Summary of recent (heavy ion) results from LHC

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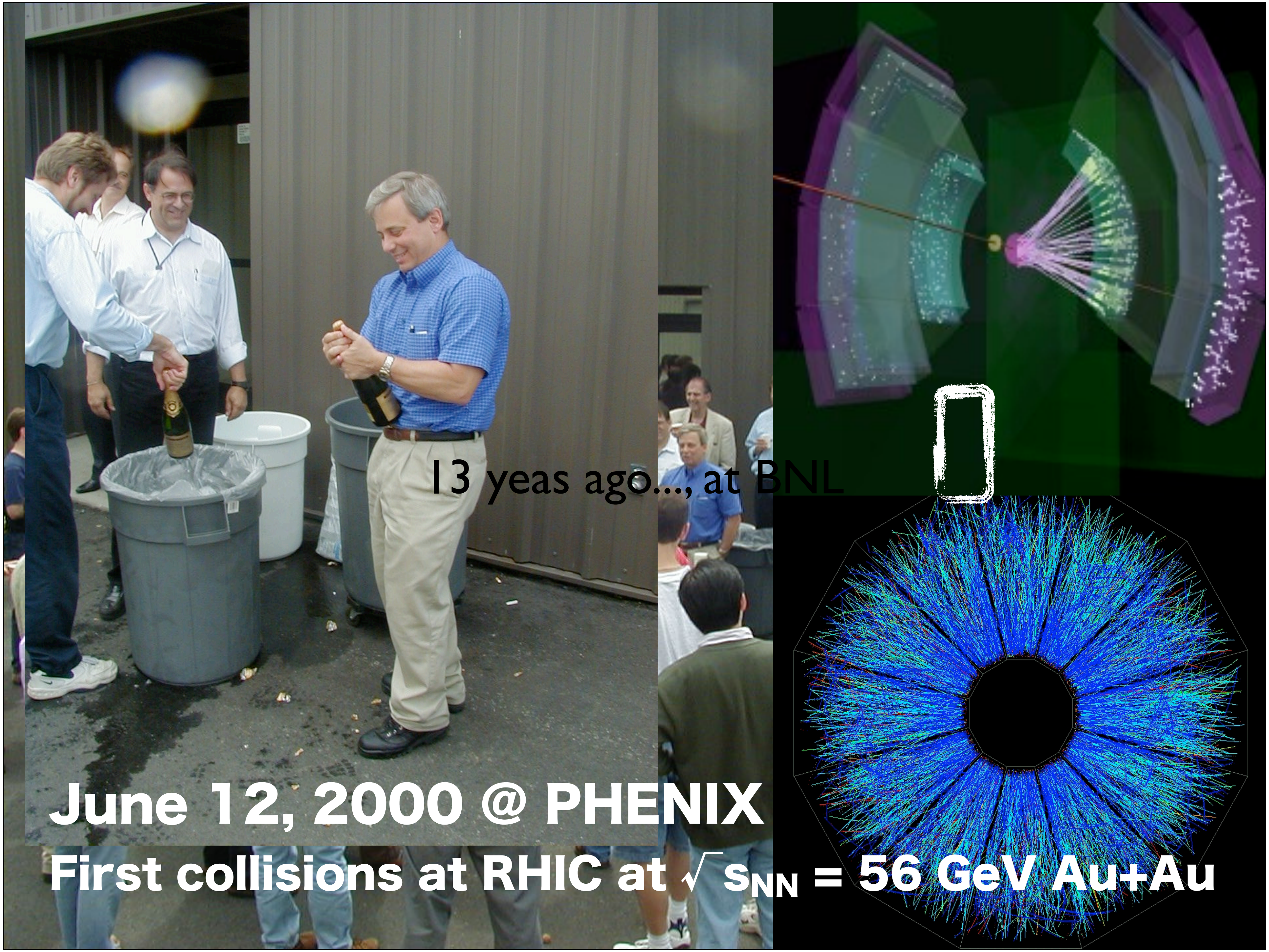
Outline

- ✦ Introduction
- ✦ First three years of LHC heavy ion runs
- ✦ Highlights from p-Pb results (2013)
- ✦ Summary

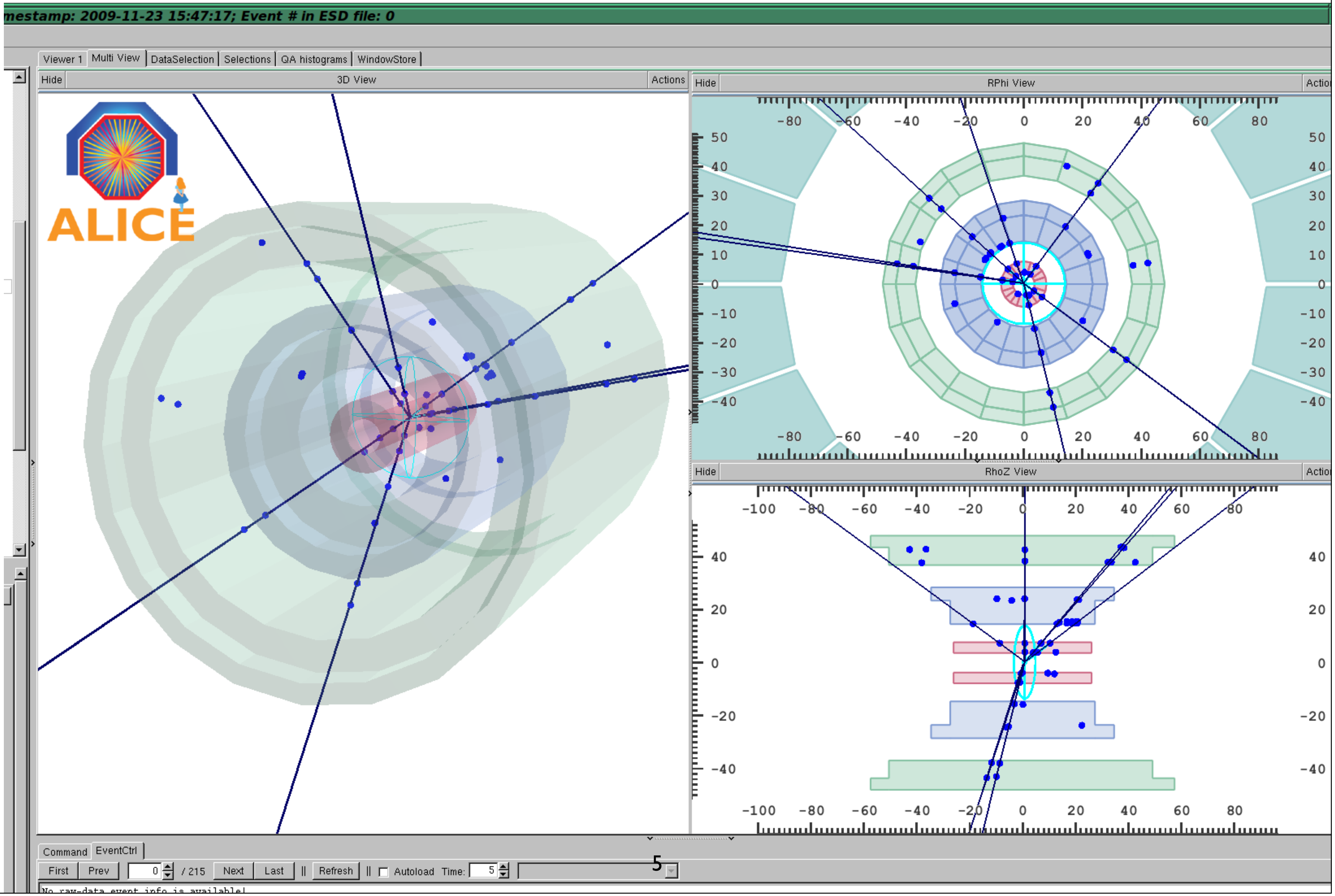

13 yeas ago..., at BNL
June 12, 2000 @ PHENIX
First collisions at RHIC at $\sqrt{s_{NN}}$ = 56 GeV Au+Au

2009.11.23 at the CERN-ALICE control room

First proton-proton collisions
p+p $\sqrt{s}$= 900 GeV

ALICE

First proton-proton collisions
p+p √s= 900 GeV in ALICE (2009.11.23)



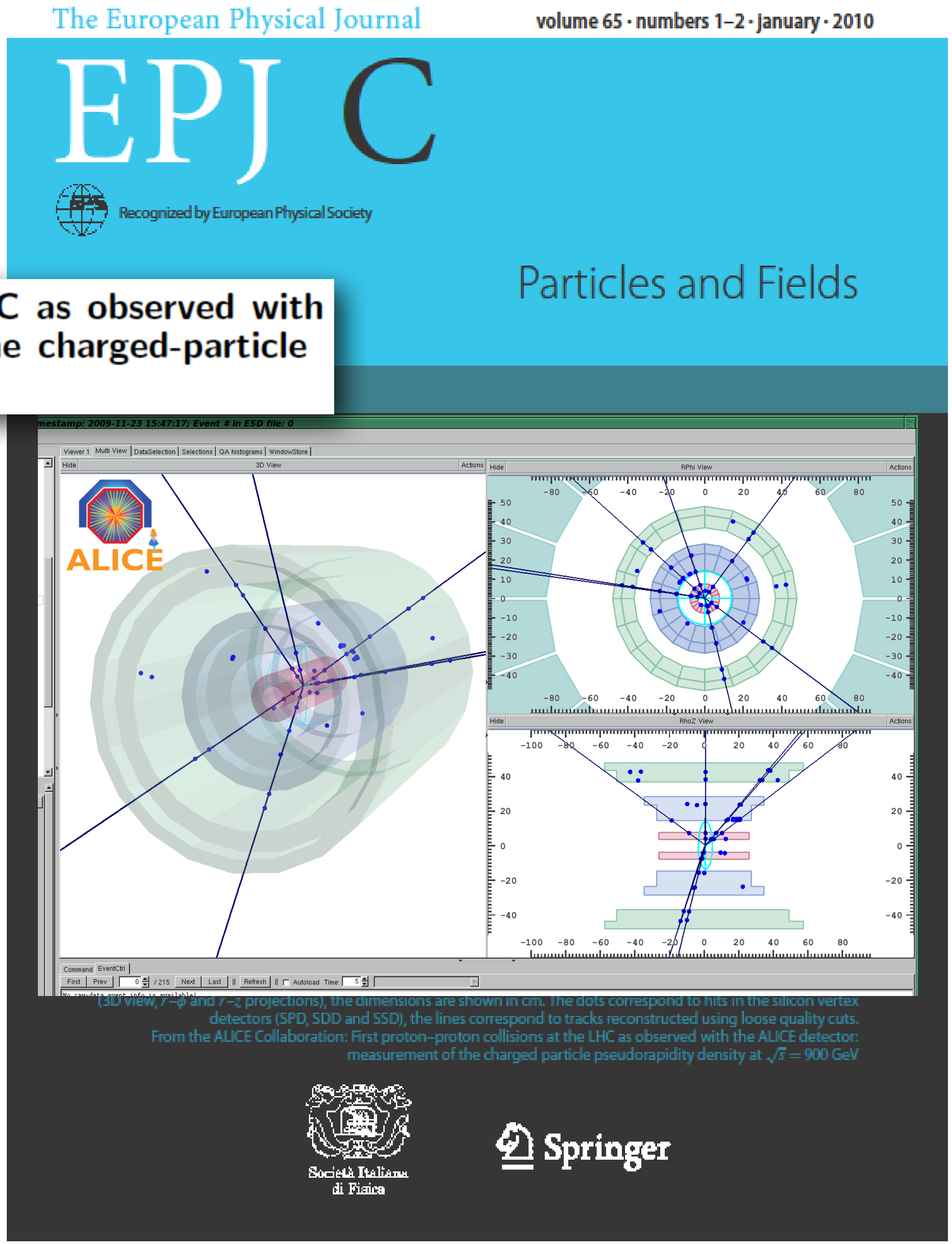
First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at $\sqrt{s} = 900$ GeV

First ALICE publication

submitted to EPJC 28 Nov 2009

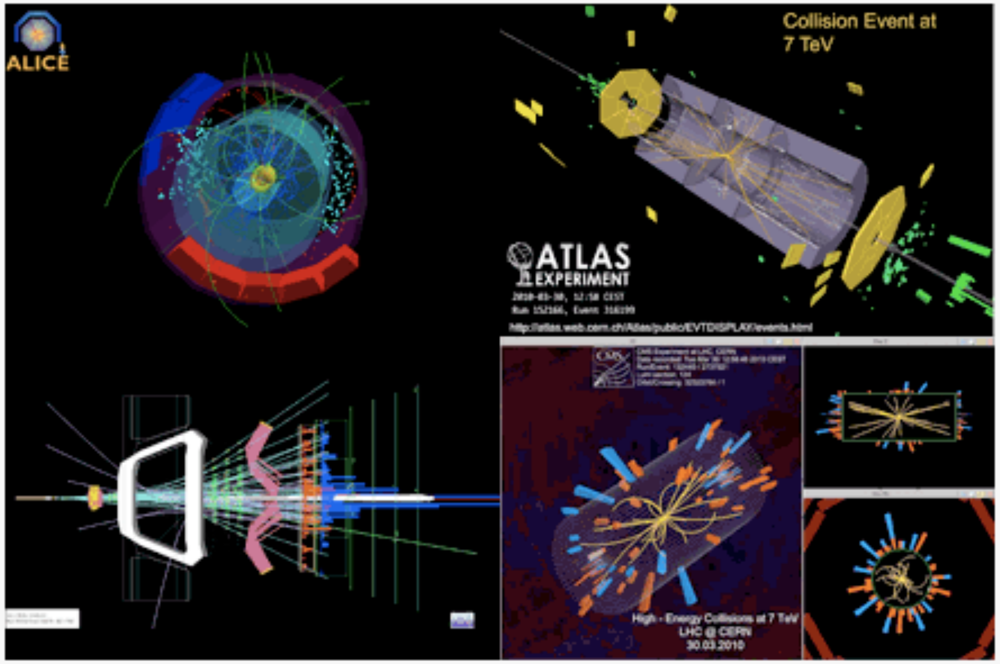
Eur. Phys. J. C (2010) 65: 111–125
DOI 10.1140/epjc/s10052-009-1227-4

arXiv:0911.5430v2



30 March 2010

LHC First Physics



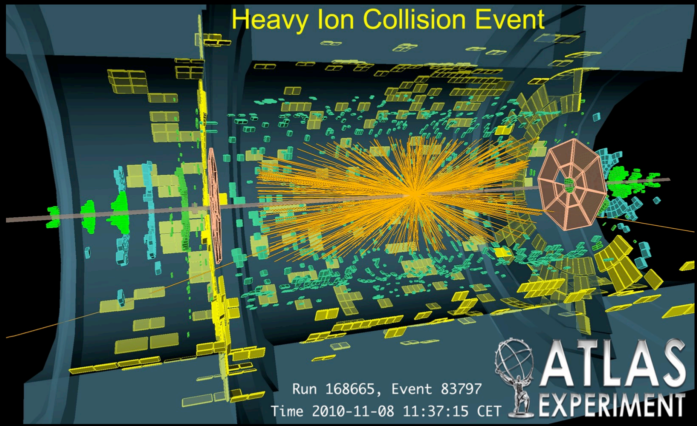
7 TeV collision events seen today by the LHC's four major experiments (clockwise from top-left: ALICE, ATLAS, CMS, LHCb). More LHC First Physics images »

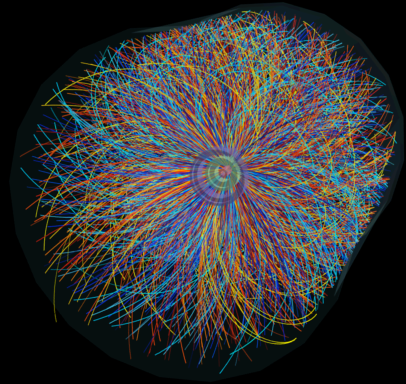
LHC research programme gets underway

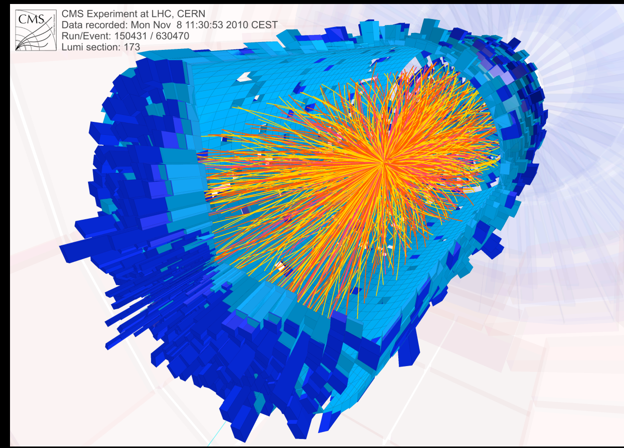
Geneva, 30 March 2010. Beams collided at 7 TeV in the LHC at 13:06 CEST, marking the start of the LHC research programme. Particle physicists around the world are looking forward to a potentially rich harvest of new physics as the LHC begins its first long run at an energy three and a half times higher than previously achieved at a particle accelerator. Read more...

