Phenomena in Heavy-Ion Collisions

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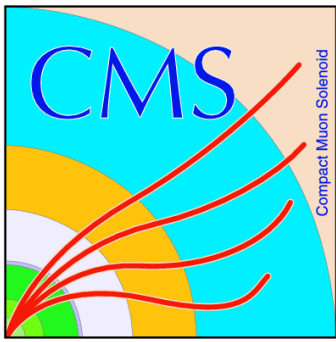
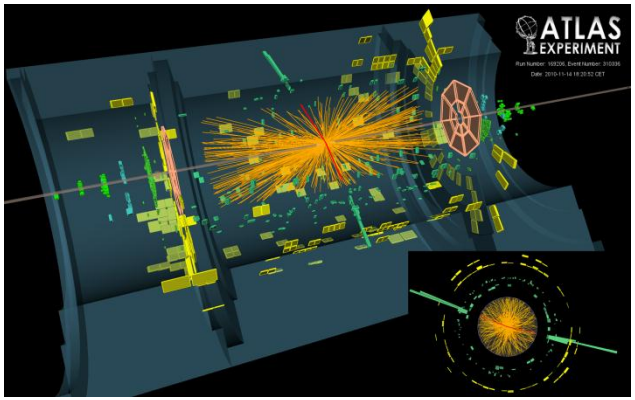
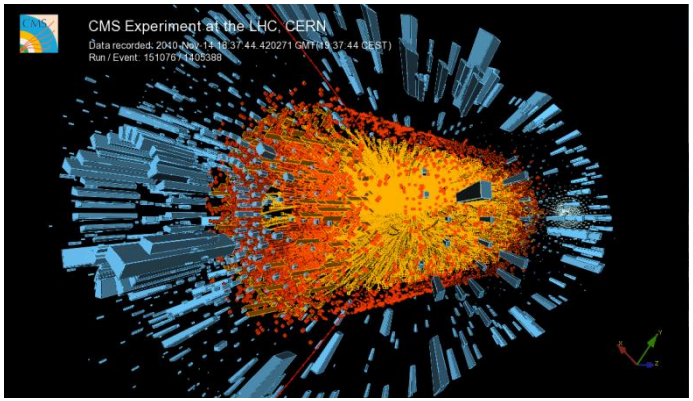


Outline

- LHC Run 1 for Heavy-Ions
- Centrality determination
- Experiments overview
- Soft Probes
  - Ridge effect
  - Elliptical and Triangular Flow
- Hard Probes
  - Medium sensitive probes
  - Electroweak probes
- Summary and Outlook





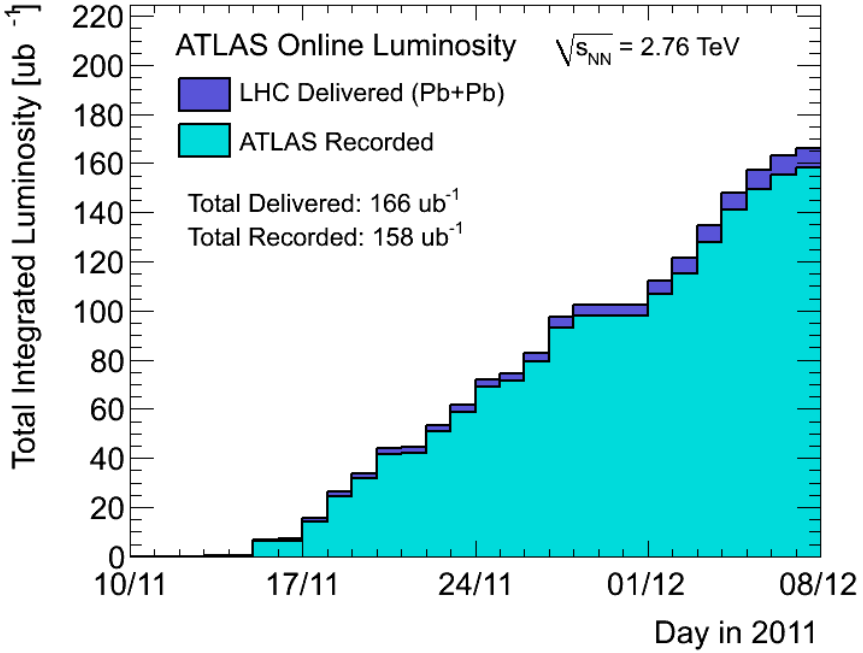
Public results:

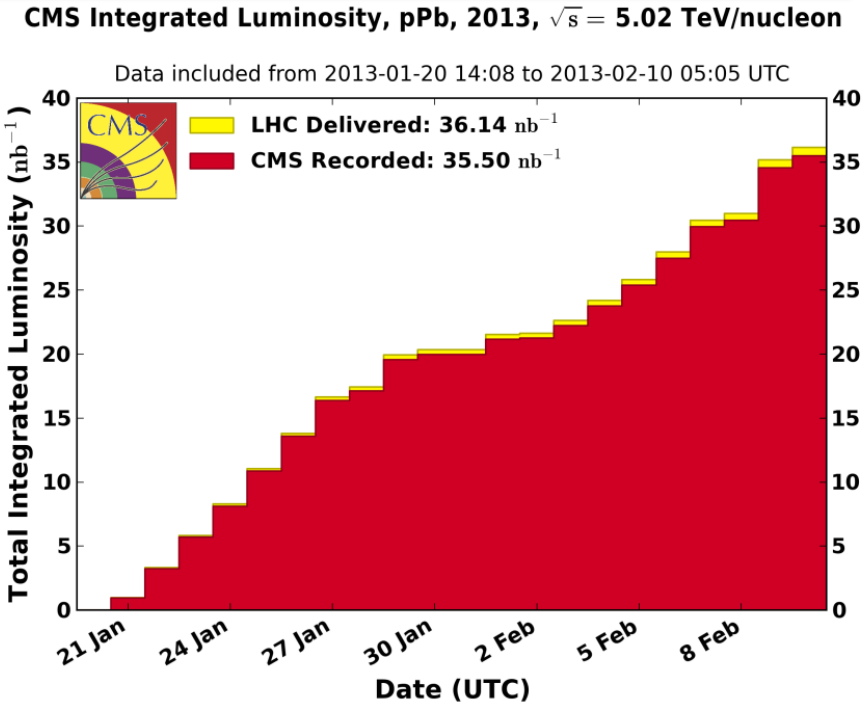
CMS : https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

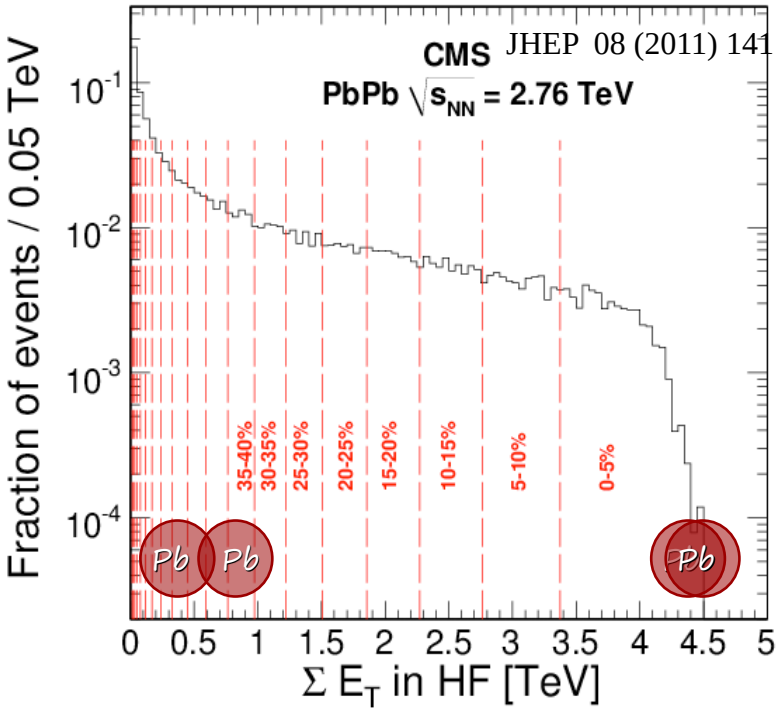
LHC Run 1 for heavy-ion physics

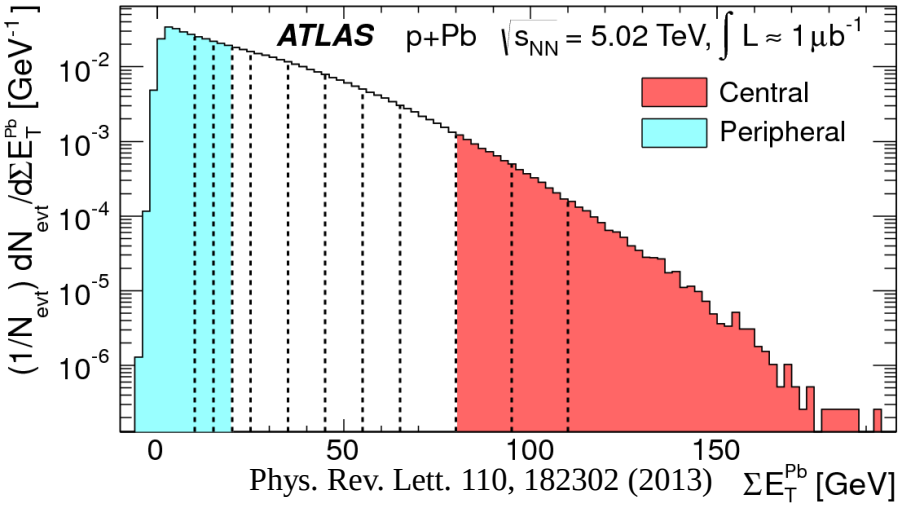
System	$\sqrt{S_{NN}}\ [TeV]$	When	L per experiment
Pb+Pb	2.76	2010+2011	0.17 nb^{-1}
p+Pb	5.02	2012+2013	36.14 nb^{-1}(CMS) 29 nb^{-1}(ATLAS)
p+p	2.76	2011	200 nb^{-1}
p+p	2.76	2013	5.6 pb^{-1}





Centrality in Pb+Pb and p+Pb

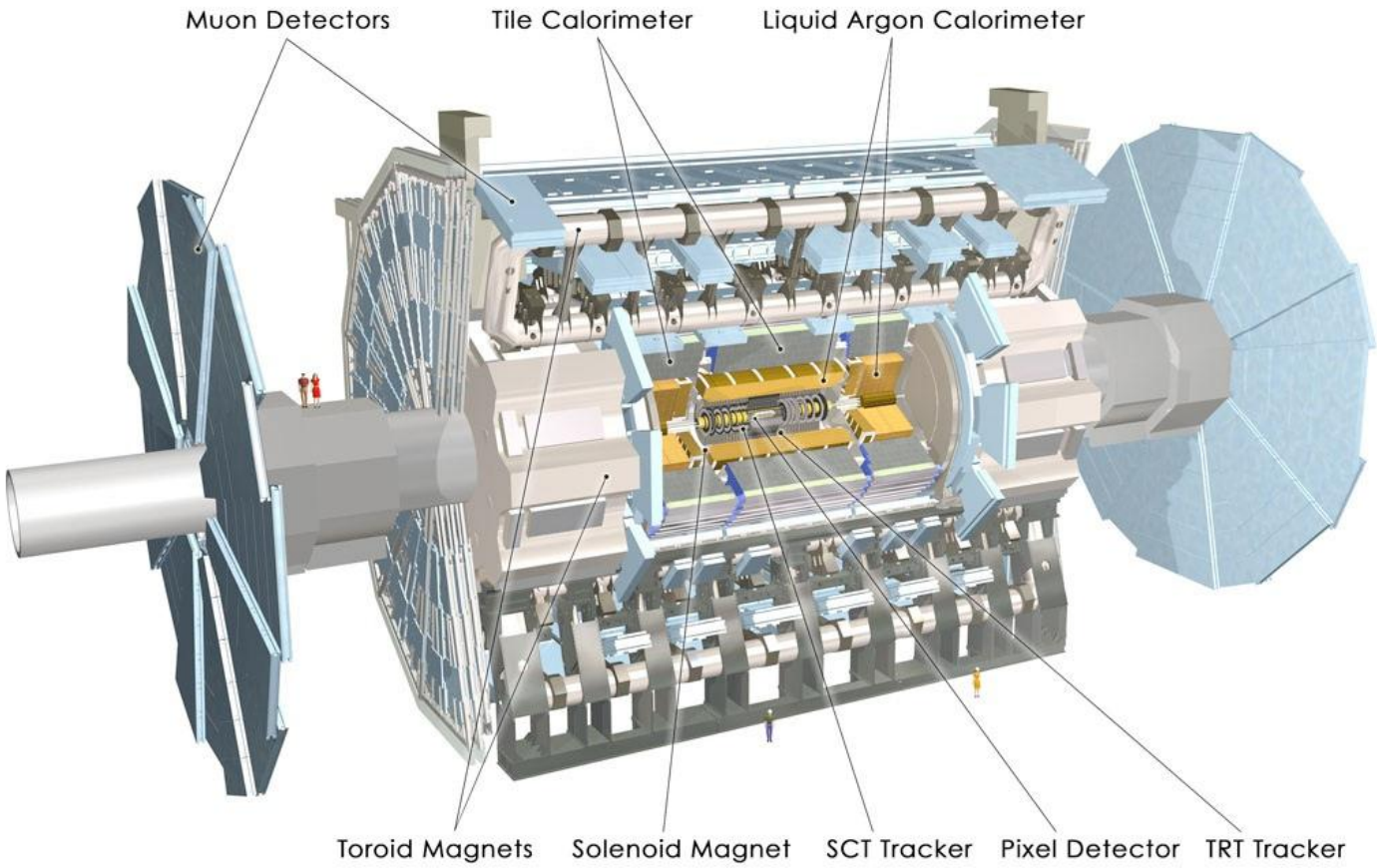




In p-Pb, only Pb-going side measurement is used

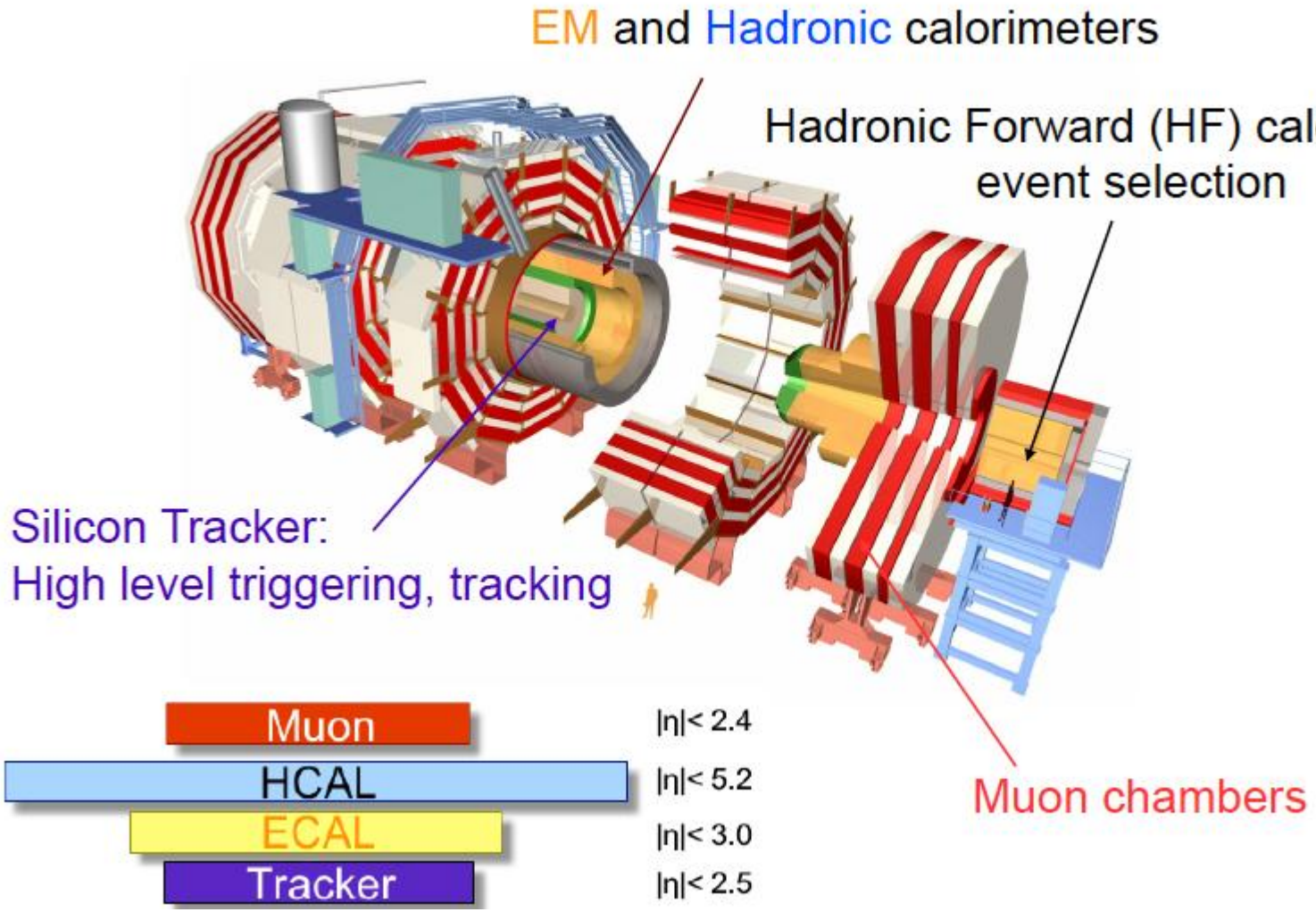
Events are classified according to the percentile of the Pb-Pb inelastic cross section based on total deposited energy in the forward calorimeters

