Heavy-Ion Physics at the LHC

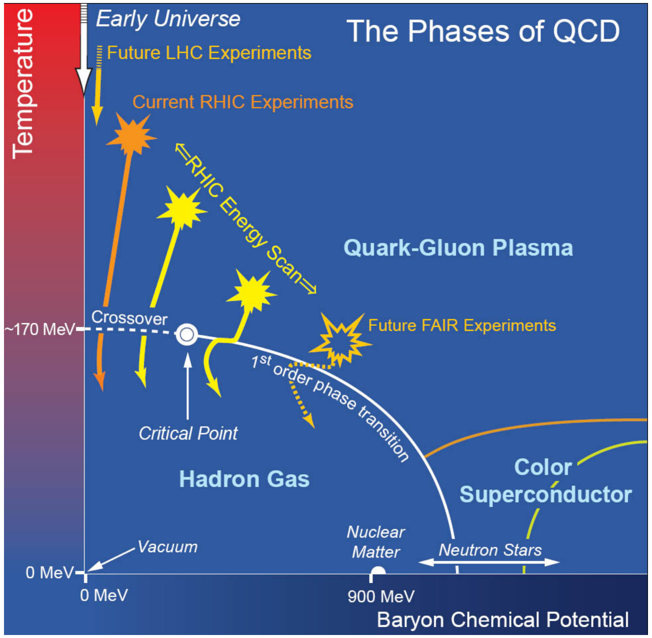
Barbara Wosiek
Institute of Nuclear Physics
Polish Academy of Sciences
Kraków, Poland

Outline

- Introduction
- LHC heavy-ion experiments
- HI data samples
- Pb+Pb results
  - Electroweak probes
  - Medium sensitive probes
  - Collective flow
- p+Pb results
- Summary and outlook

Ultra-relativistic heavy-ion collisions

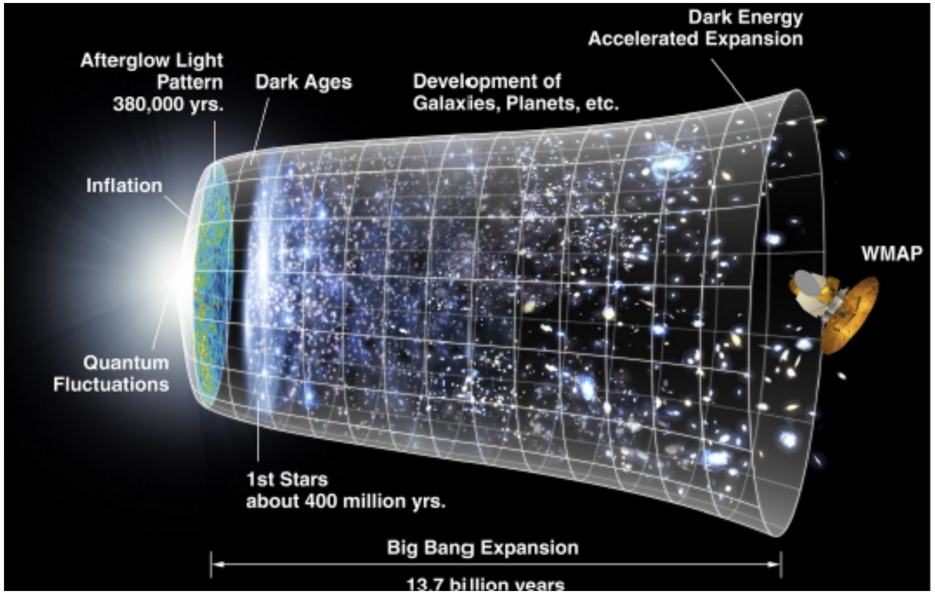
- Extraordinarily hot and dense matter is produced in heavy-ion collisions at UHE
- Initial energy densities exceed the energy density of atomic nuclei by 2 – 3 orders of magnitude
- Due to large pressure gradients, the matter undergoes explosive collective expansion → "Little Bangs"



✧ Explore the QCD phase diagram
✧ Test the predictions of the QCD

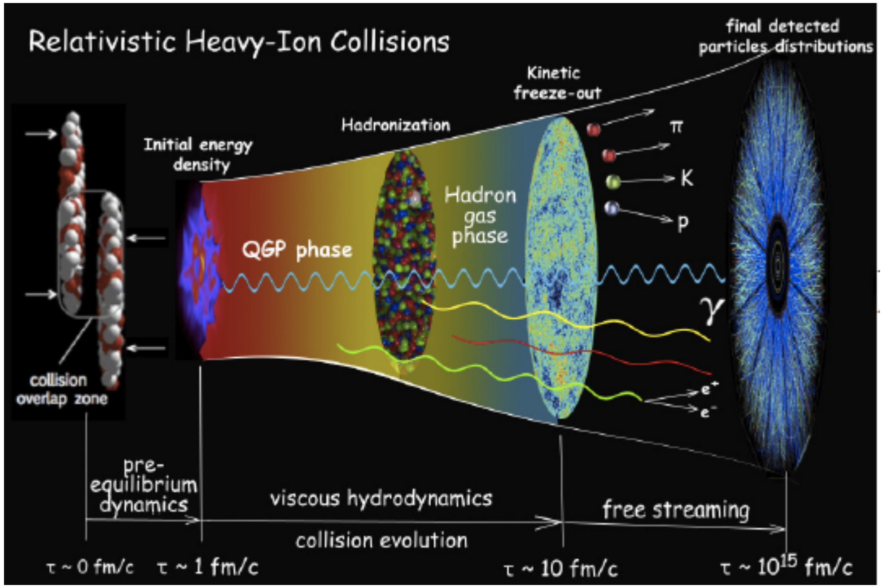
Ultra-relativistic heavy-ion collisions

Big Bang



Credit: NASA

Little Bang



Credit: P. Sorensen

Hubble-like expansion

Initial-state quantum fluctuations imprinted onto the final-state

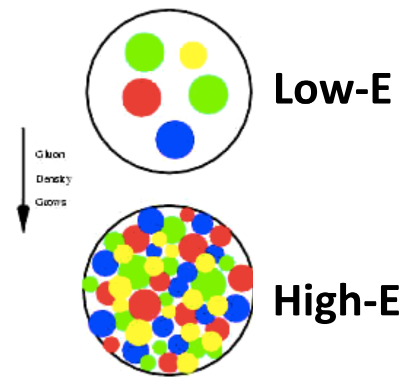
Standard Model of the Little Bang still under construction

needed input: heavy-ion experimental data

Ultra-relativistic heavy-ion collisions

Color Glass Condensate:

a universal form of matter that describes the properties of all high-energy, strongly interacting particles. These simple properties follow from first principles of QCD.



QCD at small Bjorken-x → a novel regime governed by high gluon densities and non-linear coherence phenomena

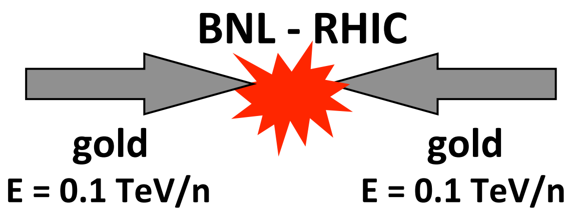
Saturation models:

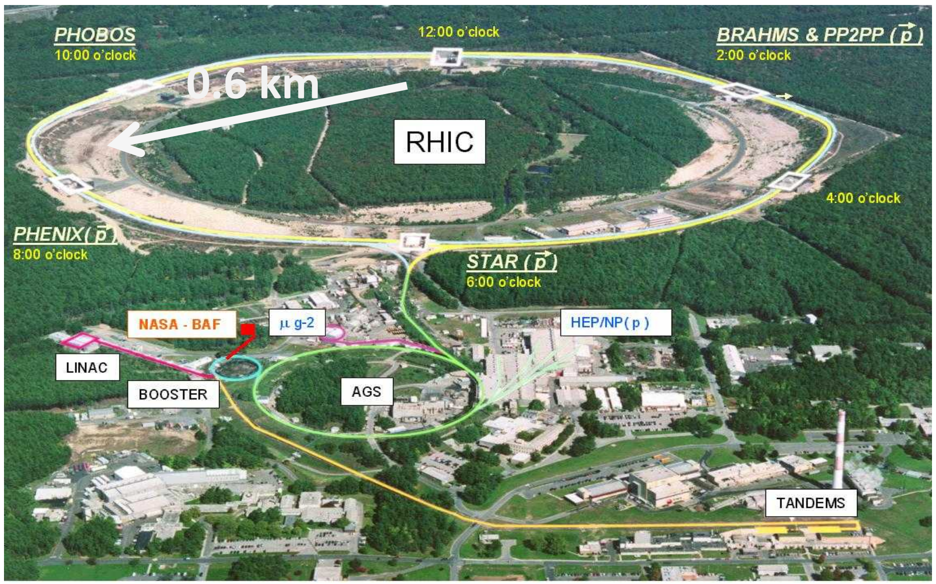
- **Gluon distribution rises rapidly at low-x:** $xG(x) \sim x^{-\lambda}$ ($\lambda \sim 0.25$ from fits to HERA data)
- **Gluons of π/Q^2 can overlap in the transverse plane**
- **At saturation scale gluons fill the entire transverse area:**

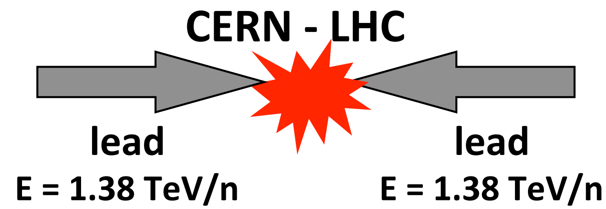
$$N_g \frac{\pi}{Q_s^2} = \pi R_A^2 \qquad\qquad Q_s^2 = \alpha_s\left(Q_s^2\right) N_g\left(x, Q_s^2\right) A^{1/3}$$

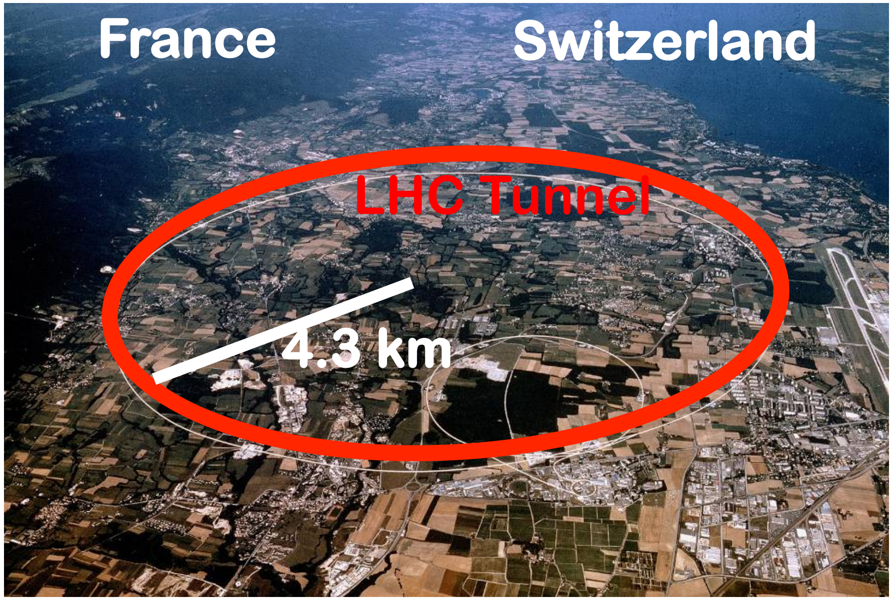
- **Below "saturation" scale Q_s^2 gluon fusion occurs** $g+g \rightarrow g$

Heavy-ion colliders









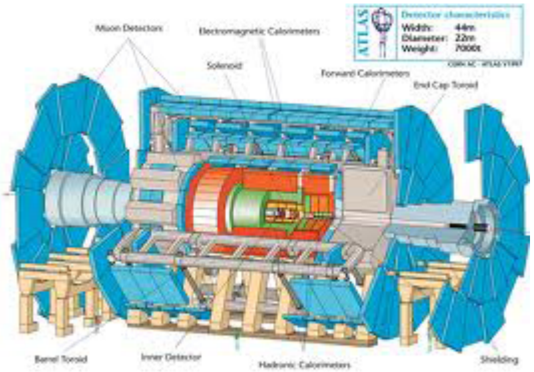
RHIC- Experiments

- **STAR**
- **PHENIX**
- **BRAHMS**
- **PHOBOS**

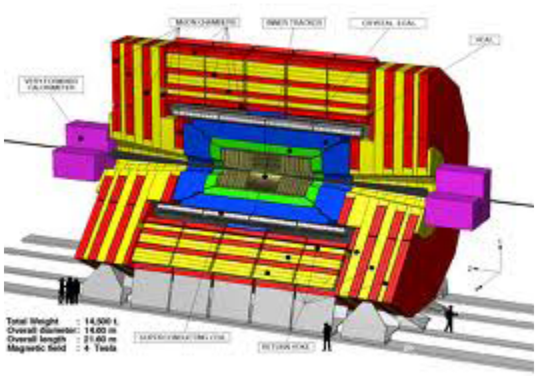
LHC- HI Experiments

- **ALICE**
- **ATLAS**
- **CMS**
- **LHCb (p+Pb)**

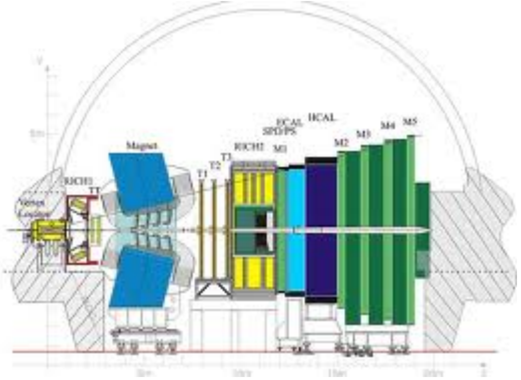
LHC experiments



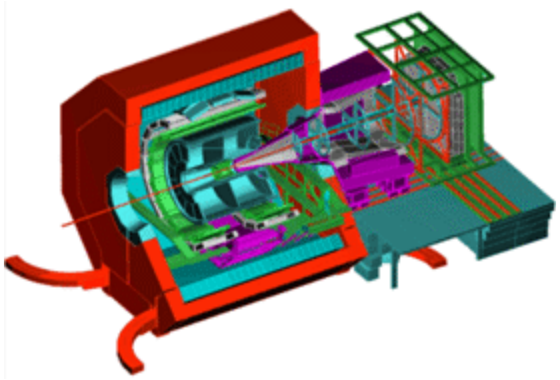
ATLAS (general purpose)



CMS (general purpose)



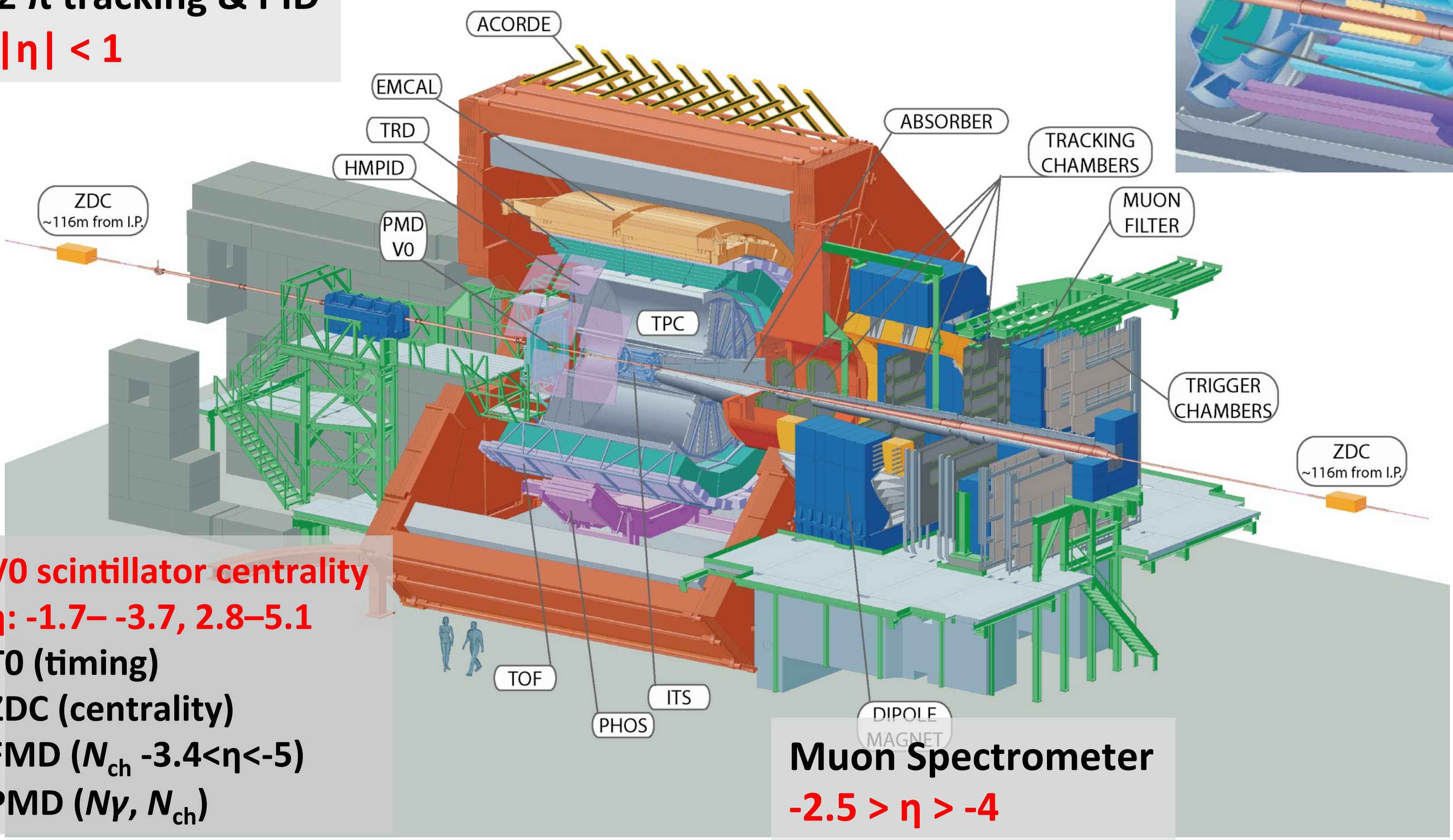
LHCb (heavy flavour physics)

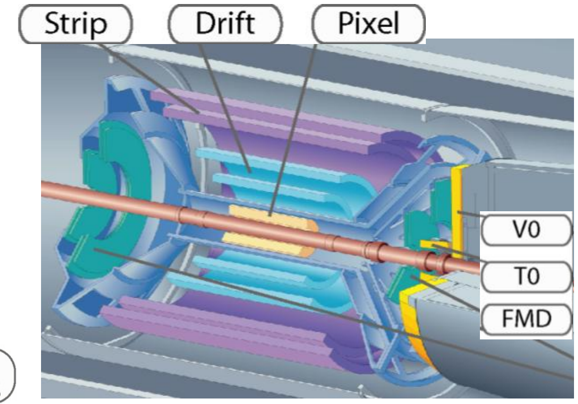


ALICE(heavy-ion physics)

The ALICE detector

Central Barrel
2 π tracking & PID
|η| < 1

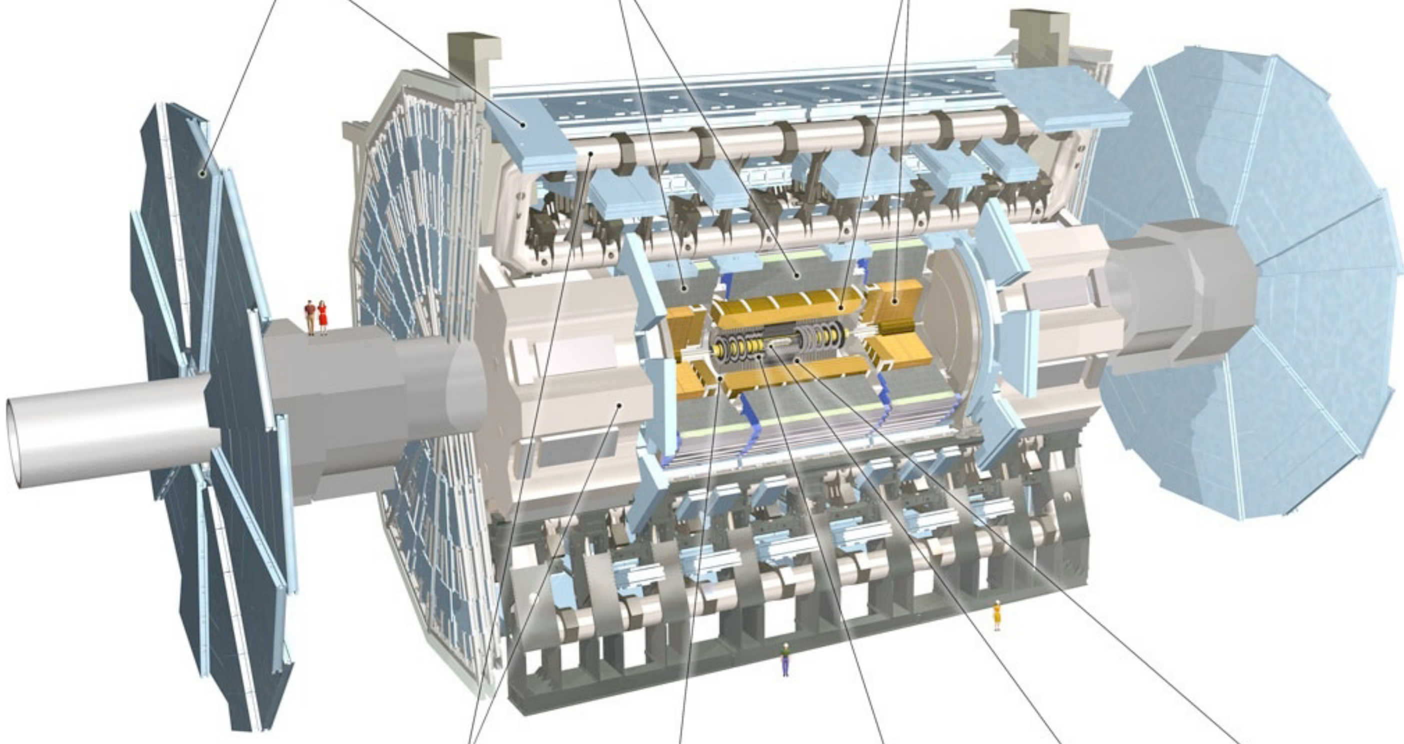




V0 scintillator centrality
η: -1.7– -3.7, 2.8–5.1
T0 (timing)
ZDC (centrality)
FMD (N_{ch} -3.4<η<-5)
PMD ($N\gamma$, N_{ch})

