Incontri di Fisica della Alte Energie
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Heavy-ion physics: status and perspectives

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Contents

- Heavy-ion physics:
  - a bit of history, motivations
  - theoretical guidelines

→ See also talk by M. Nardi

- Heavy-ion experiments:
  - hunting the QGP
  - SPS: discovering the new QCD medium
  - RHIC: opening the collider era, first QGP properties
  - LHC: first results in a new regime, ongoing programme
- Near future perspectives
- Conclusions

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Heavy-ion physics
history and motivation

- Experimental programmes:
  - started in ’70 to early ‘80 at Bevalac
  - 4 facilities with really high energy nuclear beams:
    BNL-AGS, CERN-SPS, BNL-RHIC, CERN-LHC
  - energy increase by a factor 10^4 in ~ 30 years
- Physics community:
  - joining particle and nuclear physicists
  - started by a few dozen of physicists from a handful of countries
  - today more than 2000 physicists active worldwide
- Ultimate goal: issue of the colour confinement

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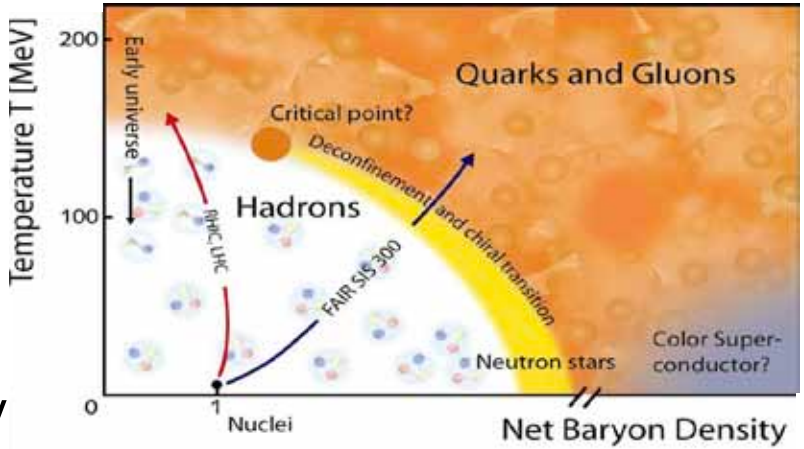
Heavy-ion physics
history and motivation

- Exploring the QCD phase diagram:
  - hadronic matter exists in different states
  - at high energy density (high temperature and/or high density) hadronic matter undergoes a phase transition to the **Quark-Gluon Plasma (QGP):**
    - colour confinement removed
    - chiral symmetry restored

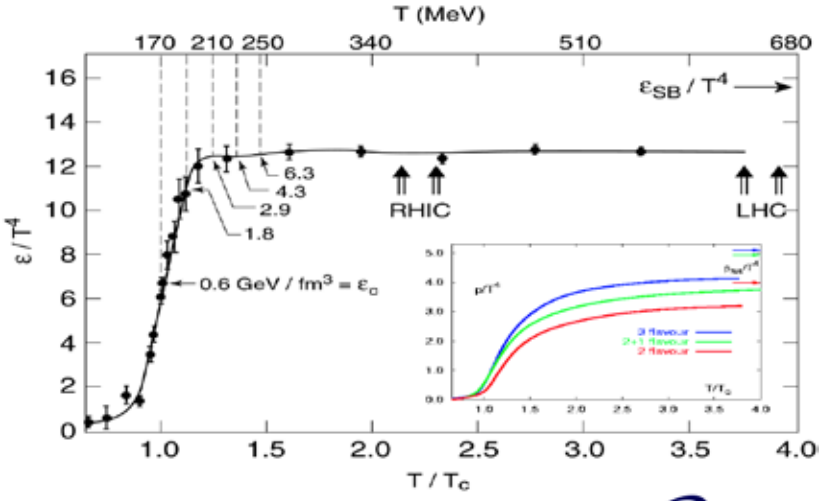


- How to create it in the lab:
  - distribute high amount of energy over large volumes (T.D. Lee '75)
    → collisions of nuclei at very high energy

Heavy-ion physics
theoretical guidelines, lattice QCD

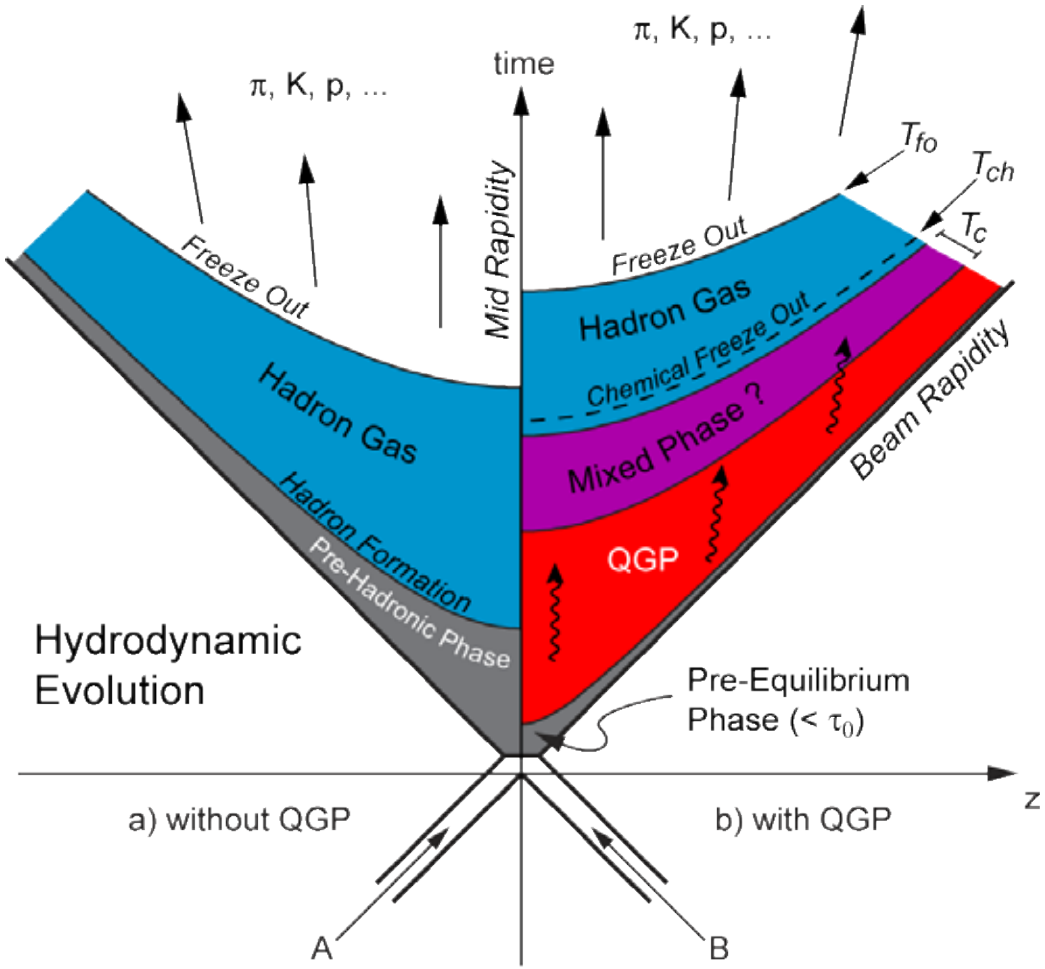
- Phase transition to deconfined hadronic matter:
  - strong interaction sector of the SM (where it is very strong)
  - non-perturbative QCD realm
    - → heavy-ion basically a data driven field

- However:
  - impressive progress in L-QCD
  - quantitative estimations:
    - critical temperature T_c
    - critical energy density ε_c
    - order of the transition



→ phase transition at: $T_c \sim 170$ MeV and $\varepsilon_c \sim 1$ GeV/fm$^3 \sim 5\ \varepsilon_{nucleus}$

Heavy-ion experiments
the nucleus-nucleus collision picture



Thermal freeze-out:
momentum spectra fixed

Chemical freeze-out:
particle composition fixed

Soft processes:
high cross section
late decouple, indirect QGP signals

Photons (real and virtual):
insensitive to the hadronization phase

Hard processes:
low cross section
probe the whole evolution of the collisions

Heavy-ion experiments
hunting the QGP, signatures, probes

- Experimental signatures:
  - **SPS** era: golden signals proving the existence of the QGP
    → strangeness enhancement, quarkonium suppression etc
  - **RHIC, LHC**: many experimental tools at the same time
    → probe the evolution of the collision (formation time, thermalization time, collective effects, hard probes etc)
    → define properties of hot and dense QCD matter

- What has been done and where we are:
  - **SPS** (Pb-Pb @ 17 A GeV): QGP evidence
  - **RHIC** (Au-Au @ 200 A GeV): first QGP properties
  - **LHC** (Pb-Pb @ 2.76 - 5.5 A TeV): just started!

