Jets and bosons in HI Collisions

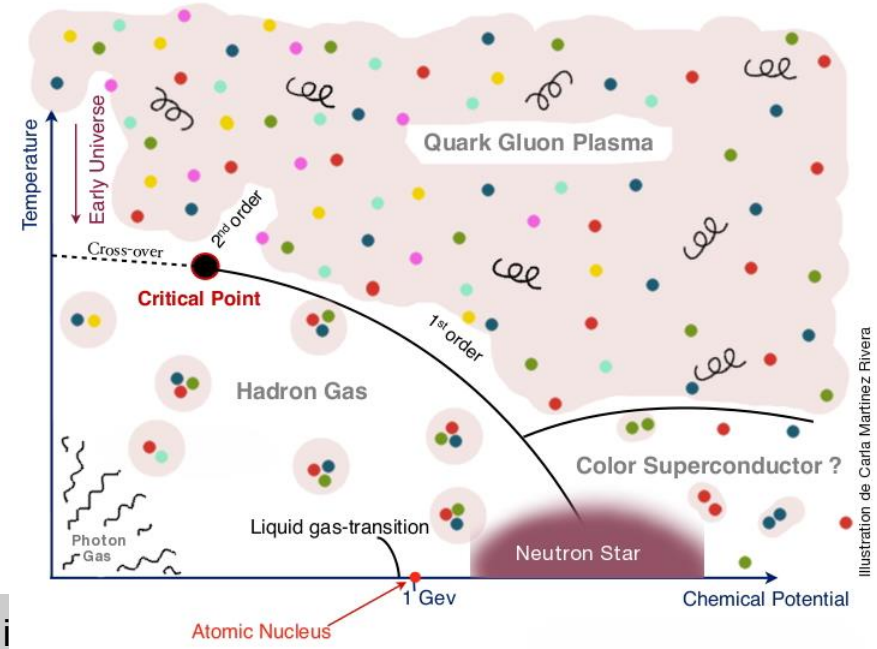
Begoña de la Cruz (CIEMAT, Madrid)

On behalf of ATLAS & CMS Collaborations

LHCP 2013 Barcelona (Spain), 14th May

Heavy nuclei collisions

- In heavy nuclei collisions at high energies,
  - quarks and gluons become free,
  - form a high density colour deconfined state of strongly interacting matter.
- Lattice QCD predicts a phase transition to QGP
  - high temperatures
  - energy density reached
- High-momentum partons from early stages in collisions, traverse hot QGP, losing energy as they interact with constituents:
  - radiative processes (gluons)
  - collisional processes



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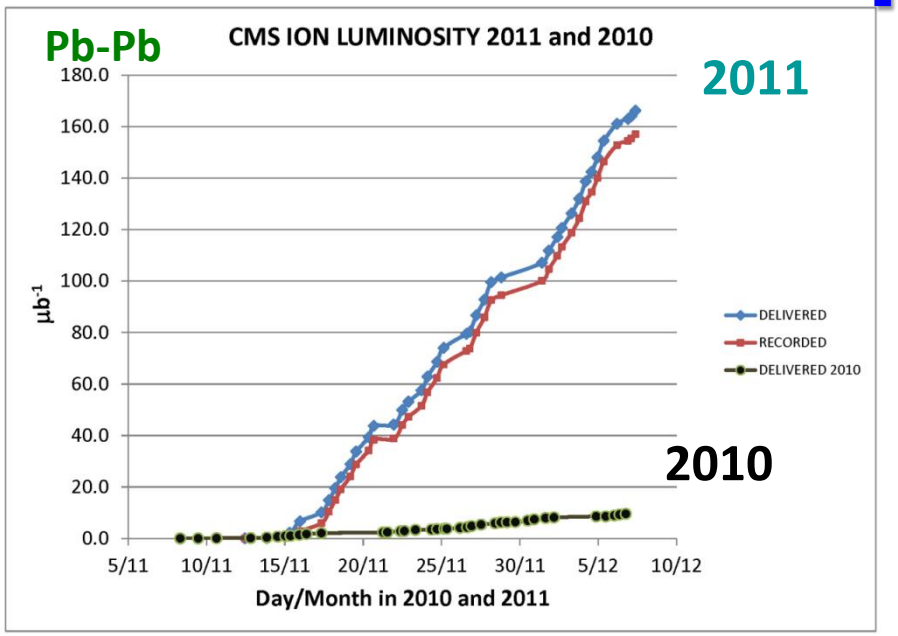
  - radiative processes (gluons)
  - collisional processes
- And give rise to final particles sensitive to either
  - electroweak interaction (W, Z, photon)
  - strong interaction (quarks, gluons ➔ jets)

Both provide valuable info on energy loss mechanism and partonic medium characteristics /spatial structure

Data samples



- Excellent LHC operation
- Triggers on several objects: MinBias, photons, μ, electrons, jets, UPC,

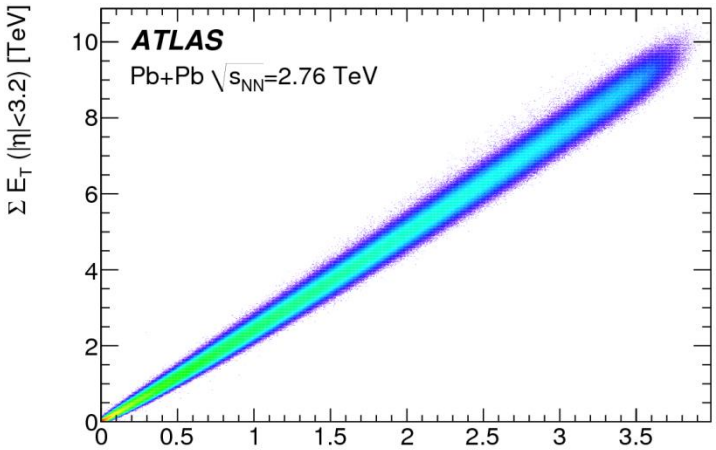
	PbPb (2010/11) $\sqrt{s_{NN}}$ = 2.76 TeV	pp (2011/13) $\sqrt{s}$= 2.76 TeV	pPb (2013) $\sqrt{s_{NN}}$ = 5.02 TeV
Lumi (nb^{-1})	0.007 / 0.15	230/5000	31
Nevts (M)	50 / 1.2 10^3	15 10^3	64 10^3

ATLAS & CMS

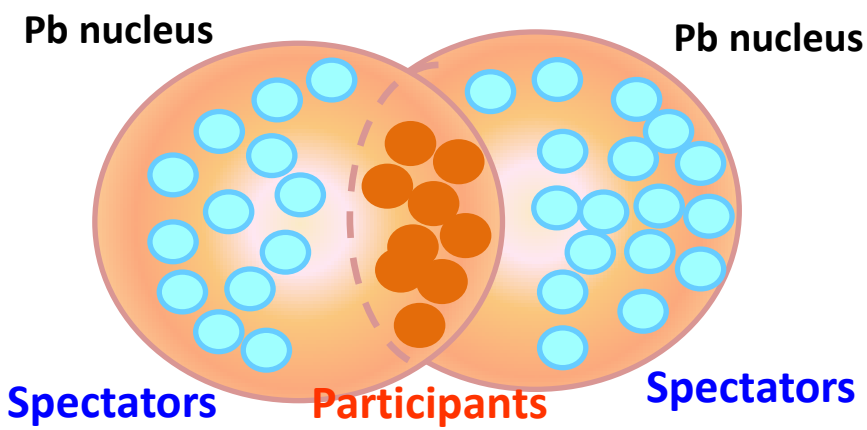
- Have optimal features for measurements in Heavy Ion collisions
  - wide rapidity coverage (almost 4π)
  - high collision energy, where interesting interactions (high p_T / Energy) distinguish clearly from underlying evt processes (low p_T / Energy).

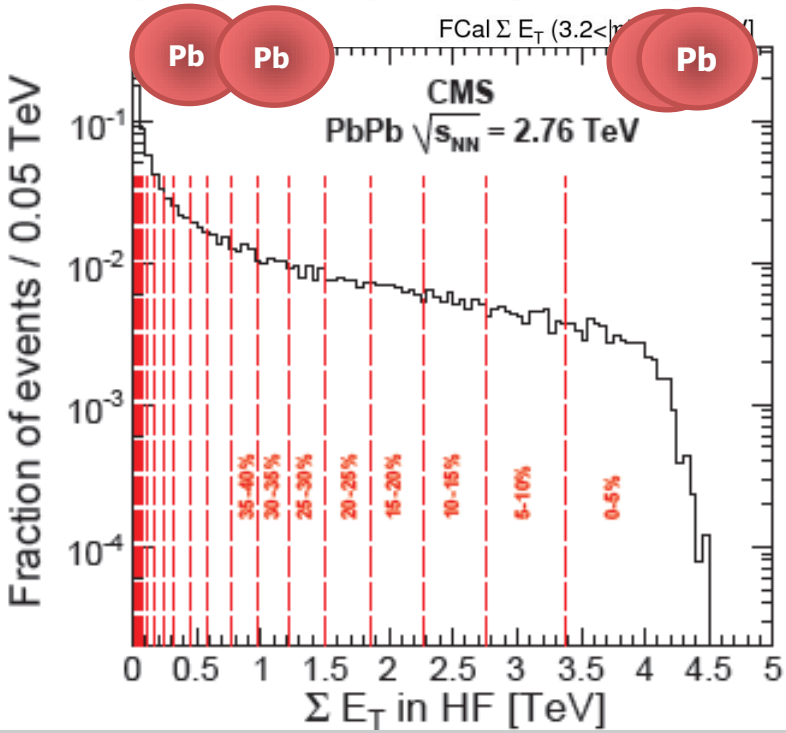
Global observable: centrality

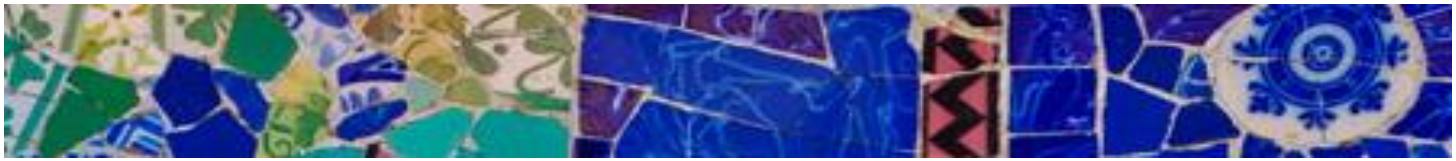
- Reflects geometrical overlap of colliding Pb nuclei
- Related to Nb of participant nucleons (**Npart**) in collision and Nb of binary collision (**Ncoll**) (through Glauber model)
- Measured with energy deposit in Forward Calorimeter



Particle production and its characteristics depend on degree of centrality of collision



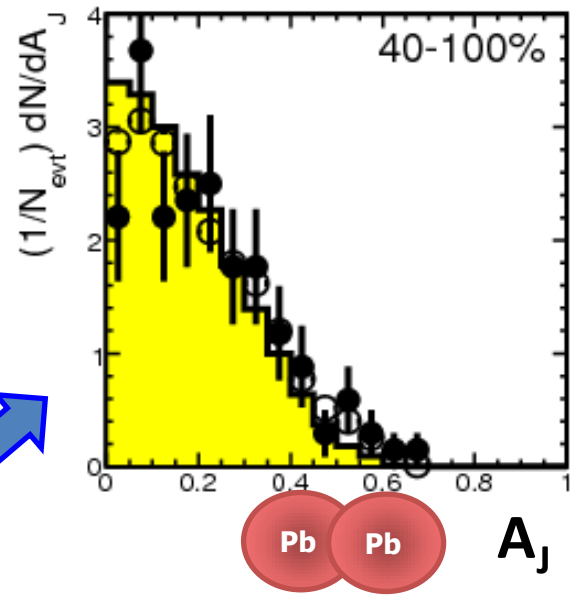




Jets

Jets : quenching

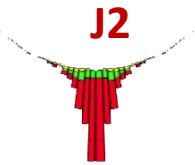
- NNLO calculations predict abundant rates of jets with $p_T > 100$ GeV/c in $|\eta| < 4.5$ ➔ useful probes to test thermodynamical/transport properties
- Already established at RHIC suppression of high p_T particles (quenching).
- ATLAS & CMS probed jet momentum suppresion using Dijet Asymmetry for central collisions



$$A_J = \frac{p_T^{J1} - p_T^{J2}}{p_T^{J1} + p_T^{J2}}$$

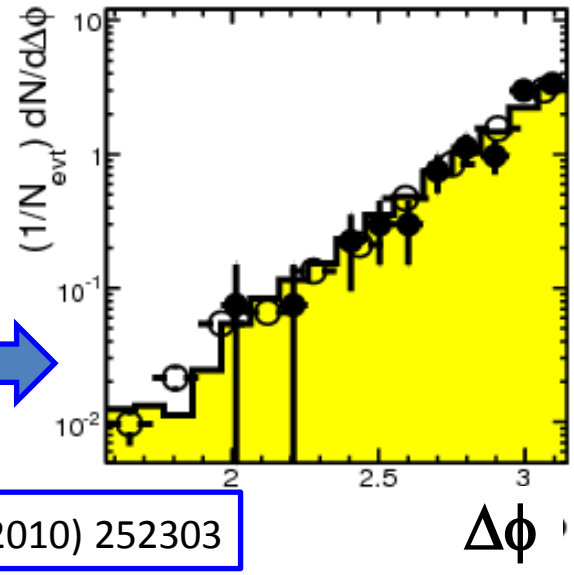
$A_J \approx 0$ balanced jets

$A_J \approx 1$ unbalanced jets



$$\Delta\phi = \phi^{J1} - \phi^{J2}$$

Jets remain essentially back-to-back



ATLAS PRL 105 (2010) 252303

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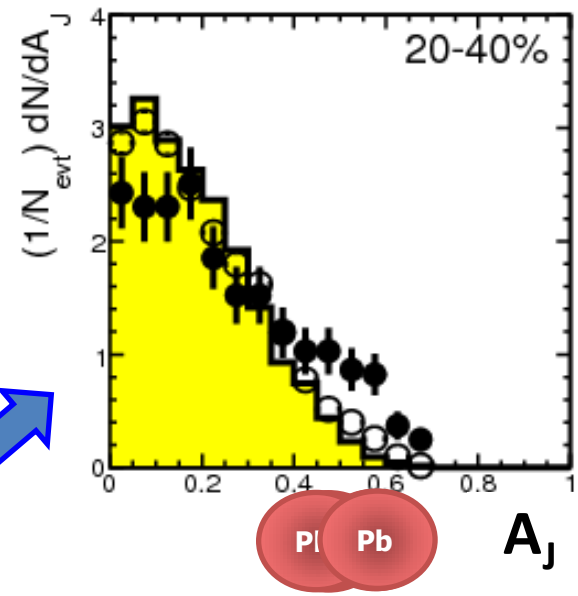

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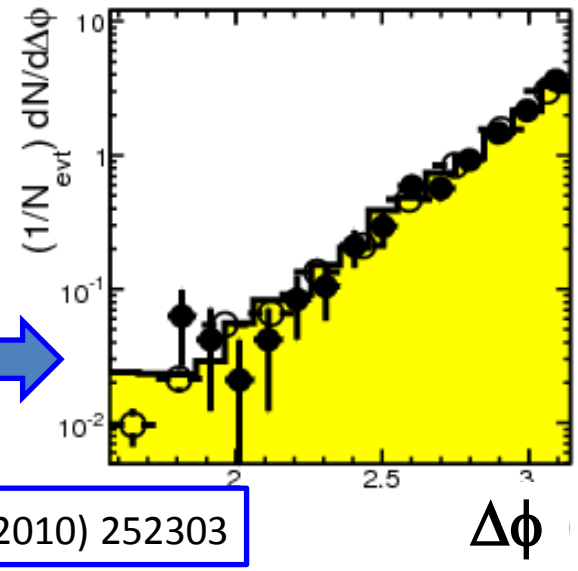

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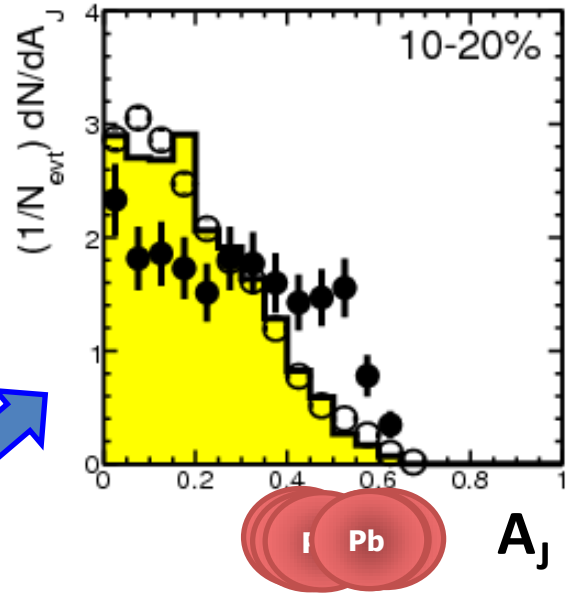

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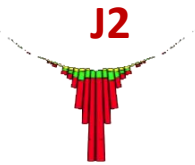

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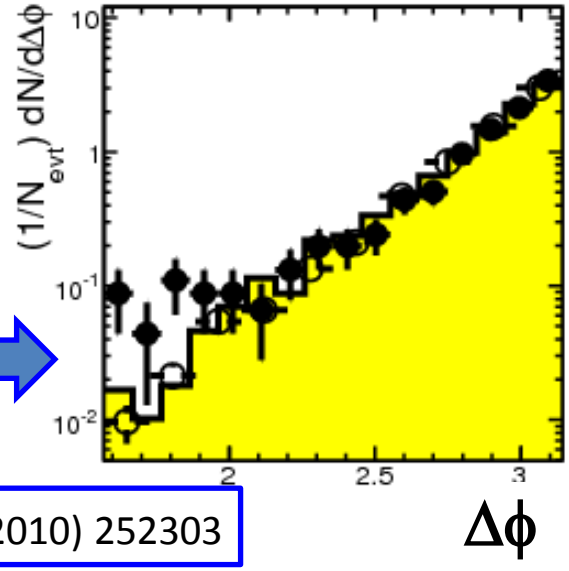

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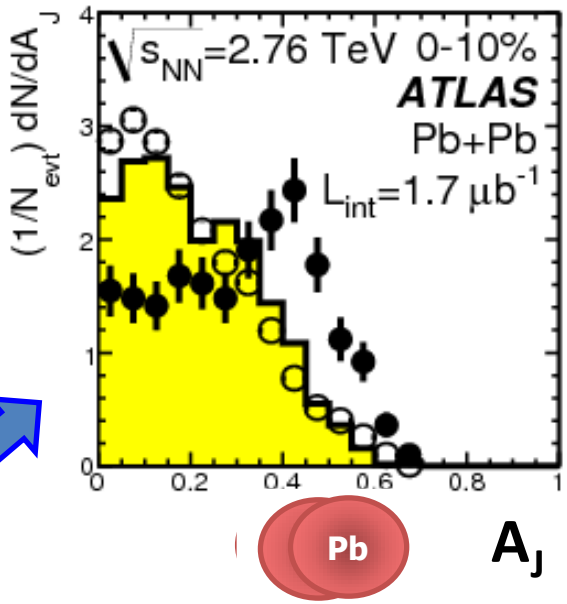

