p-Pb at the LHC:

ALICE Results and Plans

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for the ALICE collaboration

Yale

ALICE

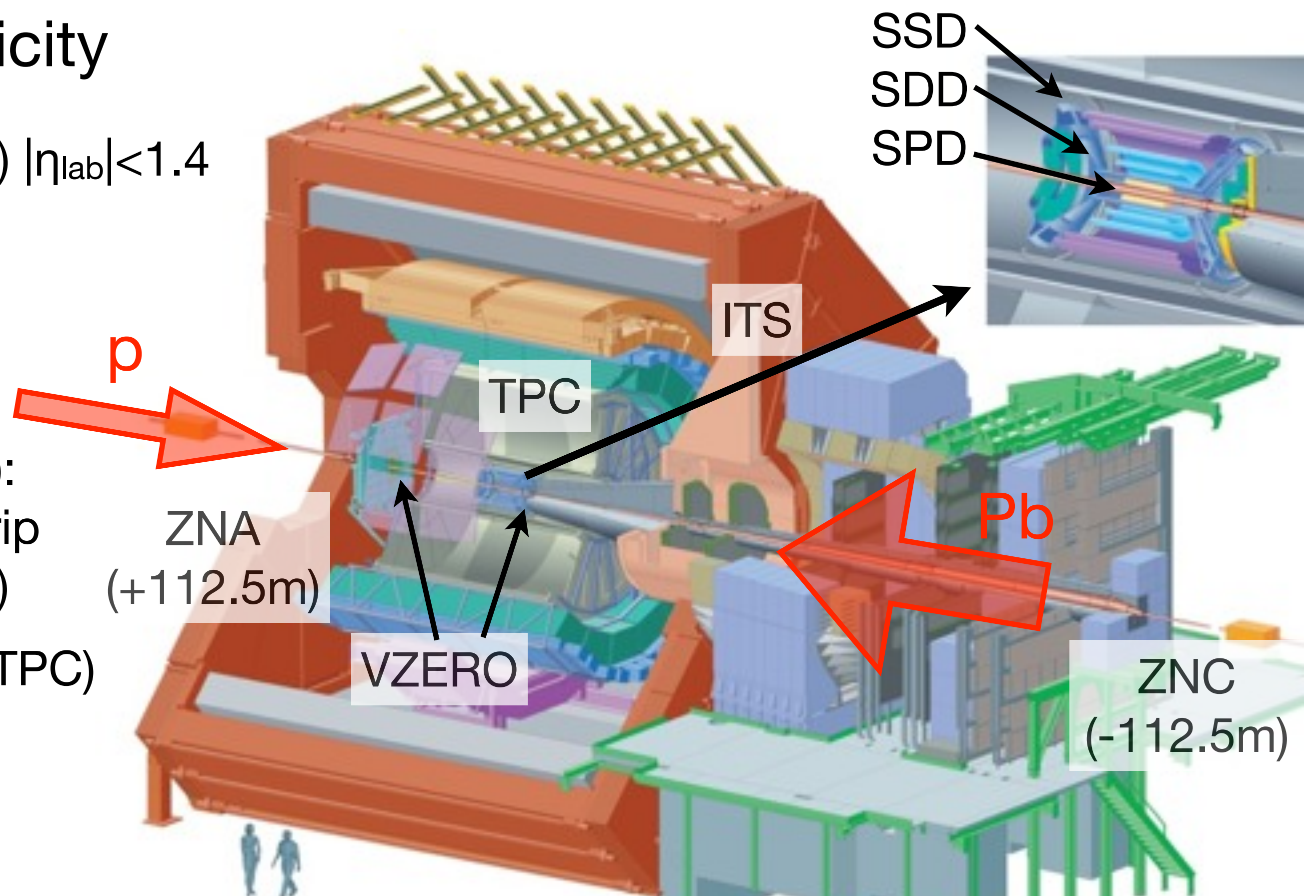
The Physics of p+A Collisions at RHIC
January 7-9, 2013, Brookhaven National Lab

ALICE p-Pb Overview

- Pilot run on September 13, 2012
  - $\sqrt{s_{NN}}$ = 5.02 TeV (4 TeV p + 1.58*A* TeV Pb)
  - center of mass moves with Δy=-0.465 in direction of p beam
  - ≈ 2M p-Pb events recorded
  - originally planned for accelerator/experiment setup, the pilot run yields physics results!
- Results from the pilot run
  - charged particle pseudorapidity density
    arXiv:1210.3615, accepted at Phys. Rev. Lett.
  - transverse momentum spectra and nuclear modification
    arXiv:1210.4520
  - di-hadron correlations
    arXiv:1212.2001, accepted at Phys. Lett. B
- Plans for the 2013 p-Pb run

The ALICE Experiment

- Event selection
  - VZERO-A ($2.8<\eta_{lab}<5.1$), VZERO-C ($-3.7<\eta_{lab}<-1.7$)
  - Neutron zero degree calorimeters (ZNA, ZNC)
- Charged particle multiplicity
  - Silicon Pixel Detector (SPD) $|\eta_{lab}|<1.4$
- p_T spectra, di-hadron correlations
  - Inner Tracking System (ITS): Silicon Pixel, -Drift and -Strip Detectors (SPD, SDD, SSD)
  - Time Projection Chamber (TPC) $|\eta_{lab}|<0.9$ to 1.5



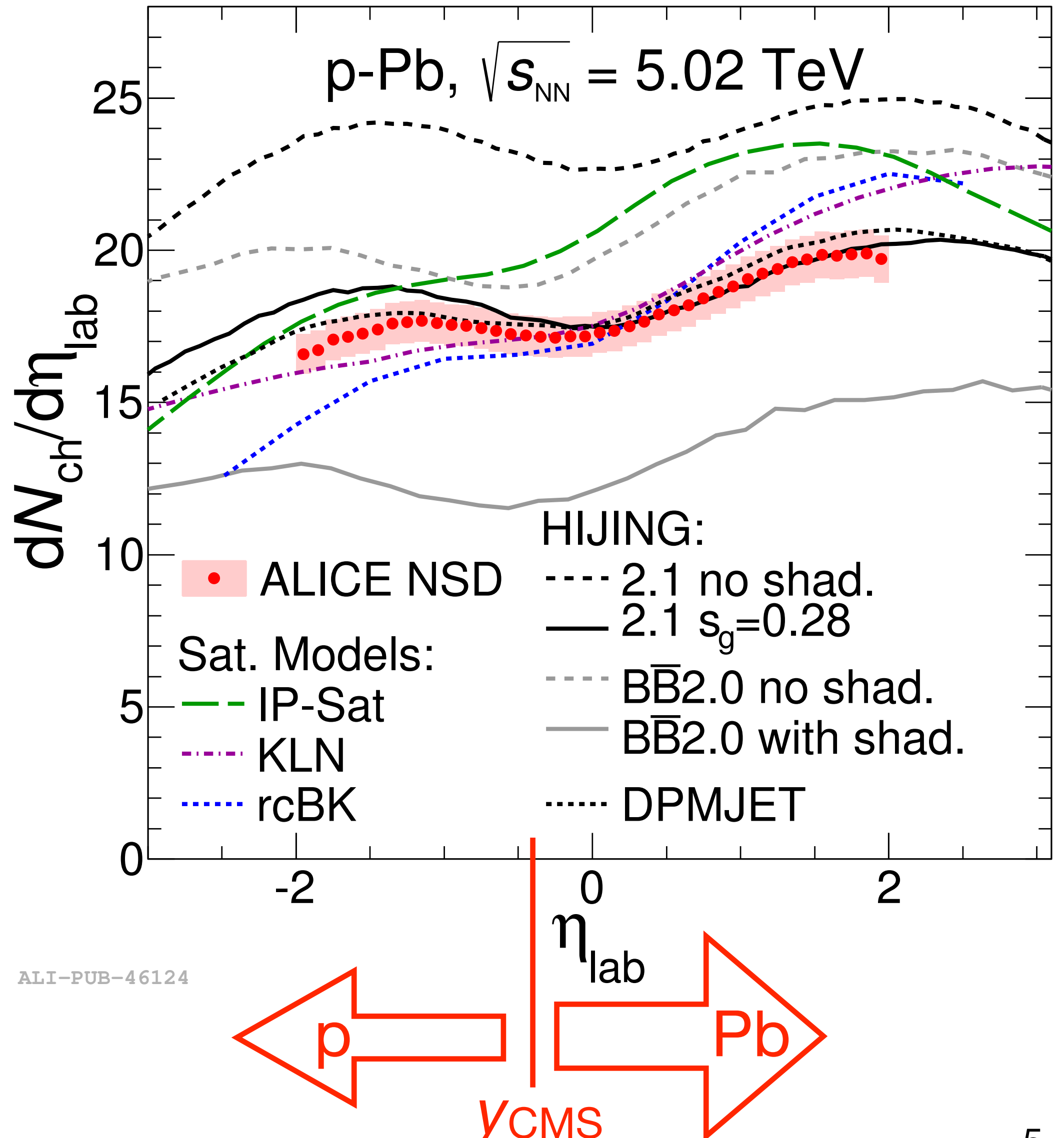
Event Selection

- Event selection
  - VZERO-A AND VZERO-C signal
  - Neutron zero degree calorimeters (ZNA, ZNC): background removal and control trigger
- Resulting event sample
  - non single-diffractive (NSD)
  - negligible contamination from SD and EM processes
- NSD in p-Pb
  - at least one binary N+N interaction is NSD (Glauber picture)
  - definition confirmed by model: in DPMJET, SD p-Pb collisions are concentrated on the surface of the nucleus (and have $N_{part} = 2$)
- Validated from cocktail of models

$dN_{ch}/d\eta$ Pseudorapidity Density

- Tracklet analysis with SPD hits
  - dominating systematic uncertainty 3% from normalization
- Reach of the SPD extended to $|\eta_{lab}| < 2.0$ using displaced vertex events
- $y_{CMS} = -0.465$
- Saturation models predict a steeper slope of the double-hump structure

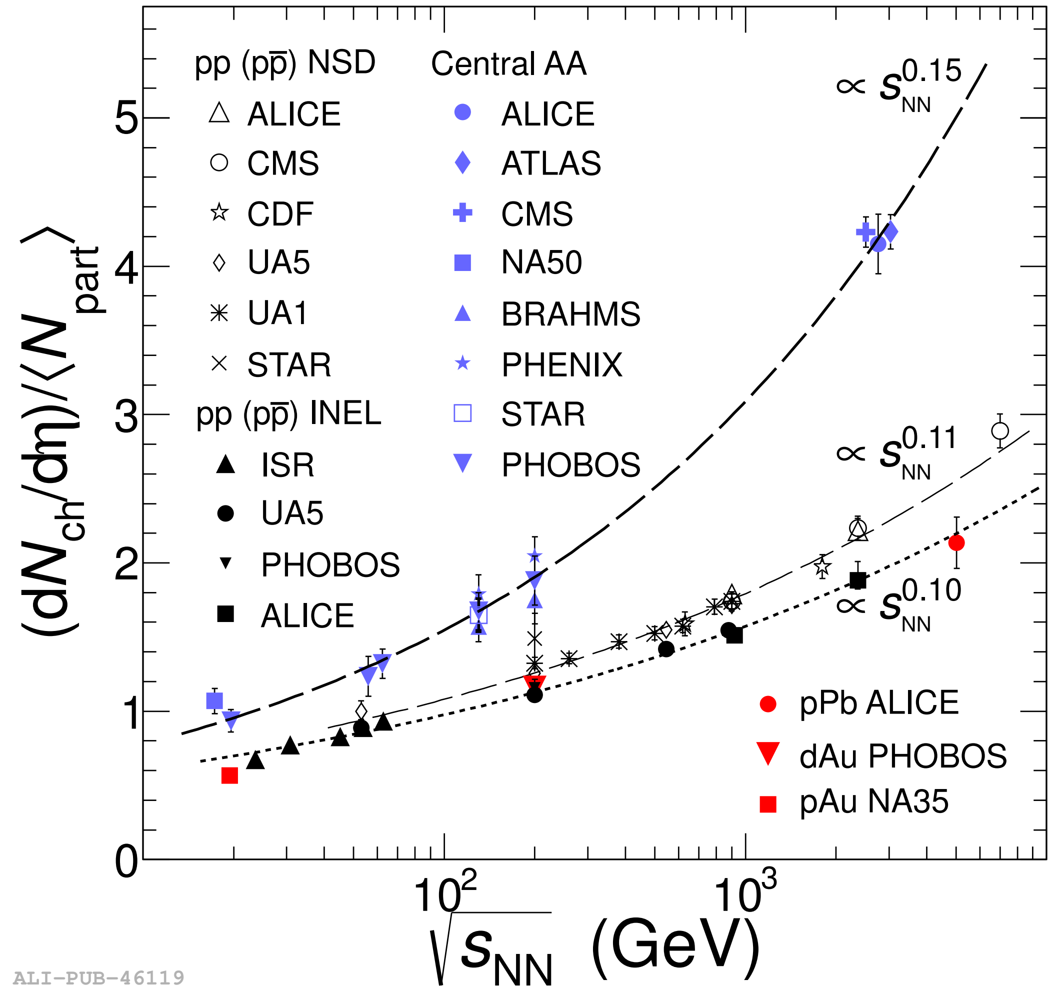
arXiv:1210.3615



Energy Dependence

- Normalization by <N_{part}> = 7.9 (Glauber MC)
- Midrapidity $dN_{ch}/d\eta$ lies
  - 15% below NSD pp collisions
  - in the systematics of inelastic pp collisions
- Inelastic p-Pb would be ≈ 4% lower (HIJING)