The ATLAS Detector



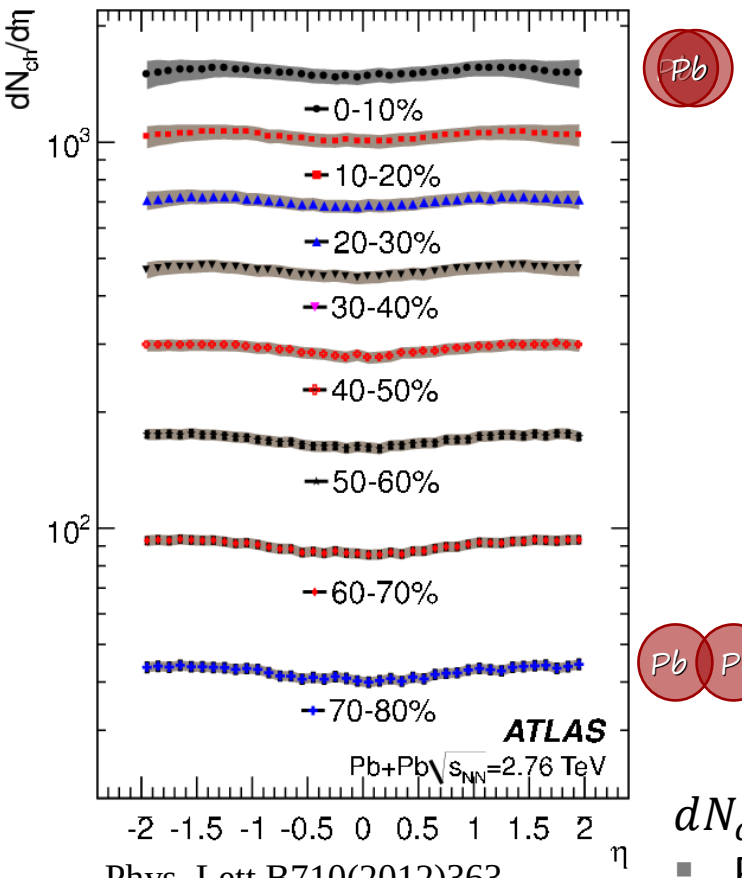
- Inner Detector - tracking $|\eta|<2.5$
- Calorimeter- $|\eta|<4.9$
- Muon Spectrometer - $|\eta|<2.7$

The CMS Detector



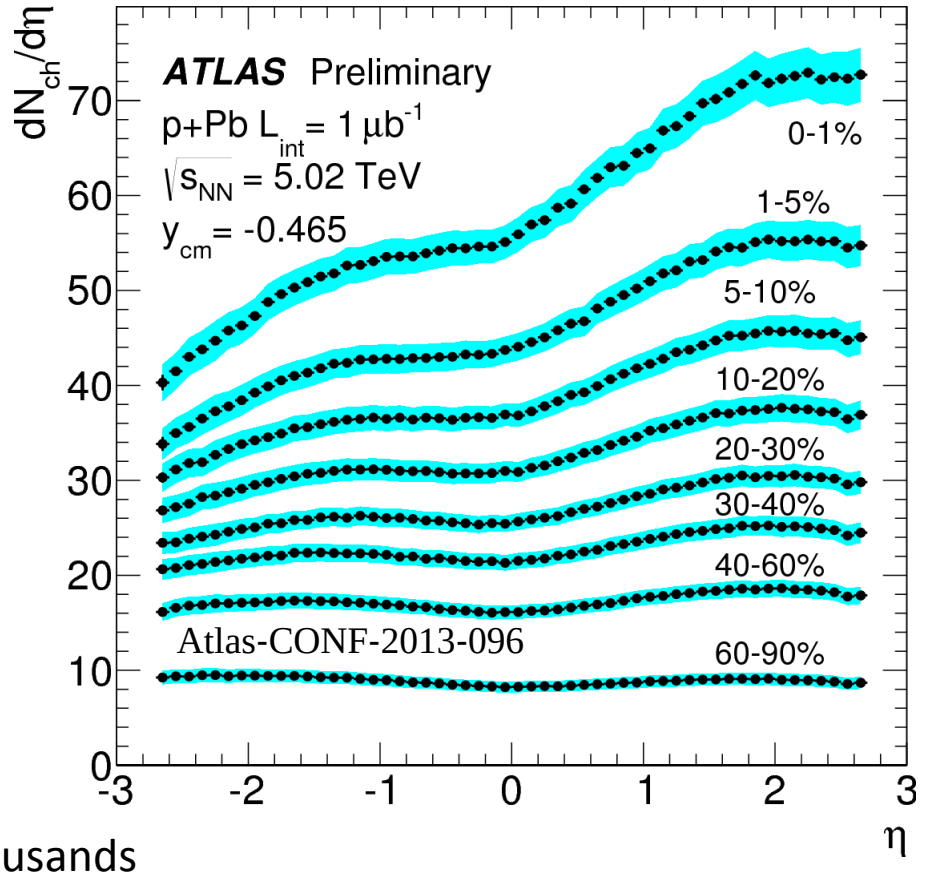
Charged particle multiplicity

Pb-Pb



Phys. Lett B710(2012)363

p-Pb



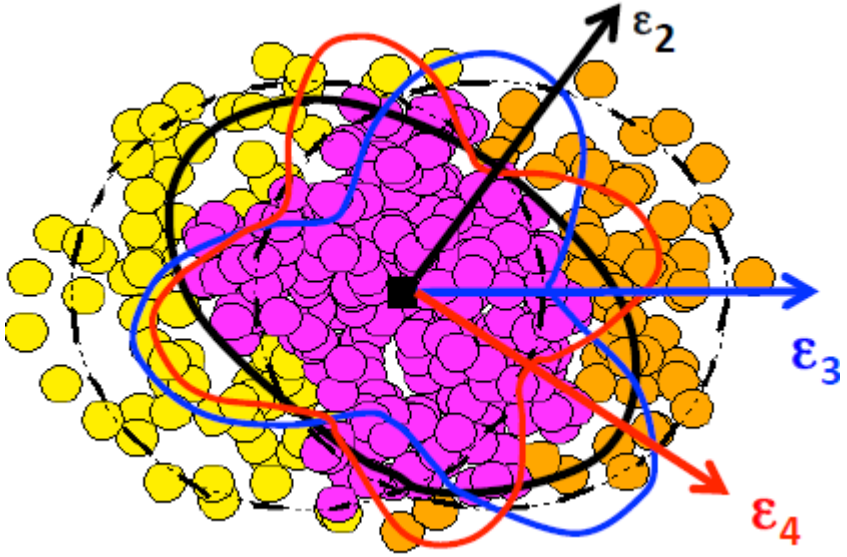
$dN_{ch}/d\eta$:

- Pb-Pb – thousands
- p-Pb – tens
- p-p – few

Soft Probes

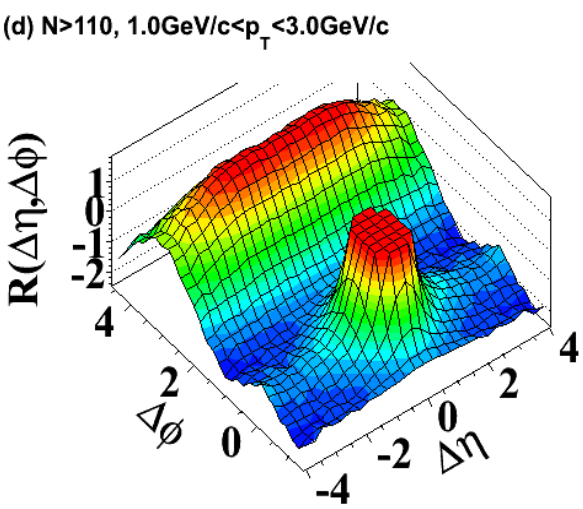
Collective particle flow:

- A useful tool to study the property of matter created in nuclear collisions
- Results from a pressure-driven anisotropic collective expansion of the matter
- Sensitive to the initial geometry and its fluctuations
- Well modelled in A+A collisions by hydrodynamic evolution



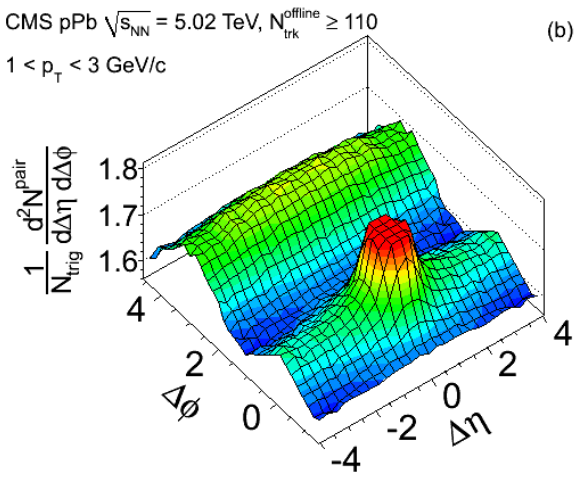
The Ridge

$p + p\ \sqrt{s_{nn}} = 7\ TeV$



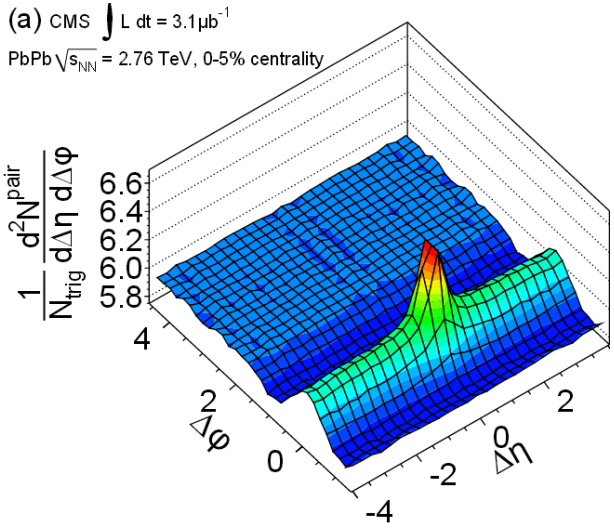
JHEP 09 (2010) 091

$p + Pb\ \sqrt{s_{nn}} = 5.02\ TeV$



PLB 718 (2013) 795

$Pb + Pb\ \sqrt{s_{nn}} = 2.76\ TeV$



JHEP 07 (2011) 076

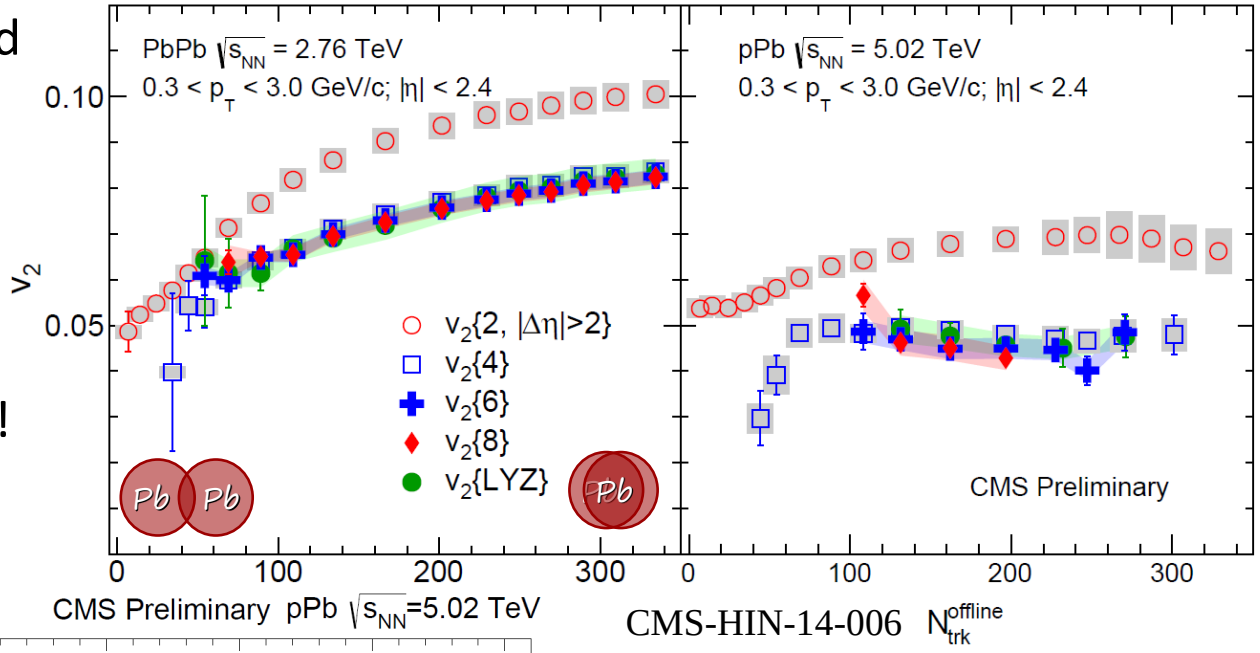
”Ridge” *(long-range near-side angular correlations)* is observed in high multiplicity p-p and p-Pb as well as in central PbPb collisions

Elliptic flow in p-Pb vs Pb-Pb

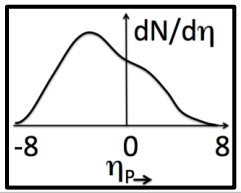
v_2 stays large when calculated with multi-particles

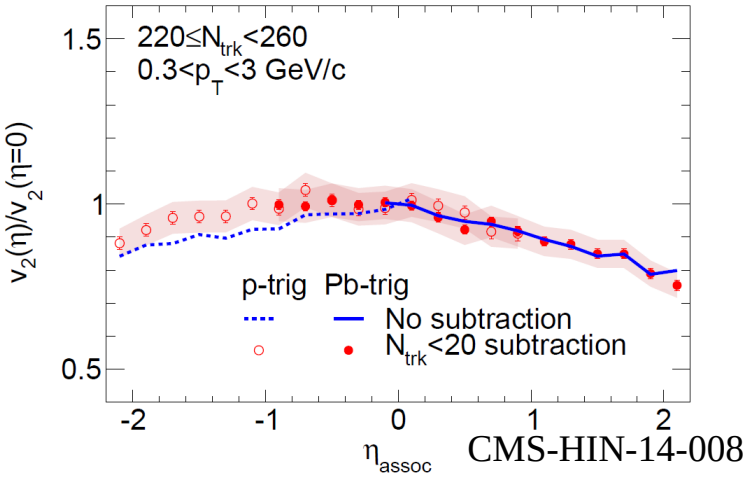
$v_2(4) = v_2(6) = v_2(8) = v_2(LYZ)$ within 10% !

The anisotropy in p-Pb is significantly similar to Pb-Pb!



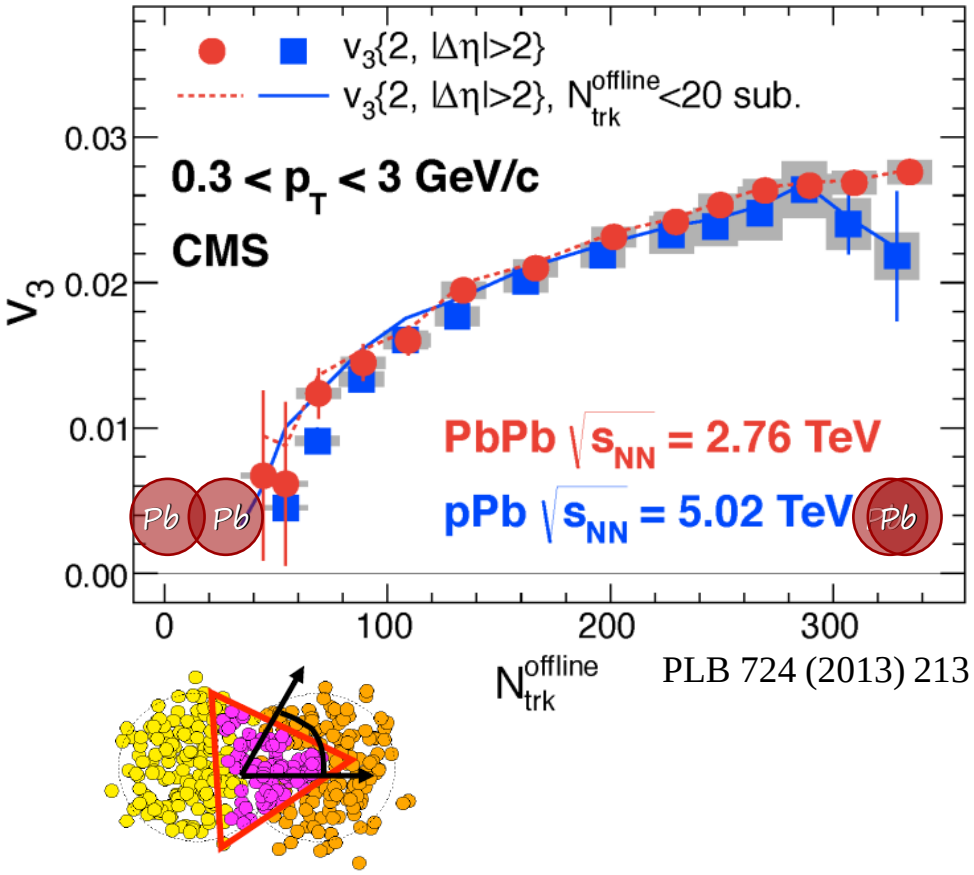
v_2 shape is η dependent in p-Pb collisions!



