Measurement of hard probes in p+Pb and Pb+Pb Collisions with the ATLAS detector

Adam Trzupek

for the ATLAS Collaboration

Institute of Nuclear Physics PAN, Kraków

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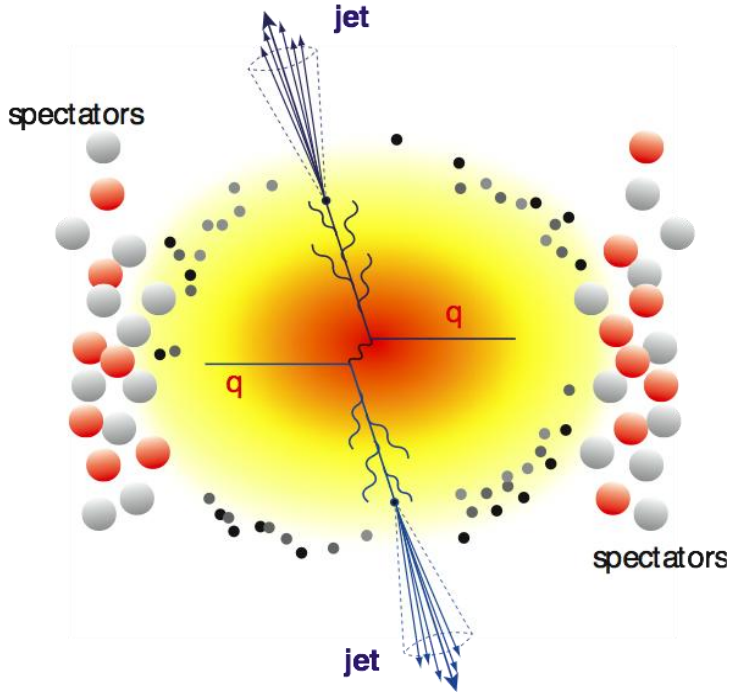
Hard Probes of the Quark Gluon Plasma

Jet quenching



- **QGP opaque to colored partons**
  Jets from hard scattering processes via interactions with the dense medium provide direct insight into the properties of QGP

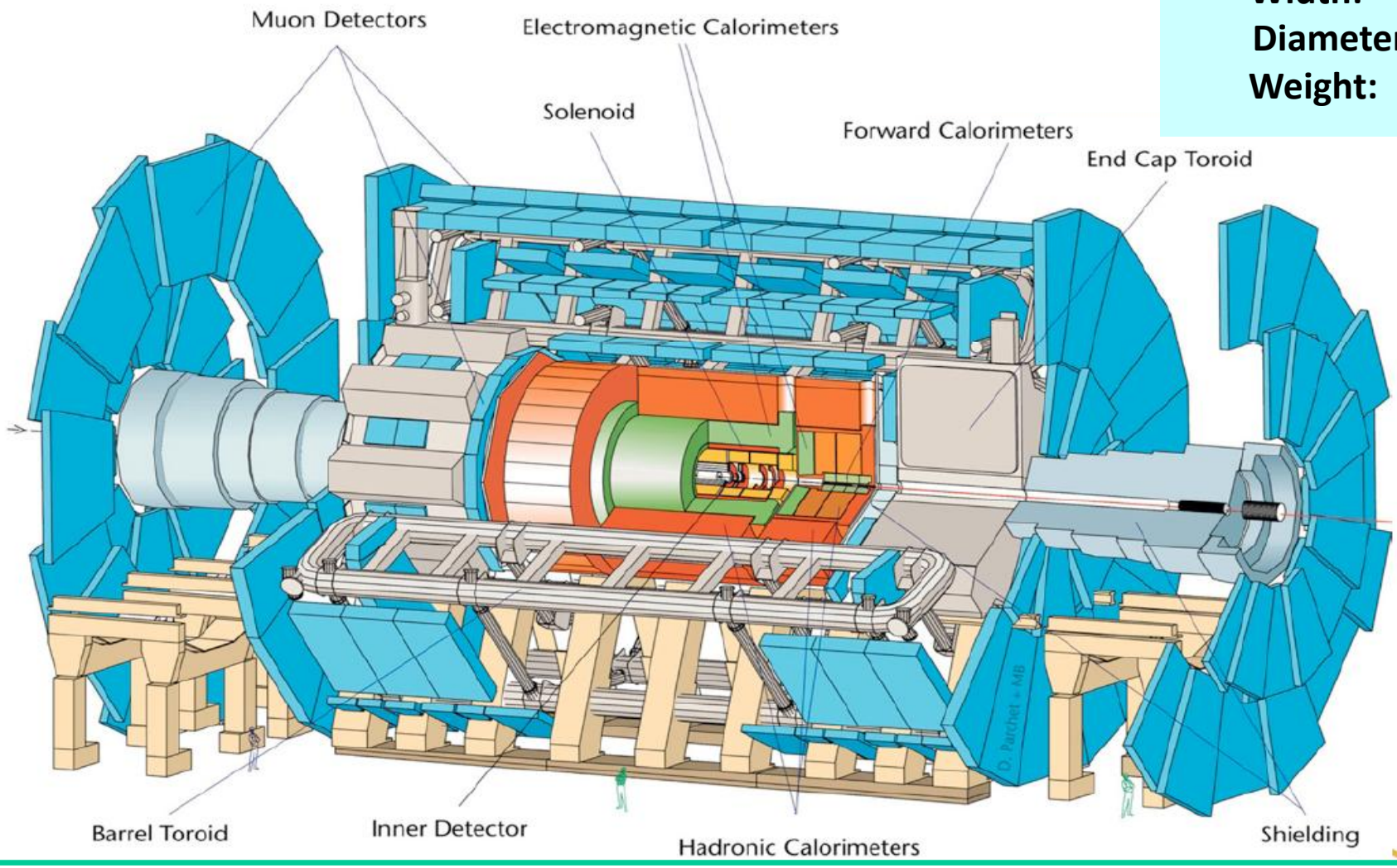
- **QGP transparent to EM and weakly interacting particles**
  Electro-weak probes (γ or Z and W bosons) provide access to initial state effects (shadowing, initial E-loss) and can be used to calibrate hard scattering rates in HI collisions

Plan

- ATLAS detector
- Electro-weak probes in Pb+Pb collisions
- Jets in Pb+Pb collisions
- Jets in p+Pb collisions
- Summary

The ATLAS Detector

Detector parameters:
Width: 44m
Diameter: 22m
Weight: 7000t



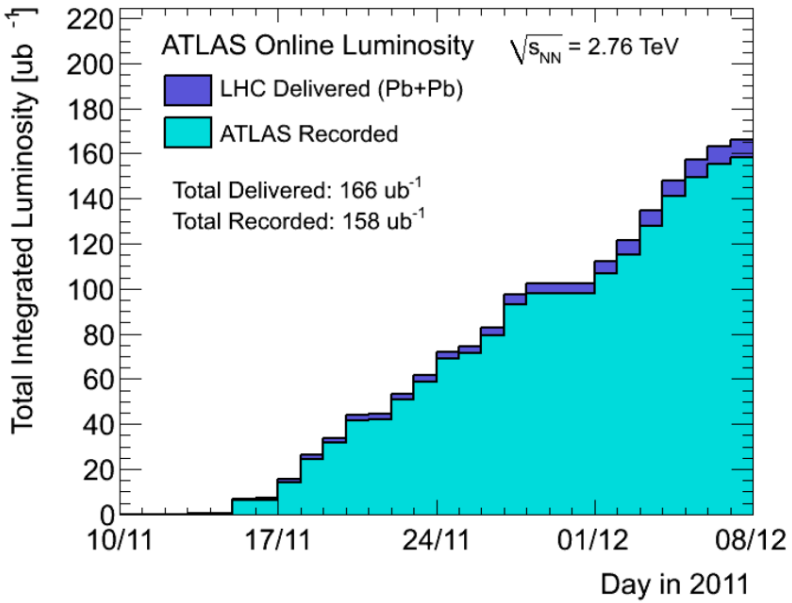
Calorimeter: jets, photons, $e^{\pm}$ ($|\eta|<4.9$)

