Some ^ Highlights of pA and AA studies with ATLAS

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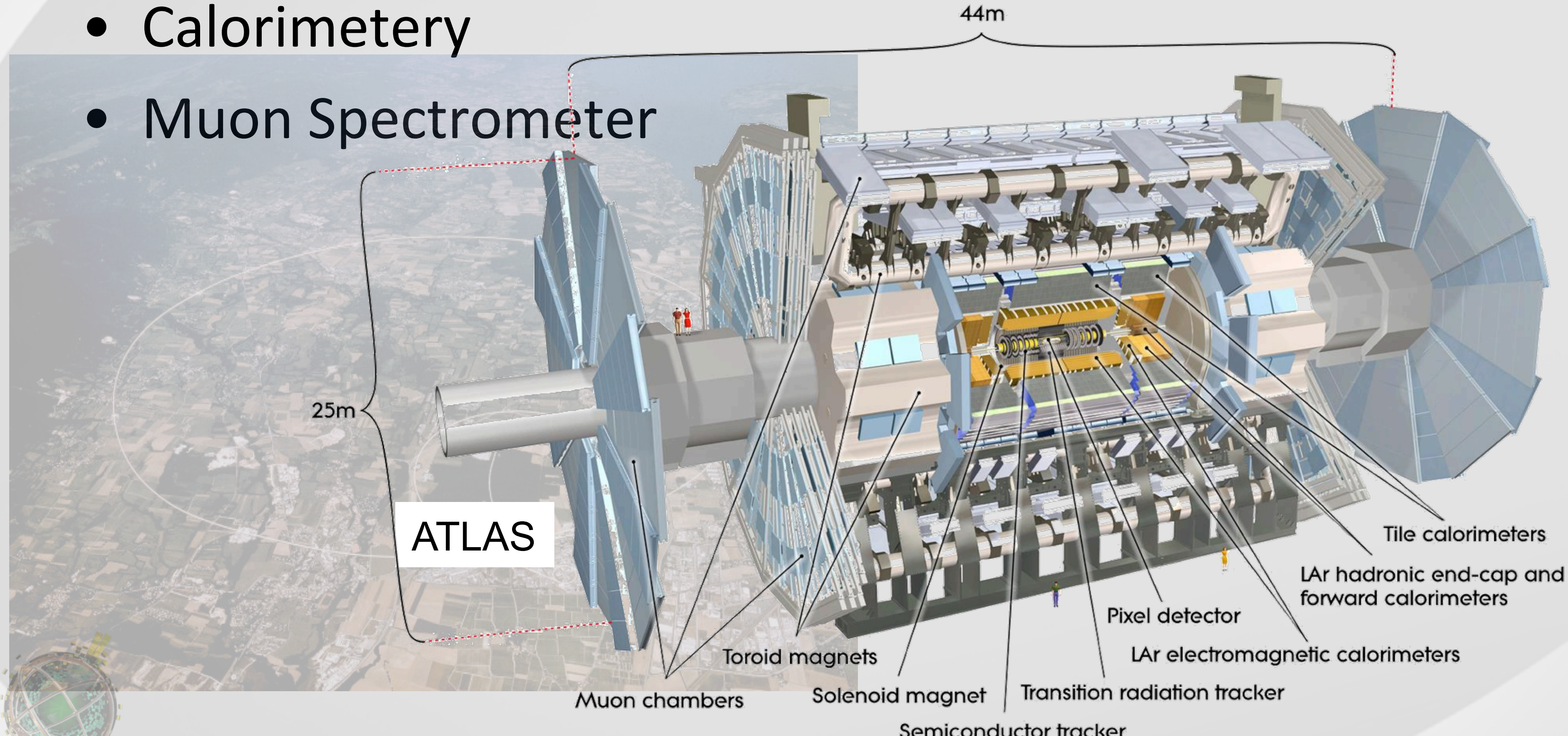
QCD at Cosmic Energies; 17 May 2016

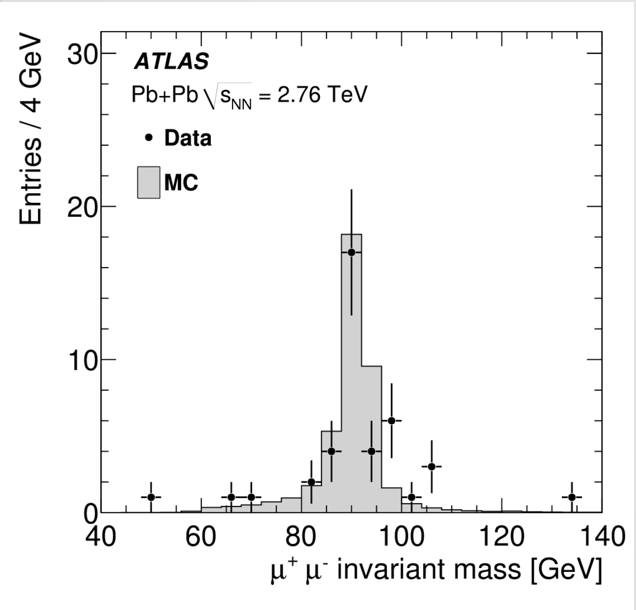
ATLAS at the LHC

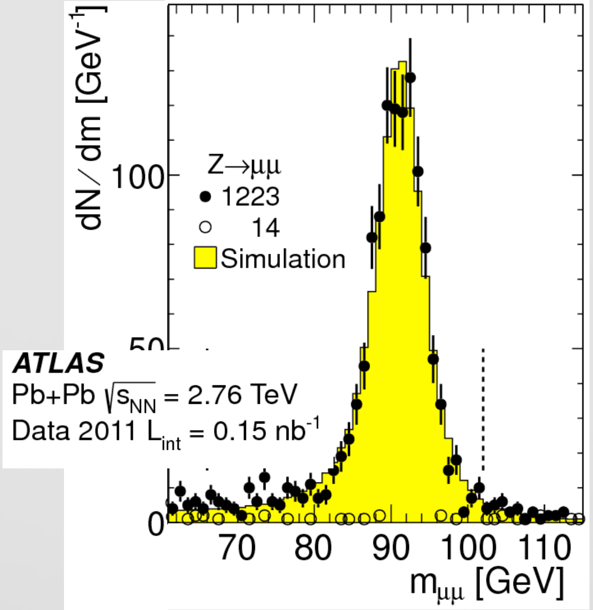
- ATLAS has:
    - Charged particle tracking
    - Calorimetery
    - Muon Spectrometer



Pb+Pb Collisions in ATLAS

- Three Pb+Pb runs at the LHC recorded by ATLAS:
  - 2010: Pb+Pb @ 2.76 TeV, 6.7 μb^{-1} → 38 Z bosons
  - 2011: Pb+Pb @ 2.76 TeV, 150 μb^{-1} → ~1.2k Z bosons
  - 2015: Pb+Pb @ 5.02 TeV, ~520 μb^{-1} → ~5k Z bosons



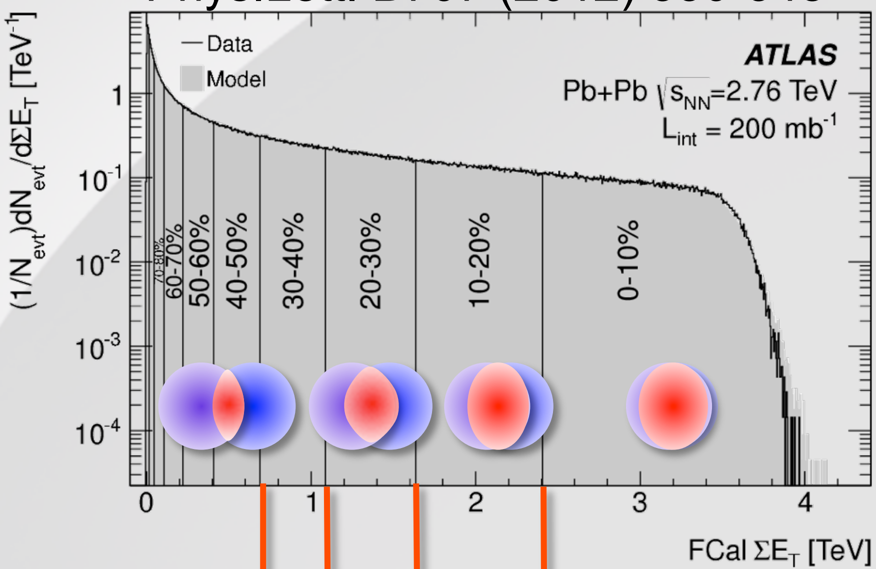


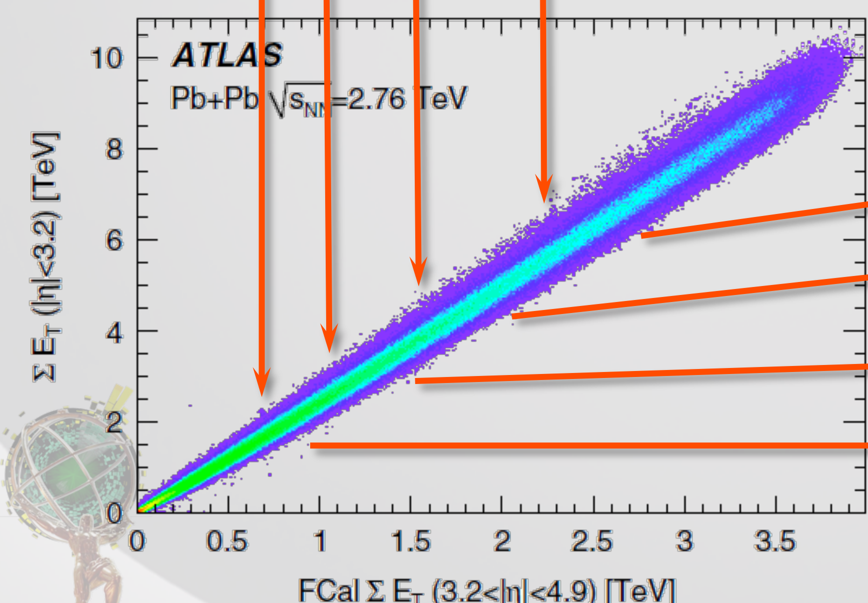
Pb+Pb Collisions in ATLAS

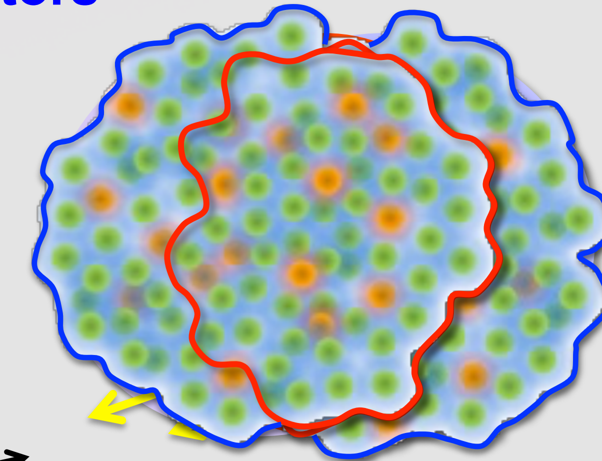
- Two* basic categories of questions for the data:
  - How do color sensitive objects (especially jets) interact with a hot dense QCD medium?
    - Look mostly at hard probes in rare events
  - What are the properties of the medium itself?
    - Look at bulk particle production in 'normal' events
  - *(Can we study nuclear initial state effects?
    - Usually better off using pA collisions)

Centrality

Phys.Lett. B707 (2012) 330-348



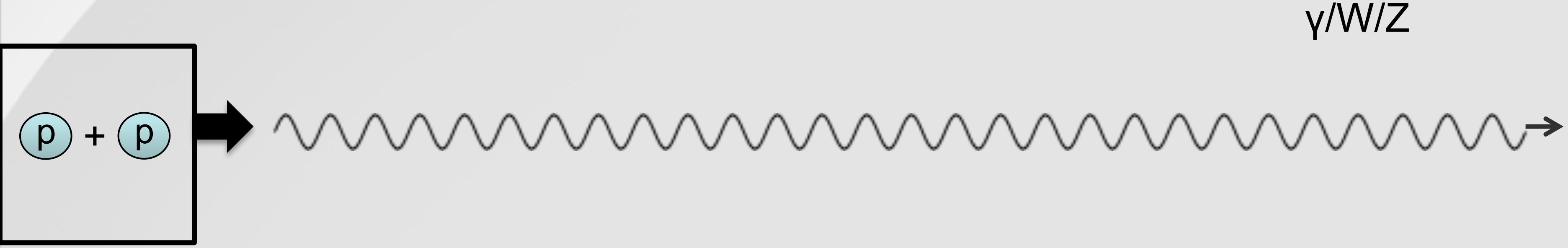




Glauber Model

	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$
0-5%	382 ± 1%	1683 ± 8%
5-10%	330 ± 1%	1318 ± 8%
10-20%	261 ± 2%	923 ± 7%
20-40%	158 ± 3%	441 ± 7%
40-80%	46 ± 6%	78 ± 9%

EW Bosons as a Probe of the Initial State



We can measure the EW boson production in p+p collisions …

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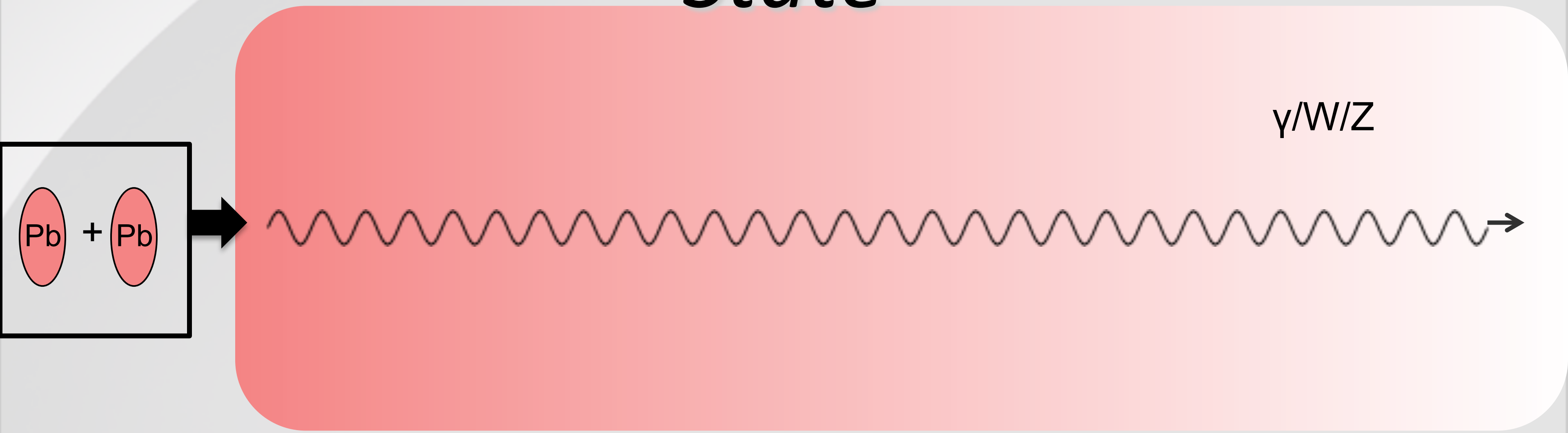
EW Bosons as a Probe of the Initial State

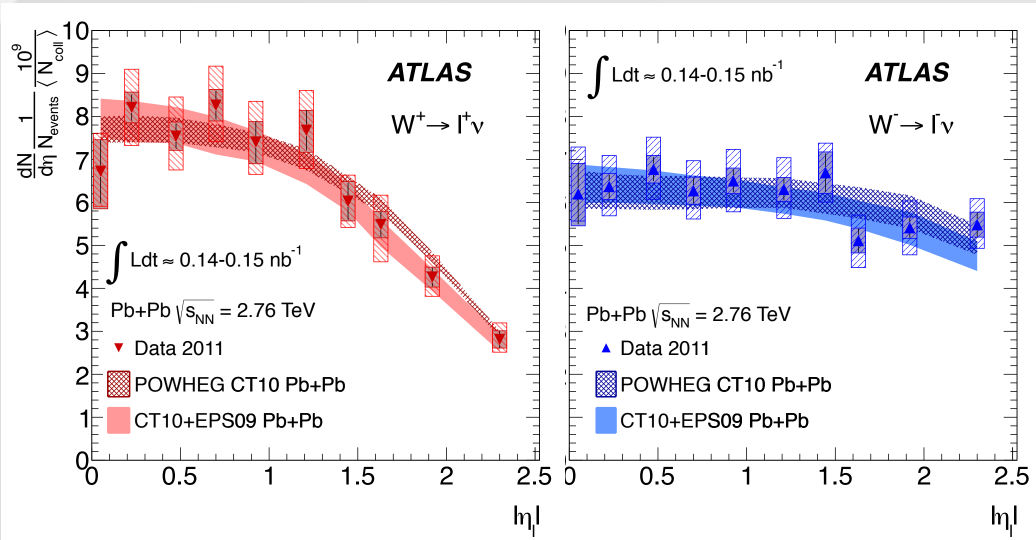


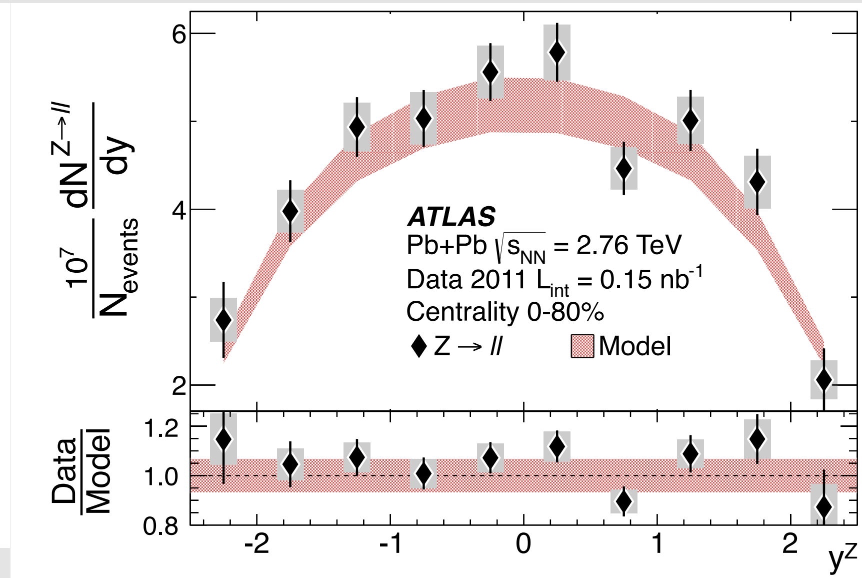
We can measure the EW boson production in p+p collisions …