Muon Spectrometer
-2.5 > η > -4

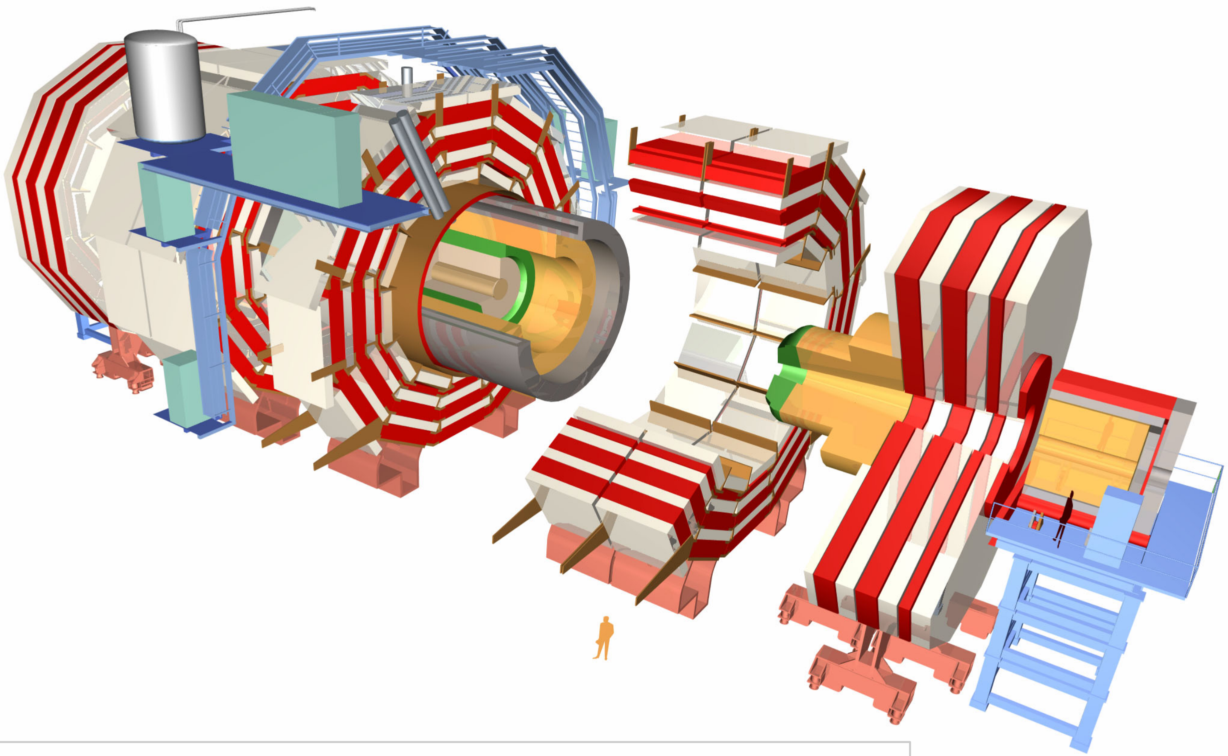
The ATLAS detector

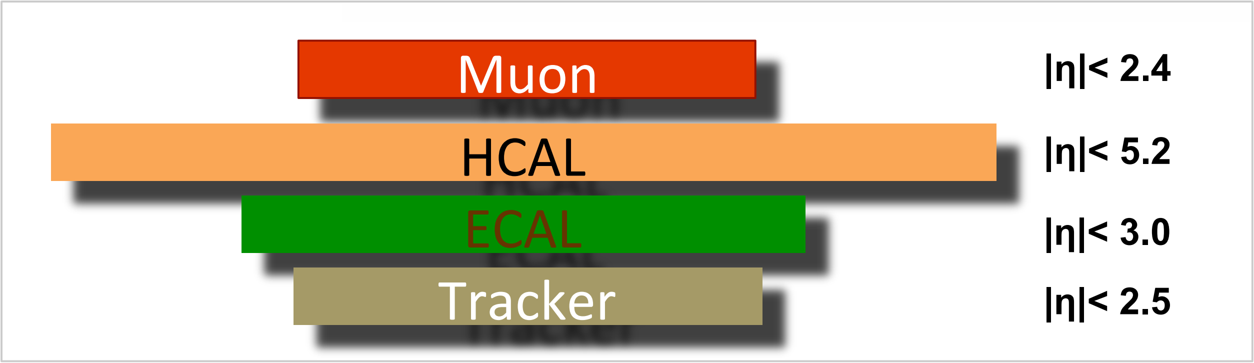


Three main subsystems with a full coverage in azimuth:

- Inner Detector – tracking $|\eta|<2.5$
- Calorimetry – $|\eta|<4.9$
- Muon Spectrometer - $|\eta|<2.7$

The CMS detector





LHC HI experiments

ALICE strengths:

- **Particle identification**
- **Efficient low momentum tracking, down to 100 MeV ($|\eta|<1$, full azimuth)**

ATLAS and CMS excel at:

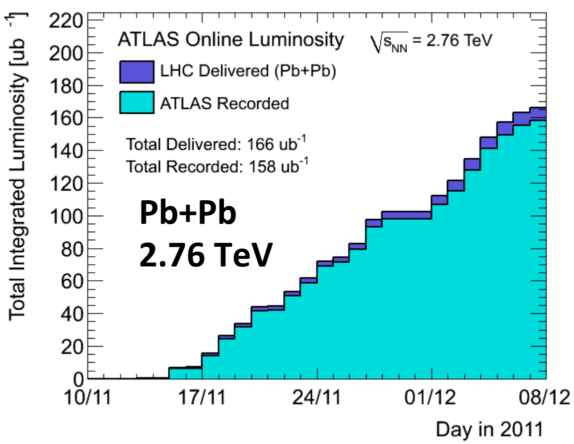
- **Tracking over $|\eta|<2.5$ and full azimuth**
- **Fine granularity calorimetry $|\eta|<5$ and full azimuth**
- **Trigger selectivity**

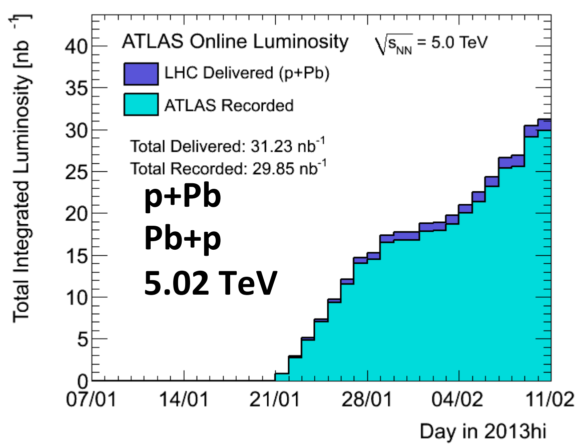
LHCb (p+Pb):

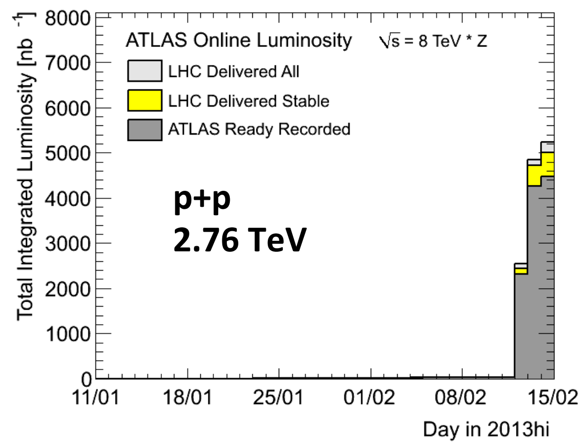
- **Heavy quark physics**
- **Forward spectrometer $1.9 < \eta <4.9$**
  (p+Pb: $1.5 < \eta < 4.5$; Pb+p: $-5.5 < \eta <2.5$)

LHC Run 1 for heavy-ion physics

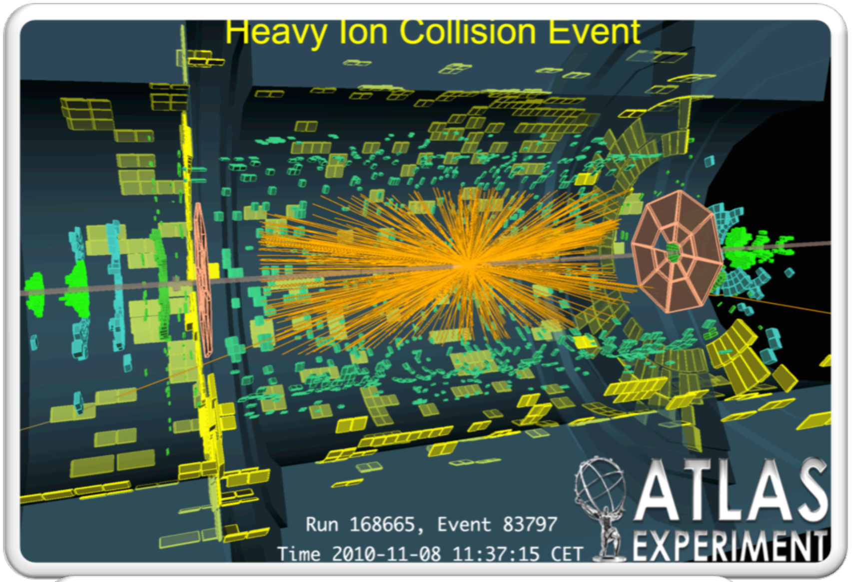
System	$\sqrt{s_{NN}}$ [TeV]	When	Integrated L per experiment
Pb+Pb	2.76	2010+2011	0.17 nb^{-1}
p+Pb	5.02	2012	0.001 nb^{-1}
p+Pb	5.02	2013	19 nb^{-1}
Pb+p	5.02	2013	~11 nb^{-1}
p+p	2.76	2011	200 nb^{-1}
p+p	2.76	2013	~4.5 pb^{-1}

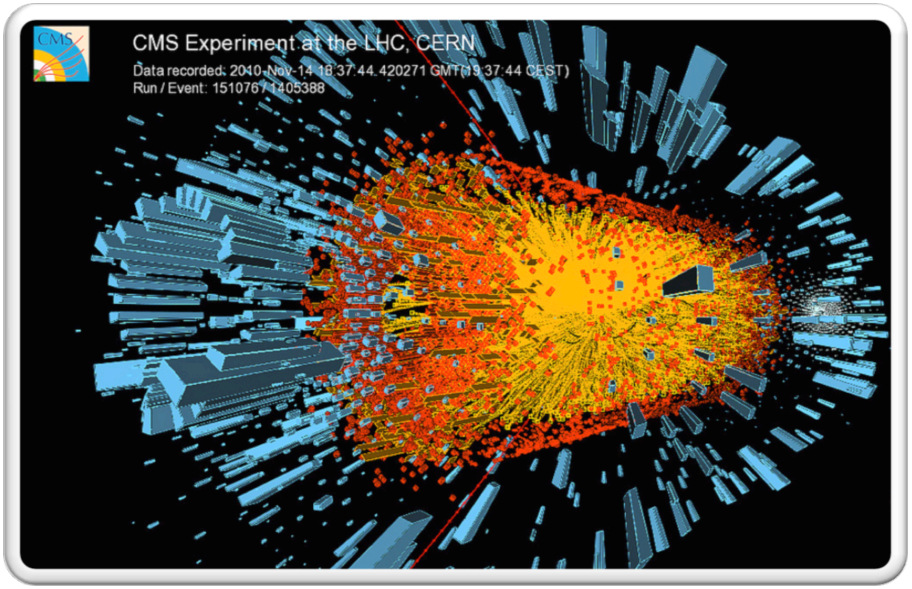


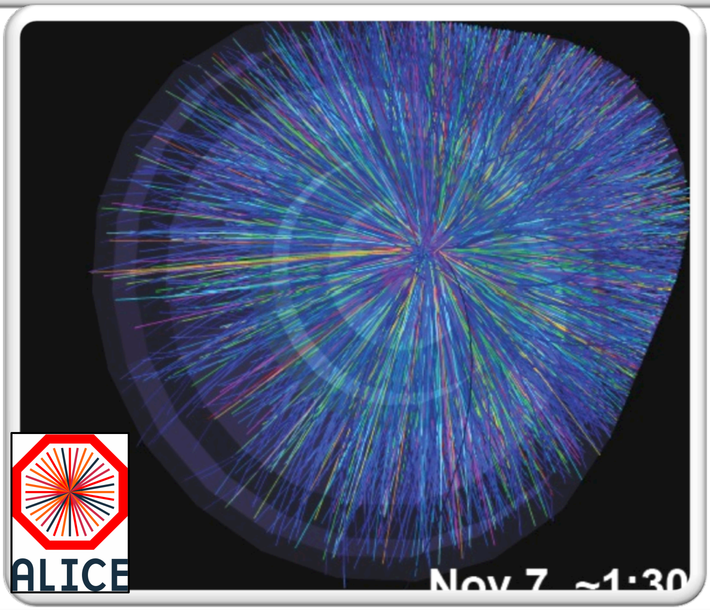


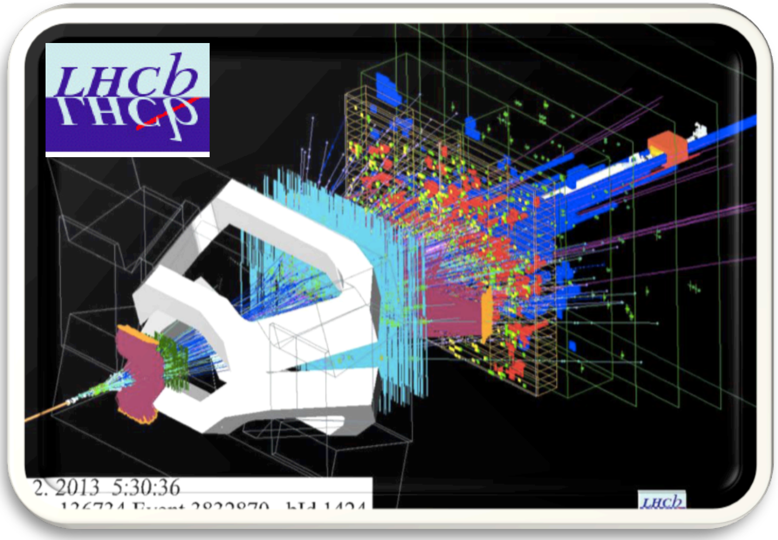


Heavy-ion collision events



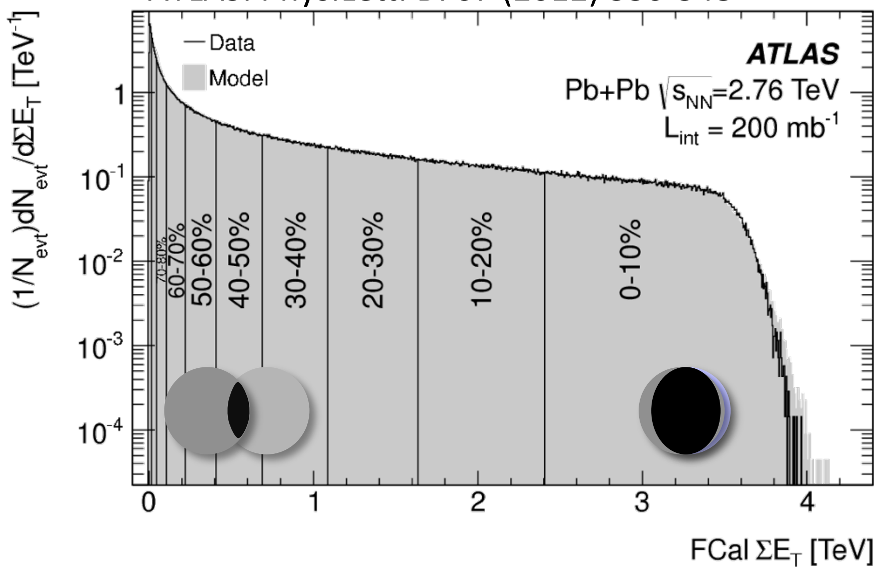


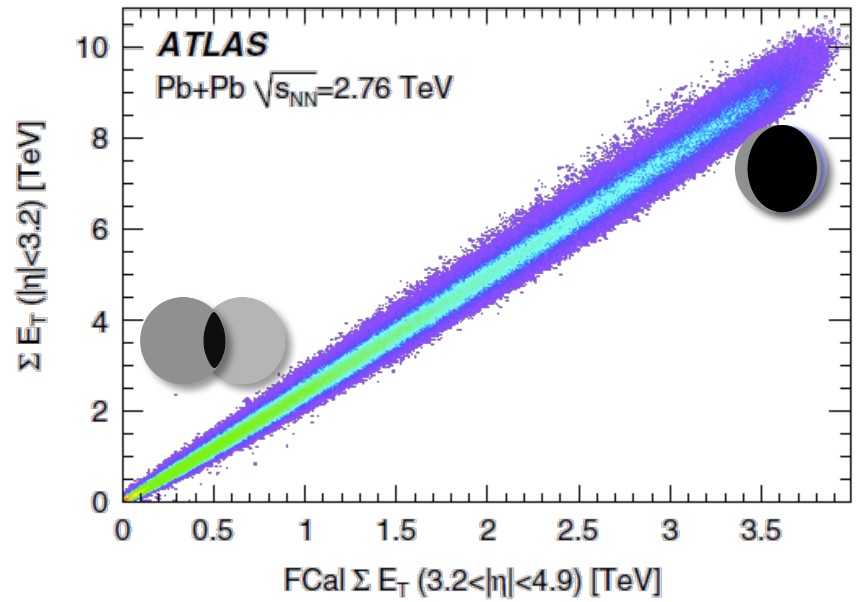




Centrality of Pb+Pb collision

ATLAS: Phys.Lett. B707 (2012) 330-348



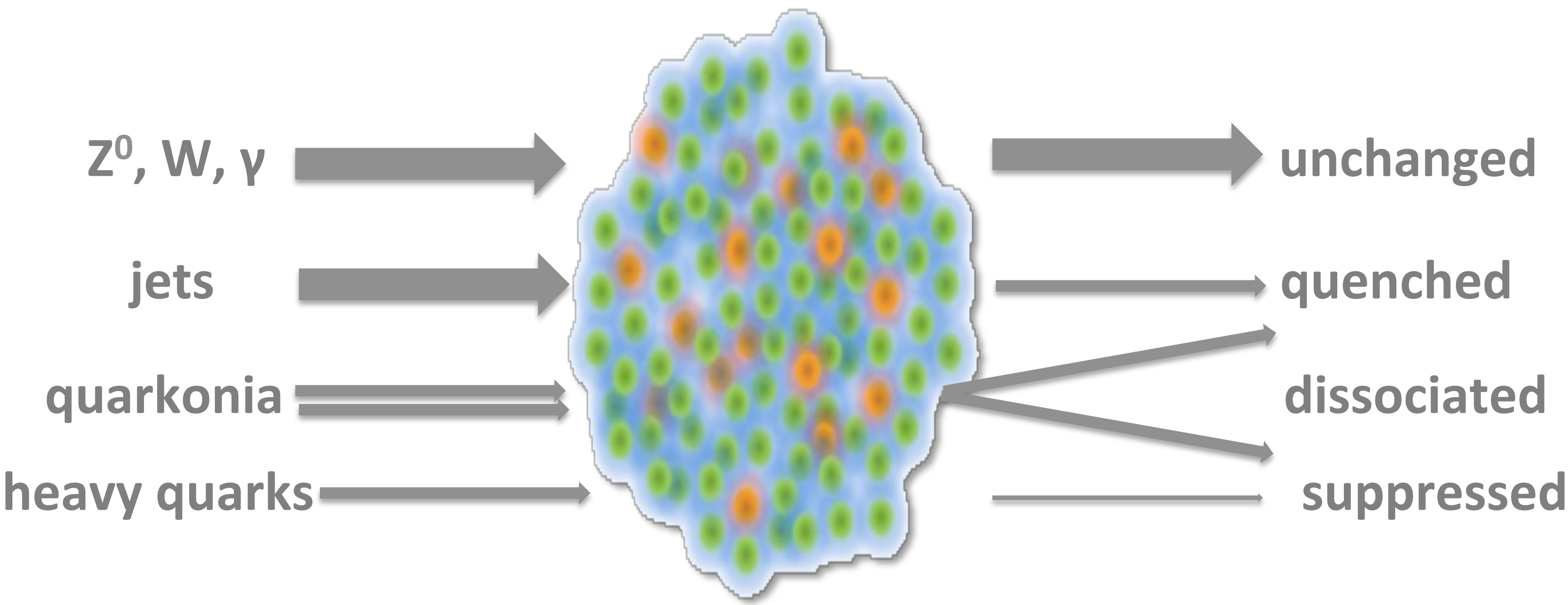


- **Energy sum in forward calorimeter (FCal) ΣE_T (3.2 |η|<4.9) compared with Glauber MC ⊗ 2.76 TeV pp data**
- **Centrality parameters $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ calculated from Glauber MC**

	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$
0-5%	382 ± 1%	1683 ± 8%
5-10%	330 ± 1%	1318 ± 8%
10-20%	261 ± 2%	923 ± 7%
20-40%	158 ± 3%	441 ± 7%
40-80%	46 ± 6%	78 ± 9%

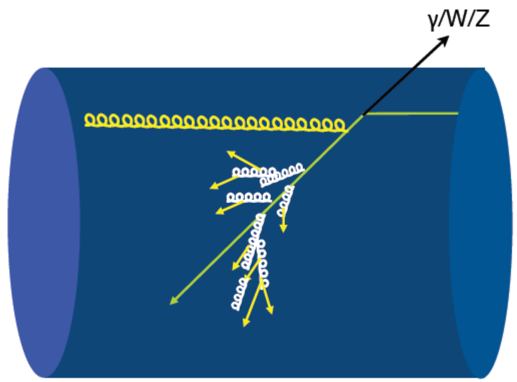
Probing the medium created in Pb+Pb

High transverse momentum probes



Electroweak probes

Z^0 and $W^{\pm}$ bosons and photons are not strongly interacting with the medium constituents:
<u>should obey QCD factorization (scaling with N_{coll})</u>



ATLAS EXPERIMENT

CMS
Compact Muon Solenoid

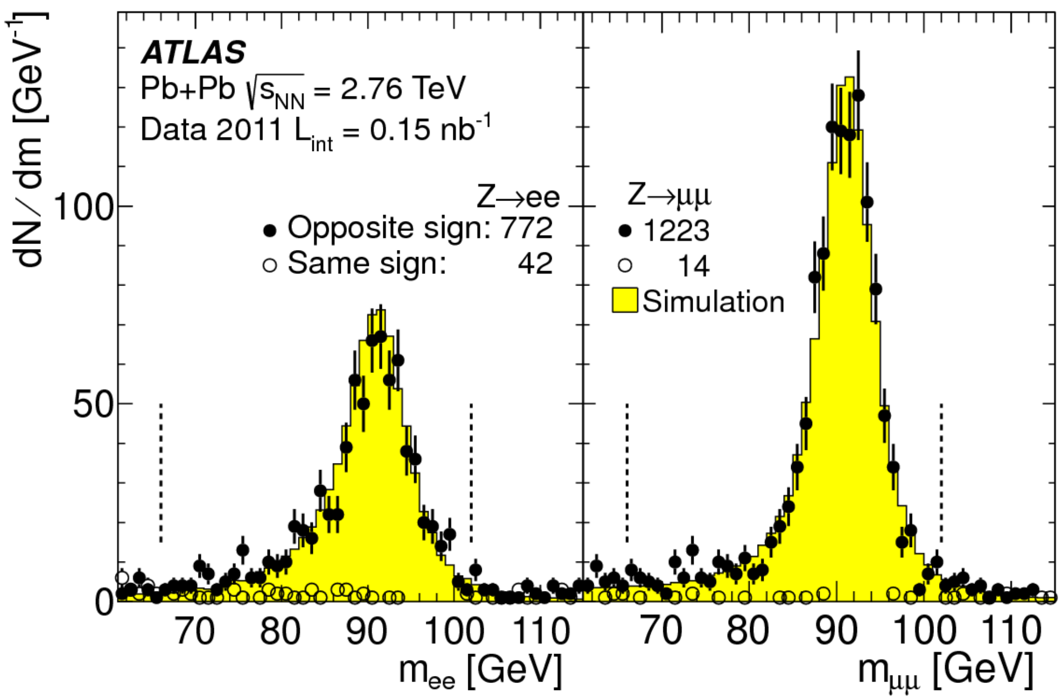
- Measurements of Z/W/γ production in Pb+Pb provide constraints on the nuclear PDF
- Z/W/γ bosons can be used as a reference
- Production of Z/W/γ in association with jets provides a handle for understanding the parton energy loss in medium

