What have we learned about the Quark Gluon Plasma, using hard probes with the ATLAS Experiment at the LHC?

PETER STEINBERG, BROOKHAVEN NATIONAL LABORATORY
FOR **THE ATLAS COLLABORATION**

HARD PROBES 2013
3-8 NOVEMBER 2013,STELLENBOSCH, SOUTH AFRICA

...or, a "forward looking" view at the recent ATLAS data

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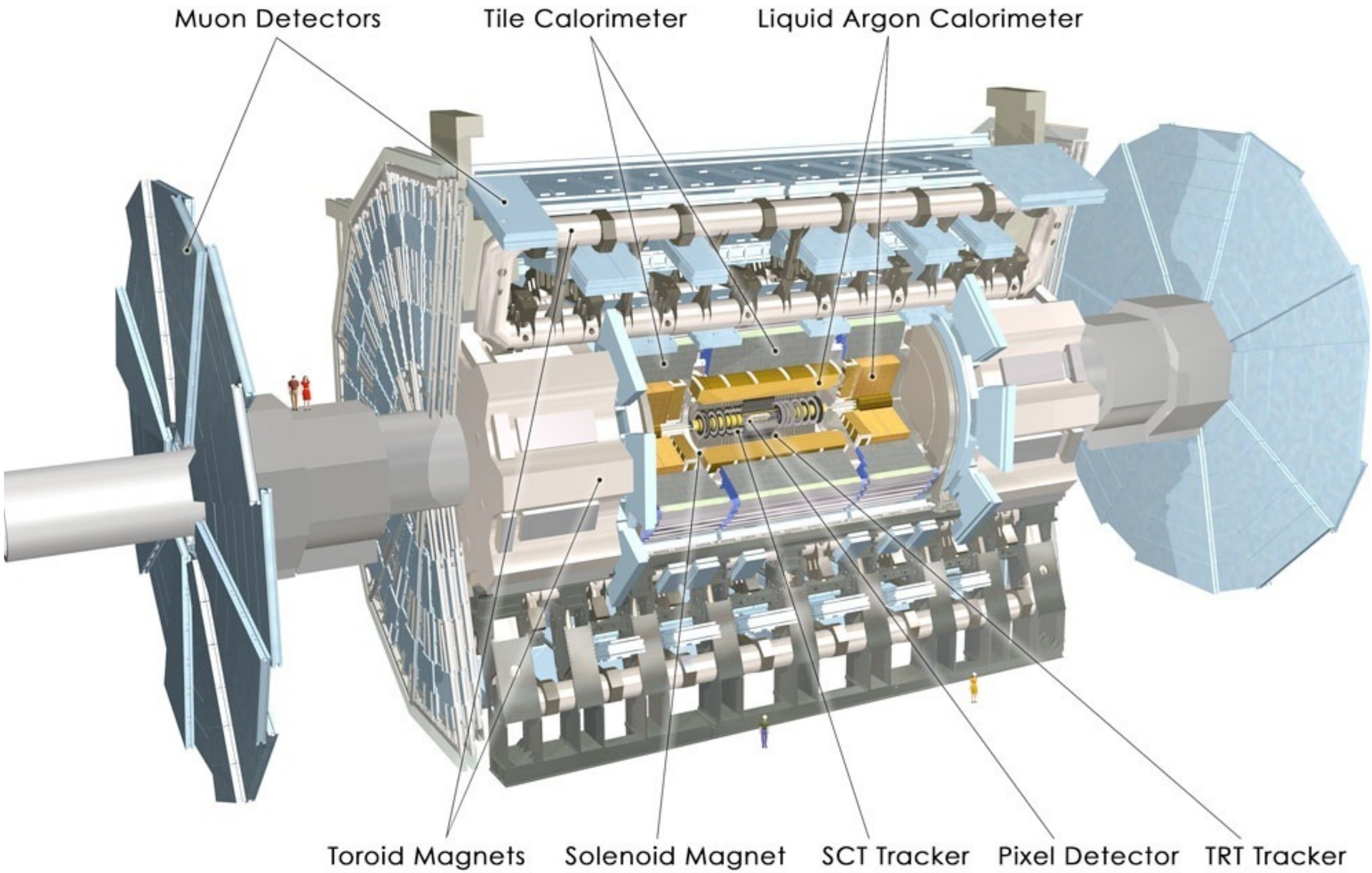
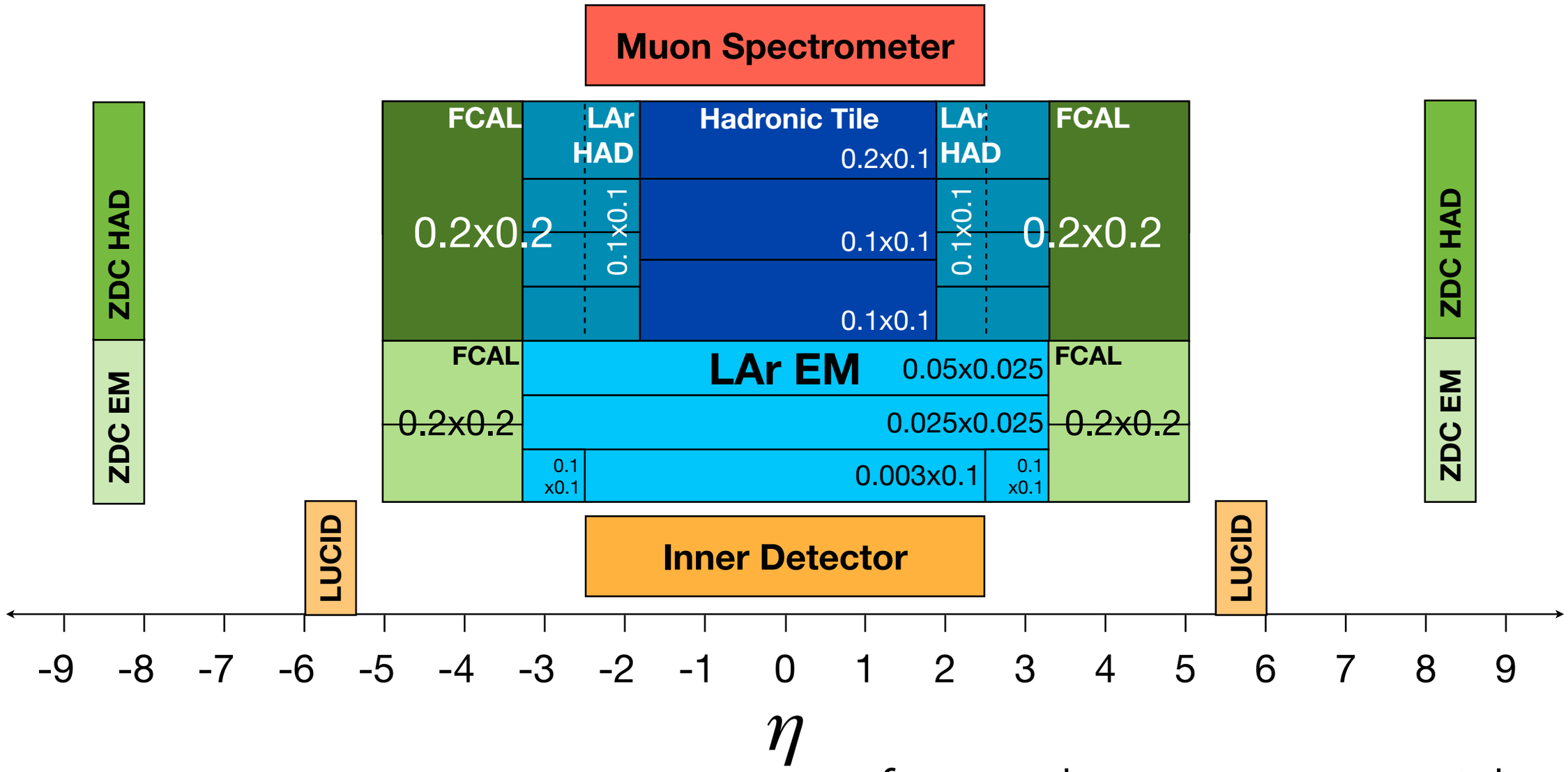
ATLAS detector systems



ATLAS acceptance



Tracking coverage out to $|\eta|<2.5$
Muon coverage out to $|\eta|<2.7$
Calorimetry out to $|\eta|<5$

forward coverage provides access to wide range in

$x_1 \sim (2p_T/\sqrt{s})e^{\eta}$

$x_2 \sim (2p_T/\sqrt{s})e^{-\eta}$

What have we learned from Pb+Pb & p+Pb?

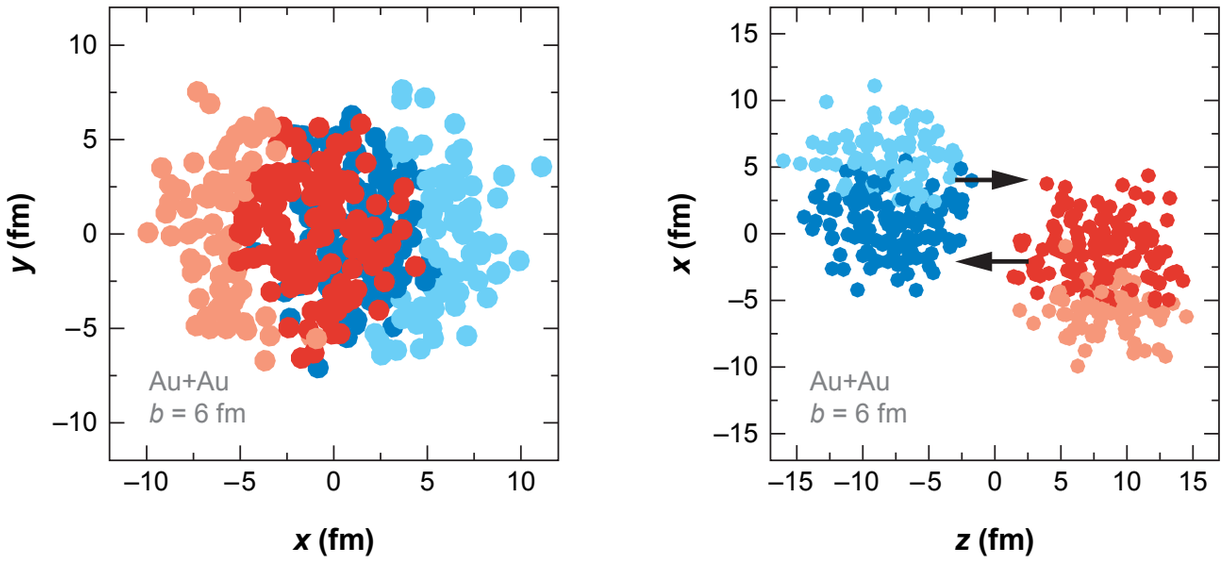
- Centrality
- Multiplicity
- Flow
- Bosons
- Jets

Soft sector provides measurements of bulk properties.

Hard probes provide access to initial state effects
(shadowing, initial E-loss) via Z/W/**γ**
and to final state effects via jet suppression

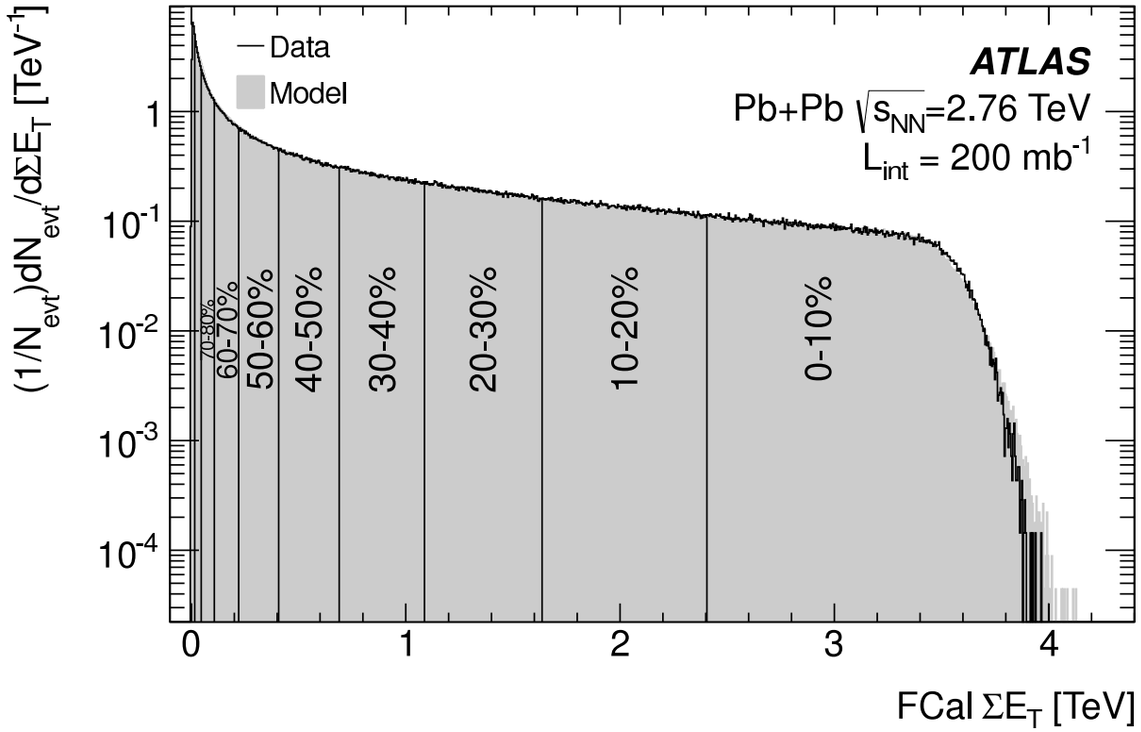
Centrality in Pb+Pb

M.L. Miller et al, Ann Rev. 57 (2007) 205



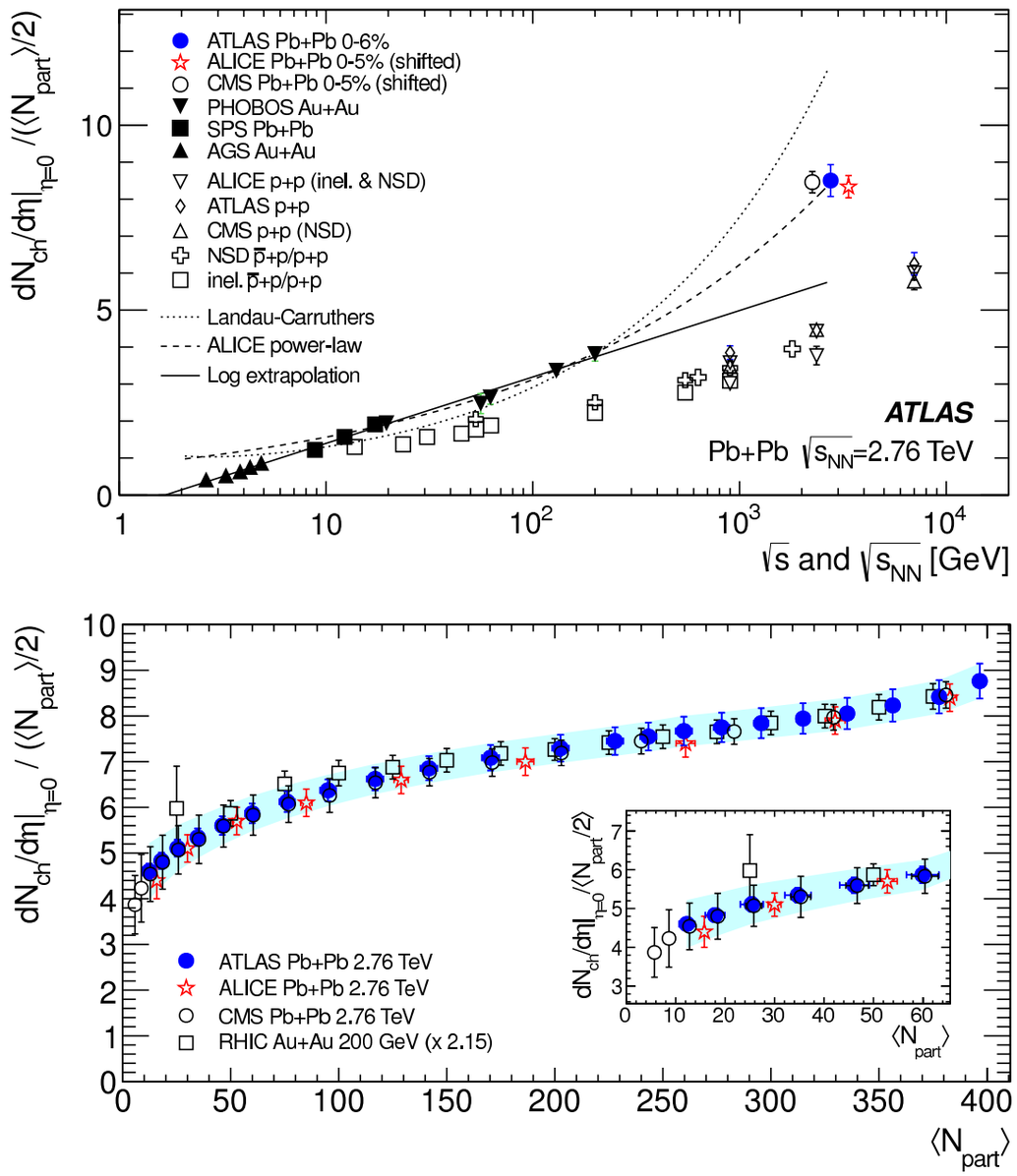
"Standard" Glauber modeling treats each nucleon as a "hard disk", with a single cross section determining interaction probability

ATLAS, Phys.Lett. B707 (2012) 330-348



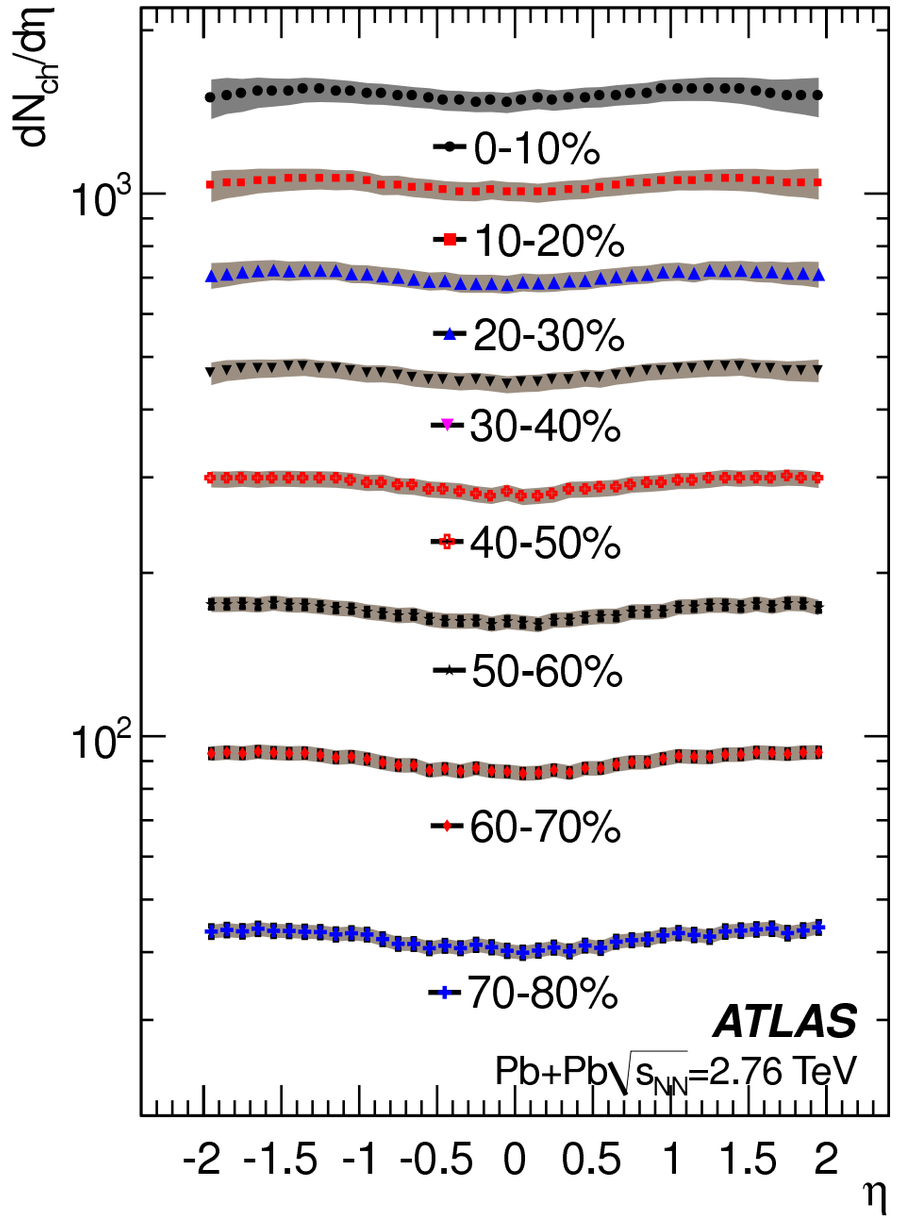
Geometry coupled with a simple particle production model (based on p+p data) provides a good description of forward transverse energy
98±2% efficiency for inelastic events

Soft Probes: Multiplicity in Pb+Pb



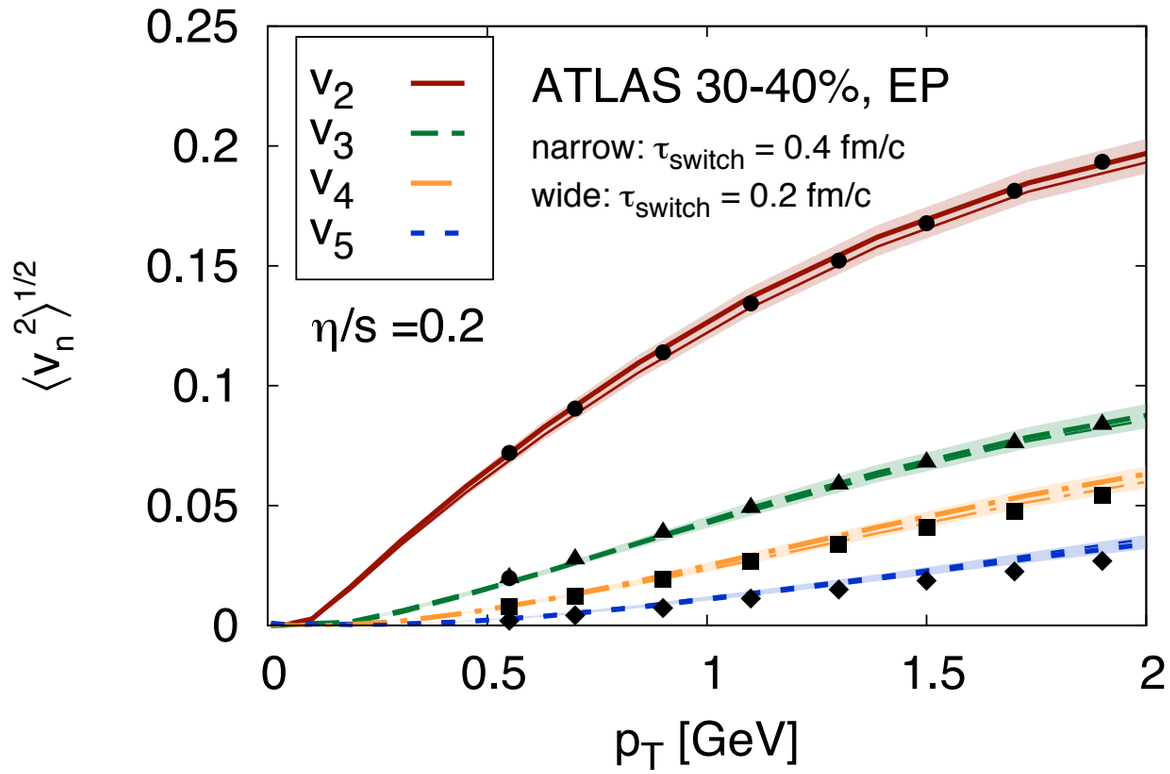
Factor of two rise in multiplicity, but essentially no change in centrality dependence

Phys.Lett. B710 (2012) 363-382



Only a small O(10%) change of dN/d**η** shape with centrality (Pb+Pb is a symmetric system)

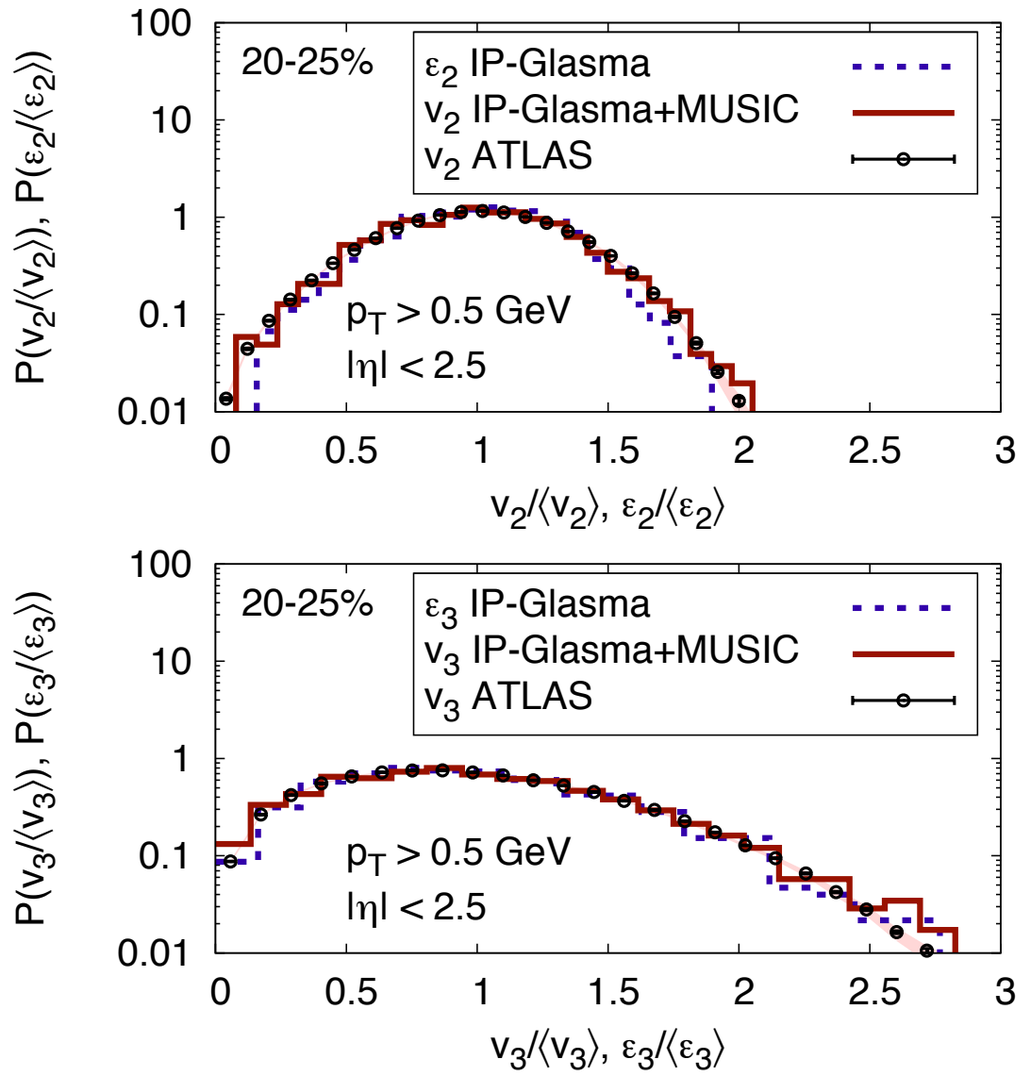
Soft Probes: Harmonic flow

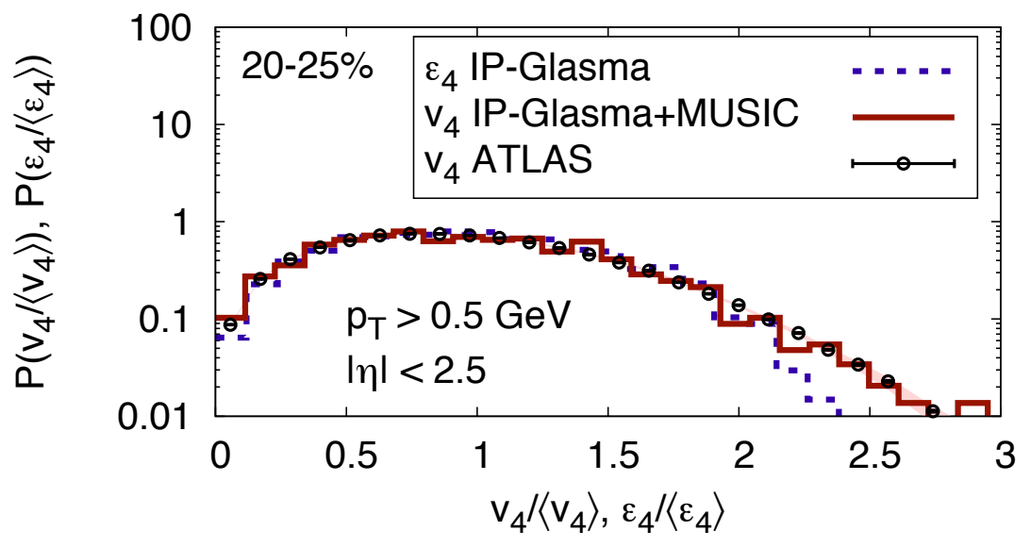


3+1D eventwise viscous hydro able to describe ATLAS data on mean v_n and $P(v_n)$: new era in understanding soft sector in HI collisions

