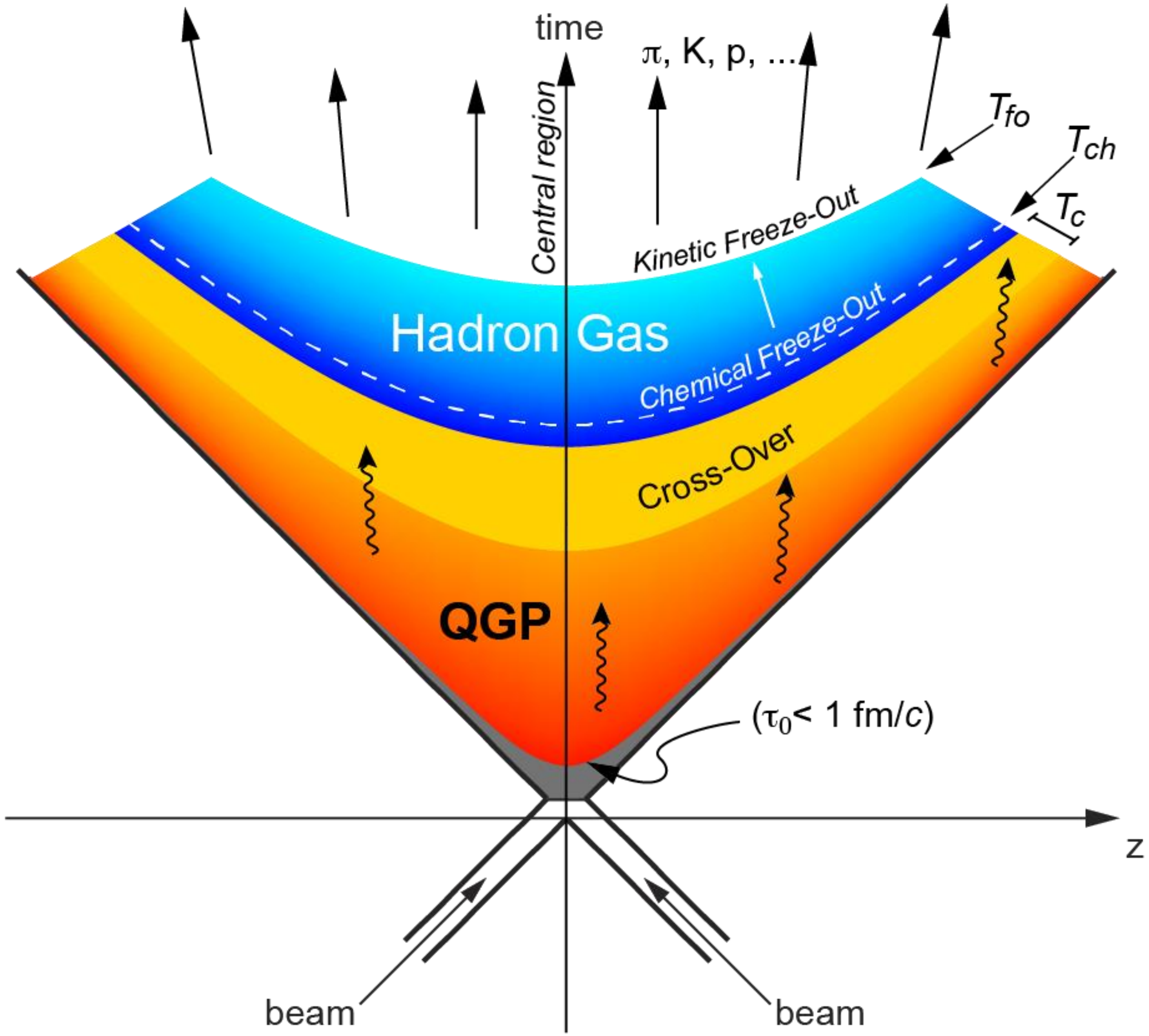
Heavy Ions: Signatures and precise measurements

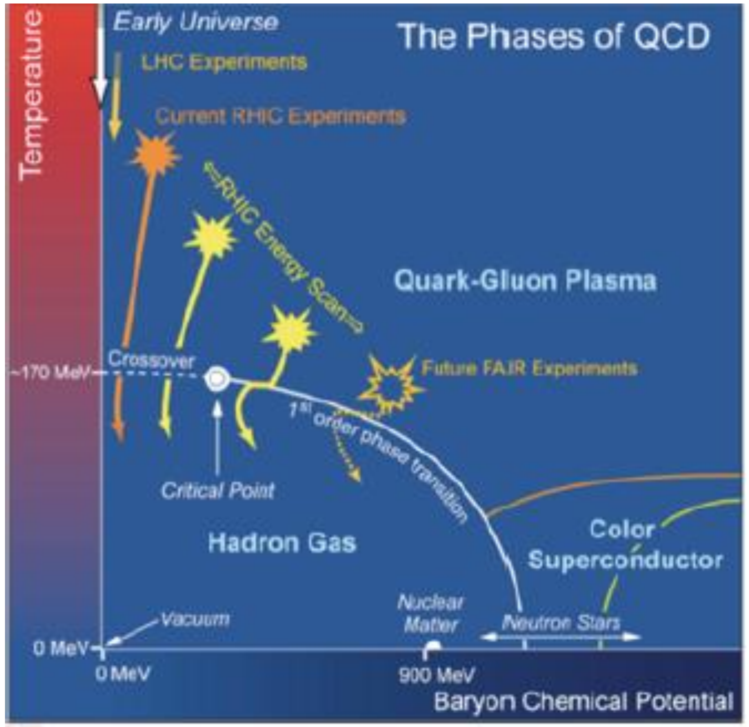
Luciano Ramello, Università del Piemonte Orientale
and INFN sez. Torino, Alessandria, Italy

Outline

- Heavy Ion experiments at the LHC
- Global properties
- Particle production
- Collective effects
- Jet quenching
- Open heavy flavours
- Quarkonia
- Summary & Outlook

Heavy Ion Collisions at the LHC



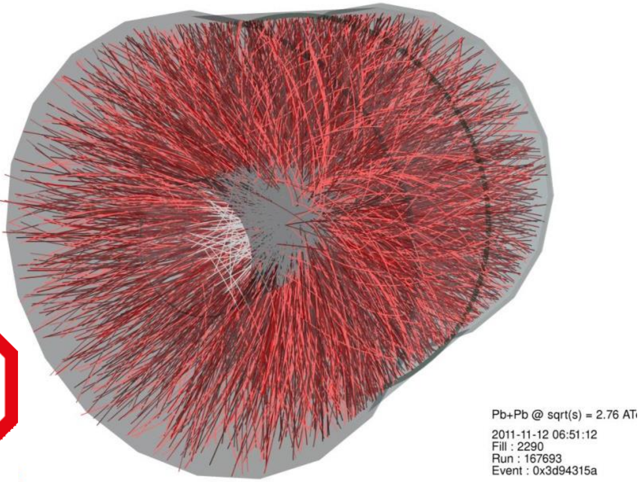


Hard processes (heavy flavours, jets, direct photons): probe the whole evolution of the system

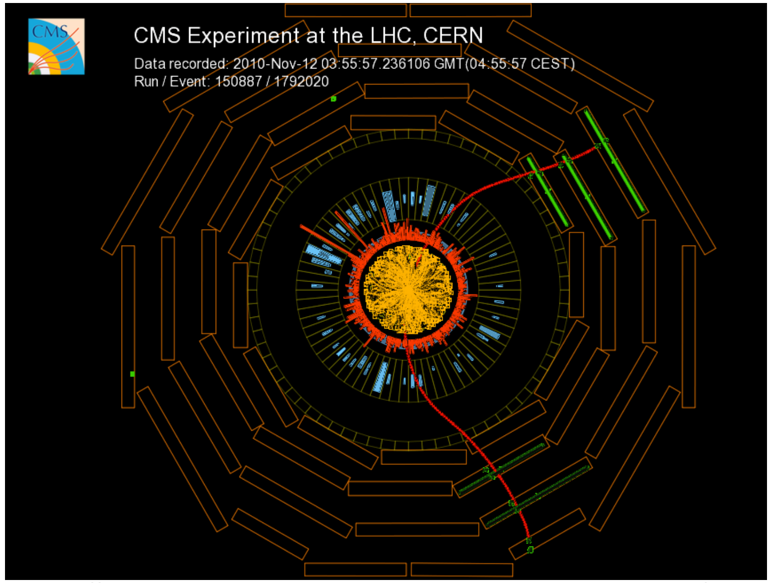
Soft processes (bulk particle production, correlations): decouple late, indirect signals of QGP

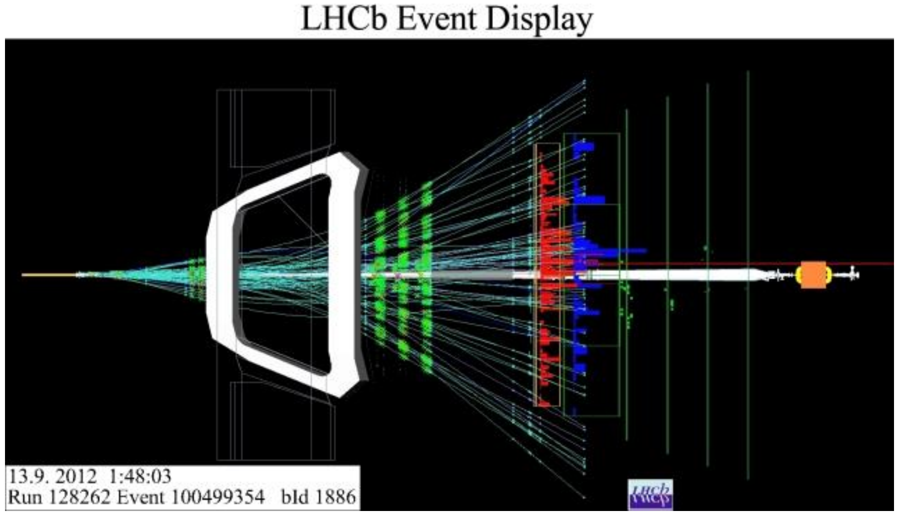
- Particle composition fixed at $T_{ch} \approx 160$ MeV
- Momentum spectra fixed at $T_{fo} \approx 110\text{-}130$ MeV

Heavy Ion Experiments at CERN



ALICE





LHCb joined since the p-Pb run of 2013

LHC Run 1 and Run 2

	Run 1		Run 2		
Colliding System	$\sqrt{s}$ ($\sqrt{s_{NN}}$)	Year(s)	$\sqrt{s}$ ($\sqrt{s_{NN}}$)	Year(s)	
Pb-Pb	2.76 TeV	2010, 2011	5.02 TeV	2015*	Quark Gluon Plasma study
p-Pb	5.02 TeV	2013*	5.02 TeV 8 TeV	2016** (upcoming)	Cold Nuclear Matter effects, Reference for Pb-Pb
pp	2.76 Tev 7 TeV 8 TeV	2011, 2012	5.02 TeV 13 TeV	2015, 2016	Reference for p-Pb and Pb-Pb; 13 TeV: onset of collectivity?

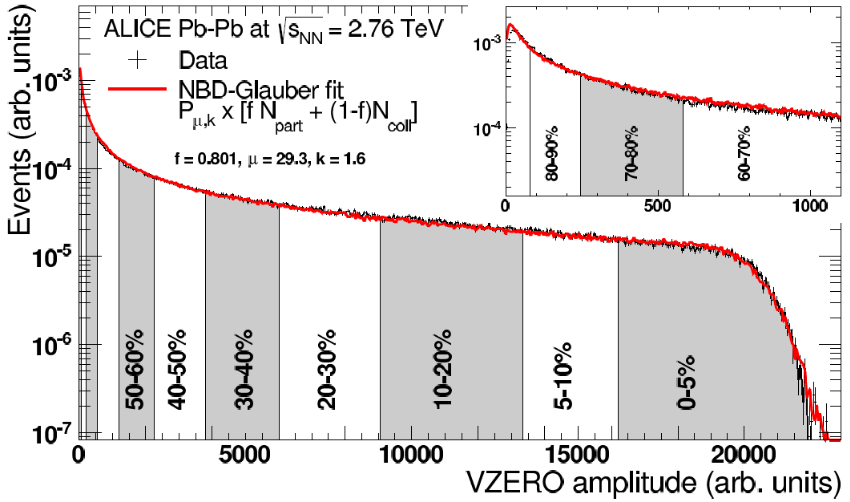
* First time for LHCb in Heavy-Ion collisions: p-Pb 2013, Pb-Pb 2015

** November-December 2016

Centrality determination

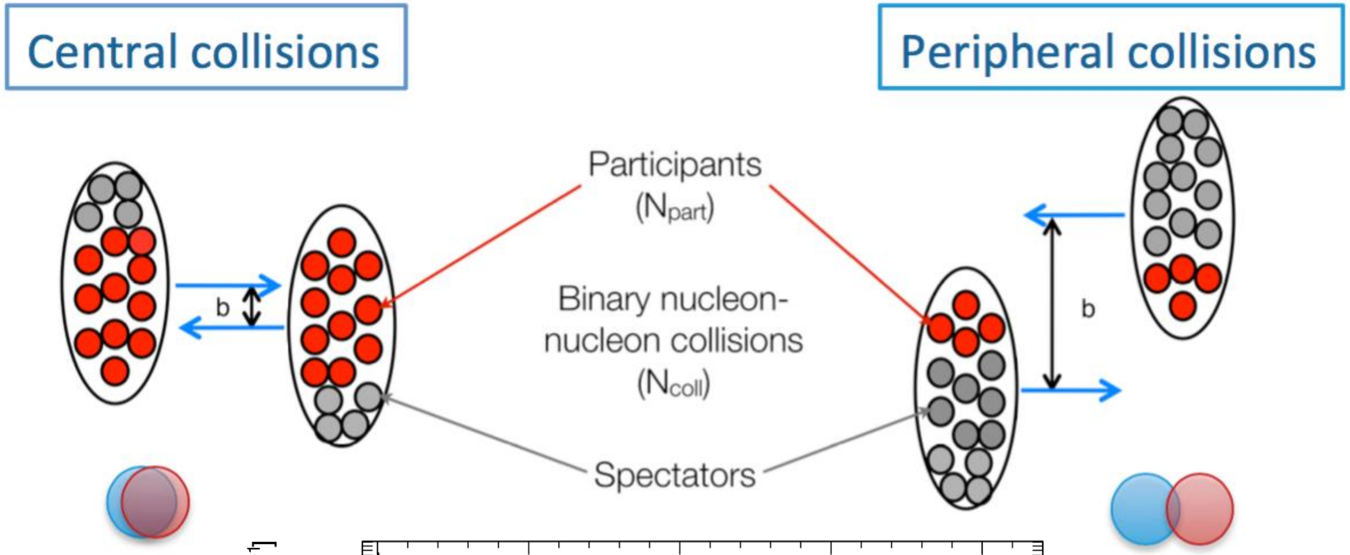
ALICE: Phys. Rev. C 88, 044909 (2013)

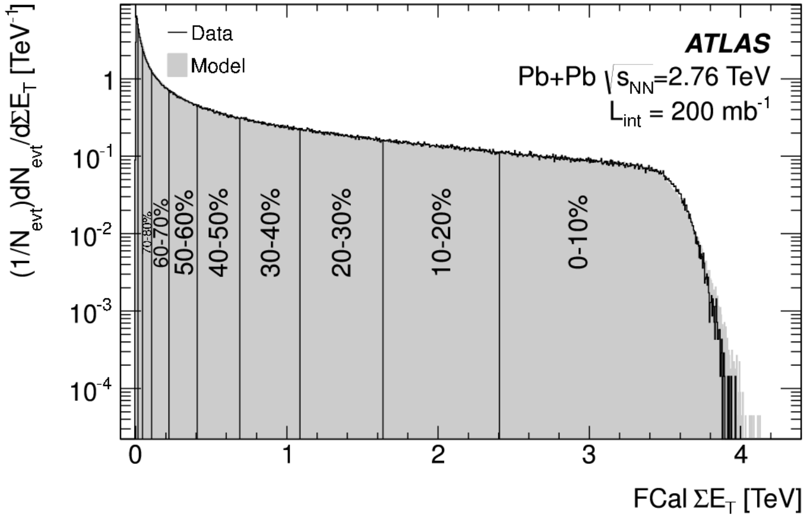
VZERO (scint. hodoscope) amplitude ⇒ determine centrality percentiles from 0% (most central) to 90%



Centrality characterized by impact parameter b, number of nucleon participants N_{part}, number of N-N collisions N_{coll}

- related to observables like multiplicity, transverse energy via Glauber model



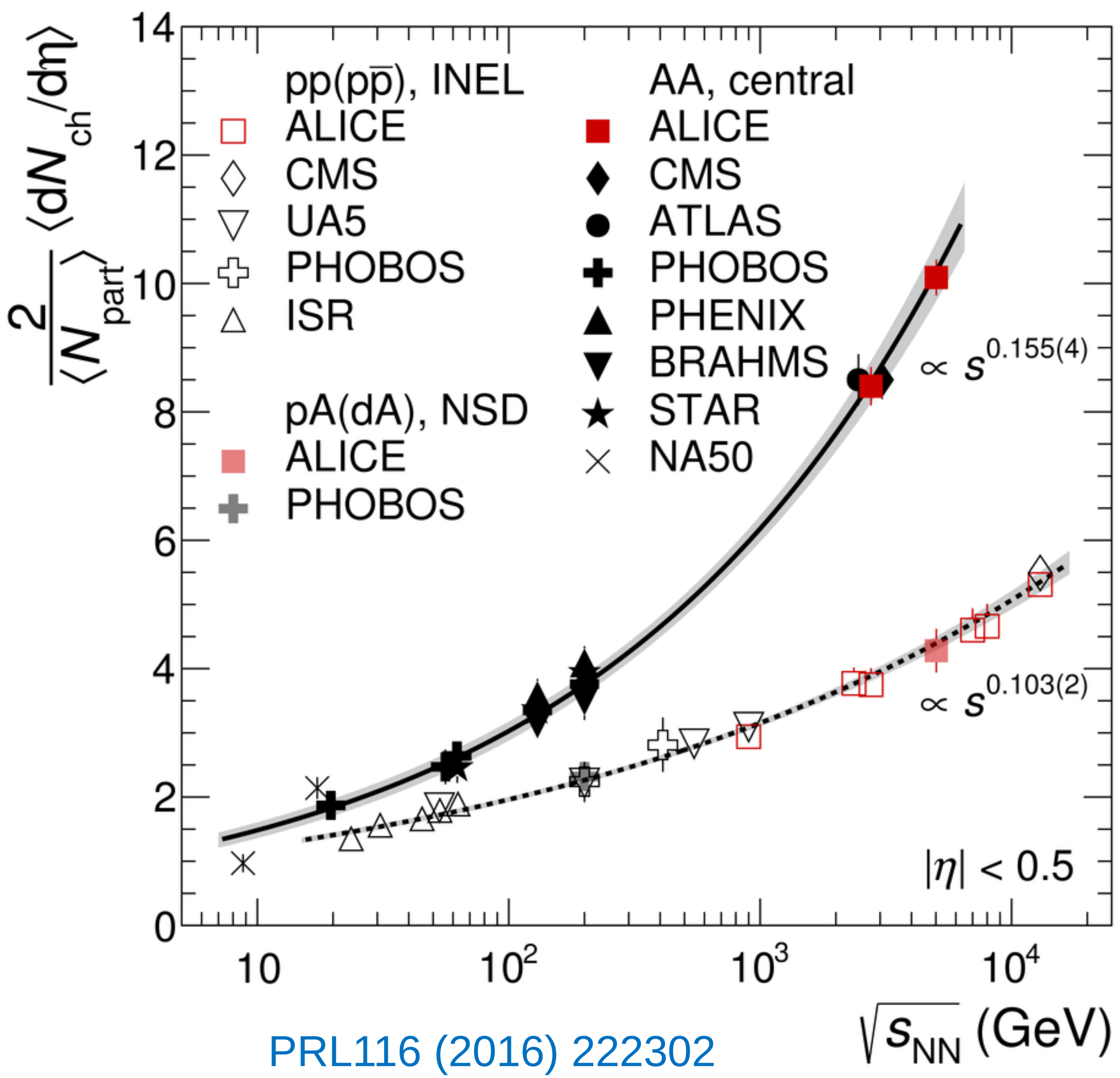


ATLAS: PLB 707 (2012) 330

Charged particle multiplicity

- $dN_{ch}/d\eta$ in $|\eta|<0.5$ for 0-5% most central collisions [ATLAS, PHOBOS: 0-6%]
- Power law fits $a \cdot s^c$:
  - A-A central collisions, $c = 0.155 \pm 0.004$
  - Min. Bias pp, pA coll., $c = 0.103 \pm 0.002$

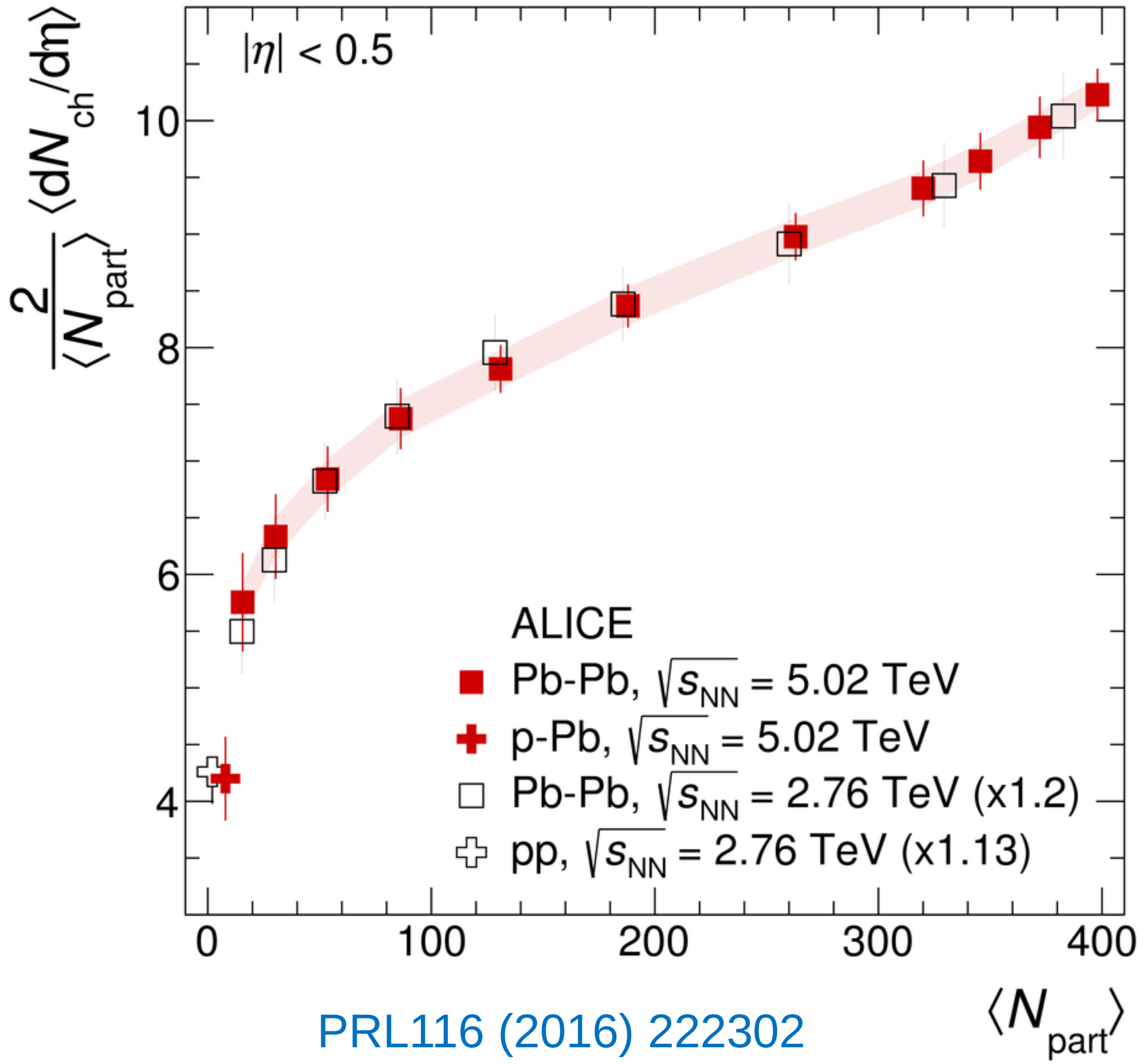
  steeper rise for A-A central collisions wrt pp collisions
- Results at $\sqrt{s_{NN}}$ = 5.02 TeV (highest energy so far) confirm trend from lower energies