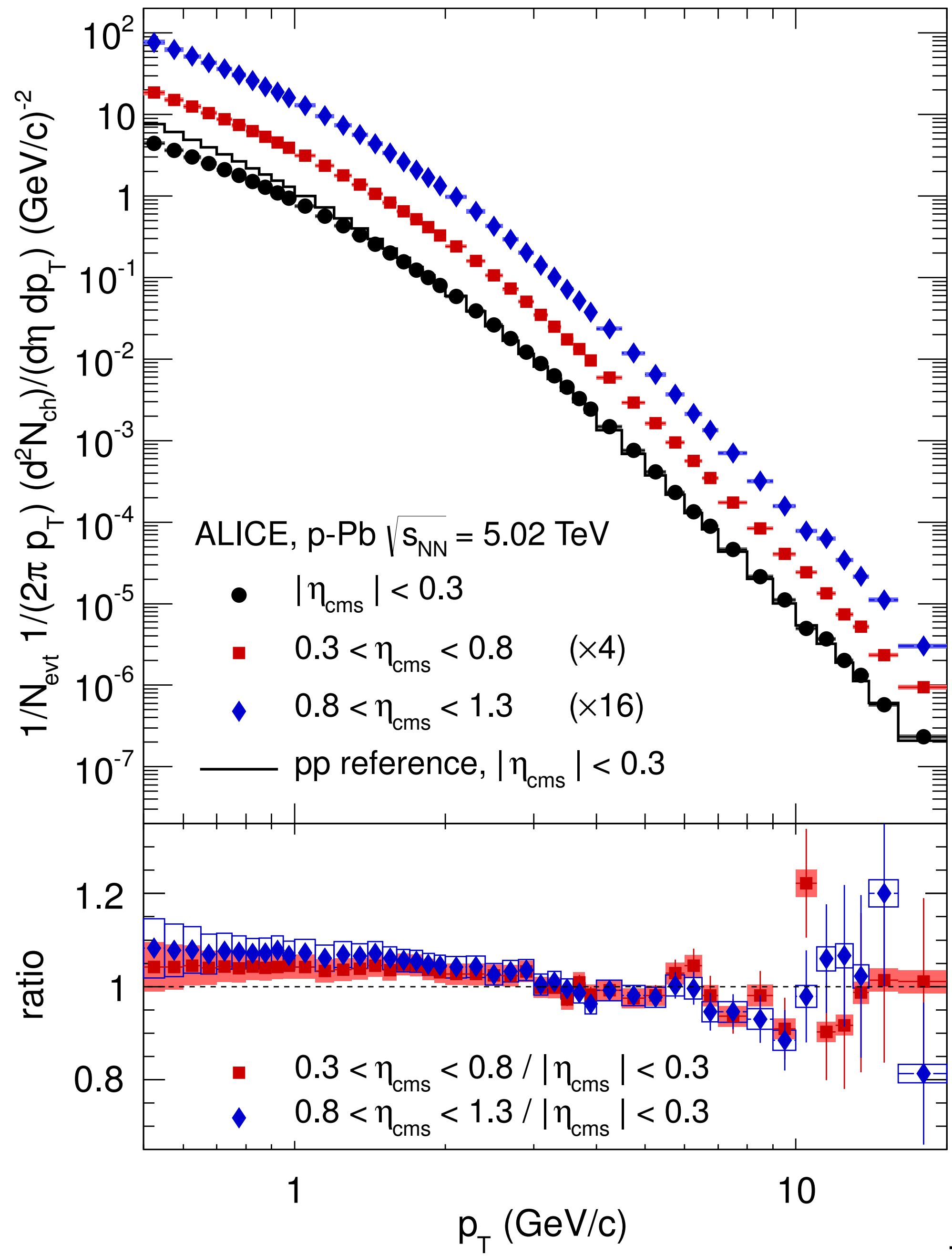
arXiv:1210.3615



dN_{ch}/dp_T Transverse Spectra

- Primary charged tracks
  - reconstructed in ITS+TPC ($|\eta_{lab}| < 0.8$)
  - assume $\eta_{CMS} = \eta_{lab} - y_{CMS}$, then correct
  - slightly softer spectrum at higher η (Pb side)?
- Compare to pp reference spectrum
  - constructed from measurements at 2.76 TeV and 7 TeV (3.6% systematic uncertainty):
    - $p_T < 5\,GeV/c$: interpolation assuming power law dependence on $\sqrt{s}$
    - $p_T > 5\,GeV/c$: scale $\sqrt{s}$ = 7 TeV data using factor from NLO pQCD
  - scaled by $T_{pPb} = 0.0983 \pm 0.0035\ mb^{-1}$ from Glauber model

arXiv:1210.4520

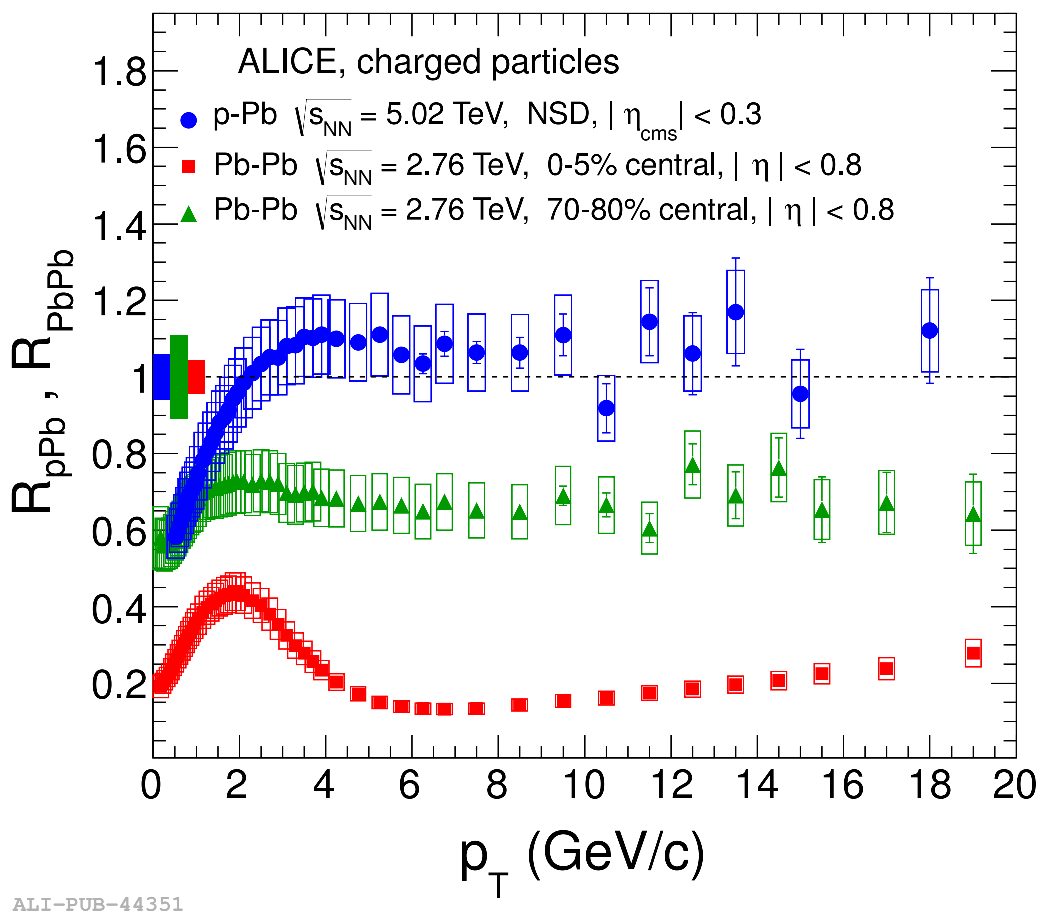


Nuclear Modification Factor

$$R_{AB} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- R_{pPb} compatible with 1 for $p_T > 2$ GeV/*c*
- Unlike in Pb-Pb, no suppression observed
- Suppression in Pb-Pb is not an initial state effect

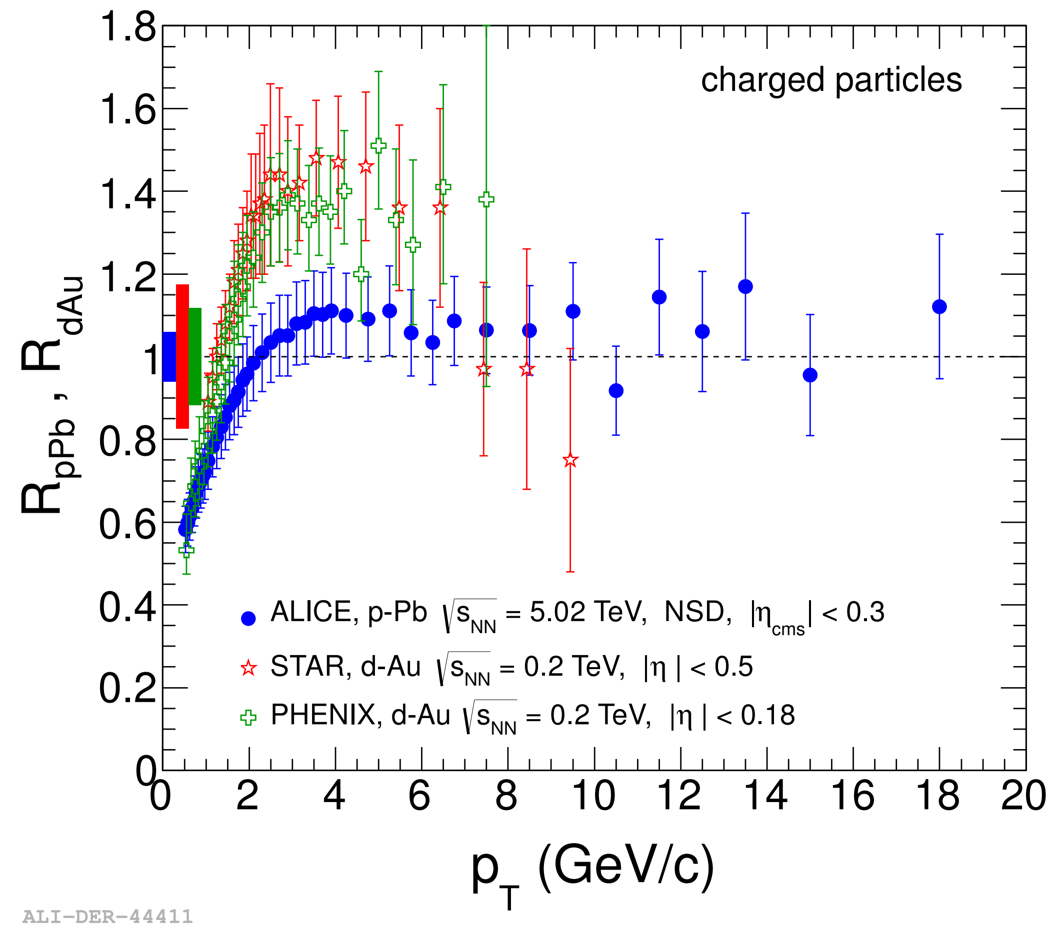
arXiv:1210.4520



Cronin Effect

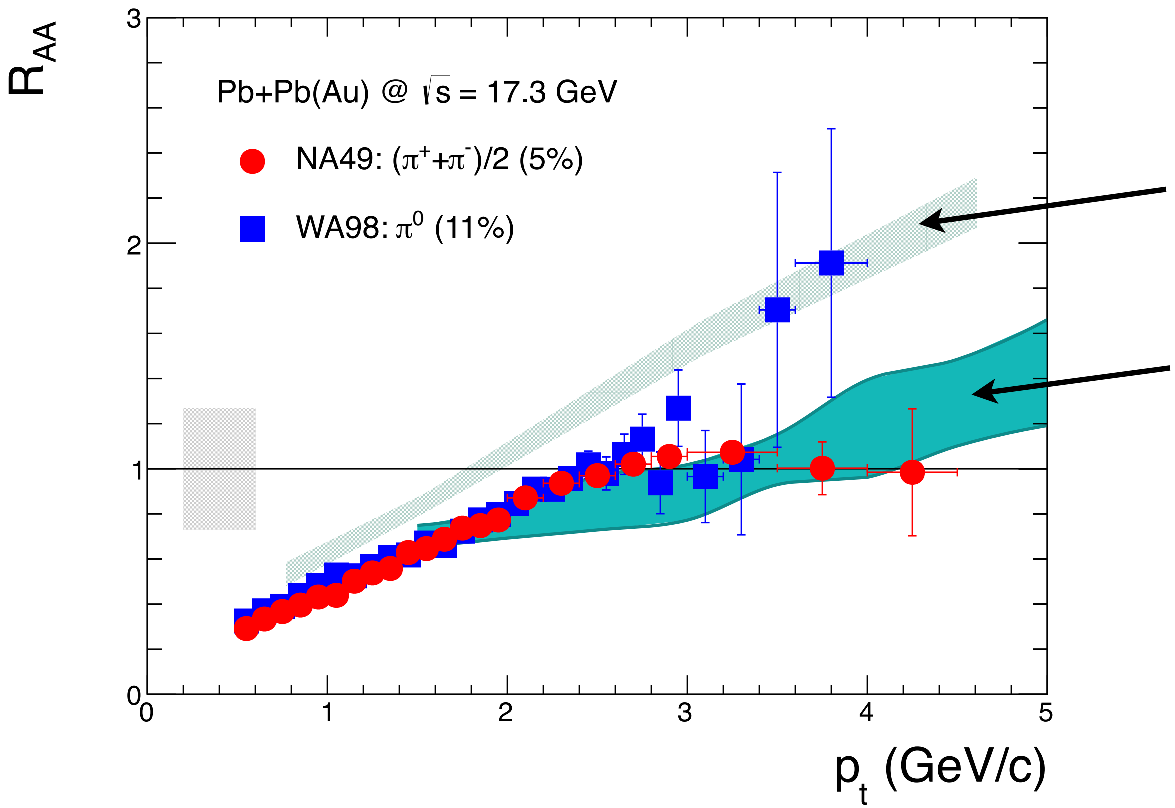
ALICE: arXiv:1210.4520
STAR: PRL 91:072304,2003
PHENIX: PRL 91:072303,2003

- $R_{AB} > 1$ at intermediate p_T observed in d+Au at RHIC typically attributed to Cronin effect
- No enhancement seen in p-Pb at LHC
- No Cronin effect?