Theory: Gale et al, http://arxiv.org/abs/arXiv:1209.6330

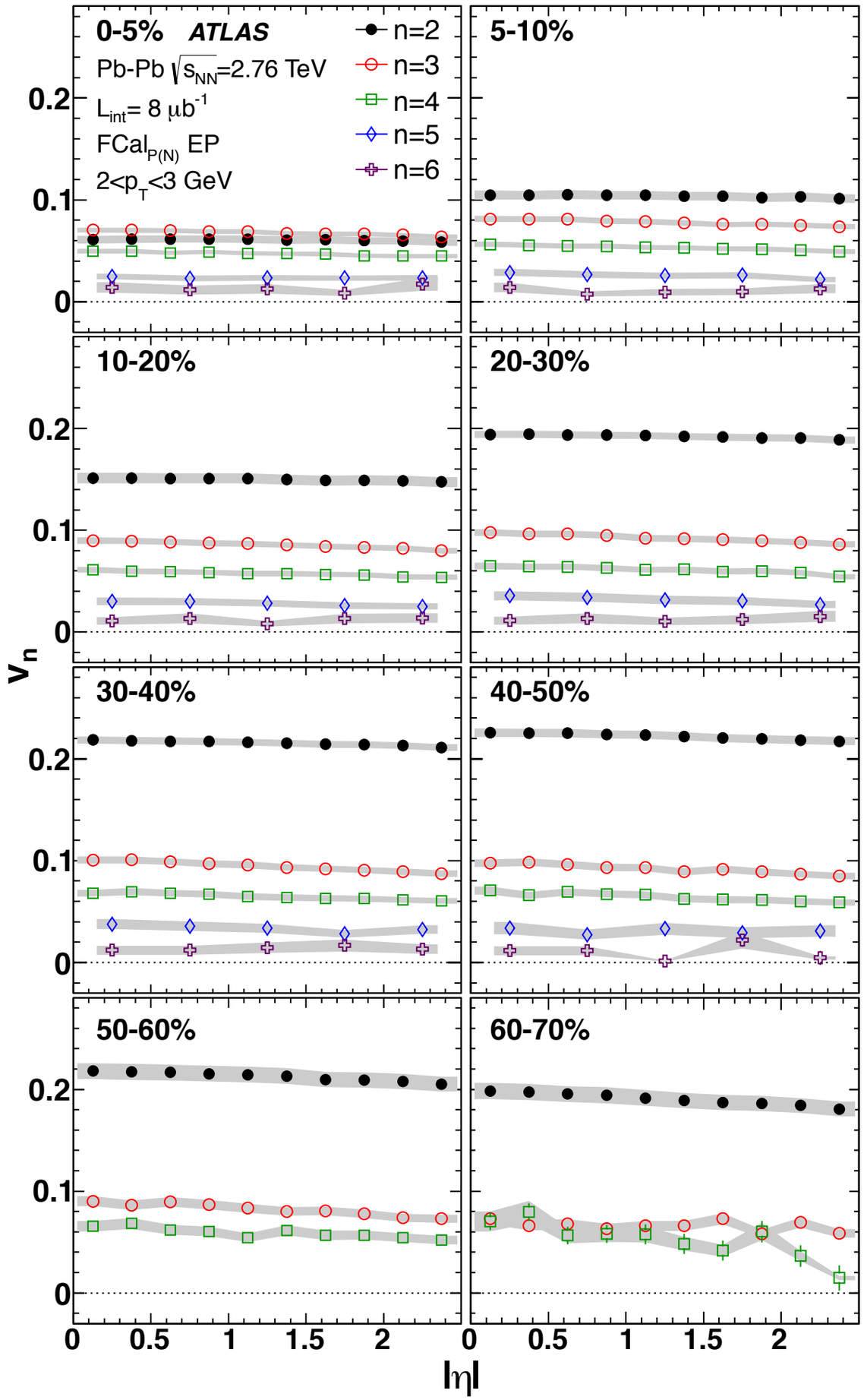
Final data: arXiv:1305.2942





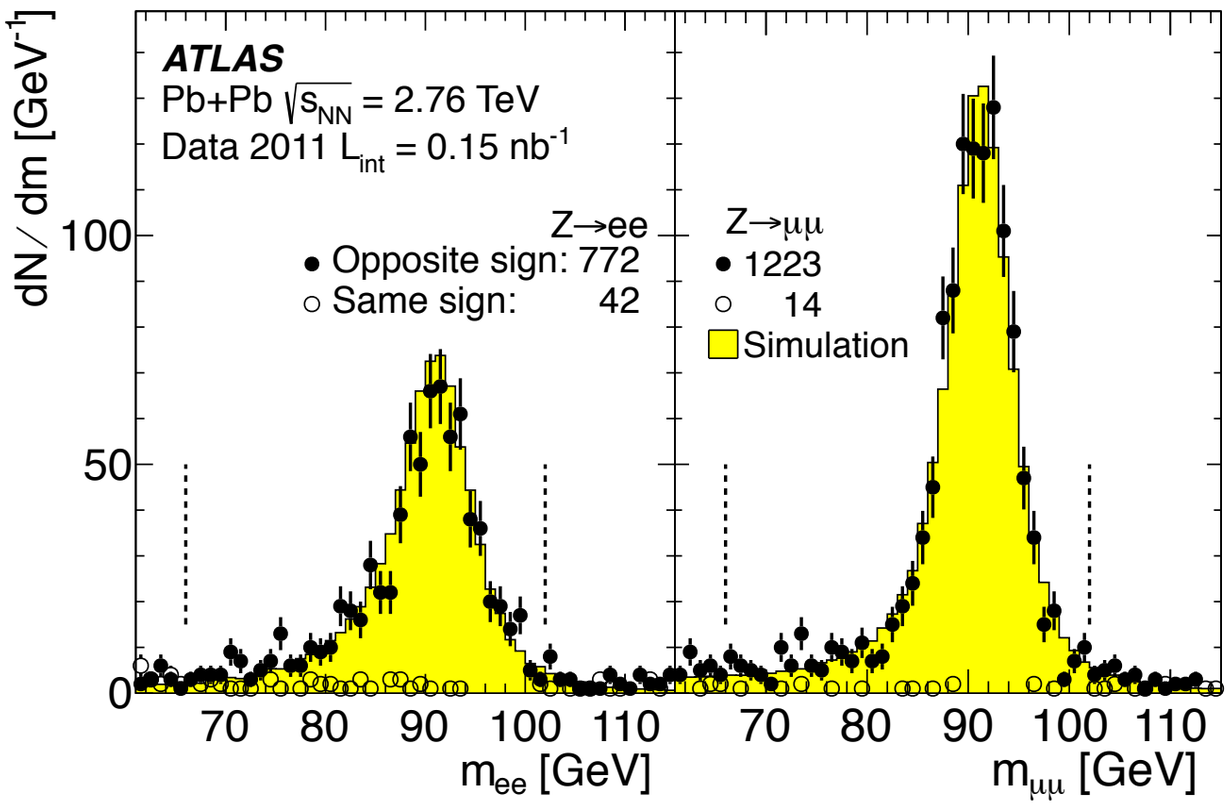
Pseudorapidity dependence of v_n

Accompanying the mild changes in dN/dη come similarly-mild changes in v_n as a function of η

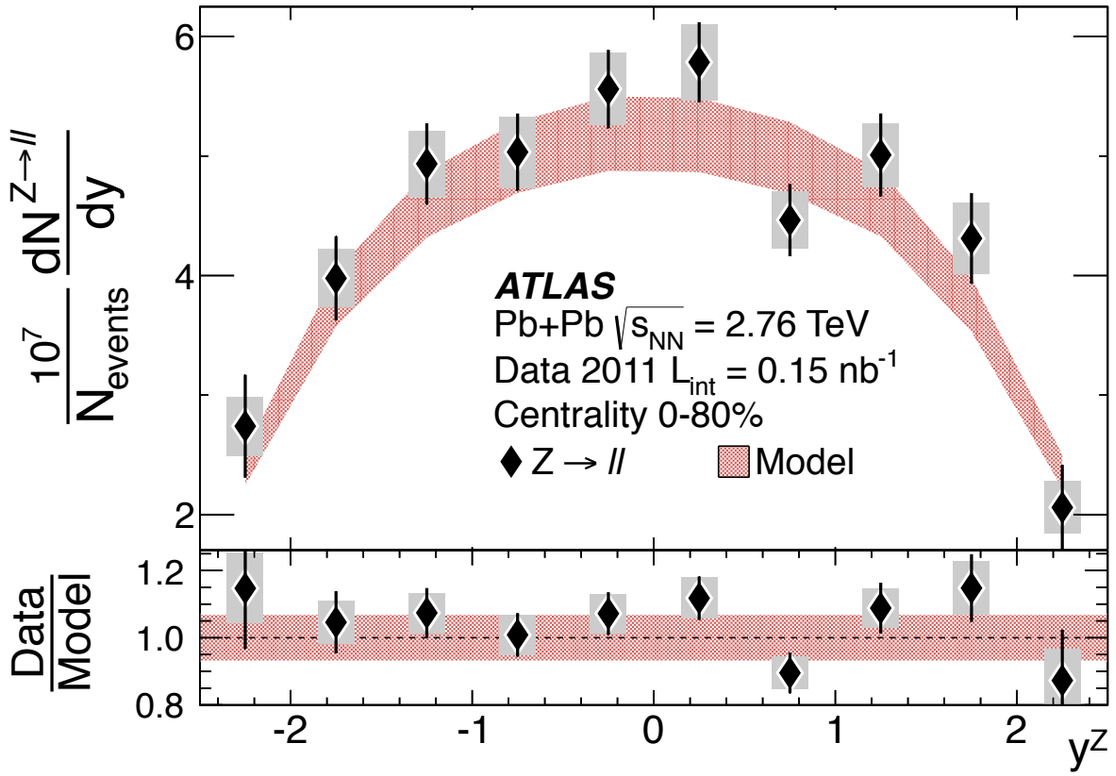


Hard Probes: Z boson yields vs. y

Phys. Rev. Lett 110, 022301 (2013)

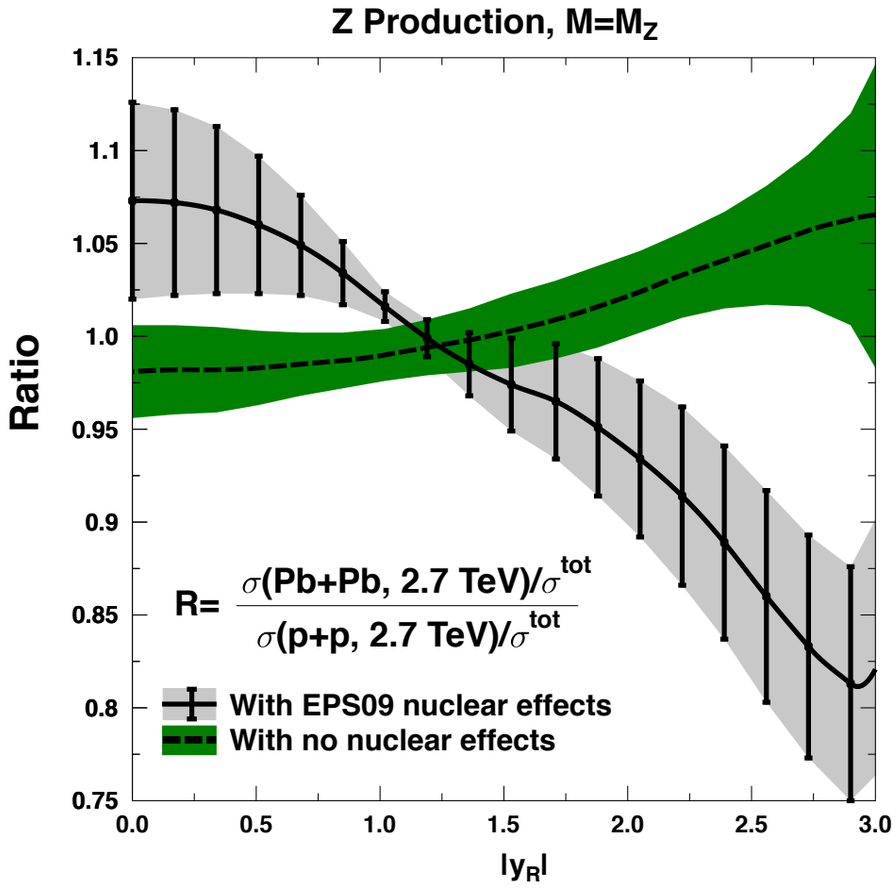


Z bosons reconstructed in both dielectron and dimuon channels: lineshape well described by ATLAS simulations

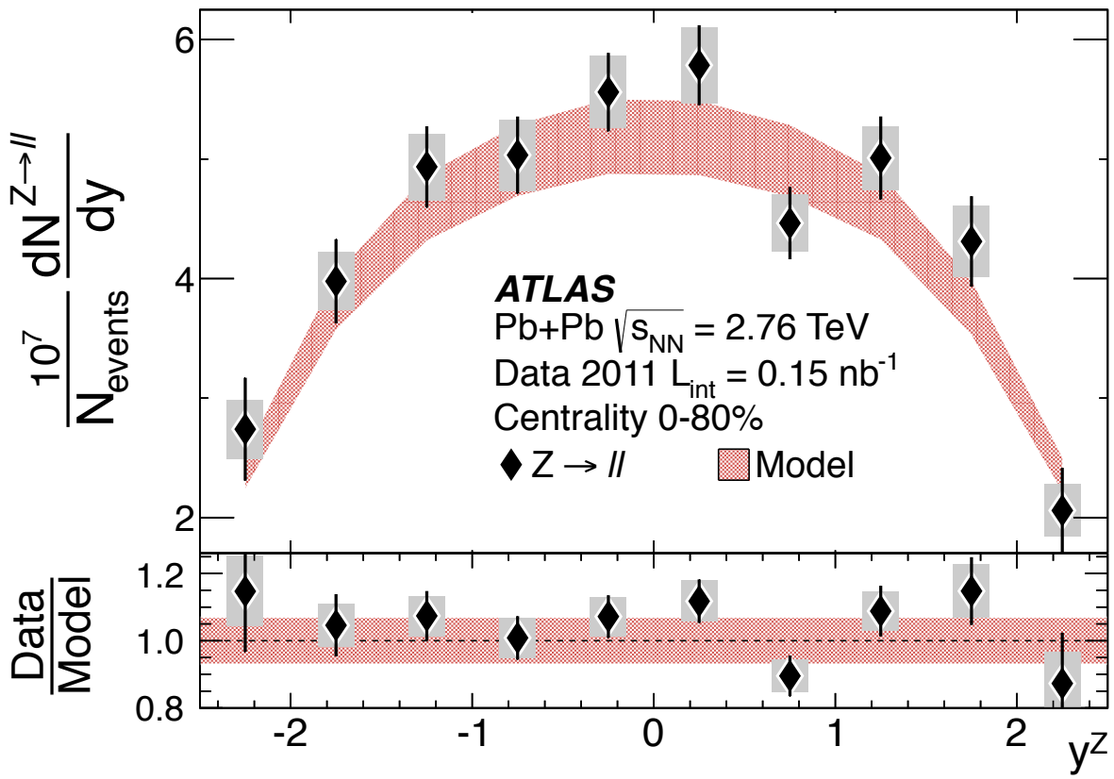


Z rapidity distribution well described by PYTHIA pp dN_Z/dy scaled to NNLO cross section

Hard Probes: Z boson yields vs. y



Phys. Rev. Lett 110, 022301 (2013)



Modifications to Z production relative to pp due to isospin expected to be small even at large p_T.
EPS09 would lead to a tilt toward large y, not suggested by experimental data.

W yields from 2011 data

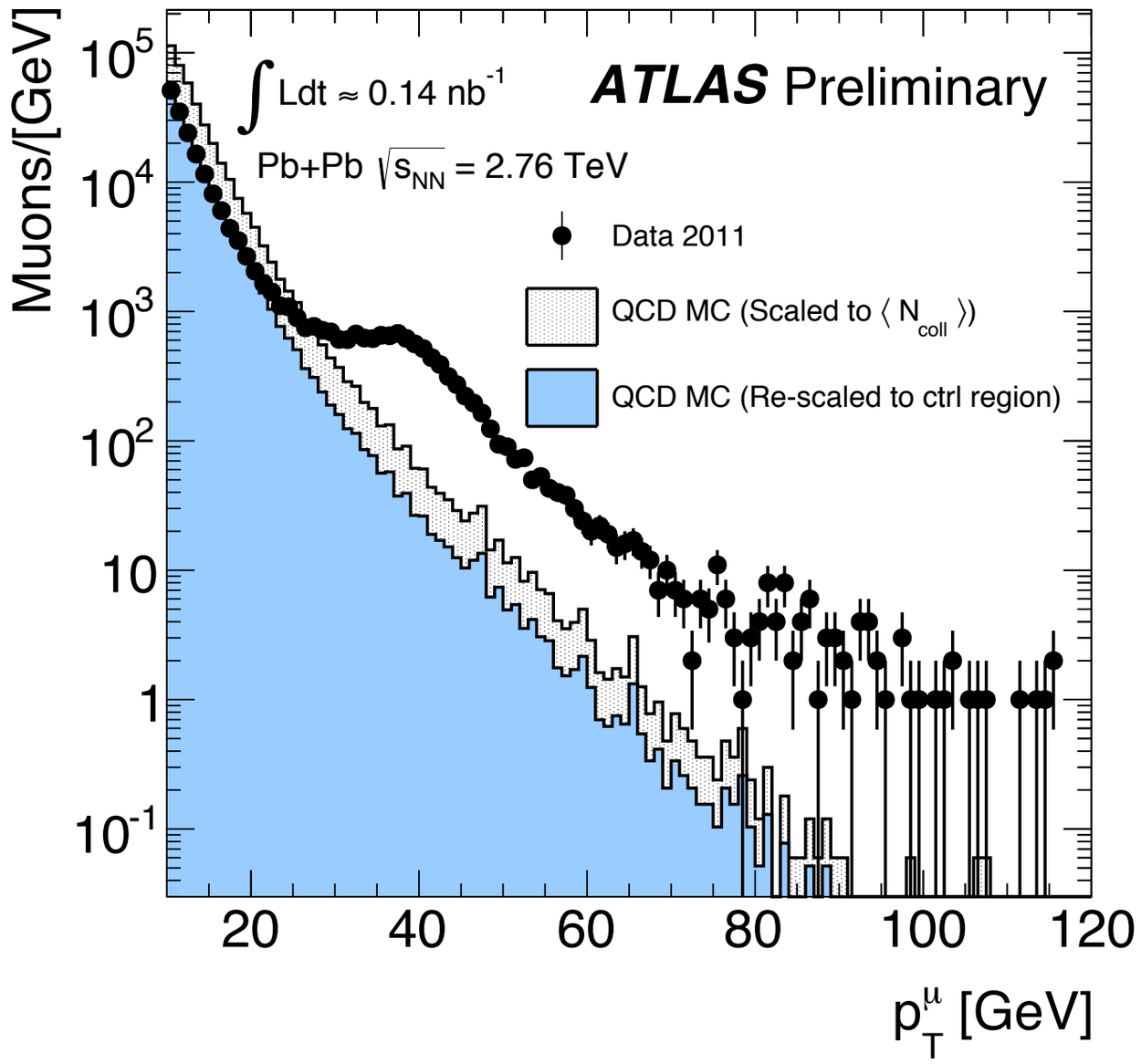
20x statistics of 2010 analysis: full reconstruction of W m_T

QCD background given by PYTHIA.

Requires rescaling (in 10-20 GeV p_T interval) to account for jet suppression

Within signal region p_T>25 GeV, 3.7% average background

ATLAS-CONF-2013-106



Hard Probes: W boson yields

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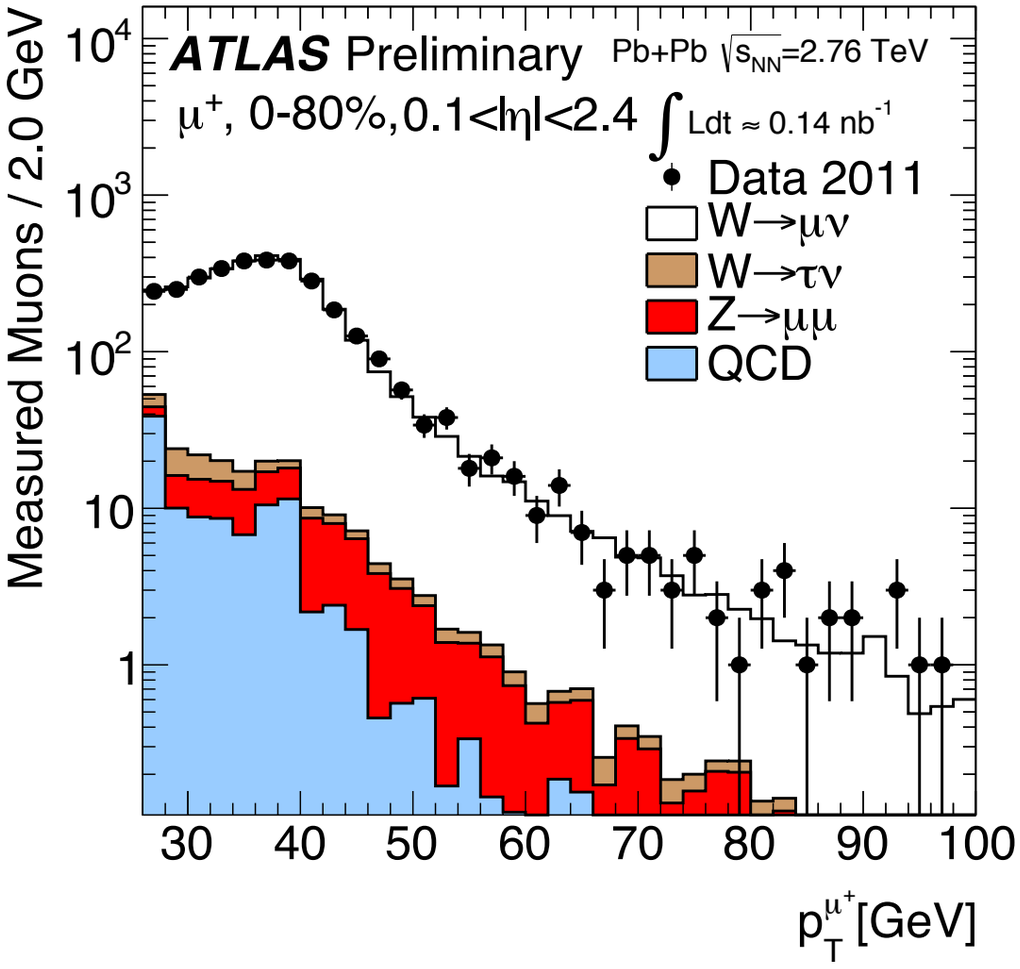

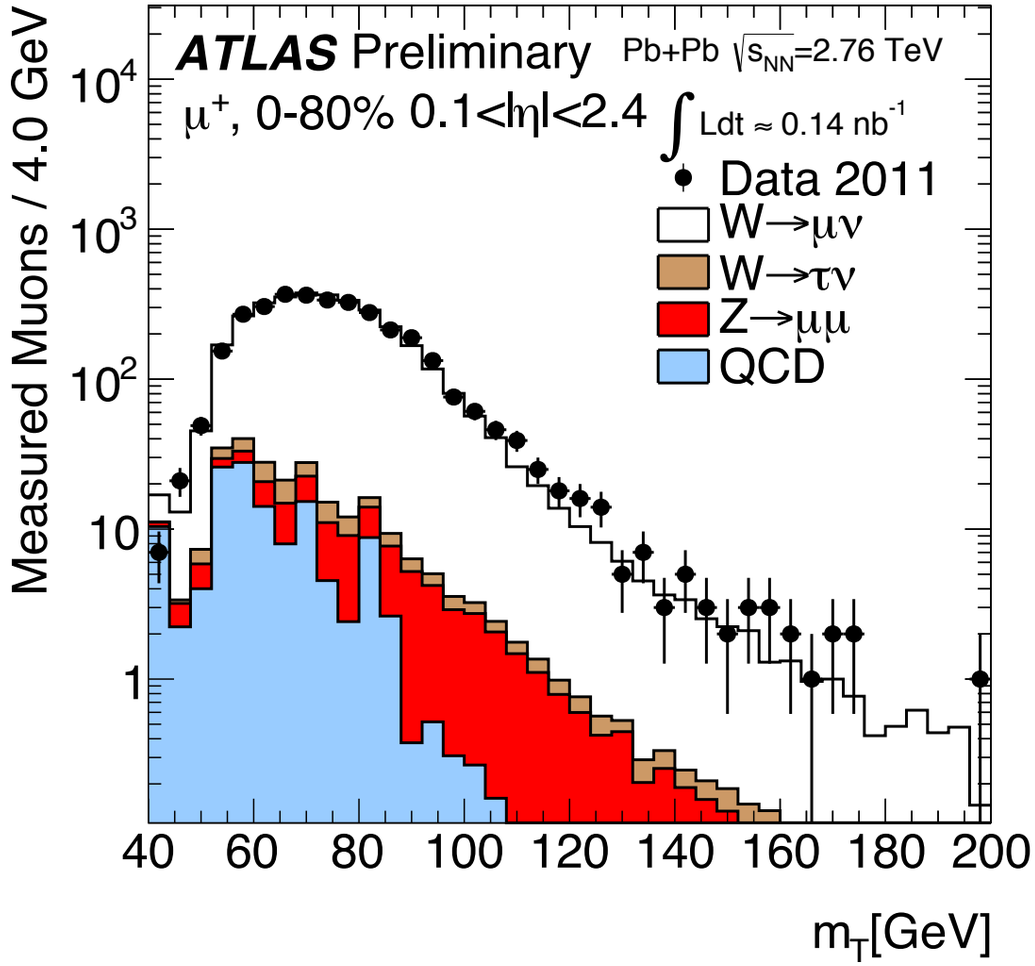

Missing p_T $\quad \not\mathbf{p} = \sum_{i=1}^{ntrks} \not\mathbf{p}_i = -(\mathbf{p}_1 + \mathbf{p}_2 + ...\mathbf{p}_{ntrks})$ **(p_T>3 GeV)**

Transverse mass $\quad m_T = \sqrt{2 p_T^{\mu} \not{p}_T (1 - \cos \Delta\phi_{\mu, \not{p}_T})}$