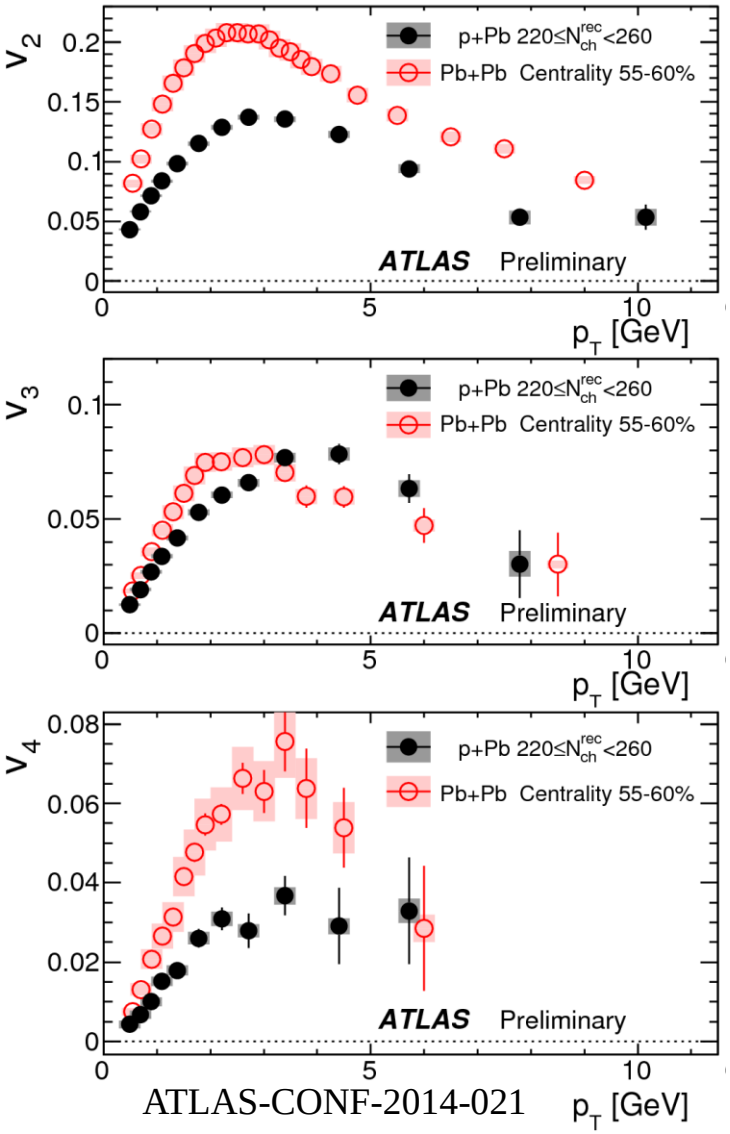


v_n flow in p-Pb vs Pb-Pb

Remarkable similarity in the v_3 signal in p-Pb and Pb-Pb!

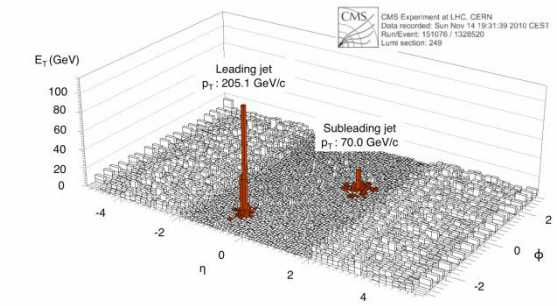


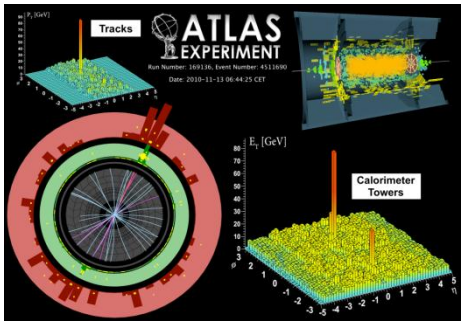
PLB 724 (2013) 213



ATLAS-CONF-2014-021

Hard probes

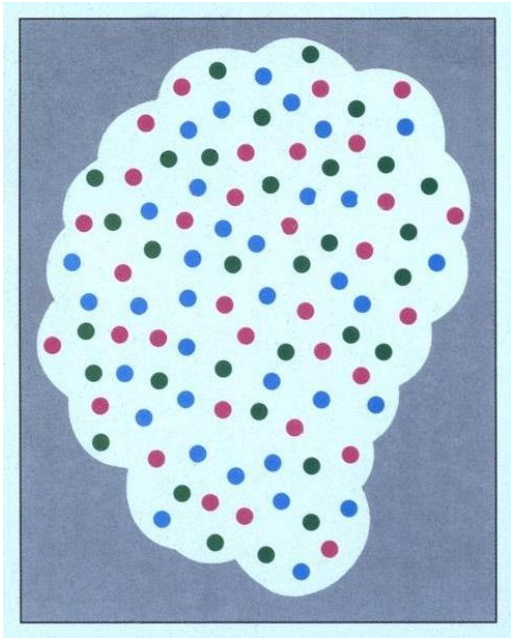




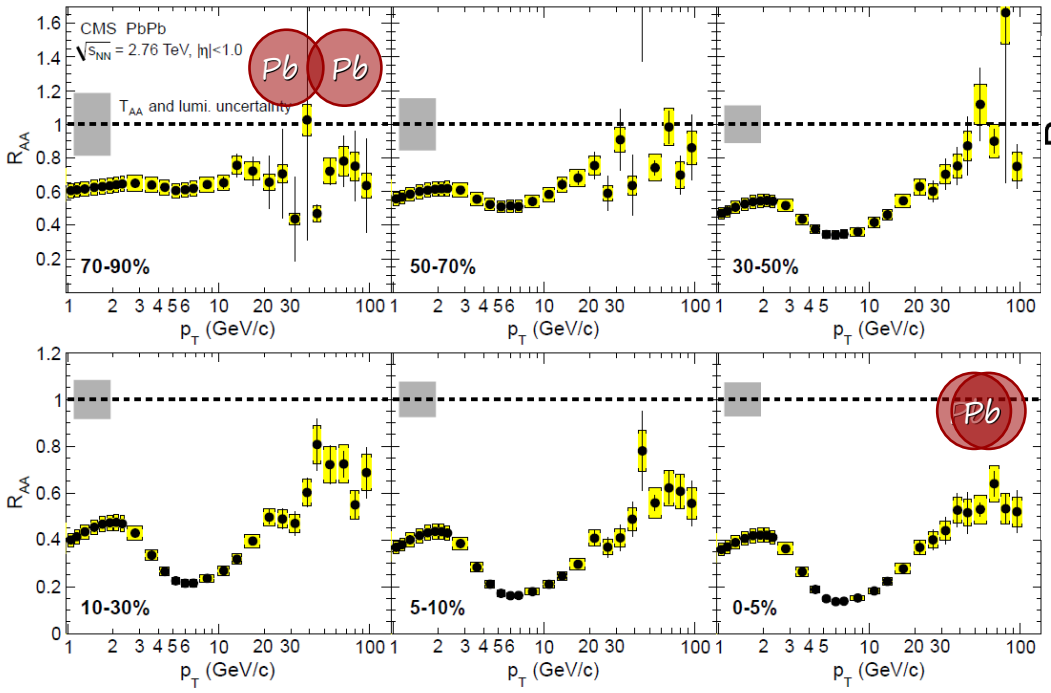
Z^0, W^{+-}, γ → unchanged

Jets → quenched

Quarkonia ⇒ dissociated

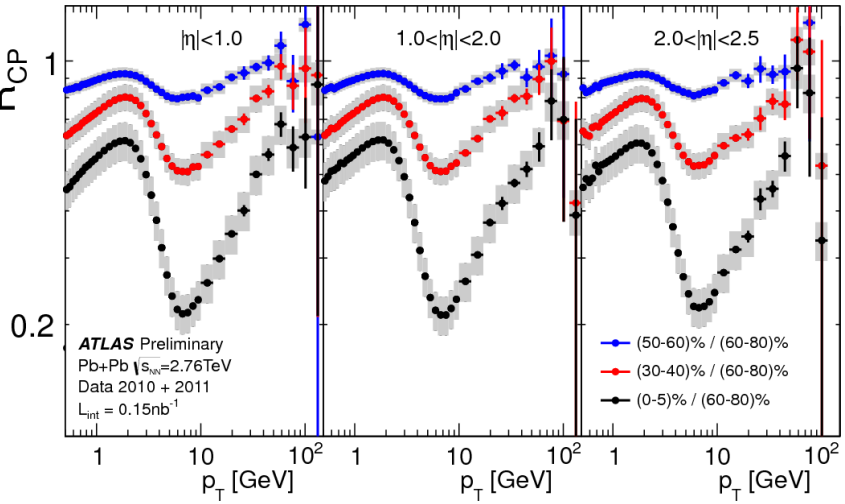


Charged hadron suppression in Pb-Pb



EPJC 72 (2012) 1945

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



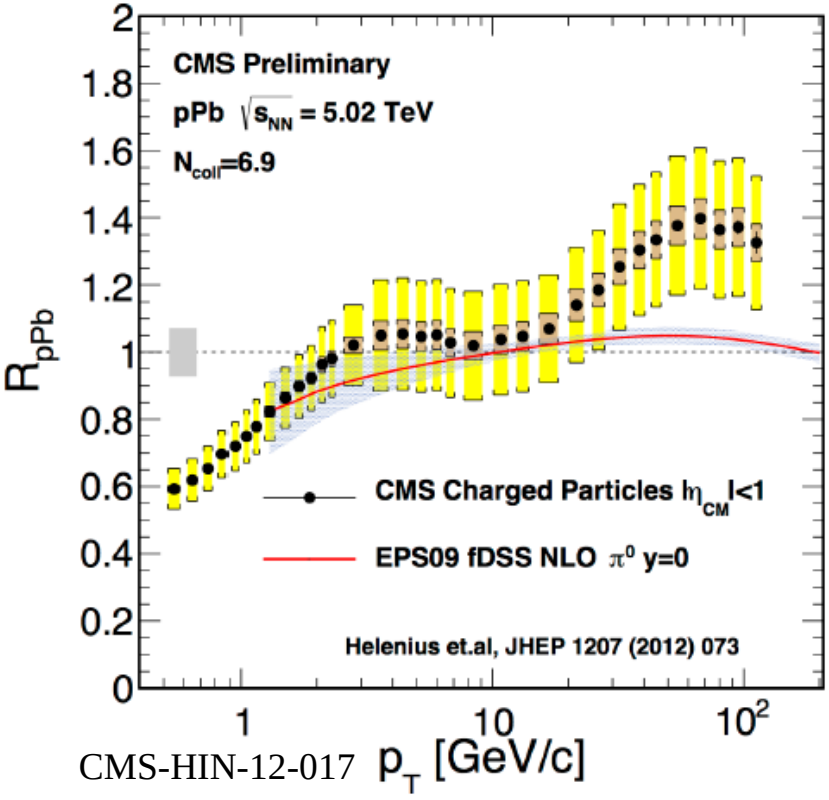
ATLAS-CONF-2012-120

$$R_{CP} = \frac{R_{AA}\,[central]}{R_{AA}\,[peripheral]}$$

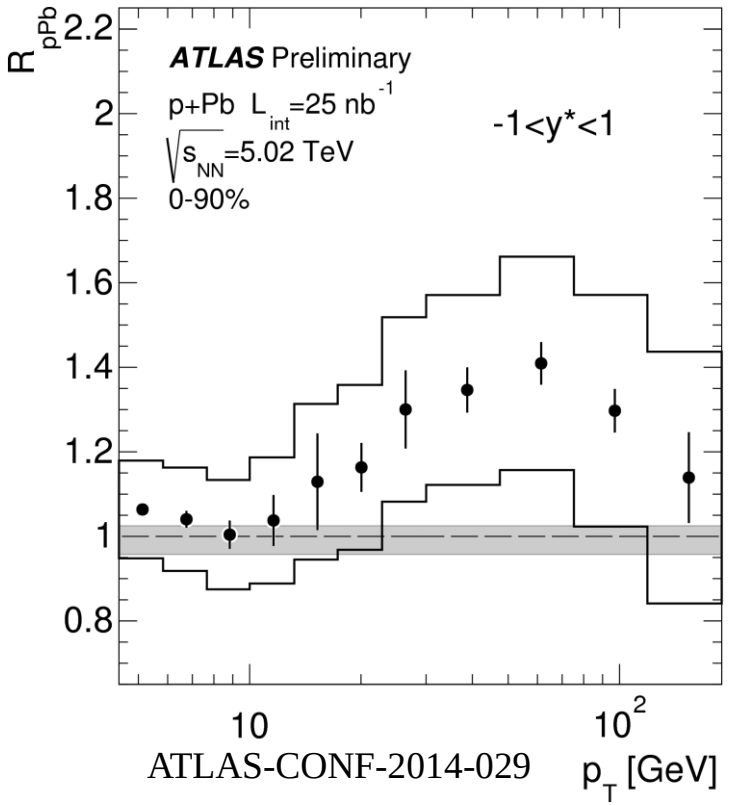
For central collisions:

- A pronounced minimum at $P_T = 6 - 7\ GeV$ where $R_{PbPb} \approx 0.13$
- At higher P_T R_{PbPb} rises and levels off above 40 GeV
- Suppression at high P_T at the same level as jet suppression

Charged hadron suppression in p-Pb



CMS-HIN-12-017



ATLAS-CONF-2014-029

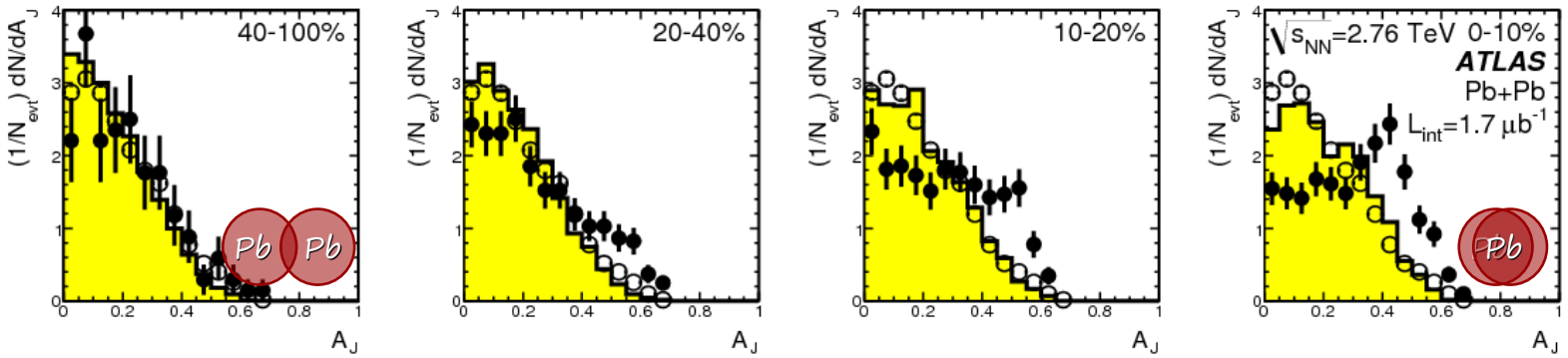
Consistent results between ATLAS and CMS

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

$R_{pPb} > 1$ above 30 GeV

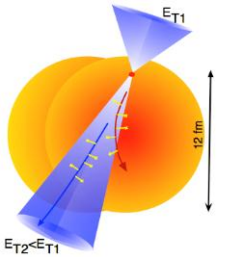
- Anti-shadowing? but stronger than predicted by models

Di-jet energy imbalance : Pb-Pb



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

$$A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$



A strong increase in the fraction of highly unbalanced di-jets in central Pb-Pb as compared with p-p and peripheral Pb-Pb

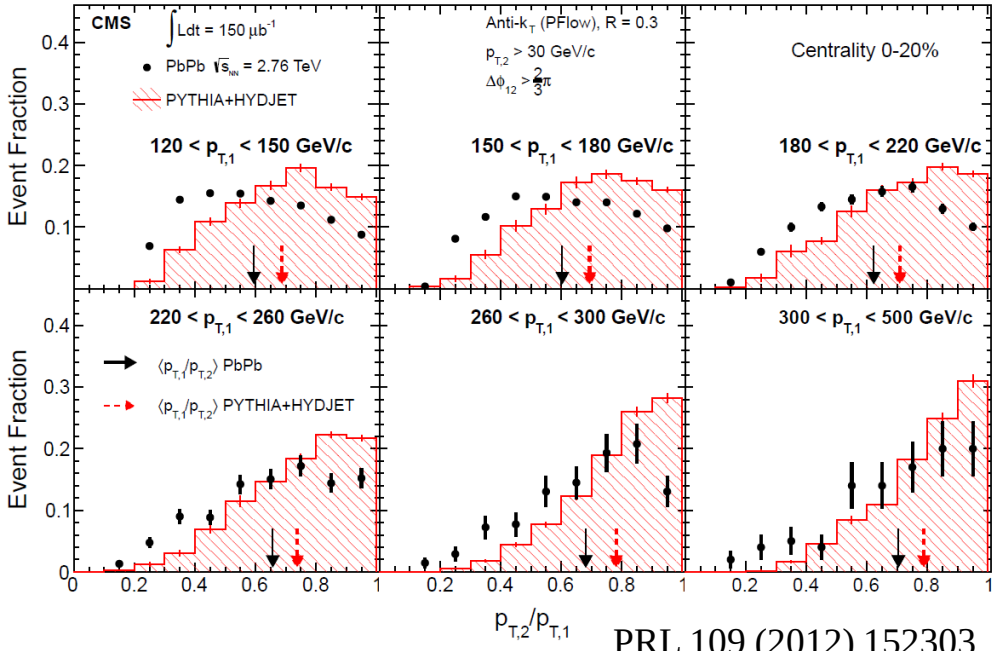
⇩

direct observation of jet quenching

The fraction of the energy that a jet loses increases monotonically with increasing collision centrality, and does not dramatically change with jet P_T

⇩

constant relative energy loss?