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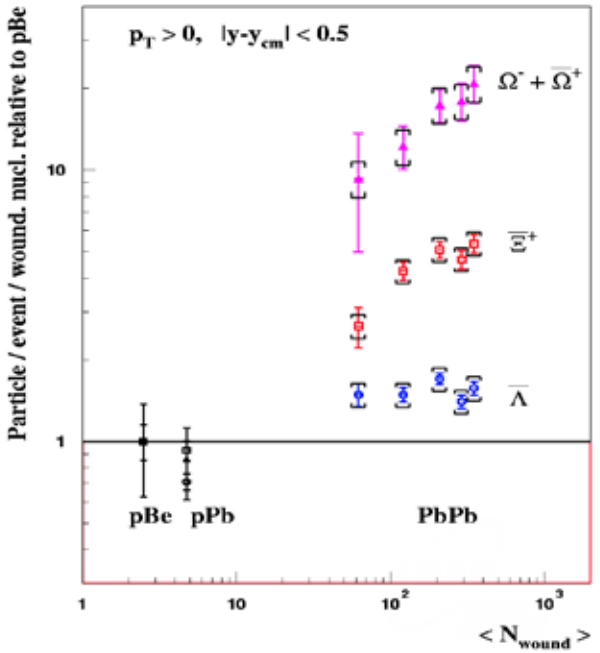
Heavy-ions @ CERN-SPS
discovering the new QCD medium

- Programme mainly developed in the '90s:
  - fixed target Pb-Pb collisions @ 17 A GeV
  - estimated energy density ~ 3 GeV/fm^3 (> ε_c ~ 1 GeV/fm^3)
  - two historical signatures of QGP:

Strangeness enhancement (WA97/NA57):

- chiral symmetry restoration
  → increased production of s-sbar via gluon fusion (Rafelski, Muller, 1982)
- deconfinement, recombination
  → stronger effect for multistrange
- Pauli blocking
  → stronger effect for multistrange anti-baryons



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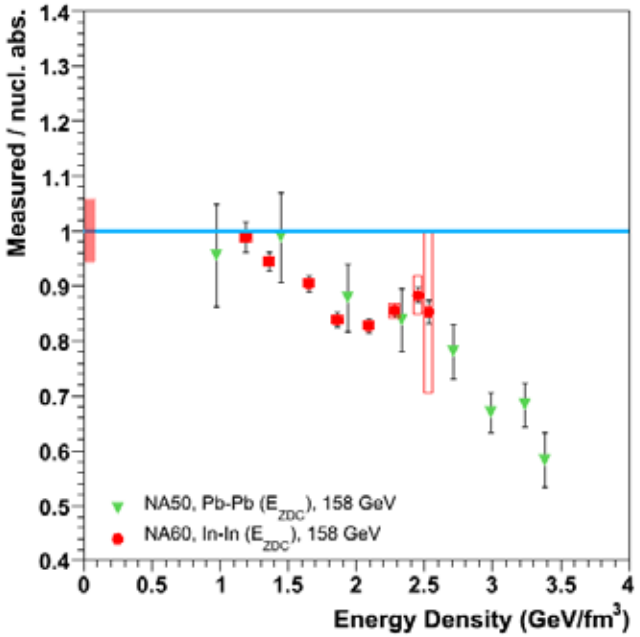
Strangeness enhancement (WA97/NA57)

J/ψ suppression (NA50/NA60)

- high colour-charge density in the QGP
  → Debye screening (Matsui, Satz, 1986)
  → quarkonium states may not bind

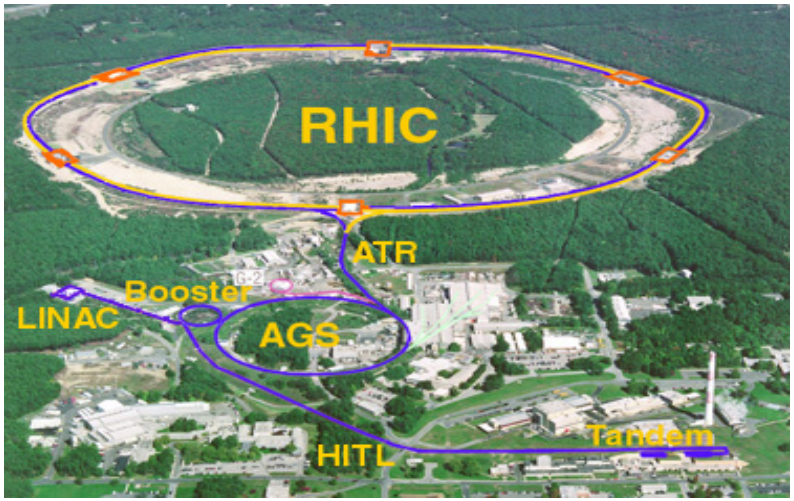


A new state of matter compatible with QGP claimed !

Heavy-ions @ RHIC
studying QGP properties

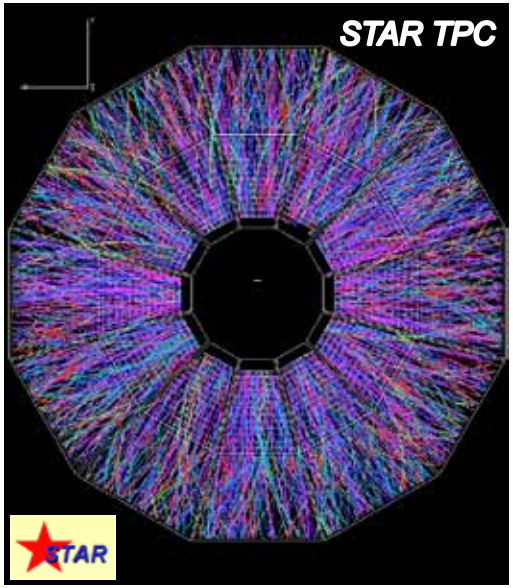
- Programme developed since year 2000:
  - Au-Au (and d-Au, Cu-Cu) collisions @ 200 A GeV
  - estimated energy density ~ 5-15 GeV/fm^3 (>> ε_c ~ 1 GeV/fm^3)
  - 4 experiments: STAR, PHENIX + PHOBOS, BRAHMS (completed)

RHIC@BNL: beginning of the collider era



Central Au-Au @ 200 GeV:

$dN_{ch}/d\eta$ ~ 650 @ y=0



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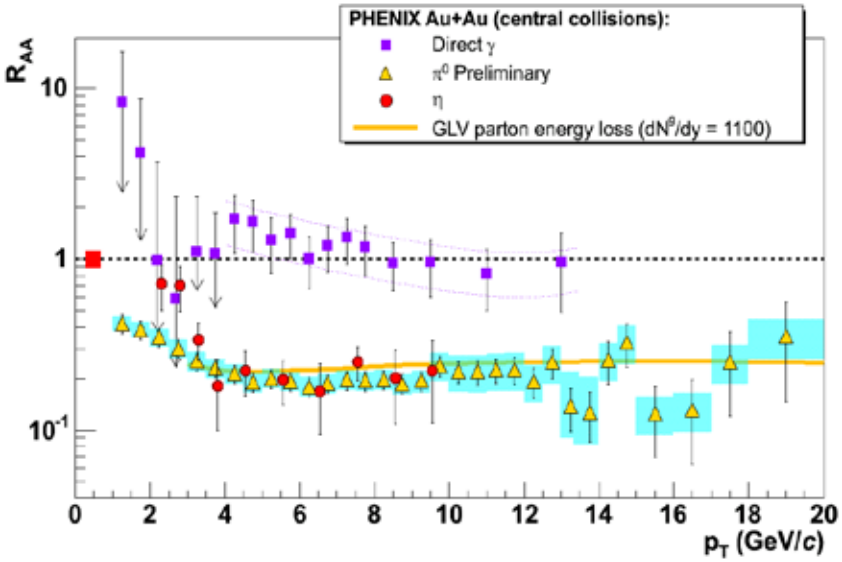
  - 4 experiments: STAR, PHENIX + PHOBOS, BRAHMS (completed)
  - major findings:

Jet quenching:

- matter opaque to high-p_t hadrons
  → nuclear modification factor R_{AA}<1

$$R_{AA} = \frac{\text{Yield}_{AA}}{\text{Yield}_{pp}} \cdot \frac{1}{\langle Nbin \rangle_{AA}}$$