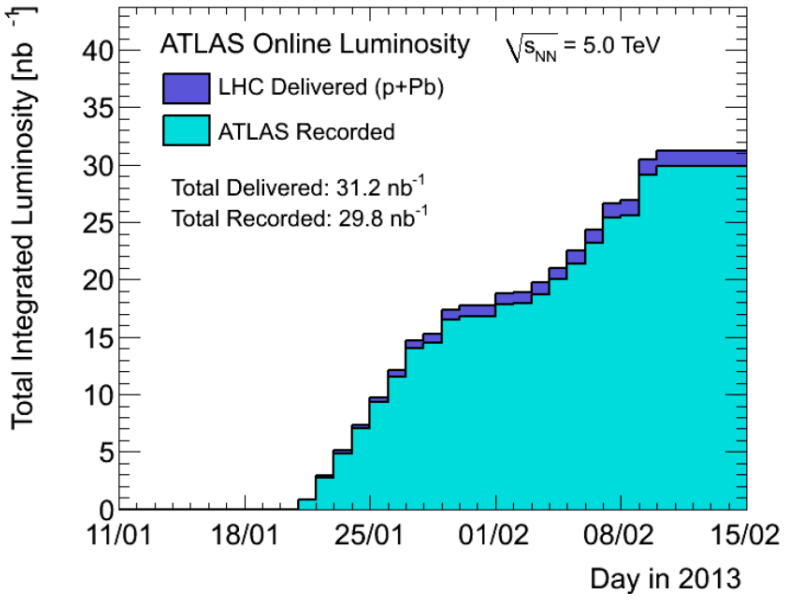
ID tracking in 2 T solenoid: charged particles ($|\eta|<2.5$)

Muon spectrometer: $\mu^{\pm}$ ($|\eta|<2.7$)

2π azimuthal acceptance

p+Pb and Pb+Pb Data

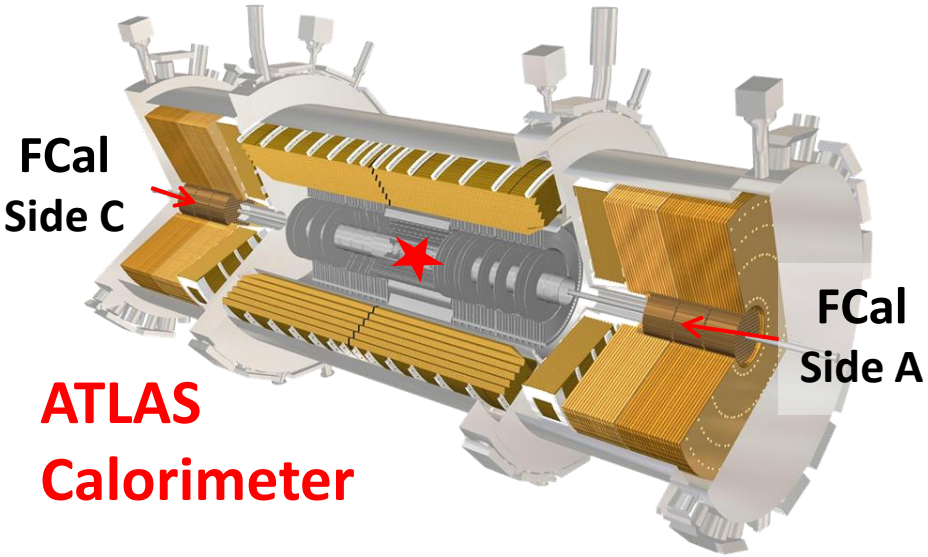




System	$\sqrt{s_{NN}}$(TeV)	Luminosity, L_{int}	Year
Pb+Pb	2.76	0.17 nb^{-1}	2010+2011
p+Pb	5.02	30 nb^{-1}	2012+2013

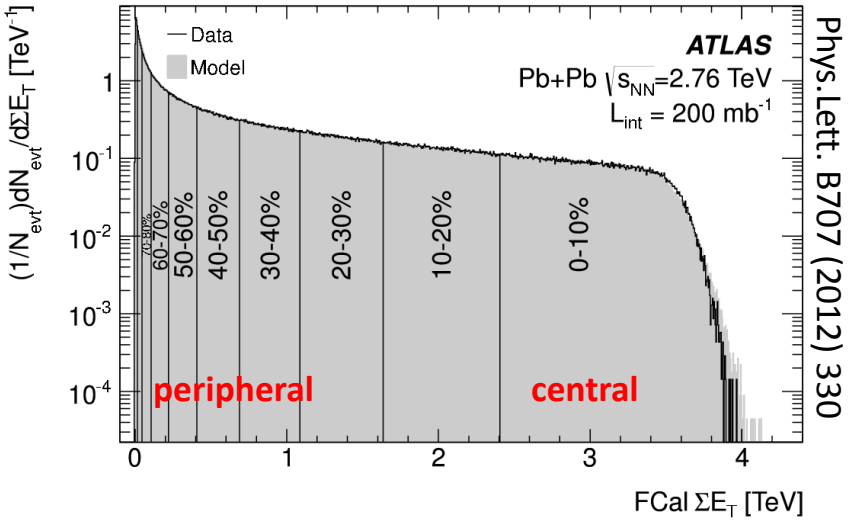
ATLAS trigger system optimized to collect high p_T jets, muons, electrons ($e^{\pm}$) and photons

Event Centrality Measurement in Pb+Pb and p+Pb

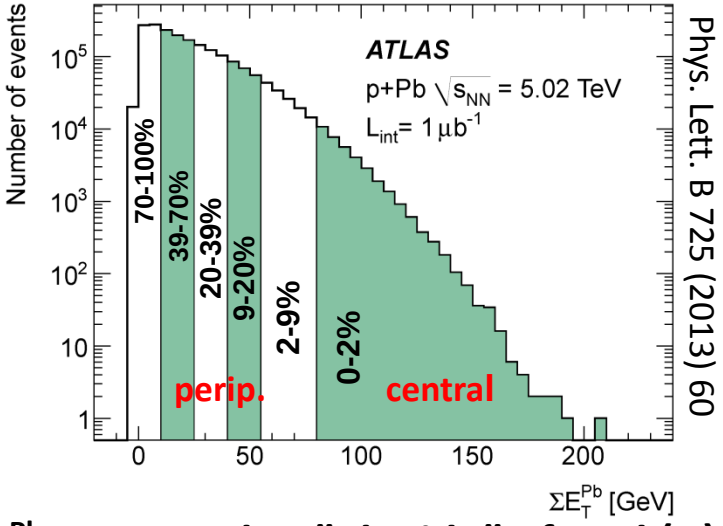


- Pb+Pb and p+Pb events are divided into centrality bins according to measured total transverse energy in forward calorimeter (FCal, $3.2<|\eta|<4.9$)
- MC Glauber model used for N_{coll} and N_{part} determination
  - N_{coll} - number of binary NN collisions
  - N_{part} - number of participating (wounded) N

Pb+Pb minimum bias events

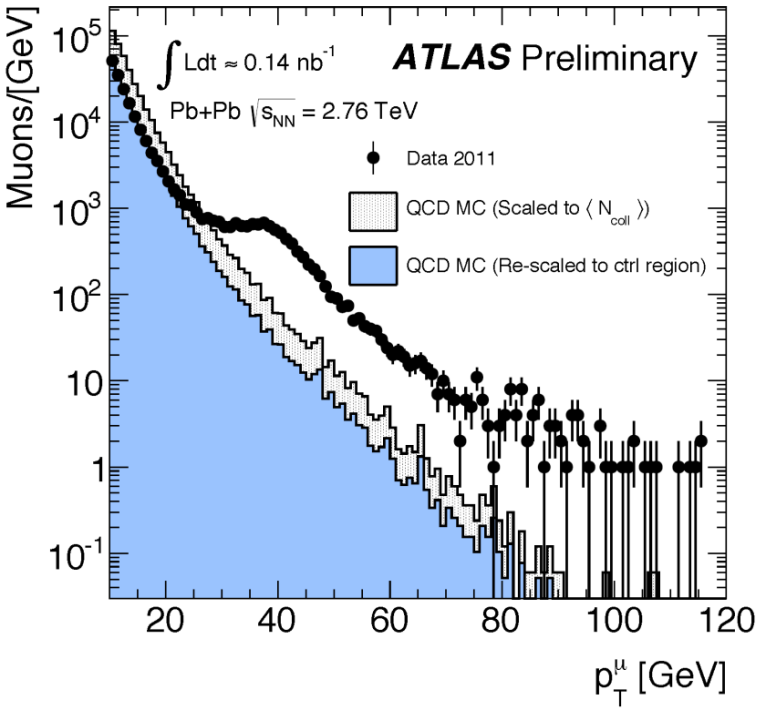


p+Pb 2012, minimum bias events



ΣE_T^{Pb} measured at "Pb-side" of FCal (A)