Mar. 30, 2010

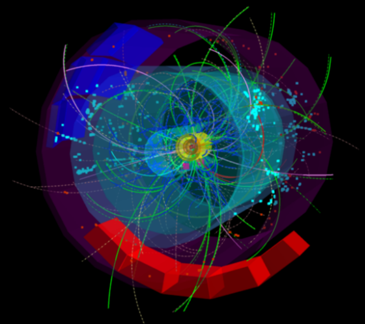
First p-p collisions at $\sqrt{s}$ = 7 TeV



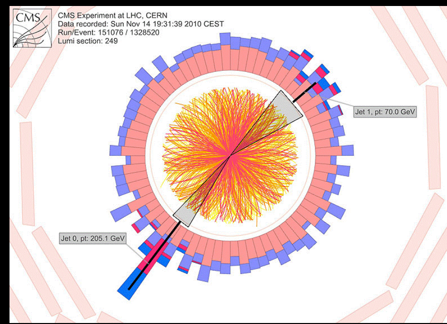


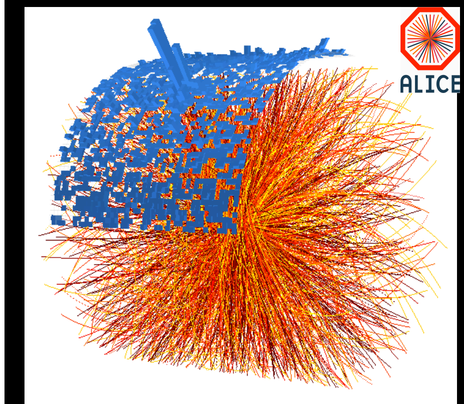


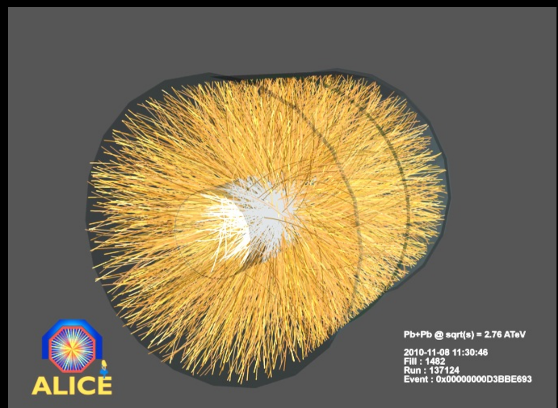
Nov. 8, 2010

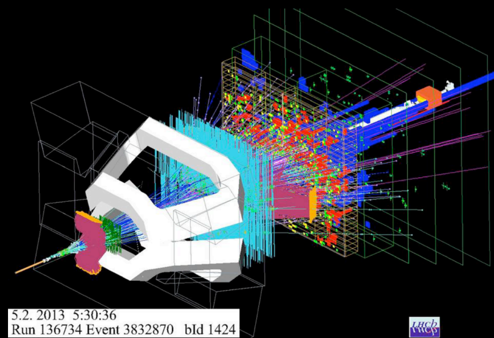


First Pb-Pb collisions at LHC,
the opening new era of
heavy ion program at LHC



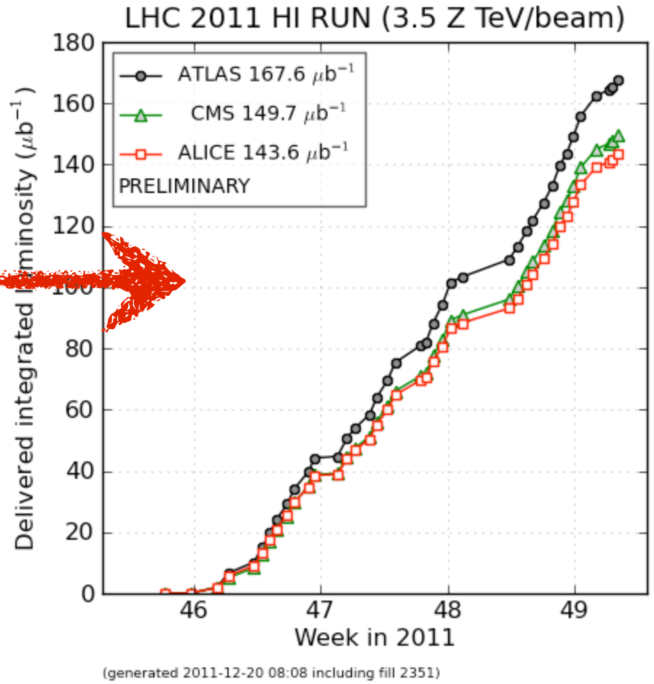




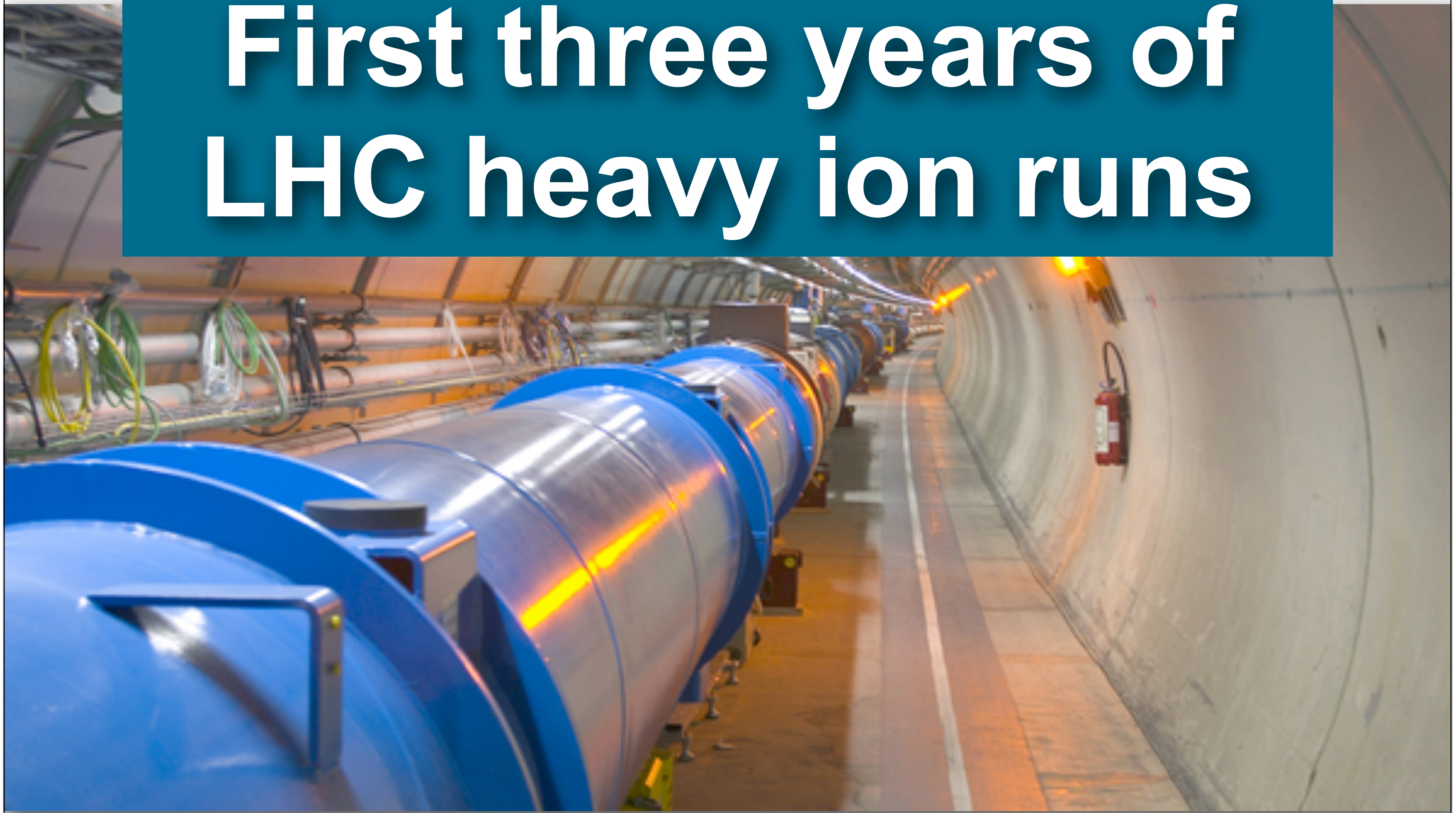


LHC run history

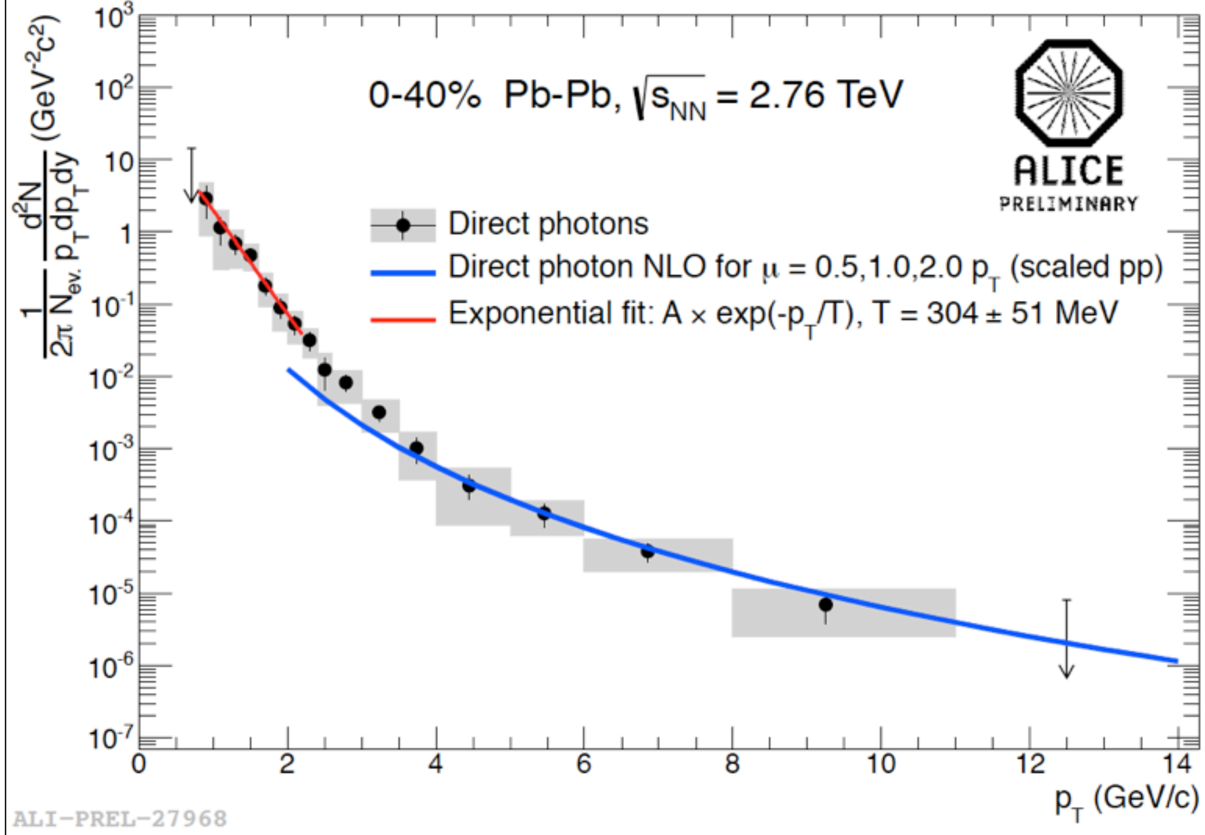
- **2009**: Commissioning and first data p-p (900 GeV)
- **2010**: First p-p run (7 TeV) and **first Pb-Pb run (2.76 TeV)**
- **2011**: Long p-p (7 TeV) and **one month Pb-Pb (2.76 TeV)** = x10 luminosity than that in 2010. first p-p (2.76 TeV).
- **2012**: Long p-p (8 TeV), one day p-Pb (5.02 TeV) pilot run
- **2013**: 1.5 month p-Pb and Pb-p run (5.02 TeV), (32 nb^{-1} in ALICE)
- **2013.02 - 2014 winter**: LHC Long Shutdown 1 (LS1) ← We are here now



First three years of LHC heavy ion runs



Initial temperature



Direct photon p_T spectra at LHC

- Observed an excess over p-p baseline at low p_T (< 2 GeV/c).

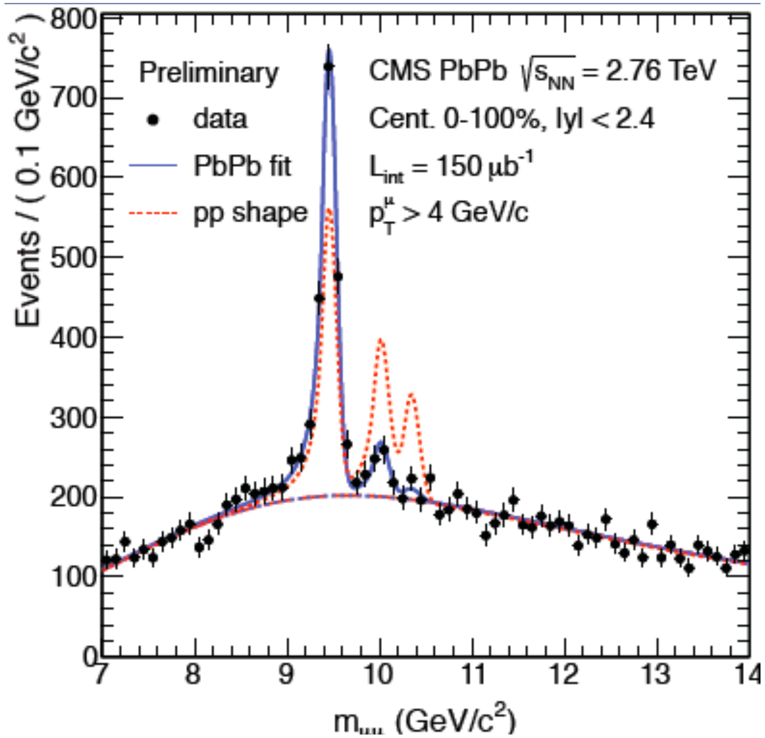
T = 304 ± 51 MeV

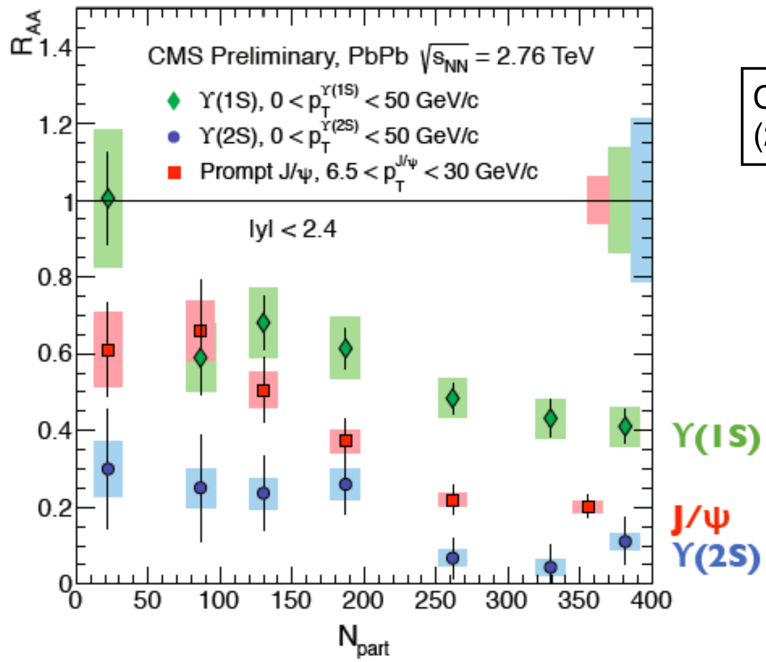
- ~30% higher than RHIC

RHIC (200 GeV Au+Au):
T = 221 ±19 ± 19 MeV

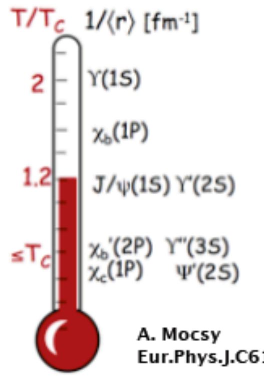
PHENIX, PRL 104, 132301 (2010)

Dissociation temperature





CMS, PRL 109 (2012) 222301

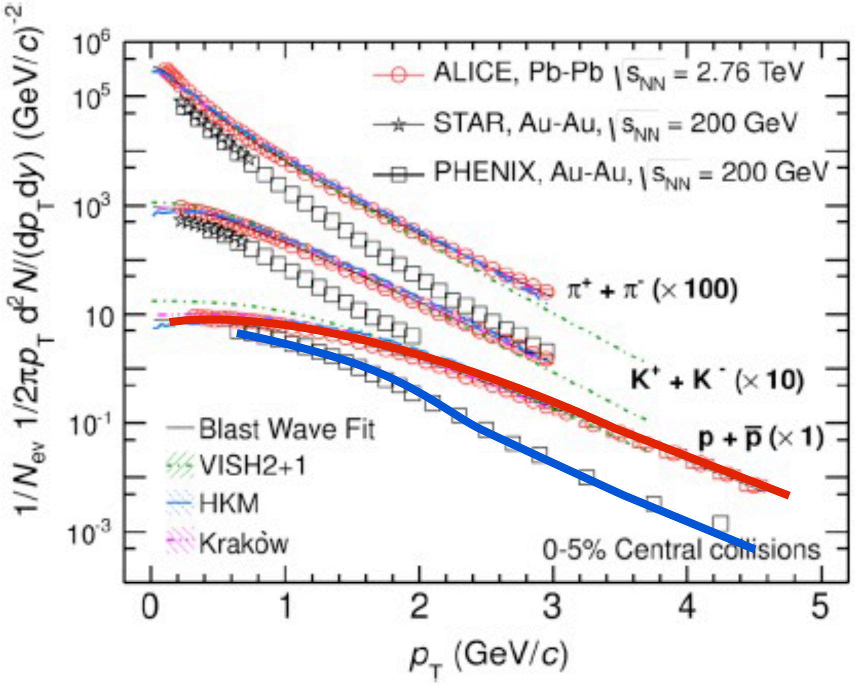


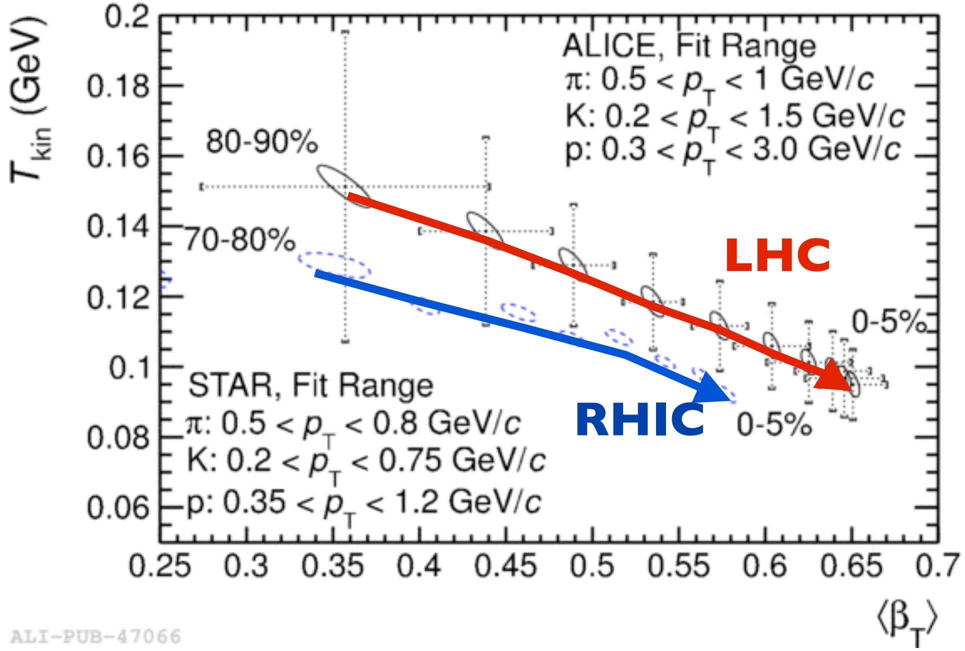
A. Mocsy Eur.Phys.J.C61,2009

Melting excited Υ states

- Suppression of ground state Υ(1s), and excited states Υ(2S) and Υ(3S).
- Consistent with **the sequential melting scenario**, Υ(3S) > Υ (2S) > Υ (1S).

