Quark Matter Research: The High Energy Frontier

- the physics context
- QGP at LHC: what do we want to learn?
- PbPb collisions at LHC: first results
- medium term plans
- the big open questions
- long term perspectives

pbm, ICFA meeting
CERN, Oct. 3-6, 2011

TECHNISCHE UNIVERSITÄT DARMSTADT

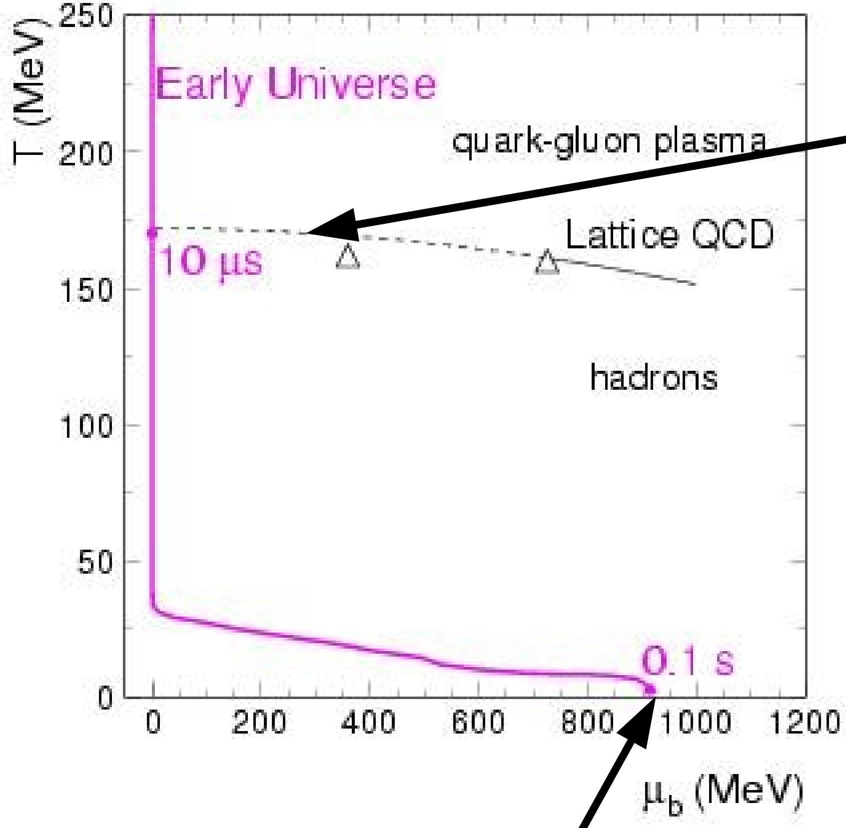
FIAS Frankfurt Institute for Advanced Studies

EMMI

HELMHOLTZ | GEMEINSCHAFT

GSI

Evolution of the Early Universe



QCD Phase Boundary

Homogeneous Universe in
Equilibrium, this matter can
only be investigated in nuclear collisions

- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

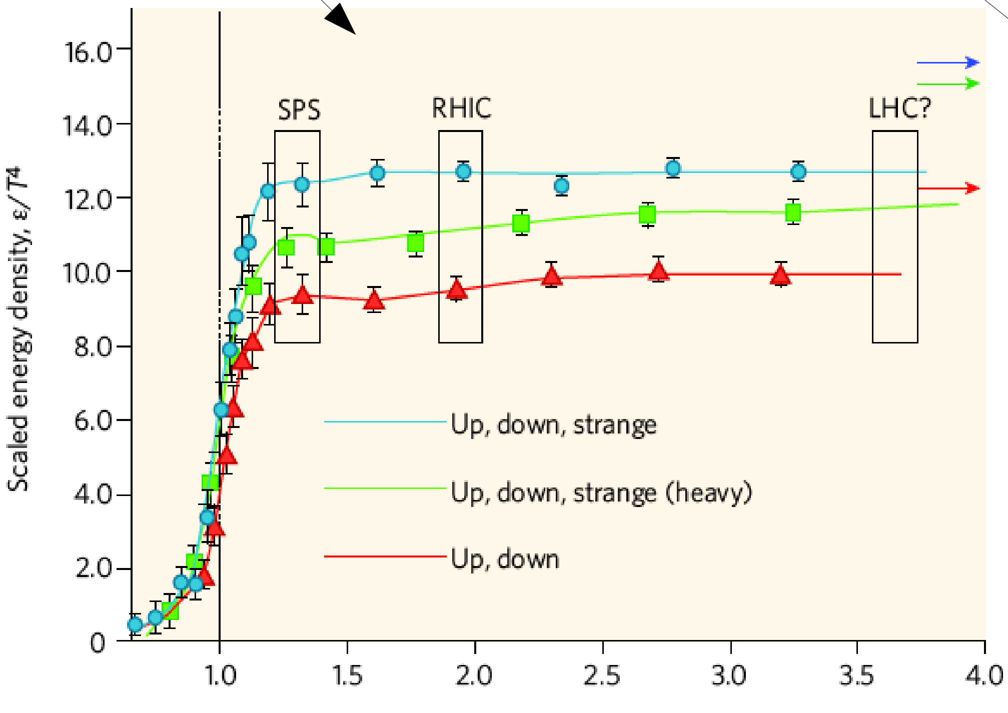
neutrinos decouple and light nuclei begin to be formed

the QCD phase diagram

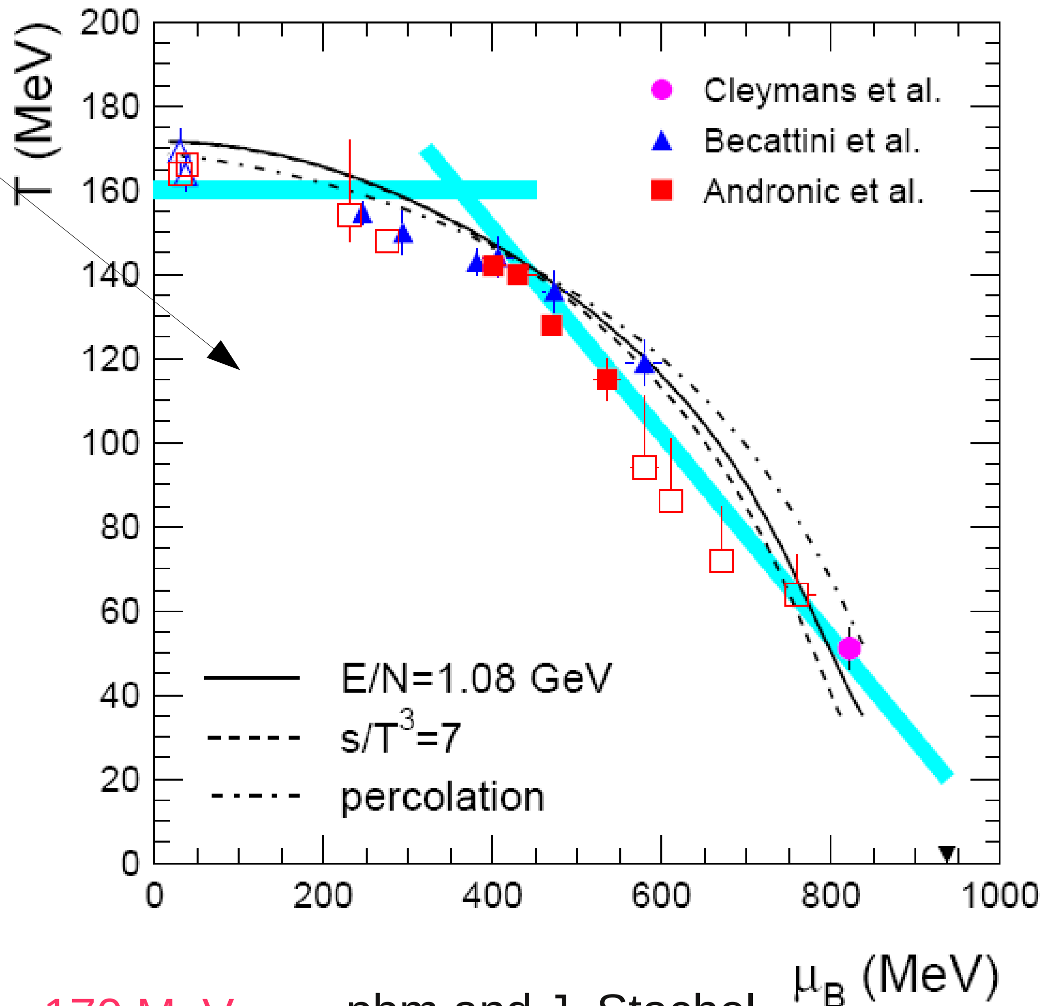
key results from theory

from experiment

data points:
'chemical' freeze-out of hadrons →
matter is at equilibrium close to T_c



temperature T/T_c



all lattice groups now agree: T_c(mu=0) is close to 170 MeV

Bazavov & Petreczky, arXiv:1005.1131 [hep-lat]

S. Borsanyi et al., arXiv:1005.3508 [hep-lat]

pbm and J. Stachel, Nature 448 (2007) 302

characterizing QGP matter at LHC

what do we want to learn?

equation of state
number of degrees of freedom
transport coefficients (viscosity etc)
velocity of sound
parton energy loss and opacity
susceptibilities
deconfinement

why LHC?

much larger energy (> 20 x RHIC)
very large volumes, temperatures, densities
copious production of jets and heavy quarks
use of quantitative tools (pQCD) possible

but also, look for the unexpected

quark matter research

recent reviews:

