Heavy-Ion Physics with the ATLAS and CMS Experiments

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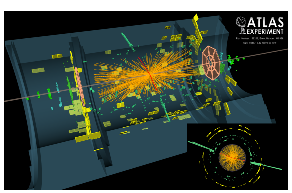
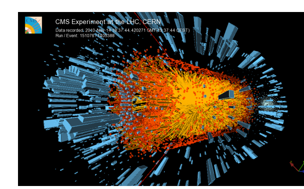




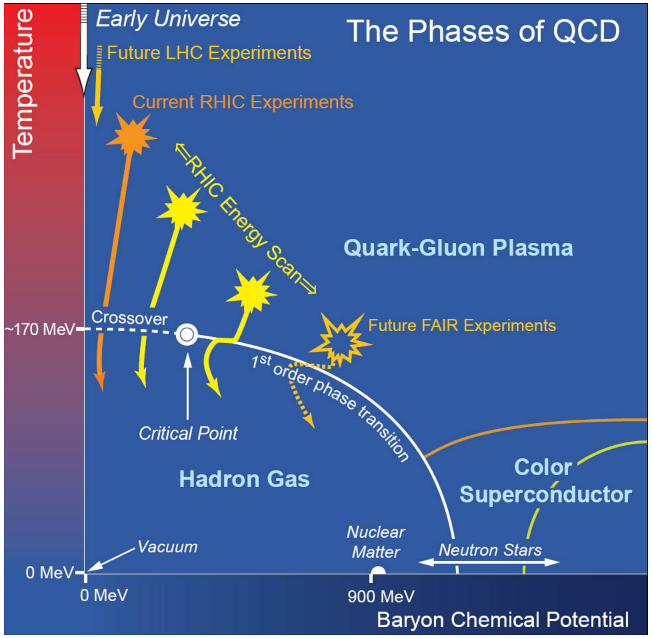
Outline

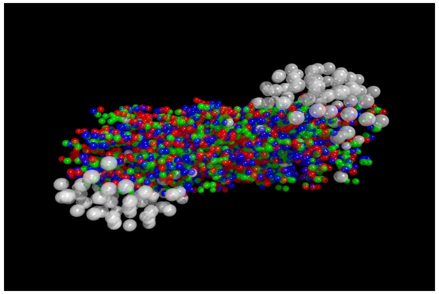
- Introduction
- LHC heavy-ion experiments
- HI data samples
- Global properties – soft sector
- High-p_T phenomena
  - Electroweak probes
  - Medium sensitive probes
- Summary and outlook

Comparison across the systems:
Pb+Pb
p+Pb
p+p

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**



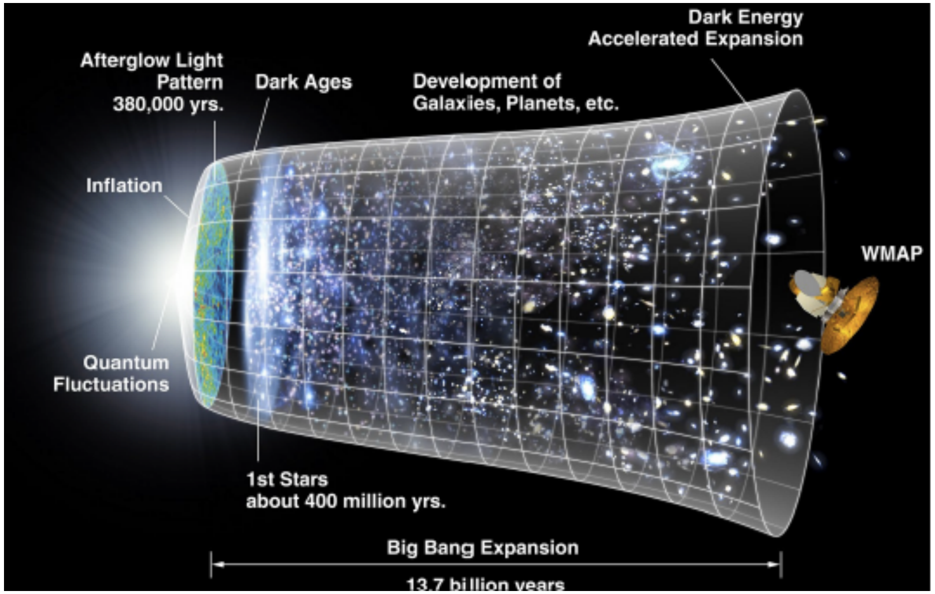


✧ **Explore the QCD phase diagram**
✧ **Test the predictions of the QCD**

Due to large pressure gradients, the matter undergoes explosive collective expansion → "Little Bangs"

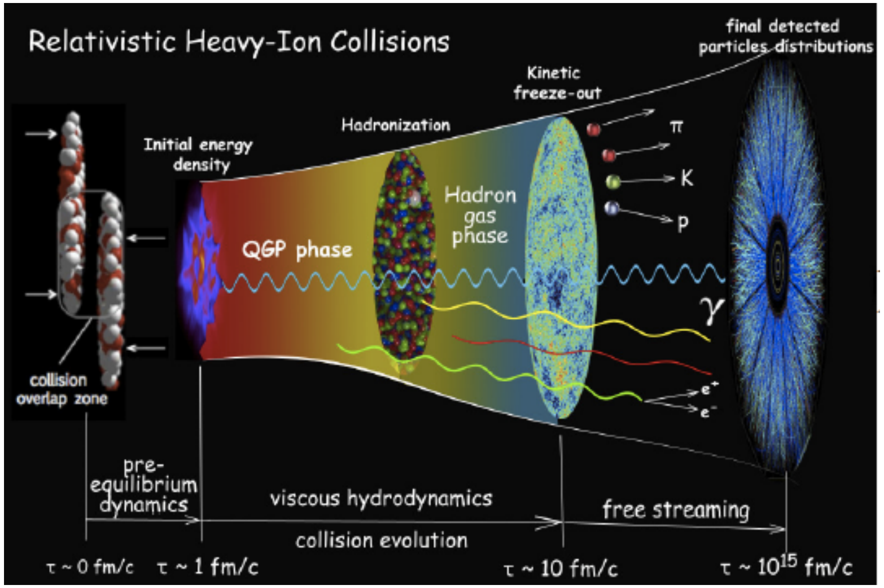
Ultra-relativistic heavy-ion collisions

Big Bang



Credit: NASA

Little Bang



Credit: P. Sorensen

Hubble-like expansion

Initial-state quantum fluctuations imprinted onto the final-state

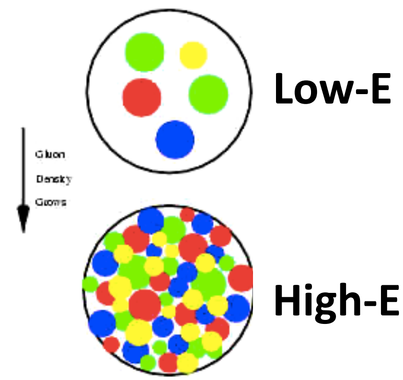
Standard Model of the Little Bang still under construction

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:

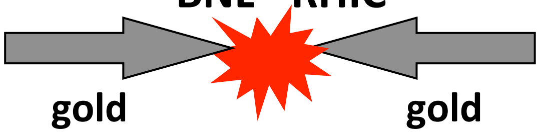
- **Gluon distribution rises rapidly at low-x:** $xG(x) \sim x^{-\lambda}$ ($\lambda \sim 0.25$ from fits to HERA data)
- **Gluons of π/Q^2 can overlap in the transverse plane**
- **At saturation scale gluons fill the entire transverse area:**

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

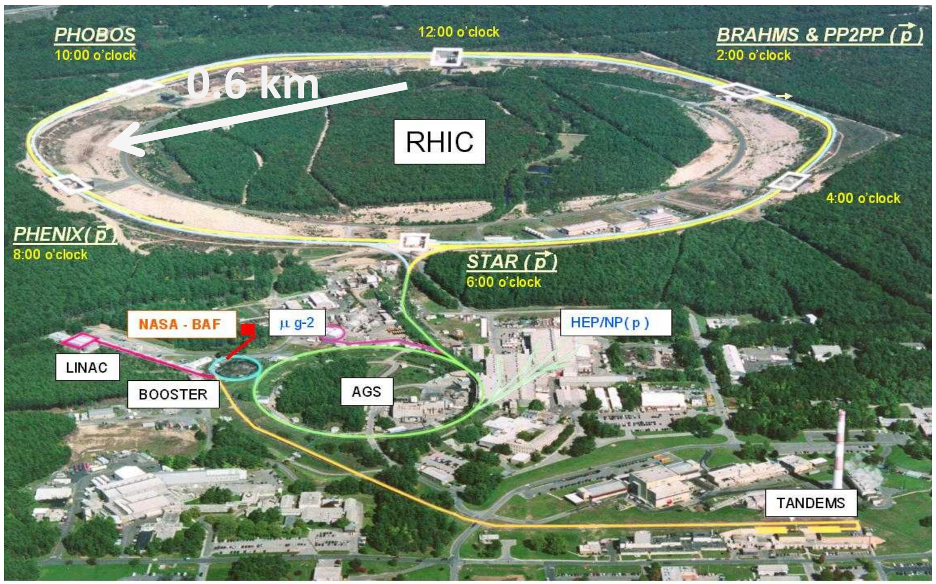
- **Below "saturation" scale Q_s^2 gluon fusion occurs** $g+g \rightarrow g$

Heavy-ion colliders

BNL - RHIC



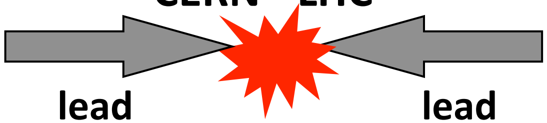
gold E = 0.1 TeV/n — gold E = 0.1 TeV/n



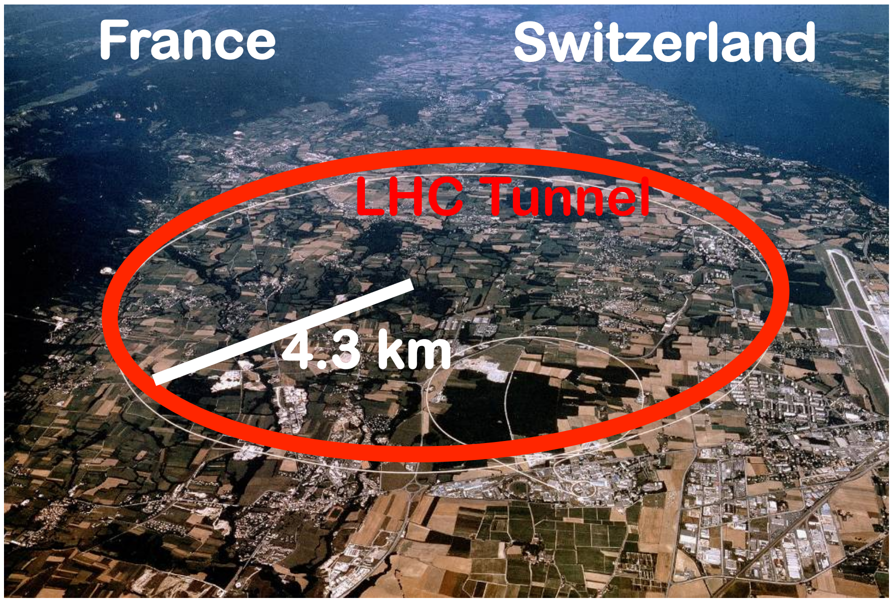
RHIC- Experiments

- STAR
- PHENIX
- BRAHMS
- PHOBOS

CERN - LHC



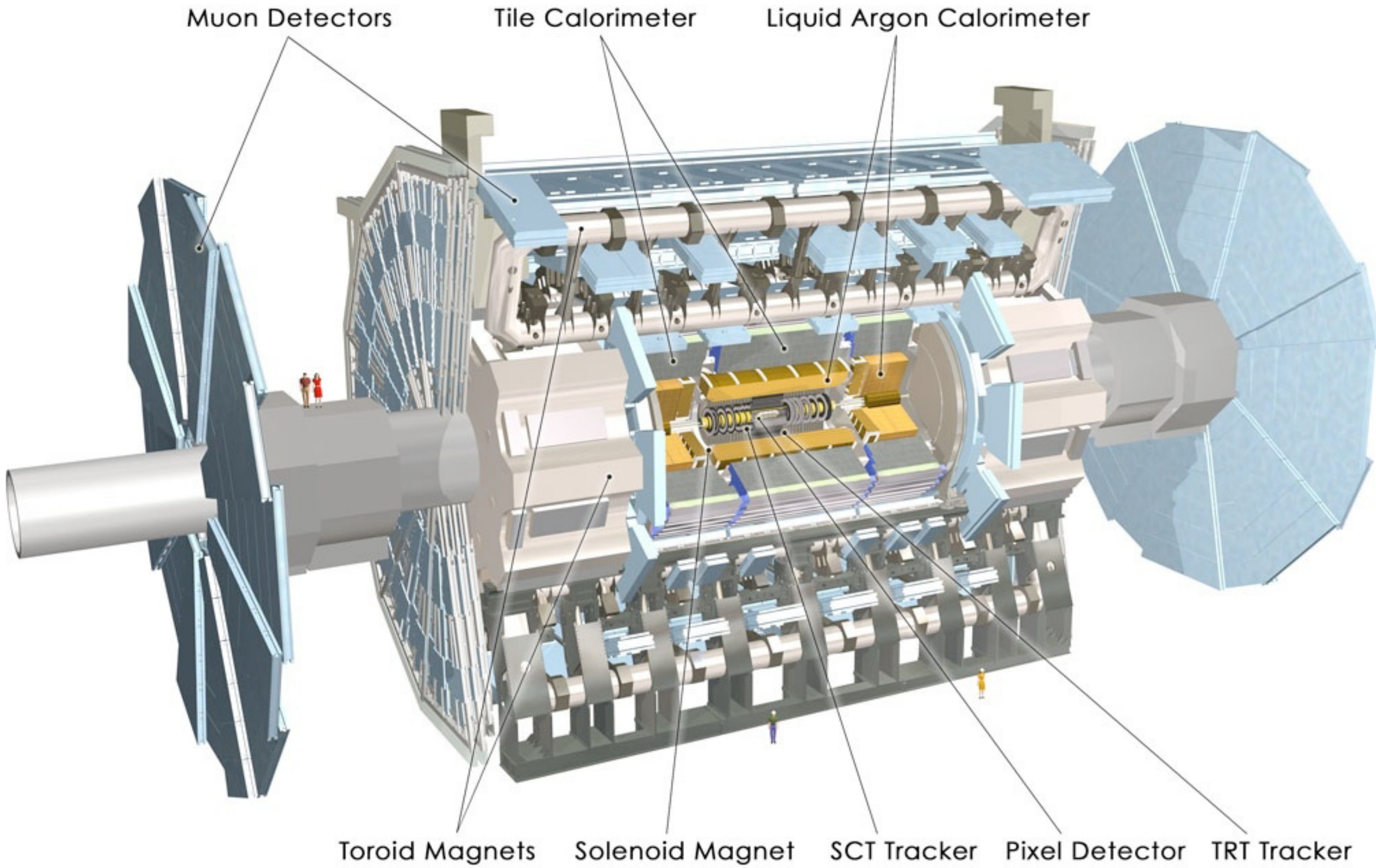
lead E = 1.38 TeV/n — lead E = 1.38 TeV/n



LHC- HI Experiments

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

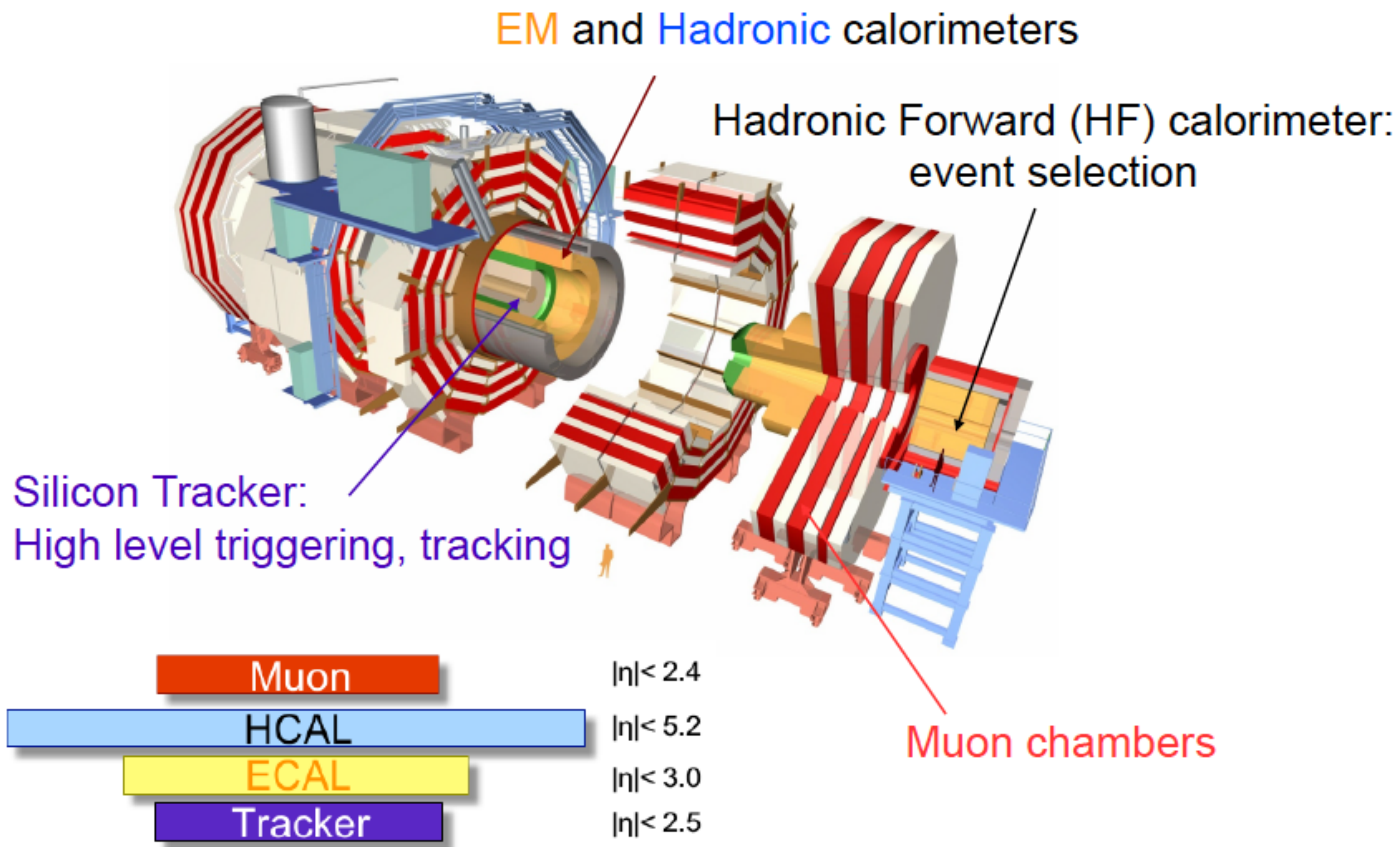
The ATLAS detector



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

ATLAS and CMS excel at:

- Tracking over $|\eta|<2.5$ and full azimuth
- Fine granularity calorimetry $|\eta|<5$ and full azimuth
- Trigger selectivity
- Also access to the bulk medium

ALICE strengths:

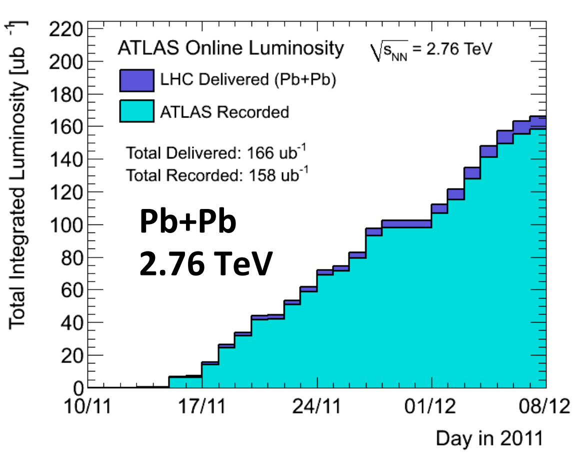
- Particle identification
- Efficient low momentum tracking, down to 100 MeV ($|\eta|<1$, full azimuth)

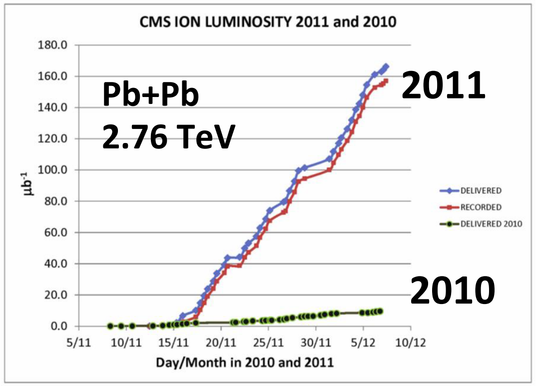
LHCb (p+Pb):

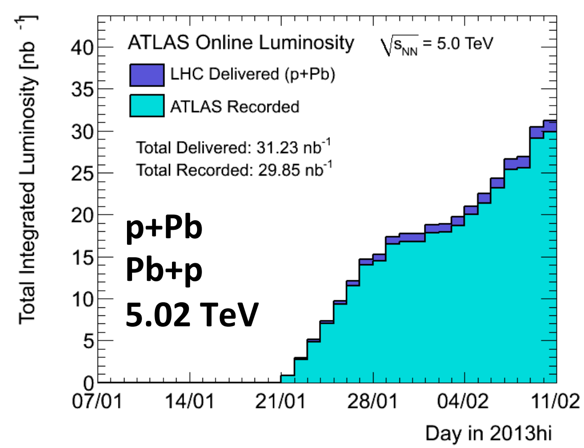
- Heavy quark physics
- Forward spectrometer $1.9 < \eta < 4.9$
  (p+Pb: $1.5 < \eta < 4.5$; Pb+p: $-5.5 < \eta < 2.5$)

LHC Run 1 for heavy-ion physics

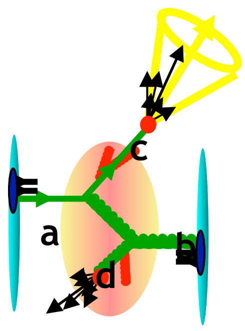
System	$\sqrt{s_{NN}}$ [TeV]	When	Integrated L per experiment
Pb+Pb	2.76	2010+2011	0.17 nb^{-1}
p+Pb	5.02	2012	0.001 nb^{-1}
p+Pb	5.02	2013	19 nb^{-1}
Pb+p	5.02	2013	~11 nb^{-1}
p+p	2.76	2011	200 nb^{-1}
p+p	2.76	2013	~4.5 pb^{-1}