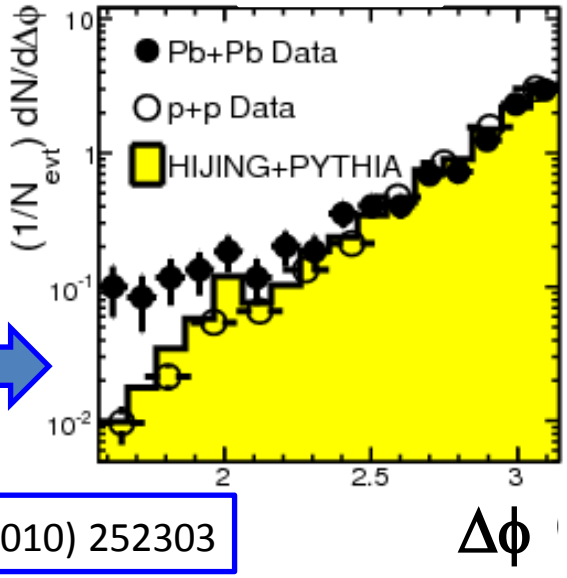

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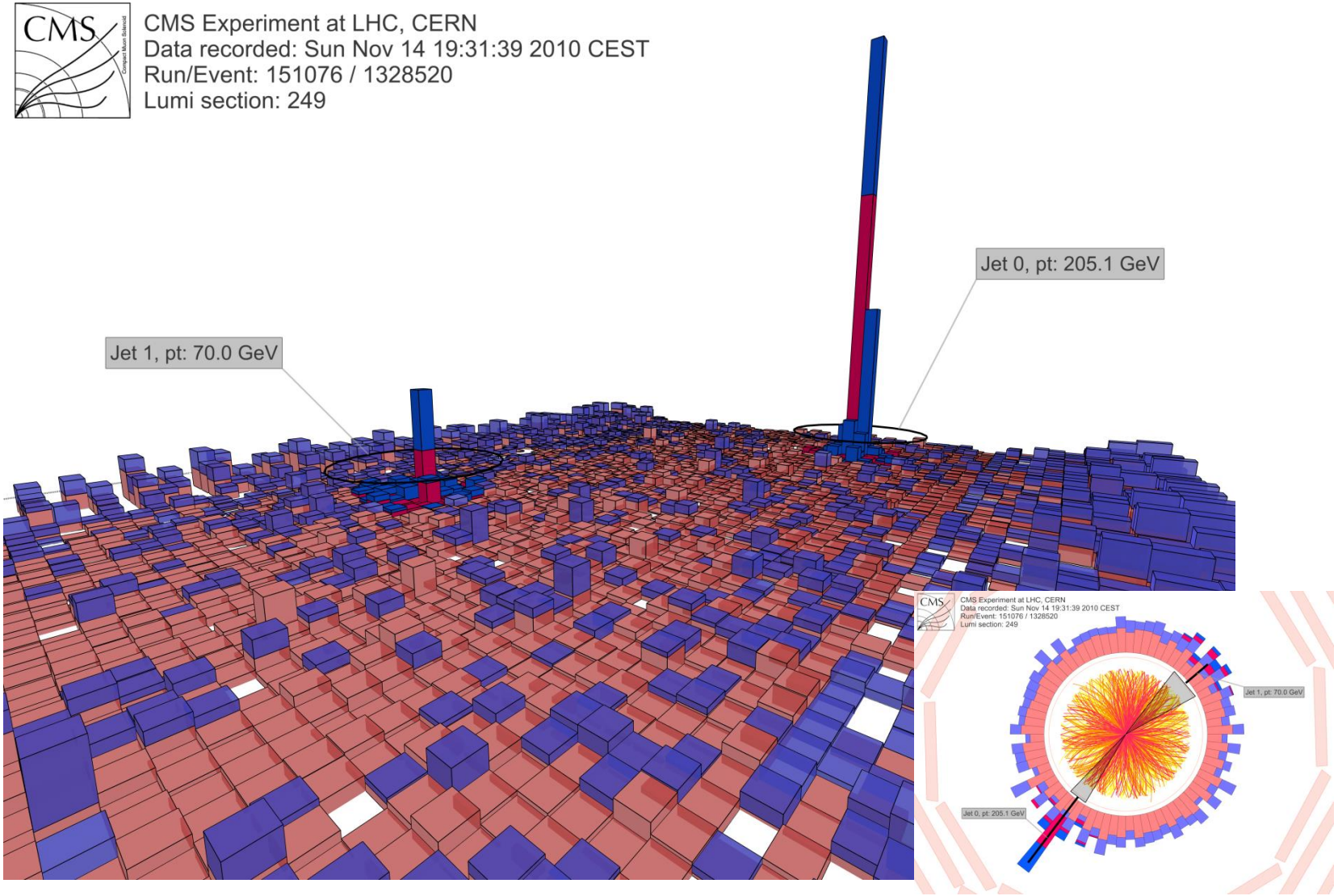

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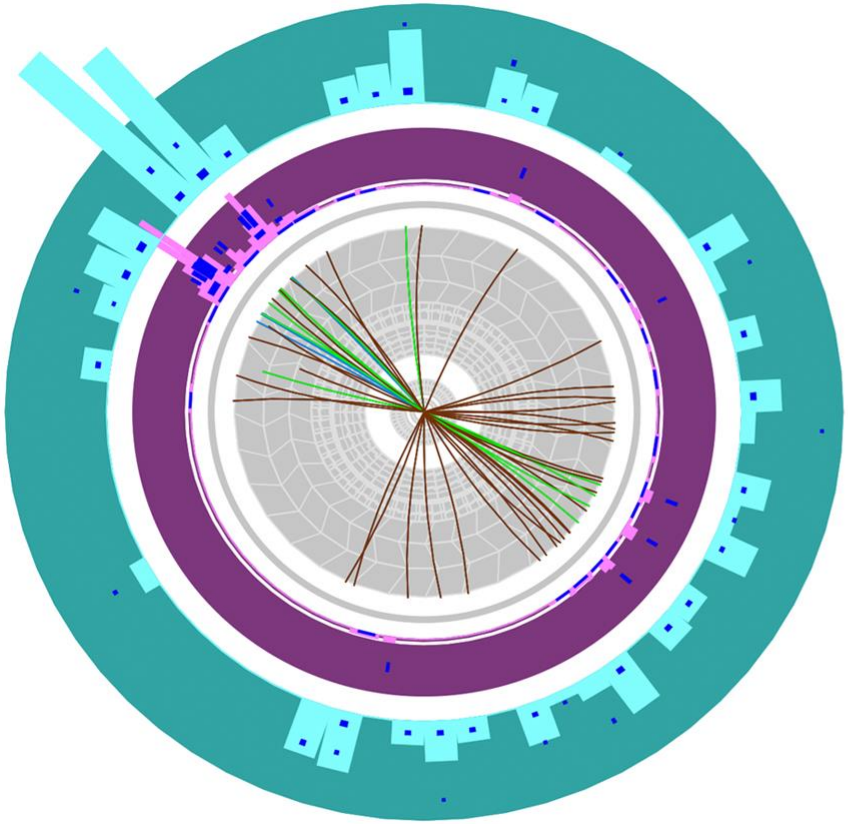
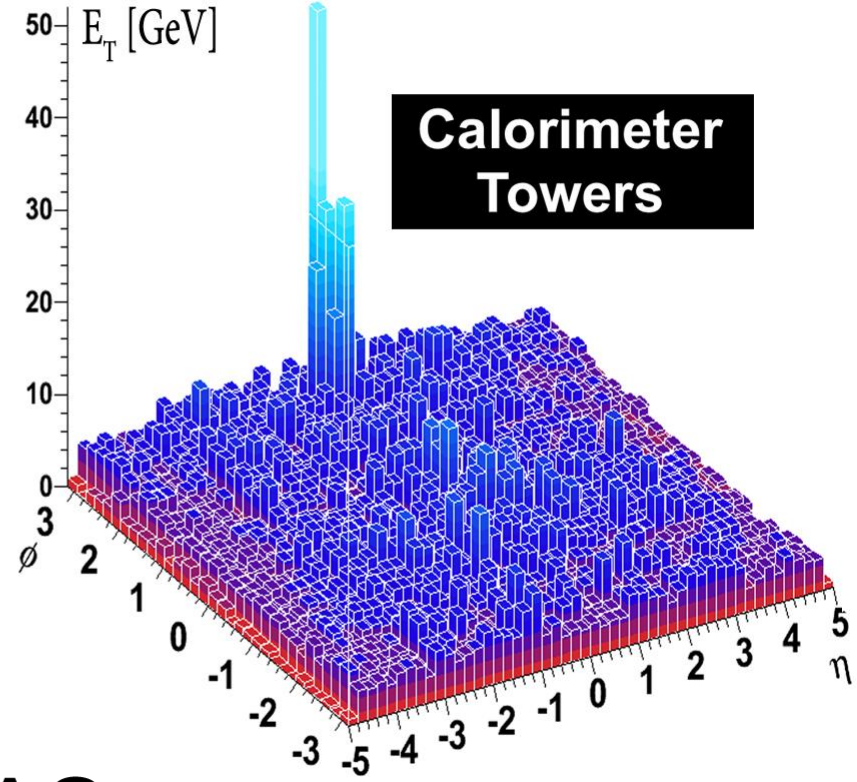




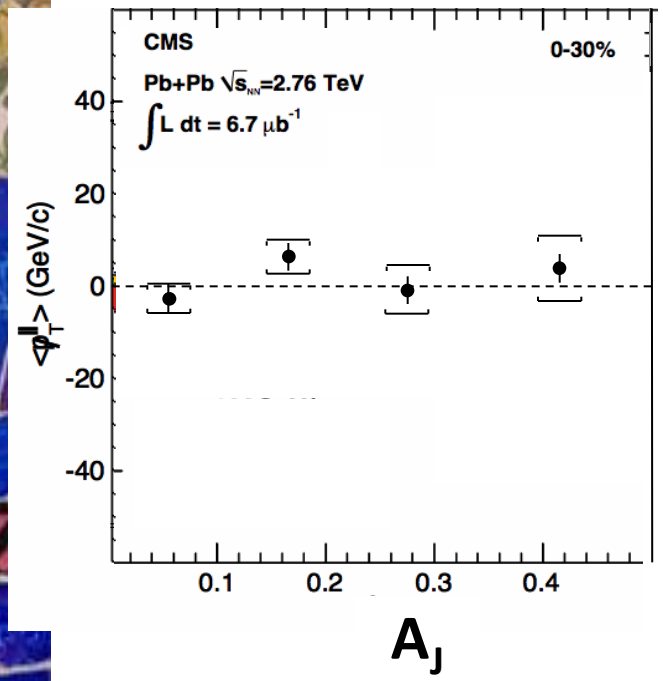
ATLAS
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET

Jets : where is p_T lost?

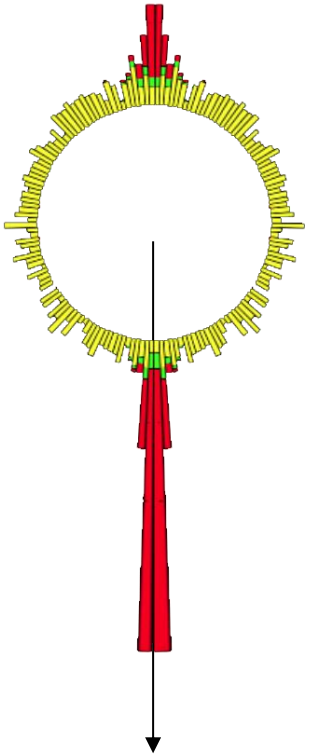
CMS Phys Rev C84 (2011) 024906

Calculate projection of p_T of tracks on leading jet axis and average over selected tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$

0-30% Central PbPb



$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$



Integrating over the whole event final state the momentum balance is restored

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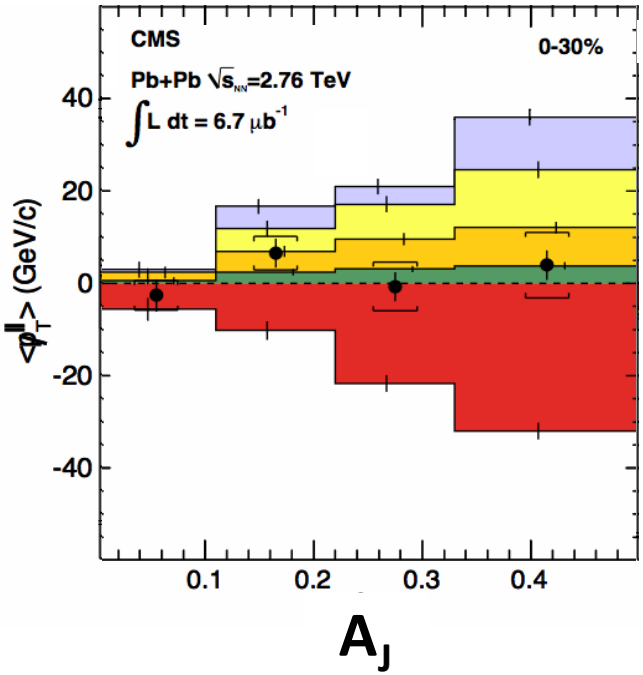

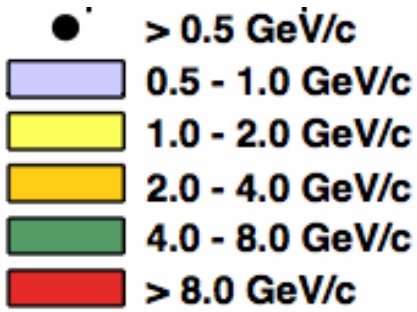

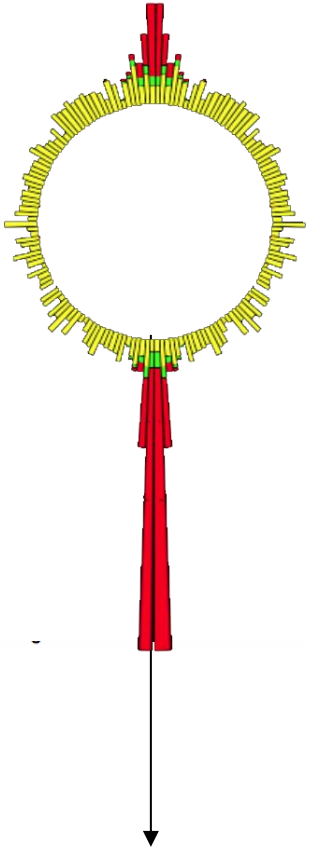

Integrating over the whole event final state the momentum balance is restored, with low p_T particles

Jets : where is p_T lost?

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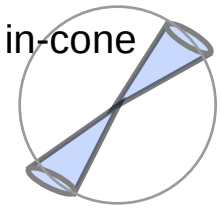

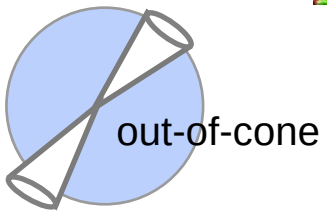

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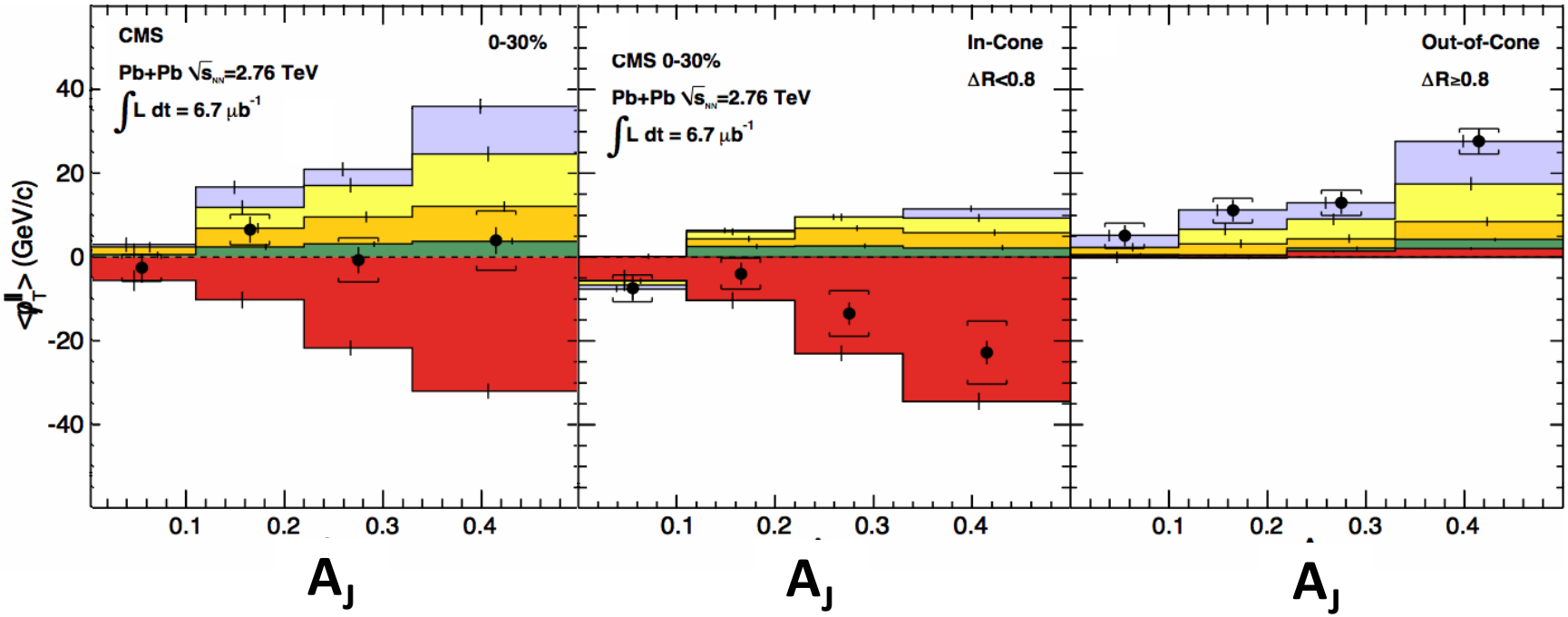
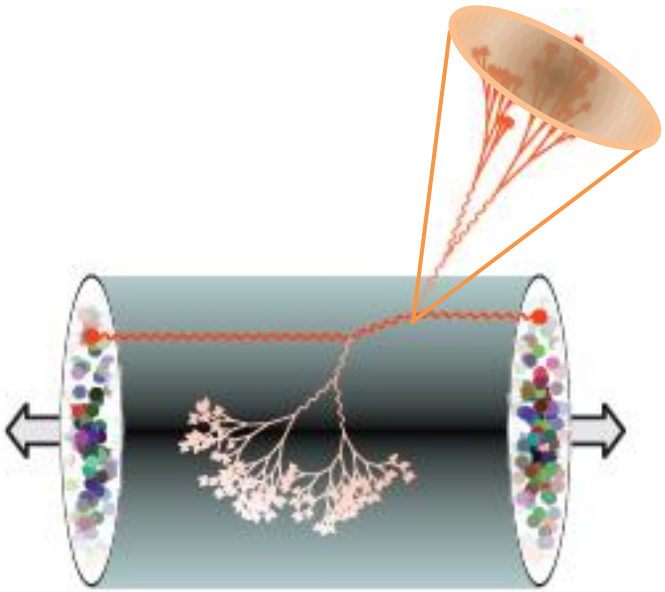


Integrating over the whole event final state the momentum balance is restored, with low p_T particles at large angles relative to the away side jet axis

Jets : quenching



- Initially produced high-p_T partons travel through QGP and emerge as showers of particles (jets) after hadronization/ fragmentation.
- The high-p_T parton loses energy in its way through QGP, depending on path length
  - Radiative
  - Collisional,
  - In-out cone jet, broadening it

What happens to the fragmentation process?

- Fragmentation functions reflect sharing of parton energy when hadronization into colourless particles. Are they modified by the energy loss mechanism?

- Evaluated correlating reco charged-particle tracks within a jet cone, with its axis.

$$Z = \frac{p_{||}^{tr}}{p^{jet}} \qquad \xi = \ln(1/z)$$

$Z \approx 1$ ➔ collimated jet ➔ $\xi \approx 0$

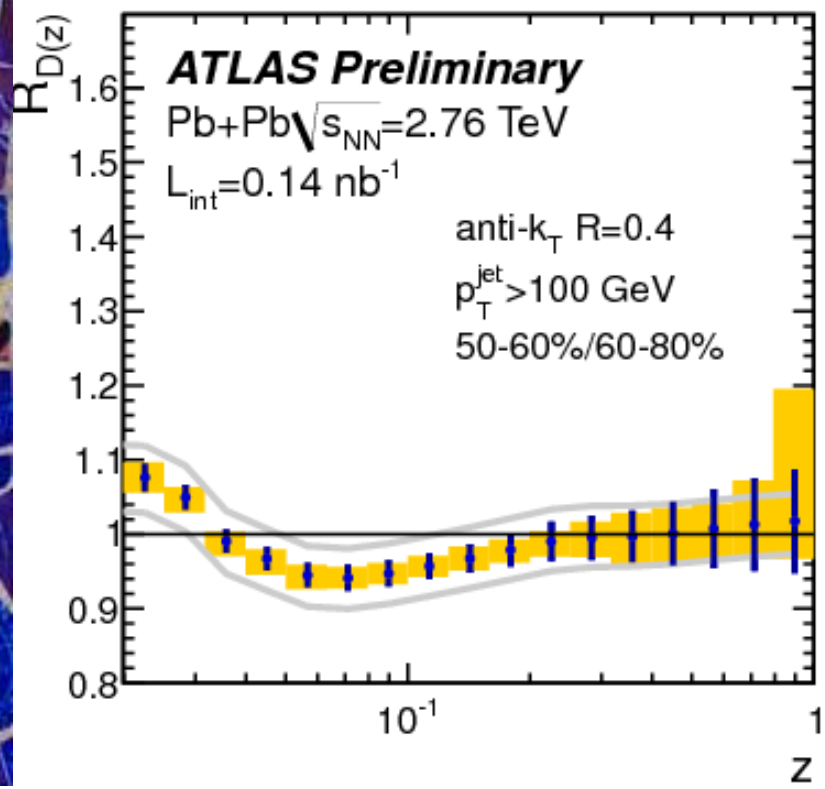
$Z \approx 0$ ➔ wide jet ➔ $\xi >>$

Jets fragmentation

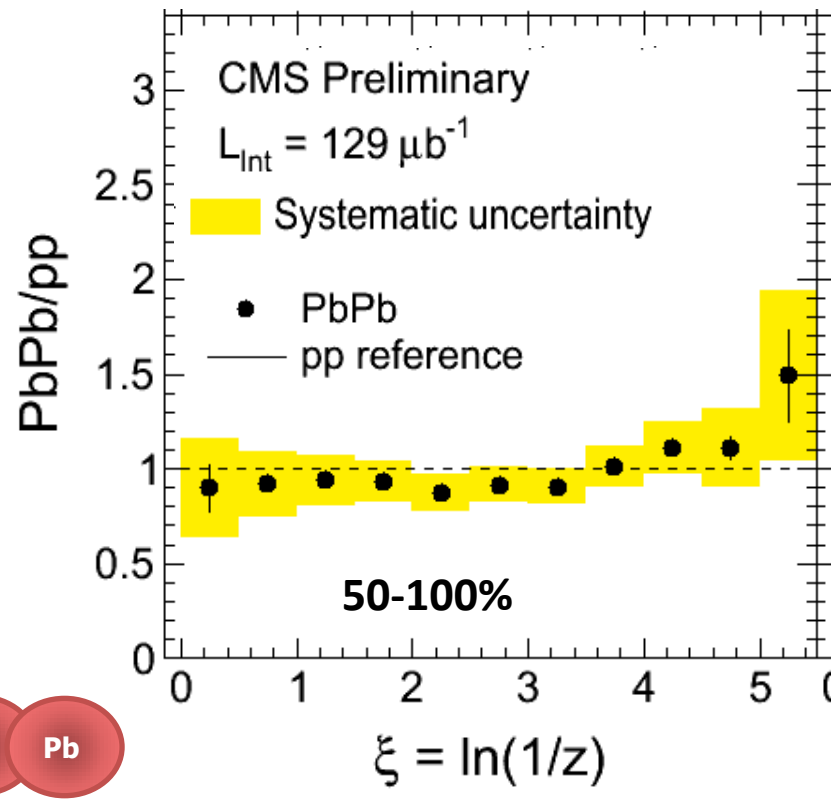
Consider tracks (p_T > 1 GeV/c) ➔ enhanced contribution of soft particles appear, broadening jet, when comparing