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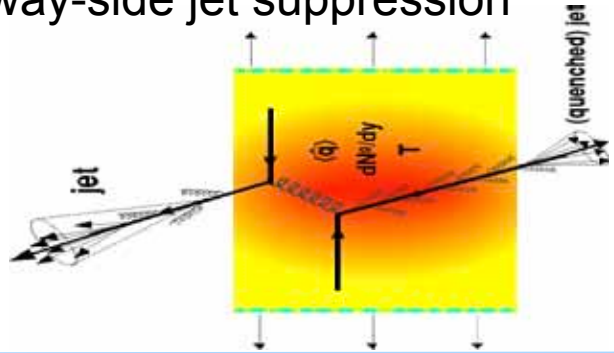
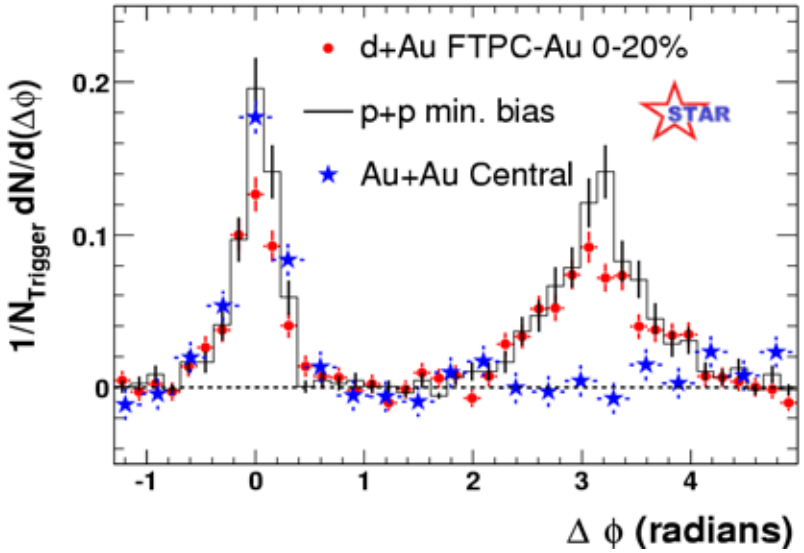
  - major findings:

Jet quenching:

- matter opaque to high-pt hadrons
  → away-side jet suppression





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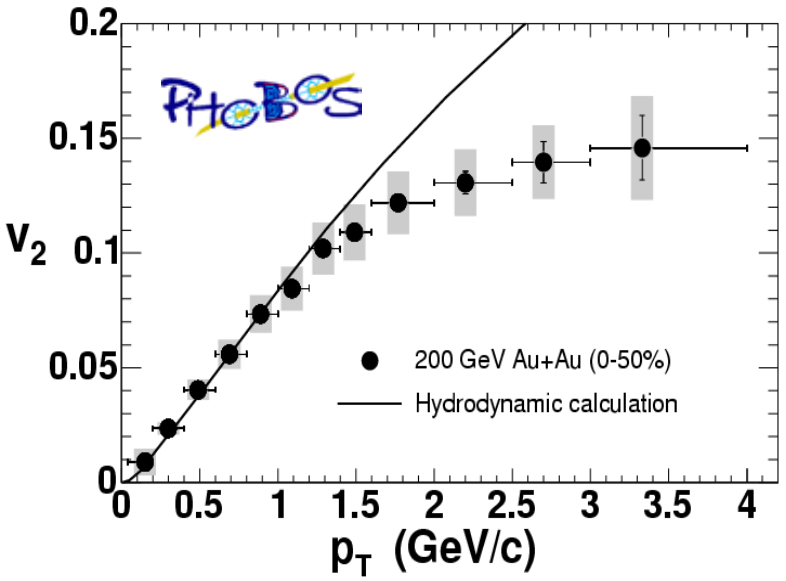
  - major findings:

Jet quenching

Strong collectivity:

- system as an (almost) ideal liquid **?**
  → v_2 in agreement with hydro at low-p_t

$v_2 = \langle \cos(2\varphi) \rangle$ → elliptic flow coefficient



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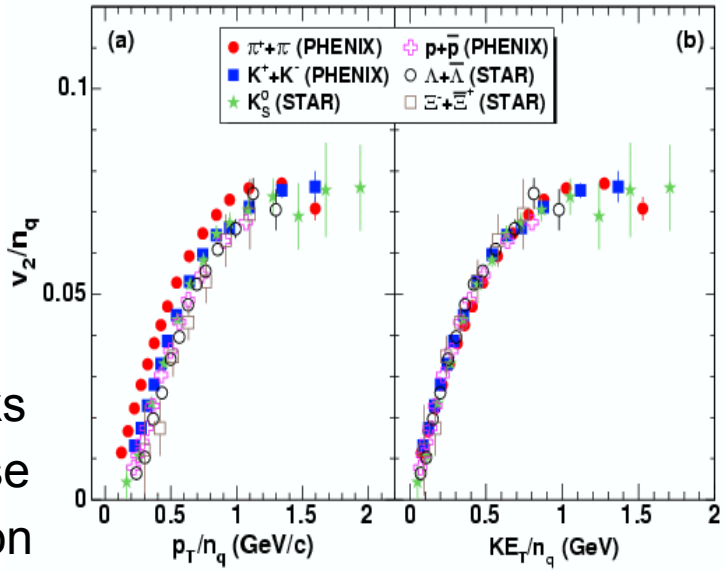
Jet quenching

Strong collectivity

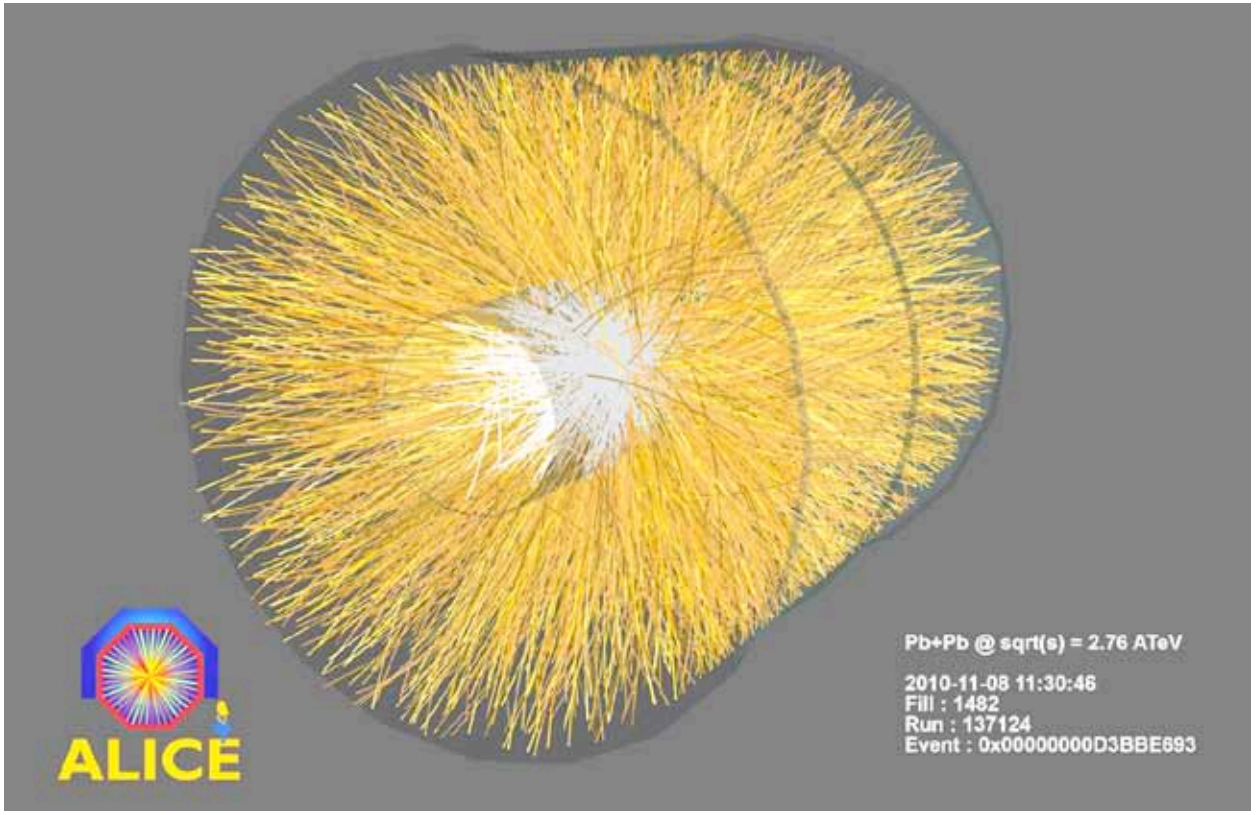
Hadronization by recombination:

- v_2 scaling with the nr. of constituent quarks
  → collective flow built in the partonic phase
  → coalescence picture of the hadronization



Heavy-ions @ LHC
factor 15-30 jump in energy wrt RHIC

- Programme just started in November 2010:



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Heavy-ions @ LHC
factor 15-30 jump in energy wrt RHIC

- Programme just started in November 2010:
  - Pb-Pb collisions @ 2.76 A TeV (top will be 5.5 A TeV)
  - running time: 1 month / year (10^6 s)
  - luminosity: 2 x 10^{25} $cm^{-2}s^{-1}$ in 2010 (top will be 10^{27} $cm^{-2}s^{-1}$)
  - experiments: ALICE (HI-dedicated) + ATLAS, CMS
- What beyond RHIC:
  - new conditions for energy density/lifetime/volume available
  - higher cross sections for hard probes
  - more quantitative and systematic studies of the QGP properties
  - RHIC data interpretation testing extrapolation to LHC
  - unexpected …