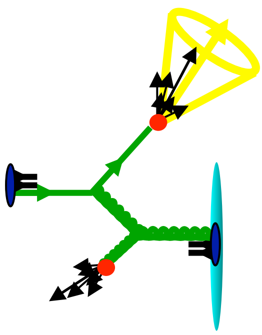


Different collision systems



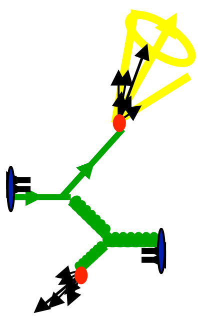
Pb+Pb

Initial state: CGC, nPDF
Final state: Hot and dense QCD medium formed



p+Pb

Initial state: CGC, nPDF
Final state: turned off

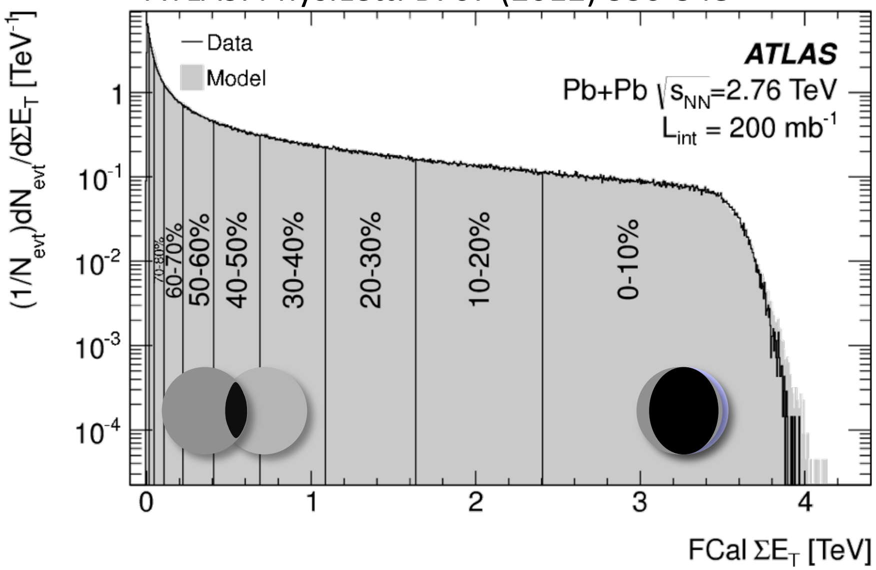


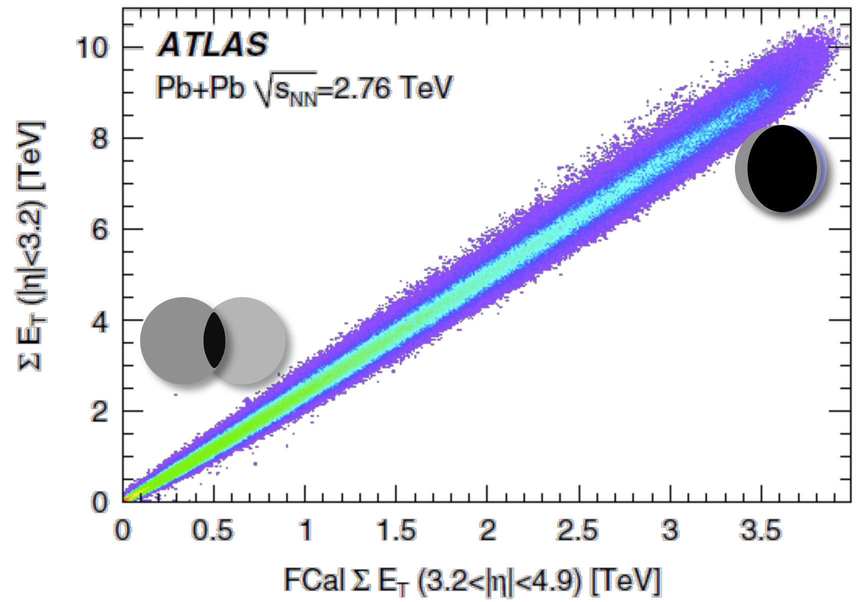
p+p

Initial state: PDF, saturation
Final state: QCD 'vacuum'

Centrality of Pb+Pb collision

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

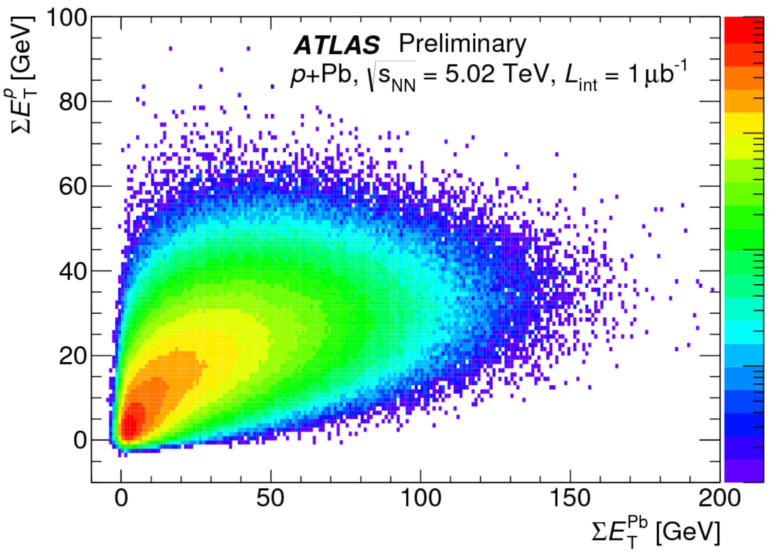




- Energy sum in forward calorimeter (FCal) ΣE_T (3.2 |η|<4.9) compared with Glauber MC ⊗ 2.76 TeV pp data
- Centrality parameters $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ calculated from Glauber MC

	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$
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%

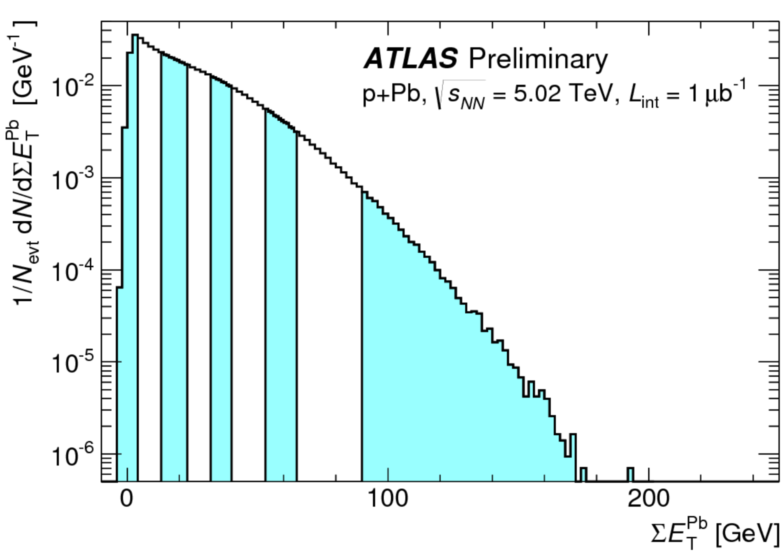
Centrality of p+Pb collision

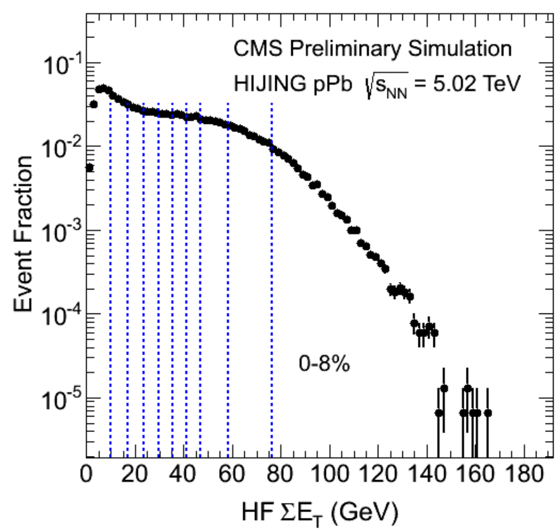


For ΣE_T^{Pb} > 35 GeV, the mean ΣE_T^{p} is only weakly varying with increasing ΣE_T^{Pb}.

! Large fluctuations in p+Pb!

N_{ch} at mid-rapidity can be used, but introduces autocorrelation bias



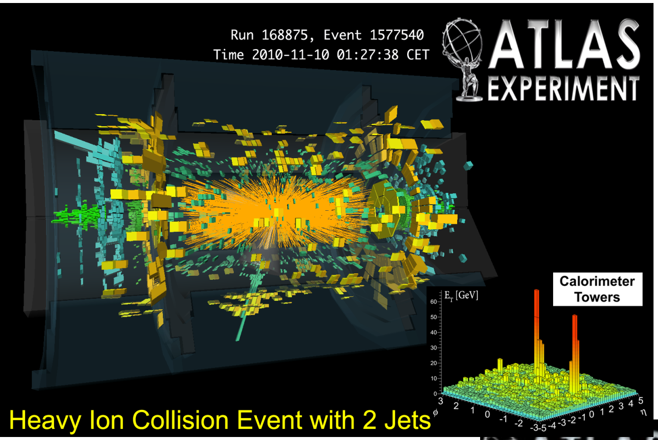


Better centrality variable is ΣET on the Pb-going side:

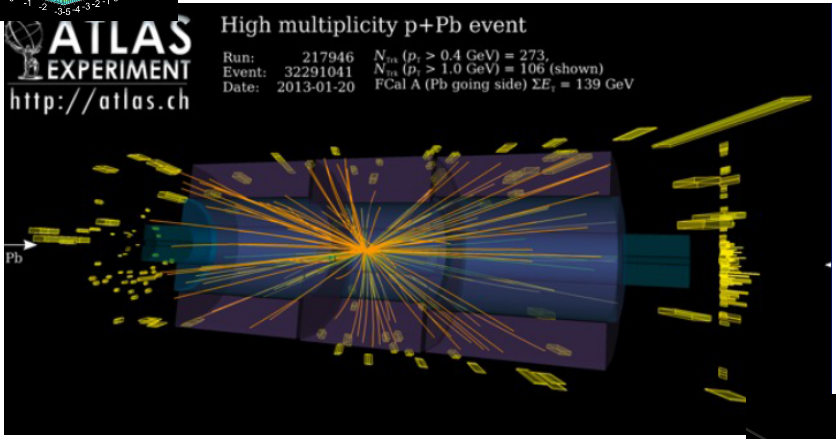
Large η-gap between centrality estimator and the measurement

Bulk matter properties

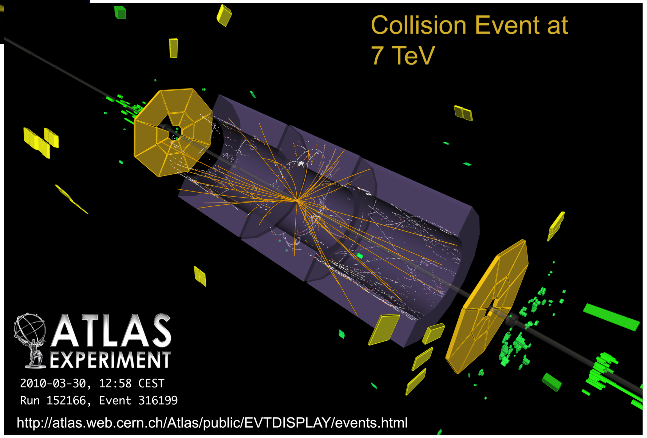
Pb+Pb 2.76 TeV



p+Pb 5.02 TeV

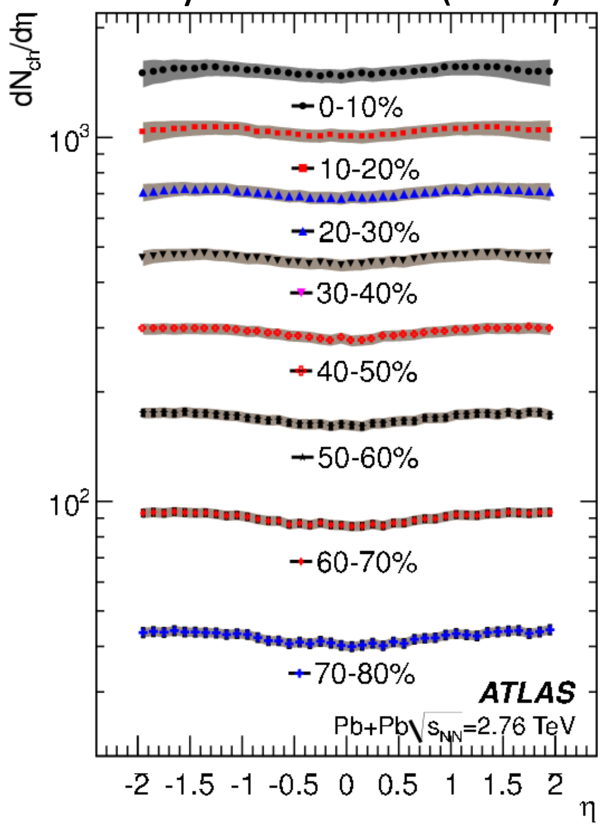


p+p 7 TeV

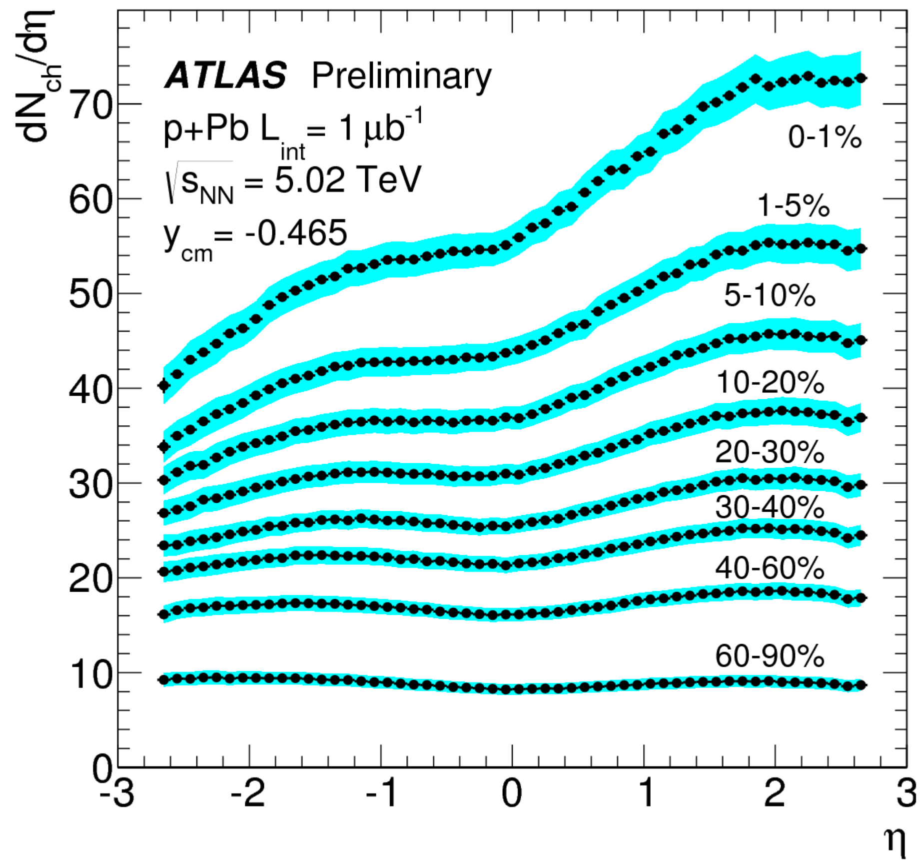


Charged particle multiplicity

Phys. Lett. B710(2012)363



Atlas-CONF-2013-096

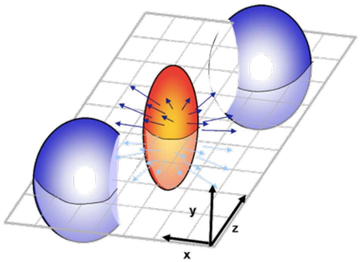


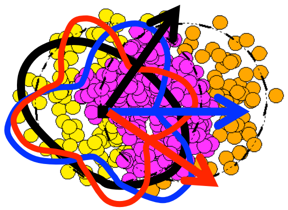
	Pb+Pb	p+Pb	p+p
$\langle dN_{ch}/d\eta \rangle$	**~ thousands**	**~tens**	**~few**

Collective particle flow

Final-state azimuthal anisotropy of the particle emission

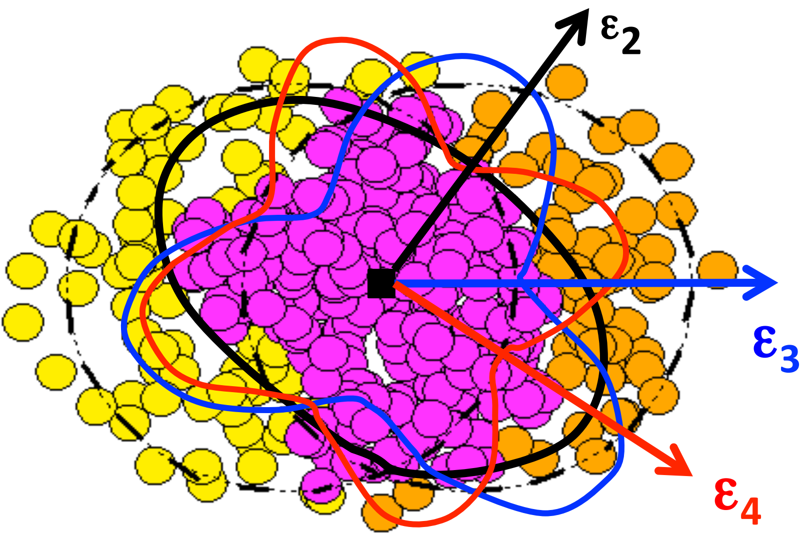
- **A useful tool to study the property of matter created in nuclear collisions**
- **Results from a pressure-driven anisotropic collective expansion of the matter**
  - **Converts spatial anisotropy to momentum anisotropy**
- **Sensitive to the initial geometry and its fluctuations**





- **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

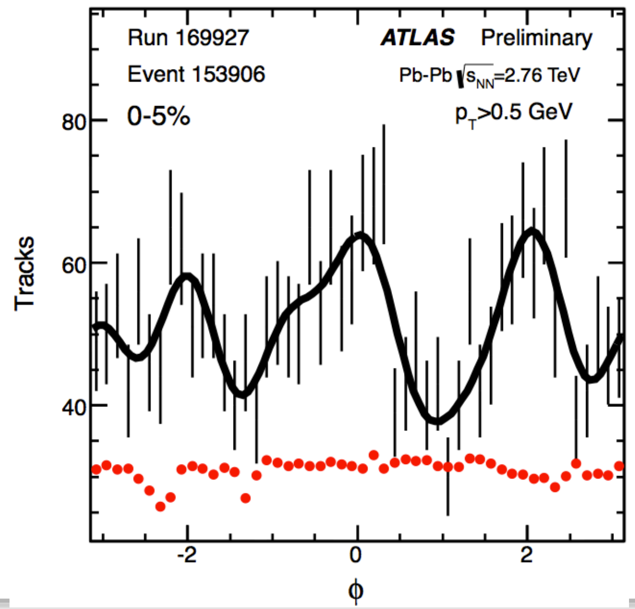
- Transverse positions of nucleons (r, ϕ)
- From Glauber, KLN, IP-Glasma models (arXiv:1301.5893)

amplitude and direction

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

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

HYDRODYNAMICS



Final state symmetry plane

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

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

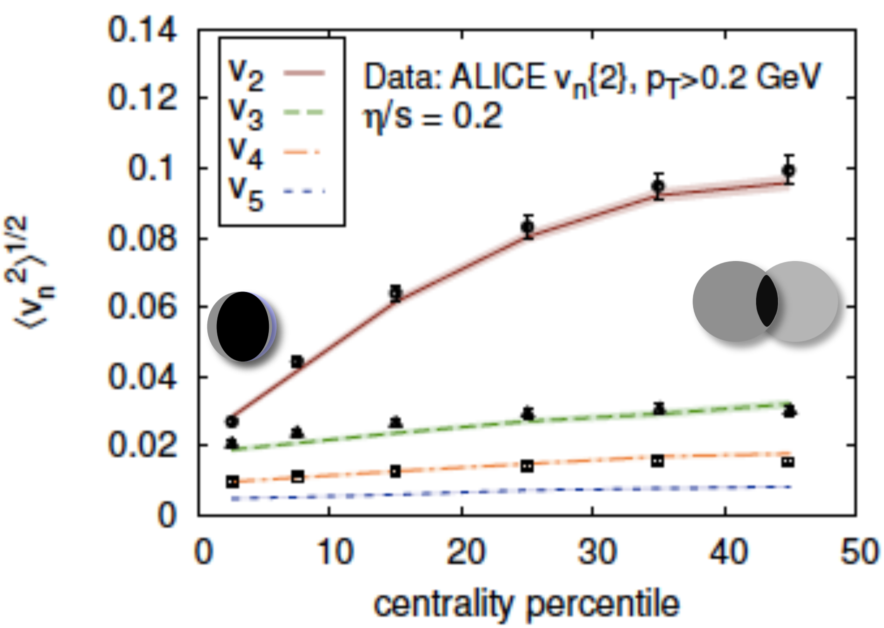
$$v_n = \langle \cos(n[\phi - \Phi_n]) \rangle$$

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

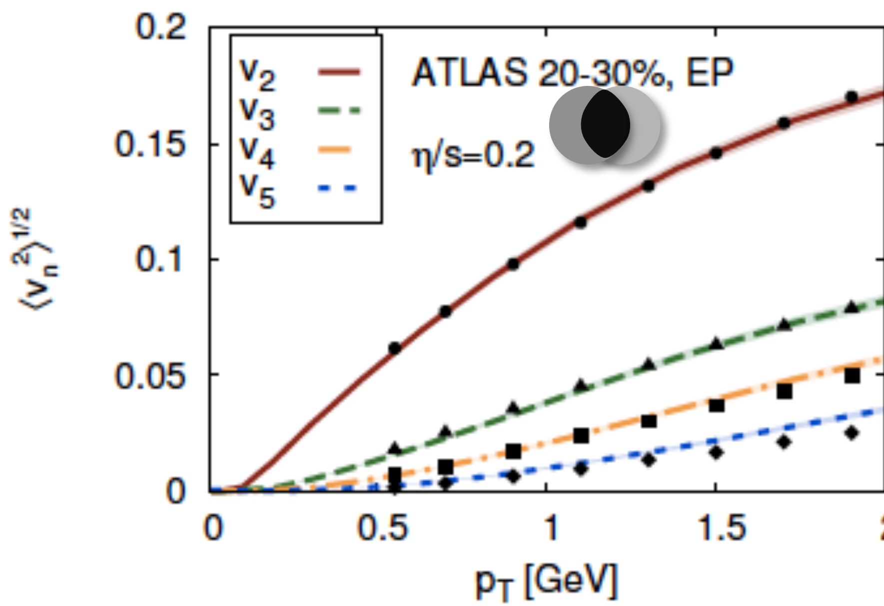
$$\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + \sum_n v_n^2 \cos n\Delta\phi$$

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

C. Gale, S. Jeon, B. Schenke,
Int. J. Mod. Phys. A28 (2013)134011

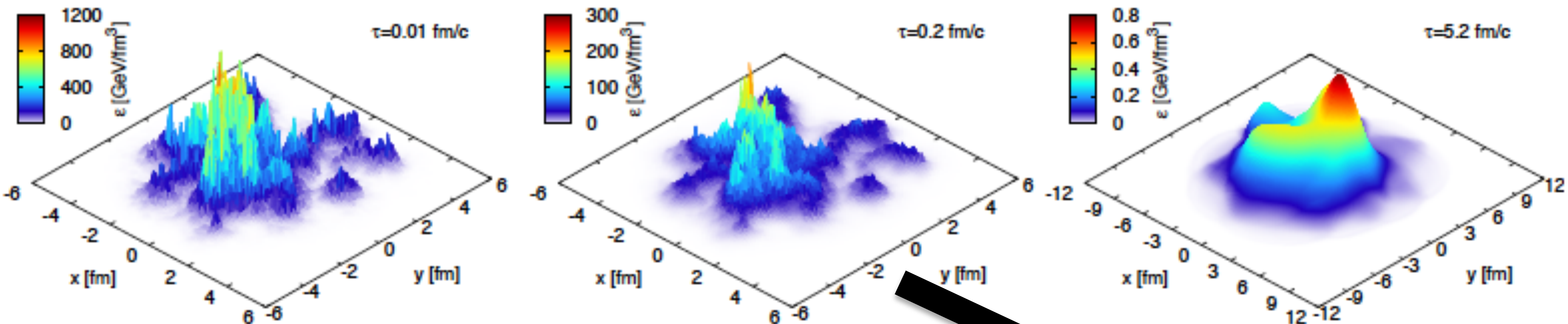
Anisotropic flow in Pb+Pb

Significant v_1, v_3, v_5

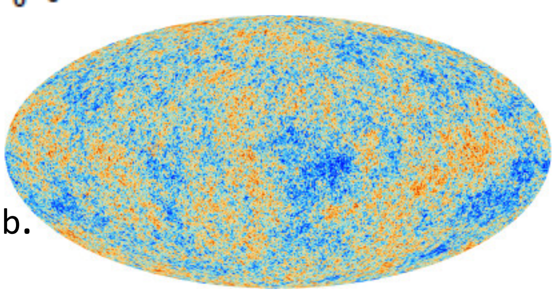
Importance of fluctuations in the initial geometric configuration

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)

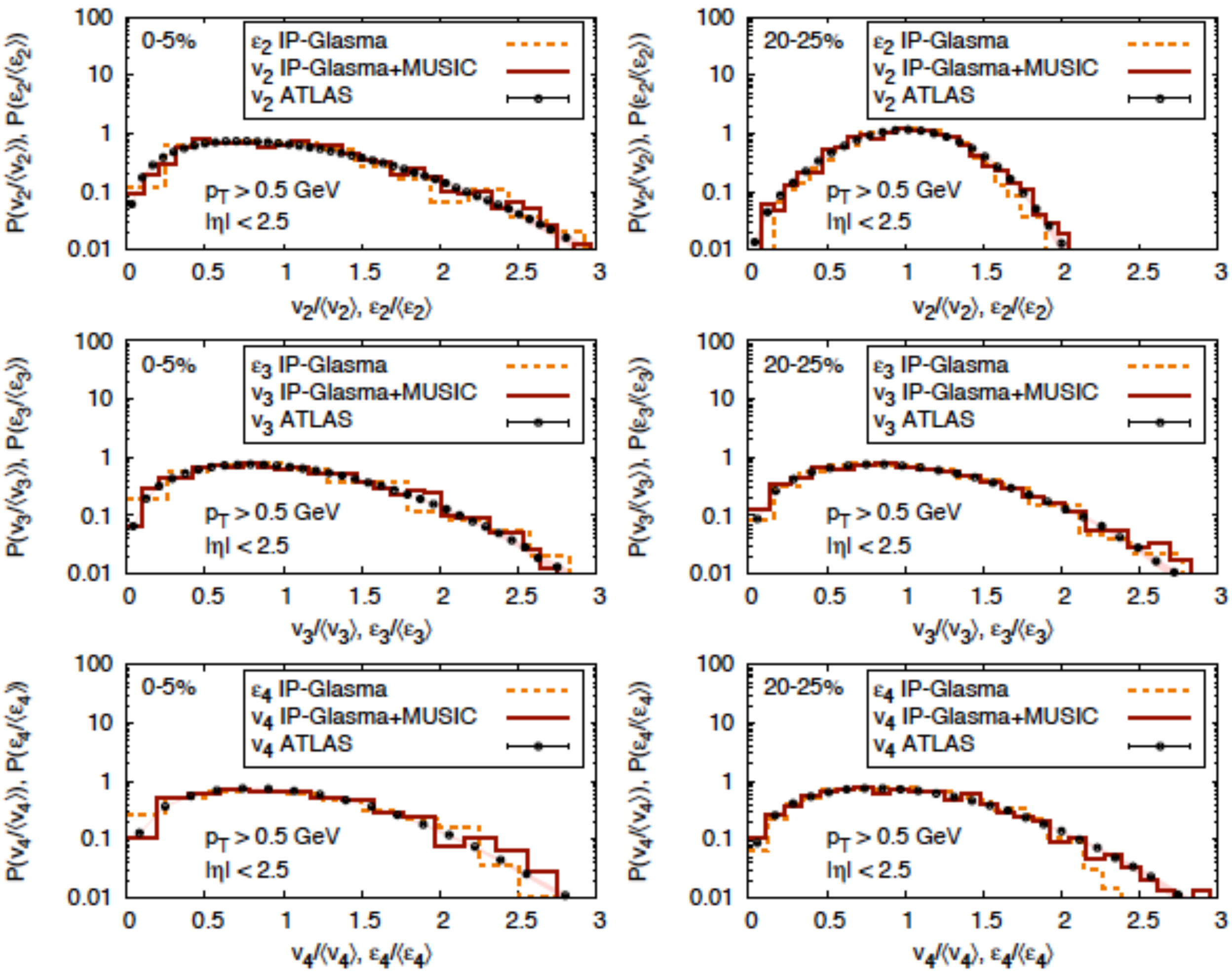


Credit:
ESA & Planck Collab.