W selection: $p_{T\mu}$>25 GeV, $\not{p}_T$>25 GeV, m_T>40 GeV

Hard Probes: W boson muon dN/dη

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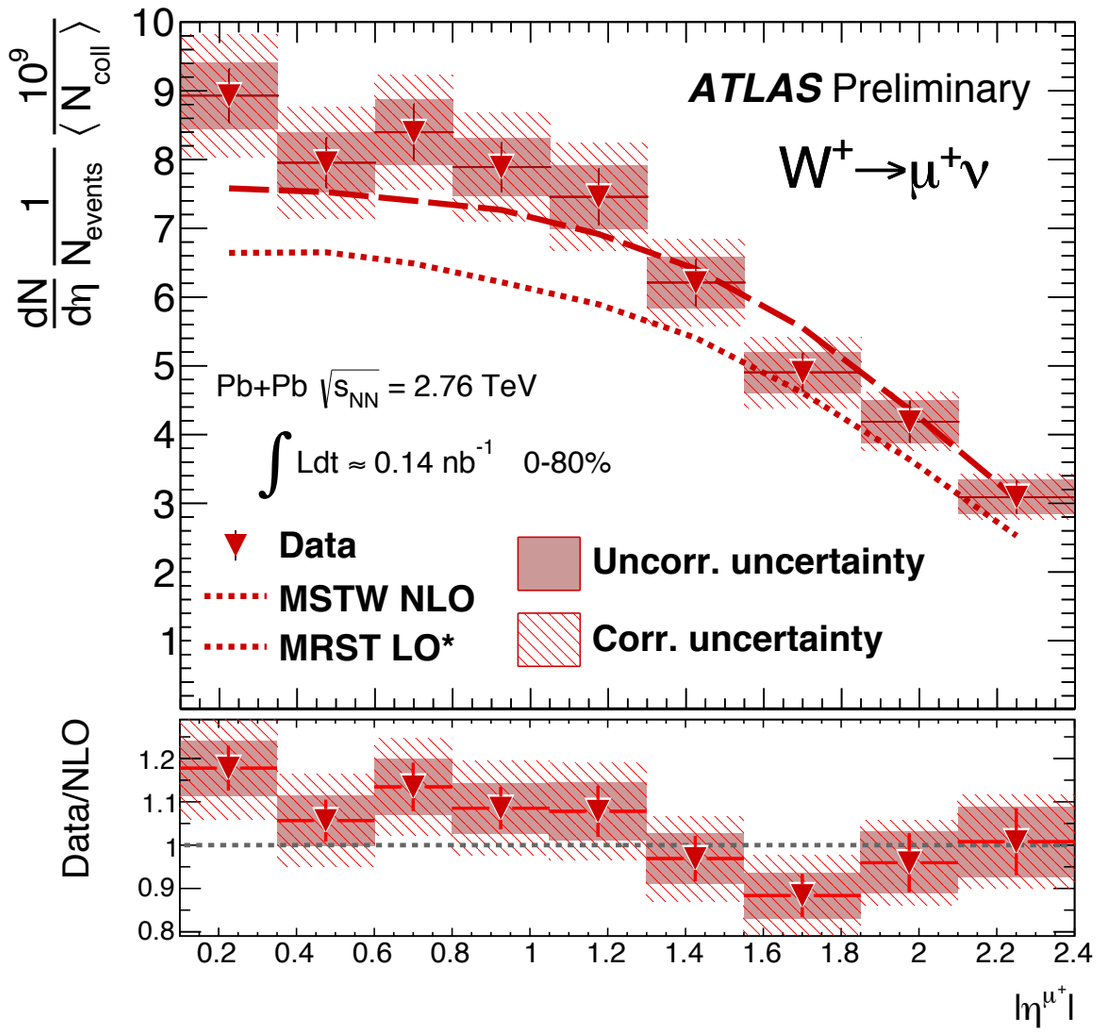

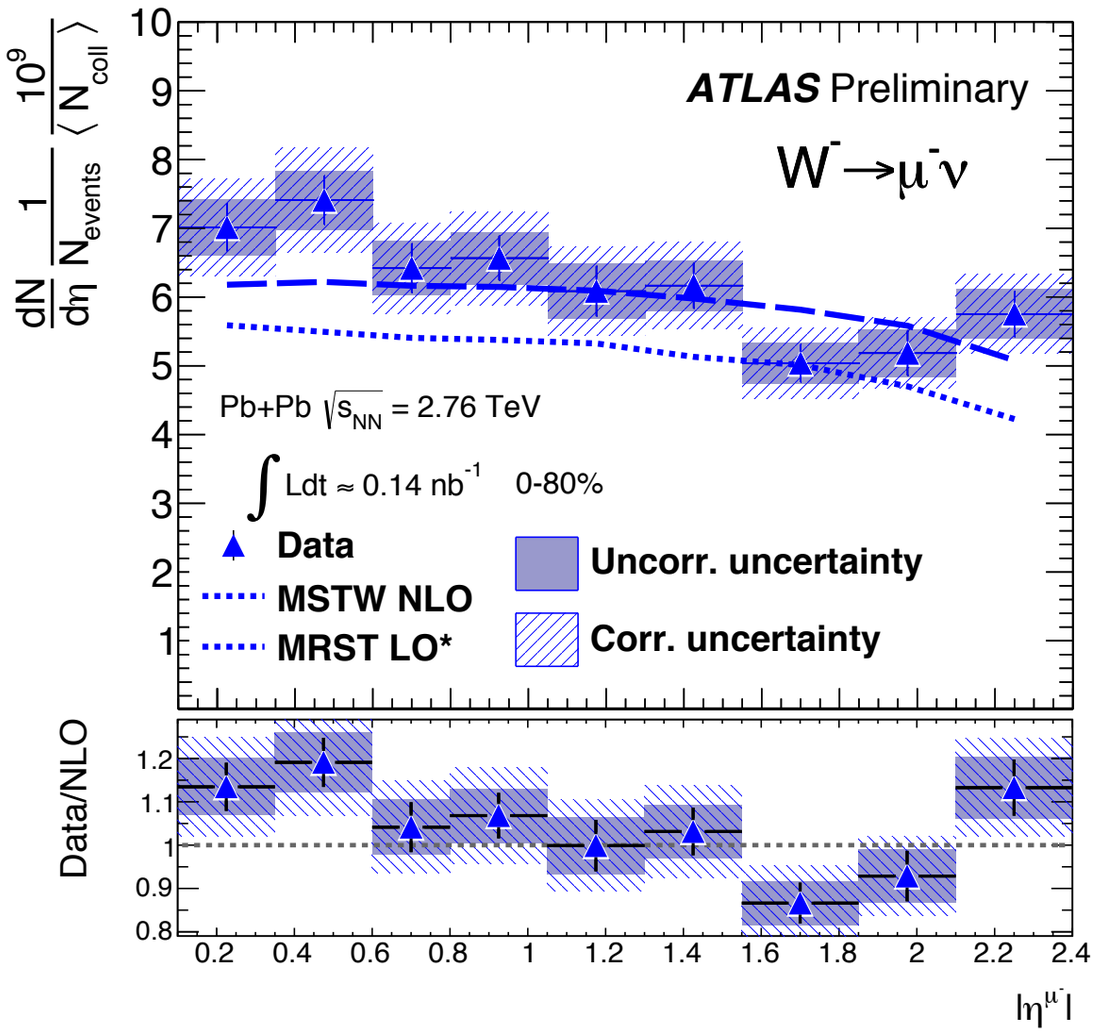

η distributions of leptons from W decays in Pb+Pb efficiency corrected to fiducial region same as selection cuts: LO* & NLO QCD calculations account for isospin in PDFs. Excess of negative charge reflects d quarks from neutrons.

W centrality dependence and $\mu^{\pm}$ asymmetry

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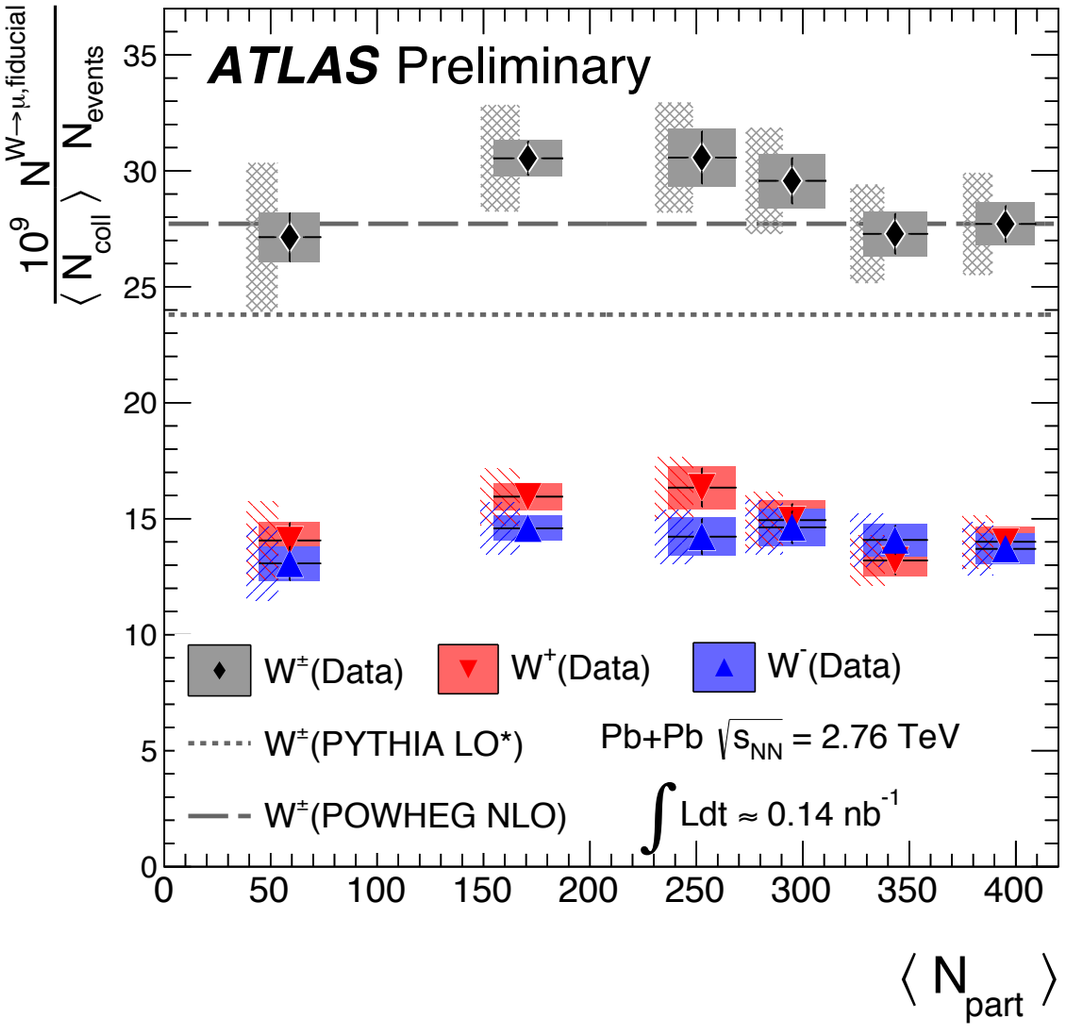
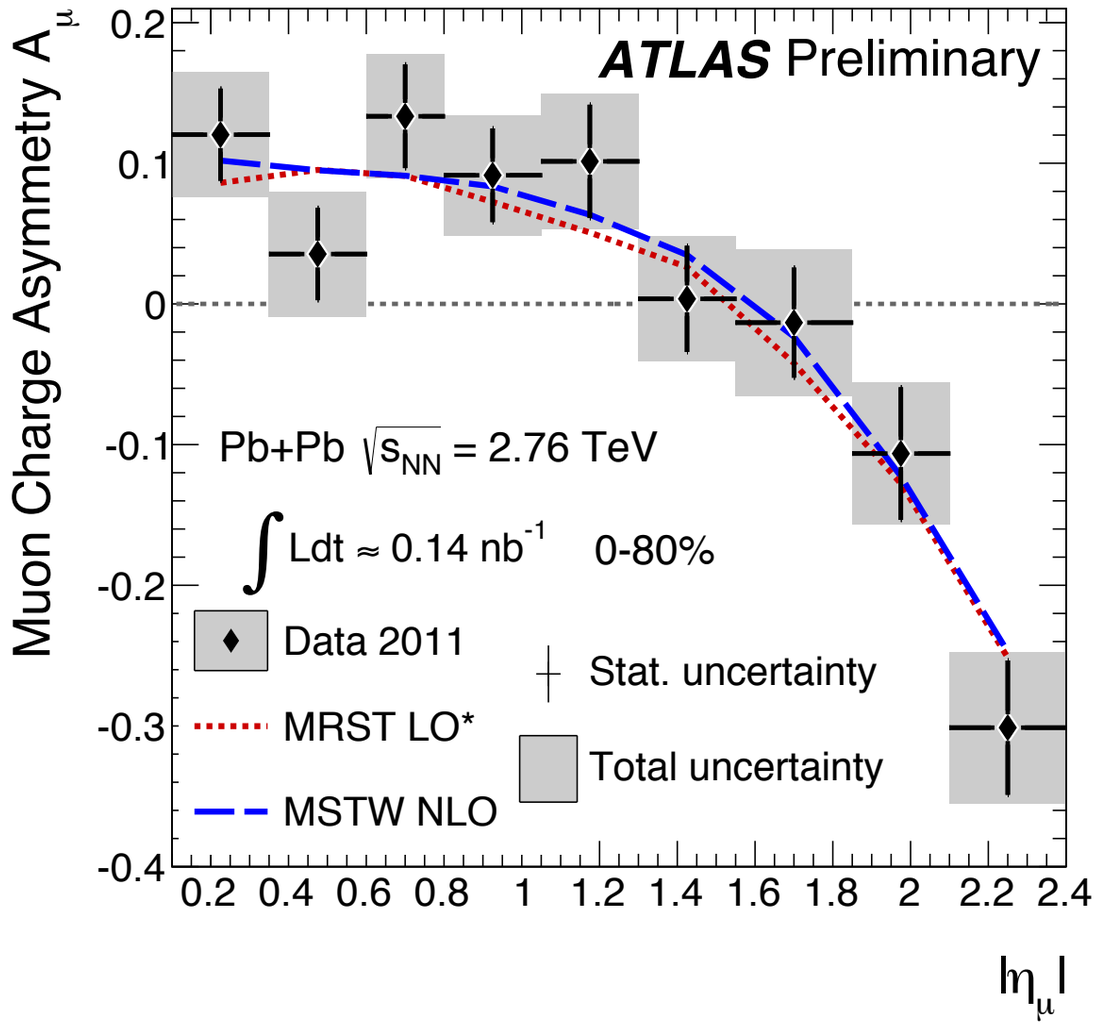


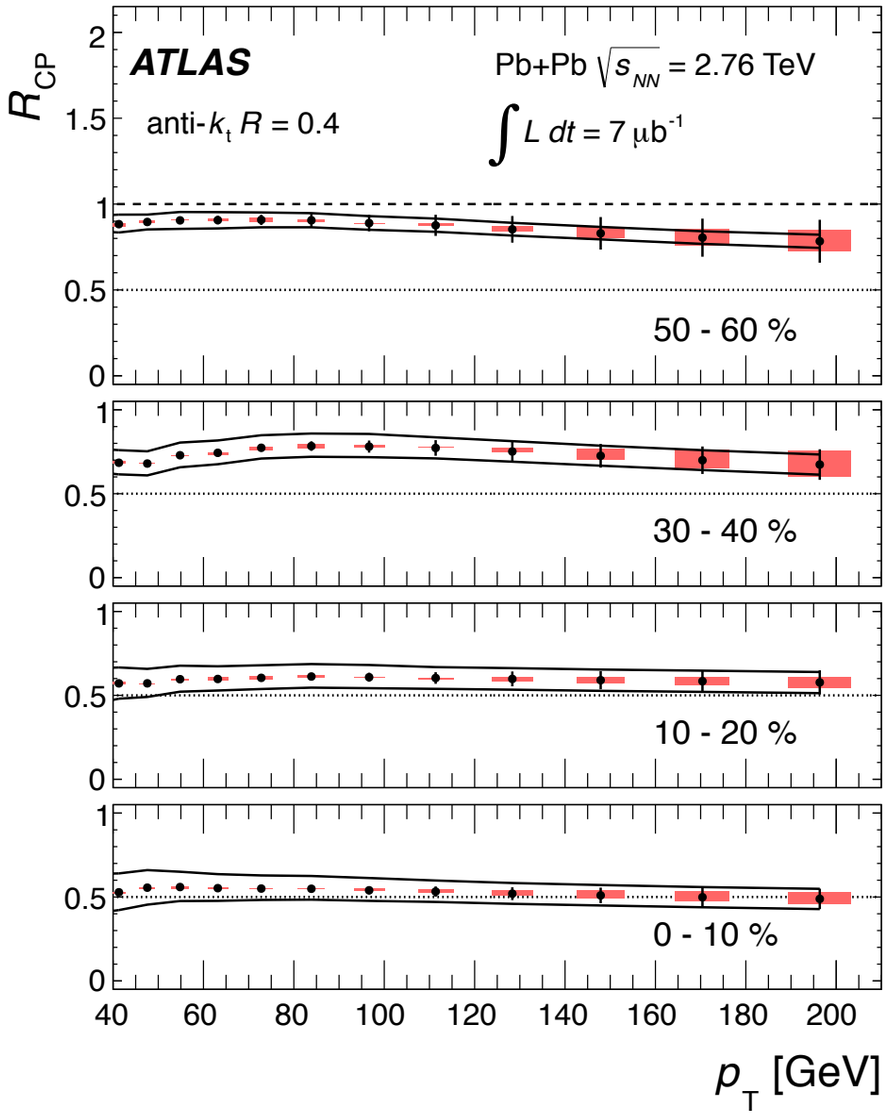
Yield per binary collision is approx. constant over 0-80% centrality range: data better described by NLO



Charge asymmetry vs. lepton η is consistent with both NLO & LO* QCD: how might nPDFs affect this?

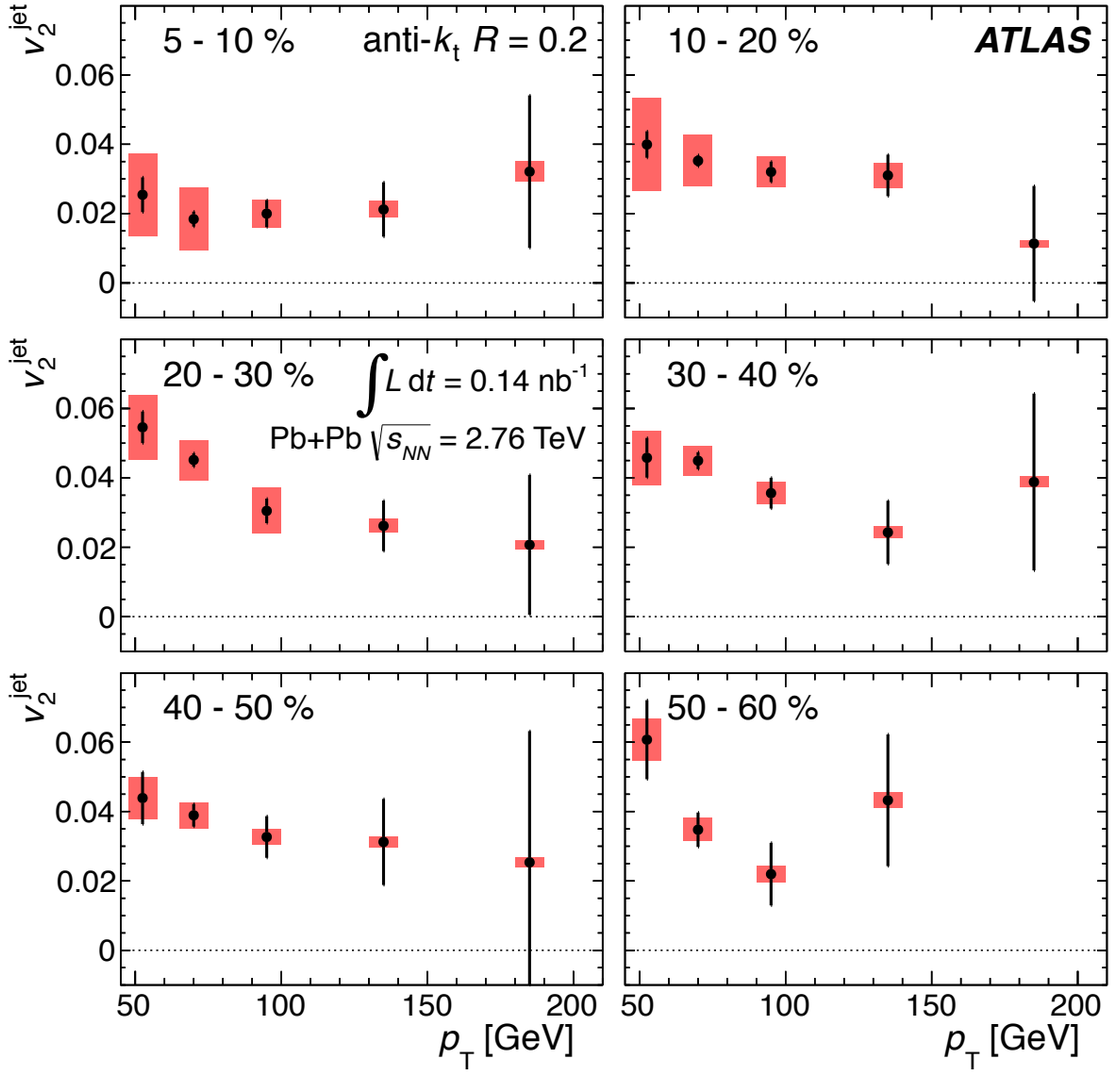
Hard Probes: Jet suppression & jet v_2

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



Inclusive jets are suppressed with a very weak p_T dependence from 40-200 GeV

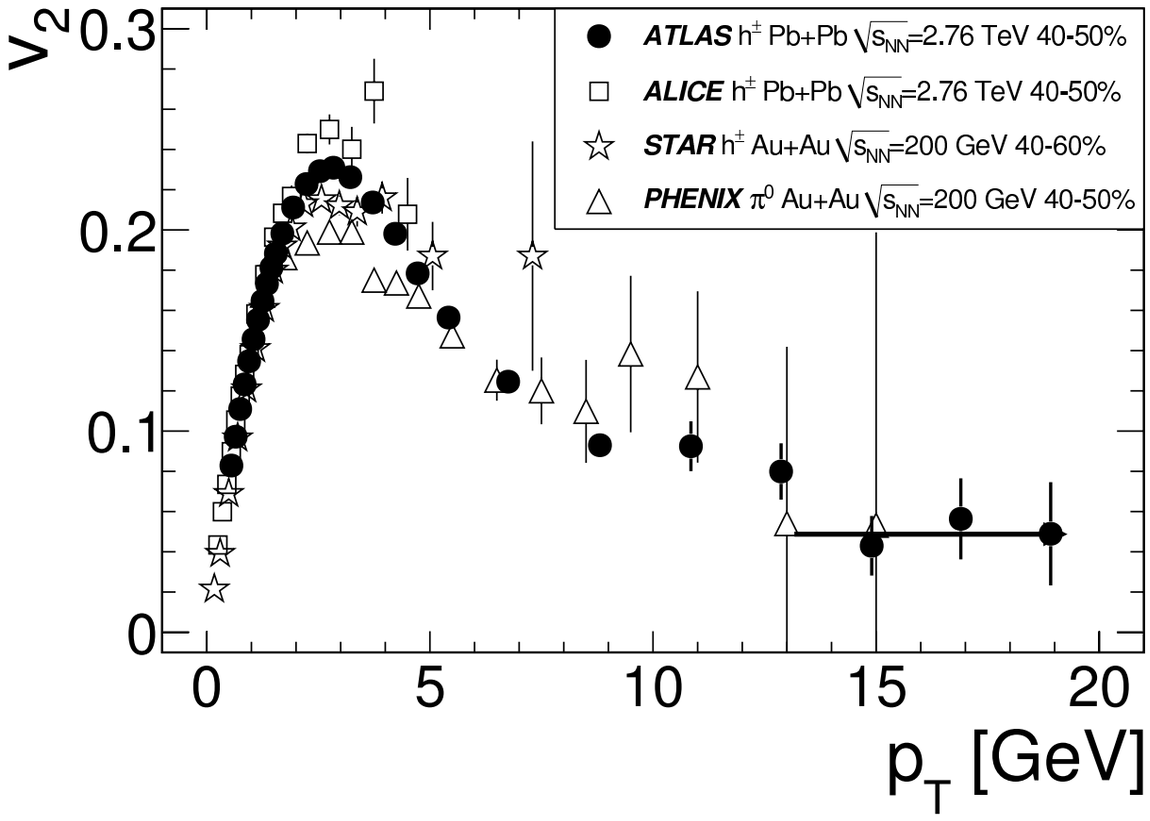
arXiv:1306.6469



Jet $v_{2,jet}$ measured out to 200 GeV, also with a generally weak p_T dependence

Jet suppression & $v_{2,jet}$

ATLAS, Phys.Lett. B707 (2012) 330-348



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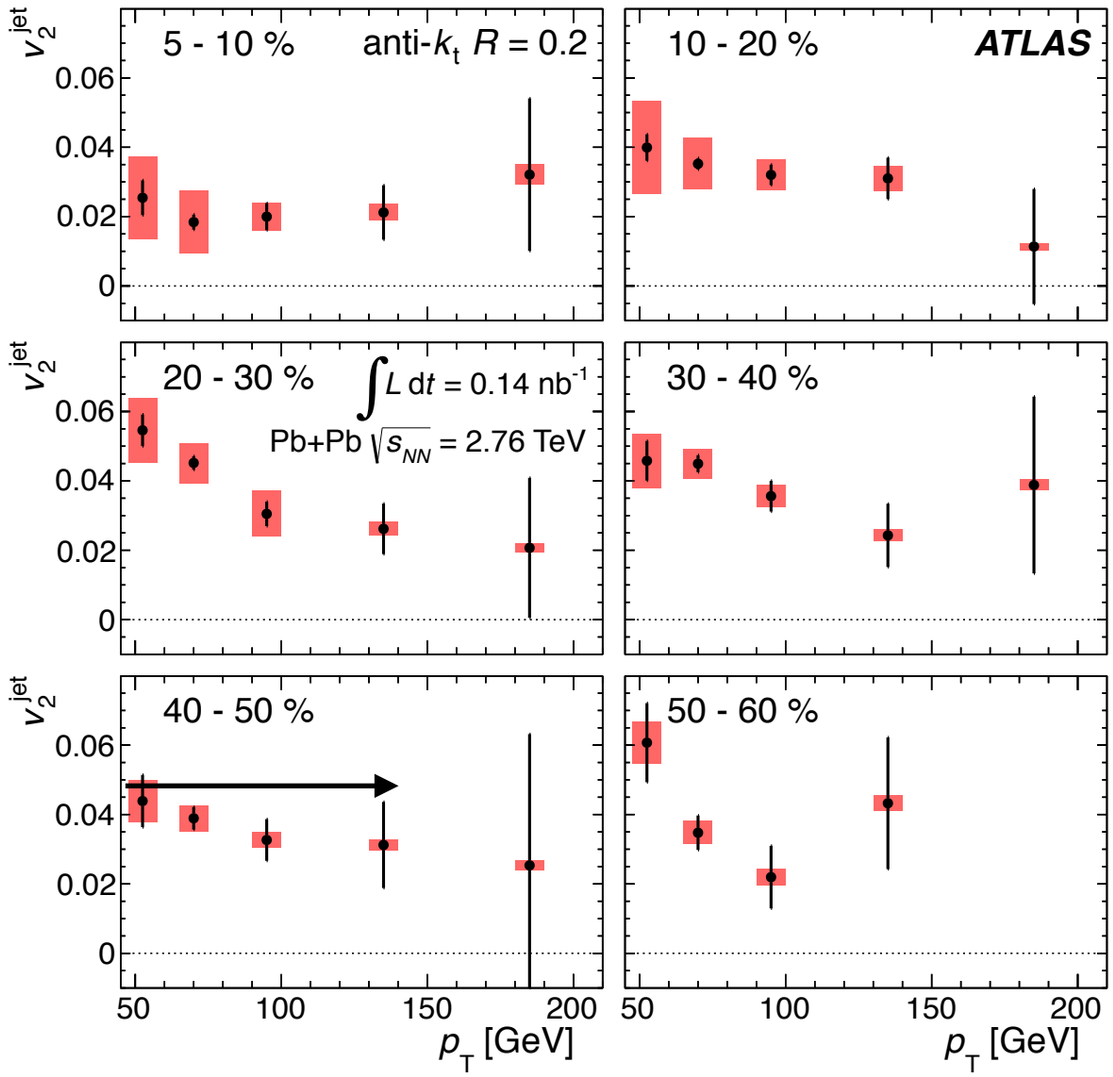


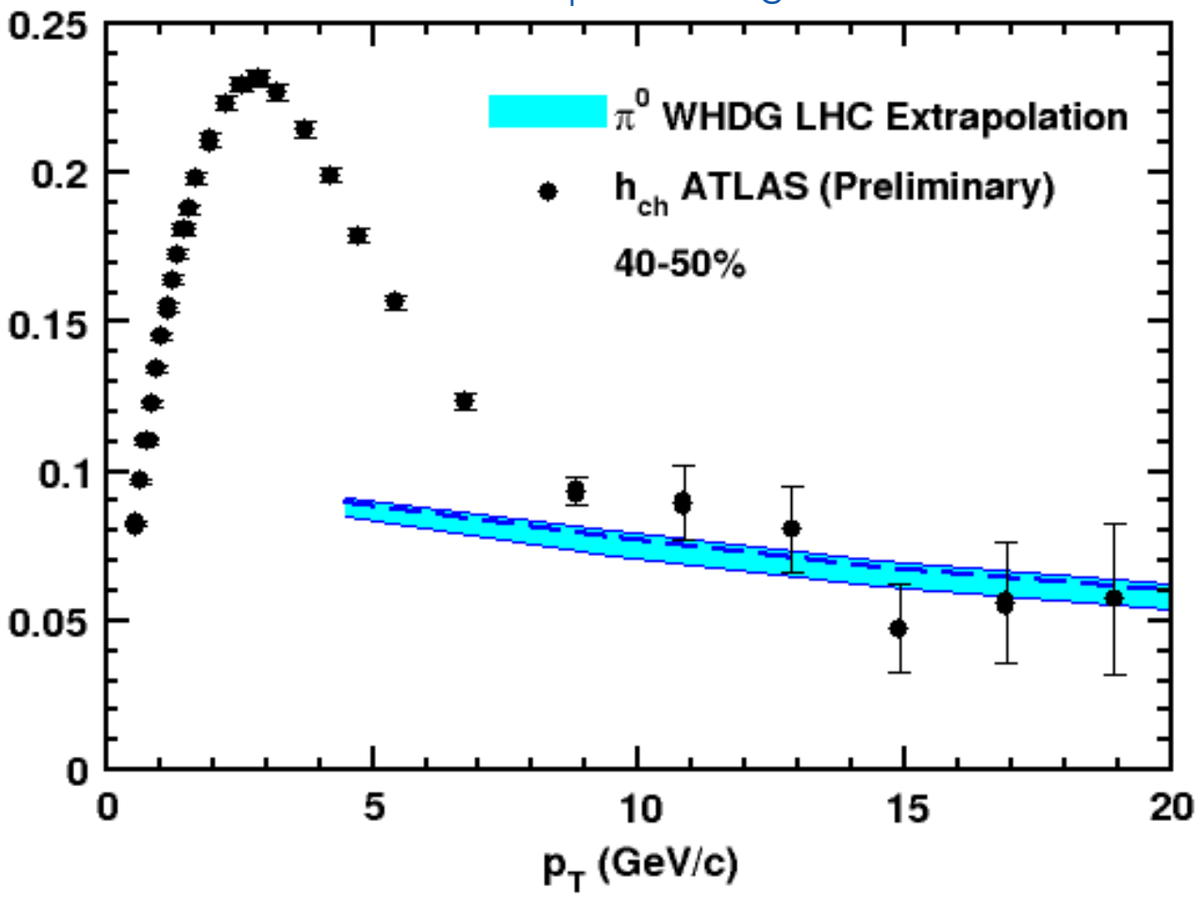
$v_{2,jet}$ is similar to magnitude seen for high p_T hadrons.