Z^0 measurements

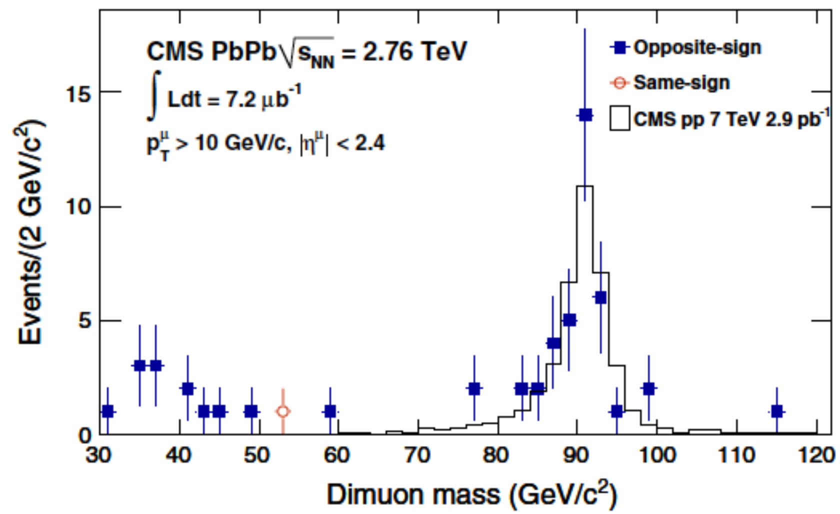
$Z \rightarrow e^+e^-, \mu^+\mu^-$

$Z \rightarrow \mu^+\mu^-$

ATLAS, Phys. Rev. Lett. 110 (2013) 022301



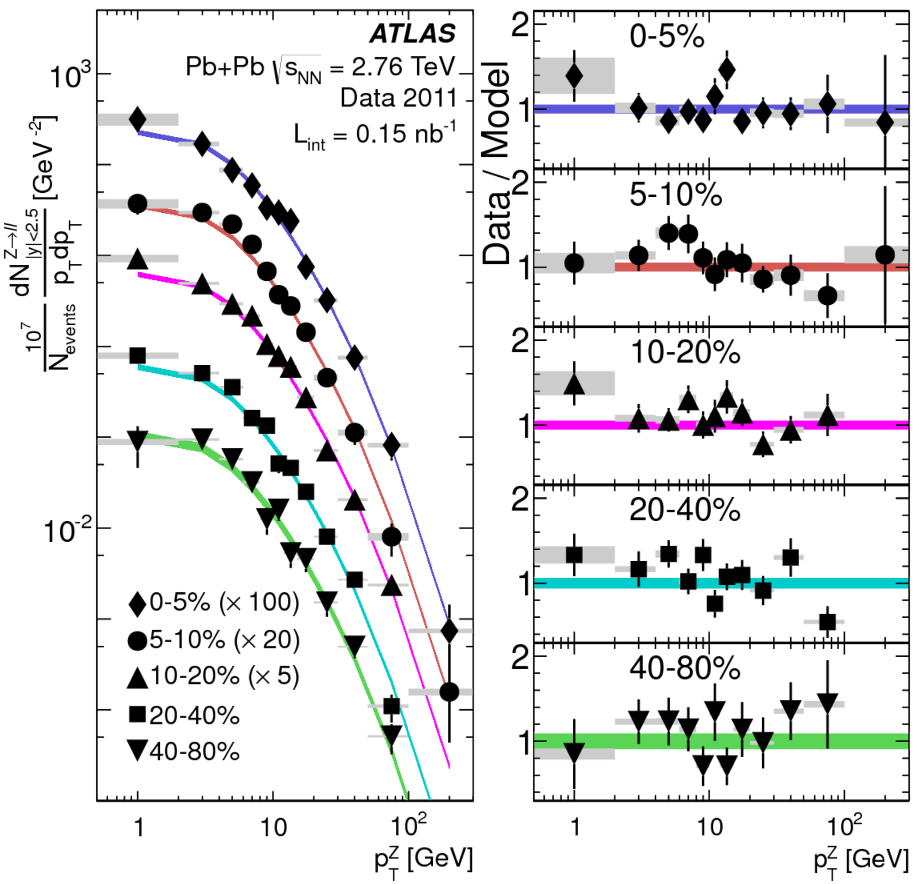
CMS, Phys. Rev. Lett. 106 (2011) 212301

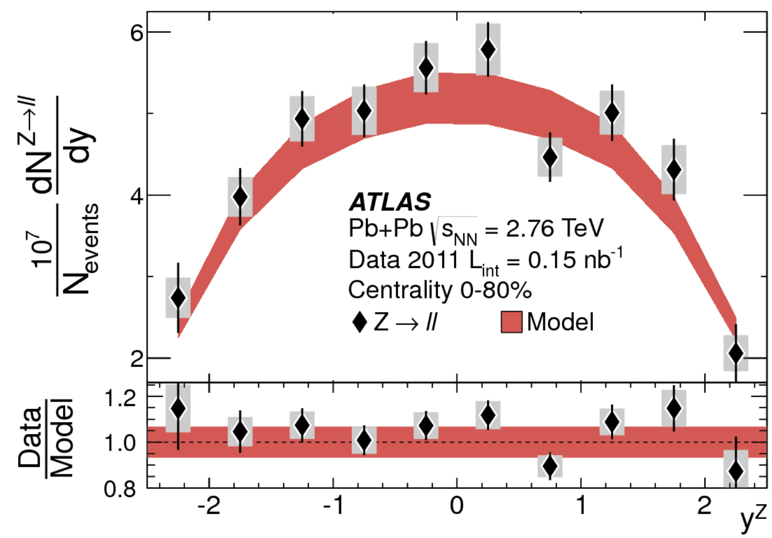


Background contamination less than 3%

p_T and y distributions of Z bosons

$Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$





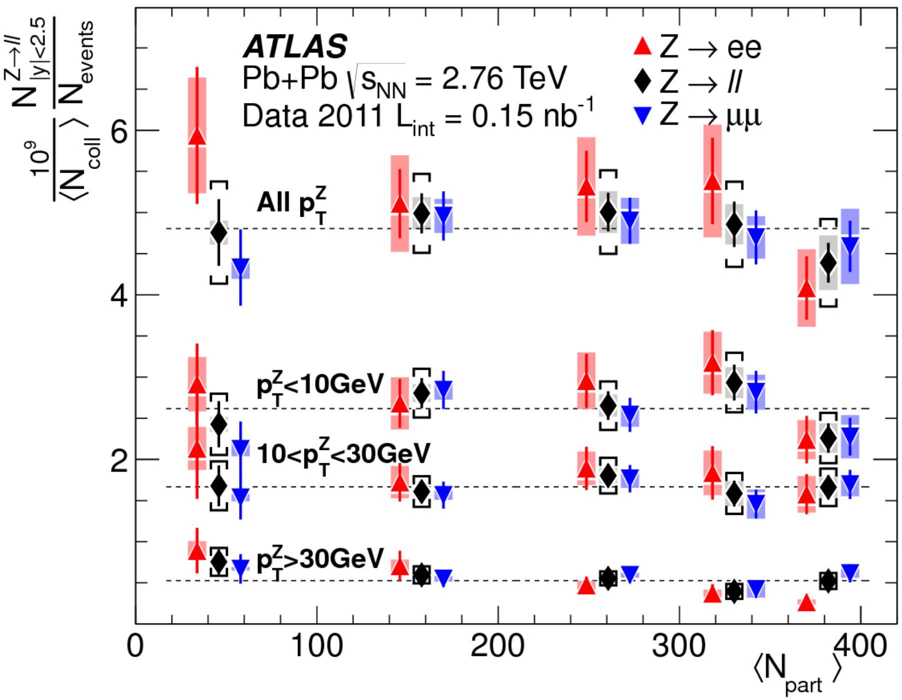
p_T and y distributions consistent with Pythia simulations for pp with NNLO cross section × <T_{AA}>

ATLAS, Phys. Rev. Lett. 110 (2013) 022301

Centrality dependence of Z production

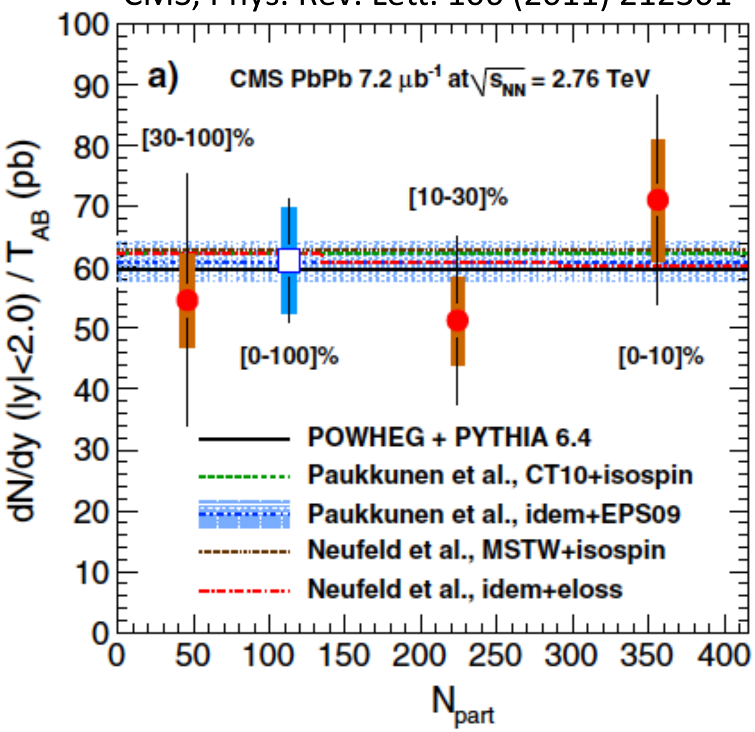
$Z \rightarrow e^+e^-, \mu^+\mu^-$

ATLAS, Phys. Rev. Lett. 110 (2013) 022301



$Z \rightarrow \mu^+\mu^-$

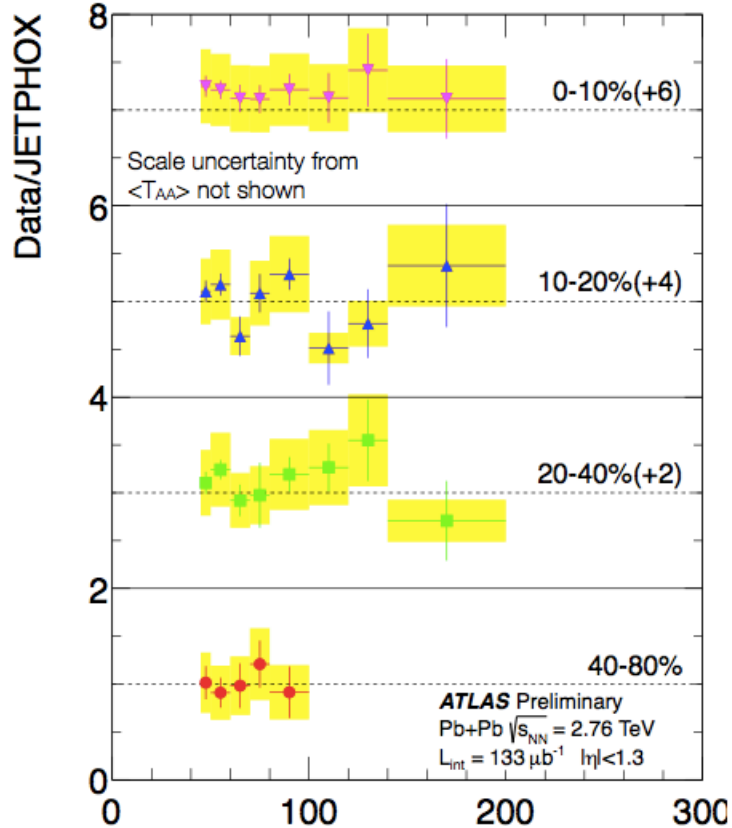
CMS, Phys. Rev. Lett. 106 (2011) 212301



Z^0 yields consistent with N_{coll} scaling

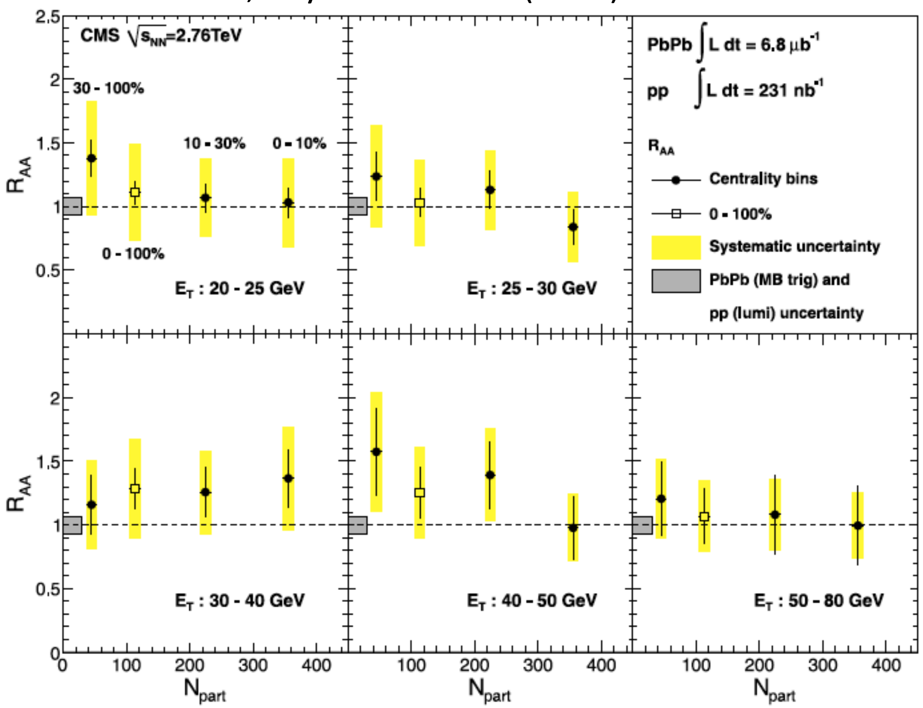
Centrality dependence of γ production

ATLAS-CONF-2012-051



$$R_{AA} = \frac{N_\gamma^{AA} / N_{coll}}{N_\gamma^{pp}}$$

CMS, Phys. Lett. B 710 (2012) 256



Data/JETPHOX ≈ 1 ($\sim R_{AA}$)

Photon yields consistent with N_{coll} scaling

Electroweak probes: Summary

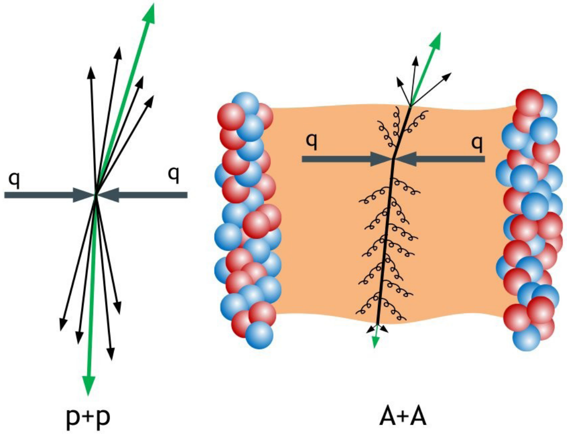
- Z, γ yields scale with N_{coll}
  - No significant violation of QCD factorization
- Using N_{coll} as a normalization of AA spectra is justified

Medium-sensitive probes

- Jet studies
- Quarkonia production
- Hadron production

Jet studies

Jet quenching:
jet energy loss in hot/dense medium
(J.D. Bjorken – 1982)



- **Suppression of the jet yields**
- Dijet energy imbalance
- Modification of the fragmentation function
- Dependence on the path length
- Jet v_2
- **γ,Z - jet correlations**

Jet suppression

ATLAS: Phys. Lett.B 719 (2013) 220

$$R_{cp} = \frac{\frac{1}{N_{coll}^{cent}} E \frac{d^3N^{cent}}{dp^3}}{\frac{1}{N_{coll}^{periph}} E \frac{d^3N^{periph}}{dp^3}}$$

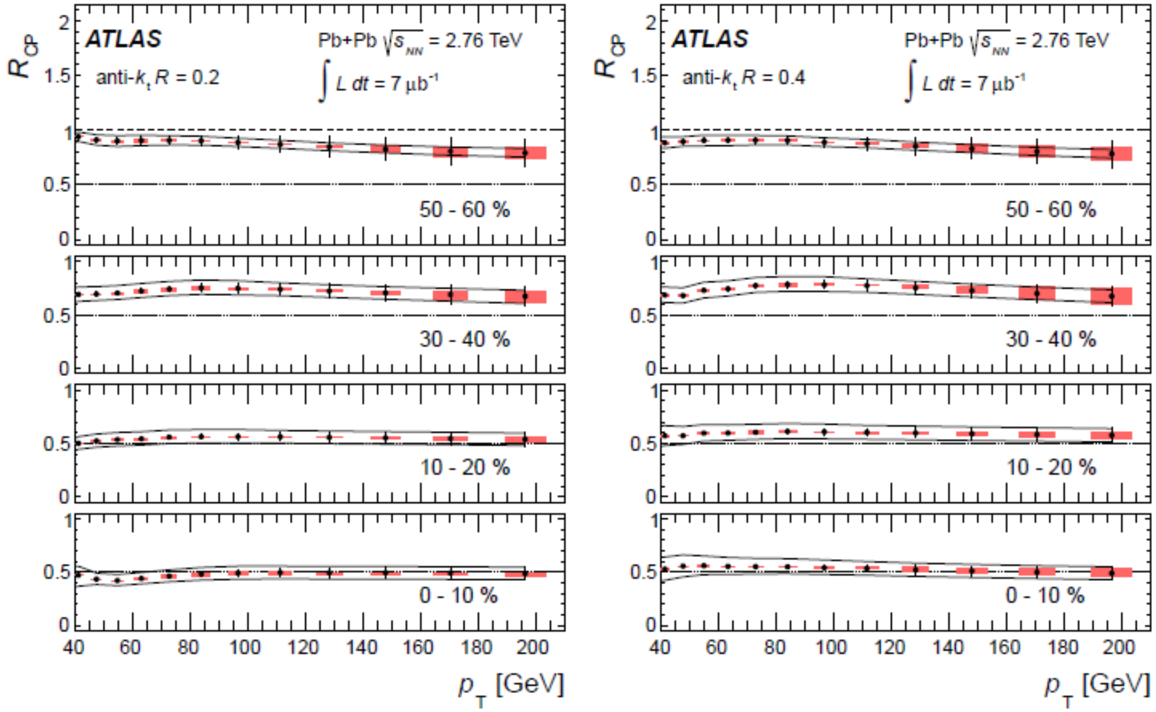
First LHC result on jet suppression

Unfolded p_T spectra

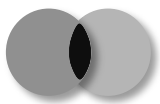
For jet sizes R=0.2, 0.3, 0.4 and 0.5

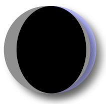
peripheral reference: 60-80%

R=0.2



R=0.4

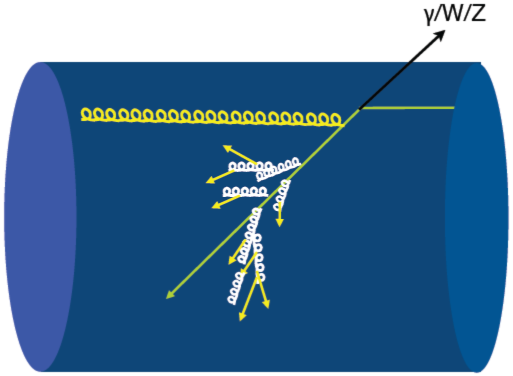




- **A factor of ~2 suppression in 0-10% most central collisions**
- **Suppression independent of jet p_T**

γ, Z – jet correlations

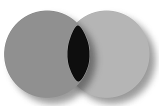
Modification of the jet energy relative to the probe not affected by the medium

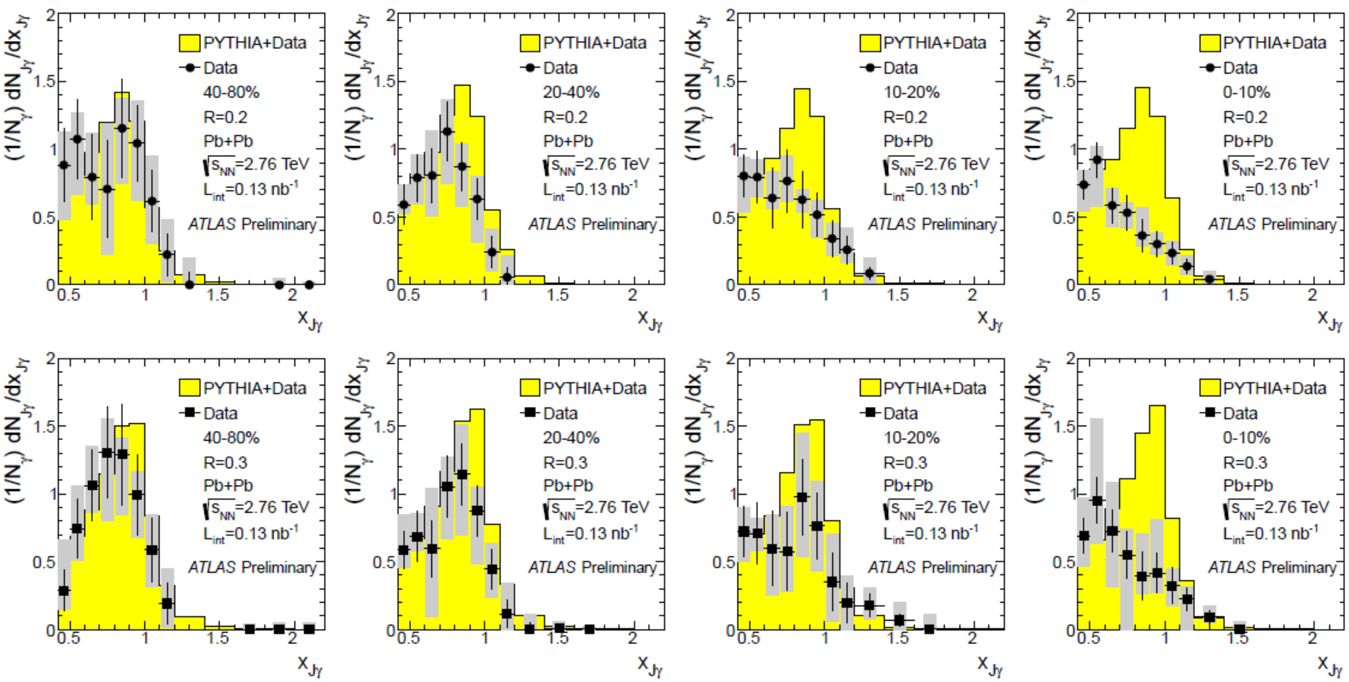


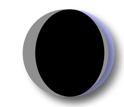
γ – jet correlations

$$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$$

- $E\gamma$ > 60 GeV: 60-90 GeV, |η|<1.3
- Jet: anti-kT, R=0.2, 0.3, p_T>25 GeV, |η|<2.1
- γ-jet separation Δϕ > 7π/8 (back-to-back)







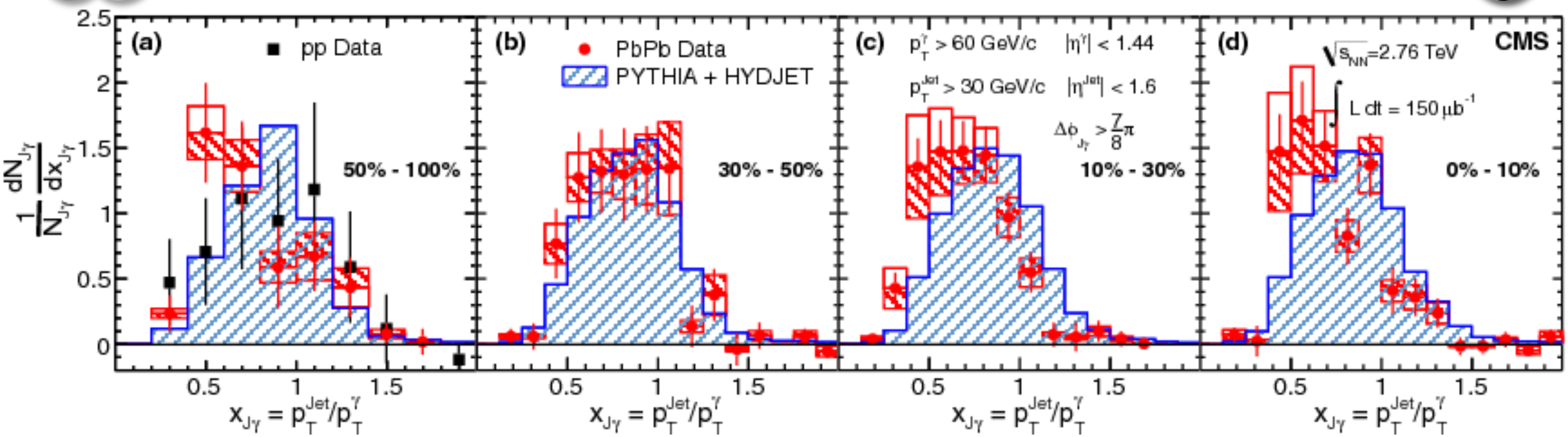
- Shape and integral compatible with PYTHIA for peripheral collisions
- With increasing centrality shift towards smaller $x_{J\gamma}$ and reduction of the integral