PRL116 (2016) 222302

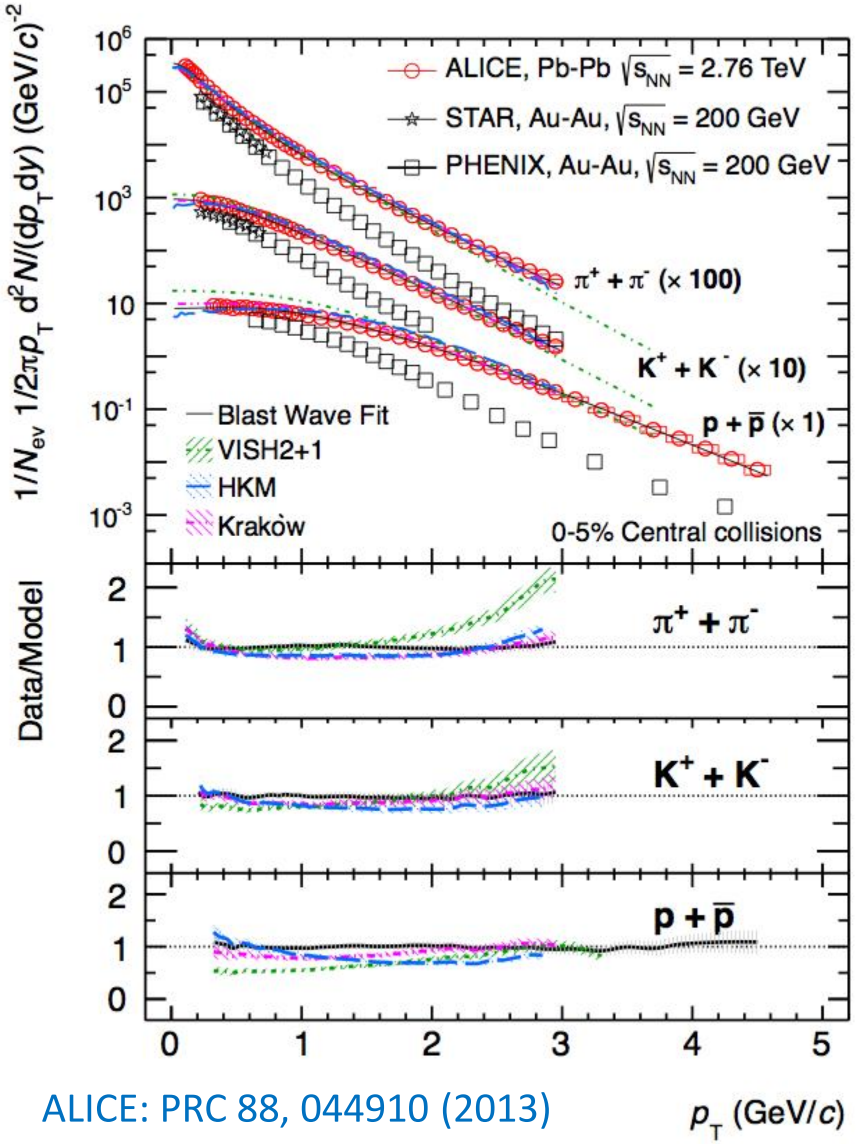
Centrality dependence of $dN_{ch}/d\eta$ at mid-rapidity

- N_{part} from Glauber model
- Similar evolution with centrality between 2.76 and 5.02 TeV
- 20% increase going from 2.76 to 5.02 TeV

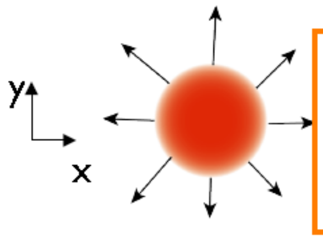


PRL116 (2016) 222302

Bulk particle production in central Pb-Pb



ALICE: PRC 88, 044910 (2013)



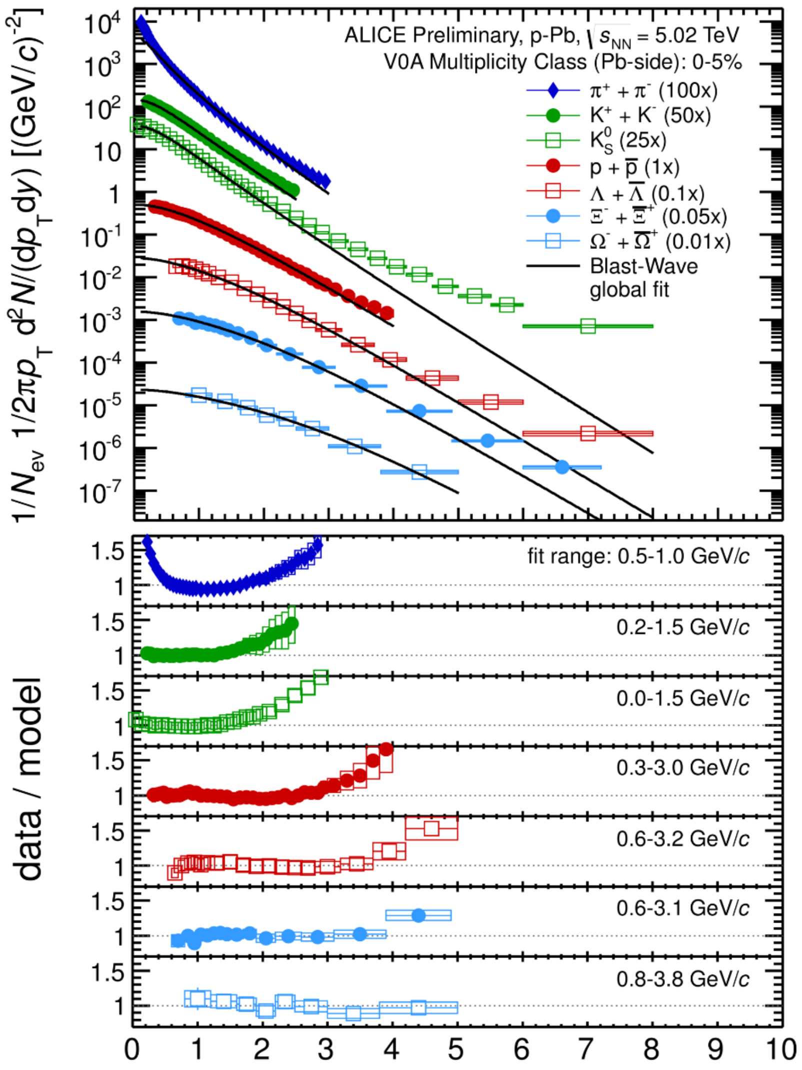
In a thermalized system the radial expansion is driven by the pressure gradient from inside to outside, resulting in boosted p_T spectra

Blast-wave fits to extract:
- kinetic freeze-out temperature
- radial flow velocity

T_{kin} ~ 95 MeV (similar to RHIC)
$\langle\beta_T\rangle$ ~ 0.65 (10% larger than at RHIC)
⇨ larger radial flow than at RHIC

Spectra become harder with increasing centrality (from peripheral to central) and more so for heavier particles, as expected by collective expansion (see backup slides for details)

Bulk particle production in p-Pb

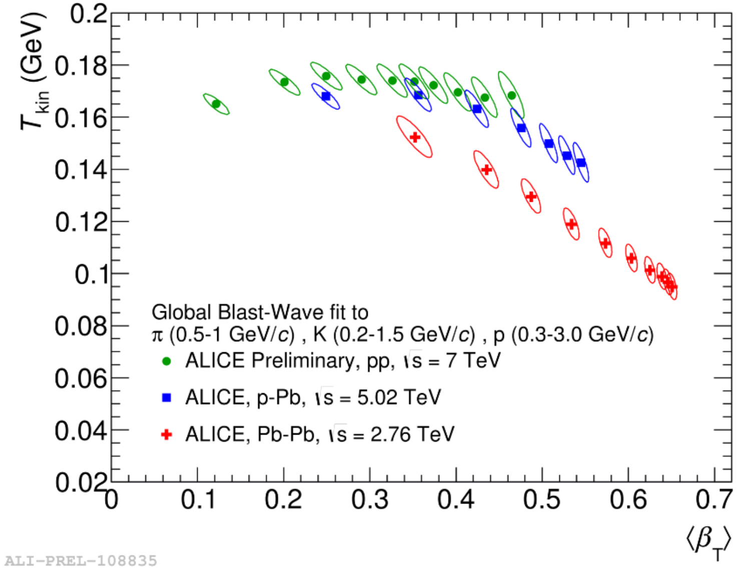


PLB 728 (2014) 25 (hyperons excepted)

ALI-PREL-73424

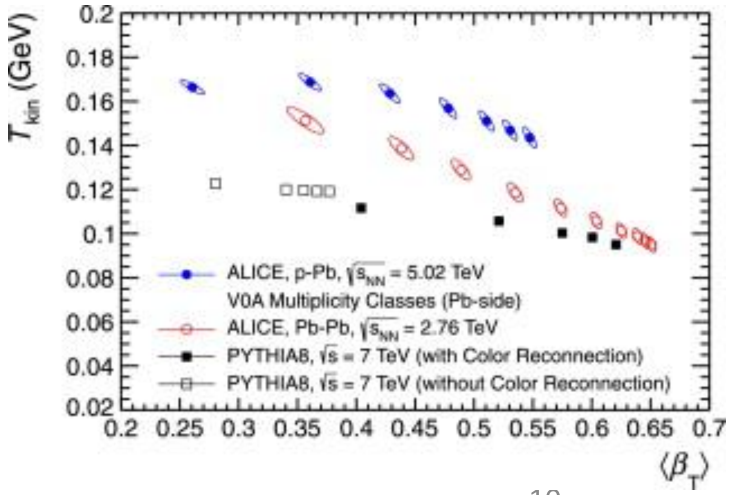
A combined BW fit describes spectra fairly well also in p-Pb

The T_{kin} - $\langle\beta_T\rangle$ correlation shows similar trends for pp and p-Pb



ALICE p-Pb and Pb-Pb:
PLB 728 (2014) 25

Qualitatively PYTHIA with Color Reconnection shows a similar trend as the data: other final state mechanisms can mimic the effect of radial flow



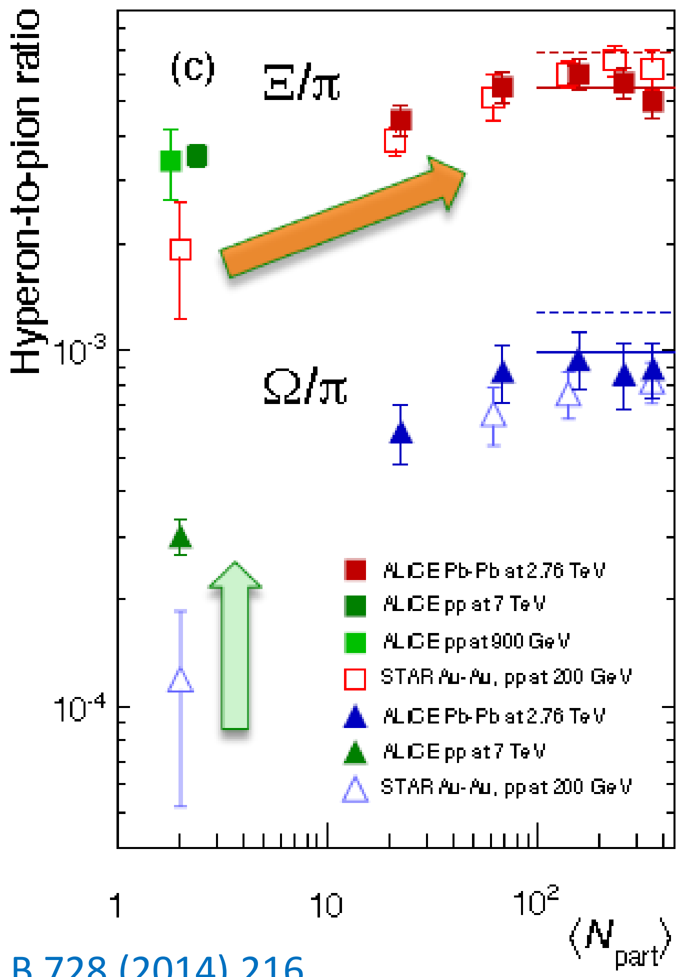
Strangeness enhancement

a historical probe for QGP formation

Rafelski and Müller, PRL 48, 106 (1982)

Rafelski and Hagedorn, in Statistical Mechanics of Quarks and Hadrons

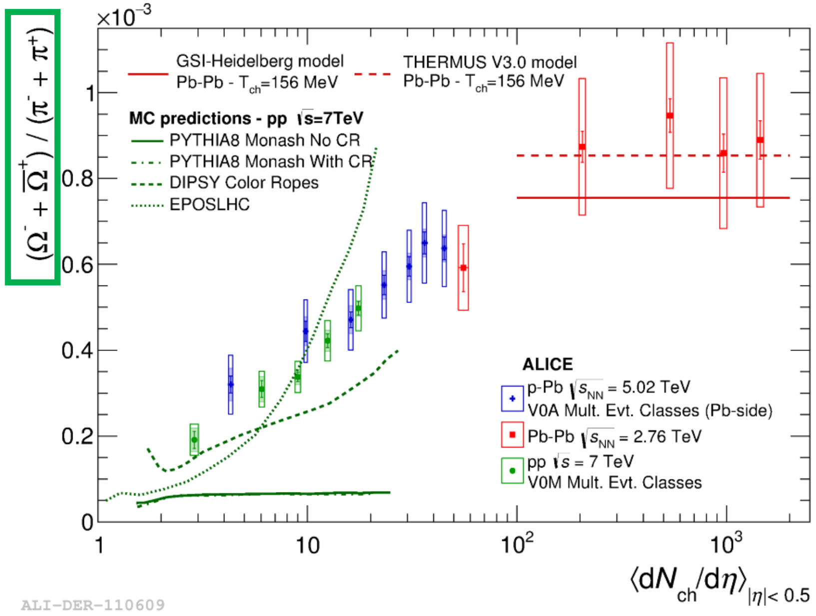
- Main idea: in the QGP there is (almost) no penalty for $s\bar{s}$ formation relative to light quarks
  - Multi-strange baryon production should be enhanced with respect to single-strange
- In pp collisions the production of strangeness relative to pions is larger at LHC than at RHIC
- From pp to Pb-Pb (or Au-Au) strangeness production increases
- For N_{part} > 150 the ratios Ξ/π and Ω/π saturate and match the grand-canonical thermal models prediction:
  - — GSI-Heidelberg T_{ch} = 164 MeV
  - … THERMUS T_{ch} = 170 MeV

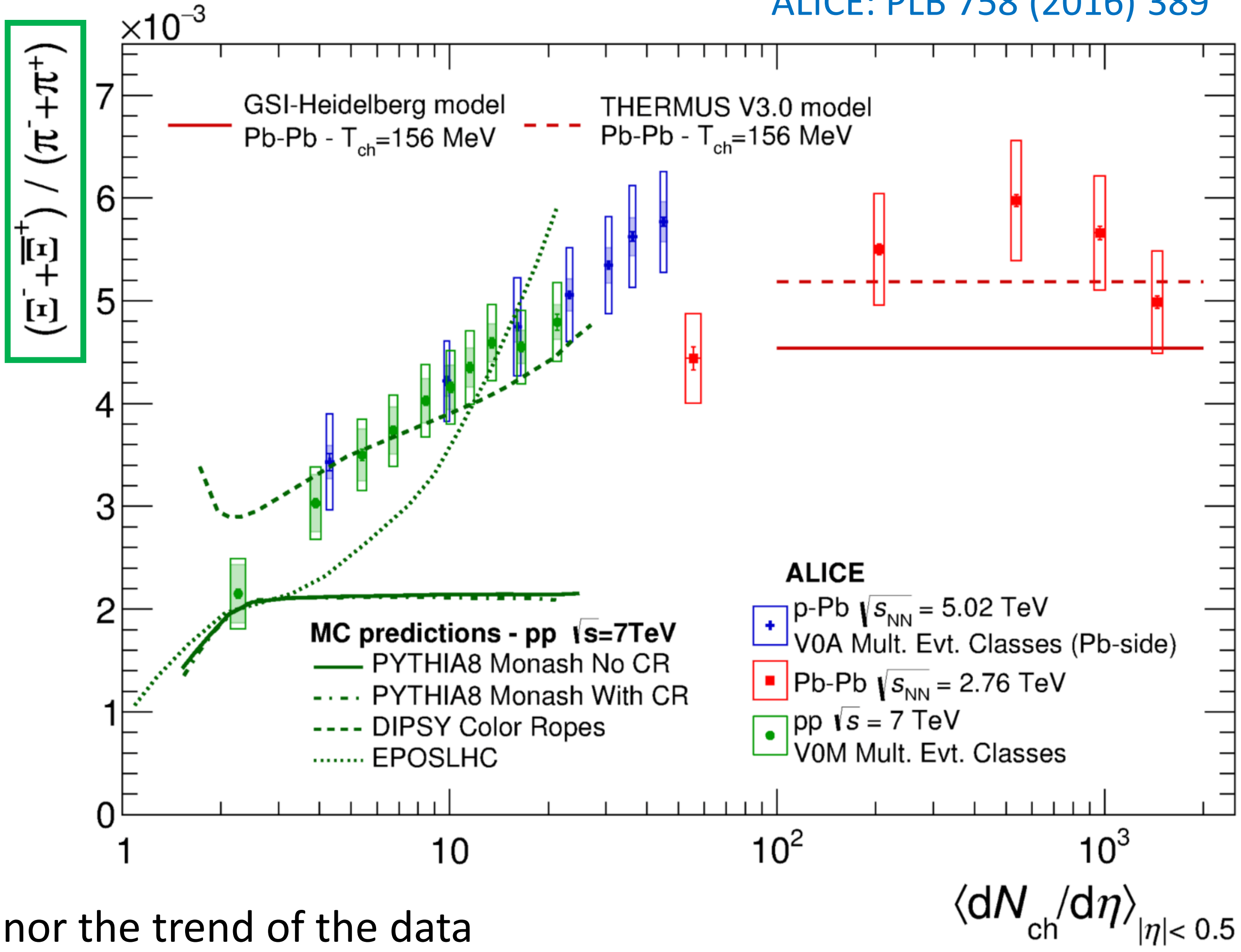


ALICE, PLB 728 (2014) 216
corrigendum: PLB 734 (2014) 409

Strangeness from pp to p-Pb to Pb-Pb

ALICE: PLB 758 (2016) 389





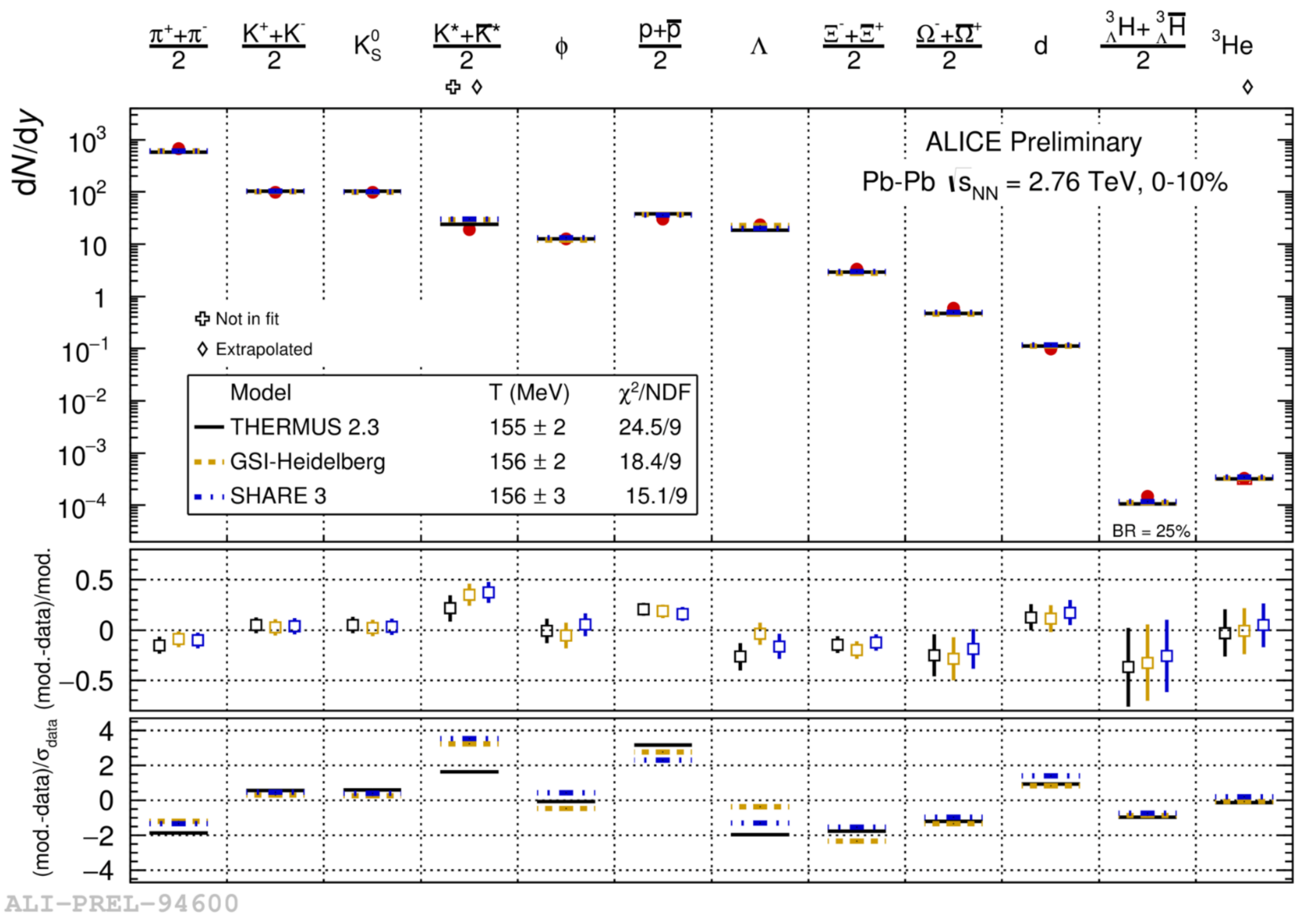
In high multiplicity p-Pb at 5.02 TeV:

- Ξ/π compatible with central Pb-Pb
- Ω/π compatible with 60-80% Pb-Pb

Also in high multiplicity pp multi-strange production rises significantly

- PYTHIA8 does not reproduce the values nor the trend of the data
- MC models as DIPSY (color ropes) and EPOS LHC exhibit a trend with multiplicity but may still need tuning

Particle yields and Thermal models



- Describes hadron production assuming **chemical equilibrium over seven order of magnitude**

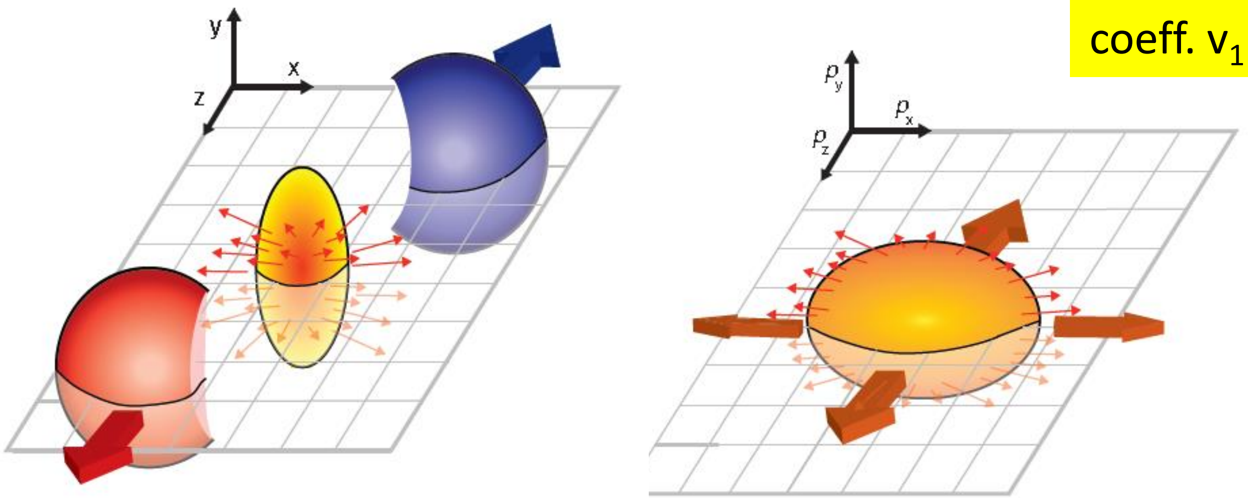
- Measured absolute yields (d*N*/d*y*) in Pb-Pb collisions are well described by a thermal model with a temperature T=156 ± 2 MeV

- Deviations for
  - Protons: incomplete hadron spectrum, baryon annihilation in hadronic phase, …?
  - K^{*0} resonance: re-scattering in the late hadronic phase?