Consistent w/ CMS v_2 at very high p_T

Jet suppression & $v_{2,jet}$

W. Horowitz & M. Gyulassy, QM2011

http://arxiv.org/abs/arXiv:1104.4958



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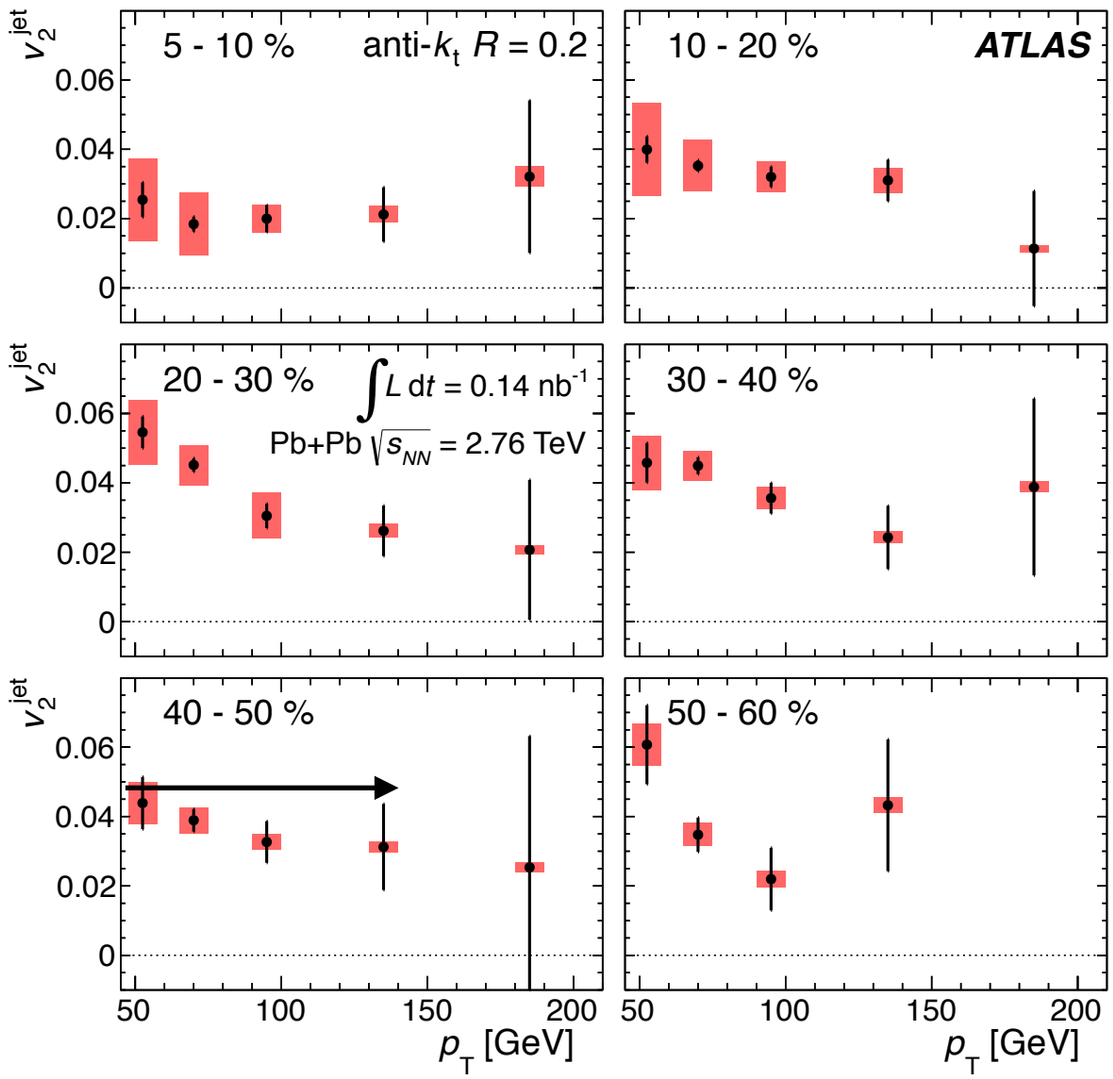


$v_{2,jet}$ is similar to magnitude seen for high p_T hadrons.

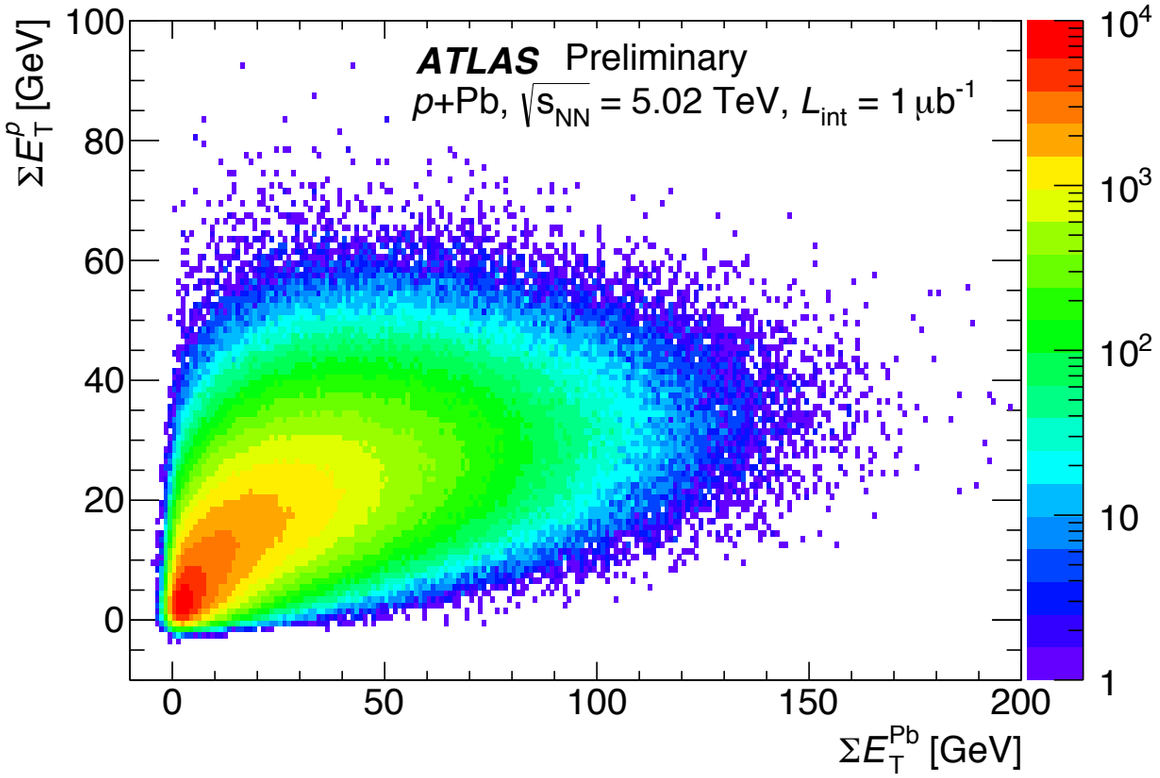
Excellent opportunity to test differential energy loss.

What have we learned from Pb+Pb?

- Centrality
  - Treating nucleons as hard disks has been sufficient so far
- Multiplicity & flow
  - Symmetric in η, little centrality dependence to shape
- Bosons
  - N_{coll} scaling holds, no evidence of large nuclear effects beyond isospin at forward angles
- Jets
  - Single jet suppression also has azimuthal modulation - potential testing ground for differential energy loss

What have we learned from p+Pb?

Centrality in p+Pb



Saturation of p-going forward E_T vs. Pb-going suggests limited role for p-going E_T

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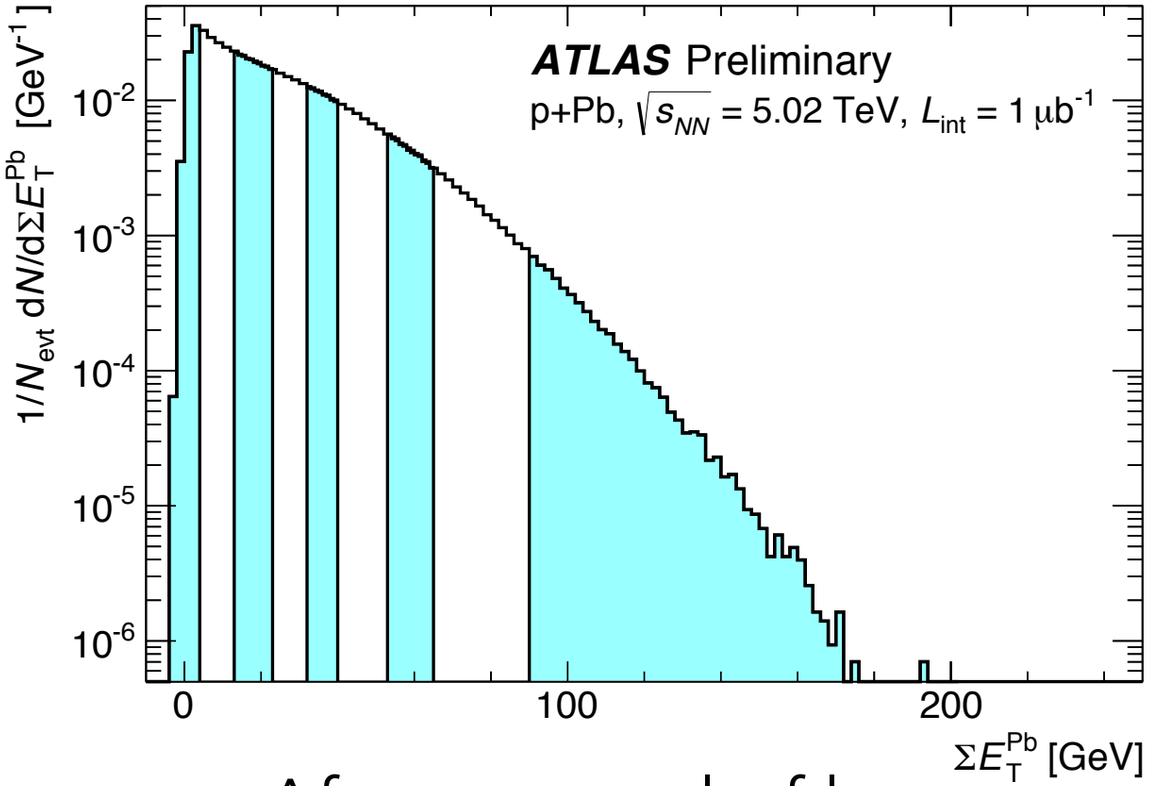
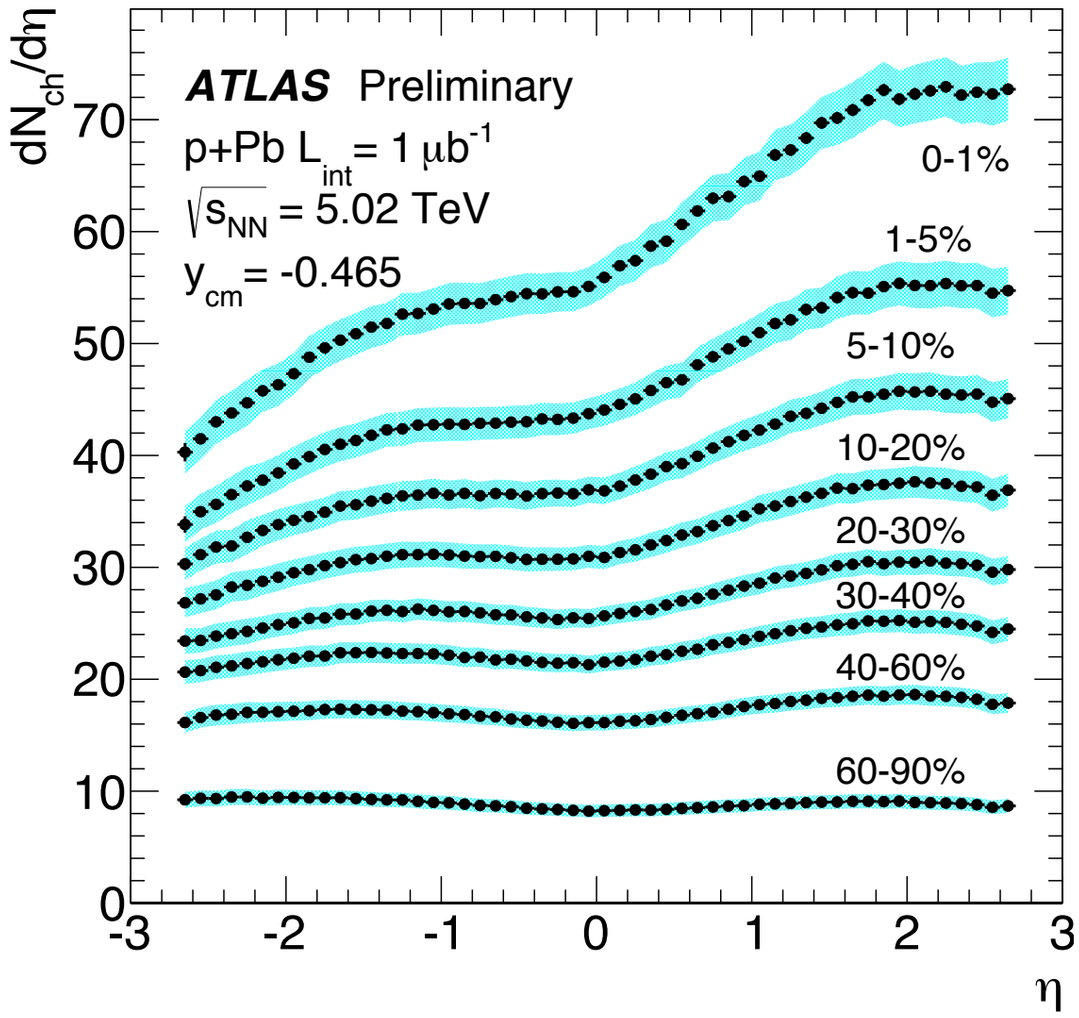


After removal of large "edge gaps" with $\Delta\eta_F>2$, distribution in Pb-going forward E_T divided into centrality intervals based on overall efficiency of 98±2% for inelastic events

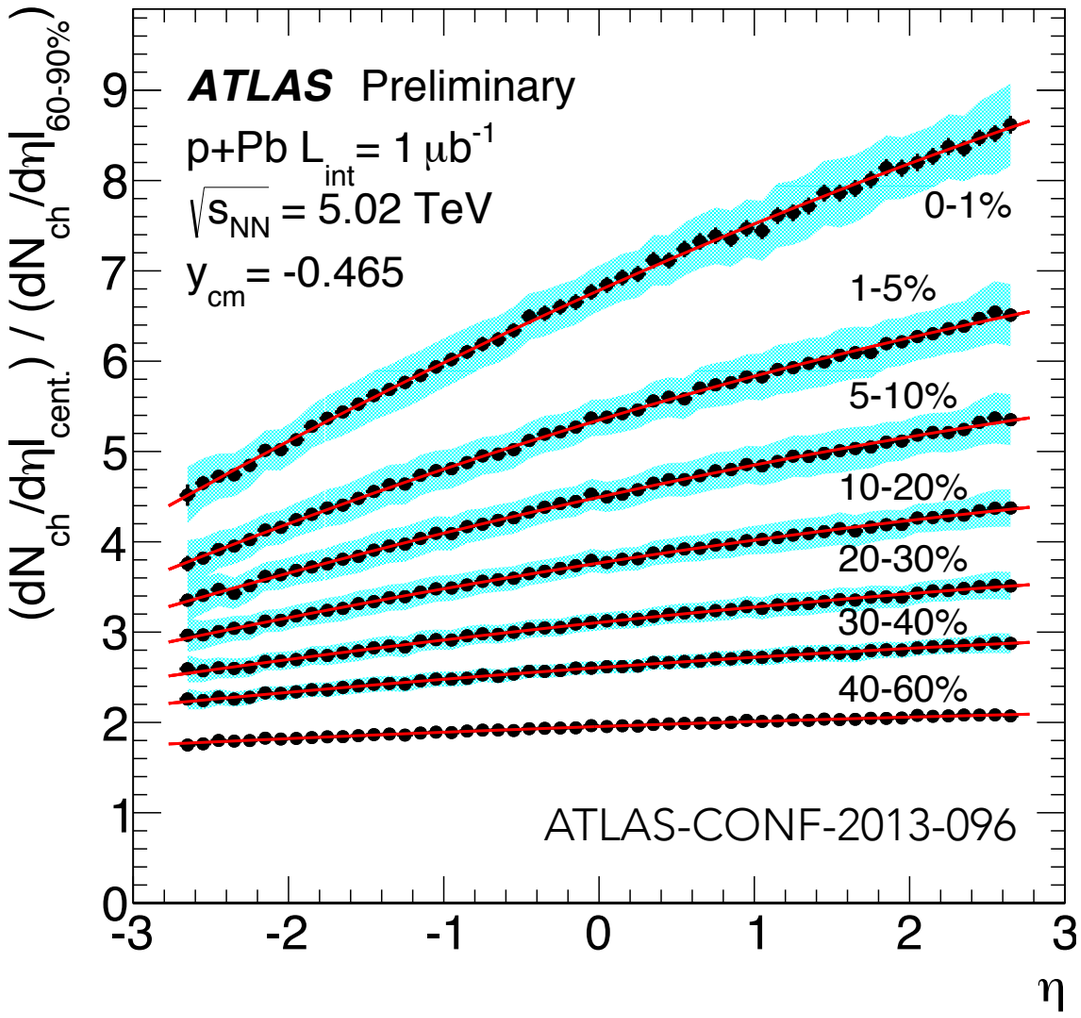
Talk by A. Milov, Thurs Plenary

Particle yields vs. centrality

Measured using 2-point pixel tracklets and
pixel tracks (systematics account for different methods)



$dN_{ch}/d\eta$ in centrality intervals:
strong change in shape (cf. Pb+Pb)



Ratio relative to 60-90%:
Jacobian removed,
slope increases with centrality

Particle yields vs. centrality

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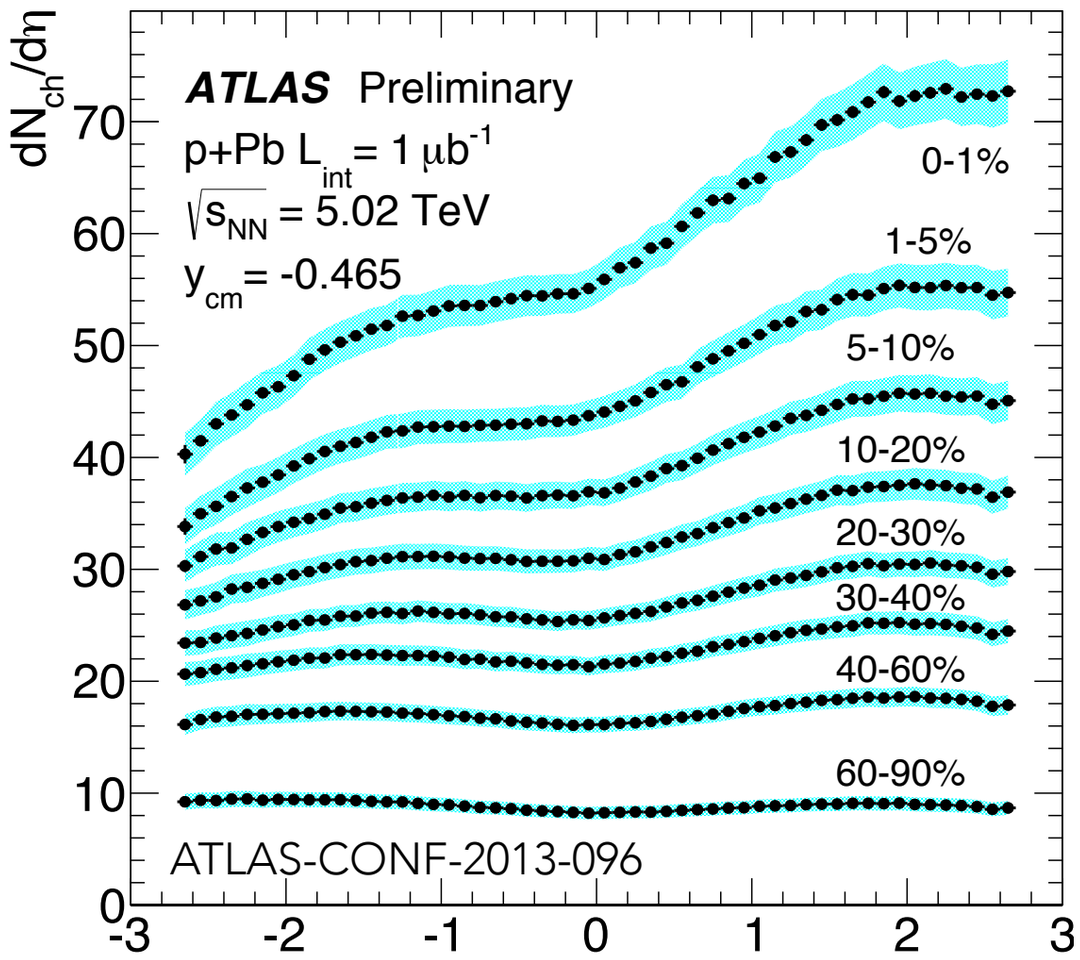
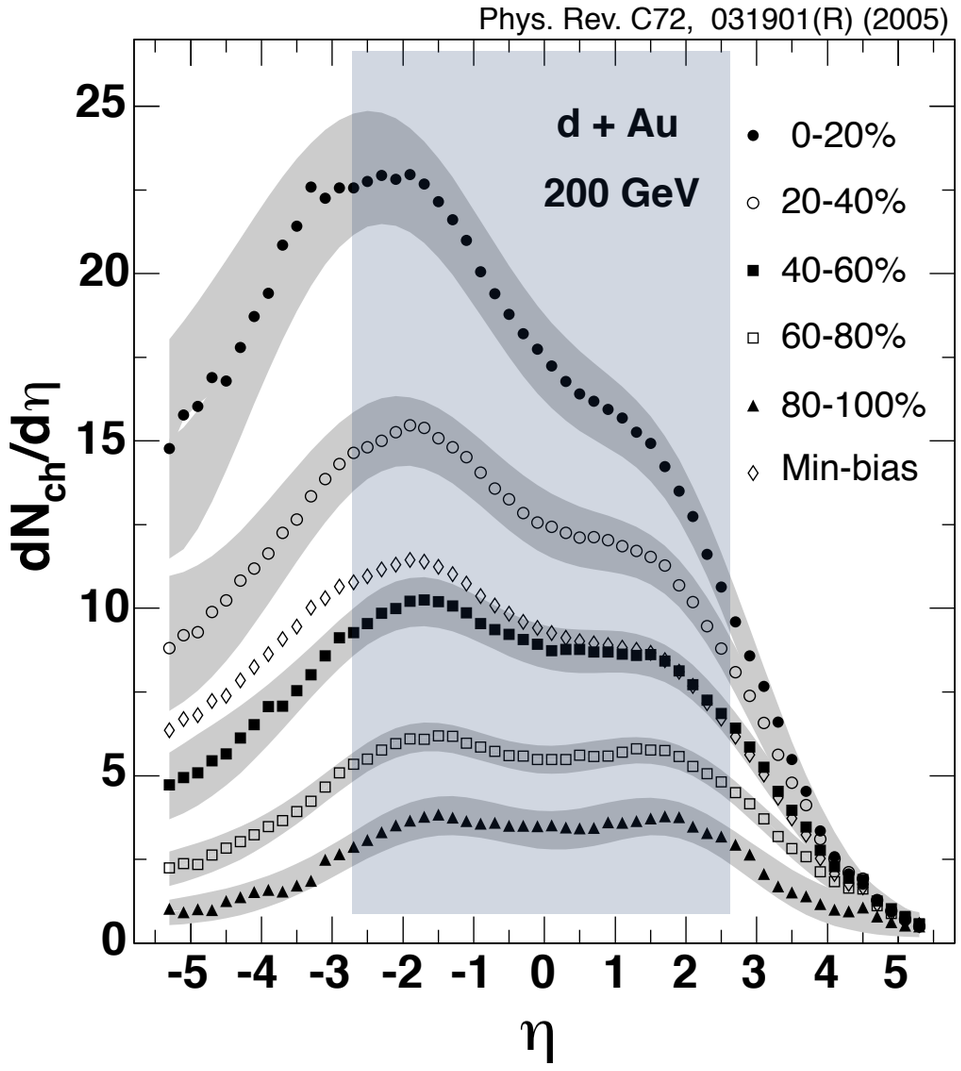