Cronin Effect

- Reminder from SPS energies: $R_{AB} = 1$ does not mean absence of effects!



Calculation taking into account:

Cronin effect, shadowing

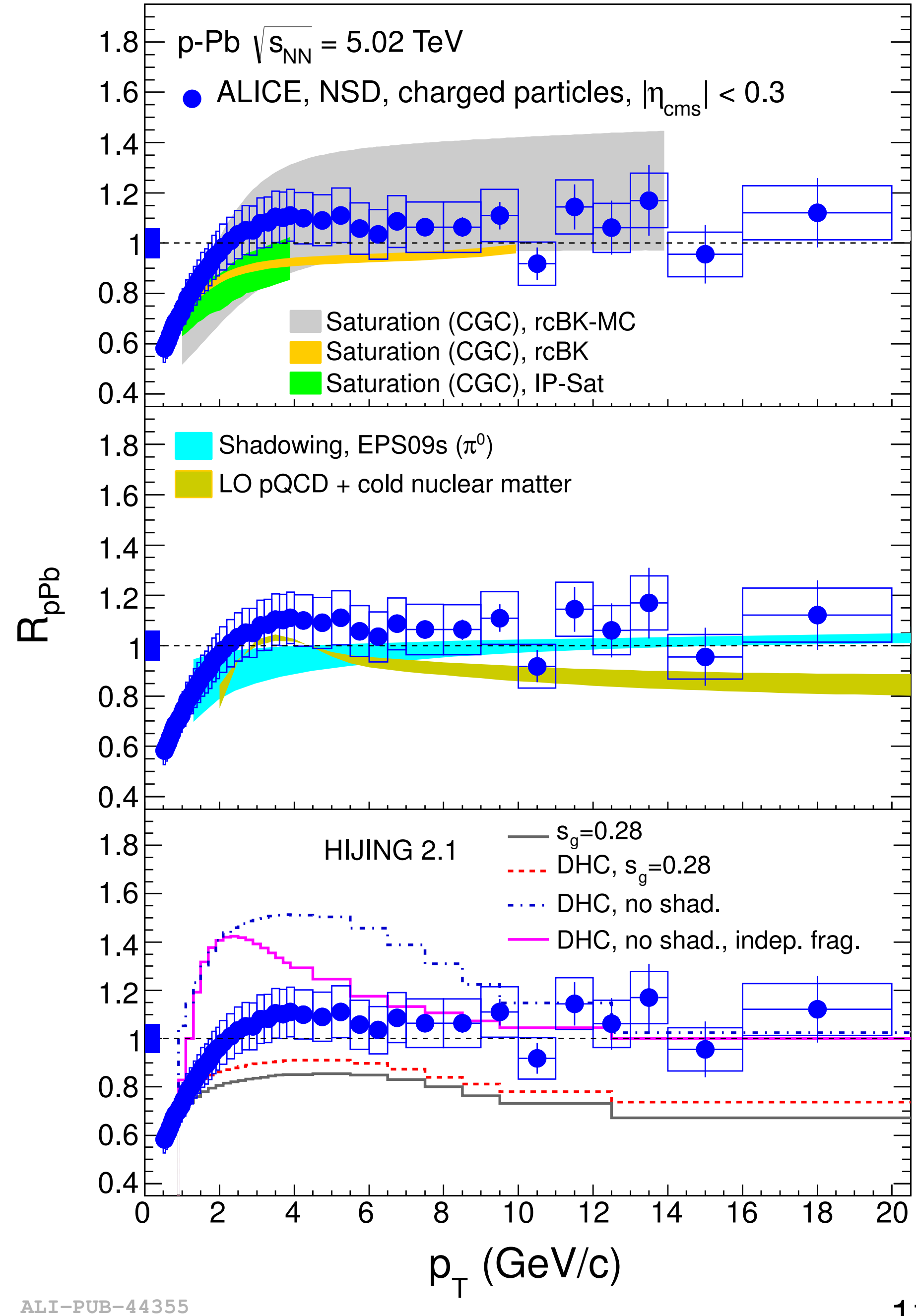
Cronin effect, shadowing + partonic energy loss

Nucl.Phys.A783:65,2007
PRL 89:252301,2002

- Model comparisons are required to understand R_{pPb} at the LHC

Nuclear Modification Factor

arXiv:1210.4520

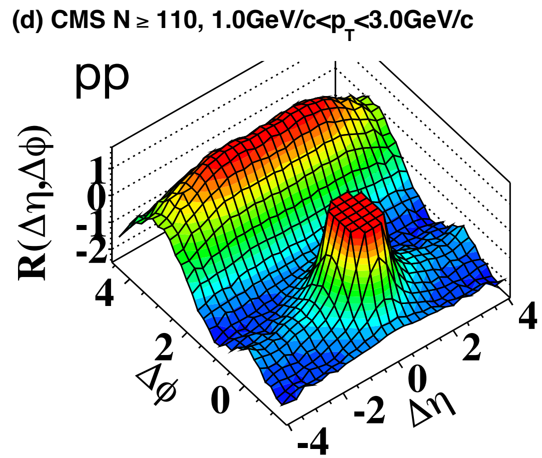


- Saturation (CGC) models:
  - consistent with the data
  - large uncertainties
- pQCD models with shadowing:
  - consistent at low p_T
  - some discrepancies at high p_T
- HIJING
  - with shadowing describes η spectrum and low p_T better
  - no shadowing better at high p_T

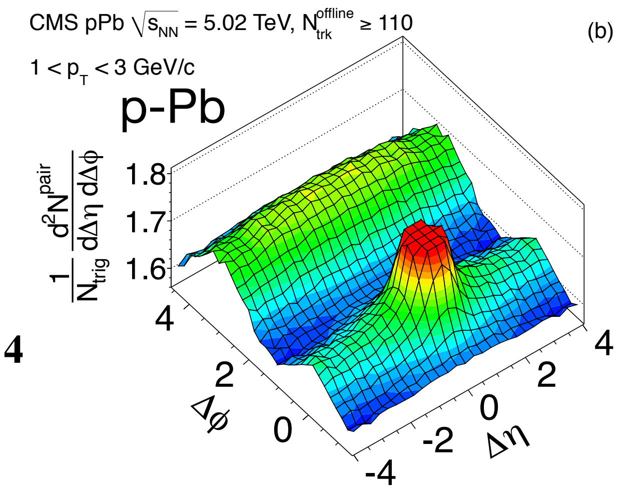
Di-Hadron Correlations Introduction

- CMS: pp, p-Pb at LHC
  - long-range correlations (near side ridge) appear in high multiplicity events
  - collective effects in pp and p-Pb?

JHEP 1009:091,2010

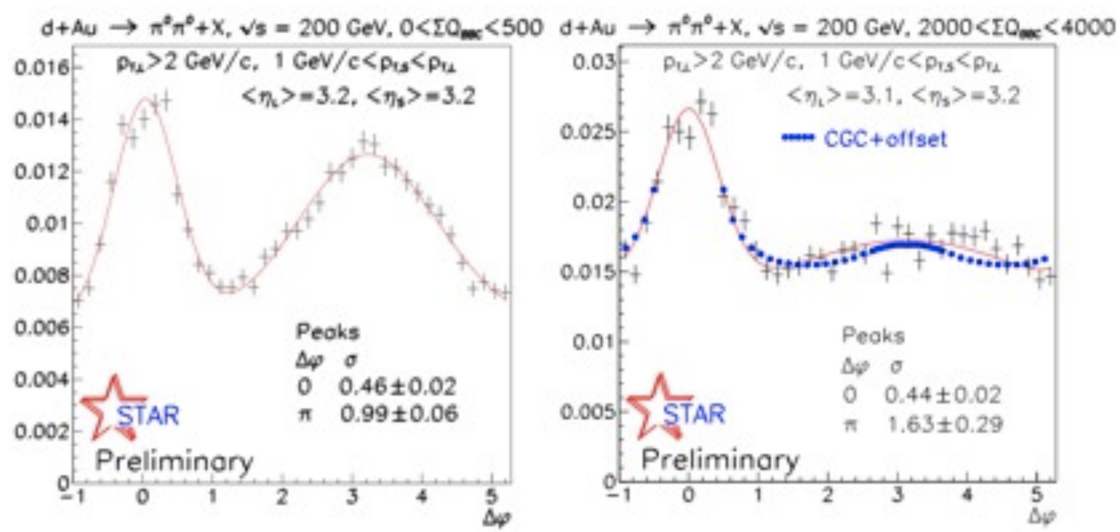


arXiv:1210.5482



- d+Au at RHIC, e.g. STAR
  - back-to-back signal in forward π^0 correlations disappears for high multiplicity events
  - compatible with CGC predictions

Nucl.Phys.A854:168,2011

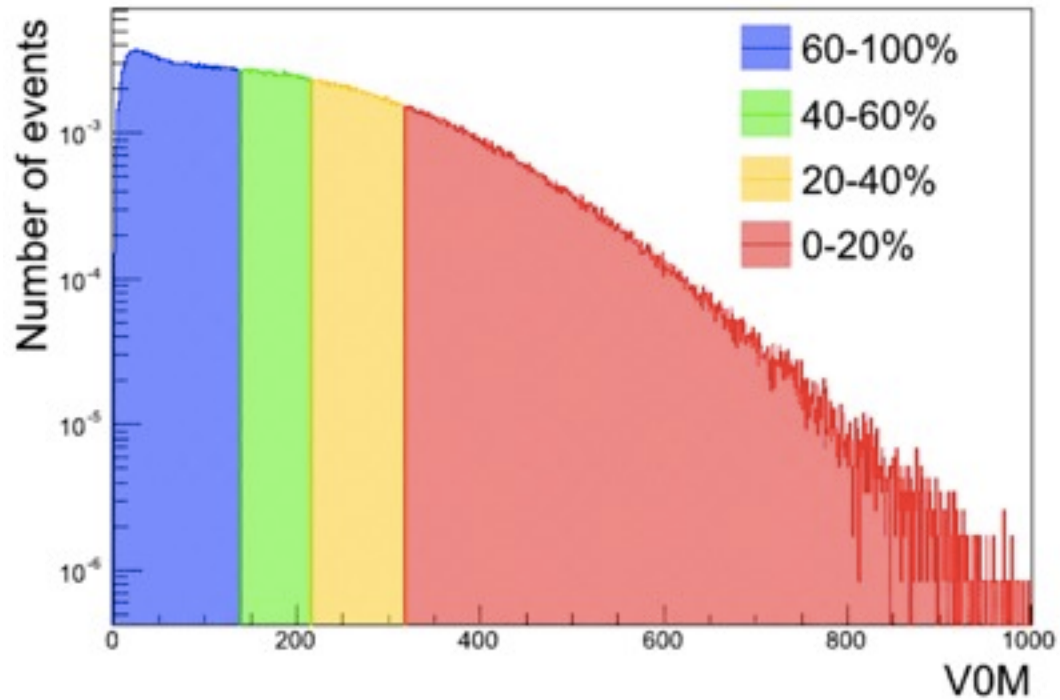


- LHC central η and RHIC forward probe a similar *x* regime

Di-Hadron Correlations Multiplicity Classes

arXiv:1212.2001

- Correlation between geometry and multiplicity in p-A is not as strong as in A-A
- Define multiplicity classes
  - using charge in VZERO to avoid correlation with analyzed tracks V0M: sum of signals from
    - VZERO-A ($2.8<\eta_{lab}<5.1$) and
    - VZERO-C ($-3.7<\eta_{lab}<-1.7$)
- Systematic checks using
  - SPD $|\eta_{lab}|<1.4$
  - ZNA (beam neutron acceptance, Pb side)