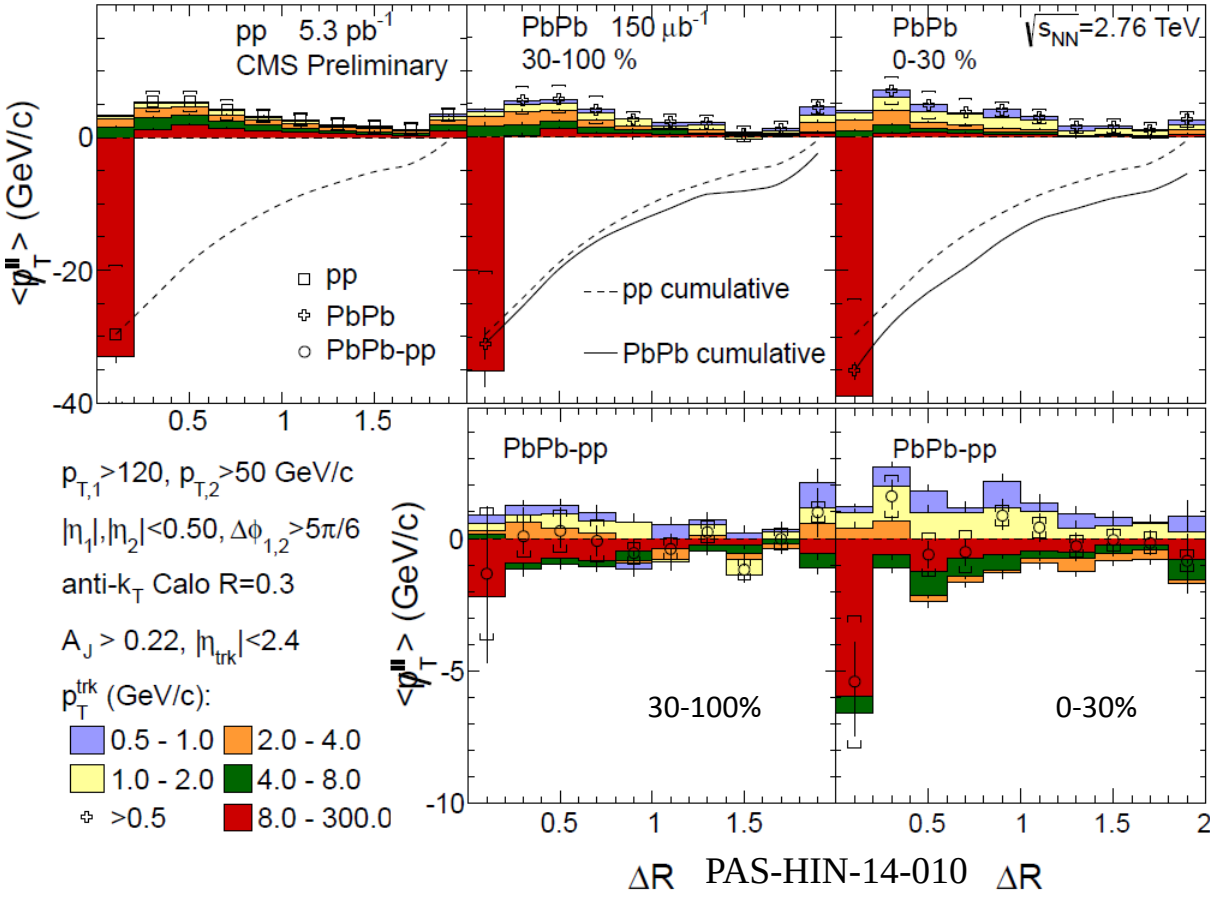


PRL 109 (2012) 152303

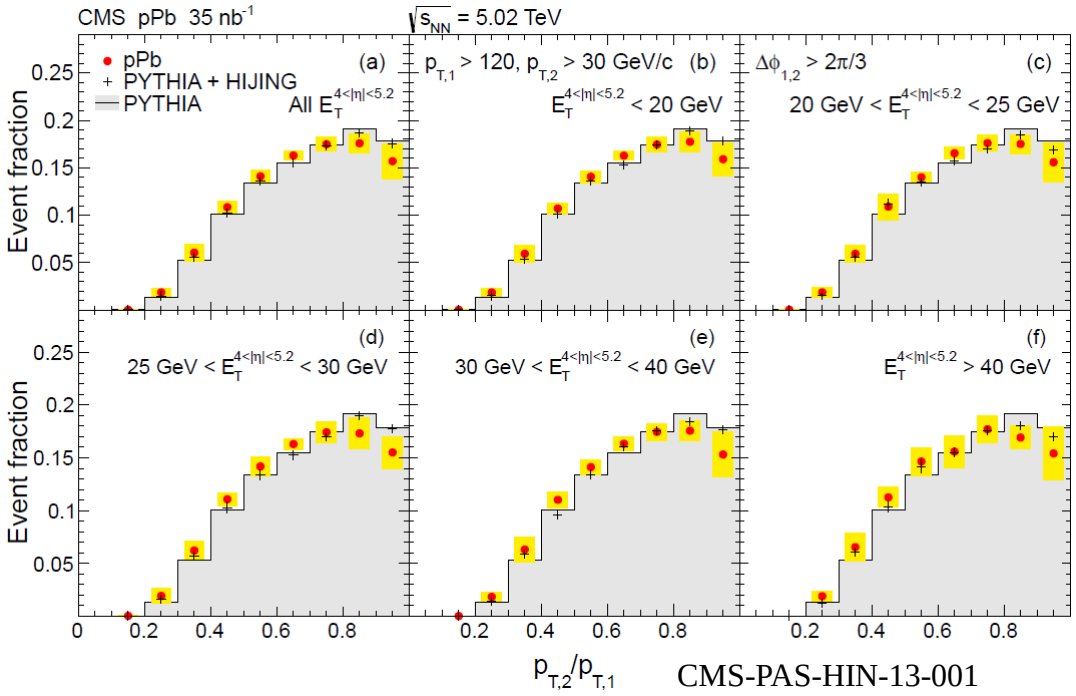
Details on di-jet imbalance in Pb-Pb

Detailed (ΔR, P_T) distributions

- Summing charged particles for unbalanced ($\boldsymbol{A_J > 0.22}$) di-jets in central (0–30%) collisions
- 35 GeV missing at ΔR<0.2, high P_T particles
- Balanced by low P_T particle up to very large ΔR
- Subtracting the same from pp shows a different P_T mix
- But a similar P_T -integrated ΔR distribution

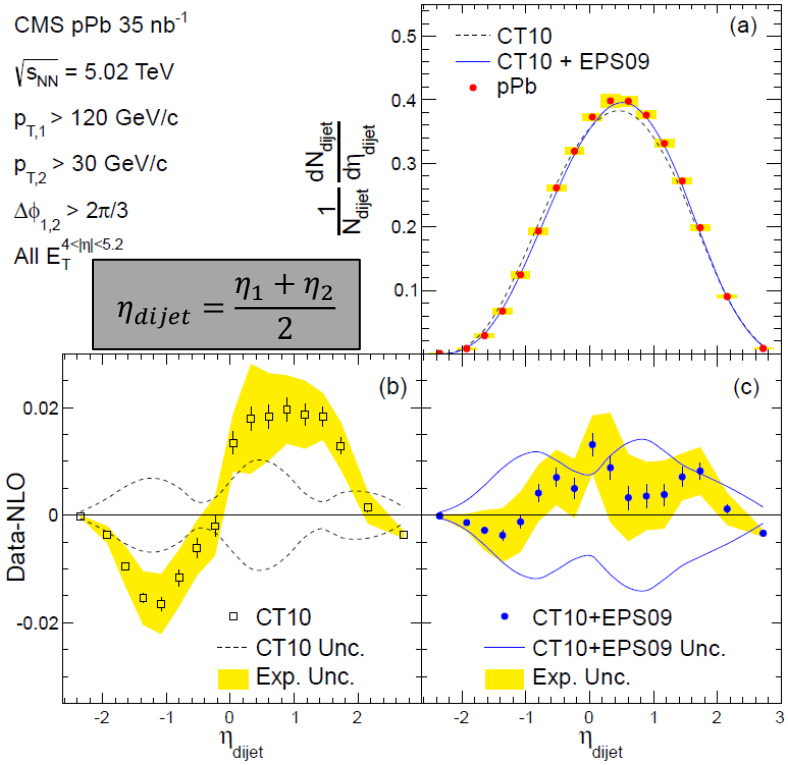


Di-jet energy imbalance : p-Pb



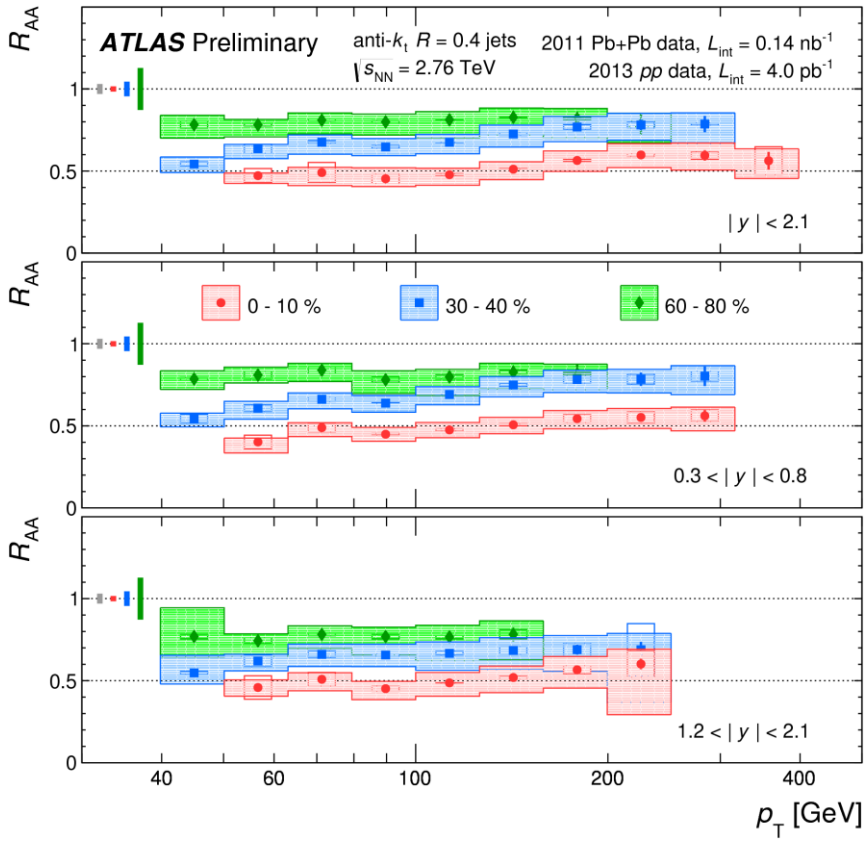
No centrality dependence of di-jet momentum balance

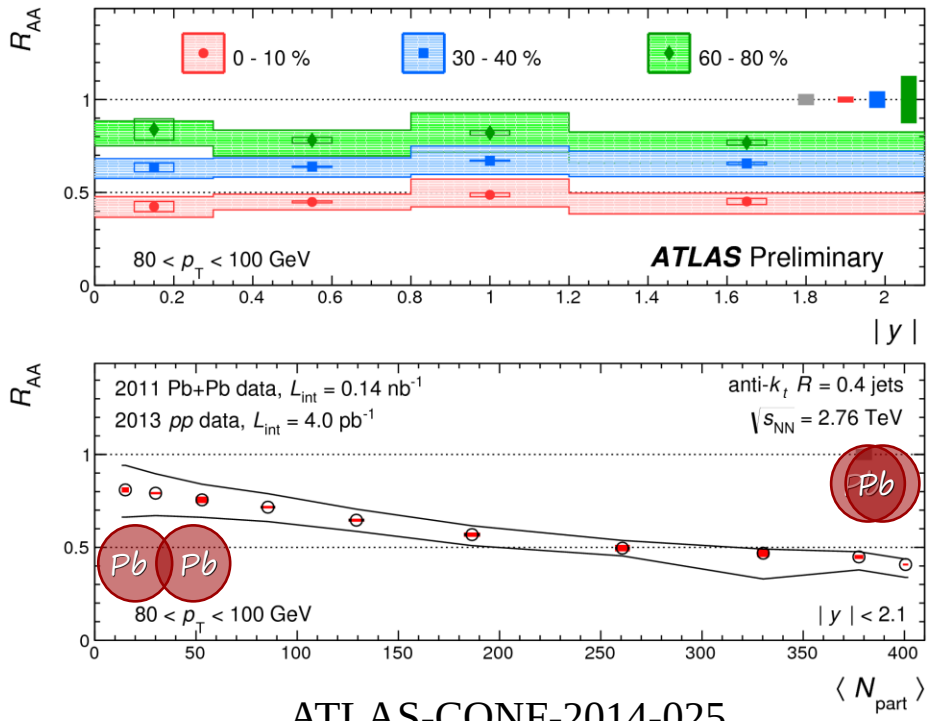
No jet quenching?



Pronounced shift of mean di-jet rapidity in Pb-going η direction vs centrality due to nPDF effects.
Better agreement with CT10+EPS09