$dN_{ch}/d\eta$ in centrality intervals:
strong change in shape (cf. Pb+Pb)
as system becomes more **asymmetric**



similar to PHOBOS d+Au data

Particle yields vs. centrality

Measured using 2-point pixel tracklets and
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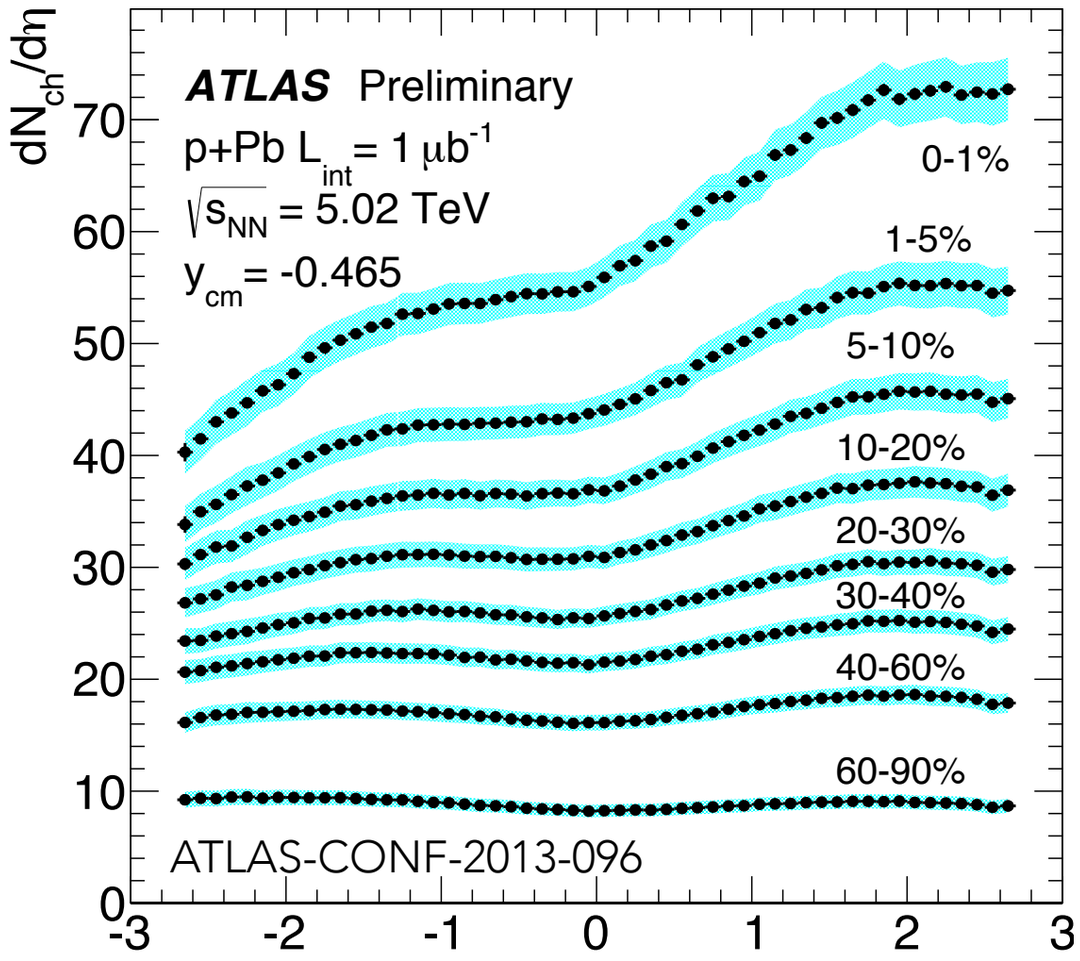

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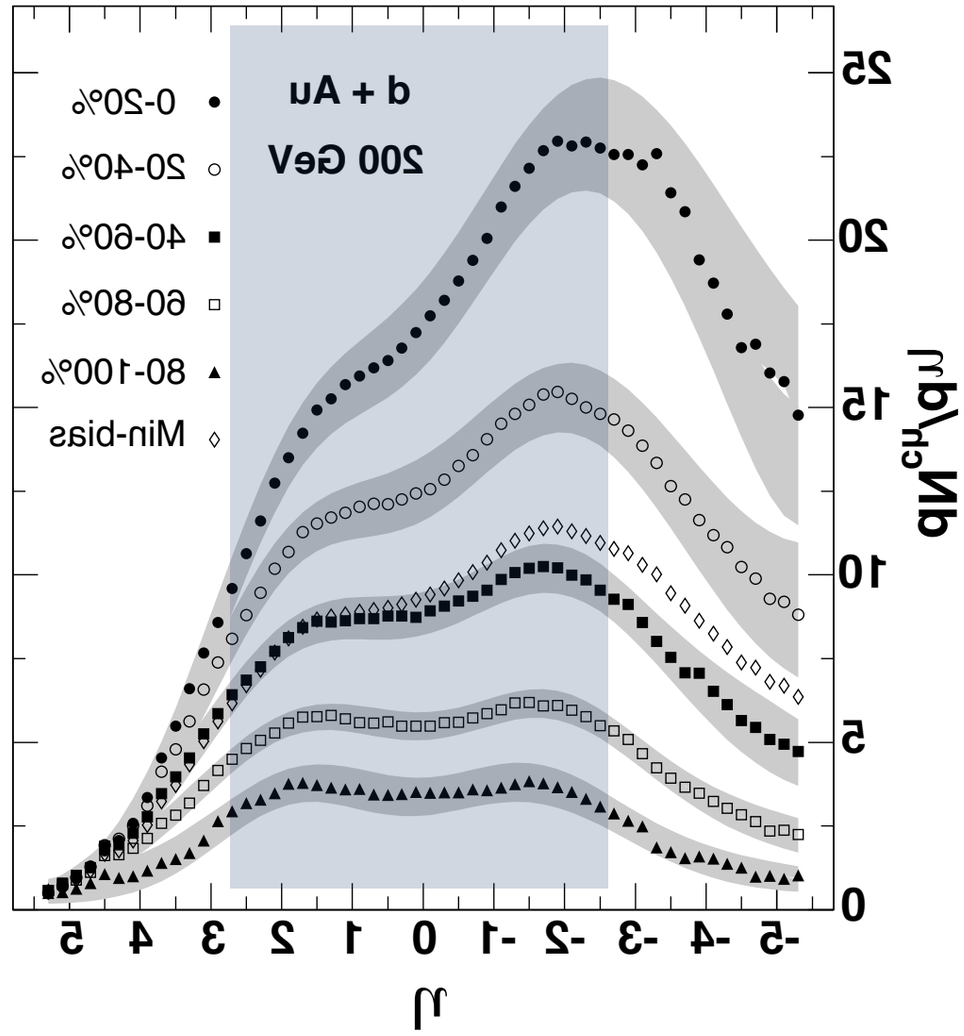
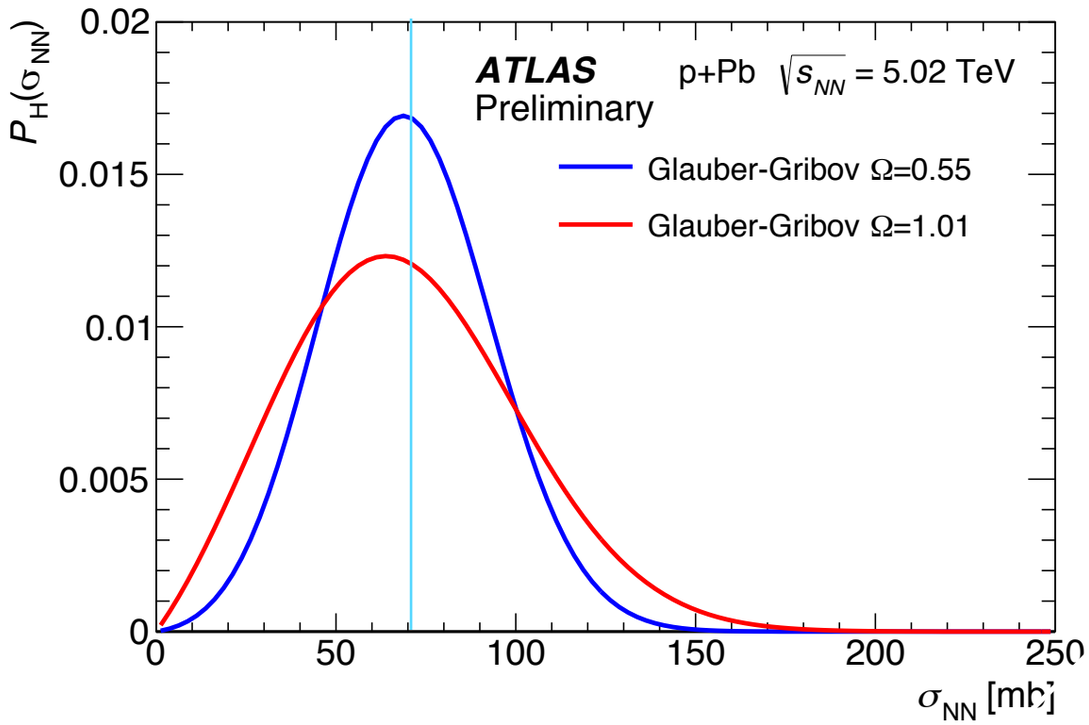


similar to PHOBOS d+Au data

From Glauber to Glauber-Gribov



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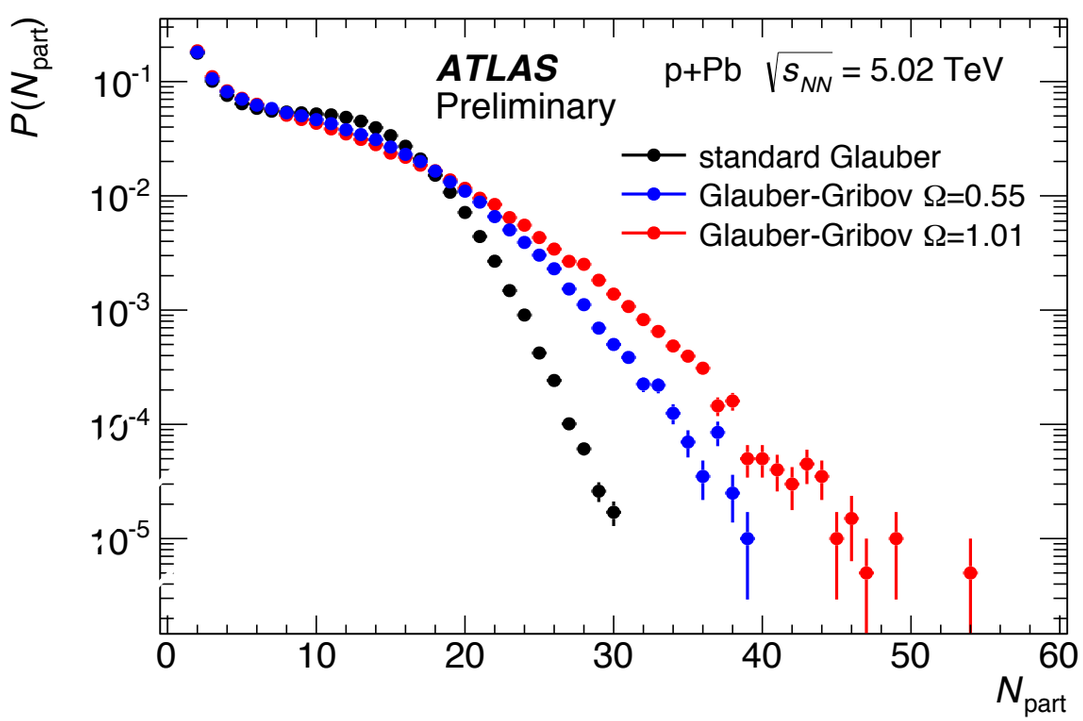
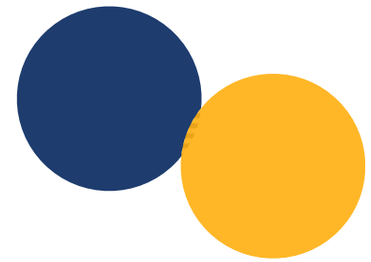
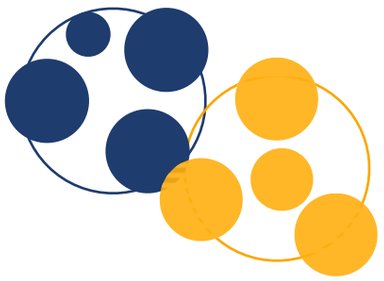


Standard Glauber modeling in most experiments assumes NN cross section is constant ("hard disk")

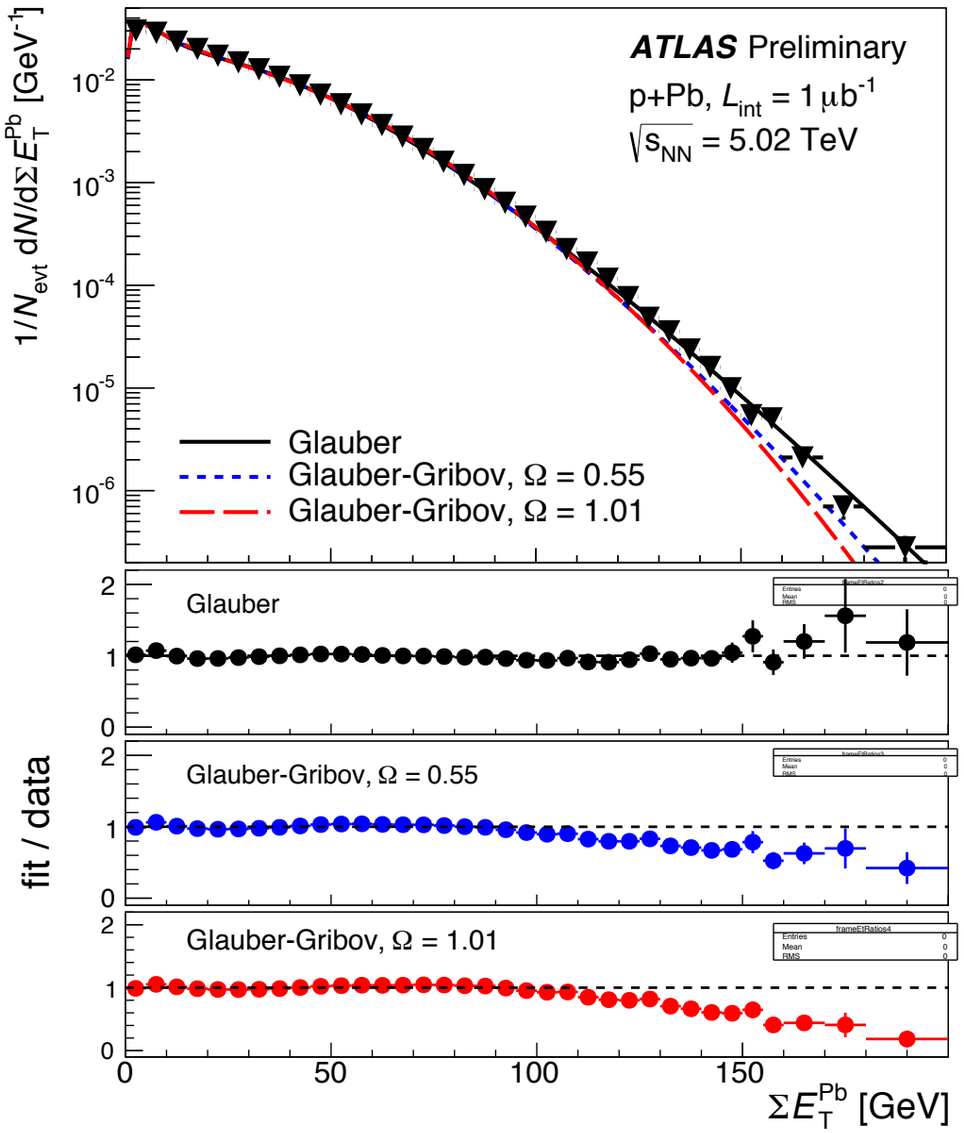


Glauber-Gribov "color fluctuation" model (Guzey, Strikman, et al): Allows pN cross section to fluctuate event to event.



Mean forced to be σ_{NN}=70 mb, width controlled with Ω (estimated using n+d, p+d, pbar+p, and extrapolated)

Fits to Pb-going forward E_T



Fits to forward ΣE_T distributions, based on convolution of pp, allowing for some non-linearity with N_{part}

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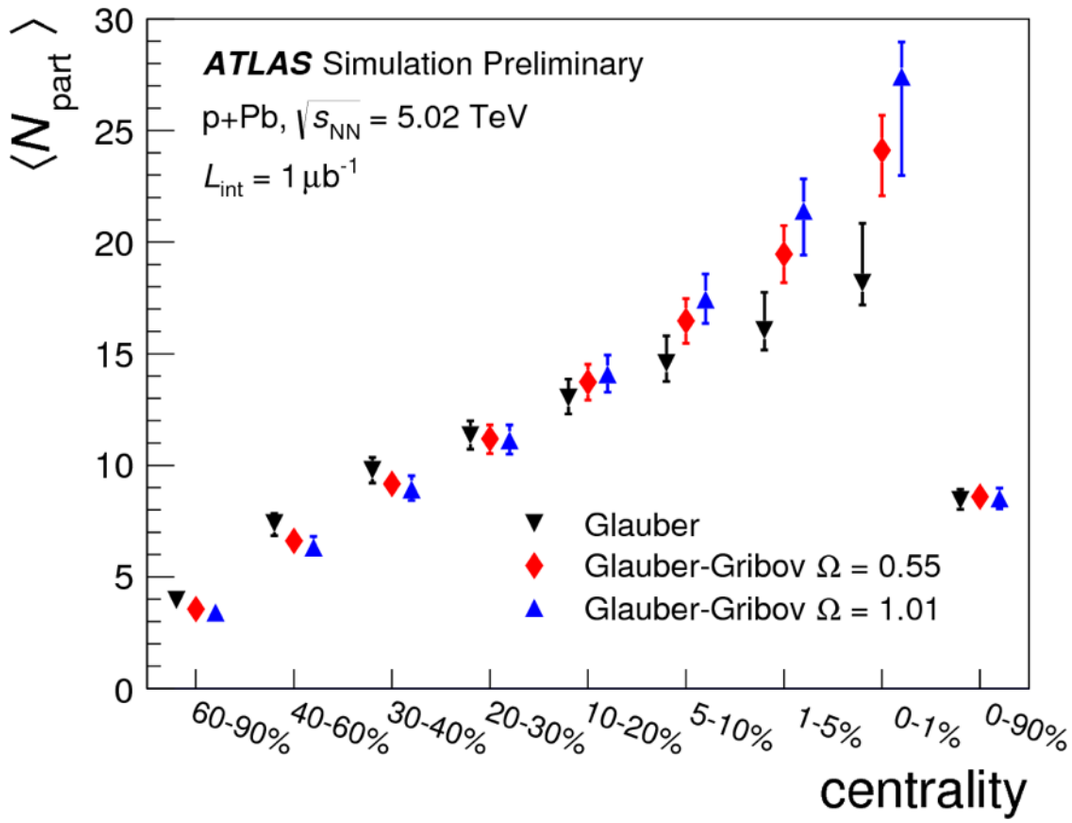

Mean Npart per ΣE_T interval, same intervals in all cases, for 3 different geometric models.

Relative to standard Glauber, GG $\langle N_{part} \rangle$ is smaller in peripheral, and larger in most central

Scaling of particle yields

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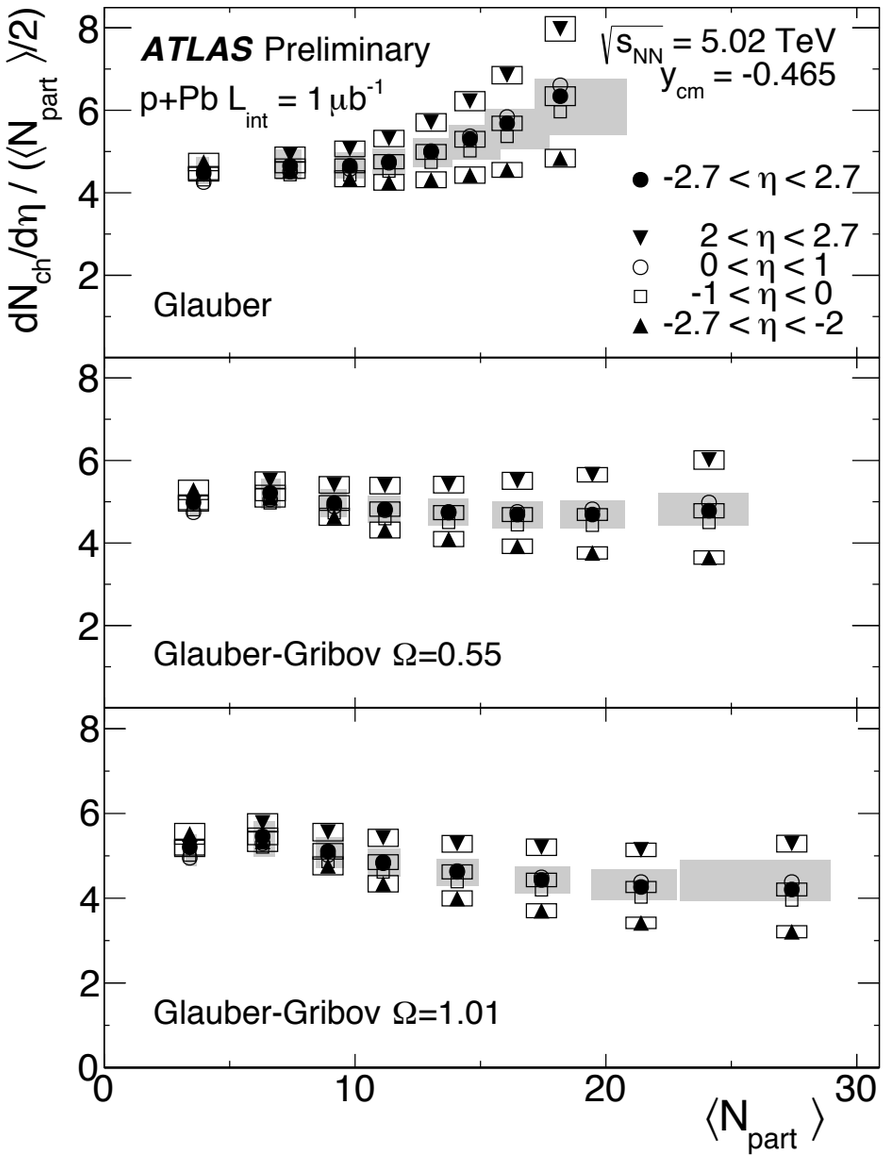
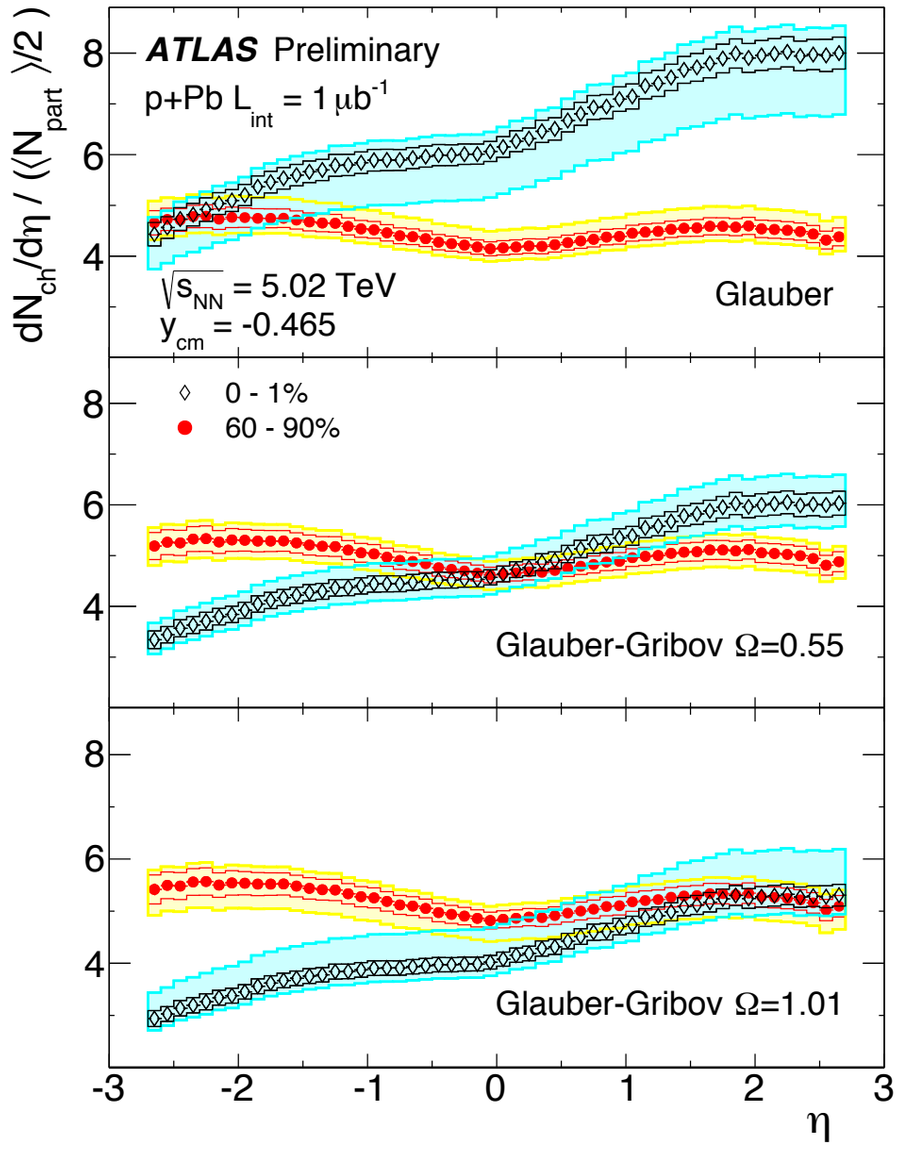


Yield per participant depends strongly on geometric model: standard Glauber increases, while Ω=0.55 is ~constant



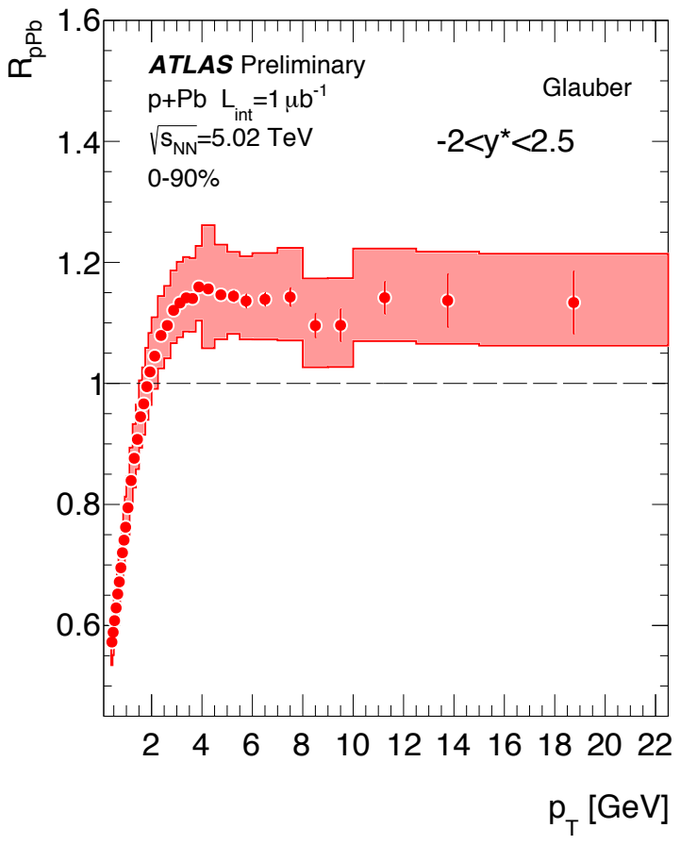
"Scaling region" depends strongly on geometric model: clearly need external input on NN collisions understand role of p+Pb!

