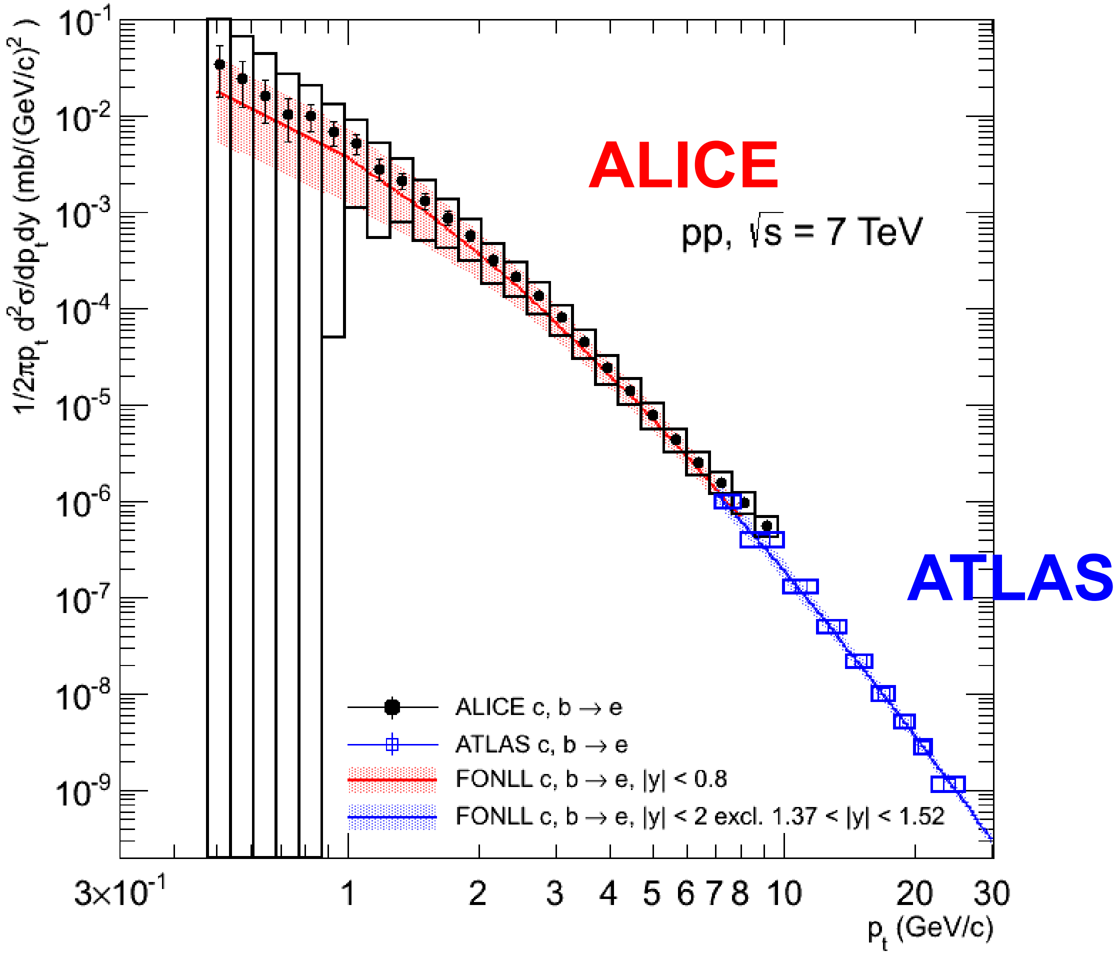


~ 6% accuracy

ALICE specialties: proton-proton

Electrons from heavy-flavour hadron decays:

Production cross section of **charm + beauty → electron + X**

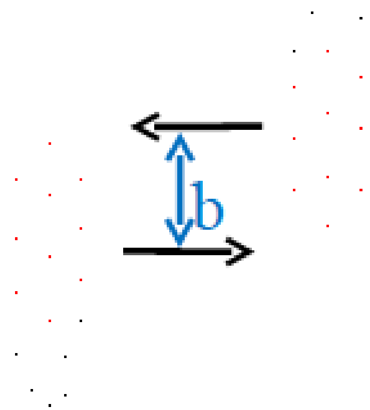


Test of pQCD

ALICE: J.Phys.G38:124069,2011

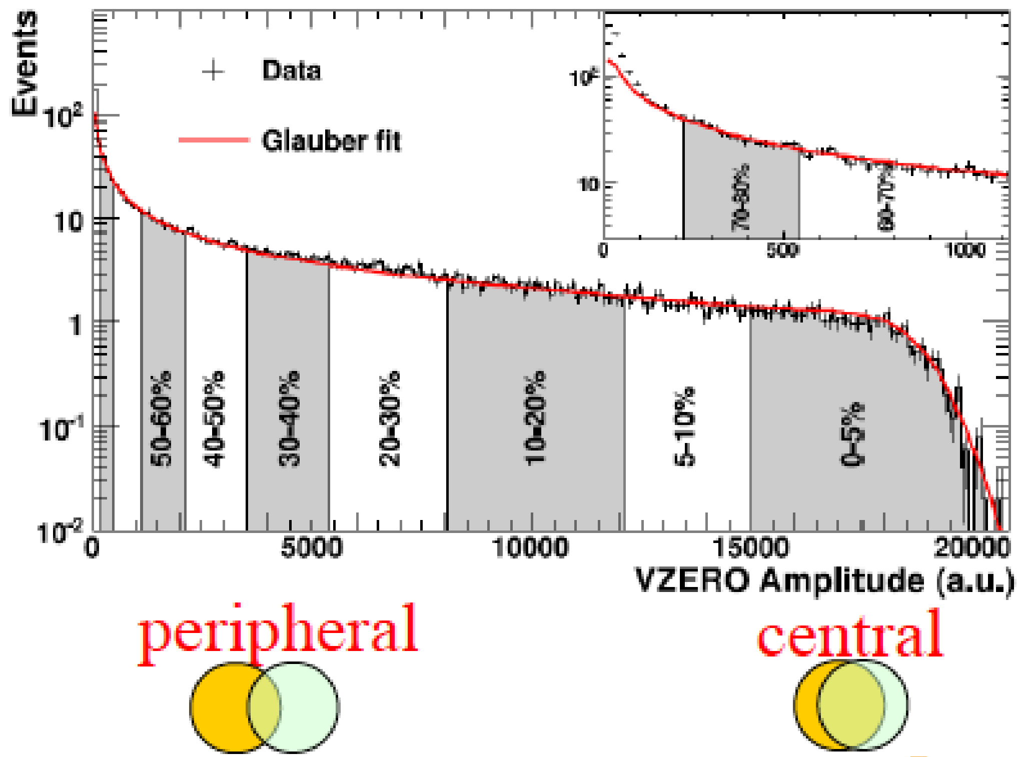
ATLAS: Phys.Lett., B707:438–458, 2012

More on centrality



- central collisions
  - small impact parameter b
  - high number of participants → high multiplicity
- peripheral collisions
  - large impact parameter b
  - low number of participants → low multiplicity

for example: sum of the amplitudes in the ALICE V0 scintillators →



reproduced by Glauber model fit (red):

- random relative position of nuclei in transverse plane
- Woods-Saxon distribution inside nucleus
- deviation at very low amplitude expected due to non-nuclear (electromagnetic) processes

Energy density

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = E_{\rm part} \times \left.\frac{dN_{\rm ch}}{d\eta}\right|_{\eta=0} \times f_{\rm neutral}$$

$$= 0.5 \text{ GeV} \times 600 \times 1.6 \approx 500 \text{ GeV}$$

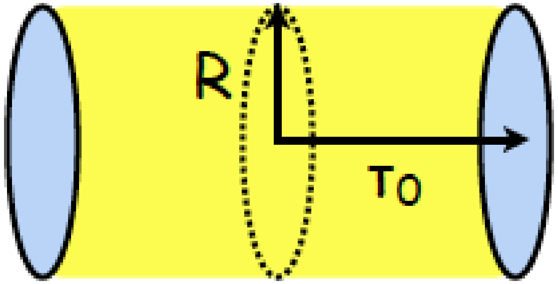
$\langle p_t \rangle$ @ $\eta=0$ $dN/d\eta$ $f_{neutral}$

Energy density:

$$\epsilon_{\rm Bj} = \frac{dE_T/d\eta}{\pi R^2 \tau_0} \approx 5 \text{ GeV/fm}^3$$

[$\sqrt{s}$ = 200 GeV]