Add the medium and measure the same thing – EW bosons won't interact with the colored QCD medium any changes observed must be due to initial state effects

EW Bosons Consistent with Expectations

pQCD calculations that work for pp collisions are scaled up to account for the number of binary collisions in PbPb …



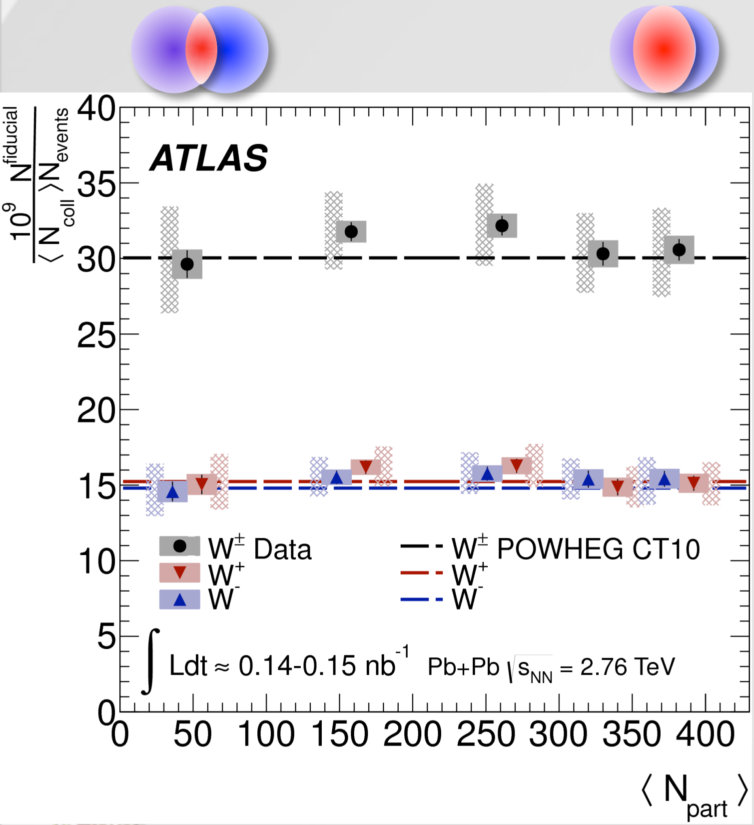


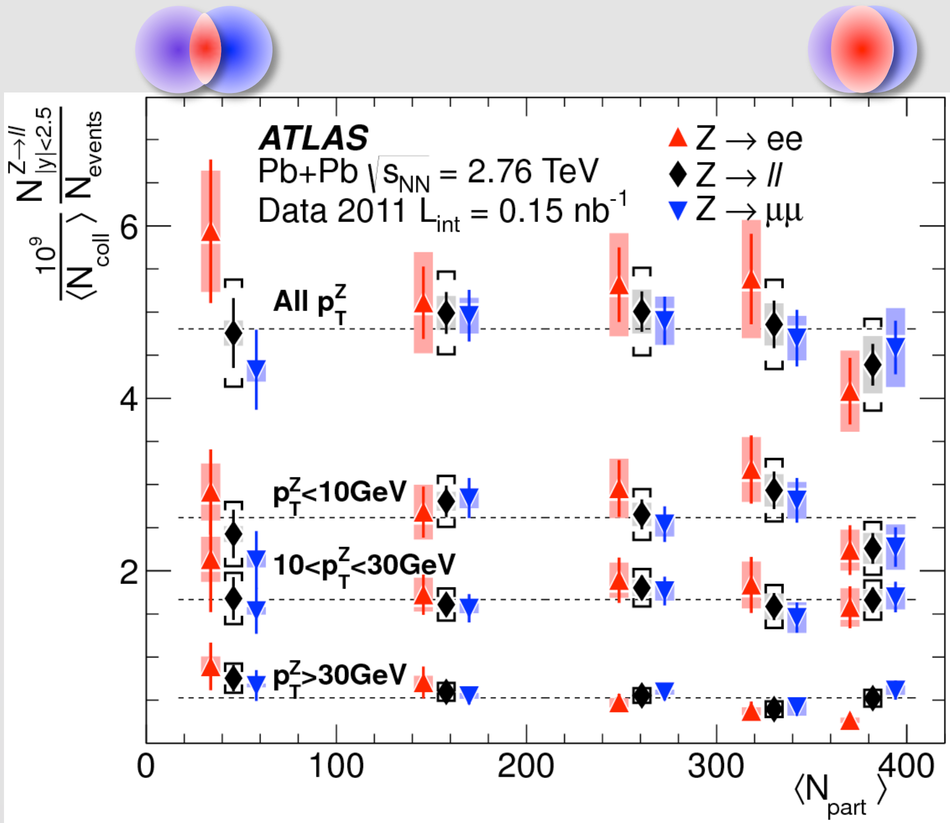
pQCD calculations describe the data (even without nuclear modification of the PDF)

Phys. Rev. Lett. 110, 182302 (2013), [EPJC (2015) 75:23]

EW Bosons Consistent with Expectations

Boson yield scales with number of binary collisions





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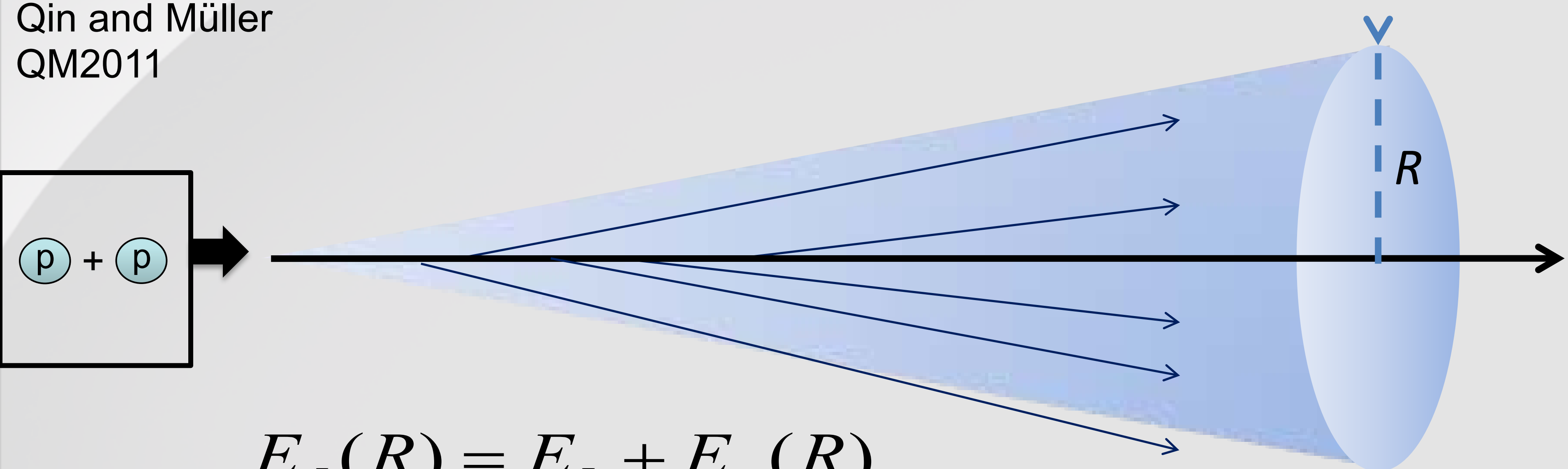
Jets as a Probe of the Medium

Qin and Müller
QM2011



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

Partonic jet shower in vacuum composed of:
<u>Leading Parton</u> and <u>Radiated Gluons</u>

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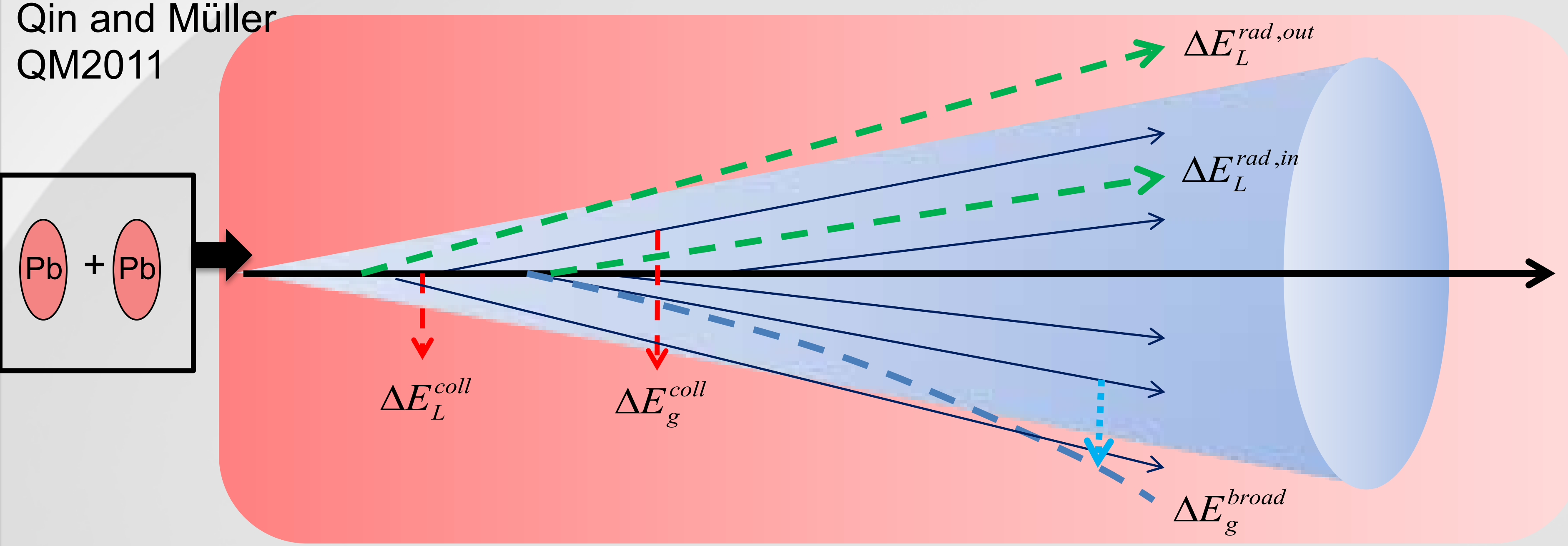


Partonic jet shower in vacuum composed of:

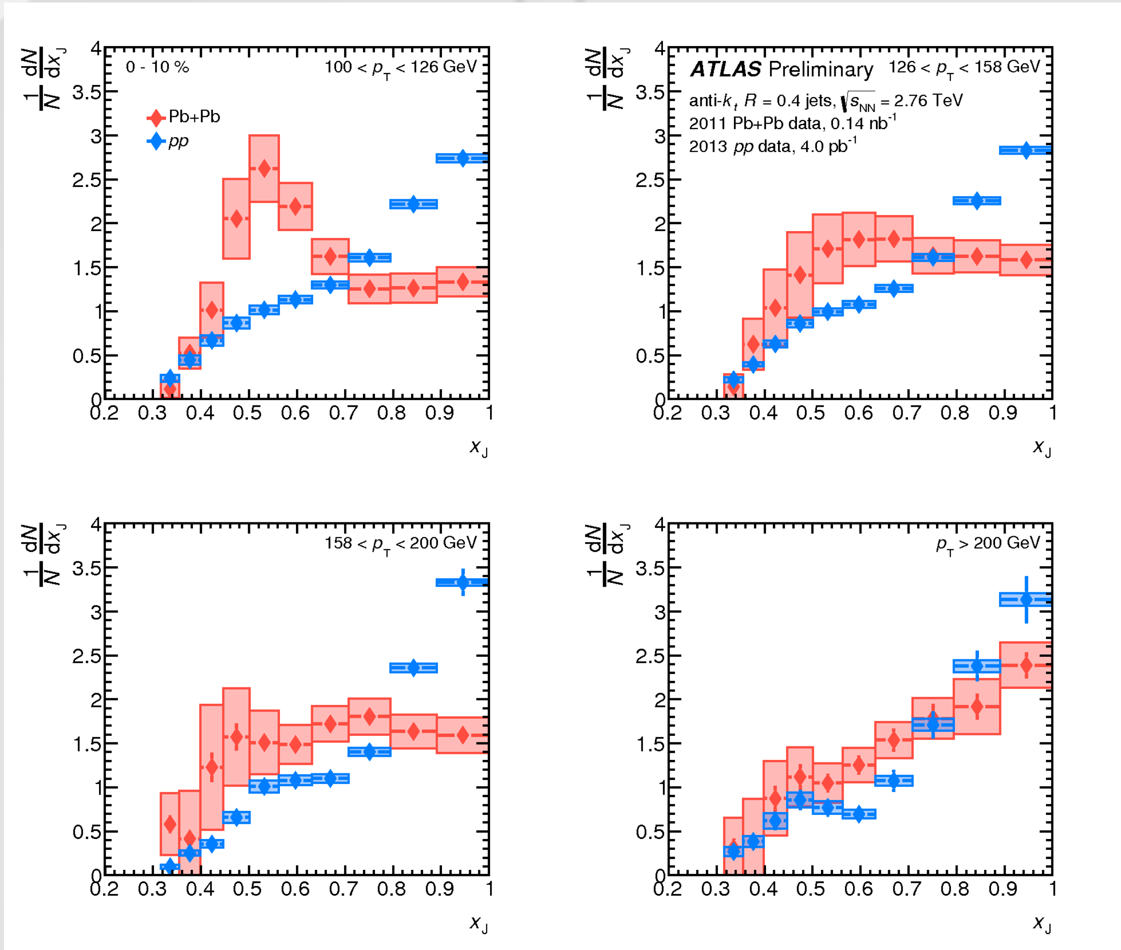
Add the medium:

<u>Leading Parton</u> and **<u>Radiated Gluons</u>**

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

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

Jet Suppression



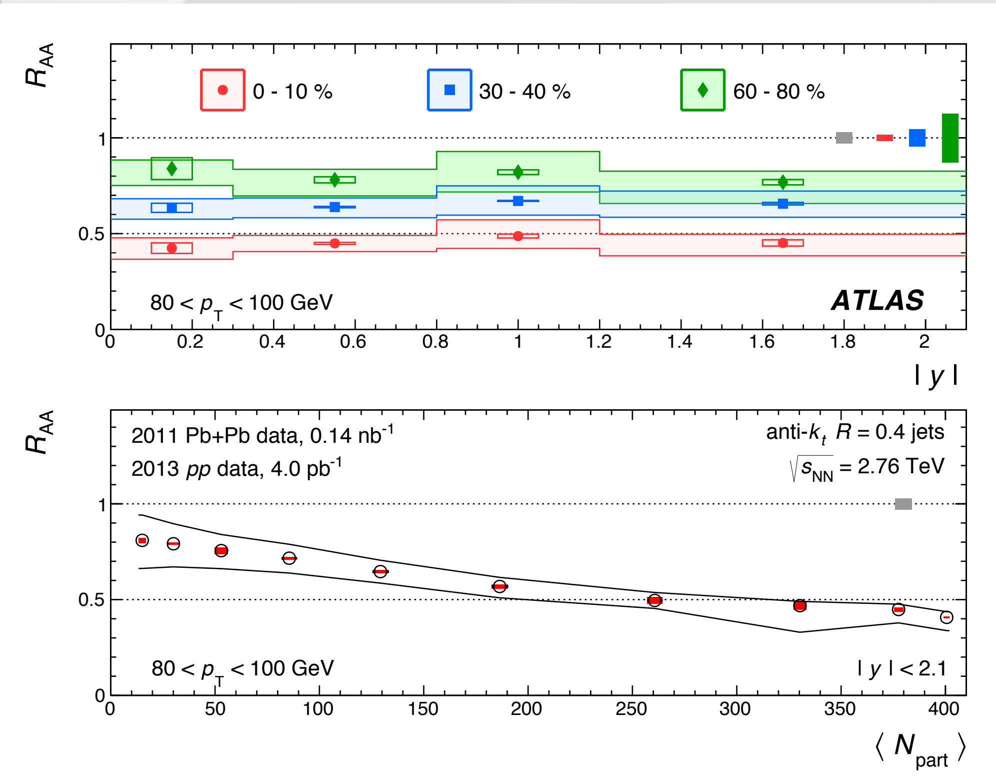
- Momentum balance not kept within di-jets produced in central collisions
- **Direct observation of 'jet quenching'**

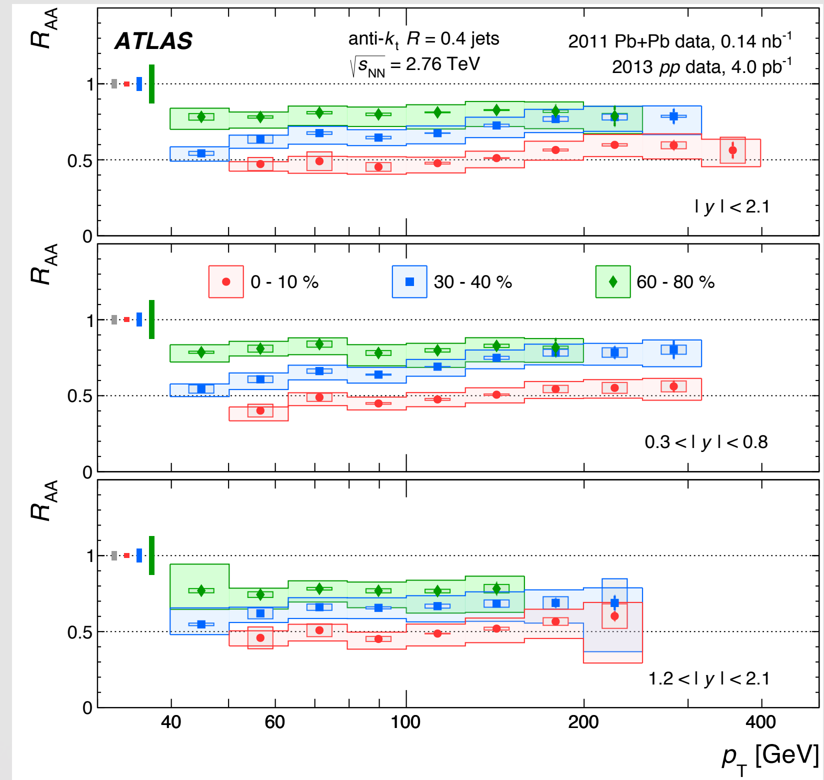
https://cdsweb.cern.ch/record/2055673

Jet Suppression

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

Phys. Rev. Lett. 114 (2015) 072302

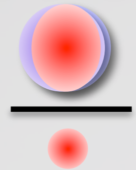




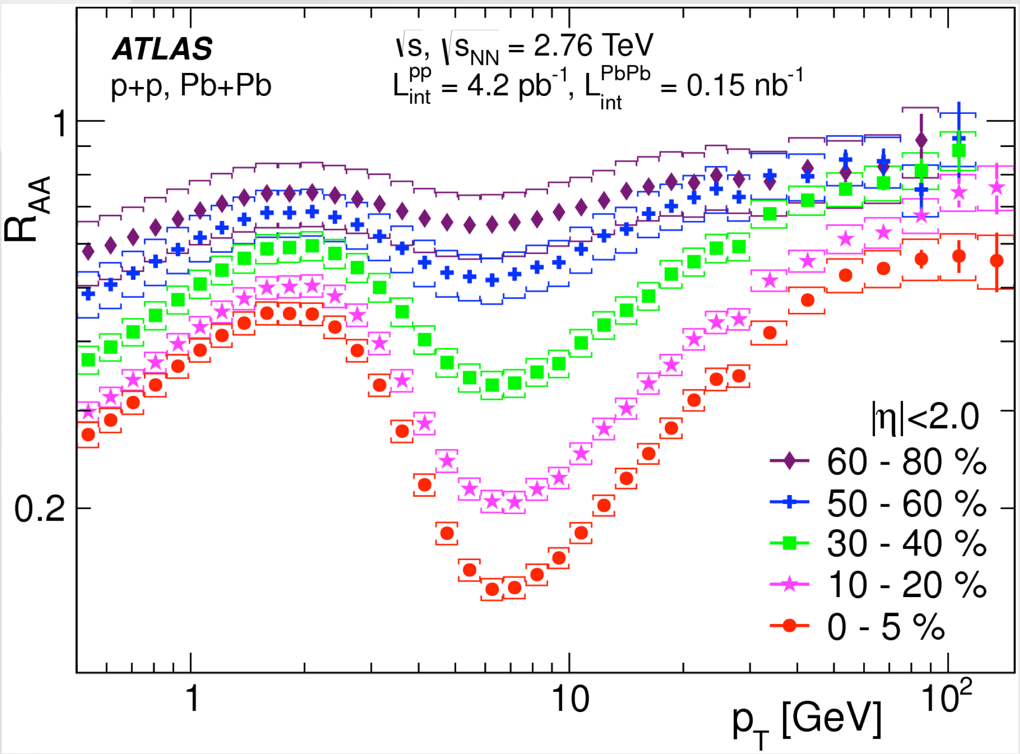
- **Number of jets is less than expected compared to pp**
- Strong centrality dependence
- Little (no) rapidity dependence
- Slight momentum dependence