W Bosons Reconstructed in Muon Channel in Pb+Pb Collisions



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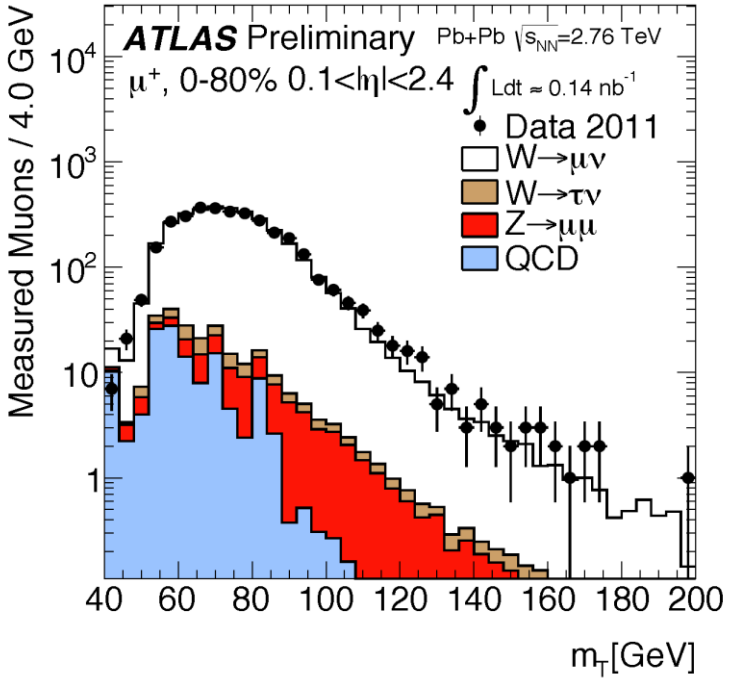

- **QCD background rescaled to the data (within control 10-20 GeV interval) to account for jet suppression**
- **Total background at the level of 7.6%**

$$p_T^{\mu} > 25 \text{ GeV}, \quad 0.1 < |\eta_{\mu}| < 2.4,$$
$$p_T^{\nu} > 25 \text{ GeV}, \quad m_T > 40 \text{ GeV}.$$

$$\mathbf{p}^{\text{miss}} = \sum_{i=1}^{ntrks} \mathbf{p}_i^{\text{miss}} = -(\mathbf{p}_1 + \mathbf{p}_2 + \ldots \mathbf{p}_{ntrks})$$

$$m_T = \sqrt{2 p_T^{\mu} p_T^{\text{miss}} (1 - \cos \Delta\phi_{\mu, p_T^{\text{miss}}})}$$

W Boson dN/dη

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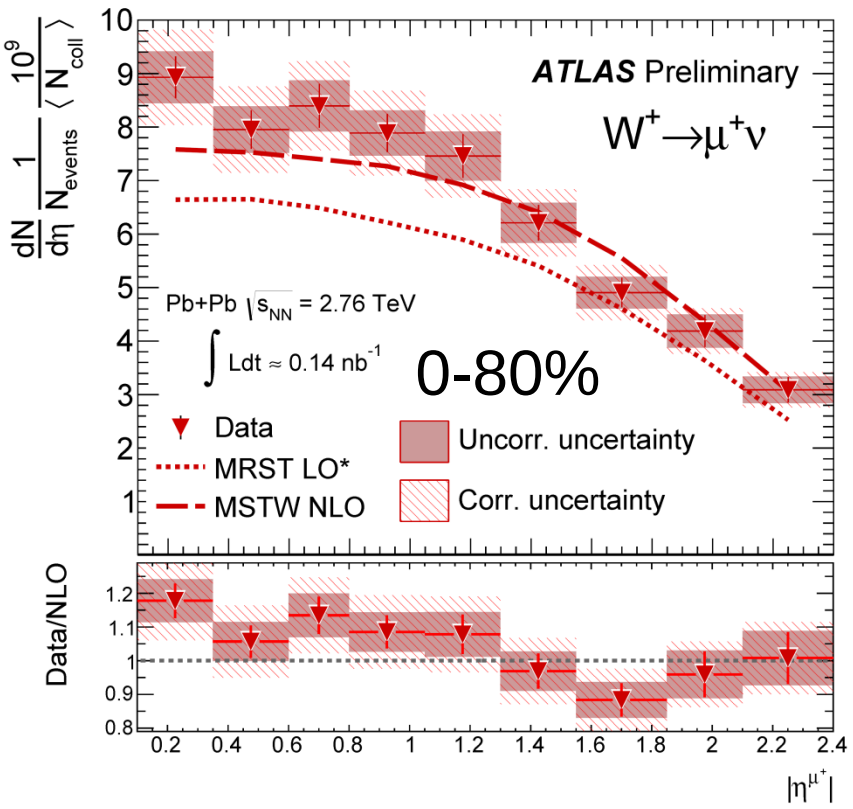
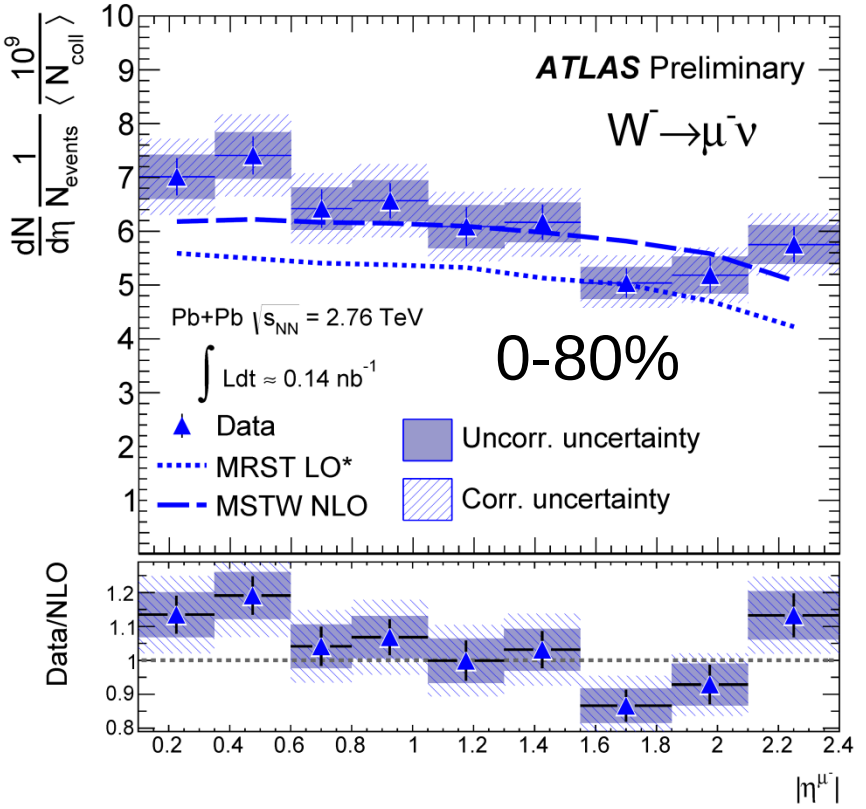
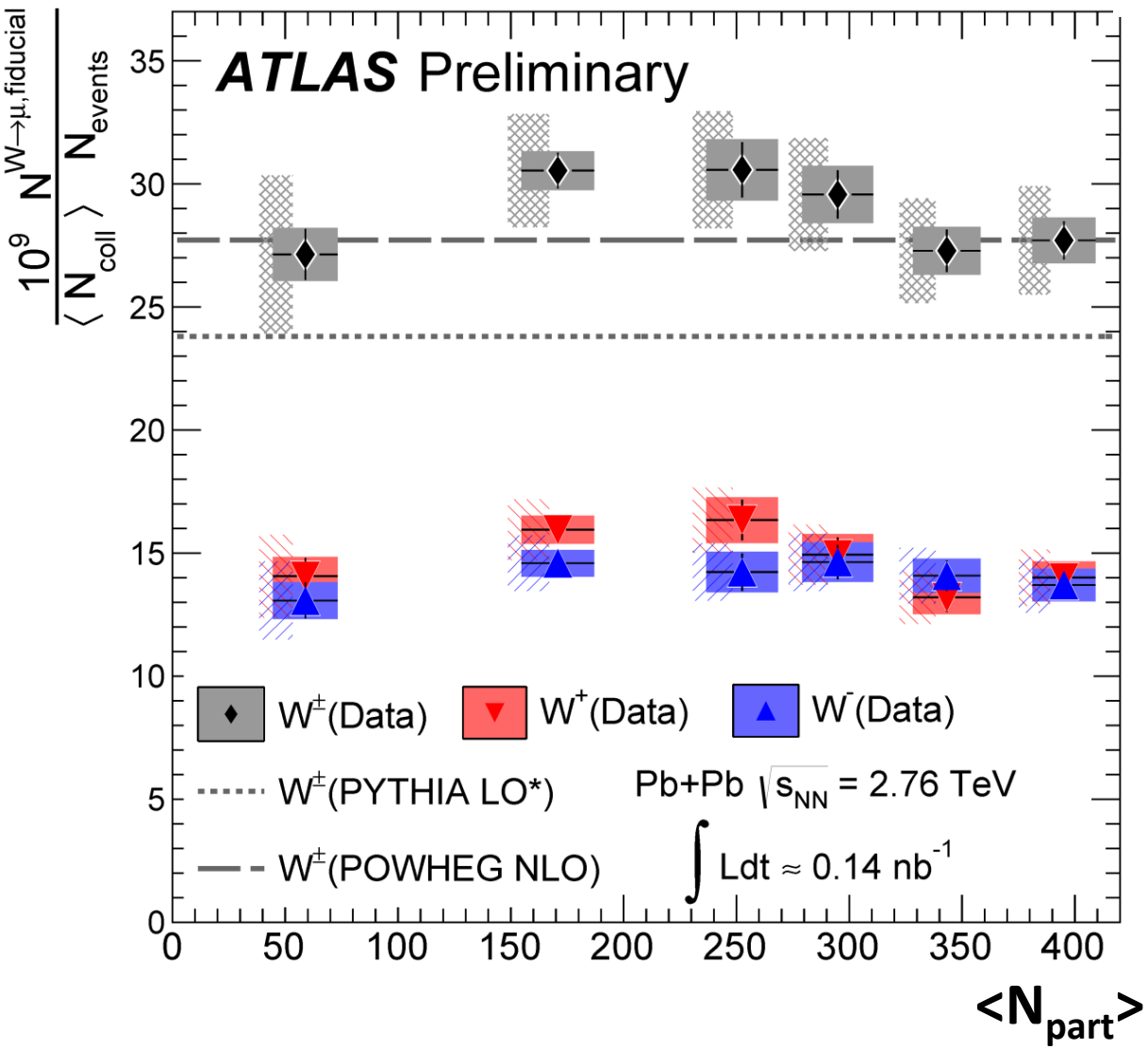