ATLAS-CONF-2012-121

γ – jet correlations

$$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$$

- $E\gamma$ > 60 GeV: 60-90 GeV, $|\eta|<1.44$
- Jet: anti-kT, R=0.3, p_T>30 GeV, $|\eta|<1.6$
- γ-jet separation $\Delta\phi > 7\pi/8$ (back-to-back)

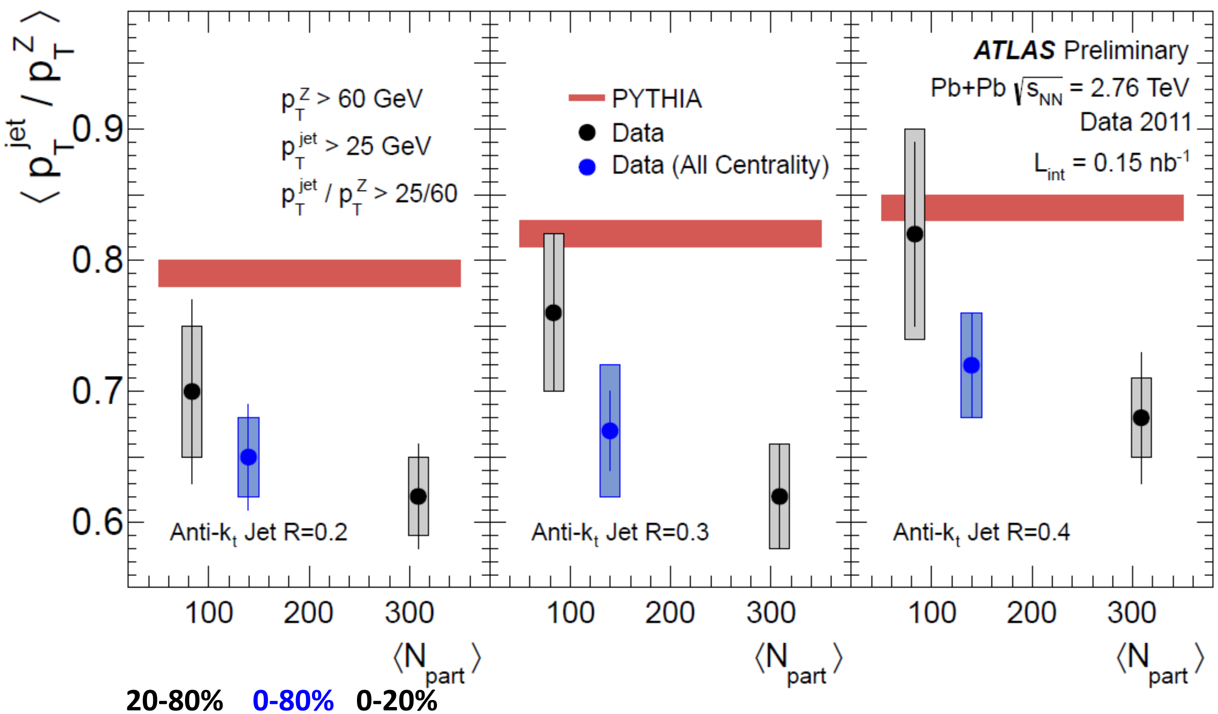


- Shape and integral compatible with PYTHIA+HYDJET for peripheral collisions
- For central events shift towards smaller $x_{J\gamma}$
- $\langle x_{J\gamma} \rangle$ = 0.73 ±0.02 (stat)±0.04 (syst) for 0-10% central (0.86 in pp and PYTHIA+HYDJET)

CMS: Phys. Lett. B 718 (2013) 773

Z – jet correlations

- $Z \to e^+e^-, \mu^+\mu^-$ p_T > 60 GeV
- Jet: anti-kT, R=0.2, 0.3, 0.4, p_T>25 GeV, $|\eta|$<2.1
- Z-jet separation > $\pi/2$ → 37 events for L_{int}=0.15 nb^{-1}



$\langle p_T^{jet} / p_T^Z \rangle$

- Suppression of the $\langle p_T^{jet} / p_T^Z \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events)
- Stronger suppression for more central collisions

ATLAS-CONF-2012-119

Quarkonia in heavy-ion collisions

- **Heavy quarks are created at the early stage**
- **Quarkonia states are Debeye-screened in the QGP** (Matsui, Satz,1986)
- **The dissociation temperatures are different for different states as predicted by lattice QCD calculation**

A. Moscy, P. Petreczky, Phys. Rev. Lett. 99 (2007) 211602

state	χ_c	ψ'	ϒ''(3S)	J/ψ	ϒ'(2S)	χ_b	ϒ(1S)
T_{dis}	$\leq T_c$	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

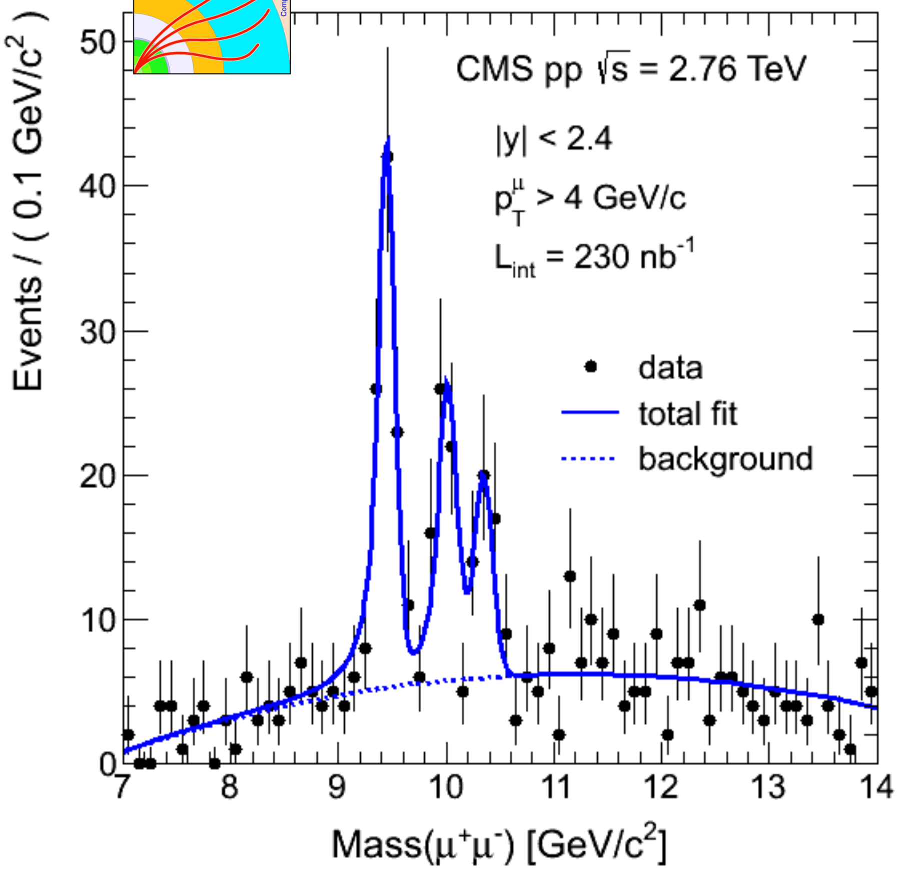
- **Can help to quantify medium properties - temperature**

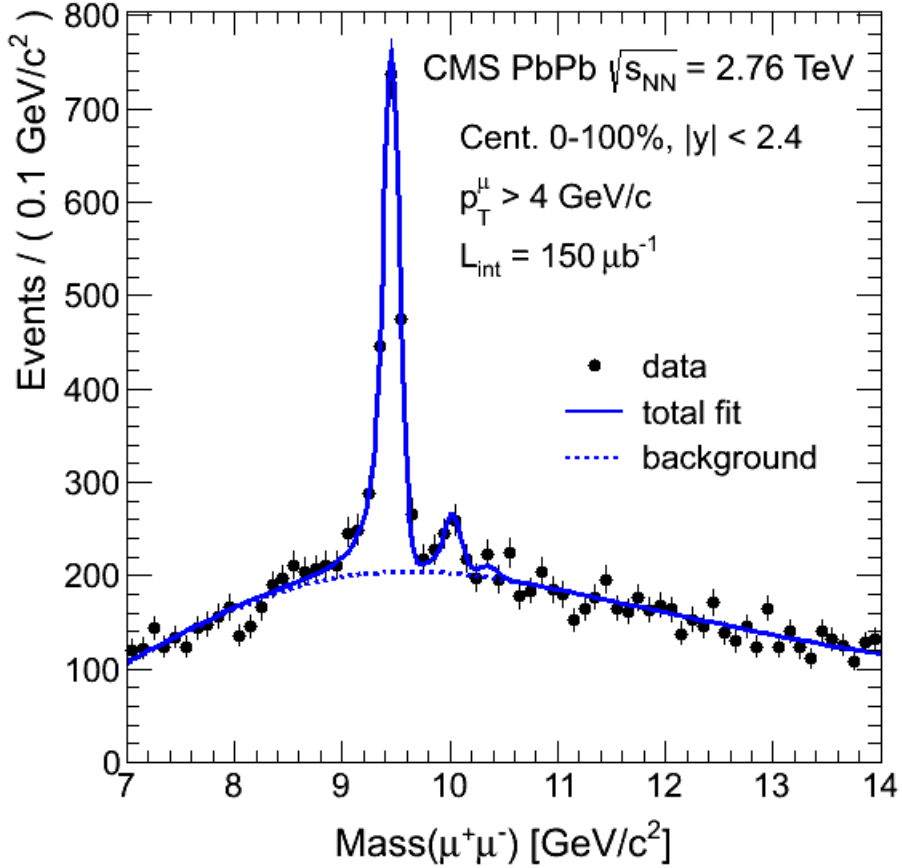
Quarkonia suppression in HI collisions expected when compared to p+p reference scaled by number of binary nucleon-nucleon collisions:

$$R_{AA} \equiv \frac{dN^{AA}}{N_{coll} dN^{pp}}$$

Sequential Υ suppression

CMS: Phys. Rev. Lett. 109 (2012) 222301



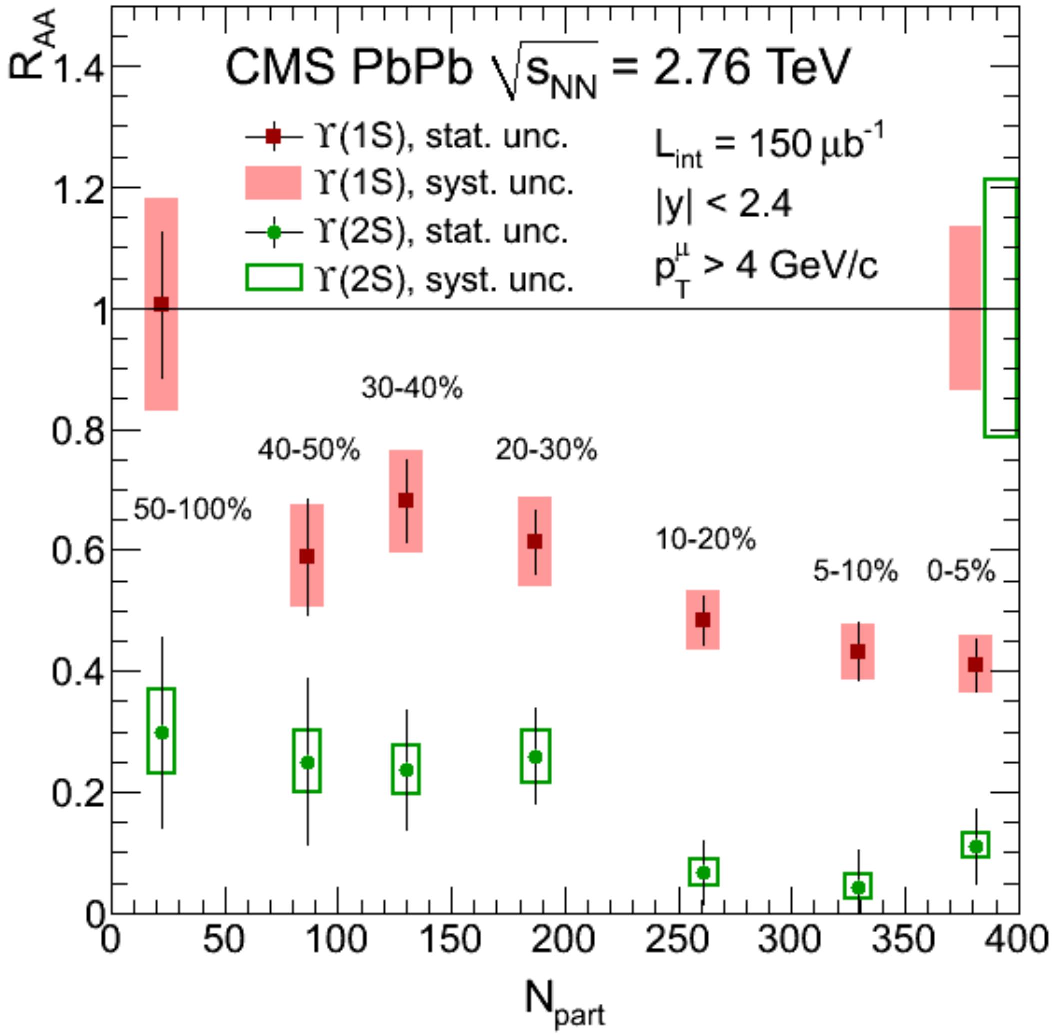


$[Y(2S+3S)/Y(1S)]_{PbPb}/[Y(2S+3S)/Y(1S)]_{pp}$ = 0.15 ± 0.05 (stat.) ± 0.02 (syst.)

> 5 σ significance

Sequential Υ suppression

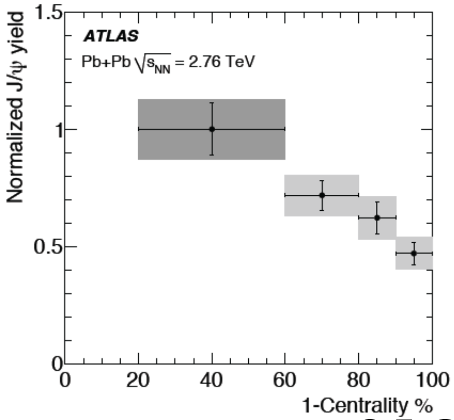
CMS: Phys. Rev. Lett. 109 (2012) 222301



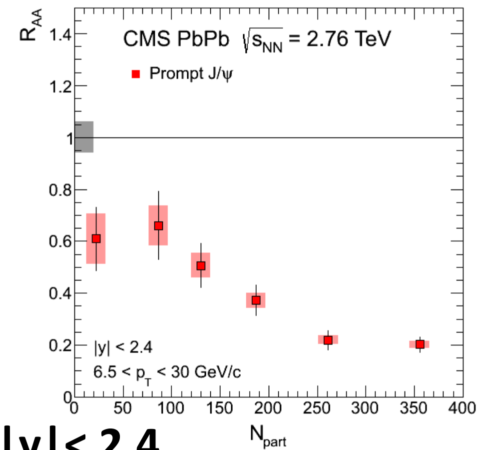
R_{AA} suppressed by factors ~2, 8 and >10 for (1S), (2S) and (3S) states respectively

Charmonium suppression

ATLAS: Phys.Lett. B697 (2011) 294

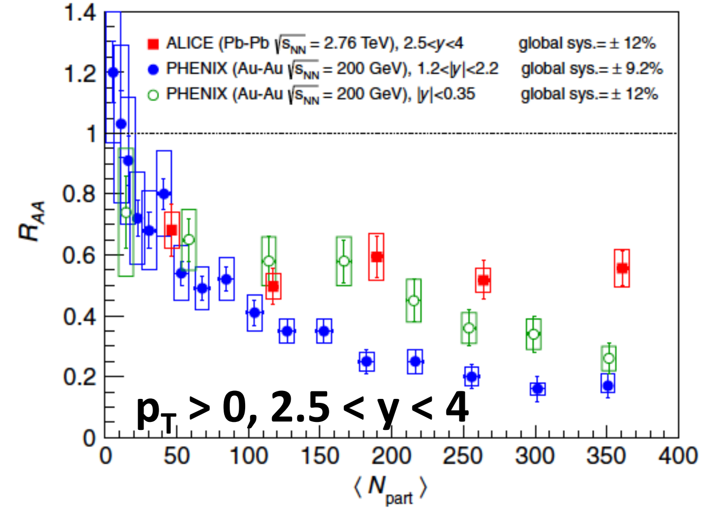


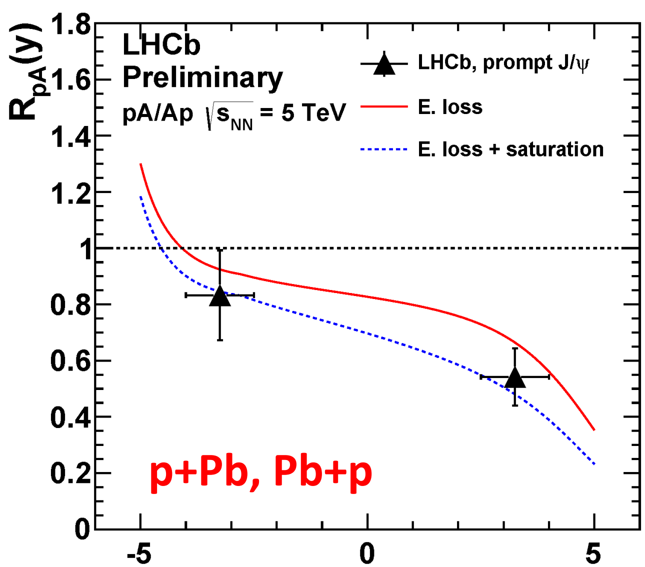
CMS: JHEP1205 (2012) 063



p_T > 6.5 GeV, |y|< 2.4

ALICE: Phys.Rev. Lett. 109 (2012) 072301



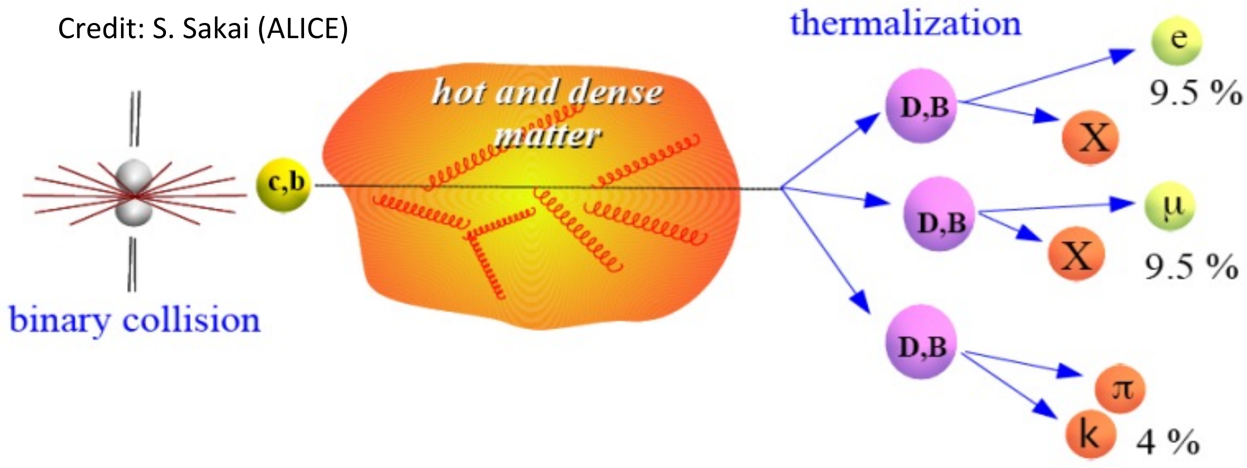


LHCb-CONF-2013-008

- R_{AA} (J/ψ yields) decrease from peripheral to central collisions
- **Suppression in Pb+Pb similar to p+Pb**
  absorption in cold nuclear matter

Heavy quarks in heavy-ion collisions

Credit: S. Sakai (ALICE)



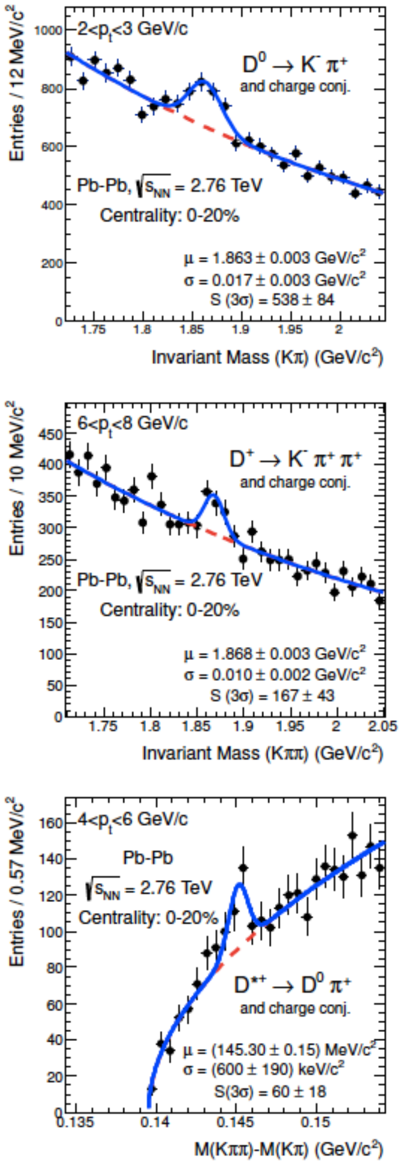
- **Heavy quarks are produced at the early stage of the collision**
- **Heavy quarks are expected to lose LESS energy than light quarks due to the reduced small-angle gluon radiation –"dead-cone effect"**

Yu.Dokshitzer, E.D. Kharzeev, Phys.Lett. B519 (2001) 199;
M. Djordjevic, M. Guylassy, Nucl. Phys. A733 (2004) 265