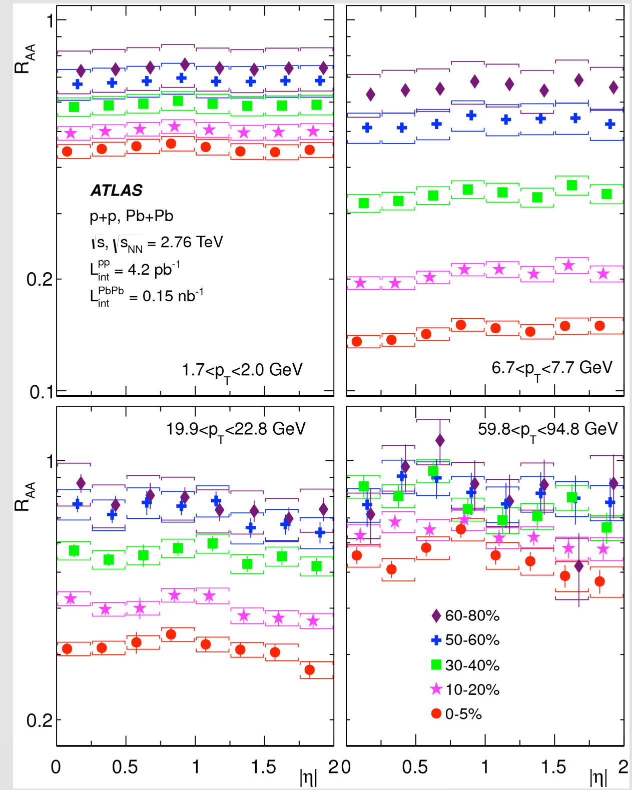
Jet Suppression

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



JHEP09(2015)050



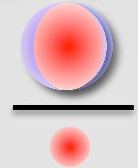


- **Number of charged particles is less than expected compared to pp**
- Strong centrality dependence
- Little (no) rapidity dependence
- Strong momentum dependence

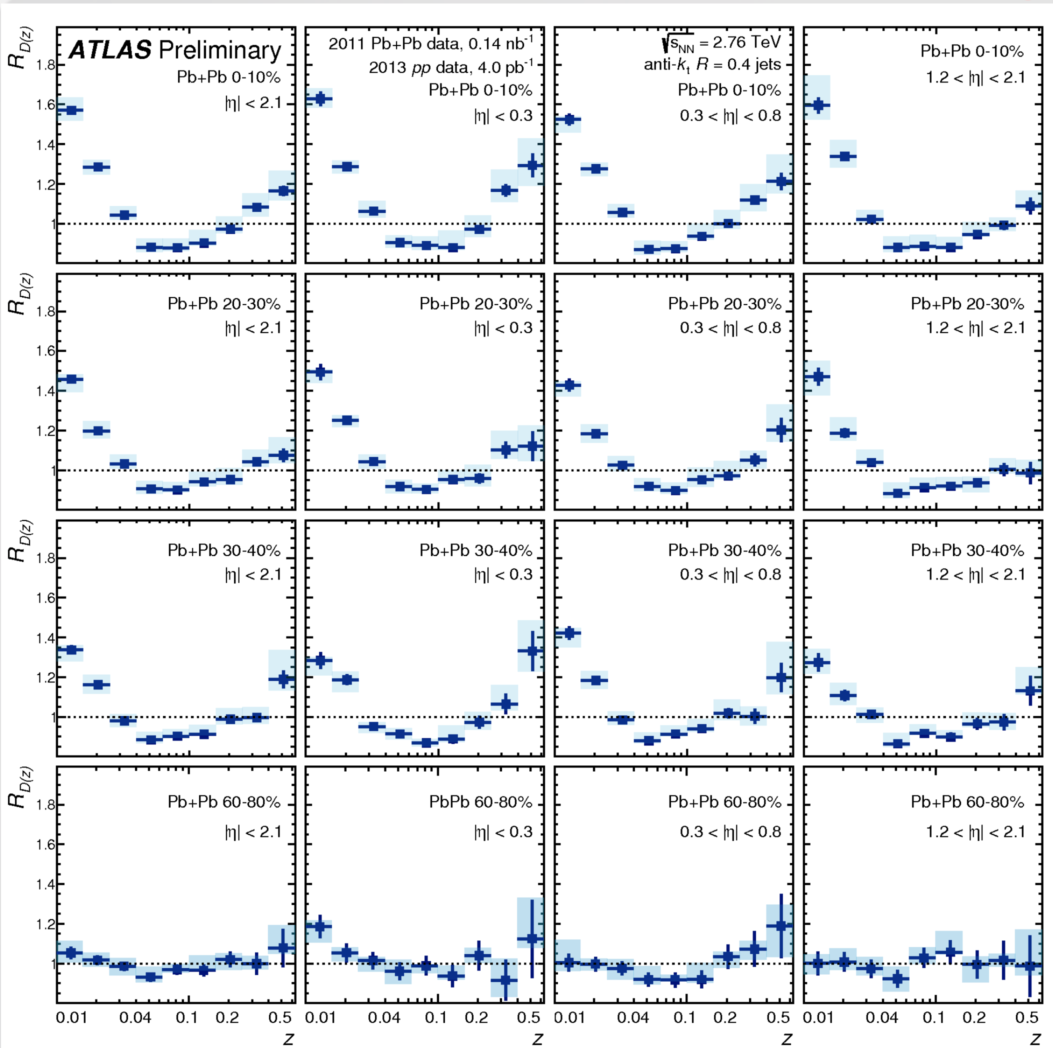
Jet Suppression

Fragmentation function

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{dN_{\mathrm{ch}}}{dz} \qquad R_{D(z)} = \frac{D(z)_{A+A}}{D(z)_{p+p}}$$



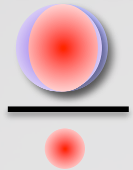
https://cdsweb.cern.ch/record/2055676



- Leading particle is enhanced!
- So are softest particles!
- Suppression of intermediate particles

Heavy Flavor Suppression

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



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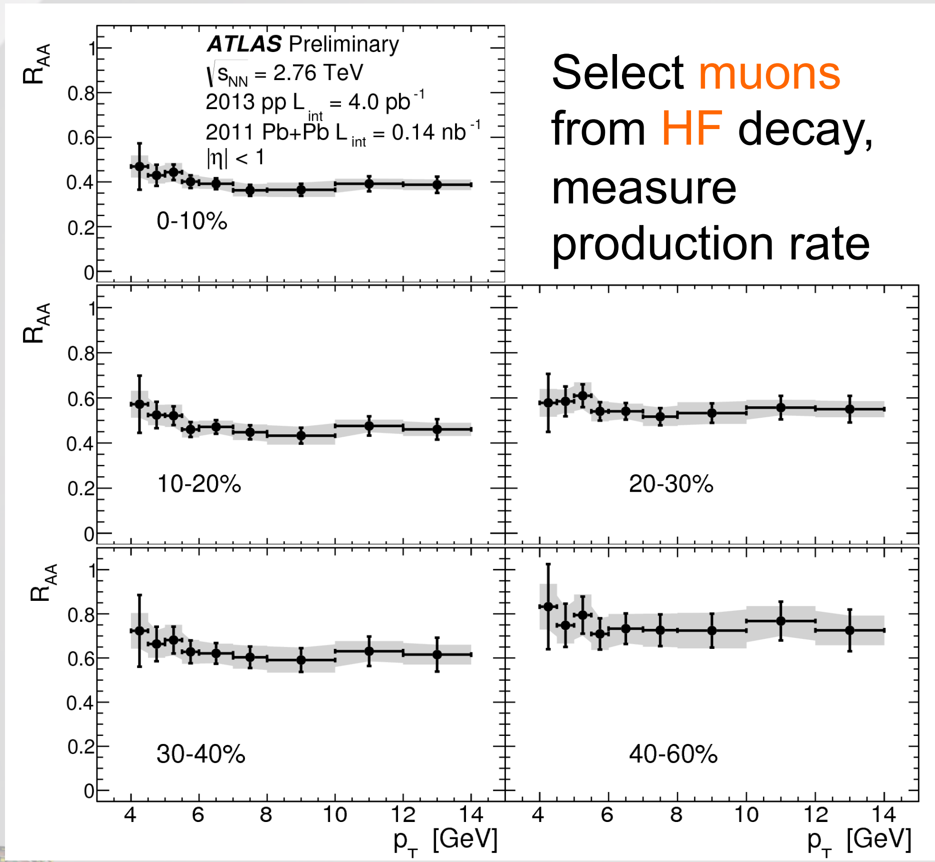
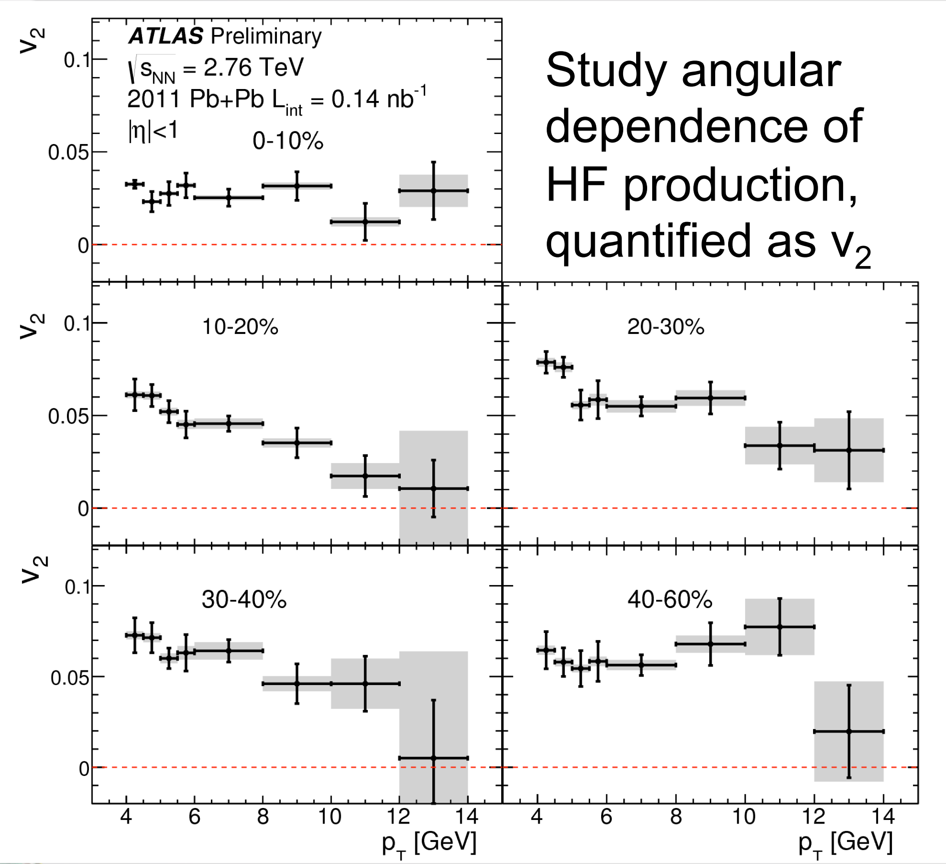


Select muons from HF decay, measure production rate

- **Heavy flavor suppressed**
- **Intermediate scale between inclusive charged particles and jet results**

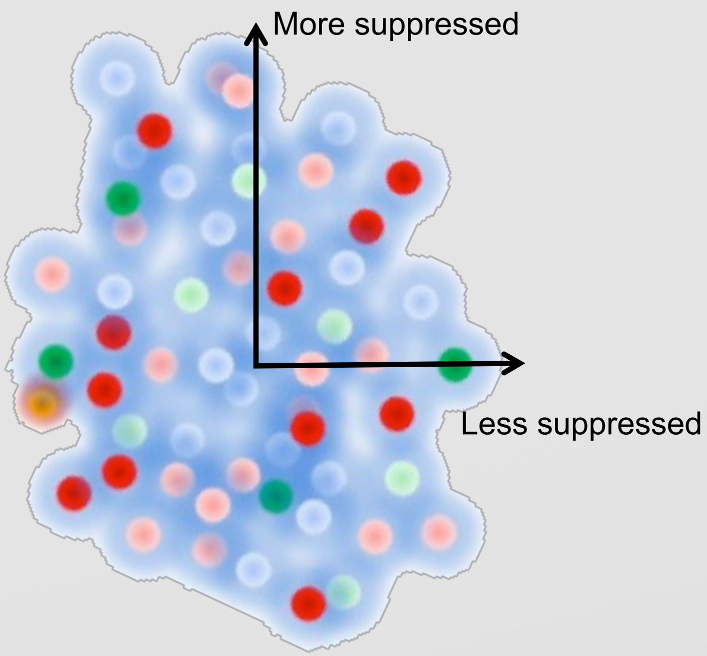
Heavy Flavor Suppression

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$$



Study angular dependence of HF production, quantified as v_2

Assume suppression is related to length of medium traversed



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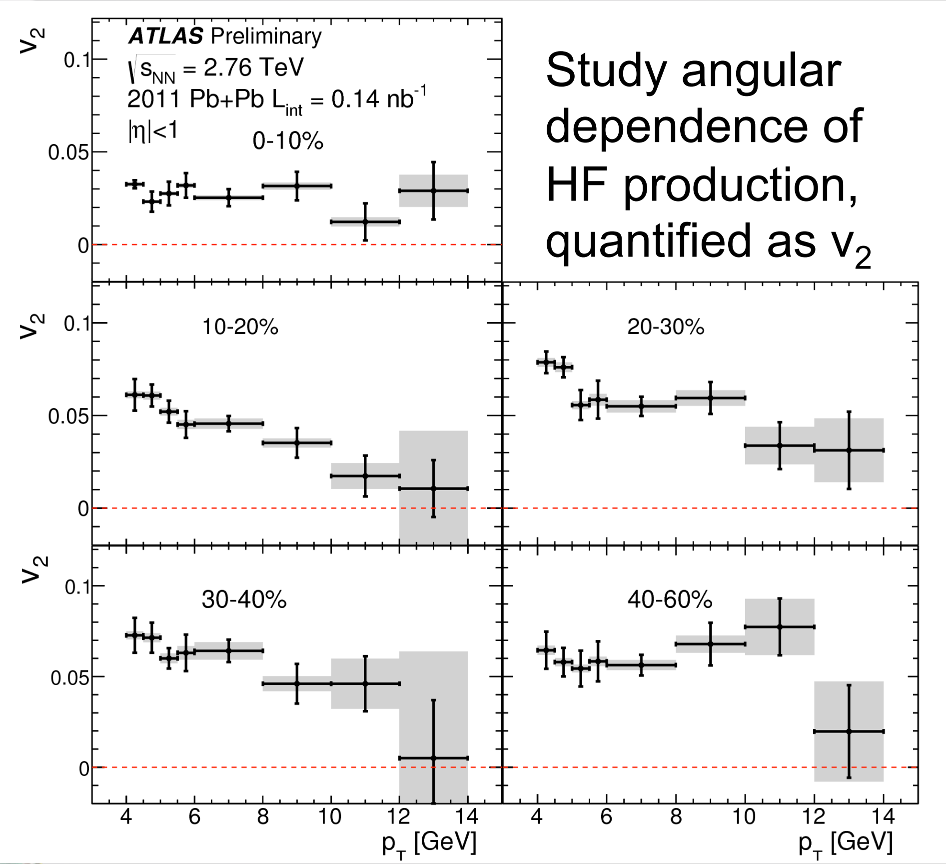
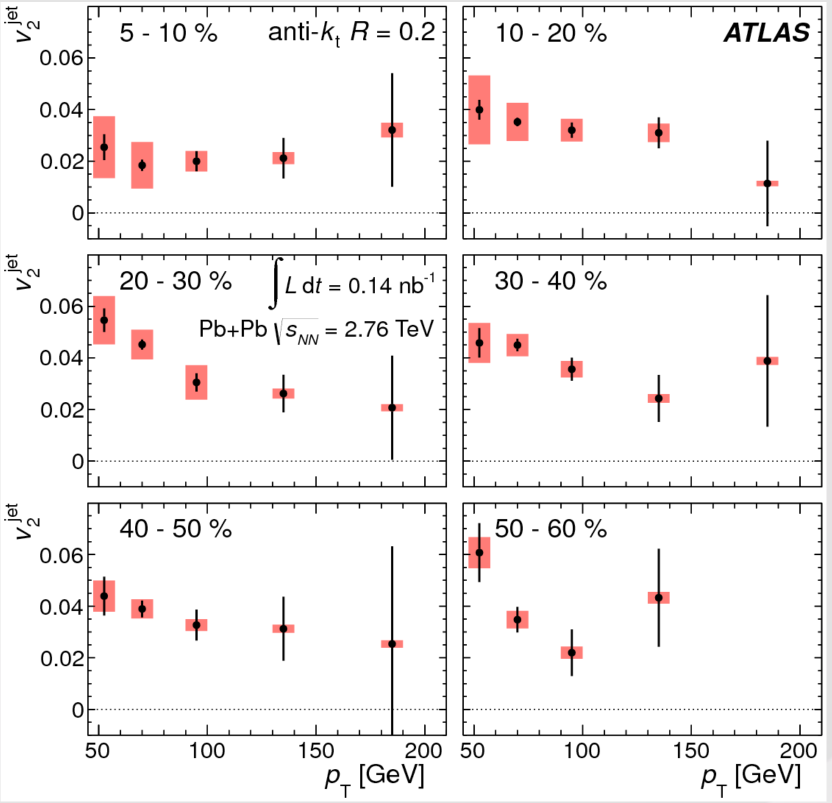


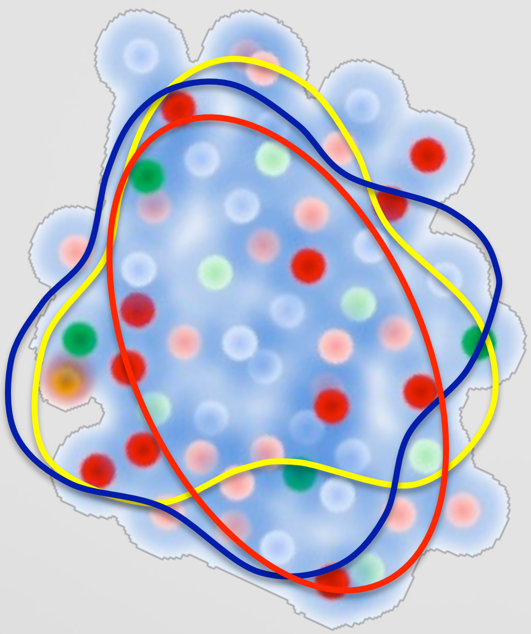


Hard Probes Story

- Many other observables that show ‘color opacity’
- Extracting detailed mechanisms of jet suppression/energy loss not trivial
- EW bosons demonstrate understanding of collision geometry and function as ‘standard candles’ unbiased by the medium

What About the Medium Itself?

