Jets, W, Z in pA and AA:

ATLAS and CMS

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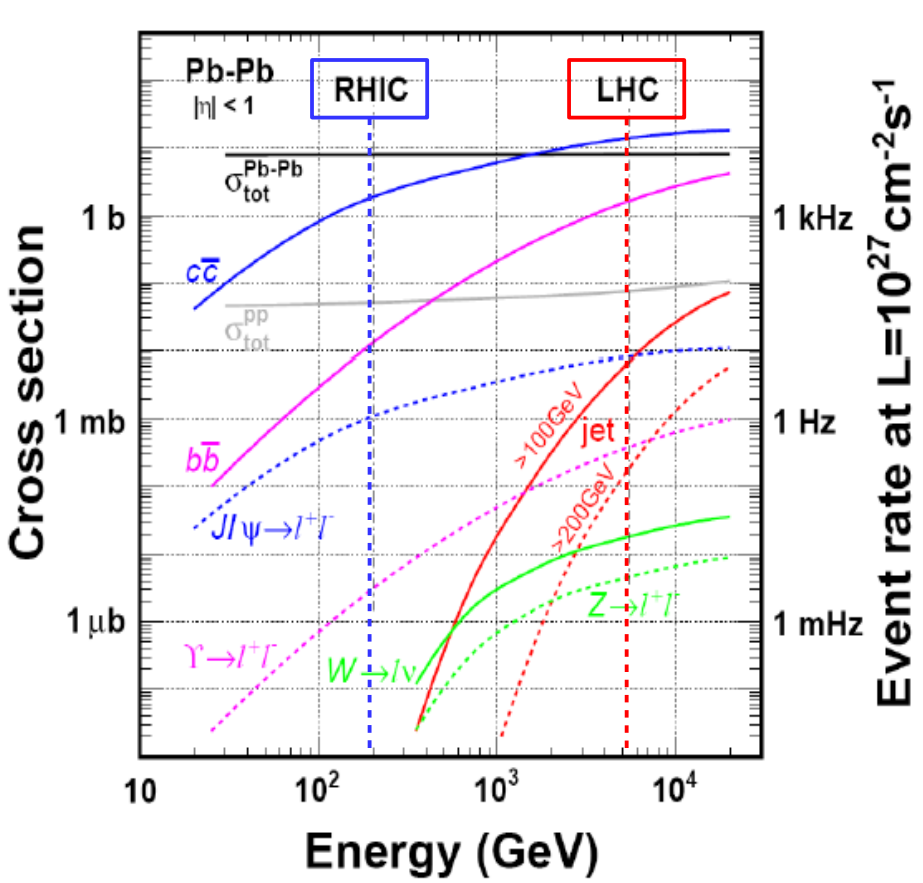
On behalf of the ATLAS and CMS collaborations

LHCP 2015
St Petersburg, Sept 2015

Outline

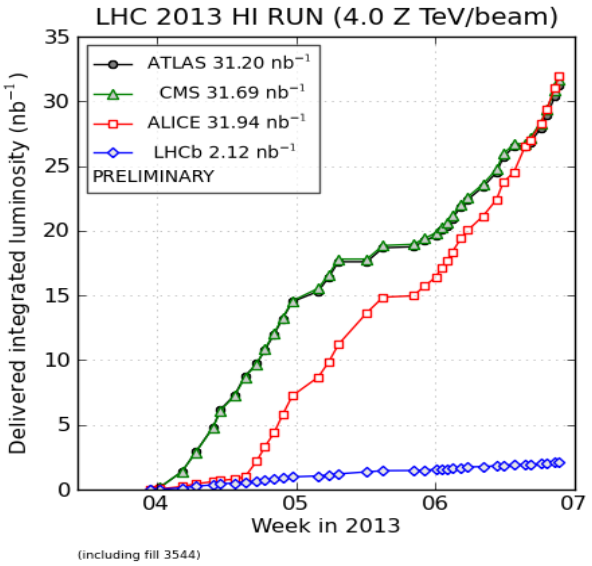
- Introduction: Heavy Ion collisions in LHC Run1
- Jet measurements
  - Jet quenching in PbPb collisions
  - Proton-Lead collisions analysis
  - Jet fragmentations studies
- W and Z bosons measurement
  - PbPb collisions
  - pPb collisions



Heavy Ions in LHC Run1

Year	Collisions	$\sqrt{s_{NN}}$ (TeV)	Integrated Luminosity (LHC Delivered)
2010	Pb-Pb	2.76	9.6 μb^{-1}
2011	Pb-Pb	2.76	166 μb^{-1}
2013	p-Pb and Pb-p	5.02(*)	31 nb^{-1}
2013	pp	2.76	5500 nb^{-1}

(*) $y_{CM}=\pm 0.465$

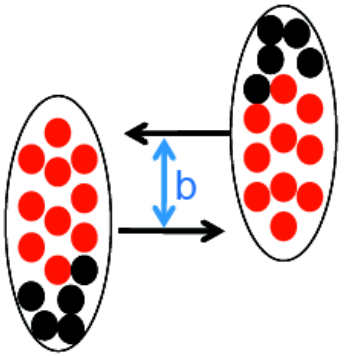


ALICE detector designed for PbPb collisions
ATLAS and CMS multipurpose experiments
→ For heavy Ions too
In 2013 p-Pb runs also LHCb joined the game!

Heavy Ion collisions characteristics

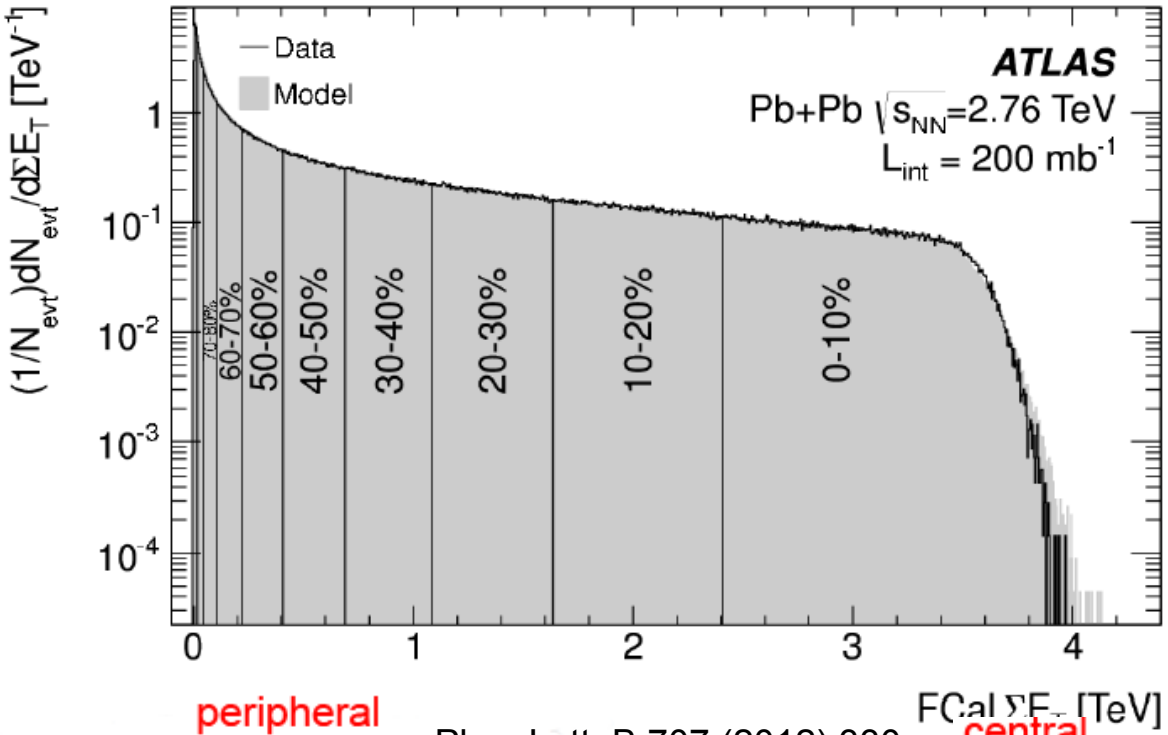
Experimentally:

- PbPb collisions are characterized by impact parameter b
  → Centrality (small b → central events, large b → peripheral events)



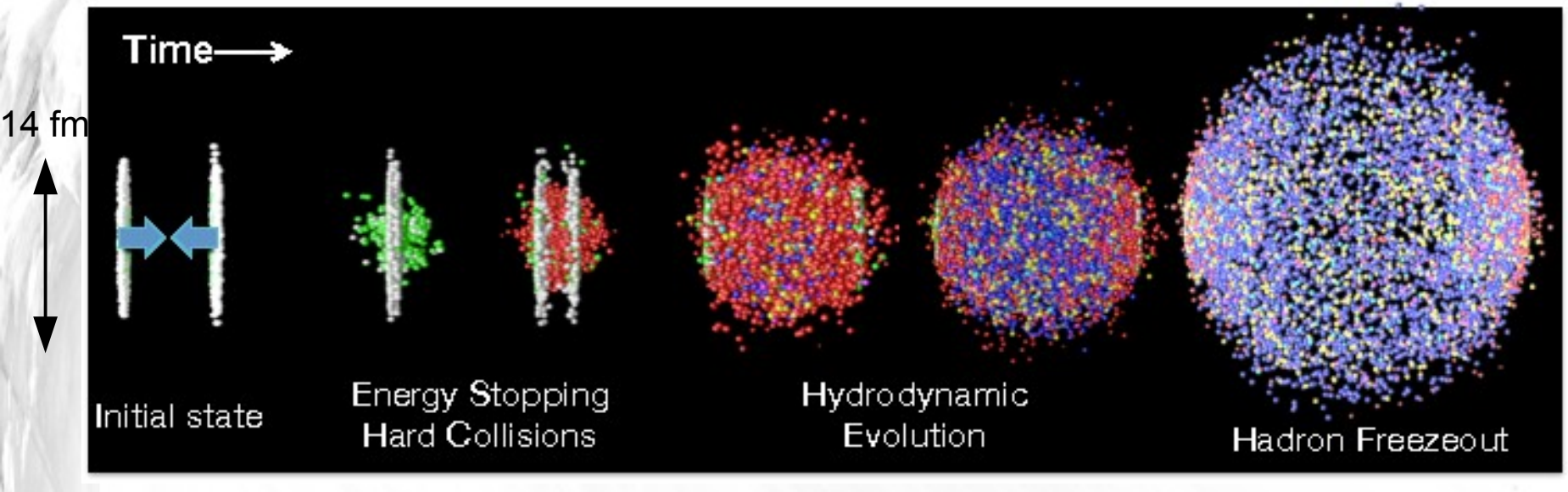
- Measuring energy deposition in forward regions (ATLAS: 3.2<|η|<4.9 CMS: 3.0<|η|<5.2)
  → Centrality and Number of binary collision N_{Coll} through Glauber model

N_{coll} is the key parameter to disentangle measurements from geometry to collective effects



Phys Lett. B 707 (2012) 330

Probes of QCD medium



Hadronic jets are produced by hard scattering process (calculable in pQCD) → Evolve in the QCD medium

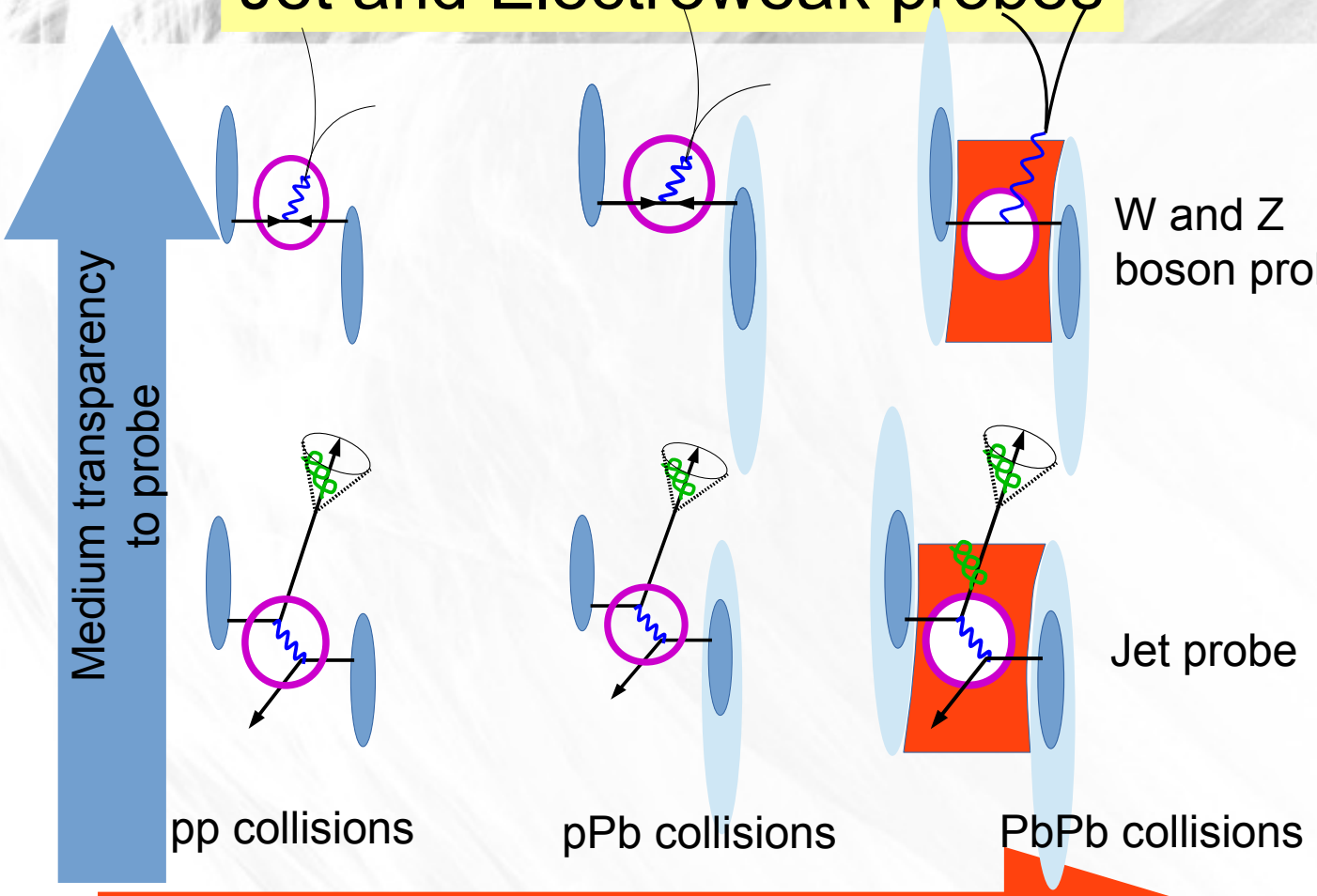
→ Probes for QCD medium produced in PbPb collisions.

Hints from decrease of energy balanced dijet events by experiments at RHIC experiments

→ Definitive proof of jet quenching in first 2010 LHC PbPb run.

However also other effects (nPDF, ...) enter the game → need non-strong probes as well (W and Z bosons)

Jet and Electroweak probes



Hard scattering
PDF
Fragmentation functions

Hard scattering
nPDF
Fragmentation functions

Hard scattering
nPDF
Fragmentation functions
Dense QCD Matter

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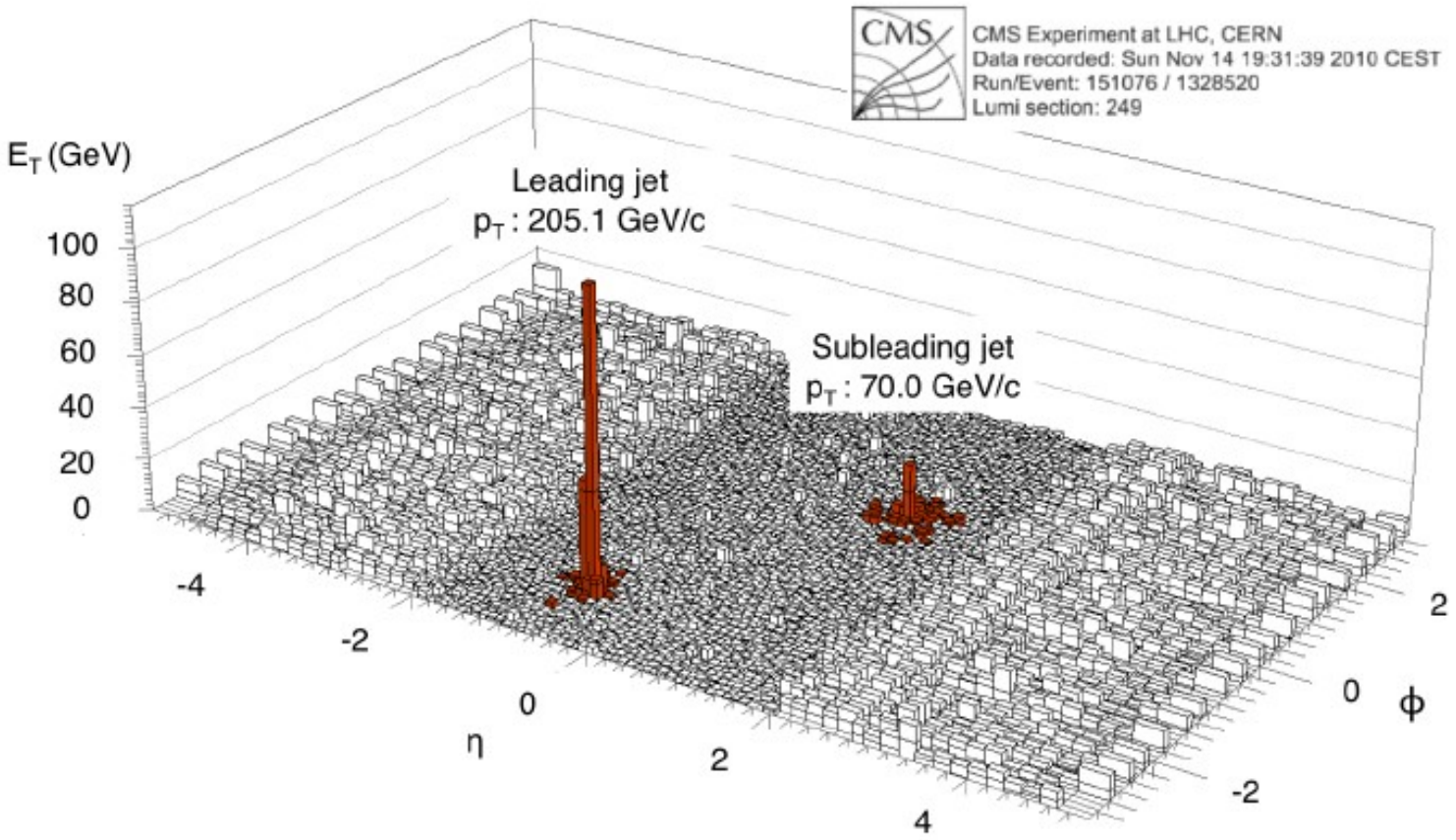
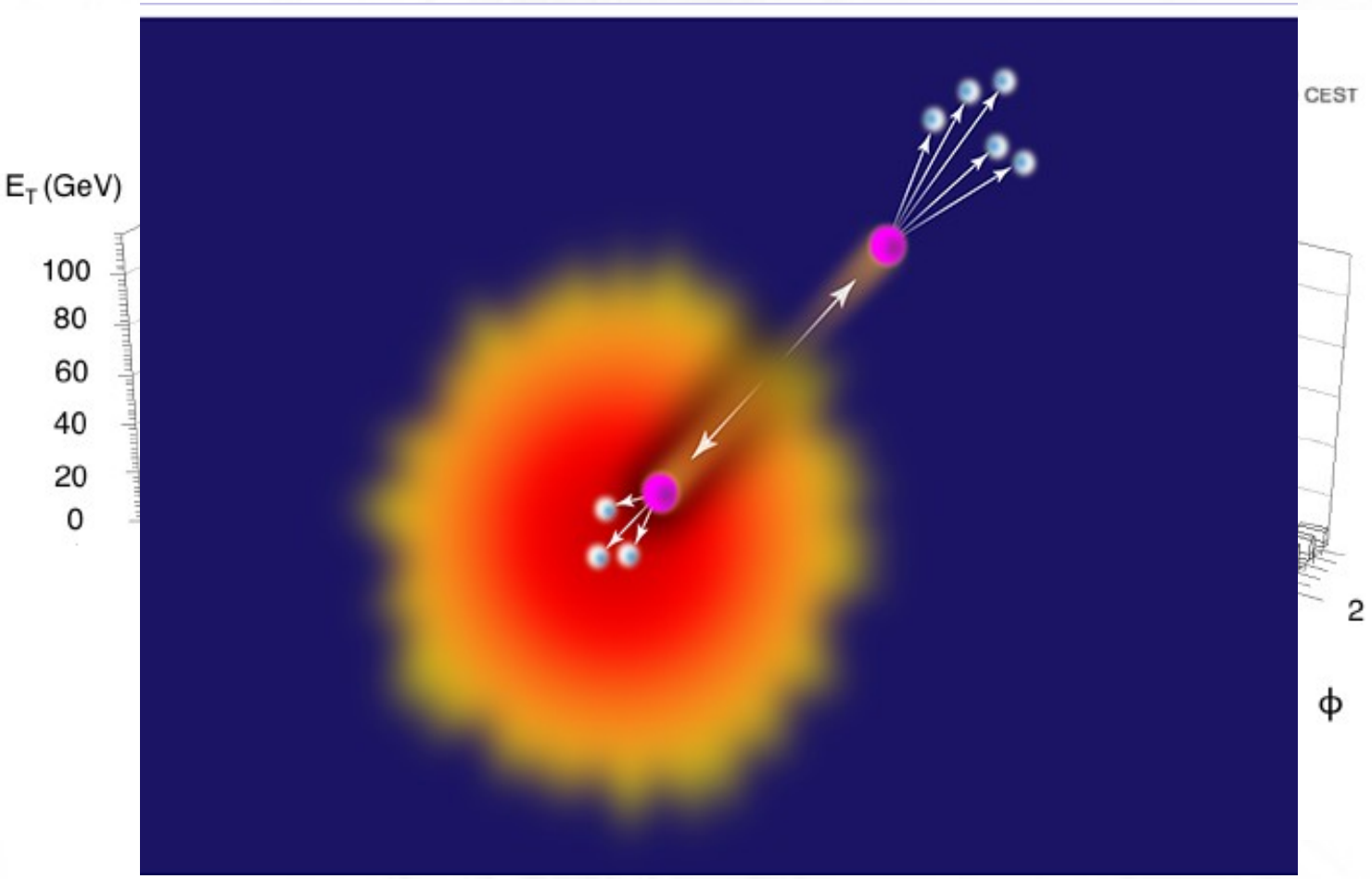
Jet Quenching