Event class	V0M range (a.u.)	$\langle dN_{ch}/d\eta \rangle \|_{\|\eta\|<0.5}$ $p_T > 0$ GeV/c	$\langle N_{trk} \rangle \|_{\|\eta\|<1.2}$ $p_T > 0.5$ GeV/c
60–100%	< 138	6.6 ± 0.2	6.4 ± 0.2
40–60%	138–216	16.2 ± 0.4	16.9 ± 0.6
20–40%	216–318	23.7 ± 0.5	26.1 ± 0.9
0–20%	> 318	34.9 ± 0.5	42.5 ± 1.5

Correlation Measure

arXiv:1212.2001

- Associated yield per trigger particle

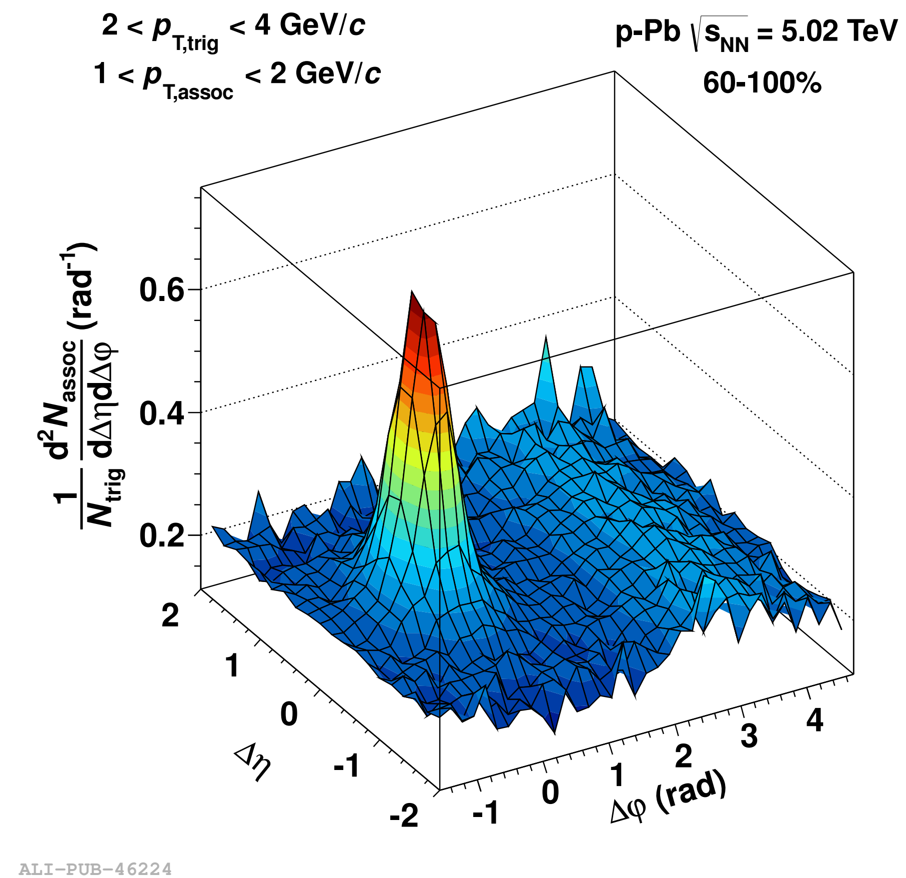
$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2 N_{\mathrm{assoc}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}$$

- Signal (same event) pair yield

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2 N_{\mathrm{same}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi}$$

- Background (mixed event) yield

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{B(0,0)}\frac{\mathrm{d}^2 N_{\mathrm{mixed}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi}$$



Correlation Measure

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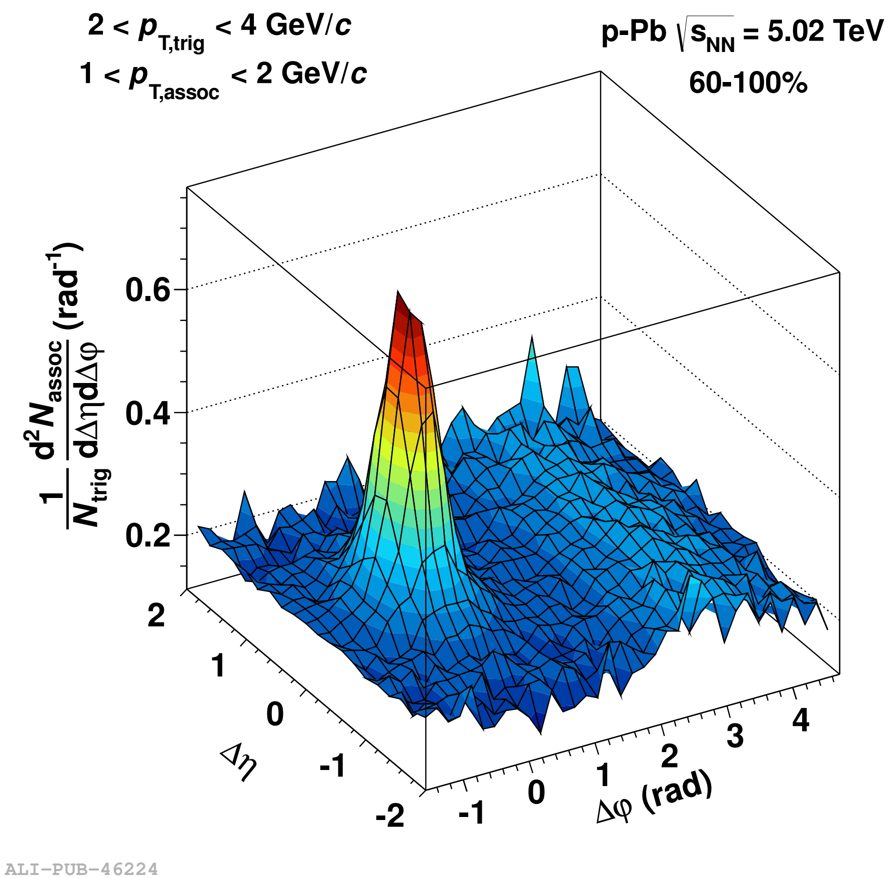


- Signal (same event) pair yield

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2 N_{\mathrm{same}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi}$$

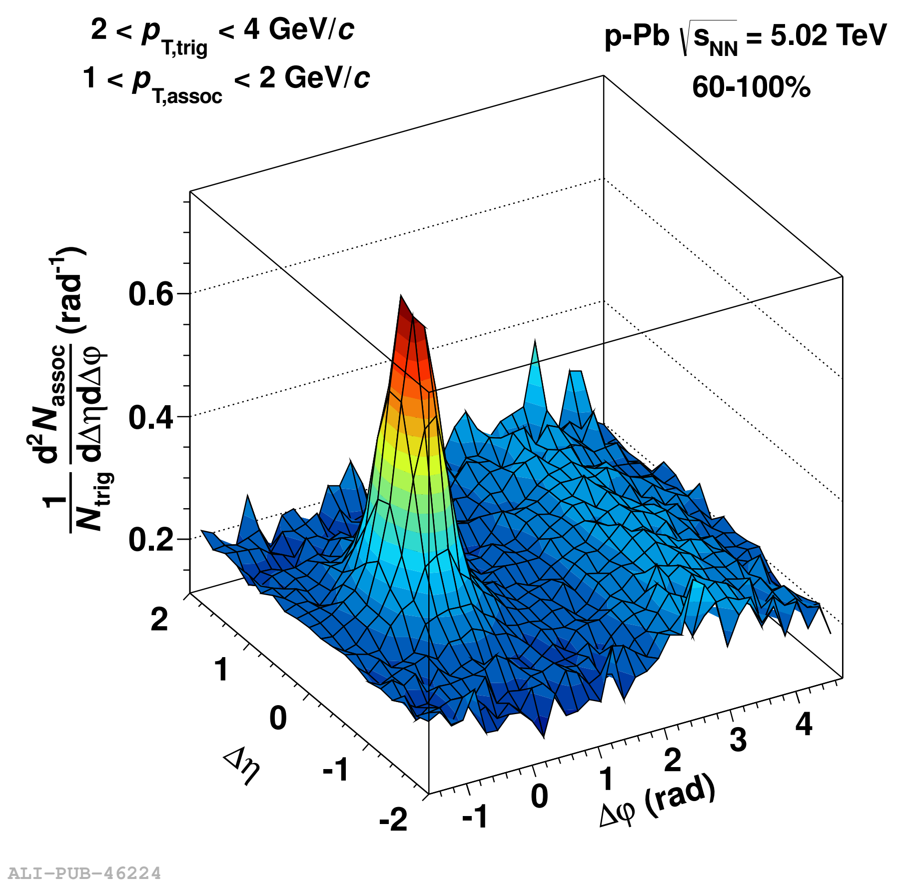
summed over all events in event class, then divided

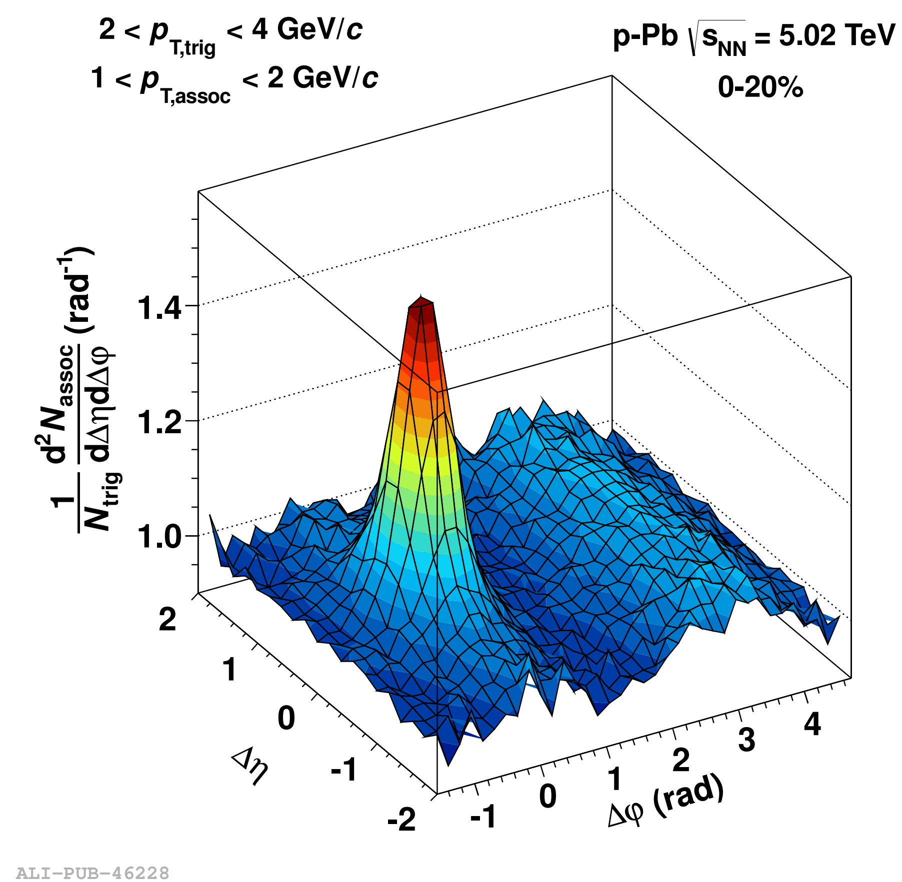
- Background (mixed event) yield

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{B(0,0)}\frac{\mathrm{d}^2 N_{\mathrm{mixed}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi}$$