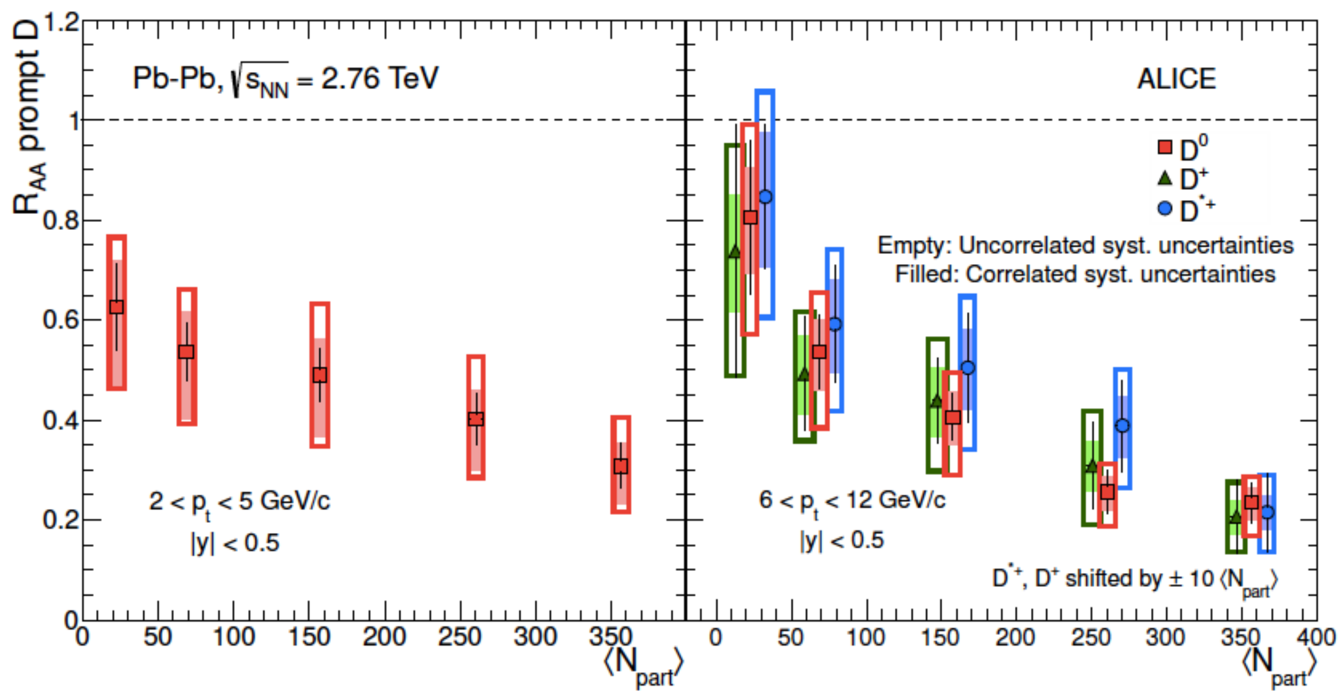
$$E_{loss}(\text{light}) > E_{loss}(D) > E_{loss}(B)$$

$$R_{AA}(\text{light}) < R_{AA}(D) < R_{AA}(B)$$

Suppression of D mesons



ALICE: JHEP 09 (2012) 112

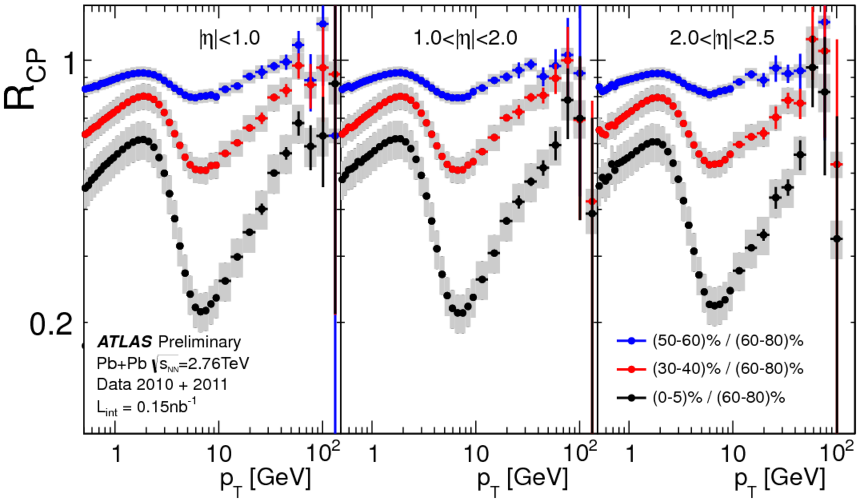


Suppression almost as large as for charged hadrons

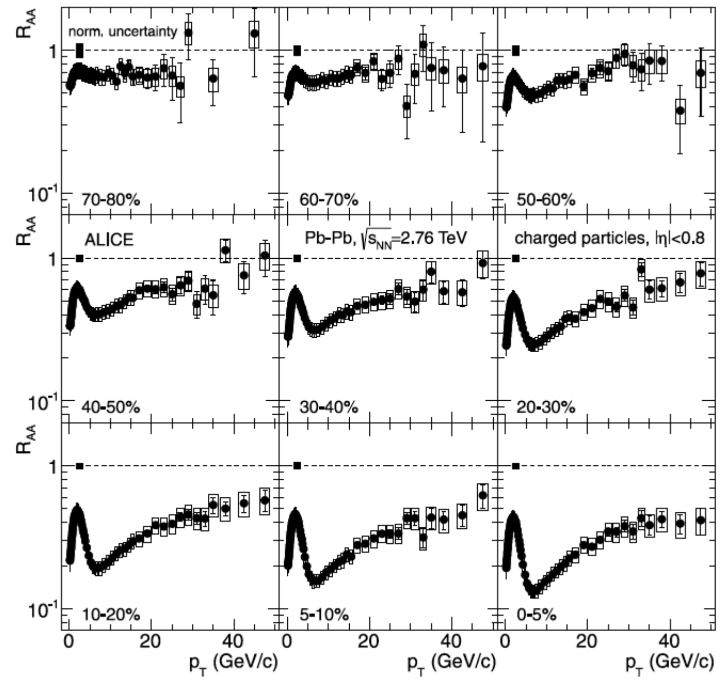
Possible indication that $R_{AA}(D) > R_{AA}(\text{charged hadrons})$

Charged hadron suppression

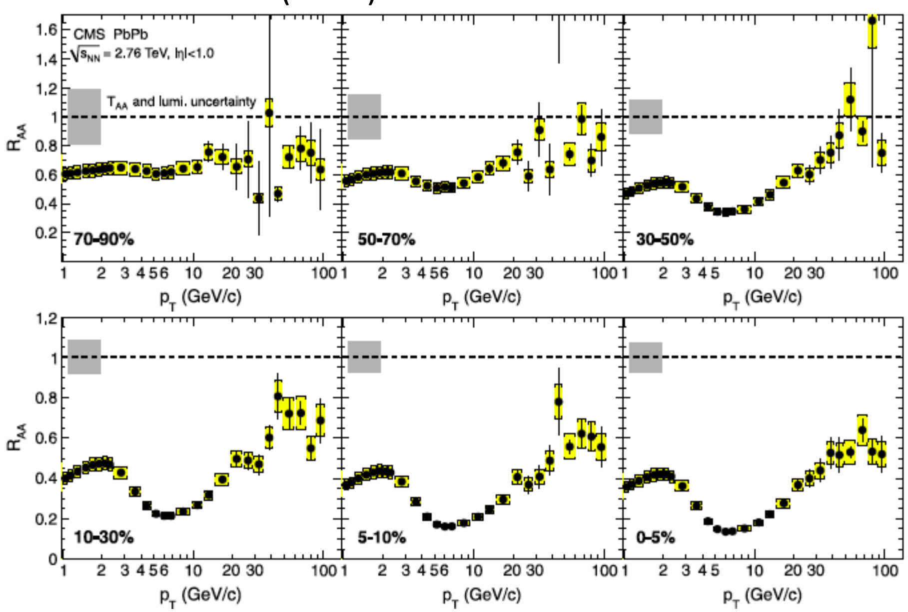
ATLAS-CONF-2012-120



ALICE: Phys. Lett. B720 (2013) 52



CMS: EPJC 72 (2012) 1945

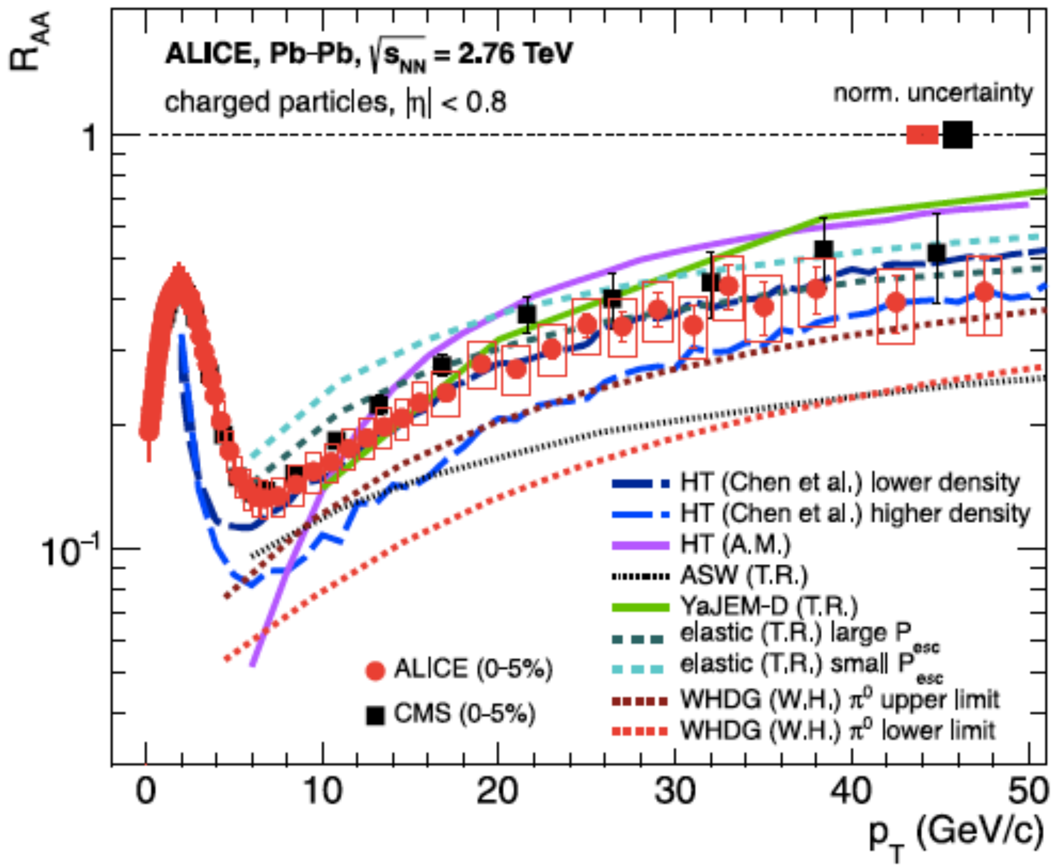


For central collisions:

- **A pronounced minimum at p_T=6-7 GeV where R_{AA}≈0.13**
- **At higher p_T R_{AA} rises and levels off above 40 GeV**

Charged hadron suppression

ALICE: Phys. Lett. B720 (2013) 52



Constraining energy loss models

Summary of medium sensitive probes

- Jet yields suppressed by a factor of 2 in central collisions
- Jet quenching also studied with Z,γ - jet correlations
- Bottomonium and charmonium are suppressed
- Heavy quarks seem to be less suppressed than charged hadrons
- And many results not shown here

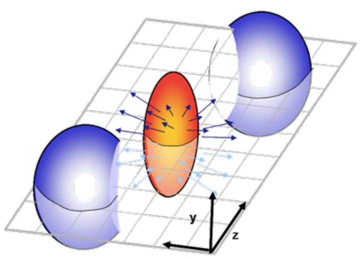
→ **Important constraints on energy loss models**

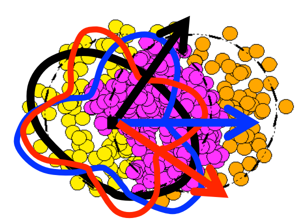
Bulk matter properties: collective expansion of the created system

Collective particle flow

Final-state azimuthal anisotropy of the particle emission

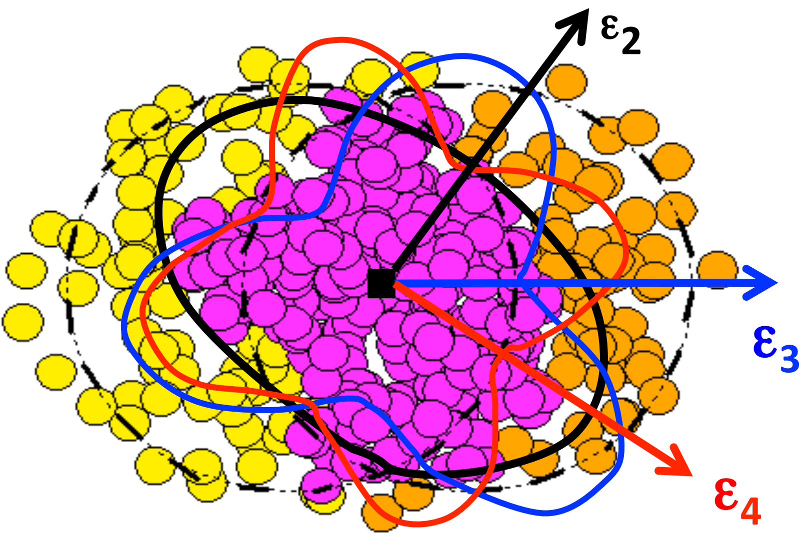
- **A useful tool to study the property of matter created in nuclear collisions**
- **Results from a pressure-driven anisotropic collective expansion of the matter**
  - **Converts spatial anisotropy to momentum anisotropy**
- **Sensitive to the initial geometry and its fluctuations**





- **Well modeled in A+A collisions by hydrodynamic evolution**
  - **Allows to extract properties of the created matter, providing constraints on η/s, EoS,…**

Anisotropy measurements



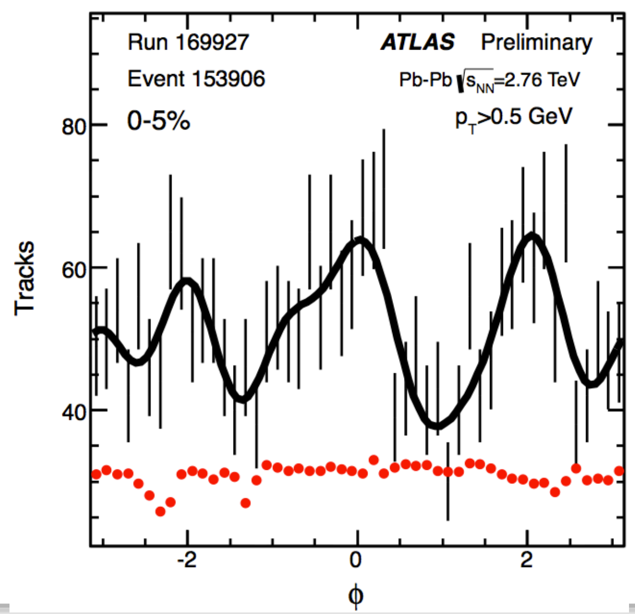
Initial configuration plane

- Transverse positions of nucleons (r, ϕ)
- From Glauber, KLN, IP-Glasma models (arXiv:1301.5893)

amplitude and direction

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

$$\tan(n\Phi_n^*) = \frac{\langle r^n \sin n\phi \rangle}{\langle r^n \cos n\phi \rangle}$$



Final state symmetry plane

Charged particle azimuthal angle $\phi = p_y/p_x$

$$n\Phi_n = \tan^{-1}\left(\frac{\Sigma w_i \sin(n\phi_i)}{\Sigma w_i \cos(n\phi_i)}\right)$$

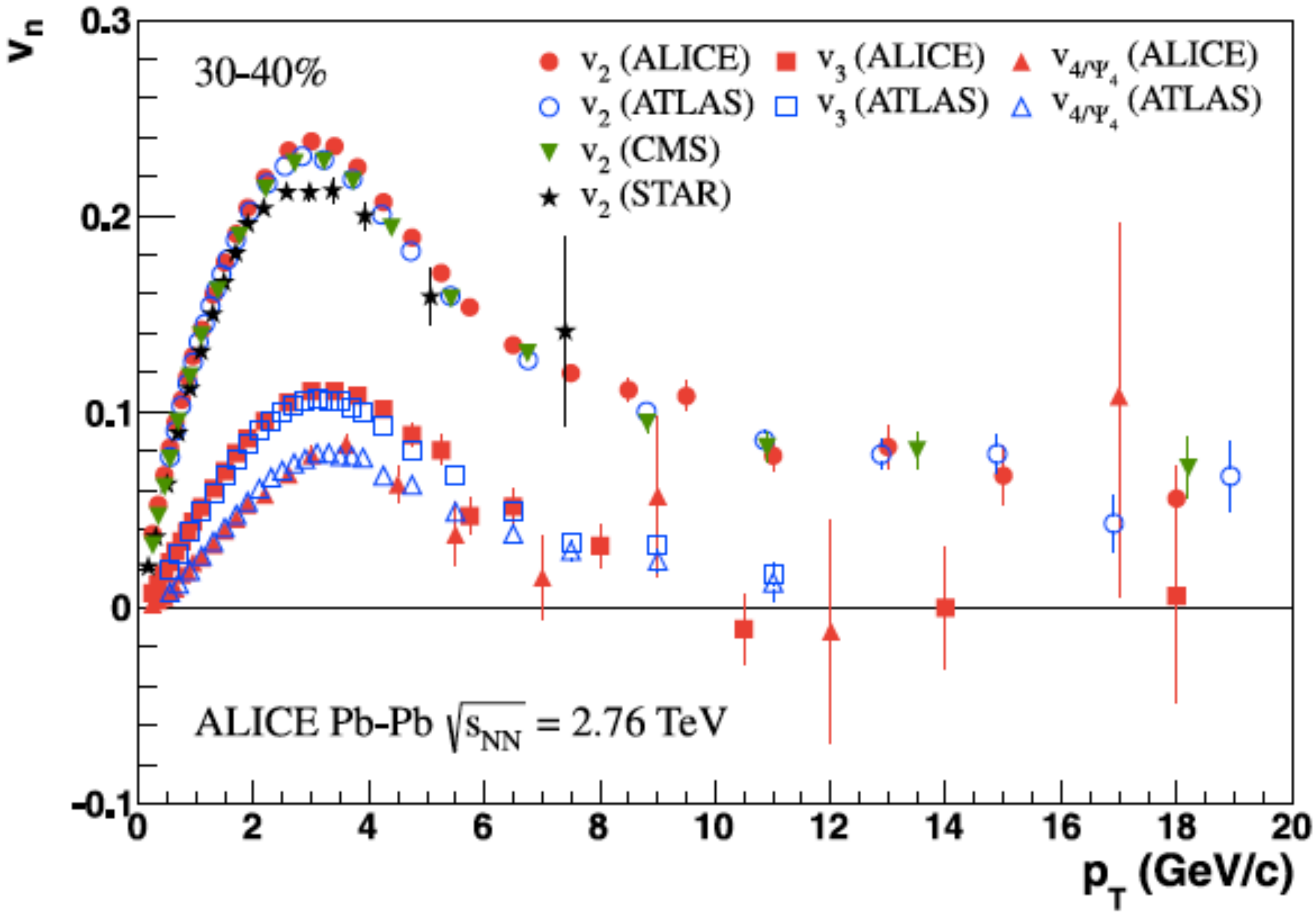
$$v_n = \langle \cos(n[\phi - \Phi_n]) \rangle$$

$$\frac{dN_{ch}}{d\phi} \propto 1 + \sum_n v_n \cos n(\phi - \Phi_n)$$

$$\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + \sum_n v_n^2 \cos n\Delta\phi$$

HYDRODYNAMICS

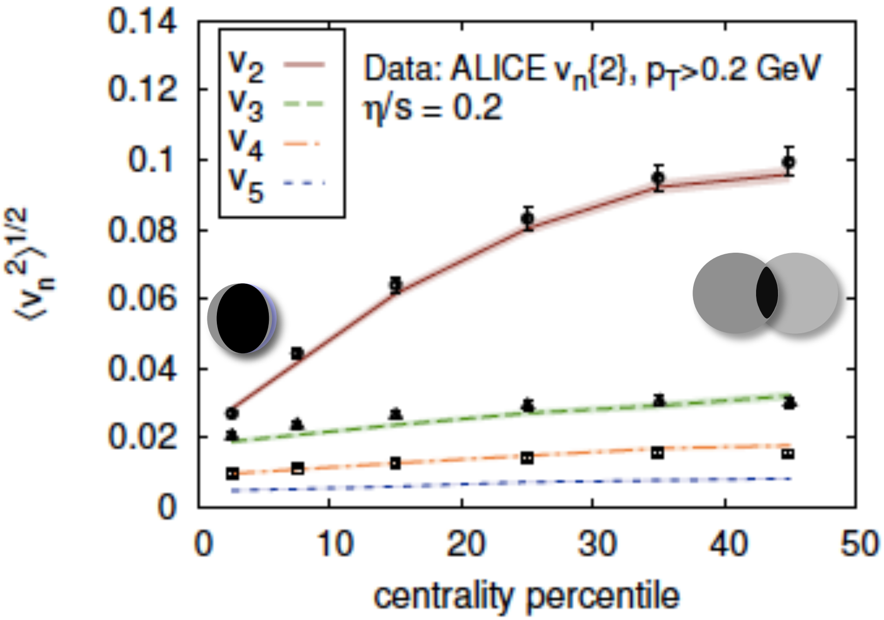
Measurements of flow harmonics



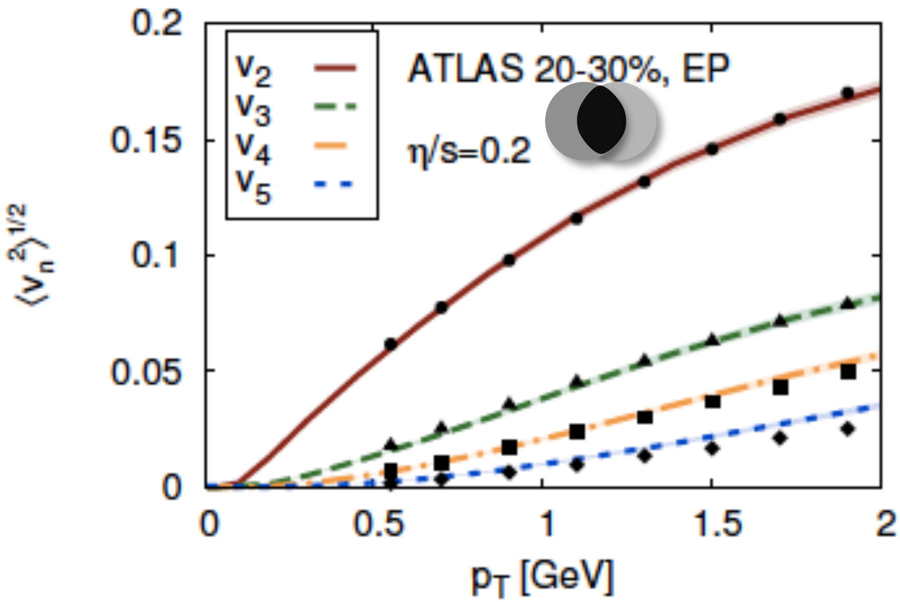
ALICE: Phys. Lett. B 719 (2013)18
ATLAS: Phys. Rev. C 86 (2012) 014907
CMS: Phys. Rev. C 87 (2013) 014902

Measurements of flow harmonics

ALICE: Phys. Lett. Lett. 107 (2011) 032301



ATLAS: Phys. Rev. C 86 (2012) 014907



Hydrodynamic calculations:
C. Gale, S. Jeon, B. Schenke,
P. Tribedy, R. Venugopolan
Phys. Rev. Lett. 110, 012302 (2013)

Well described by viscous hydro with IP-Glasma initial state
arXiv:1301.5893

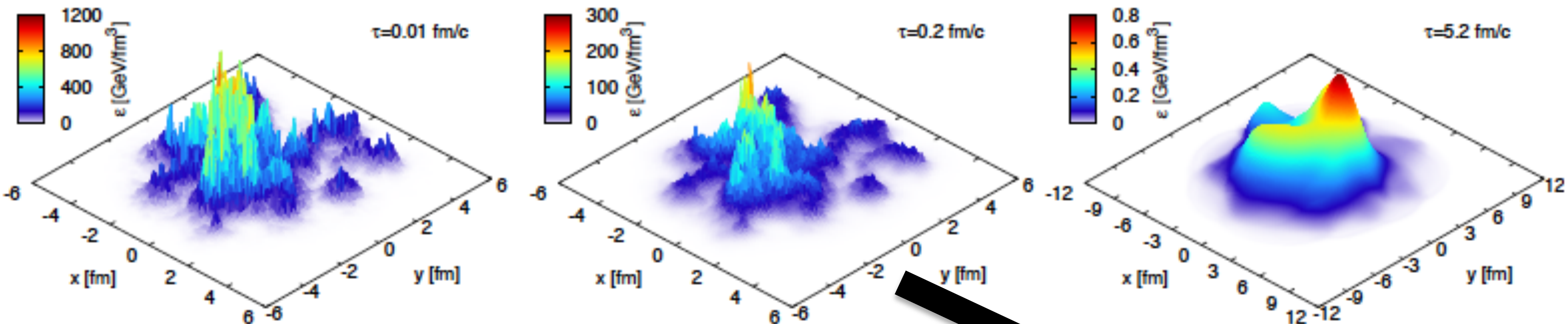
Anisotropic flow in Pb+Pb

Significant v_1, v_3, v_5

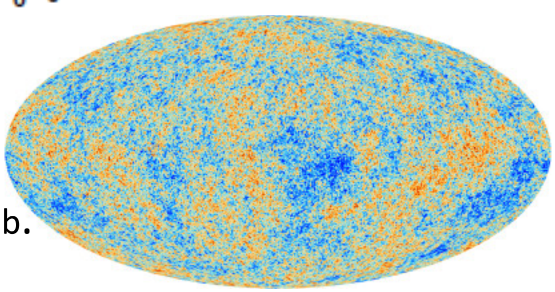
Importance of fluctuations in the initial geometric configuration