CMS event display of PbPb 2010 collisions.
Dijet event with apparent unbalance of transverse momentum

Jet Quenching



CMS event display of PbPb 2010 collisions.
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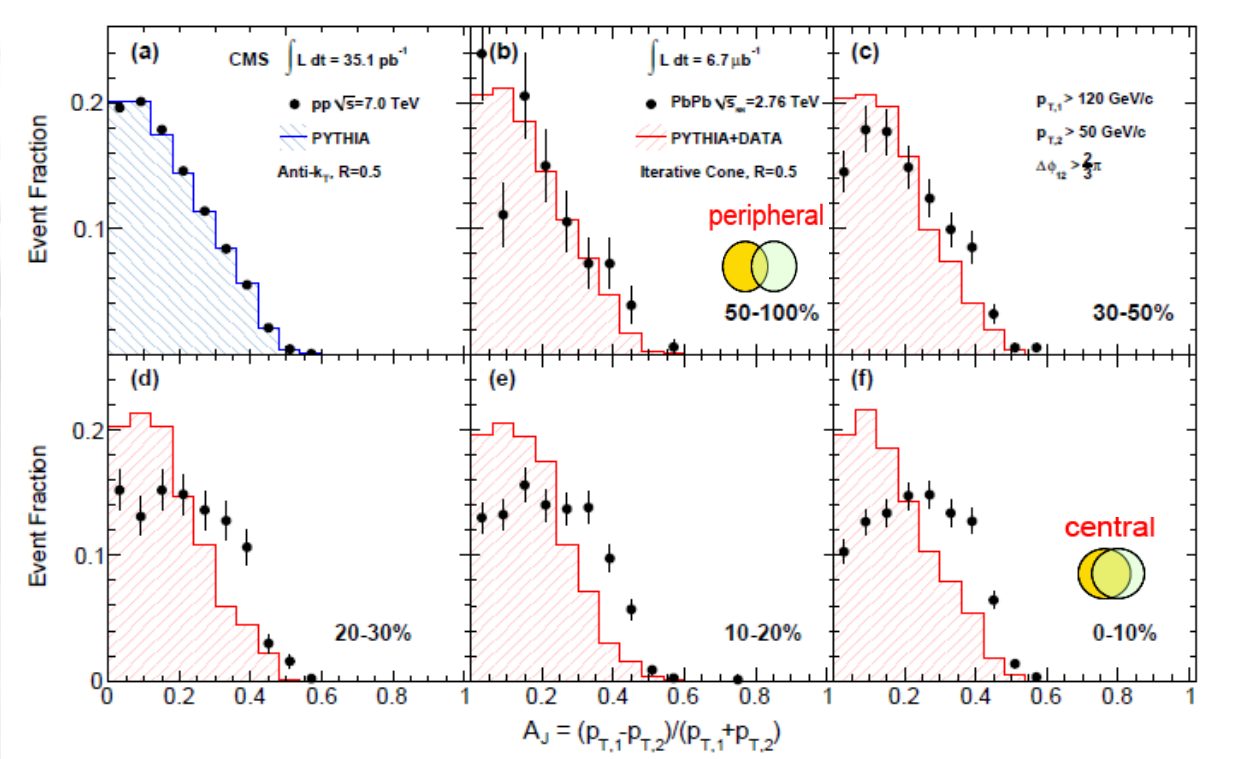
Jet Quenching: PbPb



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

Asymmetry of dijet events:
P_{T1}>120 GeV,
P_{T2}>50 GeV,
$\Delta\phi_{12}$>2π/3 (back to back)

Peripheral event asymmetry close to pp data → Asymmetry peaked at 0
Momentum unbalance with increasing centrality → Disagreement wrt pp collisions

CMS:
Phys Rev C **84** (2011) 024906
ATLAS:
Phys Rev Lett **105** (2010) 252303

Modification Nuclear Factor: PbPb

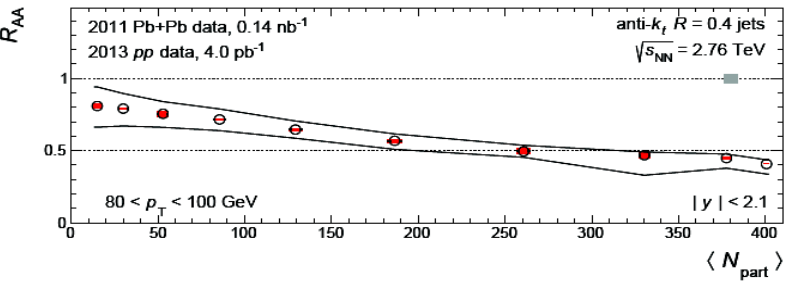
More quantititative measurement using pp data ($\sqrt{s}$=2.76 TeV) as reference and estimating R_{AA}, the nuclear modification factor

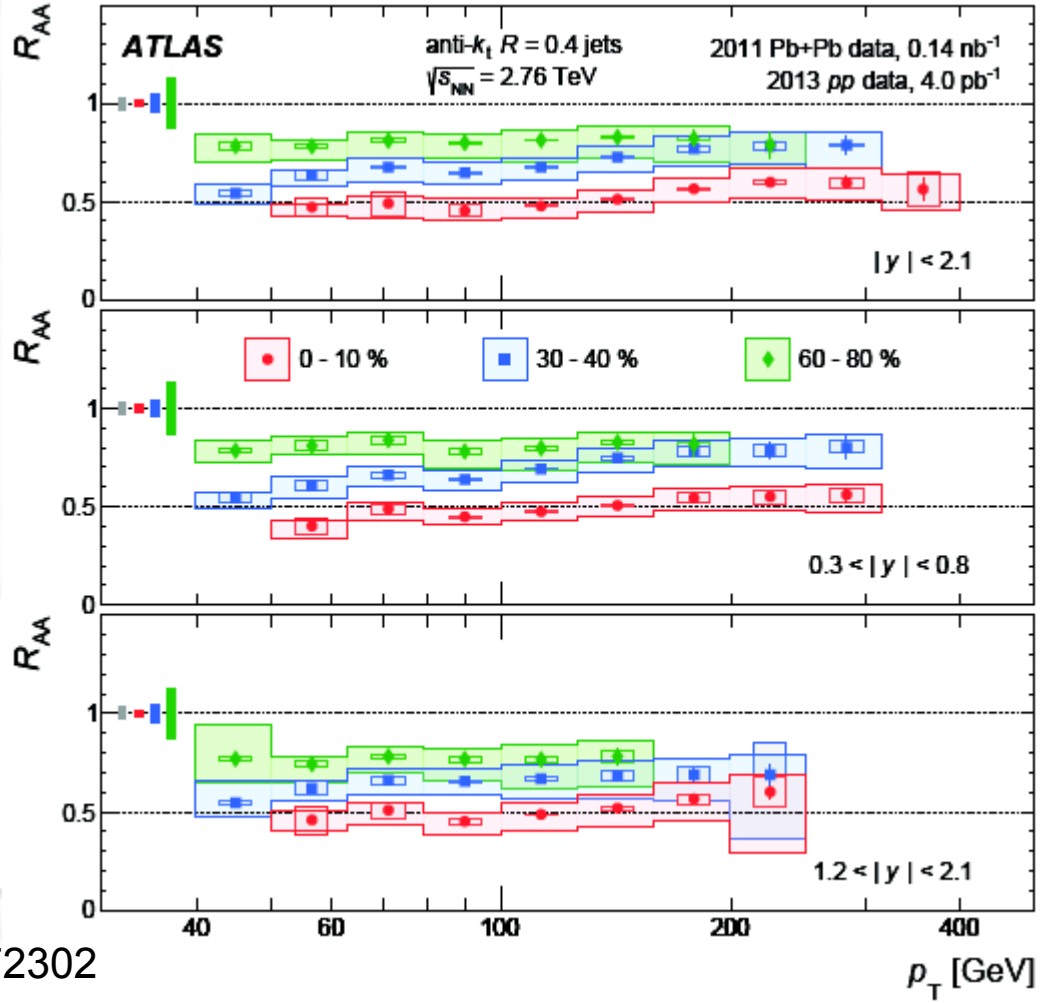
$$R_{AA} = \frac{\frac{1}{N_{evt}} \frac{d^2 N_{jet}}{dp_T dy}\Big|_{central}}{\langle T_{AA} \rangle \frac{d^2 \sigma^{pp}_{jet}}{dp_T dy}}$$

From heavy ion at given centrality, rapidity etc...

Nuclear overlap geometrical function (from Glauber)

Cross section from pp data with same $\sqrt{s}_{NN}$





ATLAS: Phys Rev Lett **114** (2015) 072302

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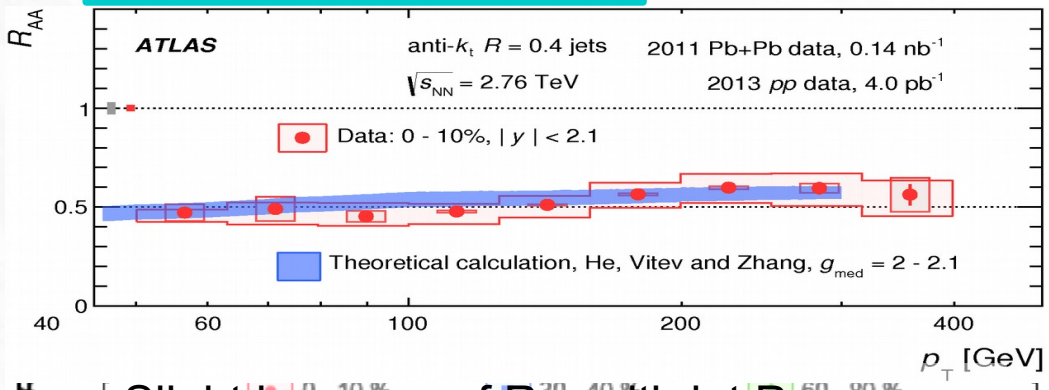
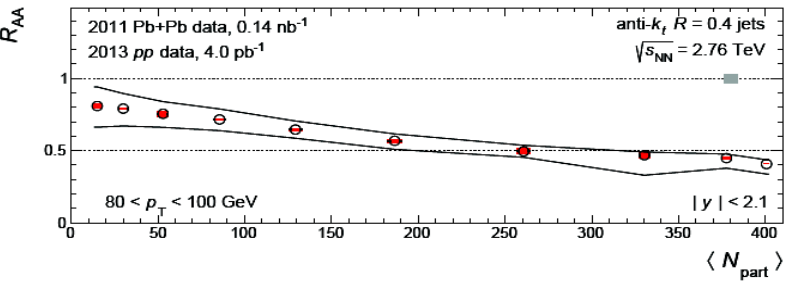
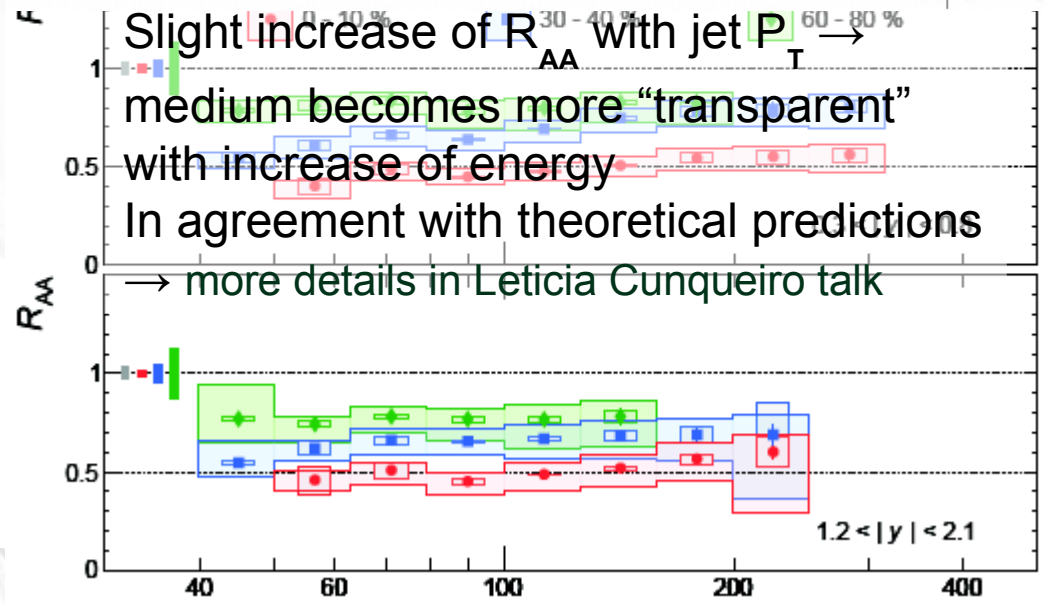




Slight increase of R_{AA} with jet P_T → medium becomes more "transparent" with increase of energy

In agreement with theoretical predictions

→ more details in Leticia Cunqueiro talk

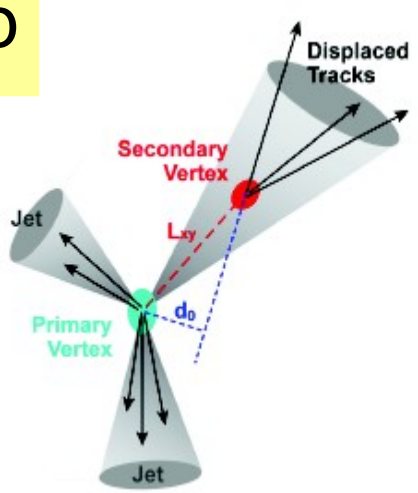


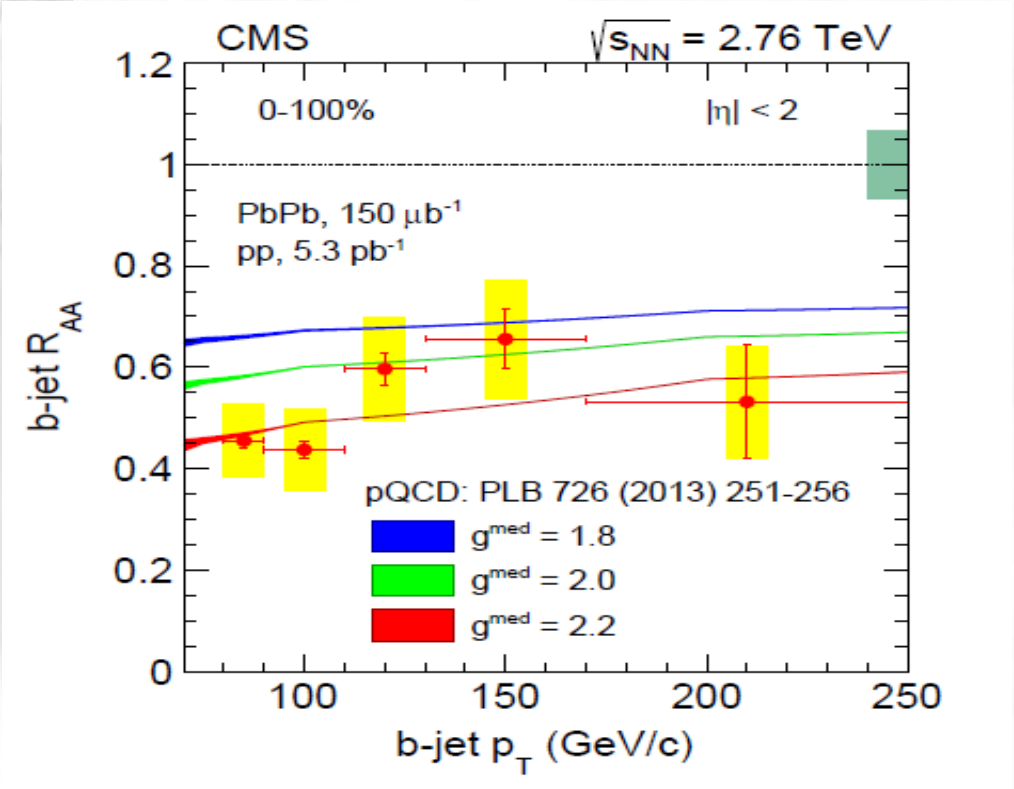
ATLAS: Phys Rev Lett **114** (2015) 072302

CMS: PAS-HIN-12-004

R_{AA} for b-quark jets: PbPb

Is jet quenching affected by the nature of the parton originating the probe jet? Check with sample enriched with b-jets using b-tagger





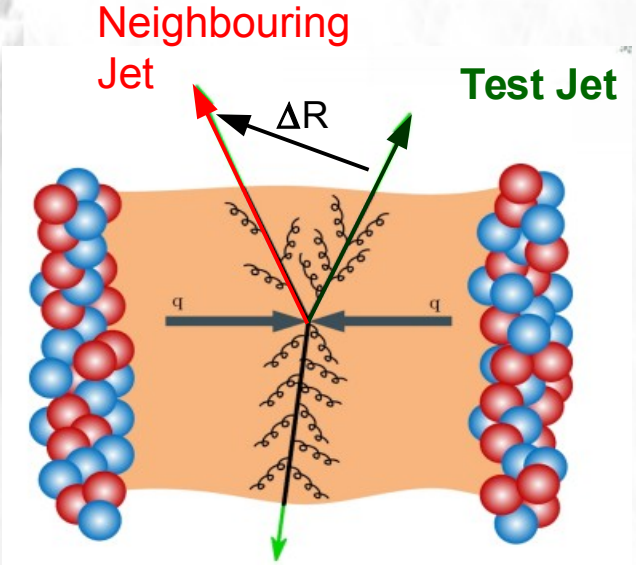
R_{PbPb} for b-jet similar value to R_{pbPb} for inclusive jet

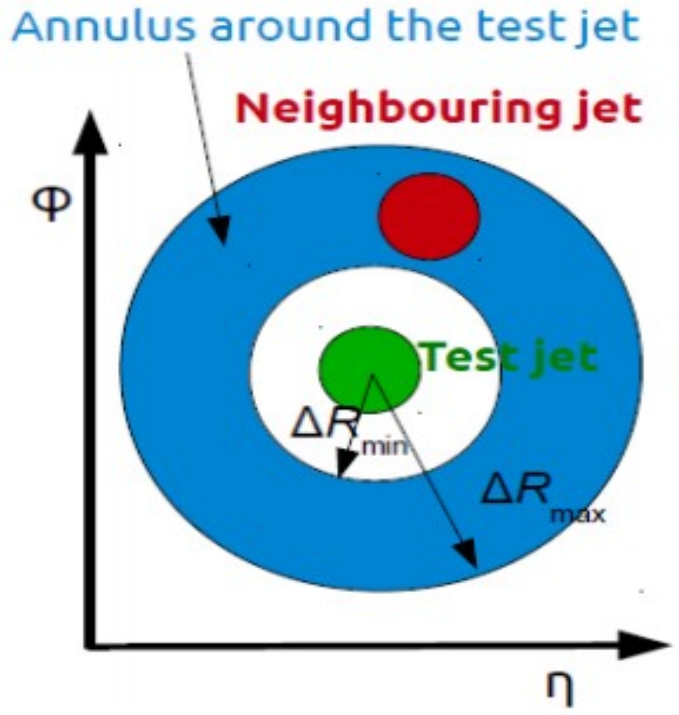
→ Jet quenching seems not to be affected by probe nature

CMS:
Phys Rev Lett **113** (2014) 132301

Neighbouring Jets: PbPb

Jets close in ΔR should have similar path lengths in QCD medium
→ Study fluctuations in energy loss in medium





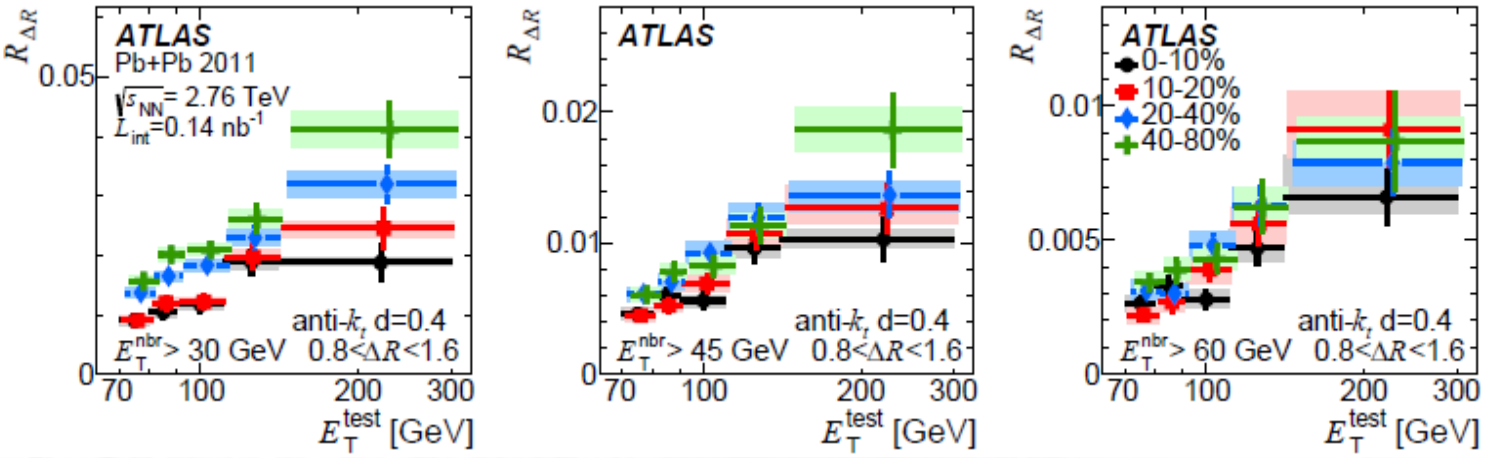
$$R_{\Delta R} = \frac{1}{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{test}}/\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}} \sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} \frac{\mathrm{d}N_{\mathrm{jet},i}^{\mathrm{nbr}}}{\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T,min}}^{\mathrm{nbr}}, \Delta R)$$