Inclusive jet suppression in Pb-Pb



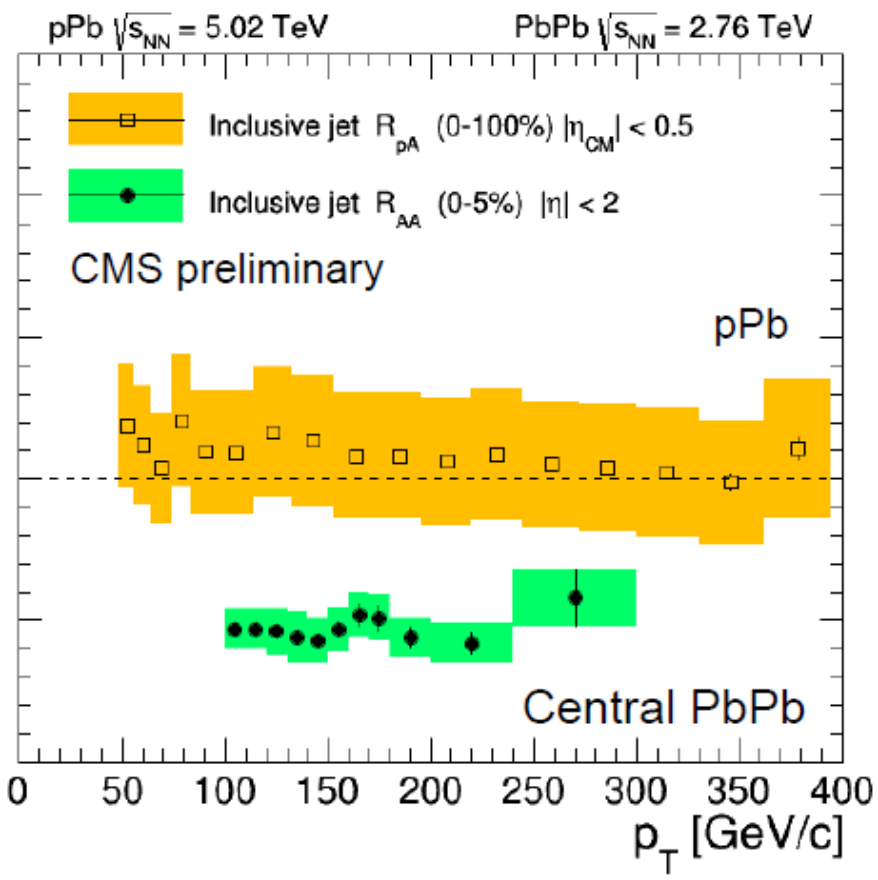


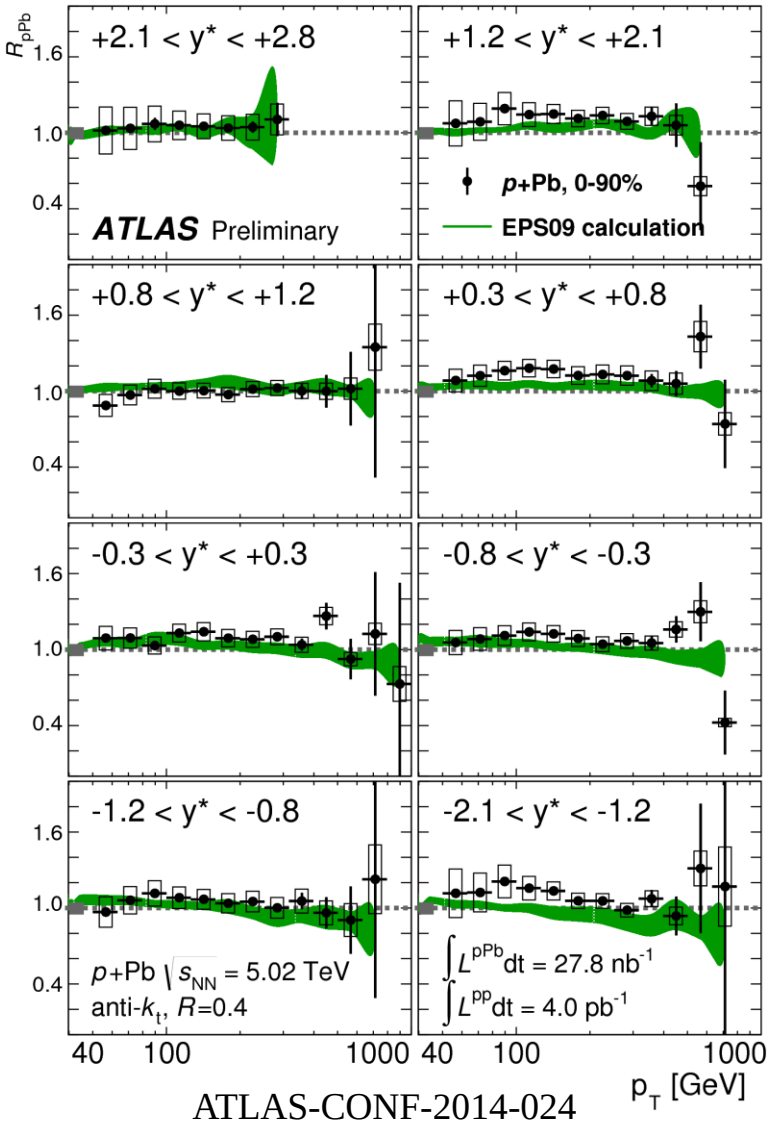
ATLAS-CONF-2014-025

- A factor of ~2 suppression in 0-10% most central collisions
- R_{PbPb} monotonically decreases vs N_{part}
- R_{PbPb} shows a slight increase with jet P_T
- No significant dependence on rapidity observed

$$R_{PbPb} = \frac{d^2 N_{ch}{}^{PbPb}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma_{ch}{}^{pp}/dp_T d\eta}$$

Inclusive jet suppression in p-Pb

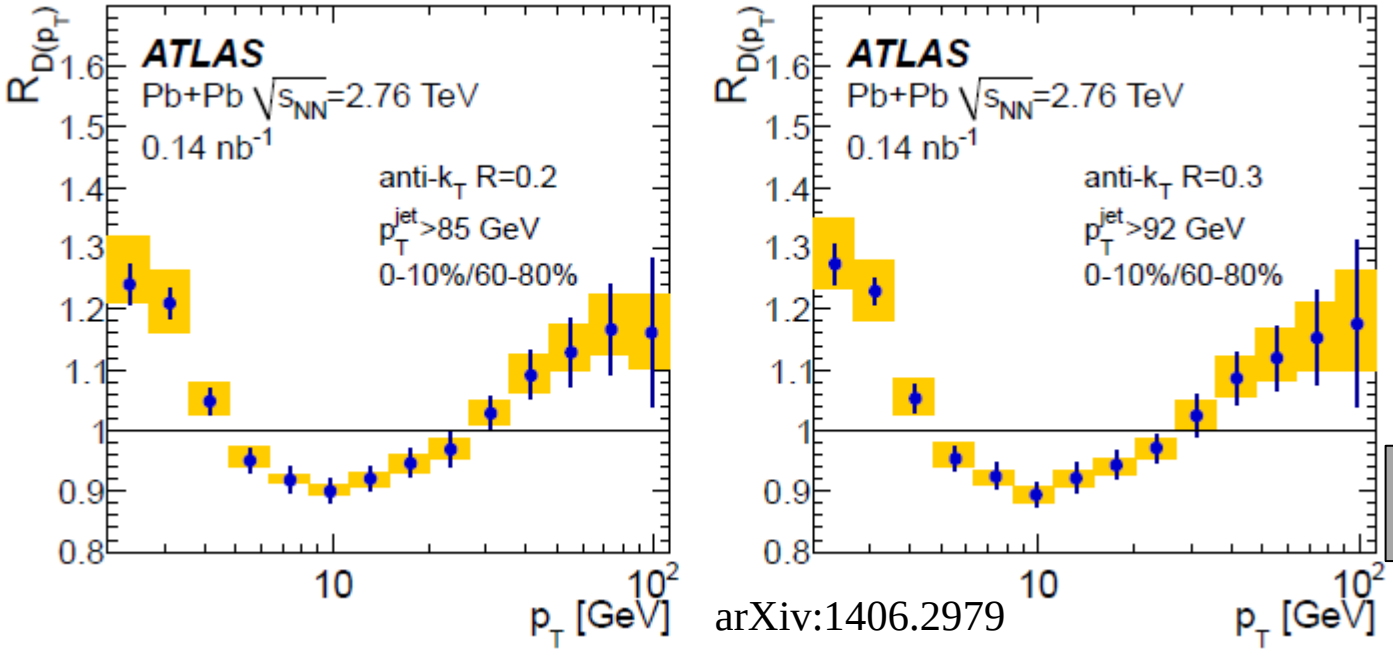




ATLAS-CONF-2014-024

- A weak P_T dependence?
- Results consistent with EPS09 prediction

Inclusive jets fragmentation functions in Pb-Pb



arXiv:1406.2979

$$D(P_T) = \frac{1}{N_{Jet}} \frac{dN_{ch}}{dP_T{}^{ch}}$$

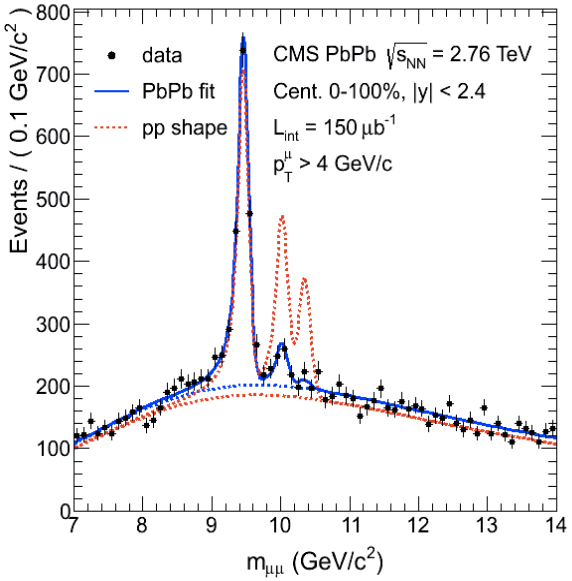
$$R_{D(P_T)} = \frac{D(P_T)[central]}{D(P_T)[peripheral]}$$

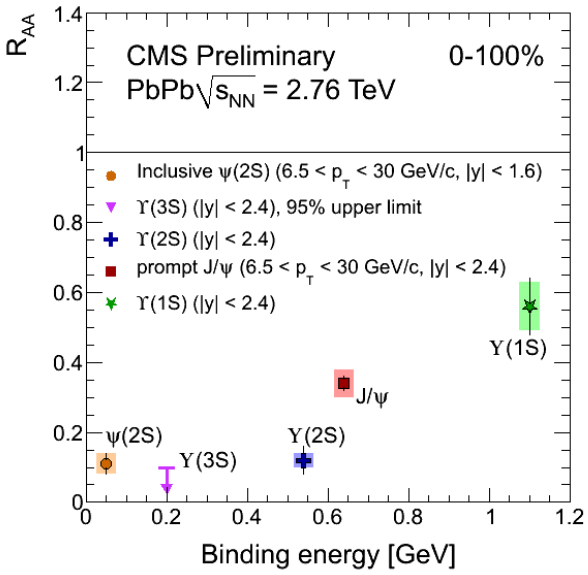
- A modest but significant modification of fragmentation seen:
  - an enhancement in fragment yield in central collisions for $P_T < 5\ GeV$
  - a reduction in fragment yield for $5\ GeV < P_T < 30\ GeV$
  - an enhancement in the fragment yield for $P_T > 30\ GeV$
- The modification decreases monotonically with decreasing centrality.
- Modifications observed for all three jet radii (R = 0.2, 0.3, 0.4)

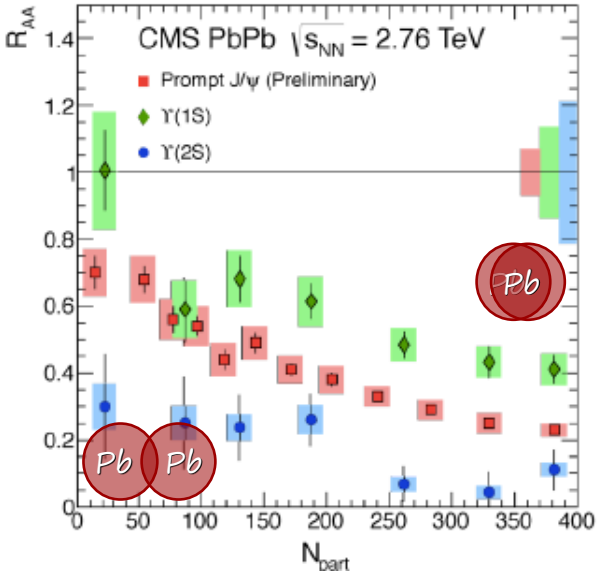
Quarkonia suppression in Pb-Pb

Sequential suppression $\Upsilon(3s) > Y(2s) > {}^{J}/_{\psi} > \Upsilon(1s)$

Well-ordered with binding energy and increases with centrality



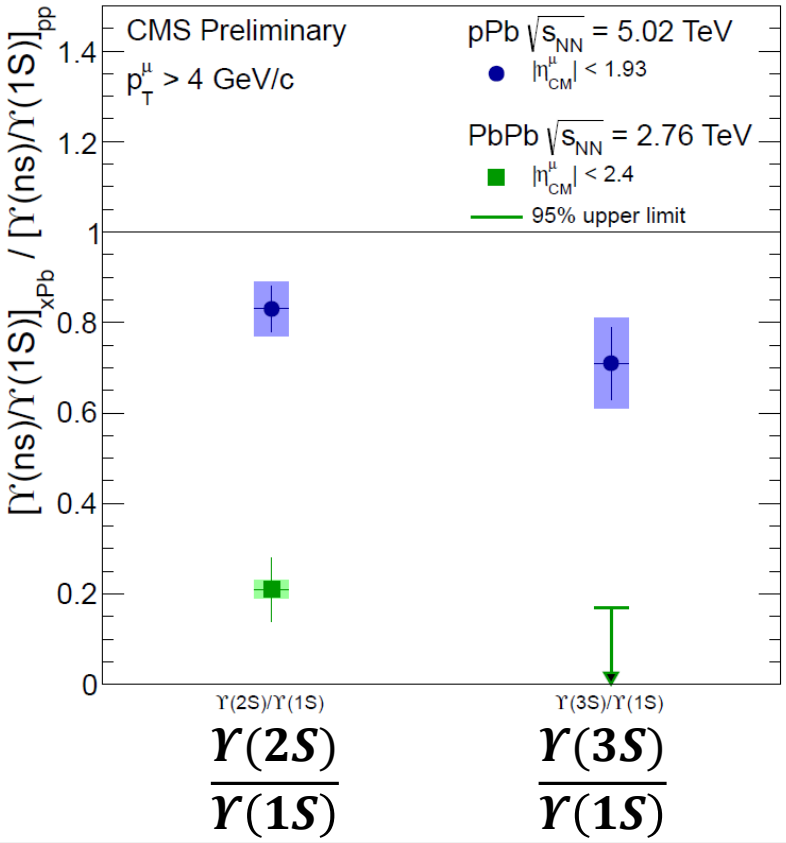




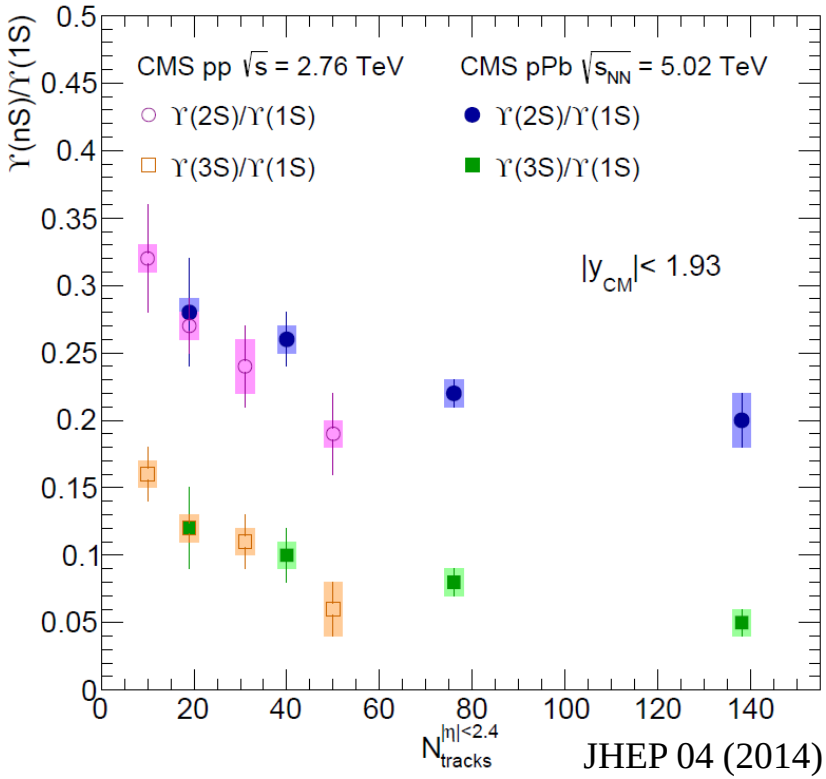
CMS: Phys. Rev. Lett. 107(2011)052302, Phys. Rev. Lett. 109 (2012) 222301, JHEP 05(2012)063

Υ suppression in p-Pb

- Moderate $\Upsilon(ns)/\Upsilon(1s)$ suppression (much lesser than in Pb-Pb) - initial or final state effect?
- $\Upsilon(ns)/\Upsilon(1s)$ decreases with event multiplicity for all systems: p-p, p-Pb, Pb-Pb



$\frac{\Upsilon(2S)}{\Upsilon(1S)}$ $\frac{\Upsilon(3S)}{\Upsilon(1S)}$



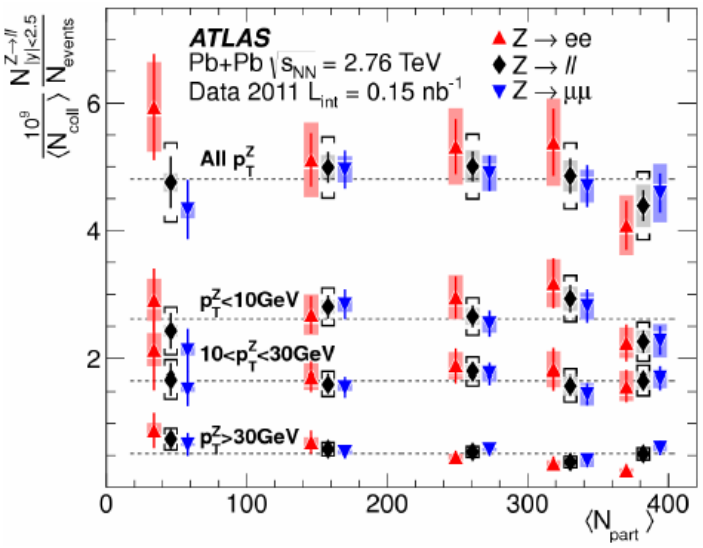
$\frac{\Upsilon(2S)}{\Upsilon(1S)}$ $\frac{\Upsilon(3S)}{\Upsilon(1S)}$

JHEP 04 (2014) 103

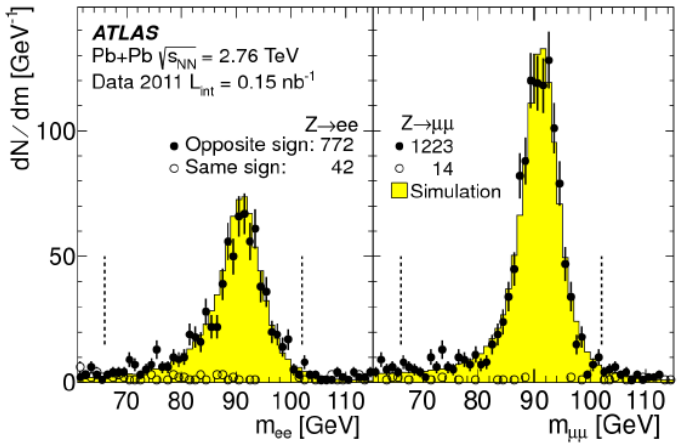
Z^0: From Pb-Pb to p-Pb

In **Pb-Pb**: No medium effects for electromagnetic hard probes. Confirmation of NN binary scaling.