- **W production is in agreement with NLO predictions**
- **LO* results underestimate yields**

W Rates: Centrality Dependence



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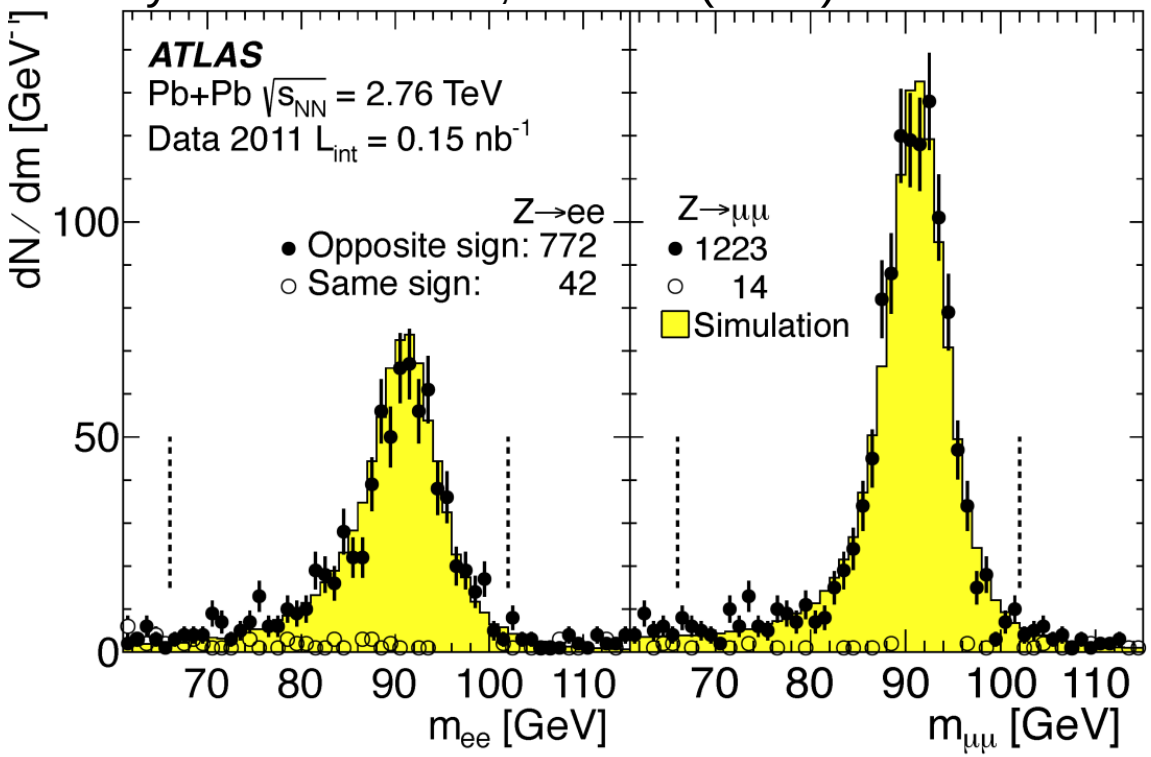
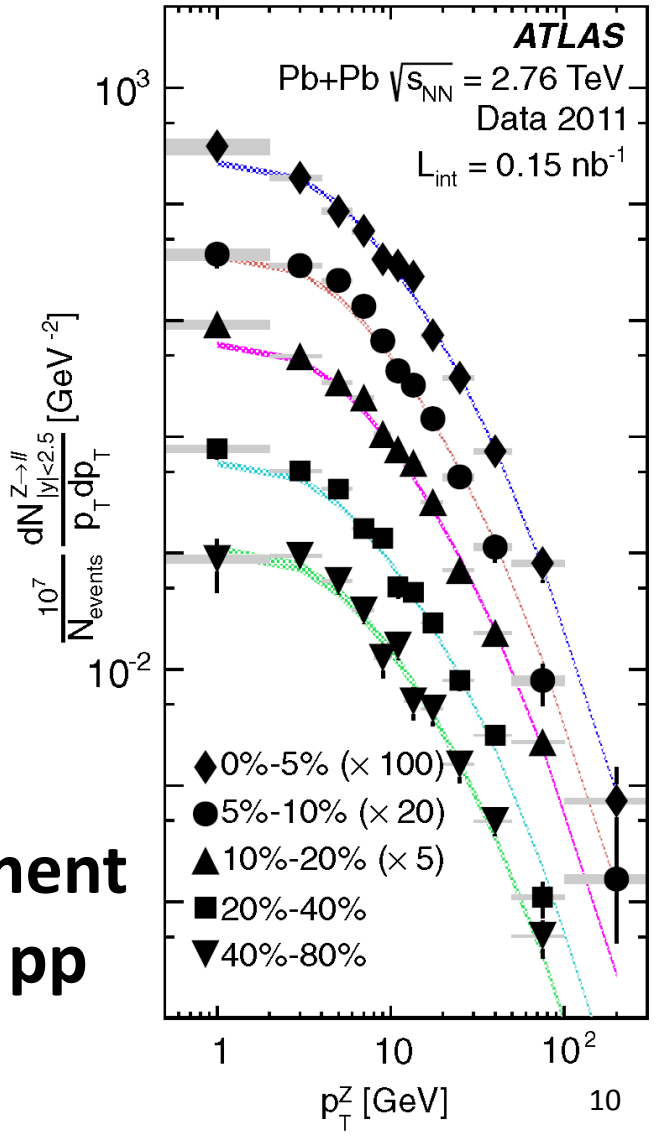
- **No centrality dependence of normlized rates is observed**
- **W rates are in agreement with NLO predictions**