M. Gyulassy and L. McLerran, Nucl. Phys. A750 (2005) 30

pbm and J. Stachel, Nature 448 (2007) 302

pbm and J. Wambach, Rev. Mod. Phys. 81 (2009) 1031
arXiv:0801.4256

see also: Heavy Ion Collisions at the LHC – Last Call for Predictions
J. Phys. G35 (2008) 054001, arXiv:0711.0974

first data from LHC PbPb collisions

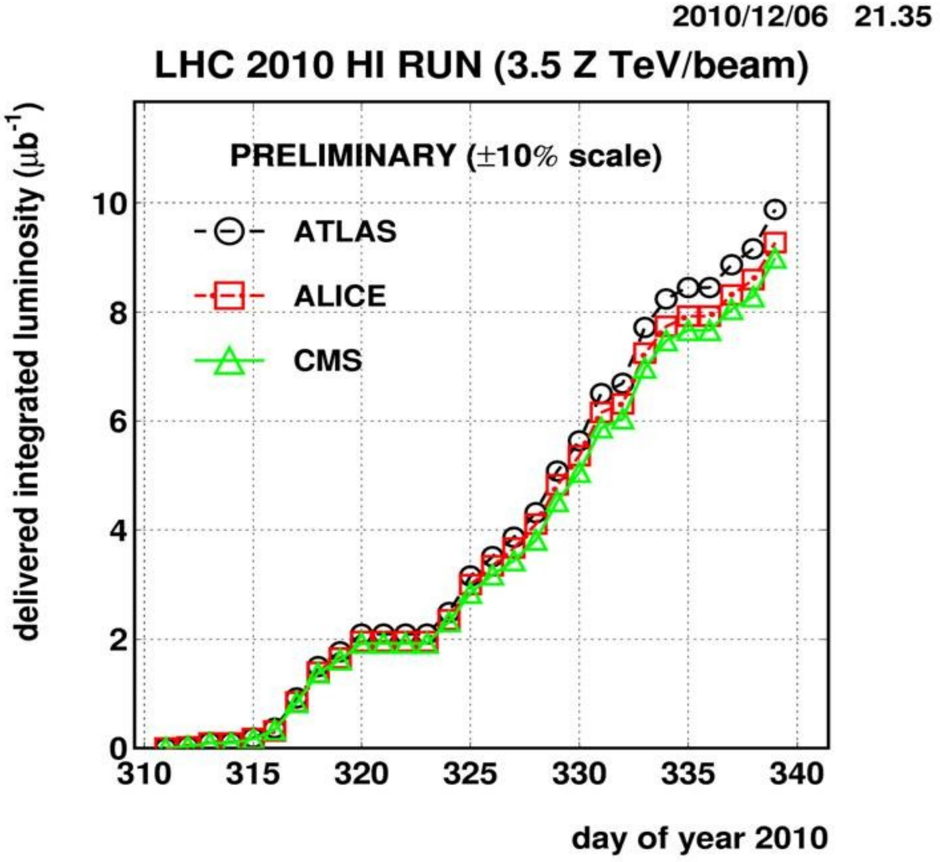
start of data taking: Nov. 7, 2010

running at about 150 Hz PbPb collisions

> 45 M PbPb inelastic events for
Each experiment

run ended Dec. 6, 2010

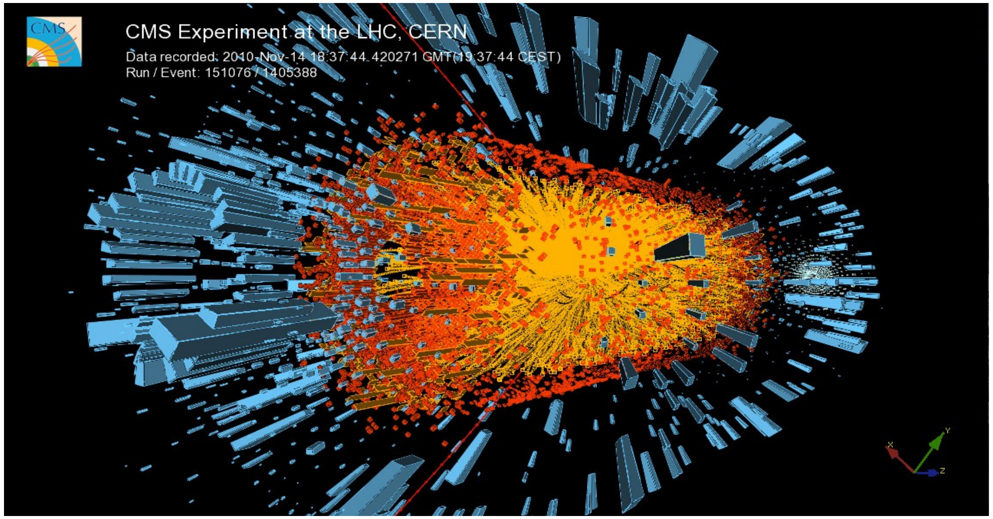
excellent performance of all detectors
ALICE   ATLAS   CMS   and the LHC

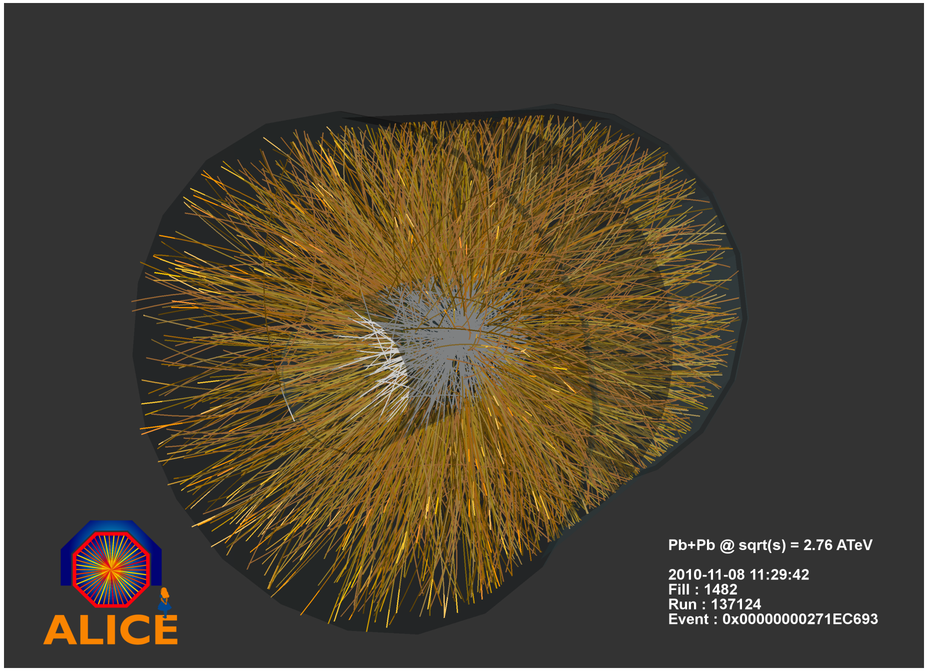


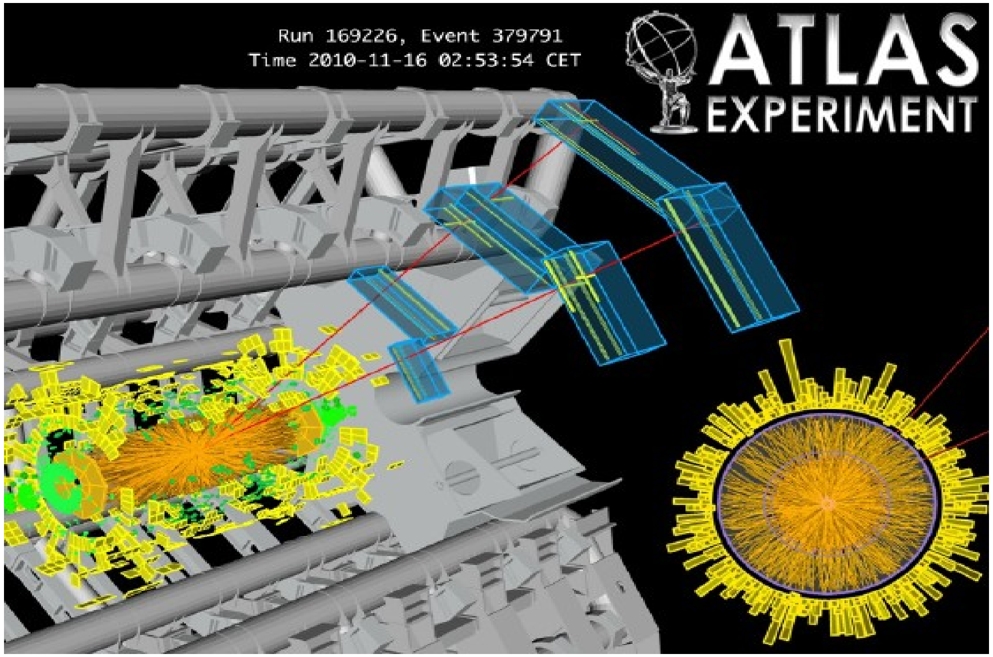
extreme matter

PbPb events at LHC in Nov. 2010

more than 10000 charged particles in one PbPb collision







the fireball formed in PbPb collisions emits particles from a state of equilibrium and expands collectively

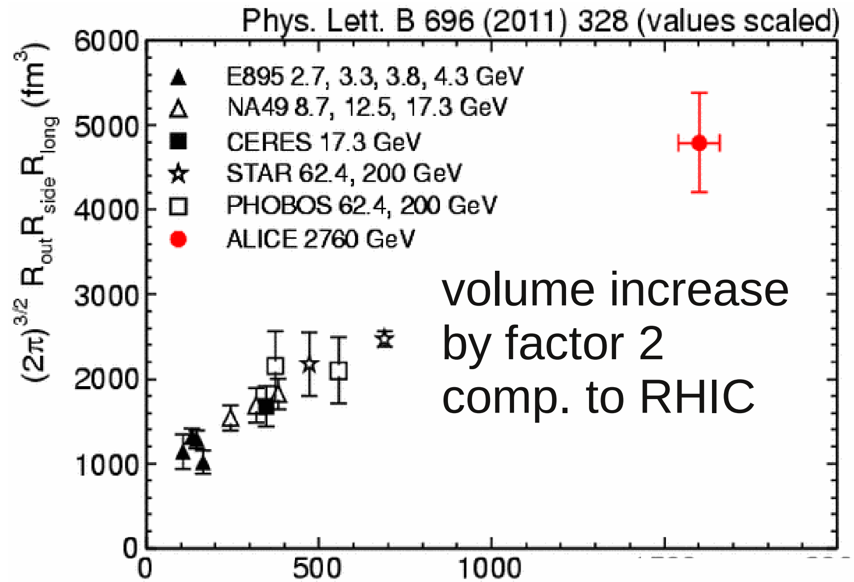
observables: collective flow pattern, initial state fluctuations (a la 'WMAP'), chemical equilibrium temperature → T_c

compared to RHIC:

volume and temperature larger
collective flow pattern similar

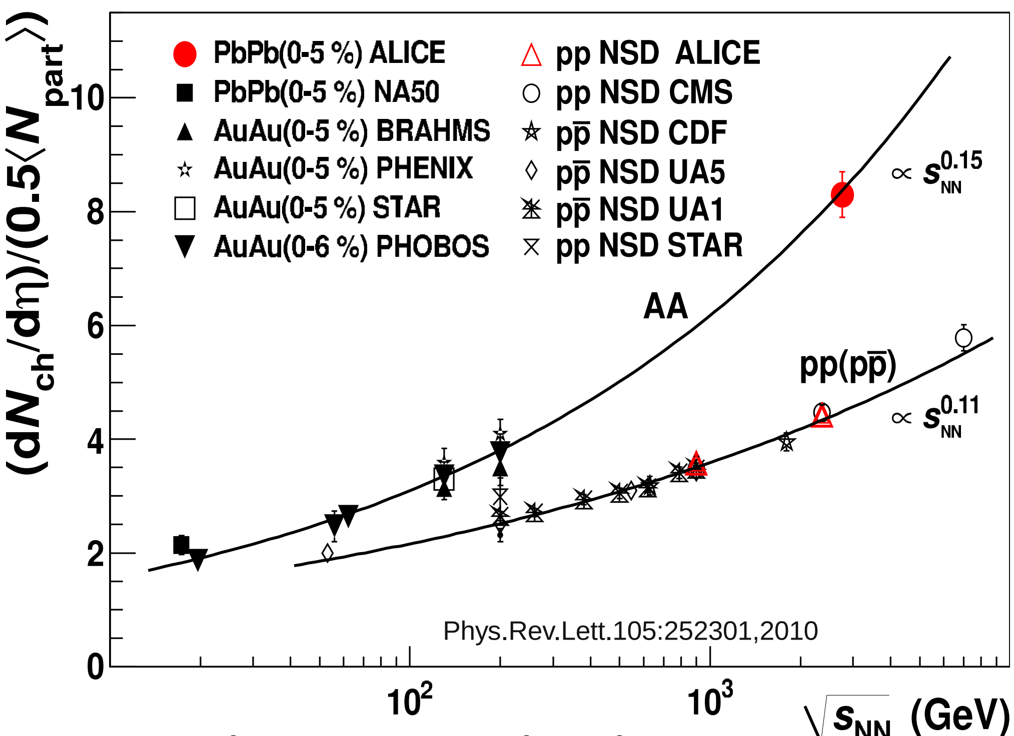
QGP: low viscosity per degree of freedom