Freeze-out T_{kin} and $<\beta_T>$





ALICE, PRL, 109 252301 (2012)
ALICE, arXiv:1303.0737

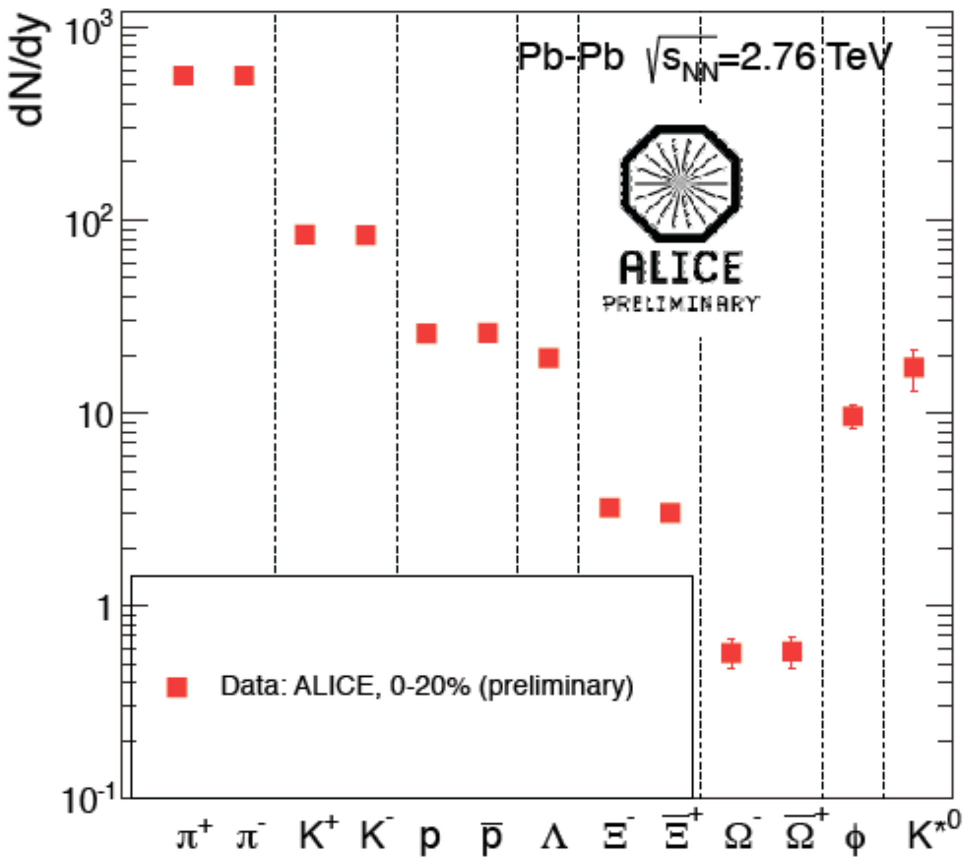
Significant changes in slope compared to RHIC, especially for protons.

Blast-wave fits

- T_{kin}= 95 ± 10MeV
  → comparable with RHIC
- $<\beta_T>$= 0.65 ± 0.02
  → 10% higher than RHIC

T_{ch} and μ_b

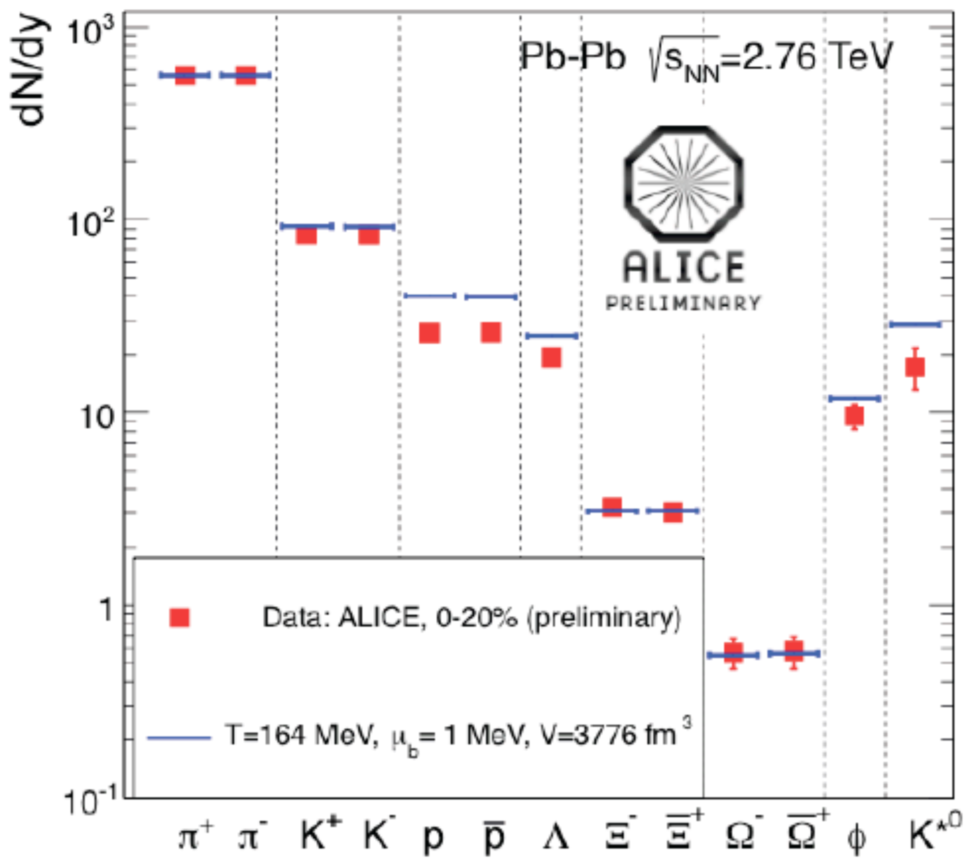
- Measured dN/dy of PID hadrons at mid-rapidity at LHC.
- Data: feed-down corrected.



T_{ch} and μ_b

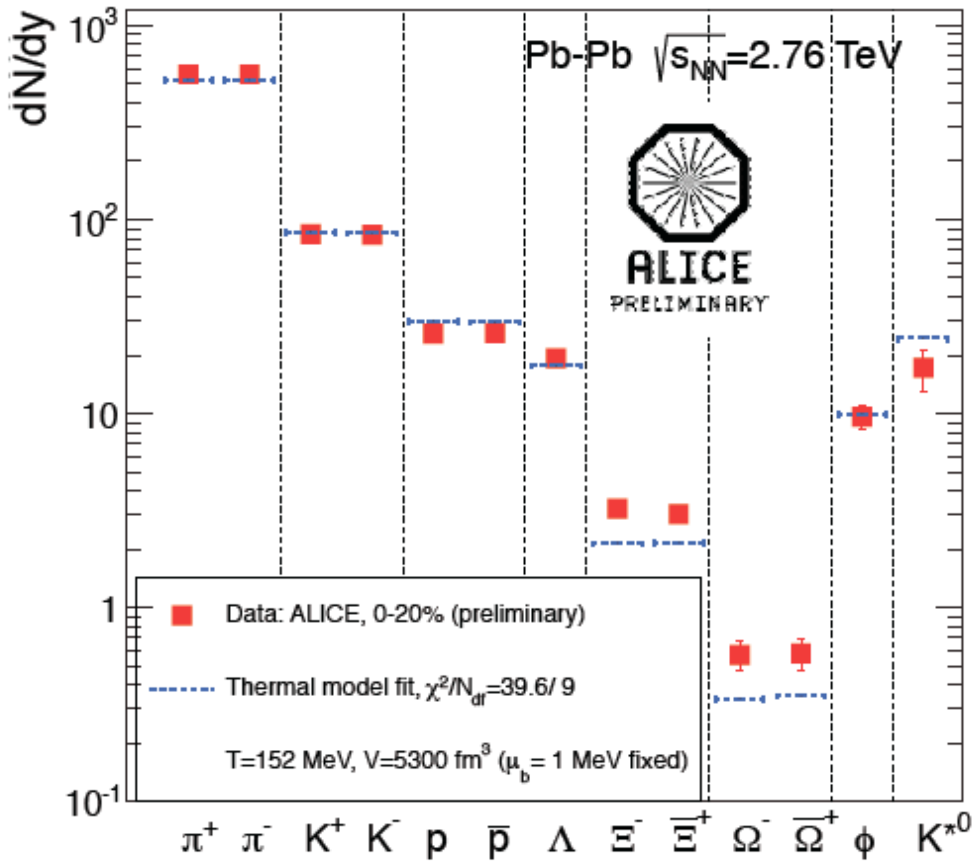
- Measured dN/dy of PID hadrons at mid-rapidity at LHC.
- Data: feed-down corrected.
- Thermal statistical model with T_{ch} = 164 MeV, μ_b = 1 MeV

➡ does not reproduce the data well, especially p, Λ, ϕ, K*



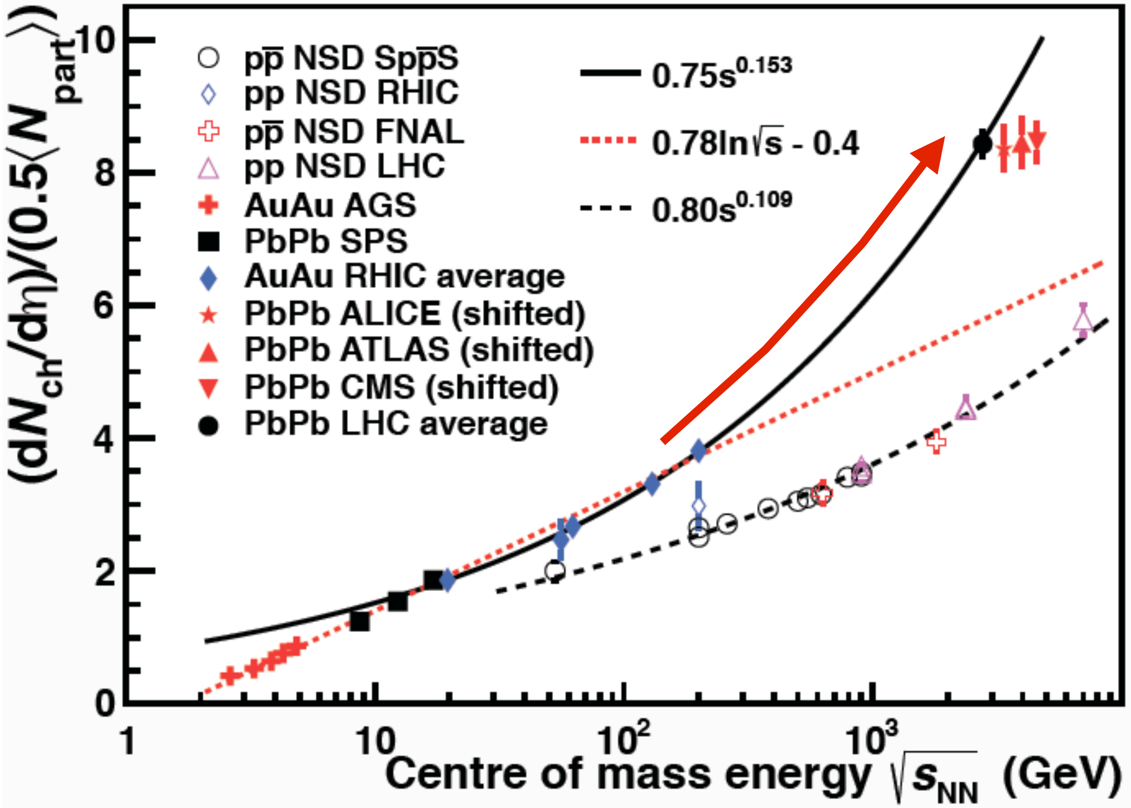
T_{ch} and μ_b

- Measured dN/dy of PID hadrons at mid-rapidity at LHC.
- Data: feed-down corrected.
- Thermal statistical model with T_{ch} = 164 MeV, μ_b = 1 MeV
  - ➡ does not reproduce the data well, especially p, Λ, ϕ, K*
- T_{ch} = 152 MeV, μ_b = 1 MeV w/o ϕ, K*, improving the fit, but multi-strangeness (Ξ, Ω) does not get right.



Indicating the importance of **re-scattering at hadronic phase?**

Energy density



Multiplicity density:

2.1x Central Au-Au at 200 GeV

Energy density:

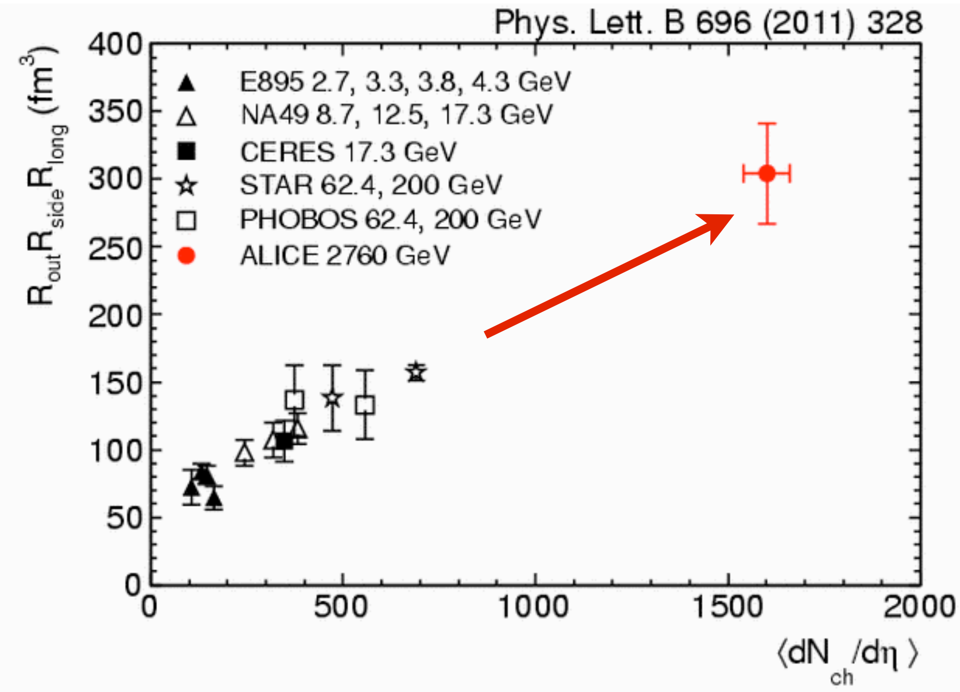
~ 3 x RHIC (larger <m_T>)

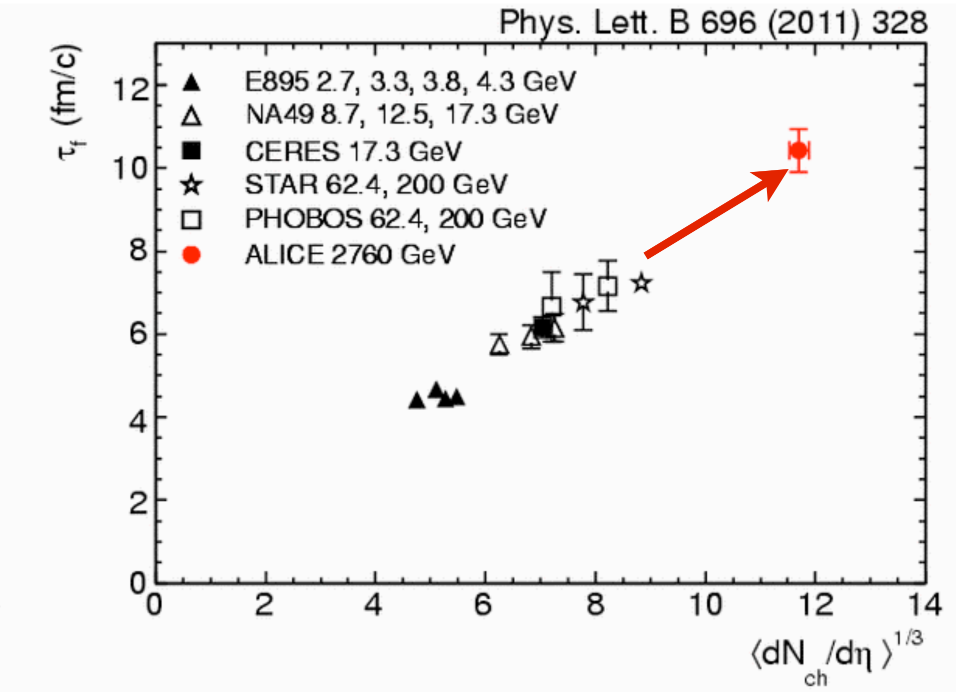
$$\epsilon\tau \approx 16 \text{ GeV}/(\text{fm}^2 c)$$