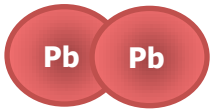
- ❑ PbPb Central to Peripheral collisions (ATLAS)
- ❑ PbPb (different centralities) to pp (CMS)

ATLAS-CONF-2012-115



CMS PAS HIN-12-013





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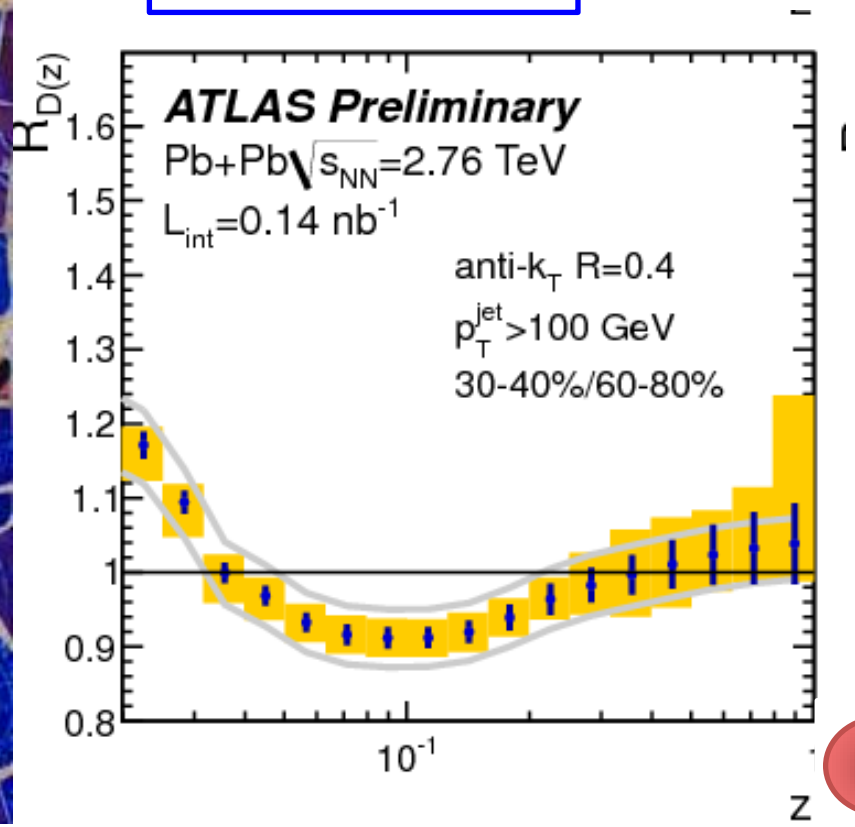

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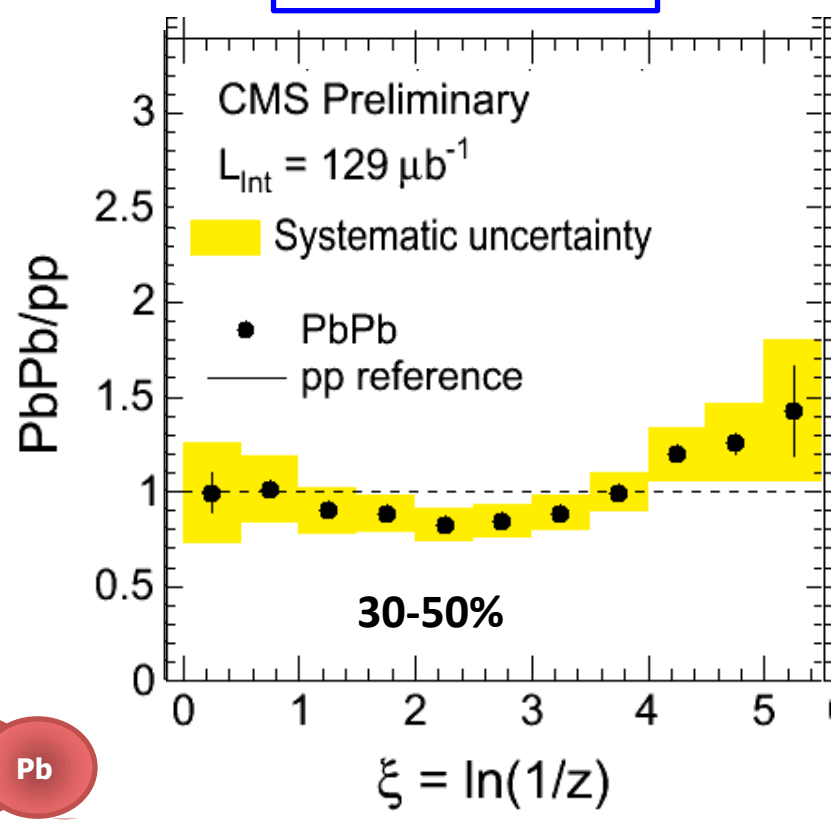

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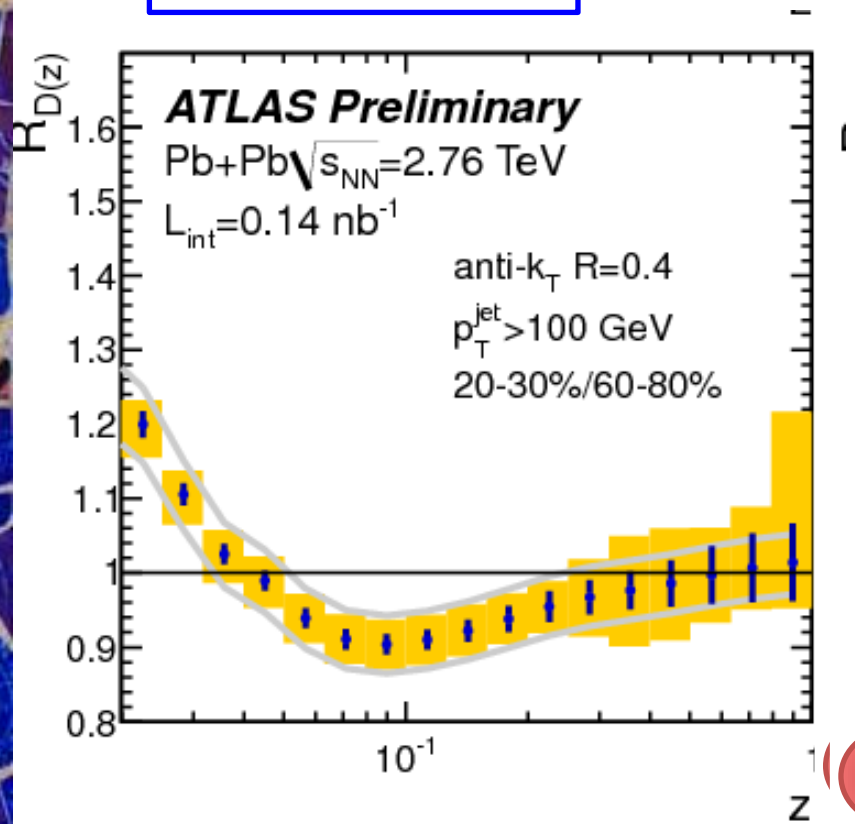

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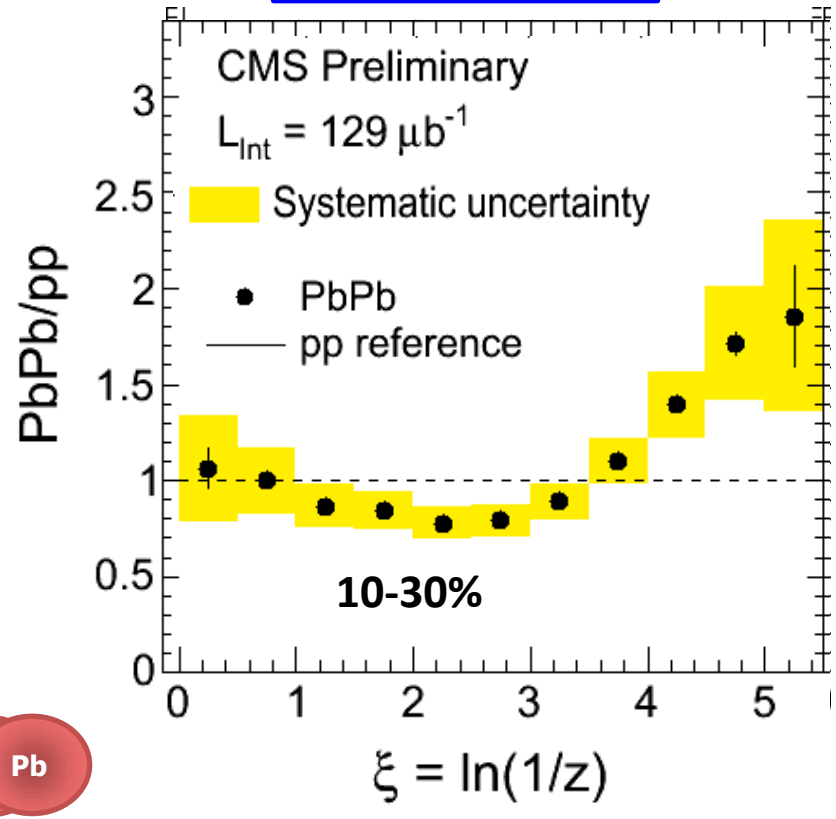

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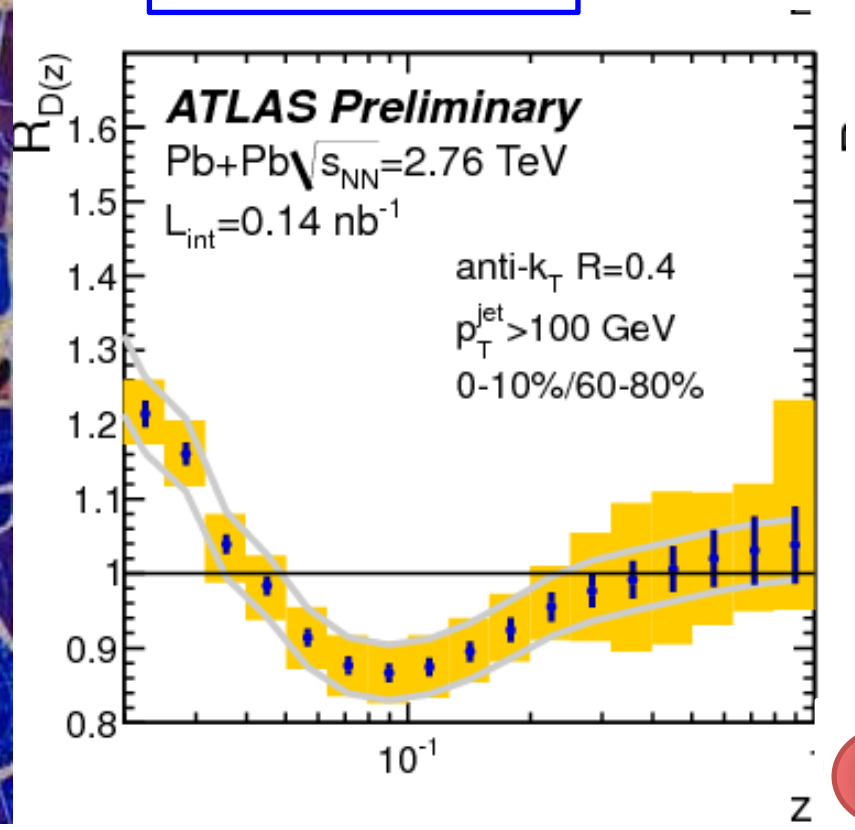

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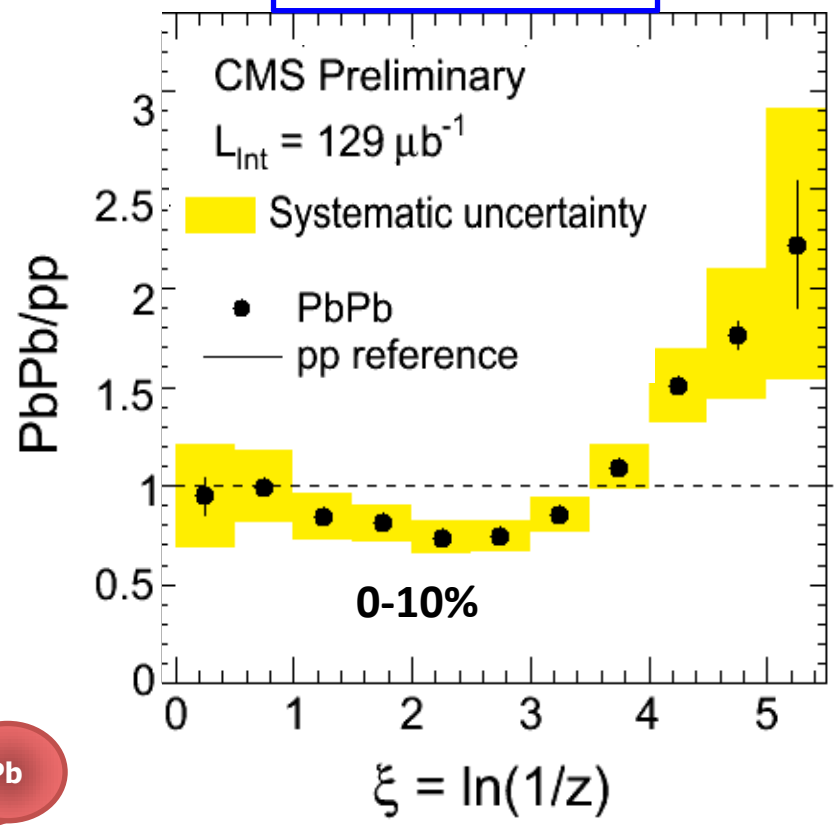

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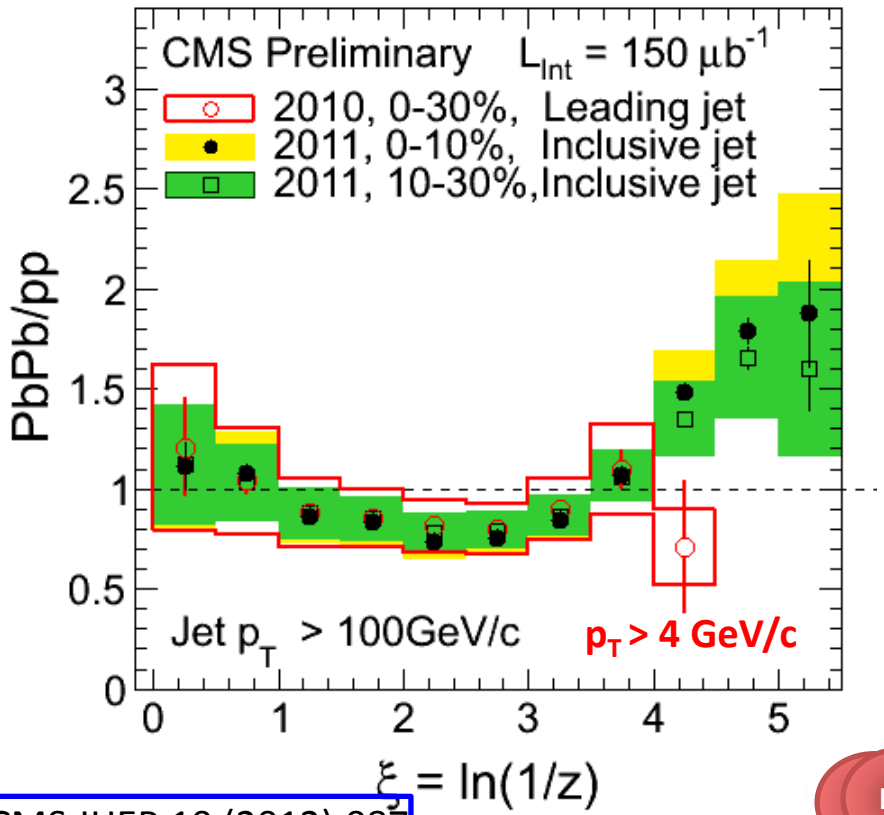
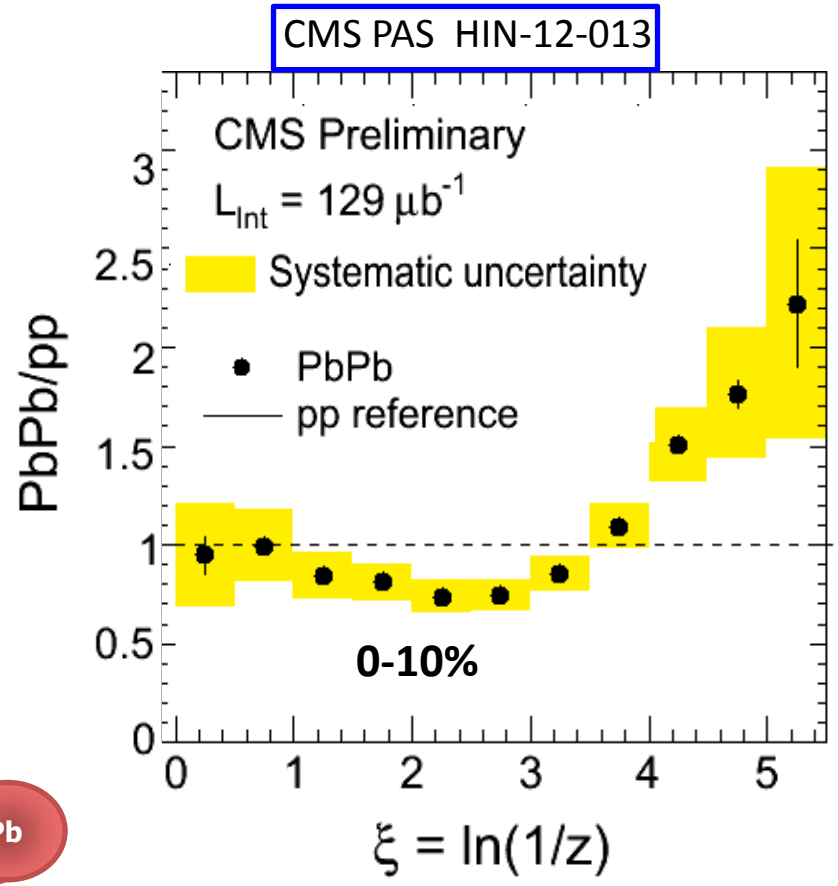


CMS JHEP 10 (2012) 087

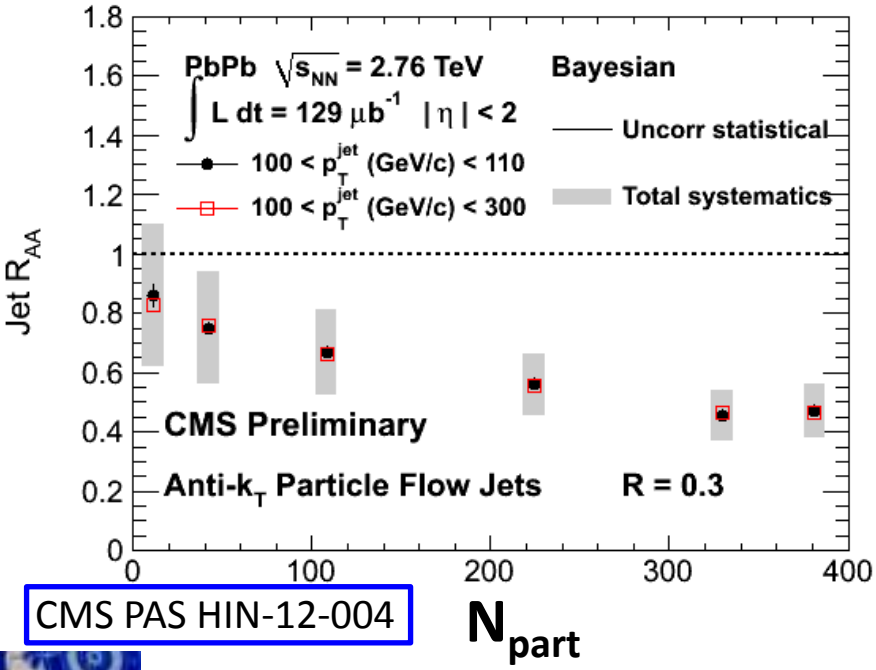


Jets yield (R_{AA})

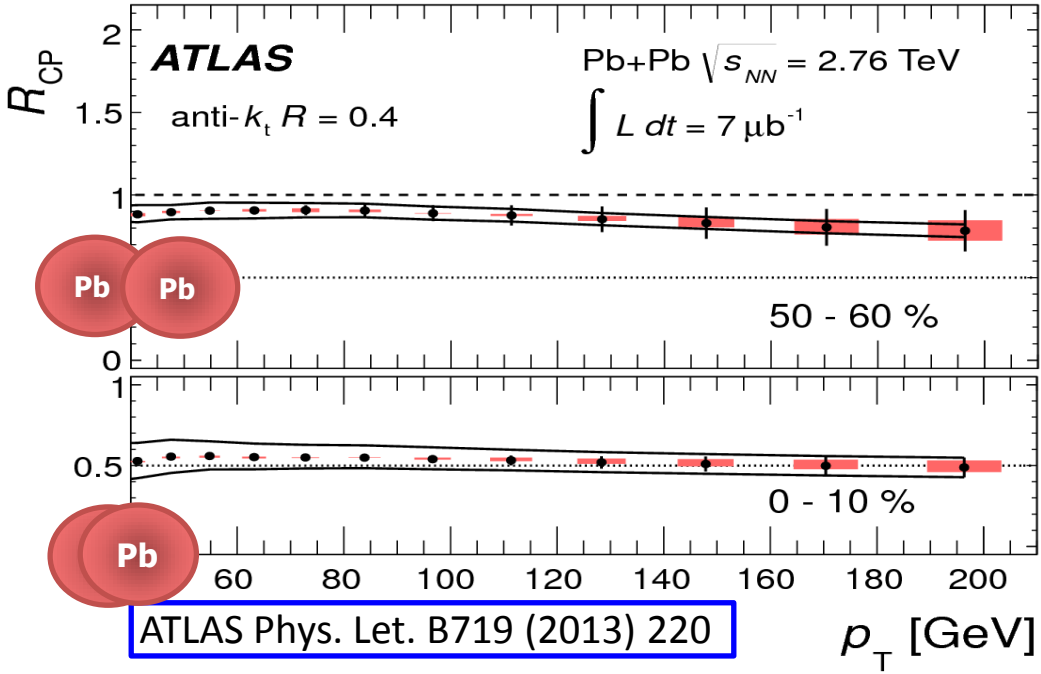
- Inclusive jet yields per event in PbPb collisions are studied through

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{A+A} / dydp_T}{d^2 N_{p+p} / dydp_T}$$

- Nuclear Modification Factor (R_{AA}) relative to jet yields in pp interactions, normalised to the average nb. of binary nucleon-nucleon collisions (N_{coll})
- R_{CP} , relative yield in central versus peripheral PbPb collisions.