Di-Hadron Correlations Multiplicity Dependence

arXiv:1212.2001



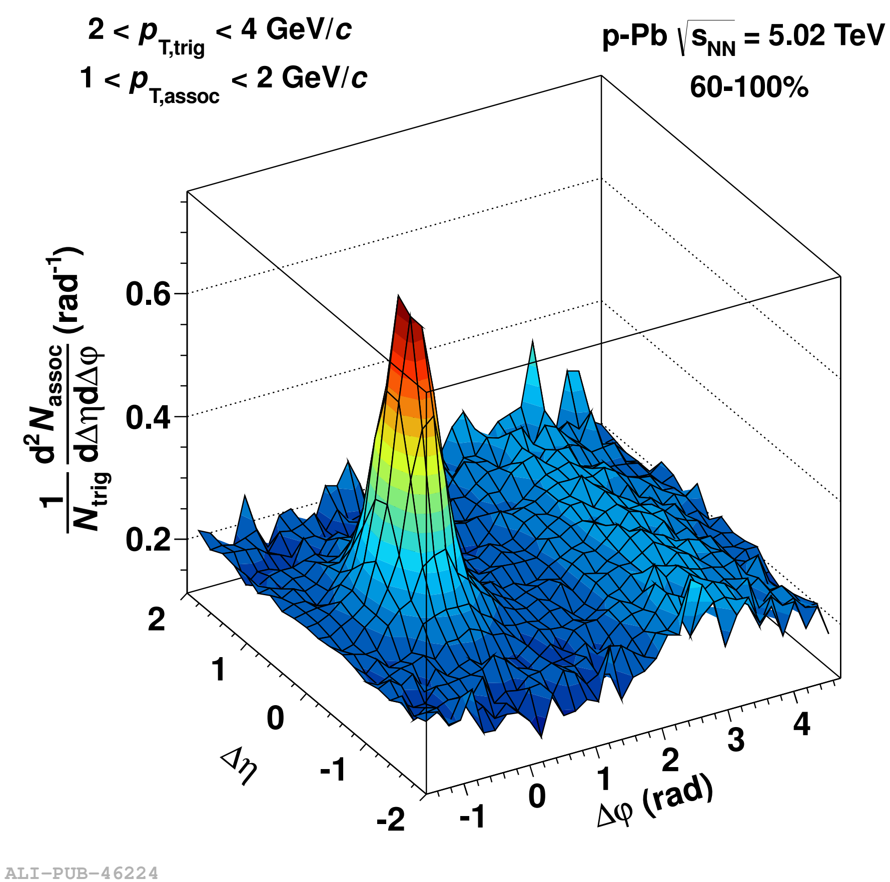


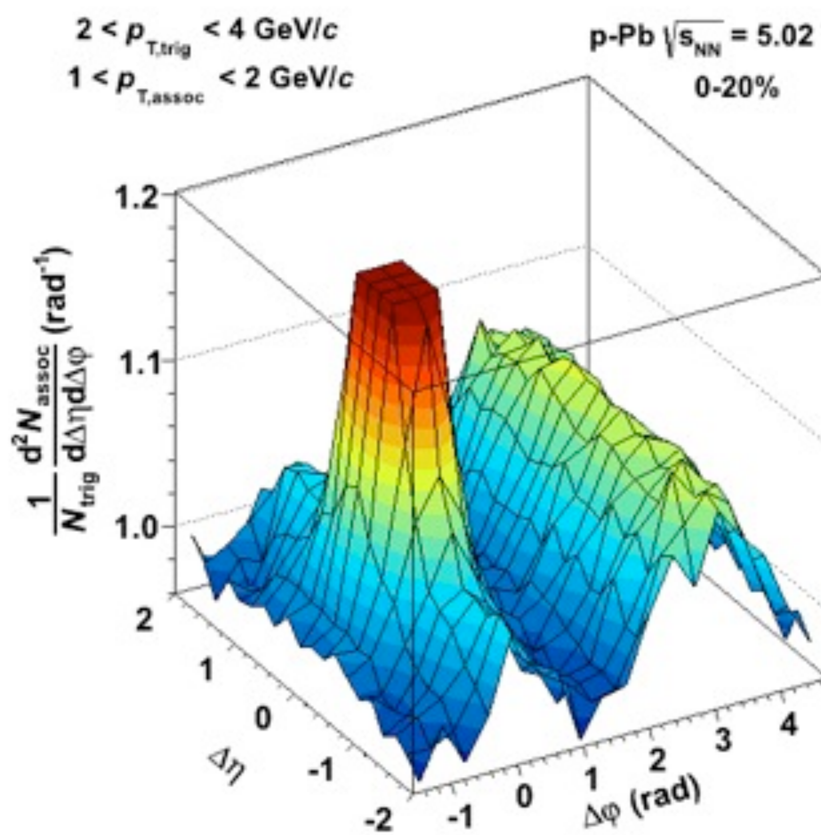
- Low-multiplicity p-Pb:
  - pp-like (jet-like) correlation

- High-multiplicity p-Pb:
  - near-side ridge appears
  - higher yields on near- and away-side

Di-Hadron Correlations Multiplicity Dependence

arXiv:1212.2001





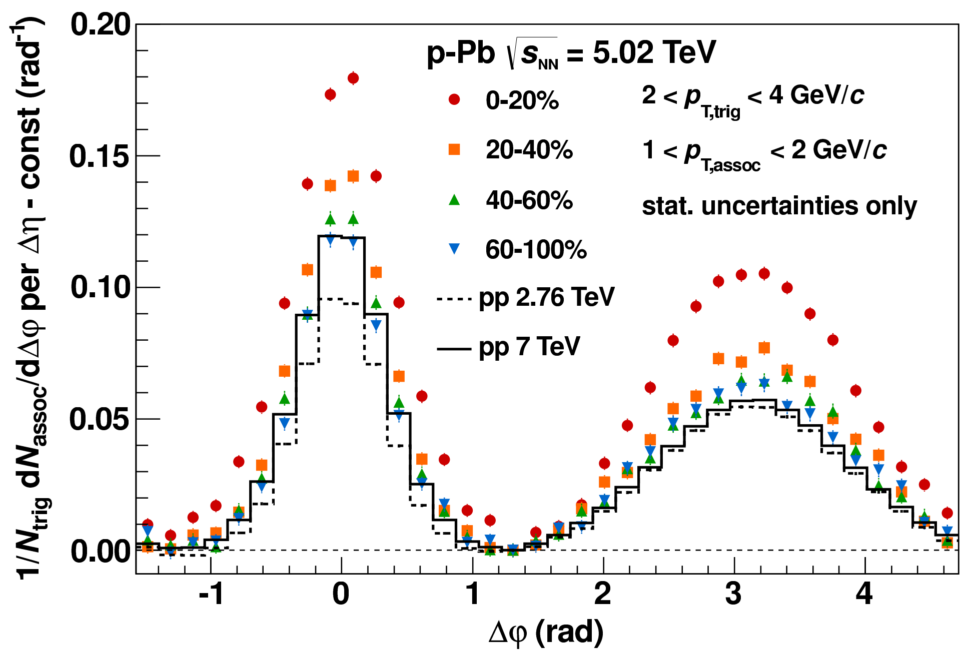
zoomed scale

- Low-multiplicity p-Pb:
  - pp-like (jet-like) correlation
- High-multiplicity p-Pb:
  - near-side ridge appears
  - higher yields on near- and away-side

Di-Hadron Correlations Multiplicity Dependence

arXiv:1212.2001

- Compare associated yield in p-Pb event classes and pp
  - project to Δφ over |Δη| < 1.8
  - subtract baseline at |Δφ|≈1.3

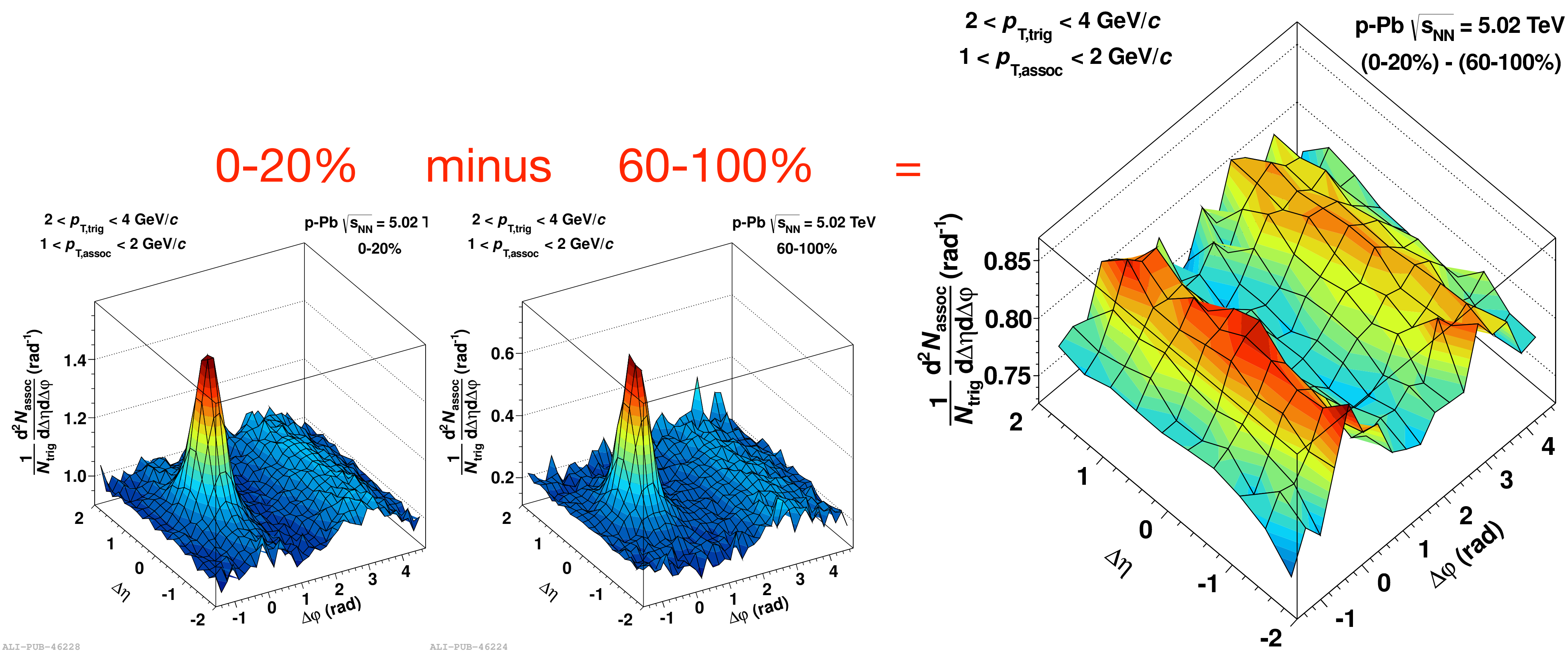


- Low multiplicity p-Pb is similar to pp
- Yield rises on near- and away-side with increasing multiplicity
- In contrast to the away-side suppression observed in d+Au at RHIC at forward η (similar *x*)

Di-Hadron Correlations Two Ridges!

arXiv:1212.2001

- Quantify the excess in high-multiplicity p-Pb: subtract jet-like correlation



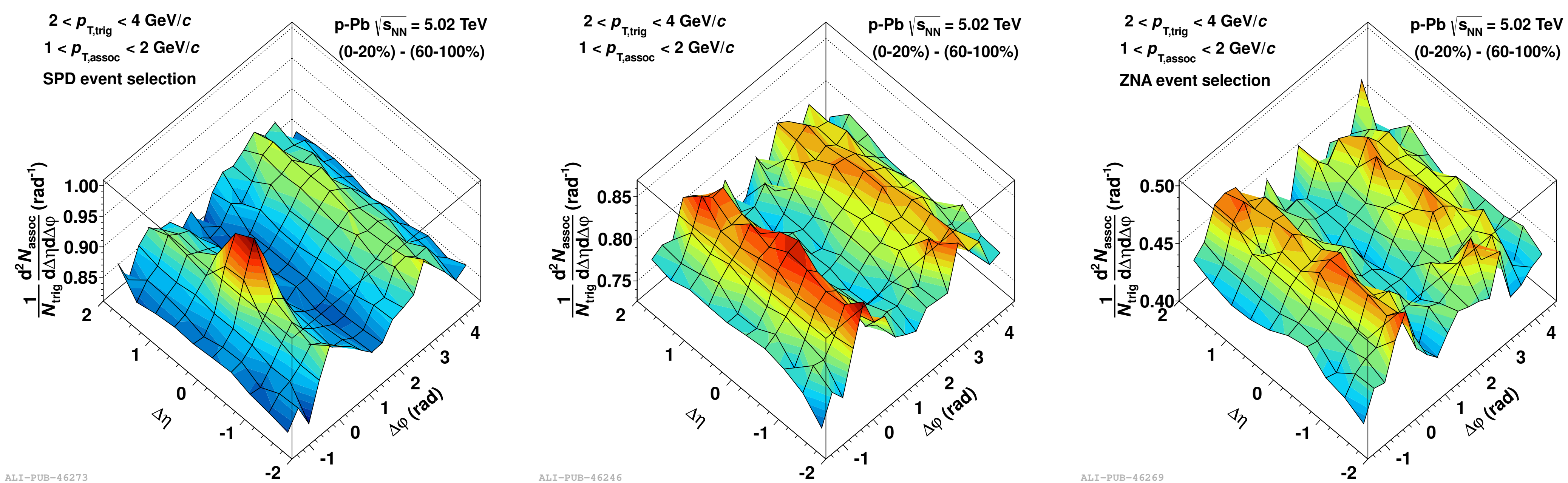
- The near-side ridge is accompanied by an almost identical structure on the away-side!