B.Mueller et al., Ann.Rev.Nucl.Part.Sci.62 (2012) 361
ALICE: PRL 106 (2011) 032301
CMS: JHEP 1108 (2011) 141
ATLAS: PLB 710 (2012) 363

Freeze-out volume and lifetime

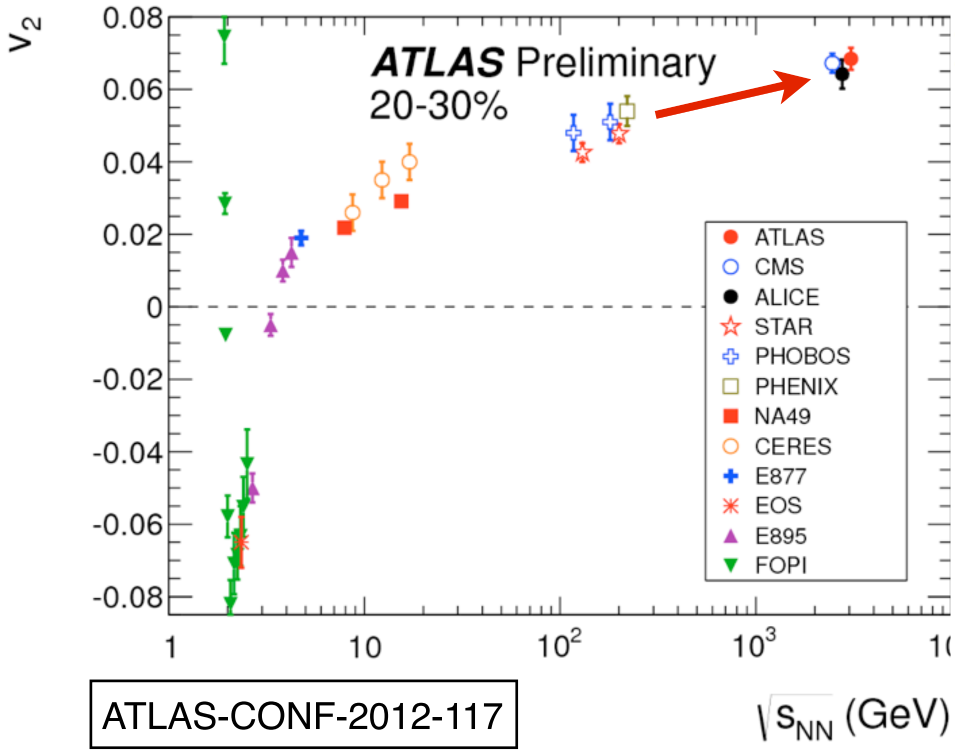
- **Freeze-out volume: 300 fm³ ~ 2 x RHIC.**
- **Lifetime: 10 fm/c ~ 40% longer than that at RHIC.**



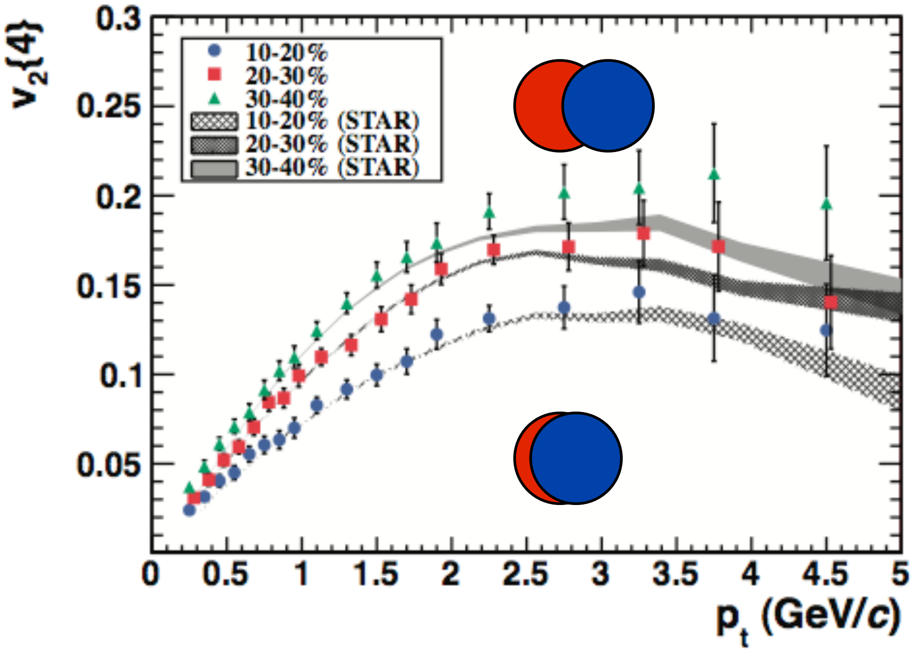


$$\tau_f = R_{long}\sqrt{m_T/T}$$

Elliptic flow v_2 at LHC



ATLAS-CONF-2012-117

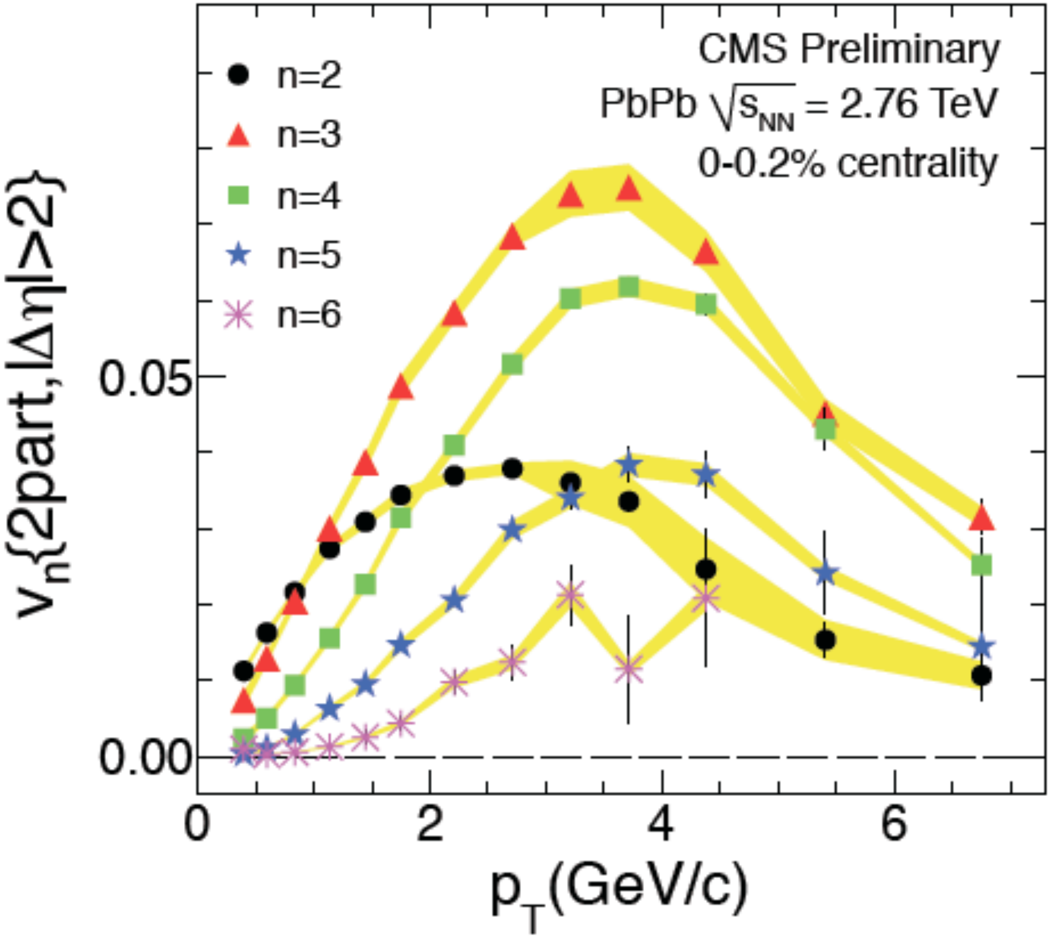


ALICE; PRL 105 (2010) 252302

- 30 % increase compared to RHIC data, due to <p_T> increase.
- p_T dependence holds from RHIC to LHC.
- **Suggesting similar η/s at LHC as RHIC produced.**

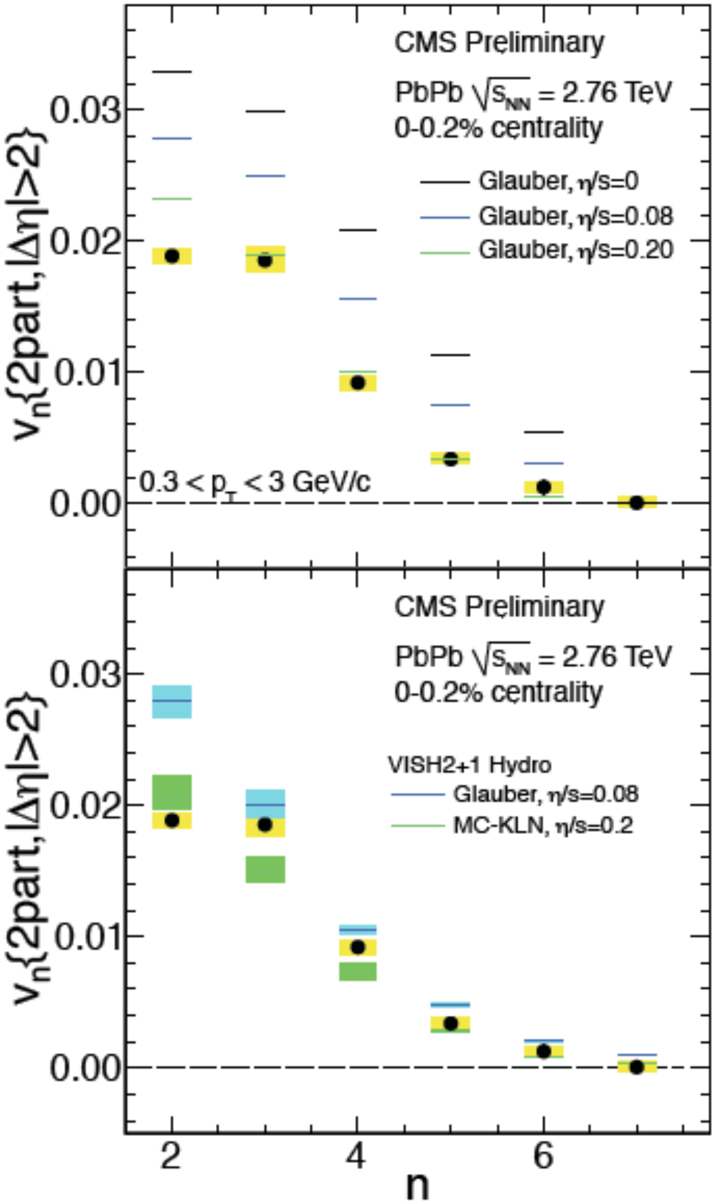
v_n and initial conditions, η/s

CMS-HIN-12-011



- v_n measurements by two particle correlations, $|\Delta\eta| > 2$, at very central collisions (0-0.2%).

v_n and initial conditions, η/s



←**Glauber with different η/s**

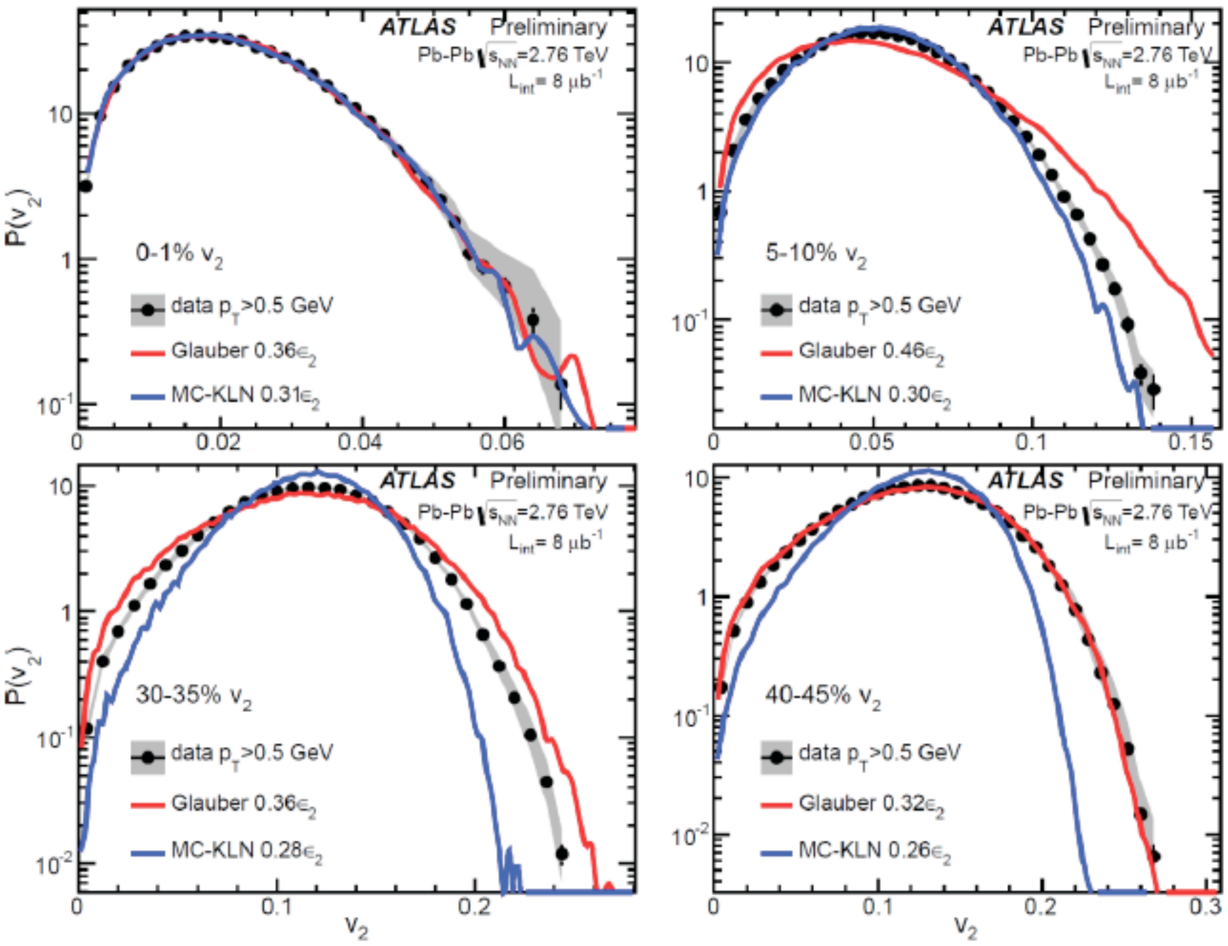
- Power spectrum of v_n.
  - disentangle initial condition and η/s.