Final-state azimuthal anisotropies

E-by-E: v_n distributions



C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopolan Phys. Rev. Lett. 110, 012302
C. Gale, S. Jeon, B. Schenke, Int. J. Mod. Phys. A28 (2013)134011

$$v_n \propto \varepsilon_n$$

EbE v_n well described by viscous hydro

ATLAS: JHEP 11(2013)183

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:

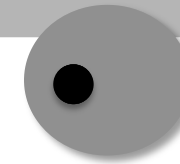
Initially very dense quark-gluon matter reaches approximate local thermal equilibrium on a very short time scale and then evolves according to the macroscopic laws of relativistic fluid dynamics

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**

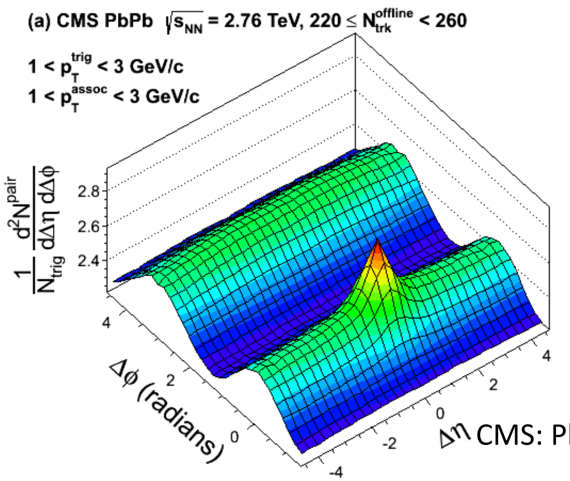
Collective flow in p+Pb collisions?



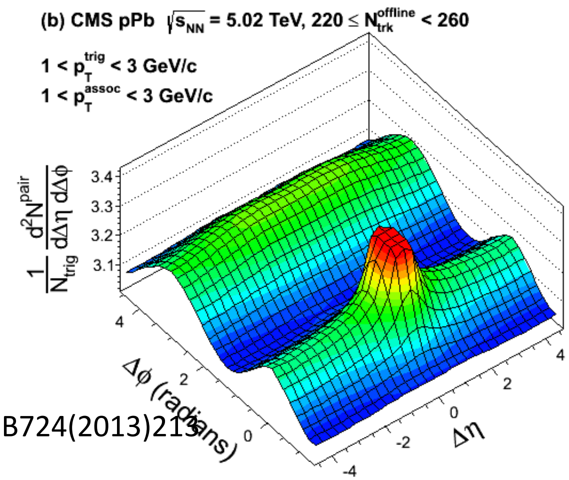
The size of the produced system is small as compared to the mfp of its constituents

weaker, if any, collective flow expected

Pb+Pb

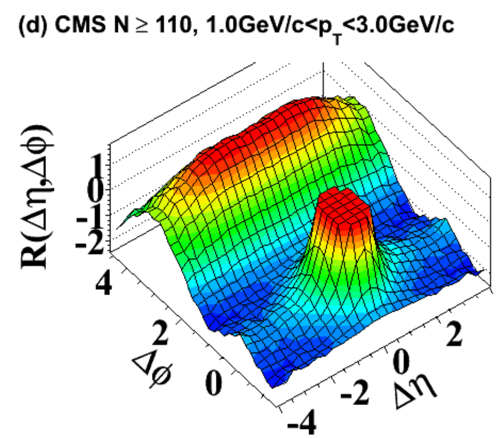


p+Pb



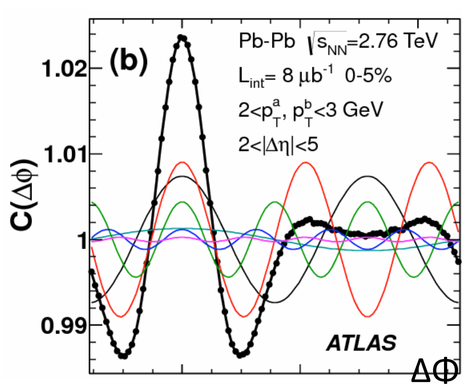
CMS: Phys. Lett. B724(2013)213

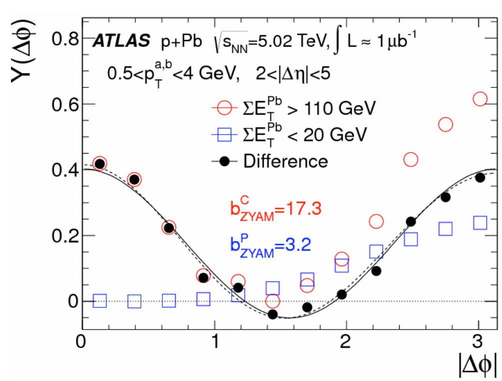
p+p



CMS: JHEP 09(2010)091

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





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

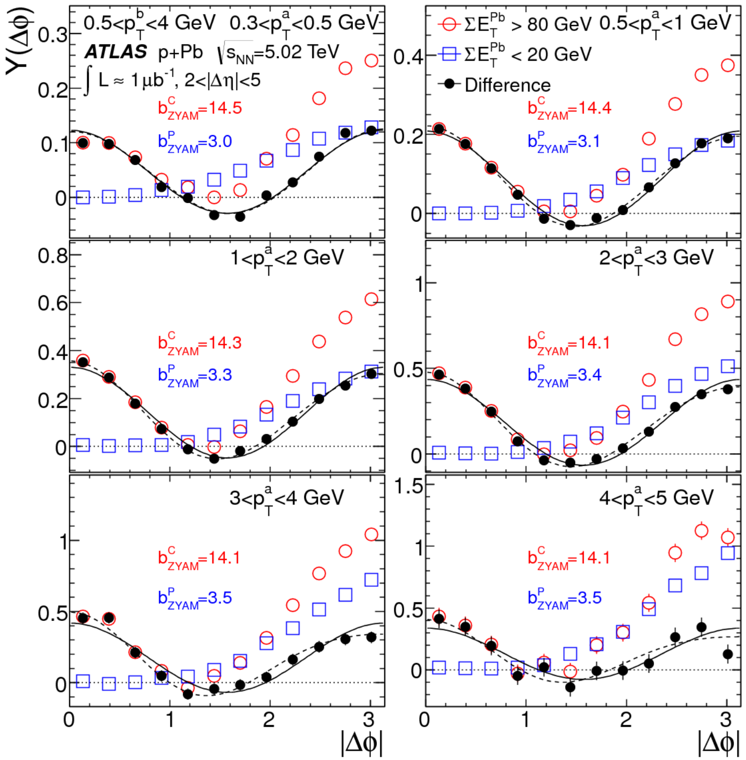
Two-particle correlations

Define per trigger yield: $$\mathbf{Y}(\Delta\phi) = \left(\frac{\int \mathbf{B}(\Delta\phi)\,\mathbf{d}\Delta\phi}{\pi \mathbf{N}_{\mathbf{a}}}\right)\mathbf{C}(\Delta\phi) - \mathbf{b}_{\mathbf{ZYAM}}$$

2<|Δη|<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%)

ΔY(Δφ) is symmetric around |Δφ|=π/2

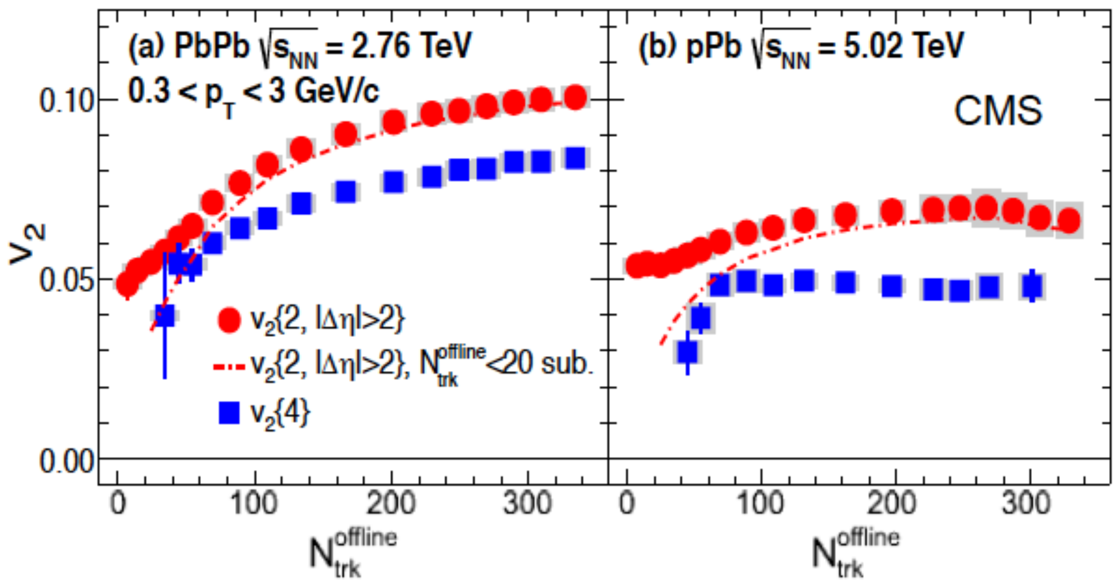
Long-range component=Recoil+ Δφ-symmetric

—— $$\mathbf{a}_0 + 2\mathbf{a}_2 \cos 2\Delta\phi$$

- - - $$\mathbf{a}_0 + 2\mathbf{a}_2 \cos 2\Delta\phi + 2\mathbf{a}_3 \cos 2\Delta\phi$$

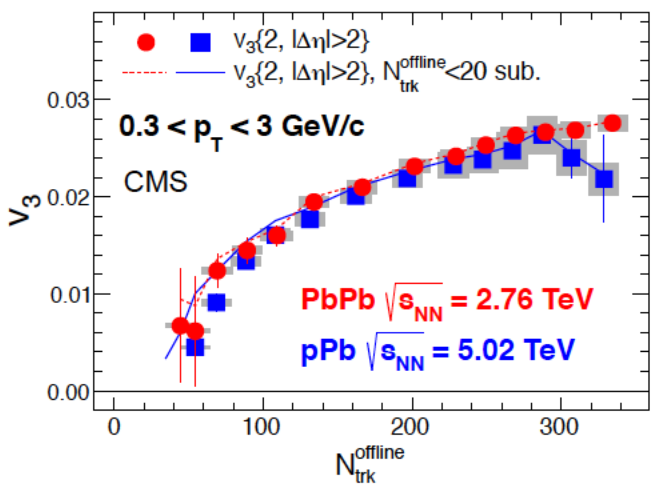
$$\mathbf{a}_{\mathbf{n}} = \langle \Delta\mathbf{Y}(\Delta\phi) \cos \mathbf{n}\Delta\phi \rangle$$

Amplitudes of cosnΔϕ modulation



CMS: Phys. Lett. B724(2013)213
ATLAS: Phys. Rev. Lett. 110 (2013) 182302;
Phys. Lett.B725(2013)60

- v_2 increases with multiplicity for both systems
- Significant $v_2\{4\} \approx 0.06$
- $v_2(p+Pb) < v_2(Pb+Pb)$

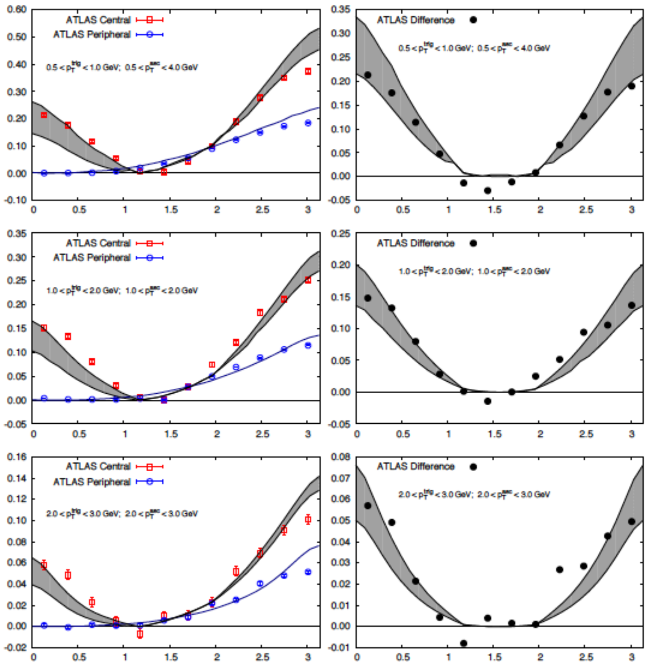


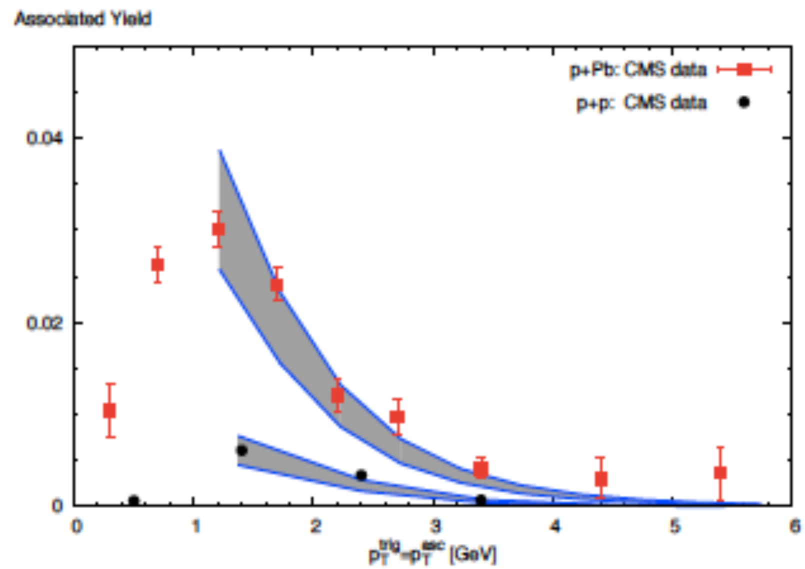
- $v_3 < v_2$ over the measured p_T
- $v_3(p+Pb) \approx v_3(Pb+Pb$
- Good agreement with the hydrodynamic predictions
  P. Bozek, W. Broniowski Phys. Lett. B718,1557 (2013)

Suggesting hydrodynamic origin?

Comparison to CGC calculations

K. Dusling, R. Venugopolan, Phys. Rev. D87(2013)094034





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?

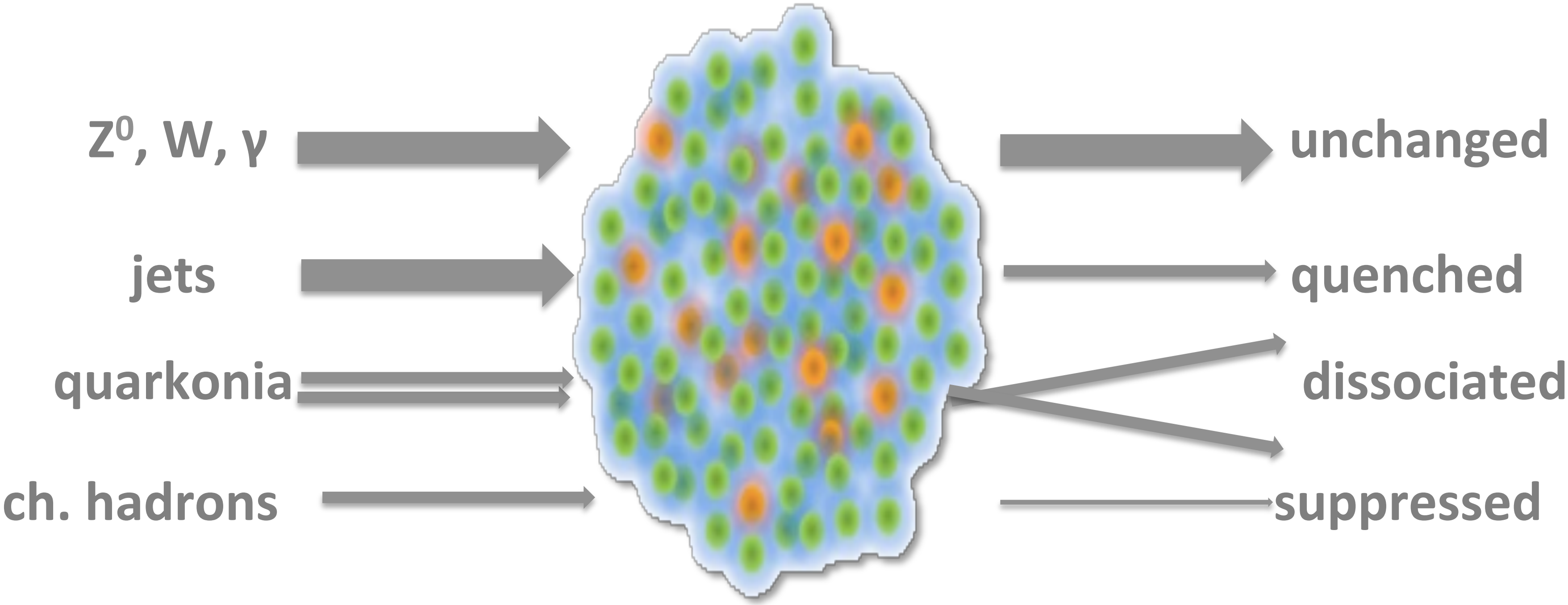
$v_2\{4\}$ and v_3 challenging for the CGC model description

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
    - Manifestation of tiny QGP droplet?
  - More detailed theoretical studies are necessary
  - Additional measurements are needed
- **p+Pb as a reference for Pb+Pb?**

Probing the medium created in Pb+Pb

High transverse momentum probes



How to measure if a probe is affected by the medium?

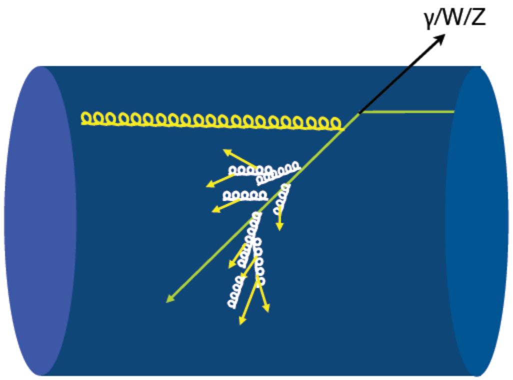
R_{AA} = ratio between the production yield in Pb+Pb (p+Pb) and the production yield in pp, normalized by the number elementary collisions

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

Electroweak probes

Z^0 and $W^{\pm}$ bosons (through their leptonic decays) and photons are not strongly interacting with the medium constituents:

should obey QCD factorization (scaling with N_{coll}, R_{AA}=1)



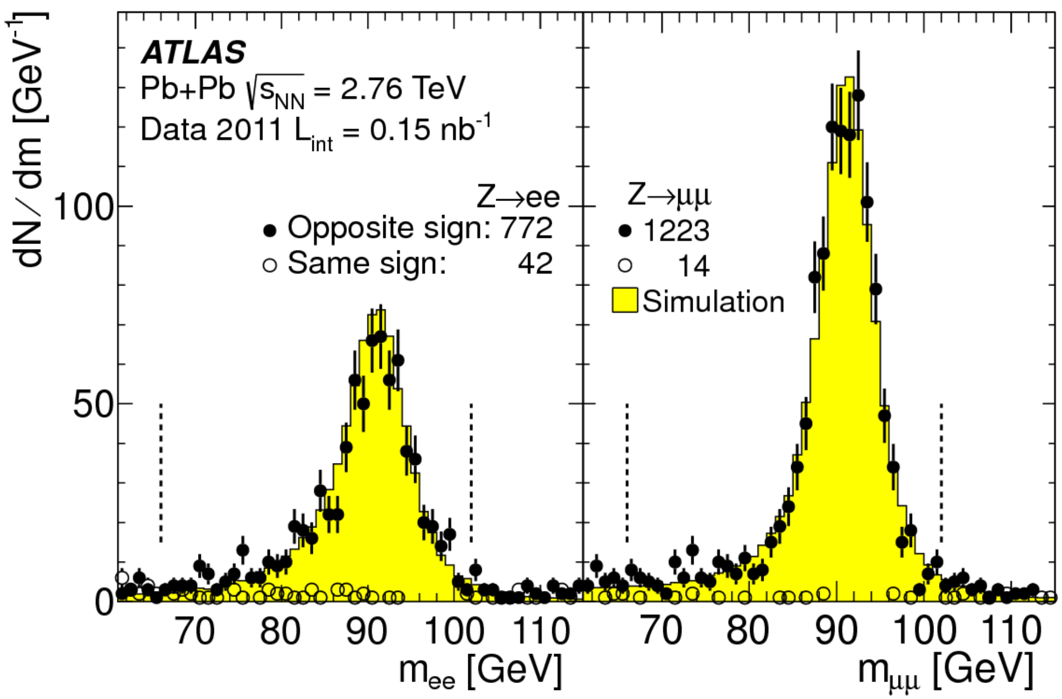
- Measurements of Z/W/γ production in Pb+Pb provide constraints on the nuclear PDF
- Z/W/γ bosons can be used as a reference
- Production of Z/W/γ in association with jets provides a handle for understanding the parton energy loss in medium