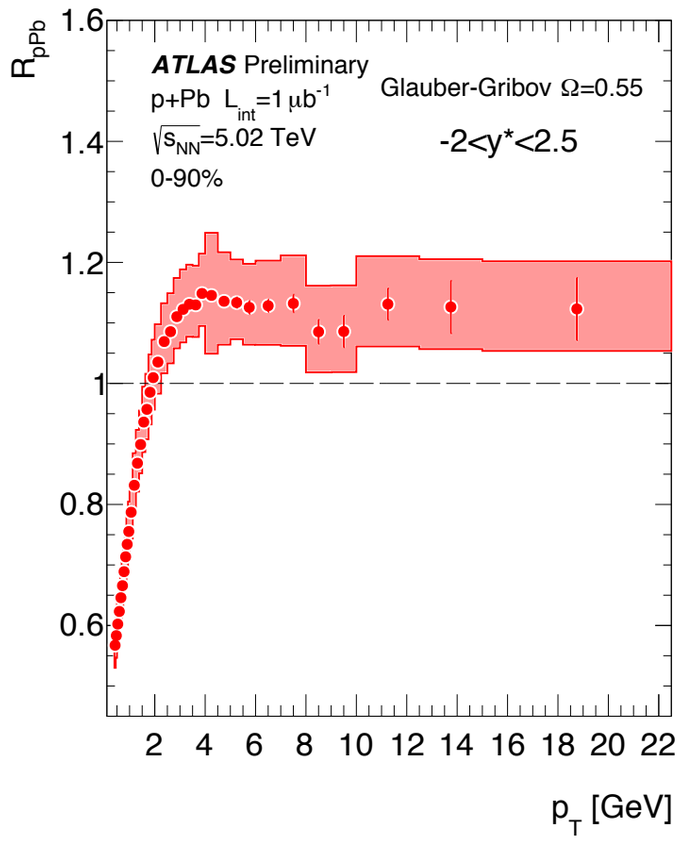
Hadron suppression in p+Pb

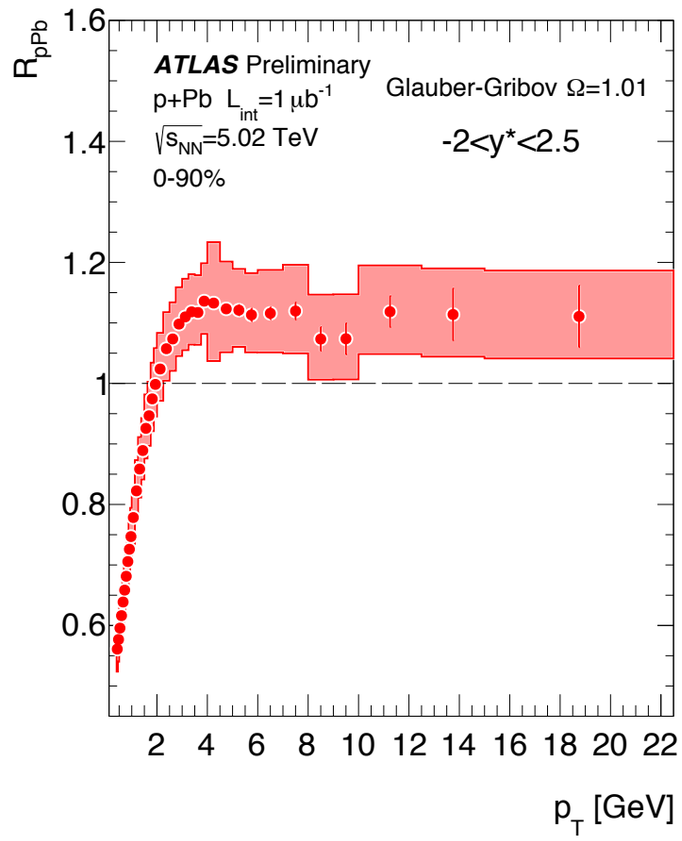
- An important first measurement in p+Pb to study transition from low p_T (multiplicity) to high p_T (jets)
  - R_{pPb} - suppression relative to pp
  - R_{CP} - suppression relative to 60-90% most peripheral
- Performed using pilot run data (low pileup) with reasonable statistics up to 22 GeV
- No compatible pp data $\sqrt{s}$=5.02 TeV, so also performed interpolation of 2.76 TeV and 7 TeV pp minimum bias data
- pp and p+Pb are in different CM frames, so data are analyzed in hadron rapidity $y^* = y - y_{CM}$
  - Corrected assuming all hadrons are pions ($y = y_\pi$)
  - Bin-by-bin "unfolded" to realistic mass spectrum (using HIJING, with assumptions cross checked with ALICE & CMS data)
- R_{CP} performed in pseudorapidity bins, with no shift to CM frame

Talks M. Spousta (Thurs. parallel)

Minimum bias, rapidity integrated R_{pPb}



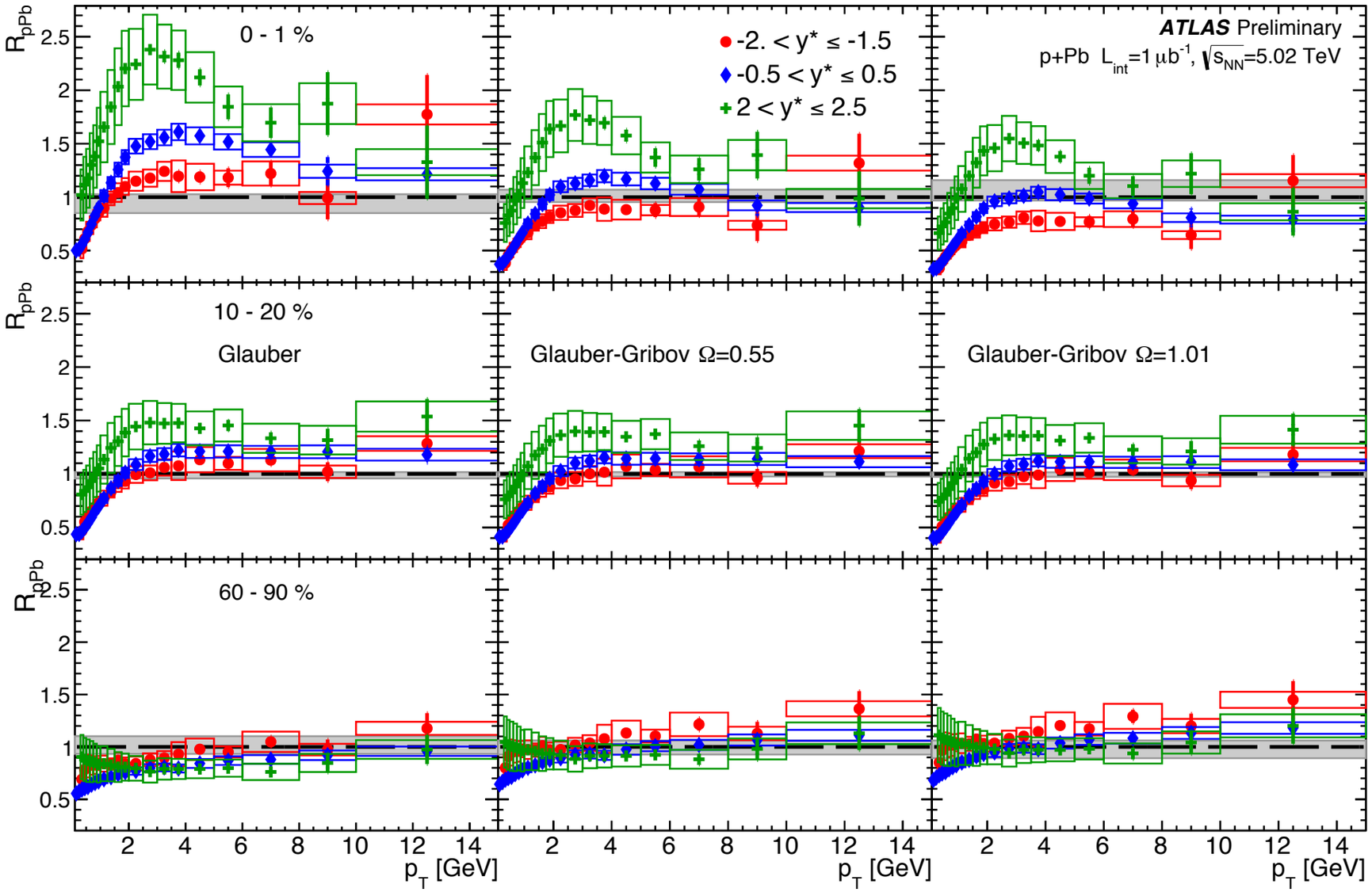




When integrating over rapidity & centrality,
little evidence of a "Cronin" like peak:
rather, a strong rise from 0.5 (participant scaling)
to a nearly-constant region at R_{pPb}~1.1

Only a weak dependence on geometric model choice

Rapidity dependence



Triple differential measurement: p_T, y* & centrality:

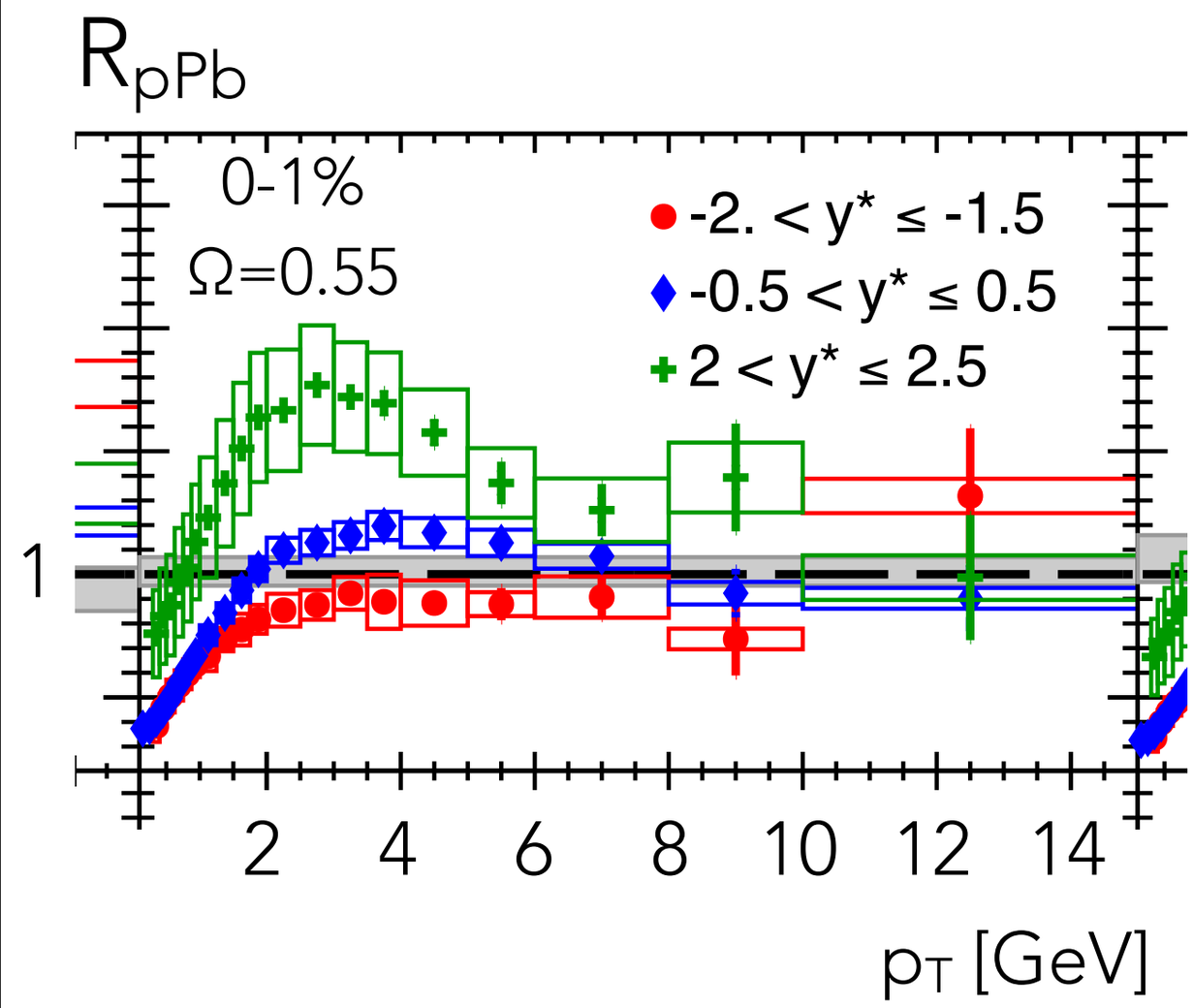
A real "Cronin peak" observed in 0-1% & in Pb-going direction

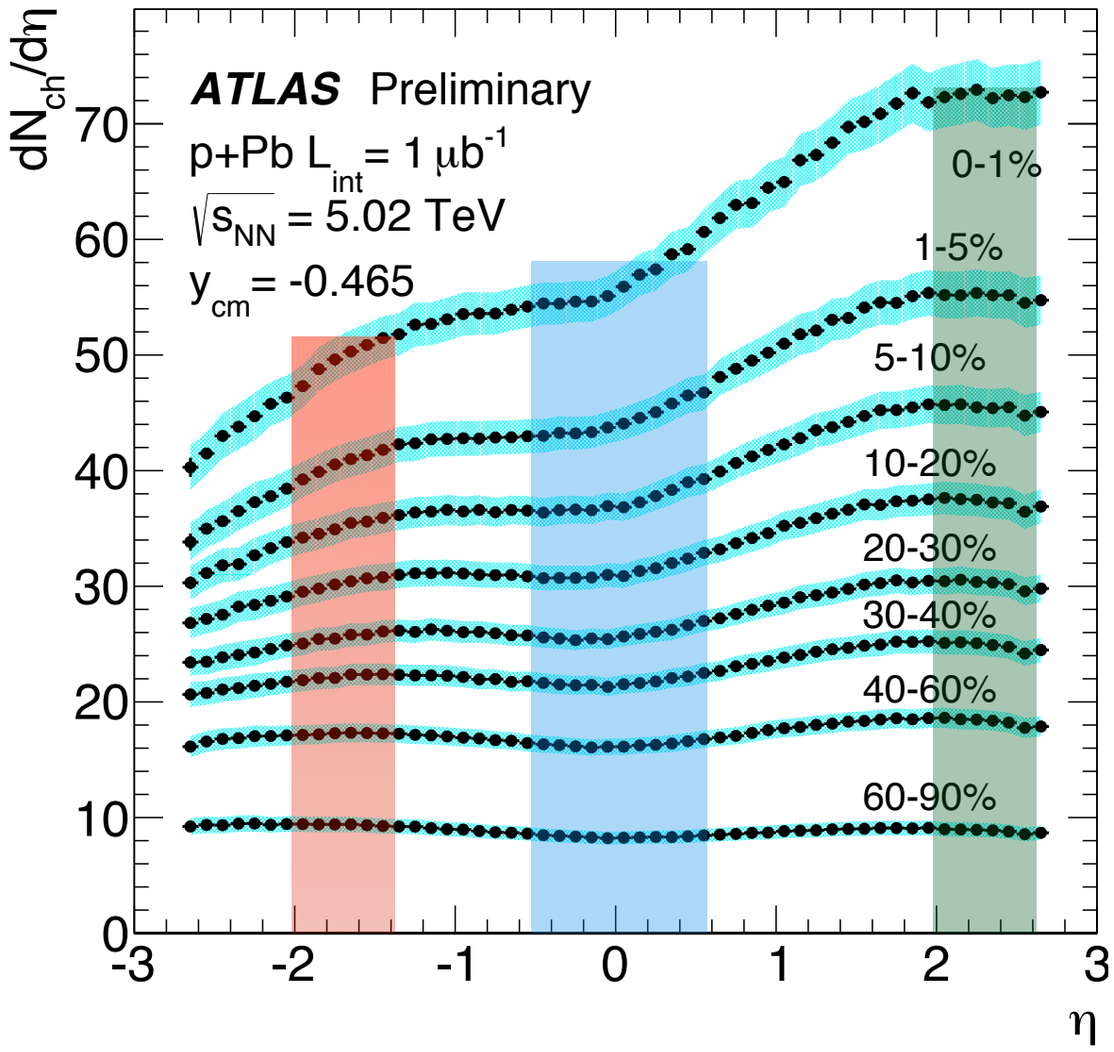
Ω=0.55 gives approximate scaling at high p_T

In general, no suggestion of suppression up to 15 GeV

Connection to multiplicity?

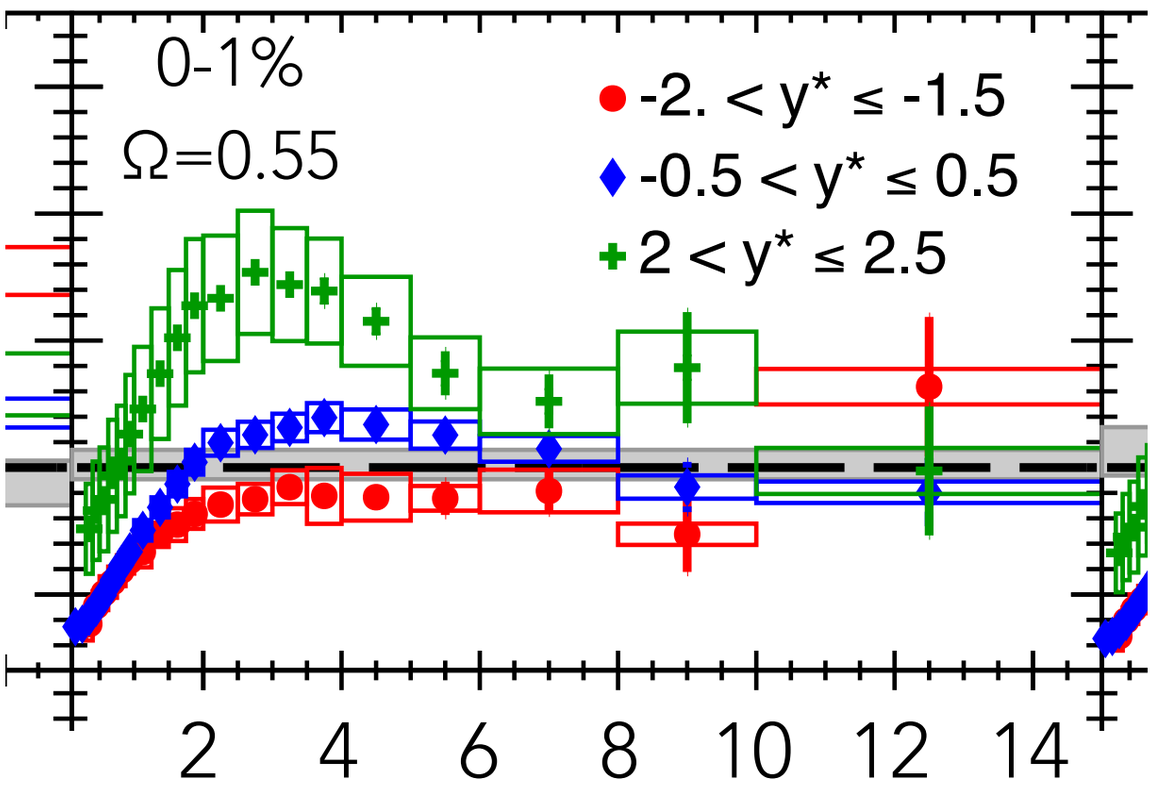
ATLAS-CONF-2013-096



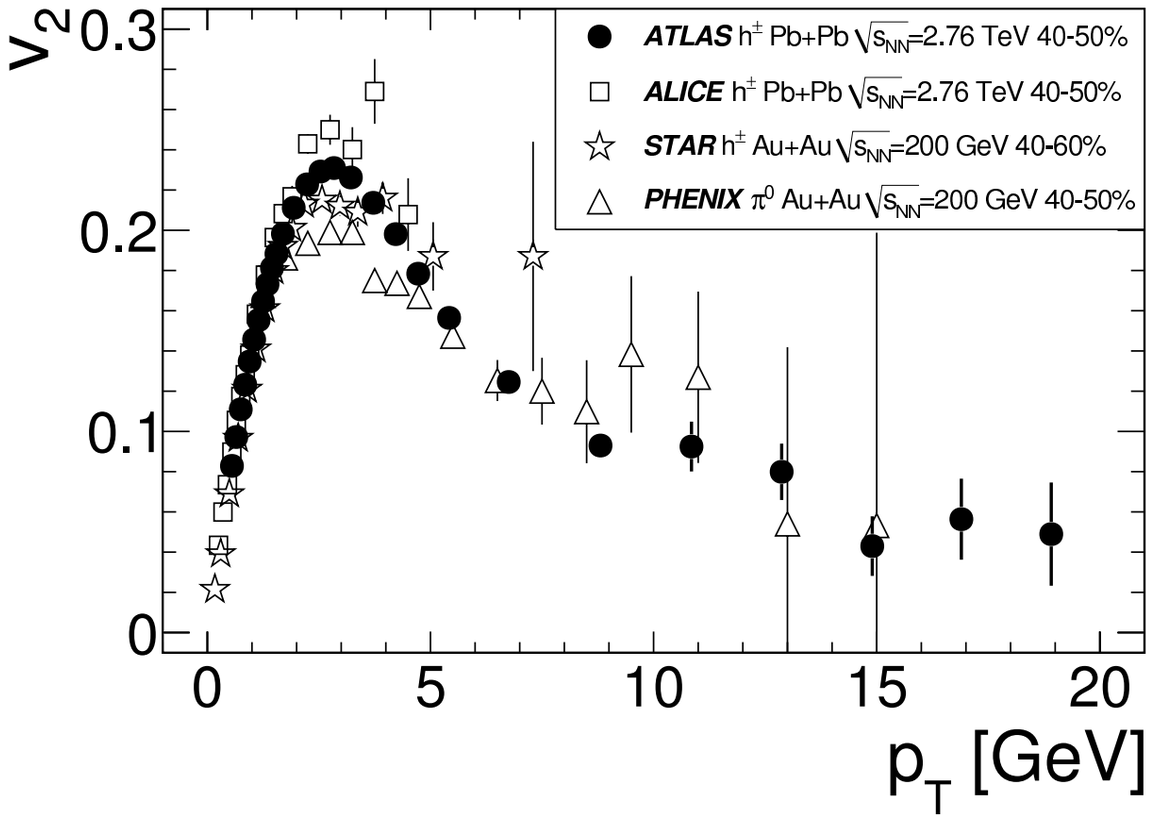


Observe correlation between multiplicity and magnitude of "Cronin" peak relative to constant region

Connection to elliptic flow?



ATLAS, Phys.Lett. B707 (2012) 330-348

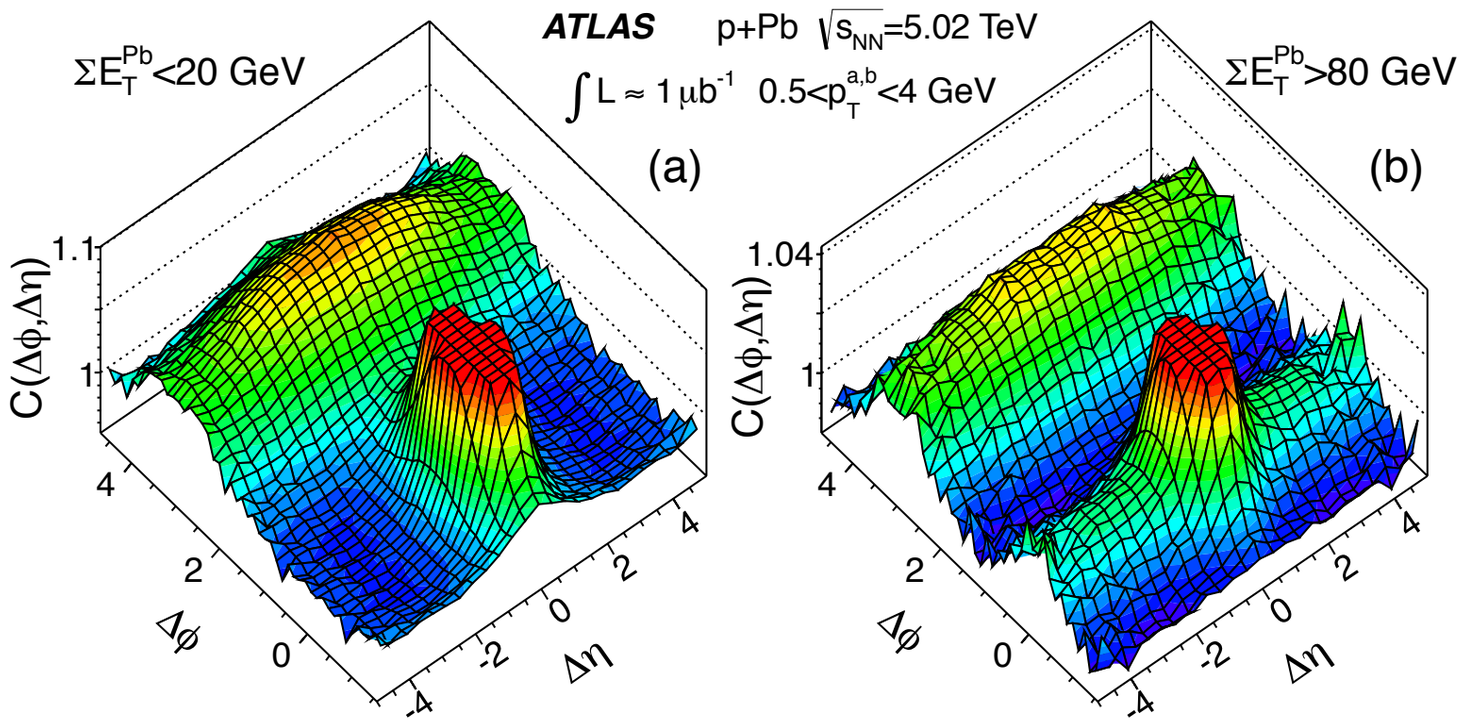


Observe similarity between "Cronin" peak and p_T dependence of elliptic flow in Pb+Pb: peak at 3 GeV and ~constant above 8 GeV: is the "Cronin" peak hydrodynamical in origin?

"Double ridge" in p+Pb: flow in p+Pb?