- Lots going on in addition to the rare processes!
- Study collective bulk properties of the medium
- Spatial anisotropies observable in momentum space due to **collective flow**
- Study of the moments, v_n, and correlations between reaction planes, Φ_n, teaches us about the **initial geometry and expansion**
- **Medium flows like a liquid**



Reaction plane

Singles: $$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$$

Pairs: $$\frac{dN_{Pairs}}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos(n\Delta\phi)$$

Fourier decomposition of azimuthal distribution

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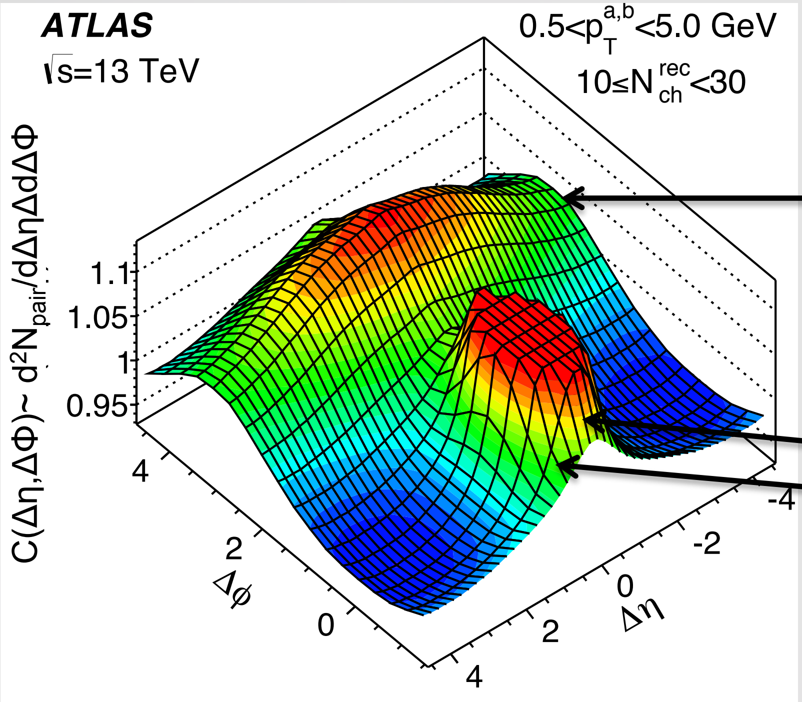
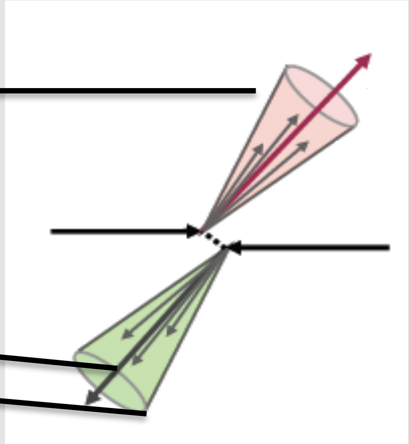
Probing the Medium Using Pair Correlations

Multi-faceted correlation patter even in pp collisions



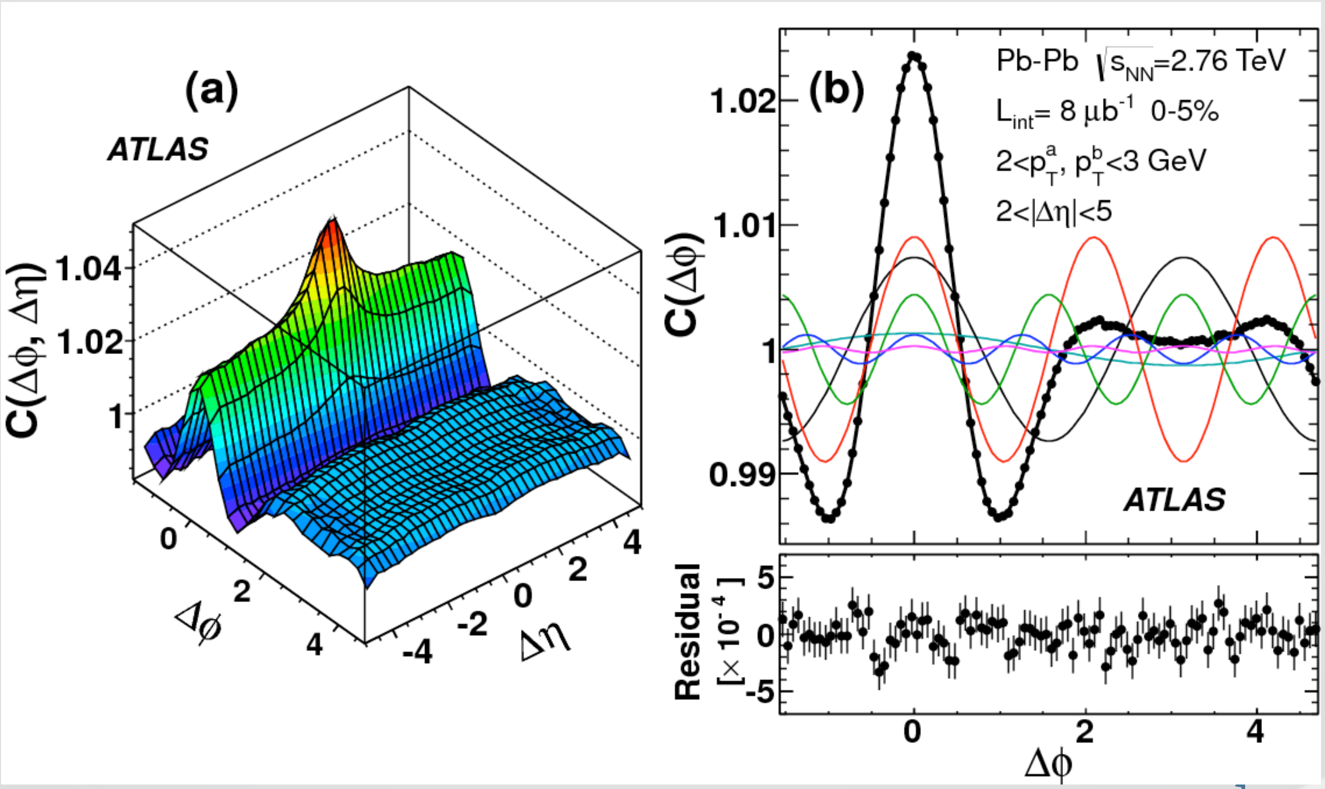


Away side
ΔΦ≈π

'Near side jet peak'
Δη≈ΔΦ≈0

Probing the Medium Using Pair Correlations

Initial spatial anisotropies propagate into azimuthal anistropies in particle production → Learn about the liquid properties of the medium with a Fourier decomposition in PbPb collisions



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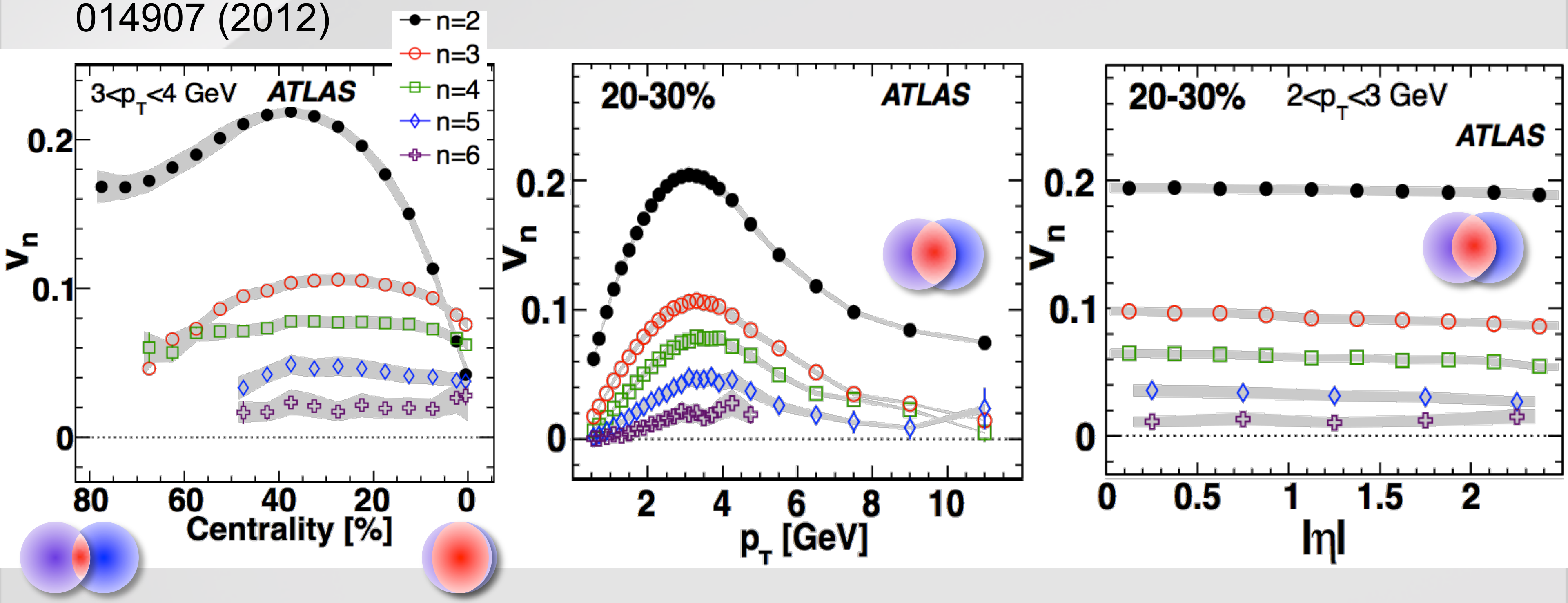
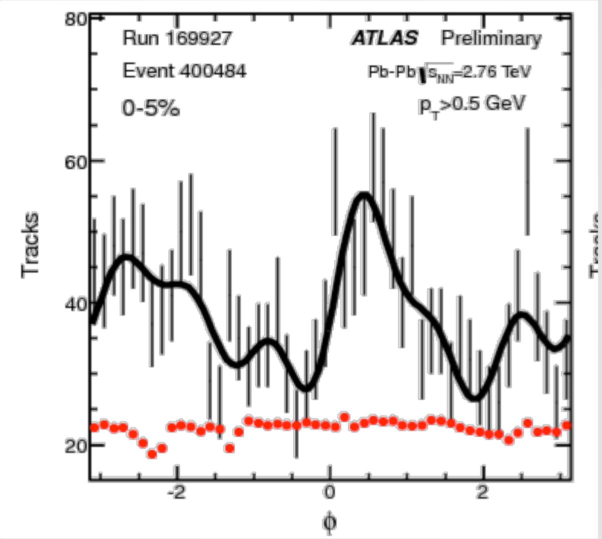
Event Averaged Flow

Phys. Rev. C 86, 014907 (2012)

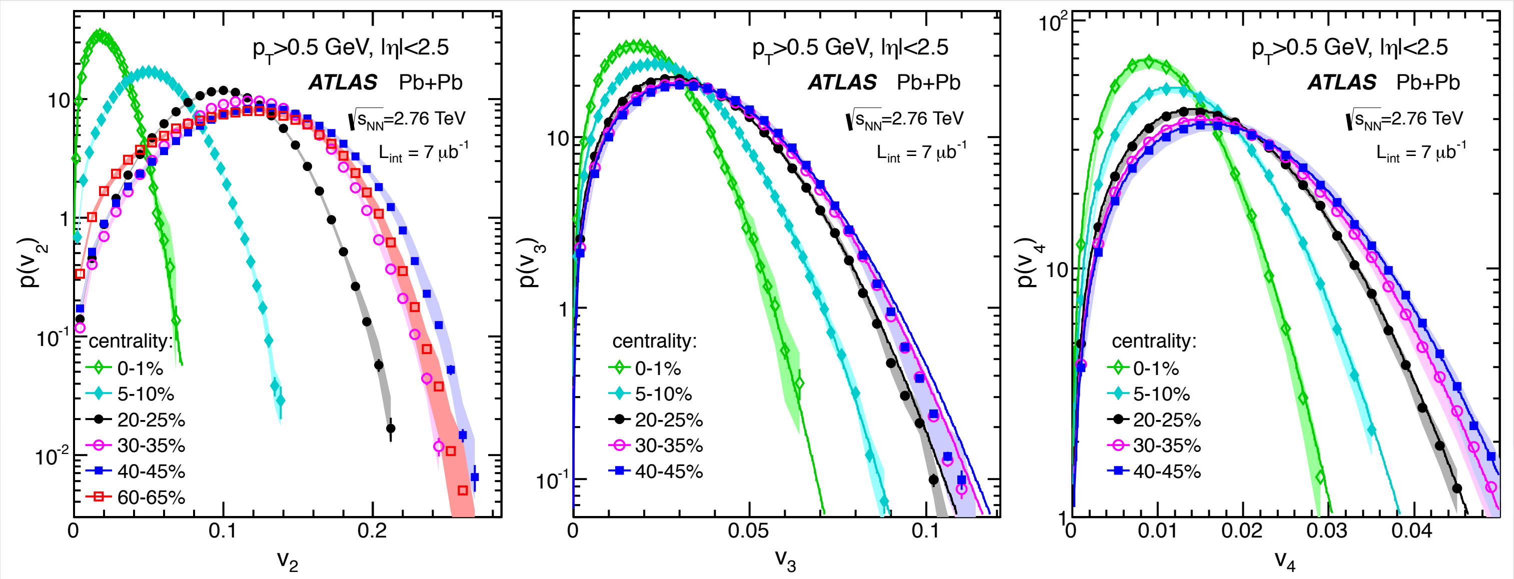


- **Higher order Fourier coefficients**
  - **v_n coefficients rise and fall with centrality.**
  - **v_n coefficients rise and fall with p_T.**
  - **v_n coefficients are ~boost invariant.**

Event by Event Fluctuations



Event by event analysis of flow parameters → Detailed description of bulk dynamics



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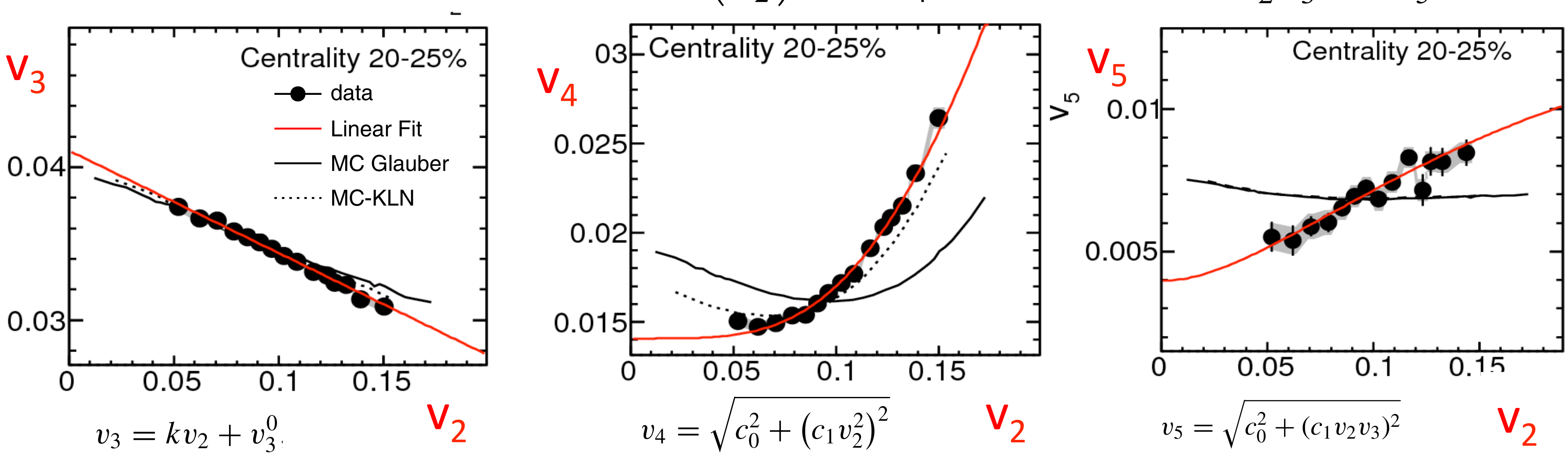
Correlation of Flow Harmonics

PRC 92 (2015) 034903

- Lower flow harmonics arise primarily from ellipticity (ε_2) and triangularity (ε_3)
- Measure how much of higher orders arise proportionally from lower order ε
- Detailed measurement shows models still need work

$$\left(\varepsilon_2\right)^2 \rightarrow v_4 \qquad \varepsilon_2\varepsilon_3 \rightarrow v_5$$



$v_3 = kv_2 + v_3^0$ $\quad v_4 = \sqrt{c_0^2 + \left(c_1 v_2^2\right)^2}$ $\quad v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$

Bulk Observables Story

- Here too many detailed observables not shown
  - Identified particle flow
  - Event plane correlations
  - Long range vs short range correlations
- Hydrodynamics are important part of but not the whole story – models are necessary and still are not consistently successful

State of Heavy Ion Data

- Seem to have a strongly coupled QGP in AA collisions
- Many measurements of jet modification and collective properties (not to mention quarkonia, etc.)
- Theory is still catching up
  - Progress but fully consistent model of suppression still doesn't exist
  - Hydro calculations have improved, but ambiguities in initial conditions and implementation remain
- Room for improvement in measurements
  - Better centrality, better reconstruction, new measurements etc
  - New data is coming
- Where else can we 'push' the physics forward?