CMS PAS HIN-12-004



ATLAS Phys. Let. B719 (2013) 220

Factor 2 suppression, in central collisions, almost independent jet p_T Cone radius

b- (c-) quark Jets

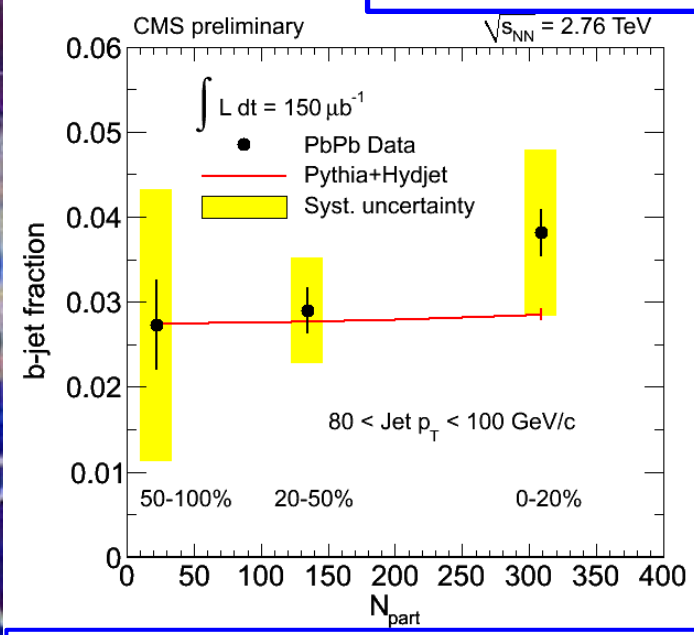
- Interesting to distinguish jets from gluons and quarks (and, if possible, flavour)
- Identification of jets originating from b-(c-)quarks.

New step forward in LHC for HI collisions!!

ATLAS: statistical discriminating signal-bckgd variable based on different p_T measurements of muons in various detectors, using muons coming in jets ($4<p_T<14$ GeV/c)

CMS: exploit long b-quark lifetime, originating secondary vertices ➔ tag b-jets

CMS PAS HIN-12-003



R_{AA}(b-jets) = 0.48±0.09(stat)±0.18(syst)
100 < p_T jet < 120 GeV/c

b- (c-) quark Jets

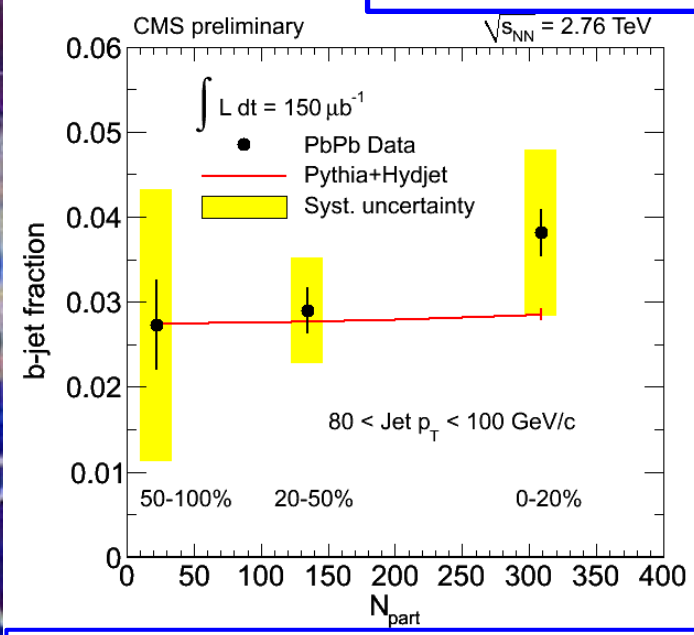
- Interesting to distinguish jets from gluons and quarks (and, if possible, flavour)
- Identification of jets originating from b-(c-)quarks.

New step forward in LHC for HI collisions!!

ATLAS: statistical discriminating signal-bckgd variable based on different p_T measurements of muons in various detectors, using muons coming in jets ($4<p_T<14$ GeV/c)

CMS: exploit long b-quark lifetime, originating secondary vertices ➔ tag b-jets

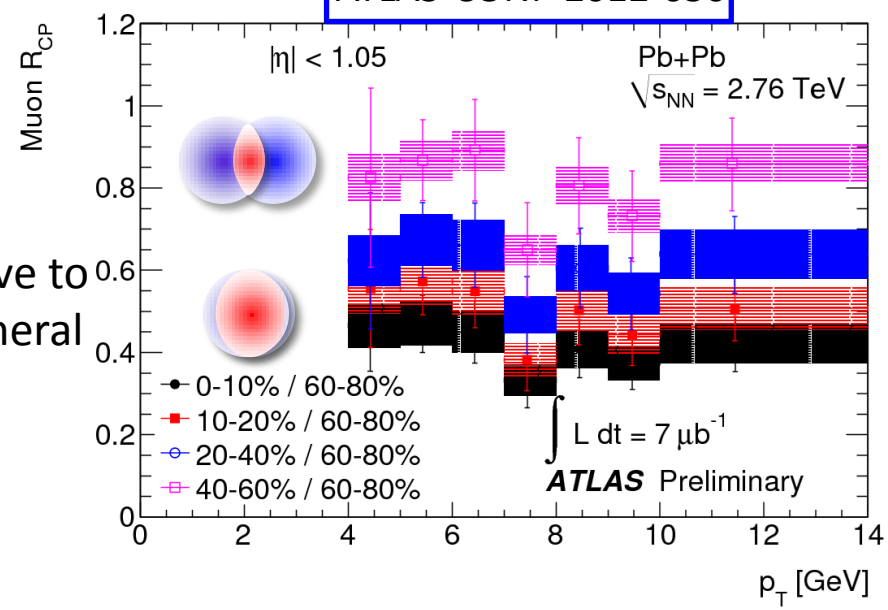
CMS PAS HIN-12-003



R_{AA}(b-jets) = 0.48±0.09(stat)±0.18(syst)
100 < p_T jet < 120 GeV/c

ATLAS-CONF-2012-050

Relative to peripheral



R_{AA}(b-jets) compatible with that of inclusive jets, weaker than for charged hadrons

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New step forward in LHC for HI collisions!!

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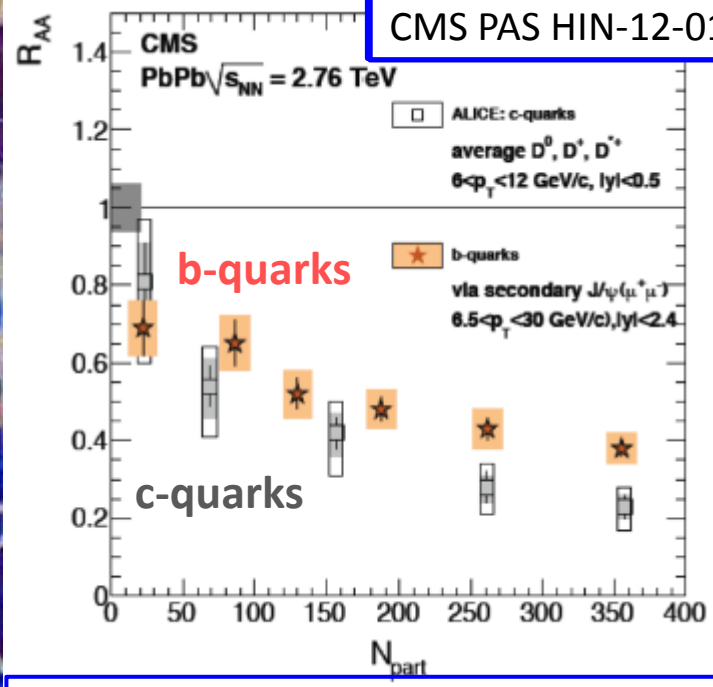
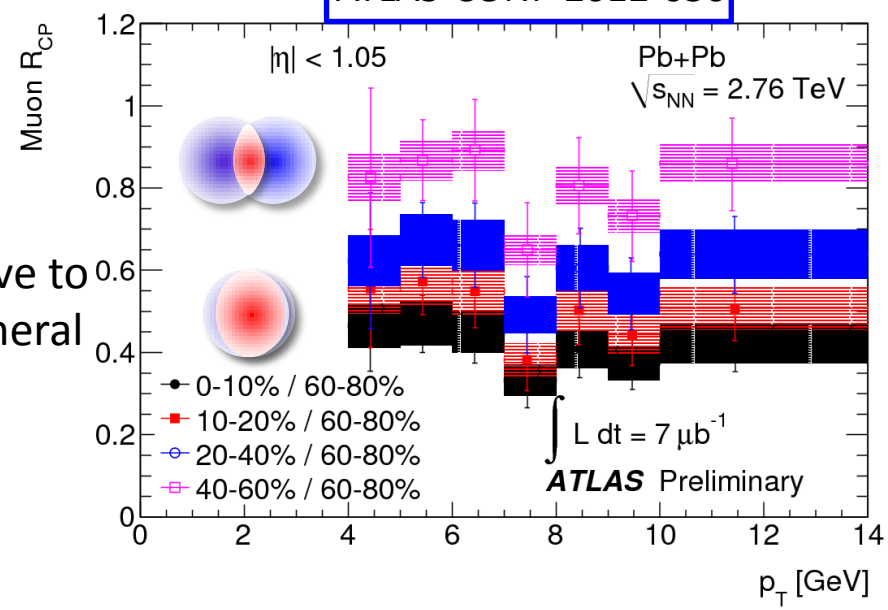
CMS PAS HIN-12-014



ATLAS-CONF-2012-050



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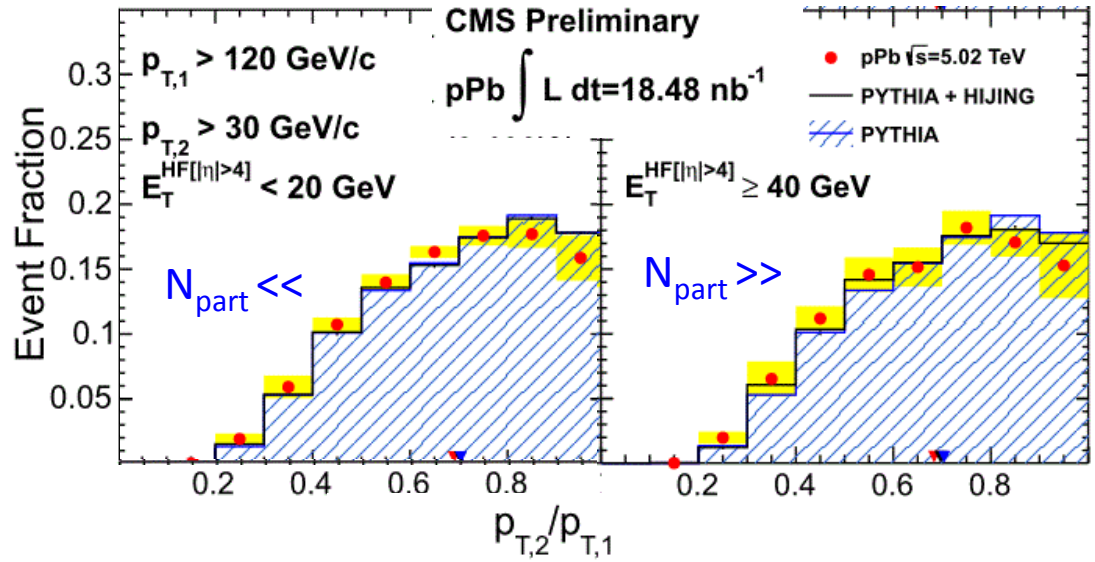
DiJets in p-Pb collisions

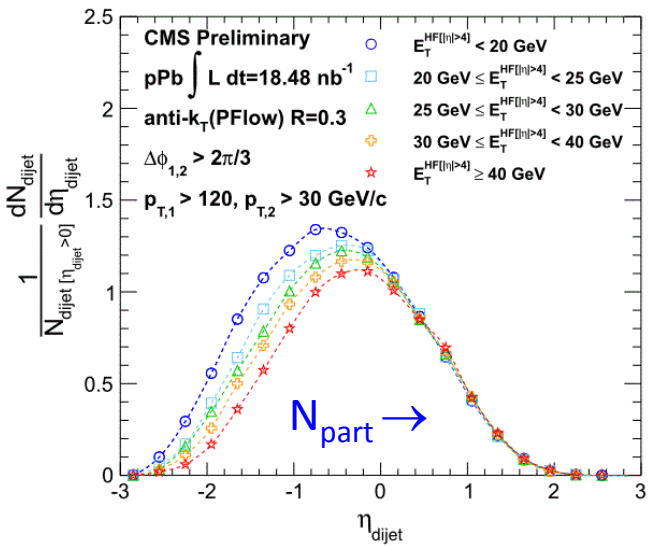
New!

Asymmetric collision

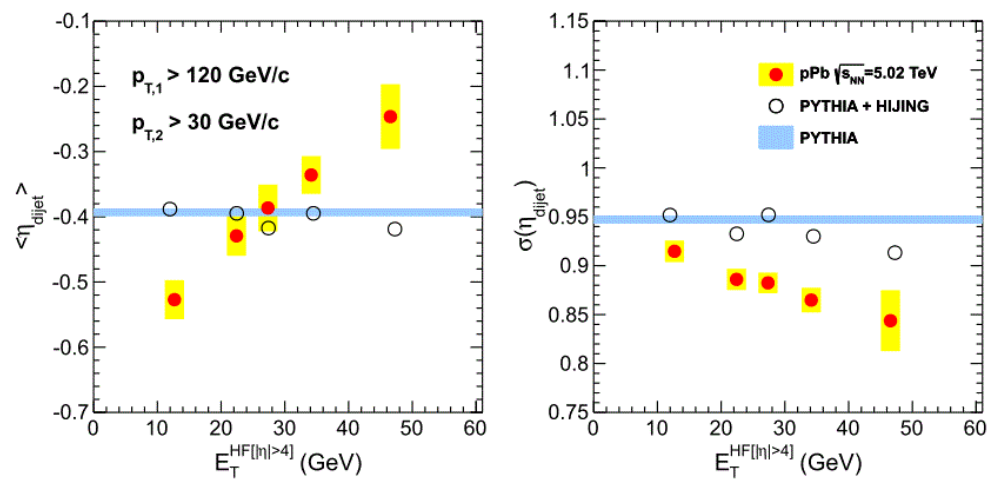
CMS PAS HIN-13-001

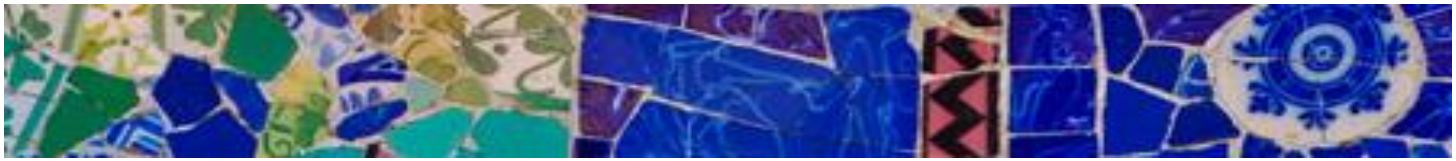


- p_T^{J2}/p_T^{J1} insensitive to N_{part} in collision ➔ no p_T imbalance
- Jets remain back to back
- Consistent with pp reference



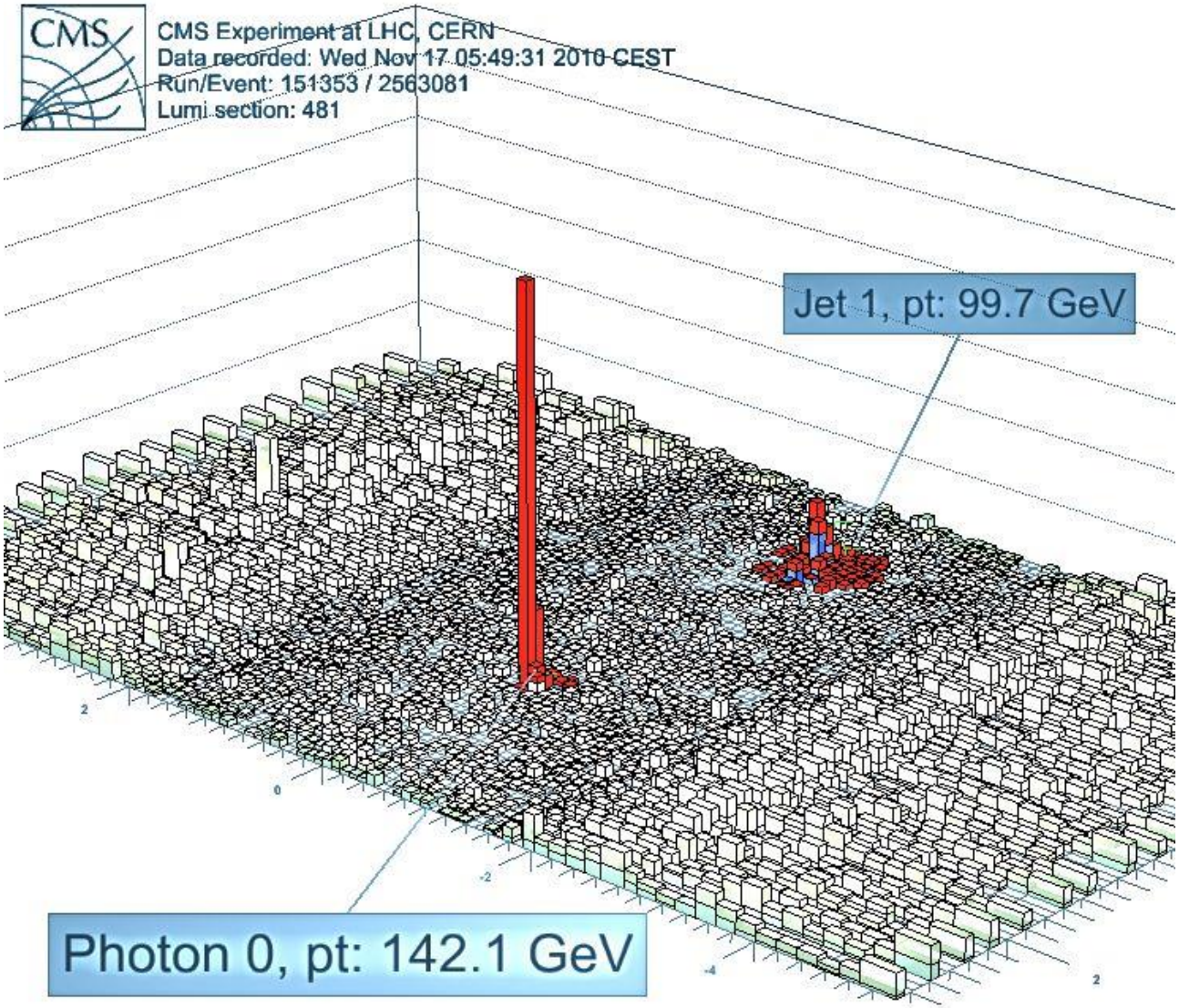
- Modification of dijet η $(\eta_1 + \eta_2)/2$ with N_{part}