←**Glauber and CGS with η/s VISH2+1 Hydro**

CMS-HIN-12-011

Further constraint on η/s; E-by-E v_n

ATLAS-CONF-2012-114

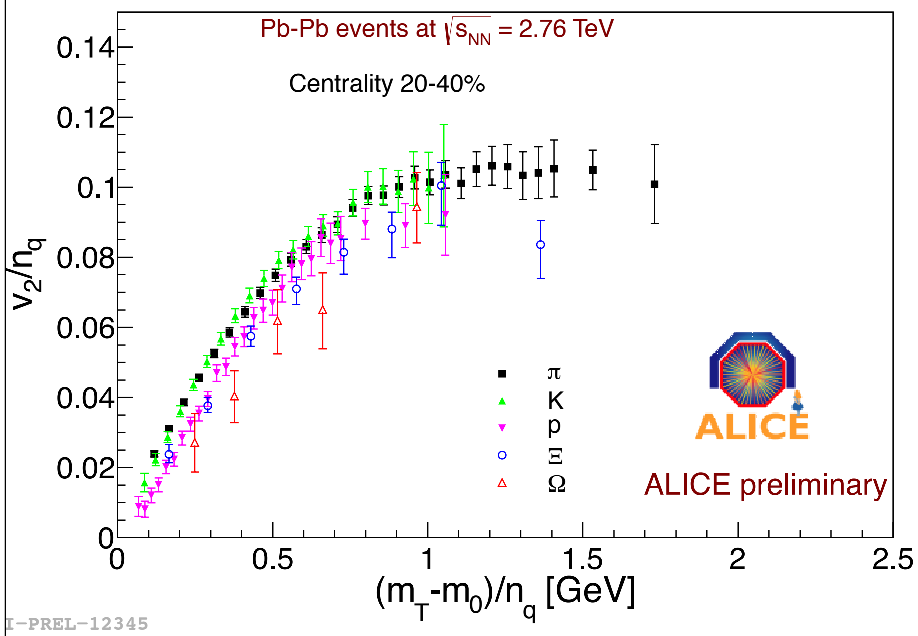


Theory: arXiv:nucl-ex/0701025, Phys. Rev. C 74, 044905 (2006)

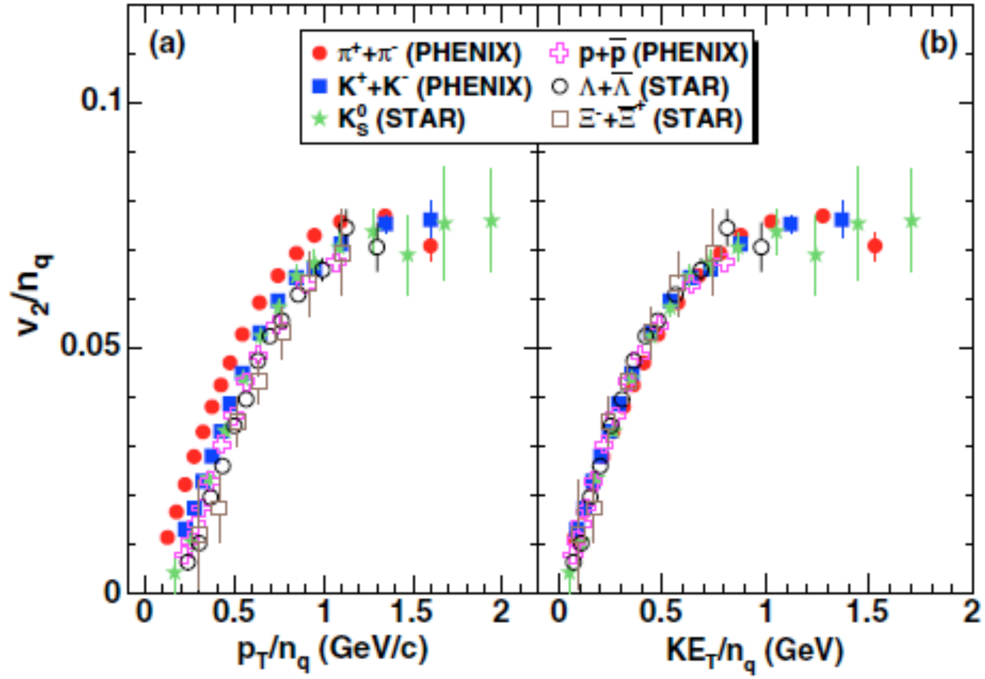
- Direct measurements of v_2, v_3, v_4 (only v_2 shown).
- Model comparison:
  - both work in 0-1%
  - **MC-KLM (CGC)** works in 5-10%
  - **Glauber** works in 40-45%
- Additional constrains by event-plane correlations (ATLAS-CONF-2012-049).

Quark number scaling of v_2

LHC



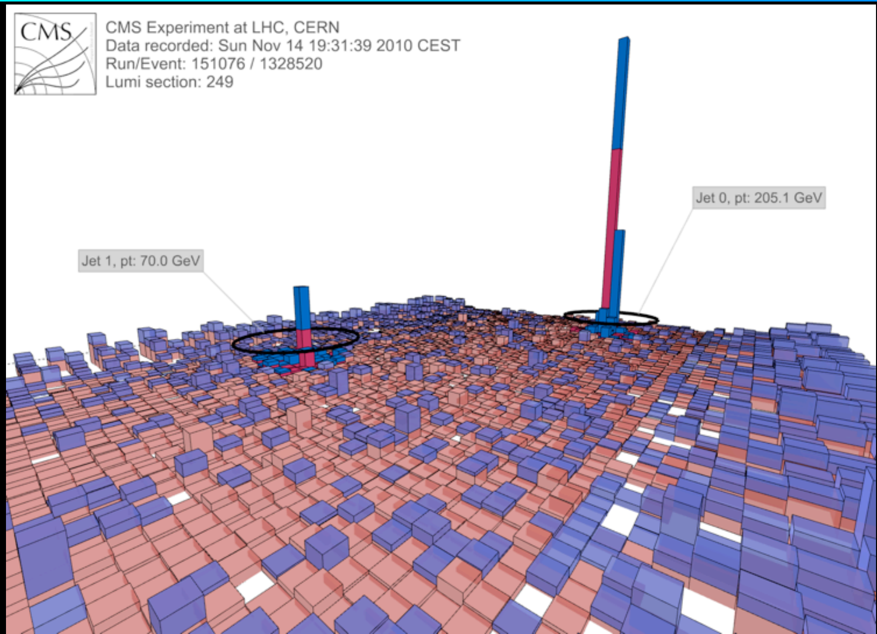
RHIC

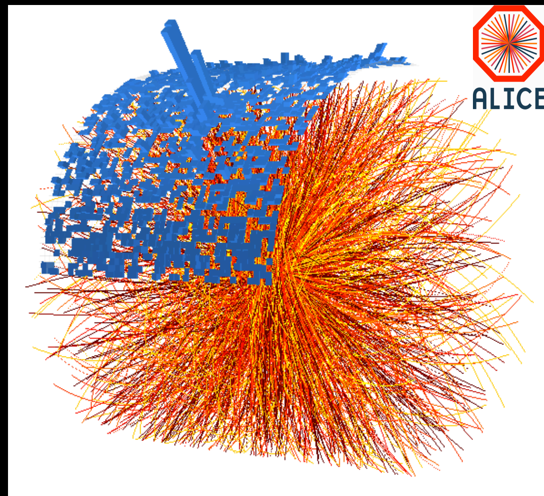


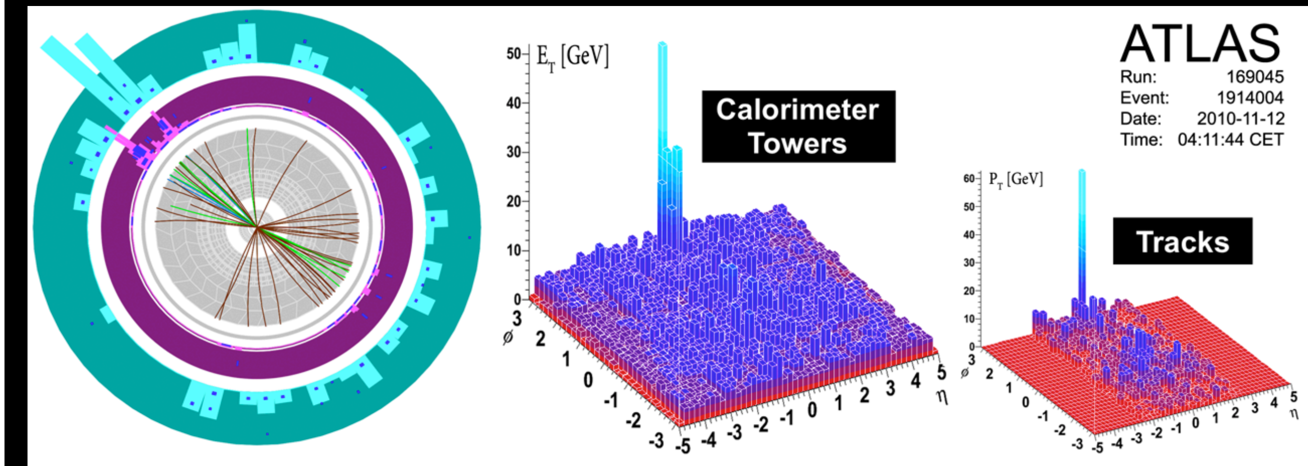
PHENIX, PRL 98, 162301 (2007)

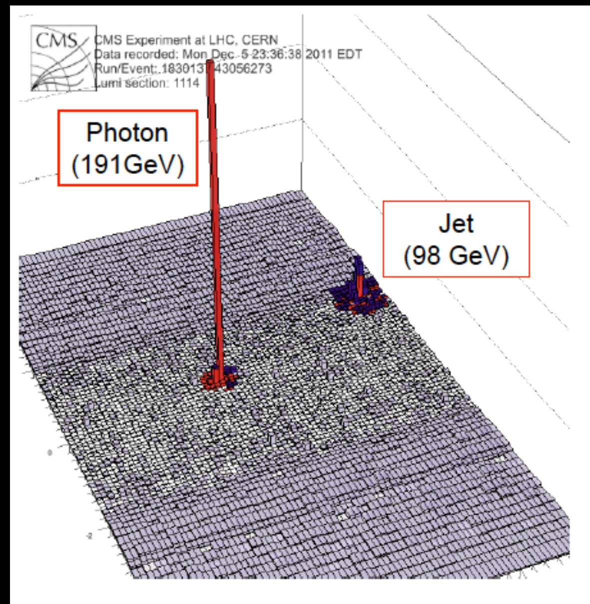
- K_{ET}/n_q scaling at LHC does not work well like those at RHIC.
- Affected by a strong radial flow for protons (hadronic re-scatterings)?

Jets in LHC heavy ion collisions



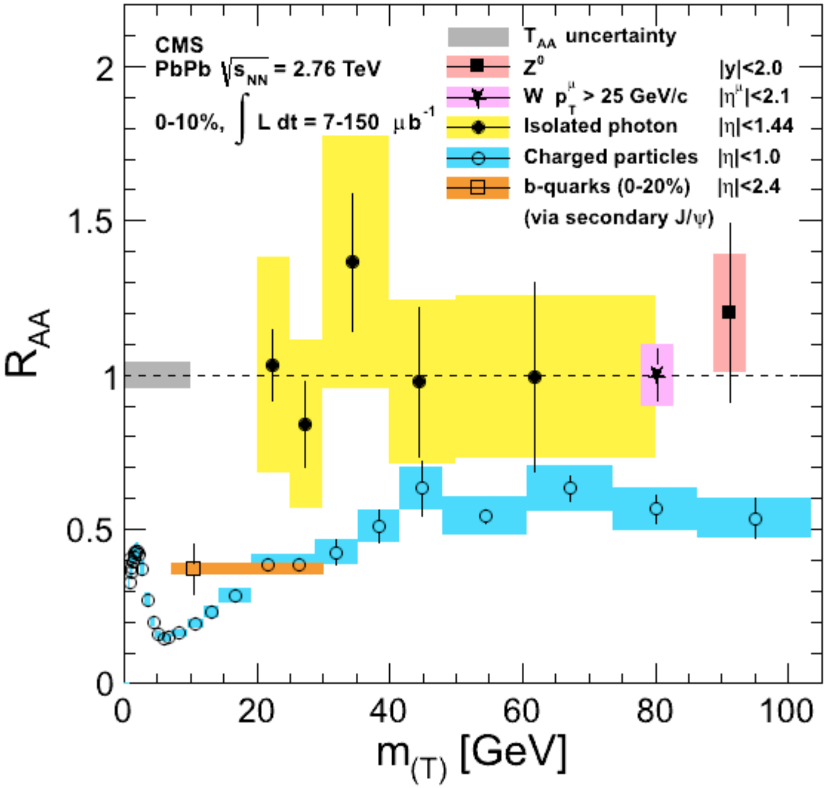






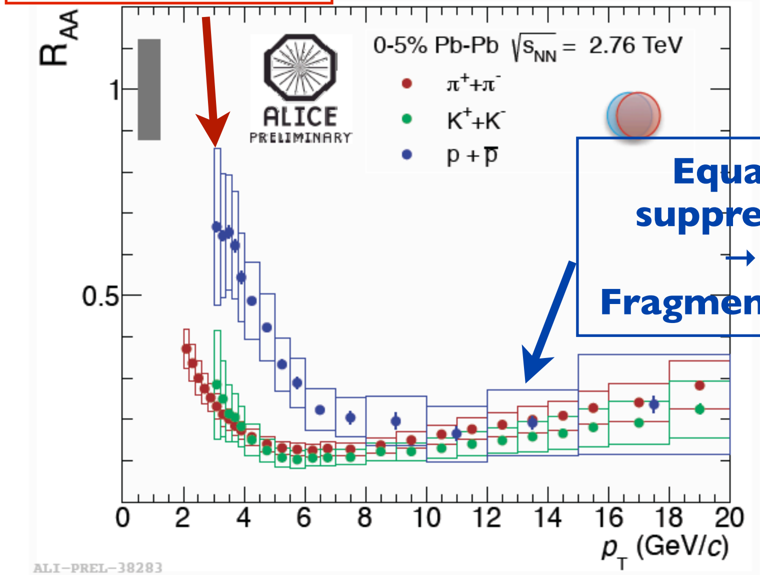
Energy loss, single hadron R_{AA}

R_{AA} for EM probes, hadrons



Baryon enhancement (p_T < 8 GeV/c) → recombination + radial flow

R_{AA} for π, K, p

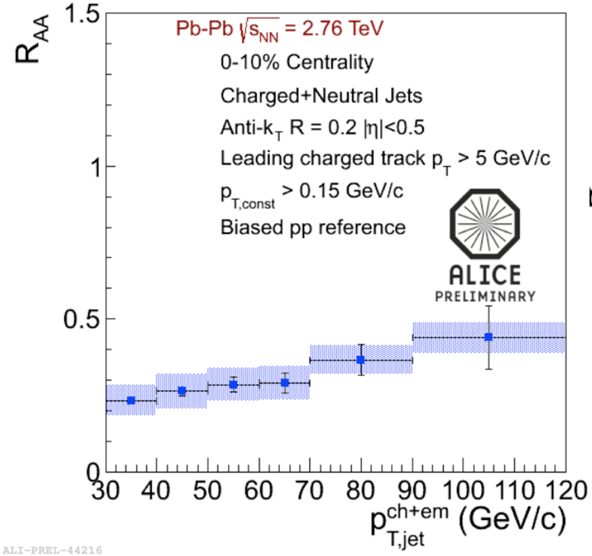


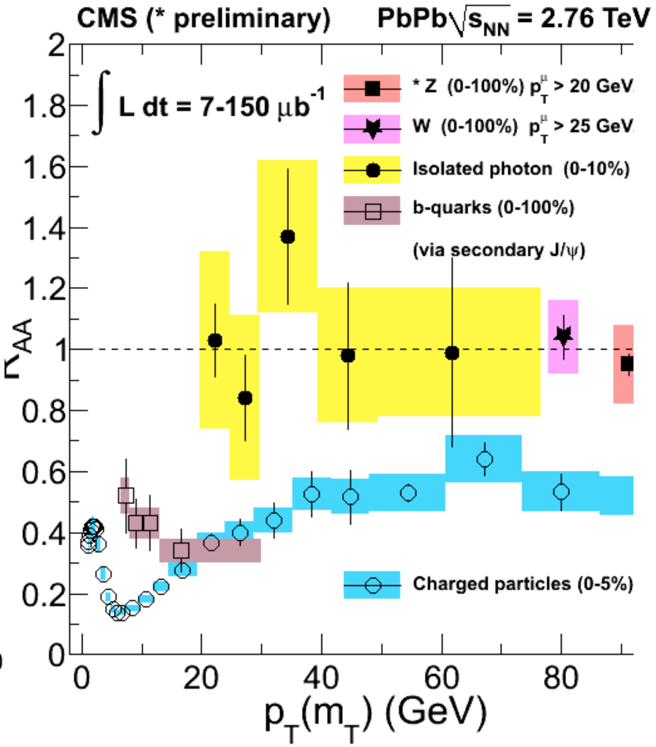
Equally suppressed → Fragmentation

- EM probes: R_{AA}~1.
- Hadrons: strong suppression R_{AA} ~0.1 at ~7 GeV/c, and a rise at higher p_T (R_{AA} ~0.5).
- Baryon enhancement is observed at intermediate p_T.

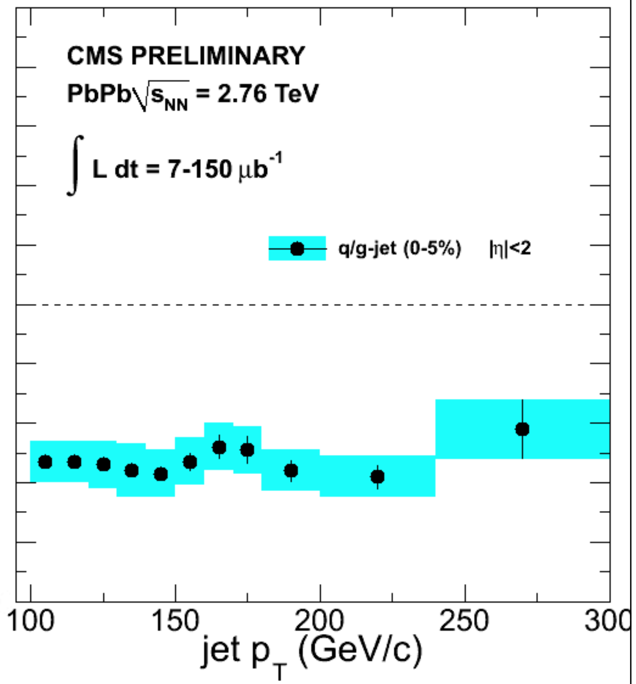
Energy loss, jet R_{AA}

ALICE (30-120 GeV)
Full jets (0-10%)





CMS (30-120 GeV)
Full (q/g) jets (0-5%)

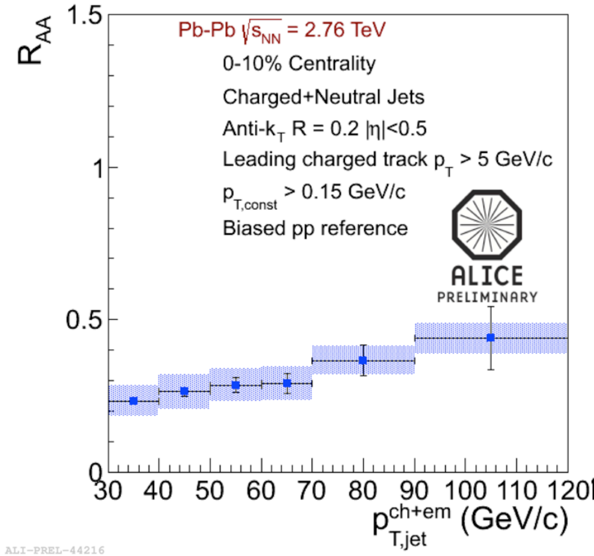


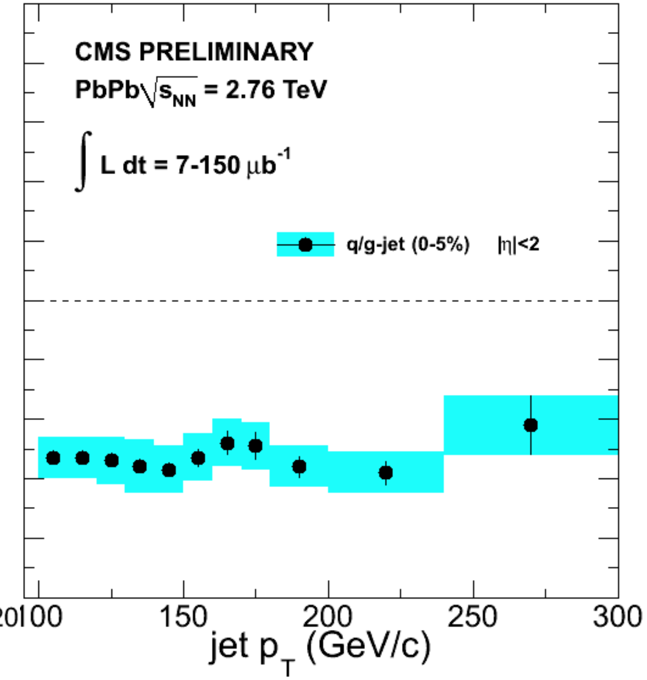
- a wide kinematic reach for jets at LHC.
- Jet R_{AA} ~ 0.5 above 100 GeV/c, consistent with hadron's R_{AA}.