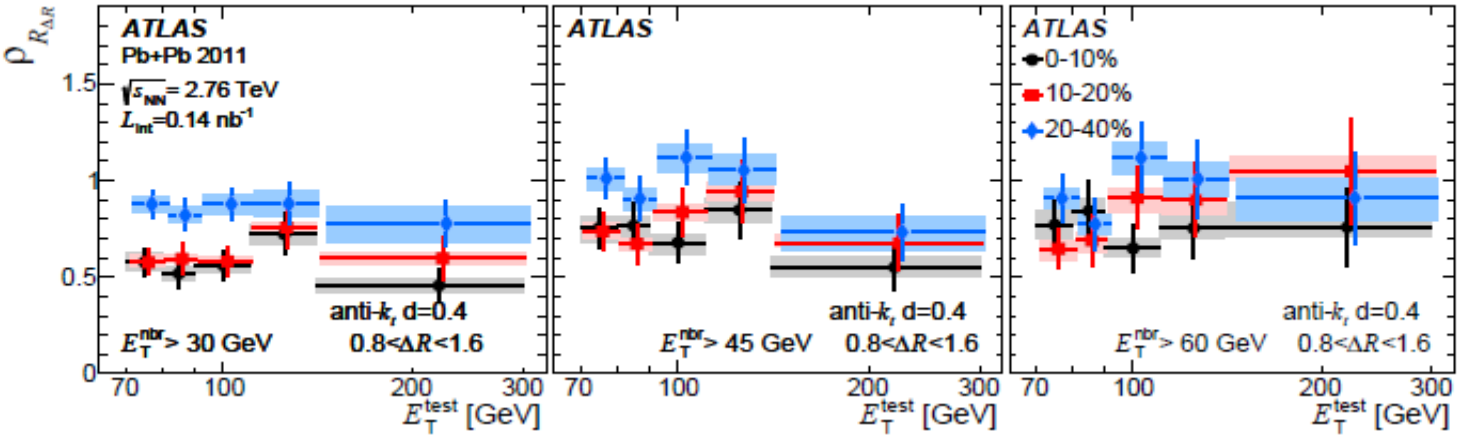
ρ(RΔR) → Normalized to 40%-80% centrality

Useful input for constraining theoretical models of fluctuations in the energy loss

ATLAS: arXiv:1506.08656
Submitted to Phys Lett B

Neighbouring Jets: PbPb





Suppression of factor ~0.5 confirmed

$\rho_{R\Delta R}$ almost independent on E^{test}

Weak increase of with $\rho_{R\Delta R}$ with E^{Nbr}

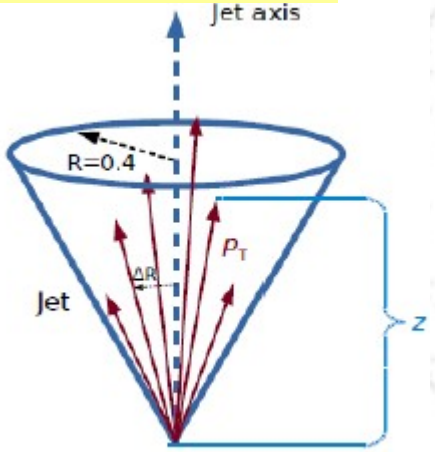
ATLAS: arXiv:1506.08656
Submitted to Phys Lett B

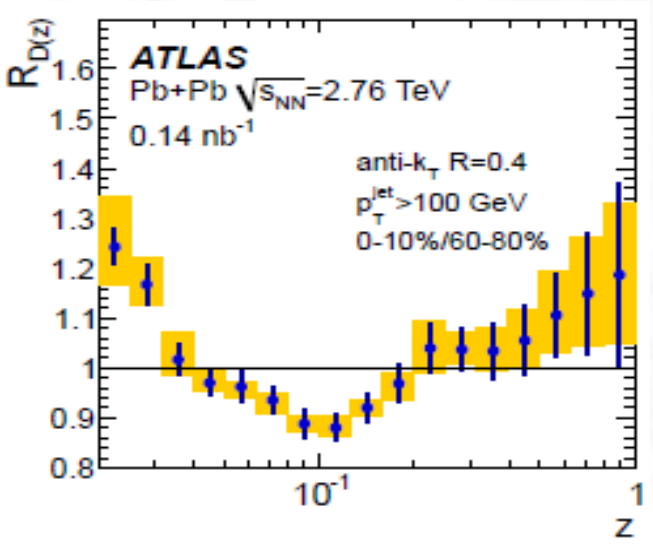
Jet Fragmentation Modifications:PbPb

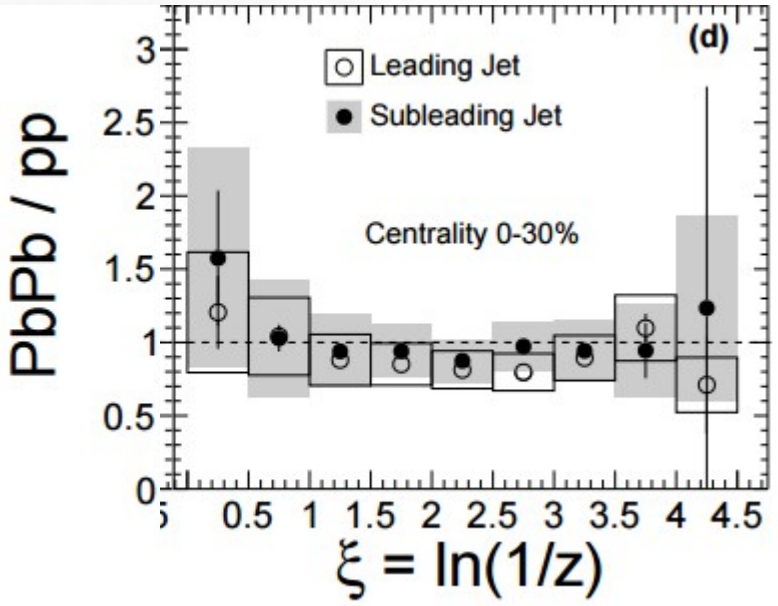
Dense QCD matter alters also the momentum of particles inside jet
→ Jet fragmentation function ratios
→ In ATLAS more deviation than in CMS

$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{\text{ch}}}{\mathrm{d}z},$$

$$z = \frac{\vec{P}_{T,ch} \cdot \vec{P}_{T,Jet}}{|P^2_{T,Jet}|}$$





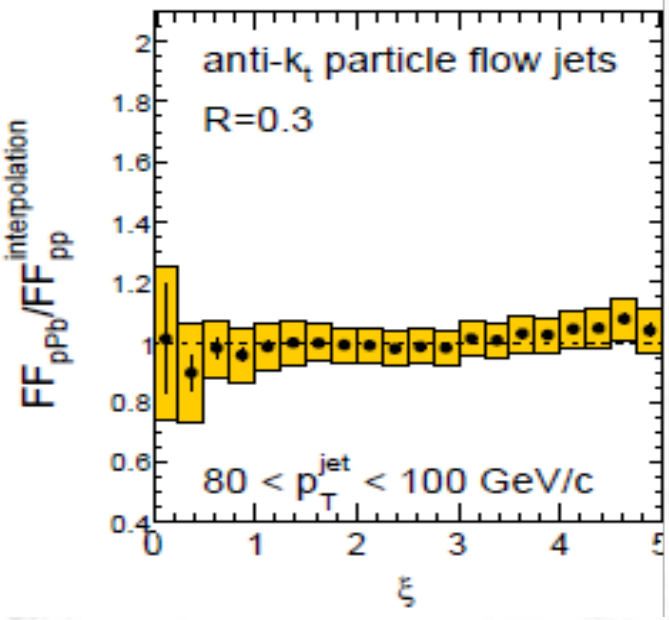


ATLAS: Phys Lett B **739** (2014) 320-342

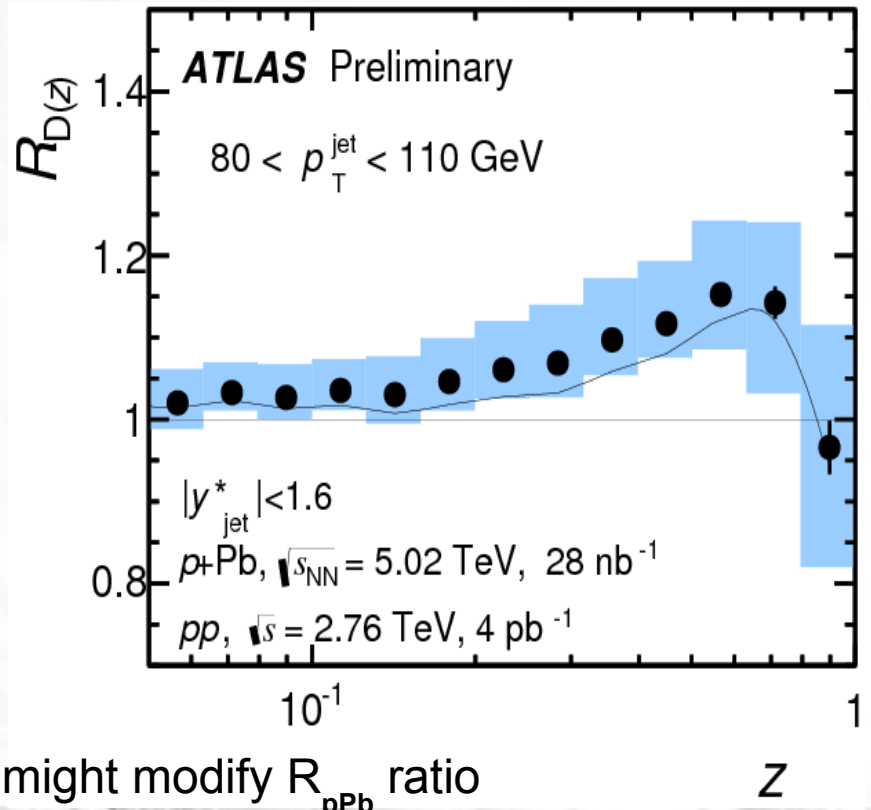
CMS: Phys.Rev. C**90** (2014) 024908.

Jet Fragmentation Modifications: pPb

In pPb collision tension between ATLAS and CMS measurements increase
no real data pp @ √s=5.02 TeV reference for fragmentation at 5.02 TeV
extrapolated from 2.76 TeV and 7 TeV
→ a pp data sample at 5.02 TeV would be very helpful in systematic reduction



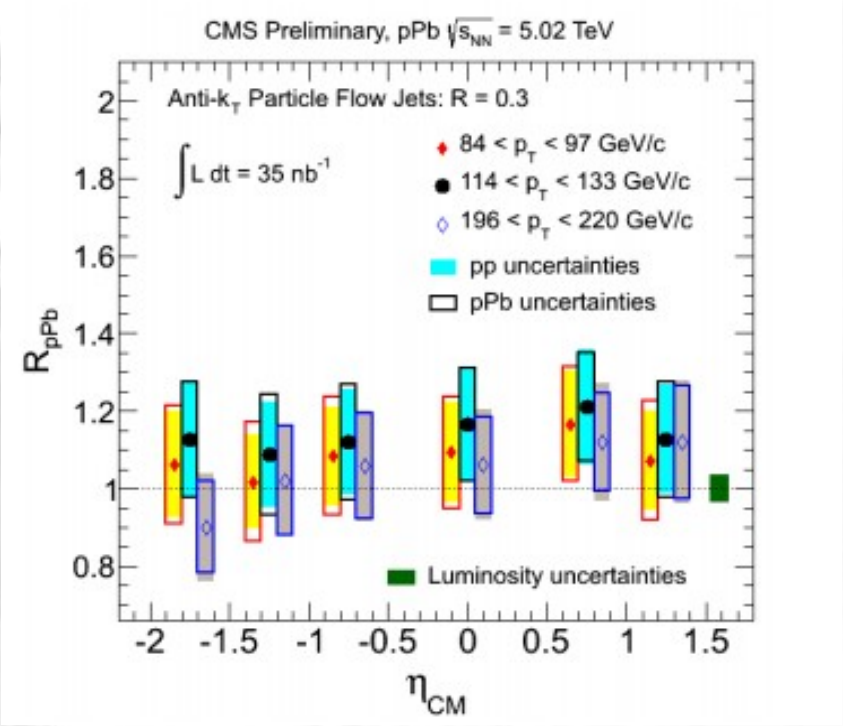
CMS PAS HIN-15-004



ATLAS-CONF-2015-022

Fragmentation function differences might modify R_{pPb} ratio

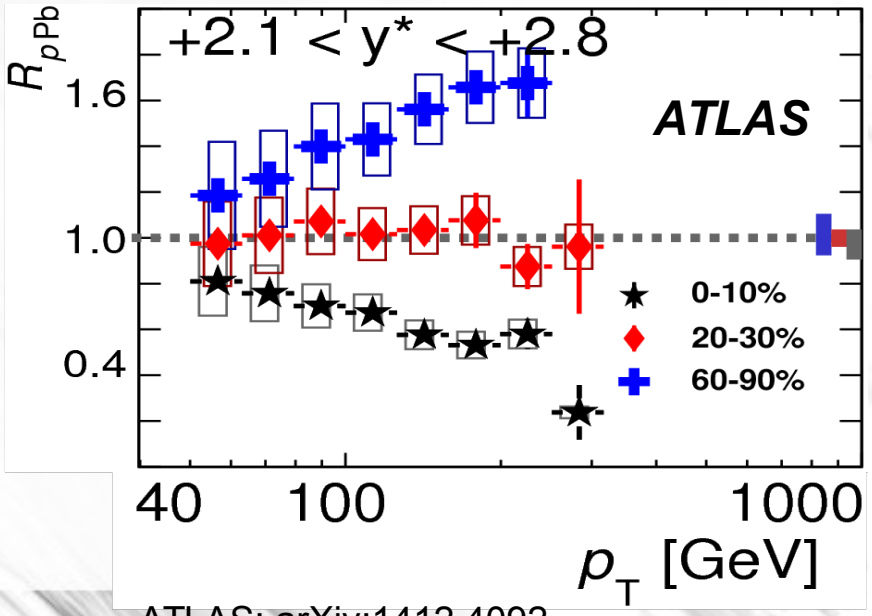
Nuclear Modification Factor in pPb



CMS PAS HIN-14-001

R_{pPb}~1 → No jet quenching in pPb collisions

Jet rapidity evaluated wrt CoM of collision (y_{CM}=0.465)

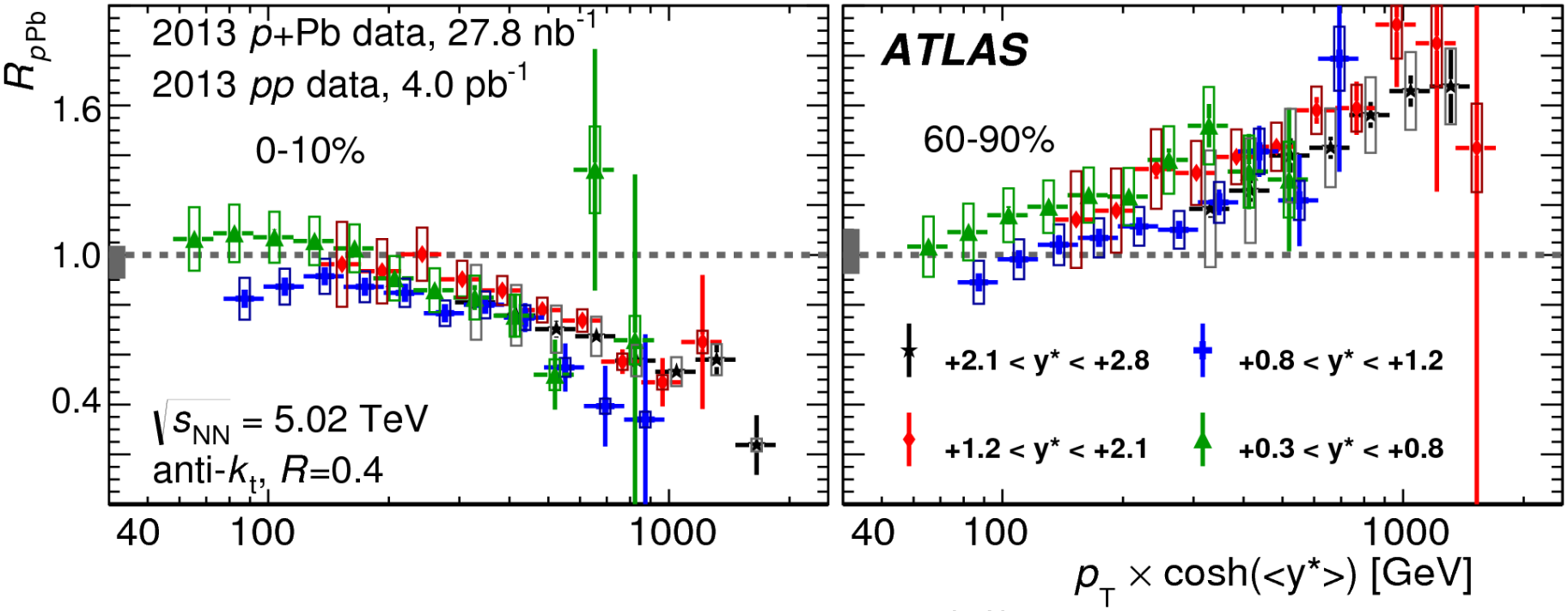


ATLAS: arXiv:1412.4092

R_{pPb} shows deviations from unity in centrality interval bins → Centrality definition slightly more problematic in pPb than in PbPb

Nuclear Modification Factor in pPb

ATLAS: arXiv:1412.4092



R_{pPb} scales with jet total energy $E \approx P_T \cosh(y^*)$

Possible explanations:

- Dependence on the initial parton kinematics (longitudinal momentum fraction of the parton) ? → Modification of nPDF?
- Correlation between kinematics of scattering and soft interaction? → Breakdown of factorization theorem in pPb colliisions?

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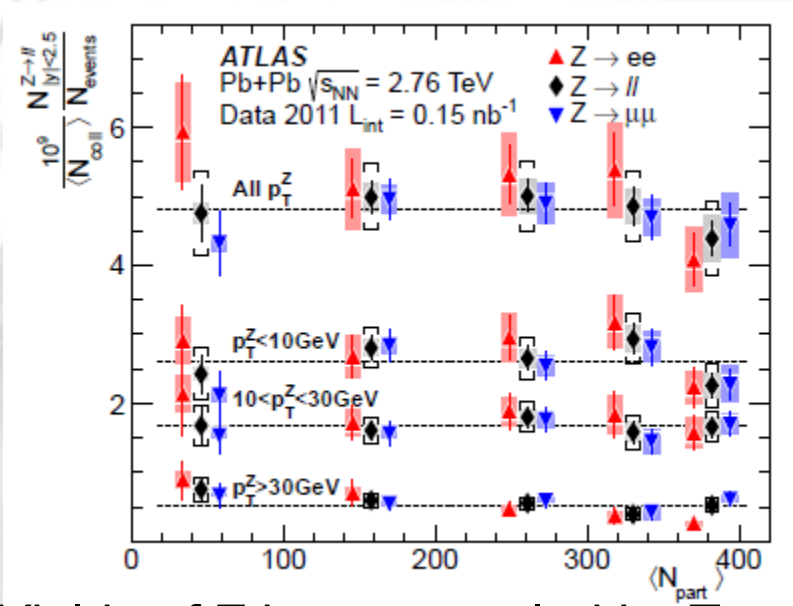
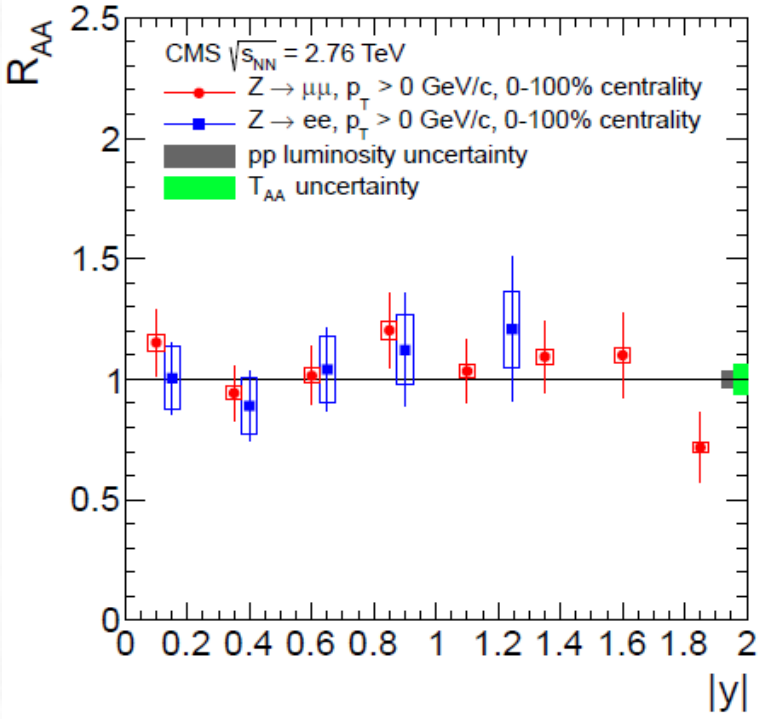
Z bosons in PbPb