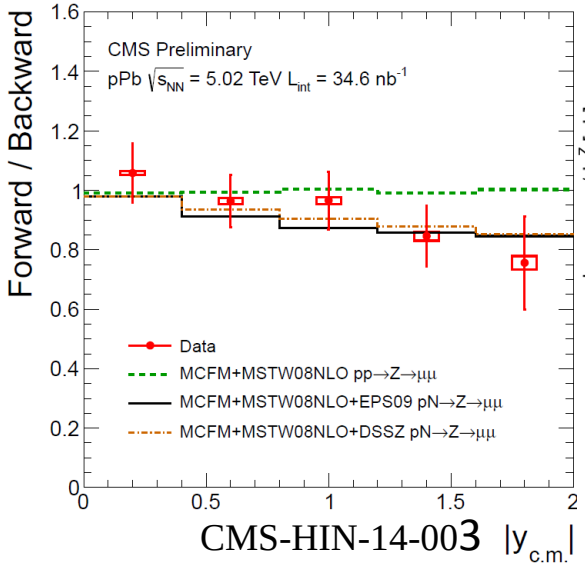
ATLAS, Phys. Rev. Lett. 110 (2013) 022301



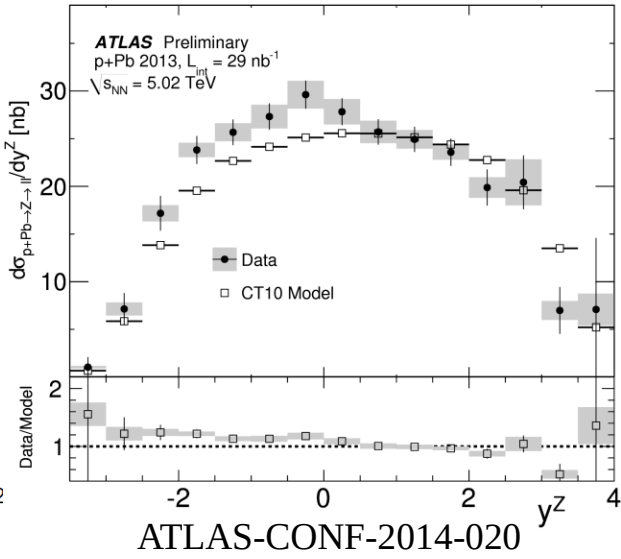
ATLAS, Phys. Rev. Lett. 110 (2013) 022301



In **p-Pb**: Showing little nuclear effect a hint of forward/backward asymmetry. A bit smaller Z yield in the Pb-direction

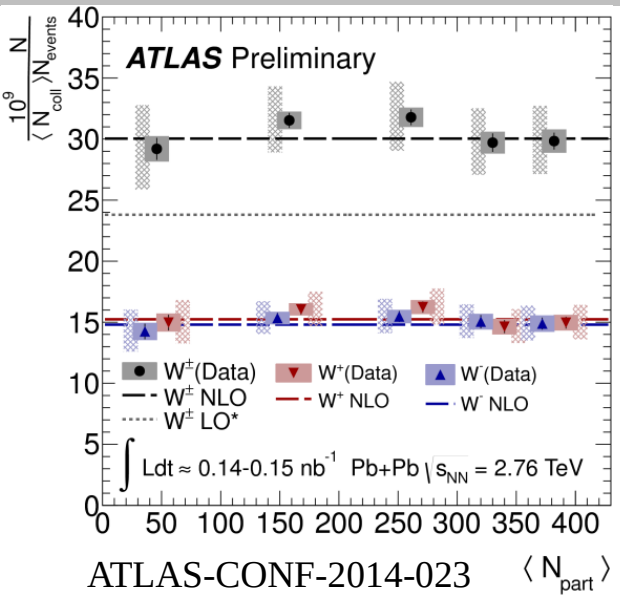


CMS-HIN-14-003



ATLAS-CONF-2014-020

W^{+-}: From Pb-Pb to p-Pb



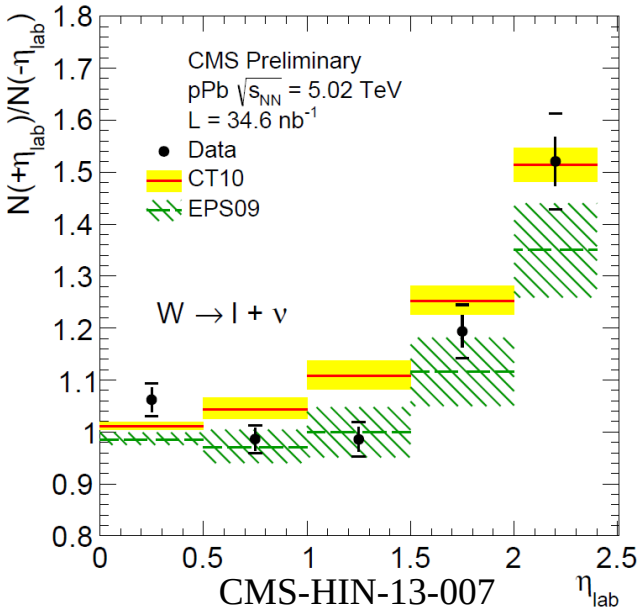
ATLAS-CONF-2014-023

In **Pb-Pb**:

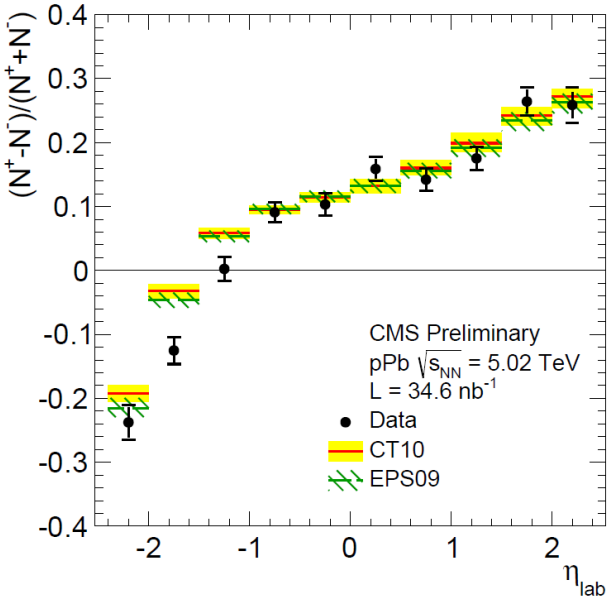
- No medium effect observed
- W yields increase proportional to Ncoll

In **p-Pb**:

- Showing small deviations from unmodified PDFs
- A hint of a different u/d modification?



CMS-HIN-13-007



Summary

- Consistent picture of dense and hot matter produced in Pb+Pb
  - collective behaviour (ridges, v_n)
  - no medium effects for EWK probes (γ,Z,W), confirmation of binary NN scaling
  - strong jet and charged hadron quenching, modification of jet shape and fragmentation function
  - quarkonia suppression, including excited Y states, sequential suppression

- Highlights from p+Pb
  - hints of possible collective behaviour (ridges, v_2 , v_3)
  - no jet quenching (R_{PbPb} ?, di-jets)? initial state effect (nuclear shadowing)?
  - excited Y states are suppressed as compared to p+p
  - the initial state nPDFs are modified (ch.hadrons R_{PbPb}?, η di-jet)

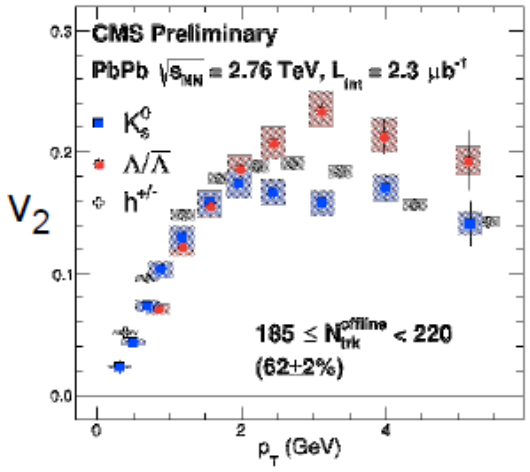
Thank you!

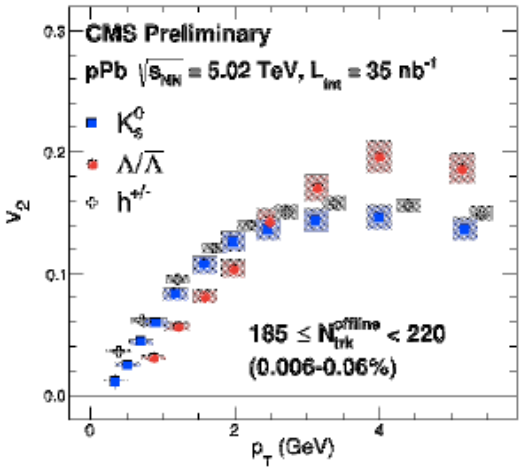
Backup slides

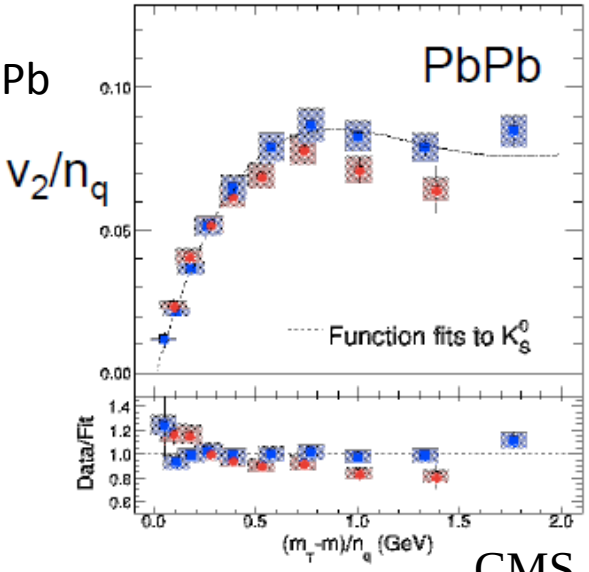
Elliptic flow of identified particles

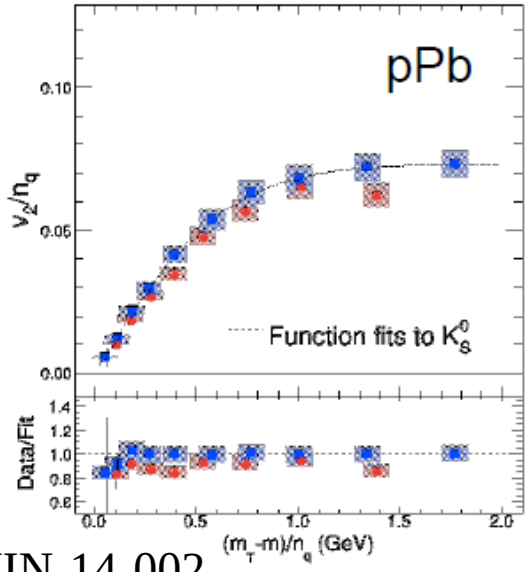
Identified K_S and Λ & charged particles

Show mass-ordering in Pb-Pb and p-Pb (Stronger in p-Pb)



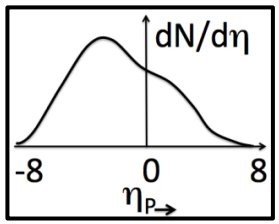


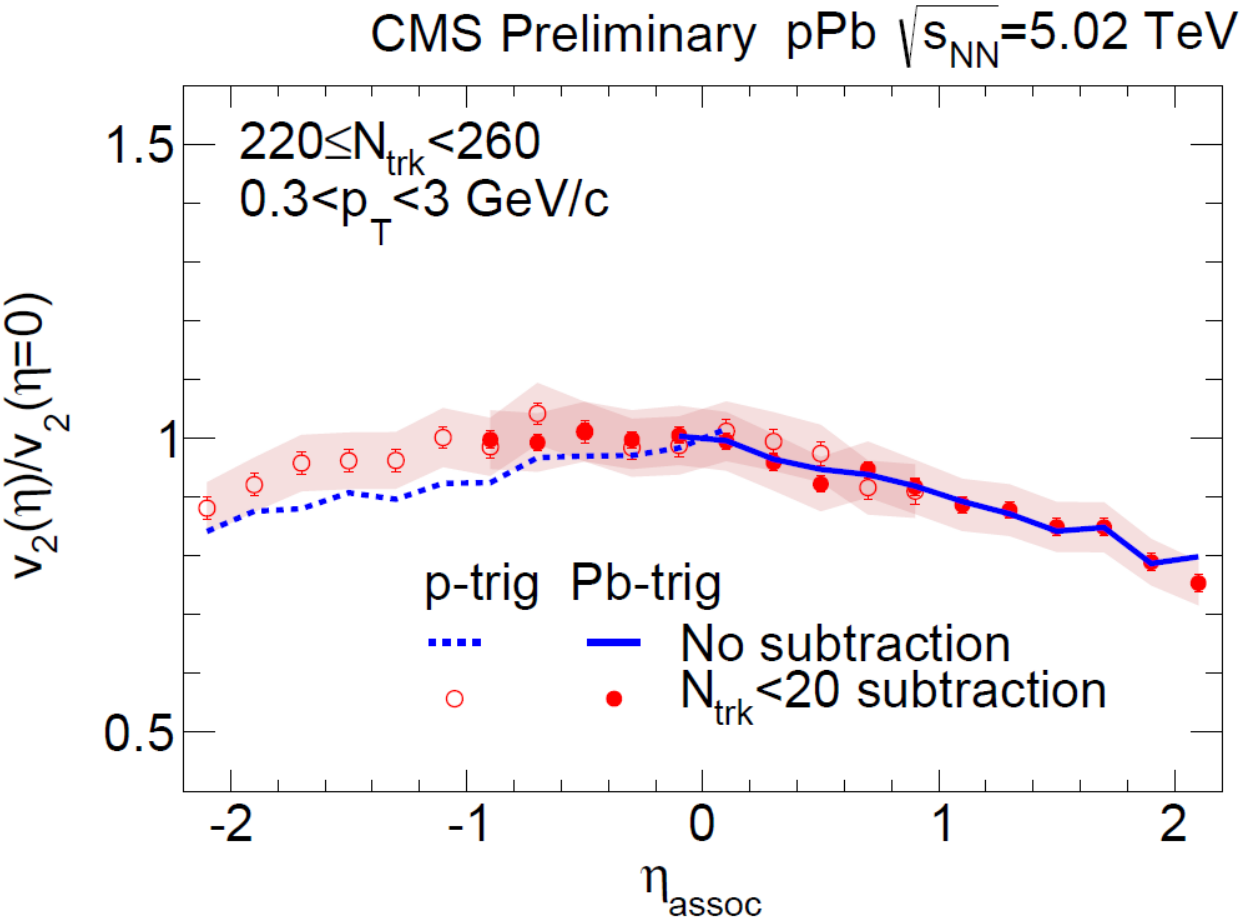




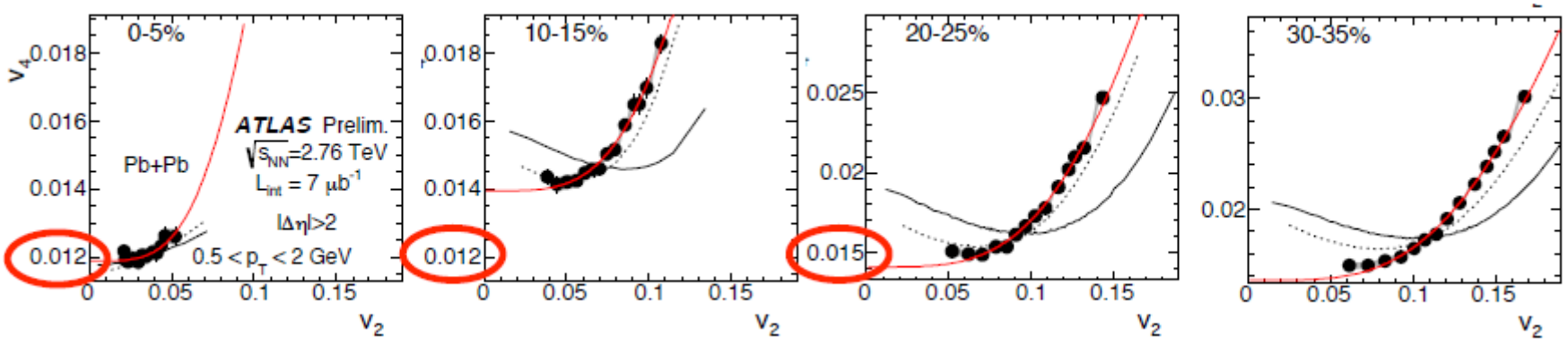
CMS-HIN-14-002

η-dependence of v_2 in p-Pb



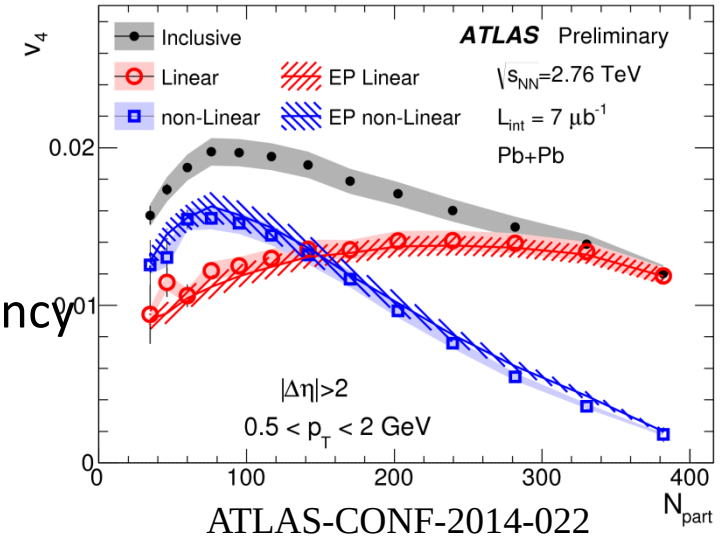


v_4 vs v_2 non-linearity in Pb-Pb



$\sqrt{{c_0}^2 + ({c_1 {v_2}^2})^2}$ fit is used to separate linear and non-linear driven contributions