Di-Hadron Correlations Systematics

- A residual jet peak at (0,0) remains after subtraction (0-20%)-(60-100%) (cf. B.Cole ATLAS talk, Monday)

- Compare different event class definitions

SPD VZERO ZNA



Auto-correlation ←

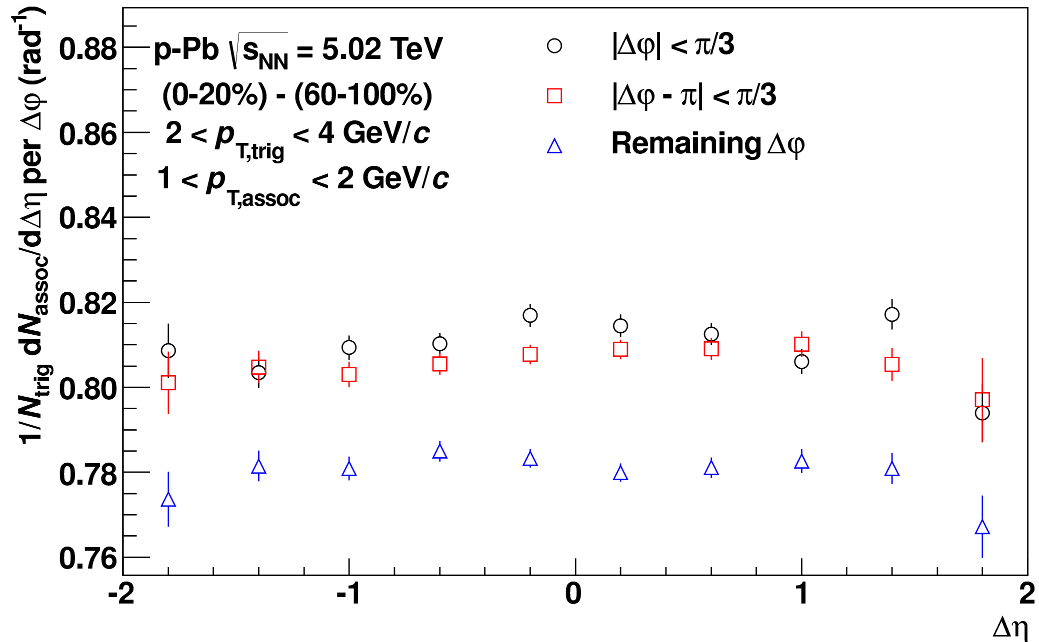
η separation →

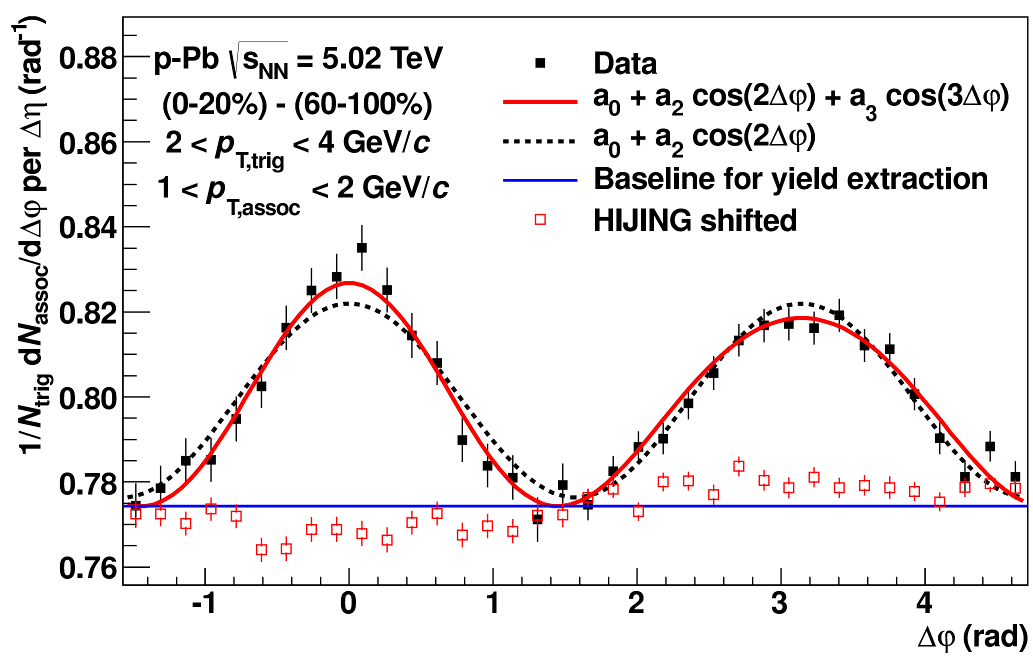
Di-Hadron Correlations Two Ridges

- A closer look at the two ridges: the near- and away-side ridges
  - have the same magnitude
  - are essentially flat in Δη (small residual near-side peak)

- Project to Δφ
  - exclude residual peak (|Δη|<0.8 on the near-side)
  - in HIJING the correlation shows no qualitative changes with multiplicity
  - quantify the ridges: extract ridge yields and Fourier coefficients

arXiv:1212.2001

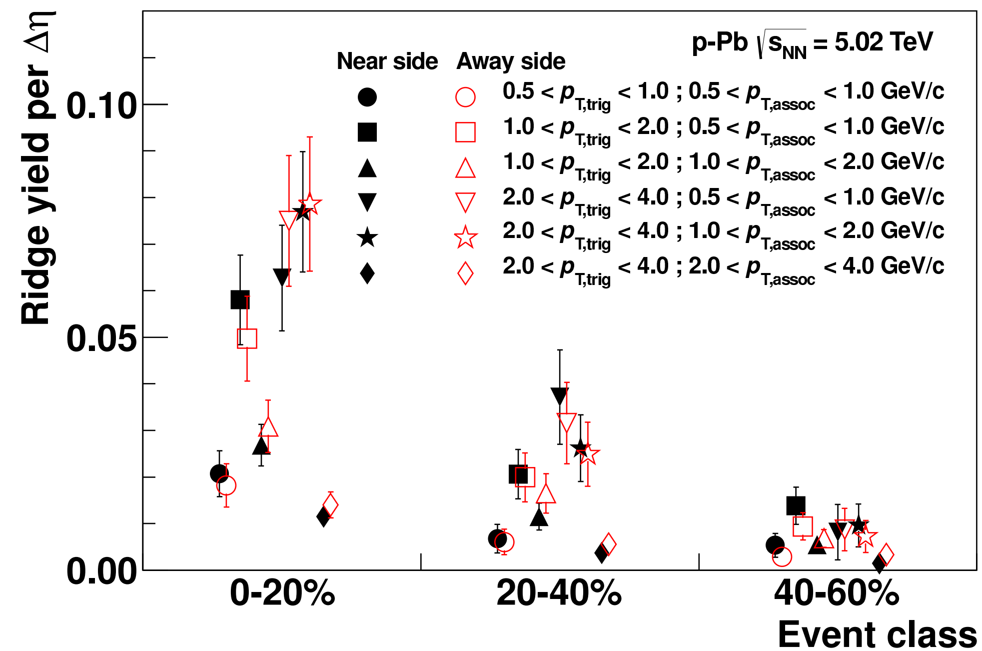


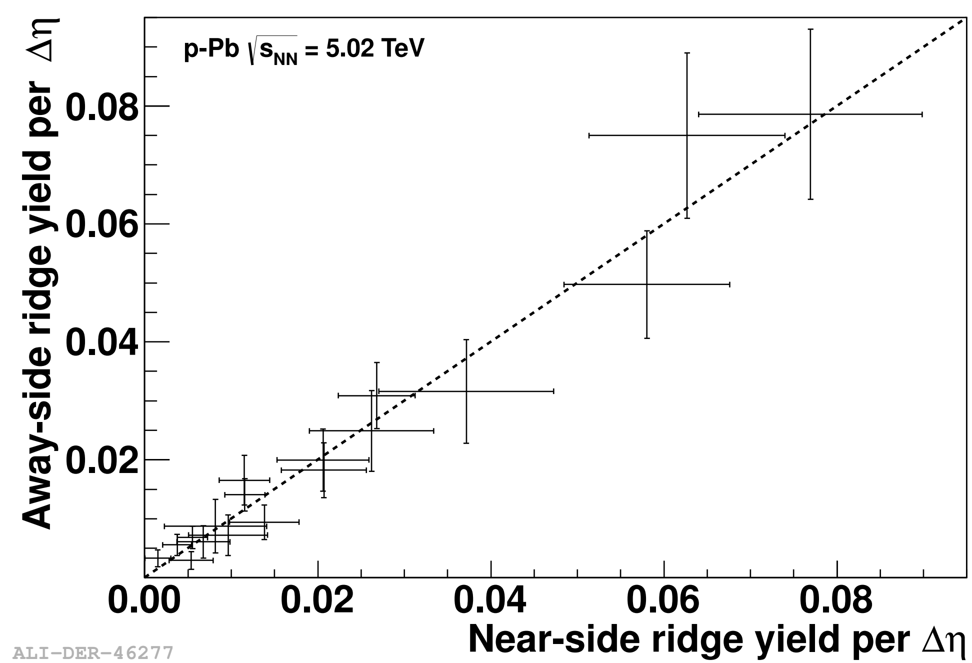


Di-Hadron Correlations Quantifying the Ridges

arXiv:1212.2001

- Ridge yields: integrate the two ridge structure on the
  - near side $|\Delta\phi|<\pi/2$
  - away side $\pi/2<\Delta\phi<3\pi/2$
- Near- and away-side yields
  - vary over a large range
  - agree for all p_T and multiplicity ranges
- The correlation between near- and away-side yields suggests a common underlying physical origin





Di-Hadron Correlations Quantifying the Ridges

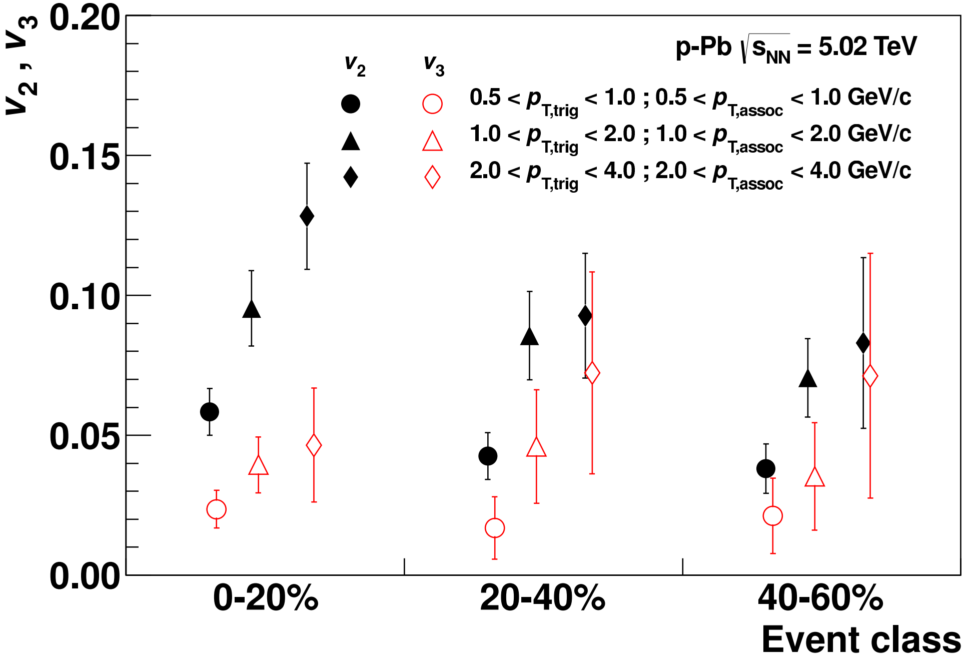
- Fourier decomposition

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{assoc}}}{\mathrm{d}\Delta\varphi} = a_0 + 2a_2\cos(2\Delta\varphi) + 2a_3\cos(3\Delta\varphi)\,,$$

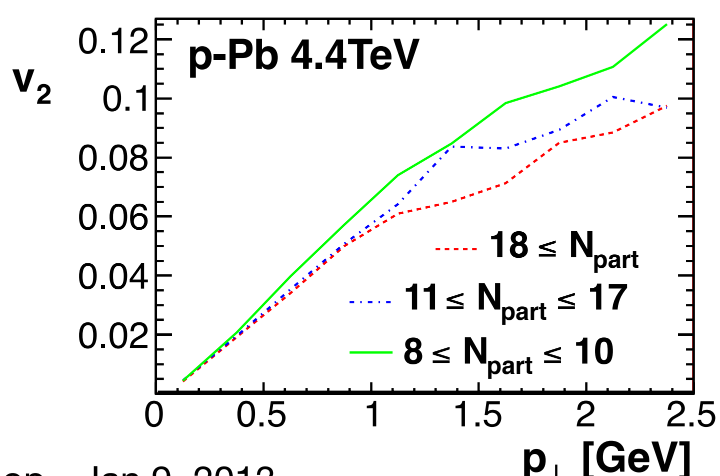
$$v_n = \sqrt{\frac{a_n}{b}}$$

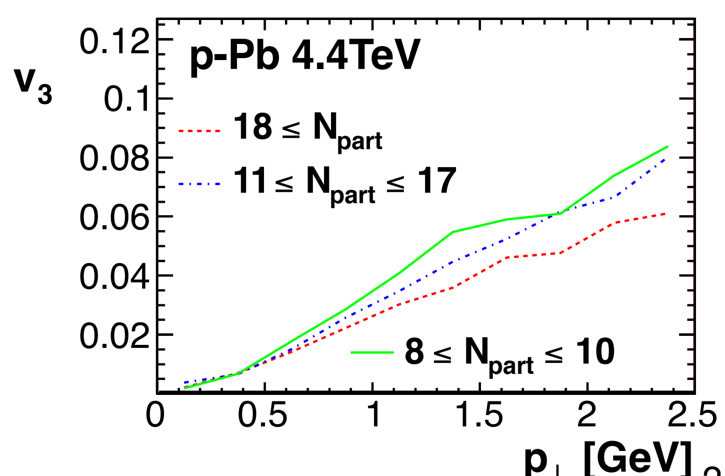
  - *b*: baseline in higher multiplicity class
  - v_2 and v_3 increase with p_T
  - v_2 increases with multiplicity
  - 3+1D viscous hydrodynamic calculation (p-Pb 4.4TeV) qualitatively describes multiplicity and p_T dependence of both v_2 and v_3