Bulk physics: dN/dη, elliptic flow, correlations…

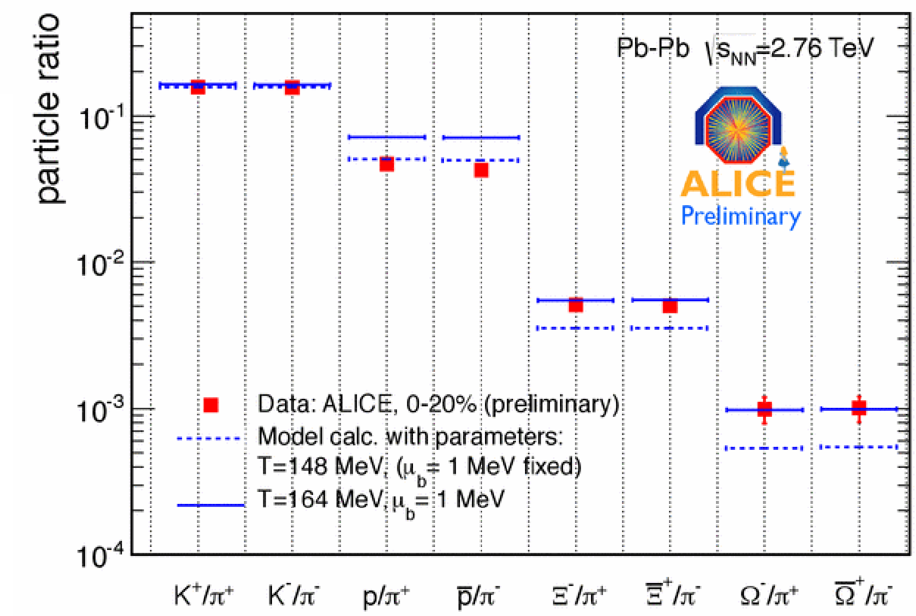


volume increase by factor 2 comp. to RHIC

.strange particles follow thermal model predictions protons??



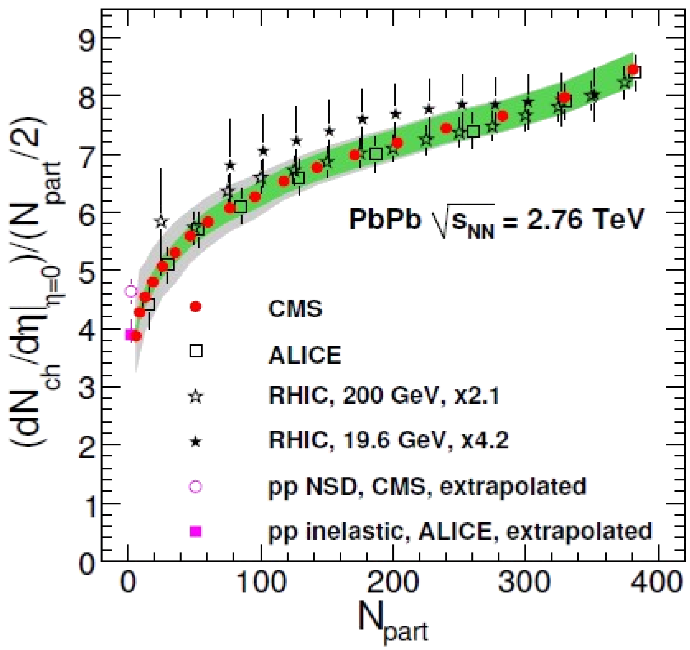
energy dep. stronger than in pp

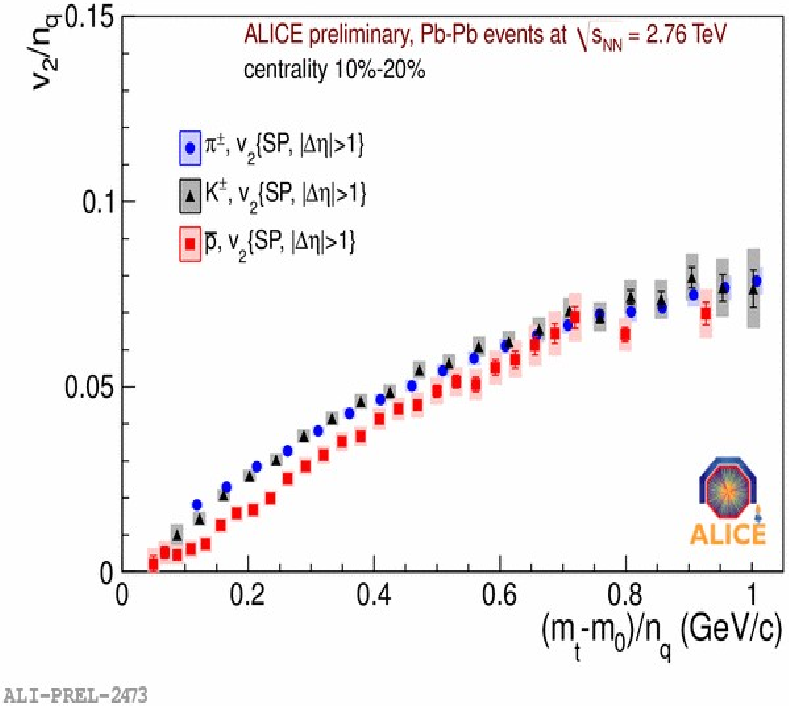


ALI-PREL-10997

predictions: Andronic, pbm, Stachel J. Phys. G35 (2008) 054001, arXiv:0711.0974

Bulk physics: dN/dη, elliptic flow, correlations…

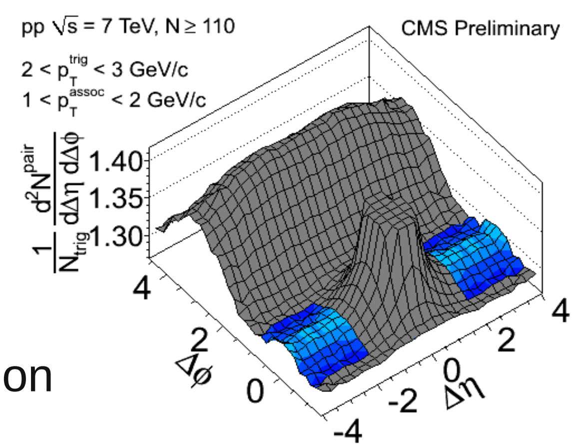




quark scaling broken?

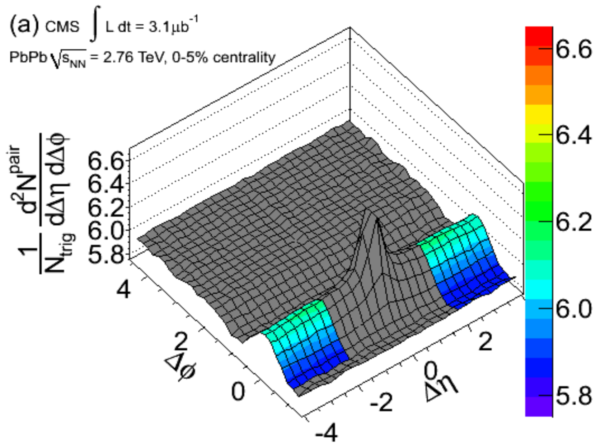
arXiv:1107.4800
Accepted by JHEP
Same trend as RHIC