Z Boson Rates in Dielectron and Dimuon Channels in Pb+Pb Collisions

Phys. Rev. Lett 110, 022301 (2013)

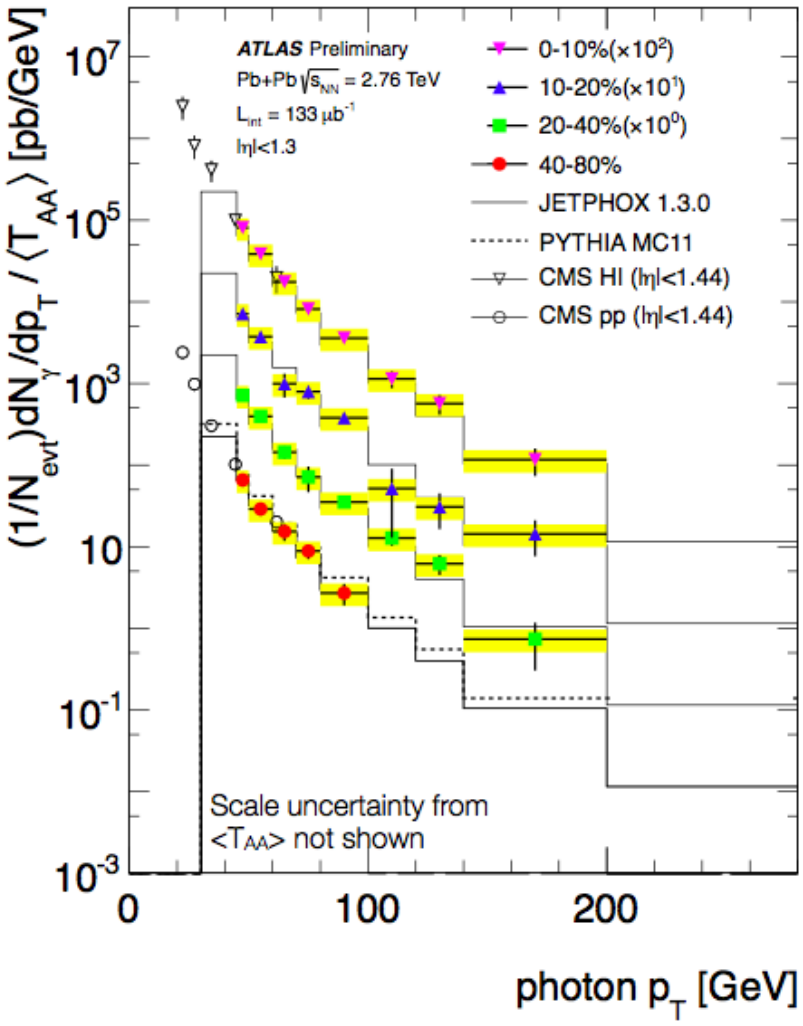


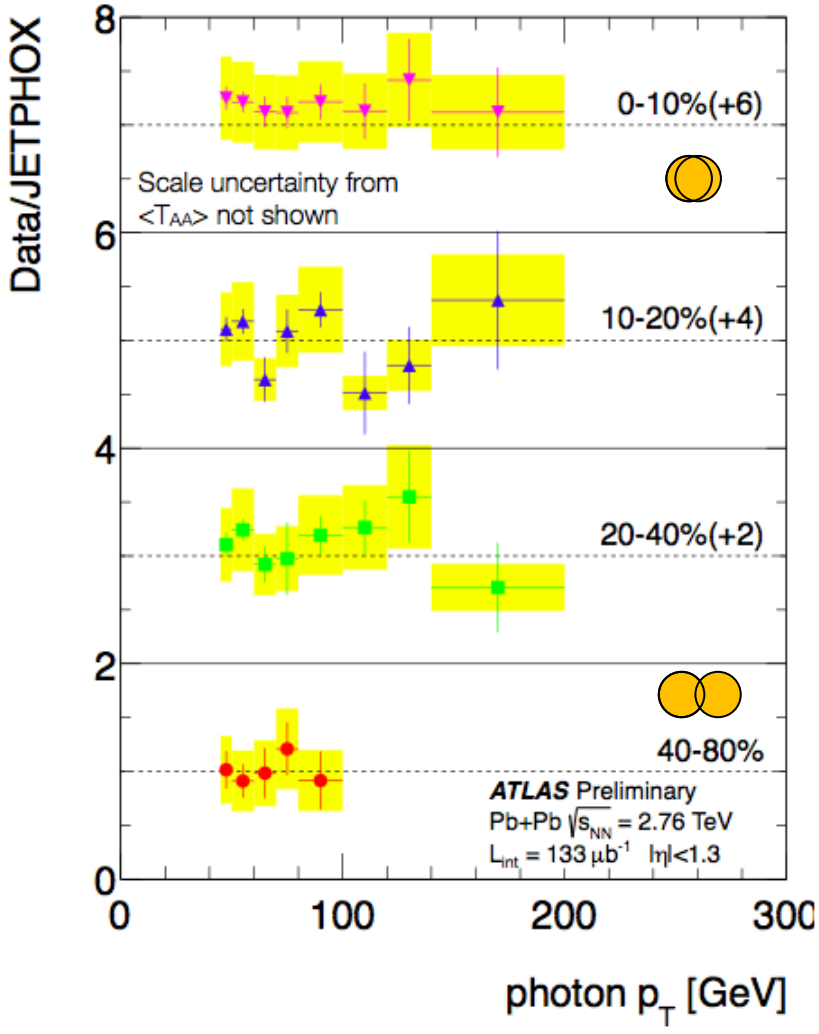


The Z boson p_T spectra are in agreement with PYTHIA simulations (NNLO) for pp scaled by $\langle N_{coll} \rangle$

Direct Photon Measurement in Pb+Pb Collisions

ATLAS-CONF-2012-051

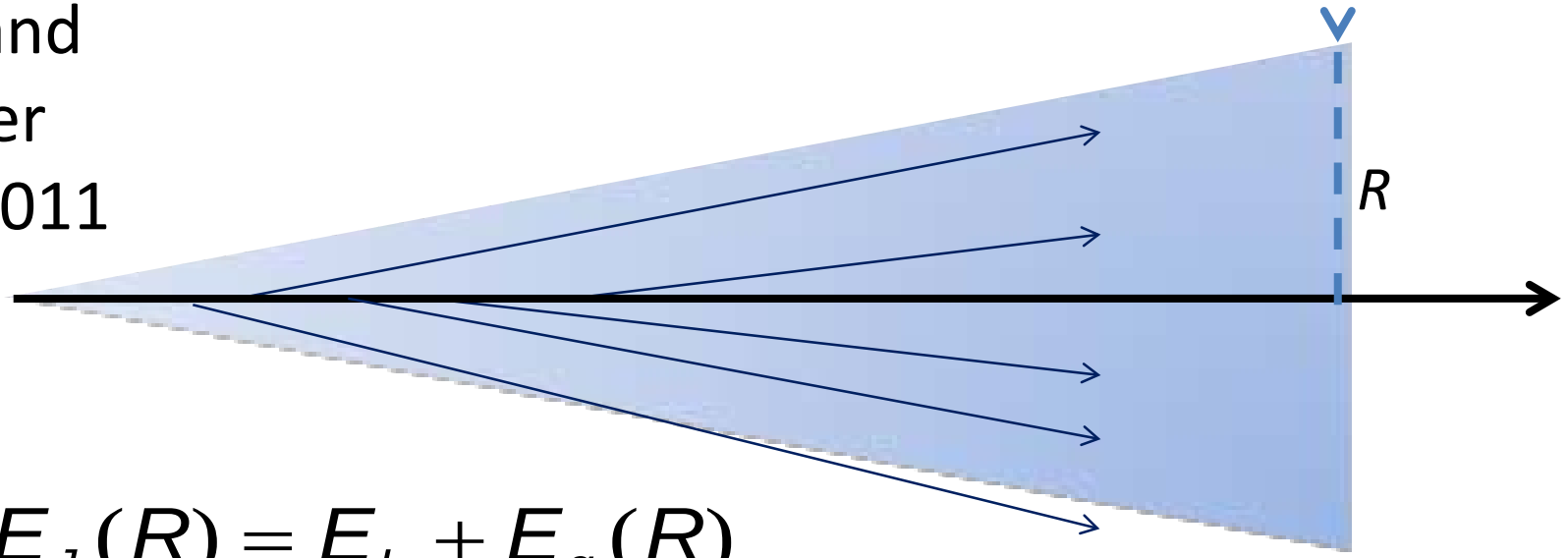




Photon p_T spectra (scaled by <N_{coll}>) are in agreement with predictions of pQCD model (JETPHOX)