Z^0 measurements

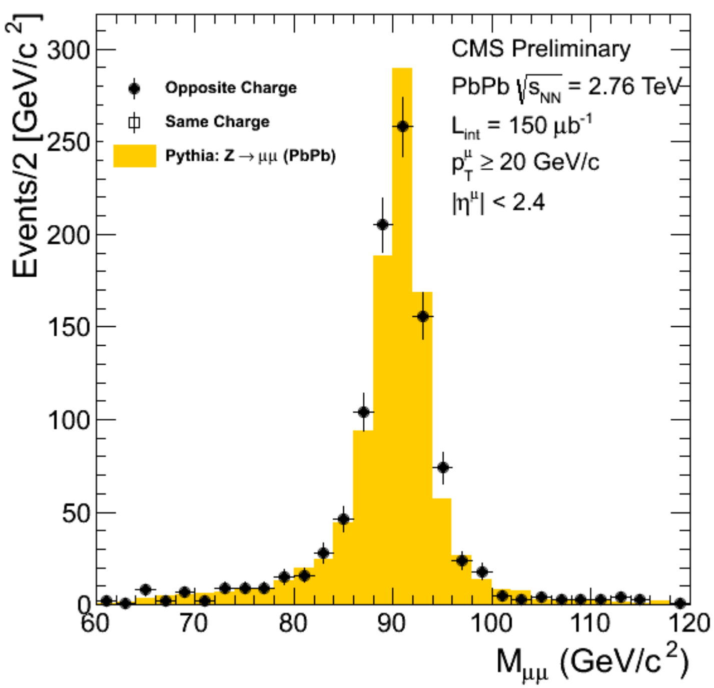
$Z \rightarrow e^+e^-, \mu^+\mu^-$

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

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



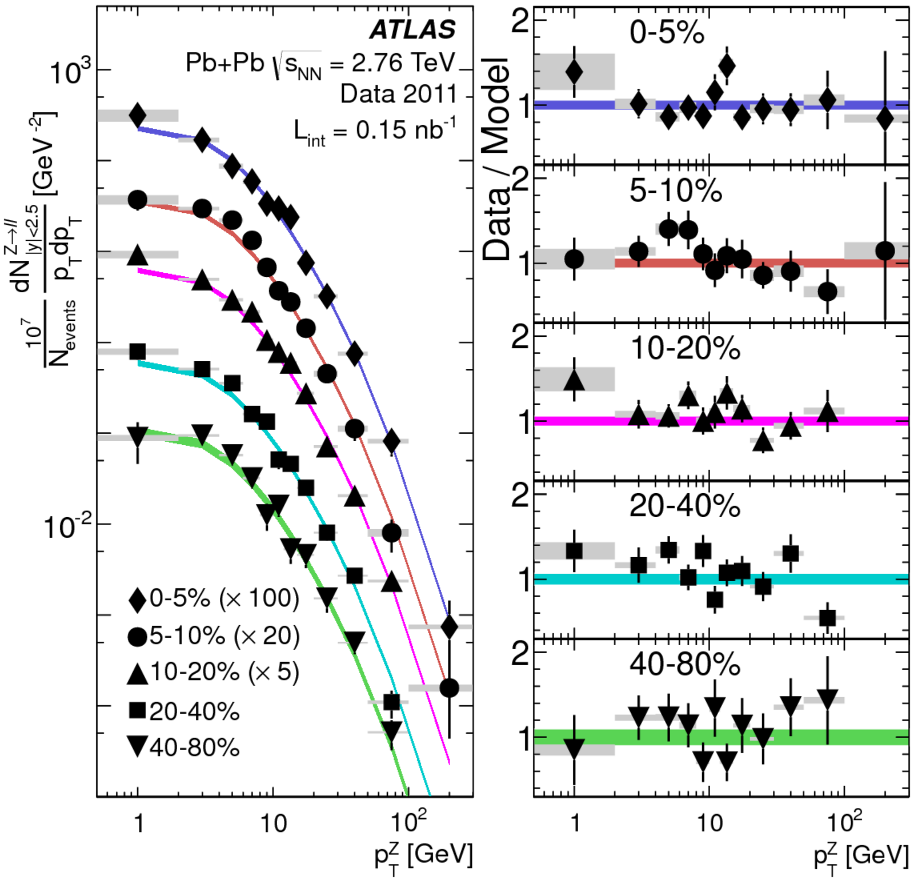
CMS-HIN-13-004

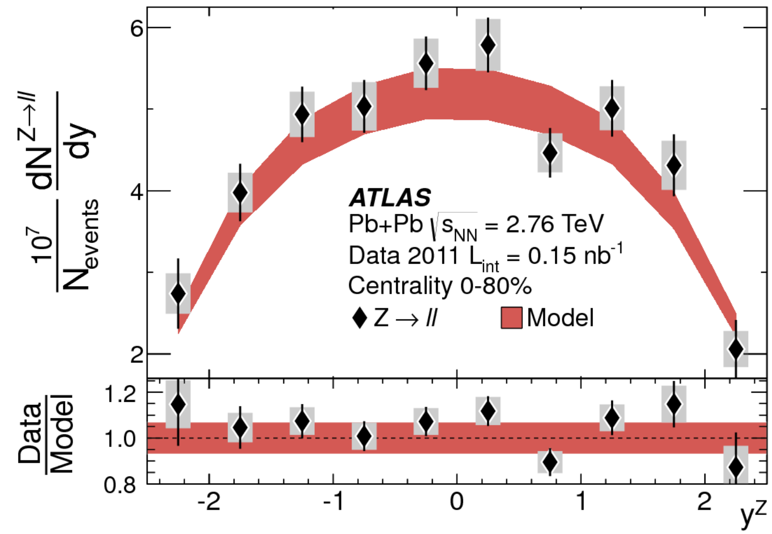


Background contamination less than 3%

p_T and y distributions of Z bosons

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





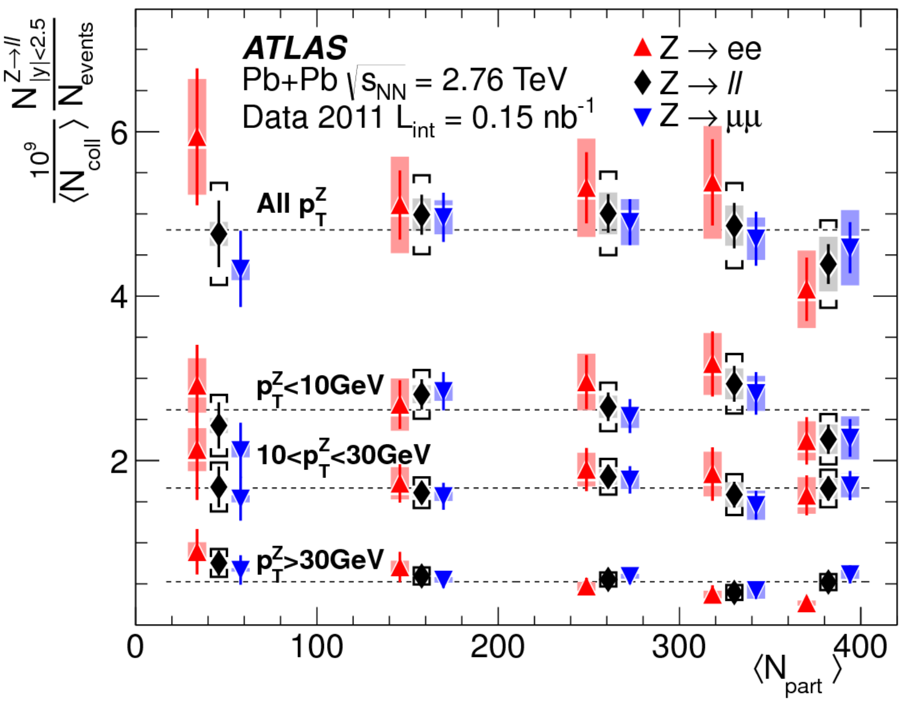
p_T and y distributions consistent with Pythia simulations for pp with NNLO cross section × <T_{AA}>

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

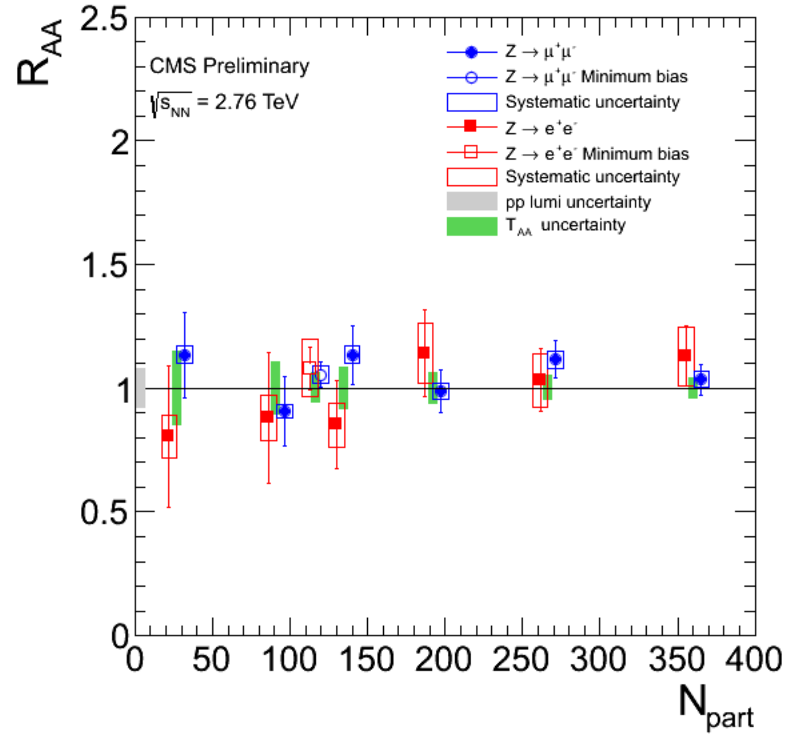
Centrality dependence of Z production

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

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



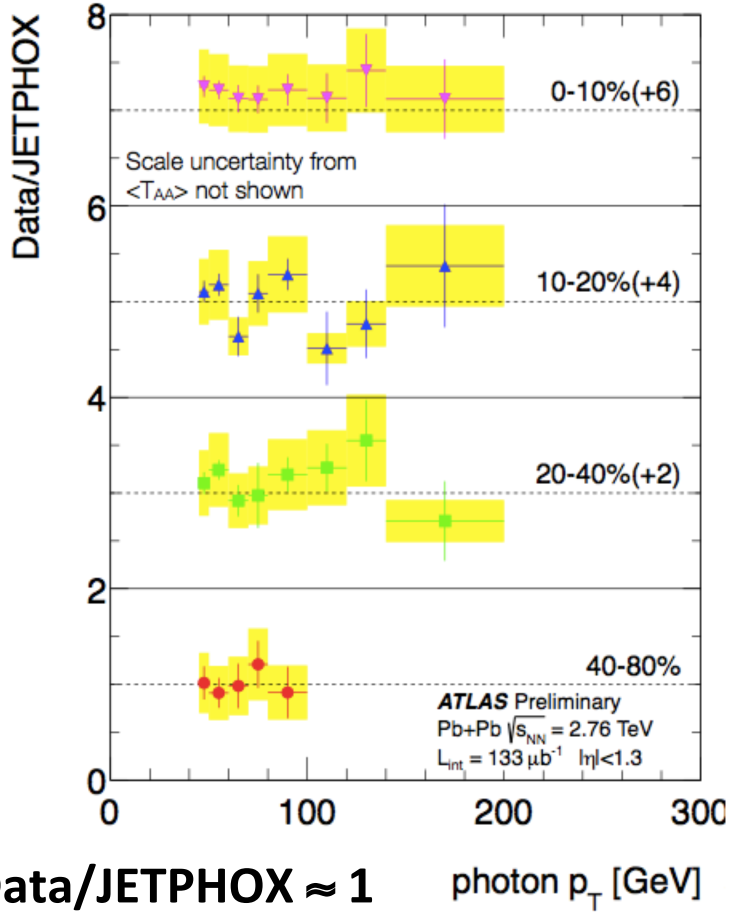
CMS-HIN-13-004



Z^0 yields consistent with N_{coll} scaling

Centrality dependence of γ production

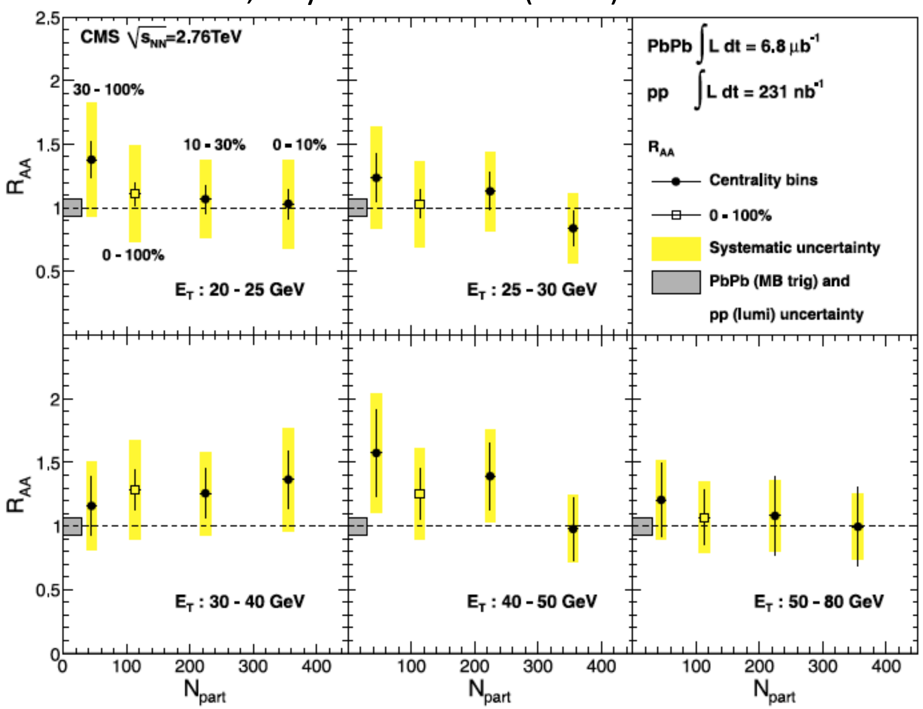
ATLAS-CONF-2012-051



Data/JETPHOX ≈ 1 (~R_{AA})

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

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



Photon yields consistent with N_{coll} scaling

Electroweak probes: Summary

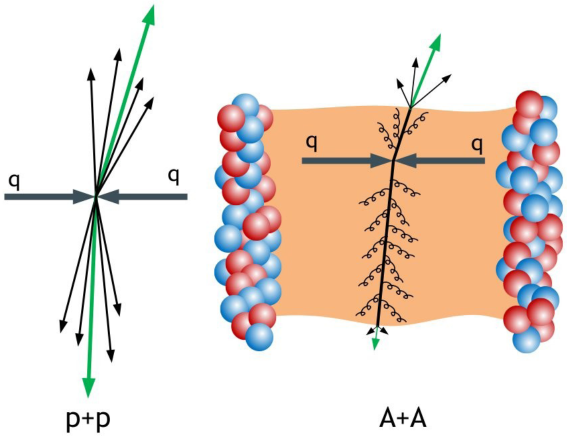
- Z, γ yields scale with N_{coll}
  - No significant violation of QCD factorization
- Using N_{coll} as a normalization of AA spectra is justified

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 + jet correlations

ATLAS EXPERIMENT
CMS

Jet suppression in Pb+Pb

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

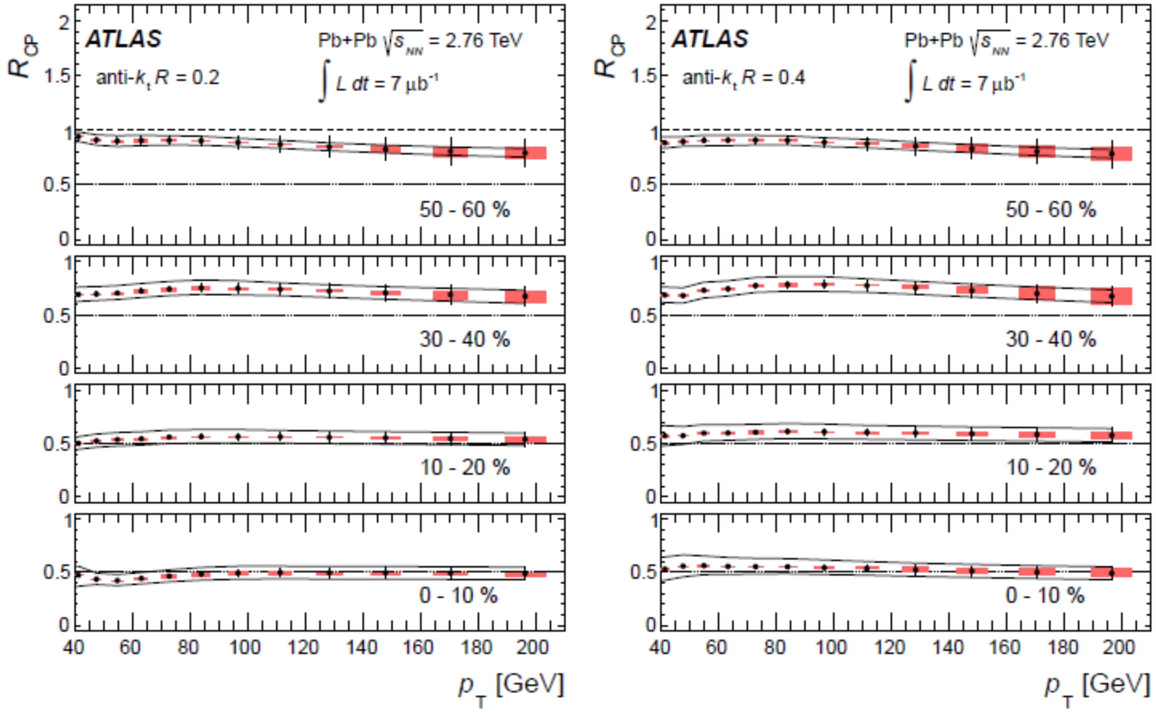
First LHC result on jet suppression

- **Unfolded p_T spectra**
- **For jet sizes R=0.2, 0.3, 0.4 and 0.5**

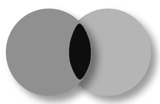
$$R_{cp} = \frac{\frac{1}{N_{coll}^{cent}} E \frac{d^3N^{cent}}{dp^3}}{\frac{1}{N_{coll}^{periph}} E \frac{d^3N^{periph}}{dp^3}}$$

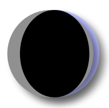
peripheral reference: 60-80%

R=0.2



R=0.4



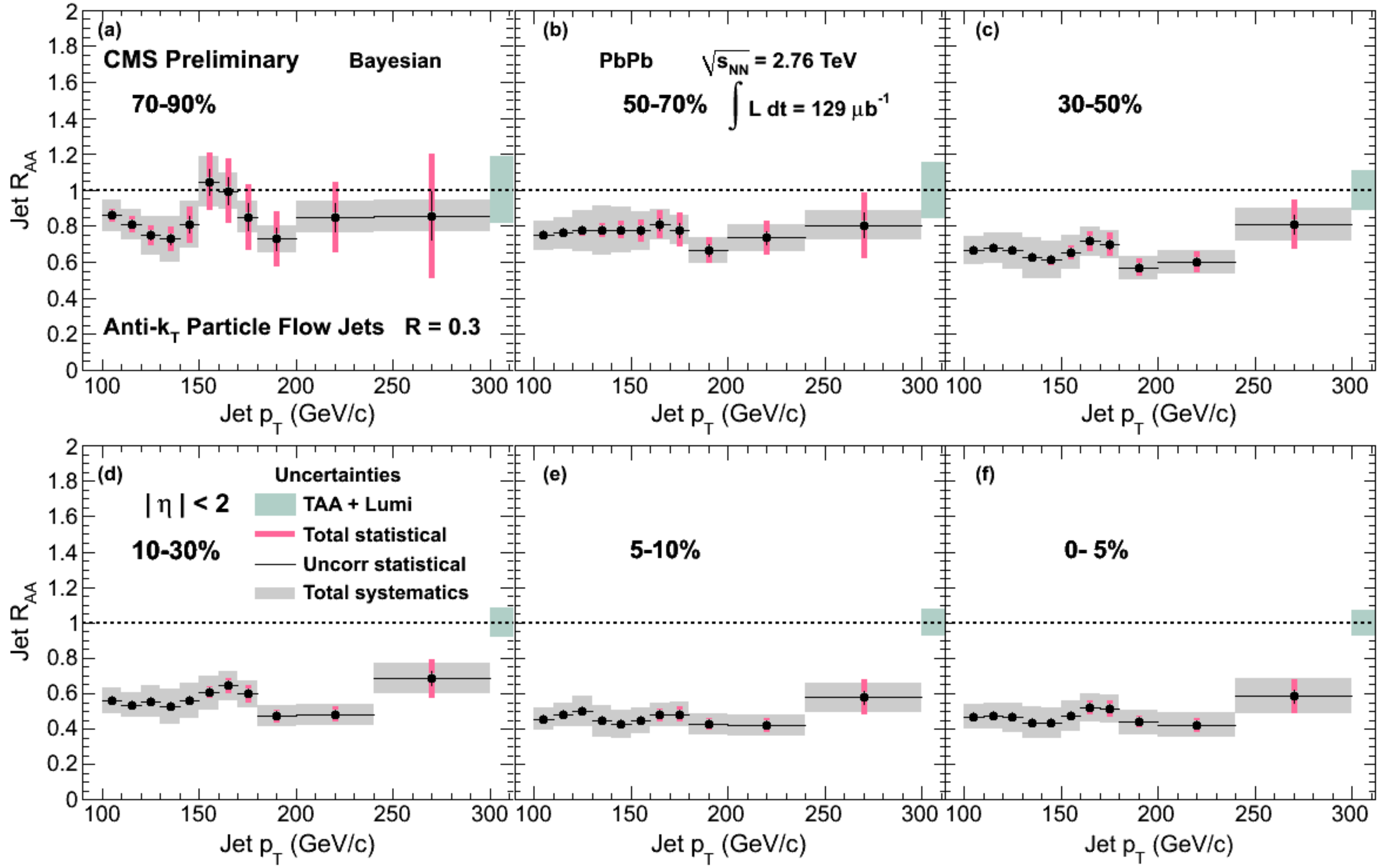


- **A factor of ~2 suppression in 0-10% most central collisions**
- **Suppression independent of jet p_T**

Jet suppression in Pb+Pb

CMS-HIN-12-004

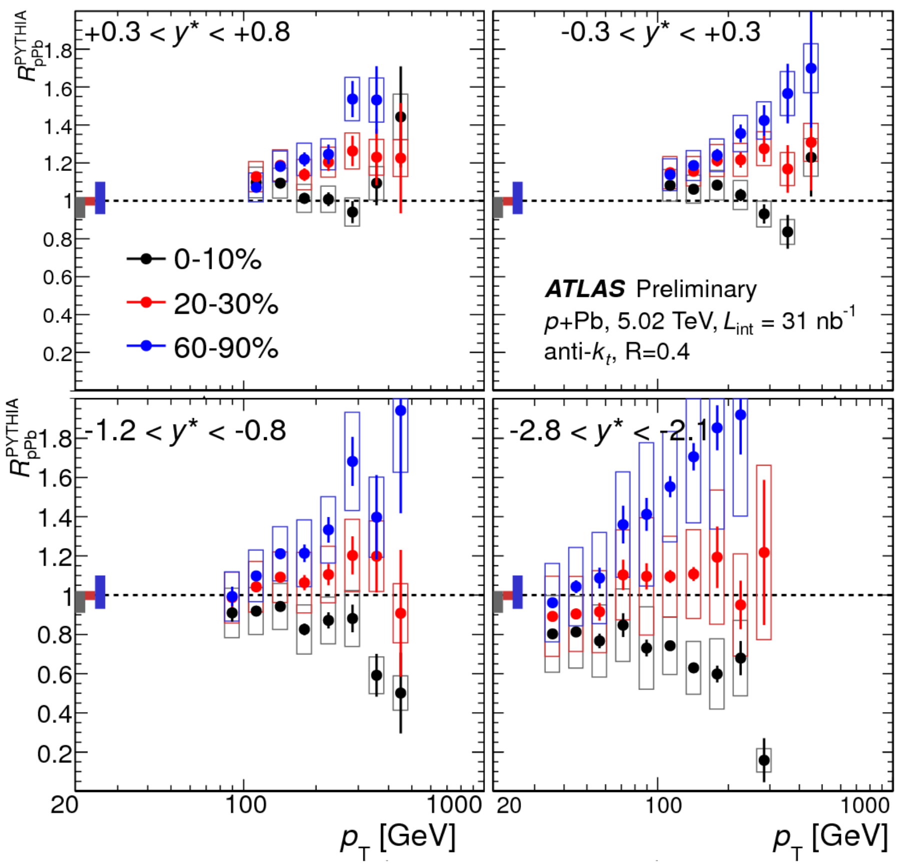
$$R_{AA} = \frac{N_{jet}^{AA} / N_{coll}}{N_{jet}^{pp}}$$