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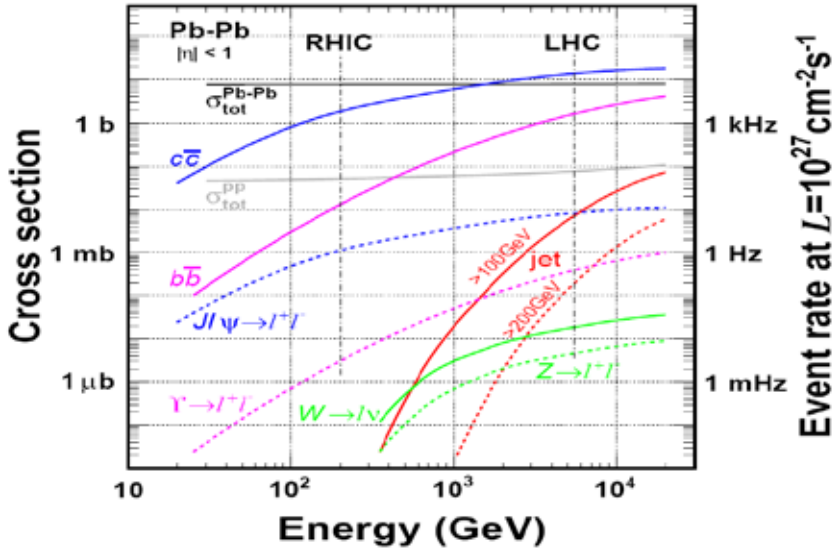
Heavy-ions @ LHC
factor 15-30 jump in energy wrt RHIC

HFs and jets LHC/RHIC:

- $\sigma_{cc} \sim$ x 10
- $\sigma_{bb} \sim$ x 100
- $\sigma_{jets > 100\ GeV} \sim \infty$



- What beyond RHIC:
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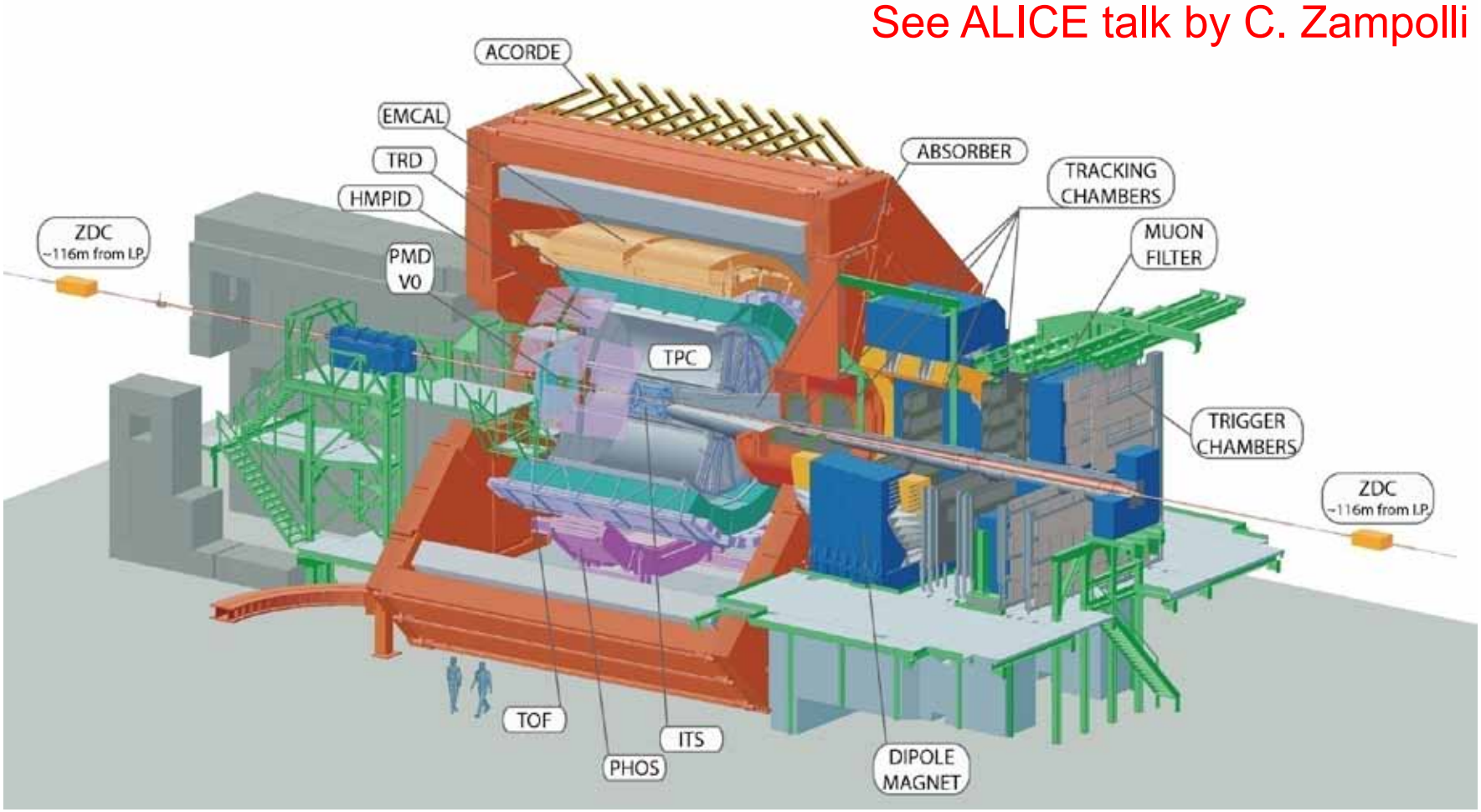
  - unexpected …

Heavy-ions @ LHC
ALICE: experimental apparatus

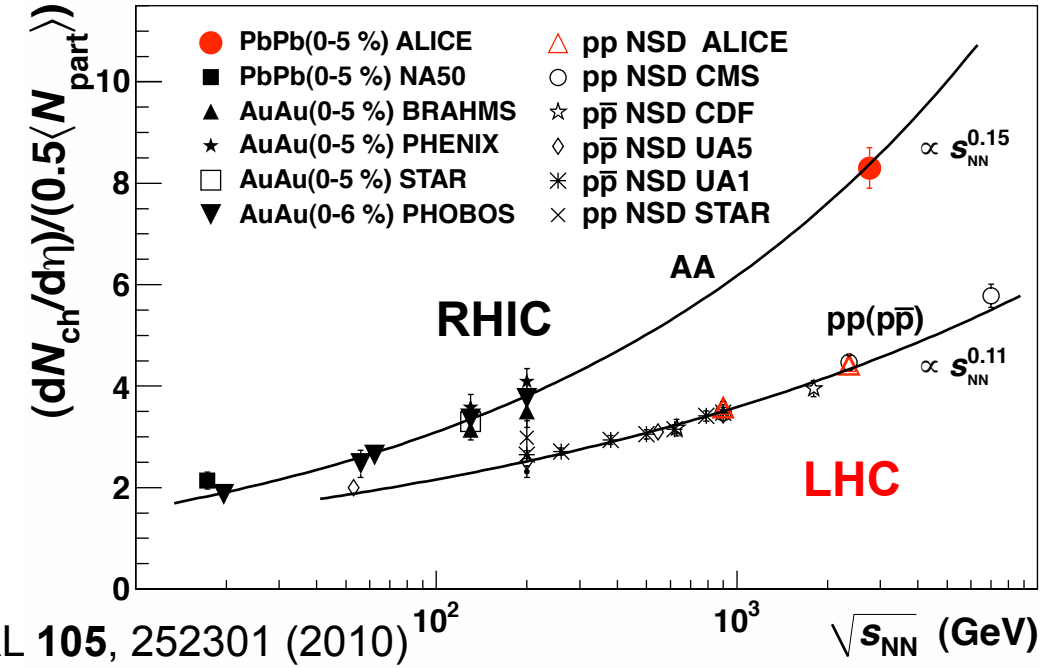
See ALICE talk by C. Zampolli



Heavy-ions @ LHC
ALICE: charged-particle multiplicity

- Particle production and energy density:
  - ~ 1600 charged particles per unit rapidity

PbPb @ $\sqrt{s_{NN}}$ = 2.76 TeV, 0-5% most central, $|\eta|<0.5$



PRL **105**, 252301 (2010)

→ highest ever achieved

→ higher than most theoretical predictions

→ 1.9 x pp @ 2.36 TeV

→ 2.2 x AuAu @ RHIC

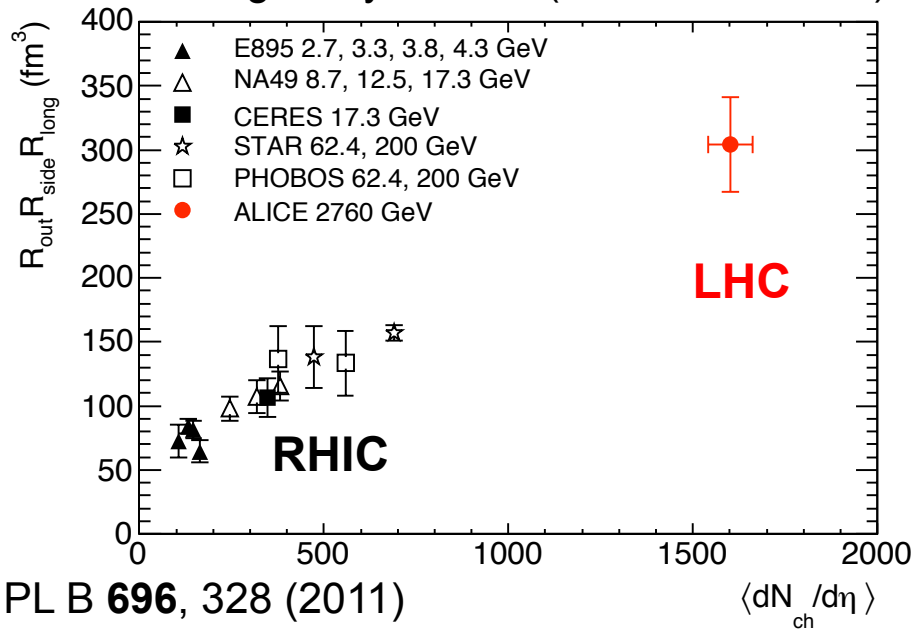
→ energy density:

$\varepsilon(\tau_0)_{LHC} > 3 \times \varepsilon(\tau_0)_{RHIC}$

Heavy-ions @ LHC
ALICE: first HBT analysis results

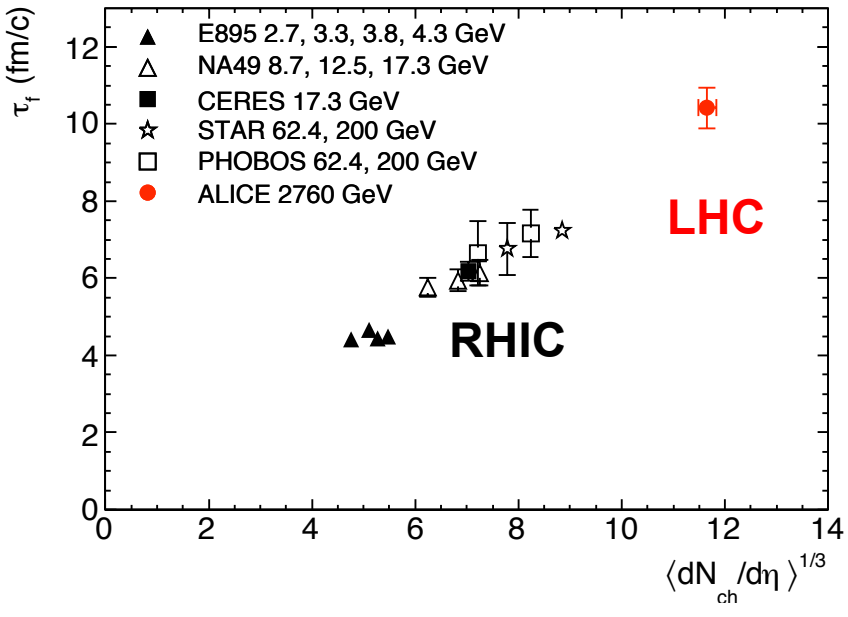
- Space-time evolution of the system:

Homogeneity volume (central collisions)



PL B **696**, 328 (2011)

Decoupling time (central collisions)



Volume at decoupling:

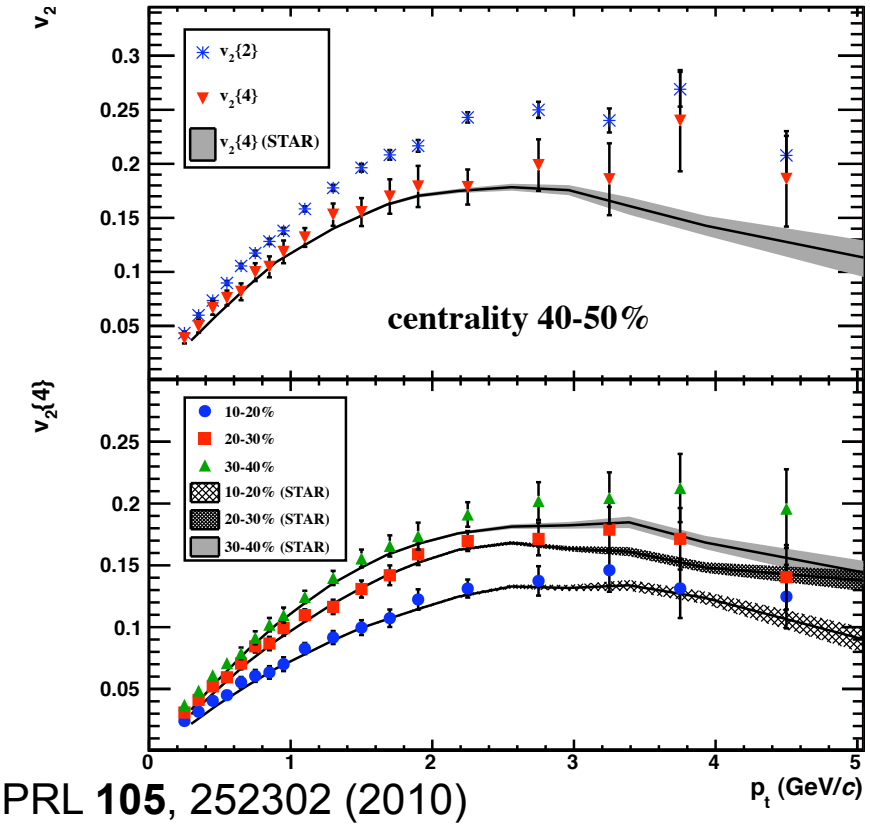
$V_{LHC} \sim 300\ fm^3 \sim 2 \times V_{RHIC}$

Lifetime (from collision to freeze-out):

$\tau_{f\,LHC} \sim 10\text{-}11\ fm/c \sim 1.4 \times \tau_{f\,RHIC}$

Heavy-ions @ LHC
ALICE: elliptic flow measurement

- Elliptic flow as a function of momentum/energy:

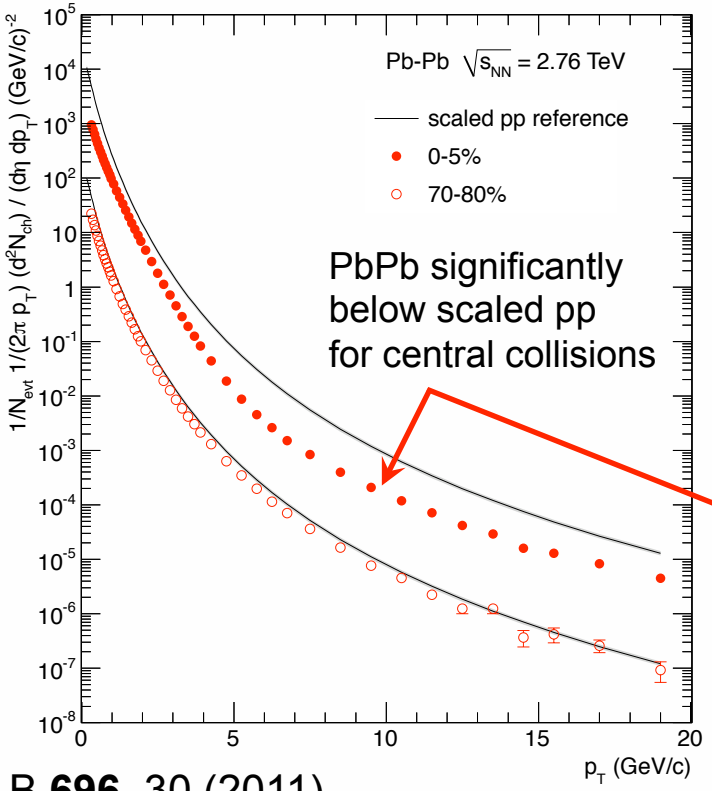


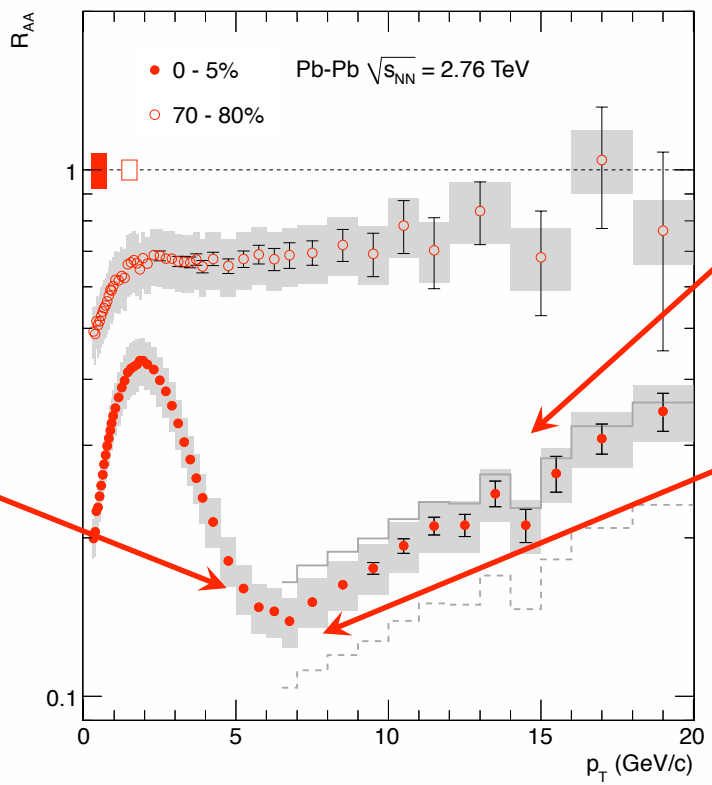
PRL **105**, 252302 (2010)