THERMUS: Wheaton et al, Comput. Phys. Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673, 142
SHARE: Petran et al, Comput. Phys. Commun, 185 Issue 7, 2056

Collective expansion: Anisotropic flow

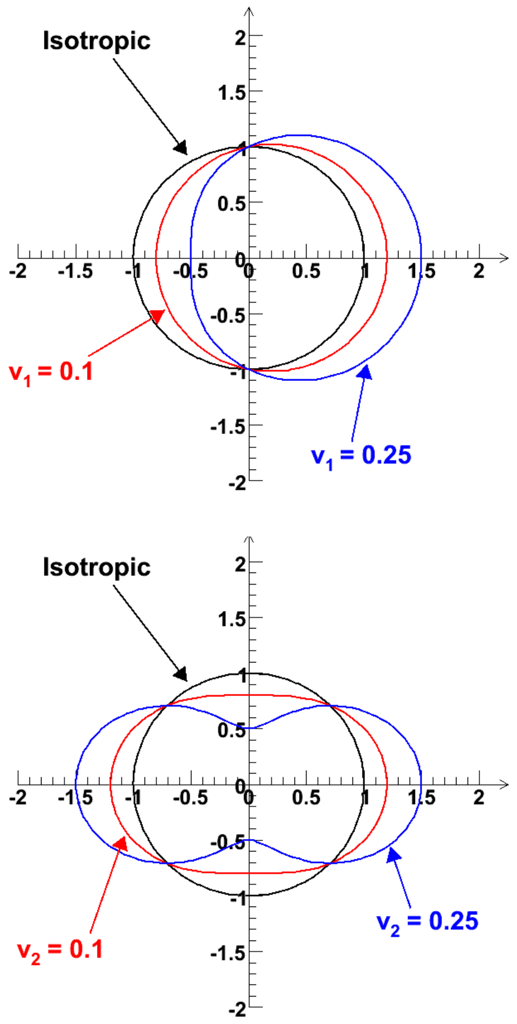
- Basic idea: space anisotropy of initial fireball ⇨ momentum anisotropy in final hadron distributions



directed flow coeff. v_1

elliptic flow coeff. v_2

Reaction plane xz

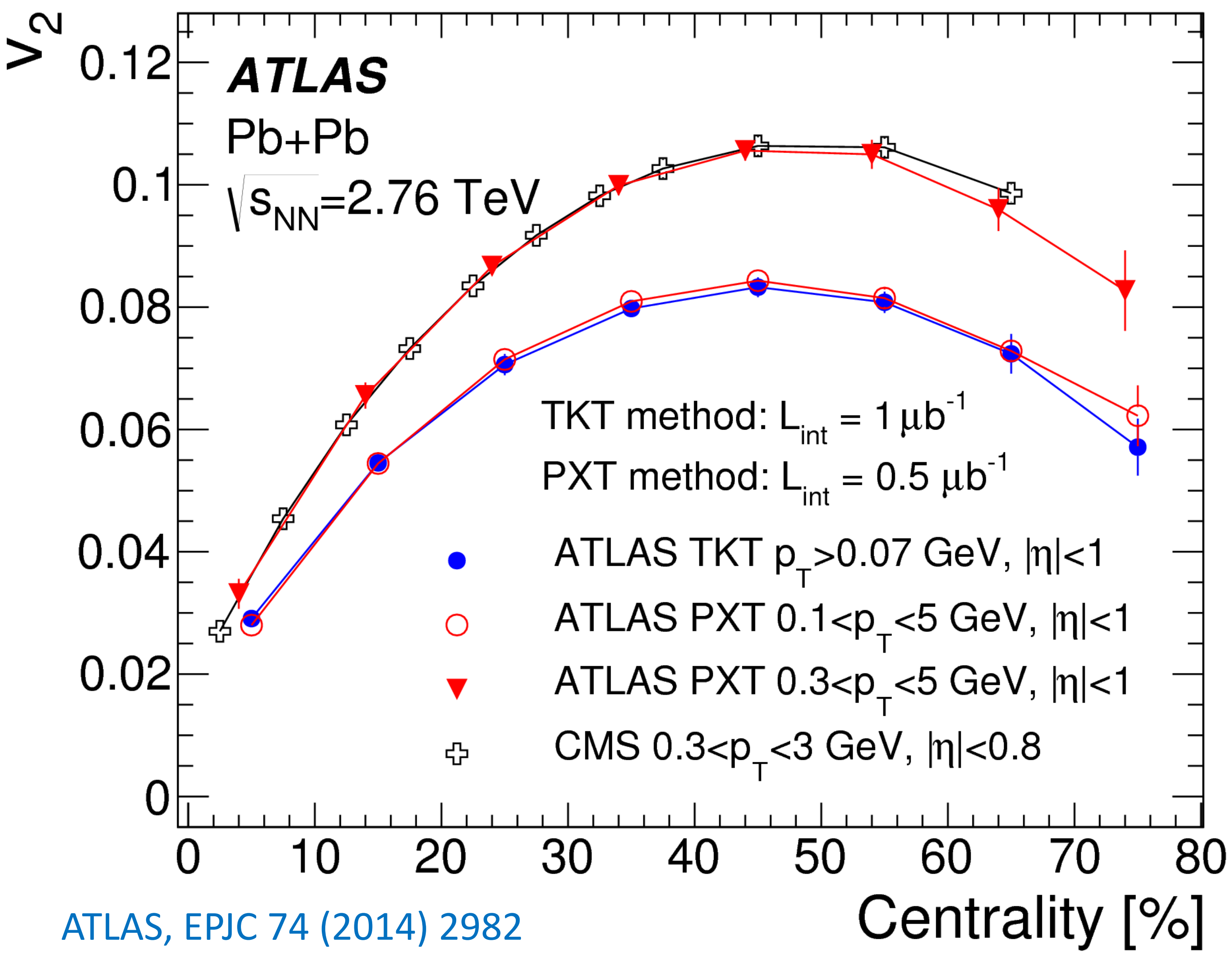


Figures courtesy F. Prino

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)\right]$$

Several methods to extract v_n: event plane, cumulants…
… each with different systematics from 'non-flow'

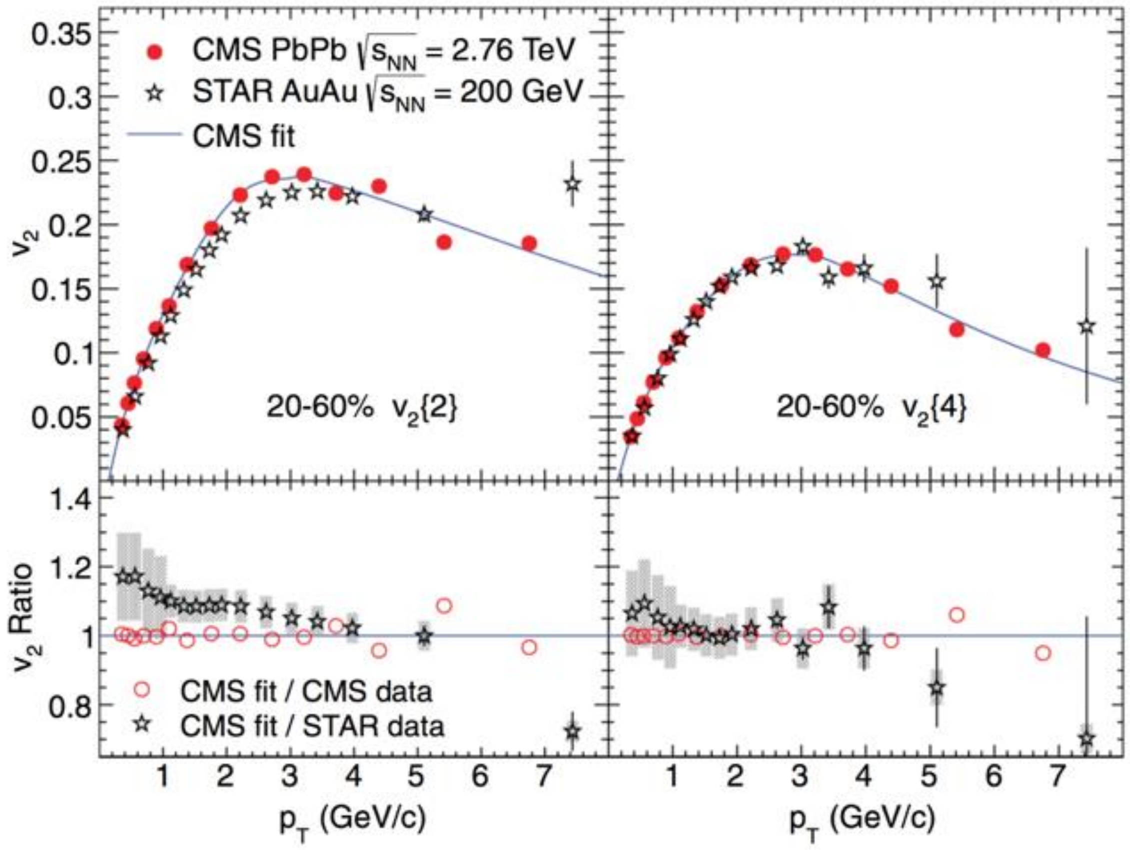
Elliptic flow vs. centrality



ATLAS, EPJC 74 (2014) 2982

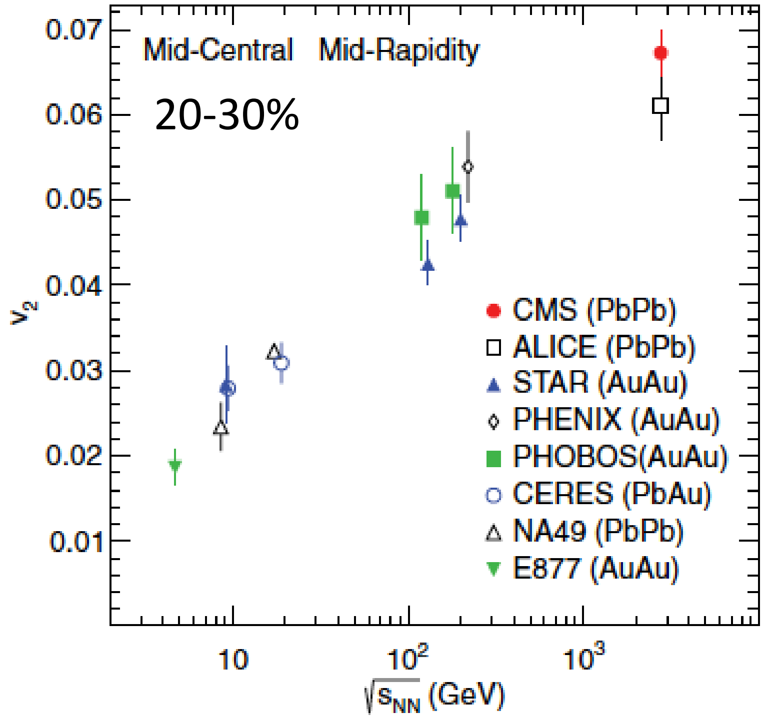
- Strong collective flow observed at LHC
- Integrated values of elliptic flow coefficient v_2 sensitive to the p_T range, since v_2 increases (initially) linearly with p_T

Elliptic flow vs. p_T

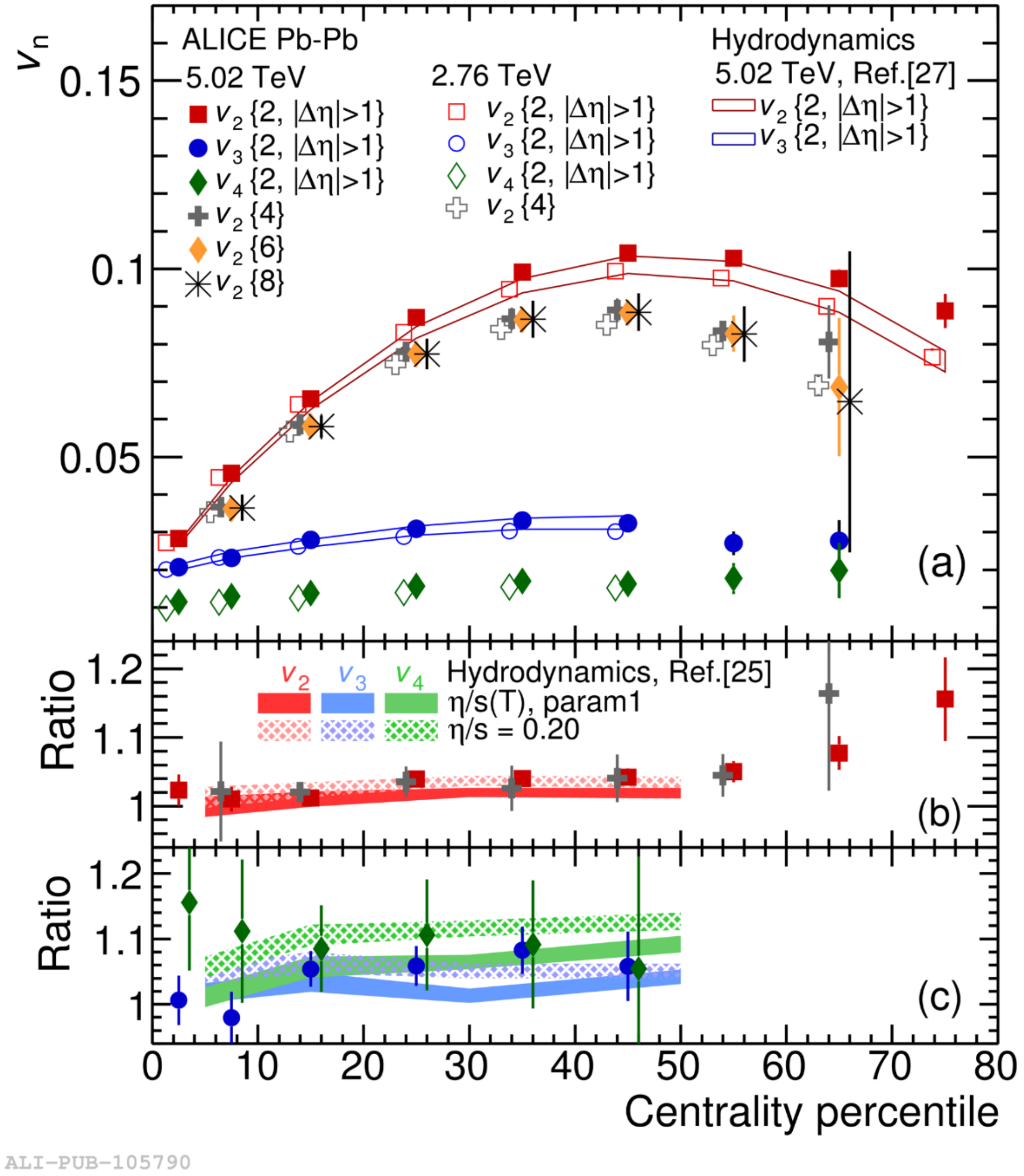


CMS: PRC 87, 014902 (2013)

- Moderate increase of $v_2(p_T)$ at low p_T from highest RHIC energy to LHC energy, for a large increase in c.m. energy
- The integrated v_2, thanks to a harder p_T distribution at higher c.m. energy, increases of 20-30% from RHIC to LHC



Elliptic flow in Pb-Pb: 5.02 TeV compared to 2.76

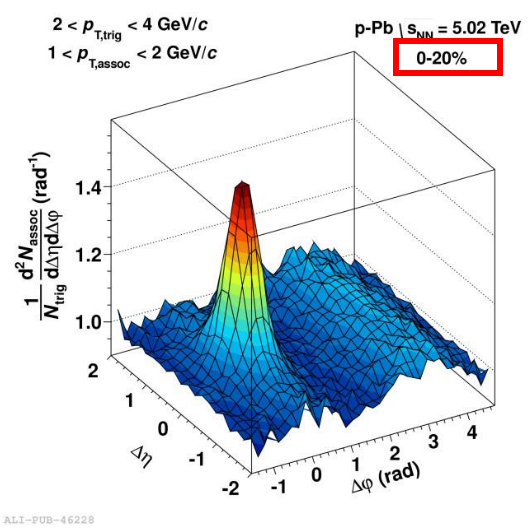


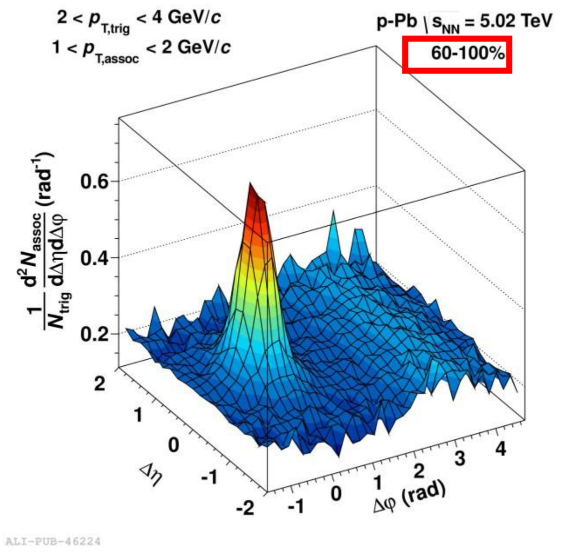
- Anisotropic flow coefficients v_2, v_3, v_4 integrated over p_T range 0.2-5.0 GeV/c as a function of centrality
- Average increase of (3.0±0.6)% for v_2, (4.3±1.4)% for v_3 and (10.2±3.8)% for v_4 from 2.76 to 5.02 TeV
- Results compatible with predictions from hydrodynamic models, ratio viscosity/entropy density η/s can be constrained by data

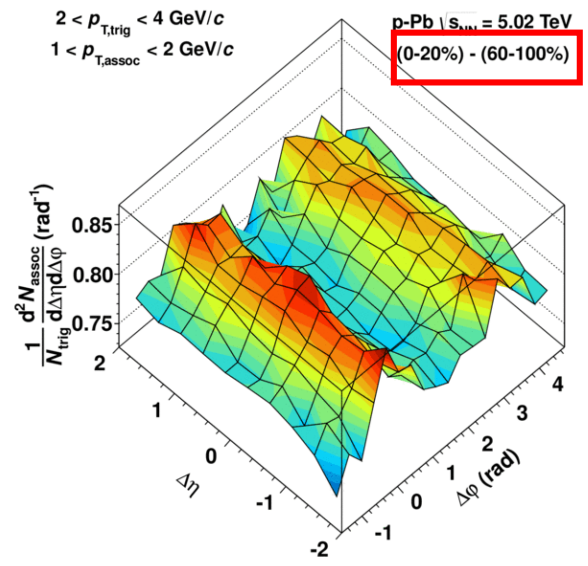
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left[1+\sum_{n=1}^{\infty} 2v_n \cos(n\phi)\right]$$

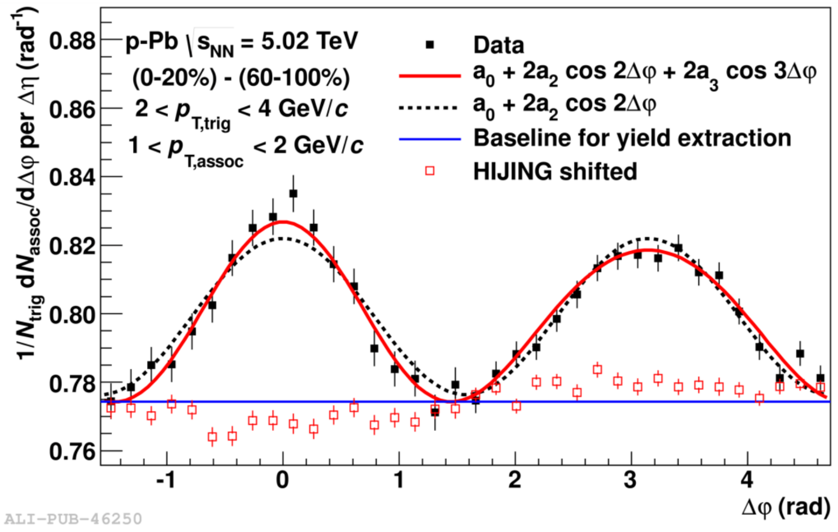
ALICE: PRL116 (2016) 132302

The ridge(s) in two-particle correlation









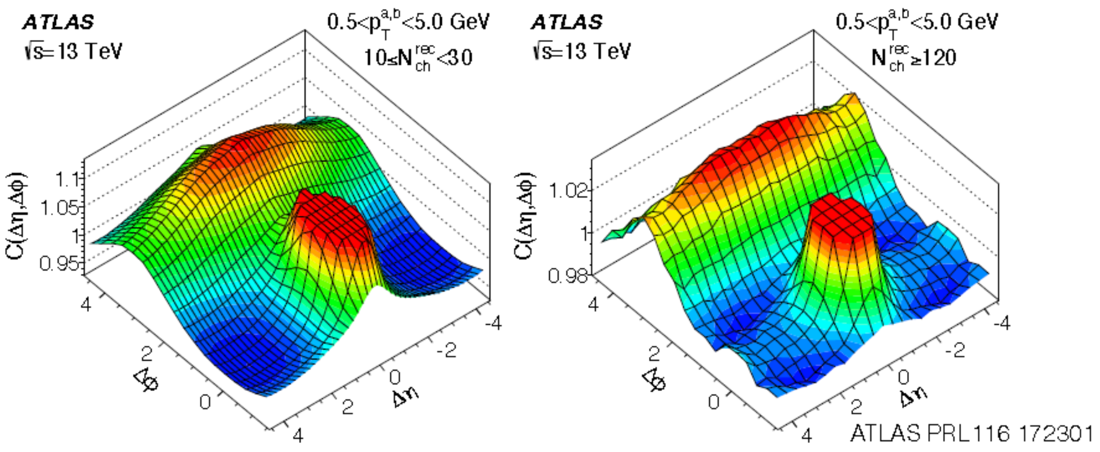
- Unexpected collective behaviour in high-multiplicity events at low p_T even in the small p-Pb system
- Described either by colour glass condensate (initial state) or hydrodynamics (final state)

ALICE, PLB 719 (2013) 29;
See also:
ATLAS PRL 110 (2013) 182302,
CMS PLB 718 (2012) 795,
LHCb arXiv:1512.00439