Jets modification in p+Pb

ATLAS-CONF-2013-105

$$R_{pPb}^{PYTHIA} = \frac{N_{jet}^{pPb} / N_{coll}}{N_{jet}^{pp-PYTHIA}}$$



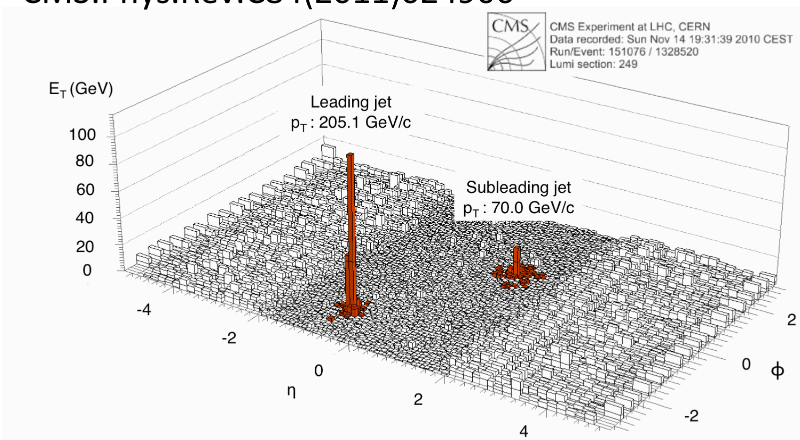
- Suppression (<1) in central
  - Initial state effect (CGC)?
- Enhancement (>1) in peripheral
  - Challenging for models
- No large modification in inclusive p+Pb

Three p+Pb centralities, each panel at fixed y*
Convention: y*<0 p-going side (large x_p, small x_{Pb})

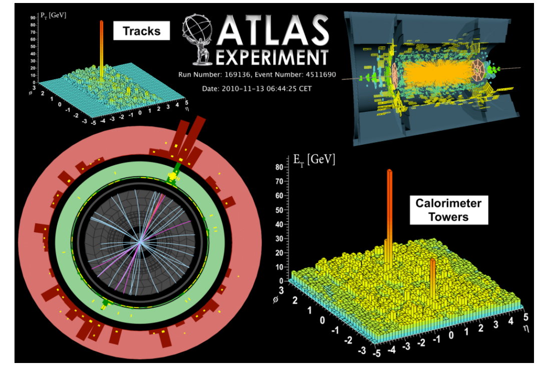
Di-jet energy imbalance in Pb+Pb

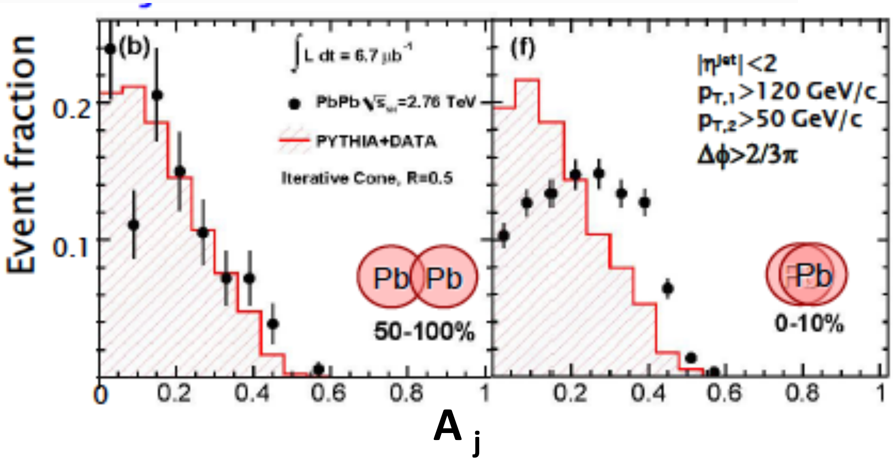
CMS:Phys.Rev.C84(2011)024906

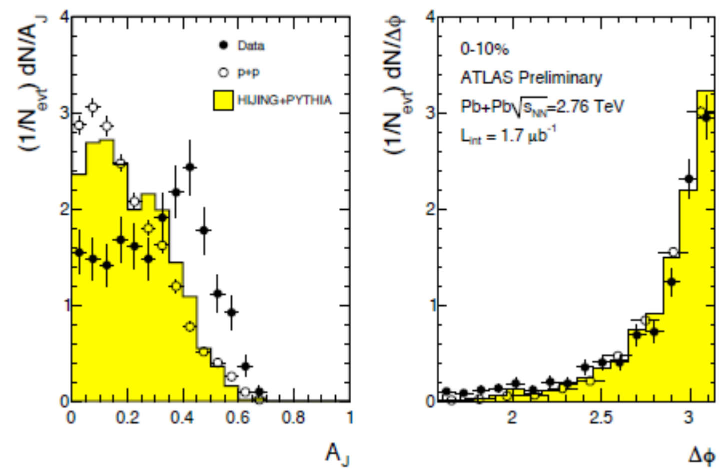
ATLAS:Phys.Rev. Lett. 105(2010)252303



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



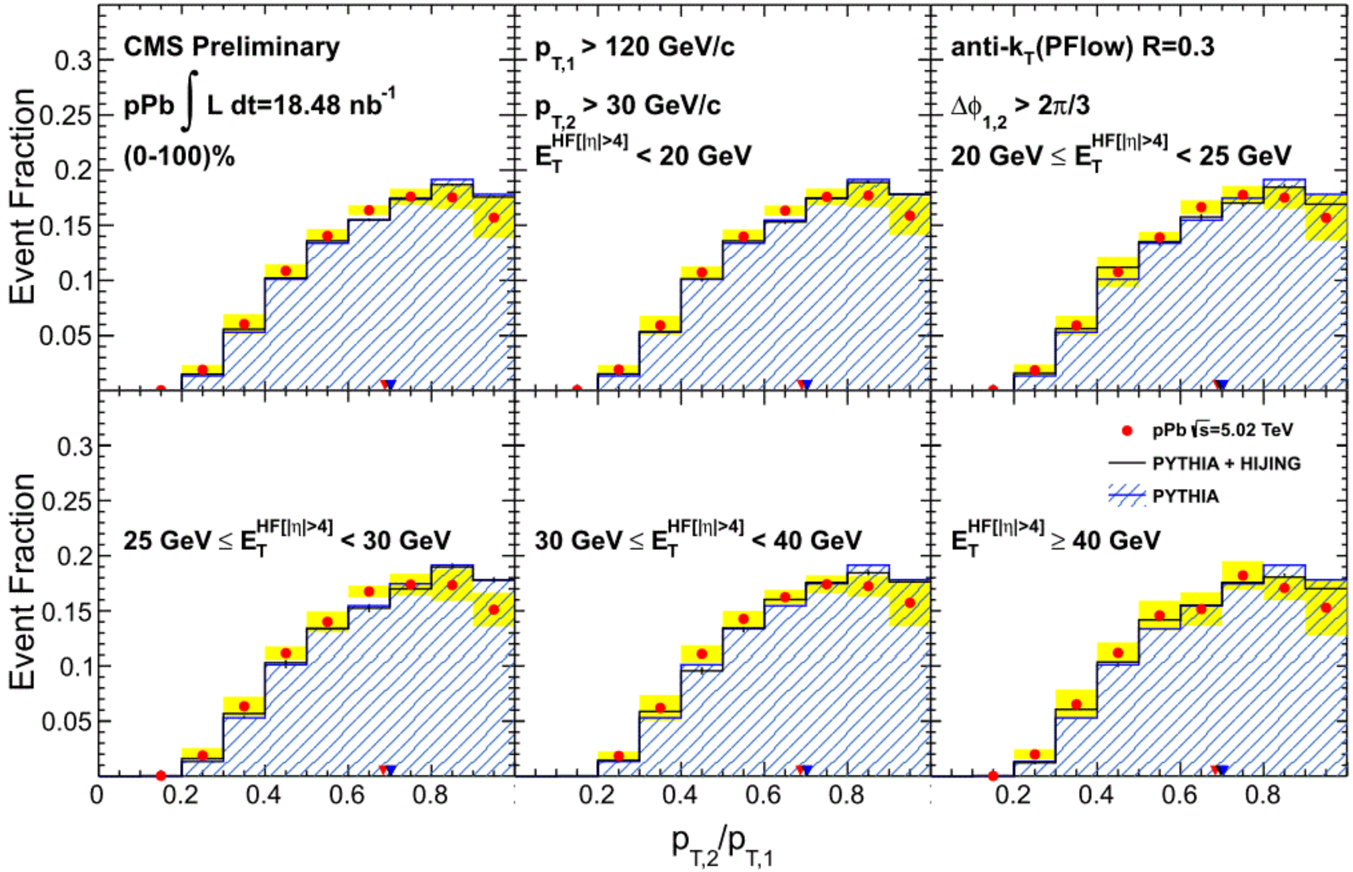




– **Asymmetry increases in more central collisions**
– **In peripheral collisions consistency with p+p/unquenched models**
–**Δϕ distribution remains peaked at Δϕ = π for all centralities**

Di-jets in p+Pb

CMS:arXiv:1401.4433 [nucl-ex]



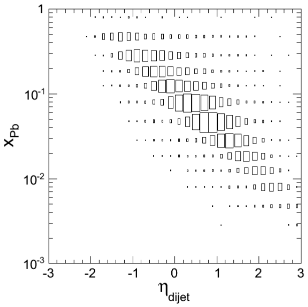
blue hatched histograms: simulated pp reference

- **No momentum imbalance (final state effect) is observed**
- **Can we access the initial state?**

Di-jets in p+Pb

CMS:arXiv:1401.4433 [nucl-ex]

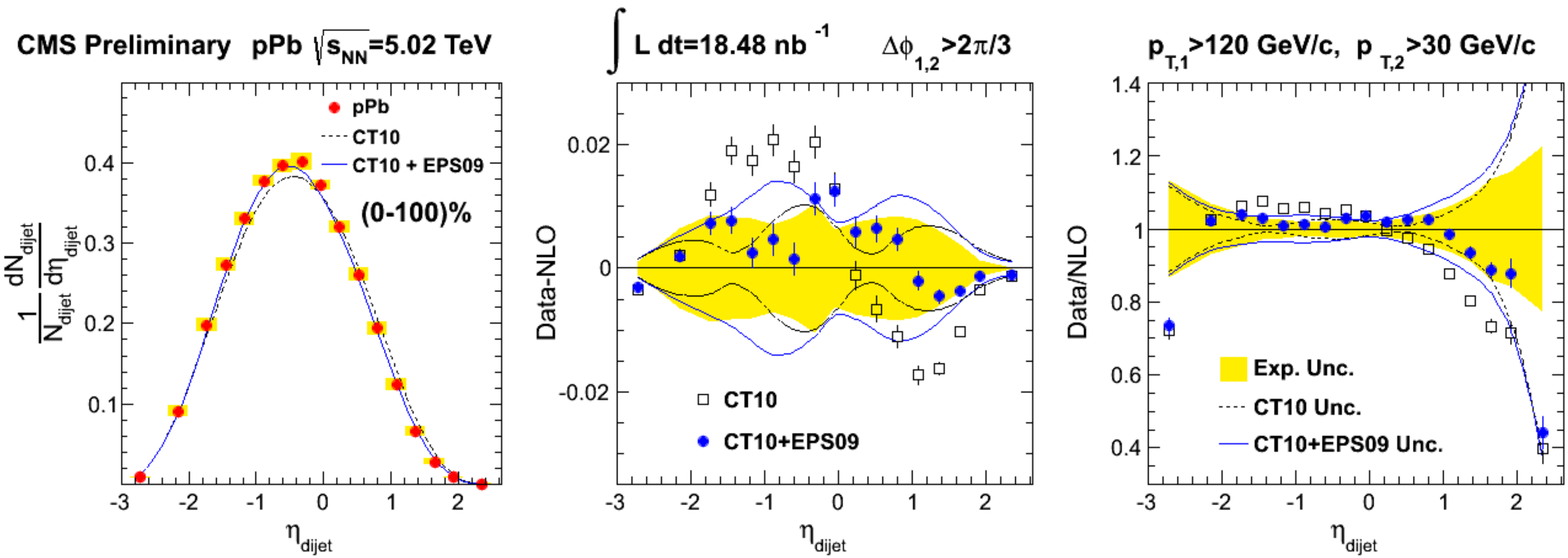
$$\eta_{\mathbf{dijet}} = \frac{\eta_1 + \eta_2}{2}$$



EMC

Antishadowing

Shadowing



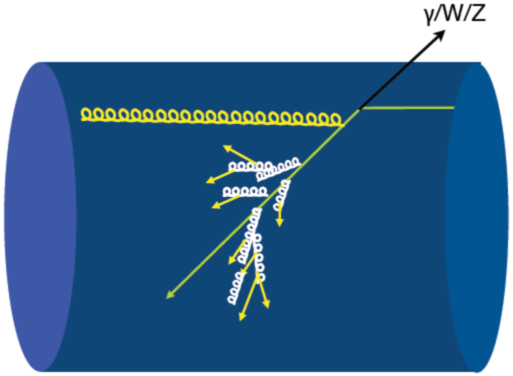
Constraints on nPDF: CT10 (pp PDF) ruled out

Better agreement with CT10+EPS09

H.L.Lai etal PRD82(2010)07424
K.J.Eskola,H.Paukkhunen,C.Salgado JHEP 04(2009)65

γ + jet correlations

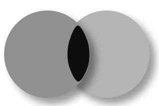
Modification of the jet energy relative to the probe not affected by the medium

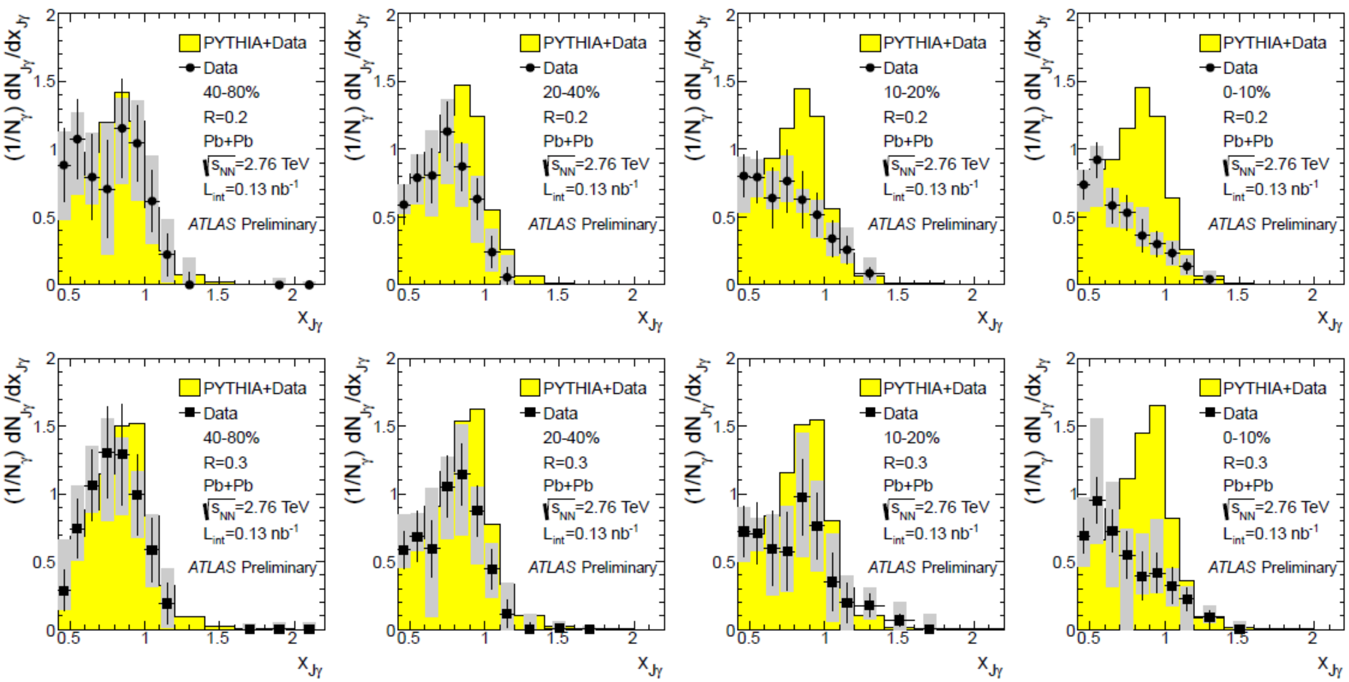


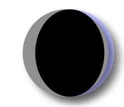
γ + jet correlations

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

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







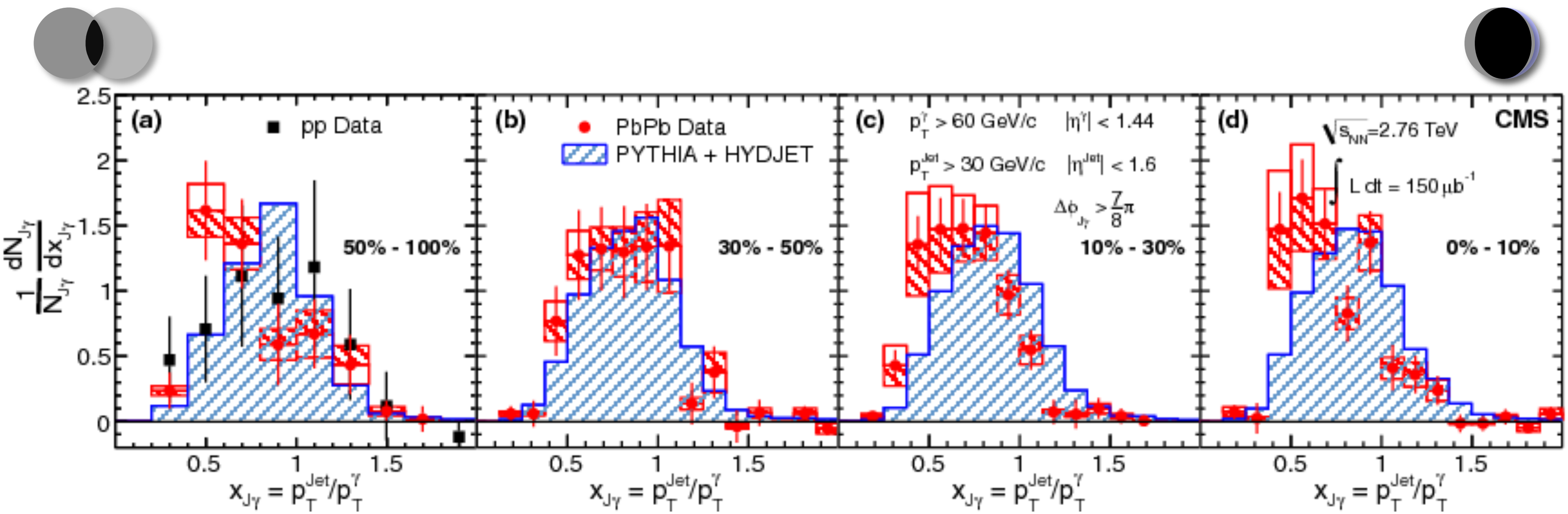
- Shape and integral compatible with PYTHIA for peripheral collisions
- With increasing centrality shift towards smaller $x_{J\gamma}$ and reduction of the integral

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

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

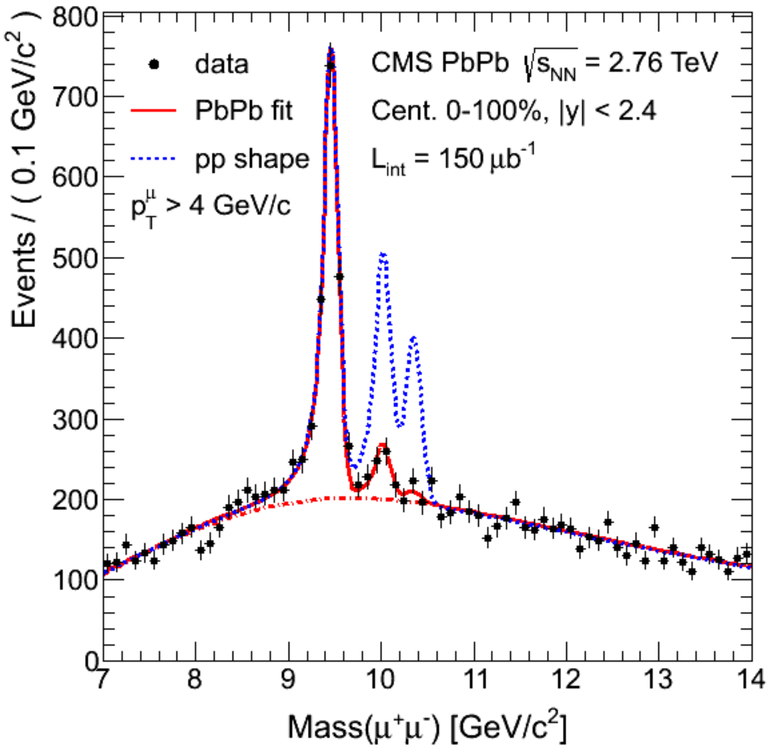
- **Can help to quantify medium properties - temperature**

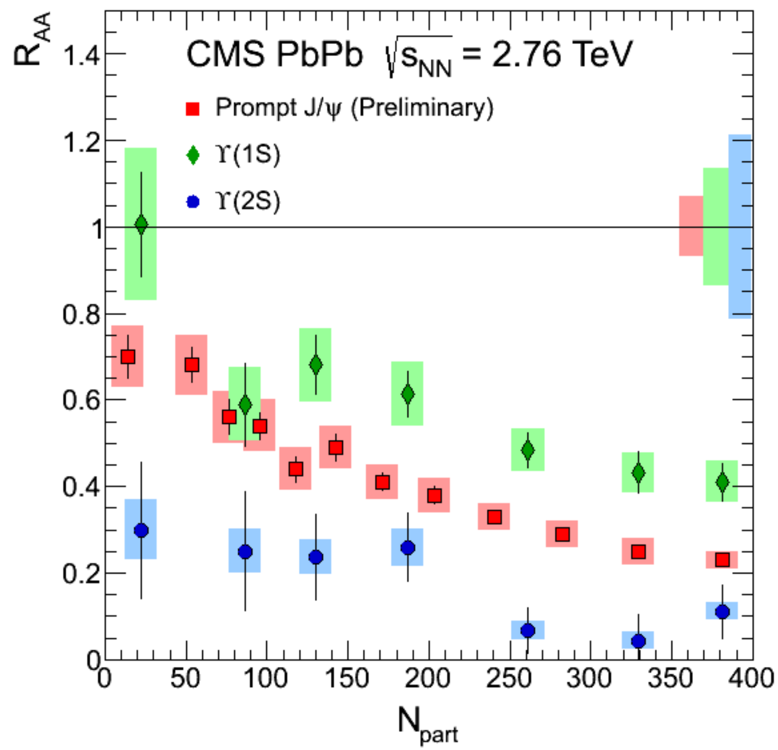
Quarkonia suppression in HI collisions expected when compared to p+p reference scaled by number of binary nucleon-nucleon collisions:

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

Sequential quarkonia suppression in Pb+Pb

CMS: Phys. Rev. Lett. 107(2011)052302, Phys. Rev. Lett. 109 (2012) 222301, JHEP 05(2012)063





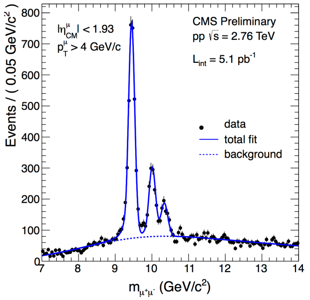
Suppression: Y(3S) > Y(2S) >J/ψ> Y(1S)