Vector Boson Production
γ, Z, W

Isolated Photons



Isolated Photons

$qg \rightarrow \gamma q$ Compton scattering

$q\bar{q} \rightarrow \gamma g$ quark–antiquark annihilation

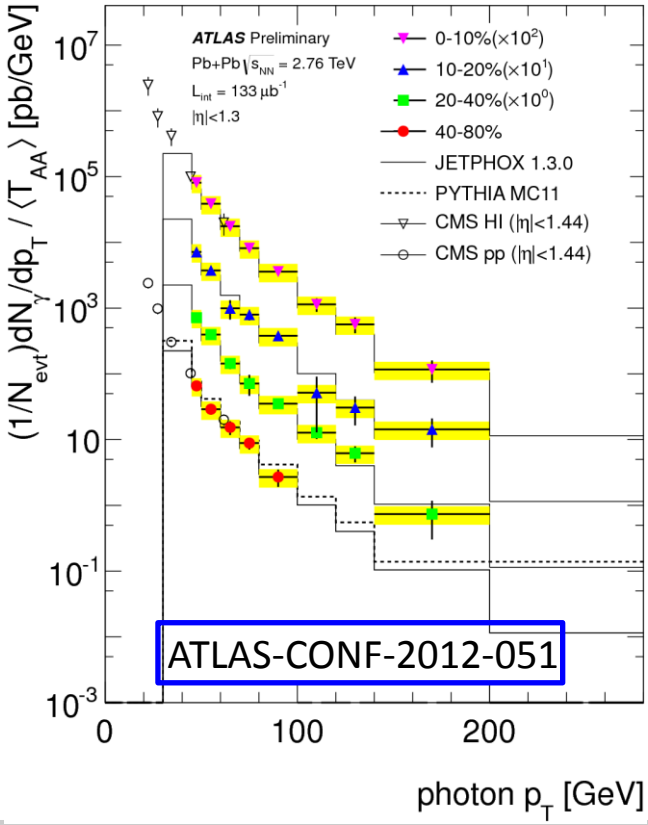
Direct photons from hard scattering

Direct probe of initial state

$q, g \rightarrow \gamma + q, g$ Parton Fragmentation (FSR)

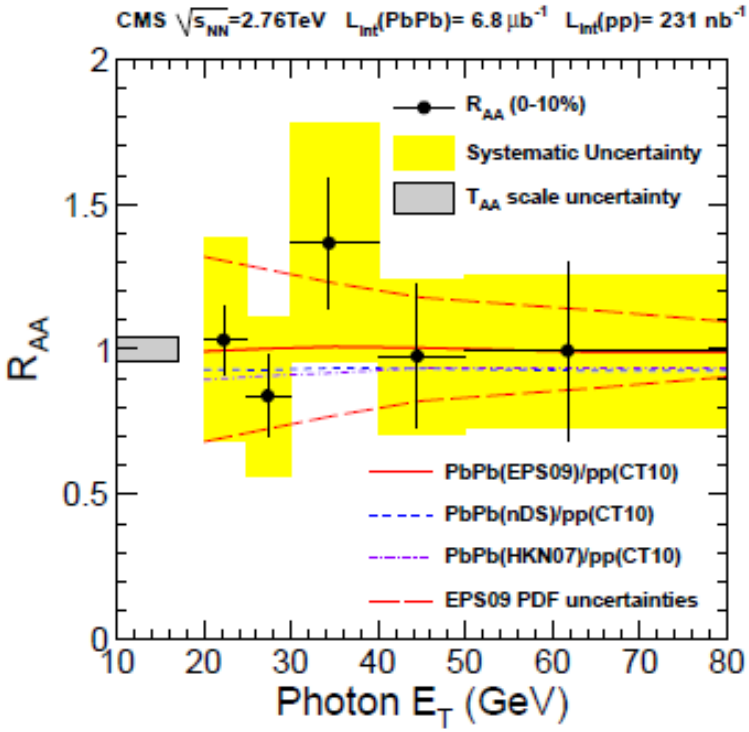
Challenge: Disentangle photons from π^0, η decays

➔Isolation techniques are crucial



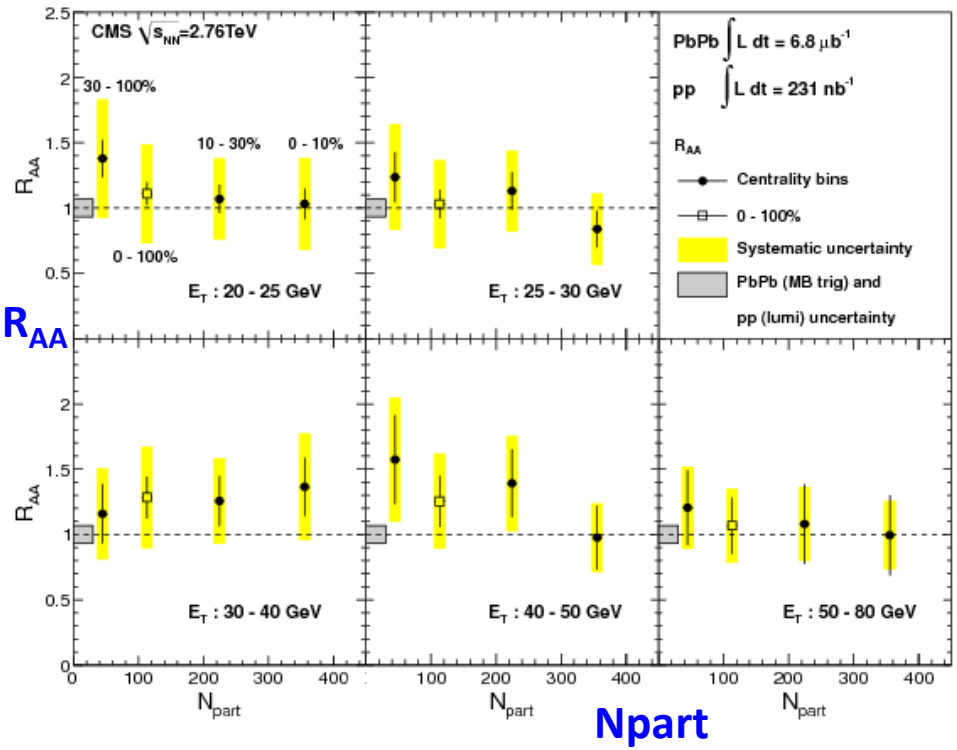
ATLAS-CONF-2012-051

CMS Phys. Lett. B710 (2012) 256

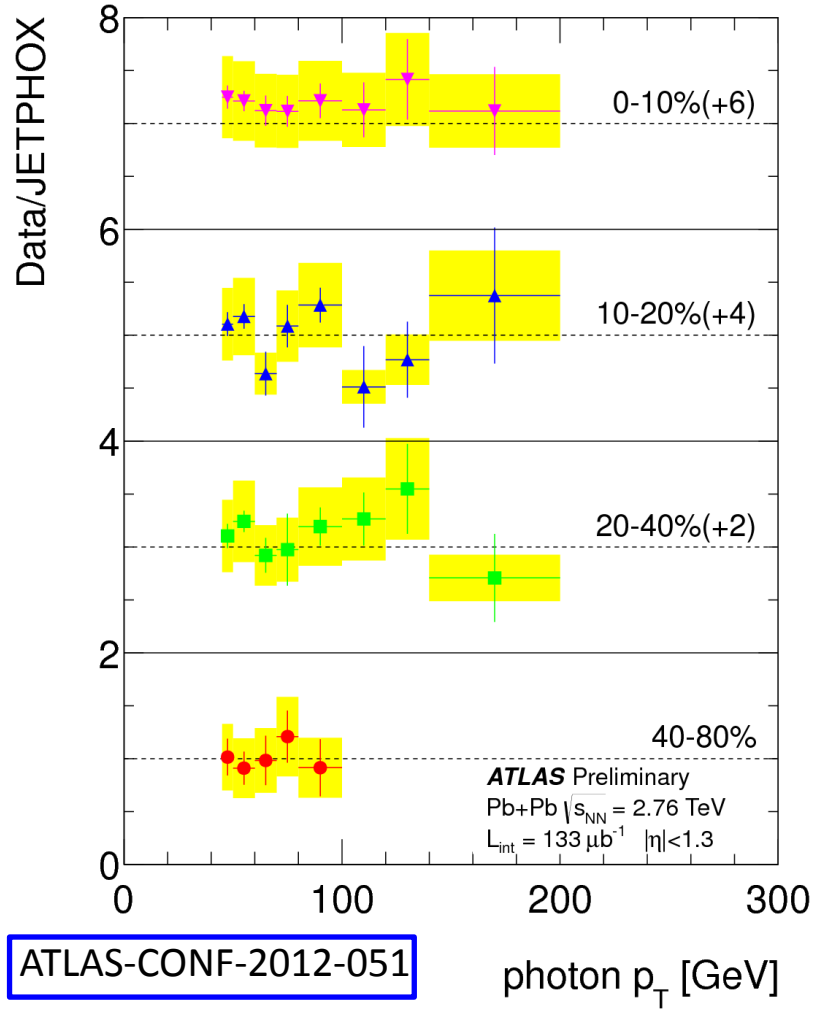


Isolated Photons

- Photons are unmodified, independent of centrality or E_T range



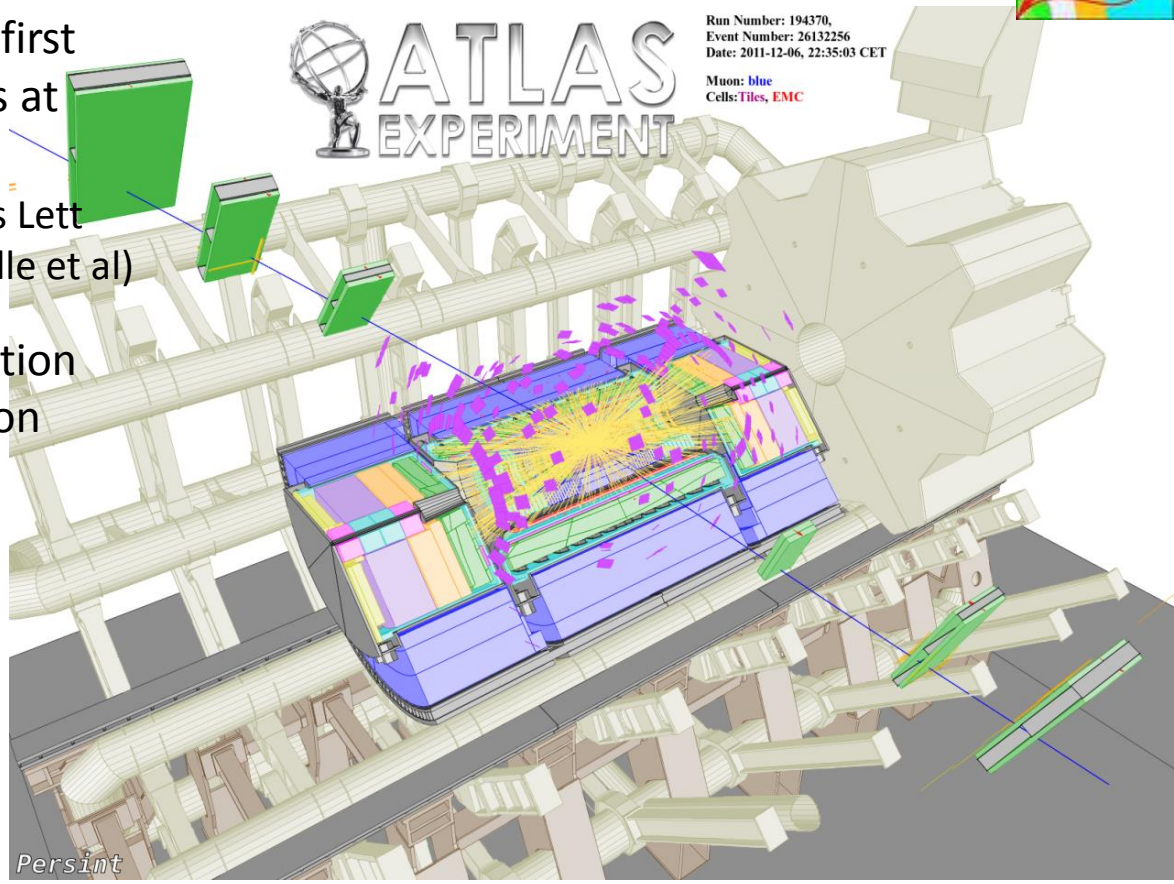
CMS Phys. Lett. B710 (2012) 256



ATLAS-CONF-2012-051

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

- Z, W bosons measured for first time in Heavy Ion collisions at ATLAS & CMS
  - Simulation studies (e.g. Phys Lett B663 (2008) 202 Z. Conesa del Valle et al)
- $q\bar{q} \rightarrow W,Z$ q–qbar annihilation Decay before QGP formation



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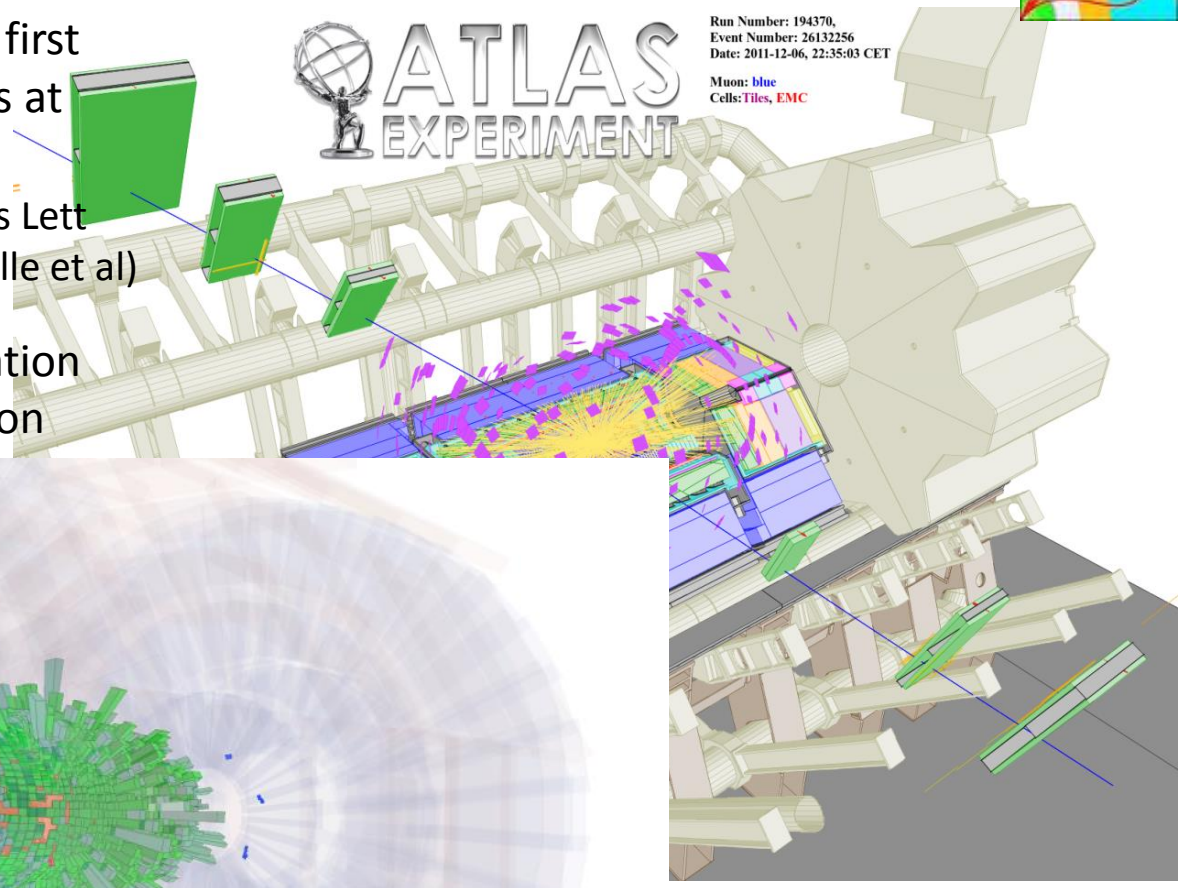
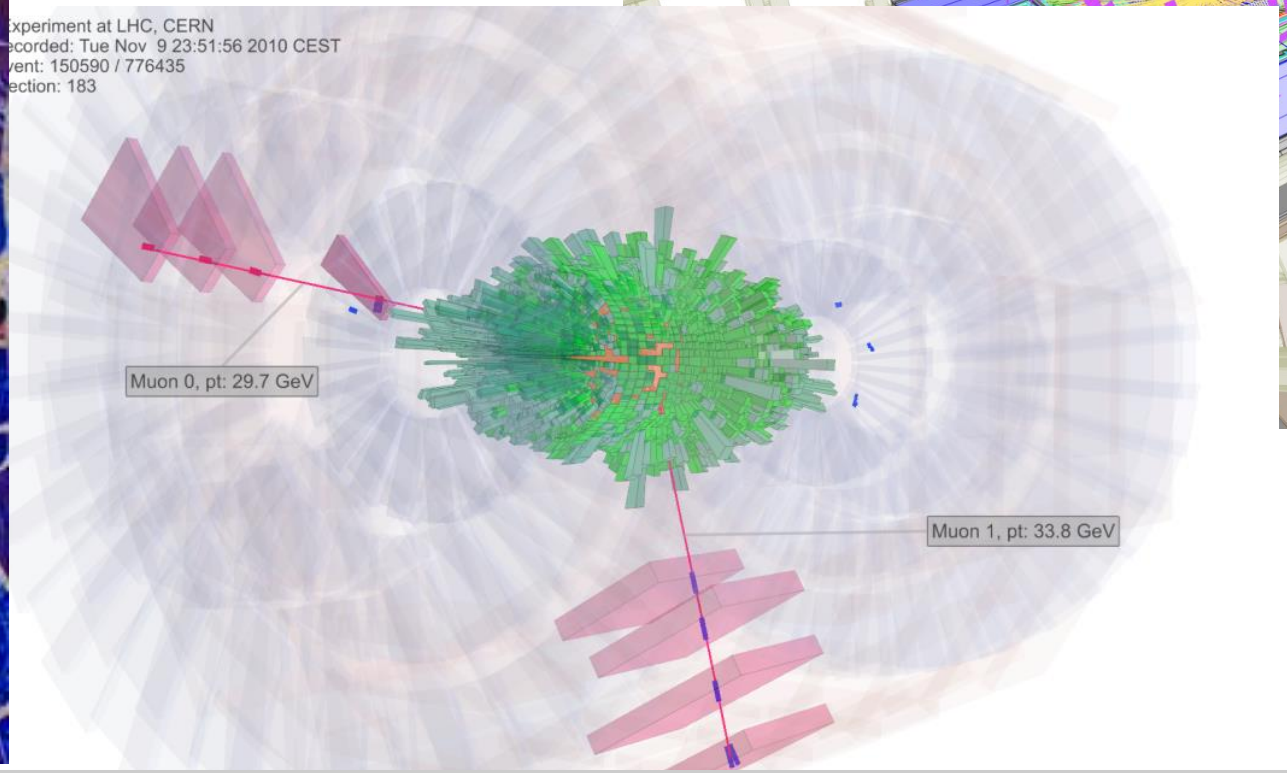
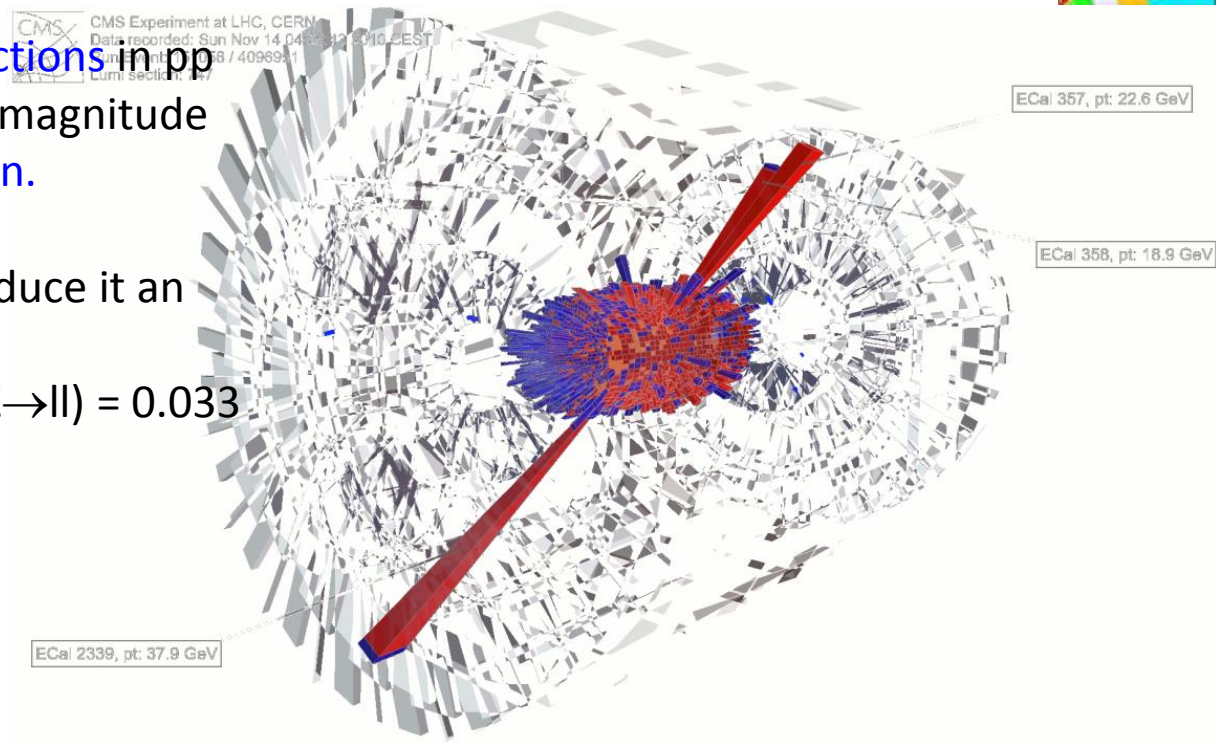




$Z \rightarrow e^+e^-$

- W-Z production cross sections in pp collisions is ~4 orders of magnitude smaller than b production.