Jets as a Probe of the Medium

Qin and Müller QM2011

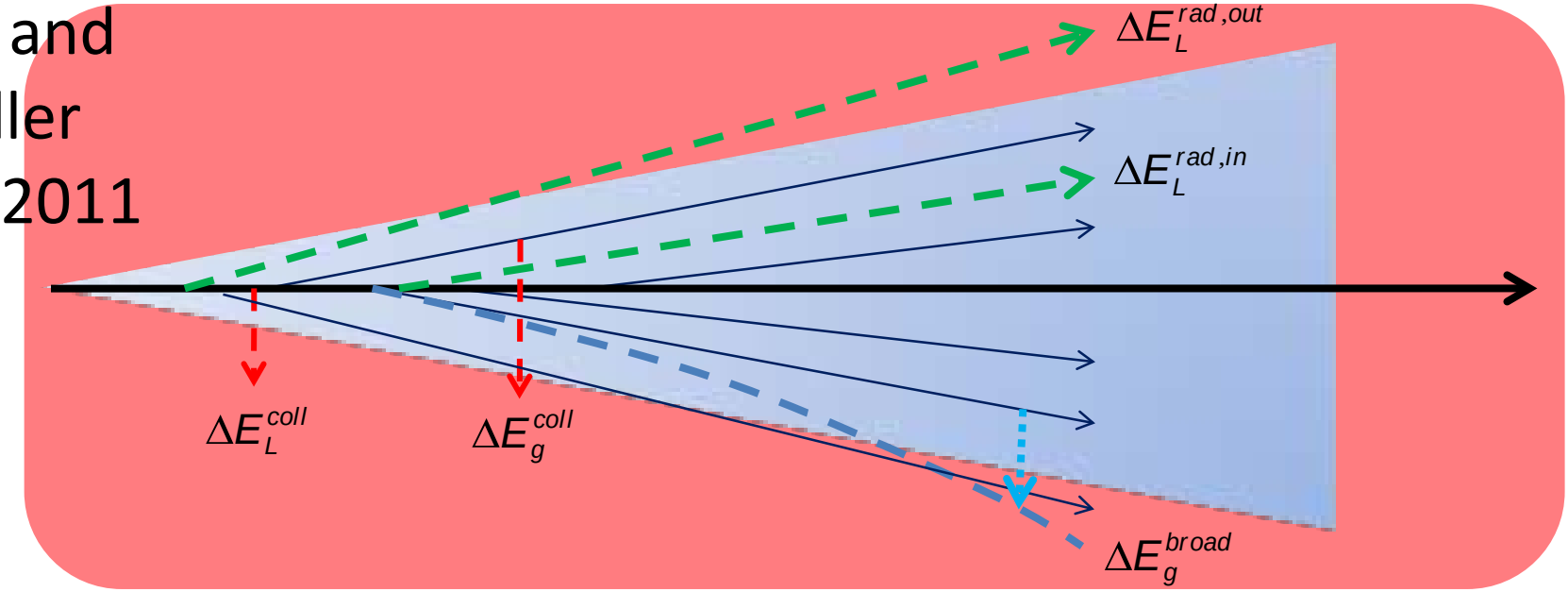


$$E_J(R) = E_L + E_g(R)$$

For pp, partonic jet shower in vacuum is composed of:
Leading Parton and Radiated Gluons

Jets as a Probe of the Medium

Qin and Müller QM2011



For AA, addional processes are present:

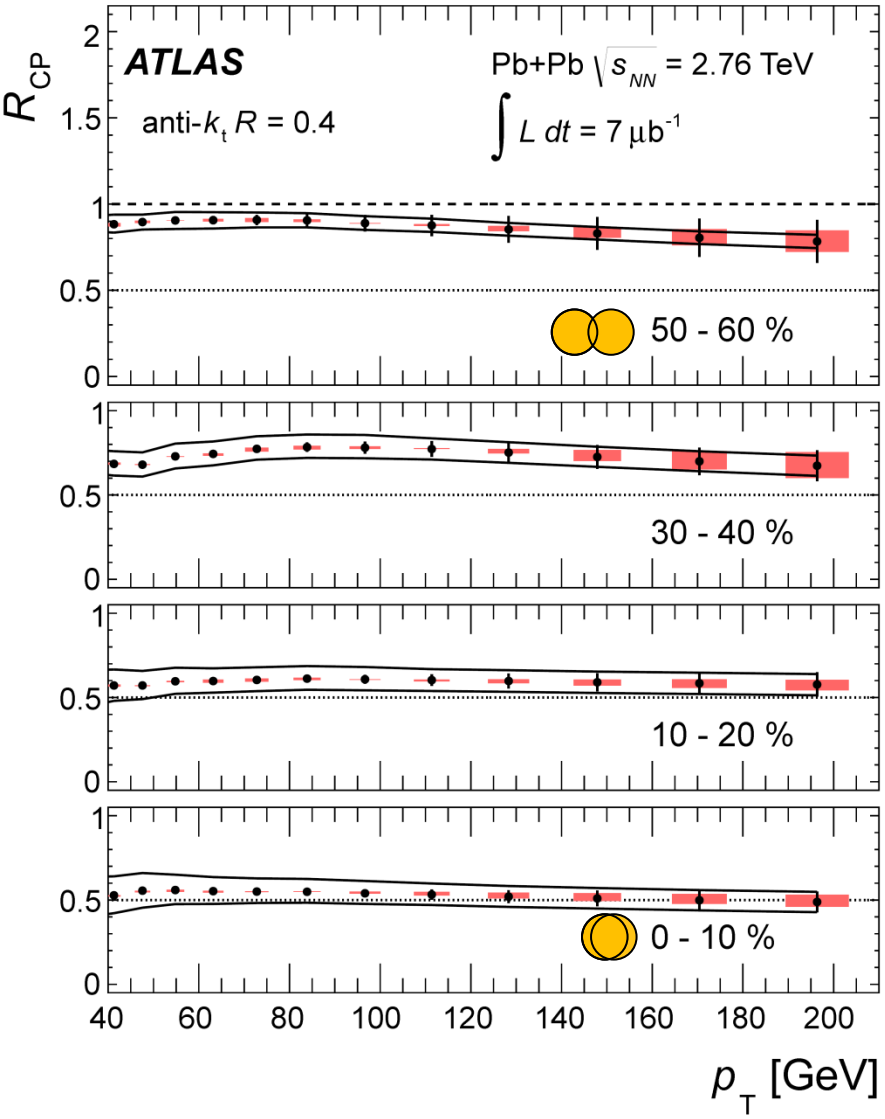
Leading Parton

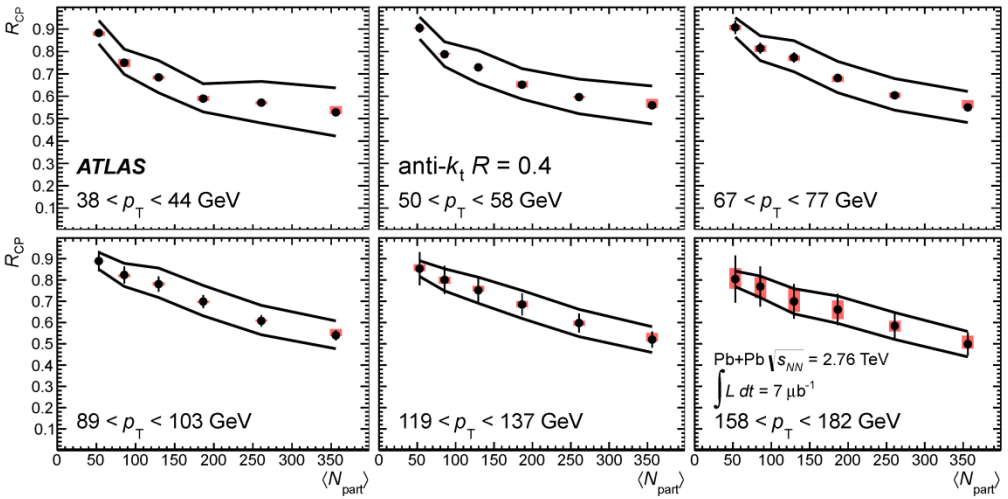
- **E transfer to medium via elastic collsions**
- **Gluons radiated due to medium interactions**