Energy loss, jet R_{AA}

ALICE (30-120 GeV)
Full jets (0-10%)

CMS (30-120 GeV)
Full (q/g) jets (0-5%)

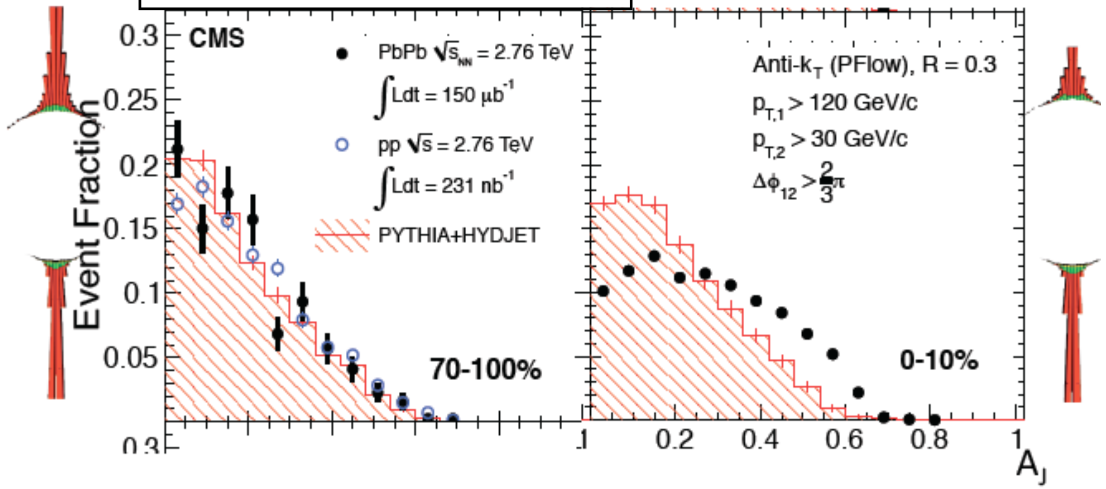




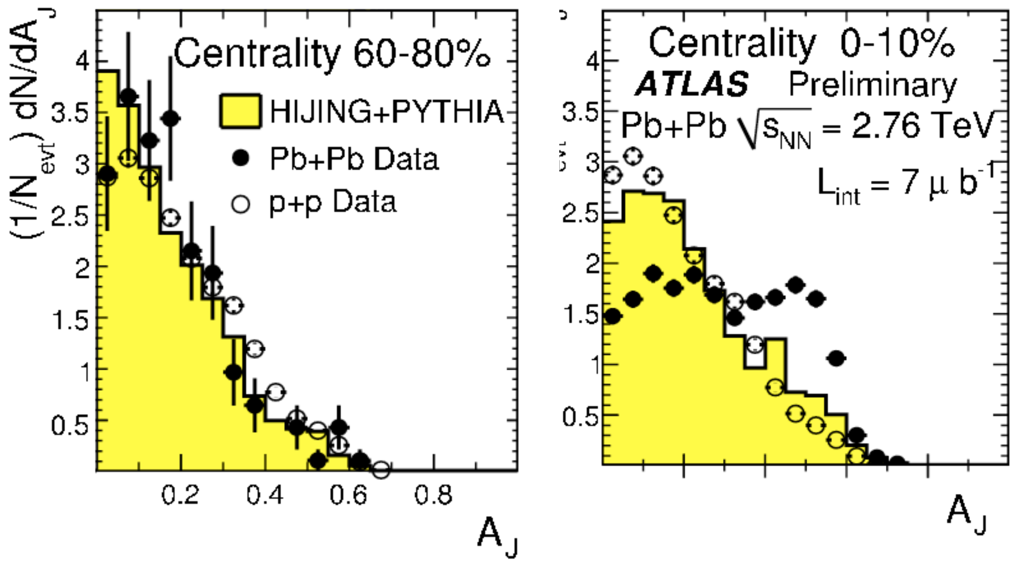
- Jet R_{AA} from p_T = 30 - 300 GeV, consistent with hadron's R_{AA}.

Di-jet energy imbalance

CMS, PRC 84, 024906 (2011)



ATLAS, PRL, 105 (2010) 252303



Large energy imbalance is observed in central Pb-Pb.

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

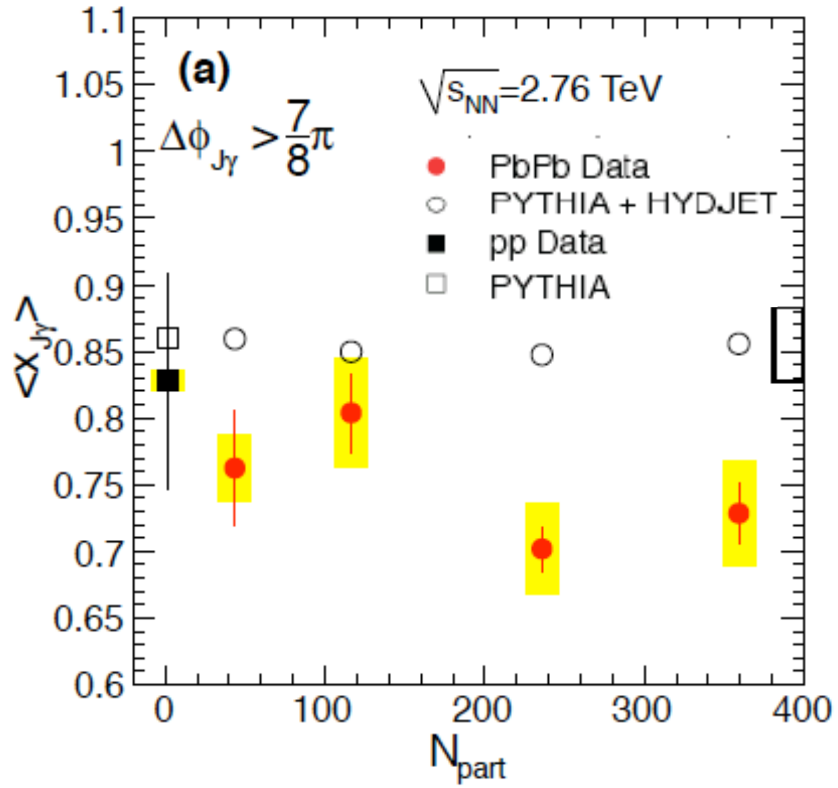
$p_{T,1}$: leading jet
$p_{T,2}$: sub-leading jet

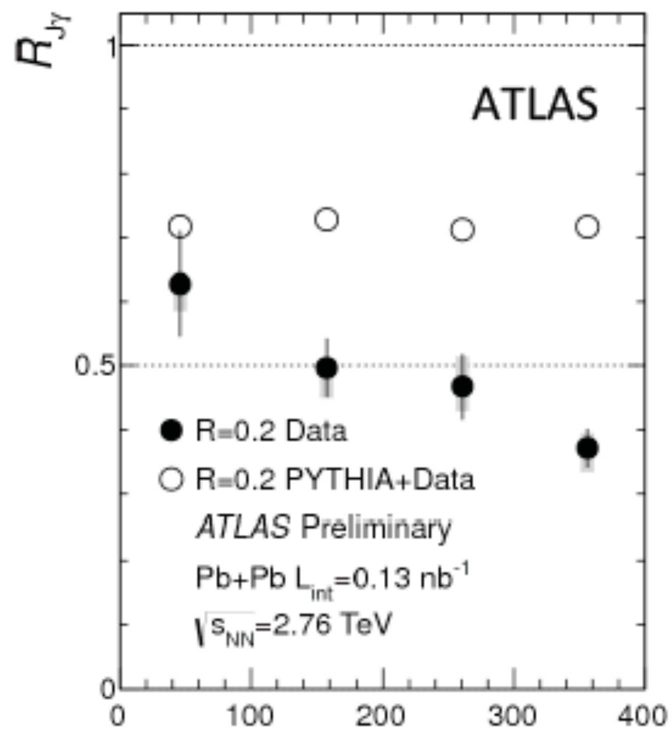
Large A_J : low momentum particle (< 4 GeV/c) emitted at large angle on away side.

γ-jet: jet tomography

CMS, Phys. Lett. B 718 (2013) 773 $< x_{J\gamma} >= p_T^{jet}/p_T^{\gamma}$

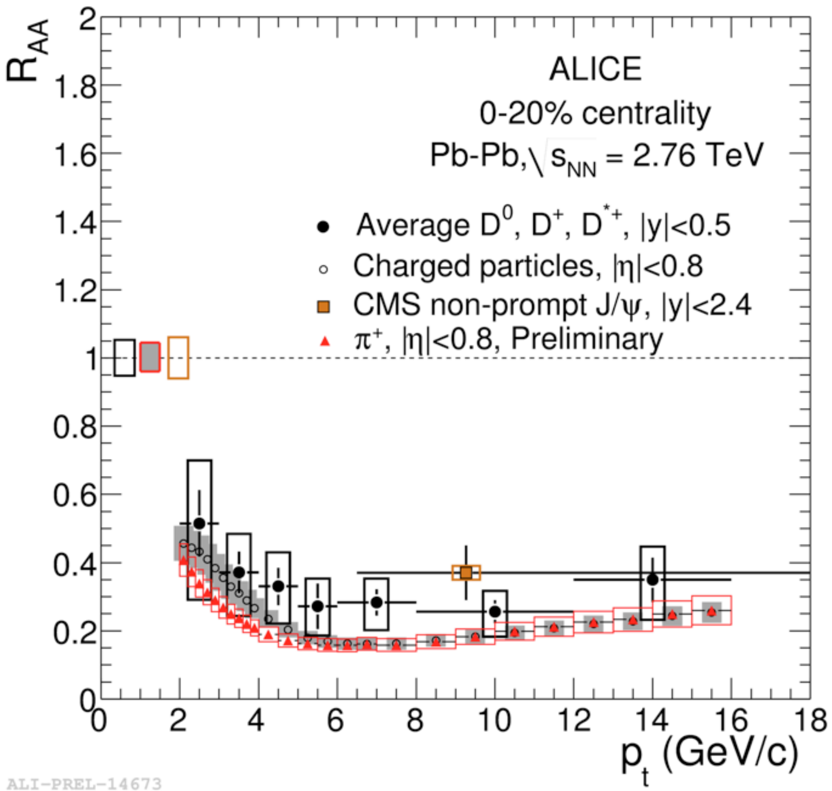
$R_{J\gamma}$: fraction of photons with jet partner

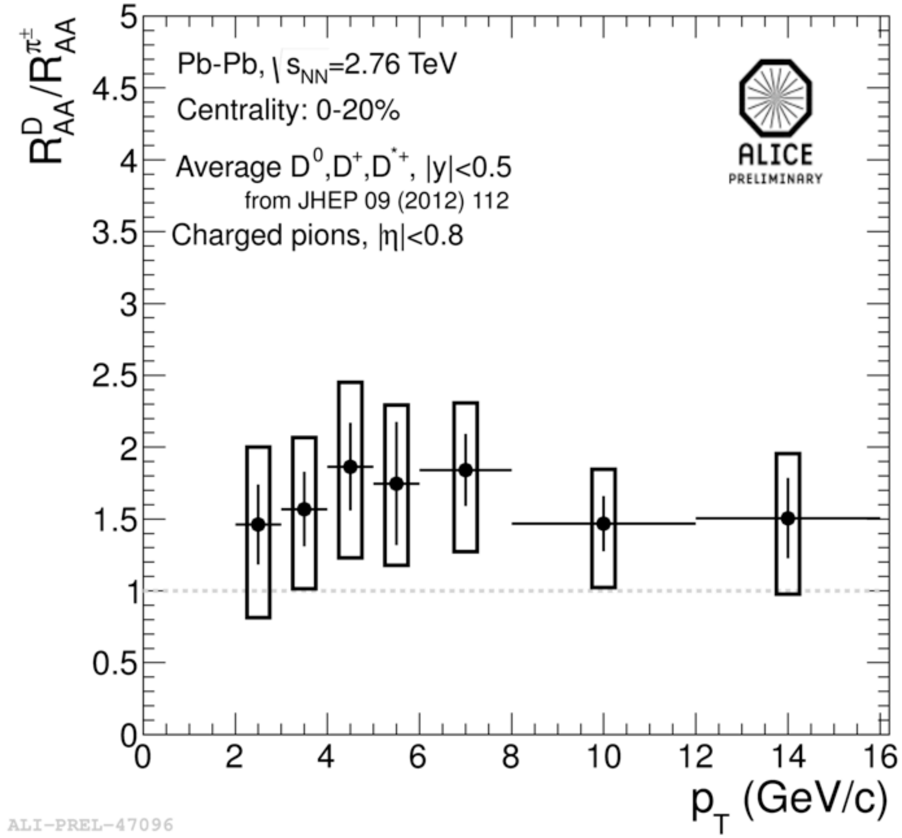




- γ as a calibrated probe of jet energy.
- significant change in $R_{J\gamma}$, $<x_{J\gamma}>$ compared to PYTHIA and pp.

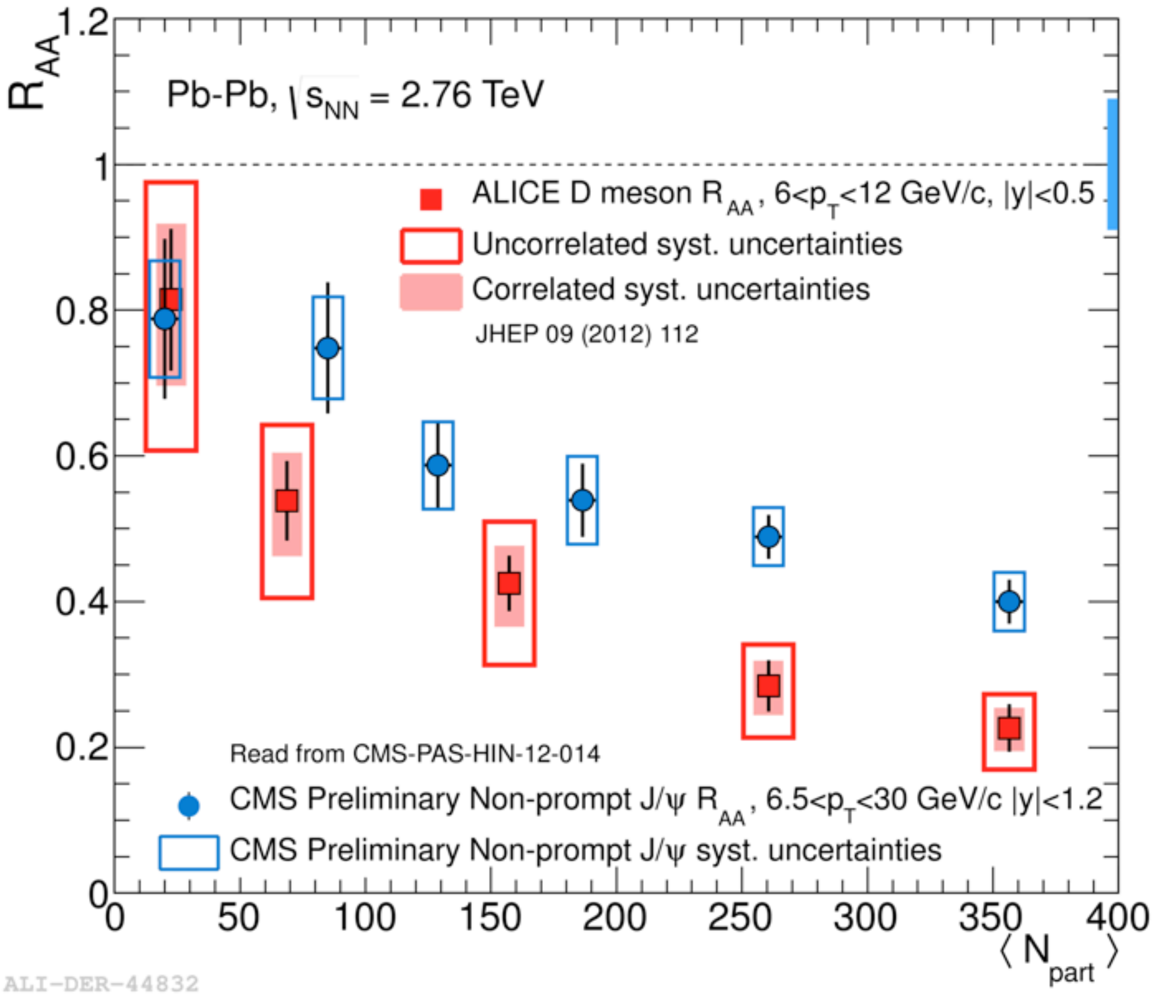
Heavy quark R_{AA}





- D mesons are also strongly suppressed.
- **A hit of $R_{AA}^D > R_{AA}^\pi$** (not yet conclusive).