- Leptonic (μ, e) decays reduce it an additional factor
- BR($W \rightarrow l\nu$) = 0.10 ; BR ($Z \rightarrow ll$) = 0.033



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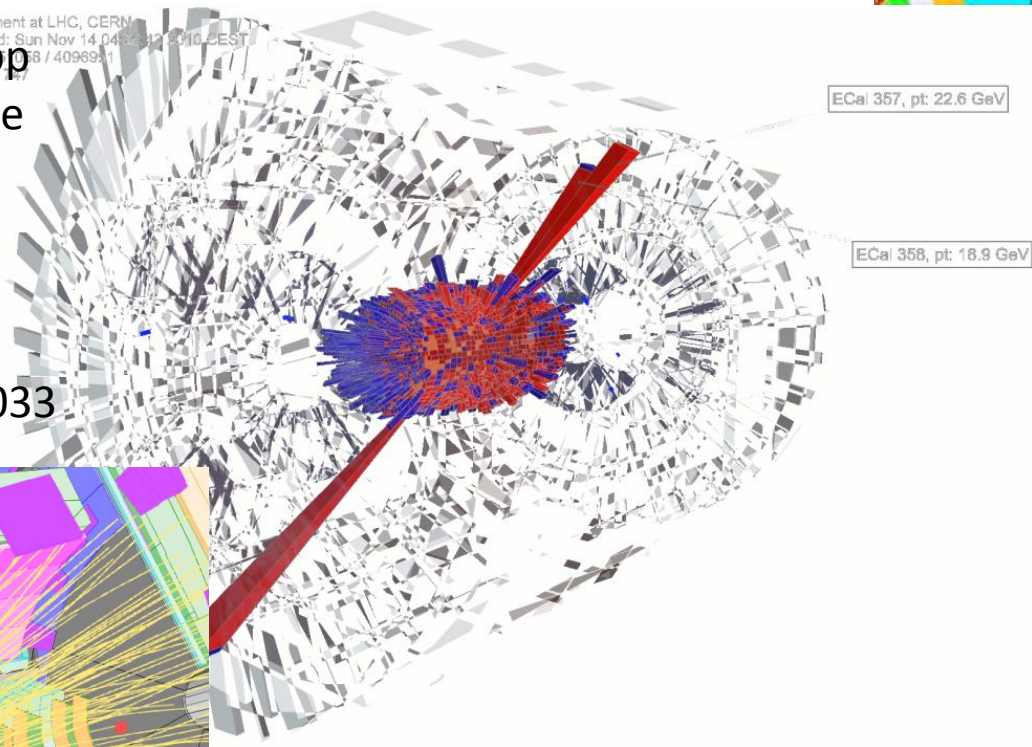
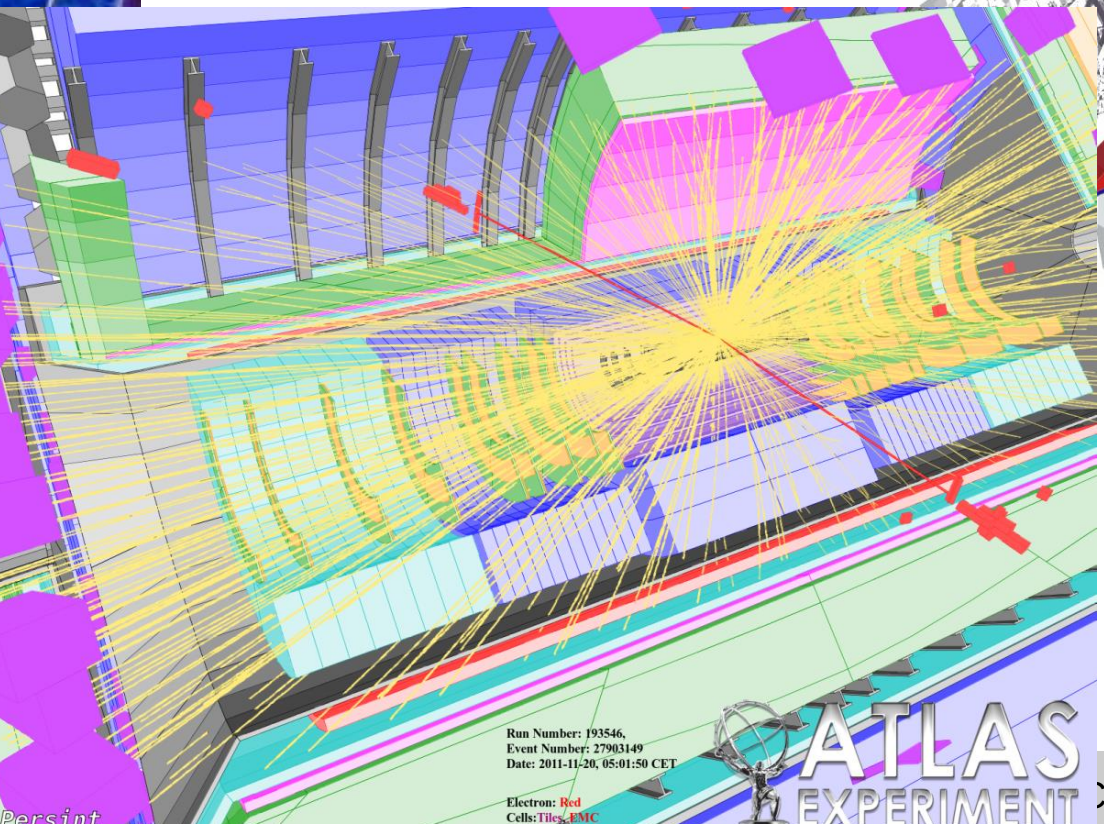


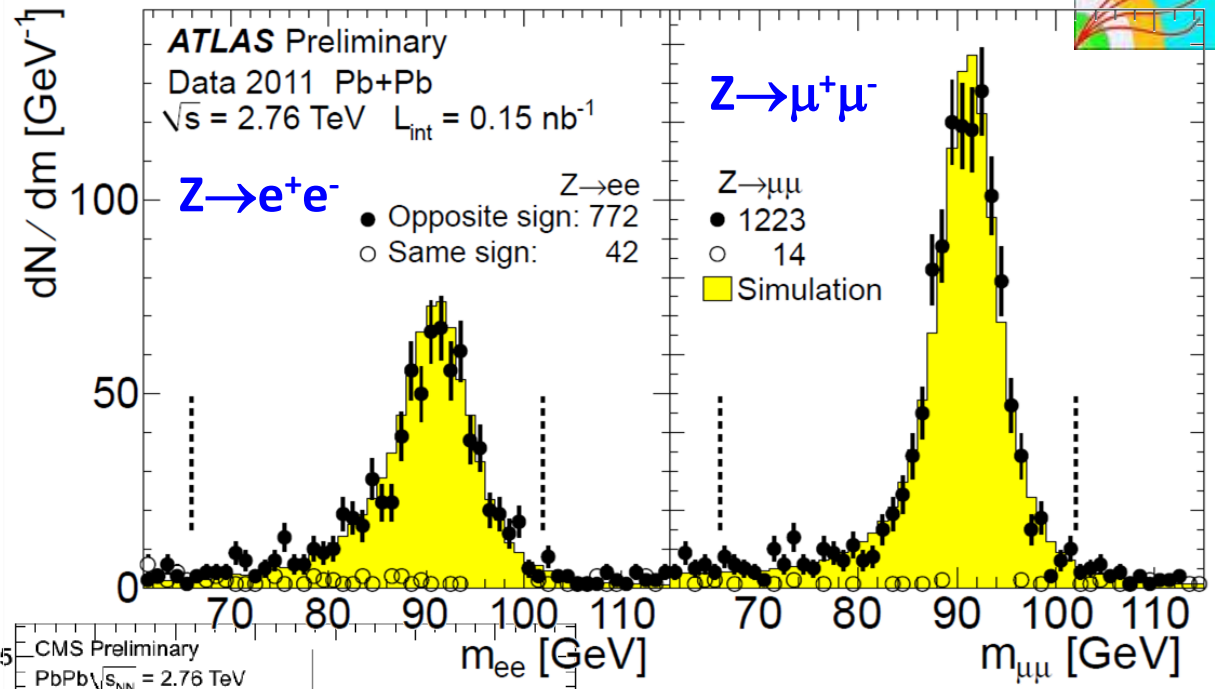


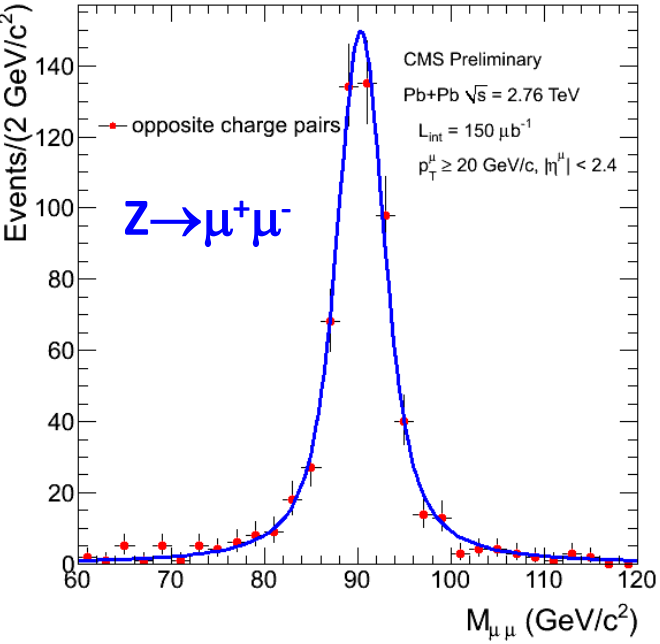
- But provide clean signals in detectors

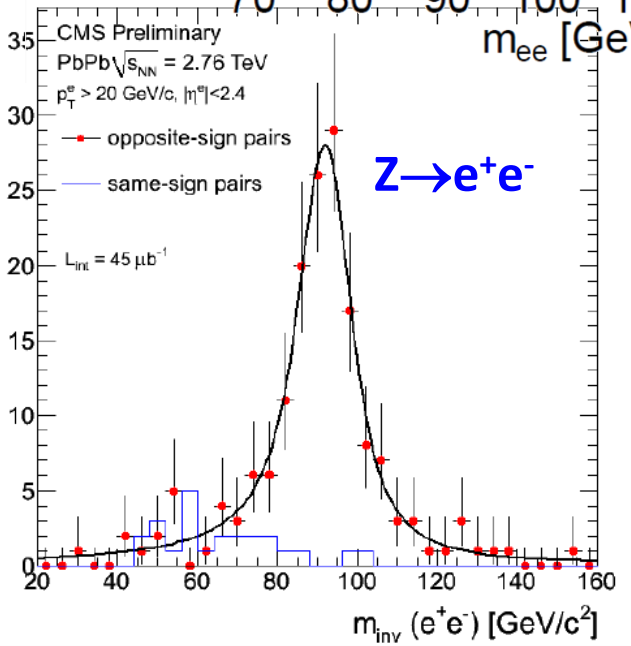
Challenge: Very small production cross sections

Z boson mass

- Clean signal with very low (≤ 3%) background
- Based on high p_T (>10-20 GeV/c) muons/electrons of opposite sign





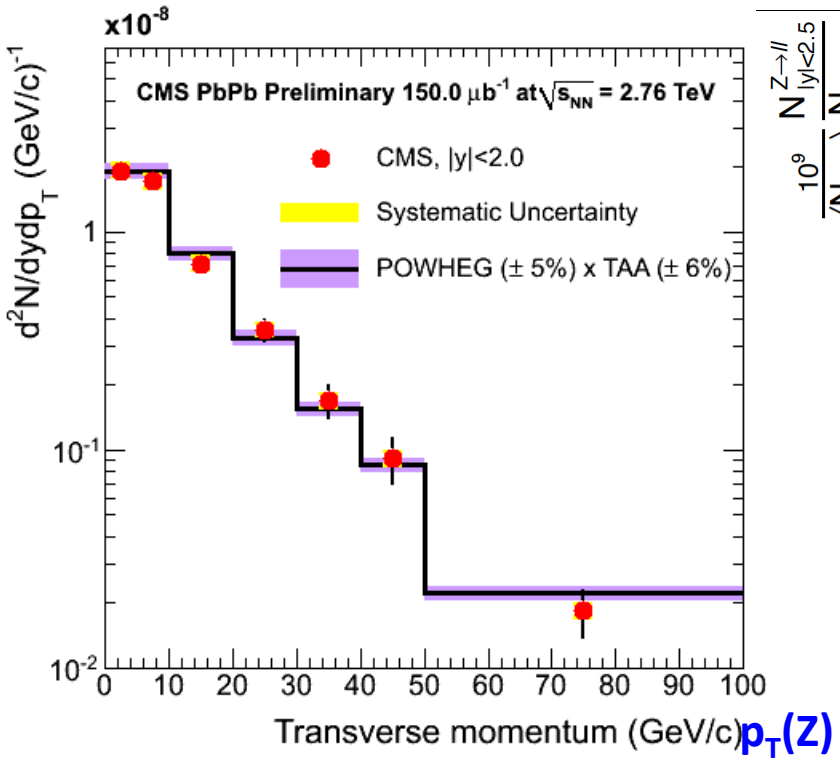


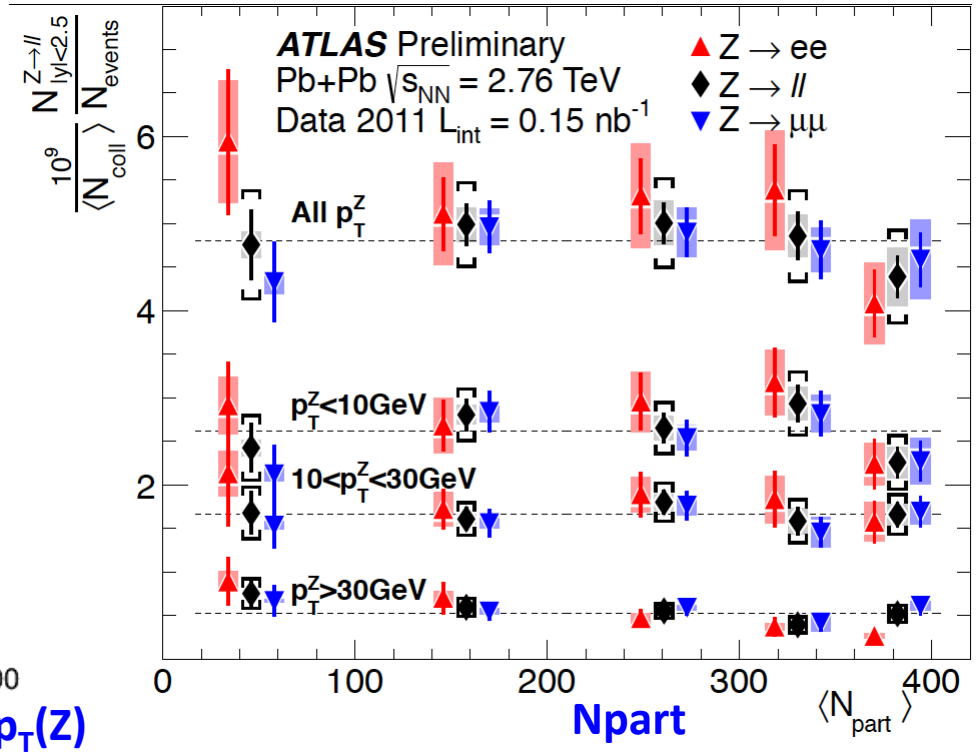
ATLAS PRL 110 (2013) 022301

Better mass resolution in muons than electrons (consistent with pp measurements)

CMS PAS HIN-12-008

Z boson R_{AA}





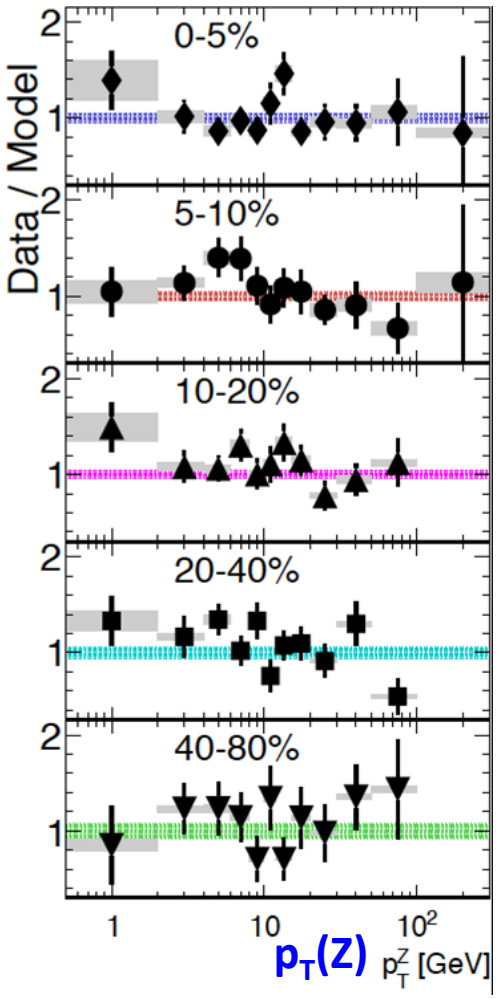
CMS PAS HIN-12-008

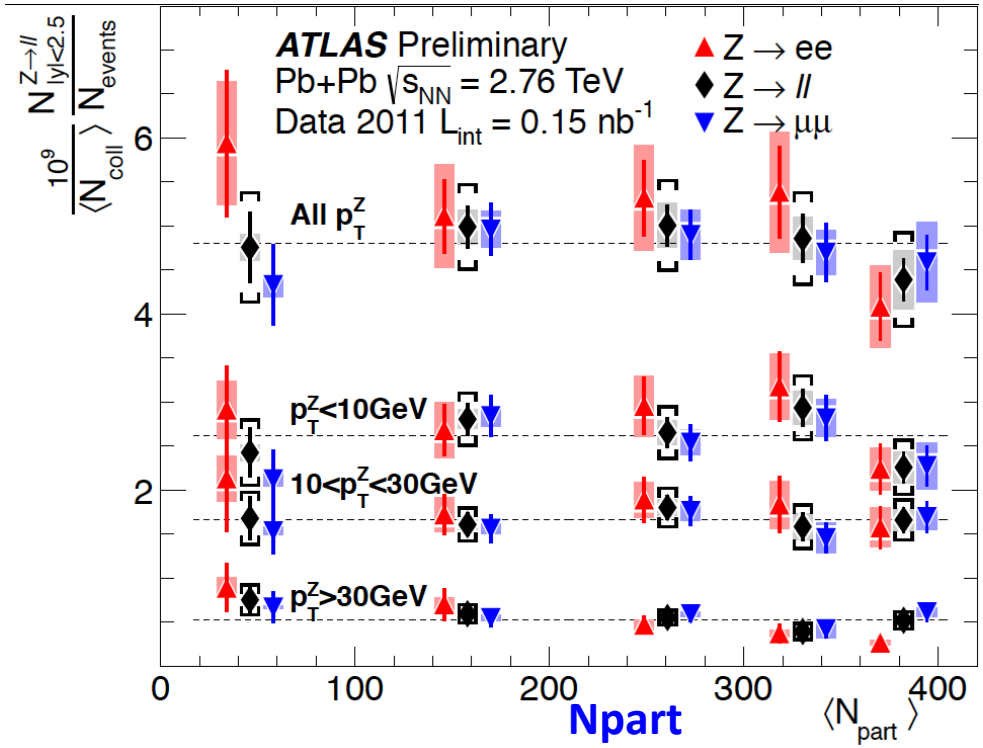
ATLAS PRL 110 (2013) 022301

Yields compared to Pythia (ATLAS) / Powheg (CMS), normalized to NNLO (FEWZ) pp production cross sections (with corresponding N_{coll} factor)

Consistent with unity as a function of p_T, rapidity and N_{part} ➔ No suppression