- v_2 vs transverse momentum:
  almost no change with energy
  → hydro prediction confirmed (fluid with little viscosity)
  → QGP still behaves like a liquid even at the LHC temperature !
- integrated v_2 vs energy:
  30% increase wrt RHIC
  → stronger collectivity at LHC ?
  → radial flow in ideal hydro ?
  → can be accomodated by viscous hydro

Heavy-ions @ LHC
ALICE: momentum spectra and R_{AA}

- Strong quenching seen in single particles @ high-p_t:





clear increase at higher p_t
→ to be understood

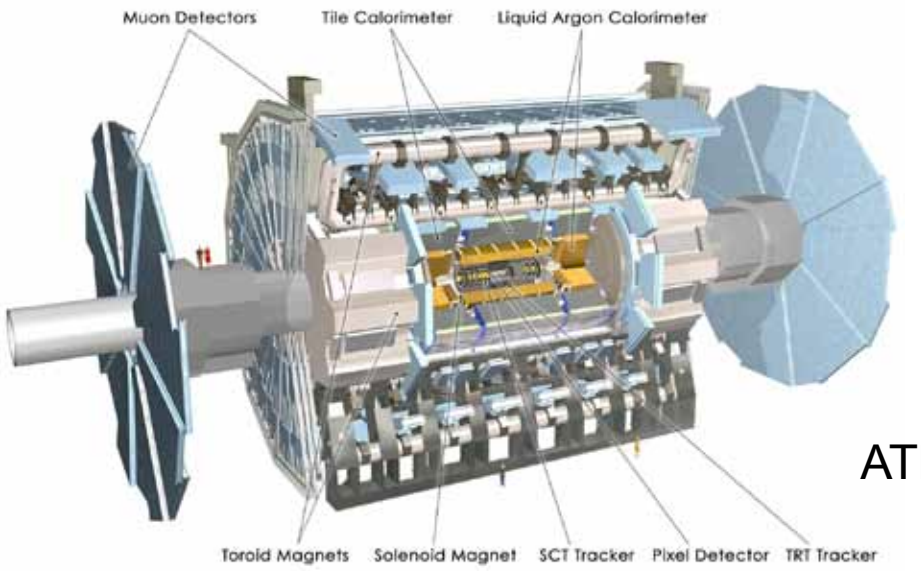
minimum at 6-7 GeV/c
→ R_{AA} ~ 0.14

stronger than at RHIC!

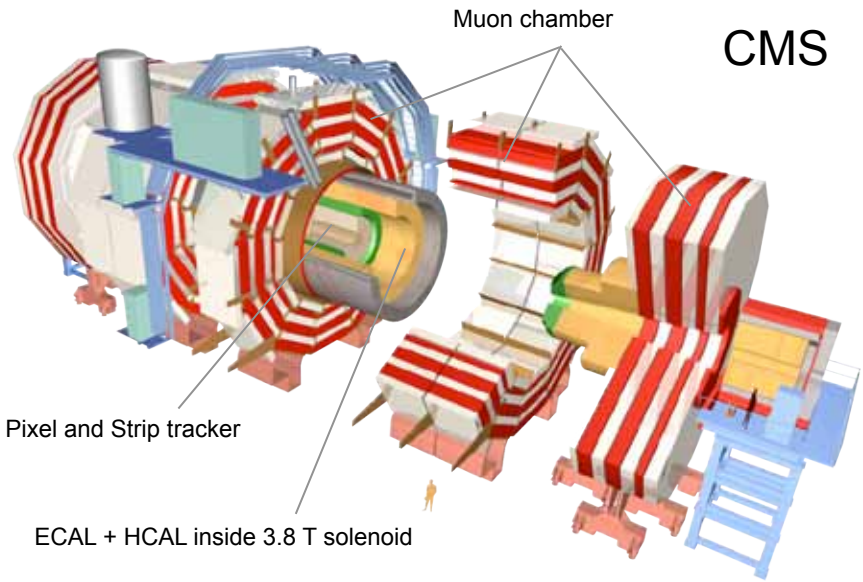
PL B **696**, 30 (2011)

Heavy-ions @ LHC
ATLAS and CMS

- Both experiments have a HI programme:
  - first exciting results on the hard probe side:
    - high E_T jets → jet quenching
    - Z^0 boson, J/ψ signals/yields



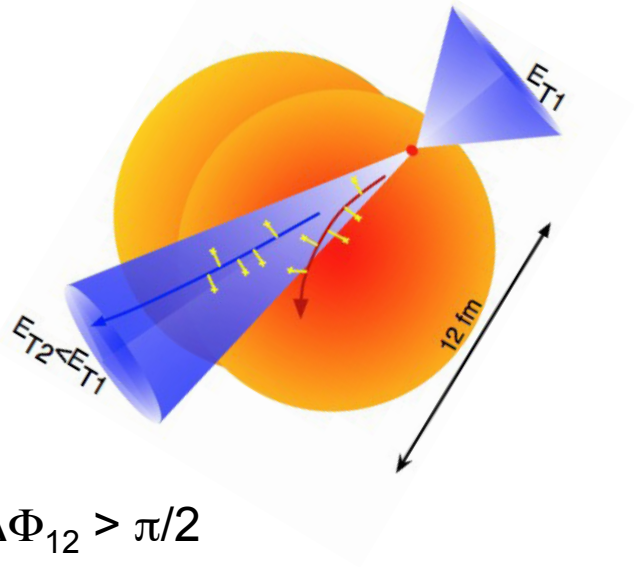
ATLAS



CMS

Heavy-ions @ LHC
ATLAS: dijets energy imbalance

- First look al high E_T jets in PbPb:
  - influence of the medium on the partons emerging from the hard scattering
  - seen at RHIC, to be confirmed at LHC
  - event selection:
    - leading jet: $E_{T1} > 100$ GeV, $|\eta| < 2.8$
    - sub-leading jet: $E_{T2} > 25$ GeV, $|\eta| < 2.8$, $\Delta\Phi_{12} > \pi/2$



  - dijet energy imbalance variable:

$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

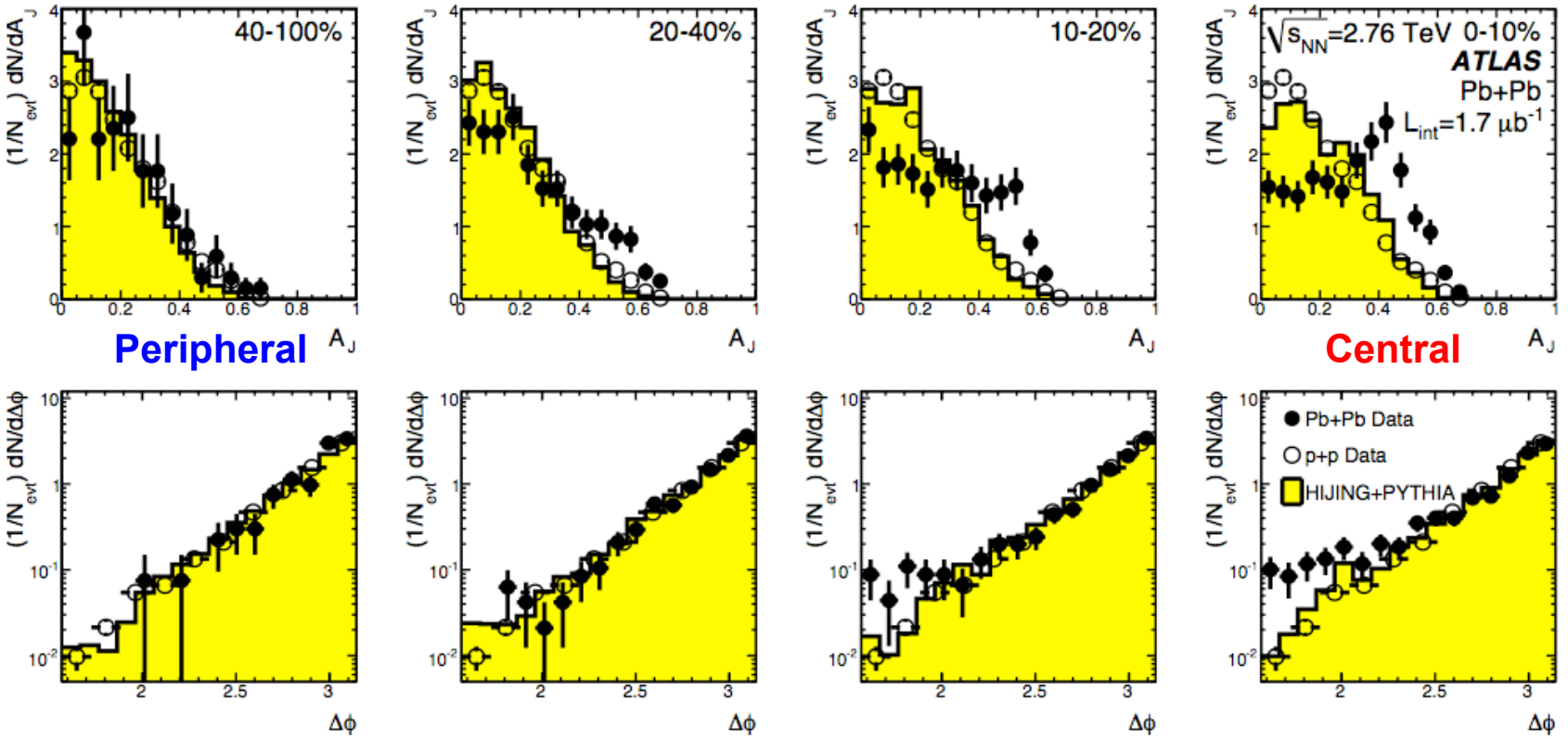
(new, not in the quenching literature)