arXiv:1212.2001



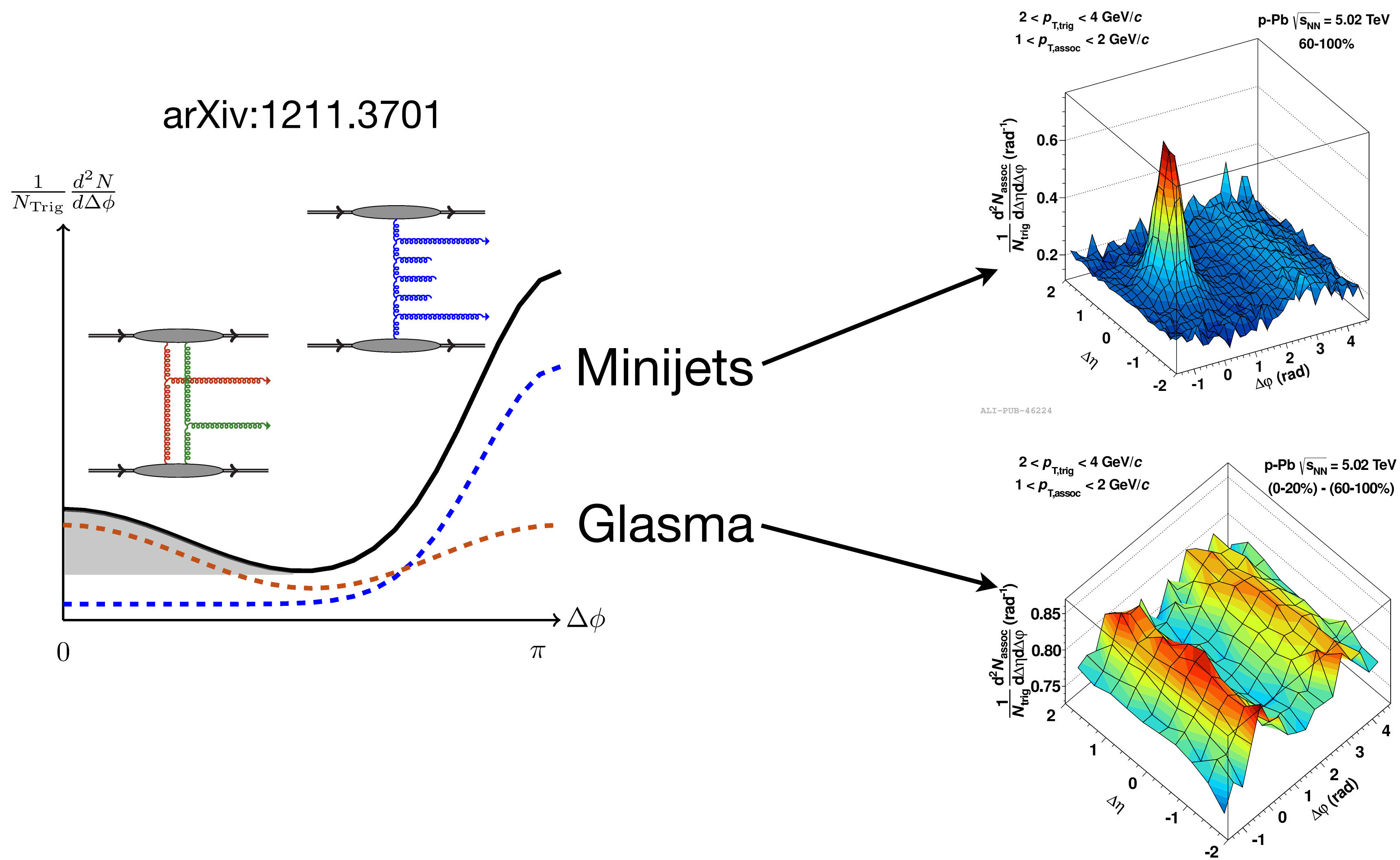
arXiv:1112.0915





Quantifying the Ridges

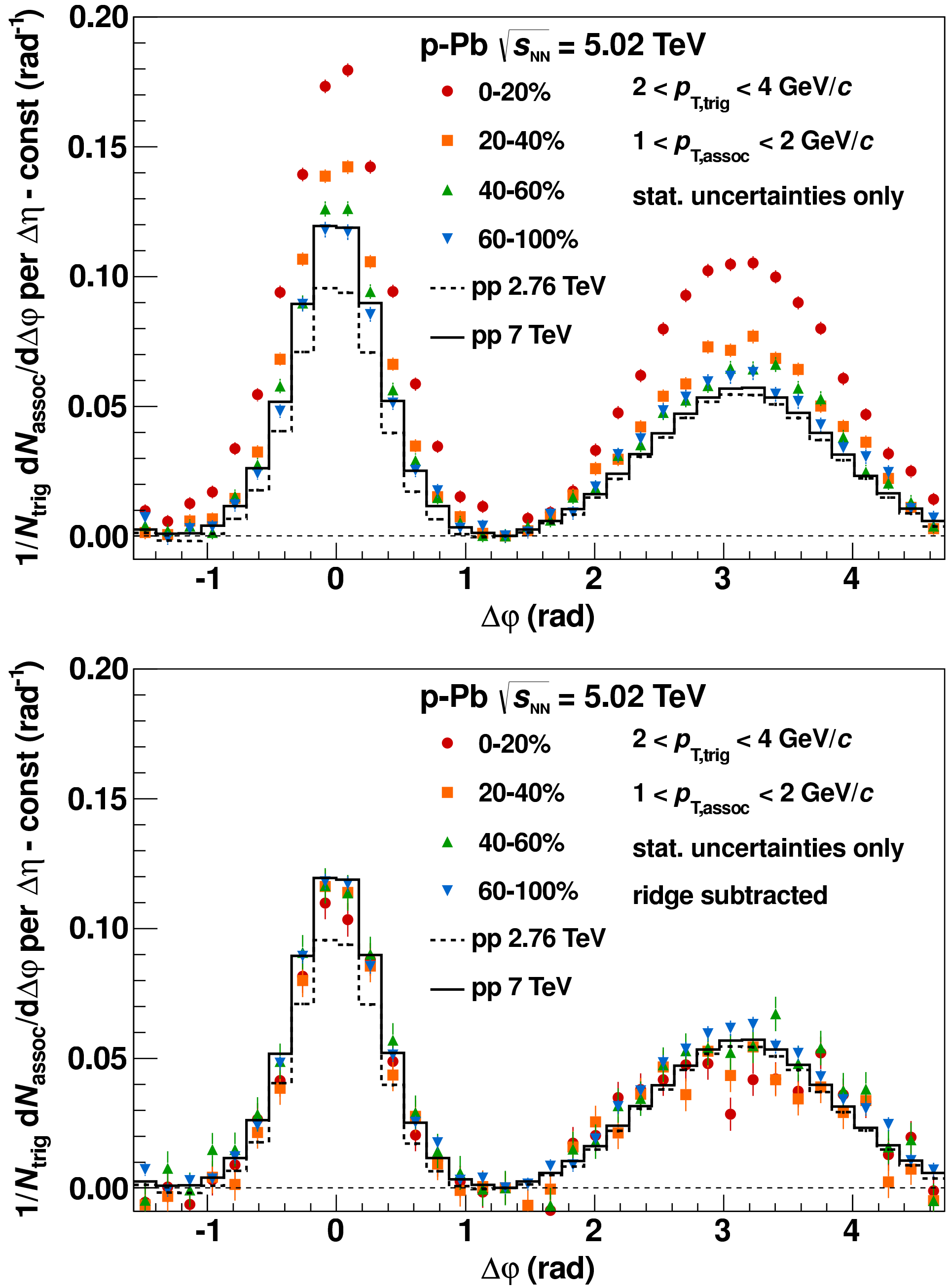
- Two ridges are also qualitatively predicted by CGC



Di-Hadron Correlations Multiplicity Dependence

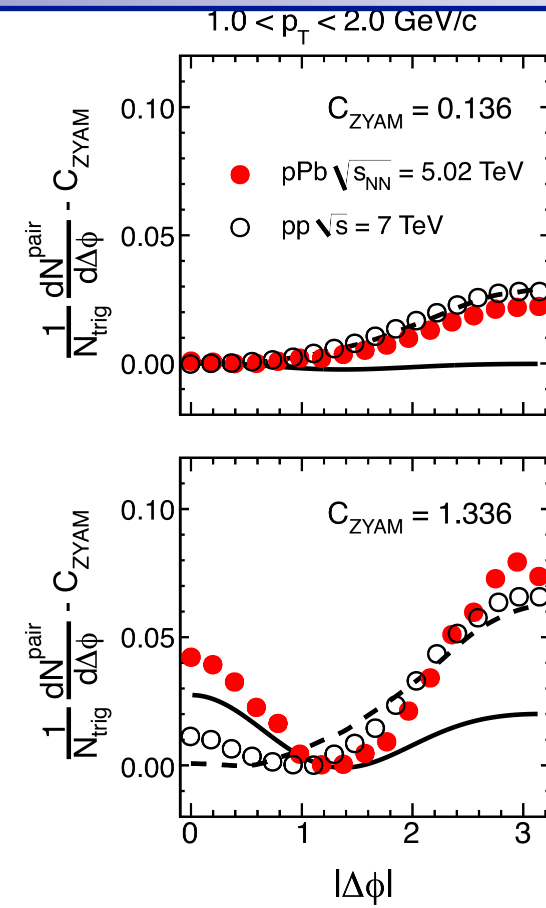
arXiv:1212.2001

- Event multiplicity hierarchy
- Subtract a symmetric double-ridge from Δϕ projection
  - projection: |Δη| < 1.8
  - evaluate near-side ridge:
    1.2 < |Δη| < 1.8
    |Δϕ| < π/2
  - mirror at π/2 to the away side
- Remaining correlation (jet-like) shows no multiplicity dependence!
  - 2013 run will give definitive answer to whether or not the away-side is modified beyond the ridge structure



Di-Hadron Correlations Other LHC Experiments

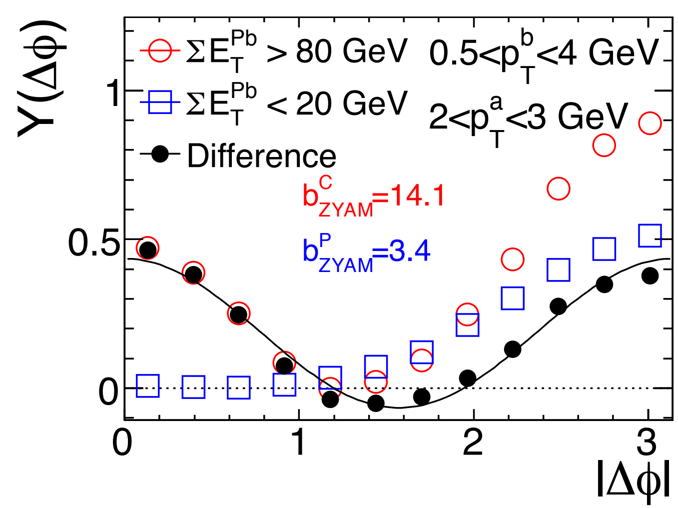
- CMS
  - reported near-side ridge
- ATLAS
  - confirms the two-ridge structure
- Structures seen in ATLAS and CMS are qualitatively similar to the ALICE results
- Different normalizations and p_T ranges among the three LHC experiments make a quantitative comparison difficult



CMS
arXiv:1210.5482

low-mult.
(N_{track}<35)

high-mult.
(N_{track}≥110)



ATLAS
arXiv:
1212.5198

LHC p-Pb Pilot Run Results

- Rich physics from one-day pilot run!

- Pseudorapidity density (arXiv:1210.3615 accepted at Phys. Rev. Lett.)
  - saturation models predict steeper slope of η spectrum
- Transverse momentum spectra and nuclear modification factor R_{pPb} (arXiv:1210.4520)
  - neither suppression nor enhancement of high p_T hadrons observed
  - no model describes η and p_T spectra simultaneously

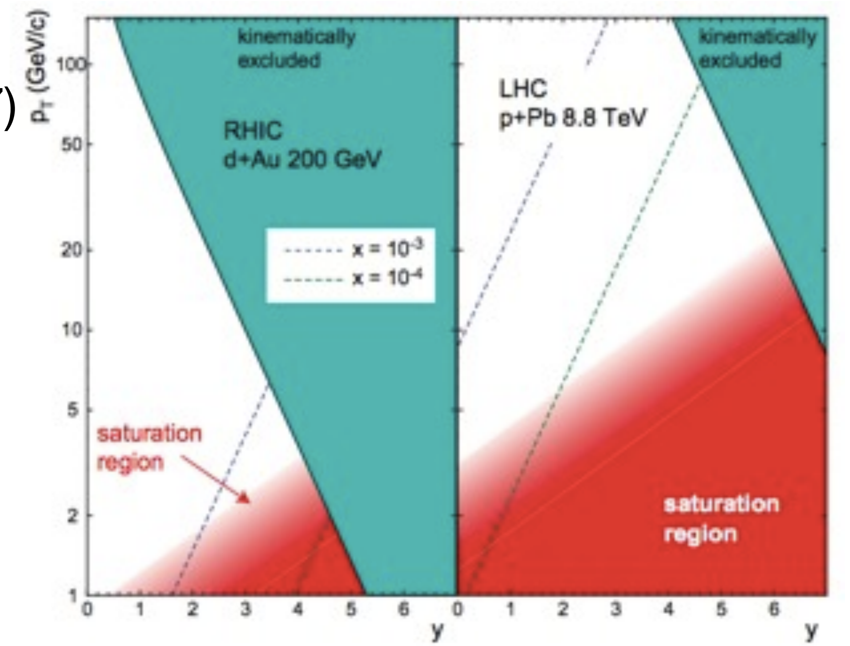
- Di-hadron correlations (arXiv:1212.2001 accepted at Phys. Lett. B)
  - high multiplicity p-Pb events show long-range correlations
  - two essentially identical ridges on the near- and the away-side
  - no suppression of the away-side (seen at RHIC in forward d+Au) observed