The ridge in pp and p-Pb collisions

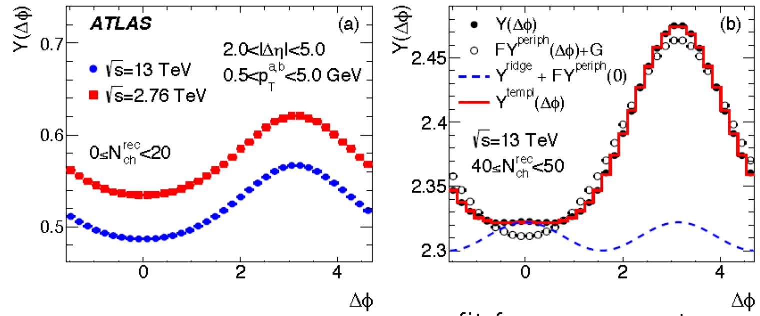
pp

low multiplicity | high multiplicity



fitting procedure

$Y^{periph}(\Delta\Phi)$, $N_{ch}^{rec} < 20$ | $40 < N_{ch}^{rec} < 50$



$$Y^{templ}(\Delta\phi) = F\, Y^{periph}(\Delta\phi) + Y^{ridge}(\Delta\phi)\,,$$

fit free parameters: F & $v_{2,2}$

$$Y^{ridge}(\Delta\phi) = G\,(1 + 2v_{2,2}\cos(2\Delta\phi))\,,$$

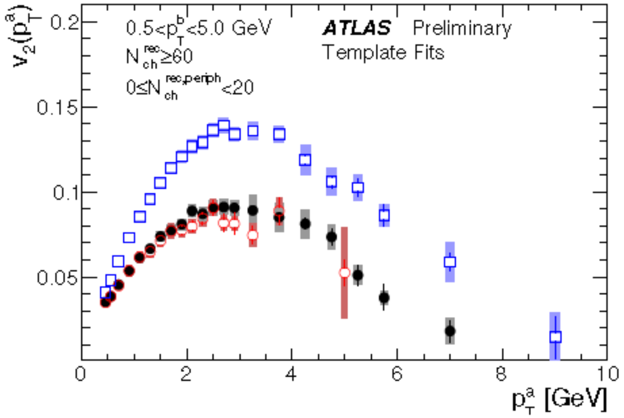
G fixed such that:

$$\int_0^\pi d\Delta\phi\; Y^{templ} = \int_0^\pi d\Delta\phi\; Y.$$

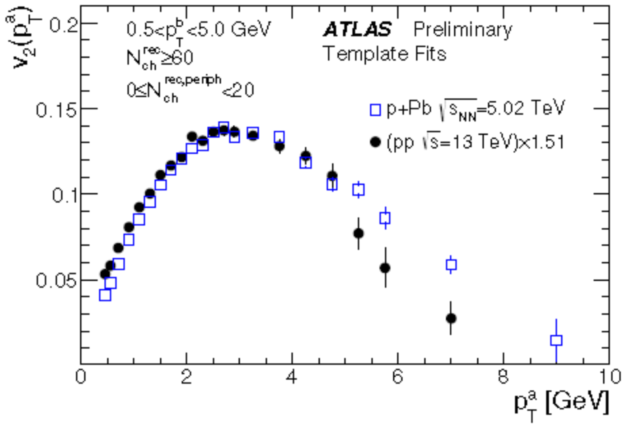
ATLAS PRL116 172301

ATLAS, PRL 116, 172301 (2016)
See also: ATLAS-CONF-2016-026

- pp collisions: no energy dependence observed between 2.76 and 13 TeV
- Similar shapes (but not magnitudes) of $v_2(p_T)$ in pp and p-Pb collisions
- In p-Pb, v_2 (also v_3, v_4) increases with multiplicity

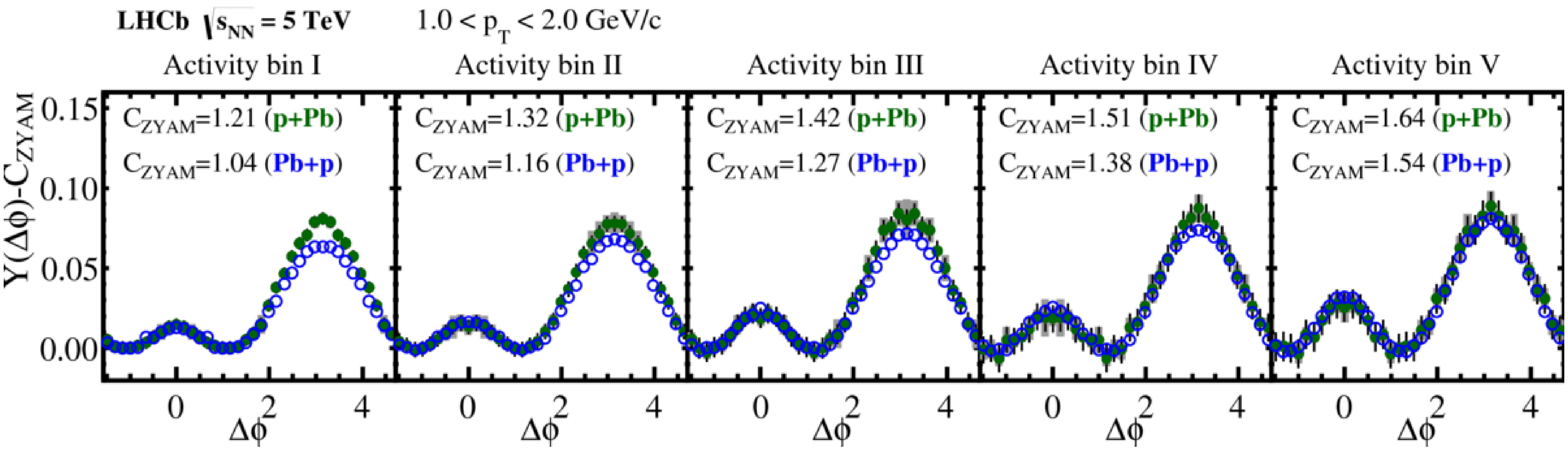


→ pp scaled by 1.51 & p-Pb



More on the ridge in p-Pb

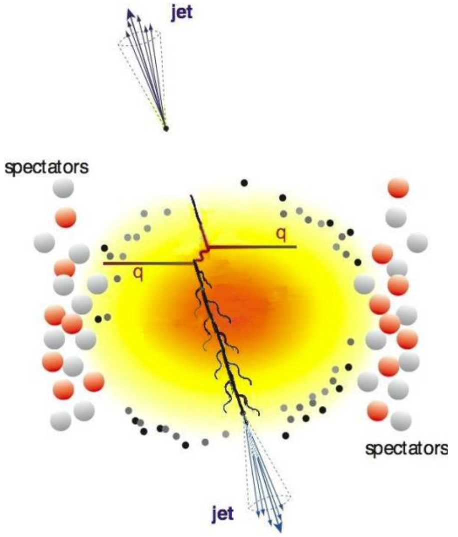
LHCb, arXiv:1512.00439



- Yield integrated over pseudorapidity in the range 2.0-2.9 as a function of $\Delta\phi$
- 1.0 < p_T < 2.0 GeV/c (where near-side ridge is most pronounced)
- Five activity (multiplicity in preudorapidity range 2.0-4.9) bins compared in p-Pb and Pb-p
- Correlation structures in the near and away side are **compatible** in both samples and **grow stronger** with increasing activity

Hard Probes in HI collisions

- Hard probes (vector bosons, direct photons, heavy flavours, jets) produced early in HI collisions, with production cross-section unmodified wrt pp collisions (pQCD)
- Yields expected to scale with number of NN collisions, N_{coll}
- Typical observable: nuclear modification factor R_{AA} (also R_{pA})
  - extract info on nuclear PDFs from pA collisions and on medium properties (transport coefficients) from AA collisions



$$R_{AA} = \frac{d^2N^{AA} / dp_T dh}{\langle N_{coll} \rangle d^2N^{pp} / dp_T dh}$$

$$\langle N_{coll} \rangle = \langle T_{AA} \rangle \times s_{pp}^{INEL}$$

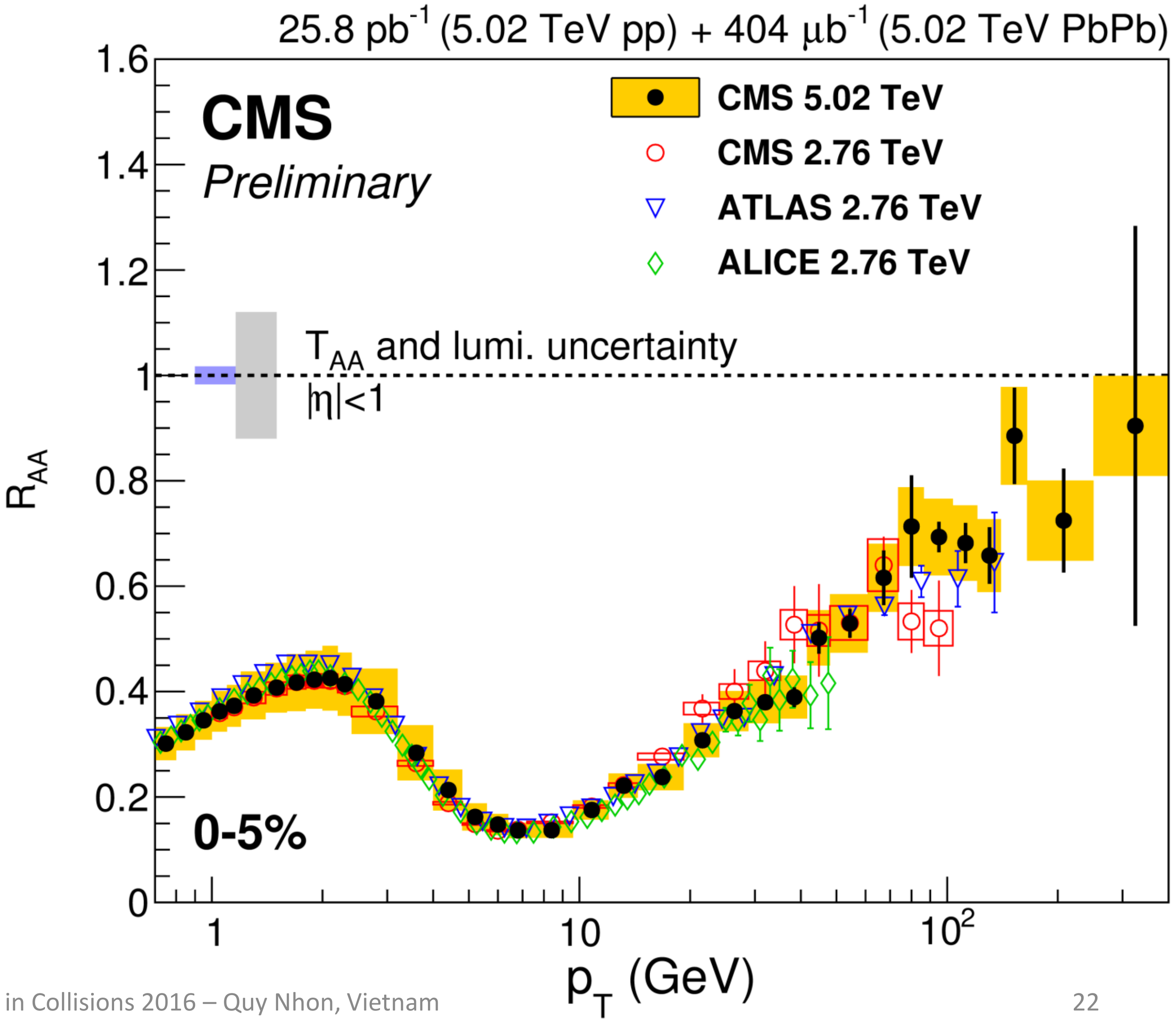
Yield in AA

pp reference

High p_T hadrons in Pb-Pb

- Strong suppression in central Pb-Pb collisions wrt pp collisions
- Nice agreement among the three experiments at 2.76 TeV
- Similar suppression between 2.76 and 5.02 TeV
  - does not necessarily imply same medium temperature at both energies

CMS 5.02 TeV (prelim.): CMS-HIN-15-015
CMS 2.76 TeV: EPJC 72 (2012) 1945
ATLAS 2.76 TeV: JHEP 09 (2015) 050
ALICE 2.76 TeV: PLB 720 (2013) 52



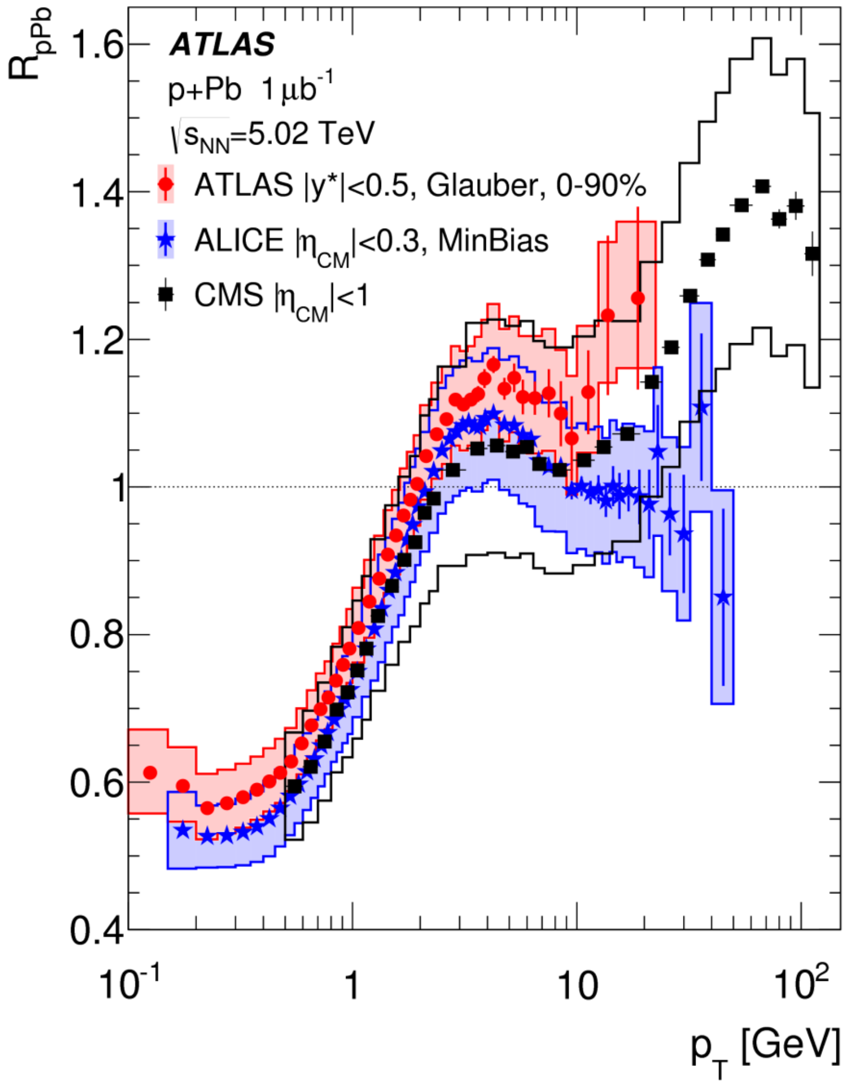
High p_T hadrons in p-Pb

R_{pPb} vs . p_T for |y*|<0.5 in p-Pb:

- peak at about 3 GeV, flat behaviour above 8 GeV, also in 8 centrality classes (not shown here)
- peak magnitude depends on rapidity and centrality

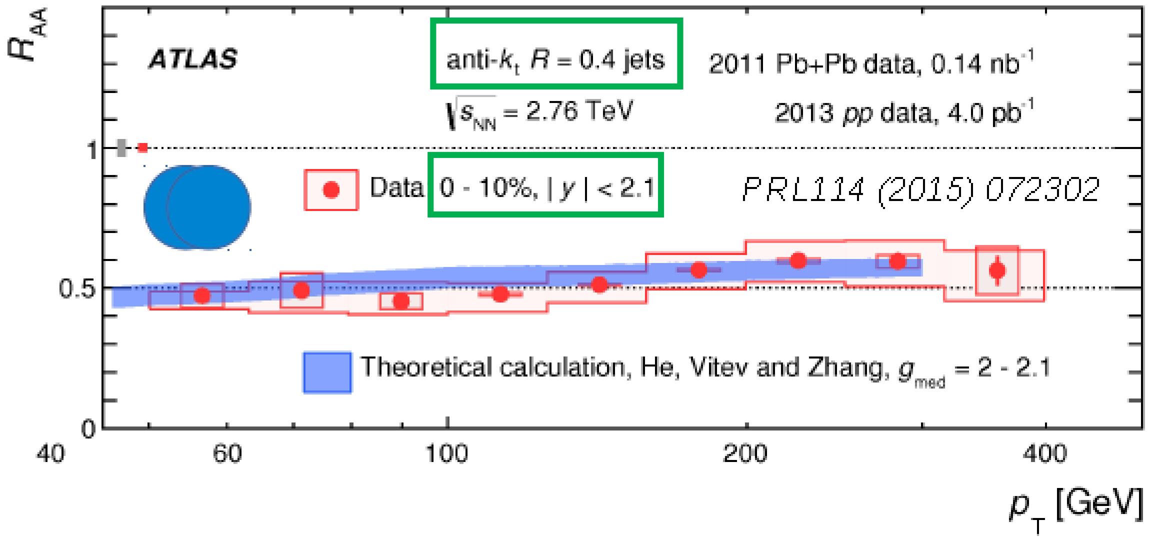
Cold nuclear matter effect negligible above 8 GeV (relevant for Pb-Pb results in previous slide)

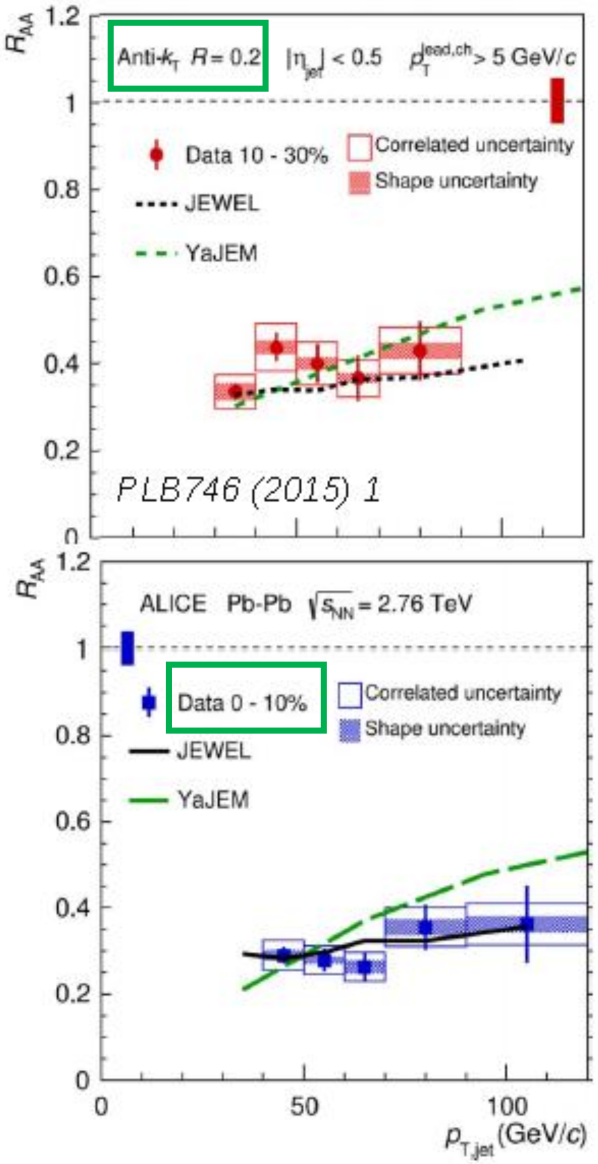
ATLAS, arXiv:1605.06436



Single Jets in Pb-Pb

ATLAS: PRL114 (2015) 072302





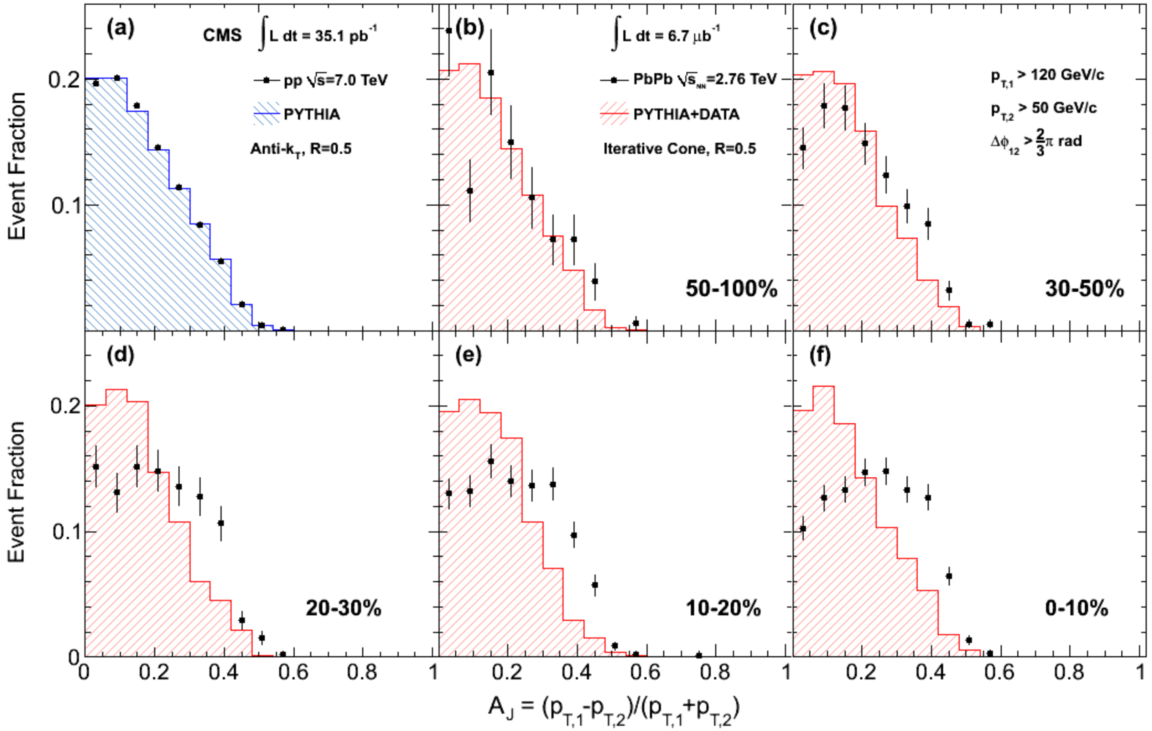
Mid-peripheral collisions

Central collisions

- The single jet nuclear modification factor shows no p_T dependence
- Also it is flat in rapidity, despite changing spectral shapes and quark fraction in jets
  - it will be interesting to see the result at 5.02 TeV
- R_{AA} is well described by models

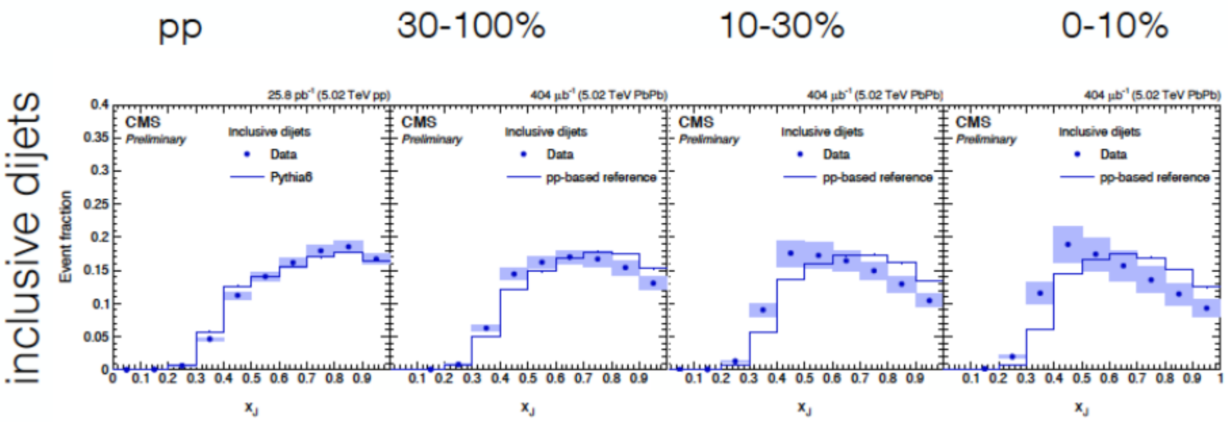
ALICE: PLB 746 (2015) 1

Di-Jet Asymmetry in Pb-Pb



CMS: PRC 84 (2011) 024906

Direct observation of jet quenching in Pb-Pb collisions at 2.76 TeV: dijet less balanced in central Pb-Pb collisions due to energy loss in the medium