- Describes well the behavior for all centrality bins
- Linear part has a non-standard increasing dependency

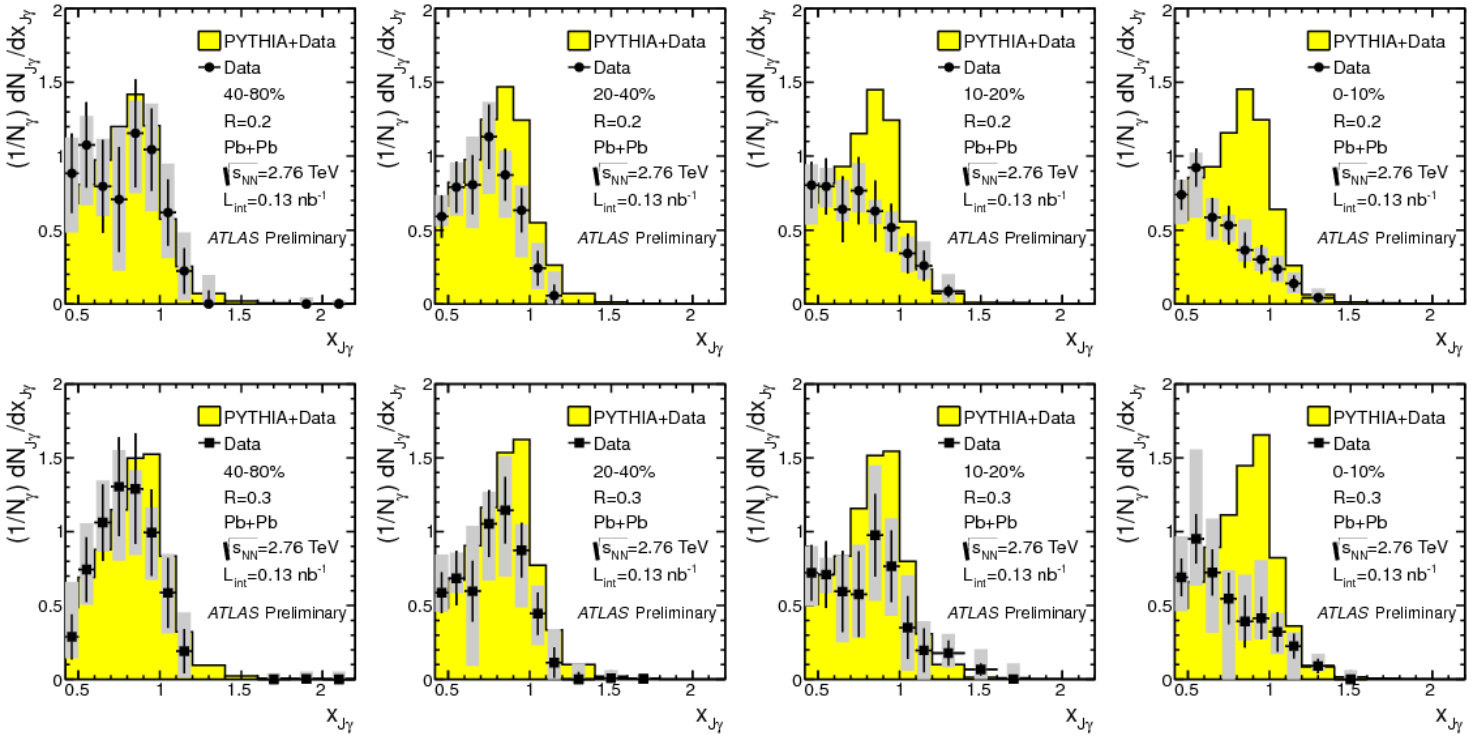


ATLAS-CONF-2014-022

γ + jet correlations in Pb-Pb

Jet energy modification relative to a probe, not affected by the medium

$$X_{J\gamma} = \frac{{P_T}^{Jet}}{{P_T}^{\gamma}}$$



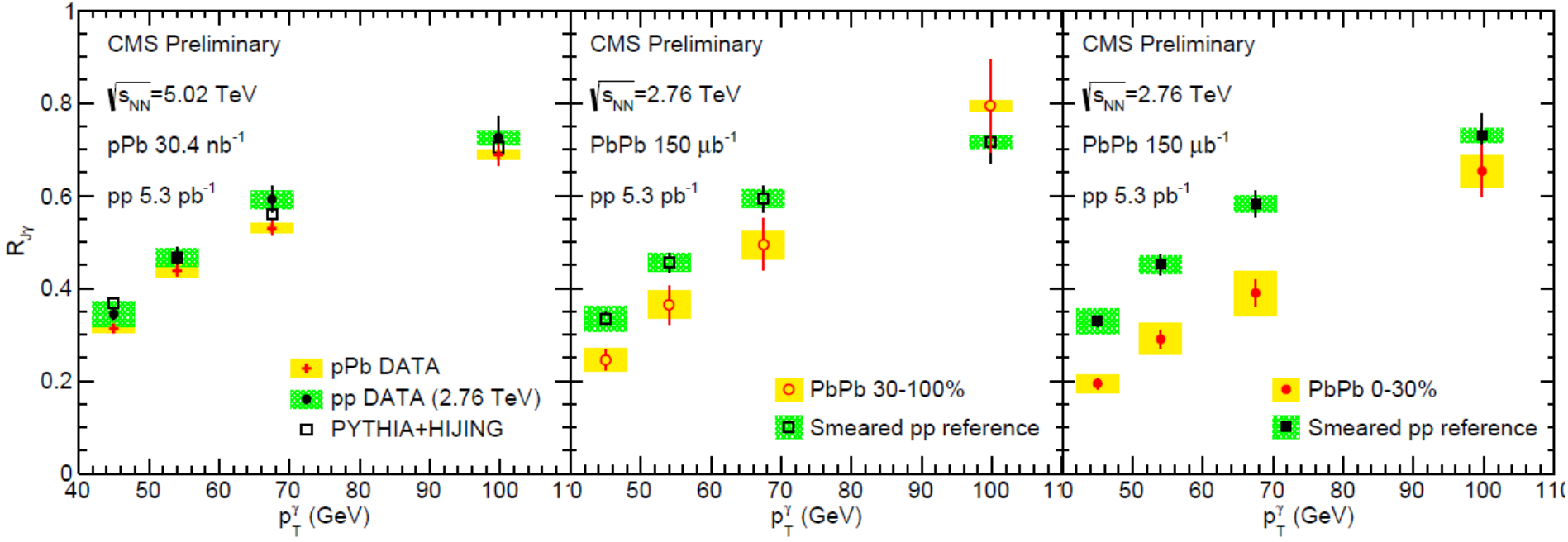
ATLAS-CONF-2012-121

- Shape and integral compatible with PYTHIA for peripheral collisions
- For central events shift towards smaller $X_{J\gamma}$

γ + jet correlations in p-Pb

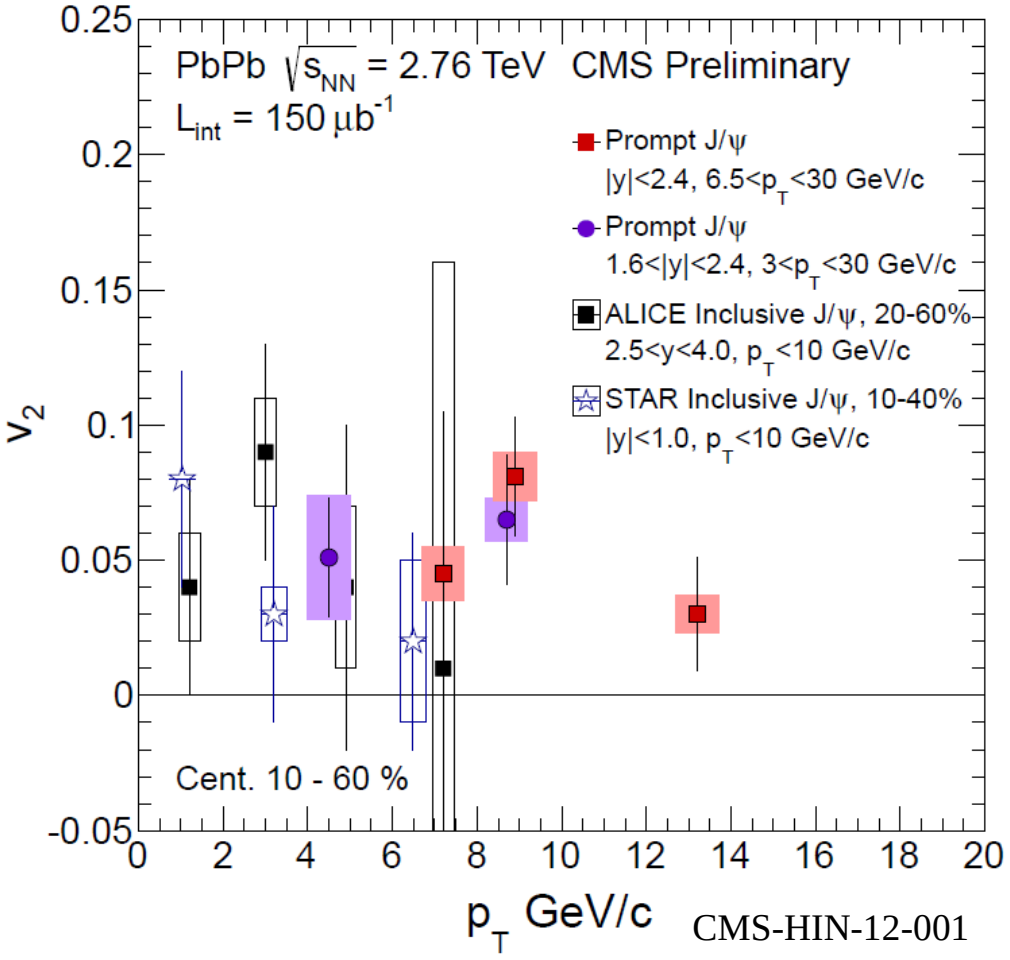
$R_{J\gamma}$ = fraction of photons with a jet of $P_{TJet} > 30\ GeV$