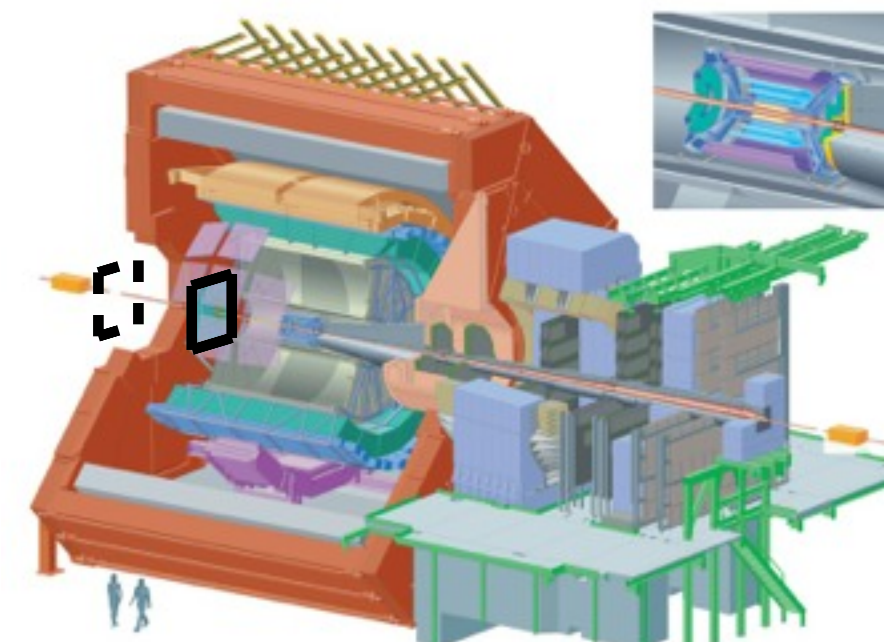
The 2013 LHC p-Pb Run

- Nuclear modification factor R_{pPb}
  - discern models at high p_T with larger statistics
  - study the event multiplicity dependence of R_{pPb} (understand p-Pb “centrality”)
- Di-hadron correlations
  - study the ridge using flow analysis techniques
  - correlation function for identified particles
- Jets, J/ψ and open heavy flavor
  - nuclear modification of jet spectra and heavy flavor yields: pp vs. p-Pb vs. Pb-Pb

ALICE p-Pb Forward Upgrade Idea

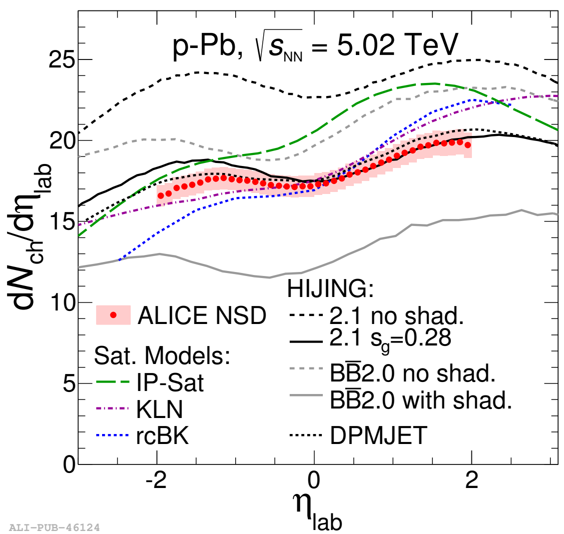
- Potential forward upgrades (arXiv:1106.5807)
  - under discussion for LHC long shutdown 2
- Electromagnetic calorimeter FoCal
  - Si/W calorimeter
  - direct γ and π^0
  - two positions considered
    3.3<η<5.3 or 2.5<η<4.5
- Optional hadronic calorimeter HCal
  - Cu/Scintillator sampling calorimeter
  - improved photon isolation
  - additionally jet, γ-jet physics
- Large kinematic reach (Q^2 and x) for direct γ and (di-)jet correlations



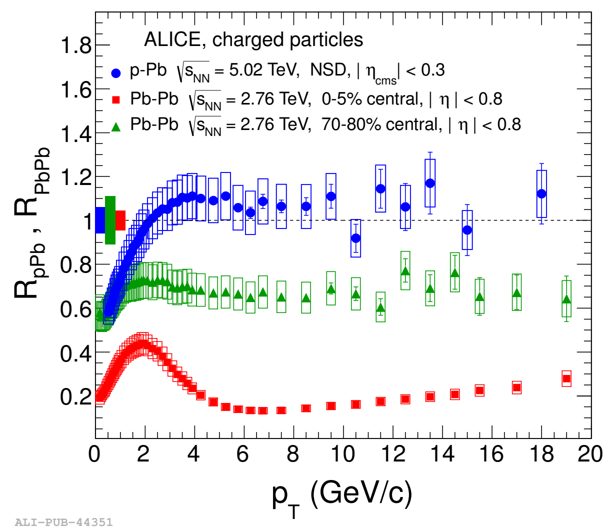


Thank you!

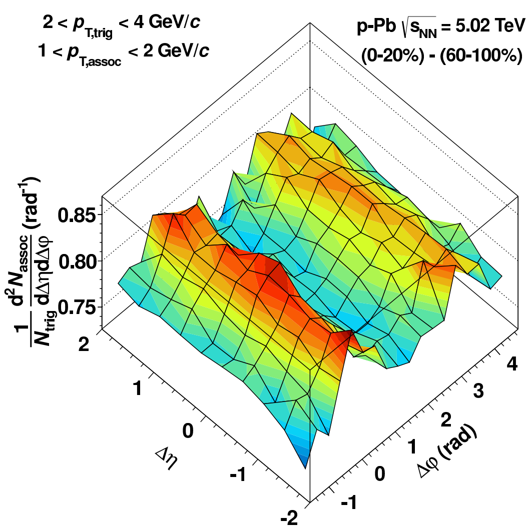
arXiv:1210.3615



arXiv:1210.4520



arXiv:1212.2001



- Looking forward to 2013 p-Pb data!

End.

Ratio of Averages or Average of Ratios

- What is measured for jet-like correlations in symmetric bins ?
- Assume event (i) composed of sum of independent N^i sources emitting n_{ij} correlated particles.
- With our way of averaging (ratio of averages):

$$
\begin{aligned}
\frac{N_{pair}}{N_{trig}} &= \frac{\sum_{i=1}^{N_{evt}} \sum_{j=1}^{N^i_{source}} \frac{1}{2} n_{ij}(n_{ij}-1)}{\sum_{i=1}^{N_{evt}} \sum_{j=1}^{N^i_{source}} n_{ij}} \\
&= \frac{N_{evt}\langle N_{source}\rangle \frac{1}{2}\langle n(n-1)\rangle}{N_{evt}\langle N_{source}\rangle \langle n\rangle} \\
&= \frac{1}{2}\frac{\langle n(n-1)\rangle}{\langle n\rangle}
\end{aligned}
$$

no source/multiplicity dependence

Average of Ratios

$$\frac{N_{pair}}{N_{trig}} = \frac{1}{N_{evt}} \sum_{i}^{N_{evt}} \frac{\sum_{j=1}^{N^i_{source}} n_{ij}(n_{ij}-1)}{\sum_{j=1}^{N^i_{source}} n_{i,j}} \quad (2)$$

It is impossible to simplify this expression for the general case. The result depends on the distribution of number of sources. This can be seen by considering two limiting cases.

(1) $N_{source} = 1$

$$\frac{N_{pair}}{N_{trig}} = \langle n-1 \rangle|_{n>0} = \frac{\langle n \rangle}{1-p_0} - 1 \quad (3)$$

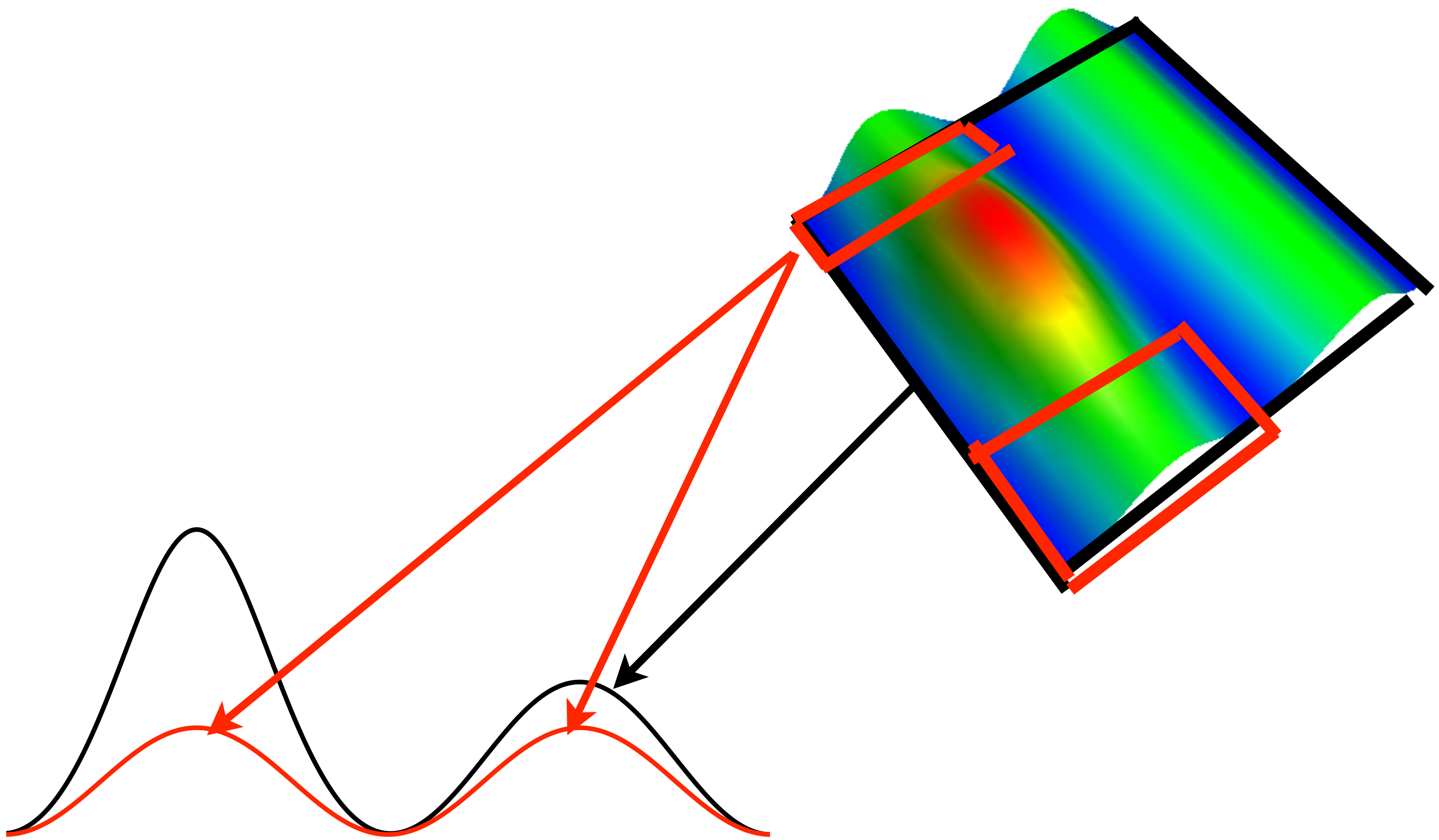
The average of ratios measures the number of additional particles under the trigger condition. This is usually called the *number of associated particles* N_{ass}

(2) N_{source} **large** In this case the source average and the event average are equal and the average of ratios is equal to the ratio of averages.

$$\begin{aligned} \frac{N_{pair}}{N_{trig}} &= \frac{1}{N_{evt}} \sum_{i}^{N_{evt}} \frac{\sum_{j=1}^{N^i_{source}} n_{i,j}(n_{ij}-1)}{\sum_{j=1}^{N^i_{source}} n_{i,j}} \\ &= \frac{\langle n(n-1) \rangle}{\langle n \rangle} \end{aligned} \quad (4)$$

multiplicity dependent

Di-Hadron Correlations Subtraction



The LHC p-Pb Pilot Run

- One-day pilot run on September 13, 2012
  - bunch intensities: 10^{10} (p), $6 \cdot 10^{7}$ (Pb)
  - 8 (out of 13) bunches collide at ALICE
  - interaction region: σ_z=6.3cm, σ_r=60μm
  - luminosity $8 \cdot 10^{25}$ $cm^{-2}s^{-1}$ → hadronic interaction rate 150 Hz
- $\sqrt{s_{NN}}$ = 5.02 TeV
  - 4 TeV p + 1.58*A* TeV Pb
  - center of mass moves with Δy=-0.465 in direction of p beam
- ≈ 2M p-Pb events recorded. Originally planned for accelerator / experiment setup, the pilot run yields physics results!

The ALICE Experiment