- Dijet imbalance

$x_J = p_{T,2} / p_{T,1}$

CMS-HIN-16-005

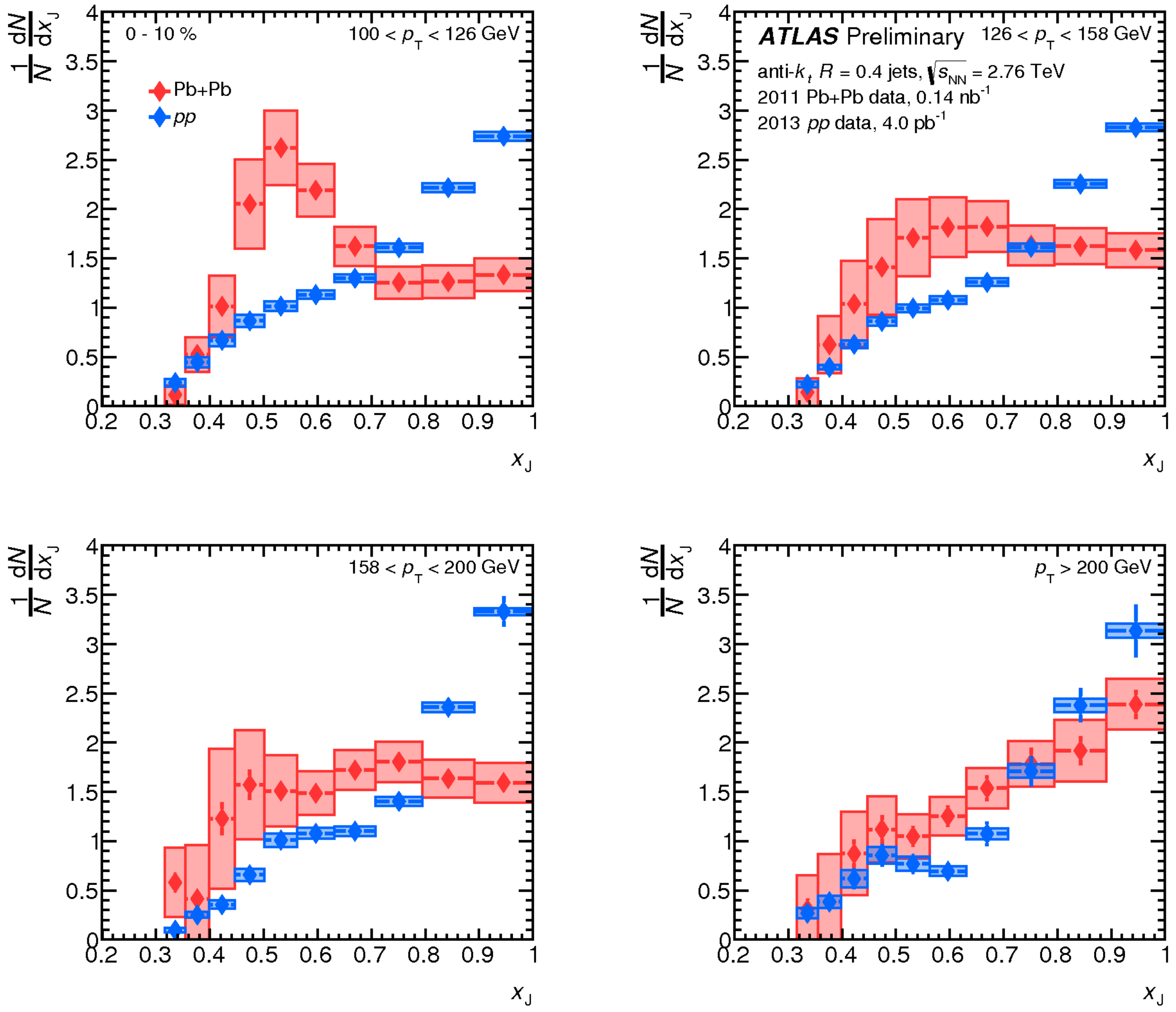
Dijet less balanced in central Pb-Pb collisions also at 5.02 TeV,
effect less pronounced than at 2.76 TeV (different underlying parton spectrum)

More on di-jets

ATLAS-CONF-2015-052

ATLAS has unfolded the dijet asymmetry observable x_J:
its distributions are shown for different selections on the leading jet p_T

- for pp collisions
- for 0-10% most central Pb-Pb collisions



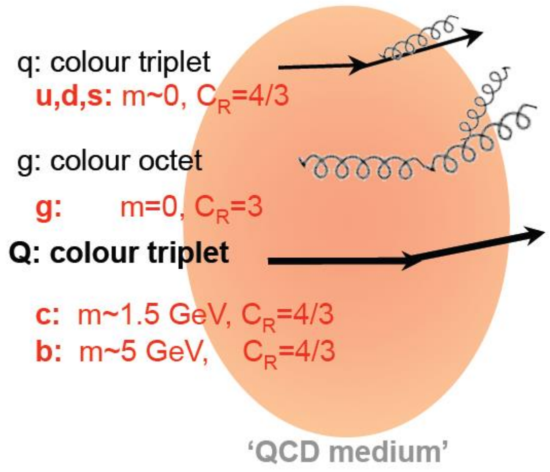
The modifications observed in central Pb-Pb collisions lessen with increasing leading jet p_T, above 200 GeV/c (bottom-right panel) the maximum at x_J=1 is restored

Open heavy flavour production at the LHC

- Heavy quarks (c, b) produced in initial high-Q^2 scattering process
  - calculable with pQCD, actually bulk of HF production in pp collisions well described by pQCD models
  - differential measurements of HF production provide strong constraints to models e.g. about MPI (multi-partonic interactions), collectivity in small systems
- Measurements in p-Pb collisions provide information on the Cold Nuclear Matter (CMN) effects
- Measurements in Pb-Pb collisions address heavy-quark energy loss mechanisms in the QGP:
  - colour-charge and mass dependence of parton energy loss
  - do c and b quarks participate in the collective expansion?

- Heavy quarks produced in initial hard scattering, experience full system evolution
- the number of HQ is conserved ⇨ unique tool to characterize the medium
- at LHC HQ are produced copiously ⇨ precision measurements
- Partons lose energy by:
  - medium-induced gluon radiation
  - elastic collisions with other partons
- Energy loss ΔE in the medium depends on:
  - medium properties (transport coefficients $\hat{q}$)
  - parton properties (mass*, colour charge)
  - path length L

$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$$

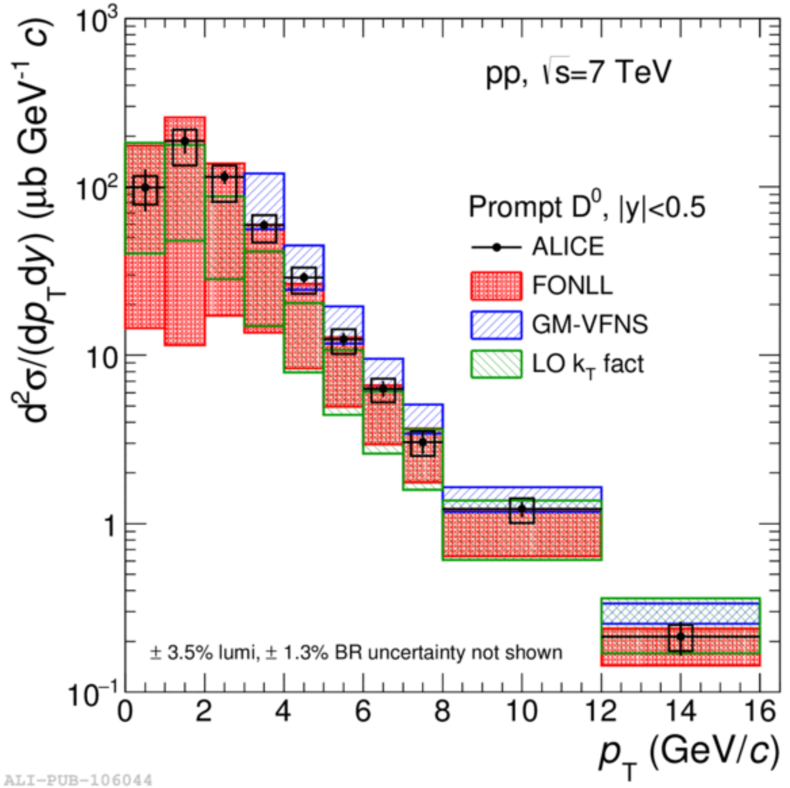


Expectation from radiative energy loss:
$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
Could be reflected in a hierarchy of meson R_{AA}:
$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$

* Gluon radiation is suppressed for angles $\theta < M_Q/E_Q$

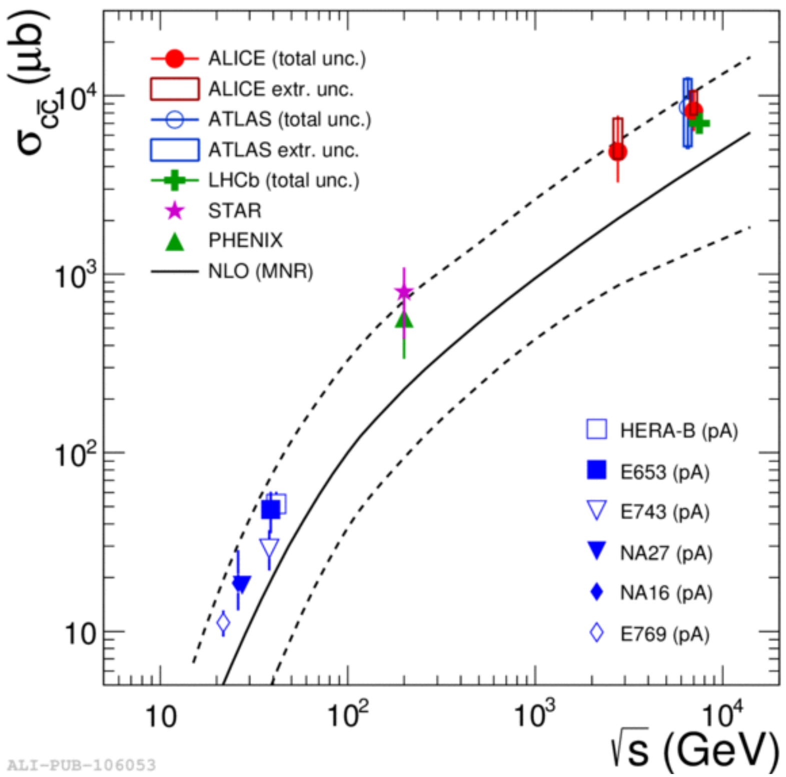
D meson and $c\bar{c}$ total cross-section in pp

ALICE, arXiv:1605.07569



Measurement down to p_T = 0 in pp @ 7 TeV
Reproduced by theoretical calculations

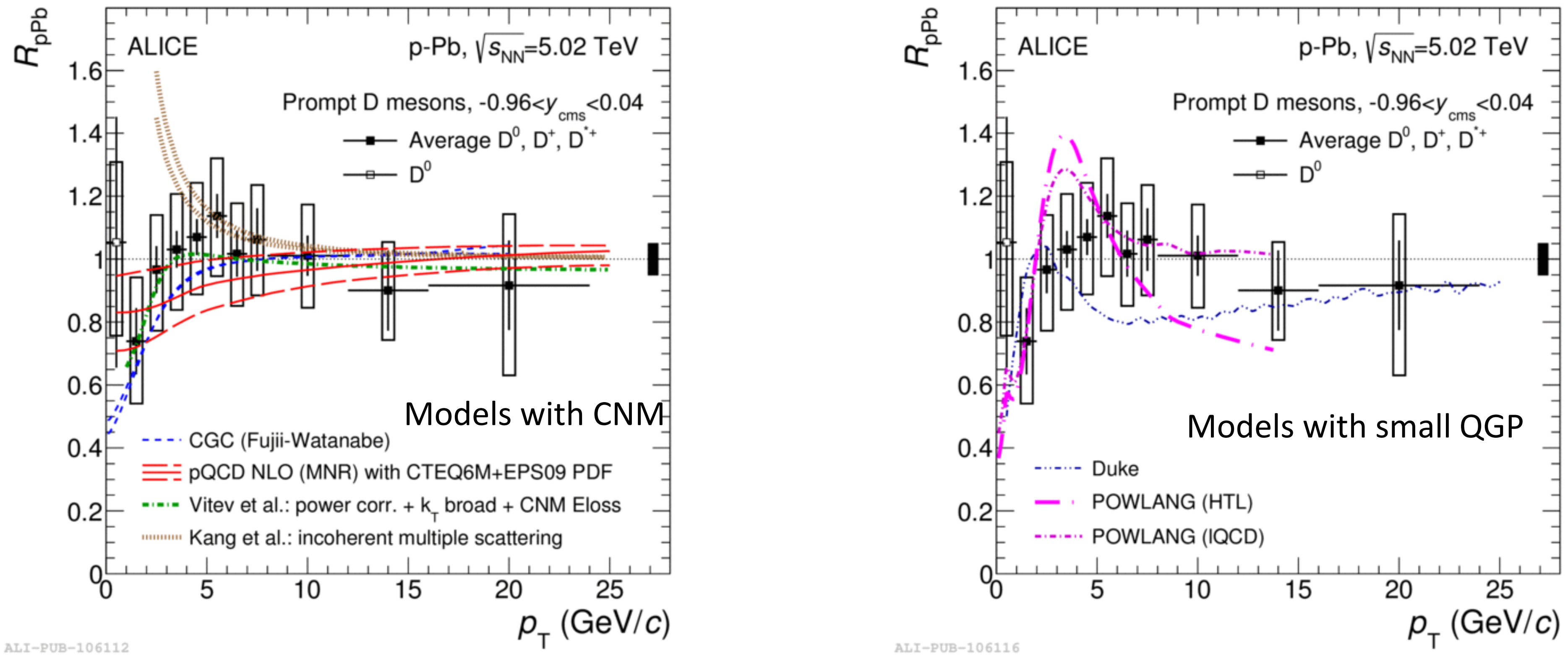
ATLAS, arXiv:1512.02913; LHCb, NPB 871 (2013) 1



⇒ Reduced uncertainty on total charm production cross-section

R_{pA} of open charm in p-Pb

ALICE, arXiv:1605.07569



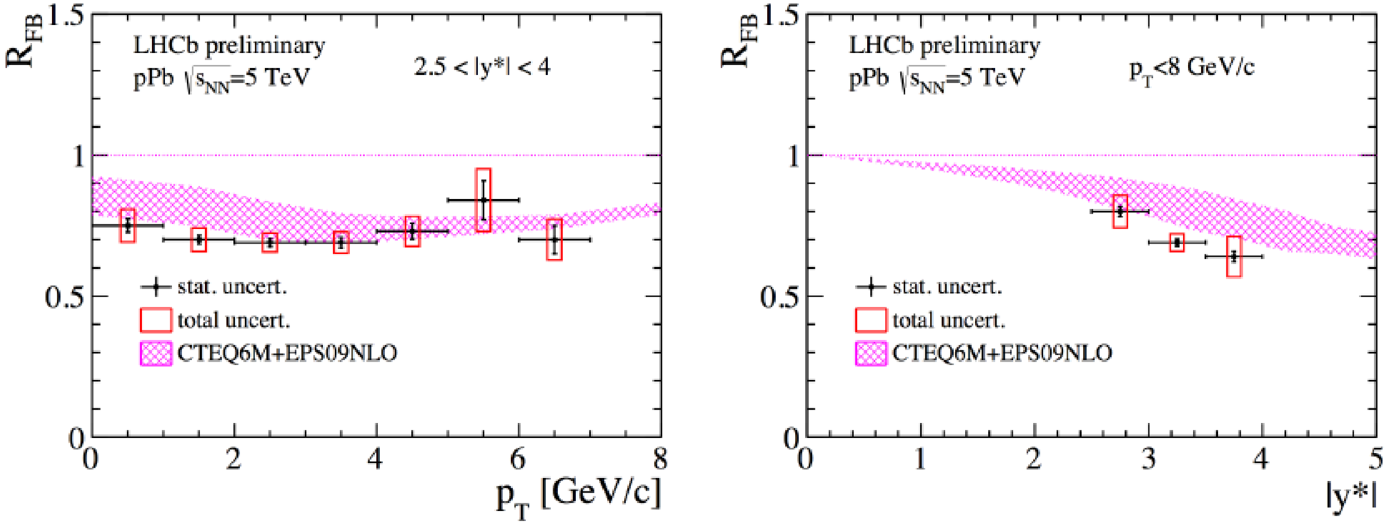
R_{pPb} of D mesons consistent with unity, no indication for suppression at intermediate/high p_T
Data do not favour suppression larger than 20% at 5-10 GeV/c p_T
R_{pPb} described within uncertainties by models including initial- or final-state effects

D^0 forward/backward ratio in p-Pb

$$R_{FB}(p_T, |y^*|) = \frac{\sigma_{pPb}(p_T, y^*)}{\sigma_{Pbp}(p_T, y^*)}$$

- Systematics uncertainties largely cancel
- Common rapidity range $2.5 < |y^*| < 4$

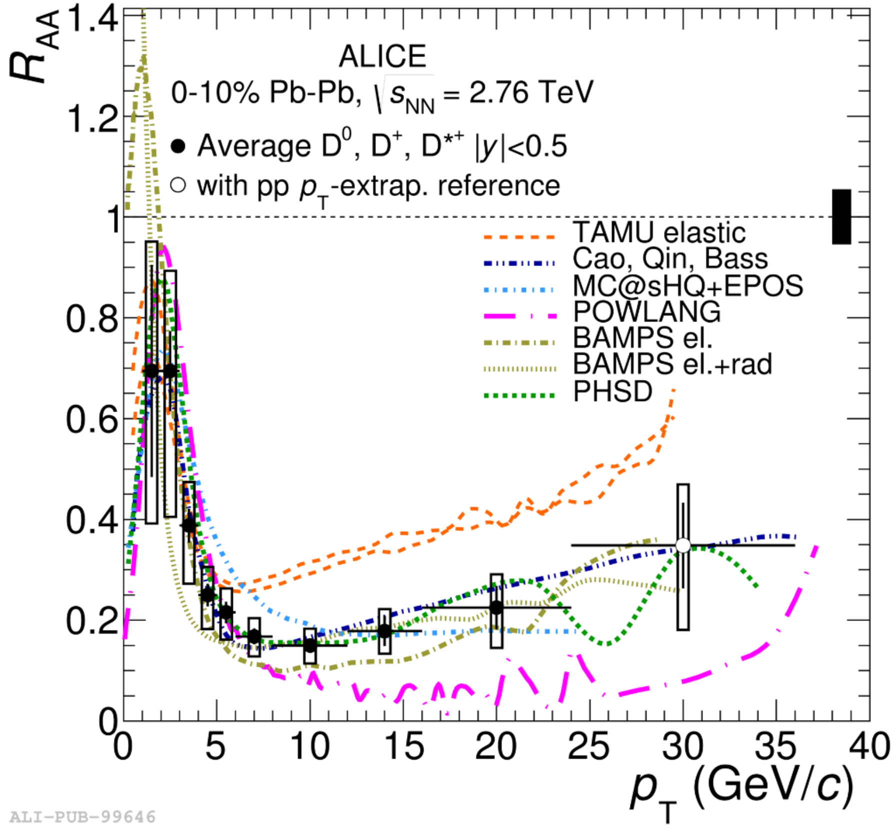
LHCb, LHCB-CONF-2016-003



- Clear asymmetry forward/backward
- No p_T dependence
- Asymmetry more important at larger y^*
- Within uncertainties, data are reproduced by pQCD calculations with EPS09 nPDF

Francesco Bossù (LHCb), ICHEP 2016

R_{AA} of open charm in Pb-Pb

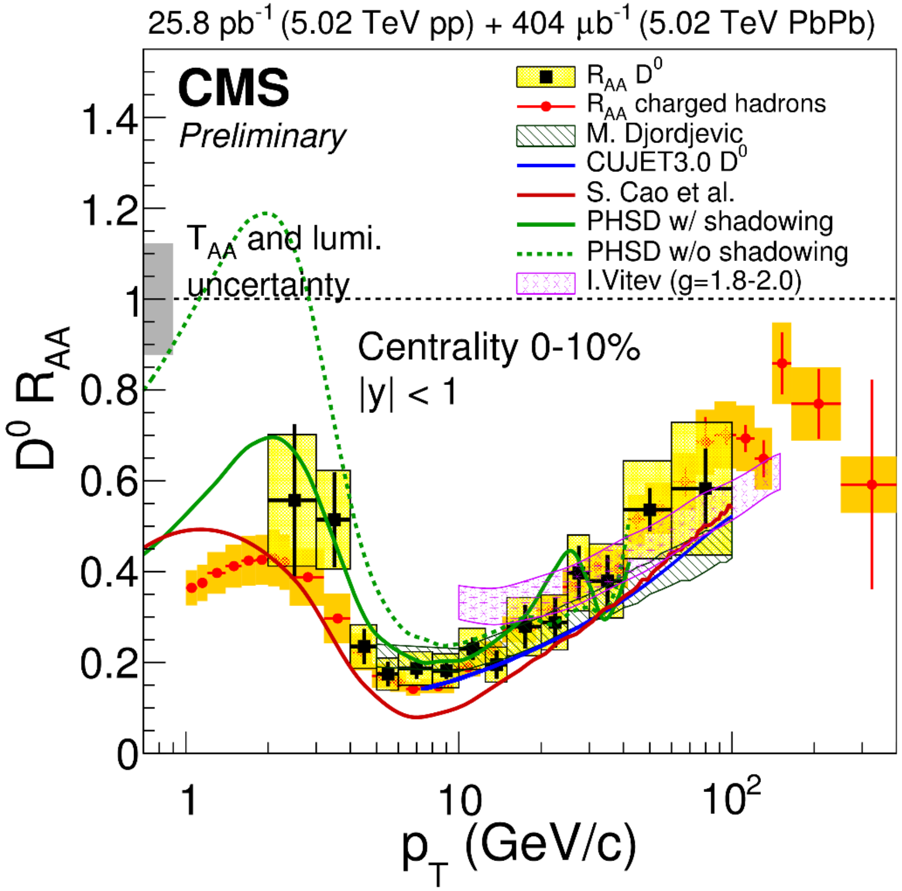


Black points: D^0

Red points: charged hadrons

CMS-PAS-HIN-16-001

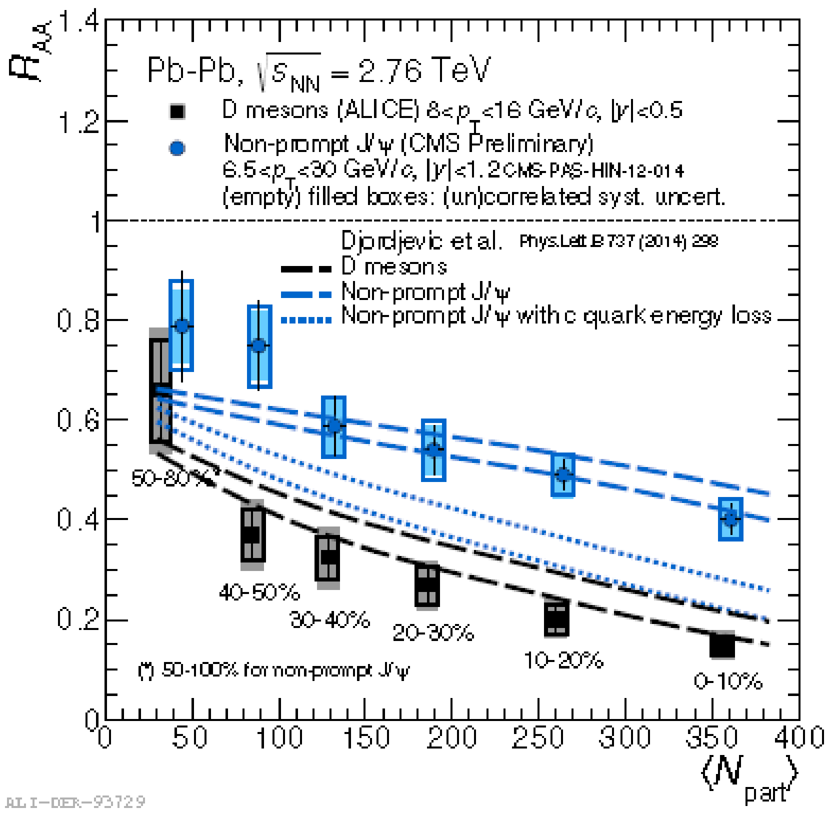
CMS-PAS-HIN-15-015



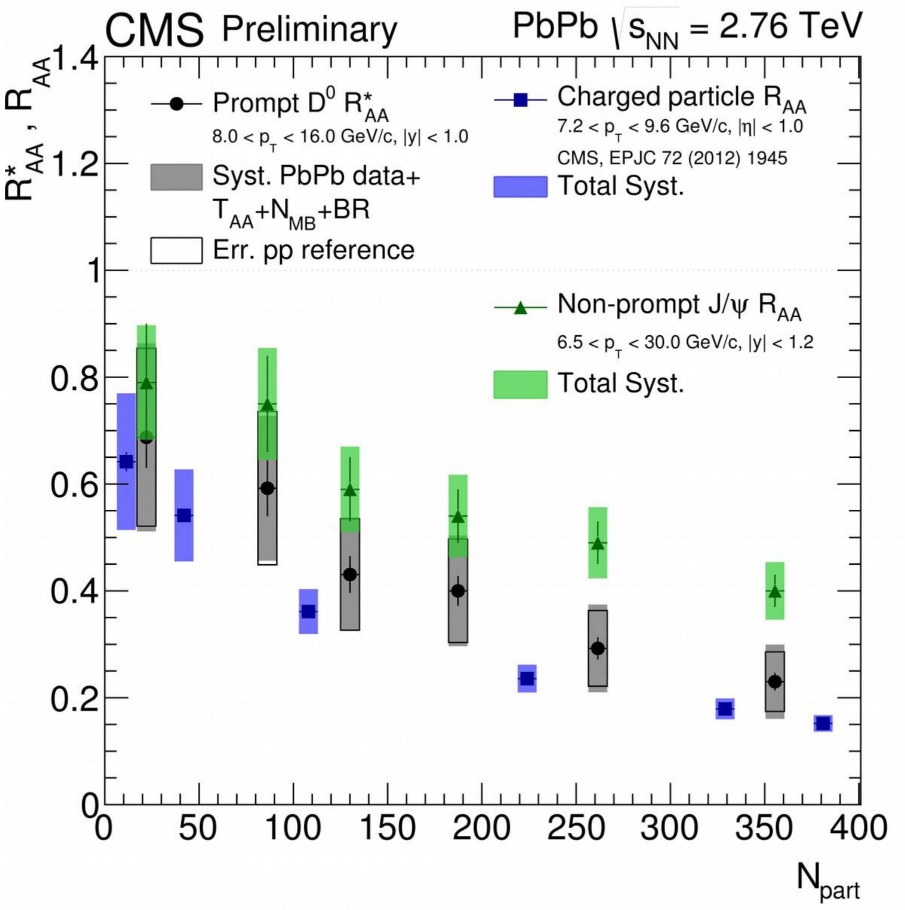
ALICE: JHEP 11 (2015) 205

At both energies, strong suppression of open charm at intermediate p_T: indication of prevalently elastic energy loss, but inclusion of radiative energy loss improves agreement with data