CMS p+p 7 TeV, N ≥ 110



JHEP 1009 (2010) 091

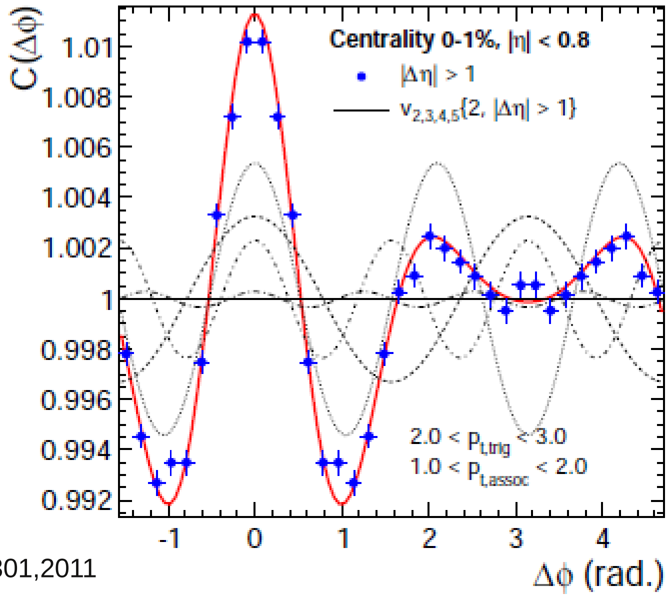
CMS Pb+Pb 2.76 TeV, 0-5%



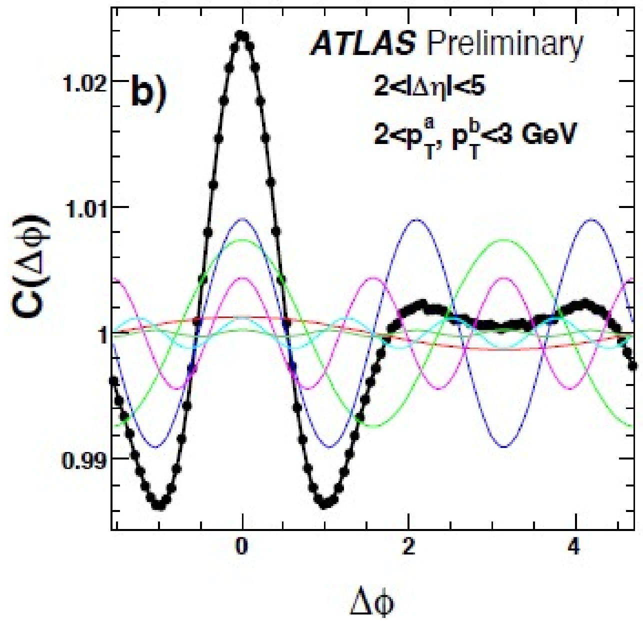
JHEP 07 (2011) 076

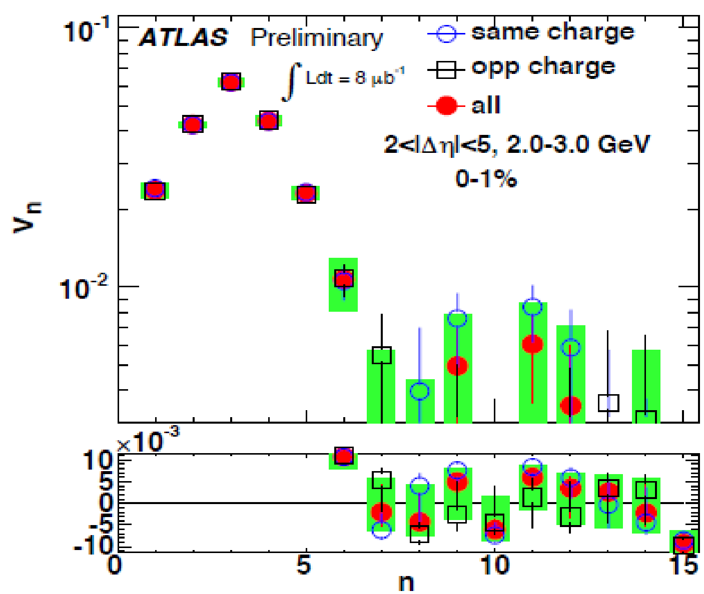
High multiplicity p+p events
as well as Pb+Pb events exhibit
a same side, long-range correlation

Bulk physics: dN/dη, elliptic flow, correlations…



Phys.Rev.Lett.107:032301,2011





all 'ridge' and mach-cone like structures consistent with collective flow pattern obtained from inclusive flow

WMAP like power spectrum of flow

high energy partons interact strongly with fireball

jet quenching, parton energy loss

compared to RHIC:

physics reach into several hundred GeV
direct measurement of heavy quarks

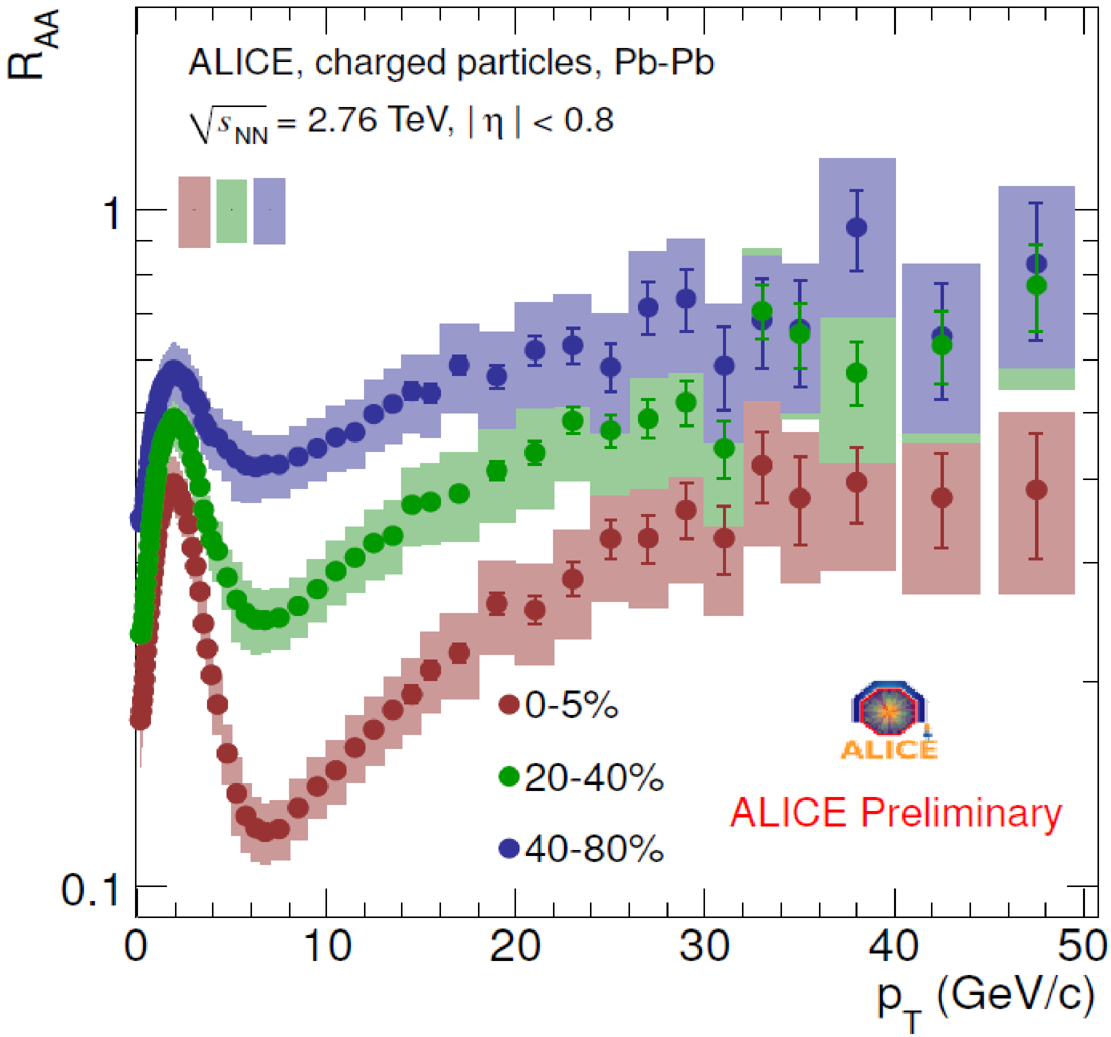
fireball is so opaque that pQCD regime
may never be reached!

electro-weak probes

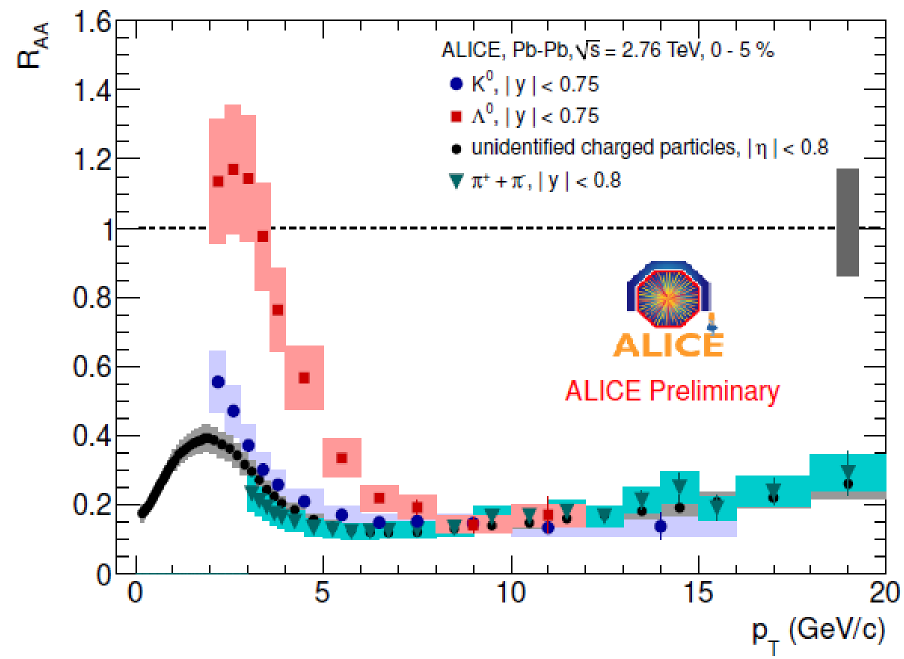
processes quantified through R_{AA}, nuclear modification factor

$R_{AA} = \sigma(AA)/(\langle Ncoll \rangle \, \sigma(pp))$ = medium/vacuum

Parton Energy loss, Jet quenching

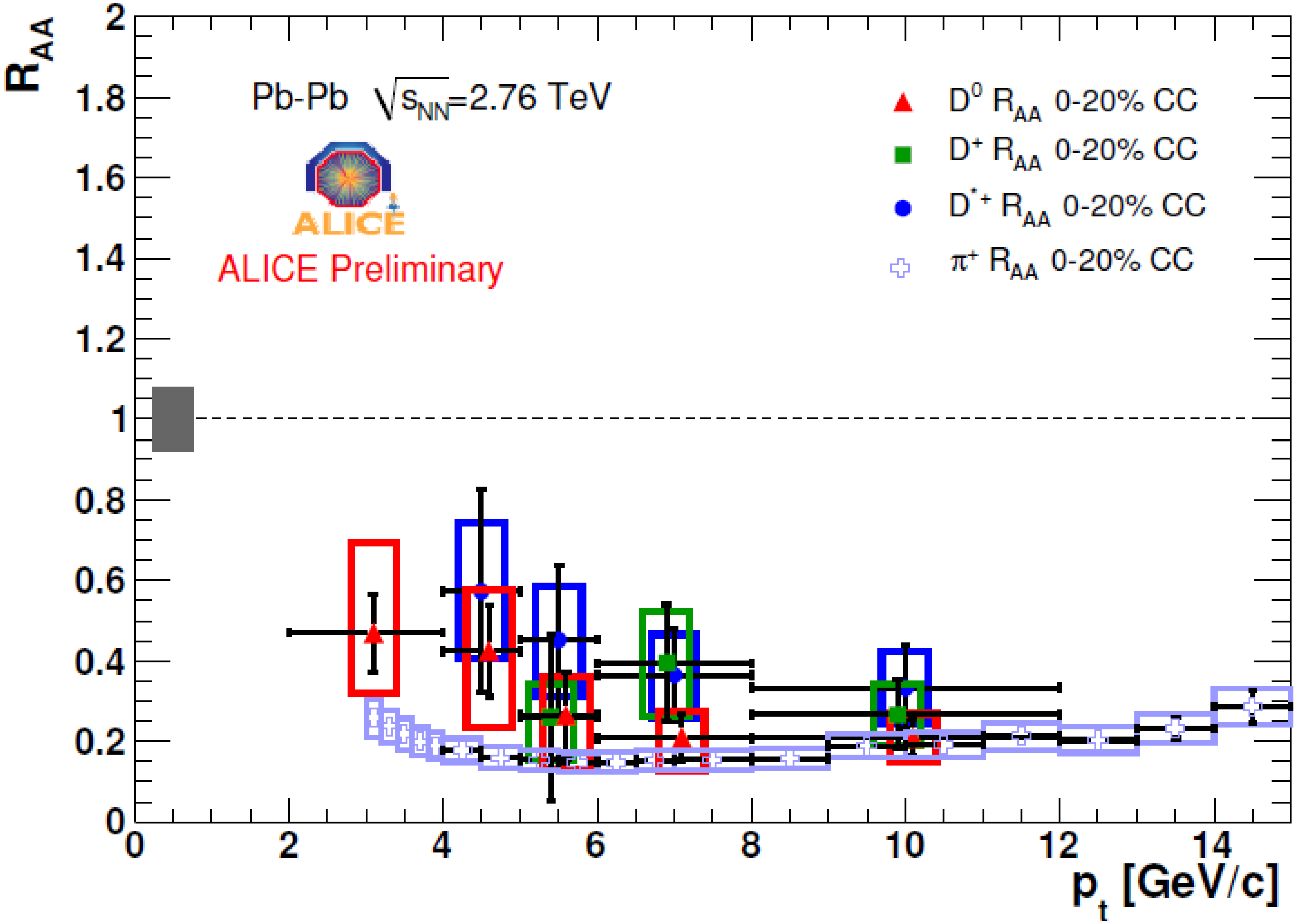


ALICE has π, K, p identification up to 50 GeV



new at LHC: increase with p_t and saturation around 50 GeV ALICE and CMS in agreement