Yields of Z bosons scaled by T_{AA} vs N_{part}



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

CMS: JHEP **03** (2015) 022

Electroweak bosons NOT affected by dense QCD matter

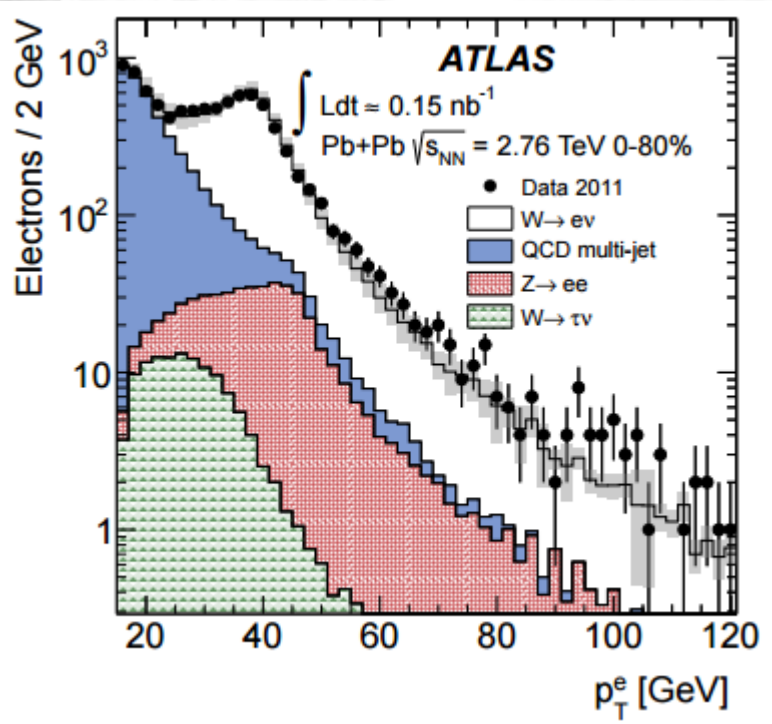
→ Electroweak probes provide an interesting framework for disentangling nPDF effects from QCD hot matter effects

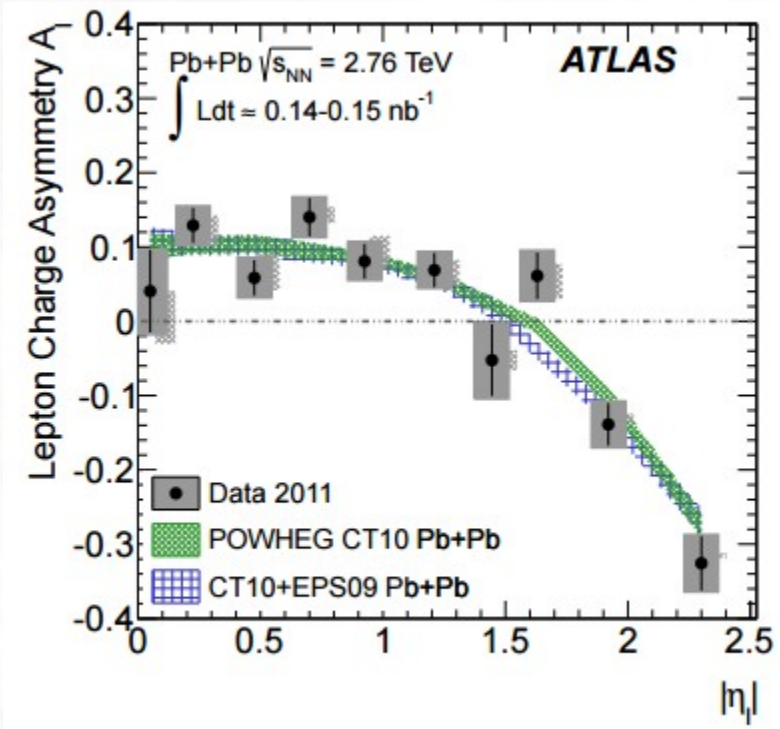
W bosons in PbPb

Use asymmetry measurements rather than differential cross section

→ Many uncertainties cancel out

$$A_\ell(\eta_\ell) = \frac{dN_{W^+\to\ell^+\nu_\ell}/d\eta_\ell - dN_{W^-\to\ell^-\bar{\nu}_\ell}/d\eta_\ell}{dN_{W^+\to\ell^+\nu_\ell}/d\eta_\ell + dN_{W^-\to\ell^-\bar{\nu}_\ell}/d\eta_\ell}$$





ATLAS: Eur. Phys. J. C (2015) 75:23

Z bosons in pPb

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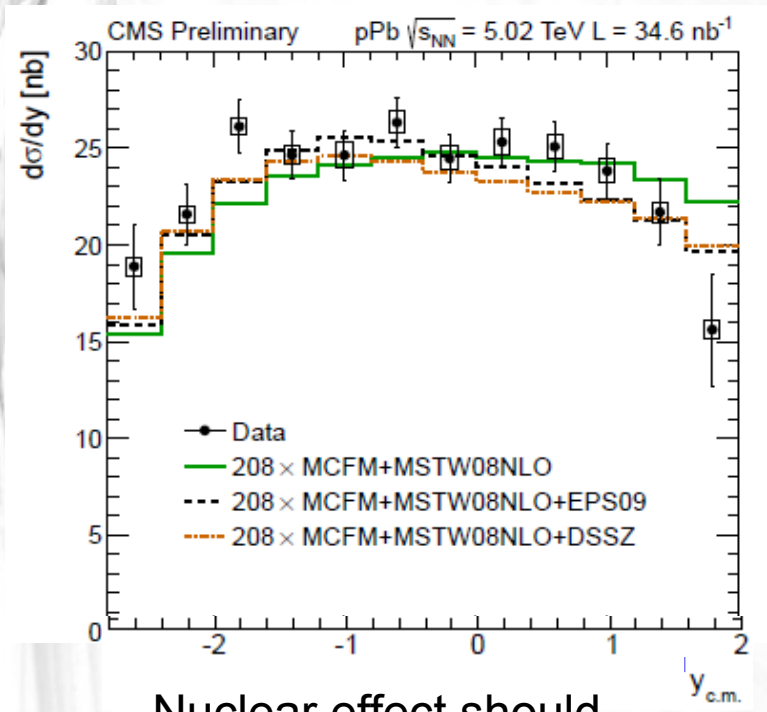
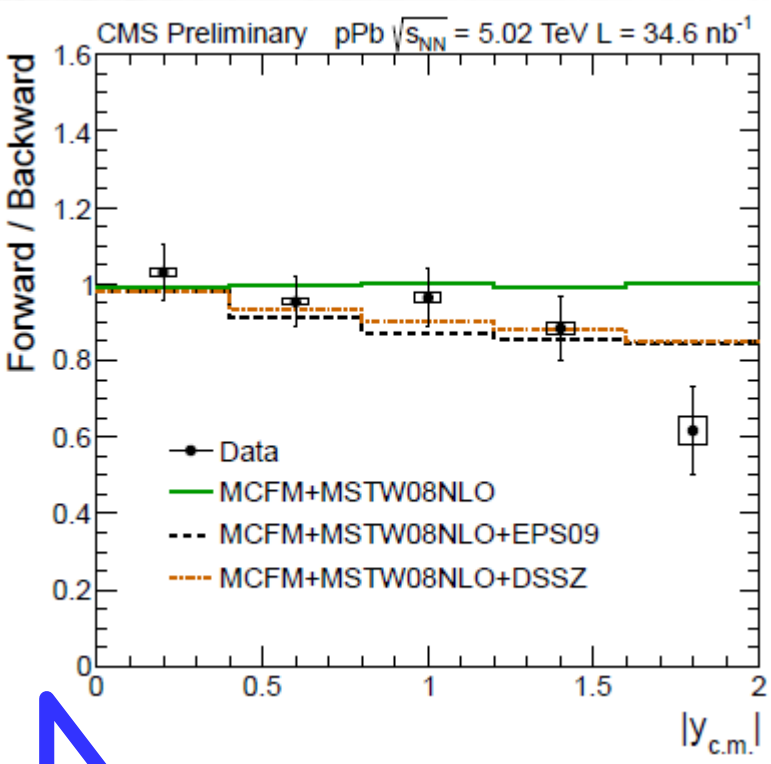




Nuclear effect should appear in forward or backward regions

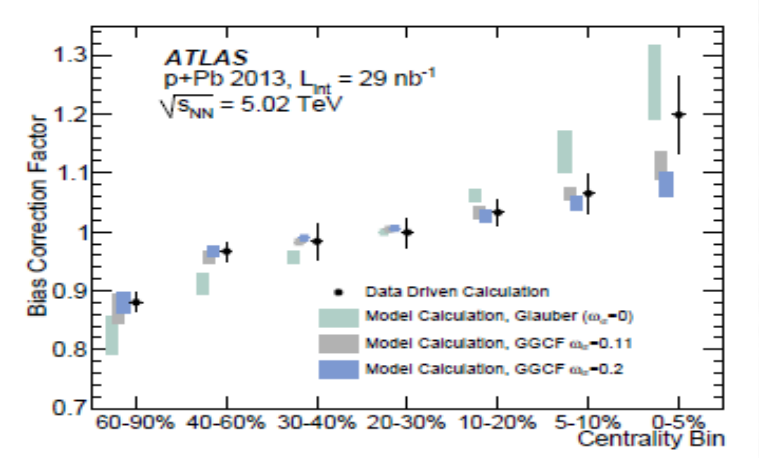
$$R_{FB} = \frac{d\sigma(+y_{\mathrm{c.m.}})/dy}{d\sigma(-y_{\mathrm{c.m.}})/dy}$$

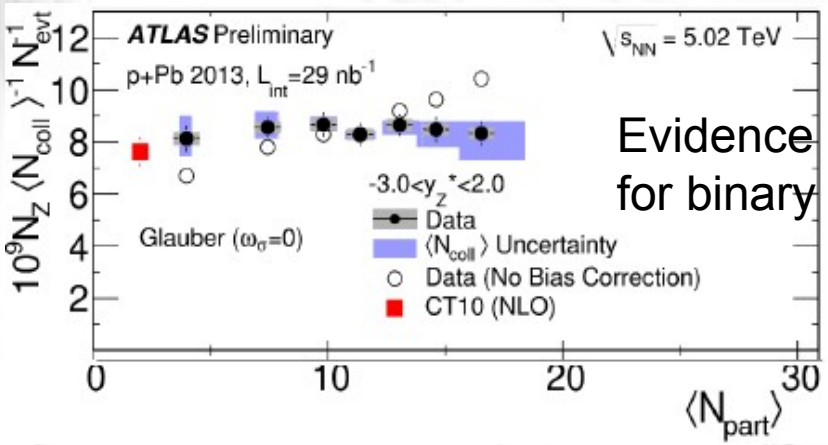
Evidence for nuclear effects in PDF

CMS-PAS-HIN-15-002
ATLAS: arXiv:1507.06232

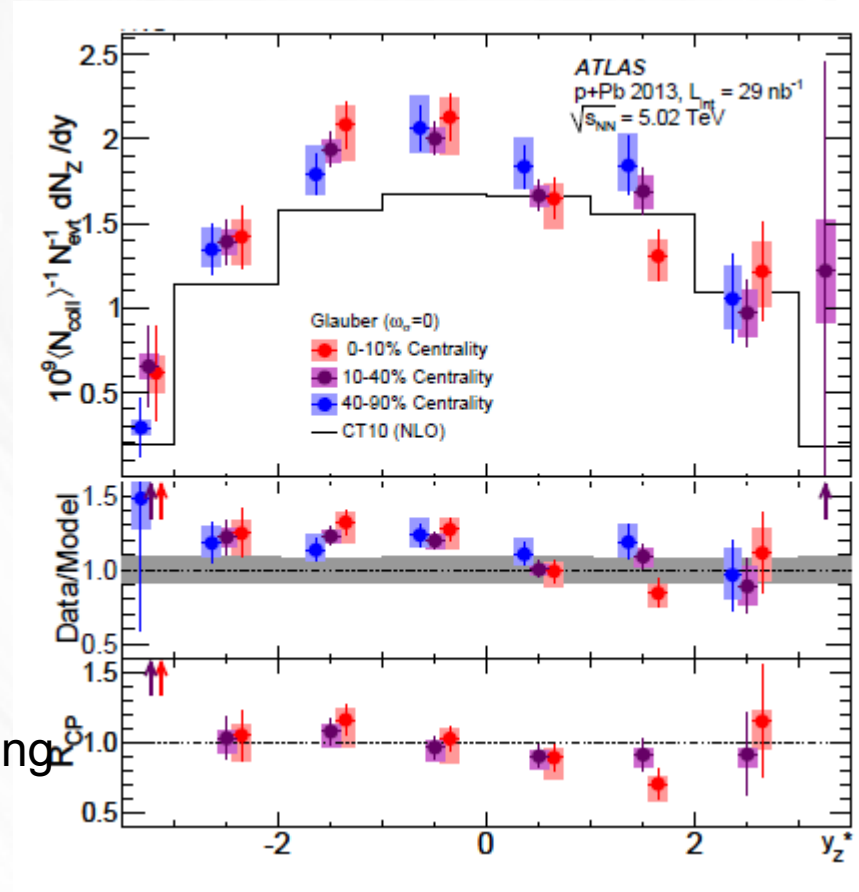
Z bosons in pPb: Centrality Measurement

How much do we understand centrality in pPb collisions?
Centrality bias → Z boson yield is enhanced in central events while depleted in peripheral ones





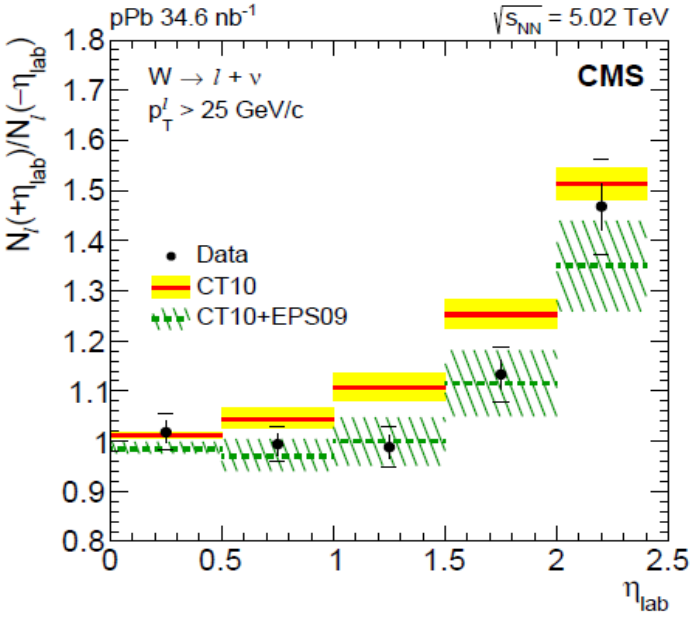
Evidence for binary scaling



Slightly larger asymmetry in central events

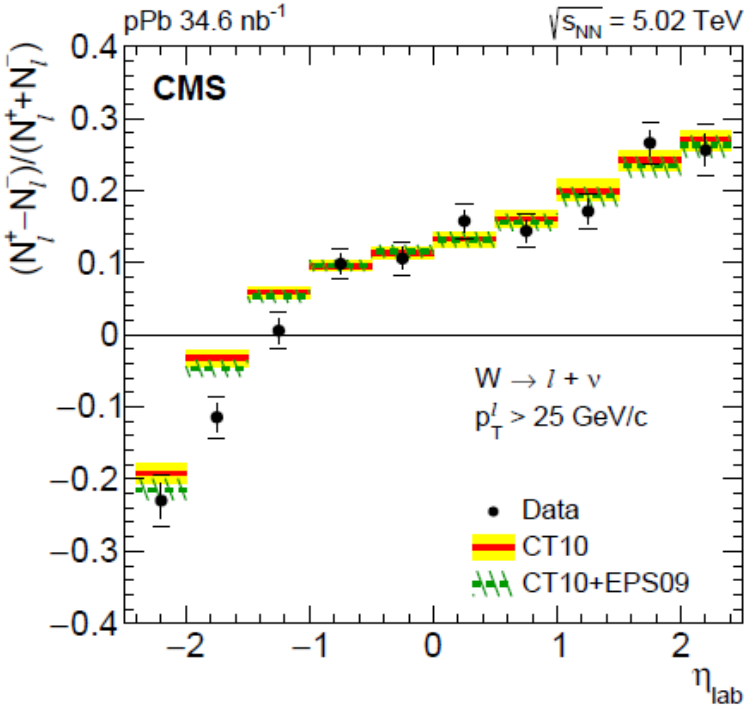
ATLAS: arXiv:1507.06232

W bosons in pPb



Forward Backward summed asymmetry shows better agreement with EPS09 nPDF

$$\frac{N(+\eta_{\rm lab})}{N(-\eta_{\rm lab})}$$



Charge asymmetry sensitive to variation in u and d quark contents in nPDF

$$\frac{N^+(\eta_{\rm lab})-N^-(\eta_{\rm lab})}{N^+(\eta_{\rm lab})+N^-(\eta_{\rm lab})}$$

Nuclear effects in EPS09 doesn't seem to recover the depletion at η~-1.5

Need to incorporate W boson pPb results in nPDF fits

CMS: arXiv:1503.05825

Conclusions

Jet probes of heavy ion collisions in ATLAS and CMS provided detailed informations about the physics of jet quenching
→ Input for theoretical mechanisms in jet suppression in QGP

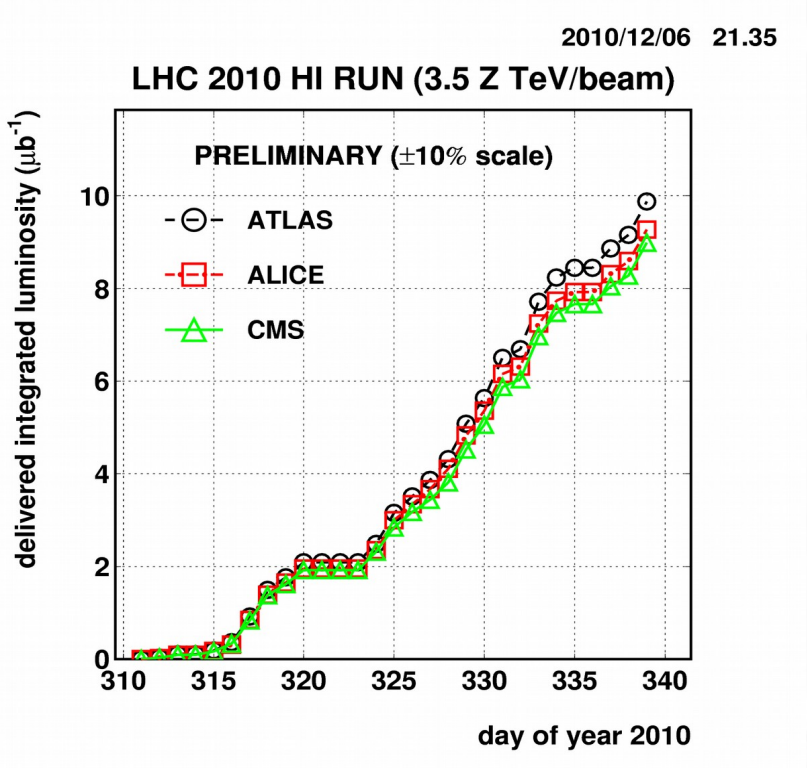
Electroweak probes and pPb collisions are input for better constraining nuclear PDF sets

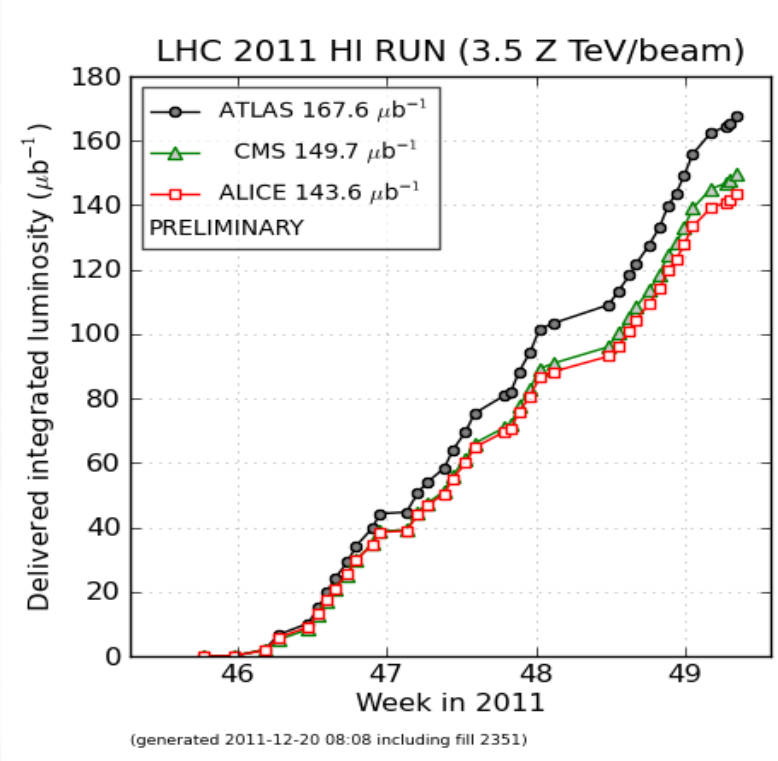
Very successful Run1 Heavy Ion program operated by LHC

First Run2 Heavy Ion runs foreseen in the next months
→ Increased statistics (10x ~ 30x)
→ pp reference for pPb runs at new $\sqrt{s}$

