Recent results from pPb collisions at the LHC

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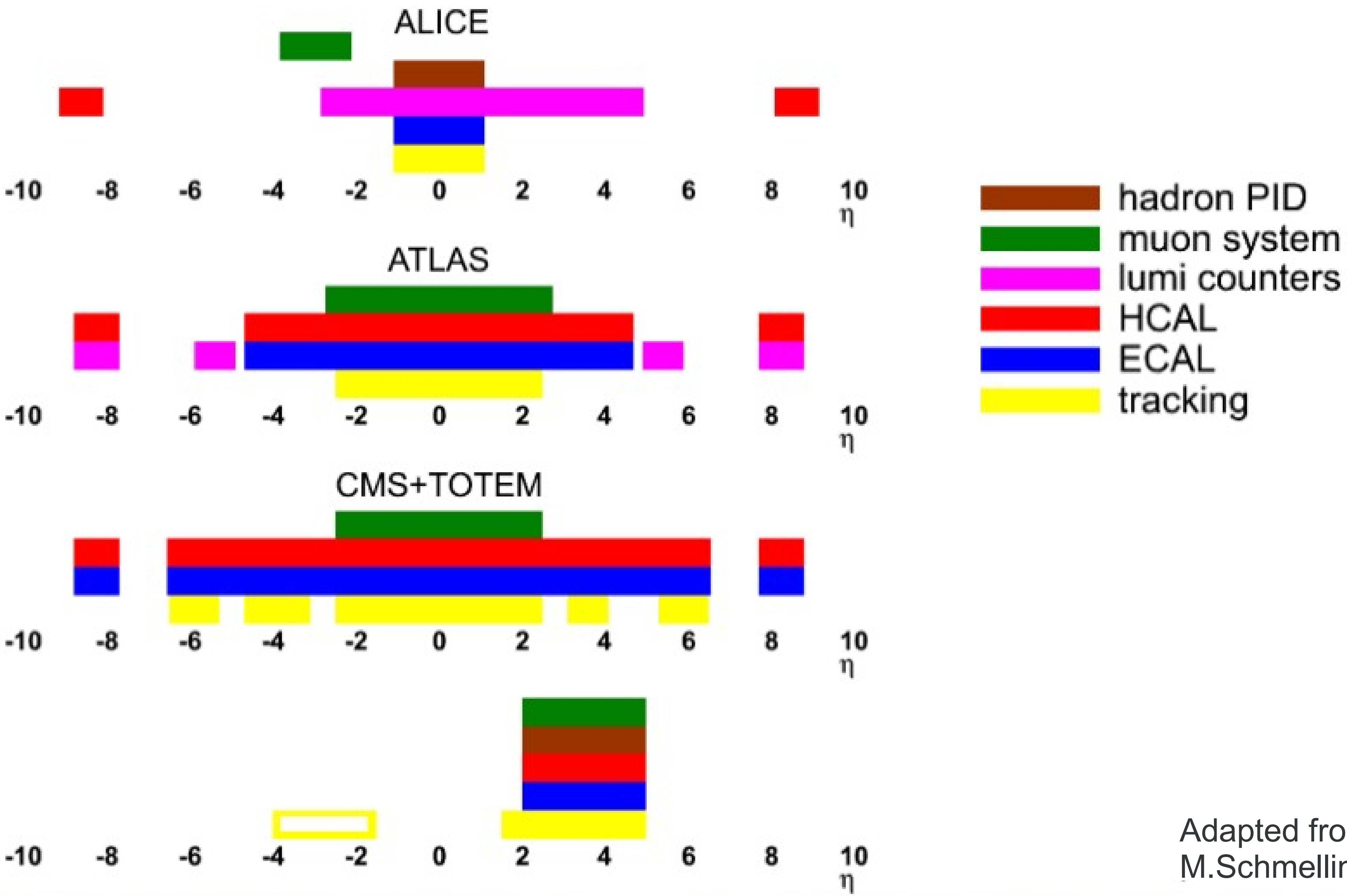
RBRC Workshop on “Jet quenching at RHIC vs LHC in light of recent dAu vs pPb controls”