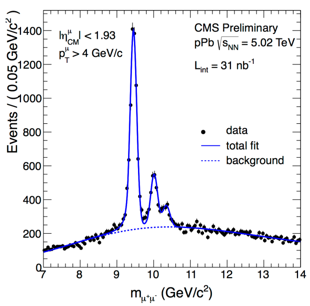
ΔE[GeV]: 0.20 < 0.54 < 0.64 < 1.10

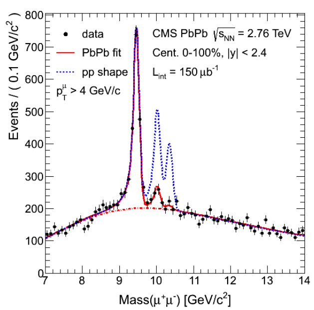
Suppression ordered by binding energy

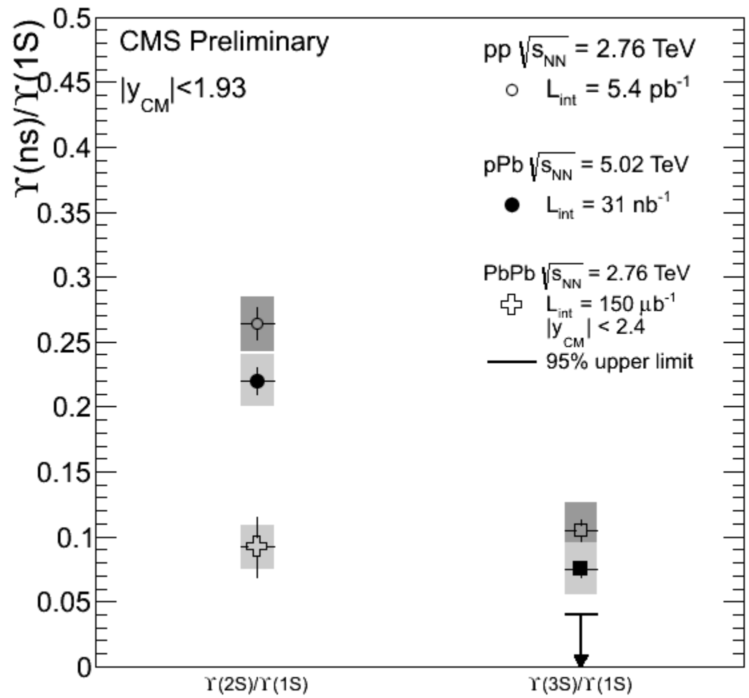
Upsilon suppression in p+p, p+Pb and Pb+Pb

CMS: arXiv:1312.6300 [nucl-ex]





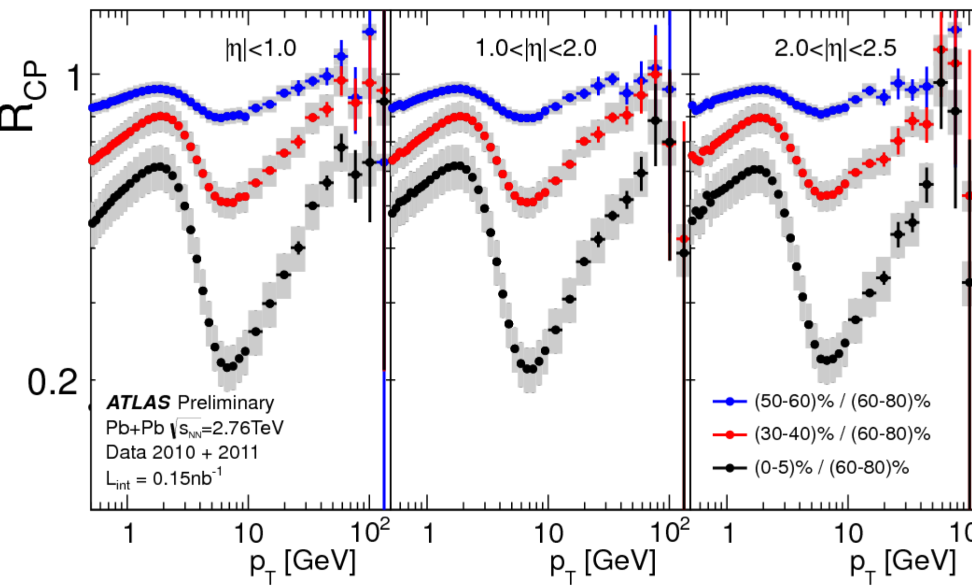




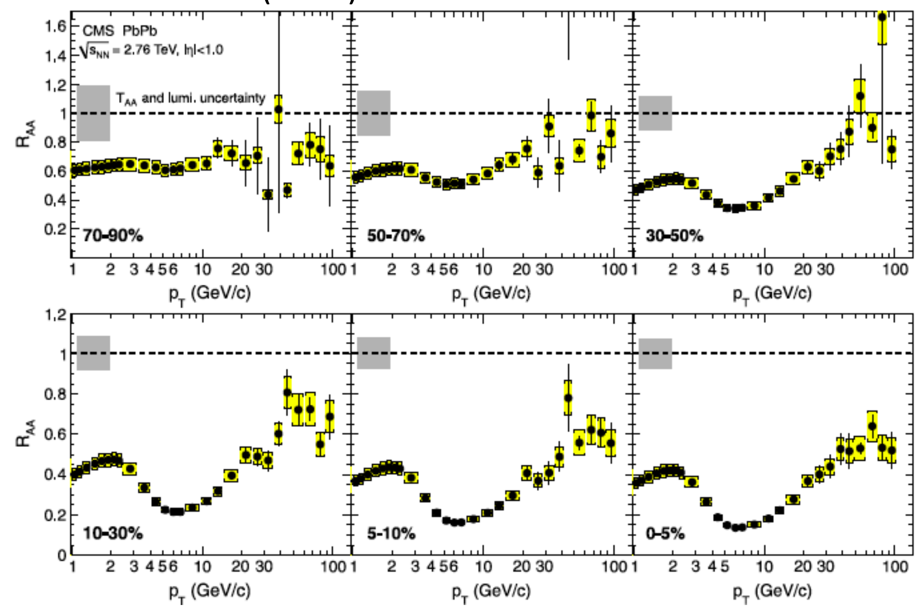
- **Y(2S,3S) suppressed in p+Pb as compared to p+p**
  - **Absorption in a cold nuclear matter?**
- **Y(2S,3S) more suppressed in Pb+Pb than in p+Pb**
  - **Additional final state effects**

Charged hadron suppression in Pb+Pb

ATLAS-CONF-2012-120



CMS: EPJC 72 (2012) 1945

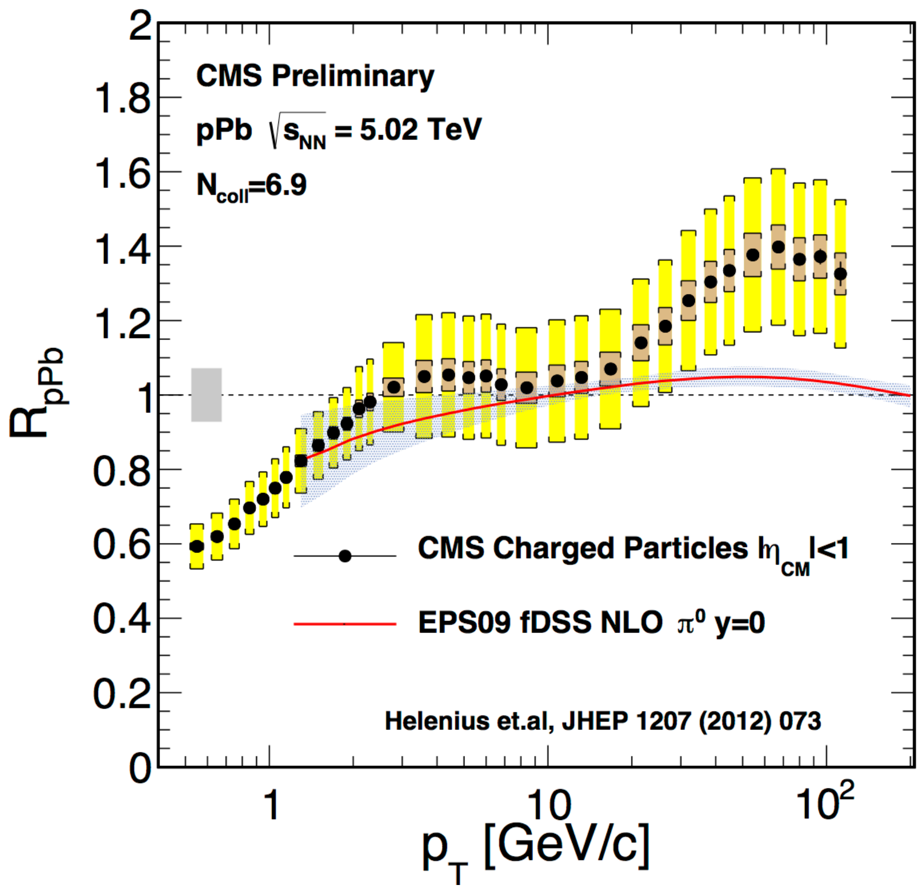


For central collisions:

- **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**
- **Suppression at high p_T at the same level as jet suppression**

Inclusive charged hadron R_{pPb}

CMS-HIN-12-017



R_{pPb} =1 no suppression from 2 – 30 GeV

R_{pPb} > 1 above 30 GeV

- **Anti-shadowing?, but stronger than predicted by models**

Summary I

Comparative studies of Pb+Pb, p+Pb and p+p collisions:

- **Consistent picture of dense and hot matter produced in Pb+Pb**
  - behaves collectively (ridges, v_n)
  - does not quench control probes (γ,Z,W)
  - strongly quenches jets, charged hadrons
  - suppresses quarkonia, including excited Y states
- **Highlights from p+Pb**
  - hints of possible collective behaviour (ridges, v_2, v_3)
  - no jet quenching (R_{pPb}?, dijets)
  - excited Y states are suppressed as compared to p+p
  - the initial state nPDFs are modified (ch.hadrons R_{pPb}?, η_{dijet})
  - what is the best centrality variable for p+Pb?

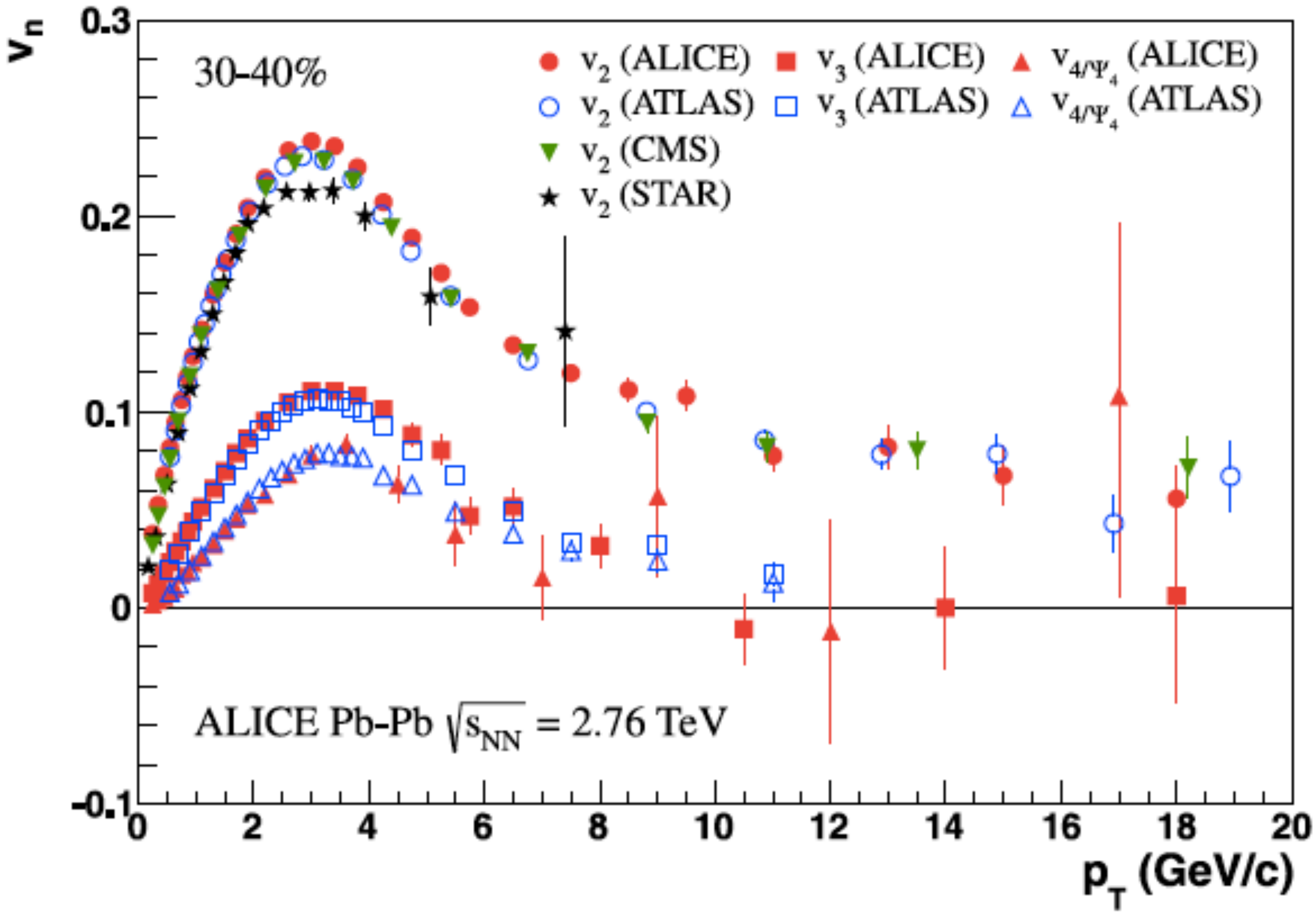
    → Need to develop more realistic model which accounts for impact parameter dependence of N-N physics (diffraction, soft, hard, MPI, x-dependence)

Summary II

- Wealth of experimental results has been obtained by the LHC experiments: ALICE, ATLAS, CMS (LHCb)
- 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

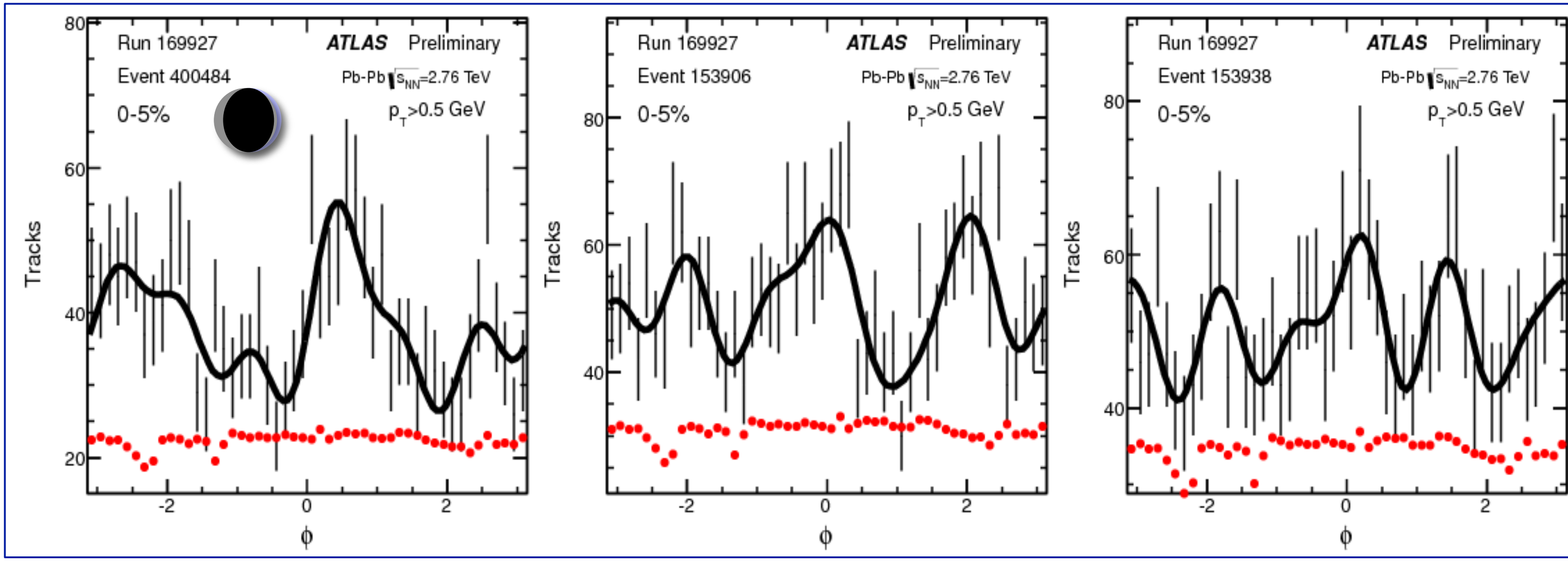
Measurements of flow harmonics



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

Event-by-event v_n

- The Fourier series can be computed for each event:

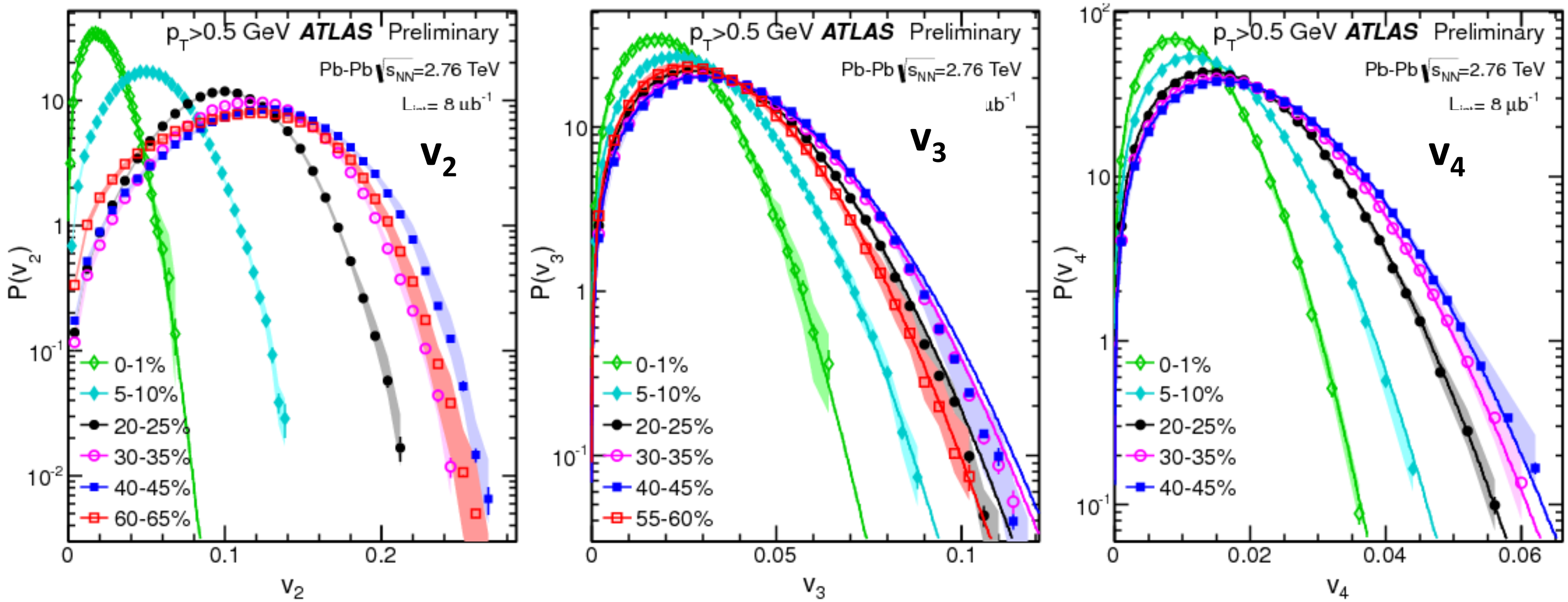


Event-plane correlations as well as v_n distributions contain more information than just $\langle v_n \rangle$

E-by-E v_n distributions

Fully corrected for detector effects and unfolded
for varying track statistics

ATLAS: JHEP 11(2013)183



- **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.**

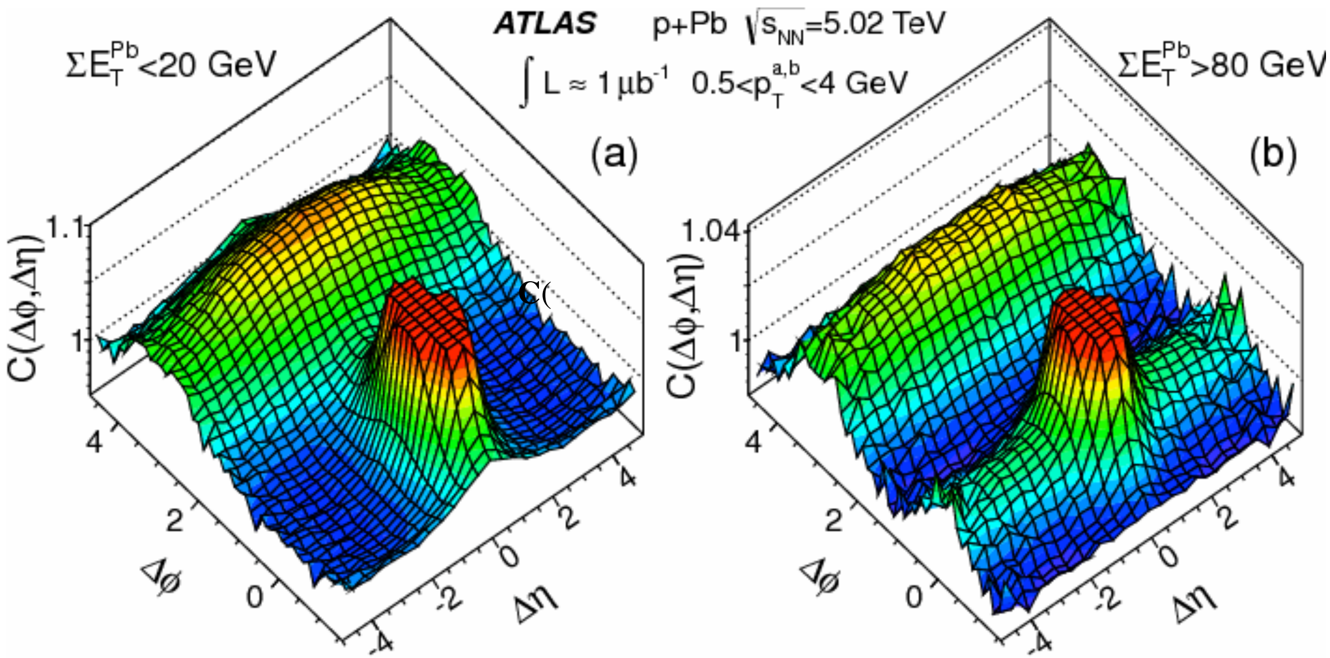
$$P(v_n) = \frac{v_n}{\delta_n^2} e^{-\frac{1}{2}\frac{v_n^2+(v_n^{RP})^2}{\delta_n^2}} I_0\left(\frac{v_n v_n^{RP}}{\delta_n^2}\right)$$

Two-particle correlations

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

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

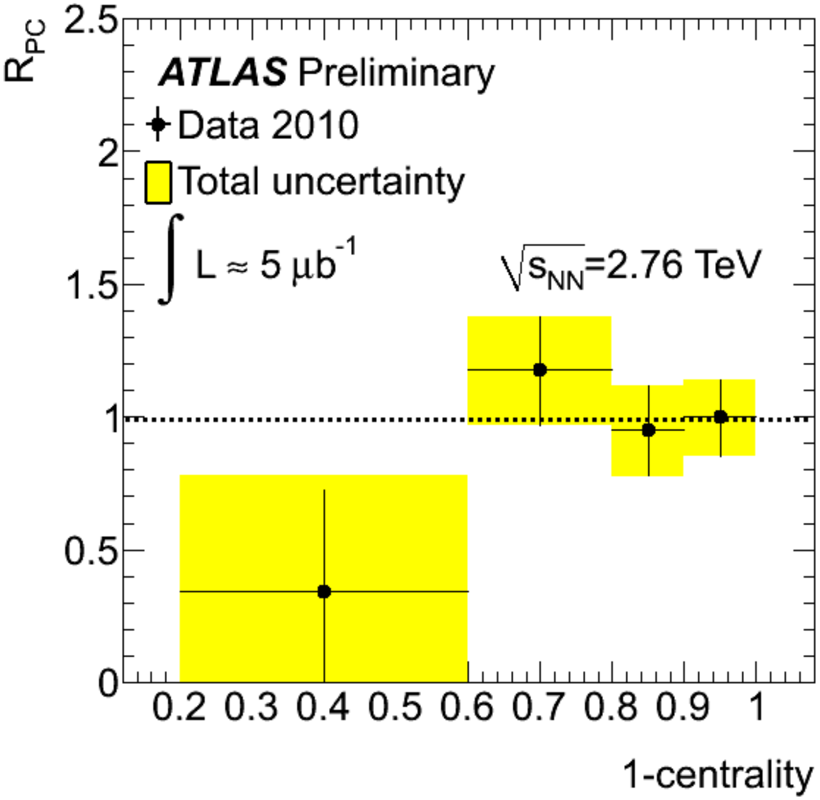
$\Delta\phi=\phi_a-\phi_b$, $\Delta\eta=\eta_a-\eta_b$
a-"trigger particle" b-"associated particle"