Radiated Gluons

- **E transfer to medium via elastic collsions**
- **E transfer out of jet cone from multiple scattering**

Jets in Pb+Pb Collisions





Nuclear modification factor (NMF):

$$R_{CP} = \frac{\left\langle N_{coll}^{peripheral} \right\rangle}{\left\langle N_{coll}^{central} \right\rangle} \frac{d^2 N_{jets}^{central} / dydp_T}{d^2 N_{jets}^{peripheral} / dydp_T}$$

reference: 60-80%

- **Weak p_T dependence**
- **Jet quenching increases with centrality (R_{CP}↘ when N_{part}↗)**

Phys. Lett. B 719 (2013) 220-241

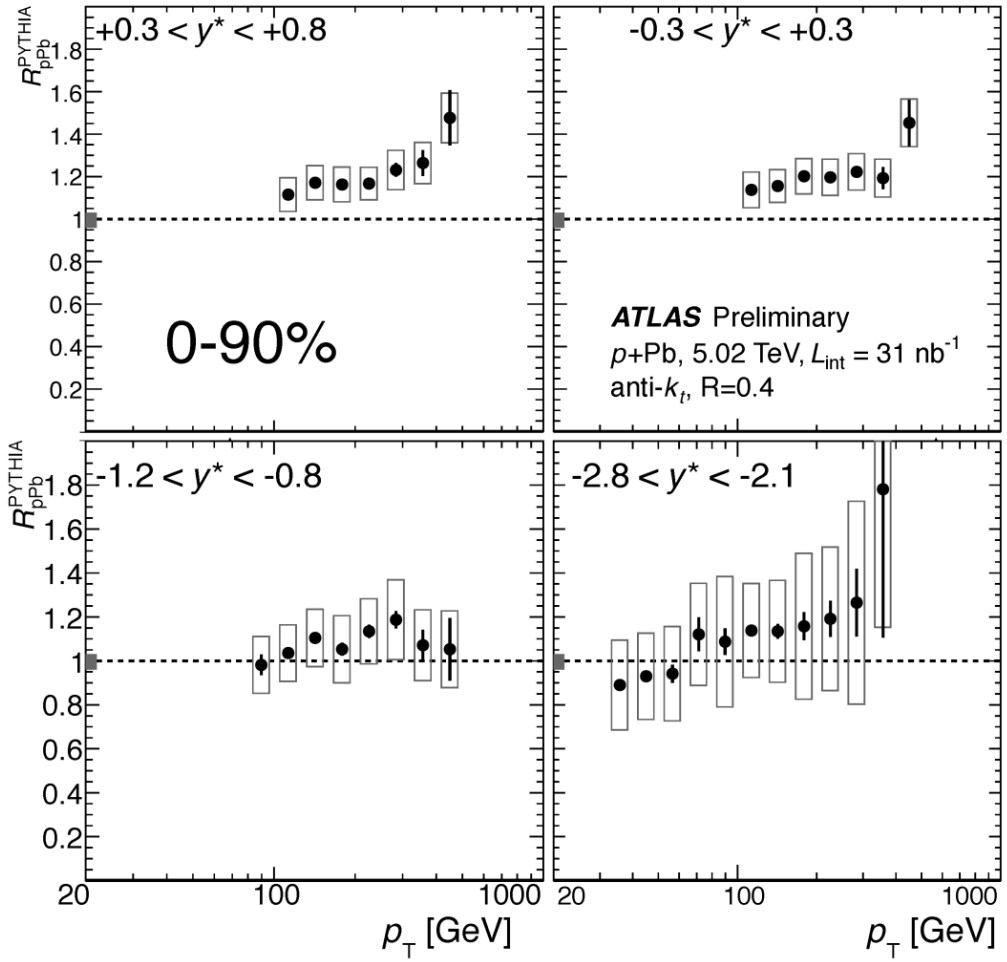
Jets in p+Pb Collisions

- **Full sample of 2013 p + Pb data (31 nb^{-1})**
  - **E_p = 4 TeV, E_{Pb} = 1.58 TeV/nucleon**
  - **y* - the centre-of-mass jet rapidity**

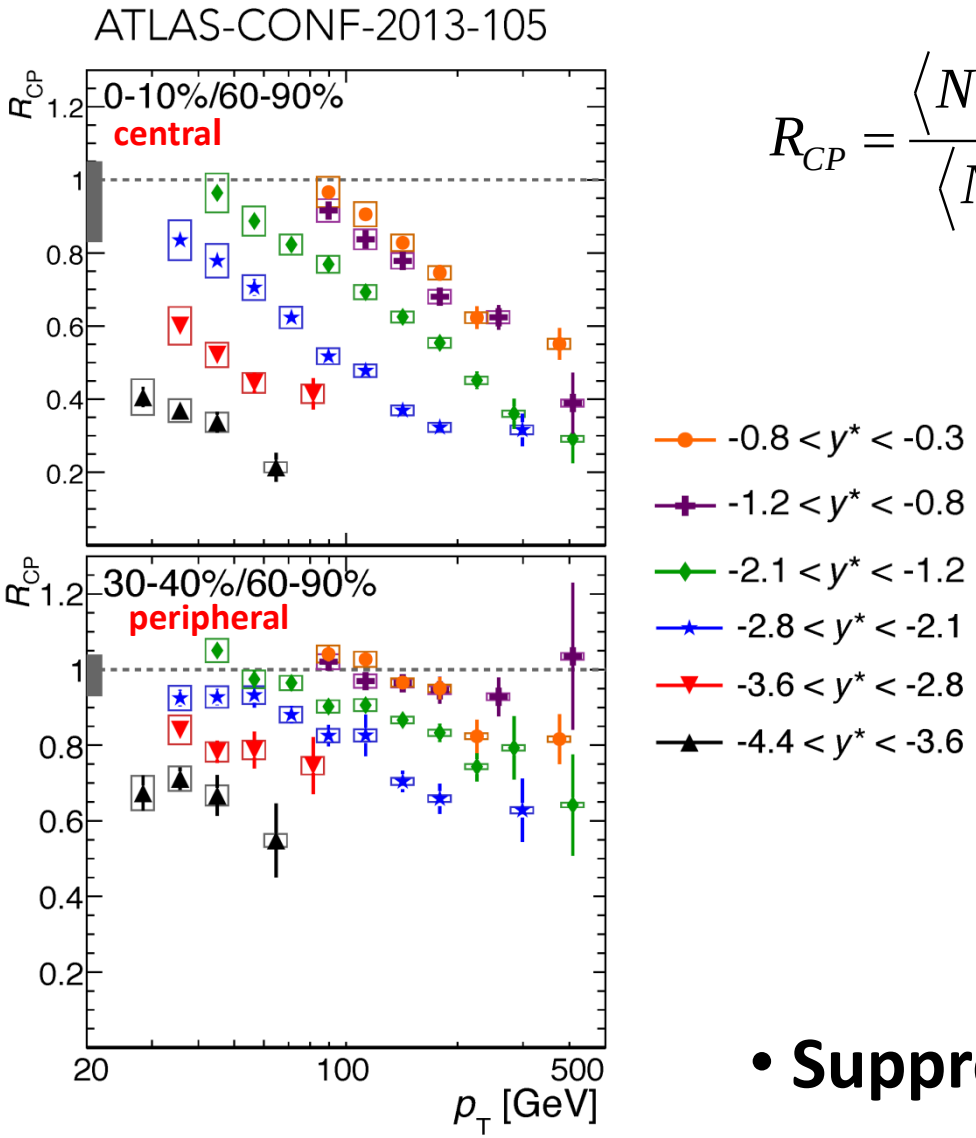
R_{pPb}^{PYTHIA} for Minimum Bias pPb Collisions

- **PYTHIA used as pp reference**
- **Approximate (20%) N_{coll} scaling observed in MB p+Pb collisions**