LHC p+Pb runs at 5.02 TeV

- LHC operated with
  - 4 TeV proton beam and 1.57 TeV / nucleon Pb beam
    - Center of mass energy 5.02 per nucleon pair
    - Center of mass rapidity shift dY = -0.465 in direction of proton
- 2012 pilot run (4 hours of data taking)
  - About 1/μb per experiment with very low pileup
- 2013 long run (3 weeks of data taking)
  - Delivered about 30/nb to ATLAS, CMS and ALICE
    - ALICE required about 50/μb with $\mu<0.003$ (for the rest $\mu<0.05$)
    - Few 1/nb for LHCb (new to heavy-ion operation)
  - Beam reversal (relevant for ALICE and LHCb) for about half of statistics
  - Van der Meer scans in both beam configuations
- No pp run at 5.02 TeV until 2015
  - Instead a run at 2.76 TeV with 0.1/pb for ALICE and 5/pb for the rest

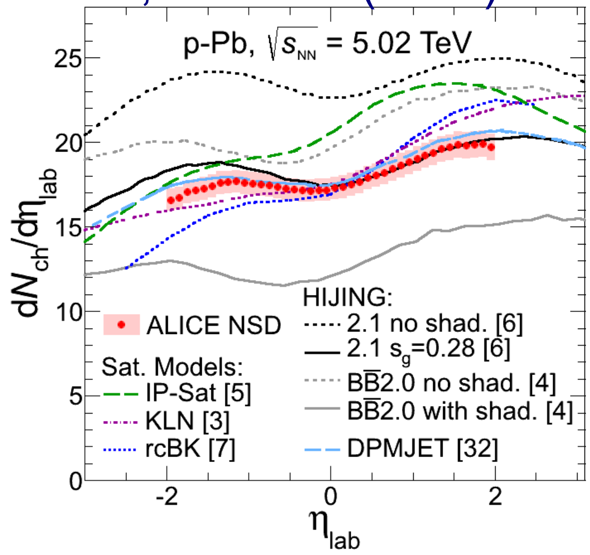
Acceptance of LHC experiments

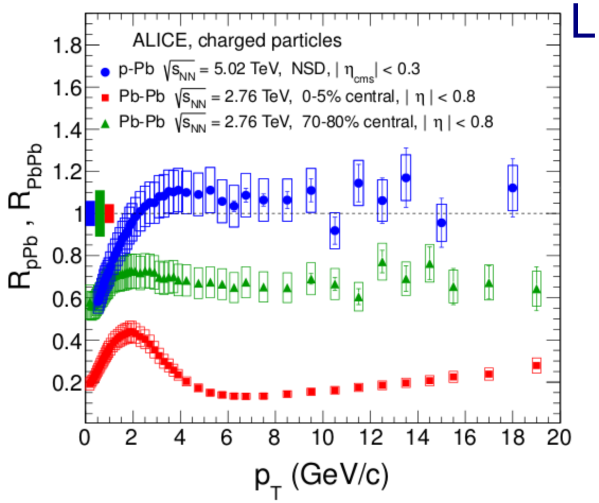


Adapted from
M.Schmelling

Physics results from pilot run

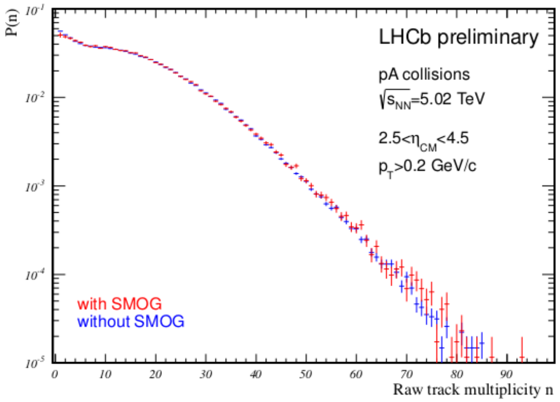
ALICE, PRL 110 (2013) 032301



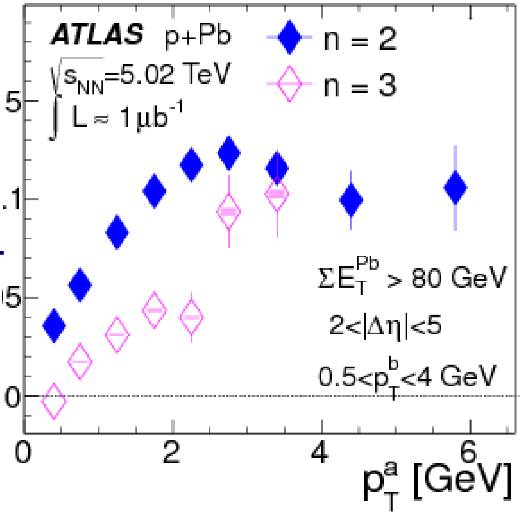


ALICE, PRL 110 (2013) 082302

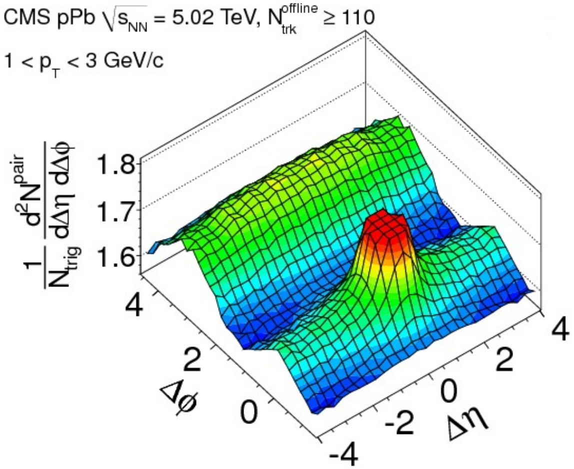
LHCb, CERN-LHCb-CONF-2012-034

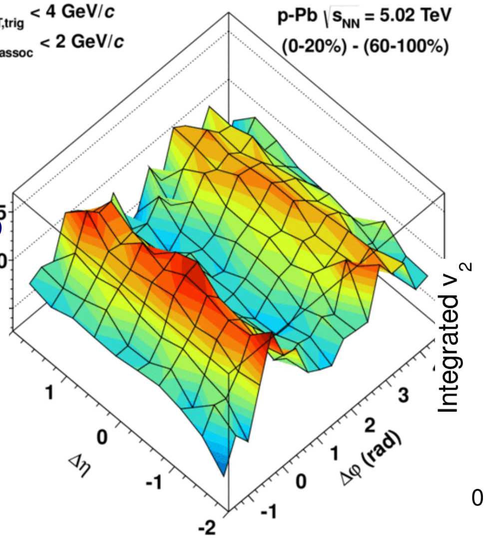


ATLAS, arXiv:1212.5198



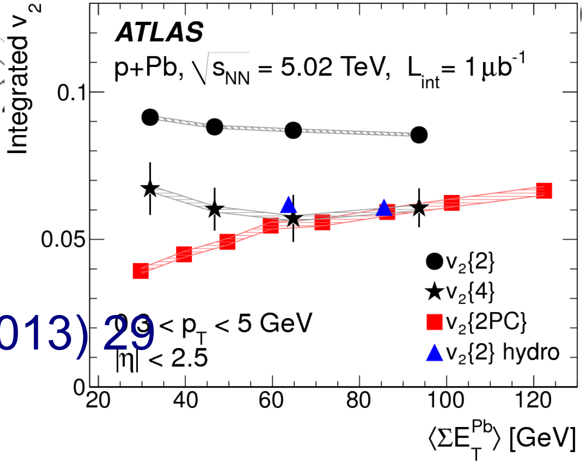
CMS, PLB 718 (2012) 795





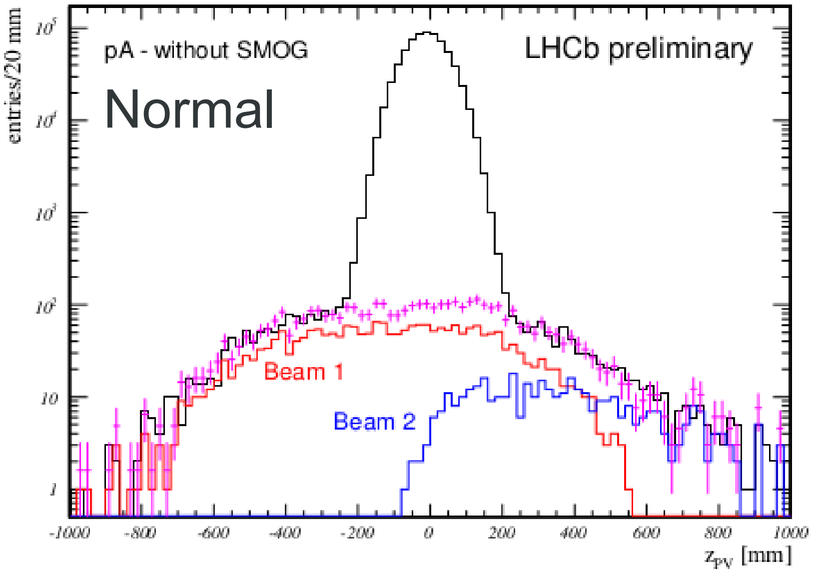
ALICE, PLB 719 (2013) 29

ATLAS, arXiv:1303.2084