Beauty vs. Charm



JHEP 1511 (2015) 205



CMS-PAS-HIN-15-005

R_{AA}(D) < R_{AA}(B→J/ψ), hint for mass hierarchy of R_{AA}; described by a model including mass-dependent and collisional energy losses

Quarkonia in HI collisions

the historical hard probe for QGP temperature

Matsui and Satz, PLB 178, 416 (1986)

Digal et al., PRD 64, 094015 (2001)

Braun-Munzinger and Stachel, PLB 490, 196 (2000)

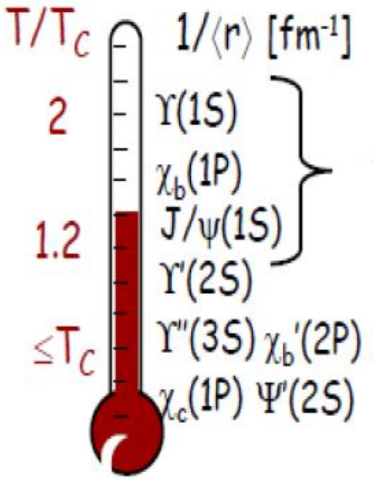
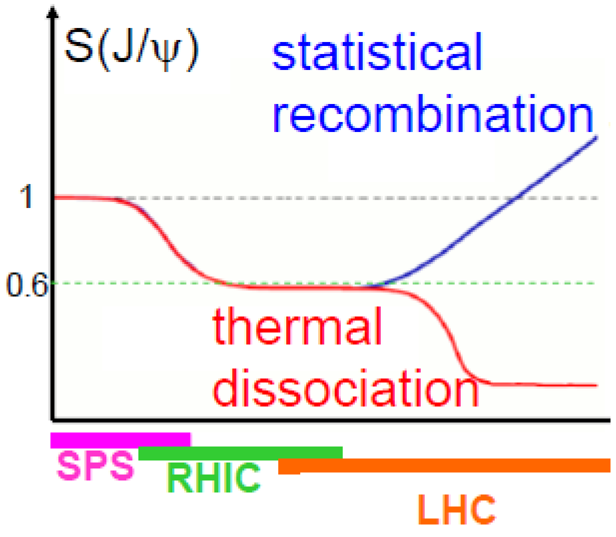


figure from A. Mocsy

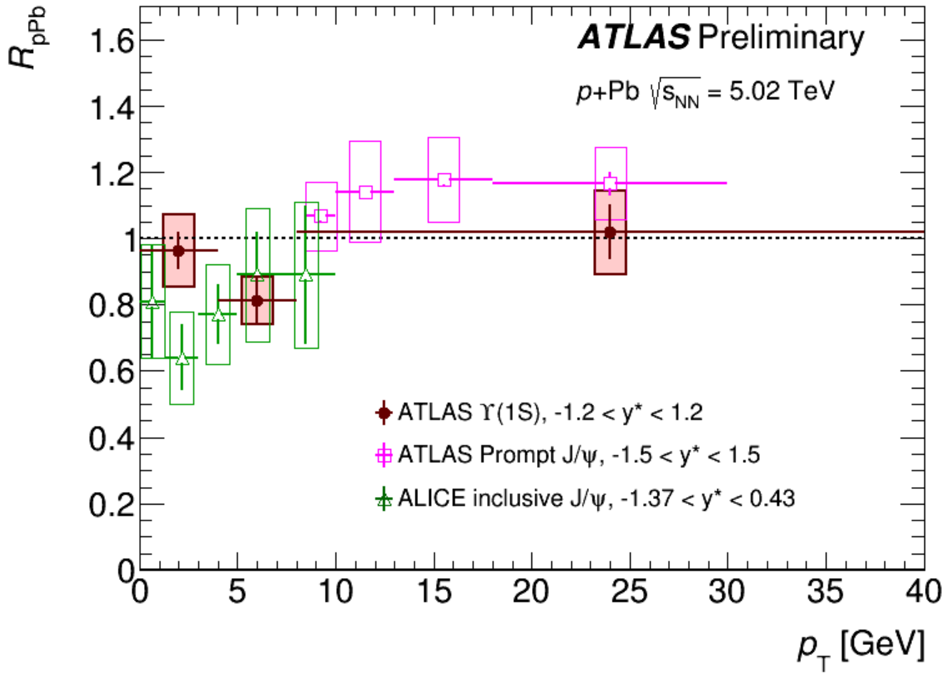


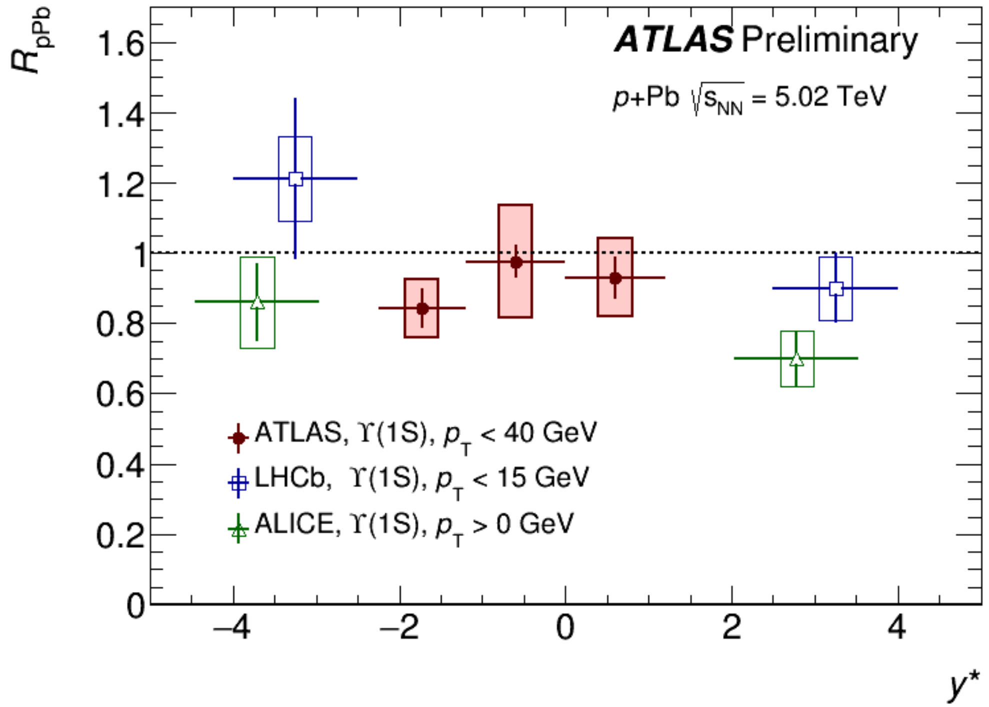
Quarkonia production at the LHC

- Heavy quark bound states production and their suppression in HI collisions are one of the historical signatures for the QGP formation
- Quarkonia production is a perturbative process while bound state formation is not
- pp and p-Pb collision provide the test of production models and an evaluation of CNM effects
- In Pb-Pb collisions quarkonia should be suppressed due to colour screening
    - with different binding energies of various states leading to sequential suppression
- However at LHC, due to the higher HQ production, regeneration of quarkonia is expected
    - Particularly for charmonium due to the larger abundance of c quarks

J/ψ and ϒ nuclear modification factors in p-Pb

ATLAS-CONF-2015-050 (Quark Matter 2015)
see also: LHCb J/ψ in JHEP 02 (2014) 072; LHCb ϒ in JHEP 07 (2014) 094

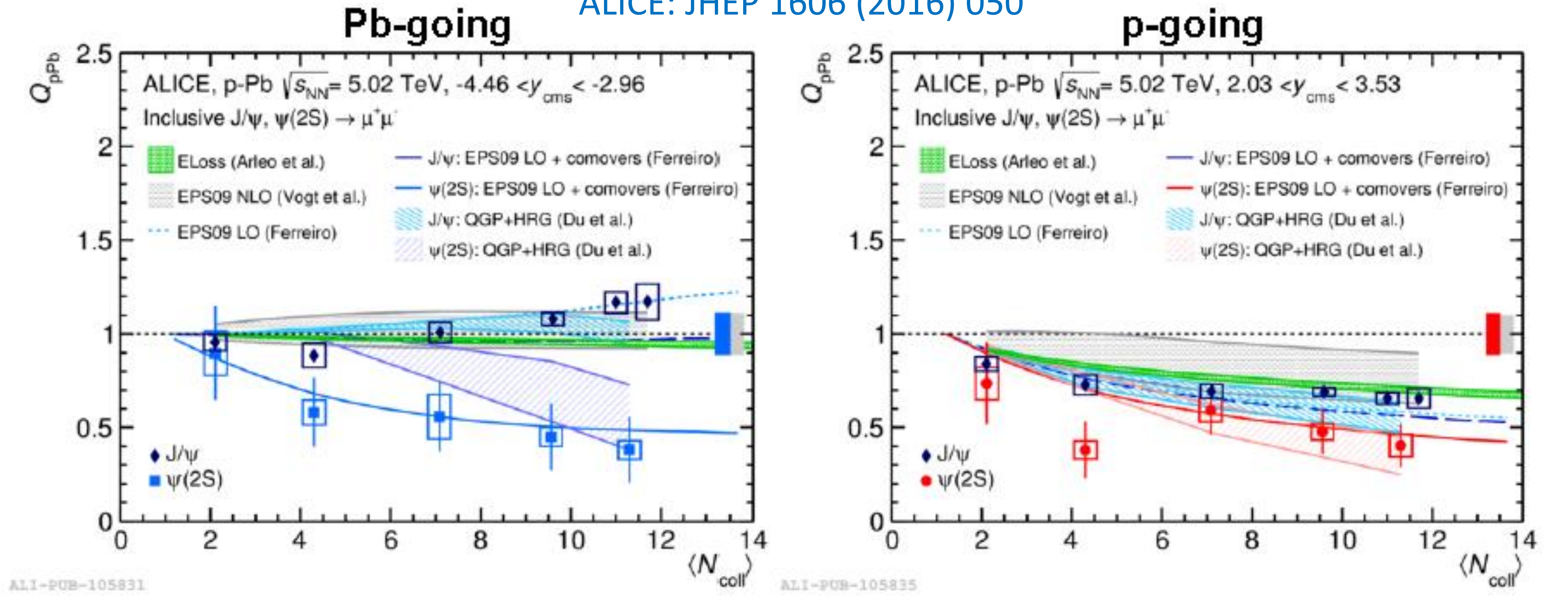




Cold Nuclear Matter effects are small as seen in p-Pb collisions (more details on J/ψ later on)
⇒ Quarkonia states are powerful hard probes for the QGP characterization

J/ψ and ψ(2S) in p-Pb at 5.02 TeV

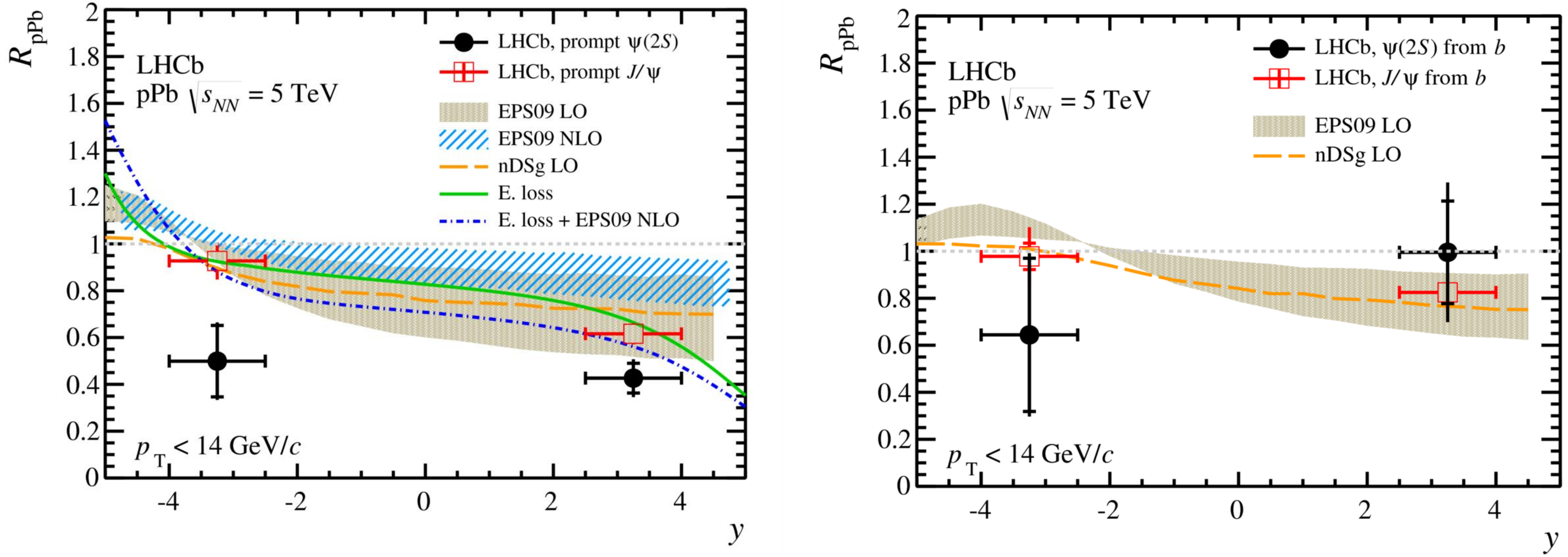
ALICE: JHEP 1606 (2016) 050



- J/ψ suppressed in p-going direction (models including shadowing or energy loss mechanisms can describe the centrality dependence)
- ψ(2S) more suppressed than J/ψ, effect stronger in Pb-going direction (only models including final-state interactions with comovers are able to reproduce the results)

More on ψ(2S) in p-Pb

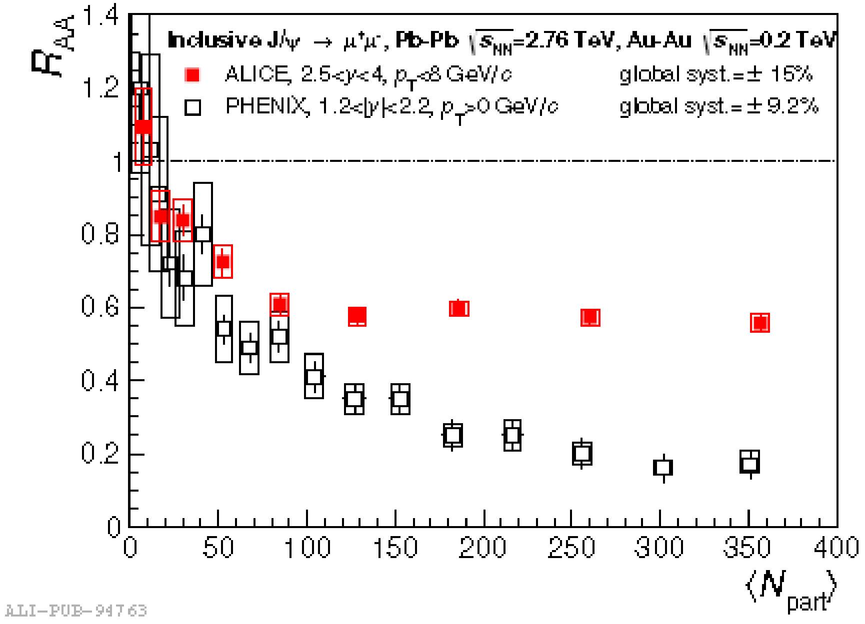
LHCb: JHEP 1603 (2016) 133

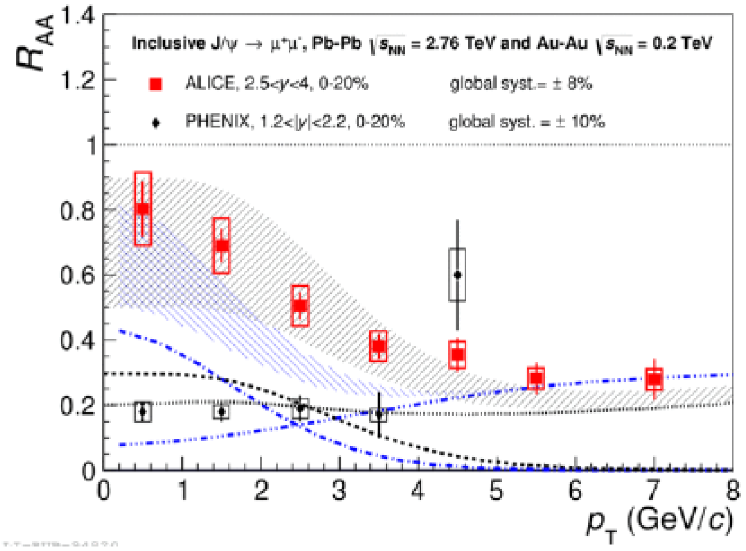


LHCb measured in the forward (backward) region the nuclear modification factor separately for prompt ψ(2S) and for ψ(2S) from *b* decays:

- Prompt ψ(2S) mesons are significantly more suppressed than prompt J/ψ mesons (left panel) in the backward region – not well described by theoretical predictions
- For ψ(2S) mesons from b, a conclusion cannot be made yet (limited statistics)

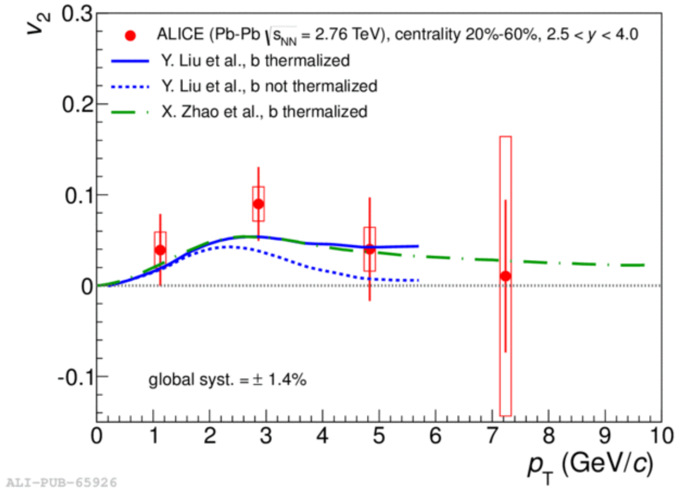
J/ψ suppression/regeneration in Pb-Pb





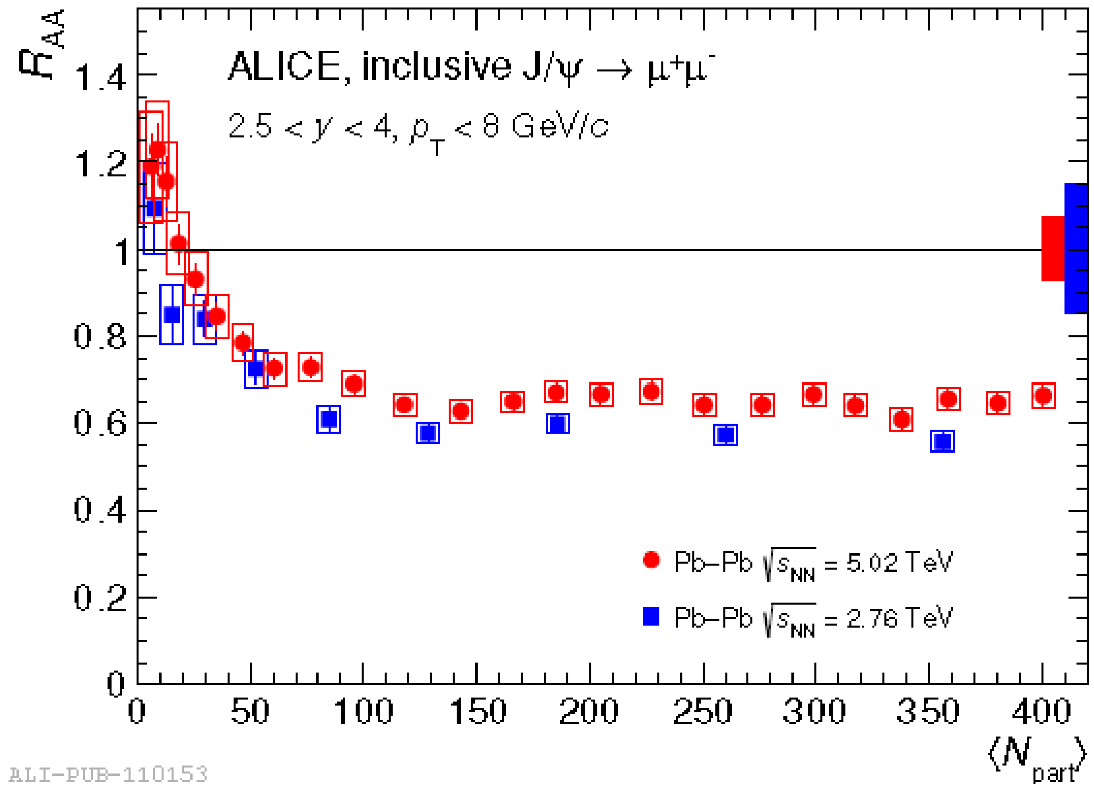
JHEP 1605 (2016) 179

PRL 111 (2013) 162301



- R_{AA} becomes flat (and higher than at RHIC) for $N_{part} > 70$
- LHC data at 2.76 TeV are well described by models including regeneration in the QGP or at hadronization
- Hint of non-zero v_2 at intermediate p_T for semi-central collisions, qualitatively described by models including regeneration

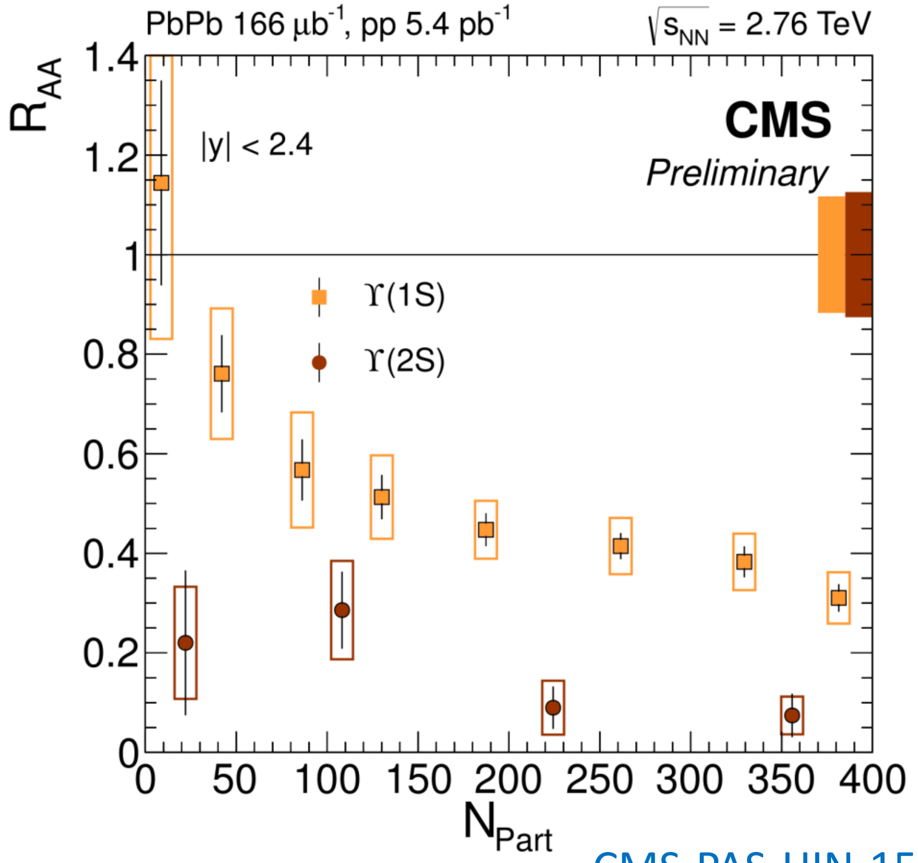
J/ψ suppression/regeneration at 5.02 TeV