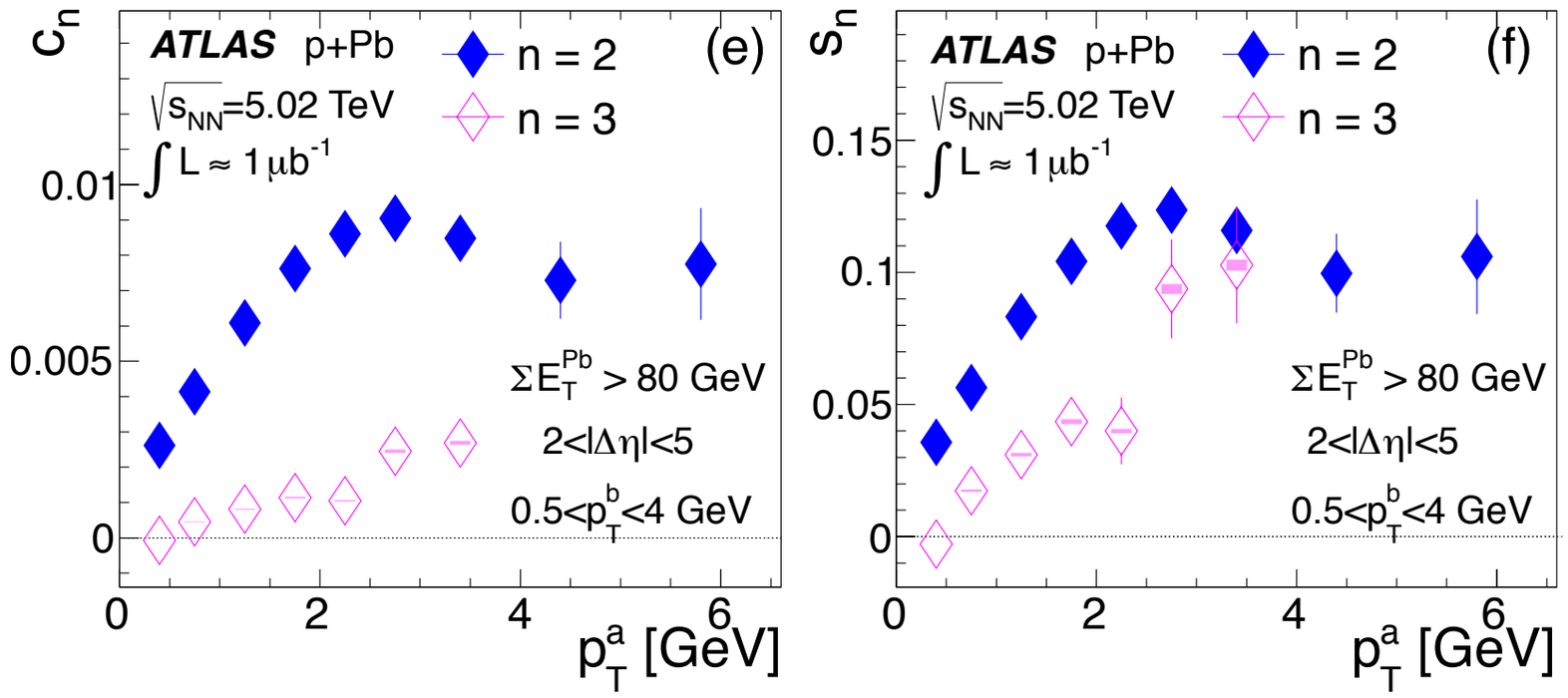
Talk by A. Milov

peripheral



central

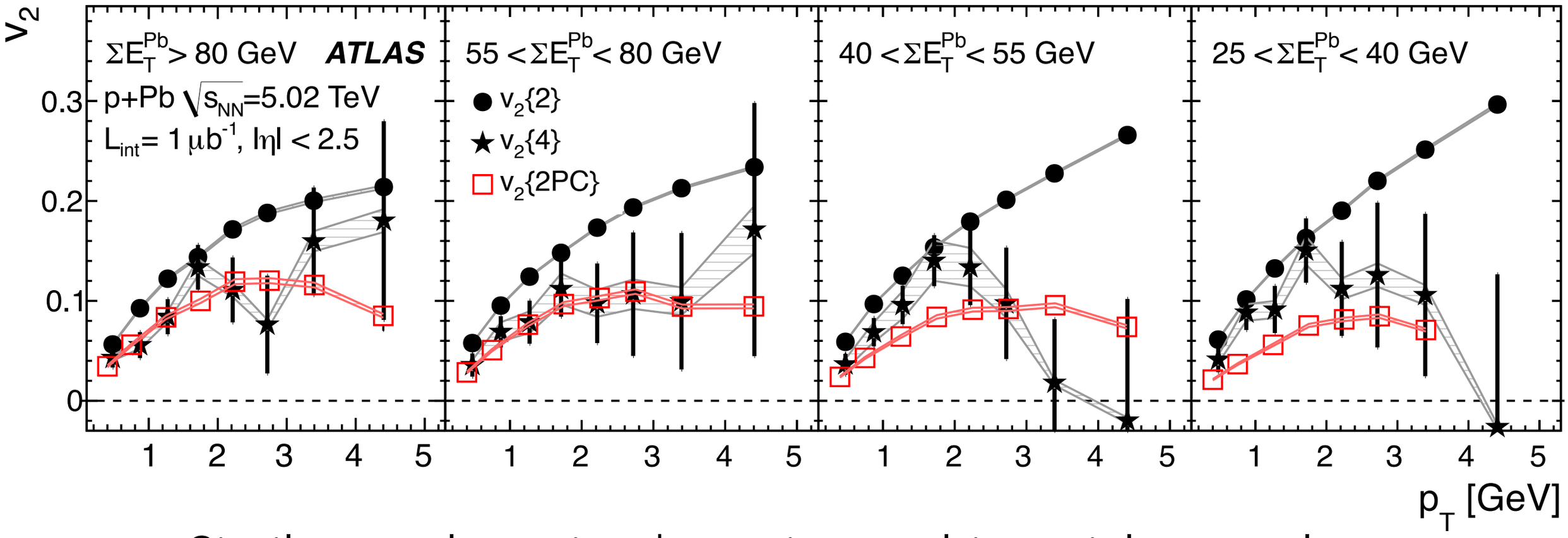
Phys. Rev. Lett. 110, 182302 (2013)



2PC shows significant v_2 & v_3

Confirmation of multiparticle correlations

Phys. Lett. B 725 (2013)



Similar results arrived at using multi particle cumulants:

2-particle cumulants still see non-flow at high p_T,

while 4-particle cumulants (*) agree with 2PC:

Coupled with data from all LHC experiments & PHENIX,

why shouldn't flow be visible in R_{pPb}?

Jets measured over a wide (pseudo)rapidity range in p+Pb collisions

- Full sample of 2013 p+Pb data
  - Both beam directions are included, 31 nb^{-1} total
- Jets reconstructed with identical algorithm as in Pb+Pb
  - Sensitive to local features (in) of the underlying event
- Corrected for trigger & reconstruction efficiency
- Unfolded using bin-by-bin correction factors
  - Only performed in regions where the corrections are relatively mild O(20%) or less, and where there is no centrality dependence on JES and JER
- Many corrections cancel in R_{CP}
  - Do not cancel when comparing with PYTHIA pp reference
- Systematics include uncertainties on:
  - JES, JER, reweighting, trigger, centrality

Talks by A. Angerami (Tuesday plenary) and D. Perepelitsa (Thursday parallel)

R_{CP} in rapidity bins vs. p_T

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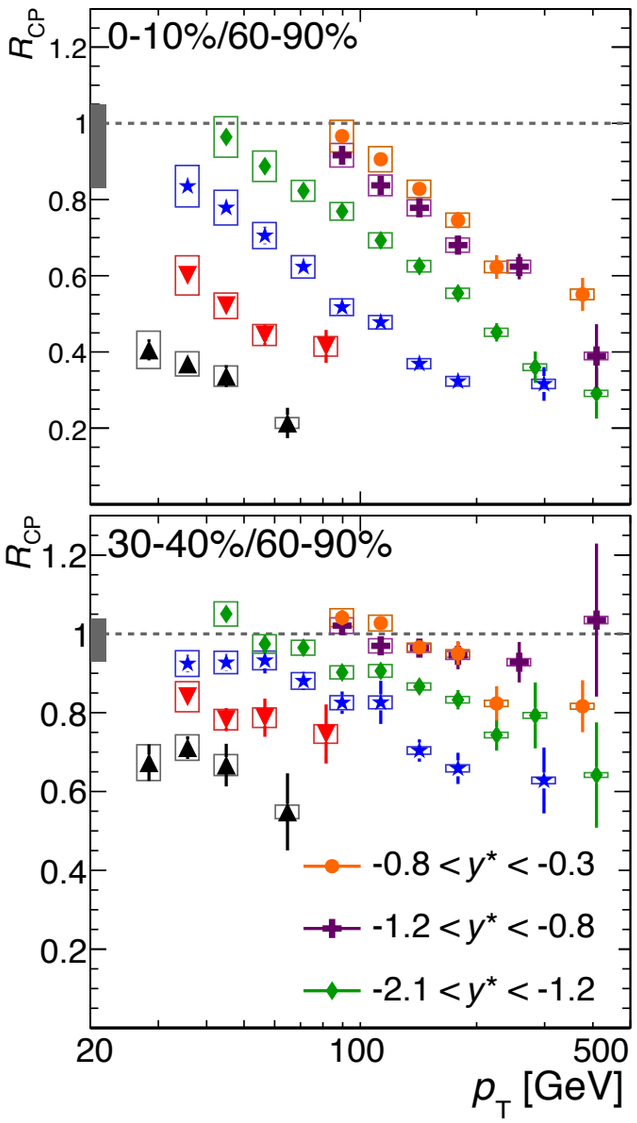
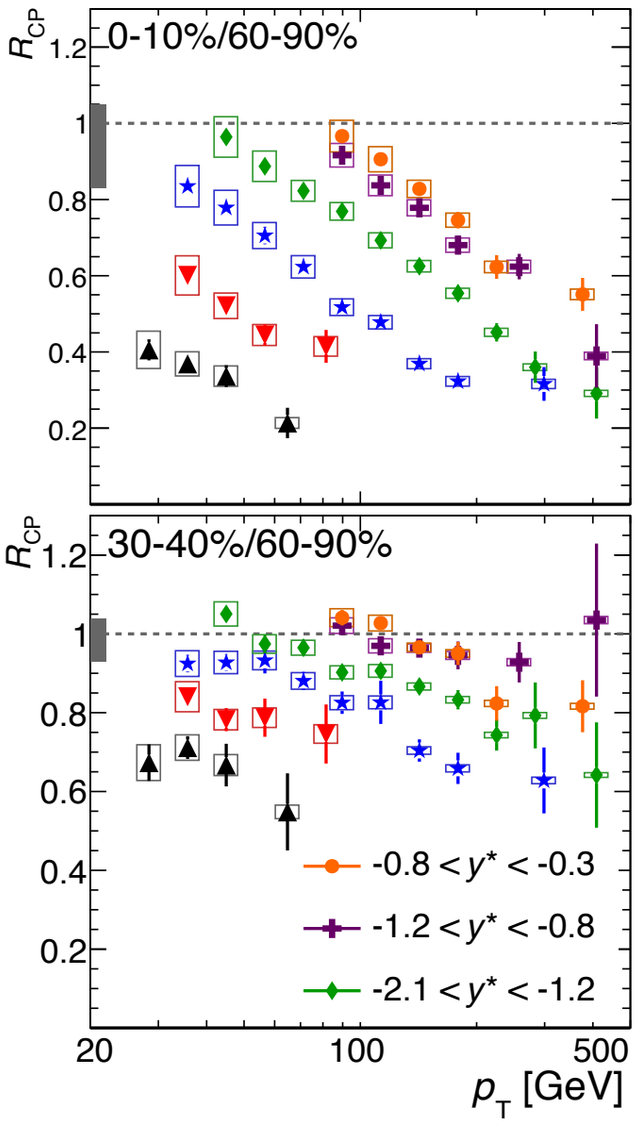


R_{CP} in rapidity bins vs. p_T

ATLAS-CONF-2013-105

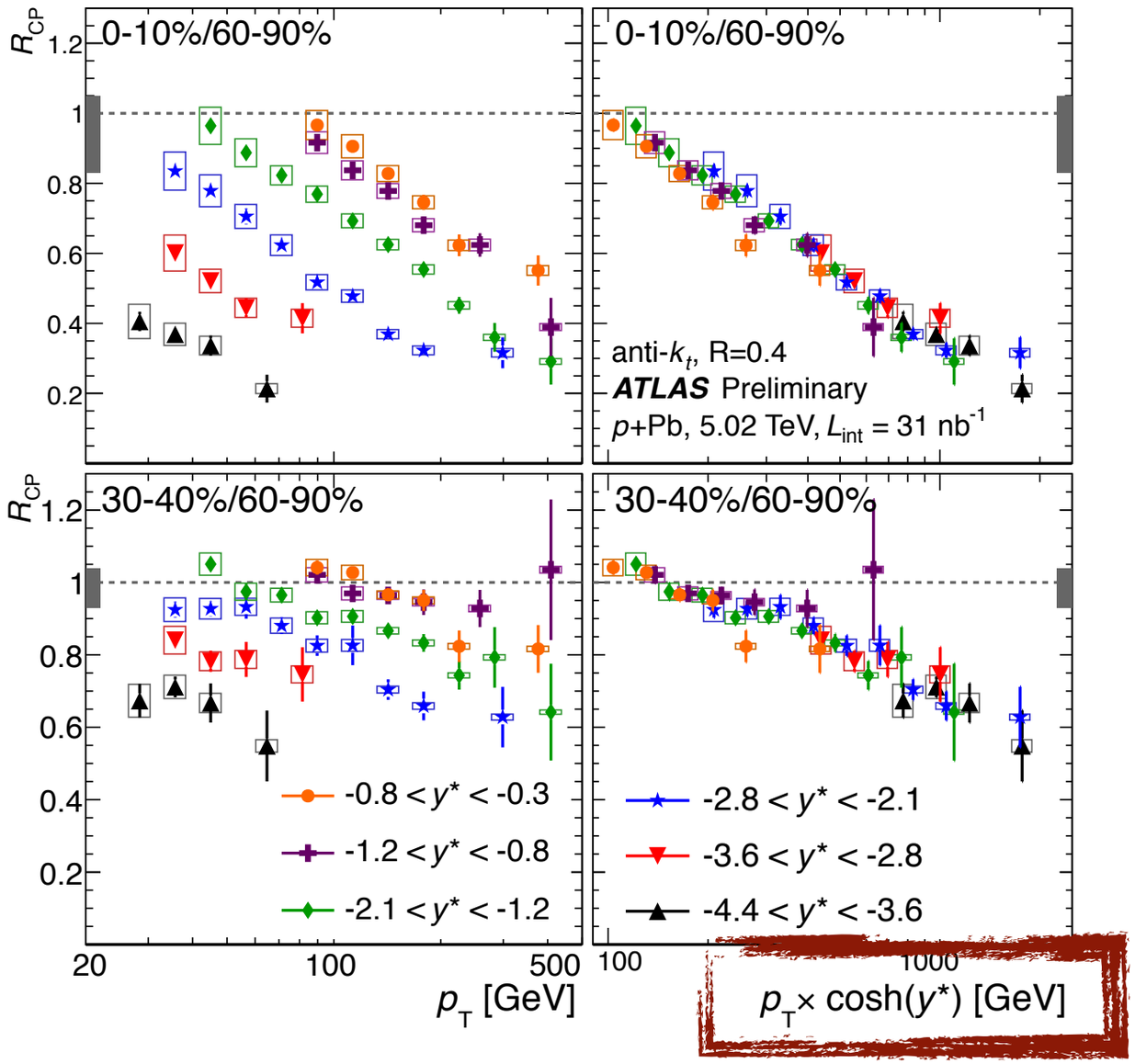


Strong suppression of central spectrum vs. peripheral

For a fixed centrality selection and **p_T**, R_{CP} decreases with increasing (p-going) y*

R_{CP} in rapidity bins vs. p_T and $\underline{p}$

ATLAS-CONF-2013-105



R_{CP} in rapidity bins vs. p_T and $\underline{p}$

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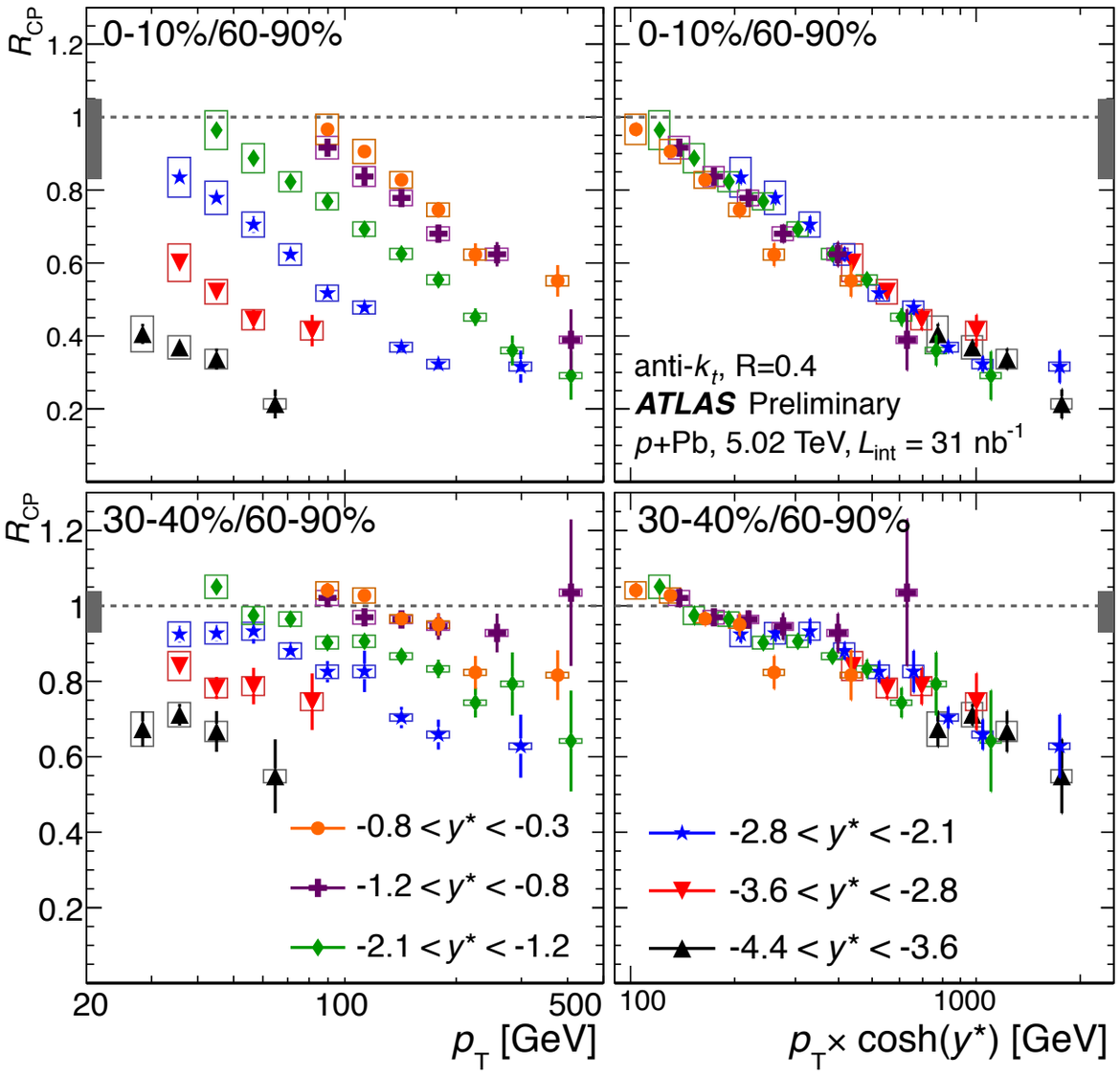

For same jet **momentum** (i.e. $p=p_T \cosh[y^*]$), scaling with rapidity, is observed at all centralities

The p-scaling is quite robust - and was not predicted (except perhaps as a scaling with Bjorken, not Feynman, "x")

Is this an indication of energy loss, e.g. initial state?

Suppression relative to PYTHIA (minbias)

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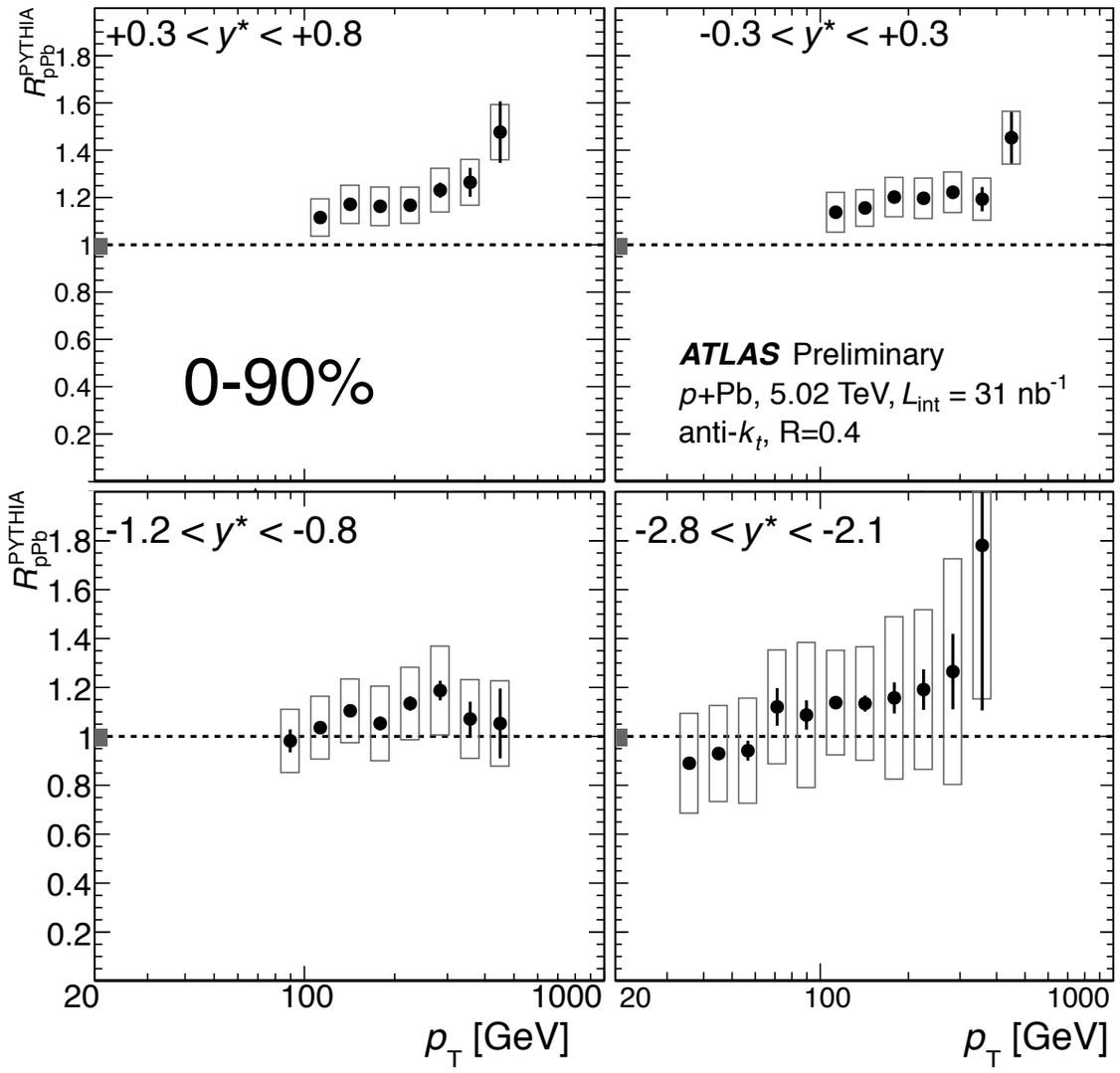

R_{pPb} in y* bins, using PYTHIA as pp reference:

~constant at 1.1-1.2 is observed from mid-y* to forward.

no substantial net suppression or enhancement

R_{pPb}(PYTHIA) in centrality bins

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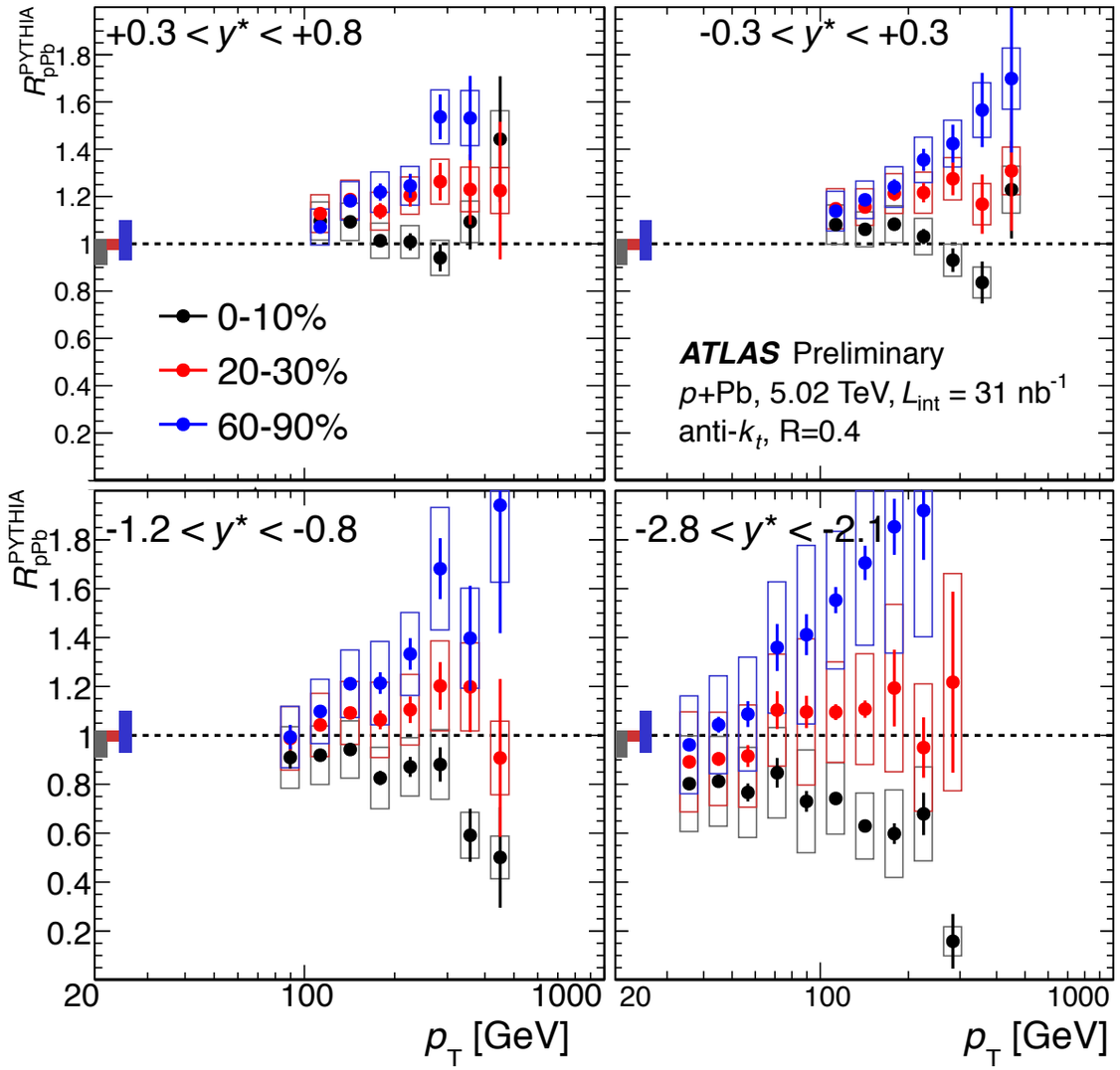


Dividing 0-90% into centrality intervals shows, that with increasing p_T

- jets are **enhanced** in peripheral collisions
- jets are **suppressed** in central collisions

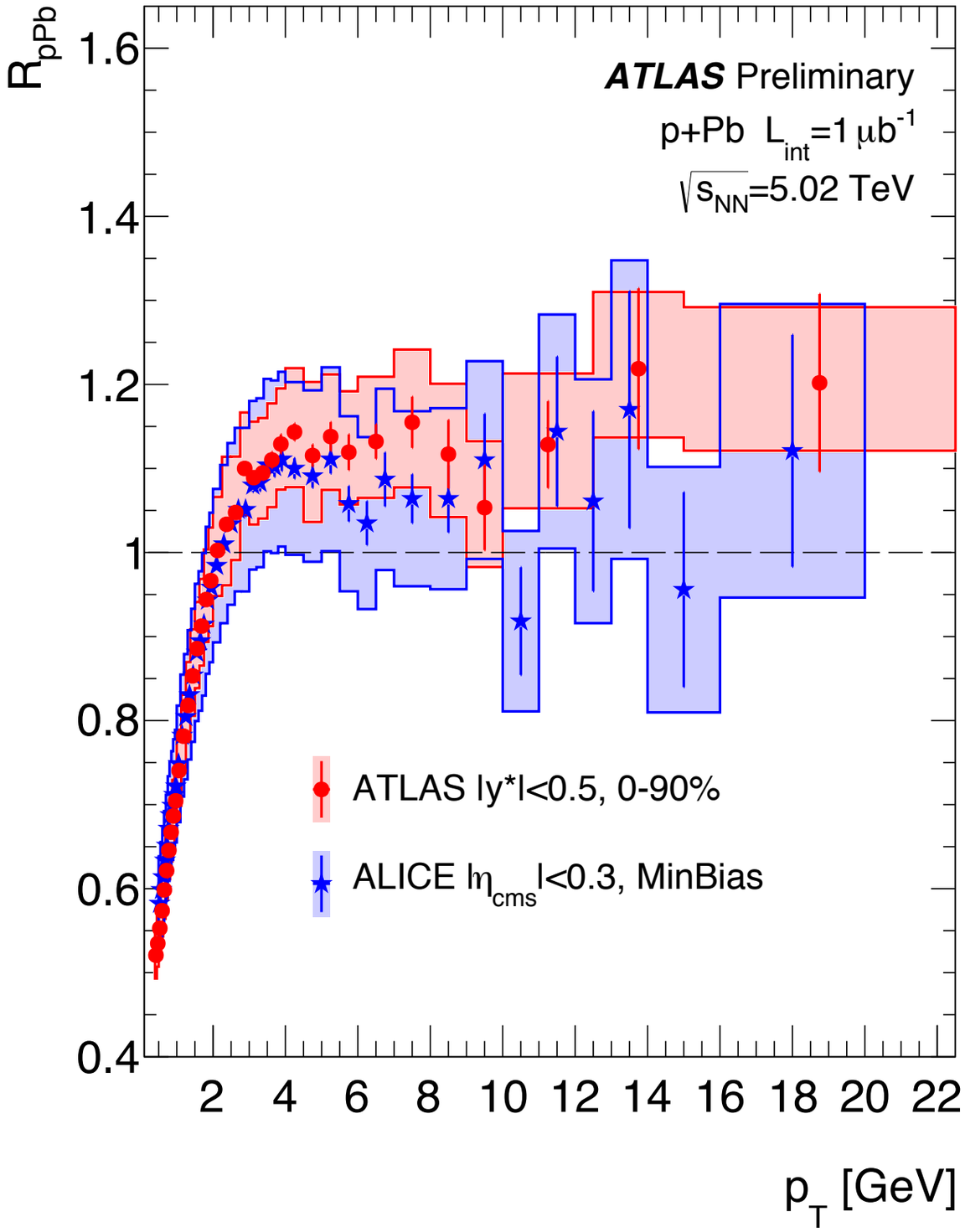
Similar effect seen in PHENIX: similar origin?