Charm vs. Bottom

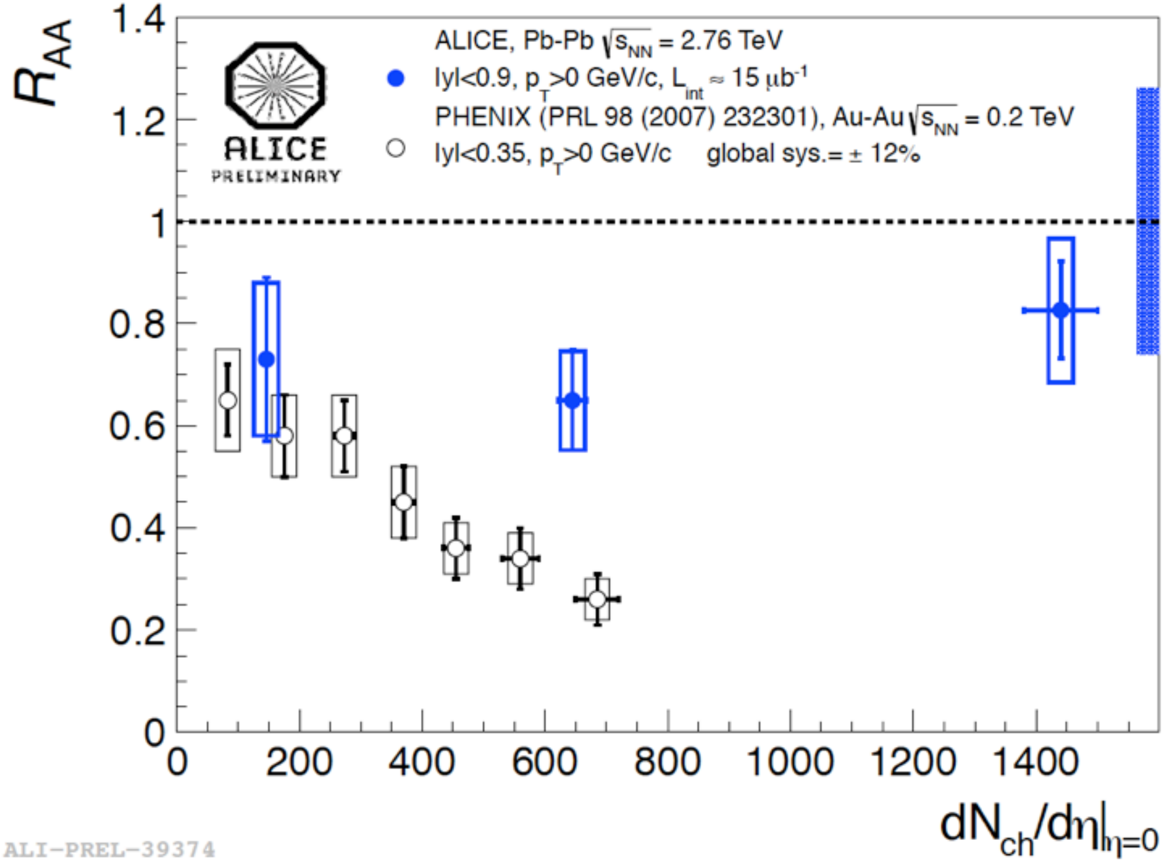


* Note: not same kinematic range.

- R_{AA} for charmed meson (D) vs. bottom meson (J/ψ from B decay).
- First indication of a mass dependence of R_{AA}.
- $R_{AA}^B > R_{AA}^D$

J/ψ (color screening vs. regeneration)

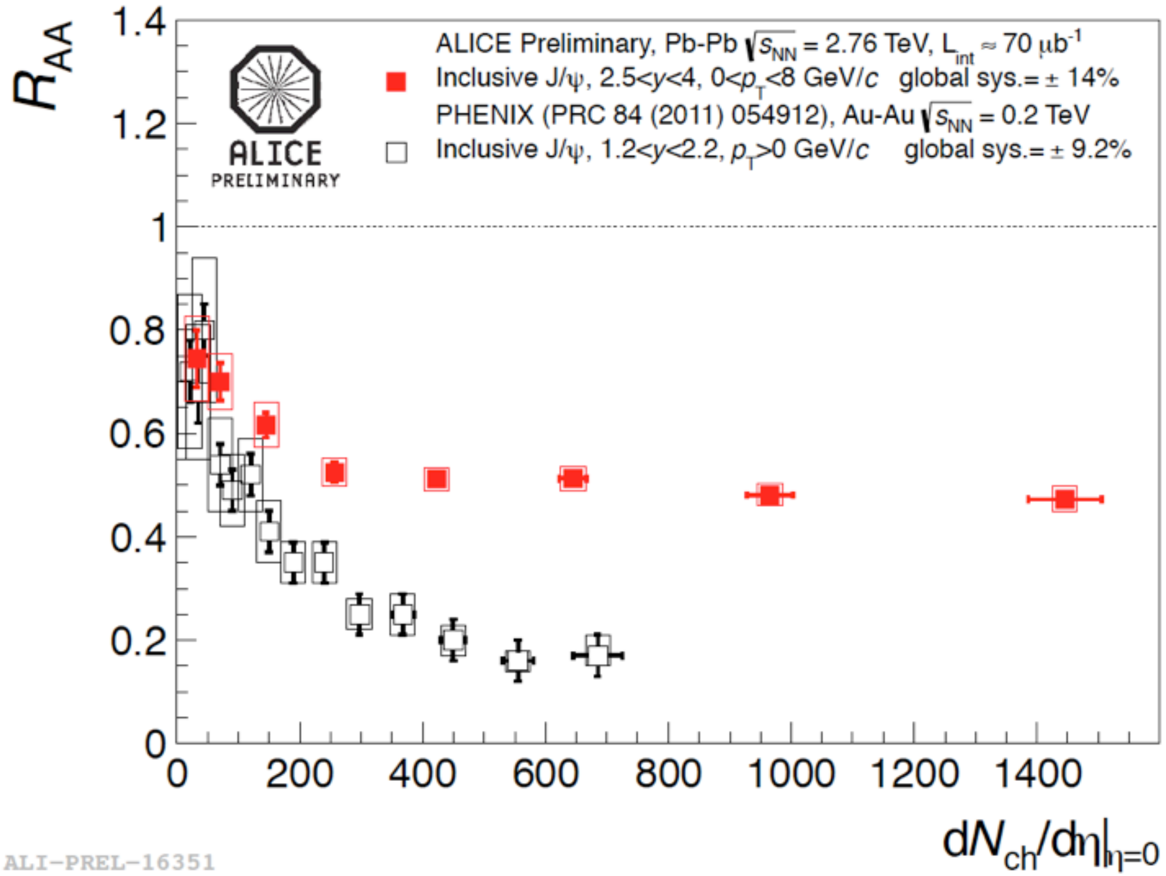
mid-rapidity R_{AA} for J/ψ



- J/ψ measured at mid-rapidity |y|< 0.9, by e^+e^- at LHC.
- Compared to RHIC mid-rapidity data.
- Significant larger R_{AA} than those at RHIC.

J/ψ (color screening vs. regeneration)

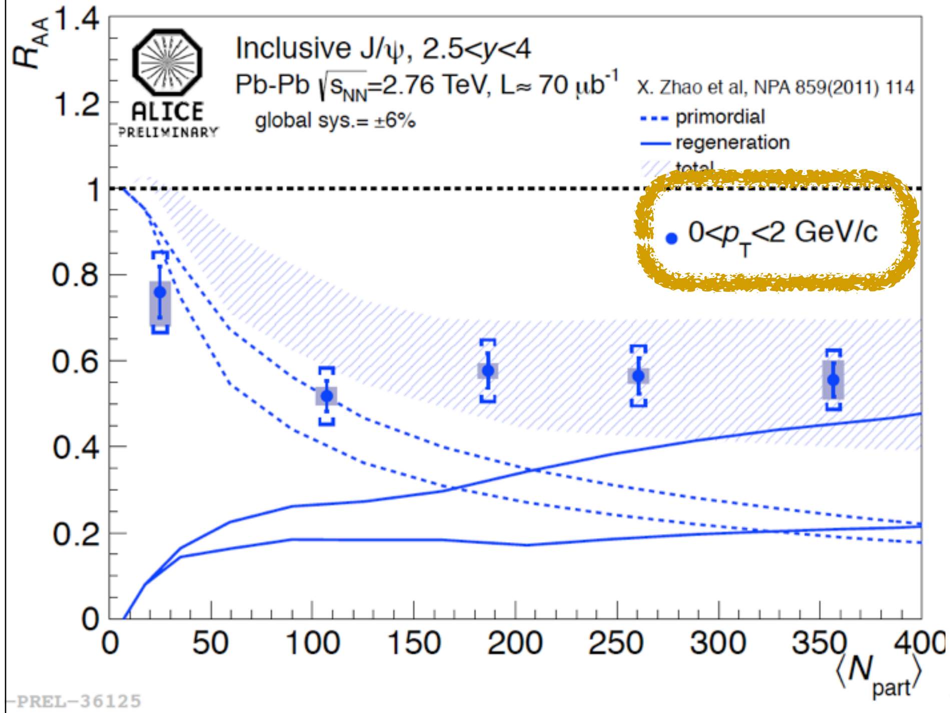
forward-rapidity R_{AA} for J/ψ



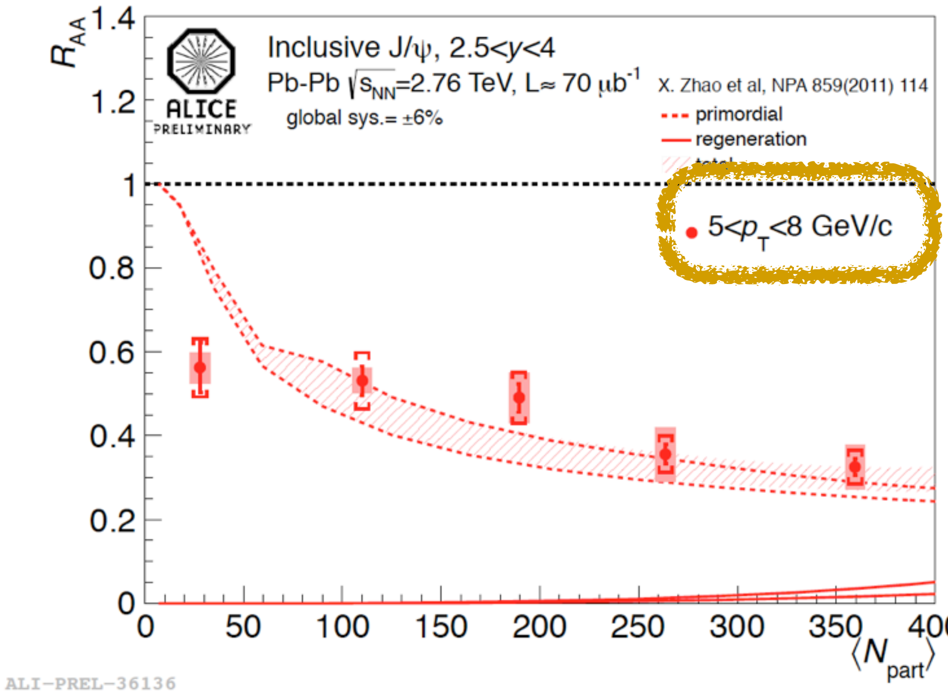
- J/ψ measured at forward-rapidity $2.5 < y < 4$, by $\mu^+\mu^-$ at LHC.
- Compared to RHIC forward data.
- Significant larger R_{AA} than those at RHIC.
- Suppression is stronger than that at mid-rap.

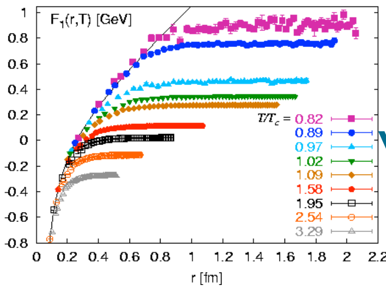
J/ψ (color screening vs. regeneration)

Low p_T: R_{AA} at forward y, $J/\psi \rightarrow \mu^+\mu^-$

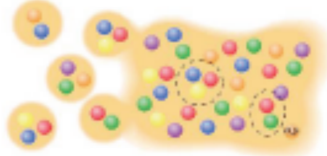


High p_T: R_{AA} at forward y, $J/\psi \rightarrow \mu^+\mu^-$





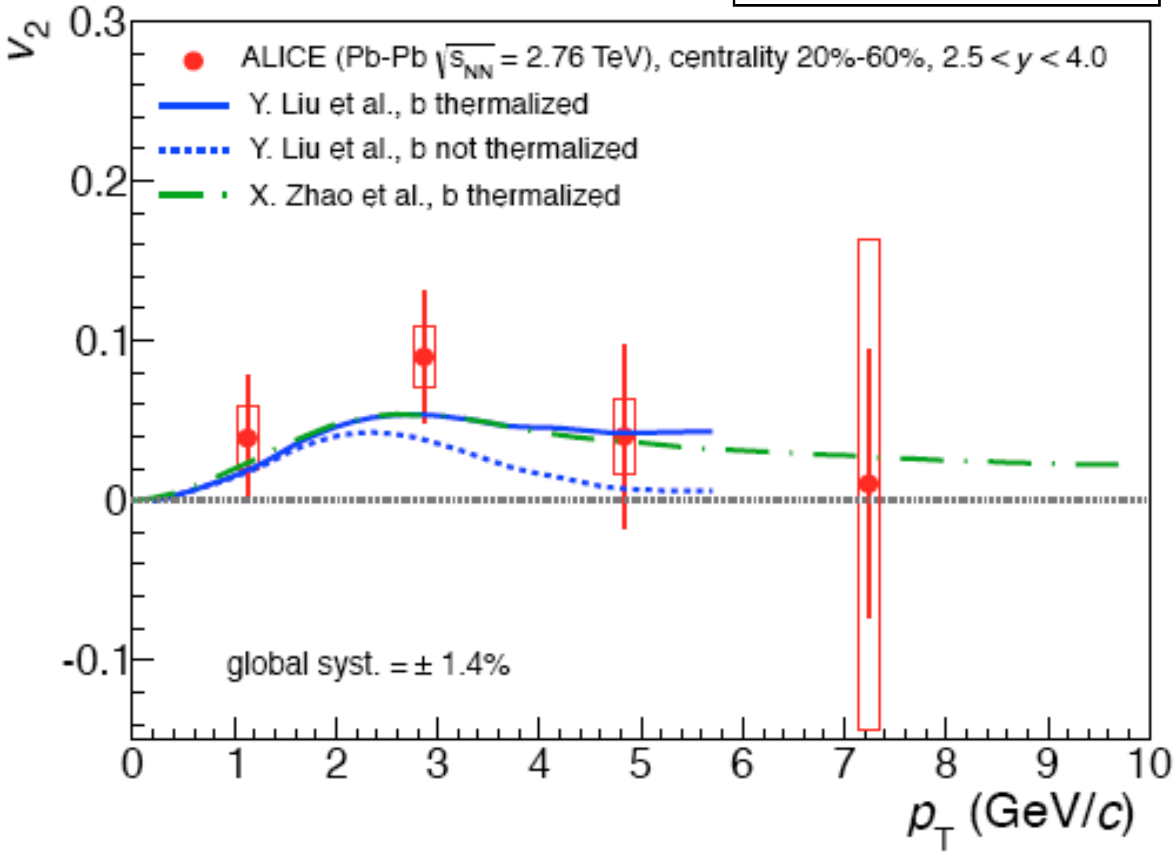
vs.



- J/ψ R_{AA} is enhanced at low p_T.
- Compatible with models including regeneration.

Charmonia flow (Inclusive J/ψ v_2)

ALICE: arXiv:1303.5880



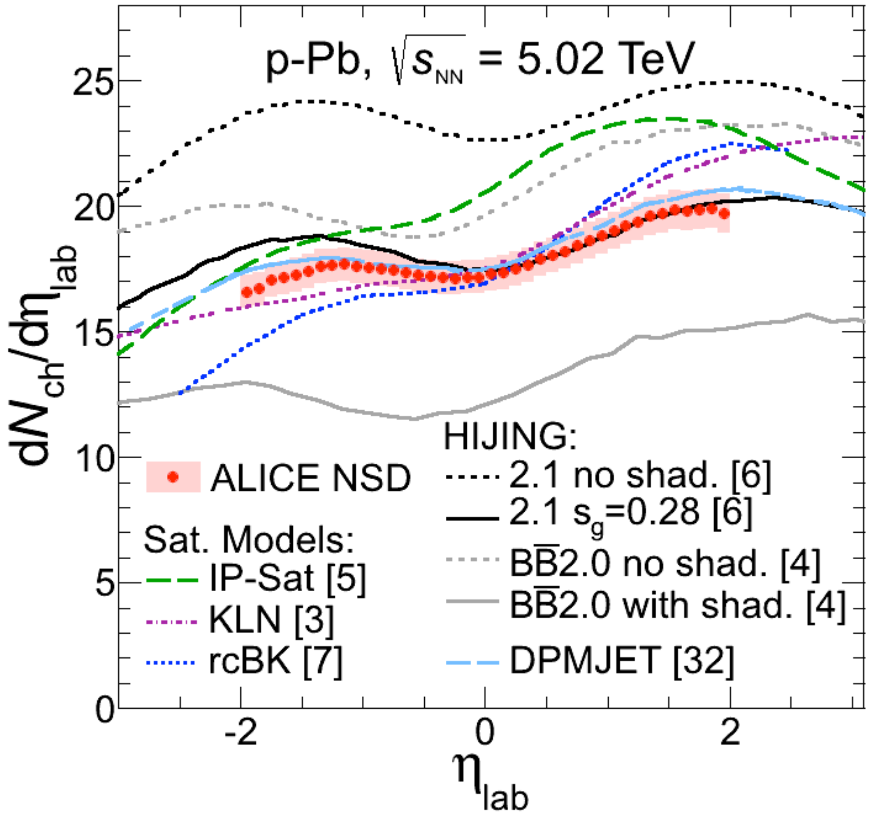
- J/ψ produced via regeneration of thermal de-confined c-quarks should show **a non zero v_2.**
- **First hint of non-zero v_2.**
- Consistent with the transport model with regeneration.