ATLAS-CONF-2013-105



Jets in p+Pb Collisions at Forward Rapidities



$$R_{CP} = \frac{\left\langle N_{coll}^{peripheral} \right\rangle}{\left\langle N_{coll}^{central} \right\rangle} \frac{d^2 N_{jets}^{central} / dydp_T}{d^2 N_{jets}^{peripheral} / dydp_T}$$

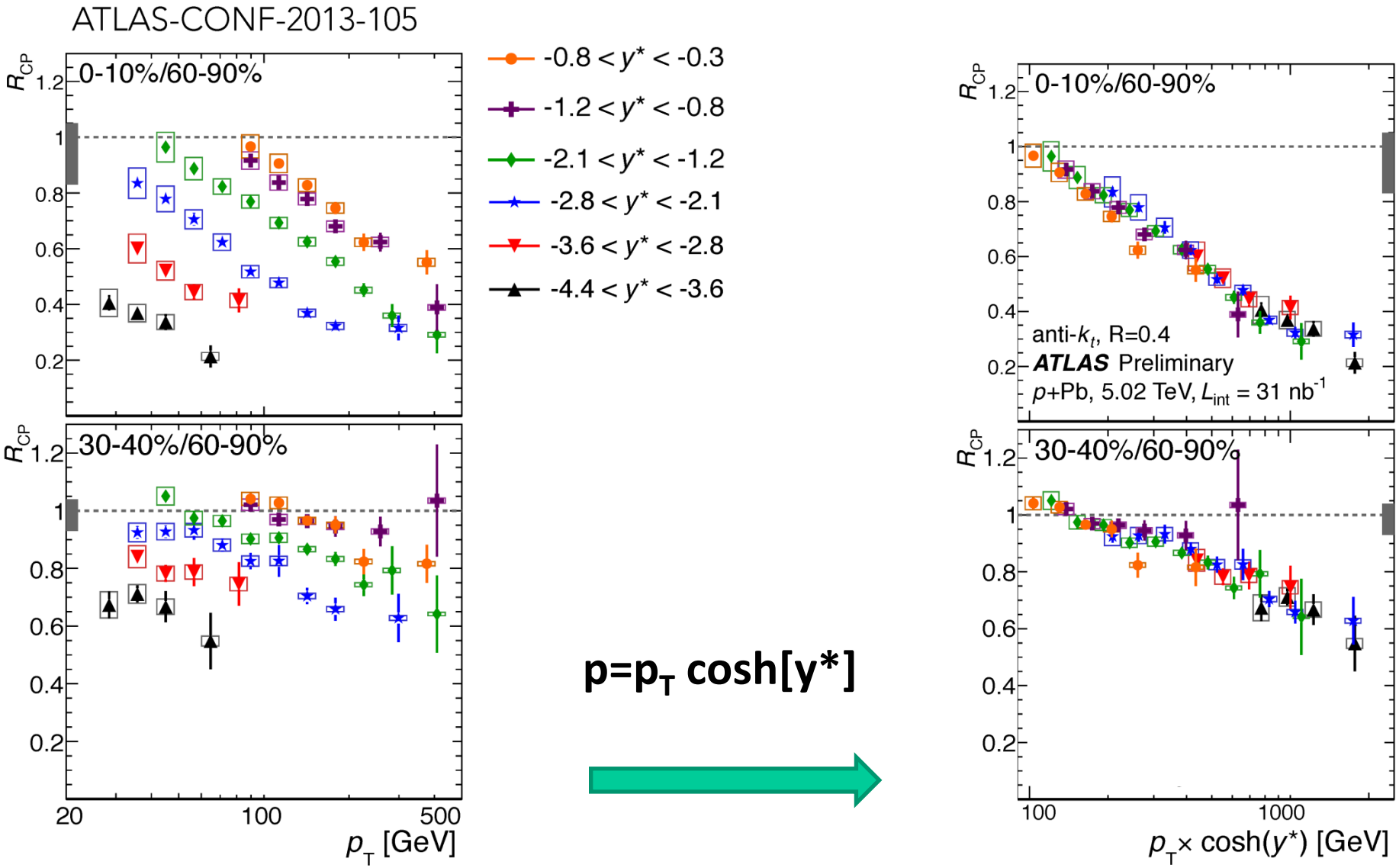
reference: 60-90%

y* < 0 , p-going side

Forward rapidity at p-going direction explores small-x_{Pb} and large-x_p

- **Suppression increases with p_T**

Jets in p+Pb Collisions at Forward Rapidities



$p = p_T \cosh[y^*]$

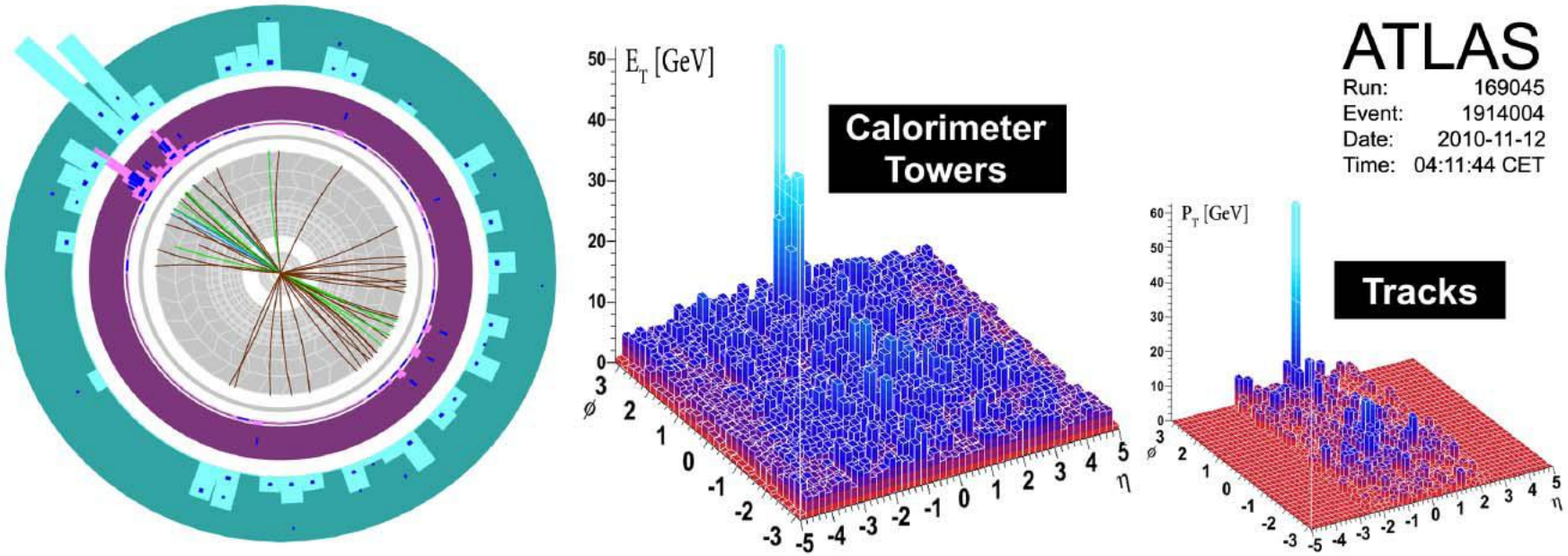
For the same jet momentum a scaling with rapidity is observed

Summary

- Outstanding performance of the ATLAS detector during LHC Pb+Pb (2.76 TeV) and p+Pb (5.02 TeV) runs
- ATLAS well suited for hard probes measurements in wide range of p_T and η
- Boson rates in Pb+Pb are consistent with N_{coll} scaling
- Strong jet suppression is measured in central Pb+Pb collisions
- For p+Pb minimum bias data (0-90%) jet production is approximately consistent with N_{coll} scaling (PYTHIA)
- In central p+Pb collisions jet suppression is observed ($R_{CP} << 1$ for $y^*<0$)
    - "p-scaling" of R_{CP}

Di-jet Energy Imbalance

PRL cover (Vol. 105, Iss. 25)



Large energy imbalance between leading (more energetic, J1) and sub-leading jet (J2) in central Pb+Pb collisions is seen at the event by event basis. ATLAS, Phys. Rev. Lett. 105 (2010) 252303

- **Di-jet asymmetry factor:**

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