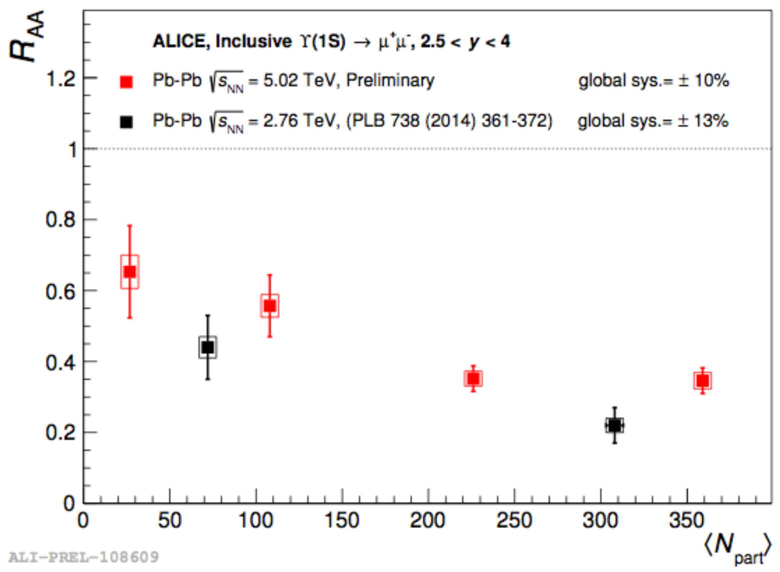


CERN-EP-2016-162
arXiv:1606.08197

At 5.02 TeV the trend with N_{part} is confirmed with higher precision (more statistics, reduced syst. errors)

Upsilon in Pb-Pb





CMS-PAS-HIN-15-001

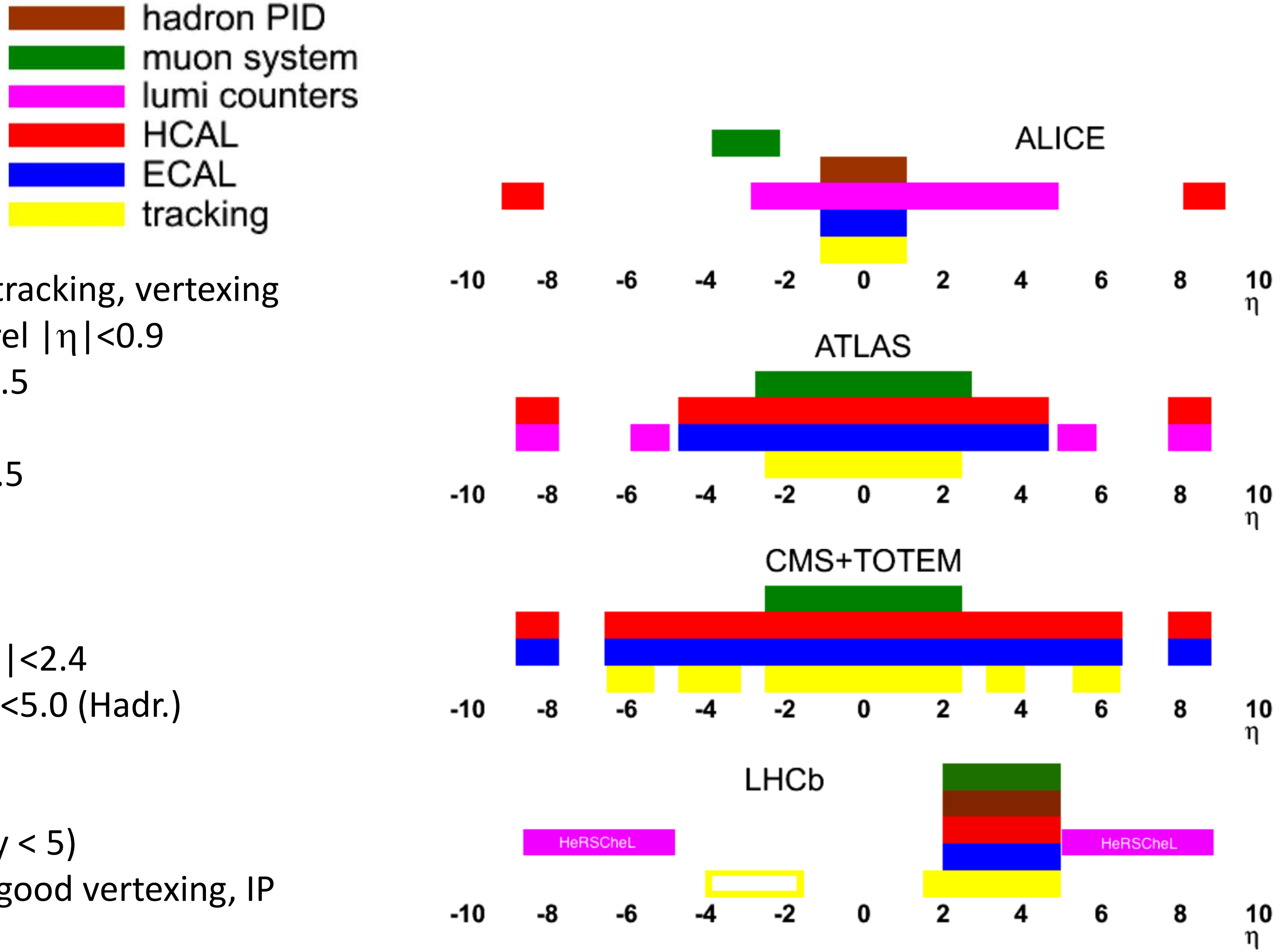
- $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S))$, suppression is largest in central collisions (no significant p_T dependence in 0-20 GeV/c)
- Clear indication for sequential melting

Summary & Outlook

- The LHC Run 1 and 2 (ongoing) have provided increased understanding of the hadronic matter under extreme conditions
- All four large experiments: ALICE, ATLAS, CMS and LHCb have provided a wealth of coherent and complementary results
- QGP signatures like jet quenching, quarkonia melting, strangeness enhancement seen at RHIC have been confirmed
- Charmonium regeneration has been established at LHC
- The hydrodynamic picture (with low η/s ratio) has been validated further
- Interesting features of collectivity in p-Pb and high multiplicity pp collisions have emerged
- The Heavy Ion community is looking forward to the upcoming p-Pb data taking in Run 2 and to the high luminosity Run 3 (2020-) for even more exciting results

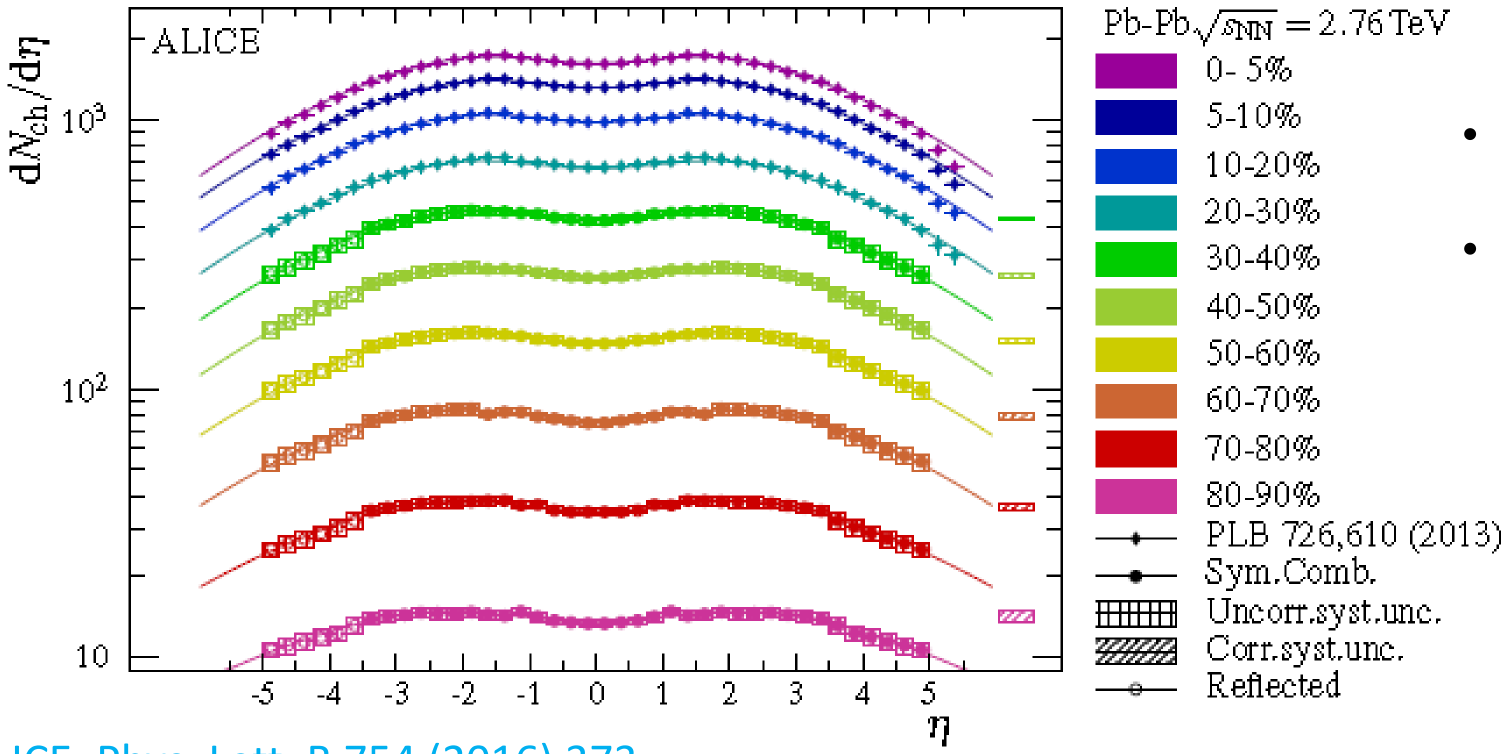
BACKUP

Phase space coverage



- ALICE:
  - Low material budget, precise tracking, vertexing and hadron PID in central barrel $|\eta|<0.9$
  - Forward muon arm $-4 < \eta < -2.5$
- ATLAS:
  - Inner detector tracking $|\eta|<2.5$
  - Calorimetry $|\eta|<4.9$
  - Muons $|\eta|<2.7$
- CMS:
  - Inner tracking (14 Si layers) $|\eta|<2.4$
  - Calorimetry $|\eta|<3.0$ (EM) $|\eta|<5.0$ (Hadr.)
  - Muons $|\eta|<2.5$
- LHCb:
  - Single arm spectrometer ($2 < y < 5$)
  - Designed for HF physics: very good vertexing, IP resolution, K and μ ID

$dN_{ch}/d\eta$ in a wide rapidity range

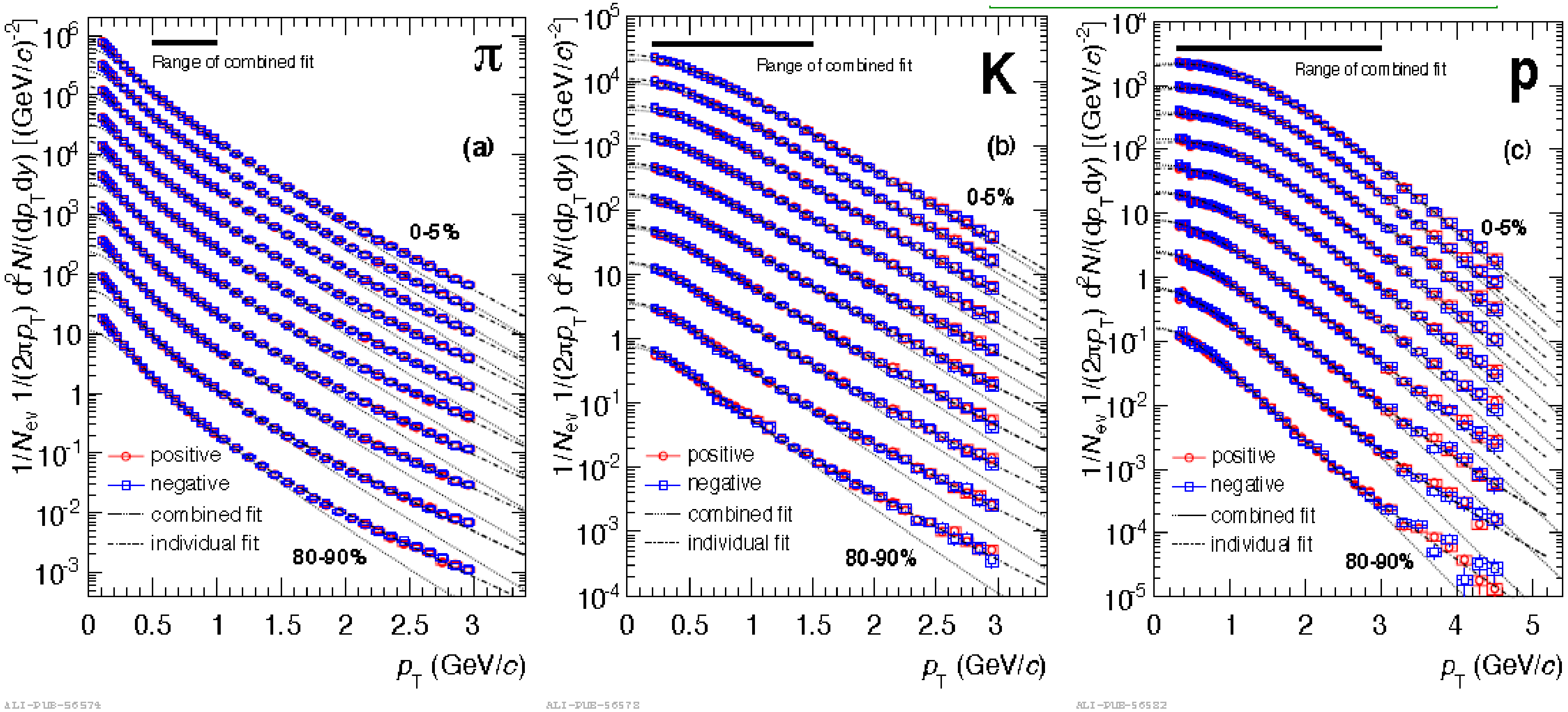


ALICE: Phys. Lett. B 754 (2016) 373

- $dN_{ch}/d\eta$ measured in $-3.5 < \eta < 5.0$ (data reflected back from -3.5 to -5.0)
- Total number of charged particles ranges
  - from 162 ± 22 (80-90%)
  - to **17170 ± 770** (0-5%)

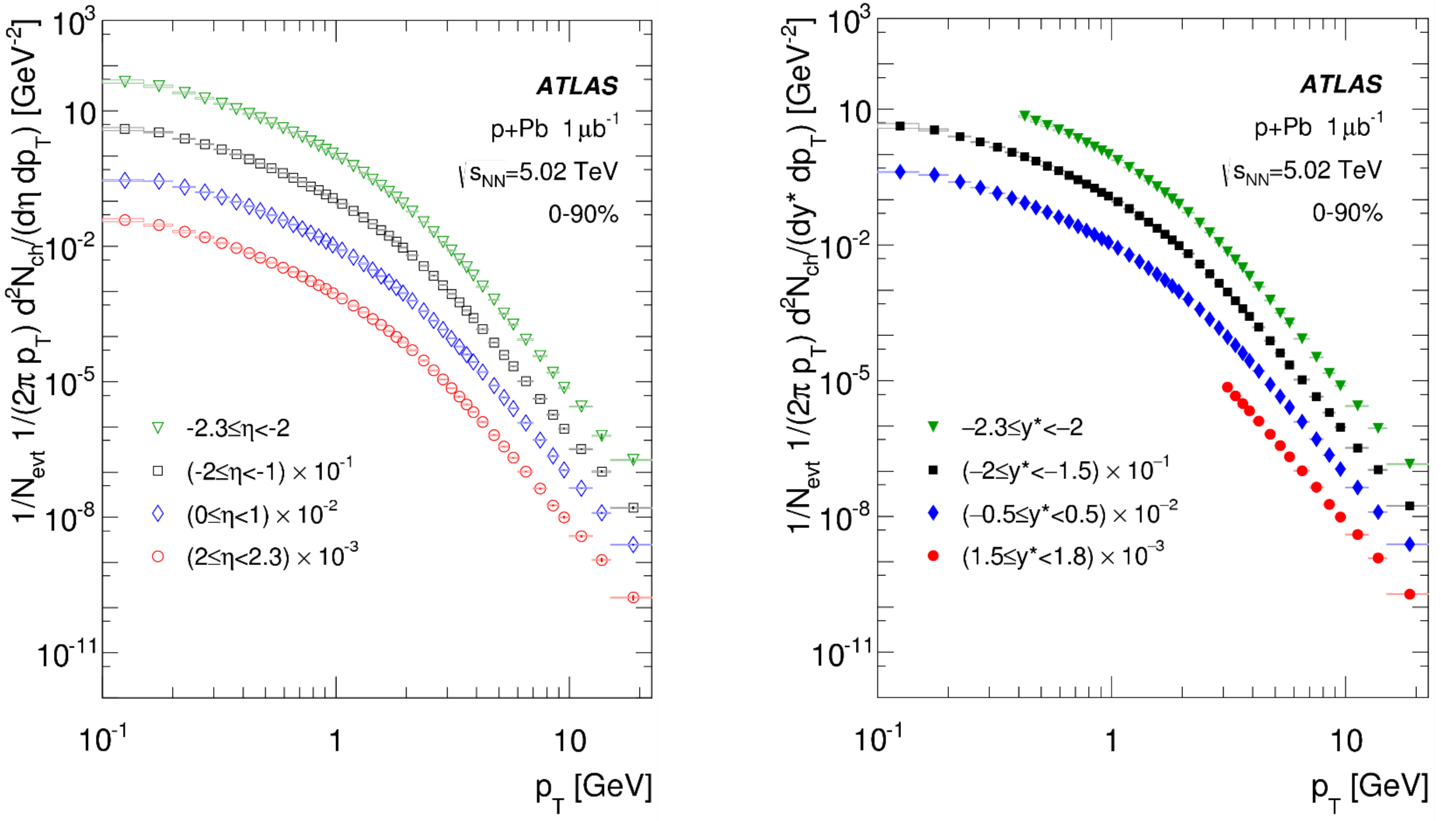
Bulk particle production in Pb-Pb

ALICE: PRC 88, 044910 (2013)



Spectra become harder with increasing centrality (from peripheral to central)
More so for heavier particles, as expected by collective expansion

Bulk particle production in p-Pb (2)

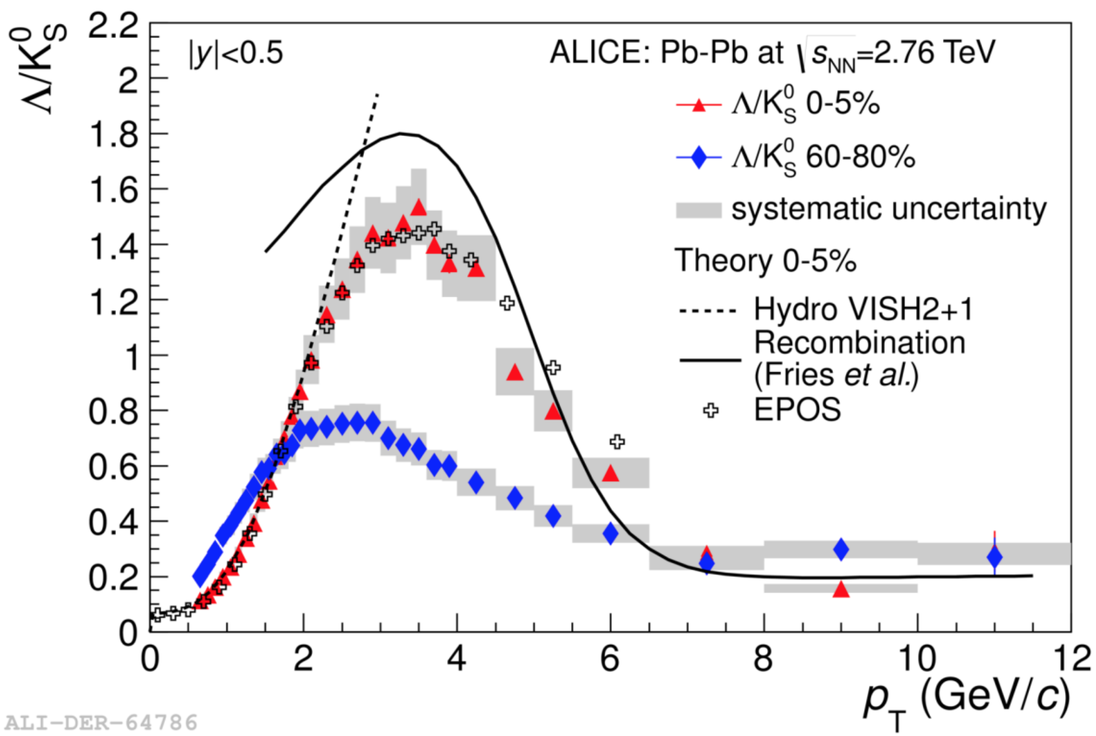


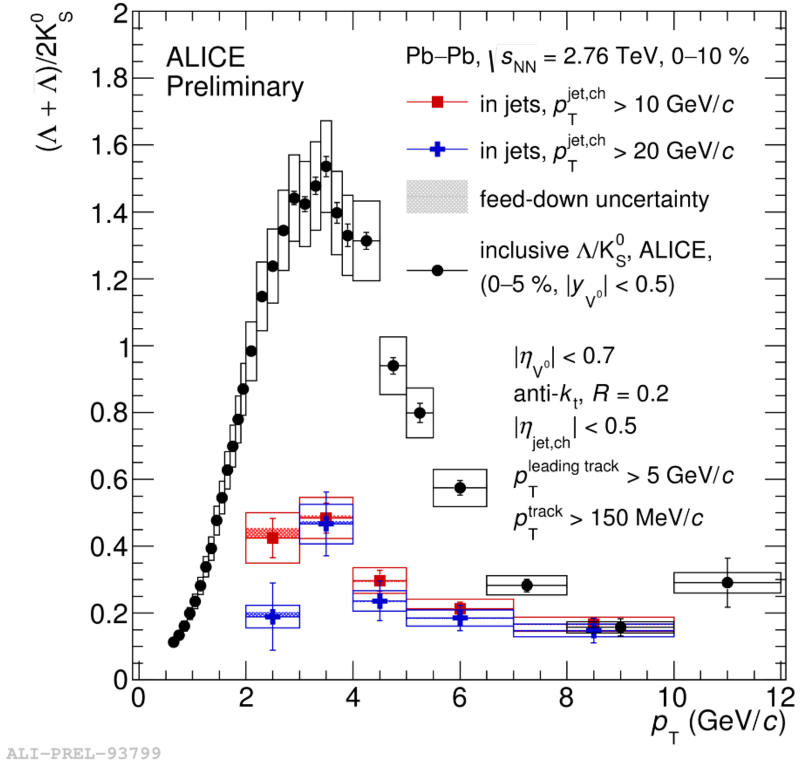
ATLAS, arXiv:1605.06436

differential invariant yields as a function of charged-particle transverse momentum for several intervals of η and y^*