Semi Heavy Ion Collisions

- Traditional Heavy Ion Playbook
  - AA: Create QGP
  - pp: Establish baseline to contrast with AA observables
  - pA: Control experiment that isolates initial state physics
- pA (or dA) has its own interesting physics – ‘cold nuclear matter’
  - Low-x physics: shadowing, saturation, etc
  - Nuclear PDFs
  - Cronin effect
- Measured at RHIC with d+Au in 2003 and 2008
- Measured at LHC with p+Pb in 2013
- Some surprises …

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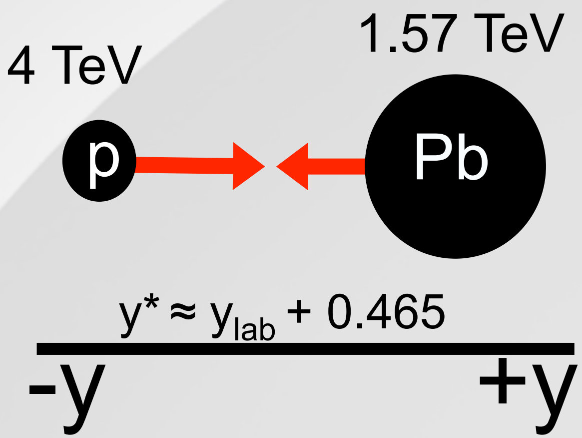
PLB 748 (2015) 392-413

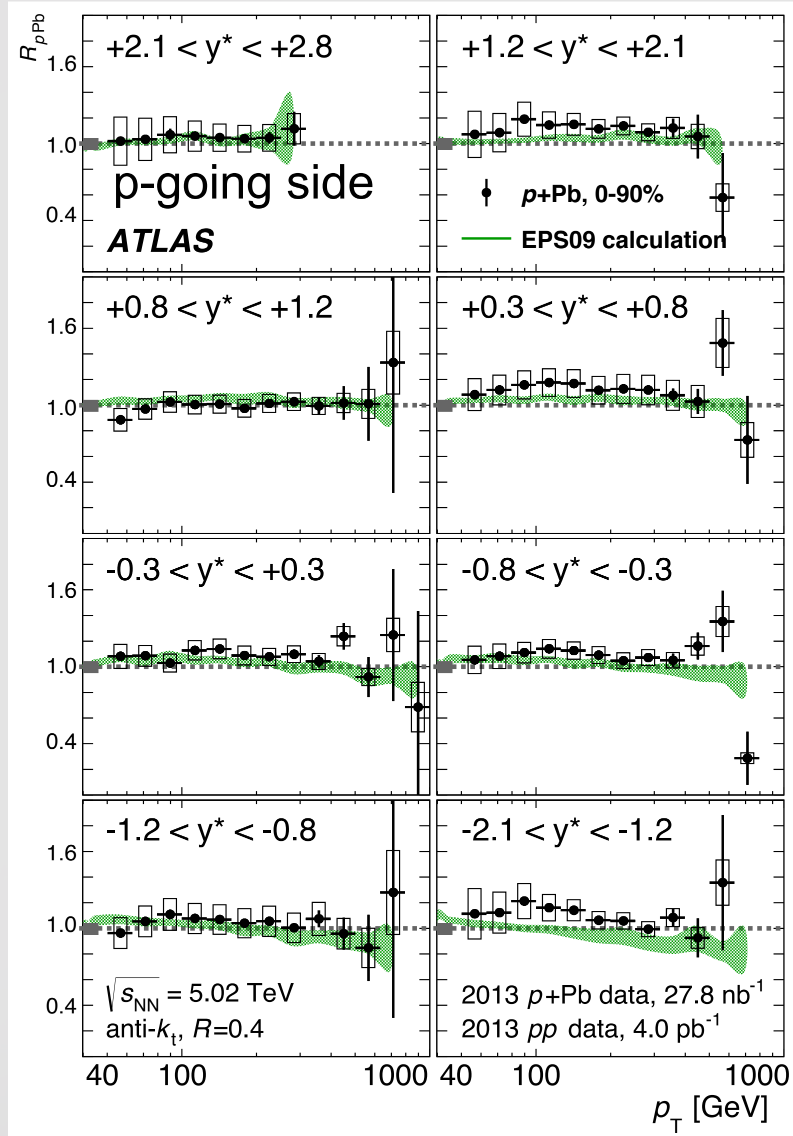
Jets in p+Pb Collisions



- Nuclear modification in p+Pb

- Overall jet production in p+Pb **scales as expected compared to p+p**
  - R_{pA} close to unity
  - Compared to pQCD calculation with **n**PDF

- Control for Pb+Pb
- Moving towards nPDF studies



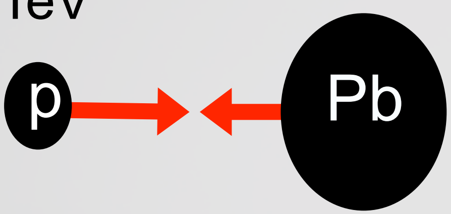
Pb-going side

PRC 92 (2015) 044915

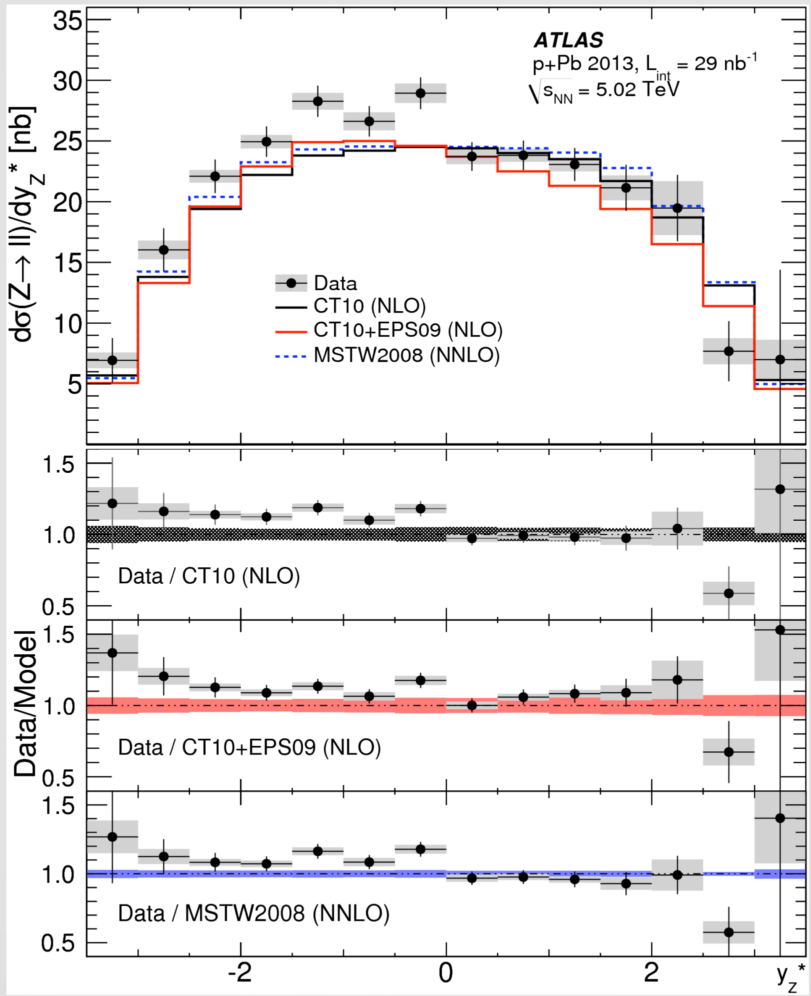
Studying nPDF with EW Bosons

4 TeV

1.57 TeV



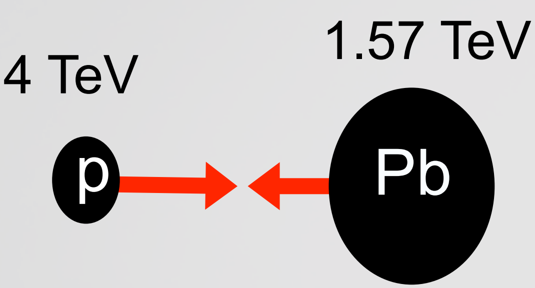
Rapidity differential Z boson cross section



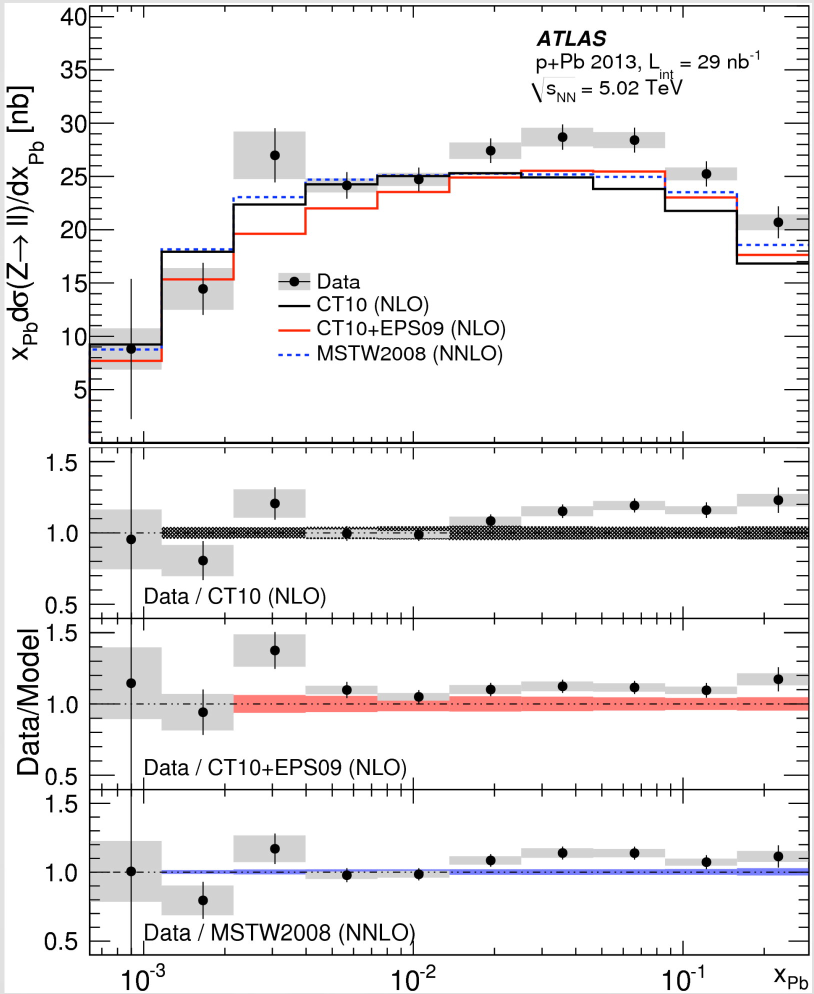
- Asymmetric in y
- Shape matched only with inclusion of nuclear PDF modification
- (Models underestimate total cross-section)

PRC 92 (2015) 044915

Studying nPDF with EW Bosons



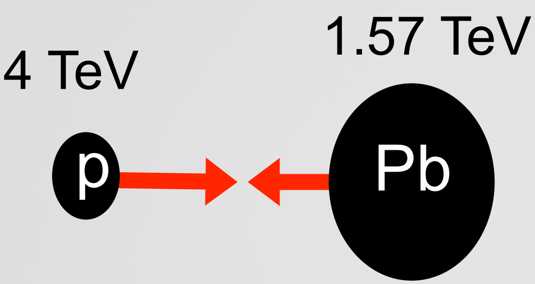
x differential Z boson cross section



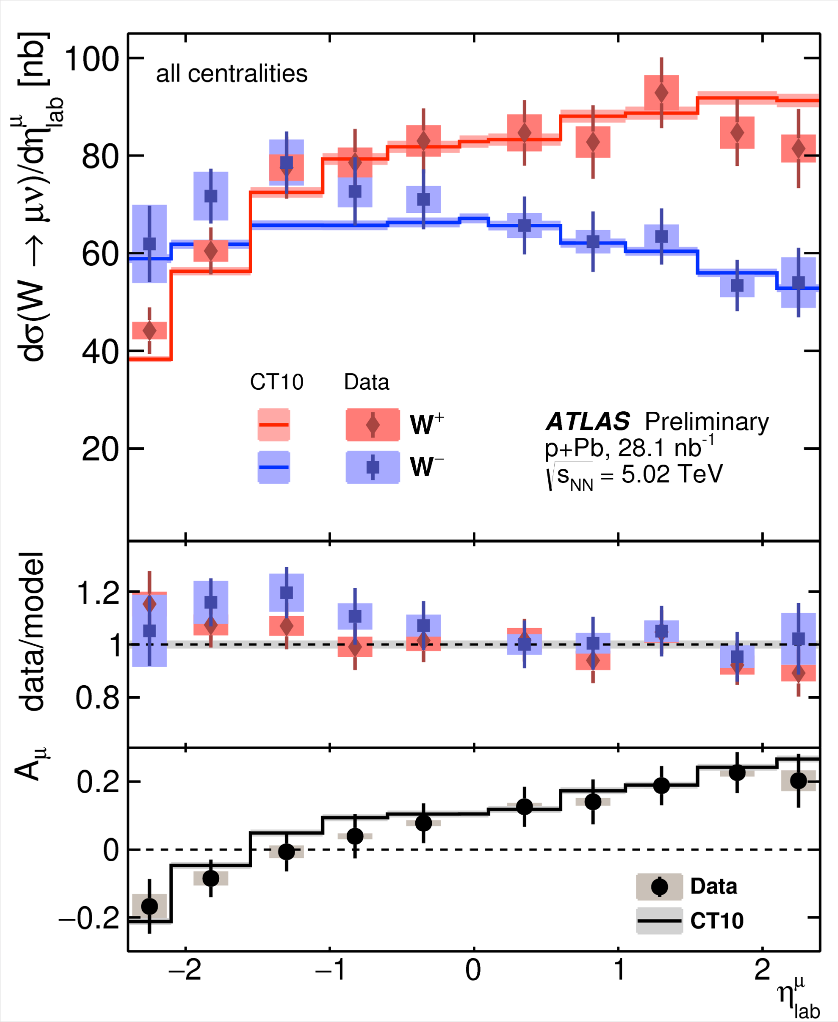
- Asymmetric in y
- Shape matched only with inclusion of nuclear PDF modification
- (Models underestimate total cross-section)
- x to <10^{-3}

https://cdsweb.cern.ch/record/2055677

Studying nPDF with EW Bosons



Lepton η differential W boson cross section

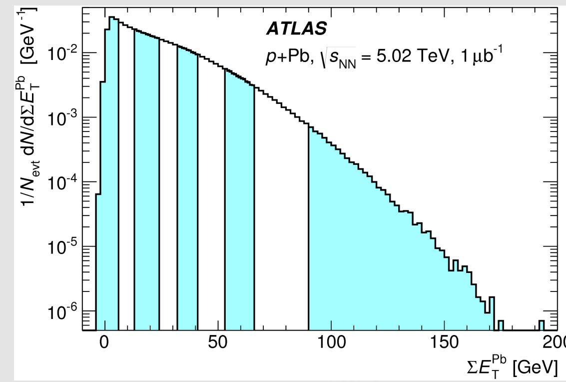


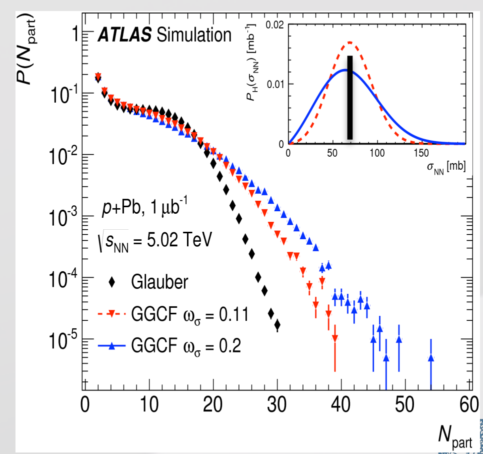
Similar trend as observed in Z bosons

Eur. Phys. J. C (2016) 76:199

Unraveling centrality & nPDF effects

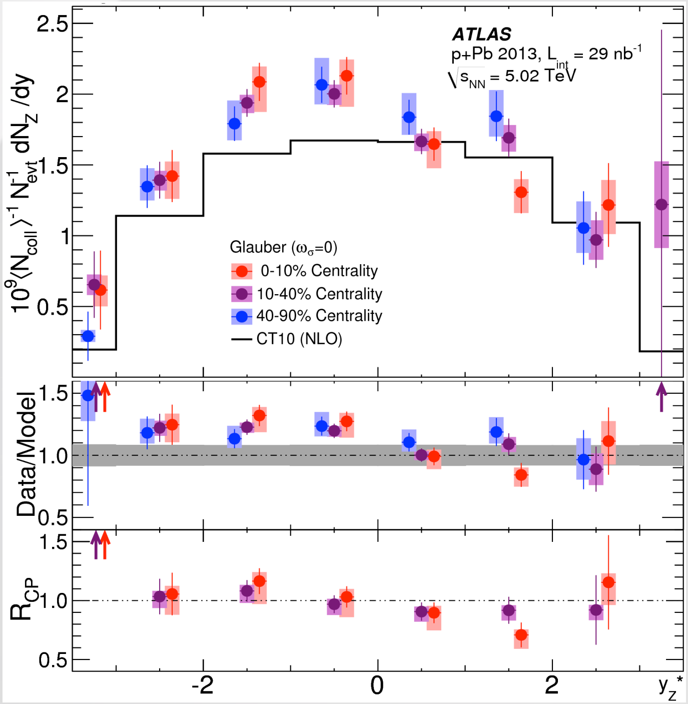
- Centrality is *difficult* in pPb collisions
  - Less overall activity and asymmetric system
  - Small **physics** effects that get averaged over in PbPb may become significant
- 'Centrality bias' - hard processes are correlated with larger underlying event
- Glauber model may not be the full story: 'Gribov' color fluctuations may be at play which allow the nucleon-nucleon cross-section to fluctuate