Heavy quark energy loss vs light quarks

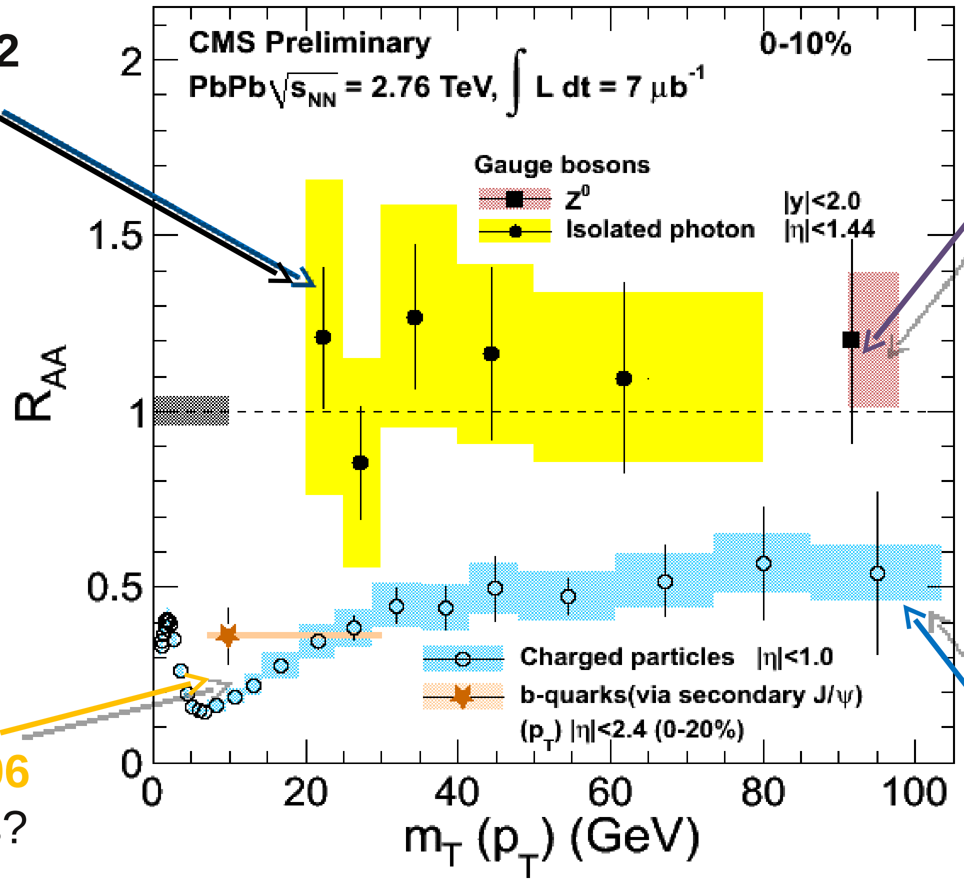


heavy quarks lose energy similar to light quarks

charm quarks are shifted to low p_t

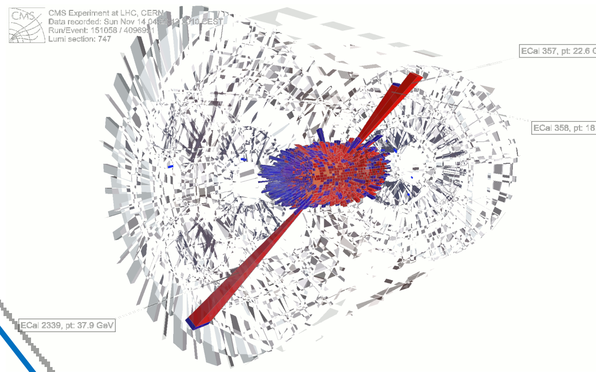
Quark energy loss vs photons and Z/W

Isolated photons in
CMS PAS HIN-11-002
No modification



Z → μμ in
PRL 106 (2011) 212301
No signifcant dependence on centrality

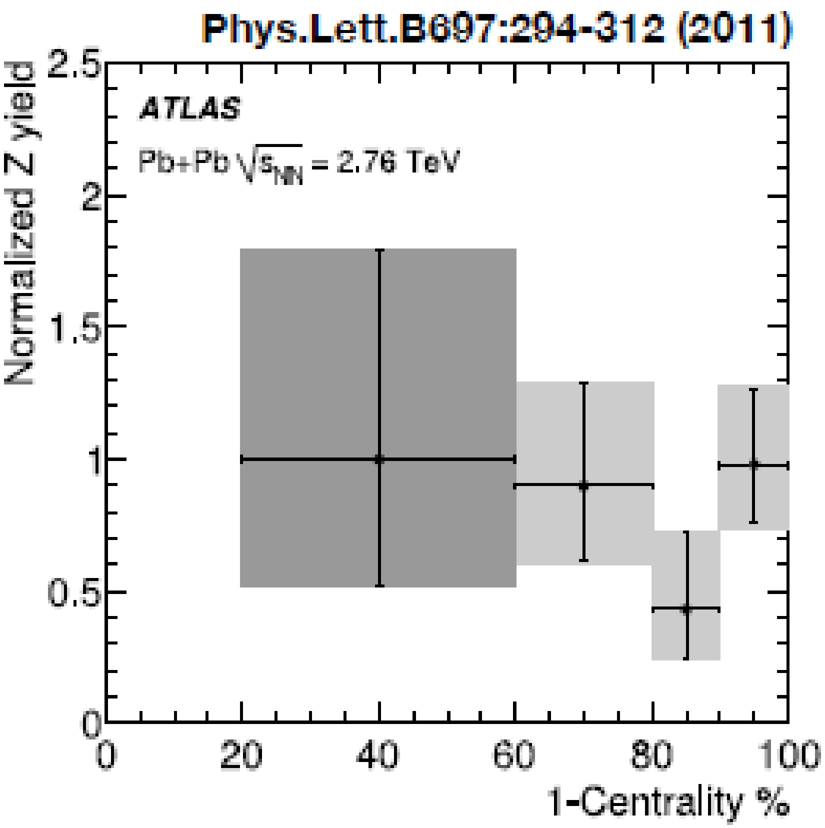
Z → ee and W → μν signals also observed

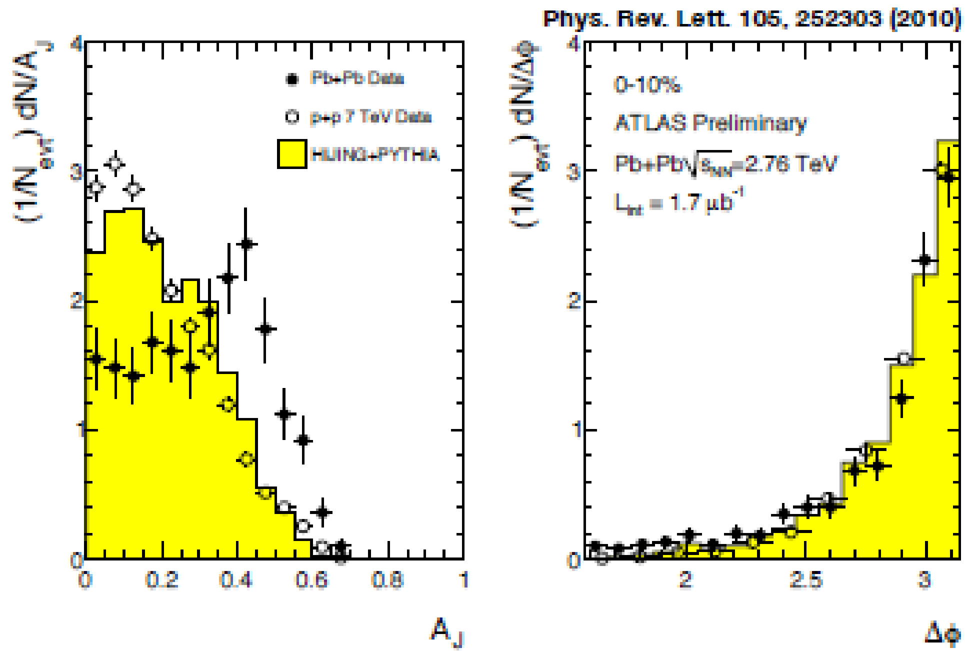


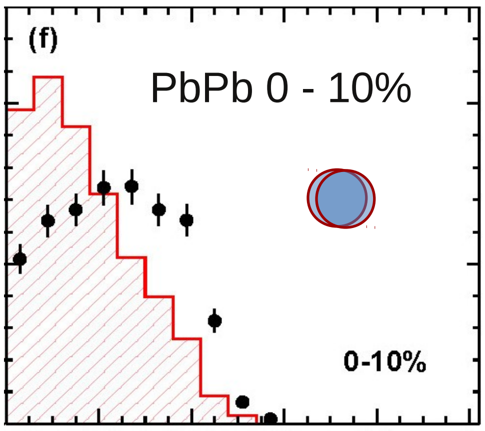
B → J/ψ in
CMS PAS HIN-10-006
B-quark energy loss?