Highlights from p-Pb results (2013)

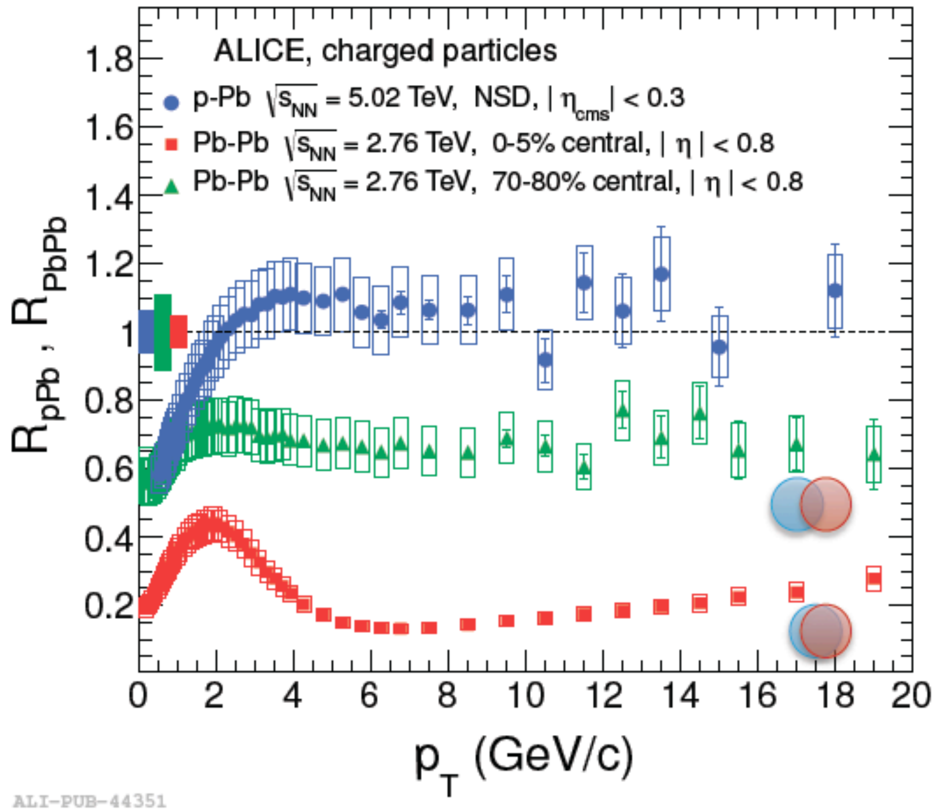
Sep. 13, 2012 (ALICE)
p+Pb test run

dN/dη, R_{AA} in p-Pb

ALICE, PRL 110 (2013) 032301



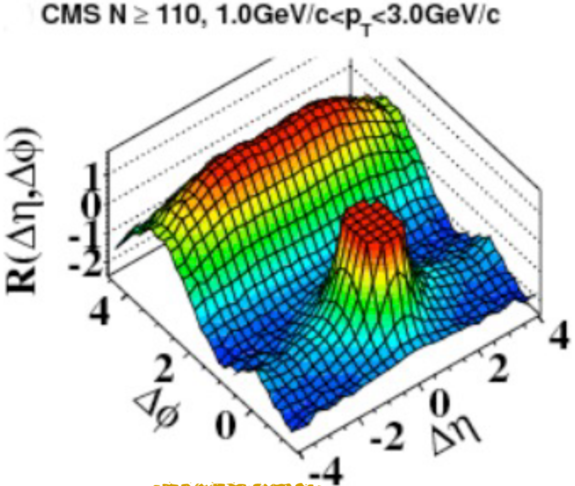
ALICE, PRL 110 (2013) 082302



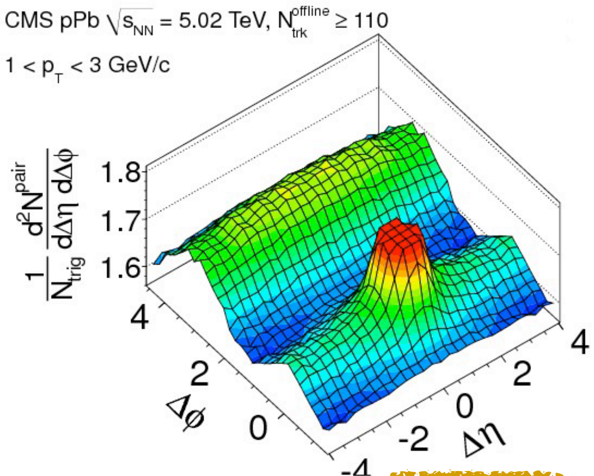
- dN/dη: most models reproduce data <20%. CGC: steeper rise on shape.
- R_{AA} ~ 1 in pPb: suppression in Pb-Pb central is a final state effect.

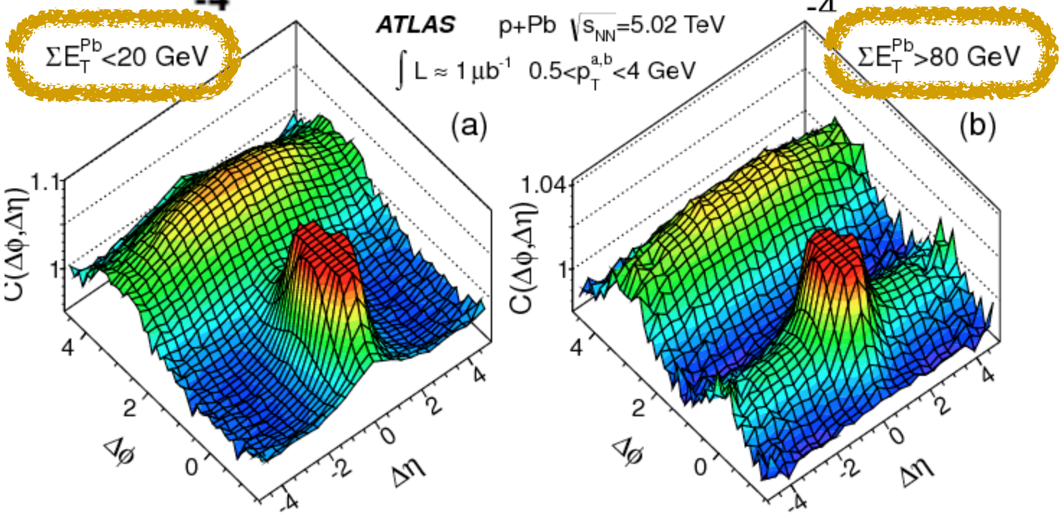
Di-Hadron Correlations in p-p & p-Pb

p-p (N ≧110)



p-Pb (N ≧110)





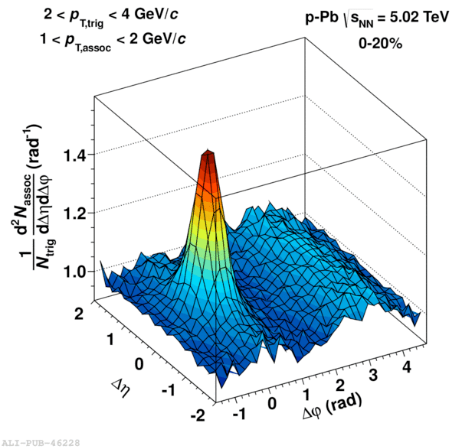
p-Pb (ΣE_T ^{Pb}) < 20 GeV **p-Pb (ΣE_T ^{Pb}) > 80 GeV**

- First observation of **ridge structure in high multiplicity p-p** (CMS).
- Also confirmed in **p-Pb high multiplicity events**.
- Alway side ridge structure is observed in high multiplicity p-Pb.

CMS, JHEP 1009 (2010) 91
CMS, PLB 718 (2012) 795
ATLAS, PRL 110, 182302 (2013)

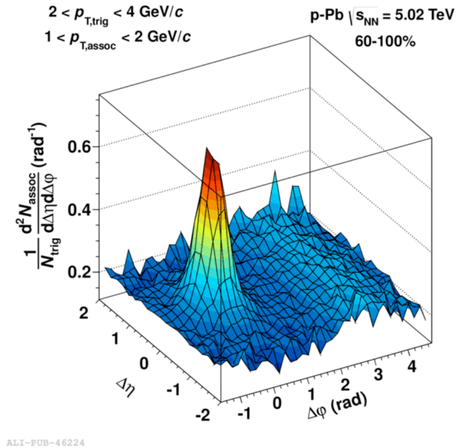
Double ridge structure in p-Pb

ALICE, PLB 719 (2013) 29



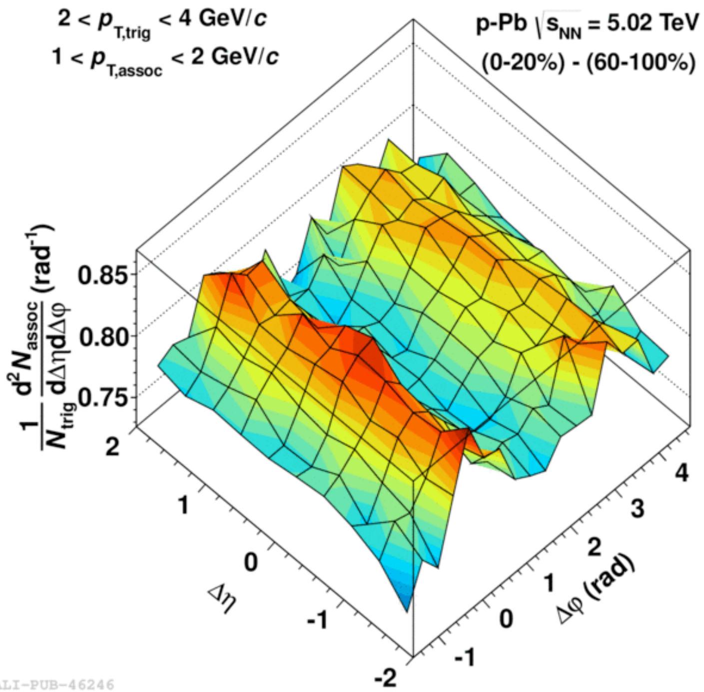
0-20%

−

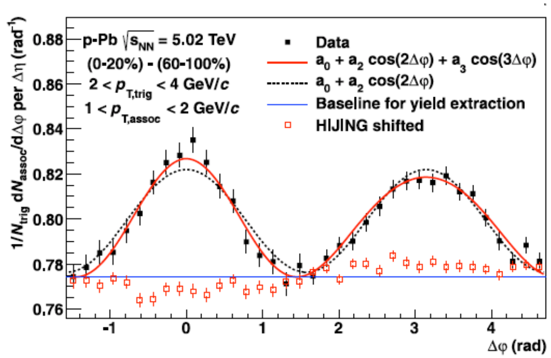


60-100%

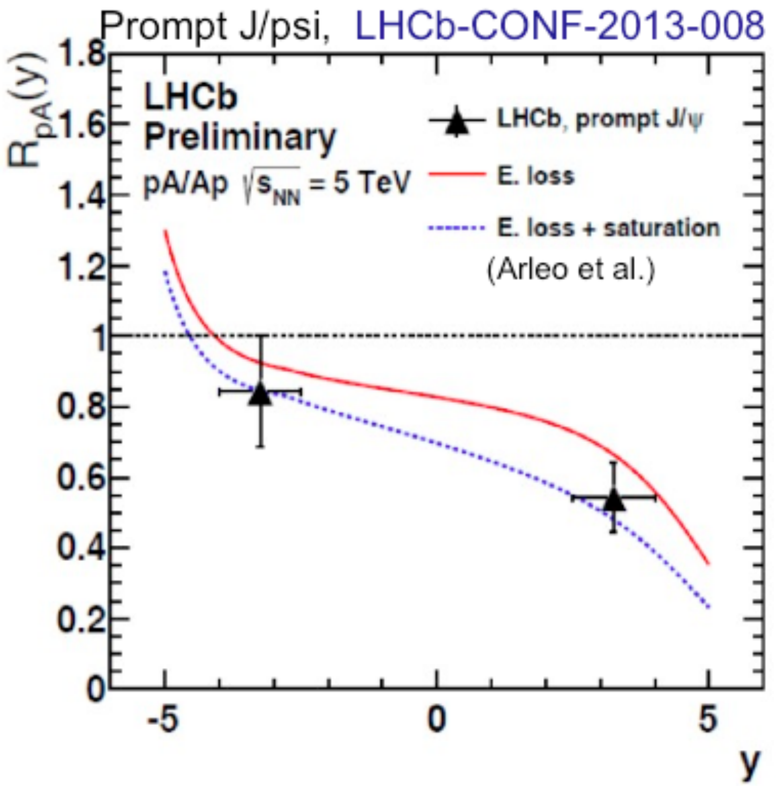
=

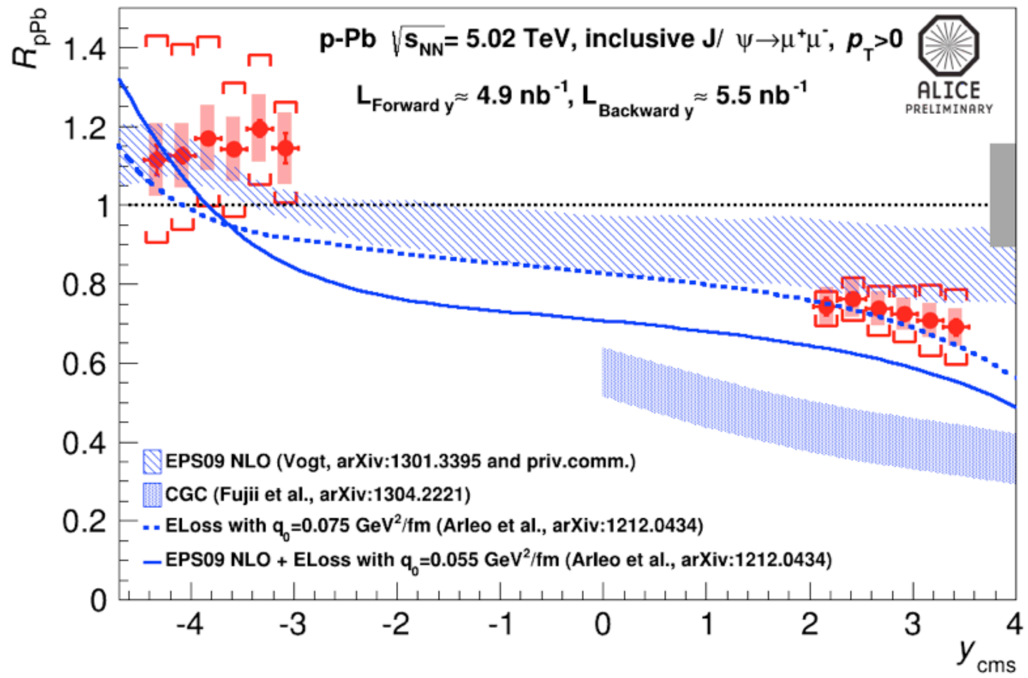


- Extract double ridge structure by subtracting p-p jet like distribution in p-Pb (60-100%) from central p-Pb (0-20%).
- Confirmed that near and away side ridges are almost same structure.
- **Strong correlation between near and away side yields, suggesting the same origin.**



J/ψ R_{pPb}



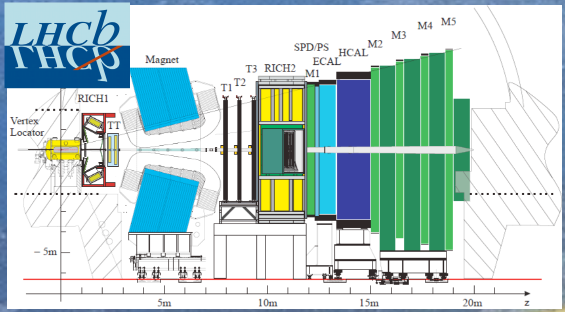


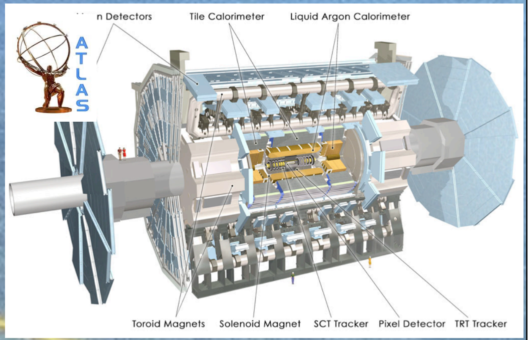
Comparison between prompt and inclusive J/ψ:

- Measurements are consistent within uncertainties, although prompt is ~ 30% lower overall.
- Provides further constraints on CGC model.

Summary

- Hottest, largest, longer lived QGP is produced at LHC heavy ion collisions.
- There are similarities, differences compared to RHIC, and newly discovered properties on QGP at LHC.
- We enter an era of determination of QGP properties by jets, photons, c/b quarks, quarkonium with bulk particles.
- **Future**
  - Run with full energy $\sqrt{s_{NN}}$ = 5.5 TeV Pb-Pb in 2015-2017 (Run-2), with upgraded detectors (LS1, ALICE).
  - Preparing the detector upgrade for higher luminosity LHC run during LS2 (2018) for Run-3 (2019-2022).





Thank you for your attentions!