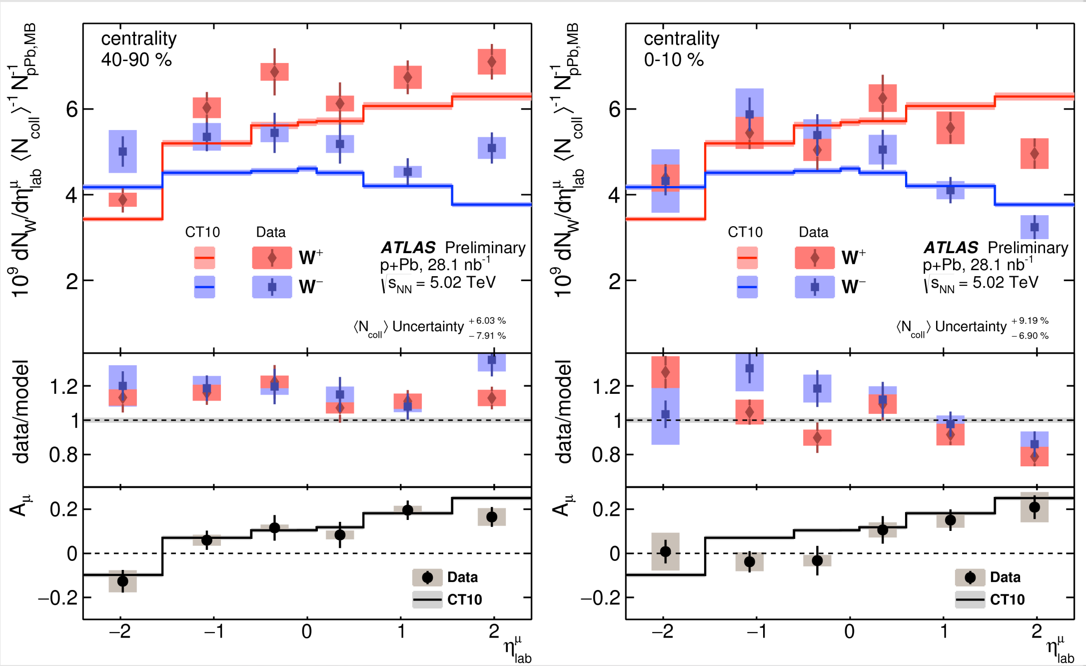


Unraveling centrality & nPDF effects

Z boson y distributions

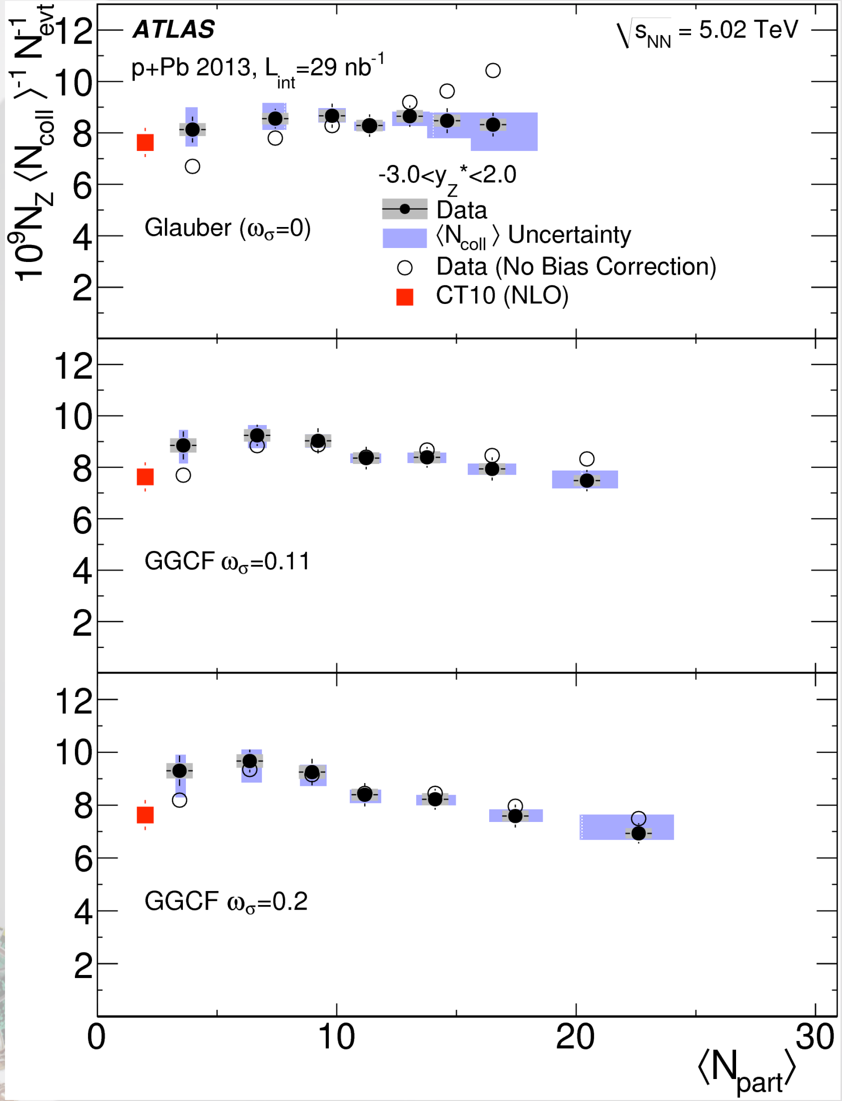


W boson η distributions

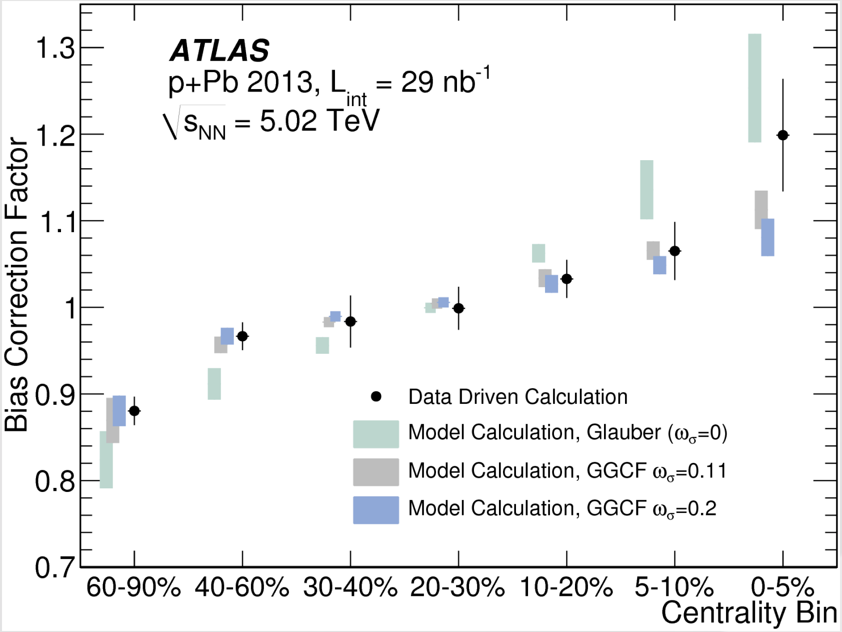


Modification of nPDF seen in both Z and W bosons looks centrality dependent

Unraveling centrality & nPDF effects



- 'Raw' Z boson yield grows with centrality
- Centrality bias ***or*** Gribov color fluctuations can 'restore' binary scaling



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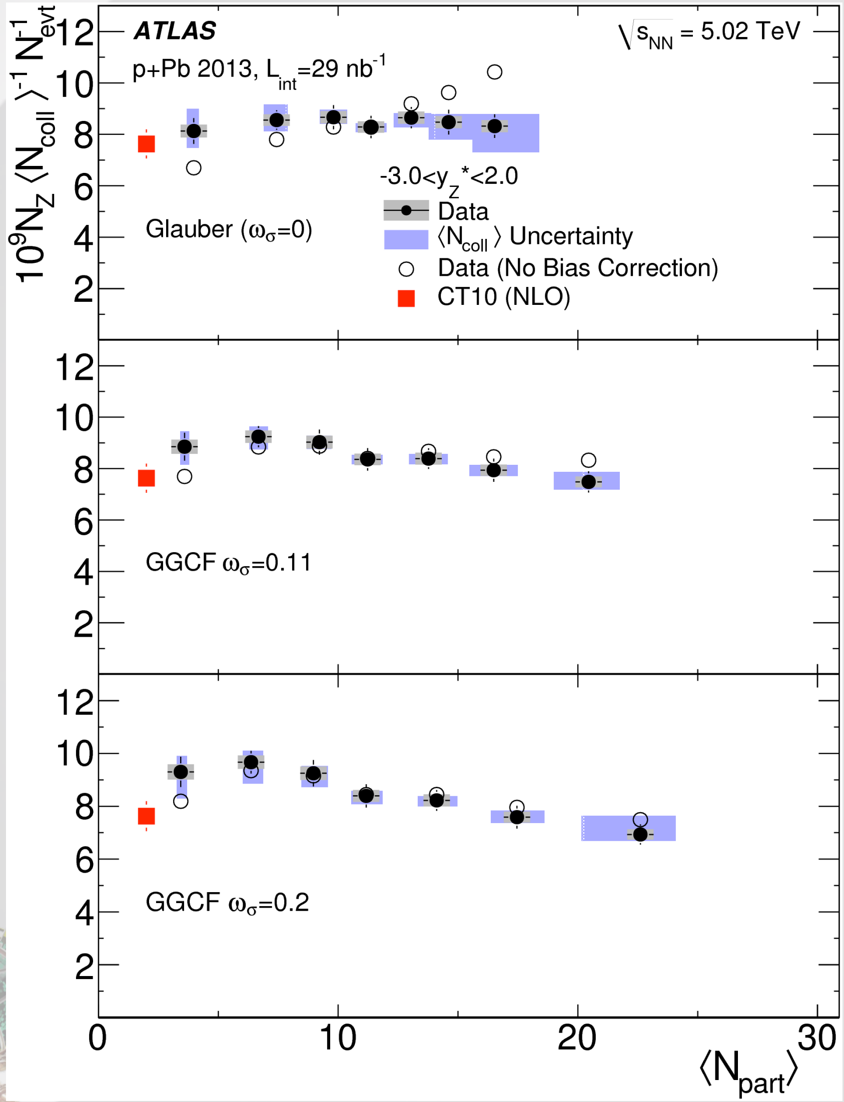
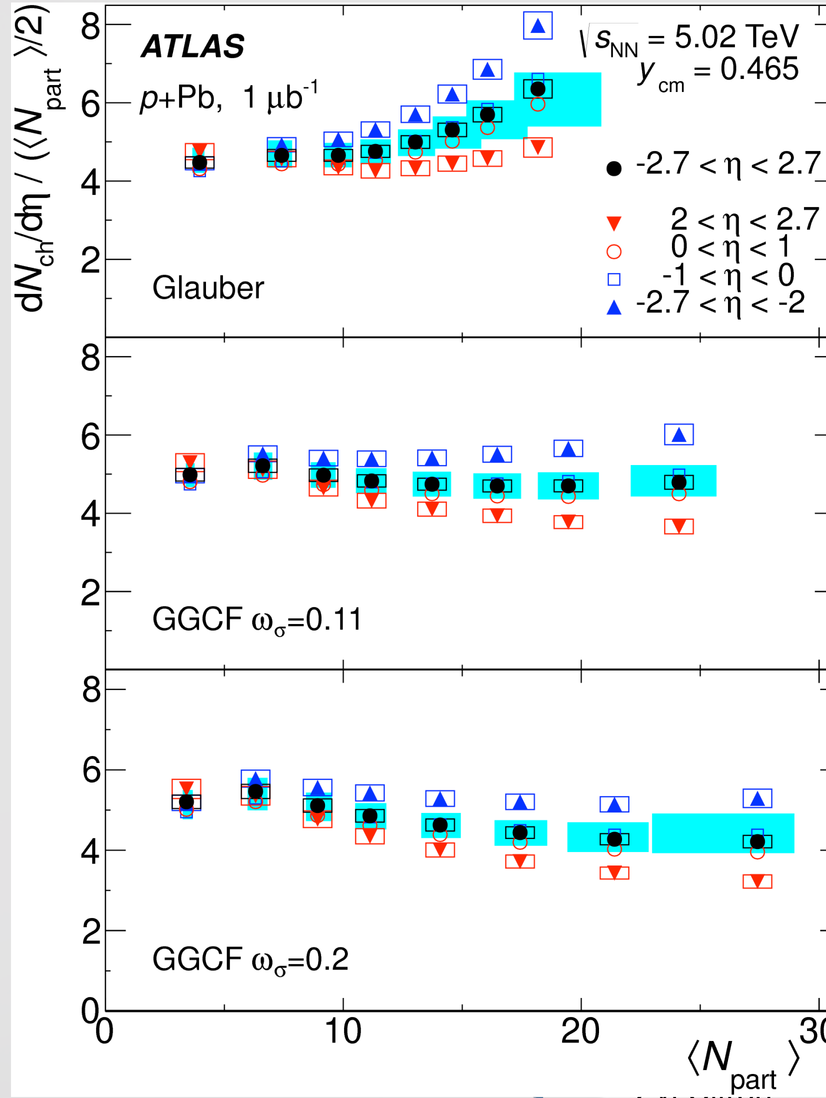
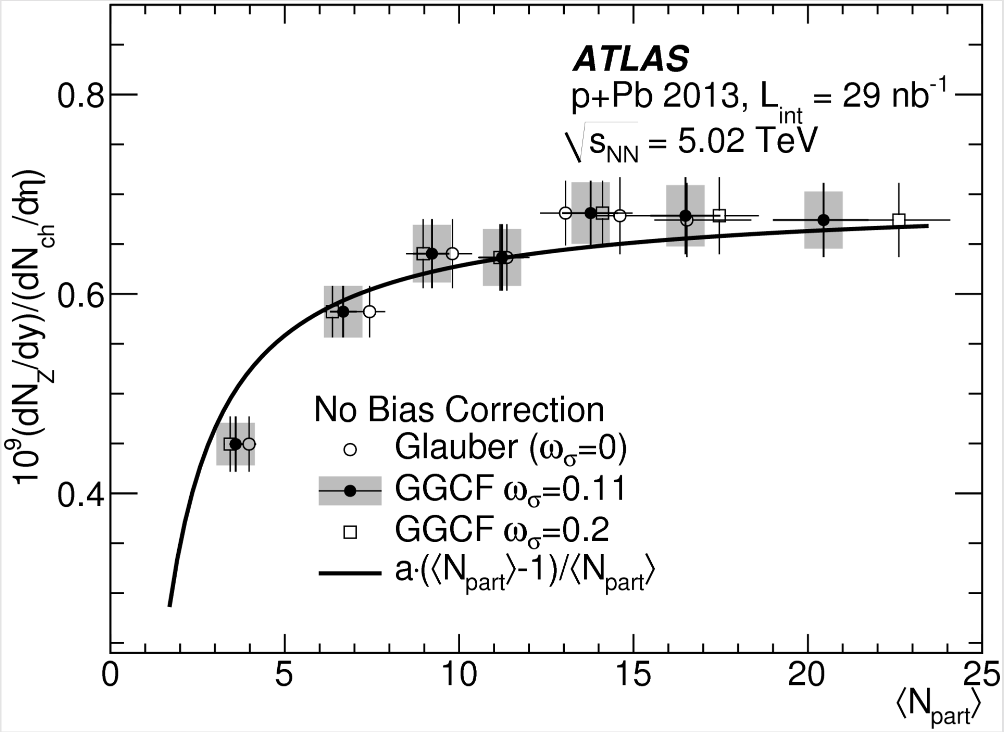
Unraveling centrality & nPDF effects