Bjorken estimate



$R \approx 1.18\, A^{1/3}$ fm

$A \approx 200$

$\tau_0 \approx 1$ fm/c

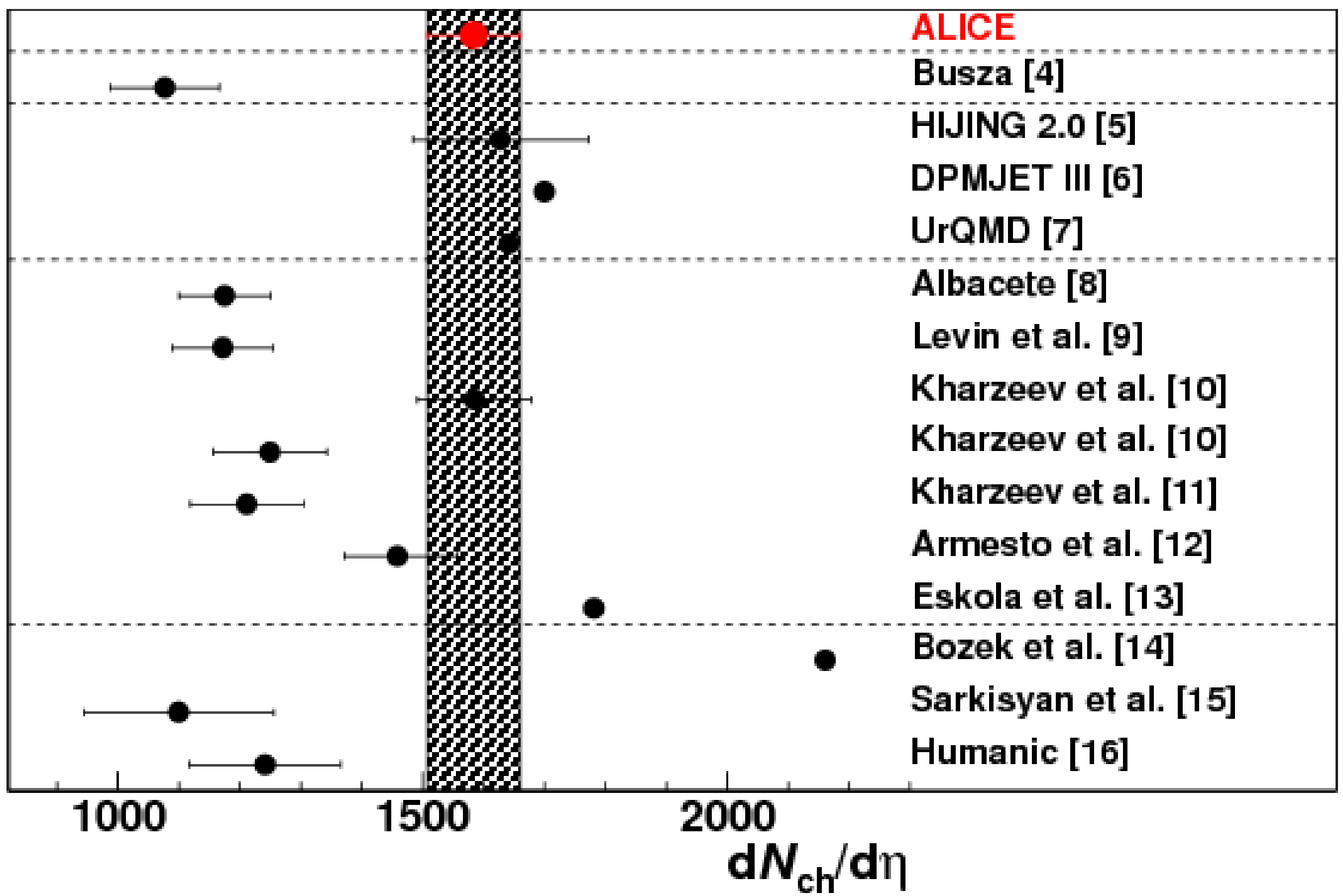
Compare to:

Nuclear Density: ρ = 0.15 GeV/fm^3

Inside Nucleon: ρ = 0.5 GeV/fm^3

Multiplicity

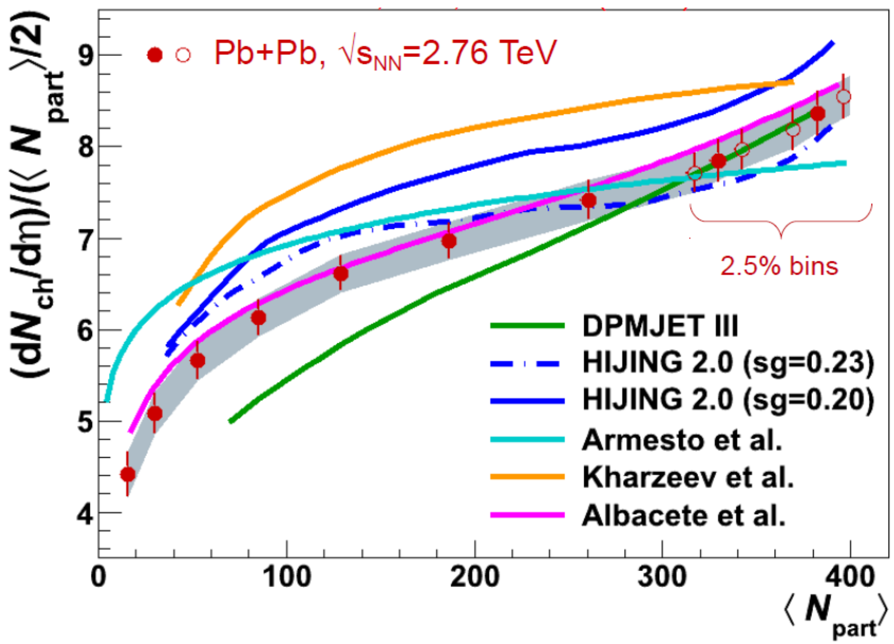
Comparison to models



Multiplicity: centrality dependence

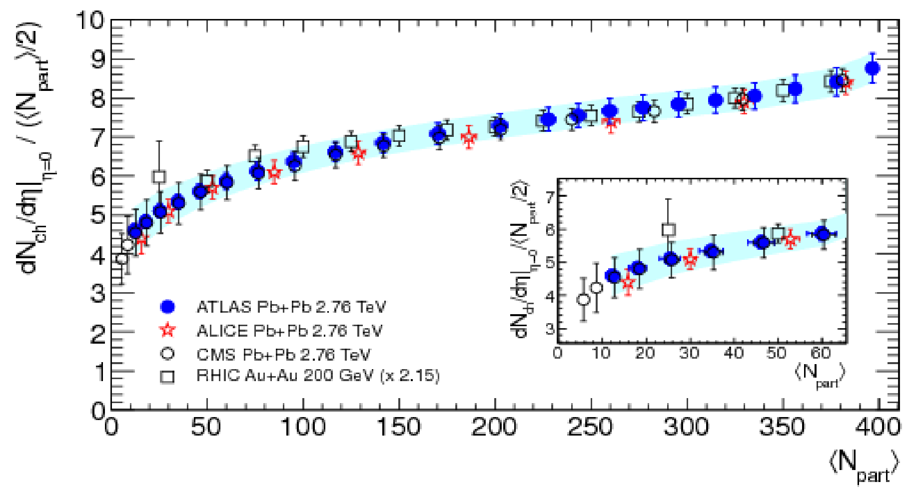
- model comparisons
  - DPMJET (with string fusion)
  - HIJING 2.0 (no quenching)
    - centrality-dependent gluon shadowing
    - tuned to multiplicity in 0-5%
  - saturation models

    (sometimes too much?)



PRL 106(2011) 032301

- very similar centrality dependence at LHC & RHIC
  - once corrected for difference in absolute values

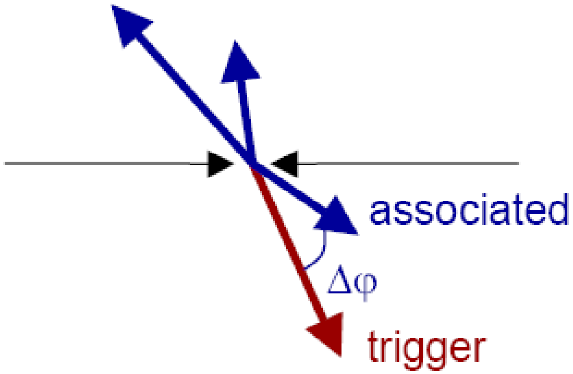


ATLAS arXiv:1108.6027

Correlations

- Anysotropic flow, v2
- Initial state fluctuations, v3 non zero
- A la WMAP
- Higher harmonics
- 2 particle correlations, long eta-range correlations