→ robust wrt “underlying event” subtraction issues

Heavy-ions @ LHC

ATLAS: dijets energy imbalance

PRL **105**, 252303 (2011)



→ more events with large asymmetry with increasing centrality

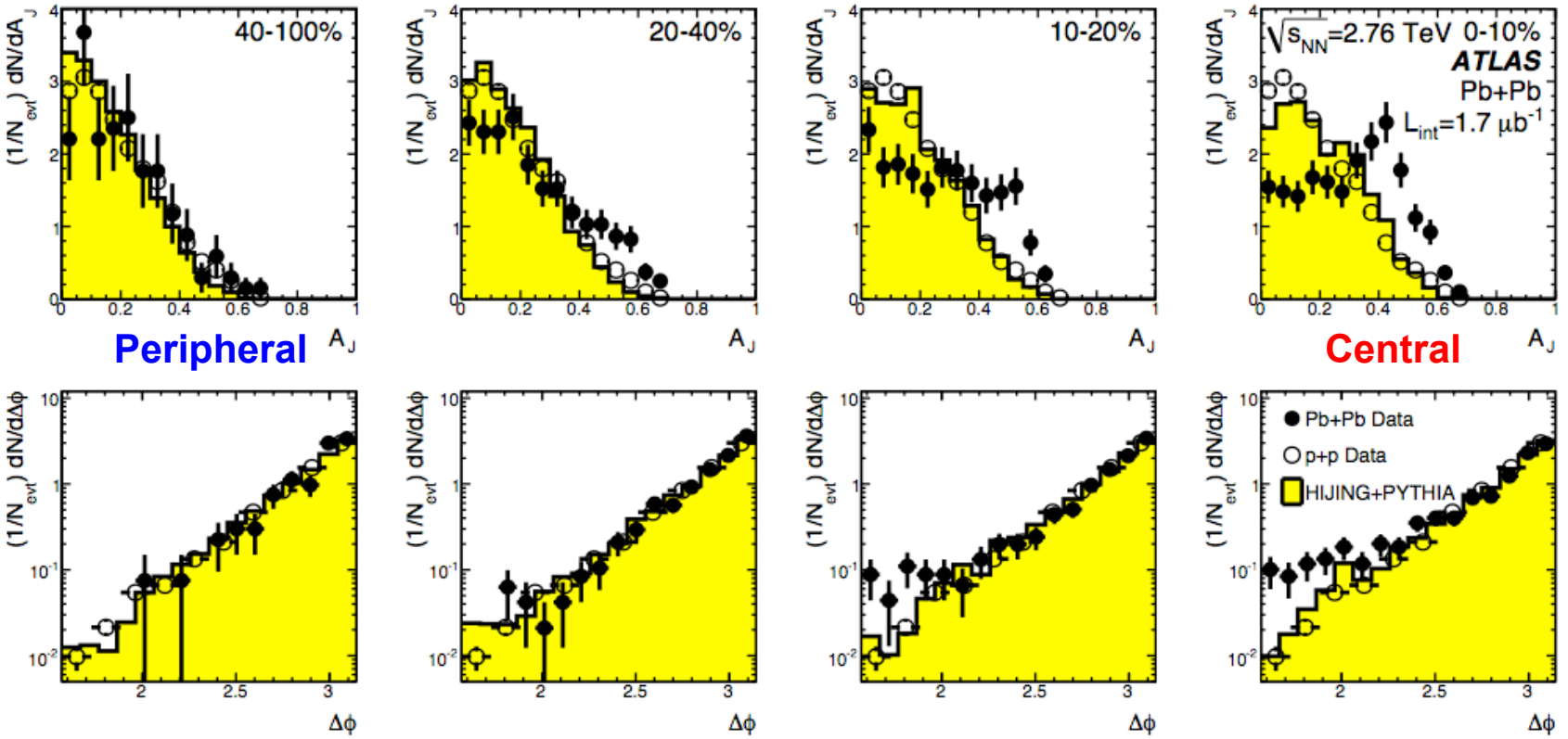
→ poorly described by MC (no quenching), different from pp

→ ΔΦ still peaked at 180°

Heavy-ions @ LHC

ATLAS: dijets energy imbalance

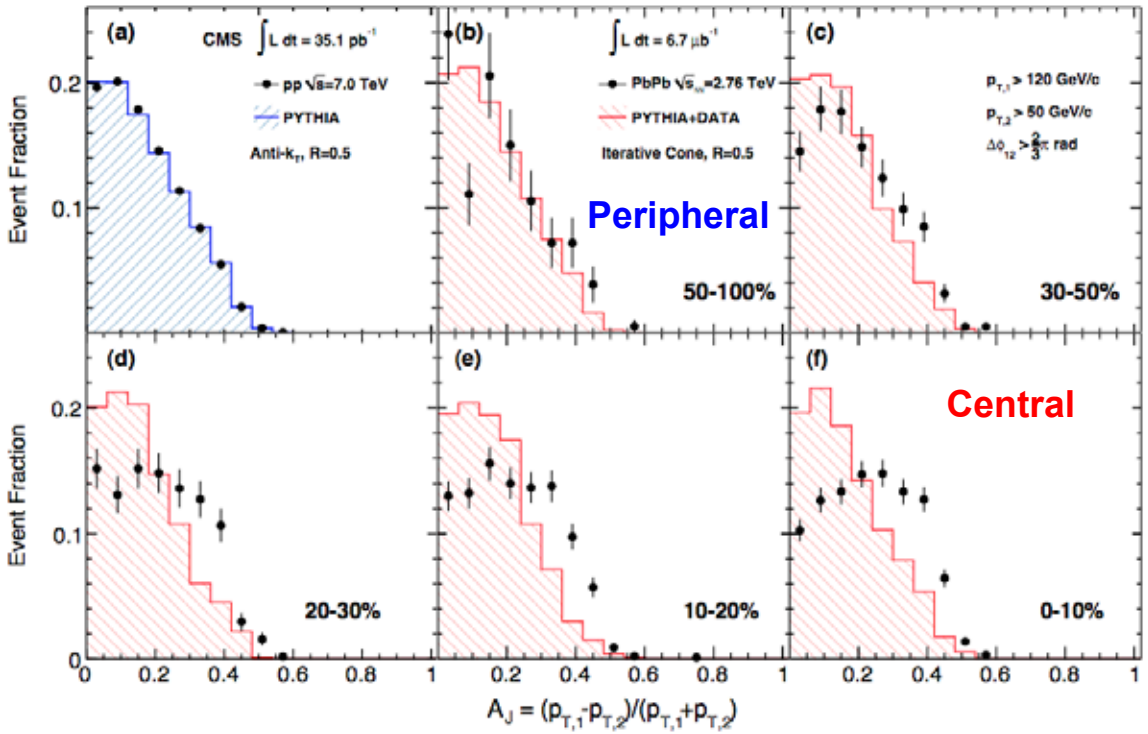
PRL **105**, 252303 (2011)



→ strong evidence for jet energy loss in the (hot and dense) nuclear medium!