Charged particles in
CMS PAS HIN-10-005
Up to 100 GeV/c using jet trigger

Parton Energy loss, Jet quenching



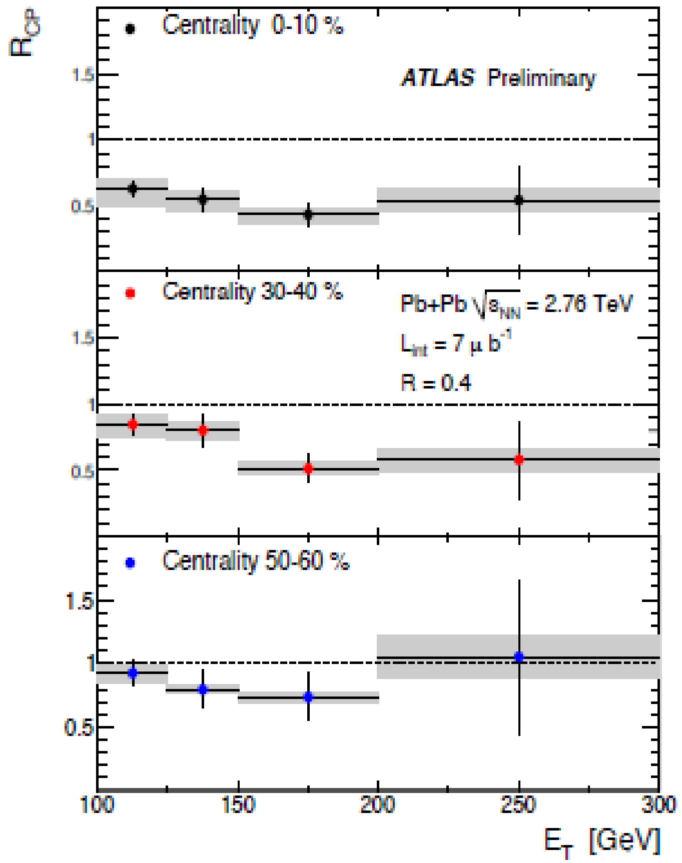


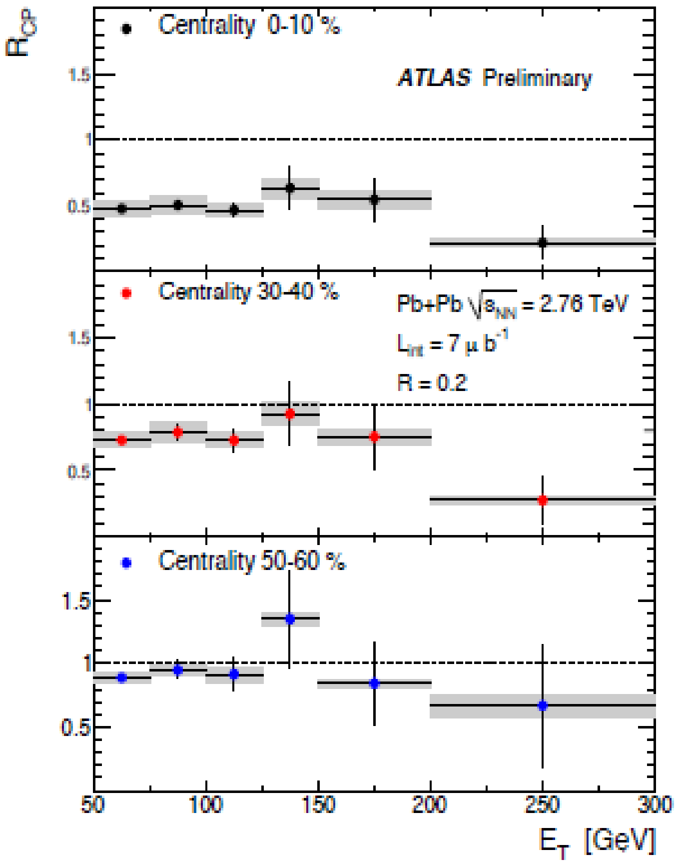


dijet energy imbalance

jets are strongly modified by fireball
weak bosons are not

Parton Energy loss, Jet quenching





jets with E_T > 250 GeV are still suppressed in central PbPb collisions quarkonia in the QGP

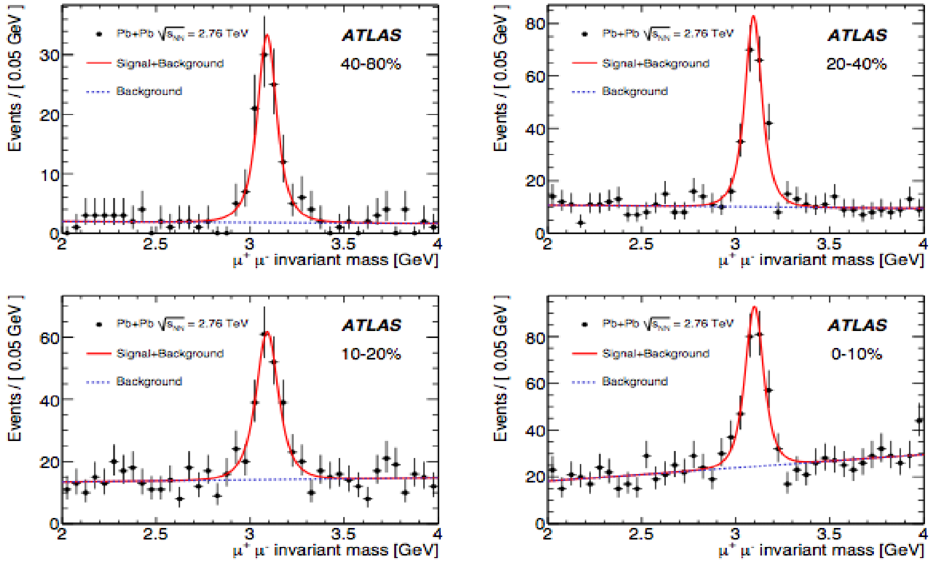
break-up of small bound states in plasma – Debye screening
suppression increasing at LHC

formation of hidden charm hadrons at QCD phase boundary
– (re-)generation
suppression disappearing at LHC
deconfined heavy quarks

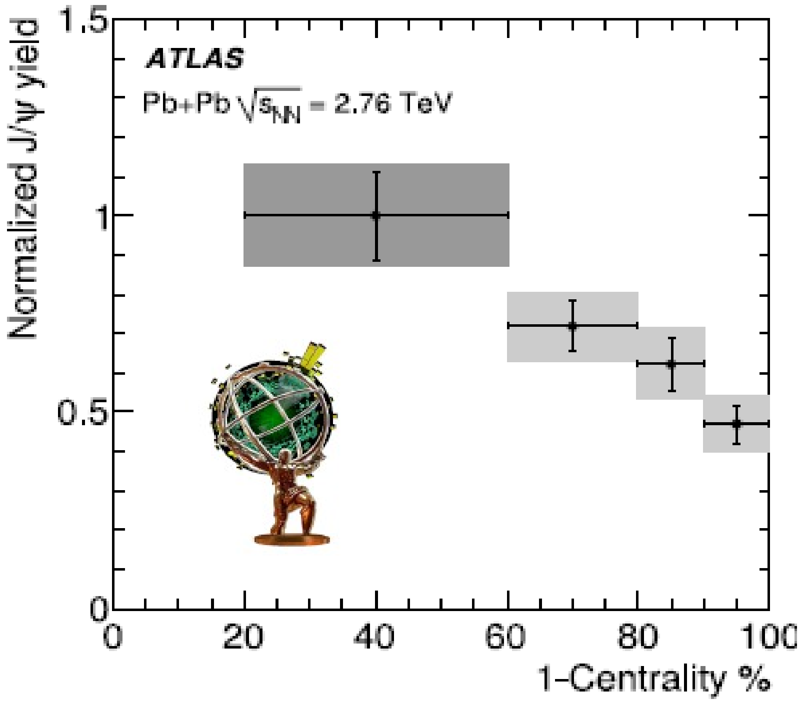
compared to RHIC:

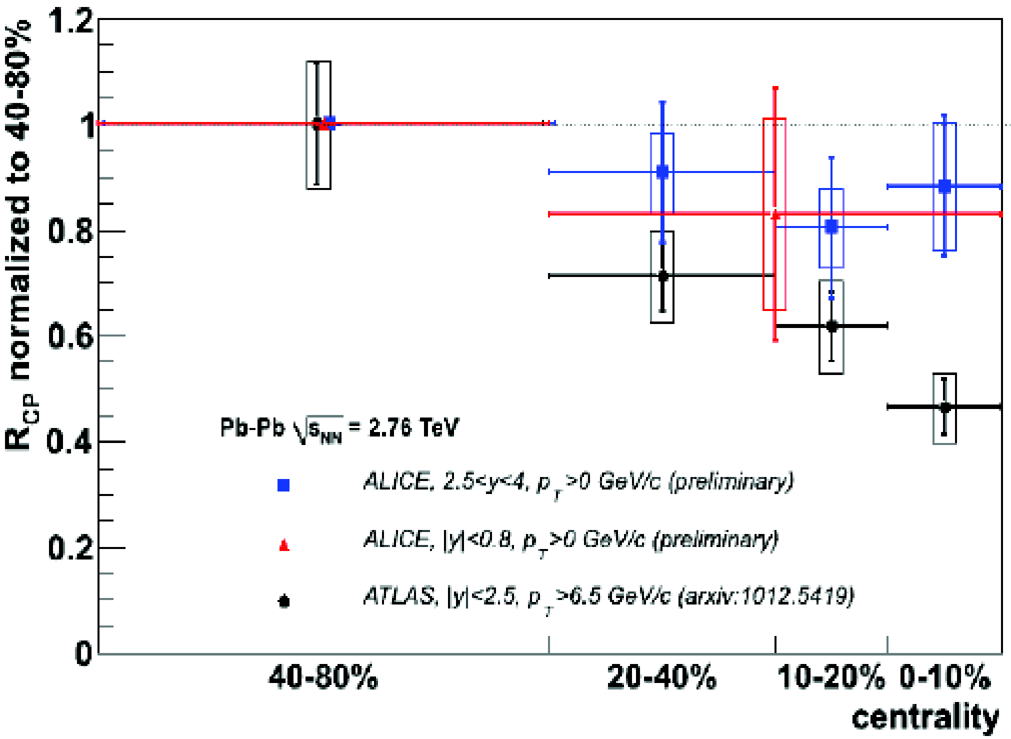
enough heavy quarks and resolution
to study complete J/ψ and Y family
together with open charm and beauty