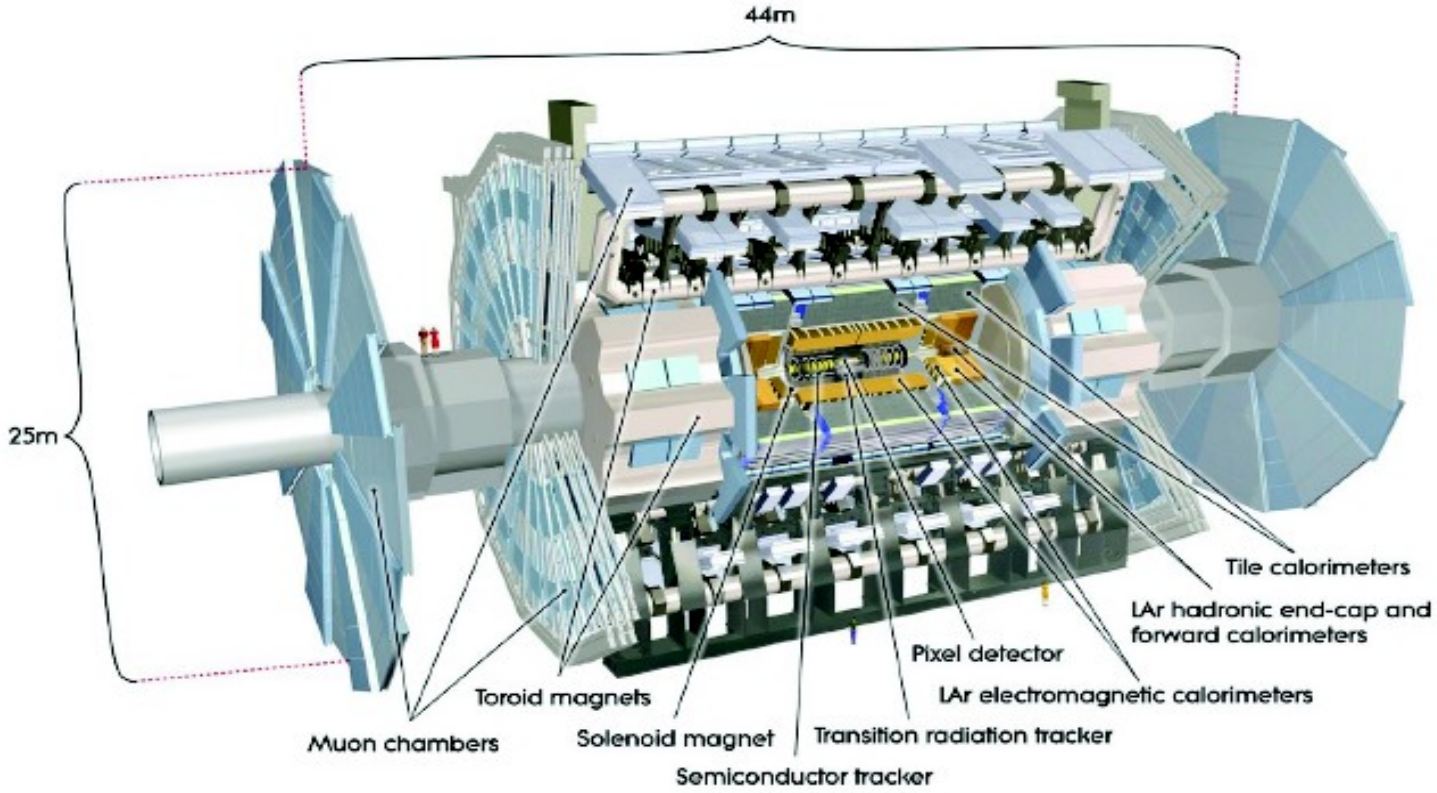
References:
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

BackUp


2010/12/06 21.35
LHC 2010 HI RUN (3.5 Z TeV/beam)
PRELIMINARY (±10% scale)
ATLAS
ALICE
CMS
delivered integrated luminosity (μb-1)
day of year 2010

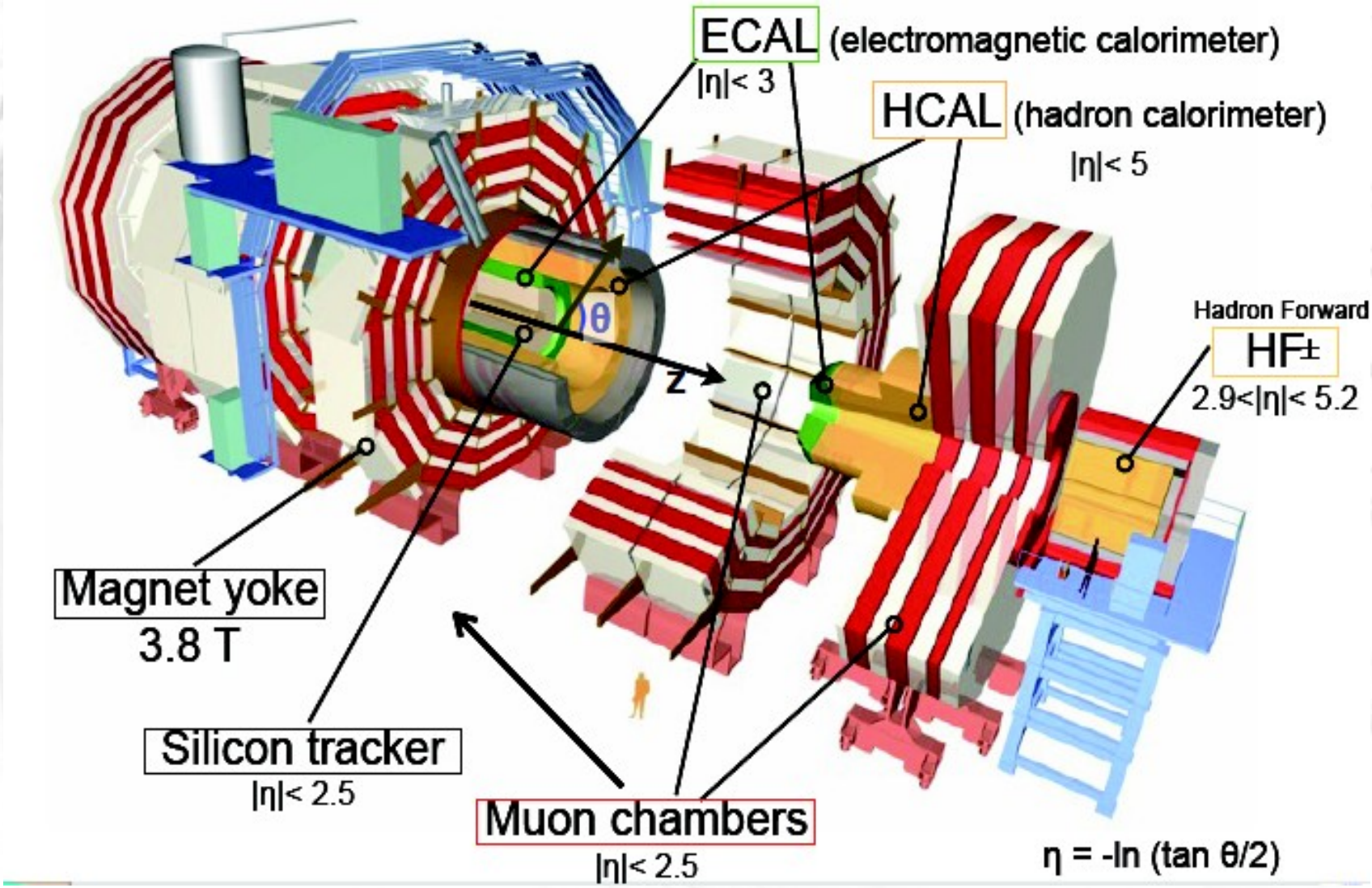

LHC 2011 HI RUN (3.5 Z TeV/beam)
ATLAS 167.6 μb-1
CMS 149.7 μb-1
ALICE 143.6 μb-1
PRELIMINARY
Delivered integrated luminosity (μb-1)
Week in 2011
(generated 2011-12-20 08:08 including fill 2351)

ATLAS Detector



Inner Detector	$\|\eta\| < 2.5$	vertex and track reconstruction
Calorimeter	$\|\eta\| < 3.2$	jet / electron / photo reconstruction
Muon Spectrometer	$\|\eta\| < 2.7$	muon recontruction
Forward Calorimeter (FCal)	$3.2 < \|\eta\| < 4.9$	centrality determination

CMS Detector

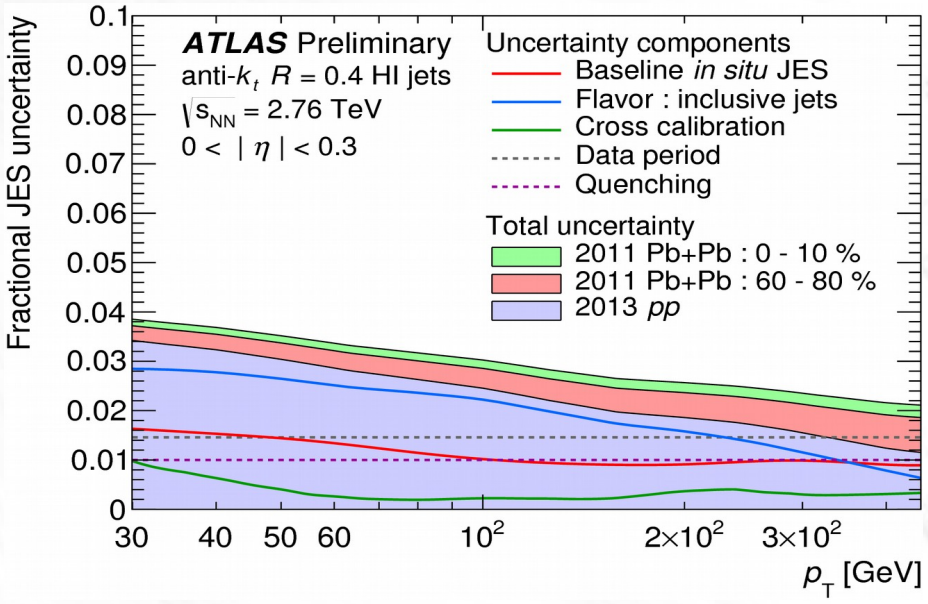


UE event estimate and Jet Energy Uncertainties: ATLAS

Jets are reconstructed with standard anti-kT algorithms ($\Delta R=0.2,0.3,0.4$)
Average UE background estimated event-by-event in η strips ($\Delta\eta=0.1$) and subtracted → Takes into account azimuthal modulation

$$\frac{dN^{\text{jets}}}{d\phi} \propto 1 + 2v_2 \cos 2(\phi^{\text{jet}} - \Psi_2)$$

pp MC overlaid with PbPb (or pPb) from Minimum Bias data → residual UE, pileup etc... in pp is identical to the data
Jet Energy in HI is cross calibrated using pp data to profit from *in-situ* calibrations (pp only)



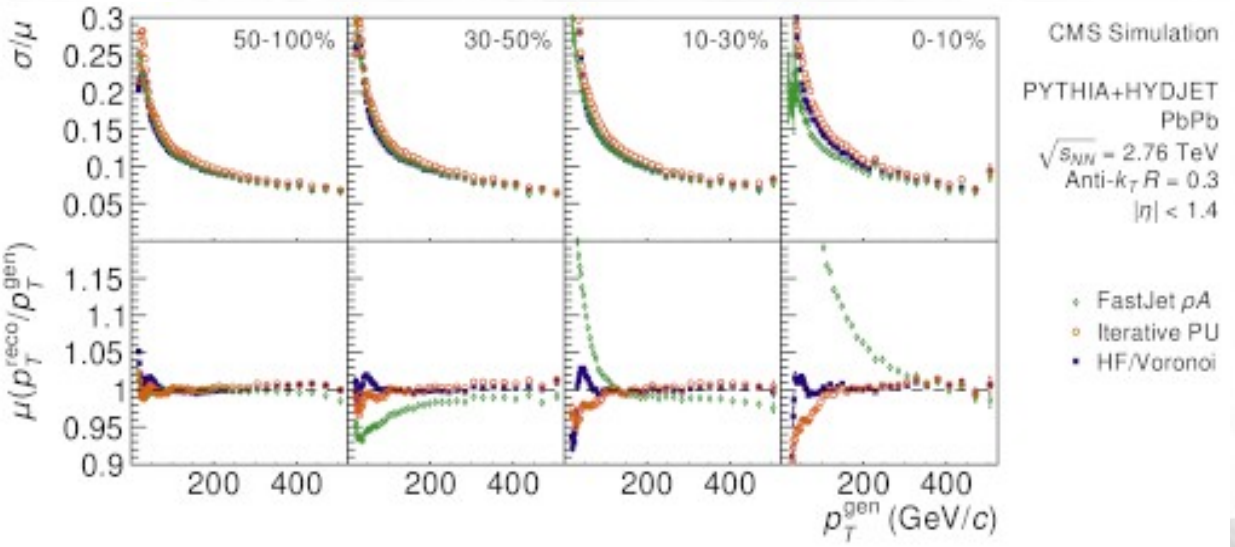
ATLAS-CONF-2015-016

UE event estimate and Jet Energy Uncertainties: CMS

Jets are reconstructed with standard anti-kT algorithms (ΔR=0.2,0.3,0.4) using particle flow techniques (combination of calorimeter deposits and tracks)

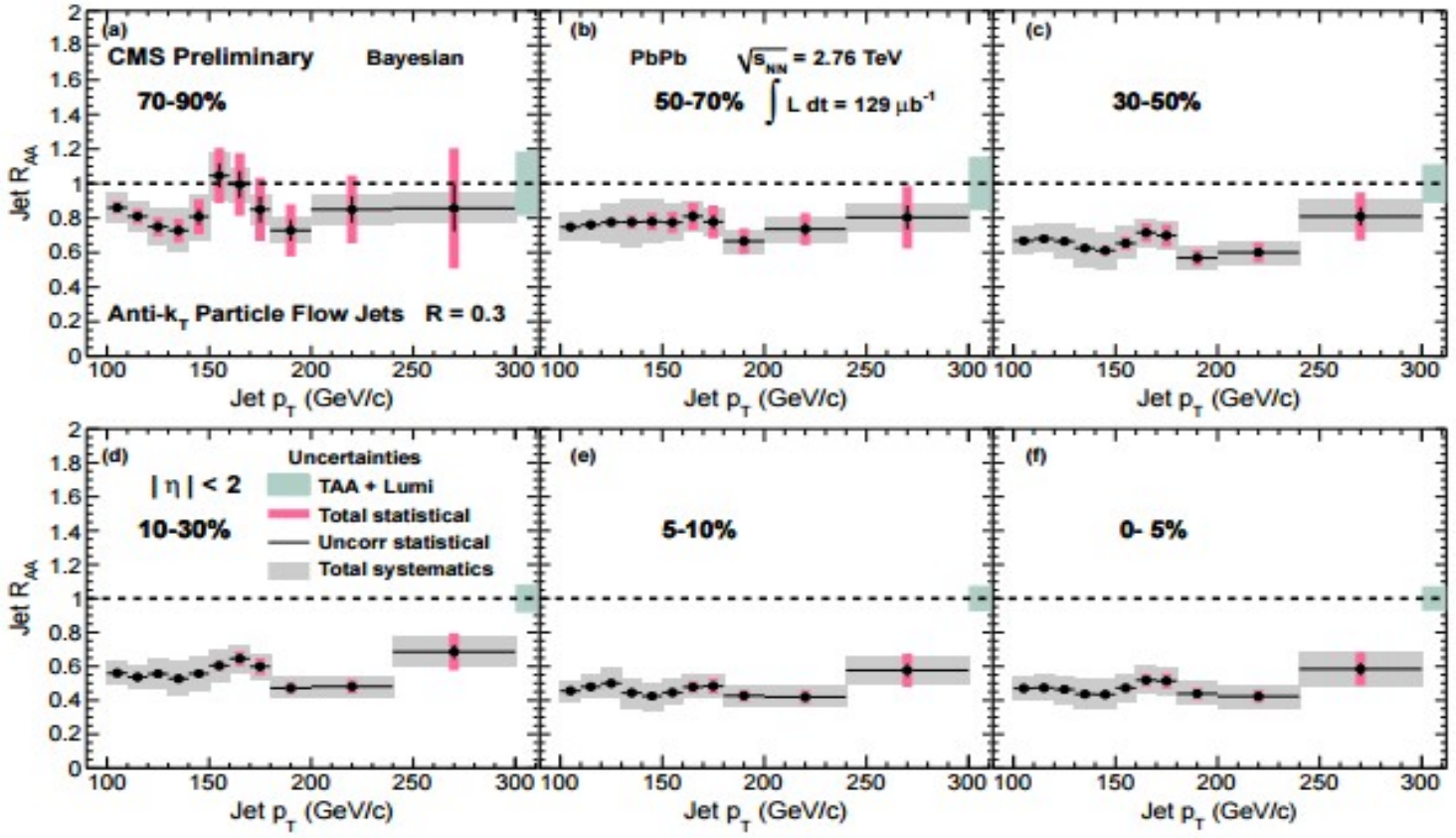
Iterative procedure in η strips to evaluate mean tower and RMS energy → subtracting background → run jet clustering → exclude jet and re-evaluate mean and RMS → subtract again → final jet

Modulation in phi from UE is parameterized as a function of impact parameter (centrality)



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsDPSUESubtractionPF

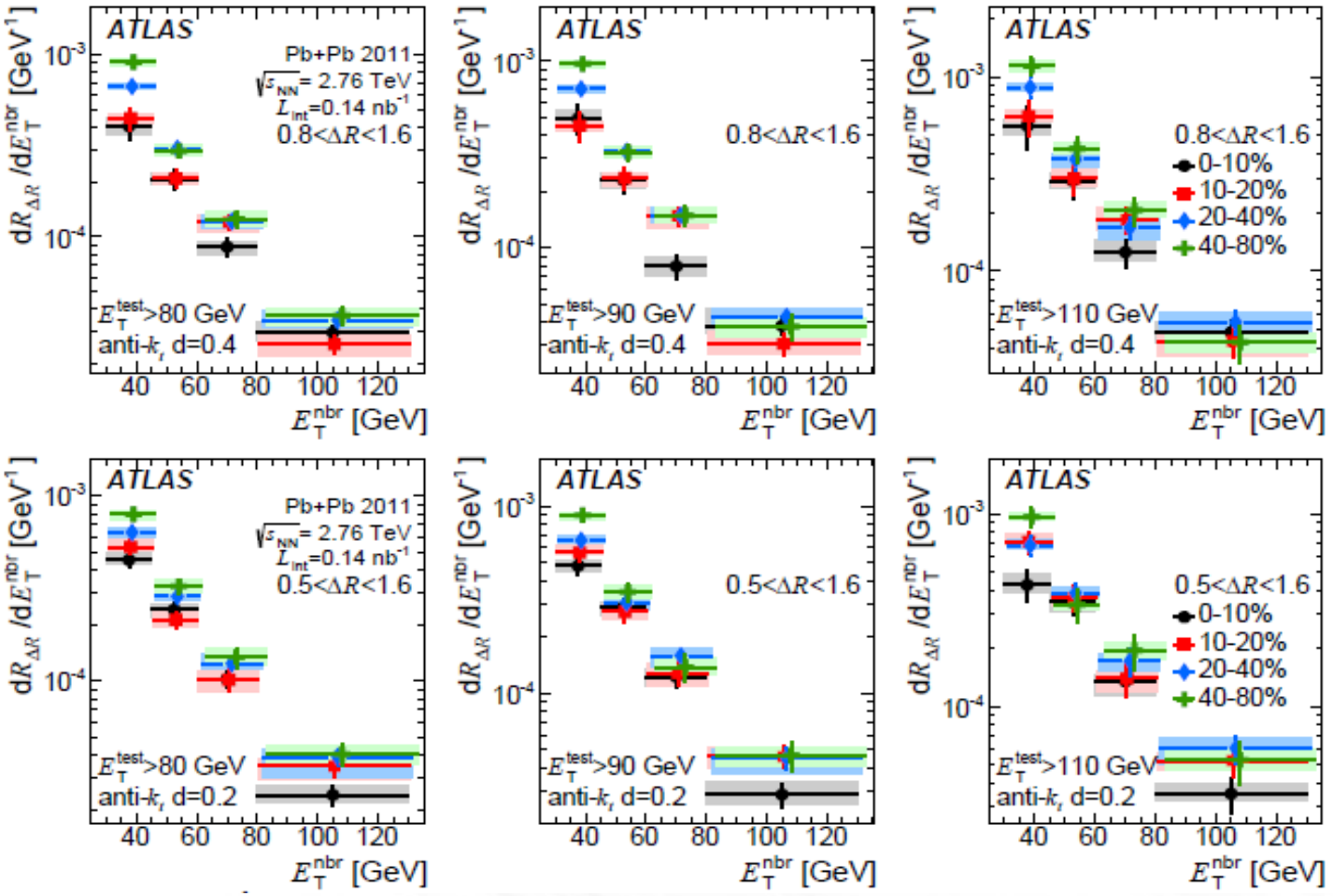
Modification Nuclear Factor: PbPb



ATLAS: Phys Rev Lett **114** (2015) 072302

CMS: PAS-HIN-12-004

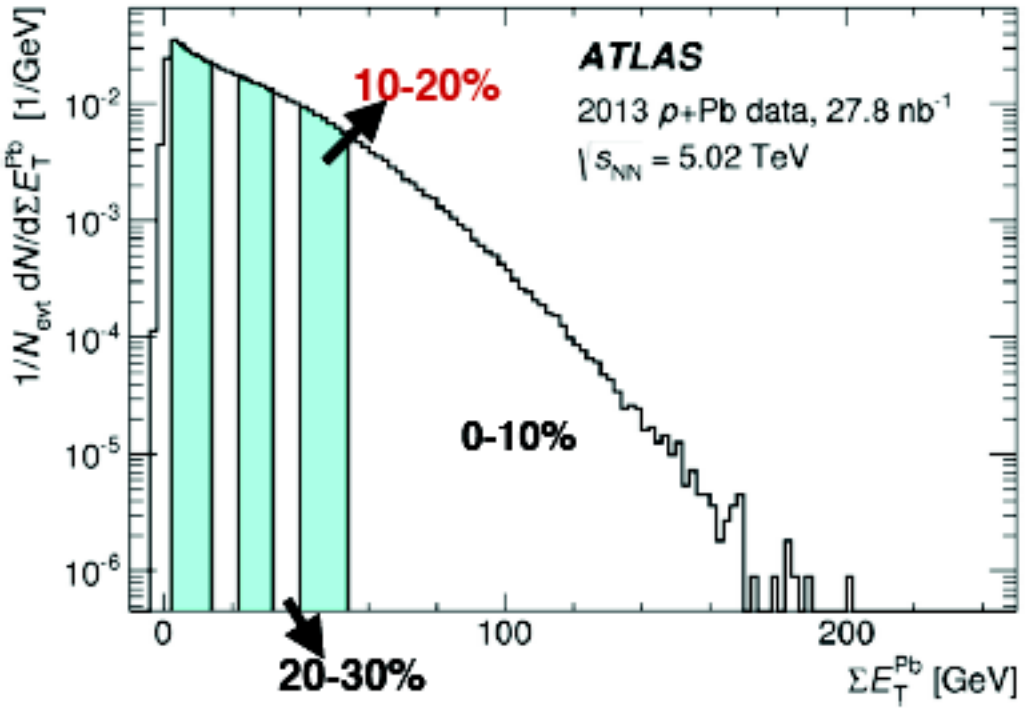
Neighbouring Jets: PbPb



Glauber Model pPb

Modified Gluaber-Gribov Color fluctuations (GGCF)
Event-by-Event fluctuations
Magnitude of fluctuation from ω_0 (In pure Glauber ω_0=0)