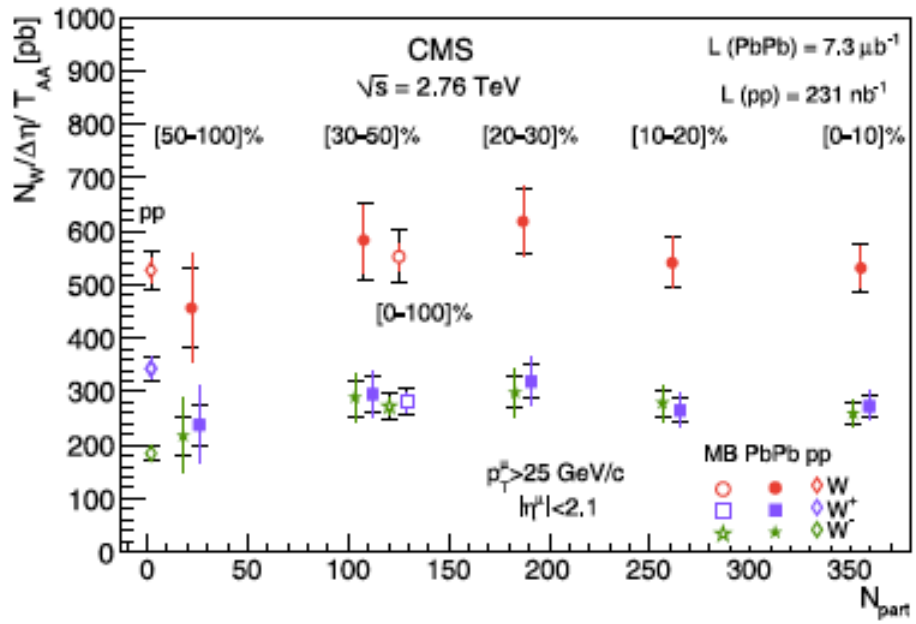
	Peripheral	Central
Near-side($\Delta\phi\approx 0$):	**jet peak**	**jet+ridge-like structure**
Away-side($\Delta\phi\approx\pi$):	**broad structure (RECOIL)**	**broader structure**

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

ATLAS-CONF-2011-078



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

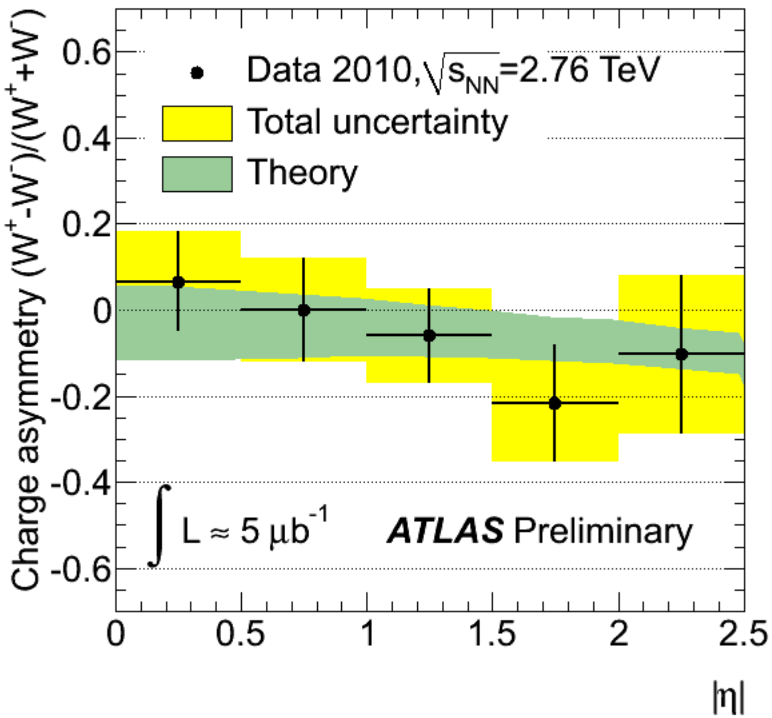


$W^{\pm}$ yields consistent with N_{coll} scaling

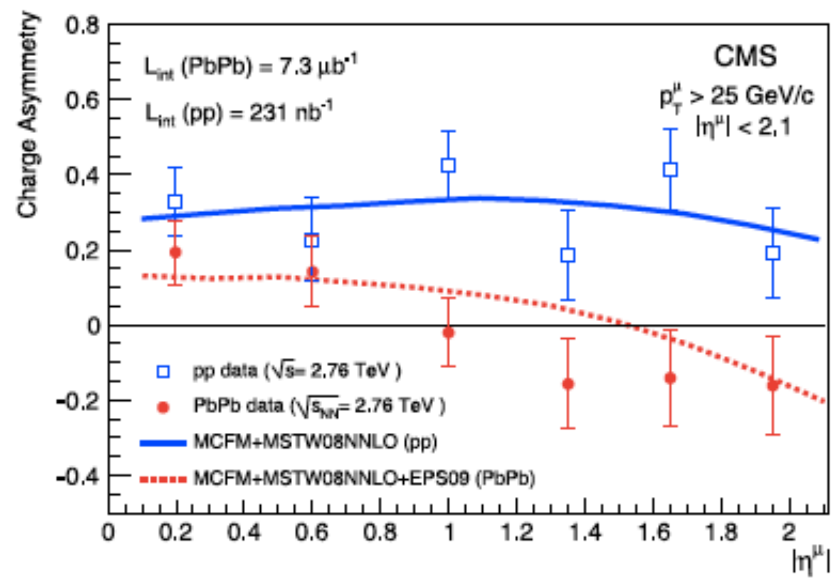
Charge asymmetry in W production

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

ATLAS-CONF-2011-078



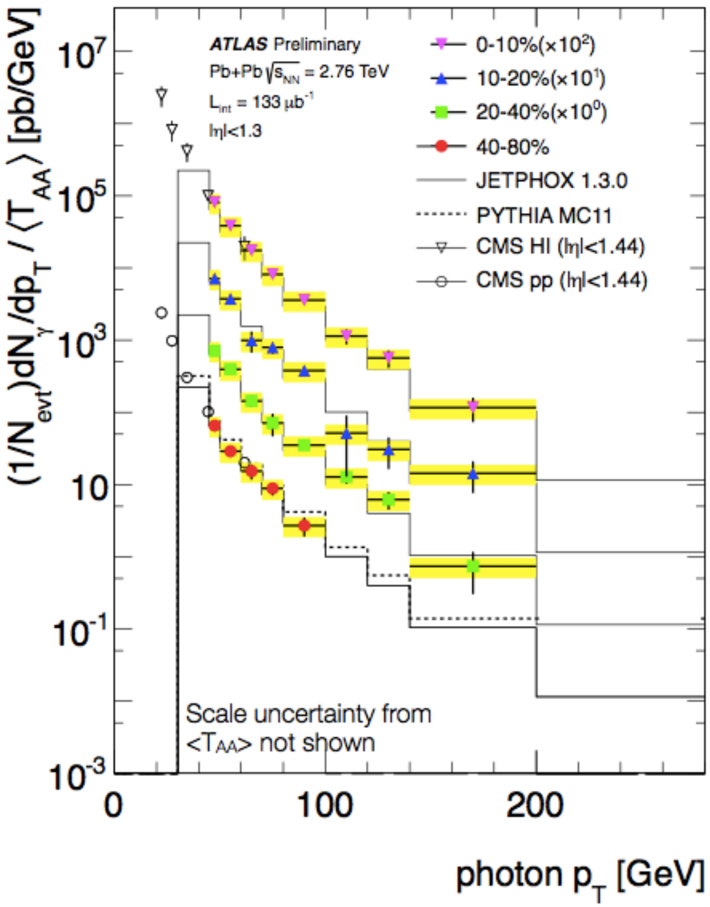
CMS, Phys. Lett. B7 15 (2012) 66



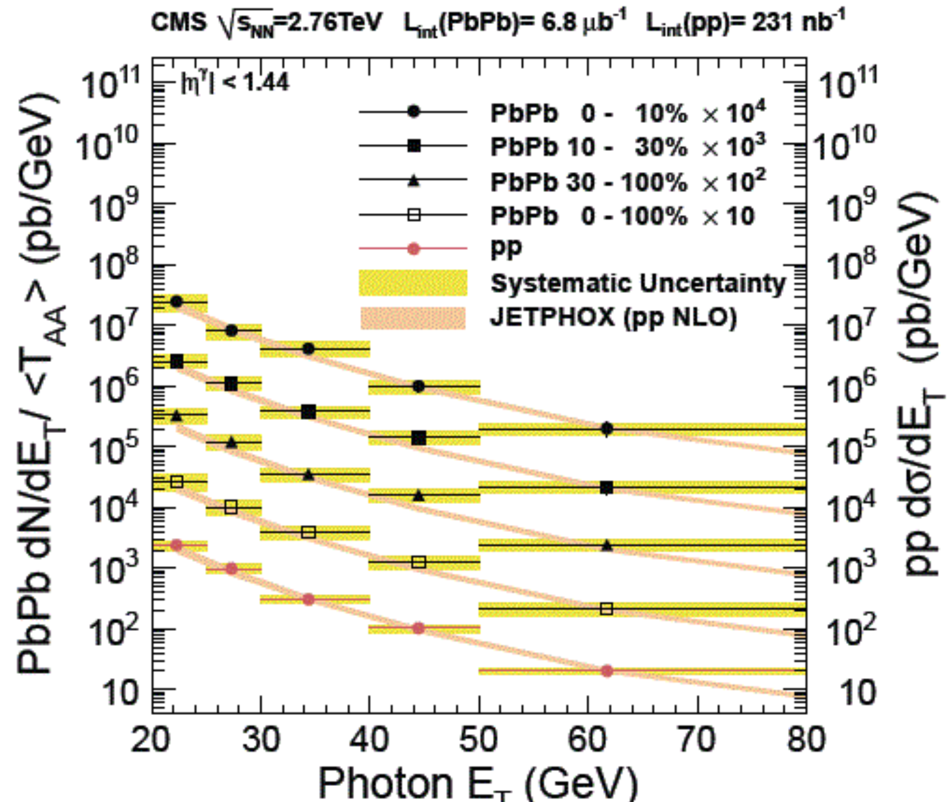
An excess of W^- over W^+ at large ημ
Consistent with the predictions which include small nuclear modification effects on the PDF

Prompt photon production

ATLAS-CONF-2012-051



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

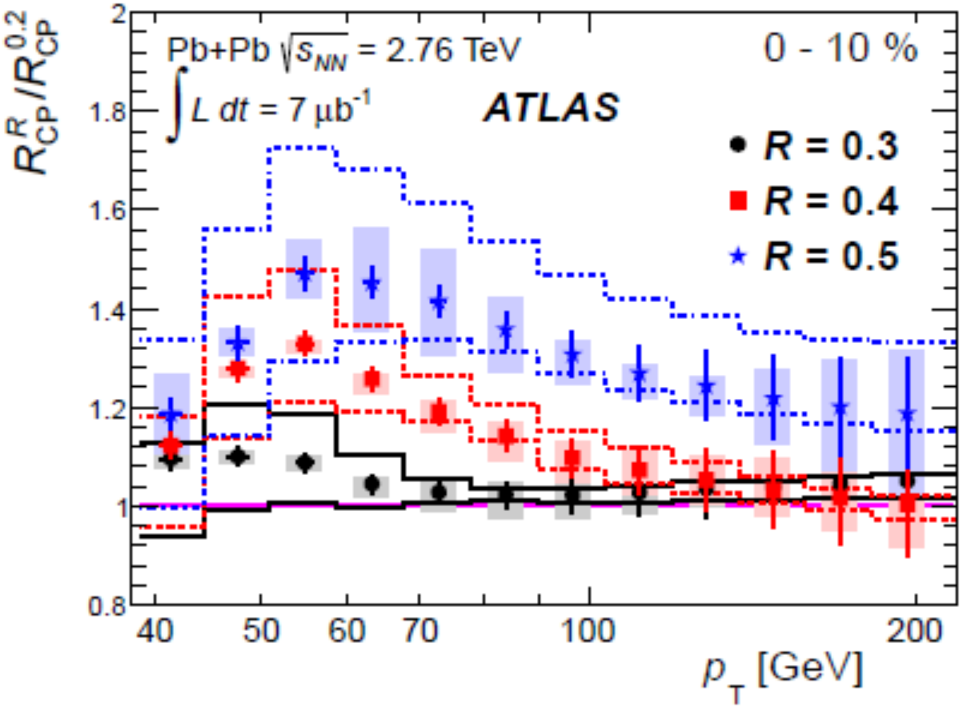


Yields scaled by T_{AA} and compared to JETPHOX predictions

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

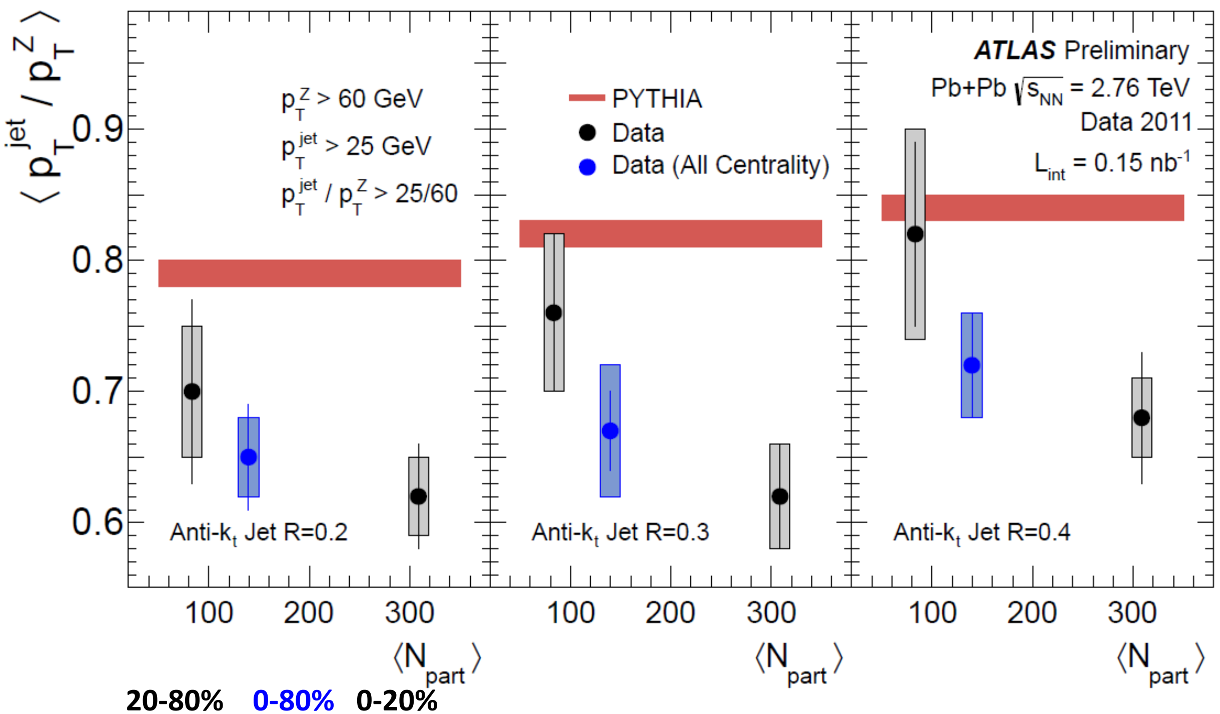
→A weaker suppression is observed for larger jet radius parameters

Qualitatively consistent with models of radiative energy loss

"out-of-cone" radiation

Z – jet correlations

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



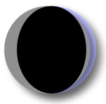
$\langle p_T^{jet} / p_T^Z \rangle$

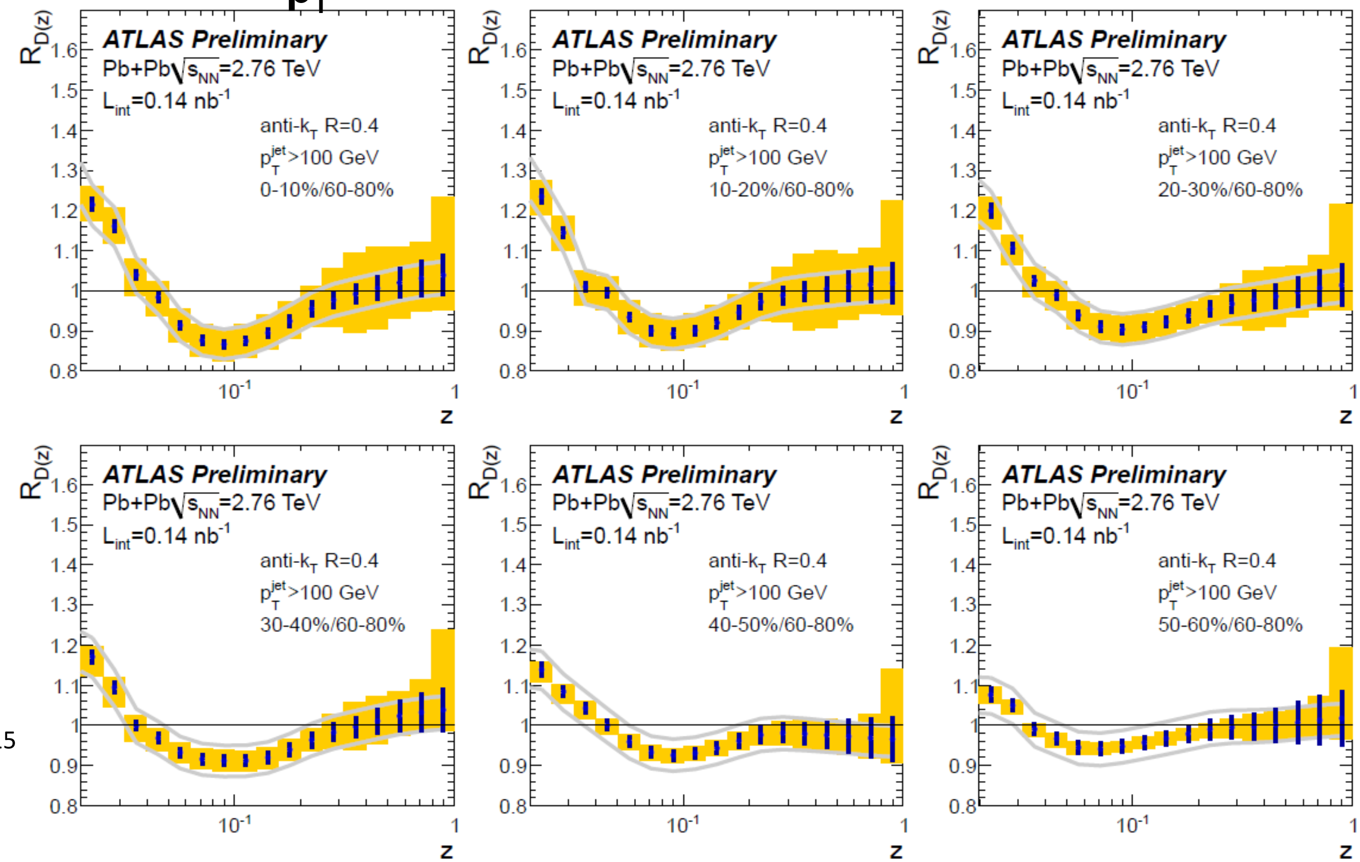
- Suppression of the $\langle p_T^{jet} / p_T^Z \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events)
- Stronger suppression for more central collisions

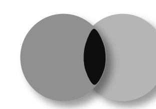
ATLAS-CONF-2012-119

Jet fragmentation

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





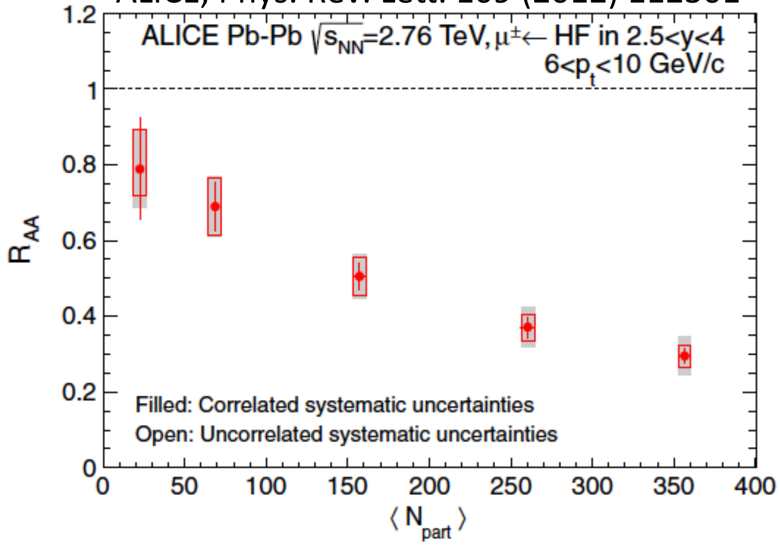


ATLAS-CONF-2012-115

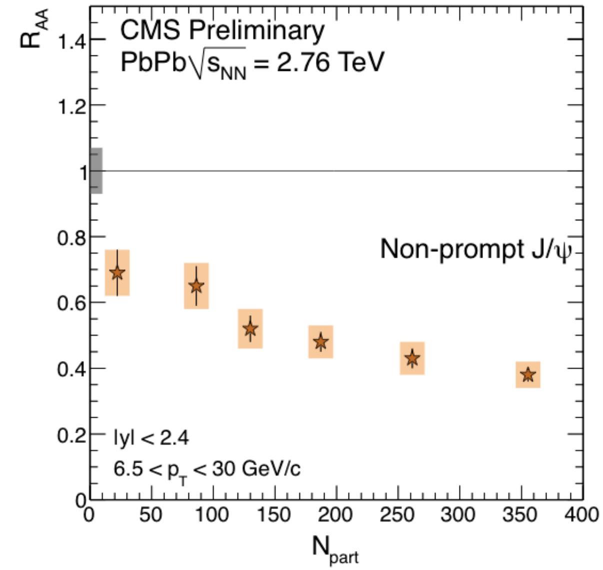
- Enhancement at low z, suppression at z≈0.1
- No modification at high z (predicted by some energy loss models)
- Similar results found for R=0.2 and 0.3 jets

Heavy quark (b,c) suppression

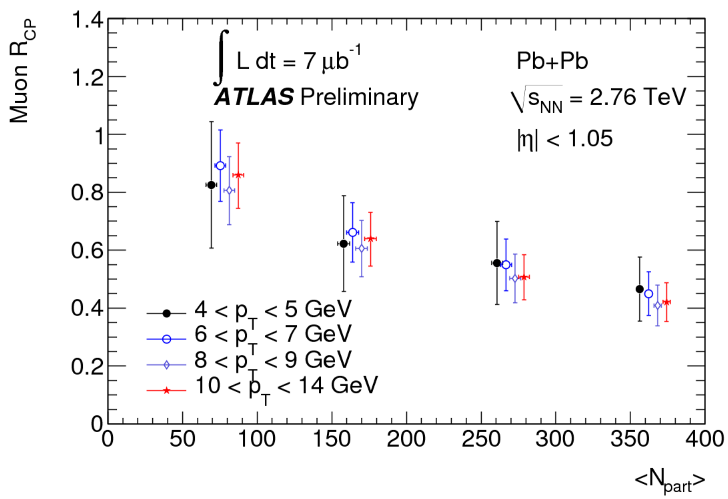
ALICE, Phys. Rev. Lett. 109 (2012) 112301



CMS PAS HIN-12-014

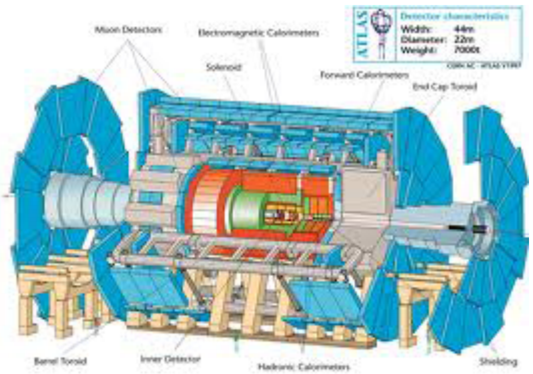


ATLAS-CONF-2012-01

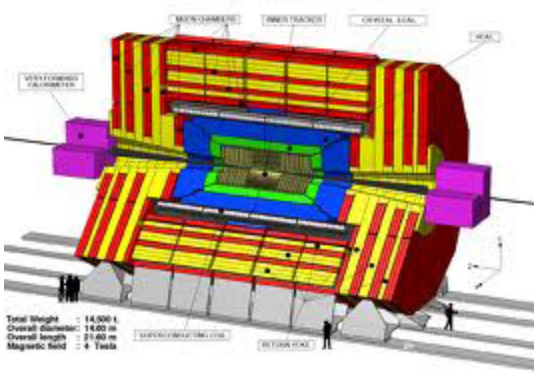


For central collisions at midrapidity:
R_{AA} suppressed by a factor ~2.5
Slightly stronger at forward rapidities