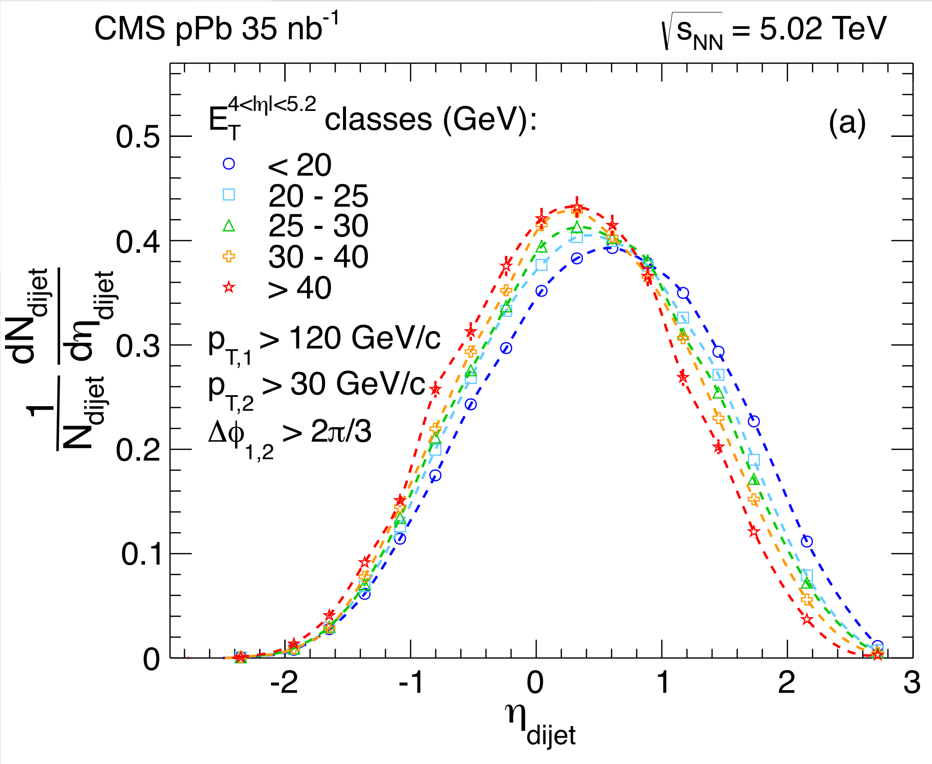


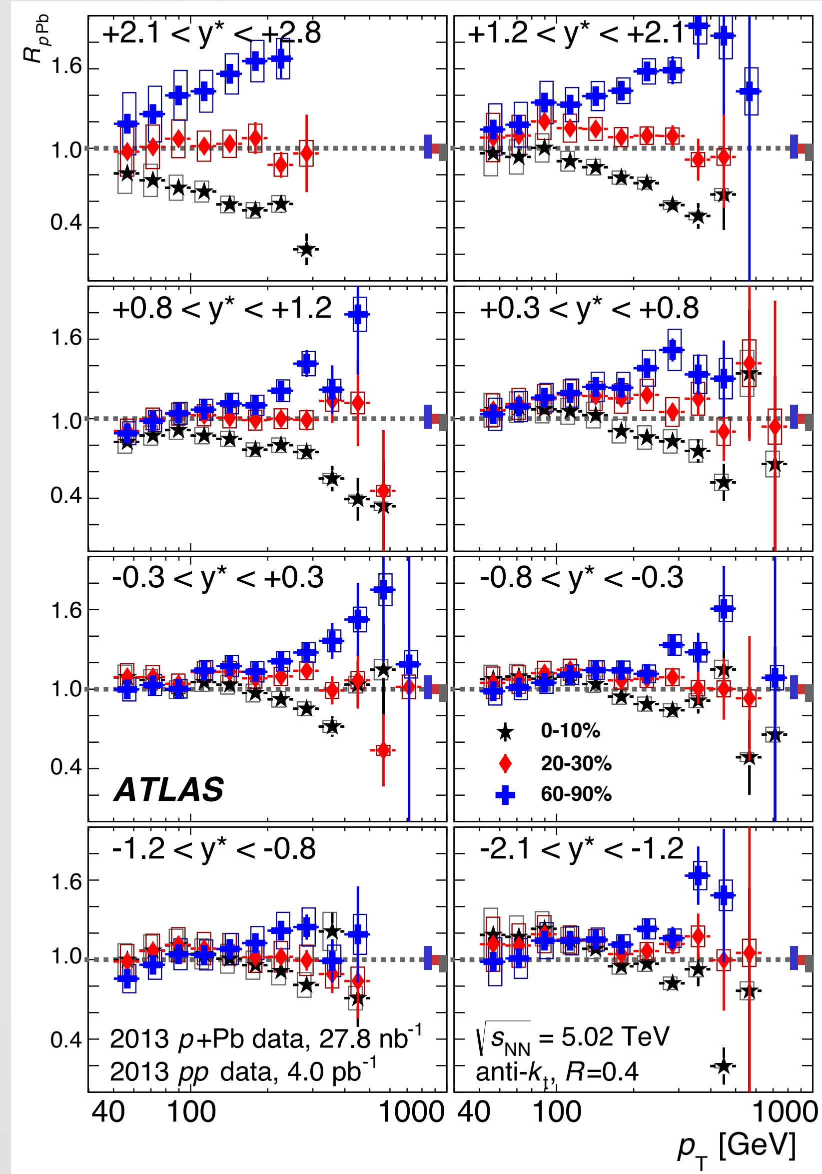
Unraveling centrality & nPDF effects

- Striking similarity between Z boson and charged particle yield
- Suggests centrality bias (inapplicable to charged particle yield) may not be the culprit
- But …



Jet Centrality Dependence



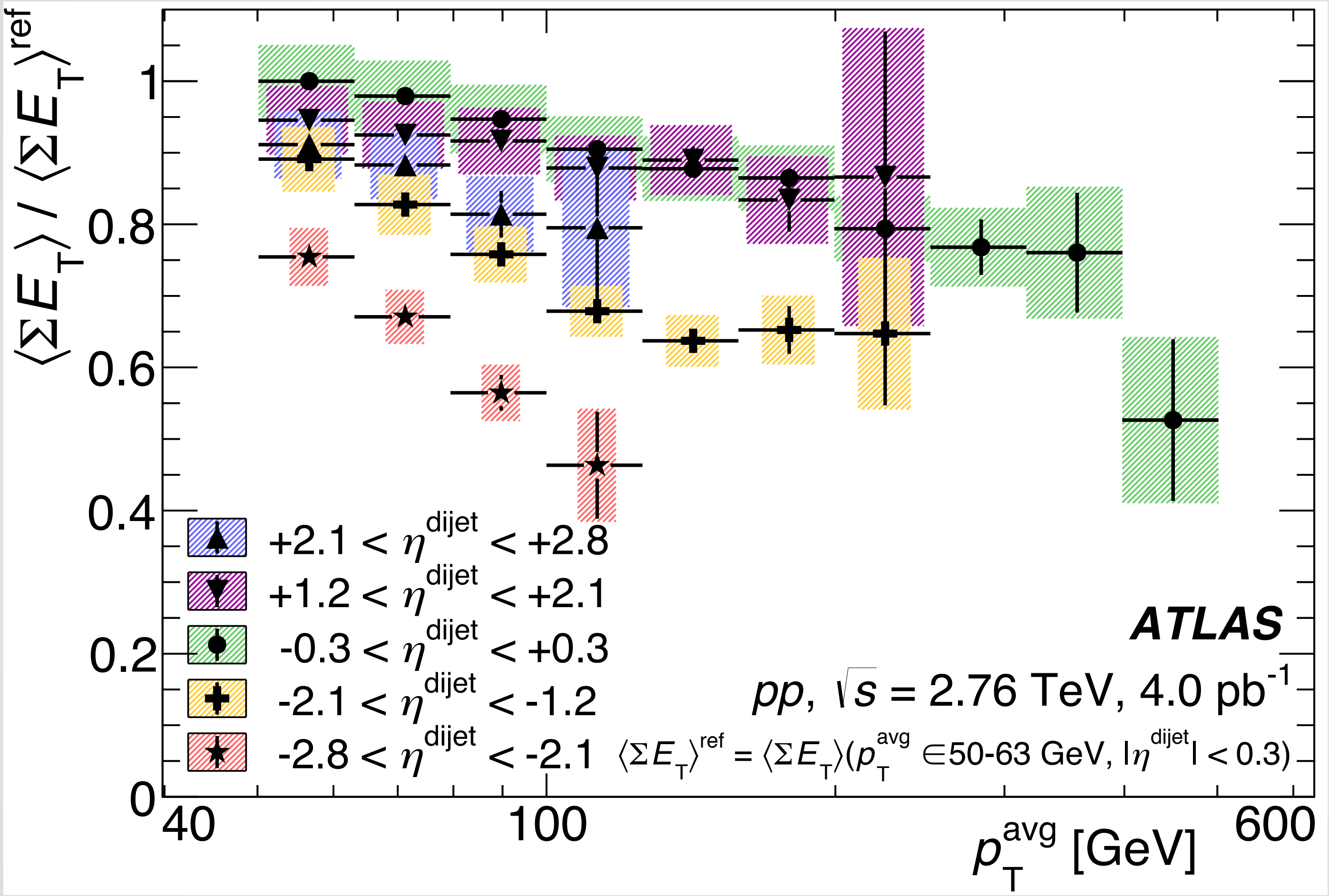


'Shift' of η_{dijet} depends on centrality
Somewhat more than nPDF can explain

Nuclear modification factor at high momentum splits in centrality bins.
… looks like some type of 'centrality bias'

PLB 756 (2016) 10-28

‘Centrality’ Jet Dependence



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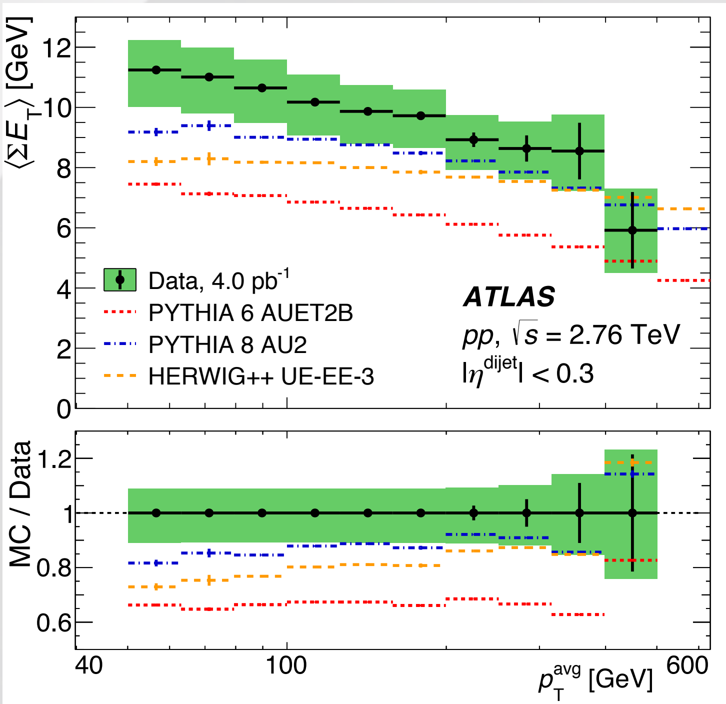
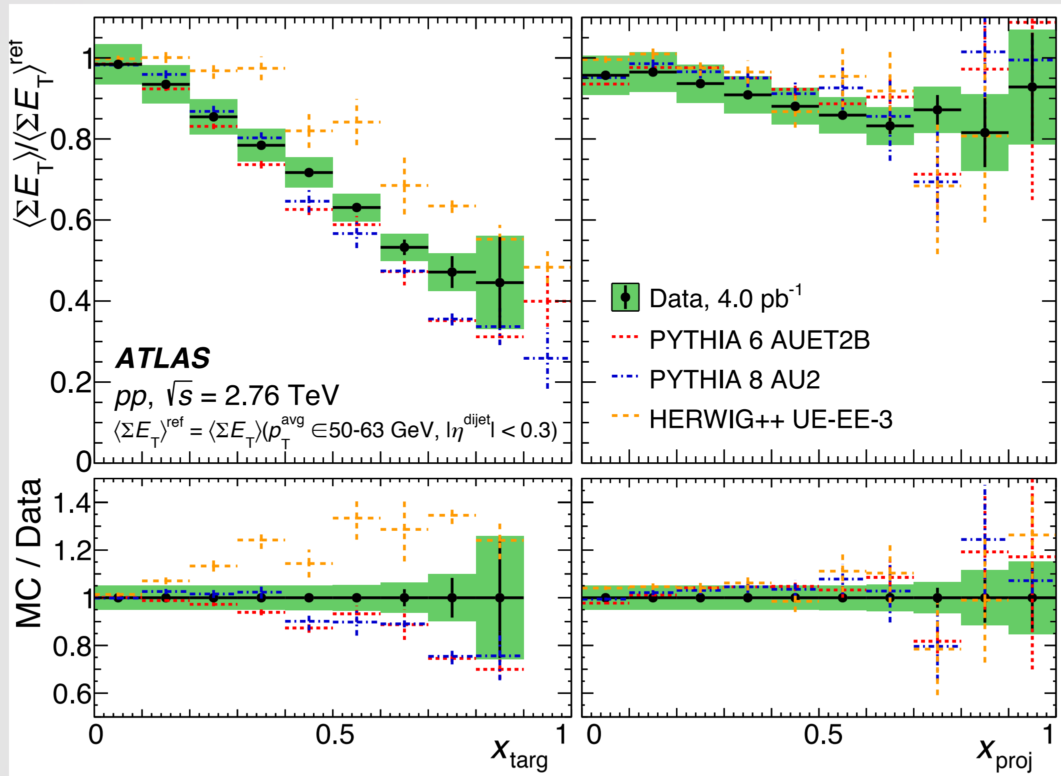
'Centrality' Jet Dependence





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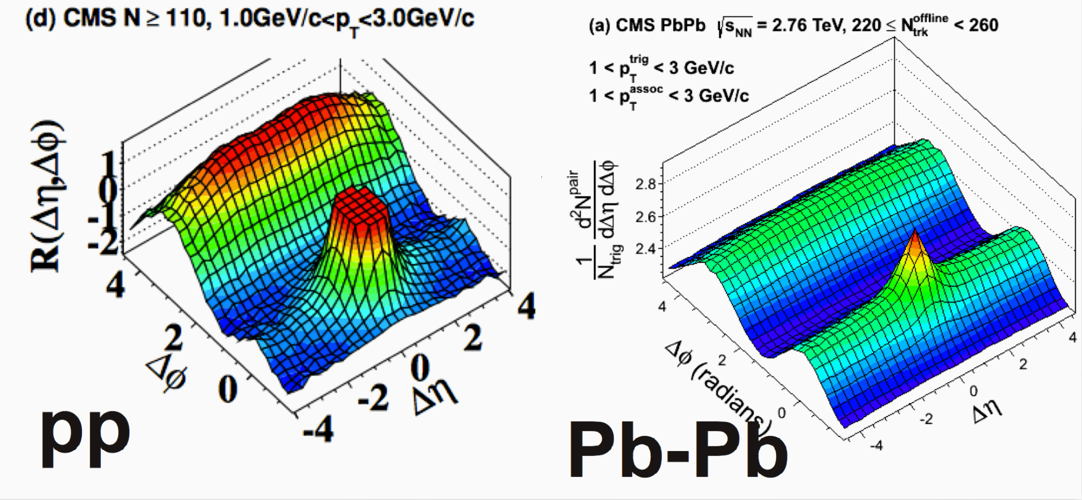
A Step Back to p+p Collisions

- Interesting physics in the hard probes of p+Pb
- Before the next surprise in p+Pb, let's consider high multiplicity p+p …

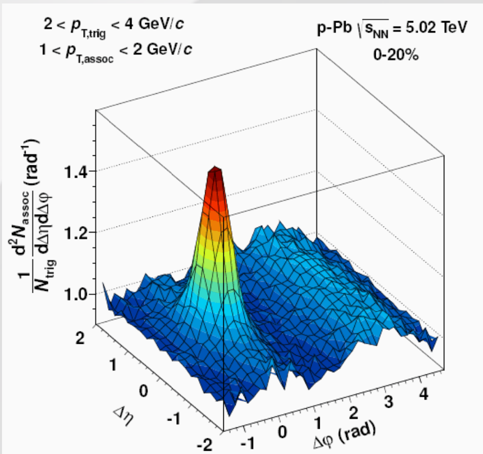
A Step Back to p+p Collisions

- Interesting physics in the hard probes of p+Pb
- Before the next surprise in p+Pb, let's consider high multiplicity p+p …

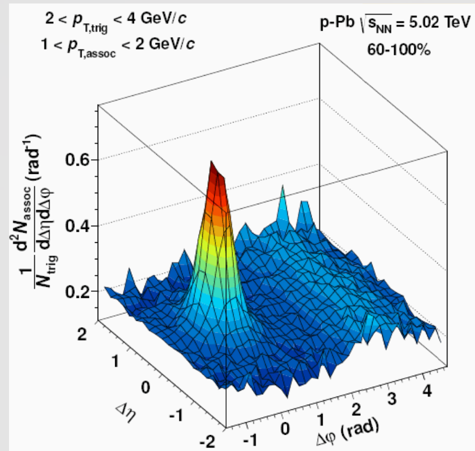
Select highest multiplicity p+p collisions
Long range y correlation observed
Similar to structure observed in HI which corresponds to collective flow



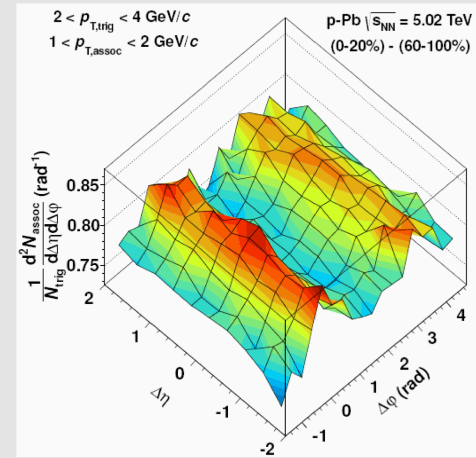
‘Double Ridge’ in p+Pb Collisions



High multiplicity



Low multiplicity



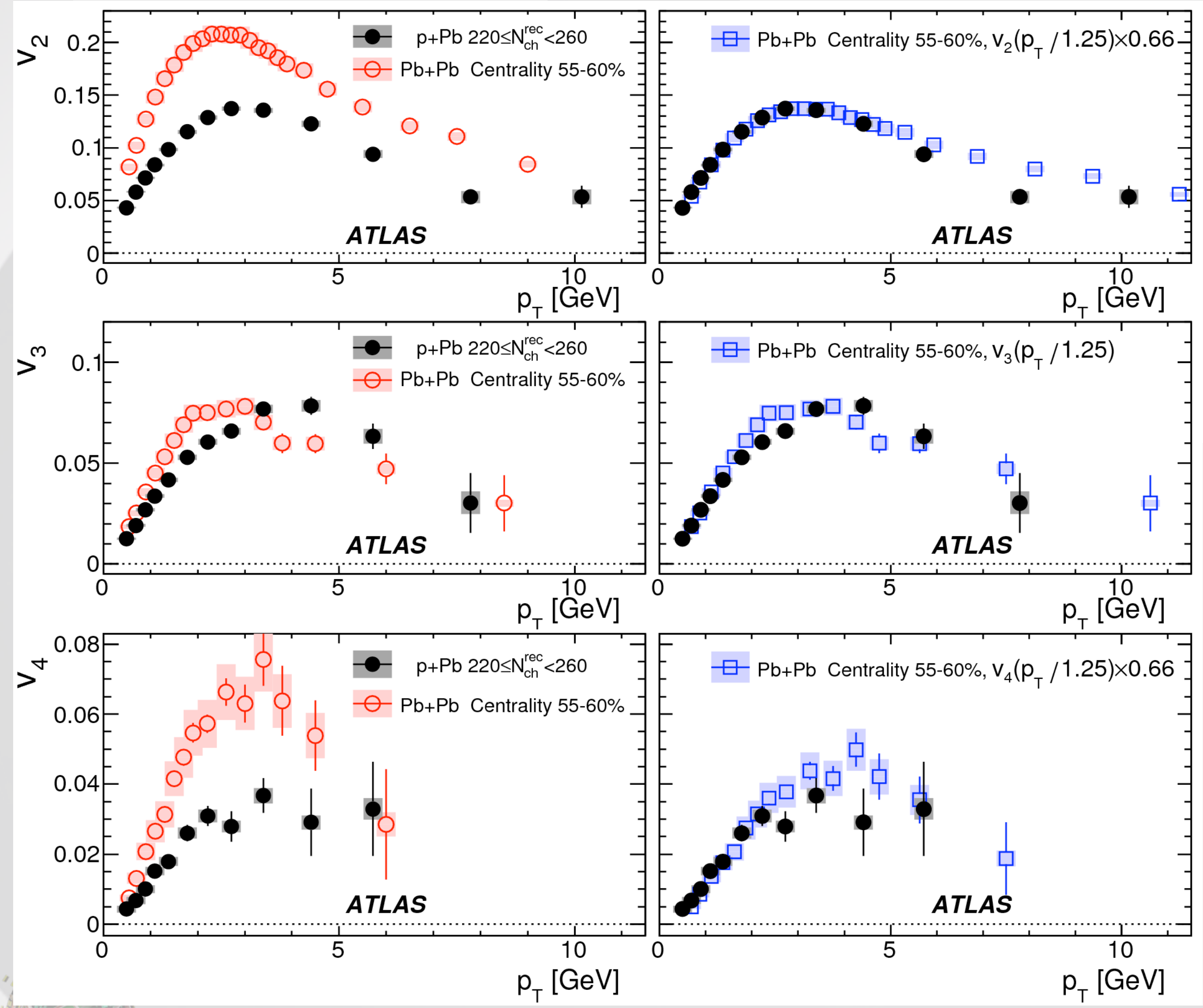
Double Ridge indicates …

Select high multiplicity p+Pb events
Look at two particle correlation

Subtract off the uninteresting part of the correlation as found in low multiplicity collisions