Z boson R_{AA}





ATLAS PRL 110 (2013) 022301

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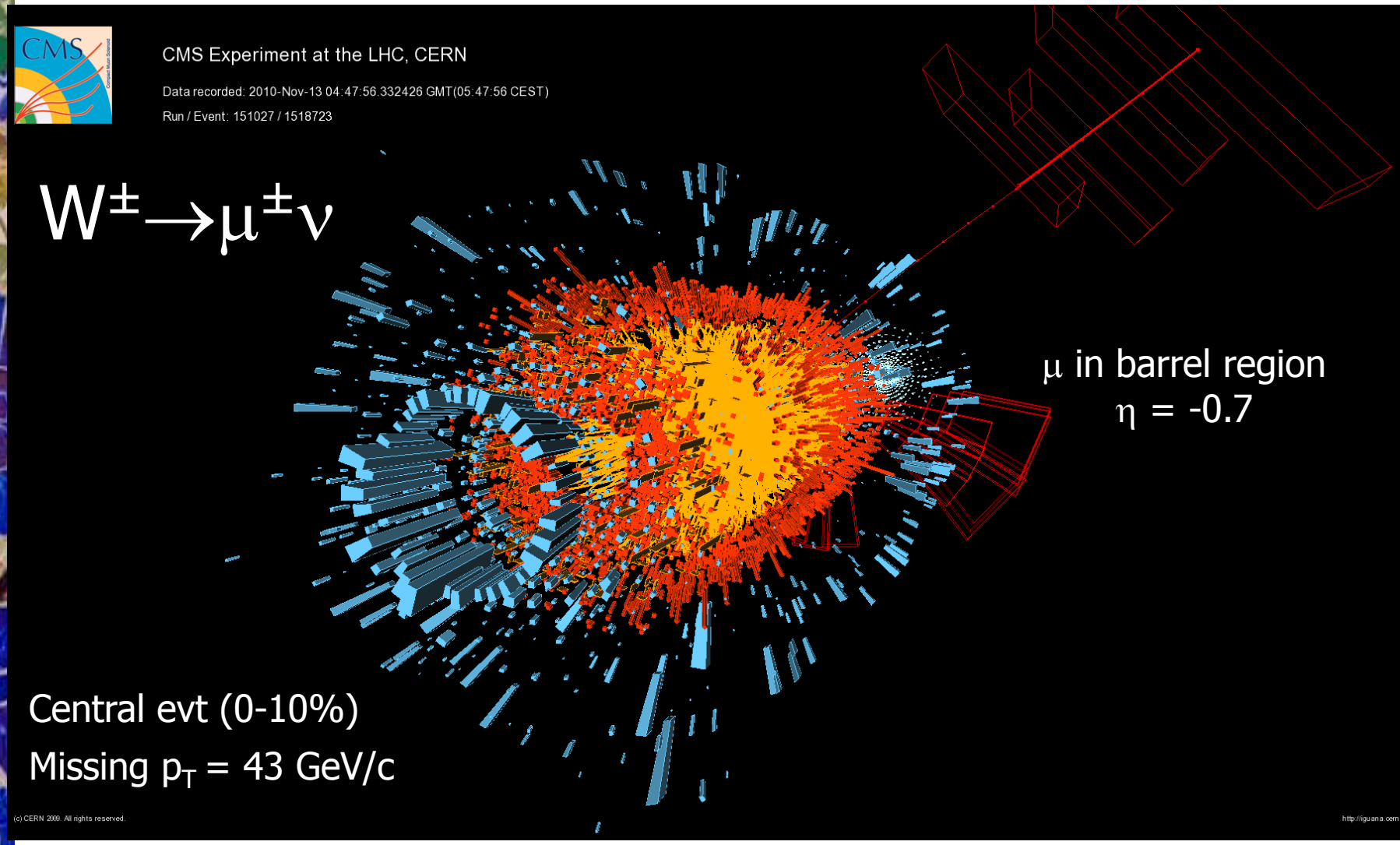
W bosons


CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-13 04:47:56.332426 GMT(05:47:56 CEST)
Run / Event: 151027 / 1518723
$W^{\pm} \rightarrow \mu^{\pm}\nu$
μ in barrel region
η = -0.7
Central evt (0-10%)
Missing p_T = 43 GeV/c
(c) CERN 2009. All rights reserved.
http://iguana.cern

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

ATLAS +CMS: High p_T (> 25 GeV/c) muon in PbPb. Fit to

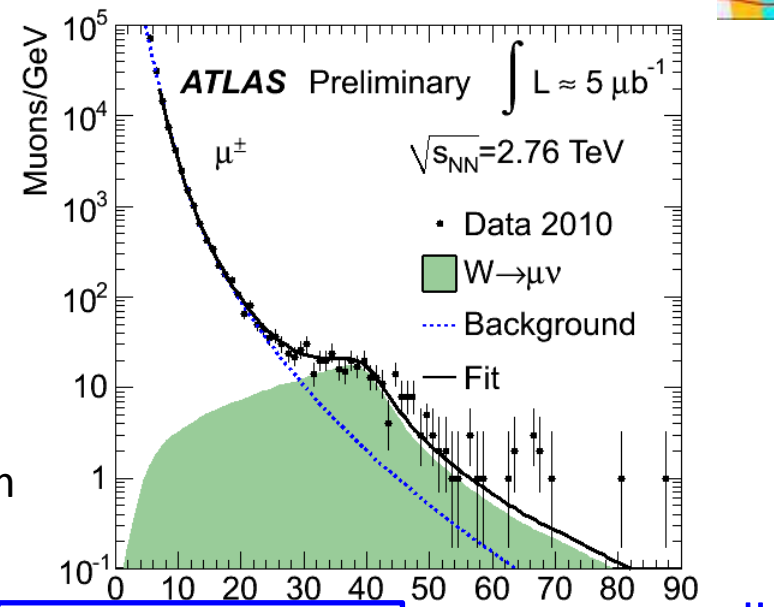
- Signal: Pythia pp → W+X
- Background: decays from b-c-quarks (ATLAS), functional form (CMS)

CMS: Additionally, High Transverse Momentum imbalance, $\not{p}_T$ (> 20 GeV/c), in event allow reconstructing

$$m_T = \sqrt{2pT^{\mu}\, \not{p}_T\, (1 - cos\phi)}$$

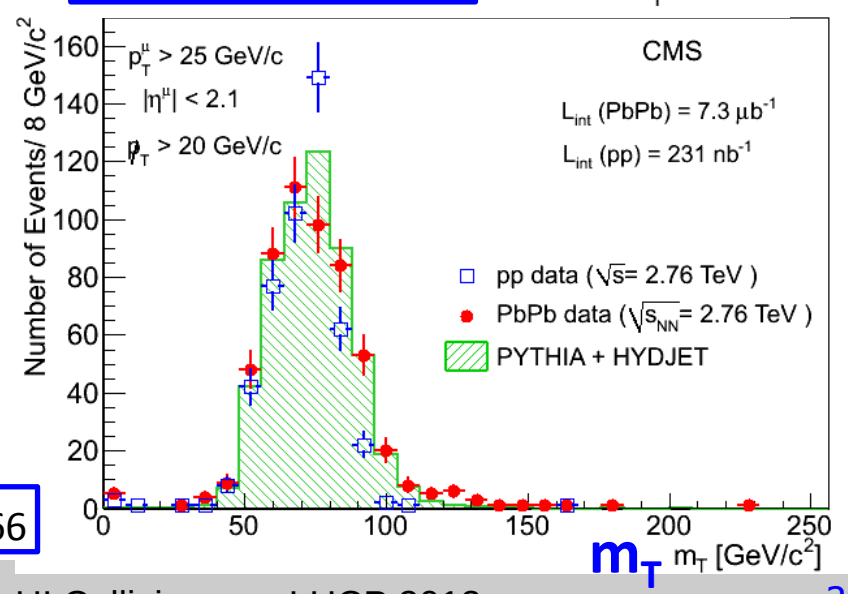
$$\phi = \phi(\mu) - \phi(\not{p}_T)$$

- Distinctive signal for W bosons
- Both for PbPb and pp collisions



ATLAS-CONF-2011-078

p_T^{μ}

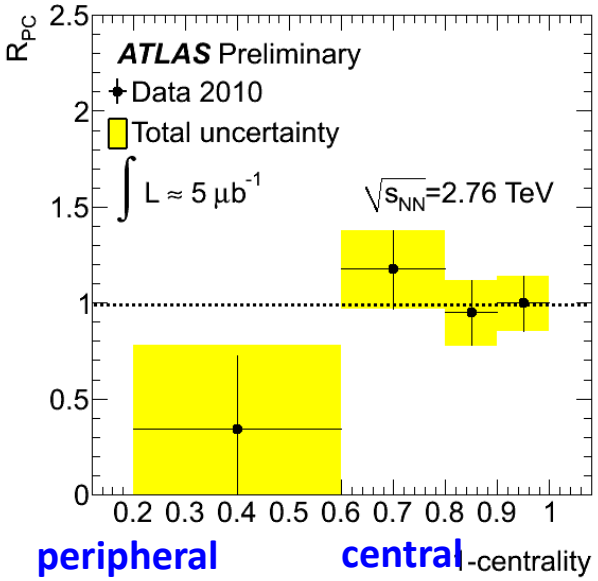


m_T

CMS Phys. Lett. B715 (2012) 66

W bosons yield

ATLAS-CONF-2011-078

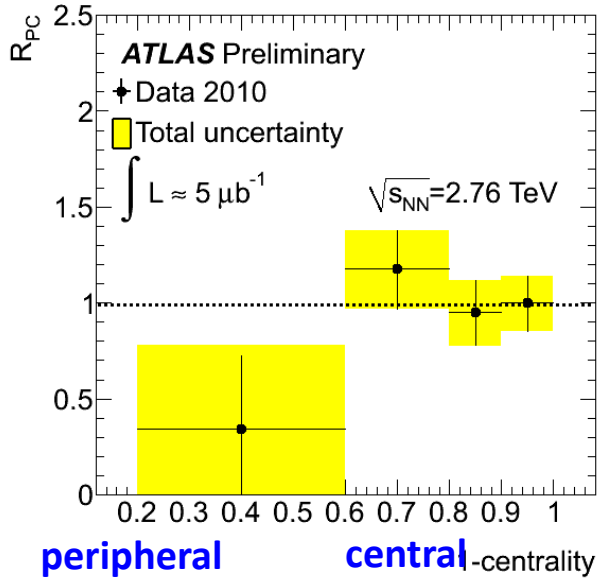


W yields in different centrality bins, relative to most central bin

Within uncertainties, no suppresion of W production with centrality of collision.

W bosons yield

ATLAS-CONF-2011-078



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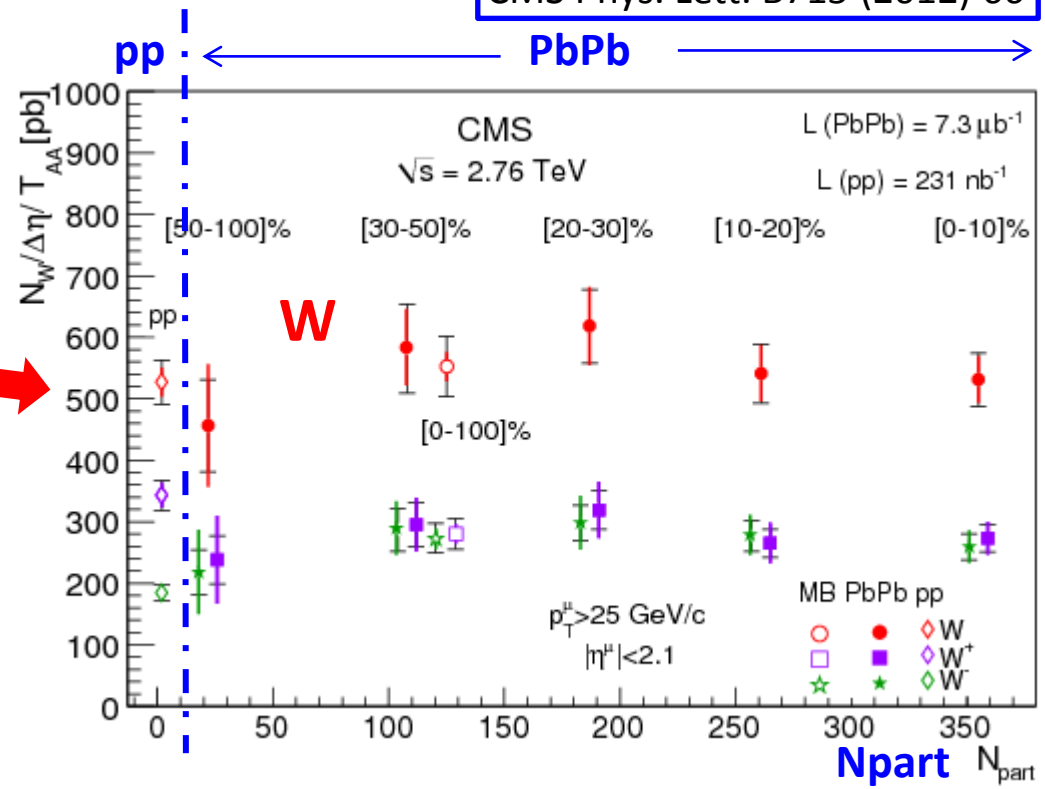
$R_{AA} = N_{PbPb}/(T_{AA} \times \sigma_{pp})$

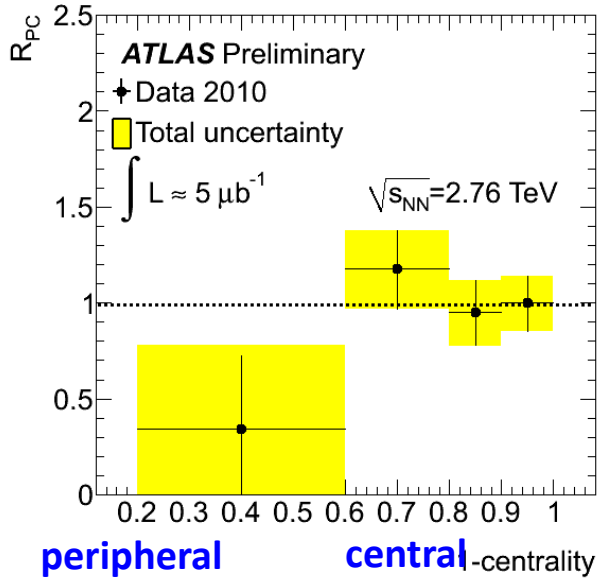
R_{AA} (W) = 1.04 ± 0.07 ± 0.12

CMS Phys. Lett. B715 (2012) 66



W bosons yield

ATLAS-CONF-2011-078



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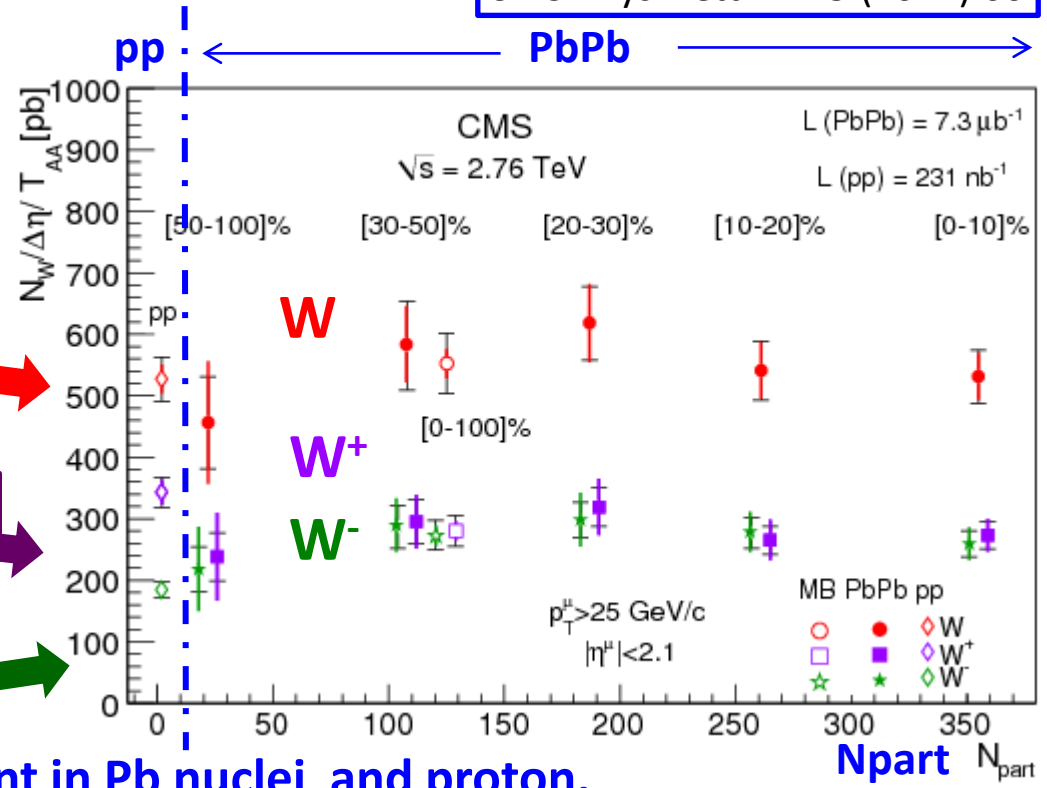
CMS Phys. Lett. B715 (2012) 66



$R_{AA} = N_{PbPb}/(T_{AA} \times \sigma_{pp})$

R_{AA} (W) = 1.04 ± 0.07 ± 0.12

R_{AA} (W^+) = 0.82 ± 0.07 ± 0.09

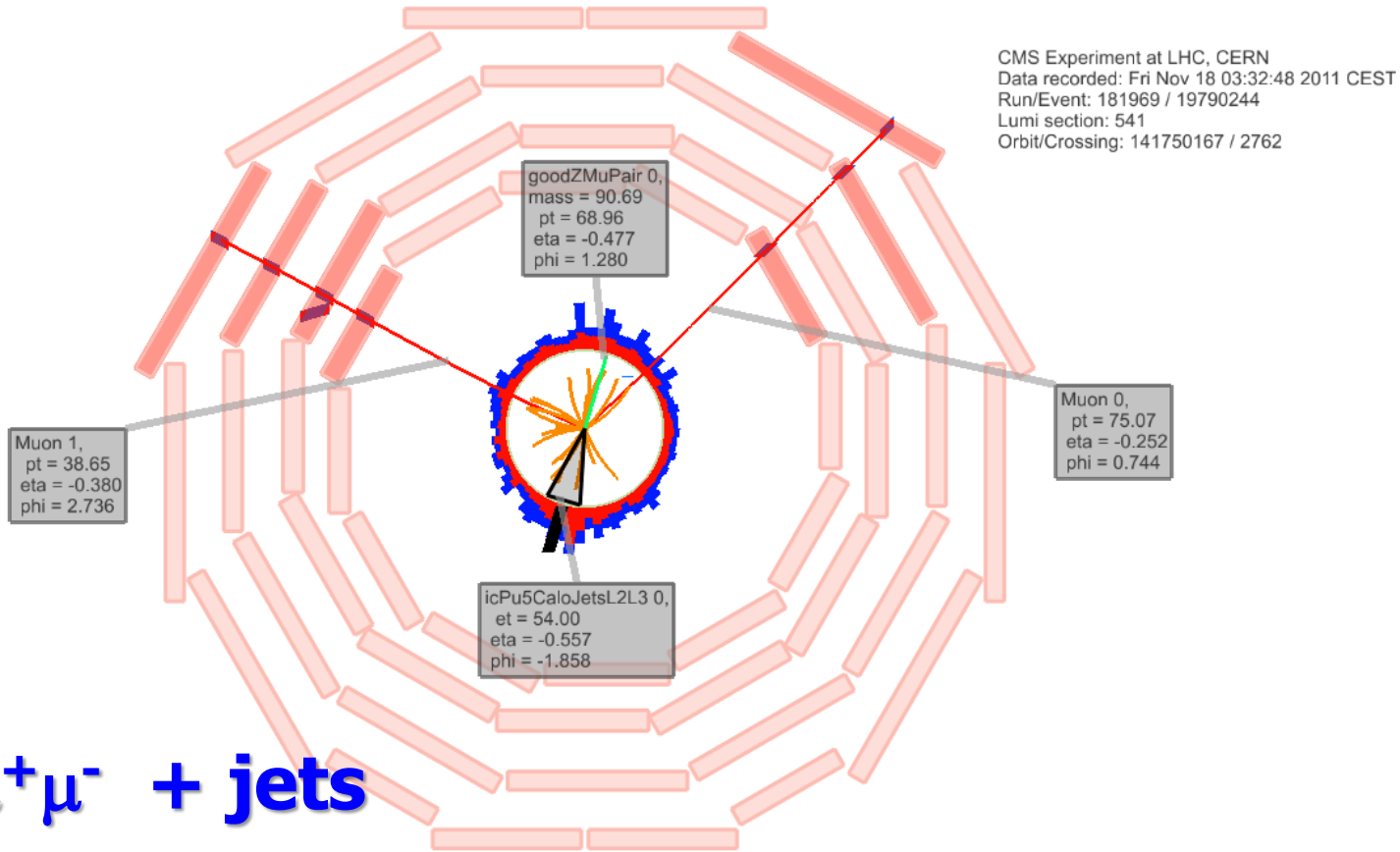
R_{AA} (W^-) = 1.46 ± 0.14 ± 0.16

- **Different u & d quark content in Pb nuclei and proton.**
- **When consider inclusively ($W^+ + W^-$) they scale with N_{coll}**

Vector boson + jets

- There is an energy loss mechanism affecting coloured particles in hot dense QCD medium, but the nature of this mechanism still unknown.