Jet energy is essentially unmodified in p-Pb



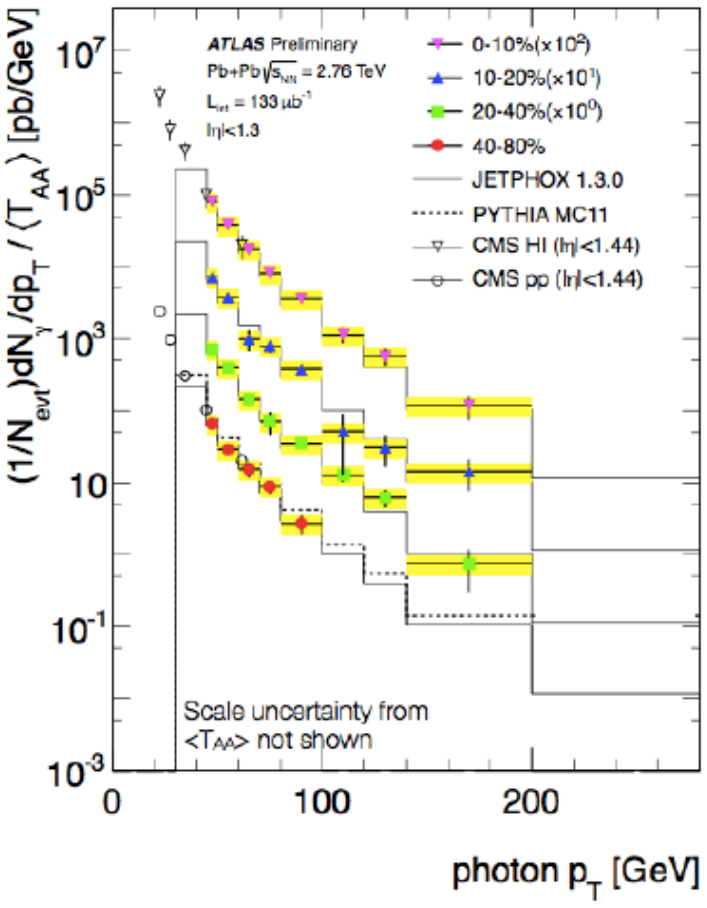
PAS-HIN-13-006

J/ψ azimuthal anisotropy

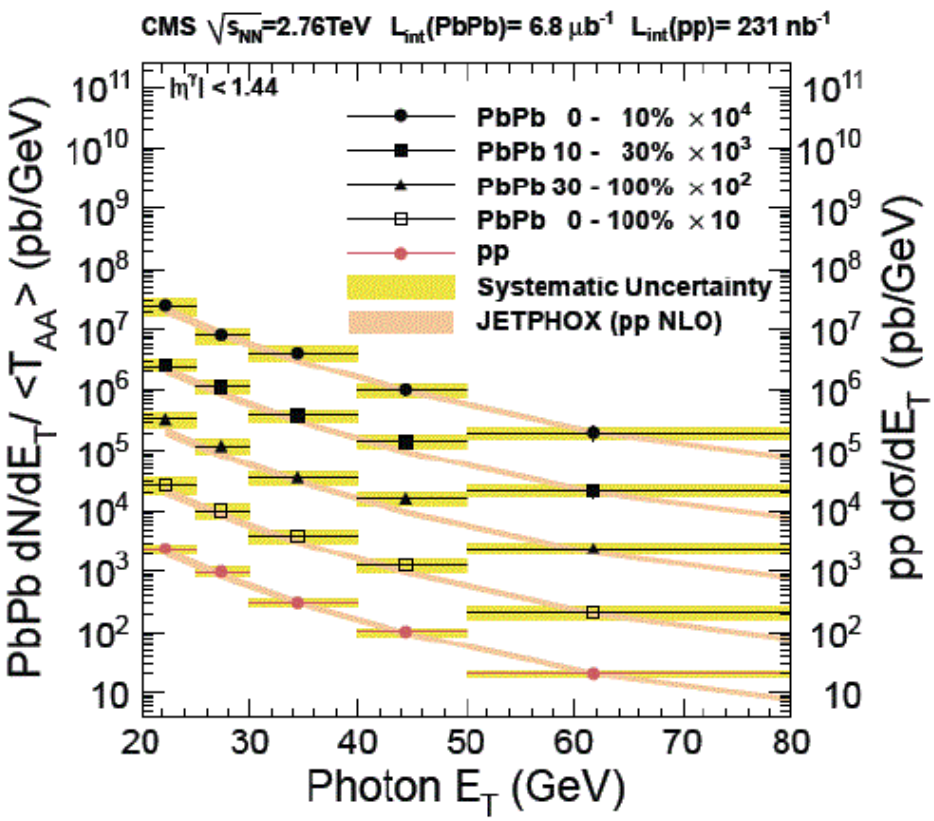


Prompt photon production

ATLAS-CONF-2012-051

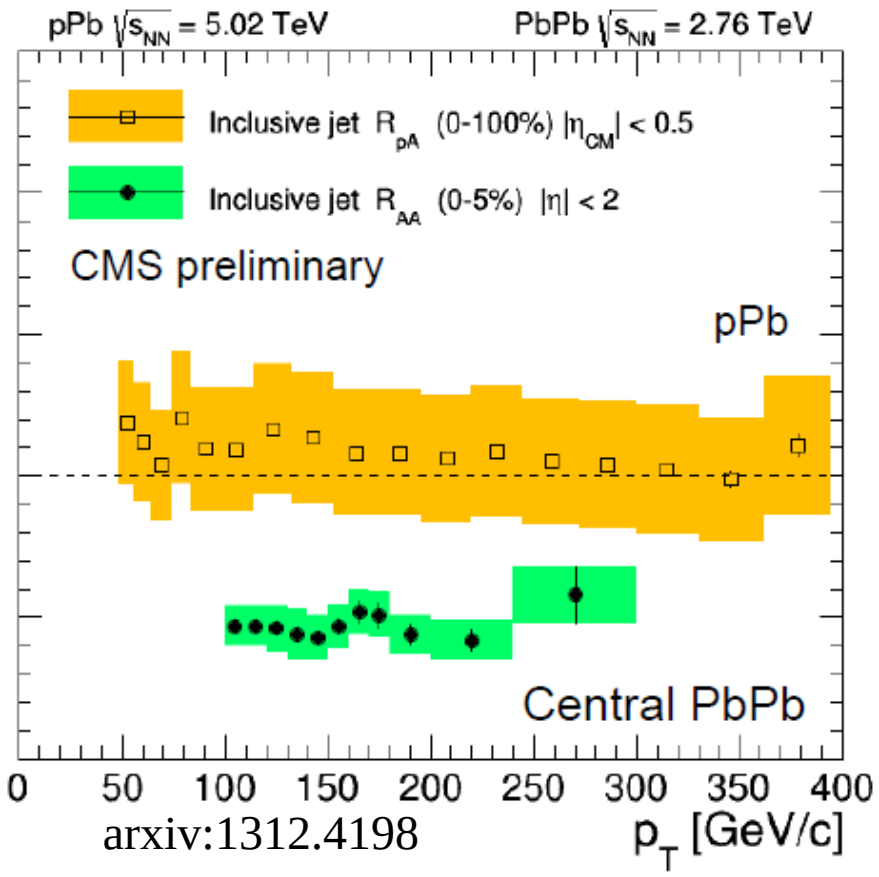


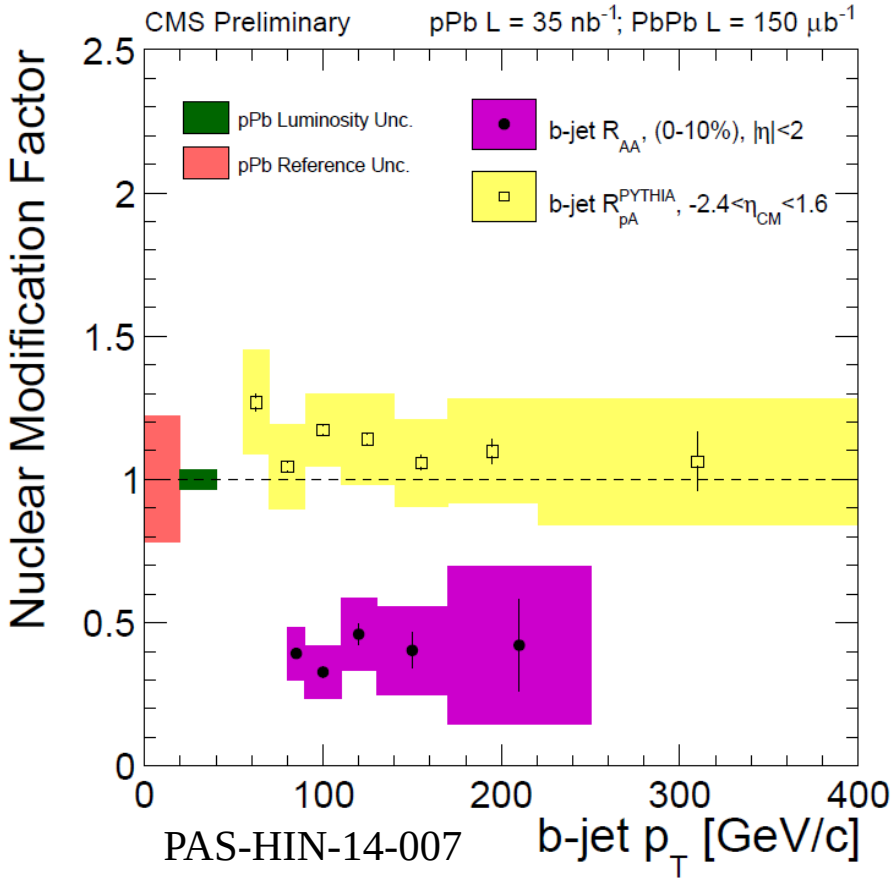
CMS, Phys. Lett. B 710 (2012) 256



Yields scaled by Taa and compared to JETPHOX predictions

R_{pA} vs R_{AA} for jets and b jets





Jets coming from b (second vertex)

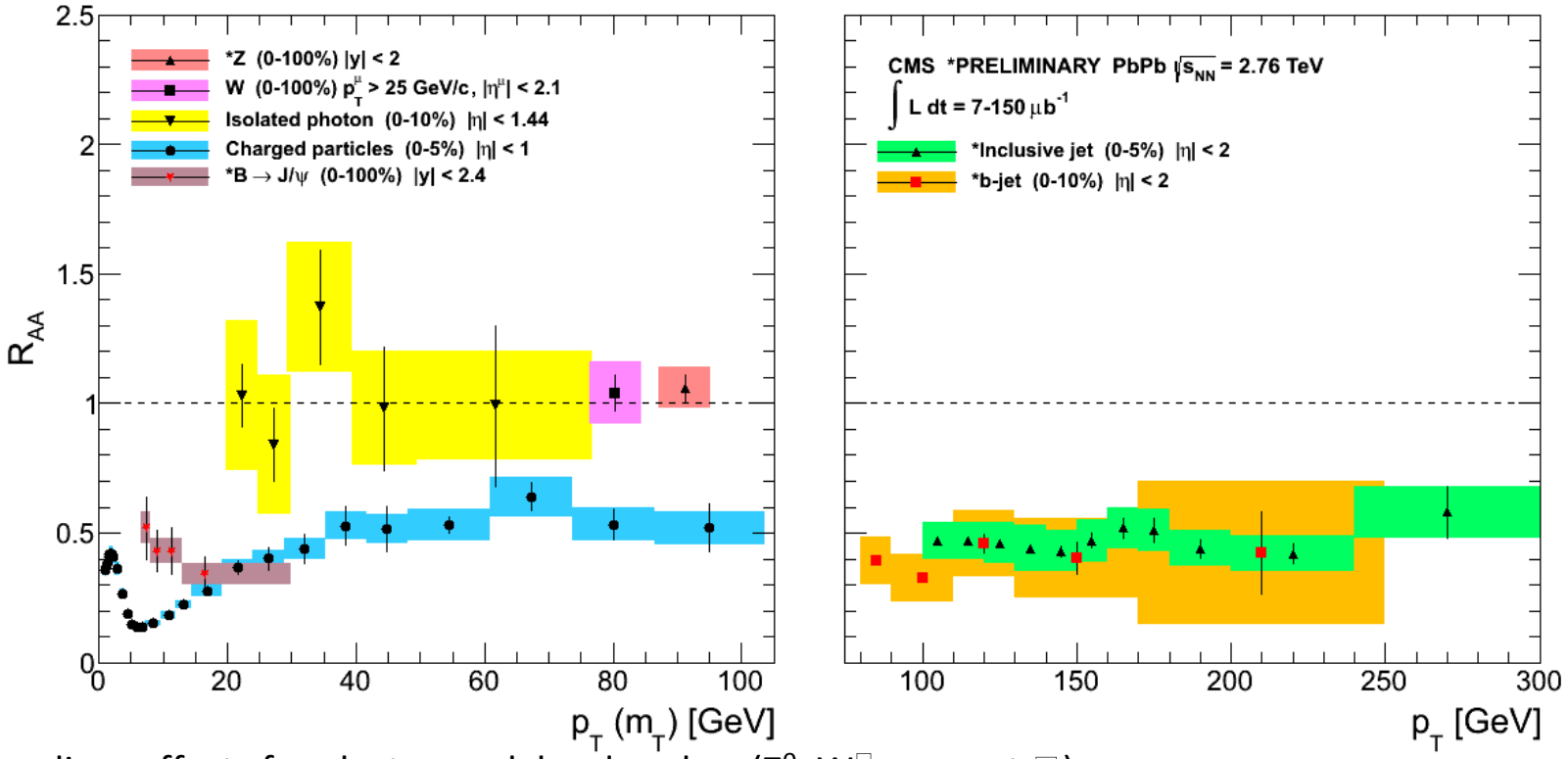
– as suppressed as incl. jets ($R_{AA} \approx 0.5$)

– not suppressed in pPb ($R_{pA} \approx 1$)

Nuclear modifications factors in Pb-Pb (hadrons, jets, b-jets, secondary J/ψ, electroweak probes)

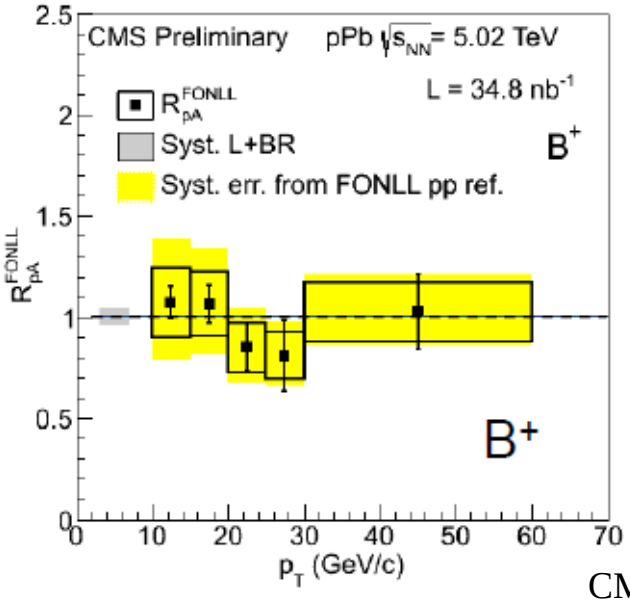
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T\, d\eta}{d^2 \sigma_{pp}/dp_T\, d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum“}}$$

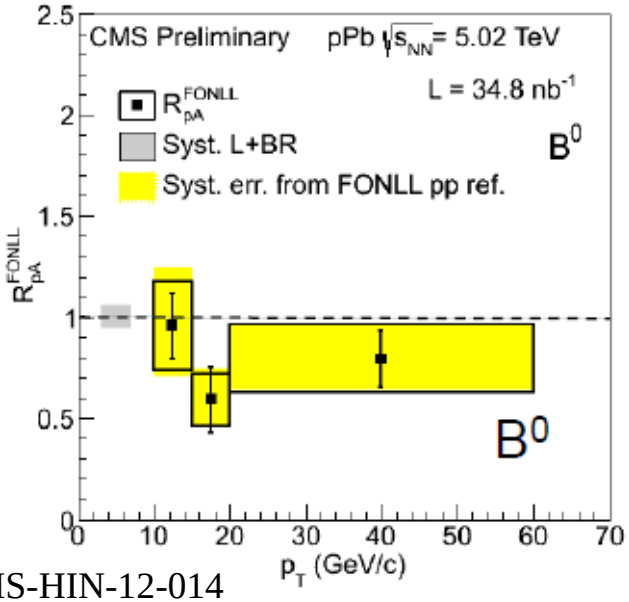
R_{AA}>1: enhancement
R_{AA}=1: no medium effect
R_{AA}<1: suppression

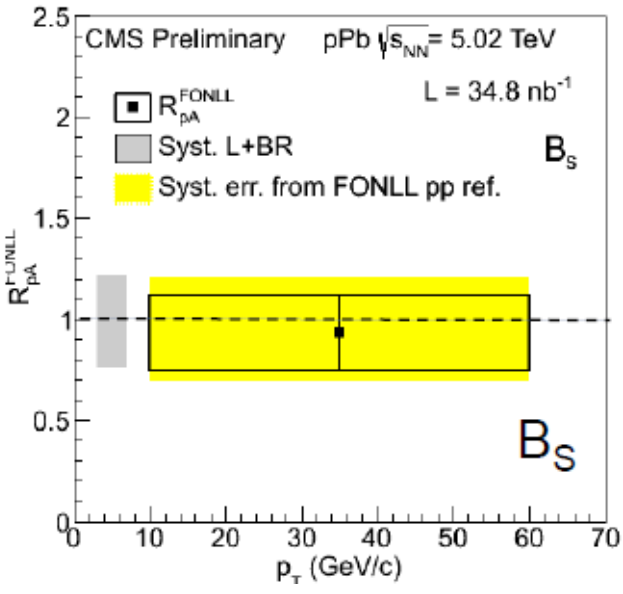


- No medium effects for electroweak hard probes (Z^0, W□, prompt □)
- Charged particles and jets are suppressed, suppression factors saturate at high transverse momentum
- Observation of b-quark (via secondary J/ψ's) suppression
- B-jets (*extracted using vertex info*) seem suppressed on the similar level as inclusive jets

B mesons in p-Pb and Pb-Pb



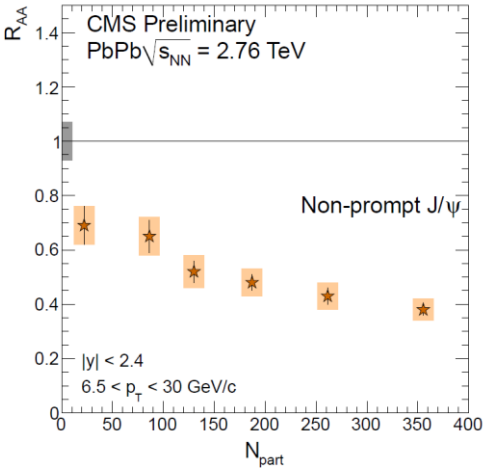




CMS-HIN-12-014

B decays shows no suppression in p-Pb

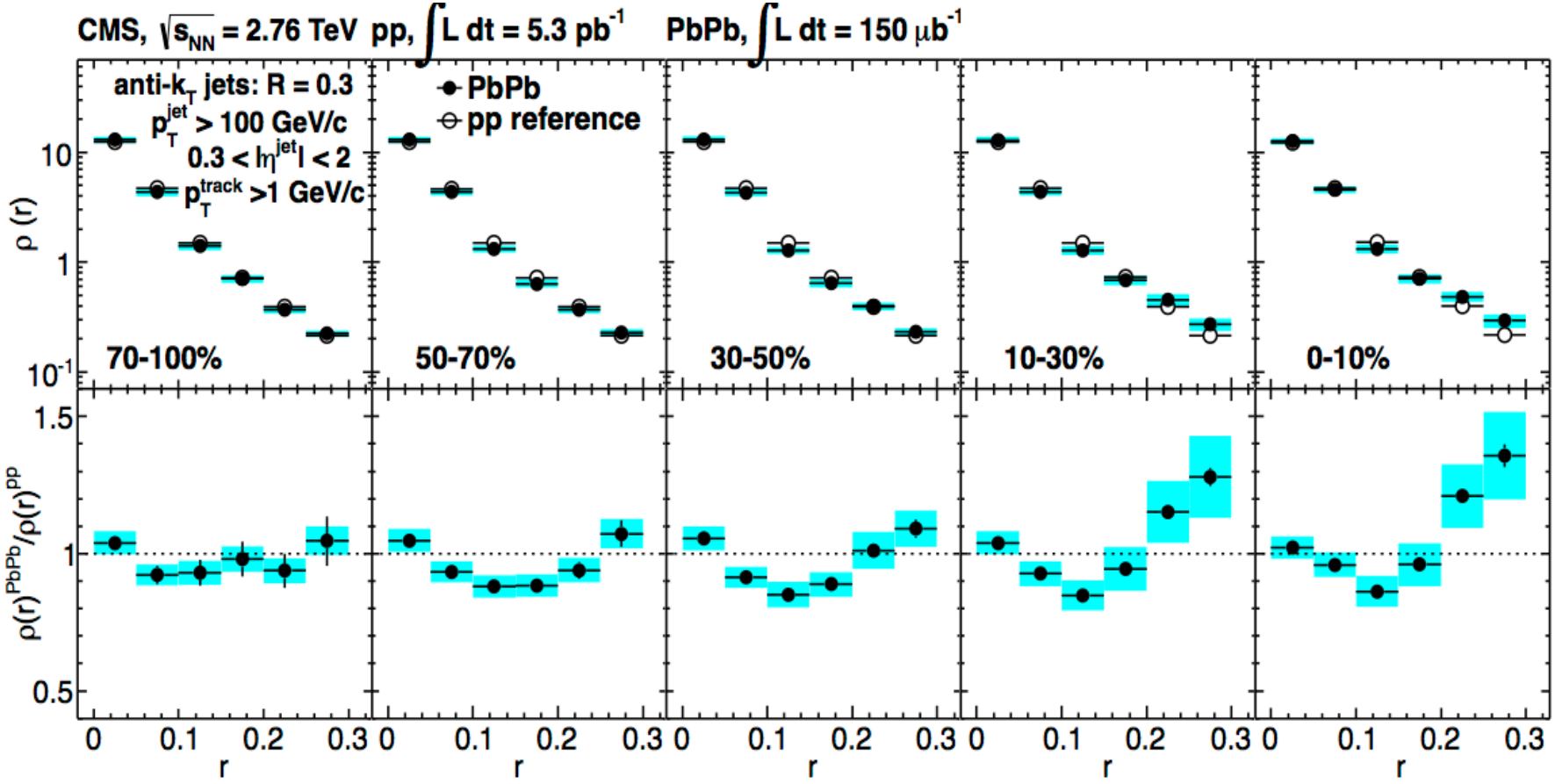
Strong suppression in Pb-Pb



arxiv:1312.4198

Jet shapes in Pb-Pb

$$\rho(r) \sim \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{p_{\text{T}}(r-\delta r/2, r+\delta r/2)}{p_{\text{T}}^{\text{jet}}}$$



The modifications of radial jet profile: excess at large radii but core is unchanged