Energy density profile in the transverse plane from IP-Glasma

B. Schenke, P. Tribedy, R. Venugopolan, Phys. Rev. Lett. 101,022301;
Phys. Rev. C86, 034908 (2012)



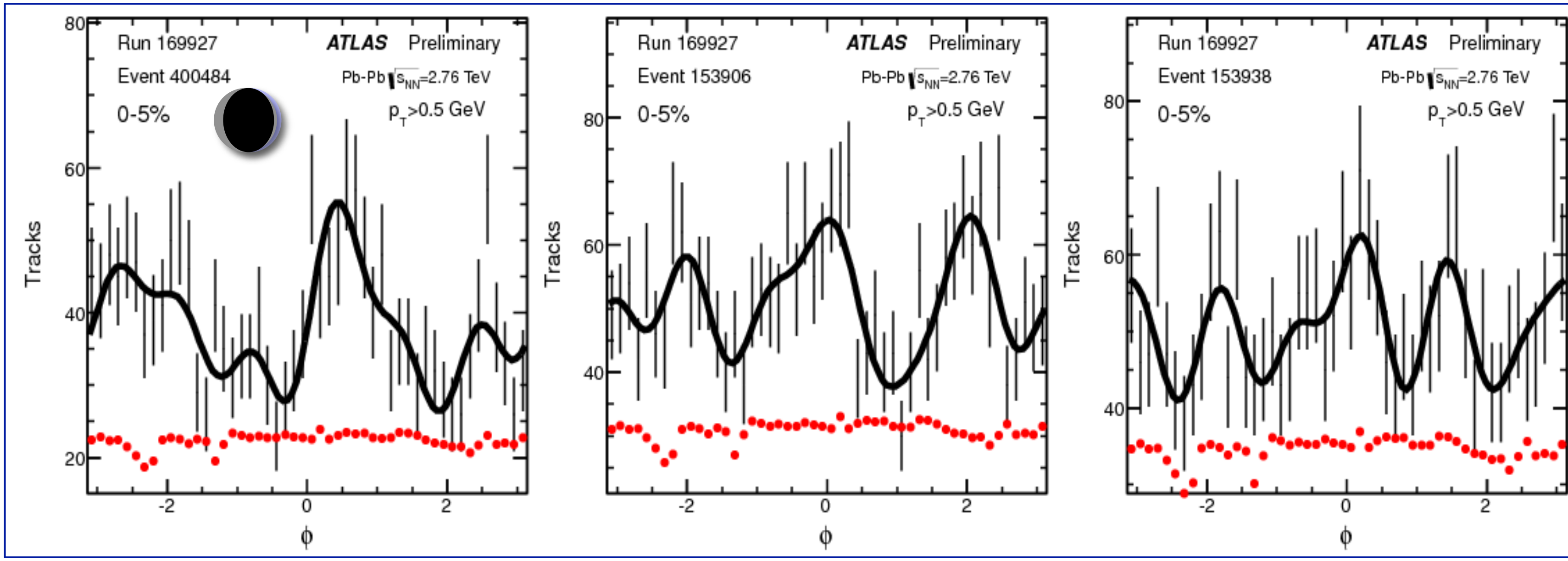
Credit:
ESA & Planck Collab.



Final-state azimuthal anisotropies

Event-by-event v_n

- The Fourier series can be computed for each event:

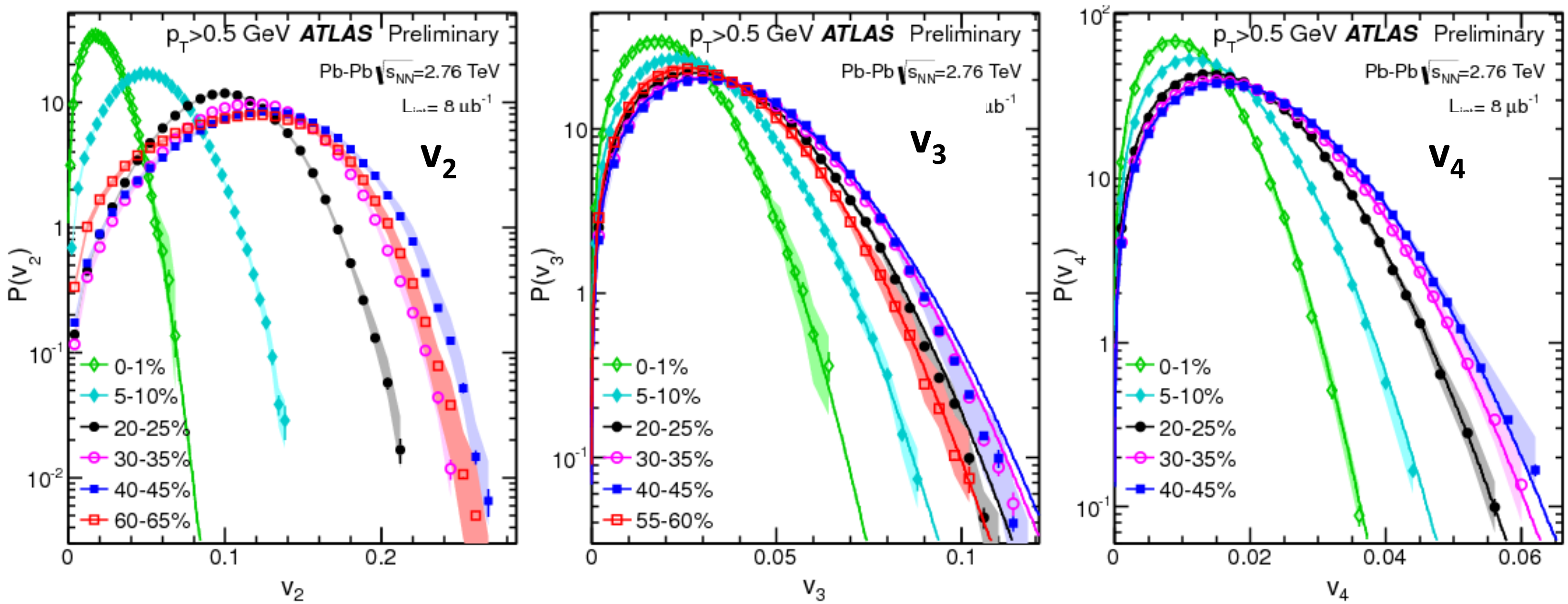


Event-plane correlations as well as v_n distributions contain more information than just $\langle v_n \rangle$

E-by-E v_n distributions

Fully corrected for detector effects and unfolded
for varying track statistics

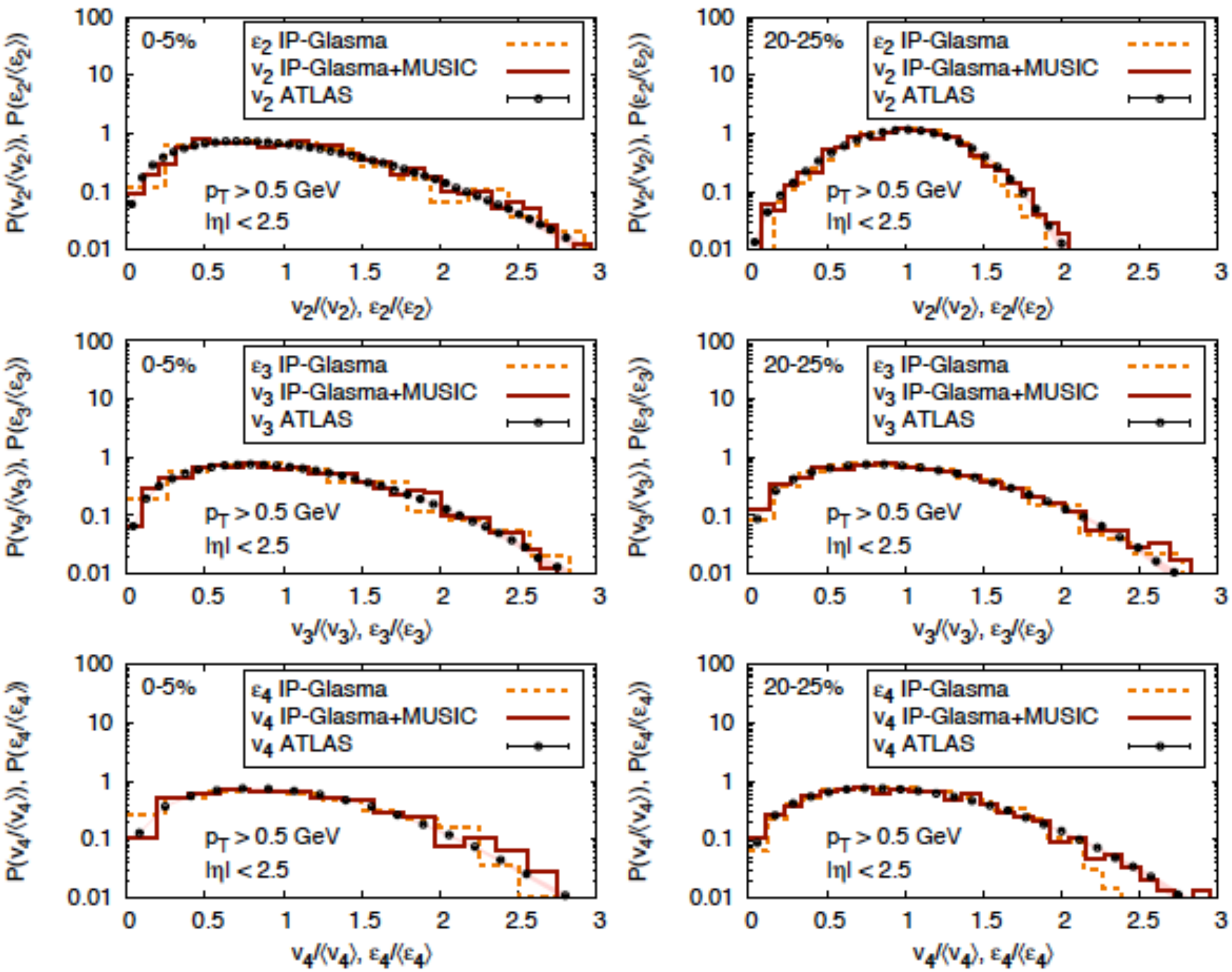
ATLAS: arXiv:1305.2942



- Parameterized by radial projection of a 2D Gaussian:
  - probability density distributions compatible with:
    - **$v_n^{RP}=0$**
    - …and Gaussian fluctuations
- **except for v_2, where a non-zero radial offset v_2^{RP} is needed.**

$$P(v_n) = \frac{v_n}{\delta_n^2} e^{-\frac{1}{2}\frac{v_n^2+(v_n^{RP})^2}{\delta_n^2}} I_0\left(\frac{v_n v_n^{RP}}{\delta_n^2}\right)$$

E-by-E v_n distributions



C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopolan
Phys. Rev. Lett. 110, 012302
arXiv:1210.5144

$$v_n \propto \varepsilon_n$$

EbE v_n well described by viscous hydro

ATLAS: arXiv:1305.2942

Flow in A+A: Summary

Detailed experimental studies:

- v_2 systematics
- Higher flow harmonics
- Event-plane correlations
- EbE v_n distributions
- Flow fluctuations

Phenomenological description:

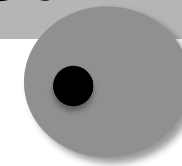
Initially very dense quark-gluon matter reaches approximate local thermal equilibrium on a very short time scale and then evolves according to the macroscopic laws of relativistic fluid dynamics

Viscous hydrodynamic calculations with the advanced models for the initial state fluctuations show remarkable agreement with measurements

This applicability of hydrodynamics requires a short mean free path as compared to the system size

→ **the created matter is strongly interacting**

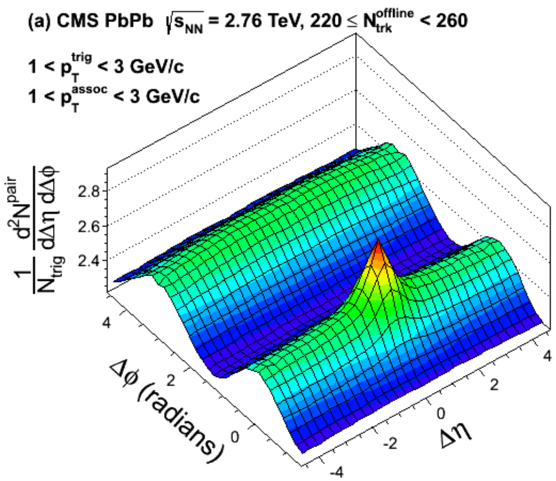
Collective flow in p+Pb collisions?



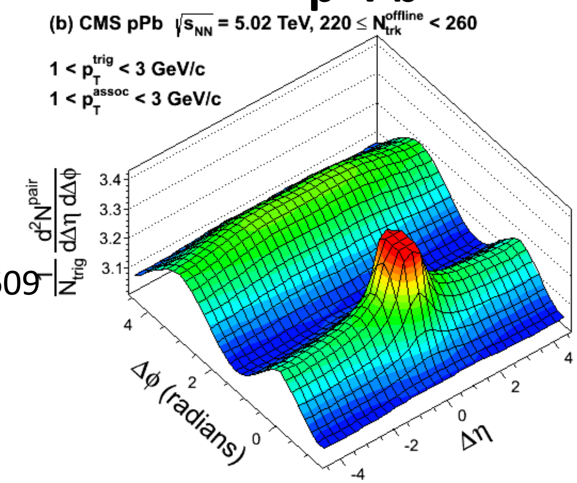
The size of the produced system is small
as compared to the mfp of its constituents

→ weaker, if any, collective flow expected

Pb+Pb

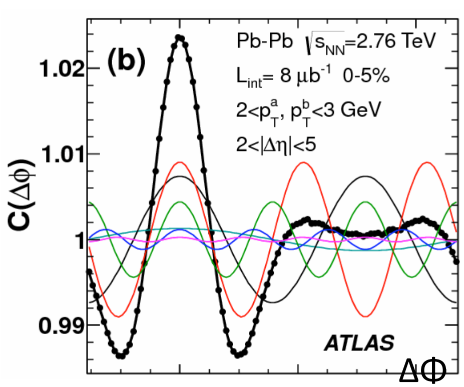


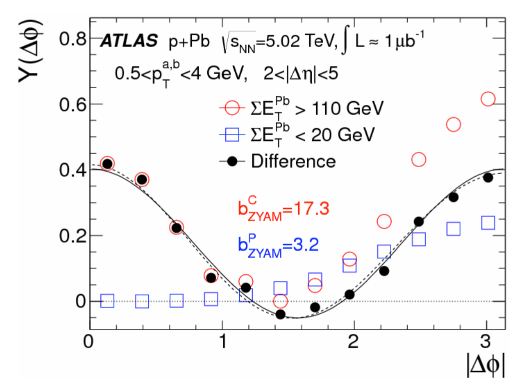
p+Pb



CMS: arXiv:1305.0609

ATLAS: Phys. Rev. C 86 (2012) 014907





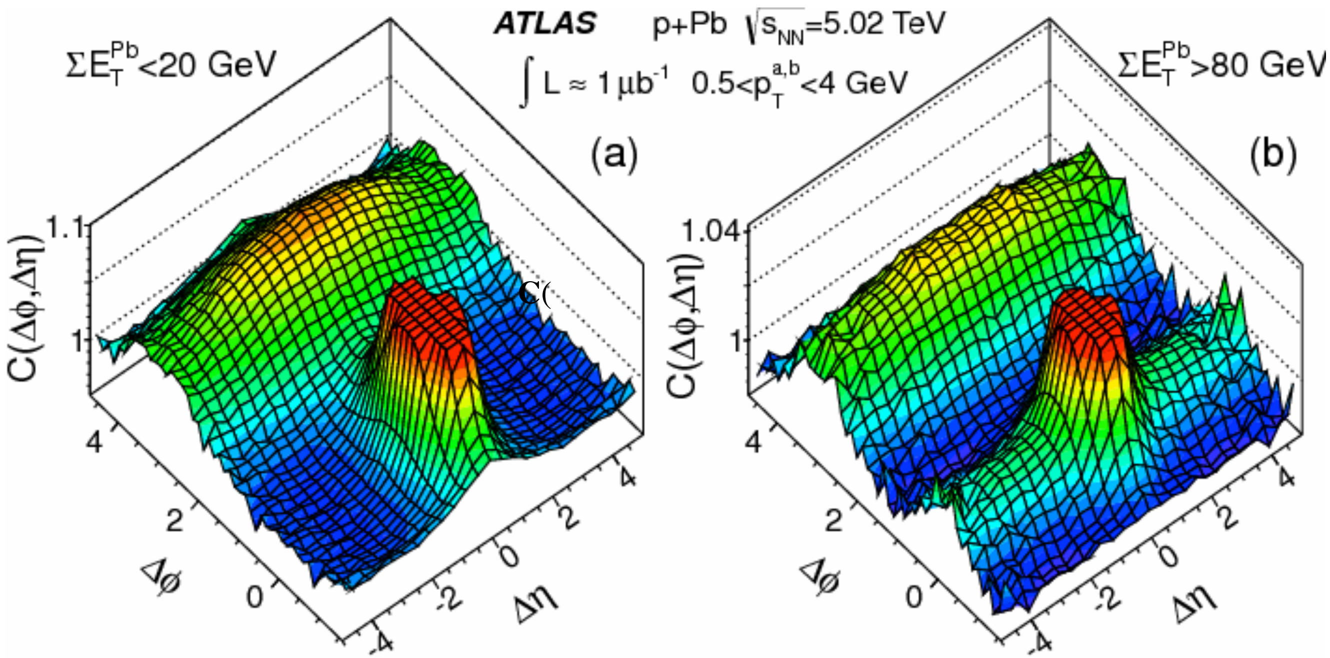
ATLAS: Phys. Rev. Lett. 110 (2013) 182302

Two-particle correlations

ATLAS, Phys. Rev. Lett. 110 (2013) 182302

$$\mathbf{C}(\Delta\phi,\Delta\eta) = \frac{\mathbf{S}(\Delta\phi,\Delta\eta)}{\mathbf{B}(\Delta\phi,\Delta\eta)}$$

$\Delta\phi=\phi_a-\phi_b$, $\Delta\eta=\eta_a-\eta_b$
a-"trigger particle" b-"associated particle"



	Peripheral	Central
Near-side(Δφ≈0):	**jet peak**	**jet+ridge-like structure**
Away-side(Δφ≈π):	**broad structure (RECOIL)**	**broader structure**

Two-particle correlations

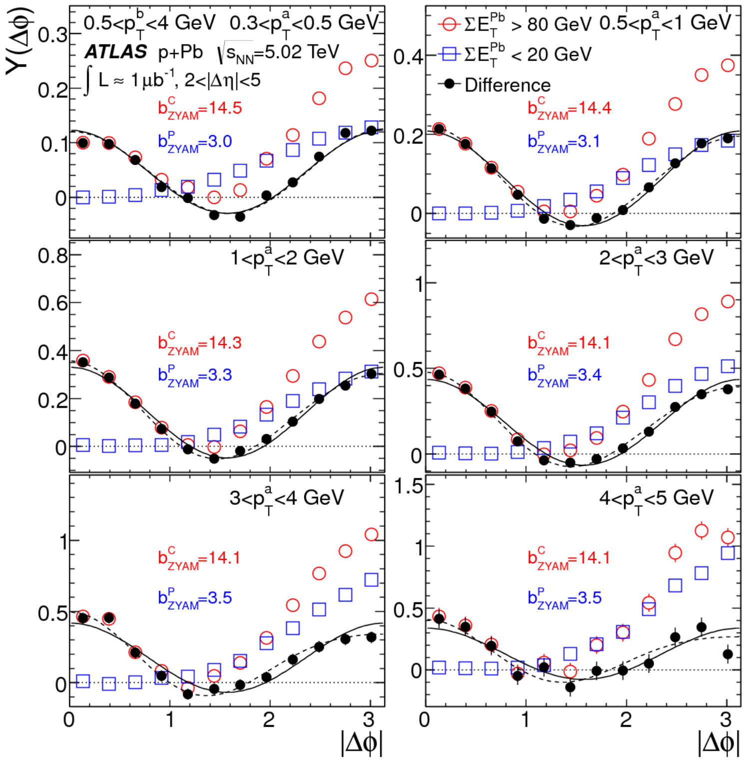
Define per trigger yield:

$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi)\, d\Delta\phi}{\pi N_a} \right) C(\Delta\phi) - b_{ZYAM}$$

$2 < |\Delta\eta| < 5$

Subtract the recoil: $\Delta Y(\Delta\phi) = Y(\Delta\phi)^{central} - Y(\Delta\phi)^{peripheral}$

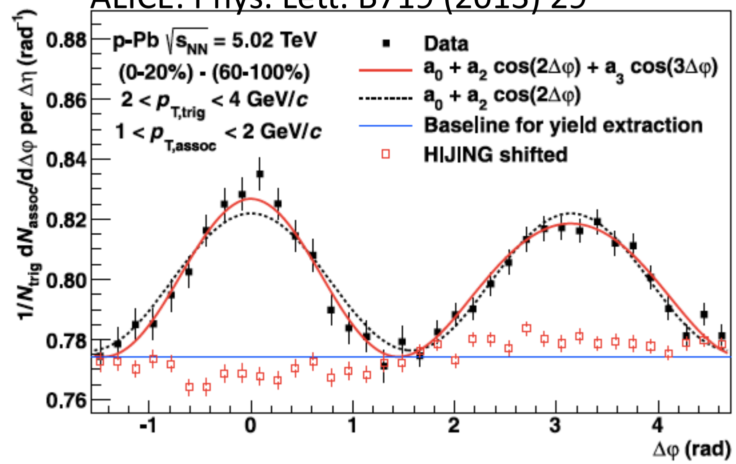
ATLAS, Phys. Rev. Lett. 110 (2013) 182302



peripheral E_T<20 GeV (48-100%)

central E_T>80 GeV (0-2%)