Quarkonia



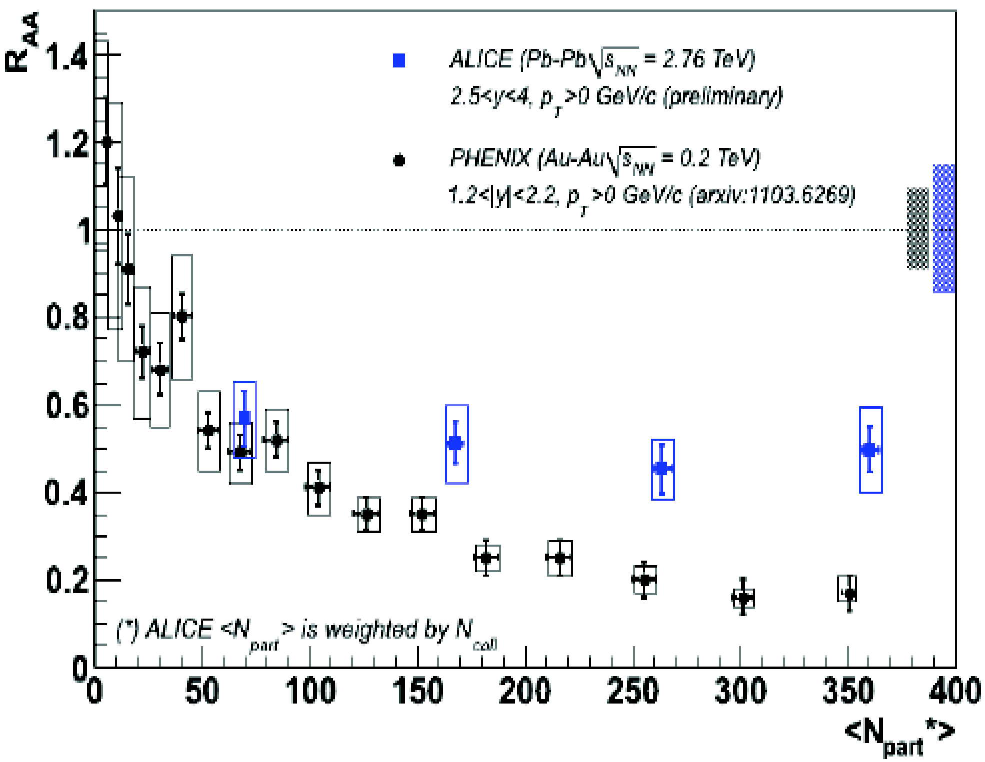
note: ALICE data are at low p_t

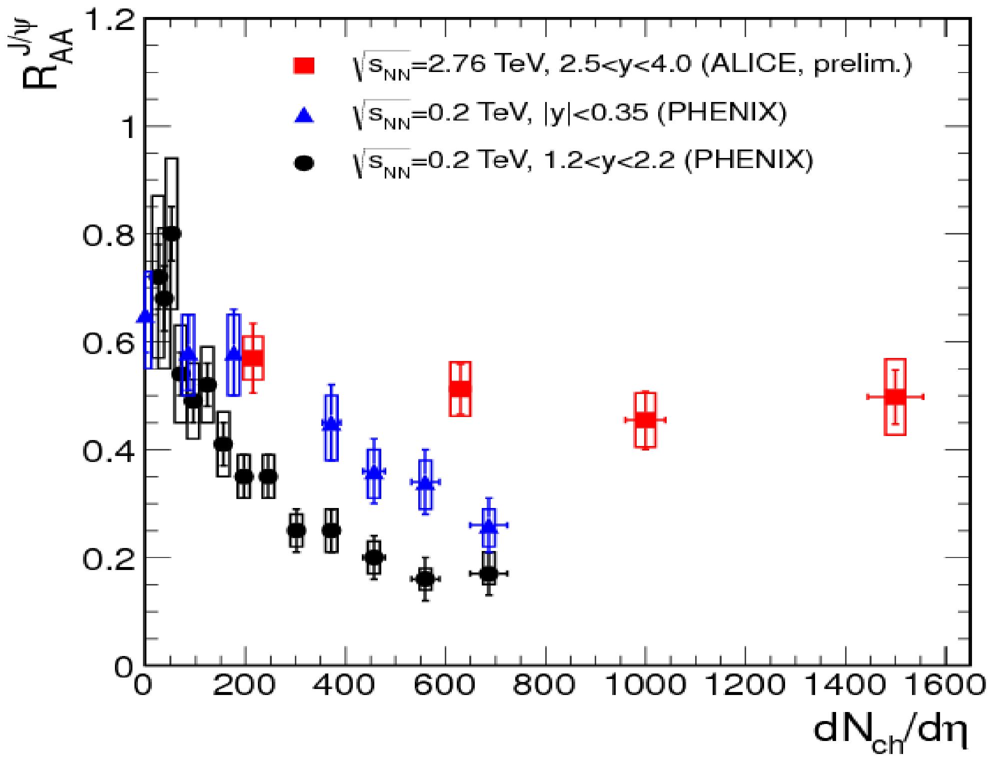




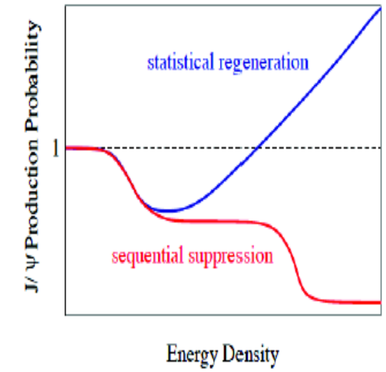
Quarkonia

with increasing multiplicity (energy density) J/ψ is less suppressed!
first sign of charmonium production at the phase boundary

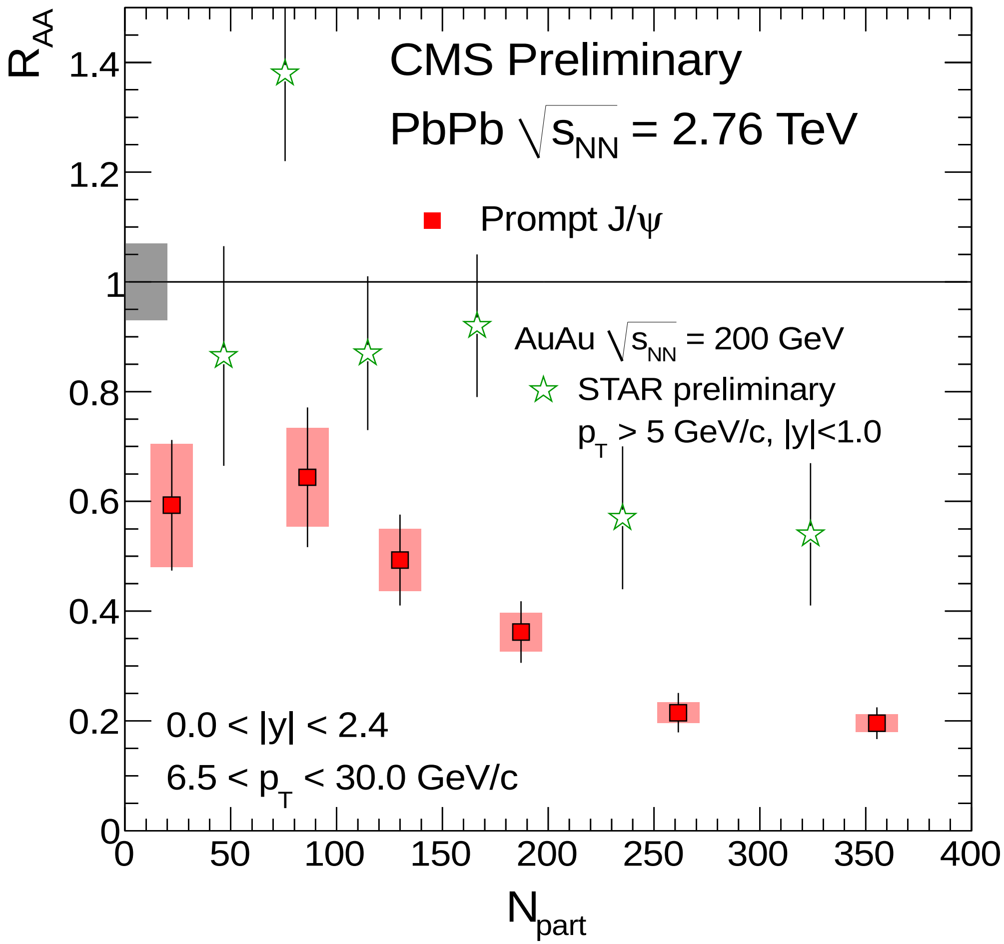




need coverage to very low p_t
to unravel the charmonium story

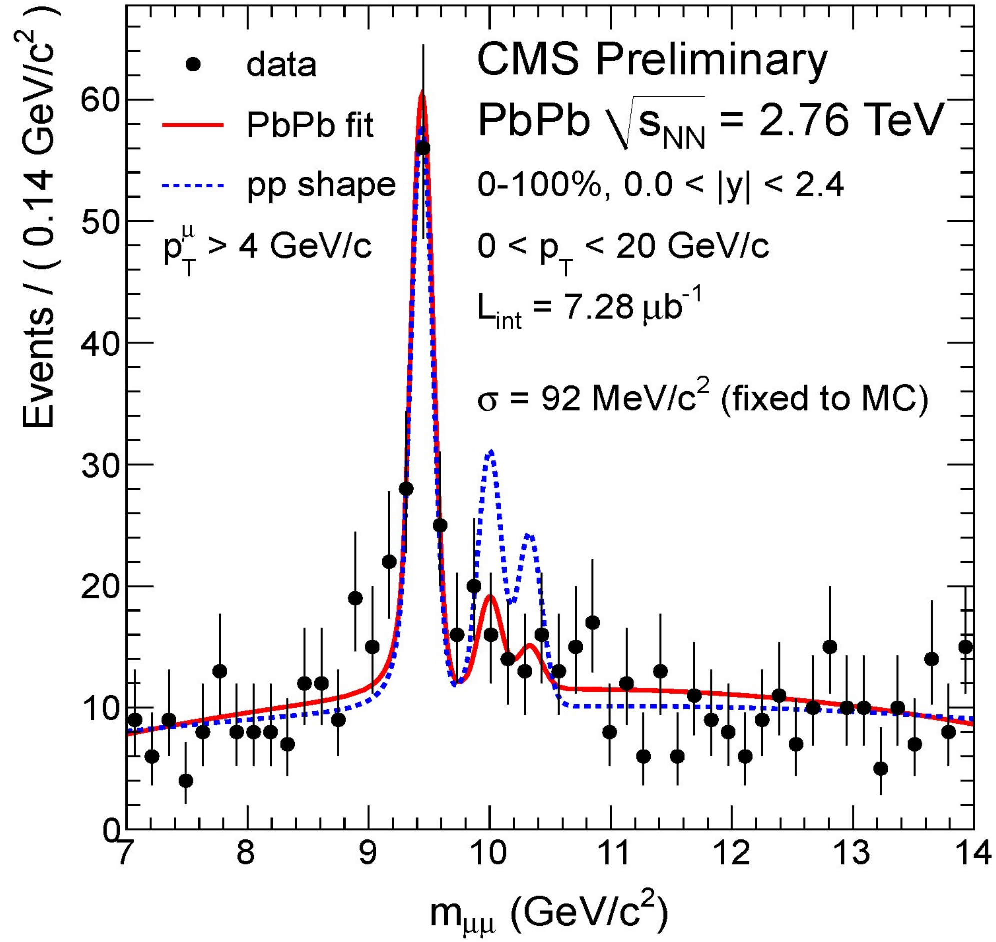


Quarkonia



CMS PAS HIN-10-006

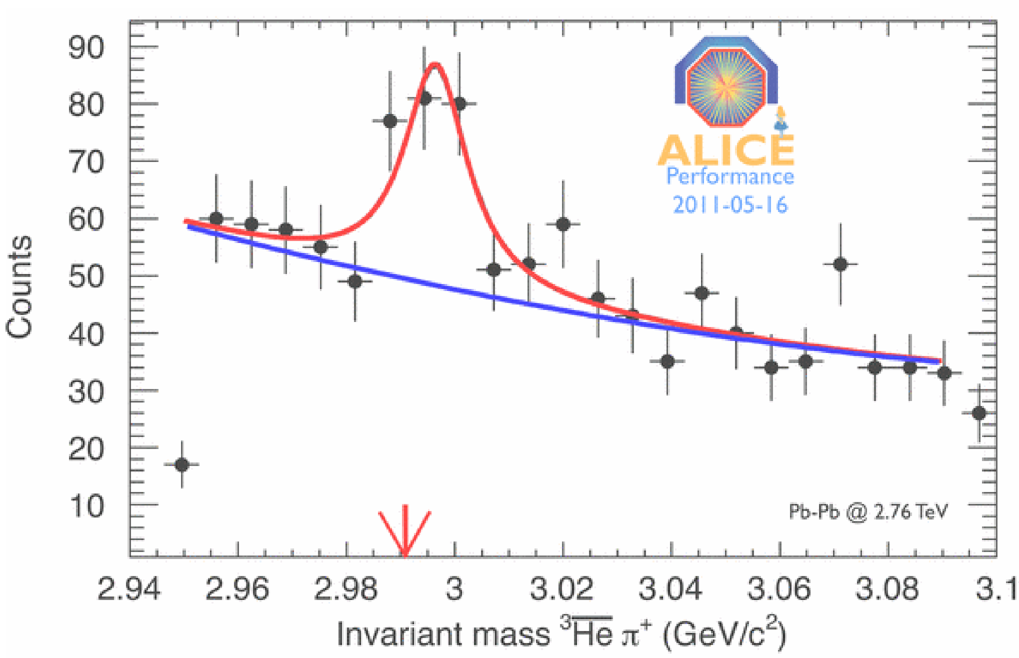
high p_T J/ψ are more suppressed than at RHIC → connected with charm quark energy loss