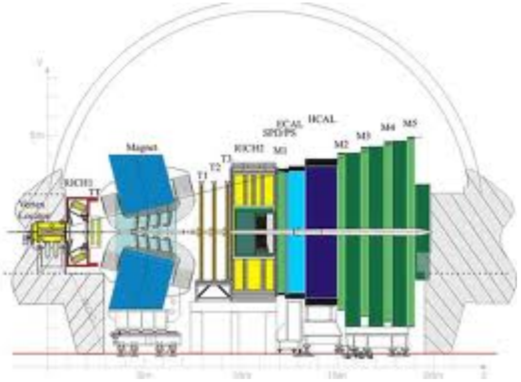
LHC experiments



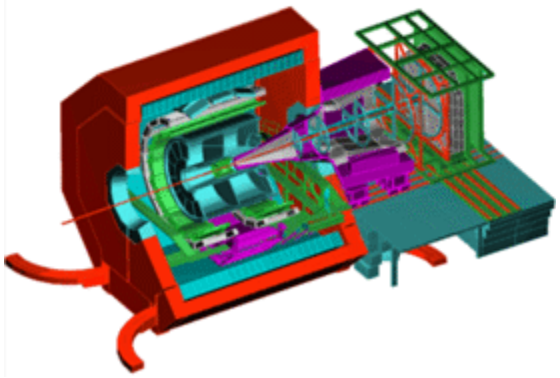
ATLAS (general purpose)



CMS (general purpose)

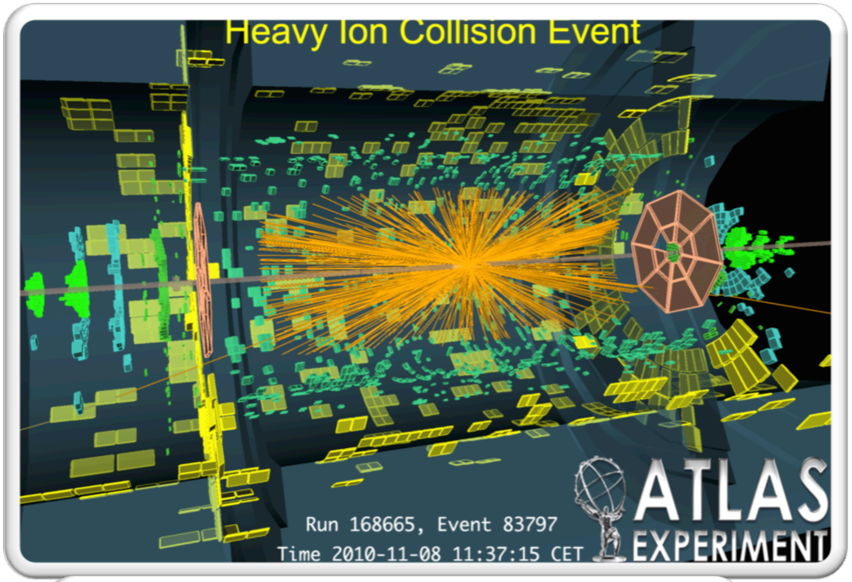


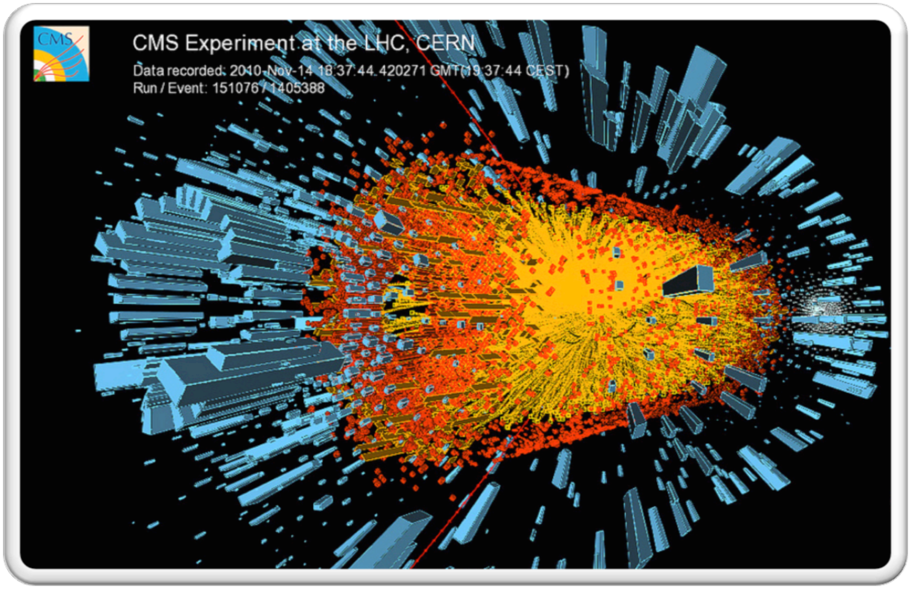
LHCb (heavy flavour physics)

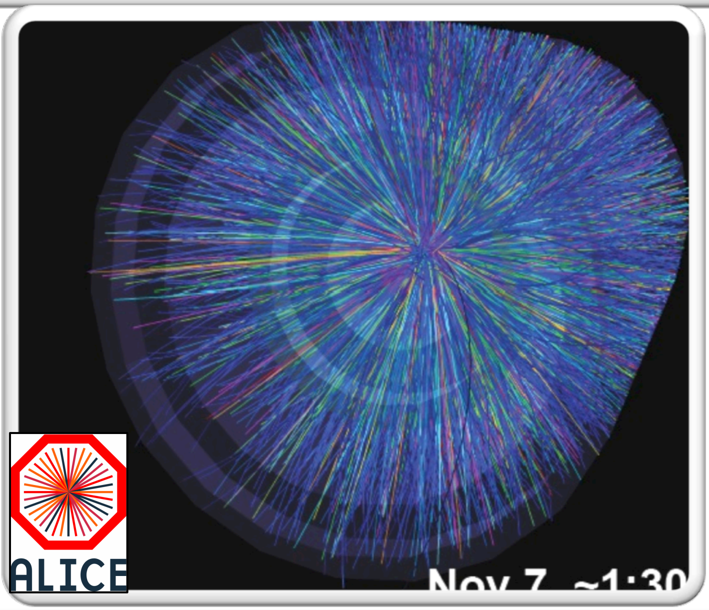


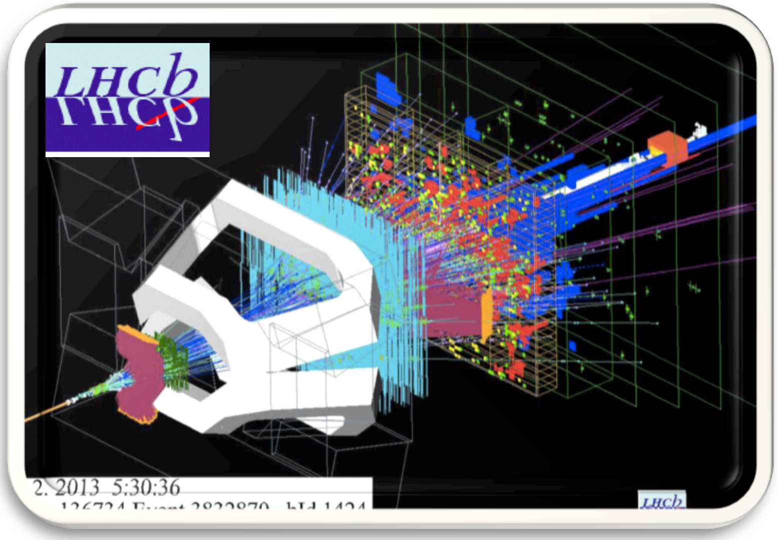
ALICE(heavy-ion physics)

Heavy-ion collision events

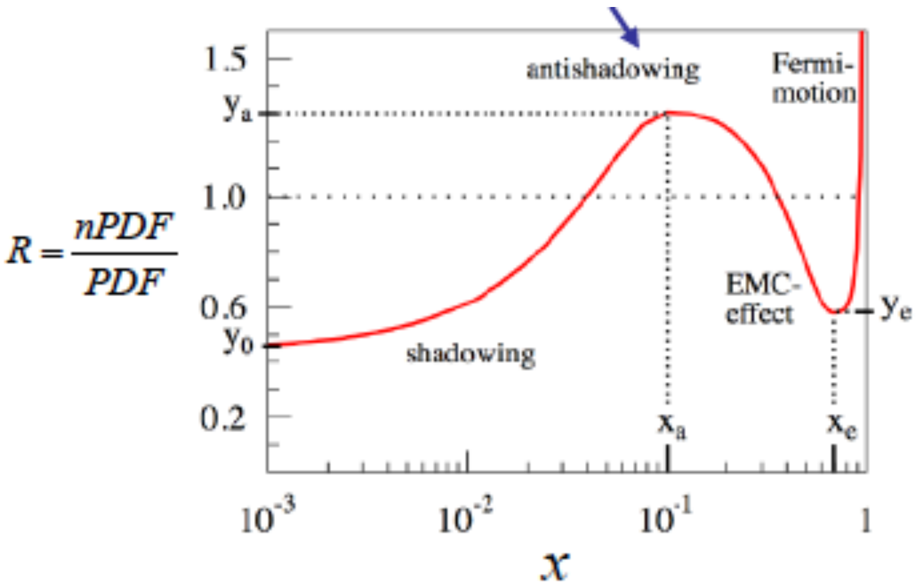






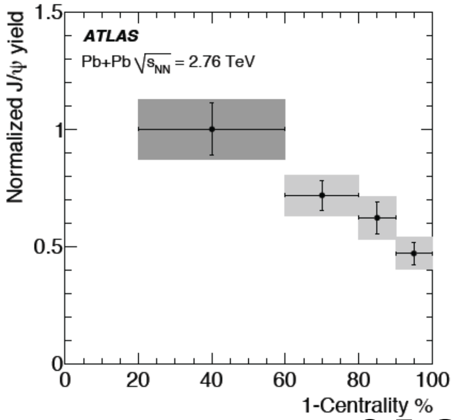


nPDF

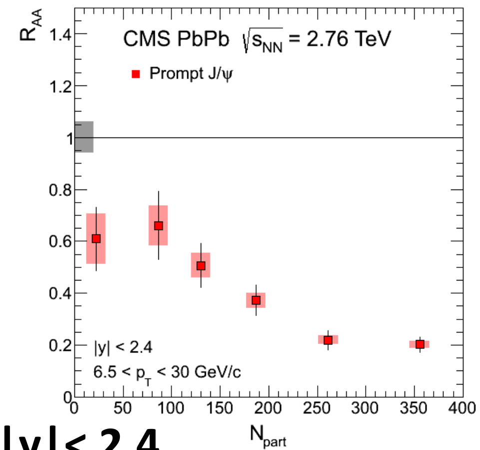

$R = \frac{nPDF}{PDF}$
1.5
y_a
1.0
0.6
y_0
0.2
antishadowing
Fermi-
motion
EMC-
effect
shadowing
y_e
x_a
x_e
10^{-3}
10^{-2}
10^{-1}
1
x

Charmonium suppression

ATLAS: Phys.Lett. B697 (2011) 294

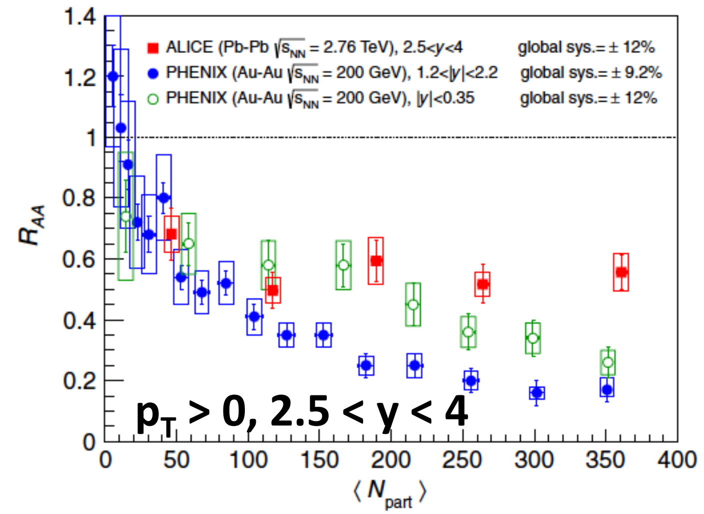


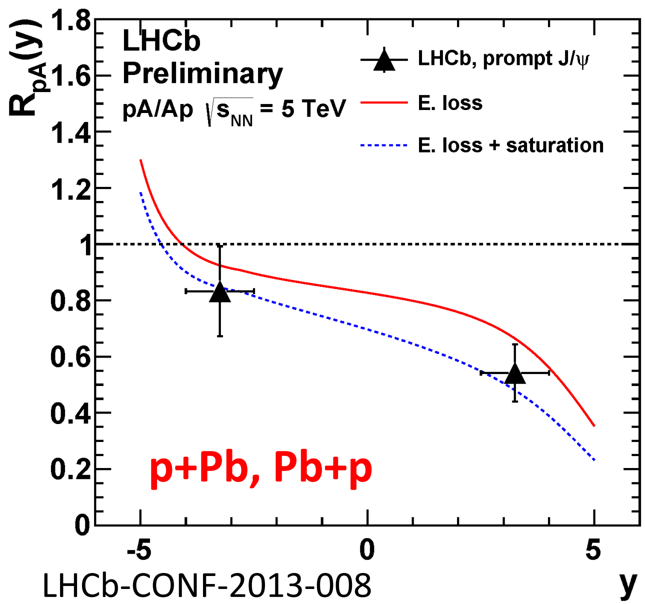
CMS: JHEP1205 (2012) 063



p_T > 6.5 GeV, |y|< 2.4

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





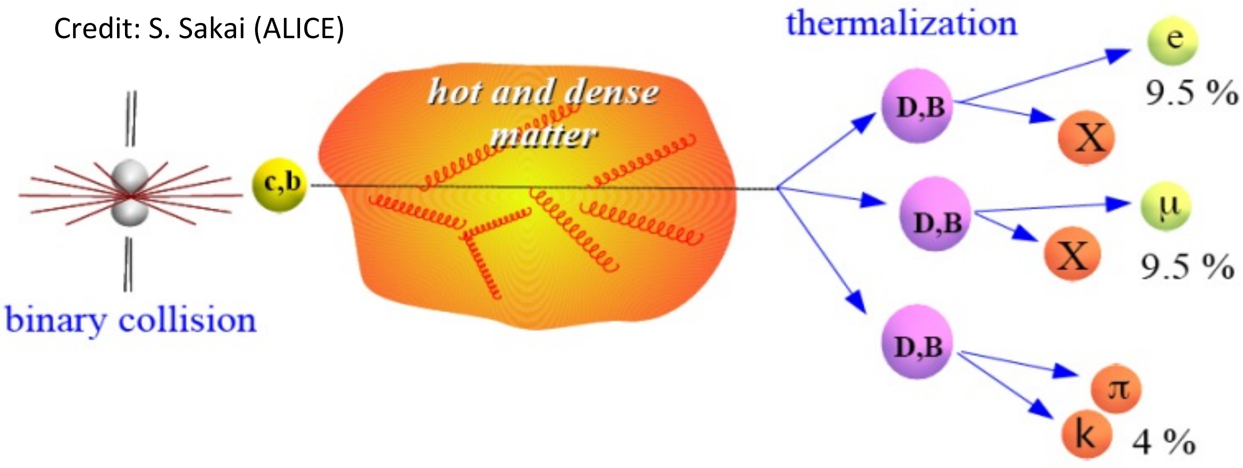
LHCb-CONF-2013-008

- 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)



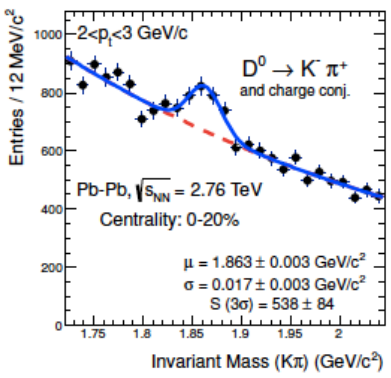
- **Heavy quarks are produced at the early stage of the collision**
- **Heavy quarks are expected to lose LESS energy than light quarks due to the reduced small-angle gluon radiation –"dead-cone effect"**

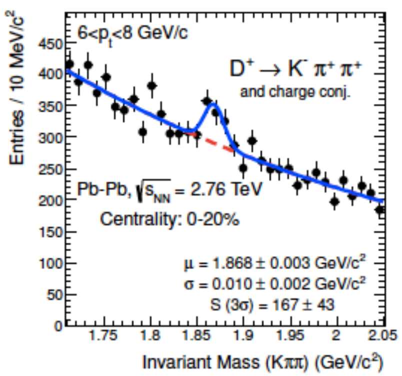
Yu.Dokshitzer, E.D. Kharzeev, Phys.Lett. B519 (2001) 199;
M. Djordjevic, M. Guylassy, Nucl. Phys. A733 (2004) 265

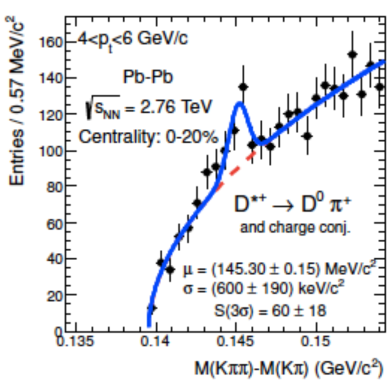
$$E_{loss}(\text{light}) > E_{loss}(D) > E_{loss}(B)$$

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

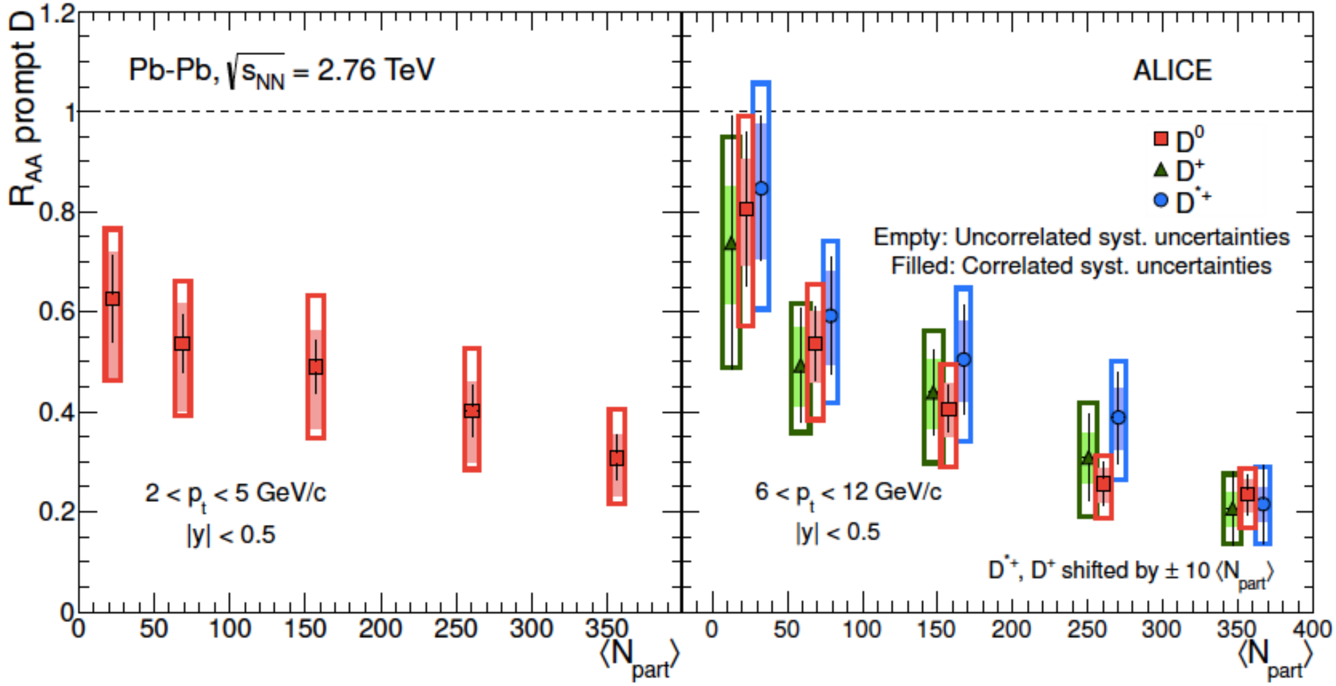
Suppression of D mesons







ALICE: JHEP 09 (2012) 112

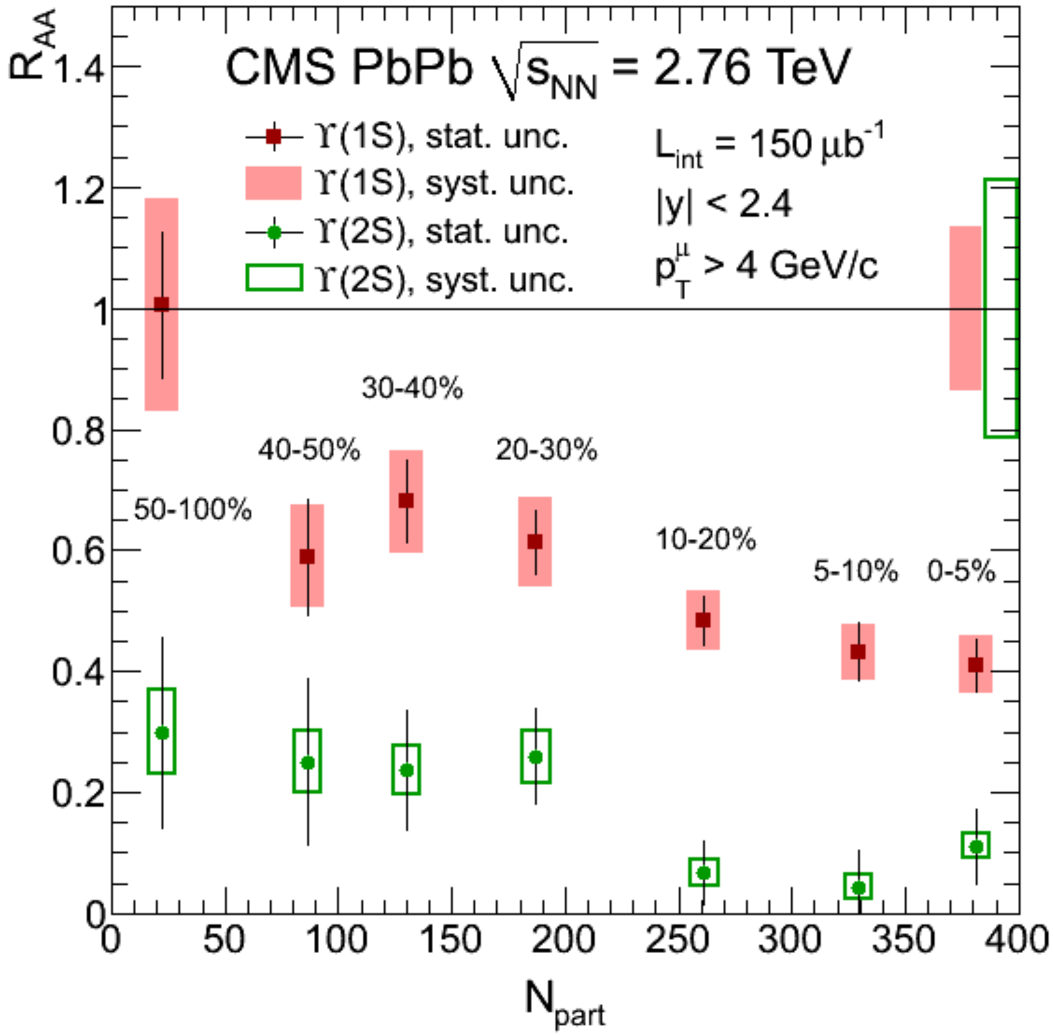


Suppression almost as large as for charged hadrons

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

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