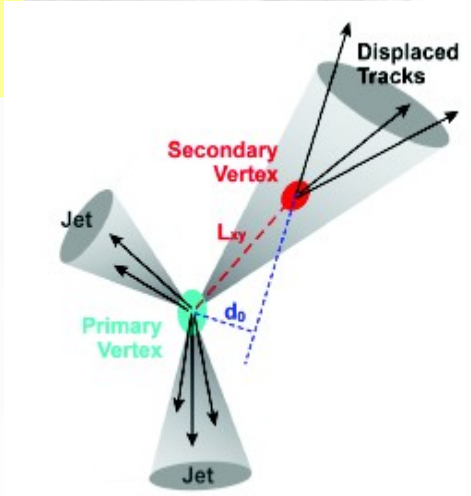
arXiv: 1412.4092

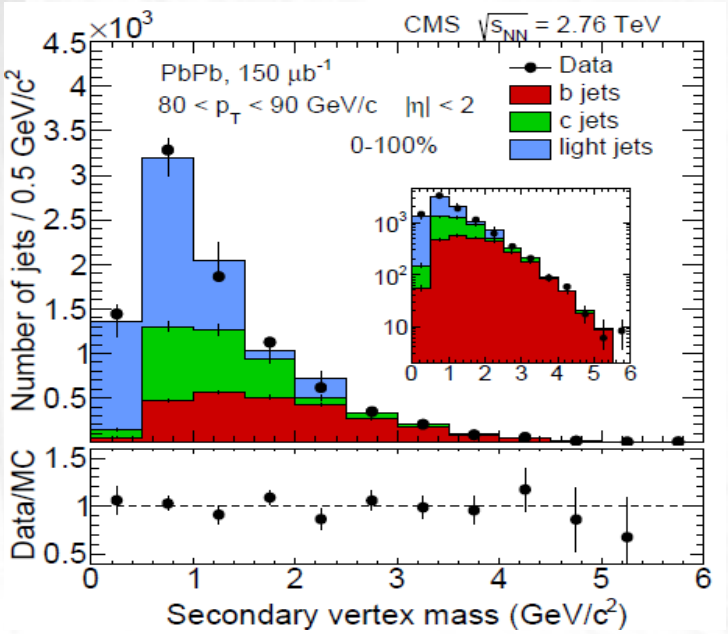


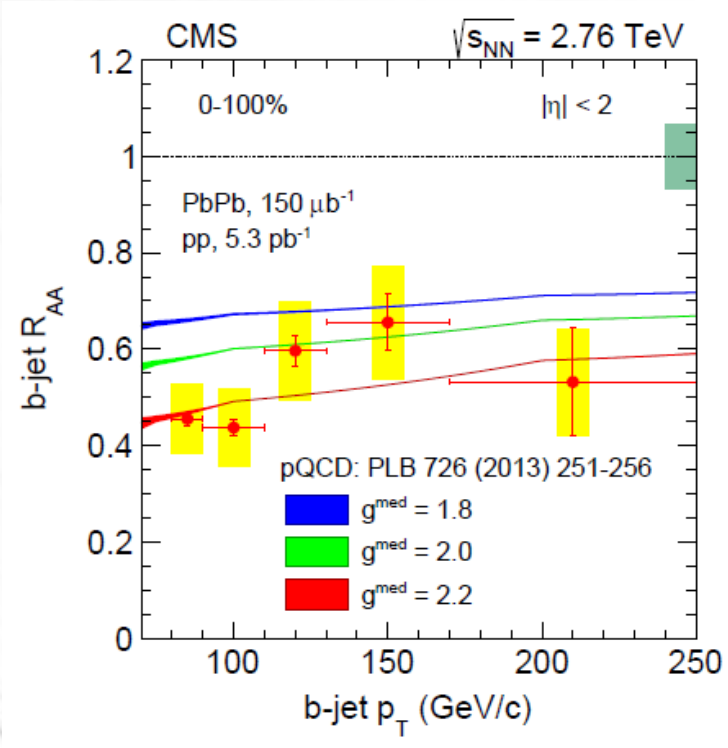
FCal total E_T in Pb beam direction

R_{AA} for b-quark jets

Is jet quenching affected by the nature of the parton originating the probe jet?
Sample enriched with b-jets using b-tagger

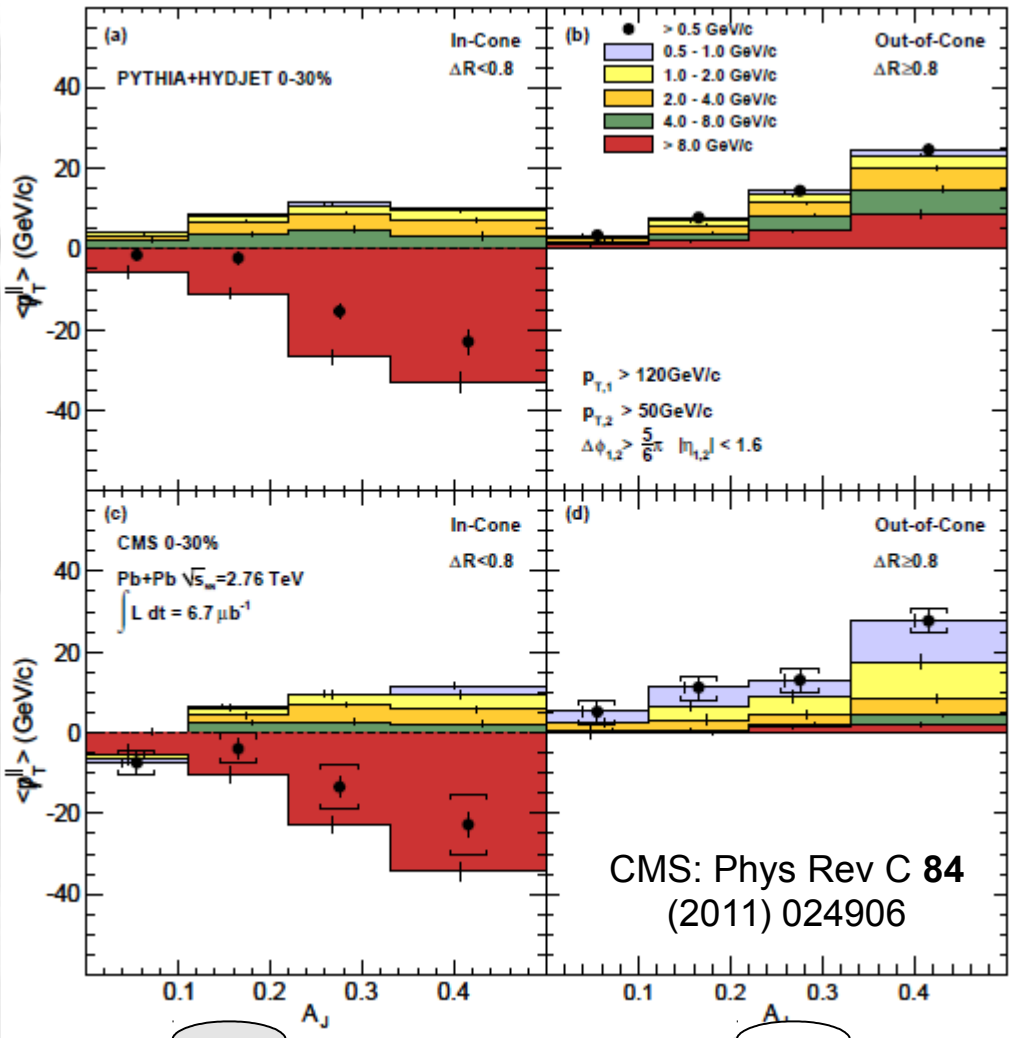






PRL 113 (2014) 132301
CMS-PAS-HIN-12-004
ArXiv:1312.4198 mettere articolo

Where the energy goes?



CMS: Phys Rev C **84** (2011) 024906

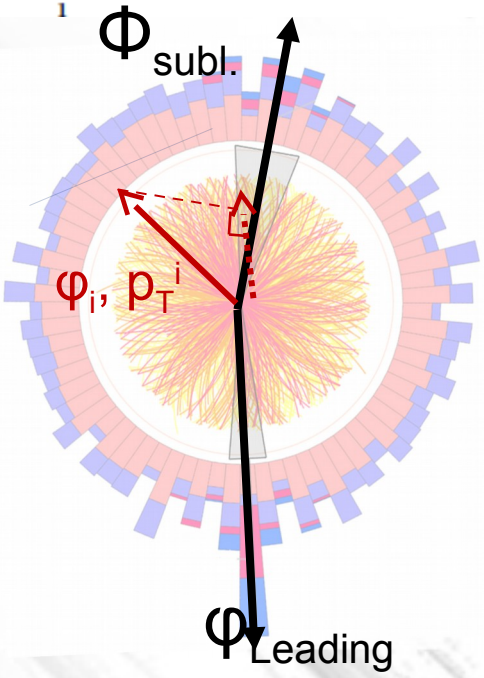
subleading jet direction

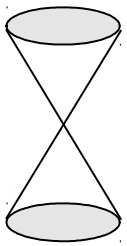
leading jet direction

In MC and Data momentum is restored in out of cone radiation

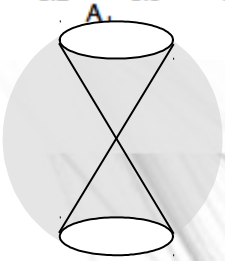
In Data larger contribution from soft component (P <1 GeV)

$$p_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Leading Jet}}\right),$$



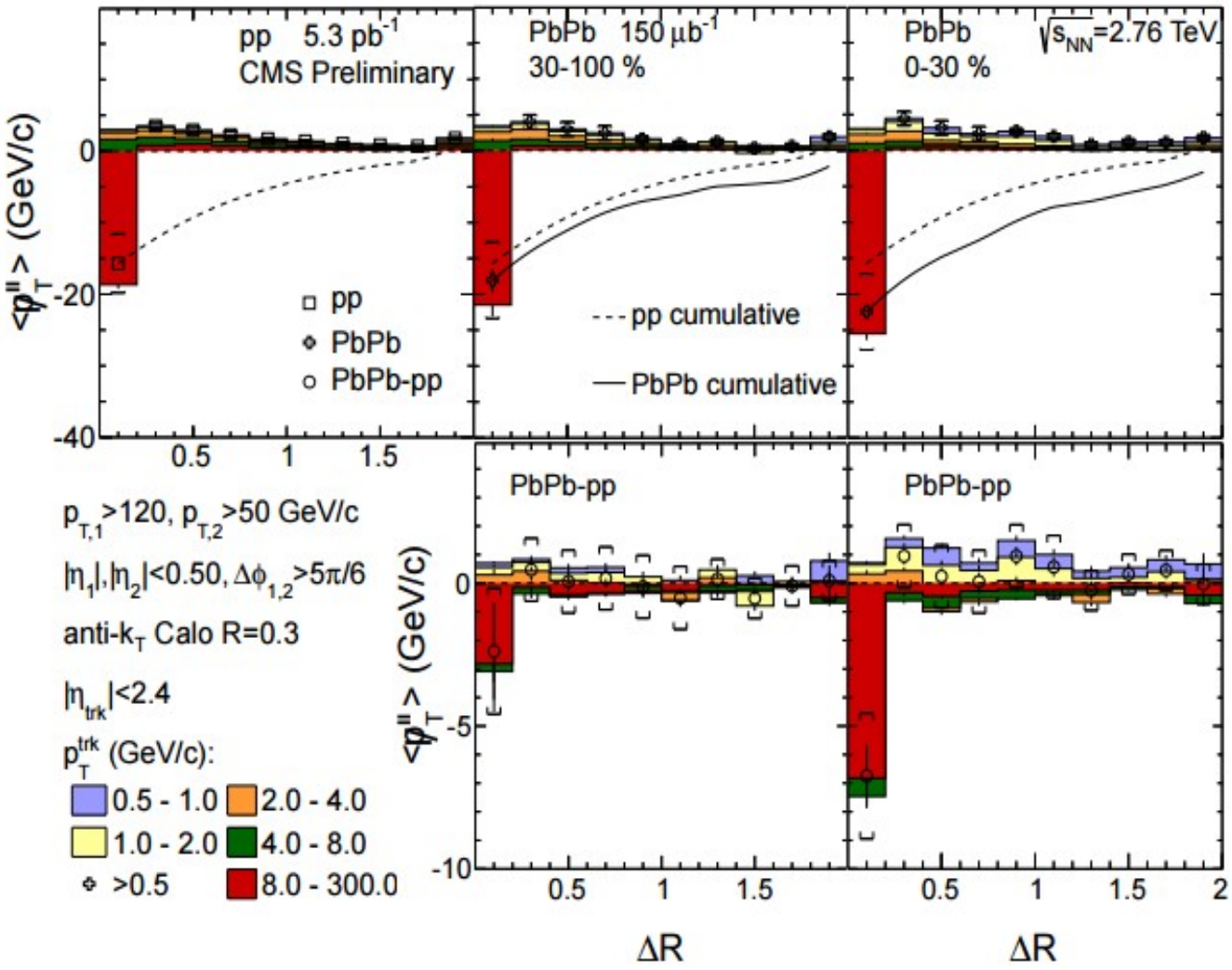


Tracks in the jet cone ΔR<0.8



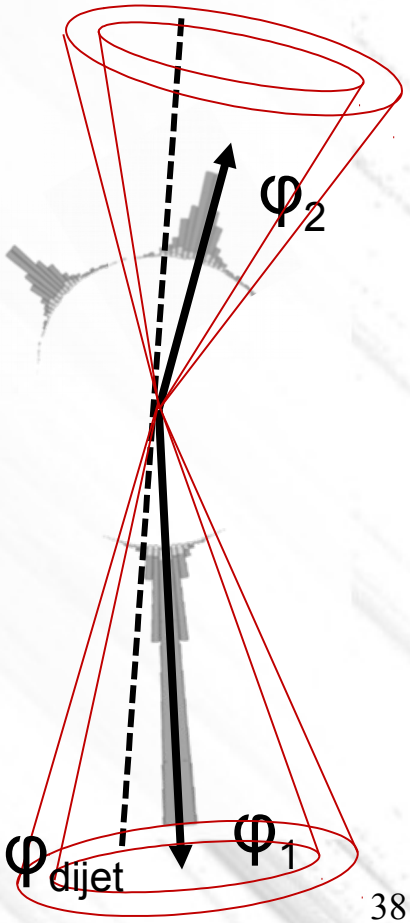
Tracks out of the jet cone ΔR>0.8

Where the energy goes?

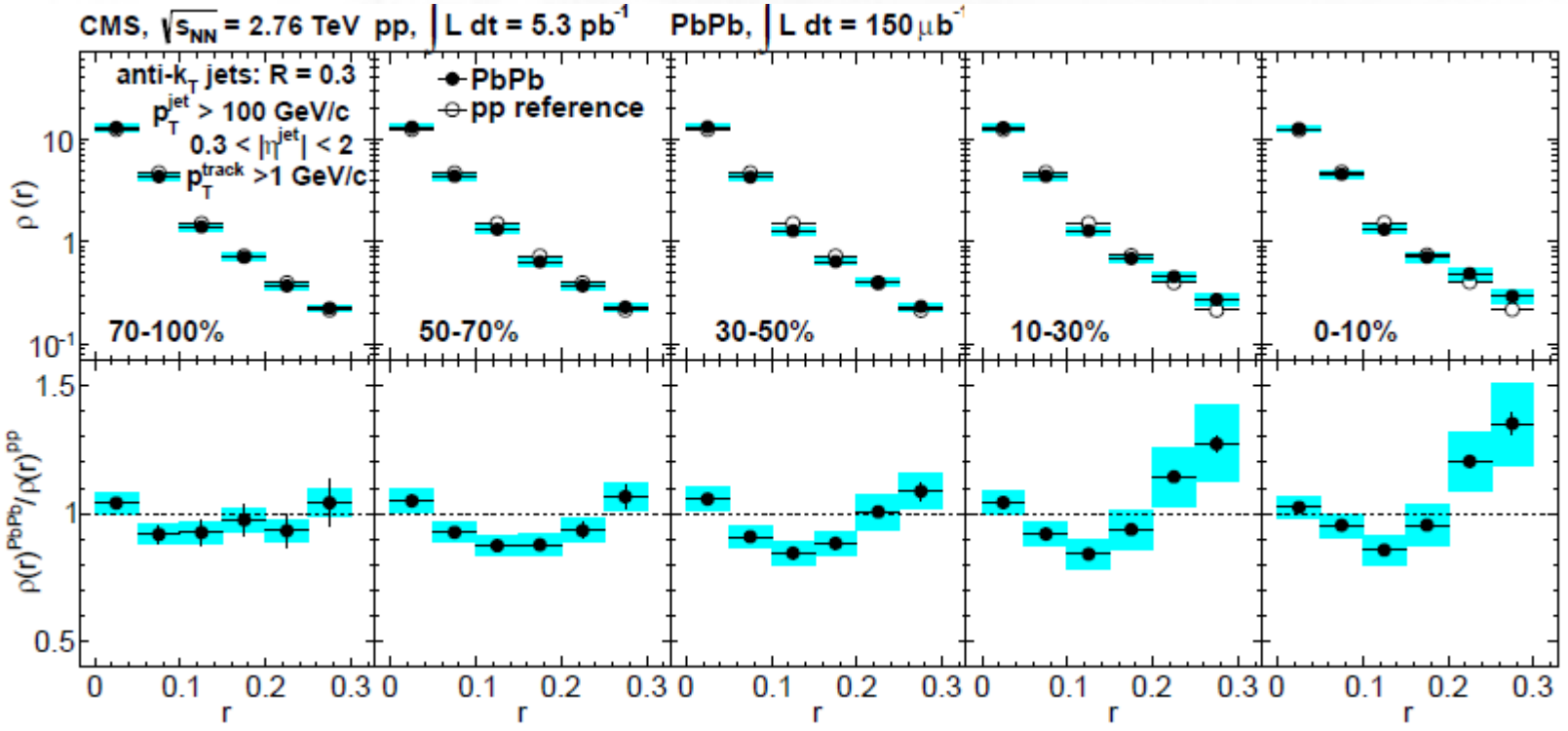


CMS: CMS-PAS-HIN-14-010

Momentum impalance caused by high Pt tracks close to the jet-axis is restored by low pt tracks at large ΔR