ALICE: Phys. Lett. B719 (2013) 29



$\Delta Y(\Delta\phi)$ is symmetric around $|\Delta\phi| = \pi/2$

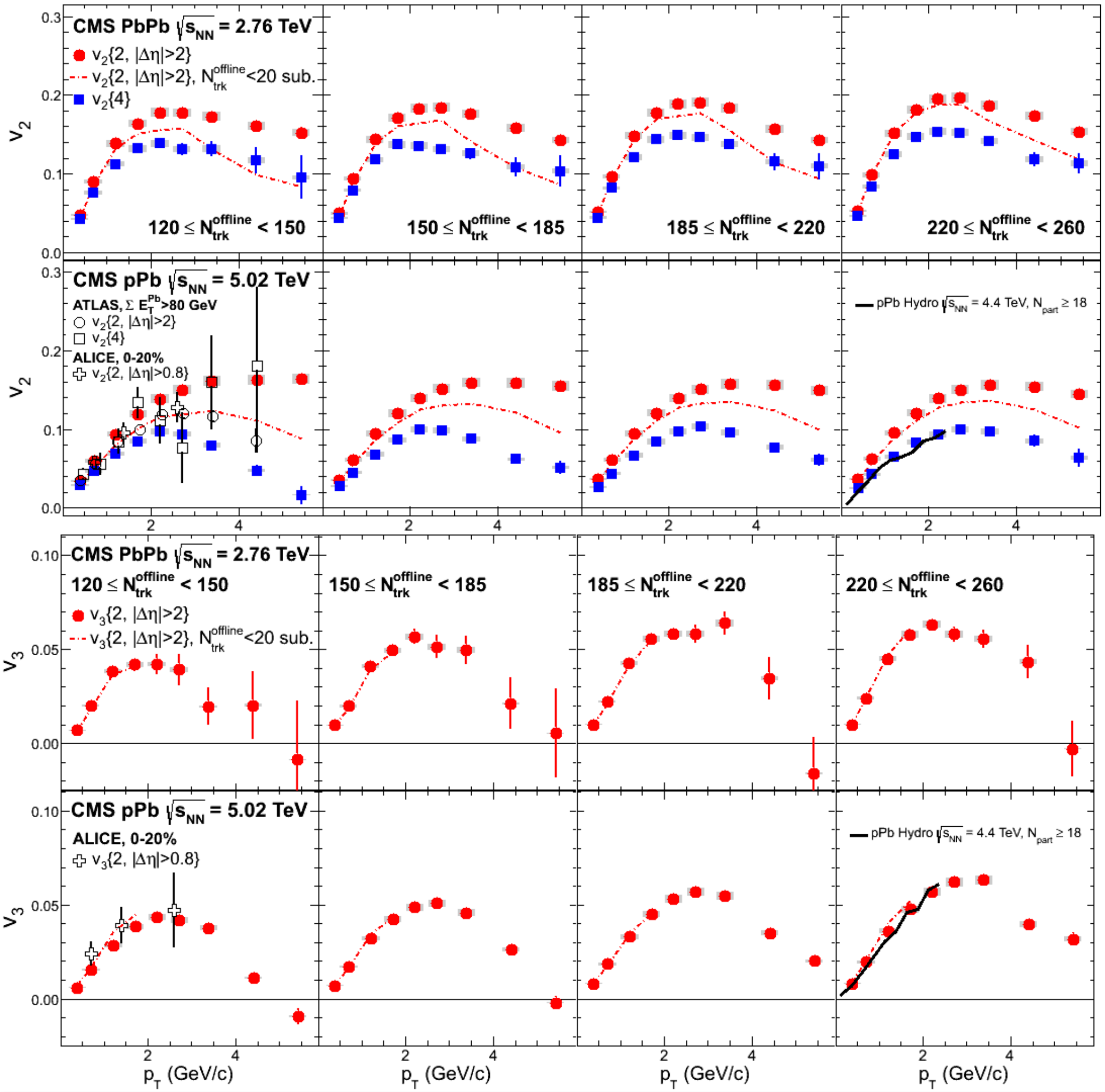
Long-range component=Recoil+ Δφ-symmetric

— $a_0 + 2a_2 \cos 2\Delta\phi$

- - - $a_0 + 2a_2 \cos 2\Delta\phi + 2a_3 \cos 2\Delta\phi$

$$a_n = \langle \Delta Y(\Delta\phi) \cos n\Delta\phi \rangle$$

Amplitudes of cosnΔφ modulation



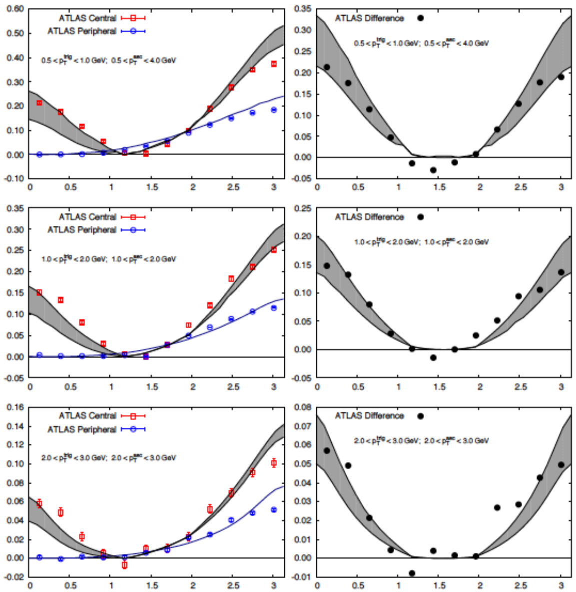
CMS: arXiv:1305.0609
ATLAS: Phys. Rev. Lett. 110 (2013) 182302; arXiv:1303.2084
ALICE: Phys. Lett. B 719 (2013) 29

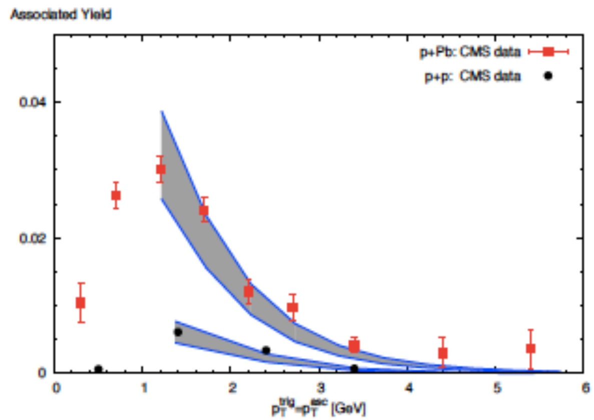
- v_2 increases with p_T up to ~3 GeV, then drops like in Pb+Pb
- Significant $v_2\{4\} \approx 0.06$
- $v_3 < v_2$ over the measured p_T
- v_3(p+Pb)≈v_3(Pb+Pb
- Good agreement with the hydrodynamic predictions
  P. Bozek, W. Broniowski Phys. Lett. B718,1557 (2013)

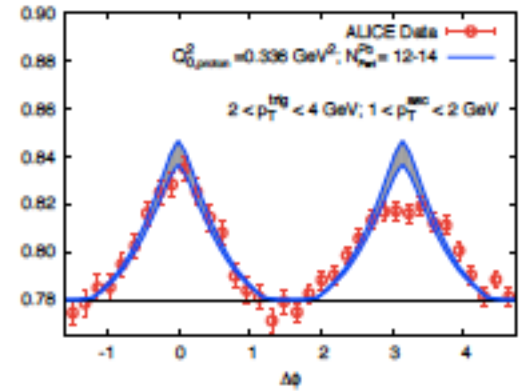
Suggesting hydrodynamic origin?

Comparison to CGC calculations

K. Dusling, R. Venugopolan, arXiv:1302.7018







Overall satisfactory agreement with the calculations within the framework of the initial state Color Glass Condensate model

Initial-state effect or final-state effect or both?

$v_2\{4\}$ and v_3 challenging for the CGC model description

Collective flow: Summary

- **In Pb+Pb collisions:**
  - Multitude of high-precision measurements
  - Well described by viscous hydrodynamics
  - System evolves collectively and is strongly coupled
- **In p+Pb collisions**
  - Observed similar anisotropies to those seen in Pb+Pb
  - Origin (initial- or final-state effects) is still debated
  - More detailed theoretical studies are necessary
  - Additional measurements are needed
- **p+Pb as a reference for Pb+Pb?**

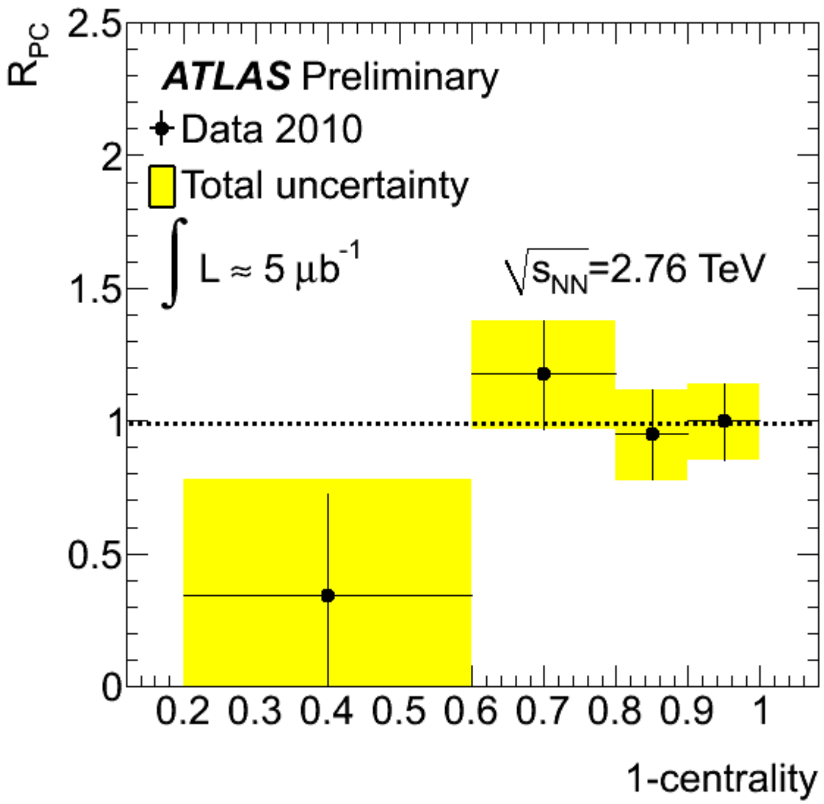
Summary

- Wealth of experimental results has been obtained by the LHC experiments
- Watch for more to come
- For a full record see experimental www pages
- The results help to understand the complex details of the created strongly interacting system
- They provide a valuable input for the development of the theoretical description of heavy-ion collisions

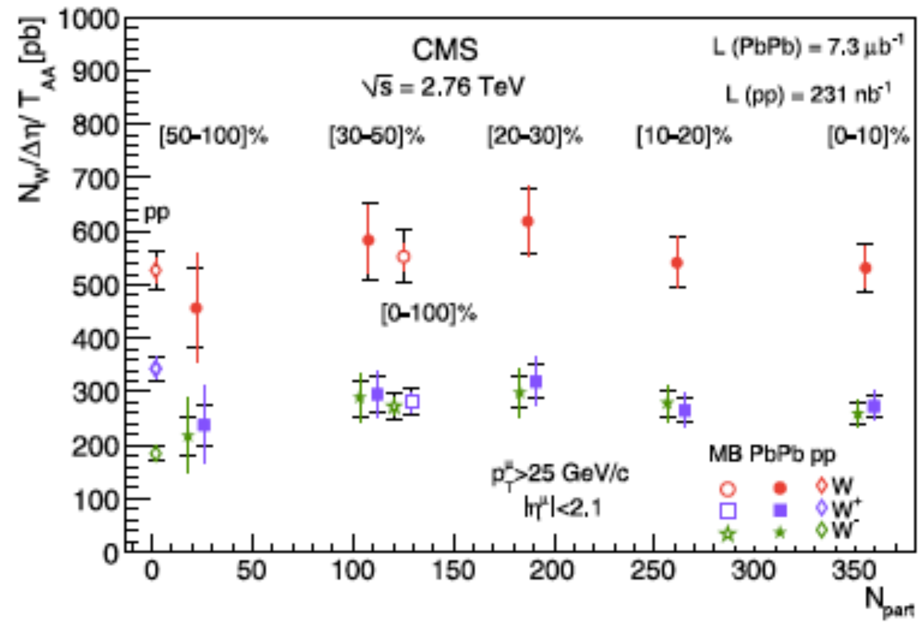
backups

$W^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$

ATLAS-CONF-2011-078



CMS, Phys. Lett. B7 15 (2012) 66

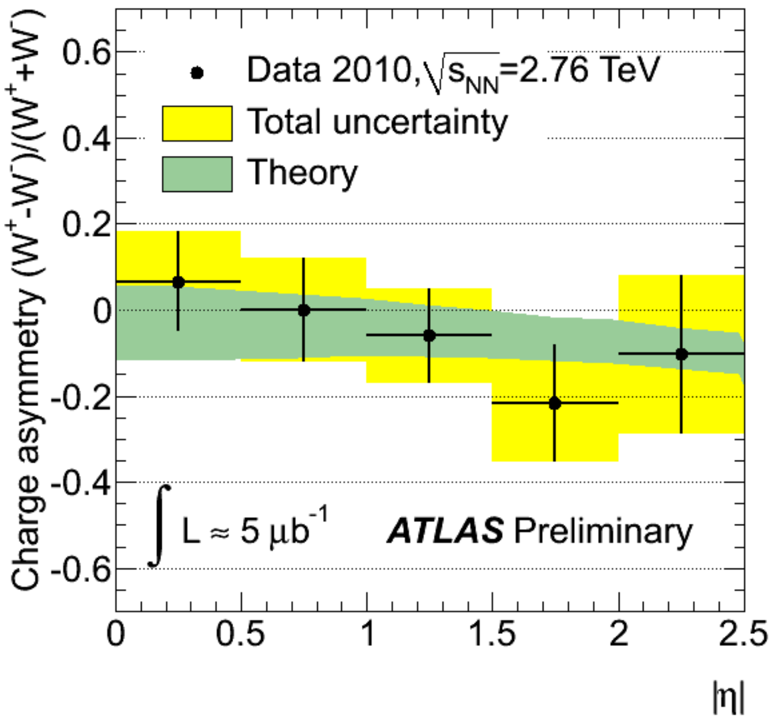


$W^{\pm}$ yields consistent with N_{coll} scaling

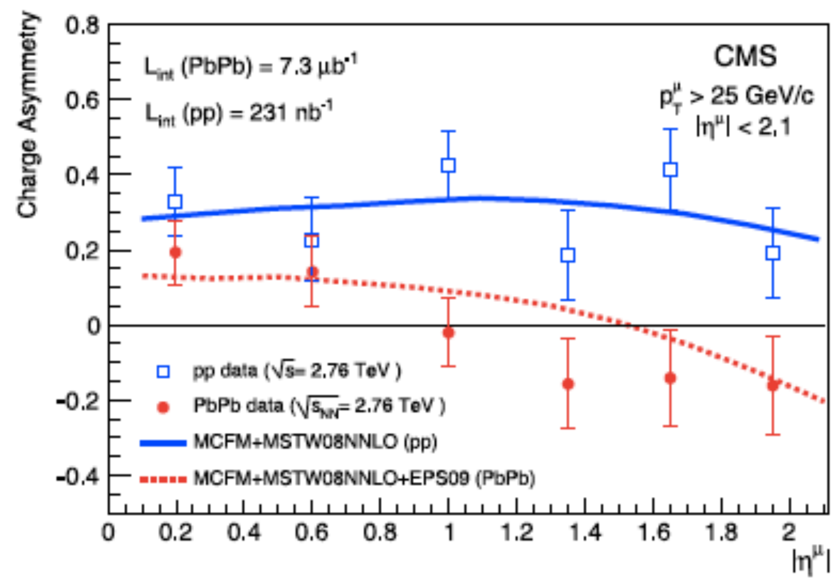
Charge asymmetry in W production

$$\frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}}$$

ATLAS-CONF-2011-078



CMS, Phys. Lett. B7 15 (2012) 66

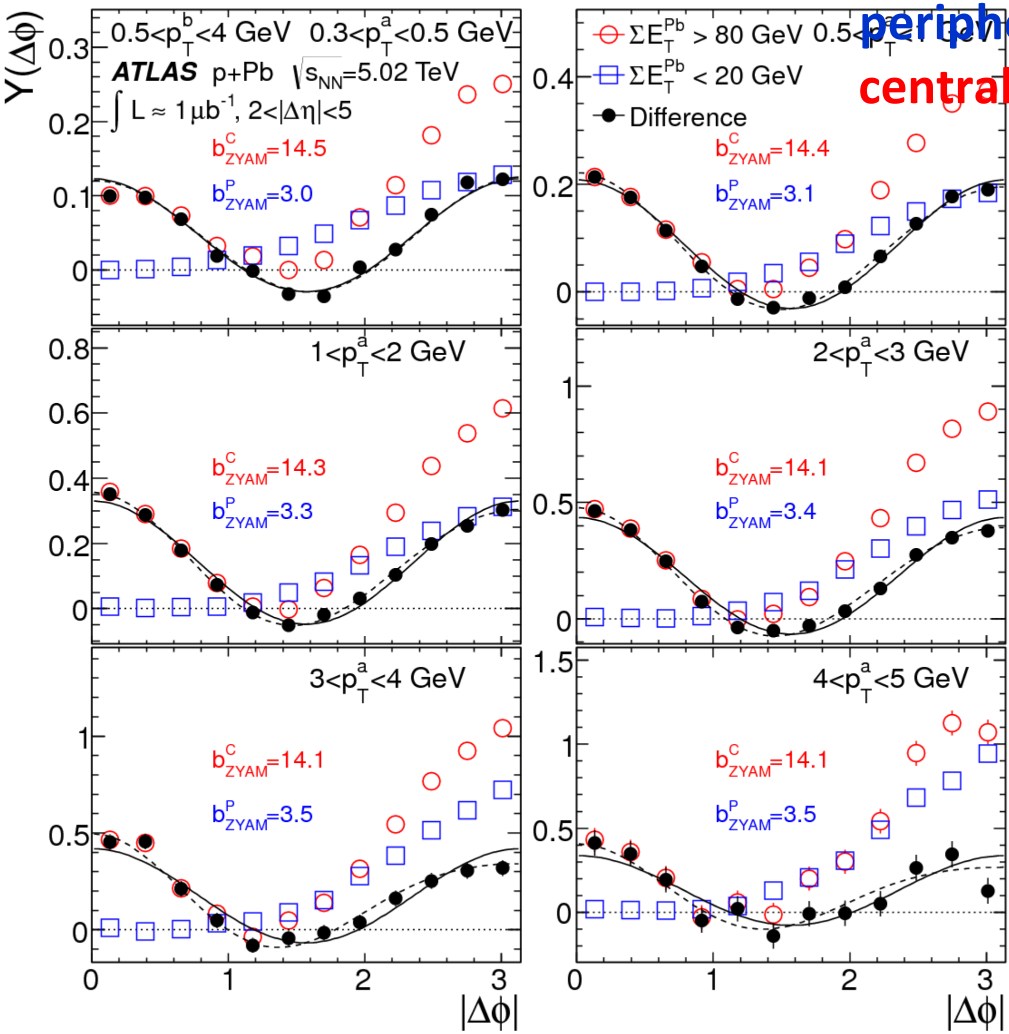


An excess of W^- over W^+ at large ημ
Consistent with the predictions which include small nuclear modification effects on the PDF

After recoil subtraction: $\Delta Y(\Delta\varphi)$

$\Delta Y(\Delta\varphi) = Y(\Delta\varphi)^{central} - Y(\Delta\varphi)^{peripheral}$

different ranges in p_T^a



peripheral $E_T<20$ GeV (48-100%)

central $E_T>80$ GeV (0-2%)

$\Delta Y(\Delta\varphi)$ is symmetric around $|\Delta\varphi|=\pi/2$

Long-range component
Recoil+ $\Delta\varphi$-symmetric

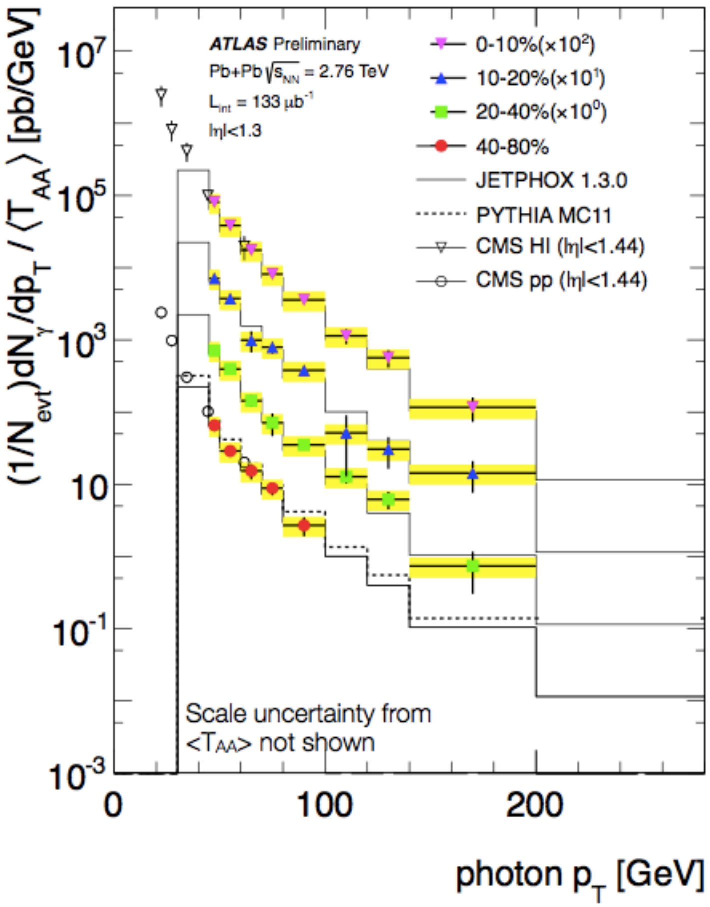
—— $a_0 + 2a_2 \cos 2\Delta\phi$

- - - $a_0 + 2a_2 \cos 2\Delta\phi + 2a_3 \cos 2\Delta\phi$

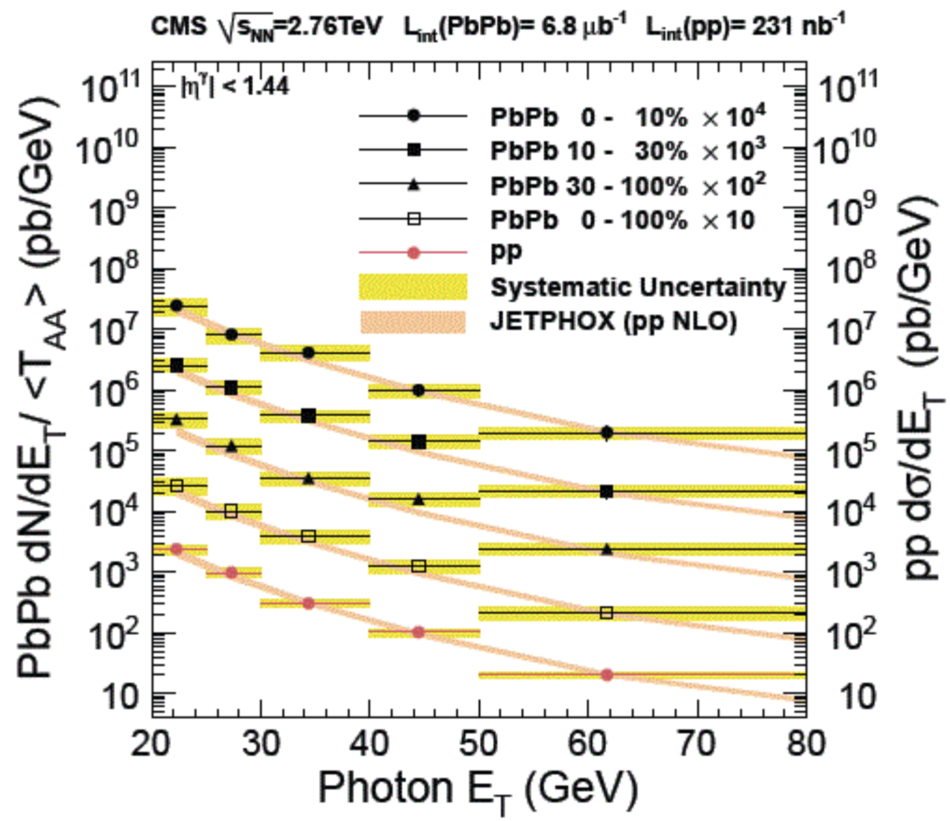
$$a_n = \langle \Delta Y(\Delta\phi) \cos n\Delta\phi \rangle$$