Baryon/meson ratio

ALICE: PRL 111 (2013) 222301





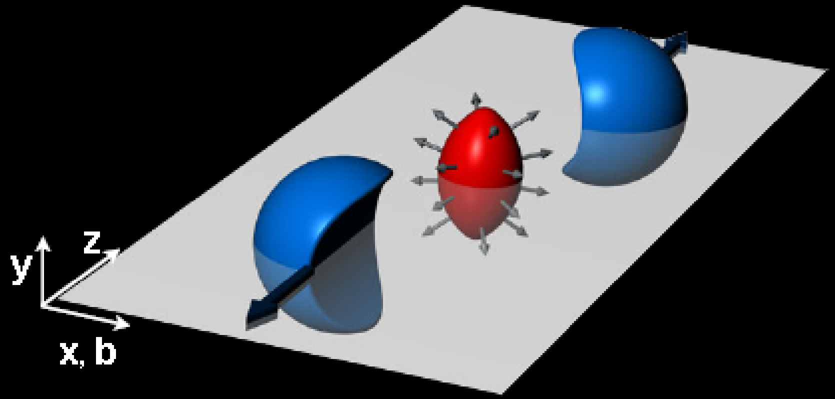
- Hydro (PLB 658 (2008) 279) describes only the rise < 2 GeV/c
- Recombination (Ann. Rev. Nucl. Part. Sci. 58 (2008) 177) overestimates the effect
- EPOS (PRL 109 (2012) 102301) describes data well

- Baryon/Meson ratio in jets is significantly lower than in inclusive
- Baryon excess arises from the bulk rather that from jet fragmentation

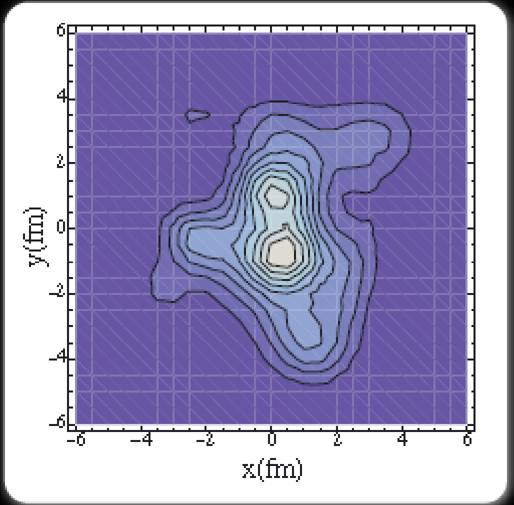
Flow higher harmonics

Initial conditions and v_n

R. Snellings, Moriond 2012



G. Qin, H. Petersen, S. Bass, and B. Muller

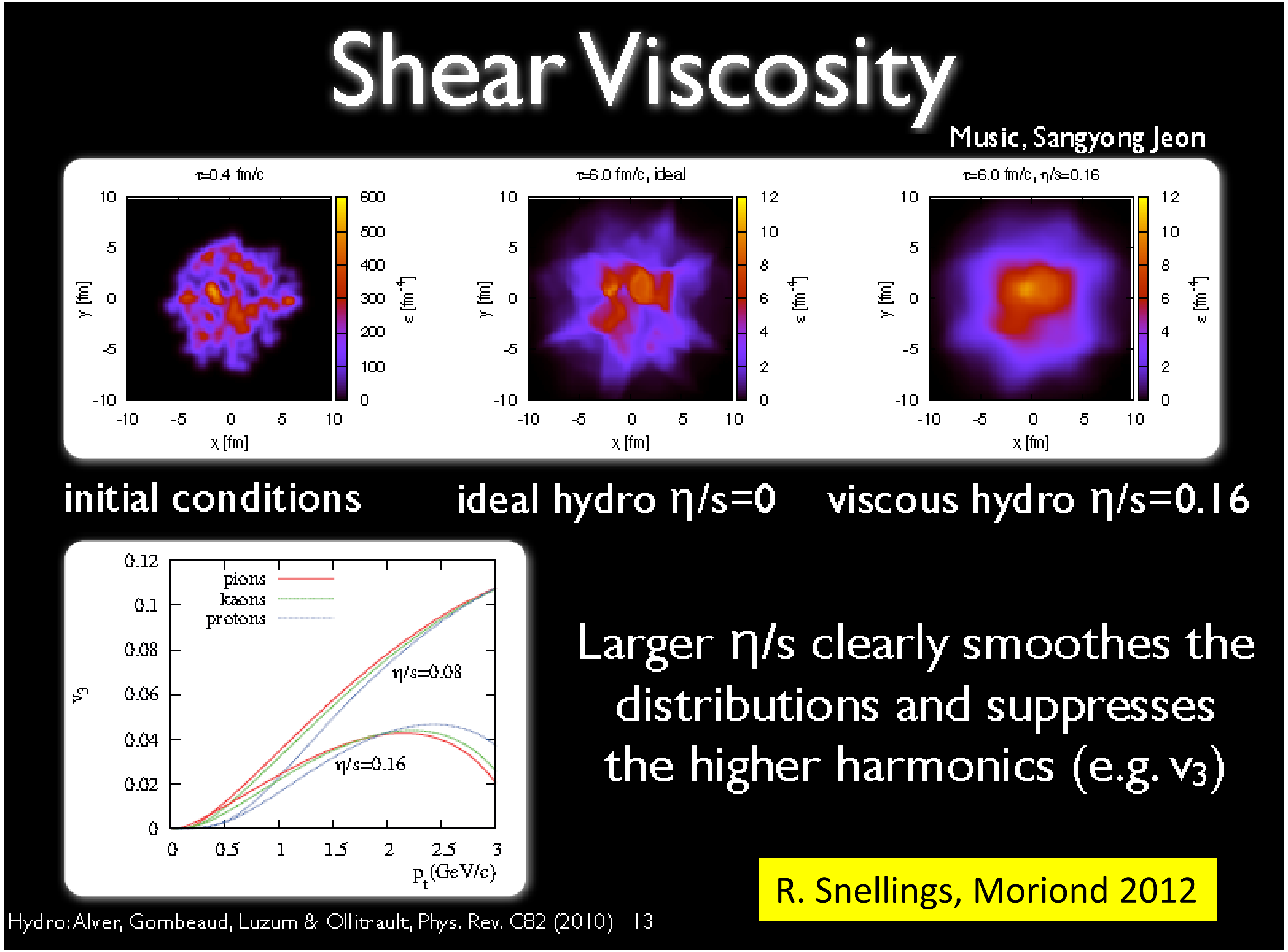


$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=2,4,6,\ldots}^{\infty} 2v_n \cos n(\phi - \Psi_R)$$

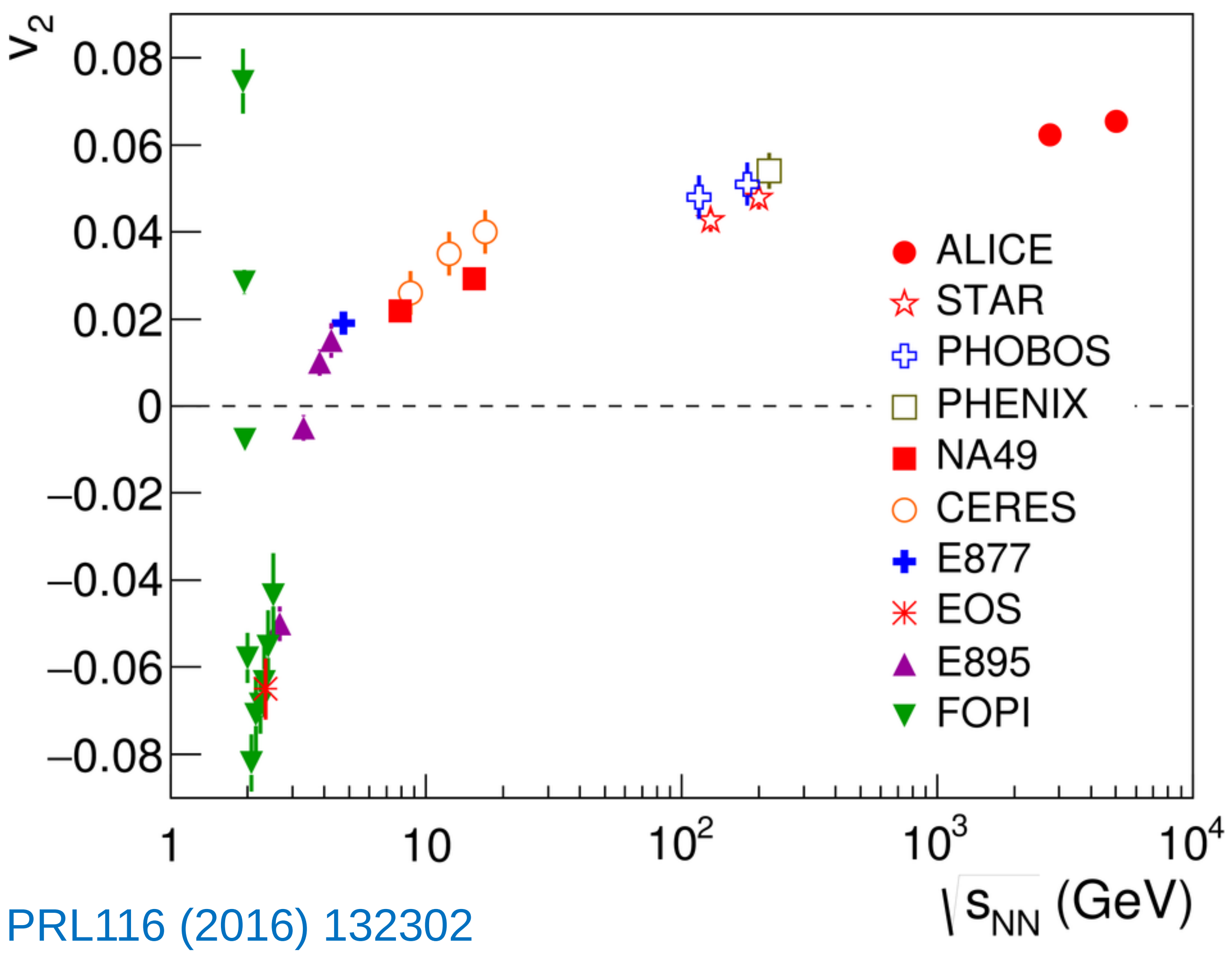
$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)$$

initial spatial geometry not a smooth almond (for which all odd harmonics and sin n(Φ-Ψ_R) are zero due to symmetry) may give rise to higher odd harmonics and symmetry planes

Flow higher harmonics



Evolution of elliptic flow with c.m. energy



PRL116 (2016) 132302

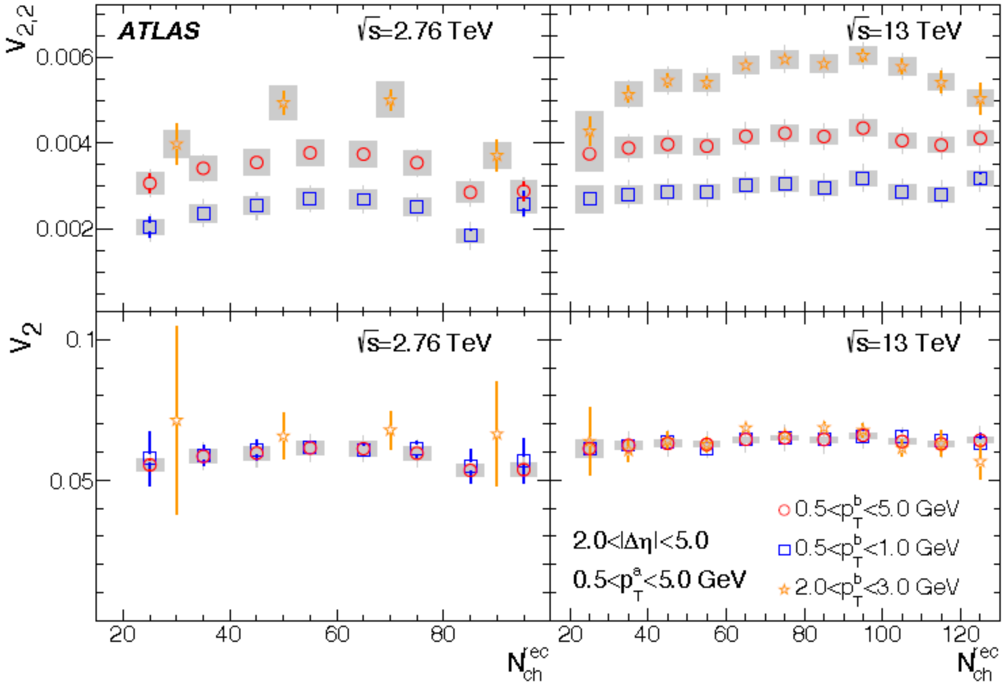
The p_T-integrated v_2 (20-30% central AA collisions) shows smooth evolution with c.m. energy between 10 GeV and 5 TeV

extracted v2,2

$$v_2(p_{T1}) = v_{2,2}(p_{T1}, p_{T2}) / \sqrt{v_{2,2}(p_{T2}, p_{T2})}\,,$$

$V_{2,2}$

V_2

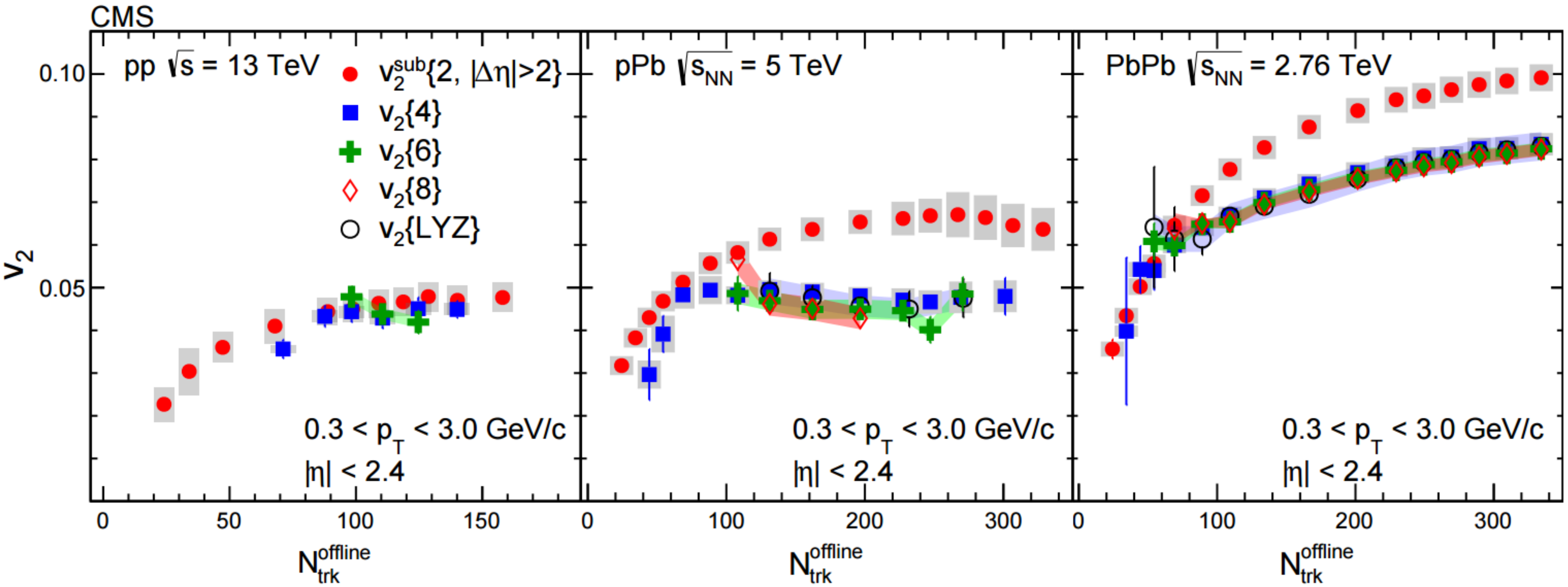


extracted v_2 independent of $p_{T,2}$ range: **factorization**

6

Anne M. Sickles (ATLAS), ICHEP 2016

arXiv:1606.06198

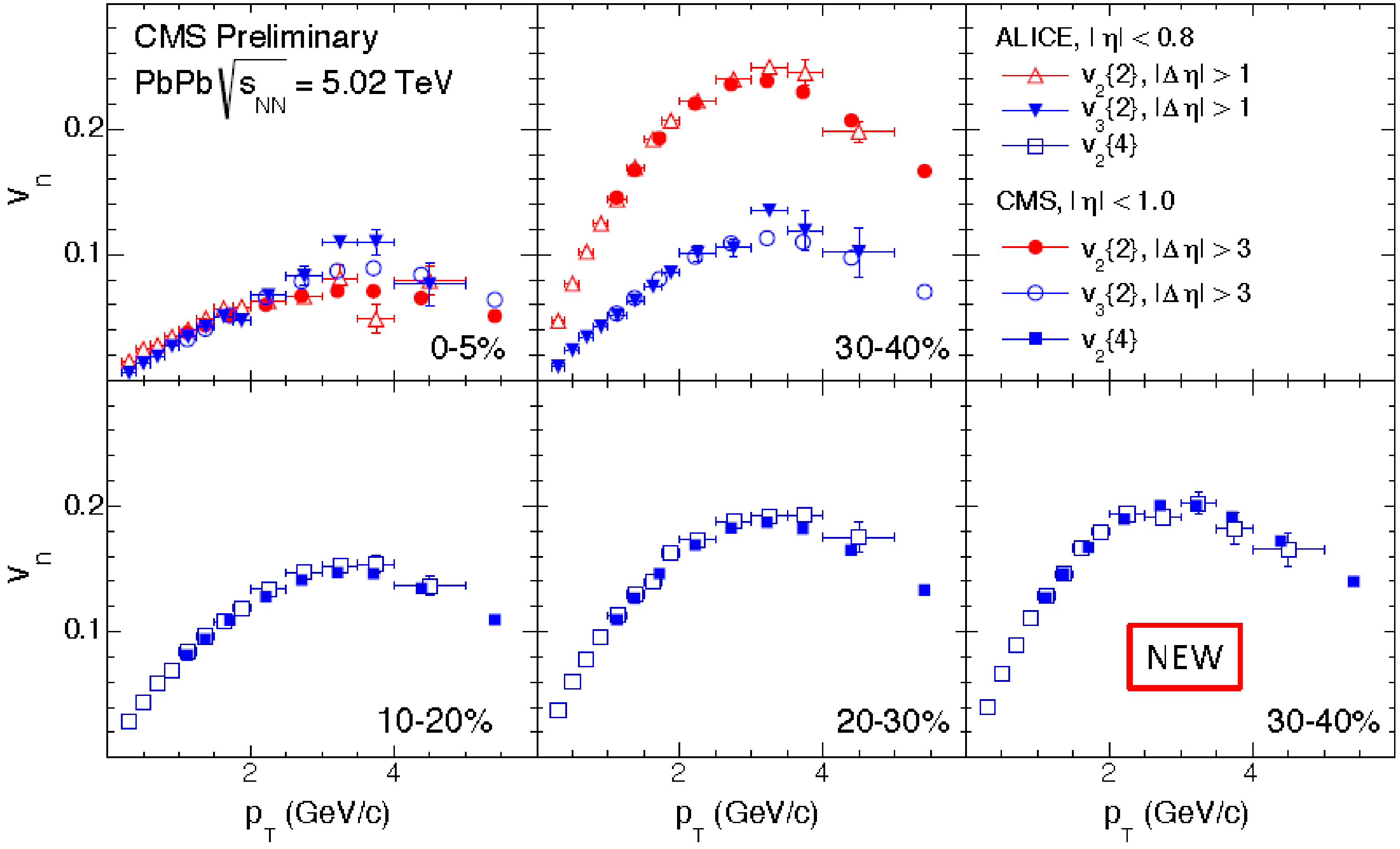


Observation of significant v_2 signal with 4- and 6-particle cumulant in high multiplicity pp collisions:

Multi-particle correlation!

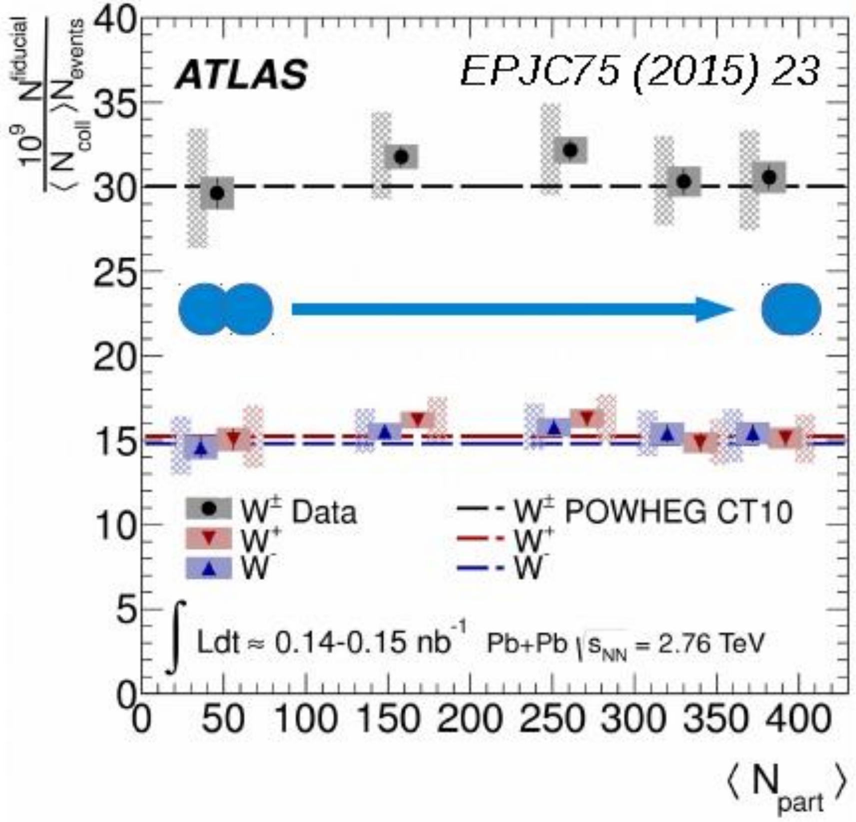
Tiziano Camporesi (CMS), ICHEP 2016

Soft probe, low p_T v_2 @ 5TeV

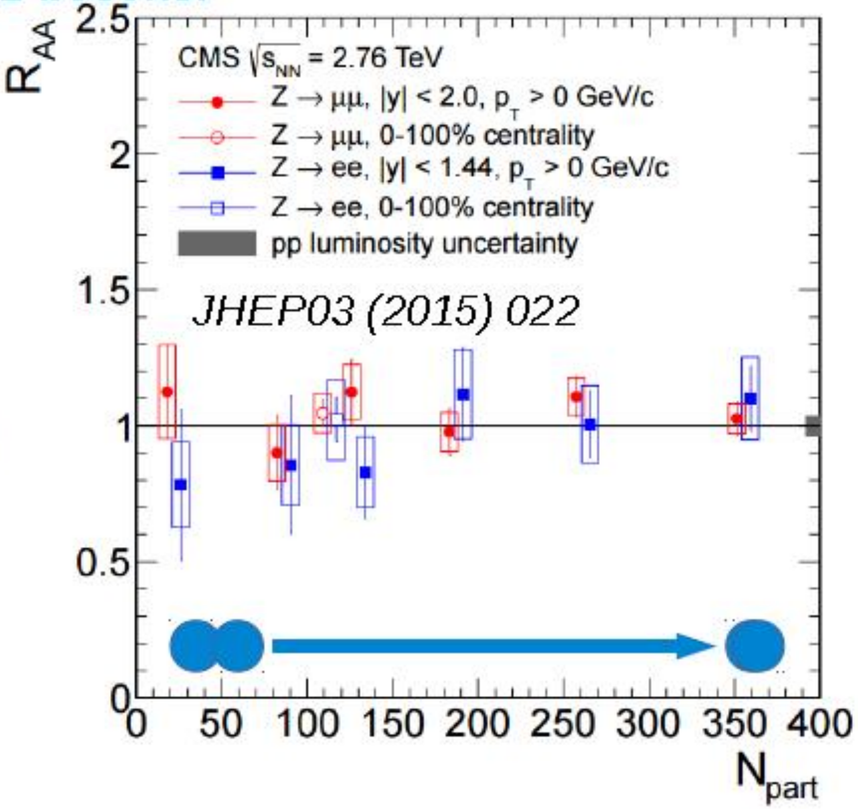


Z. Tu (CMS), LHCP 2016

W bosons:



Z bosons:



- No deviation from N_{coll} scaling.

Martin Rybar, LHCP 2016