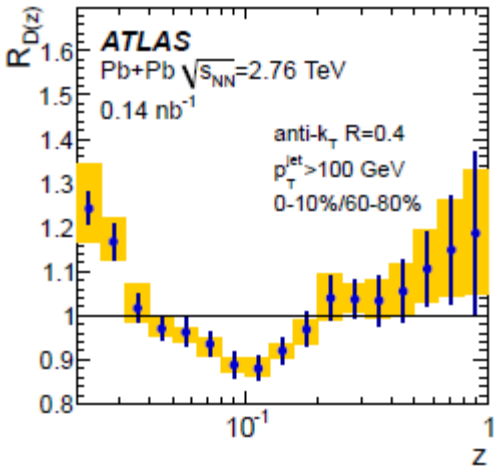


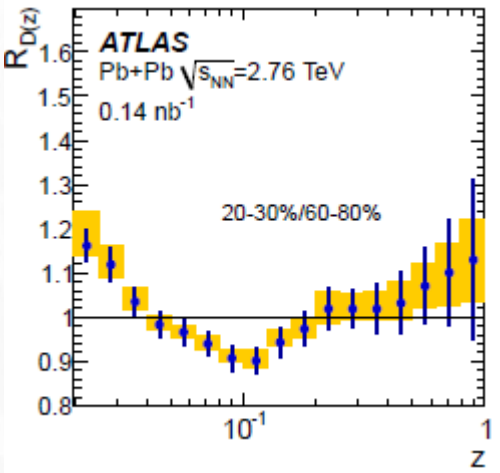
Jet Shapes

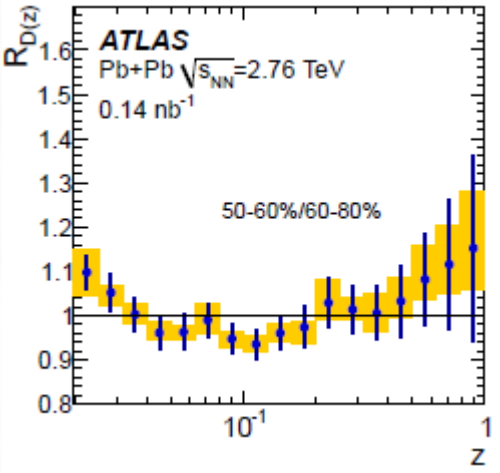


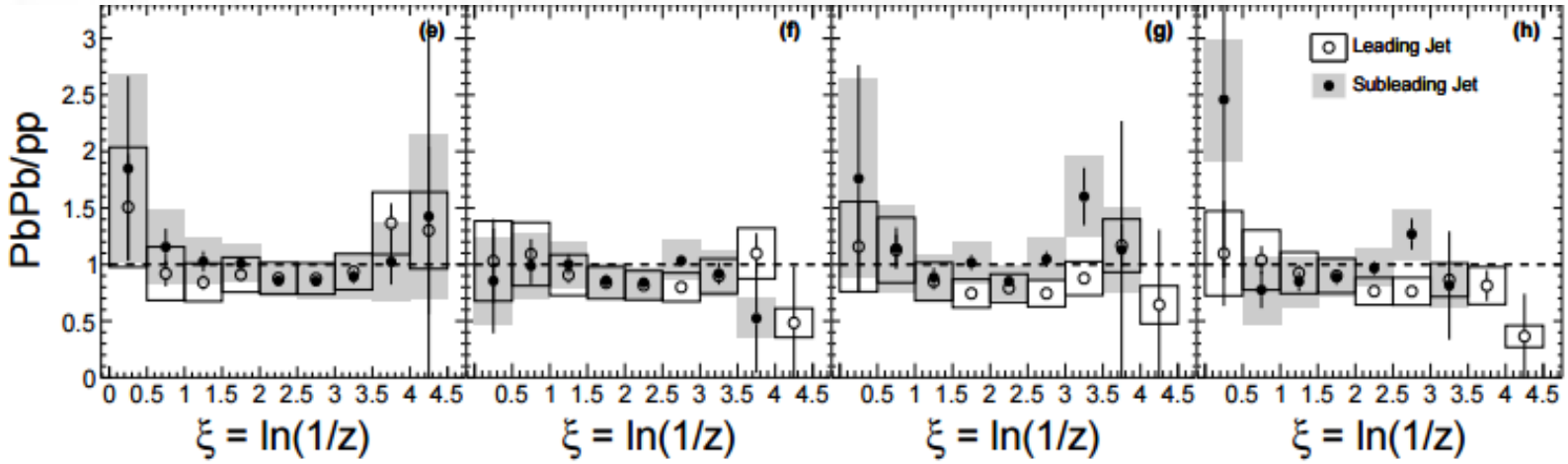
Phys Lett B **730** (2014) 243

Jet Fragmentation Modifications:PbPb



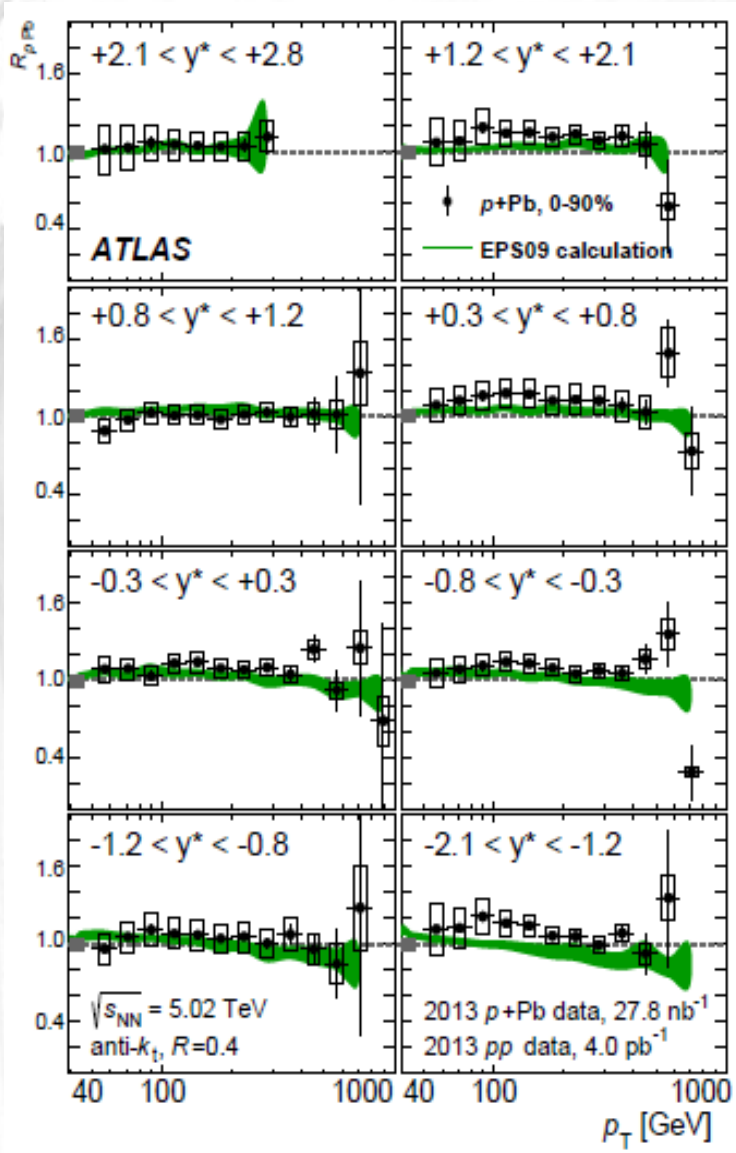


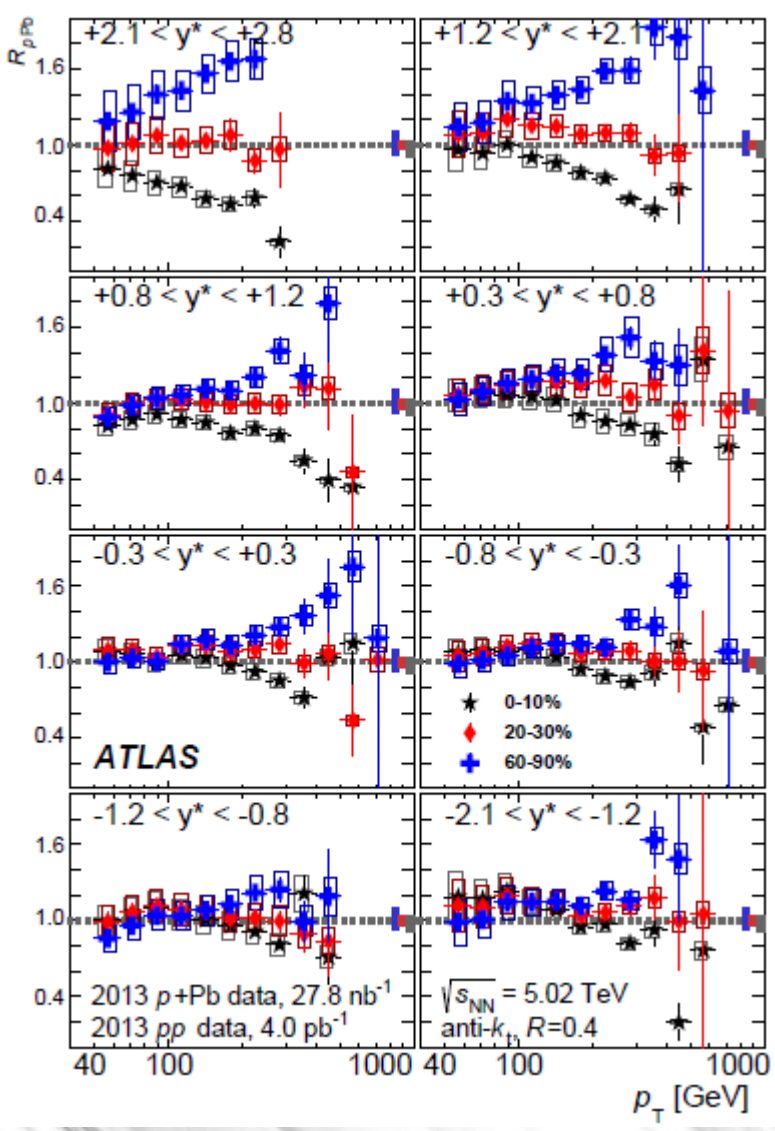




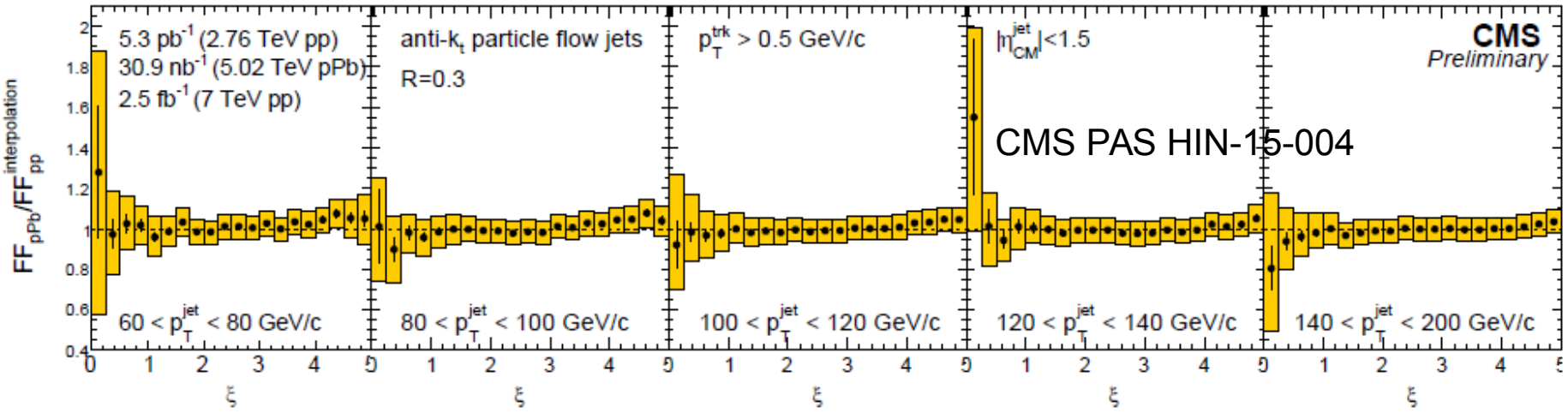
ATLAS: Phys Lett B **739** (2014) 320-342 CMS: Phys.Rev. C**90** (2014) 024908.

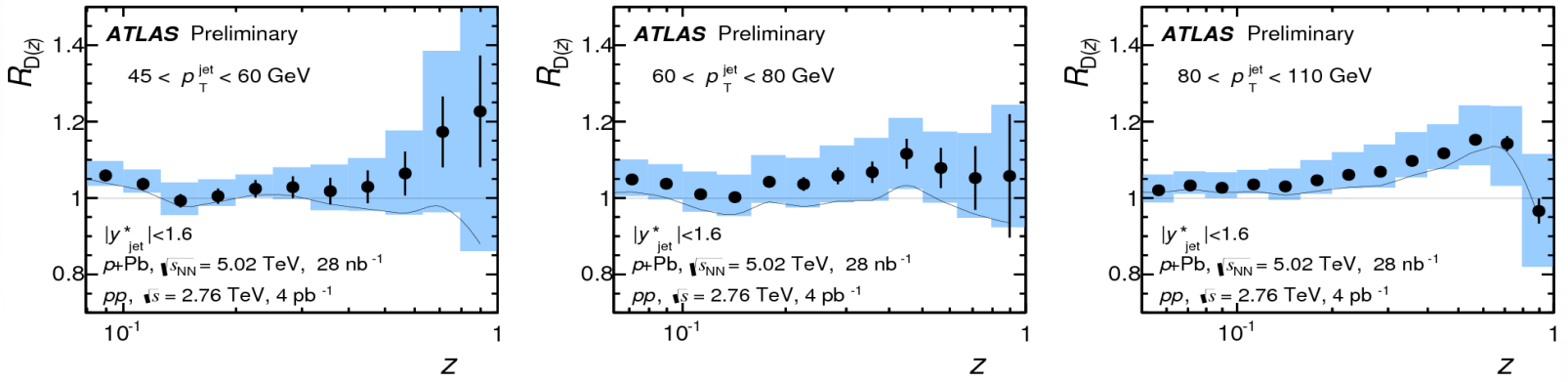
Nuclear Modification Factor in pPb

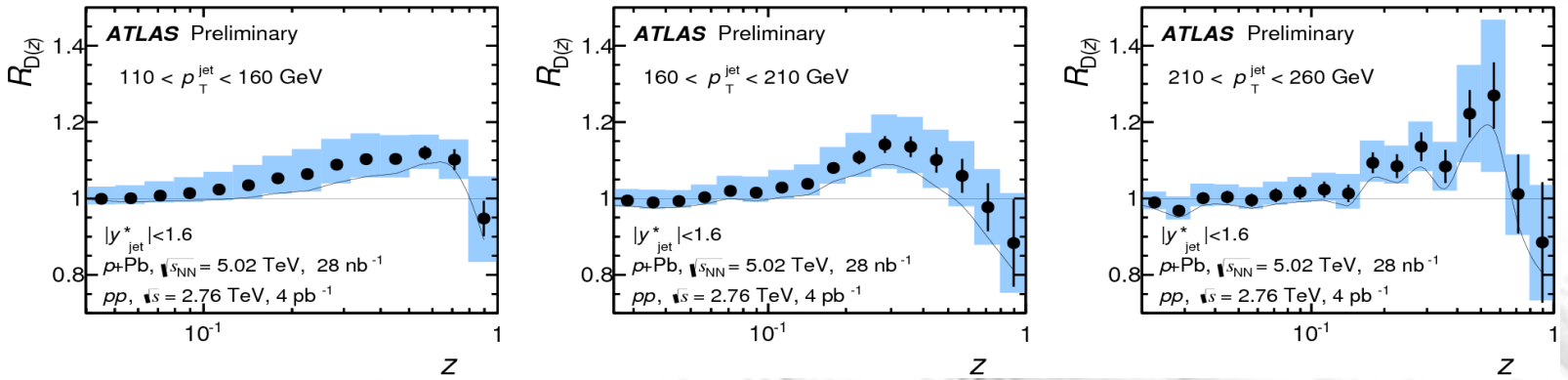




Jet Fragmentation Modifications: pPb

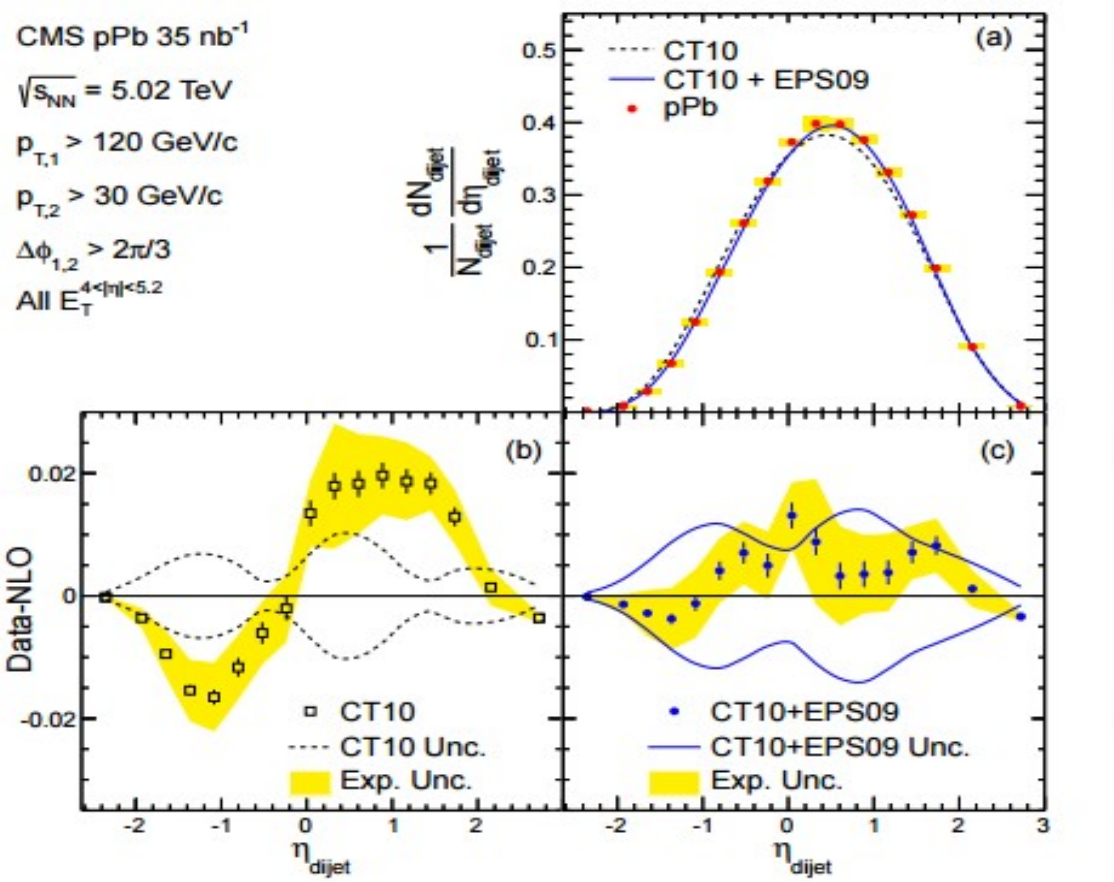






ATLAS-CONF-2015-022

Nuclear Modification Factor in pPb

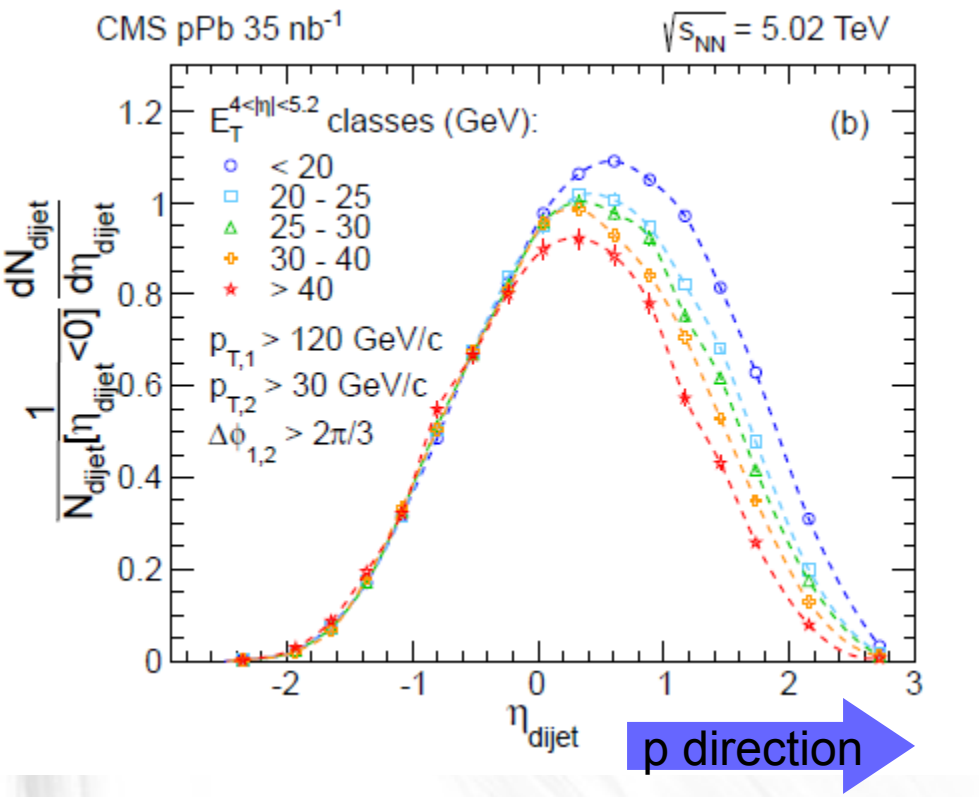


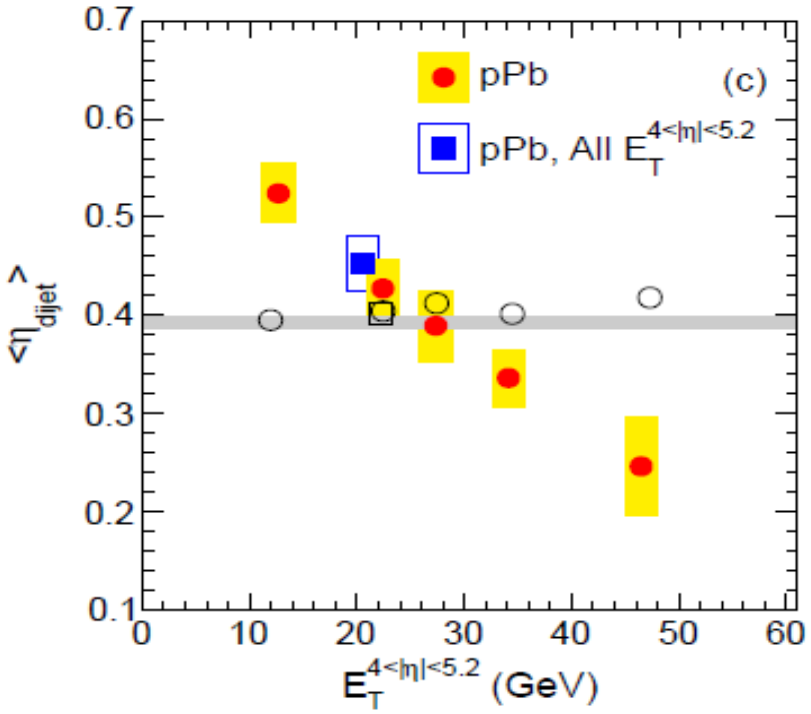
$\eta_{dijet} = (\eta_1+\eta_2)/2$ sensitive to different nPDF sets