Lessons from comparing Pb+Pb & p+Pb

- Symmetric (Pb+Pb) vs. asymmetric (p+Pb) systems
  - Leaves clear signature in $dN_{ch}/d\eta$ at forward angles
  - Strong rapidity dependence to magnitude of "Cronin" peak in R_{pPb}
- New ideas about the NN aspect of Glauber calculations
- Collective effects
  - Correlations show clear signatures of collective effects
  - Does similar p_T dependence of R_{pPb} and flow correlations suggest common origin?
- Nuclear wave function at forward rapidities
  - Clear evidence of isospin effects in W production in Pb+Pb
  - Z in Pb+Pb shows little modification relative to pp
  - No striking evidence of nPDFs even at forward rapidities from W/Z
- Jet suppression
  - Clear suppression by a factor of 2 between peripheral and central
  - Essentially no suppression observed in minimum bias p+Pb
  - "p scaling" of forward jet suppression in p+Pb an intriguing, unexpected feature

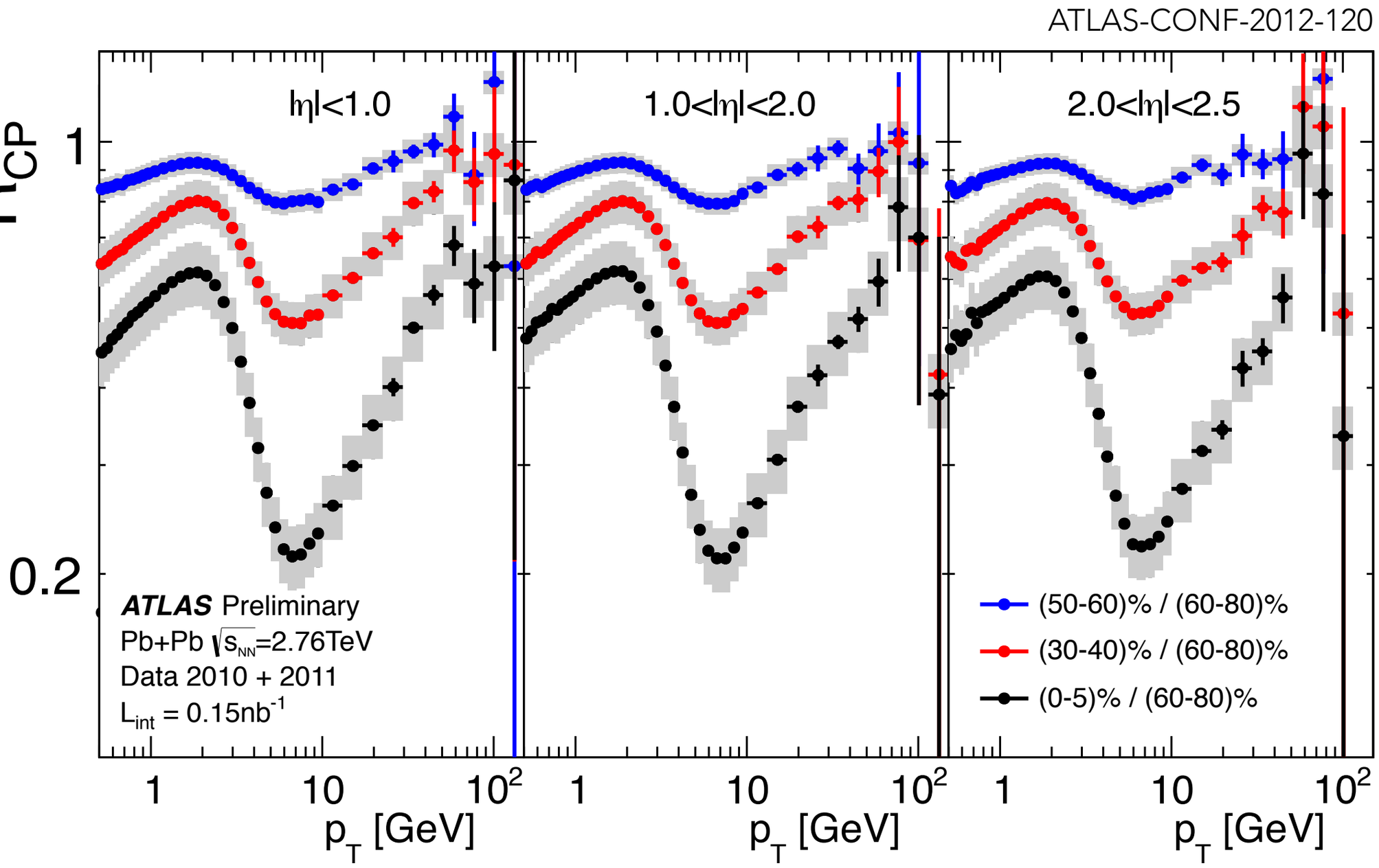
We are "looking forward" to the next HI and p+Pb runs, with higher energy and higher luminosity

R_{pPb} comparison with ALICE



Extra slides

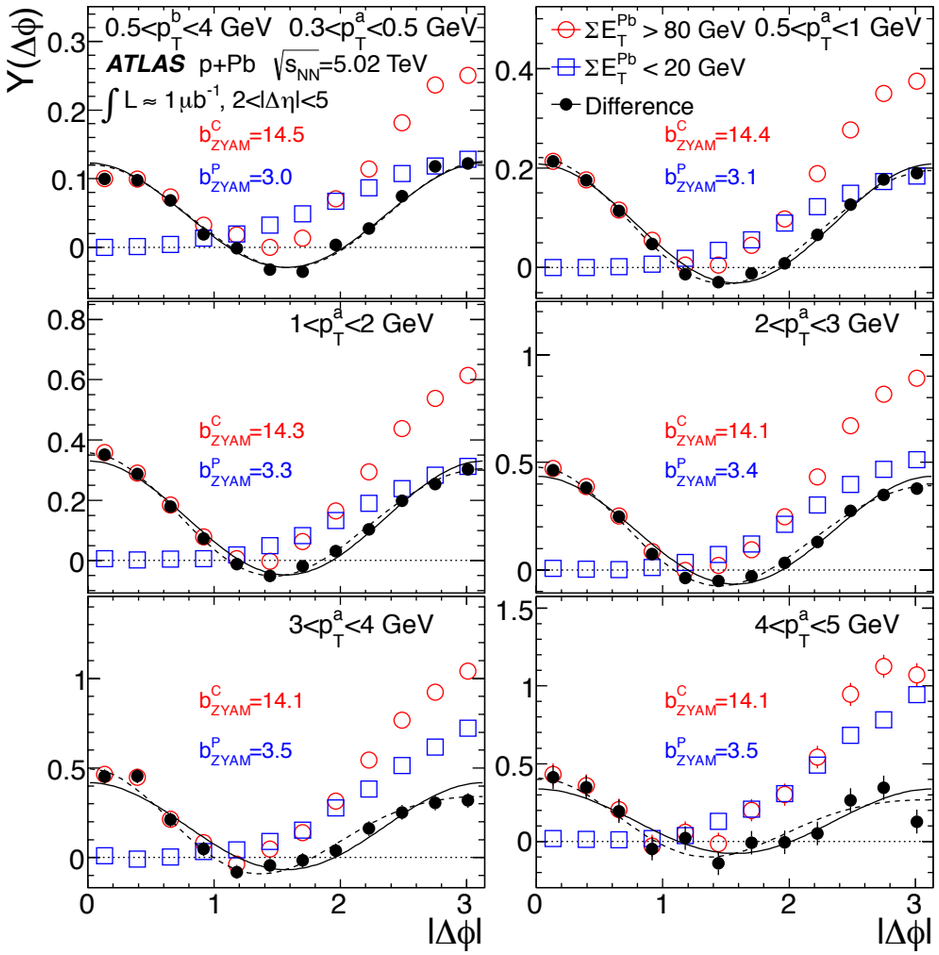
"Cronin" peak in R_{CP} vs. η

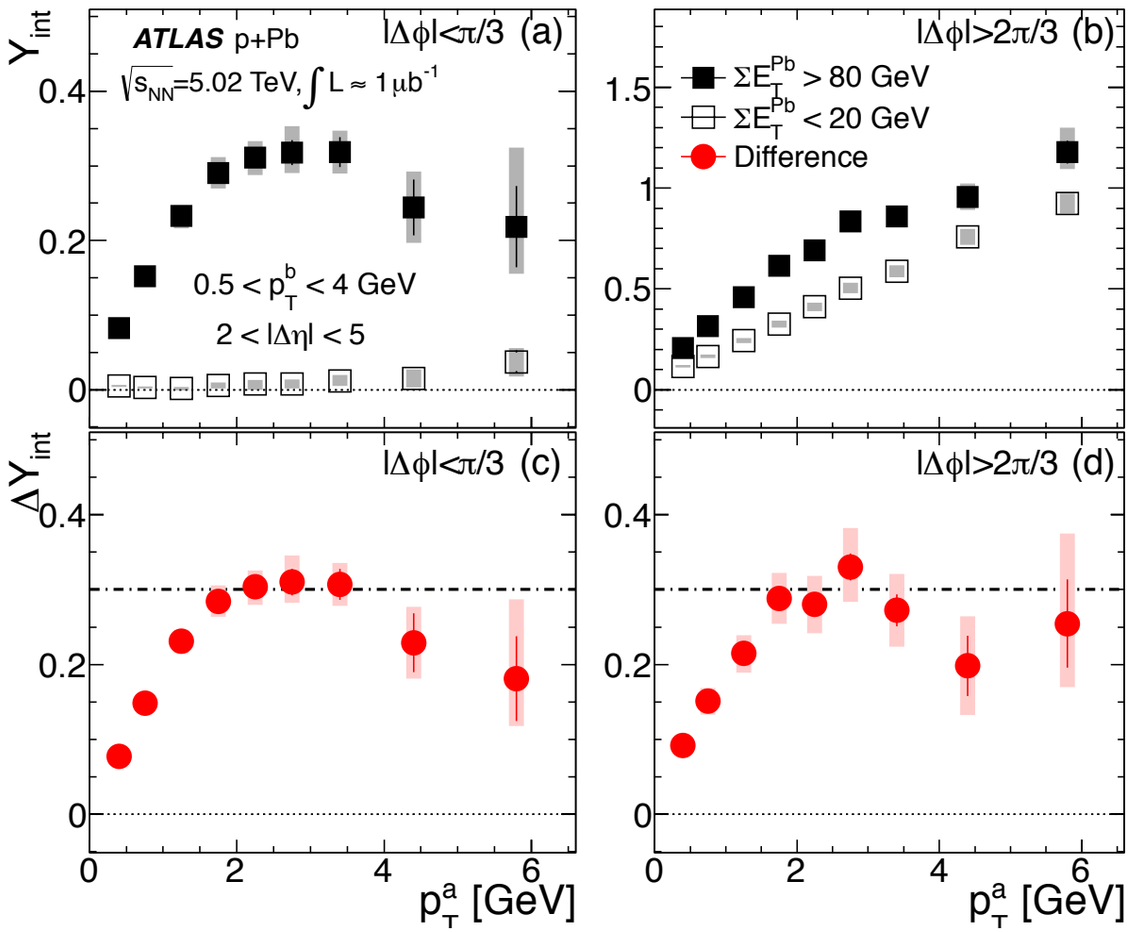


Very mild change in "Cronin" peak vs rapidity

The symmetric ridge

Phys. Rev. Lett. 110, 182302 (2013)

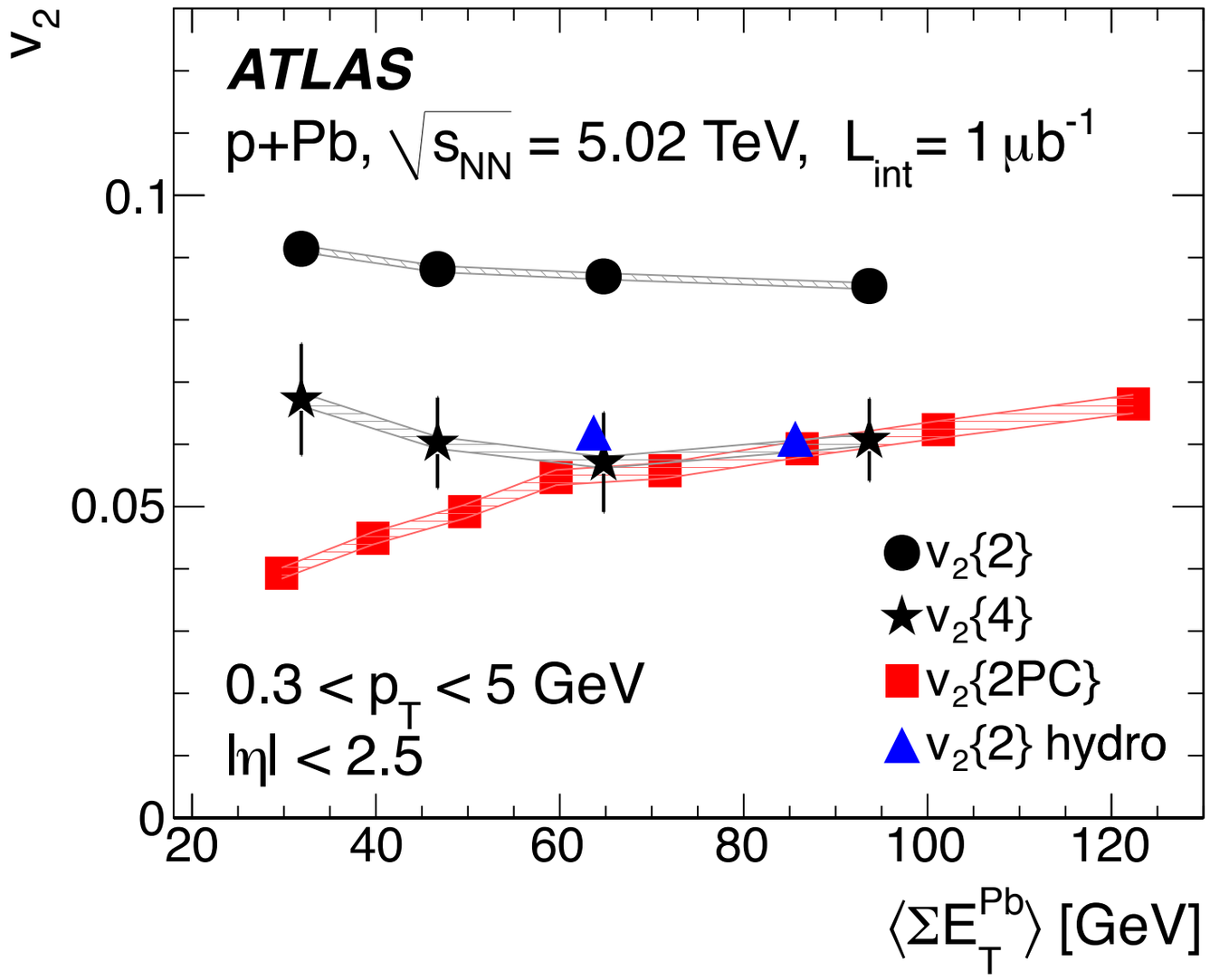




Subtracting the constant recoil contribution leaves a sinusoidal yield vs. $\Delta\phi$: near and away side yields are nearly identical, and behave similarly to Pb+Pb

Integrated v_2 vs. centrality

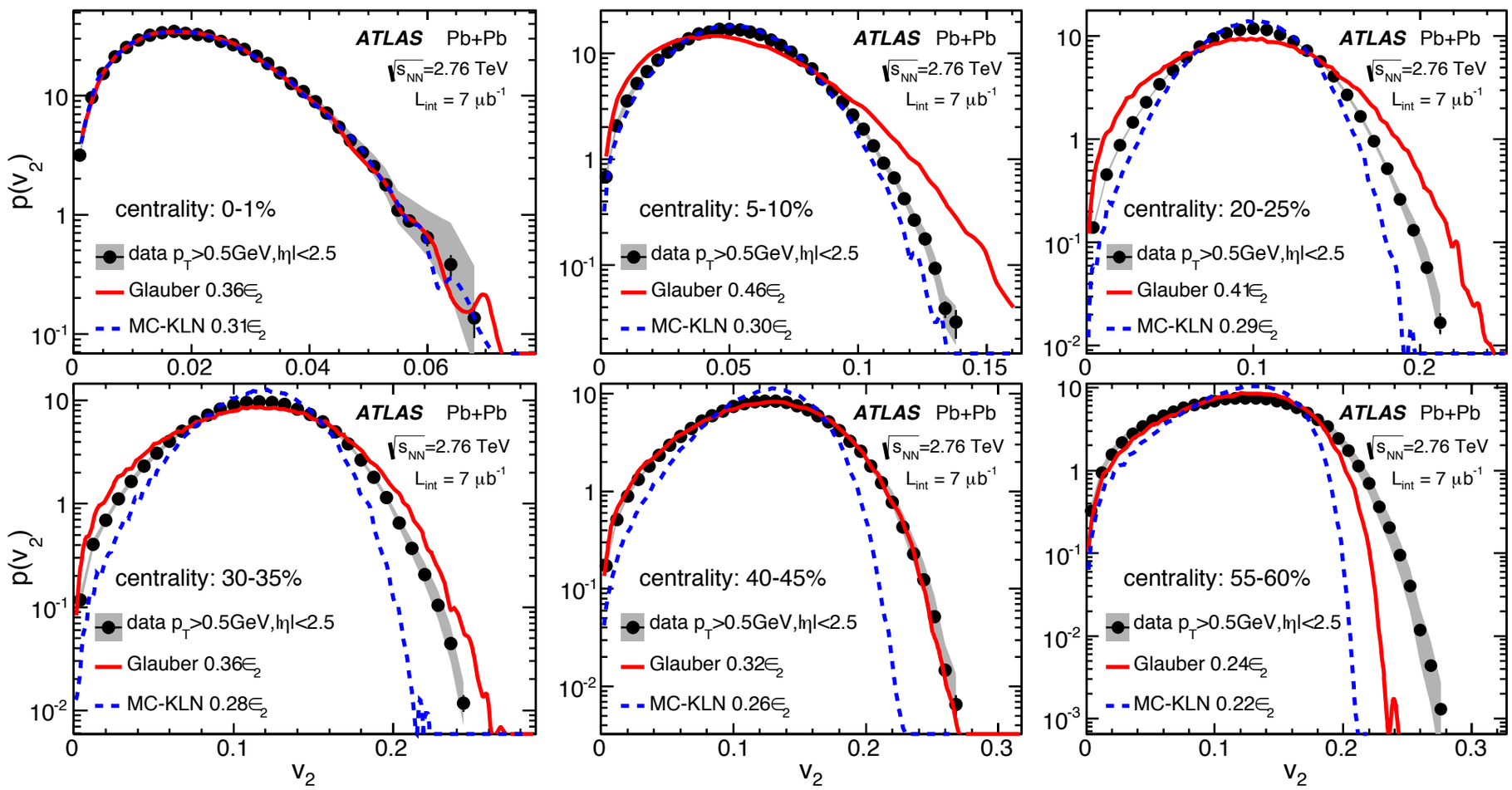
Phys. Lett. B 725 (2013)



For mid-central and beyond, 2PC and $v_2\{4\}$ tell the same story, similar to hydro calculations

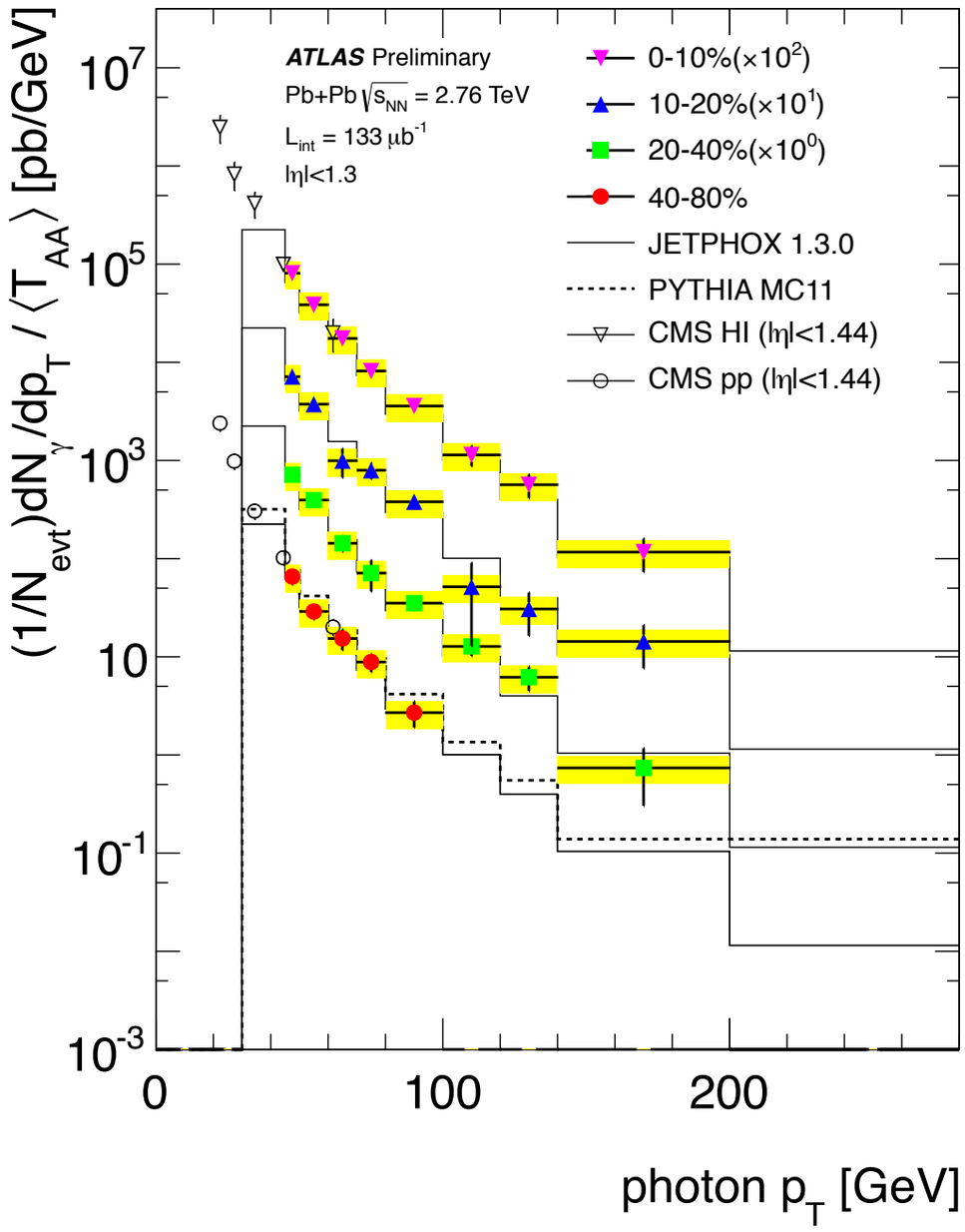
Flow fluctuations

arXiv:1305.2942



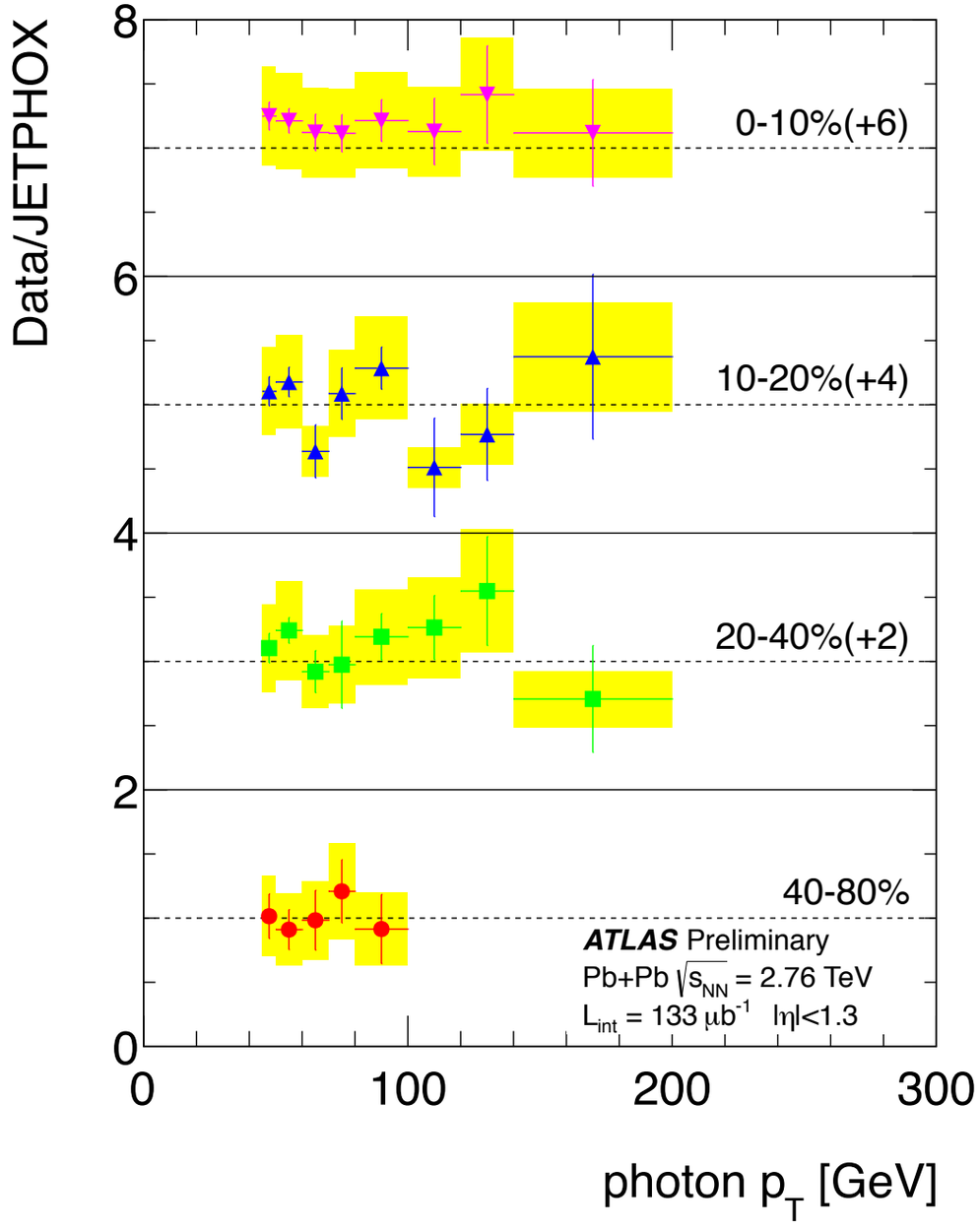
Detailed distributions of P(v_2) are 2D Gaussians in most central events, but agree better with Glauber or MC-KLN in different centrality bins!

Hard Probes: Photon yields



Photon yields reconstructed in $|\eta|<1.3$

ATLAS-CONF-2012-051



Yields compare well with JETPHOX 1.3.0 (NLO QCD)