- Bring together both kind of probes : neutral coloured (Z, γ) and jets



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

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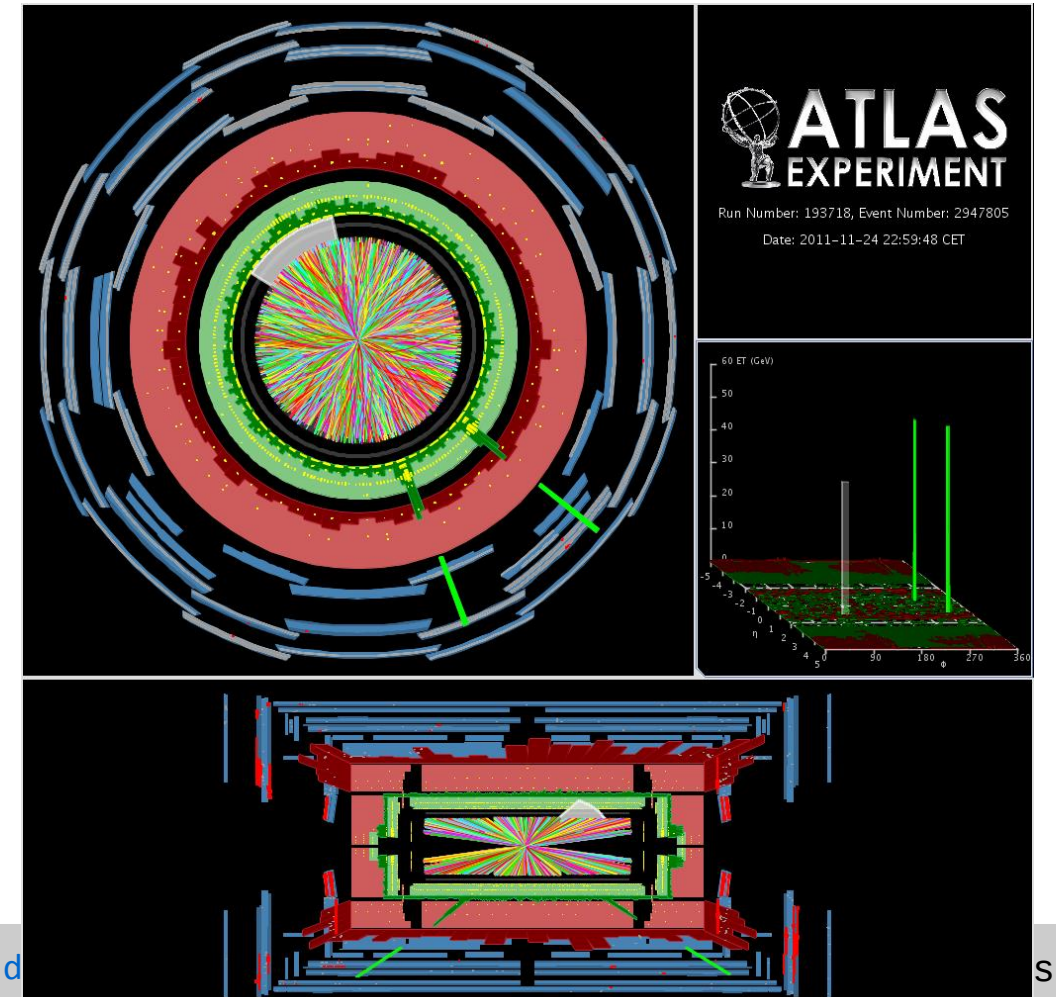


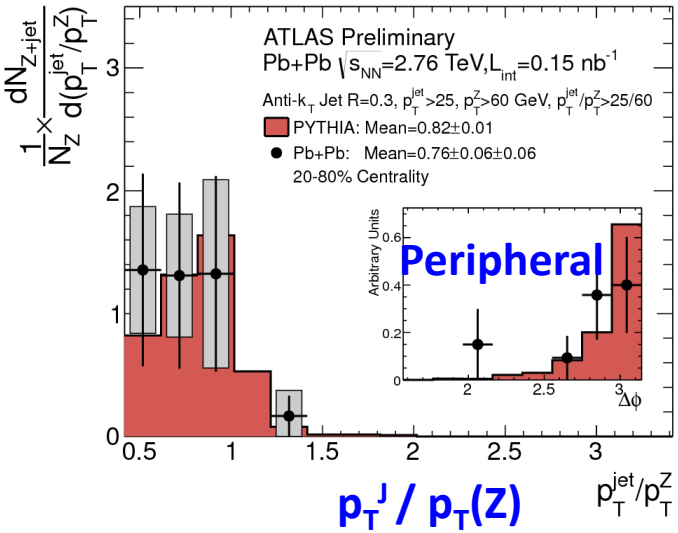
$Z \rightarrow e^+e^-$ + jets

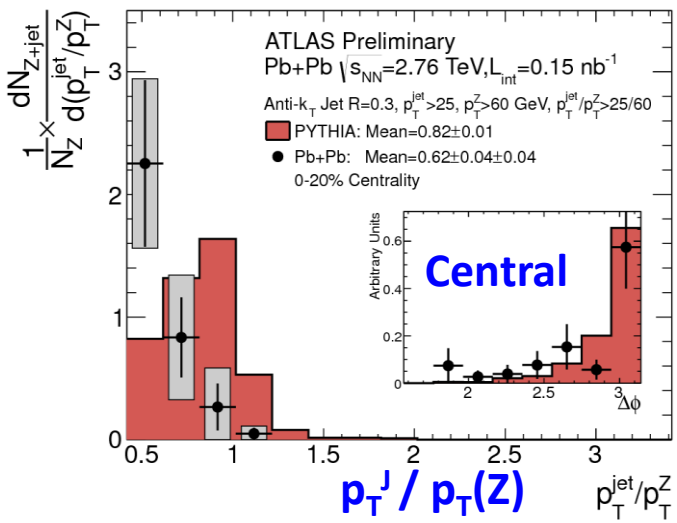
ATLAS-CONF-2012-119

Z + jets

From Z →ee/μμ candidate sample of 2011 PbPb data, select those with

- $p_T(Z) > 60$ GeV/c , p_T (jet) > 25 GeV/c , $\phi(Z) - \phi(jet) > \pi/2$ ➔ 36 Z + jets evts





ATLAS-CONF-2012-119

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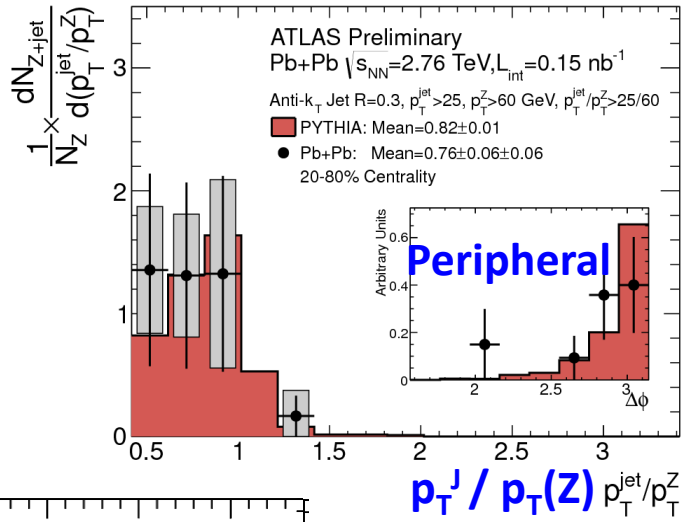
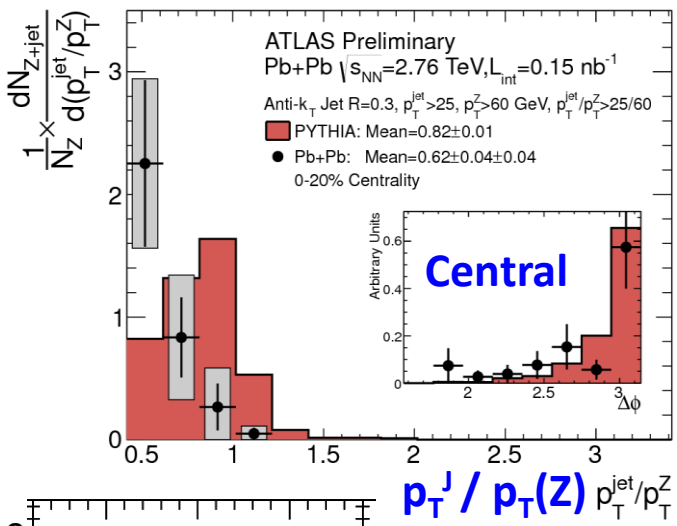
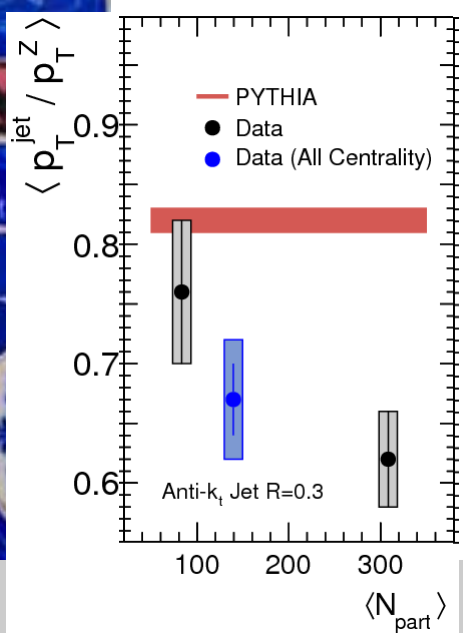
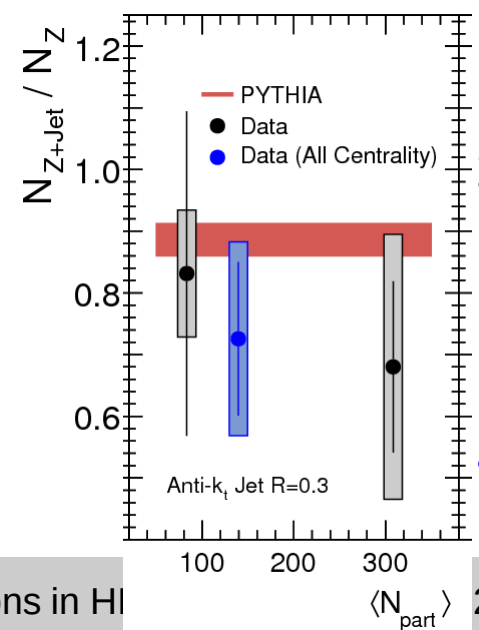






Suppression of jet p_T versus Z p_T in PbPb collisions compared to Pythia pp simulation.

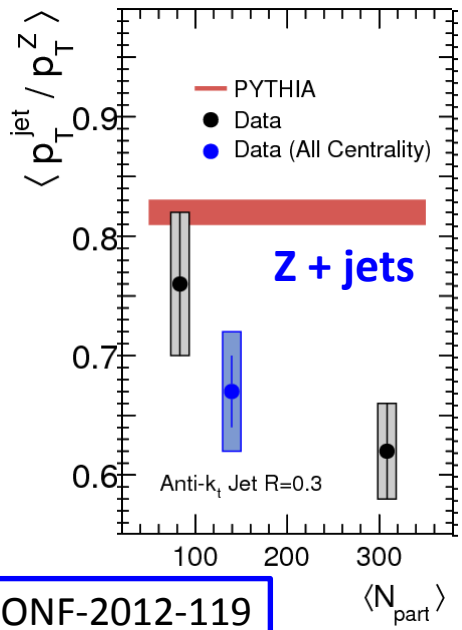
Jet quenching



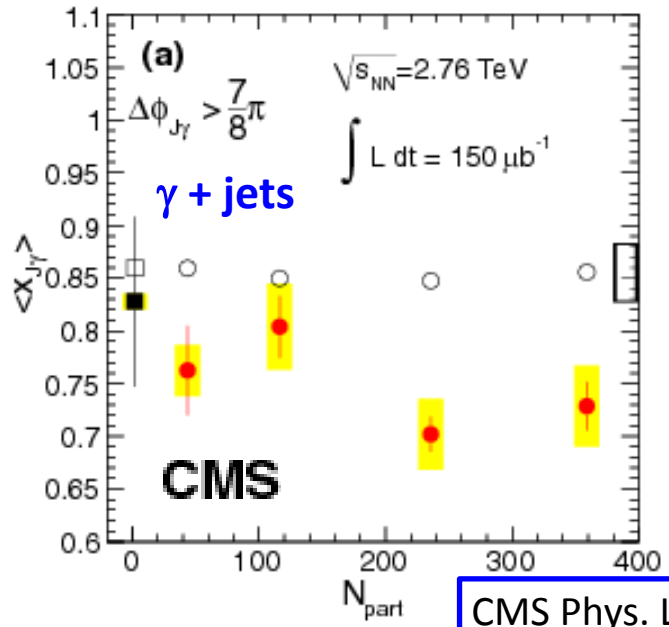
Reduction of yield of Z+jet events referred to number Z (with p_T>60 GeV/c)

Nuclear modification factor < 1

Boson (Z, γ) + jets



ATLAS-CONF-2012-119

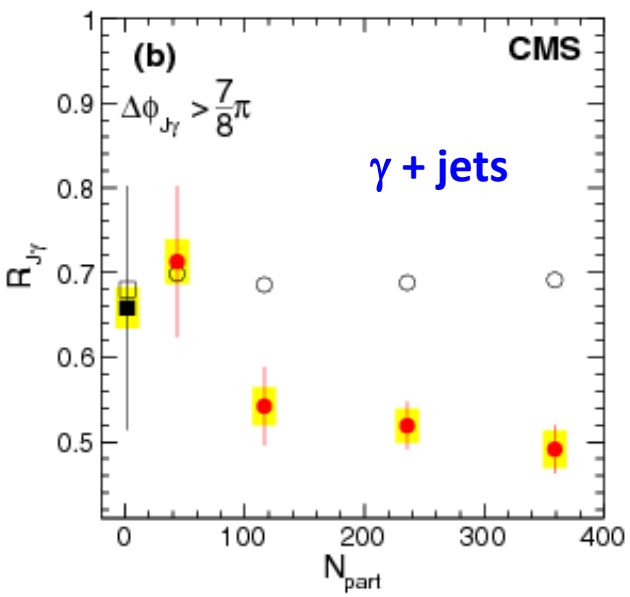


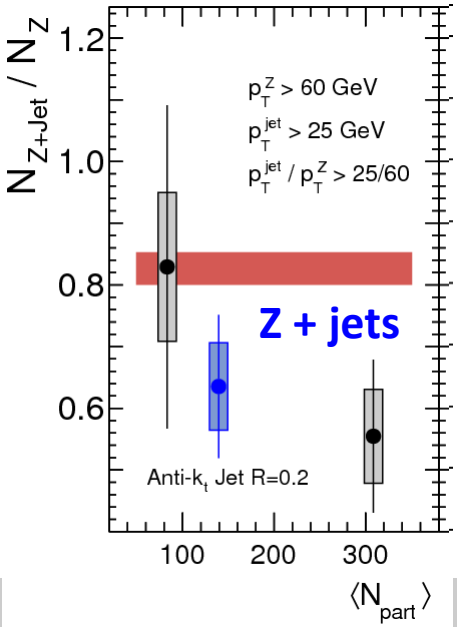
PbPb Data
PYTHIA + HYDJET
pp Data $\sqrt{s}$ = 2.76 TeV
PYTHIA

Jet quenching

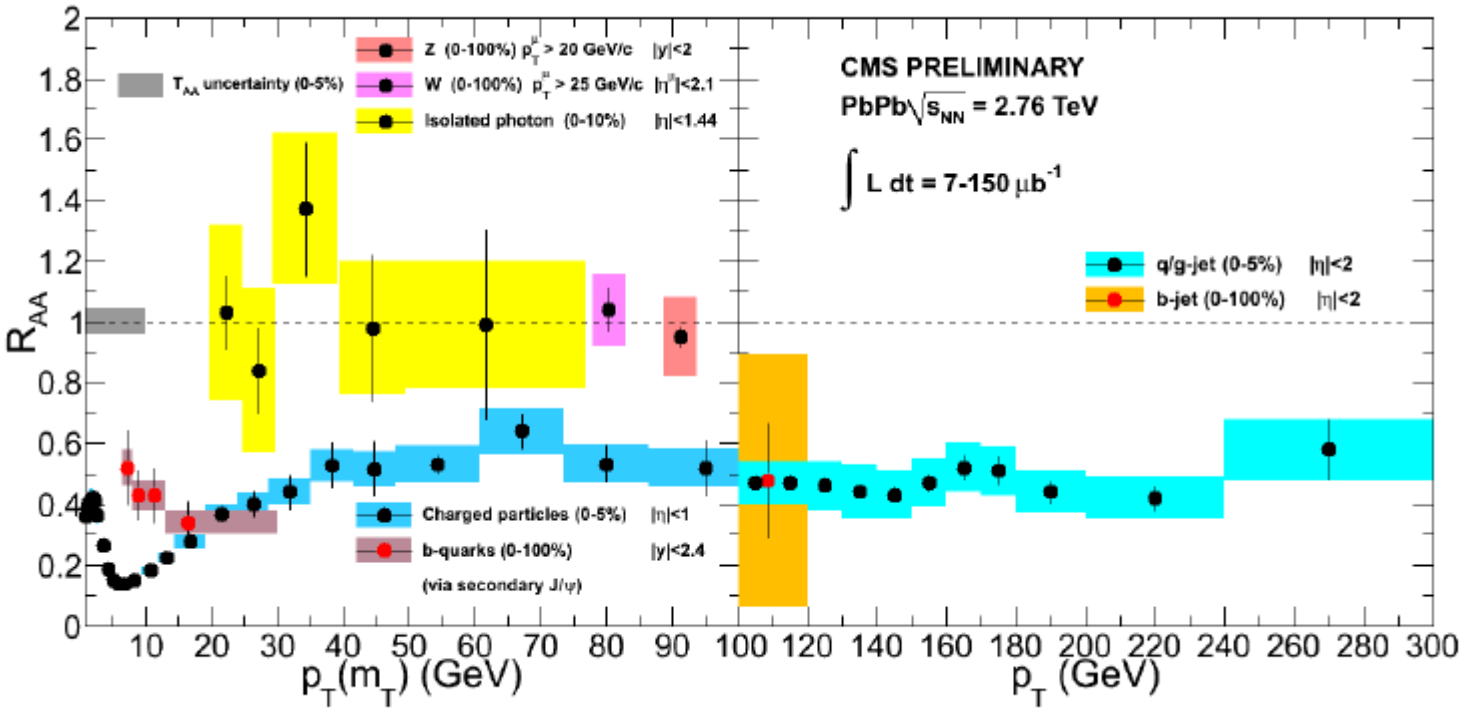
CMS Phys. Lett. B718 (2013) 773

Nuclear modification factor < 1





Outlook

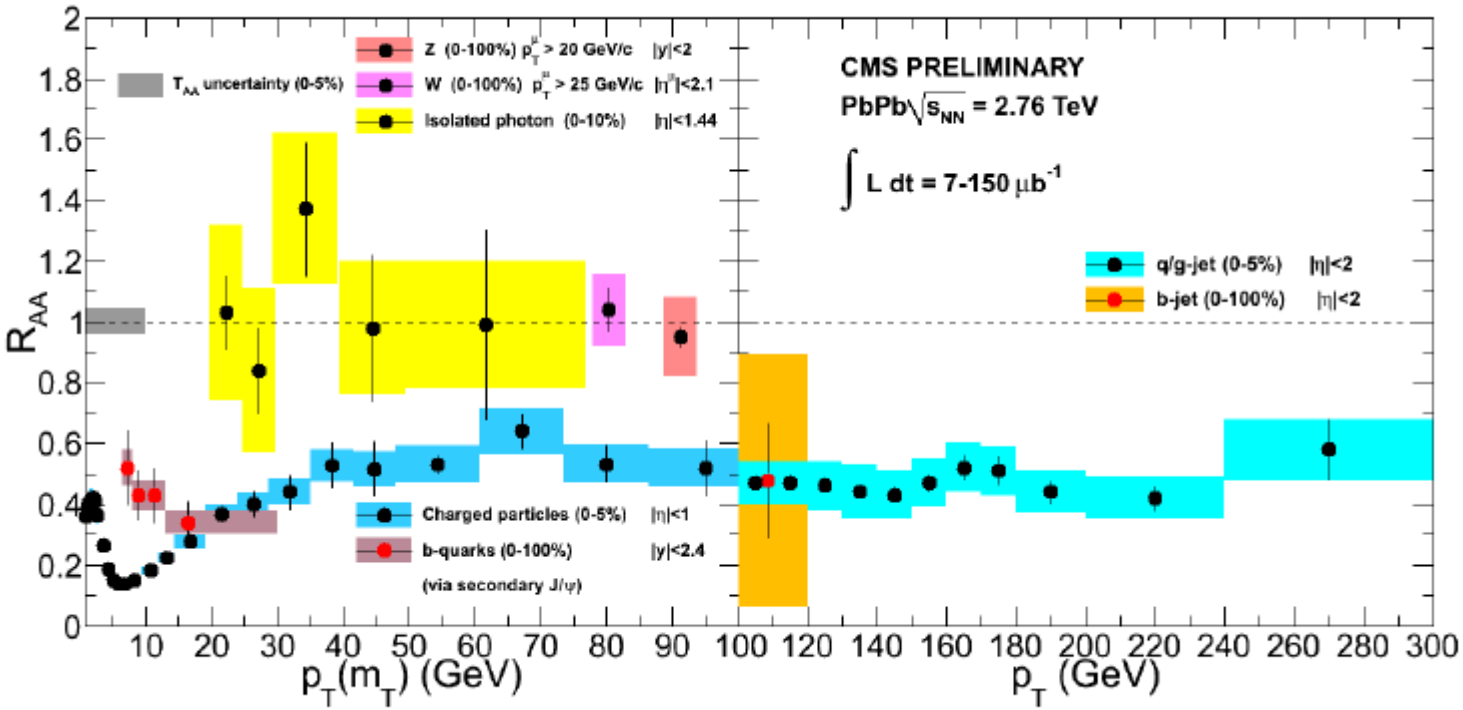


Picture of modified & unmodified particles

- The confirmation of unmodified probes (isolated photons, Z and W bosons). validate and confirm some of the tools used (Ncoll)

- An interesting picture is emerging, with detailed results on jet quenching, jet fragmentation, inclusive jet production, jet flavour dependence… in PbPb and already starting to appear in pPb ➔ input for models

Outlook



Picture of modified & unmodified particles

Thank You!