CT10 + EPS09 → nuclear PDF effects

CMS:
ArXiv:1401.4433
EPJC 74 (2014) 2951

Nuclear Modification Factor in pPb

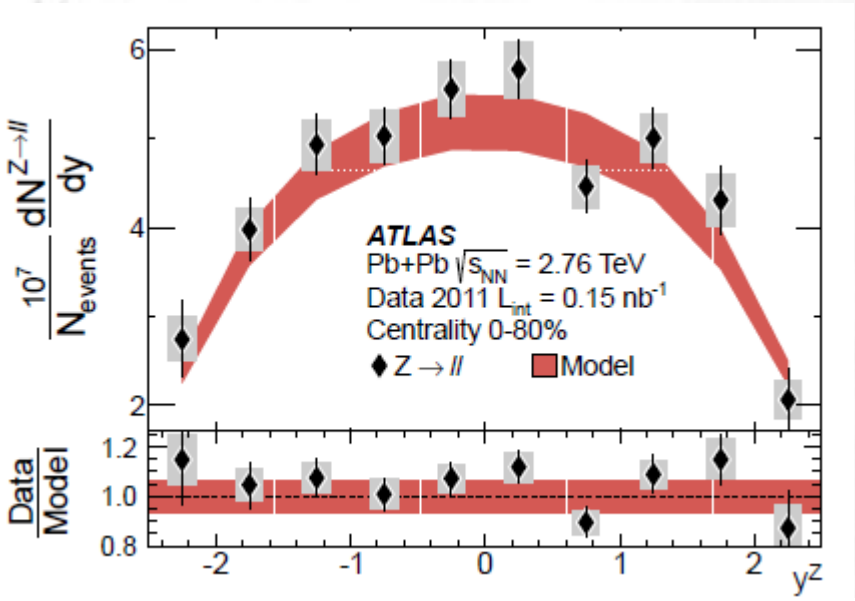


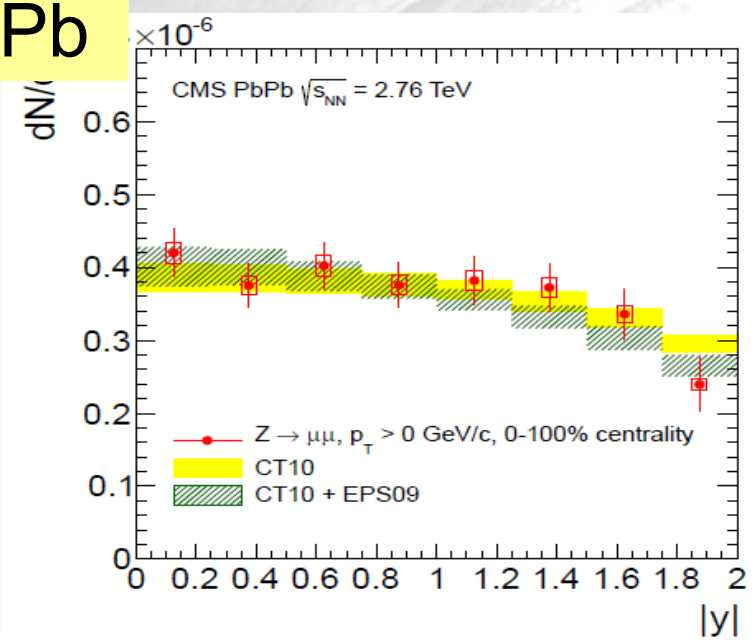


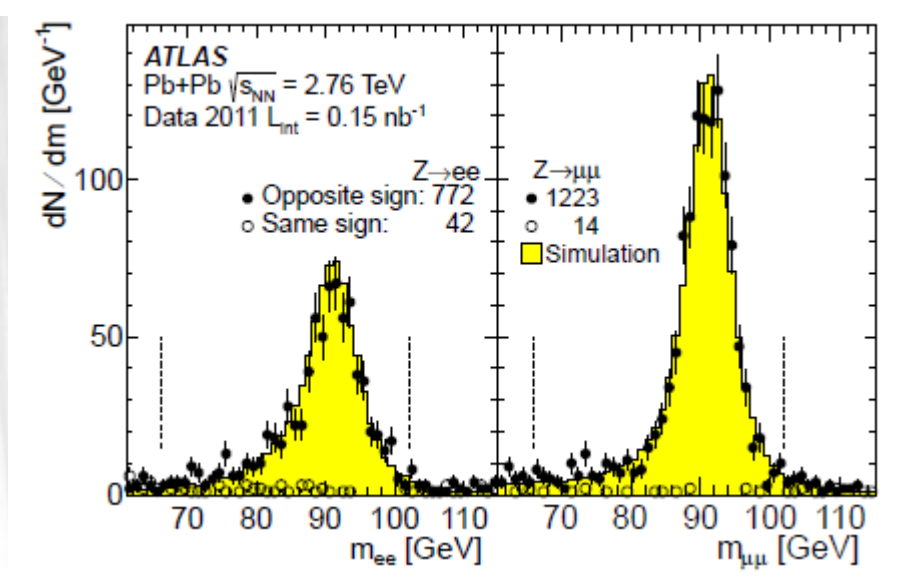
Could be explained by the modification of the PDFs due to the fluctuating size of the proton, as well as the impact parameter dependence of the nuclear PDFs

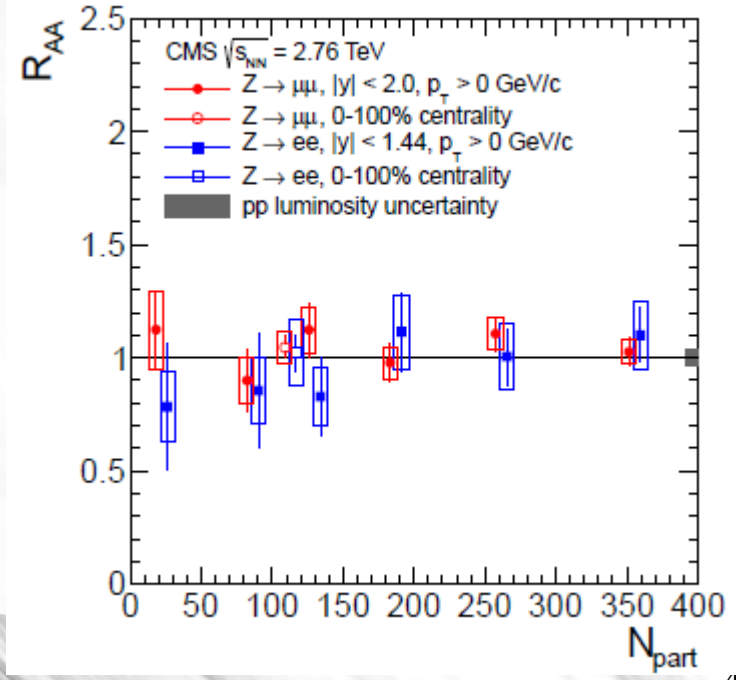
CMS:
ArXiv:1401.4433
EPJC 74 (2014) 2951

Z bosons in PbPb





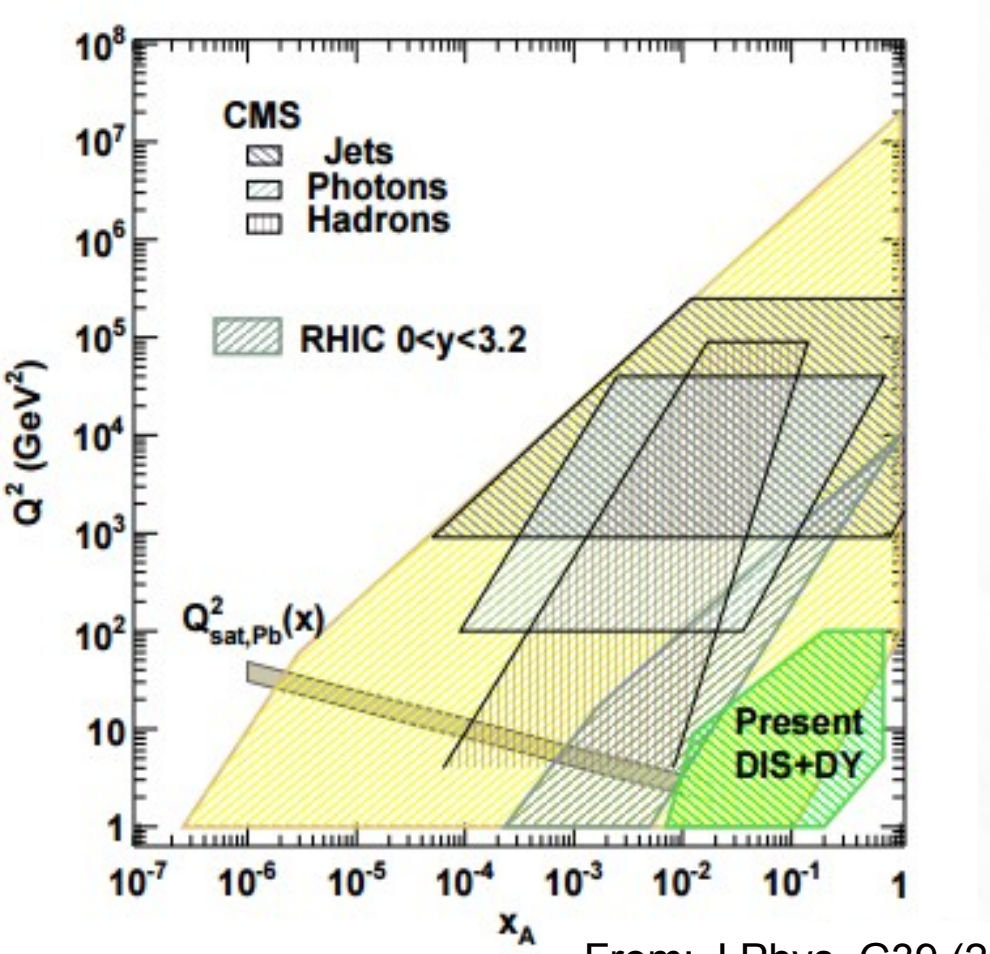




ATLAS: Phys Rev Lett. **110**, 022301 (2013)

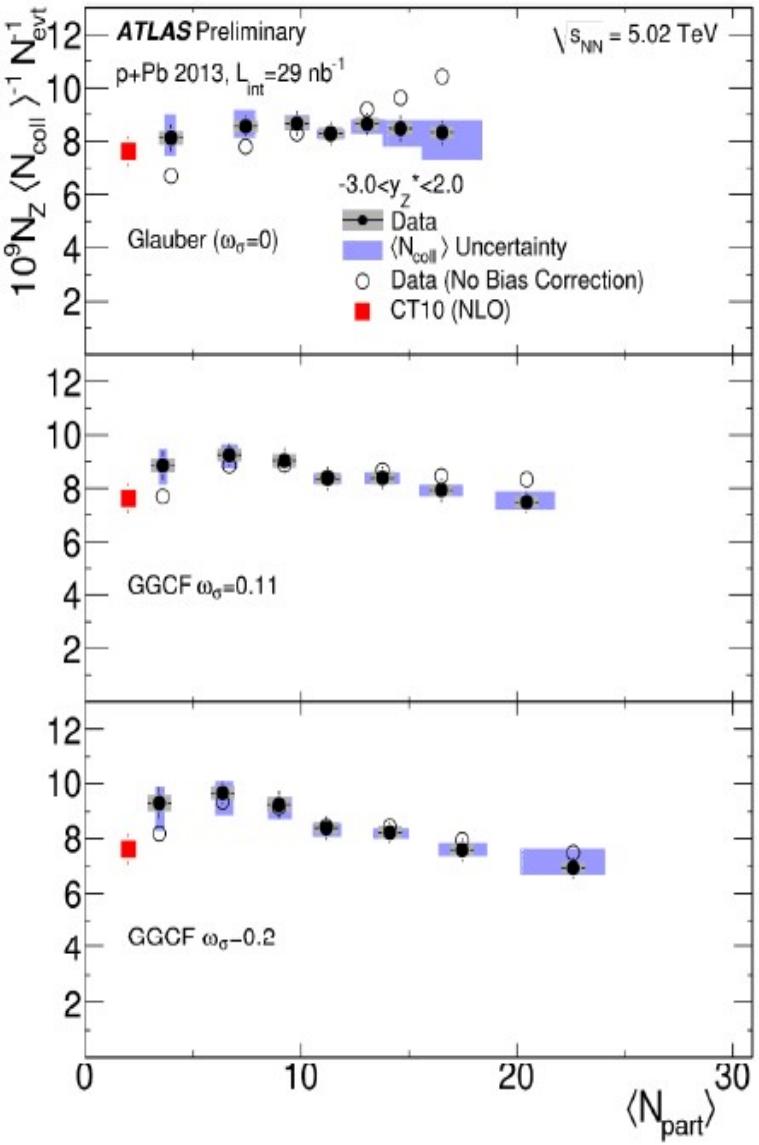
CMS: JHEP **03** (2015) 022

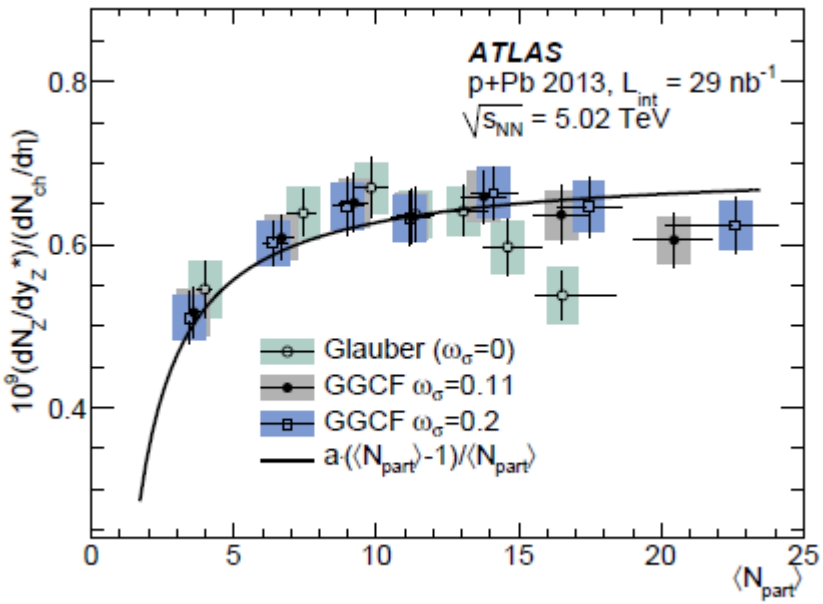
nPDF reach in pPb LHC



From: J.Phys. G39 (2012) 015010

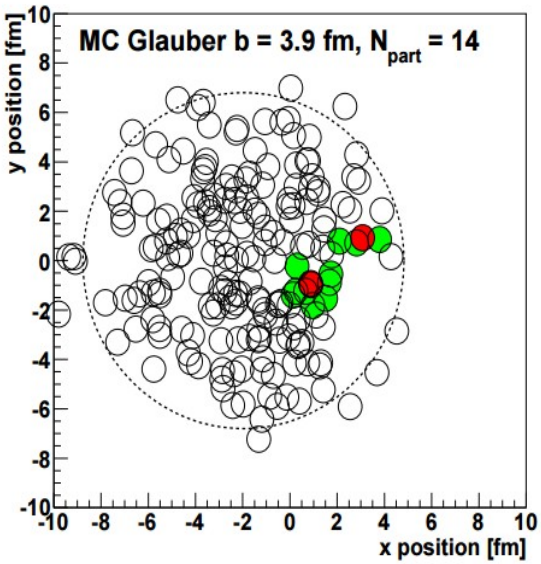
Z bosons in pPb: Centrality Measurement

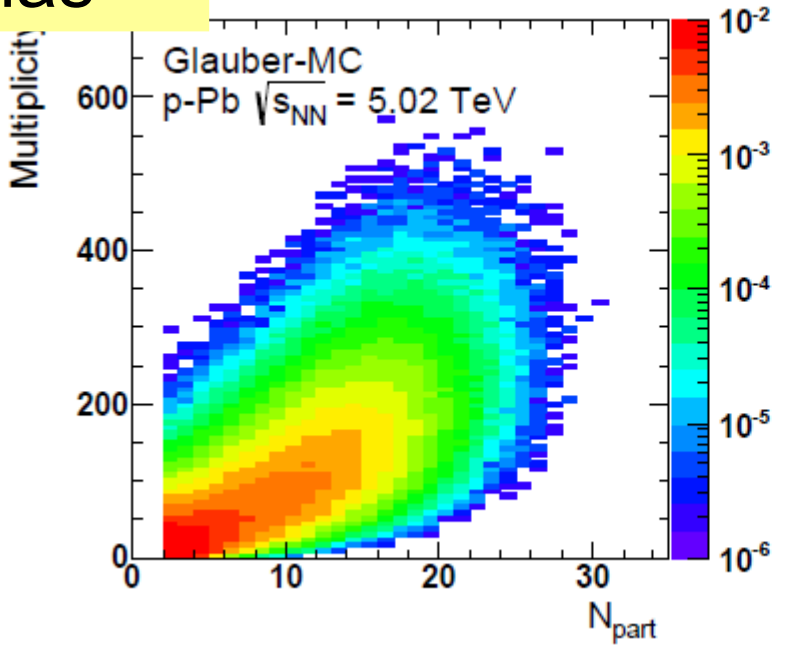




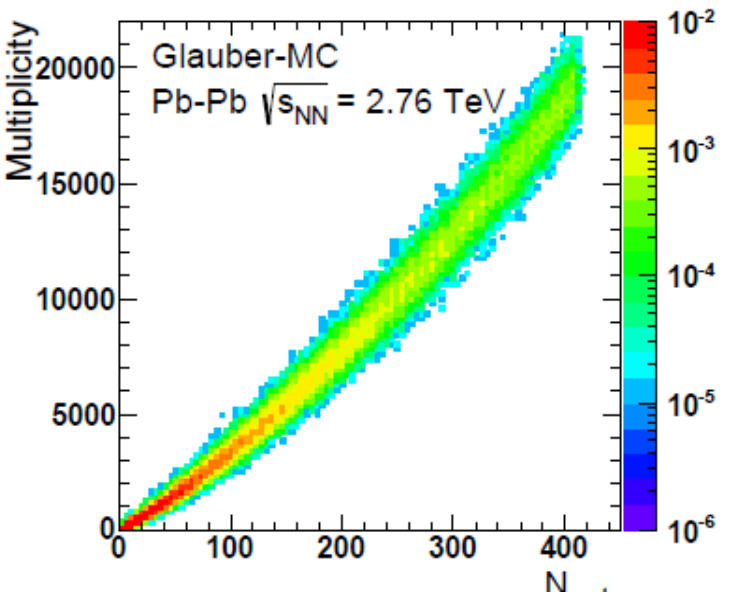
ATLAS: arXiv:1507.06232

Centrality Bias





d+Au collision (Glauber MC)
PHENIX arxiv: 1310.4793



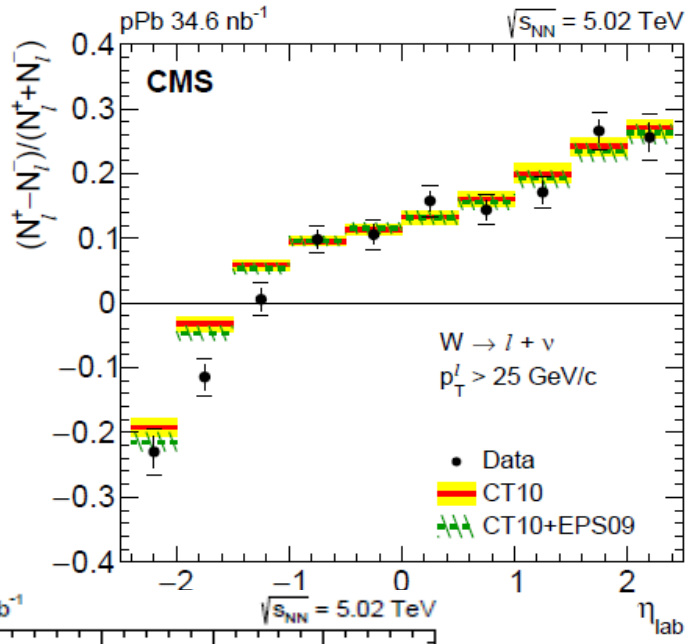
ALICE: arXiv:1412.6828

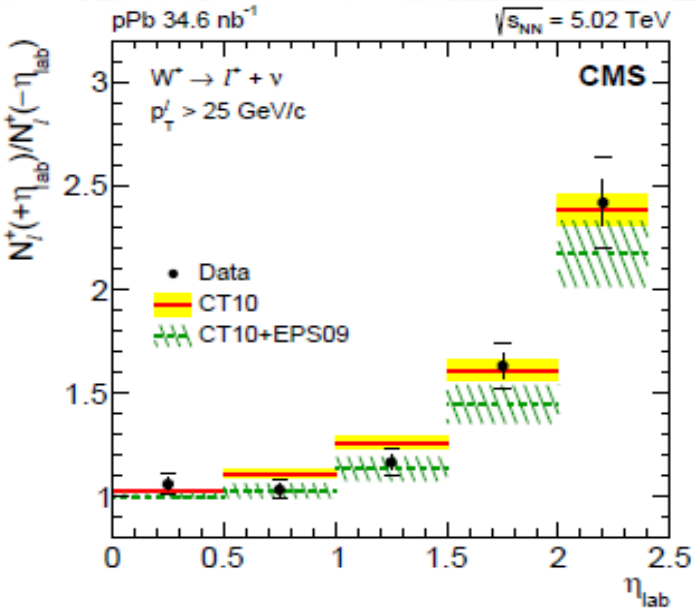
W bosons in pPb

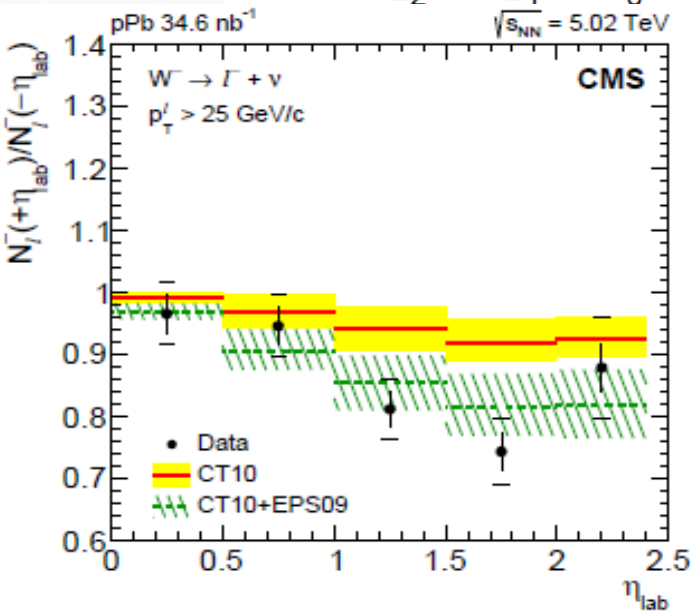
Charge asymmetry sensitive to variation in u and d quark contents in nPDF

$$\frac{N^{+}(\eta_{\mathrm{lab}}) - N^{-}(\eta_{\mathrm{lab}})}{N^{+}(\eta_{\mathrm{lab}}) + N^{-}(\eta_{\mathrm{lab}})}$$

Nuclear effects in EPS09 doesn't seem to recover the depletion at η~-1.5







CMS: arXiv:1503.05825