Triggered di-hadron correlations



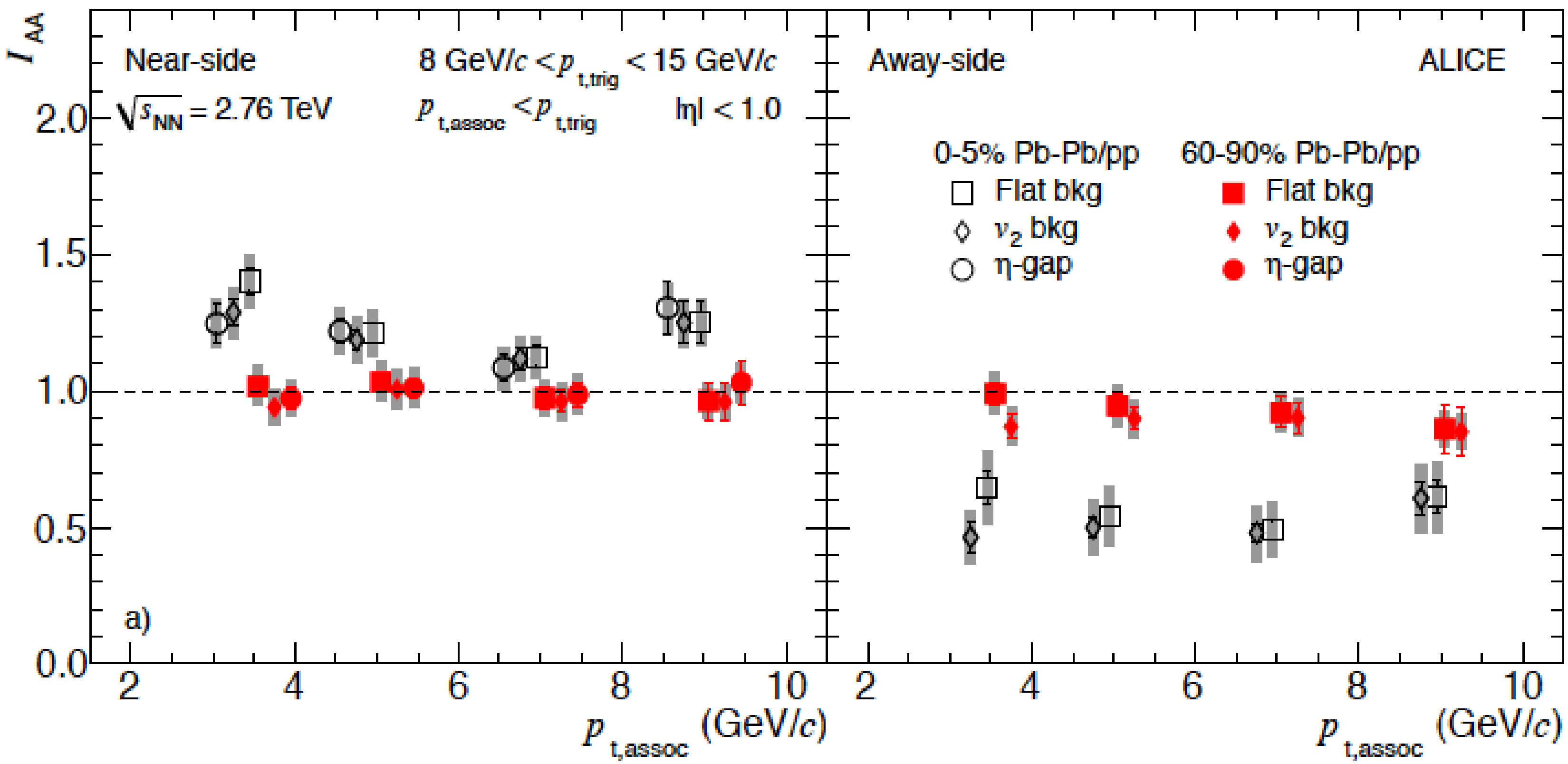
- Angular correlations between trigger particle and associated particles $p_t^{trig} > p_t^{assoc}$
- Expressed as yield per trigger particle:

$$Y(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{assoc}}{d(\Delta\phi)}$$

- Choose p_t where background and v2 are small: $8 < p_t < 15$ GeV/c
- Look at near side ($\Delta\varphi = \pm 0.7$) and away side ($\Delta\varphi = \pi \pm 0.7$)

$$I_{AA} = \frac{Y_{Pb-Pb}}{Y_{pp}}$$

Triggered di-hadron correlations



arXiv:1110.0121 [nucl-ex]

- Central events: away side I_{AA} clearly suppressed (~0.6)
- Near side enhancement (~1.2)
- Peripheral events: I_{AA} consistent with 1
- Small flow contribution (except in lowest bin)