Prompt photon production

ATLAS-CONF-2012-051



CMS, Phys. Lett. B 710 (2012) 256

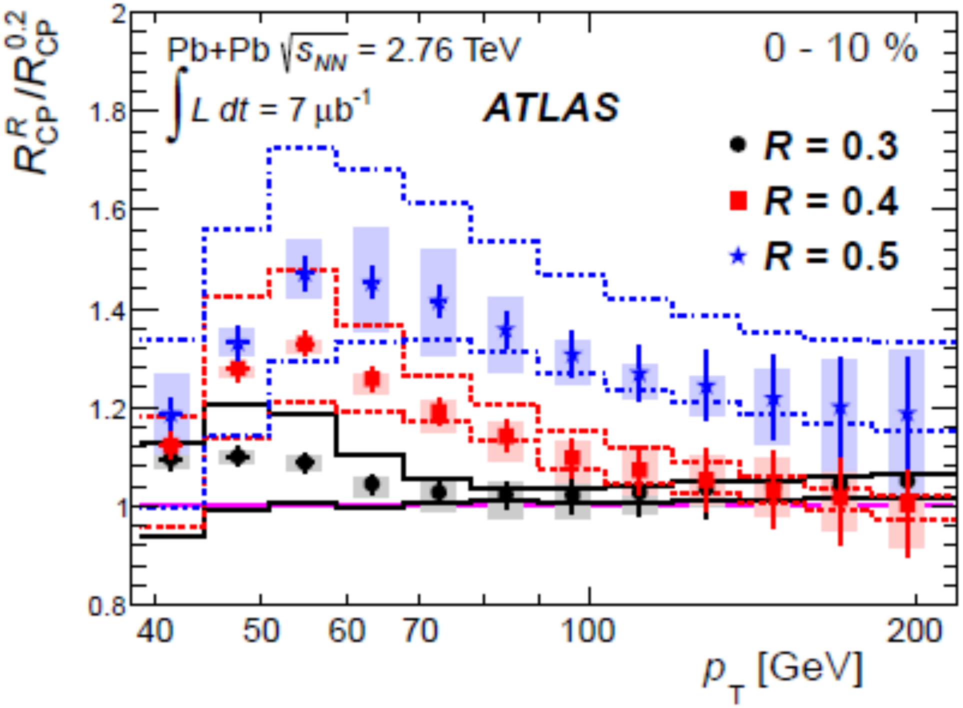


Yields scaled by T_{AA} and compared to JETPHOX predictions

R-dependence of jet suppression

ATLAS: Phys. Lett.B 719 (2013) 220

Ratio of R_{CP} values between R=0.3, 0.4 and 0.5 jets and R=0.2 jets



Dependence on jet radius for p_T<100 GeV in 0-10% central

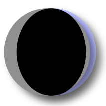
→A weaker suppression is observed for larger jet radius parameters

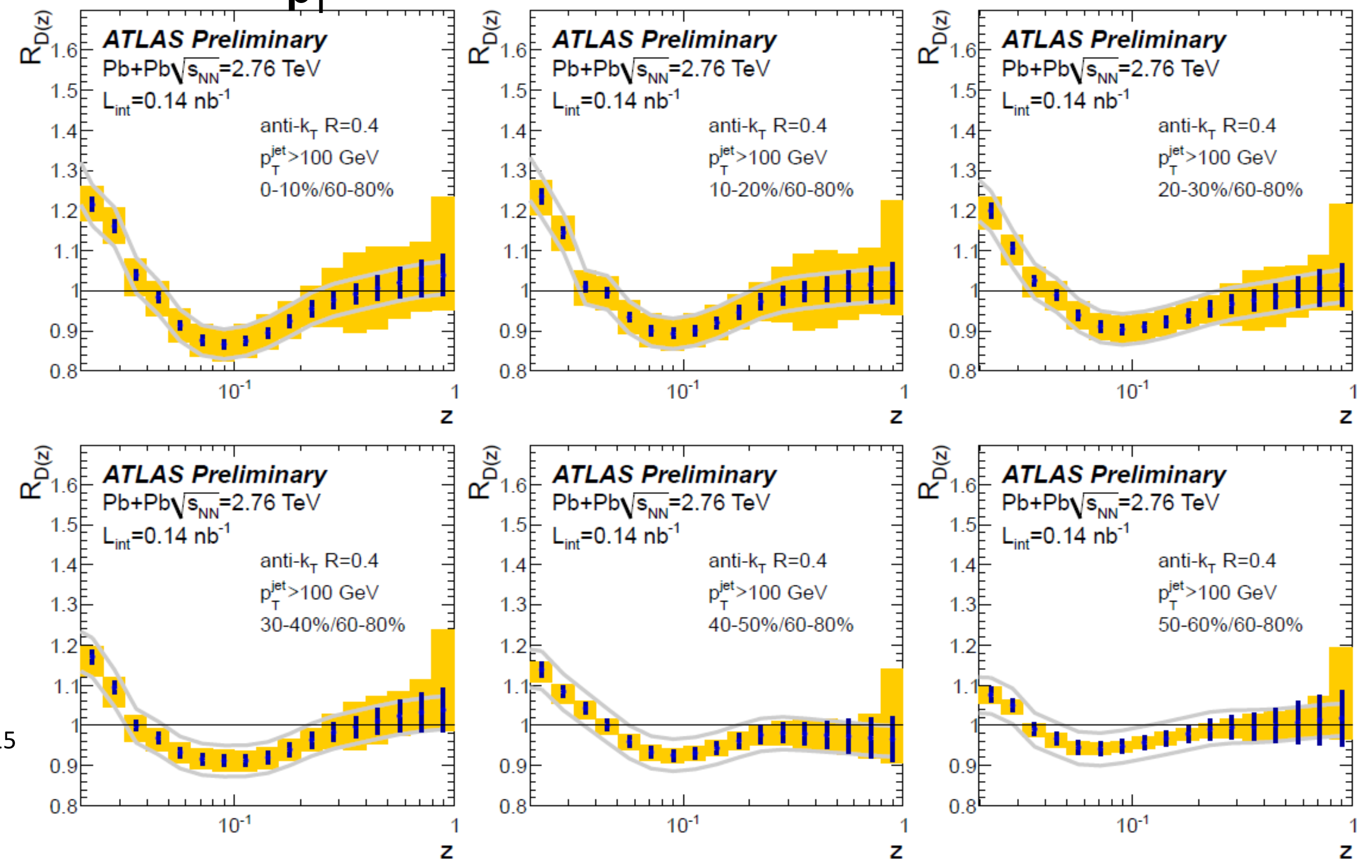
Qualitatively consistent with models of radiative energy loss

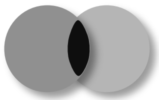
"out-of-cone" radiation

Jet fragmentation

$p_T^{had} > 2\text{GeV}$ $\quad z \equiv \frac{p_T^{had}}{p_T^{jet}} \cos\Delta R$ $\quad R_{D(z)} \equiv D(z)_{cent} / D(z)_{60-80\%}$





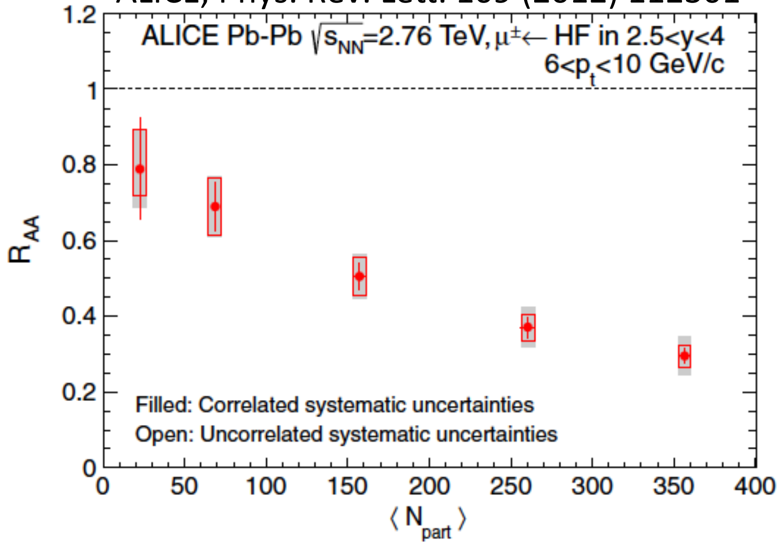


ATLAS-CONF-2012-115

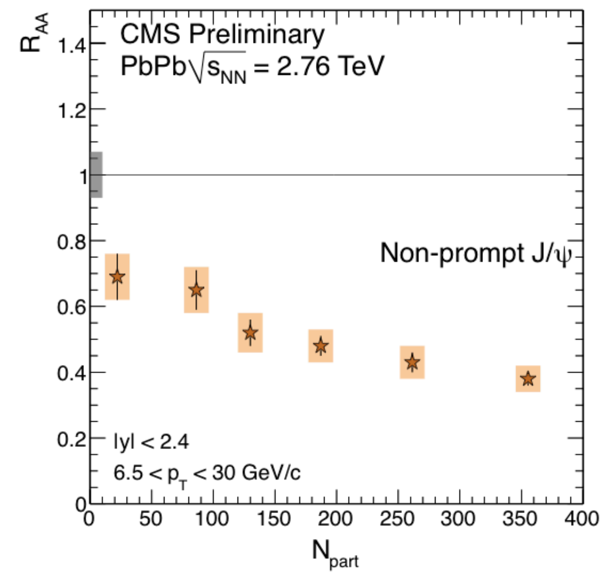
- Enhancement at low z, suppression at z≈0.1
- No modification at high z (predicted by some energy loss models)
- Similar results found for R=0.2 and 0.3 jets

Heavy quark (b,c) suppression

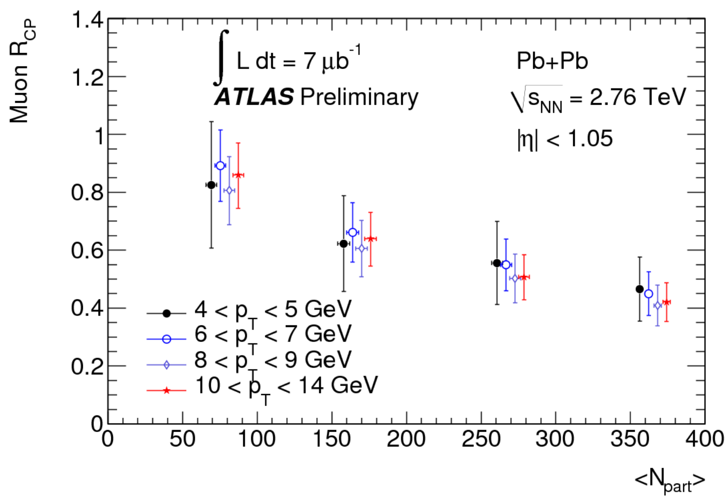
ALICE, Phys. Rev. Lett. 109 (2012) 112301



CMS PAS HIN-12-014



ATLAS-CONF-2012-01



For central collisions at midrapidity:
R_{AA} suppressed by a factor ~2.5
Slightly stronger at forward rapidities

v_2, v_3 for identified particles

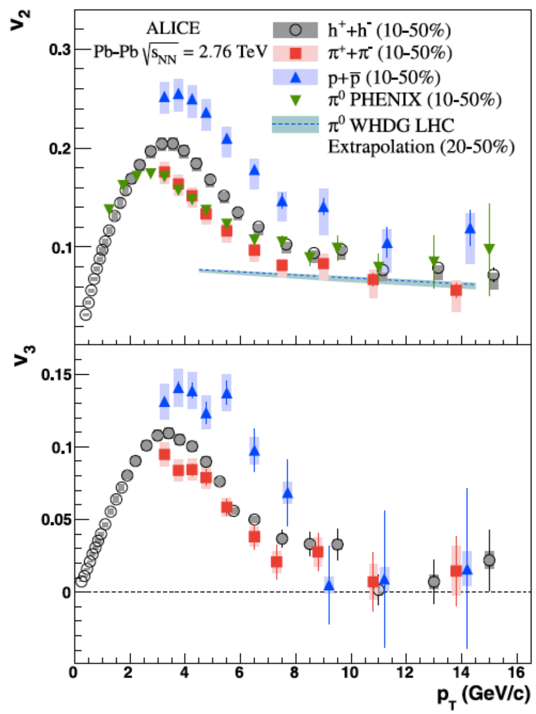
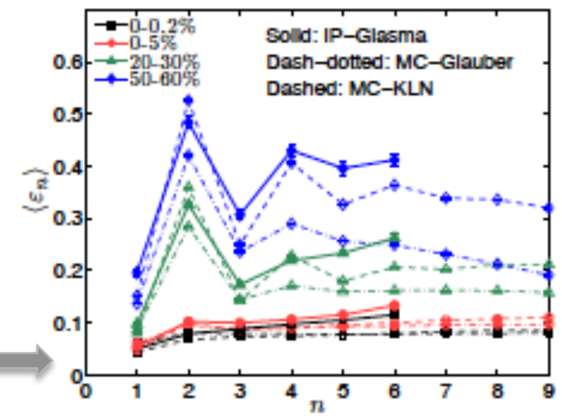


Fig. 5 presents charged pion and proton v_2 and v_3 as a function of p_T in the 10–50% centrality range from the event plane method. The proton v_2 and v_3 are higher than that of pions out to $p_T = 8$ GeV/c where the uncertainties become large. This behavior is qualitatively consistent with a picture where particle production in this intermediate p_T region includes interaction of jet fragments with bulk matter, e.g. as in model [45].

Significant v_1, v_3, v_5

Importance of fluctuations in the initial geometric configuration

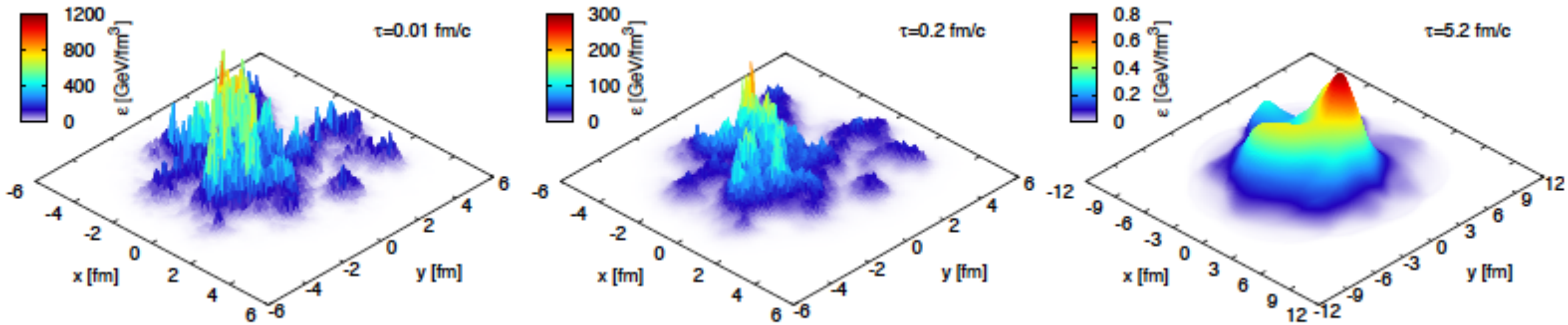
Initial fluctuation power spectrum



U. Heinz, R. Snellings
arXiv:1301.2826

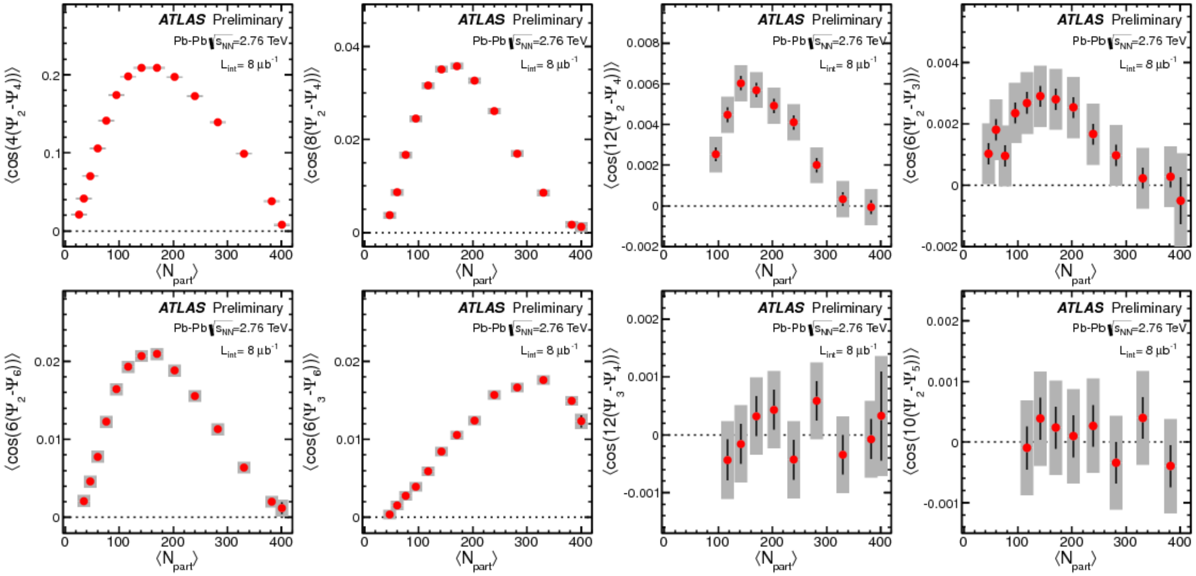
Energy density profile in the transverse plane from IP-Glasma

B. Schenke, P. Tribedy, R. Venugopolan, Phys. Rev. Lett. 101,022301; Phys. Rev. C86, 034908 (2012)



Event-plane correlations

- The resolution corrected correlations between EP of different orders: (Φ_n,Φ_m), (Φ_n,Φ_m,Φ_k)
- Observed correlations can be partially attributed to the fluctuations in the initial geometry, but may also arise during the dynamical evolution of the created system

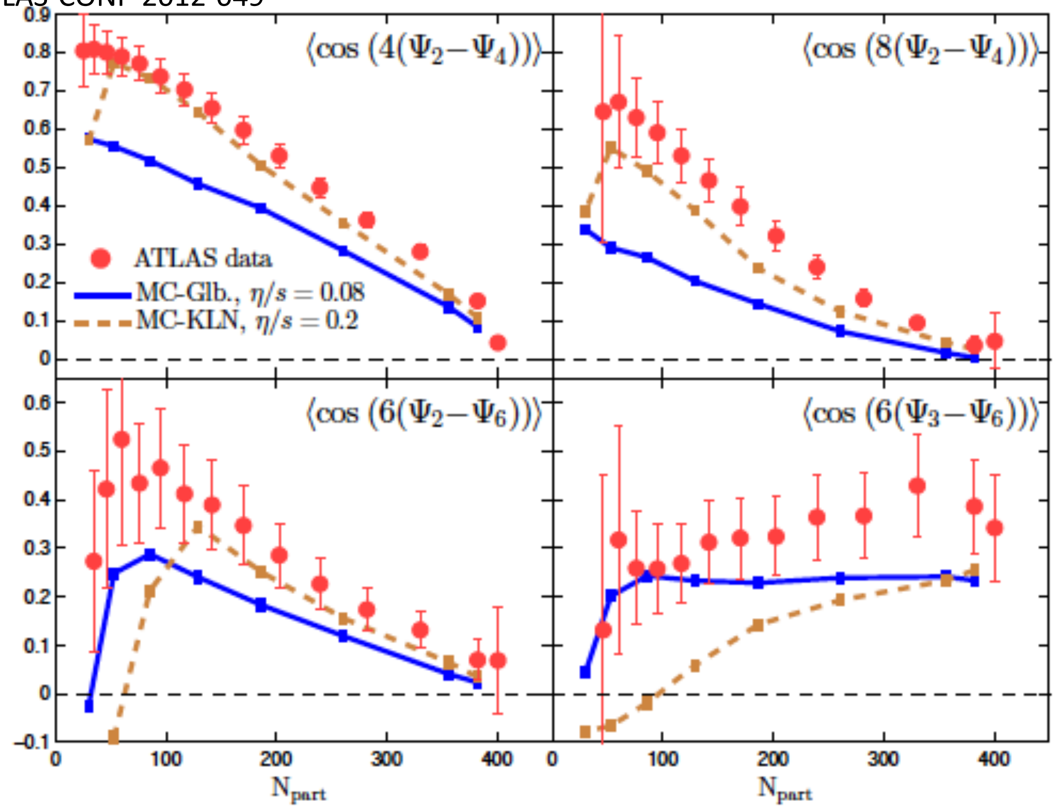


ATLAS-CONF-2012-049

Event-plane correlations

- **Correlations can be attributed to the initial geometry fluctuations and can be generated dynamically via hydrodynamic evolution**
  - Z. Qiu and U. Heinz, arXiv:1208.1200
  - **D. Teaney and L. Yan, arXiv:1210.5026, Phys. Rev. C86,044908(2012)**

ATLAS-CONF-2012-049



Initial fluctuations & Flow response => Event-plane correlations

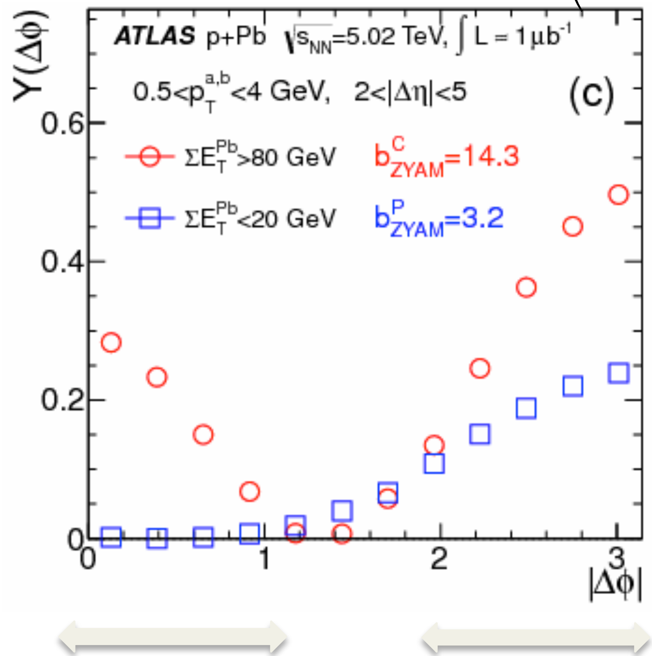
Qualitative agreement with viscous hydro

Importance of nonlinear effects in hydro evolution

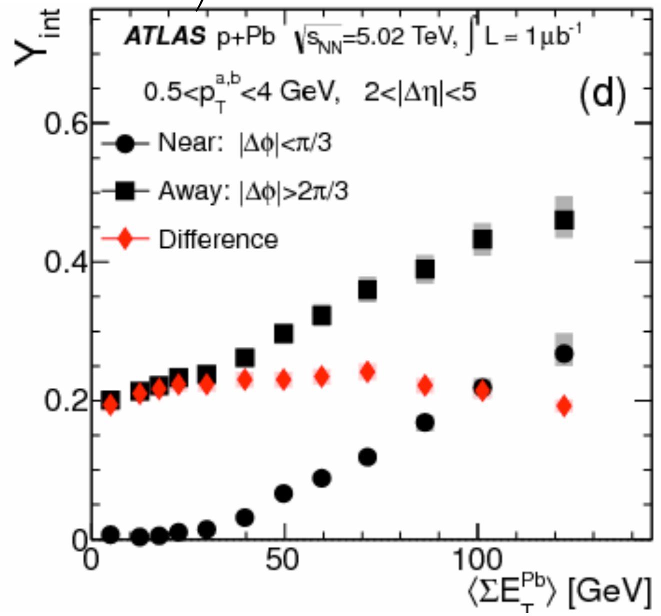
Two-particle correlations

Define per trigger yield:

$$\mathbf{Y}(\Delta\phi) = \left(\frac{\int \mathbf{B}(\Delta\phi)\,\mathbf{d}\Delta\phi}{\pi \mathbf{N_a}} \right) \mathbf{C}(\Delta\phi) - \mathbf{b_{ZYAM}}$$



Excess (ridge) seen on the away-side also



The difference of the integrated yields is approximately independent of centrality

Summary

- **Collective flow**
  - New results on flow harmonics fluctuations
  - Constraints on hydrodynamic models
- **Electroweak probes**
  - Z and γ production consistent with N_{coll} scaling
- **Medium sensitive probes**
  - Heavy quarks are less suppressed than charged hadrons
  - Jet yields suppressed by a factor of 2 in central collisions
  - Jet suppression depends on the jet size in central collisions
  - Jet fragmentation function shows no modification at high z, but significant suppression with centrality at $z \approx 0.1$ and enhancement at very low z is observed
  - Azimuthal dependence of jet yields shows expected path length dependence
  - Jet v_2 weakly depends on jet p_T out to 200 GeV
  - Jet quenching also studied with Z,γ - jet correlations