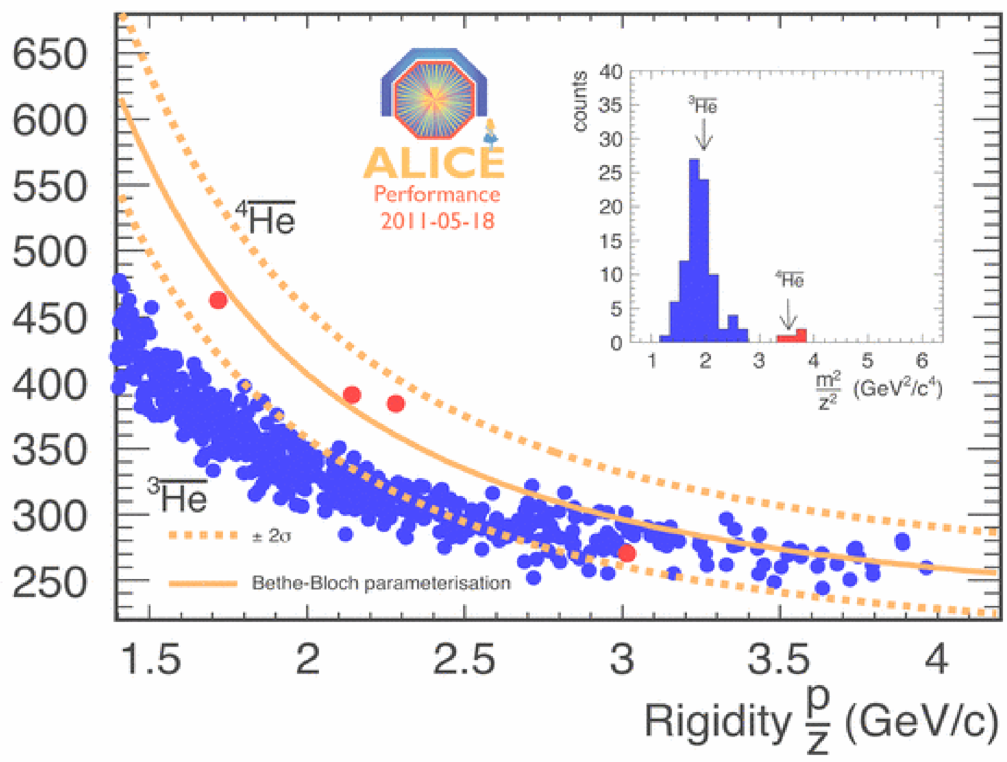
PRL 107 (2011) 052302

Excited upsilon states are suppressed relative to Y(1s), compared to p+p collisions

Exotica



Counts
90
80
70
60
50
40
30
20
10
2.94
2.96
2.98
3
3.02
3.04
3.06
3.08
3.1
Invariant mass $^{3}\overline{He}$ π^{+} (GeV/c^{2})
ALICE
Performance
2011-05-16
Pb-Pb @ 2.76 TeV



650
600
550
500
450
400
350
300
250
1.5
2
2.5
3
3.5
4
Rigidity $\frac{p}{z}$ (GeV/c)
$^{4}\overline{He}$
$^{3}\overline{He}$
± 2σ
Bethe-Bloch parameterisation
ALICE
Performance
2011-05-18
counts
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
$\frac{m^2}{z^2}$ (GeV^2/c^4)

Key Physics Goals of LHC Heavy Ion Program
medium – long term

My own summary of info from ALICE, ATLAS, and CMS

1. min bias: fully characterize QGP through hadron production, flow, and correlations (2011 – 2015)
   critical temperature, viscosity, speed of sound, degrees of freedom

2. heavy quarks: open charm and open beauty in PbPb, quarkonia (2011 – 2016)
   deconfinement, opacity, quasi-particles, AdS/CFT

very delicate inclusive measurements at low p_t are mandatory here

Key Physics Goals of LHC Heavy Ion Program
medium – long term

3. jets and gamma-jet correlations (2011 – 2016)
   in-medium fragmentation functions, parton energy loss for light quarks, heavy quarks, gluons, AdS/CFT, strongly coupled systems

particle ID up to high p_t important for thermalization studies

4. rare probes, Z, W, very high p_t processes (2014 – 2020)
   can pQCD limit ever be reached?

5. exotica, strange anti-matter states, … (2011 – 2020)

6. ultra-peripheral collisions (2011 – 2020)
   from the Pomeron to exotica

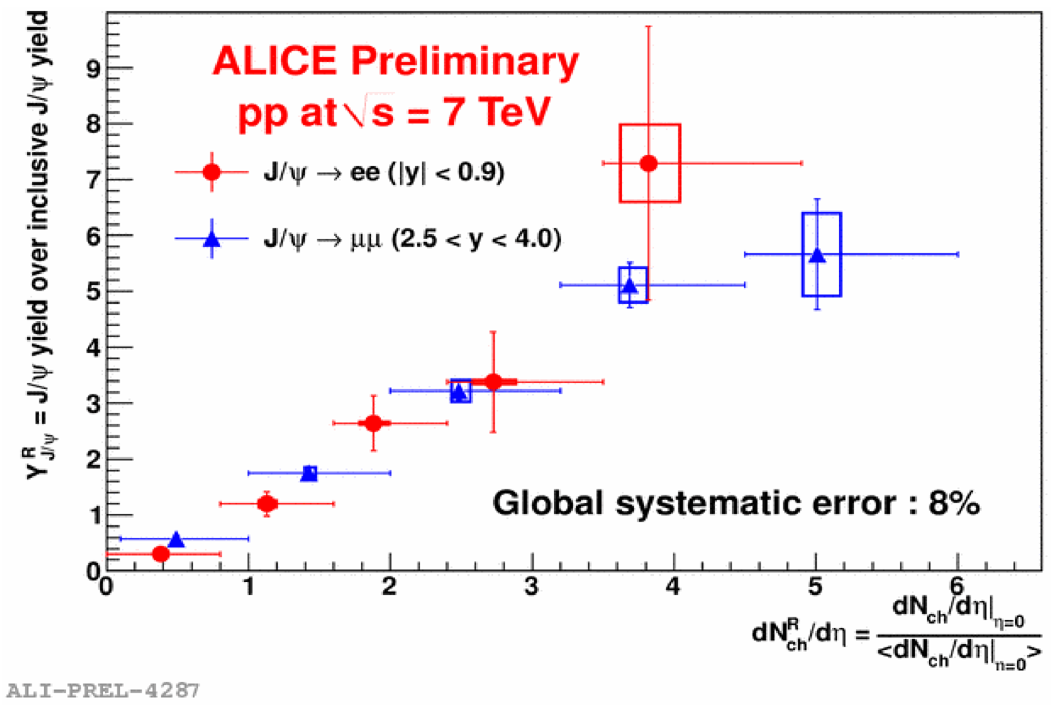
Heavy Ions and LHC pp/pA Program

1. collection of comparison data for jet quenching, heavy quark physics

2. comprehensive study of pp min. bias physics

3. pp at very high multiplicity

4. precision studies of shadowing, saturation effects



Medium Term Heavy Ion Running LHC Experiments

2011 PbPb collisions 1 kHz interaction rate 60 μb^{-1}

2012 pPb at 4.4 TeV or high lumi PbPb

2013 shutdown

2014 PbPb at 5.5 TeV (or top energy)

Long Term Heavy Ion Running LHC Experiments

2015 PbPb collisions 5 kHz interaction rate 300 μb^{-1}

2016 high lumi PbPb or pPb if not done before

2017 upgrade of experiments
installation of dispersion suppressor collimator at IP2

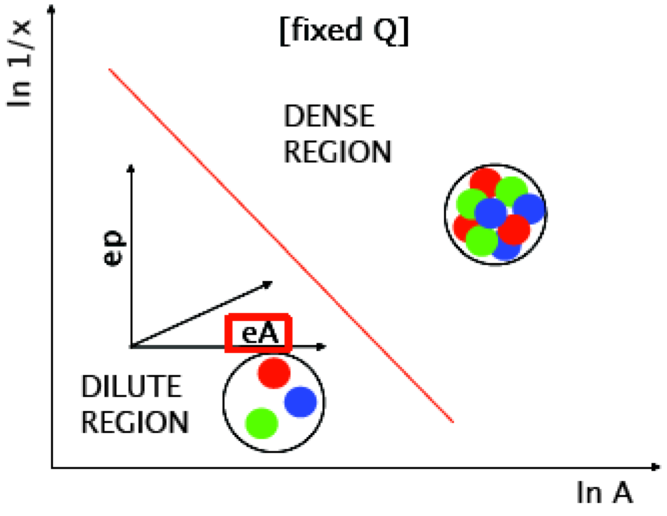
2018
2019 very high lumi PbPb 1 nb^{-1}

> 2019 pPb or ArAr or PbPb depending on physics results

… of great interest for LHC heavy ion program

➜ **LHeC**: $e^{\pm}p/A$ accelerator to collide $e^{\pm}$ with the LHC beams at $\sqrt{s}$~0.8-2 TeV per nucleon.

small x physics, saturation, non-linearities in QCD



summary

- the LHC heavy ion program is off to an excellent start

- experimental upgrade programs are currently defined after experience of first runs

- pp and pA running driven by QGP physics needs and complementarity to high energy/high luminosity LHC program

- many fundamental physics opportunities in the medium term

- long term physics goals focus on rare probes and require increased luminosity