Phys. Rev. C 90, 044906

'Double Ridge' in p+Pb Collisions



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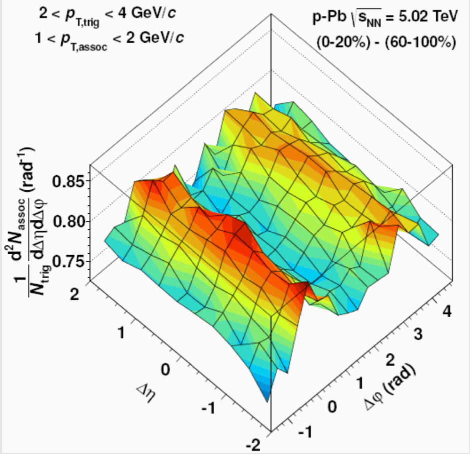


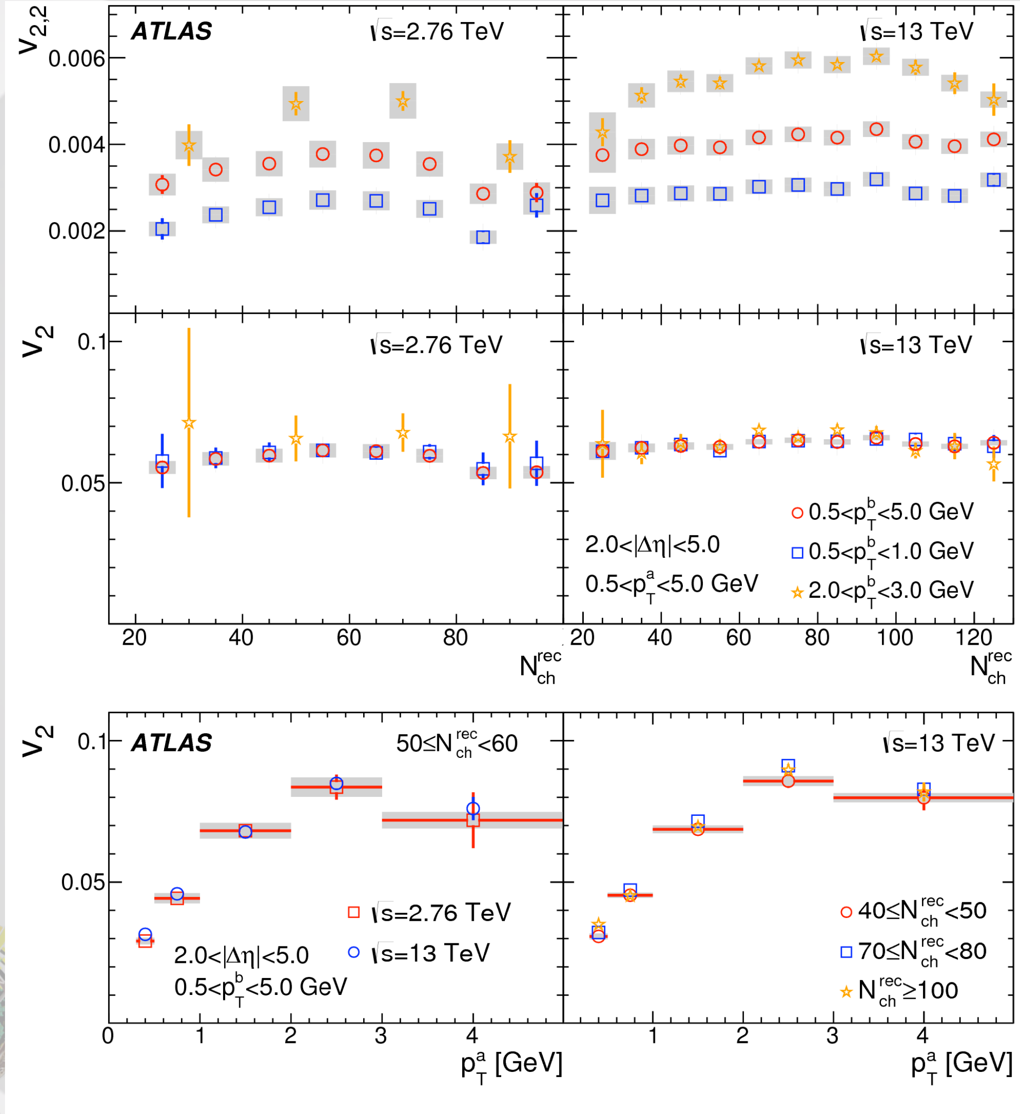
Double Ridge indicates …
Flow?

Similar magnitude to Pb+Pb at about 1/6 density

p_T scaled to match $\langle p_T \rangle$

PRL 116 (2016) 172301

Liquid Drops Everywhere?



Once we know to look for it:

- Comprehensive analysis in pp collisions at two different energies
- Effect seems to persist to collisions with fewer than 30 tracks!

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State of the Data

Heavy Ion Collsions

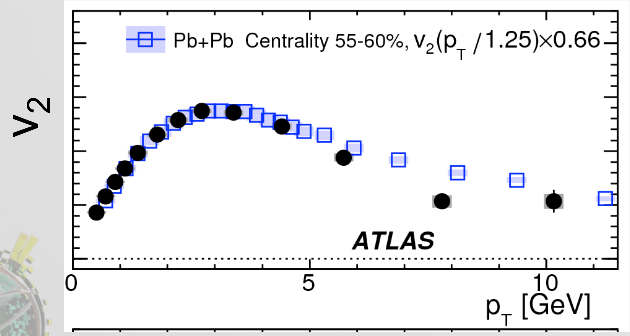
- The hot dense medium in HI collisions suppresses color sensitive jets and attenuates their momentum
- EW bosons do not interact with the QCD medium
- The medium looks like a liquid

Semi Heavy Ion Collisions

- pQCD is a reasonable start
  - Learn about initial state modification, nPDFs, etc.
- Unexpected centrality phenonmena
  - Maybe gets at fundamental proton properties
- Also look like a liquid(!) and so do pp collisions (!!)

State of the Data

- 'Simple' story of a color opaque strongly coupled liquid, i.e. QGP!, uniquely in high energy AA collisions doesn't seem to be the case
- Do liquid properties have nothing to do with QGP/color opacity?
- Might we have reached small system QGP?



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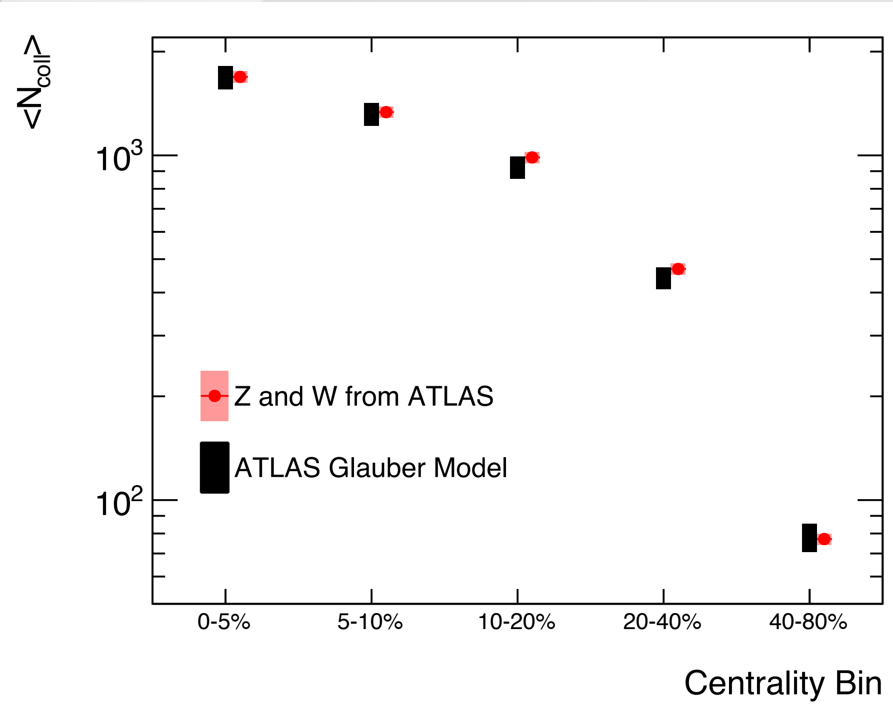
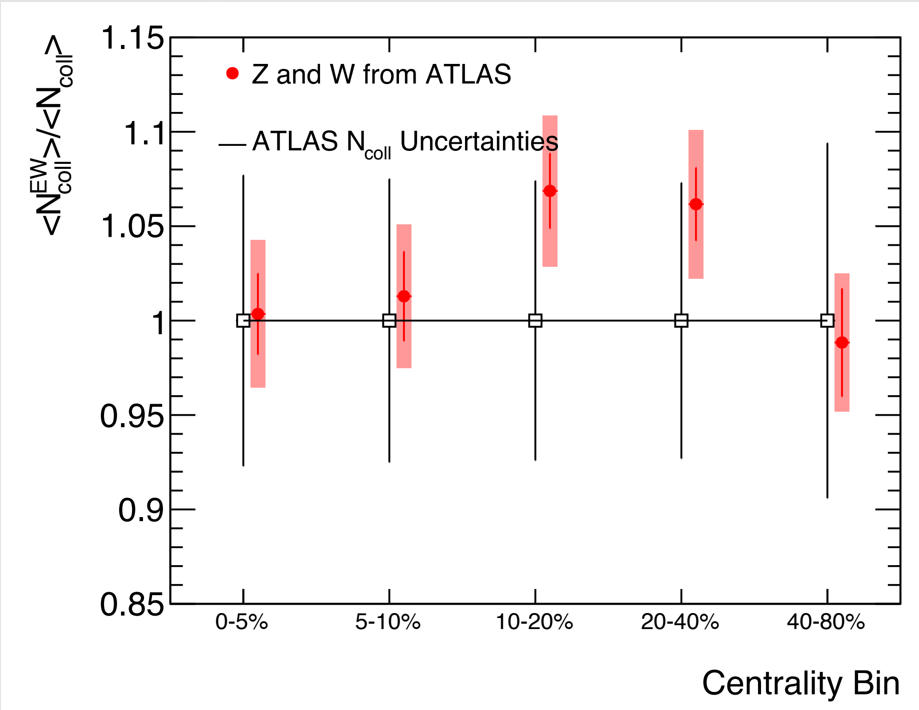
Where Can We Go From Here?

- There is some collectivity in pA and pp collisions
- All the details are important! Must understand at least:
  - Most peripheral AA collisions
  - Multi-parton interactions
  - Fluctuations in proton 'size'
  - Underlying event everywhere
- Can we find (other?) signatures of QGP in small systems?

Additional Information

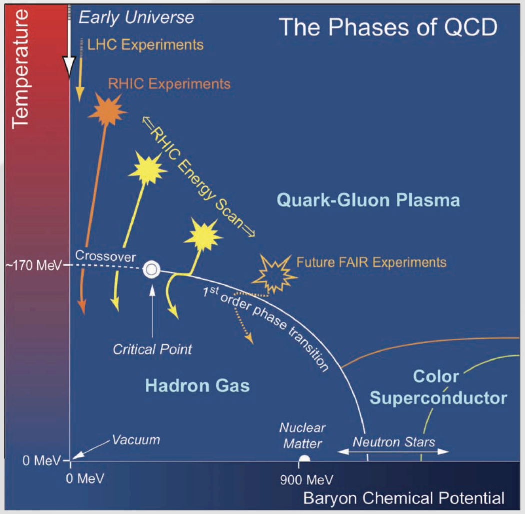
EW Bosons To Define Centrality (?)

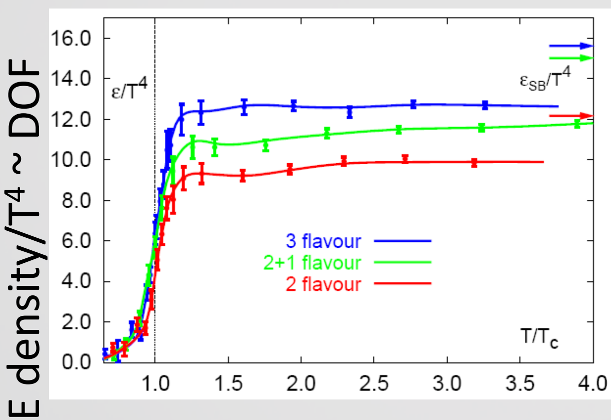


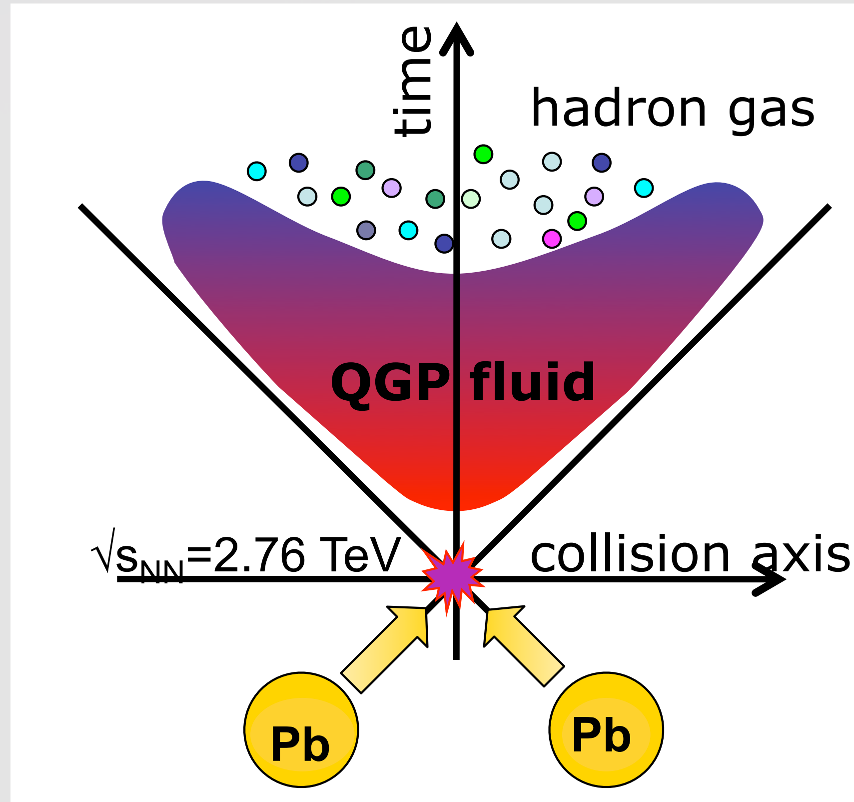


- Agreement with scaling measured
- Reverse our assumptions – assume scaling calculate geometric factor necessary for ‘perfect’ scaling
- **Derive geometric factors from EW bosons**
- Competitive uncertainties

Heavy Ion Collisions



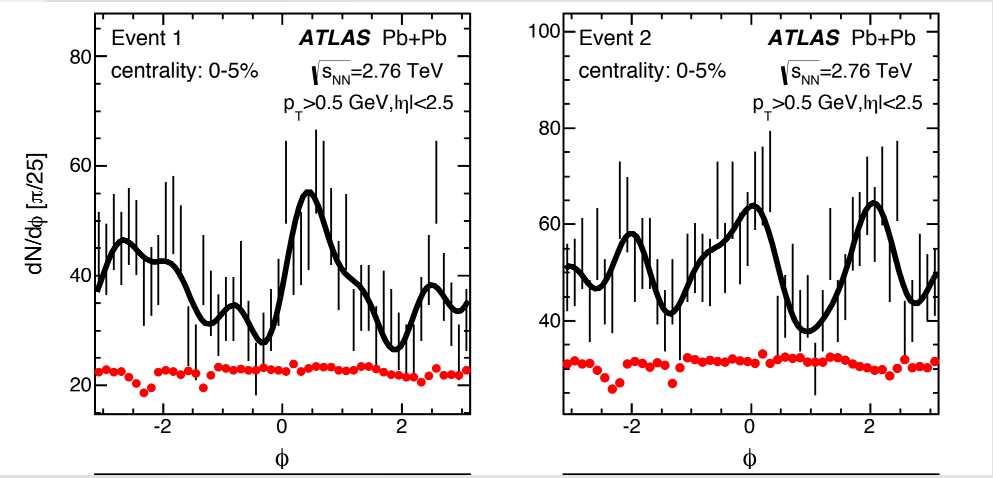




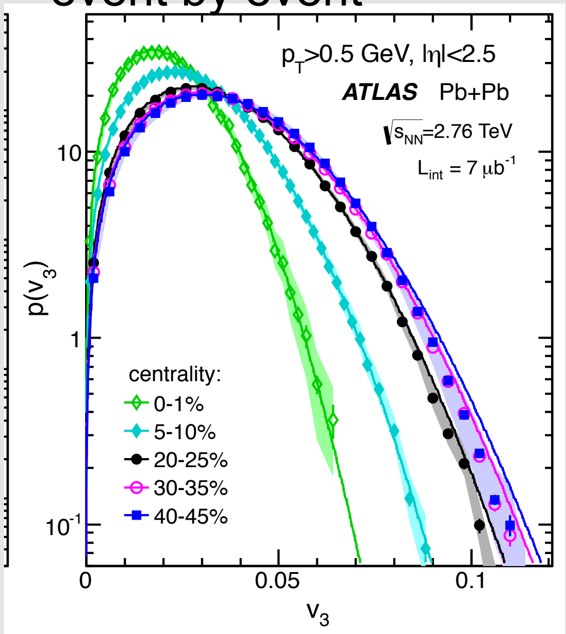
- Can we probe QCD dynamic properties, cross a phase transition?
- Time scale too short for external probes
- Rely on probes produced by the collision
- Reconstruct final state particles and work our way back

Event by Event Data Looks Like 'Ideal' Liquid

Sample event azimuthal distributions



Characterize shape event by event



Event be event fluctuations close to ideal hydro-dyanmic calculations