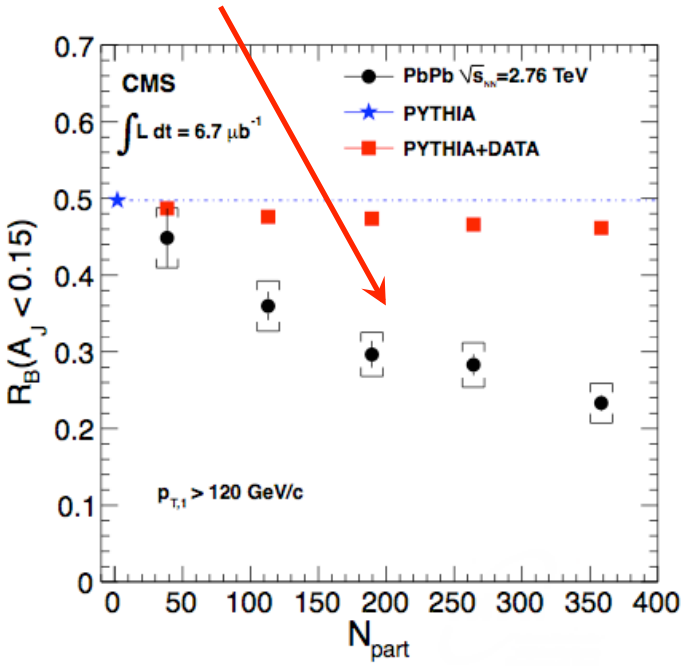
Heavy-ions @ LHC
CMS: dijets energy imbalance

- Same effect seen also by CMS:



http://arxiv.org/abs/1102.1957

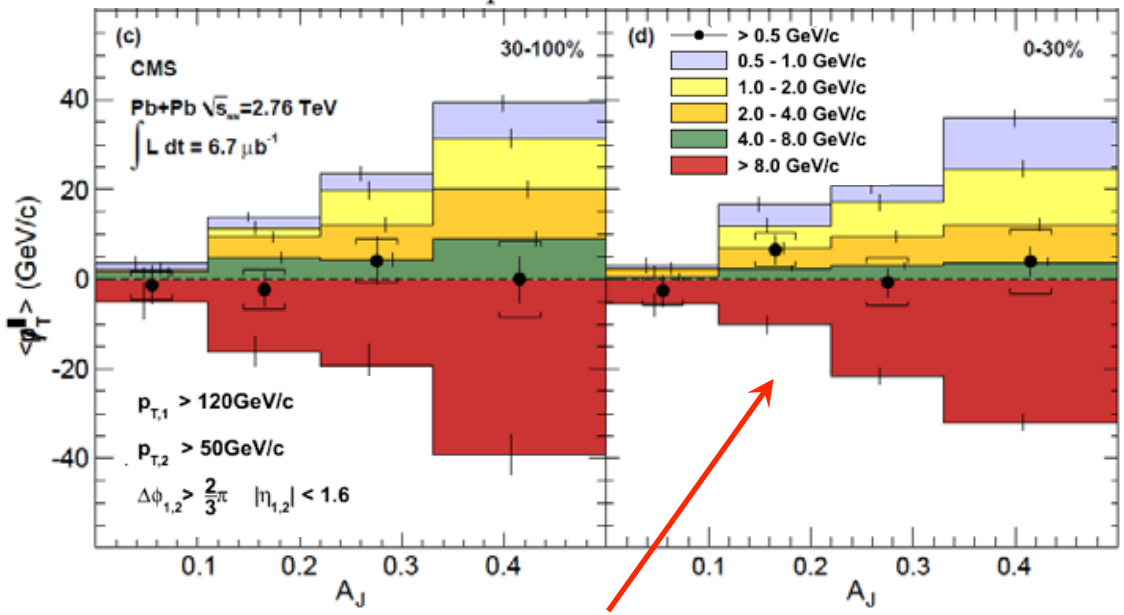
Fraction of balanced dijets: smoothly decreases with increasing centrality!



Heavy-ions @ LHC
CMS: dijets energy imbalance

- Checked momentum balance:

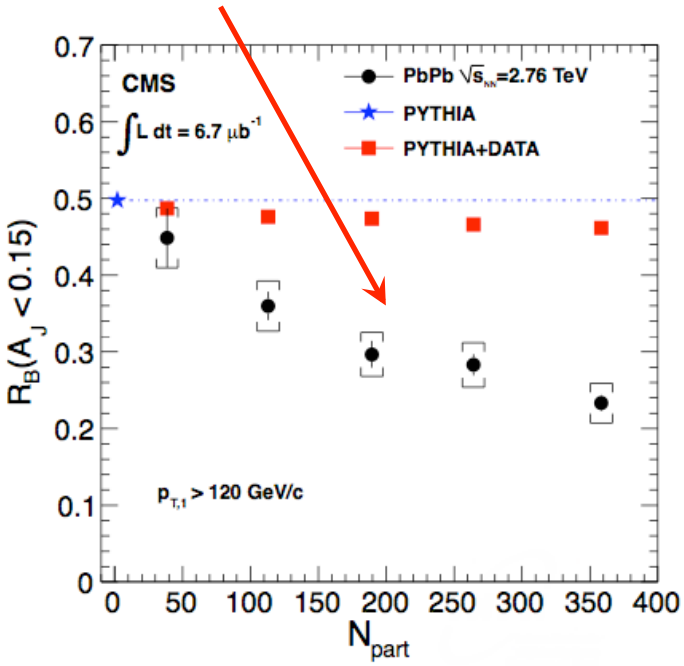
Missing p_T: $\not{p}_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}})$



Momentum balance recovered by low-p_T tracks, especially in more central events!

http://arxiv.org/abs/1102.1957

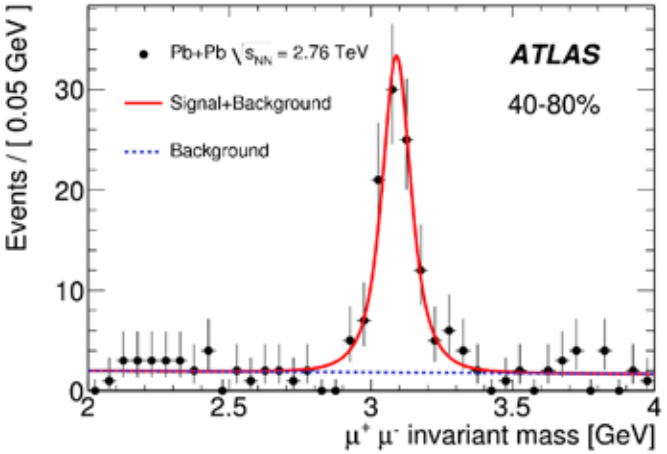
Fraction of balanced dijets: smoothly decreases with increasing centrality!

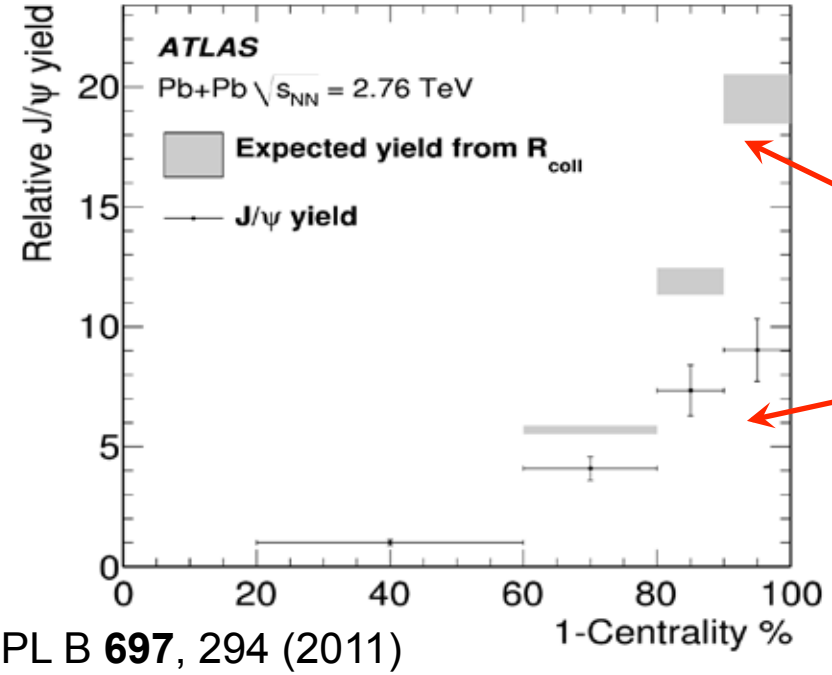


Heavy-ions @ LHC
ATLAS: J/ψ dimuon signal

See talk by C. Maiani

- Reconstructed J/ψ signal:
  - statistics enough to investigate centrality dependence (4 bins)





PL B **697**, 294 (2011)

centrality dependence assuming scaling with the number of binary collisions

yields normalized to the most peripheral

→ Strong evidence for centrality dependent suppression of the yield (as seen by NA50/ NA60 and PHENIX) → colour screening!

Perspectives
near (and medium) term future

- HI@LHC: we have had just a taste of
  - only 3 weeks in a 10 year programme, the best has still to come
  - rare signals need a factor ~ 100 in integrated luminosity:
    - expected to approach design luminosity this year (~ x 20 wrt 2010)
    - quarkonia (J/ψ, Ψ', Υ, Υ'), heavy flavour (b,c), γ-jets, …
  - running at full LHC energy:
    - 10-15% gain in energy density, larger cross section for rare probes
  - running p-A for comparison data:
    - distinguish QGP effects from nuclear effects ("shadowing")
    - study Color Glass Condensate
  - running lower mass ions (Ar-Ar?):
    - study volume effects
    - much higher luminosity can be achieved

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Summary

- Heavy-ion physics:
  - deconfinement issue, exploring QCD in a new domain
  - the field went from the periphery to central activity of contemporary Nuclear Physics
- Experiments @ SPS and RHIC:
  - first properties of the (hot and dense) QCD medium
- Starting HI @ LHC:
  - evidence for a collectively evolving medium, living longer and expanding to a larger size than at lower energies
  - created medium is dense (jet quenching), more statistics needed for quantitative statements on hard-probe side
  - plenty of work (and exciting physics) ahead!

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