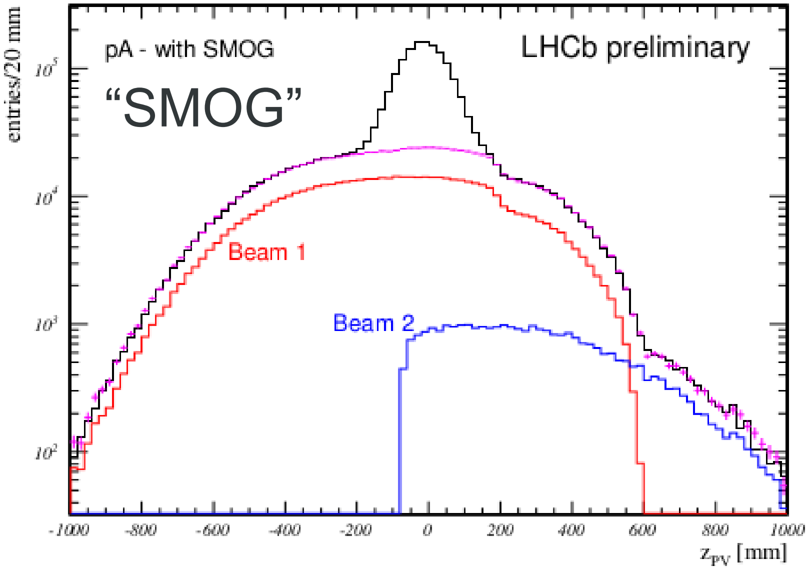


LHCb: Normal and SMOG running

- Two running scenarios:
  - Normal background conditions
  - Running with “SMOG” (System for Measuring Overlap with Gas)
    - Ne injection to measure beam-profile + luminosity (JINST 7 P01010)
    - Increase beam-gas factor by ~100
    - Obtain 0.569/μb (SMOG) and 0.361/μb (normal) with 5.2% systematic uncertainty
- Need to perform beam-gas subtraction
  - Measure observables with BX1 (beam1), BX2 (beam2) and BX3 (coll.beams)
  - Calculate BX3 – a_1 BX1 – a_2 BX2
  - Determine a_1 and a_2 from primary vertex distribution for |z|>300 mm
    - Common for w and w/o SMOG
    - Same weights apply for other observables



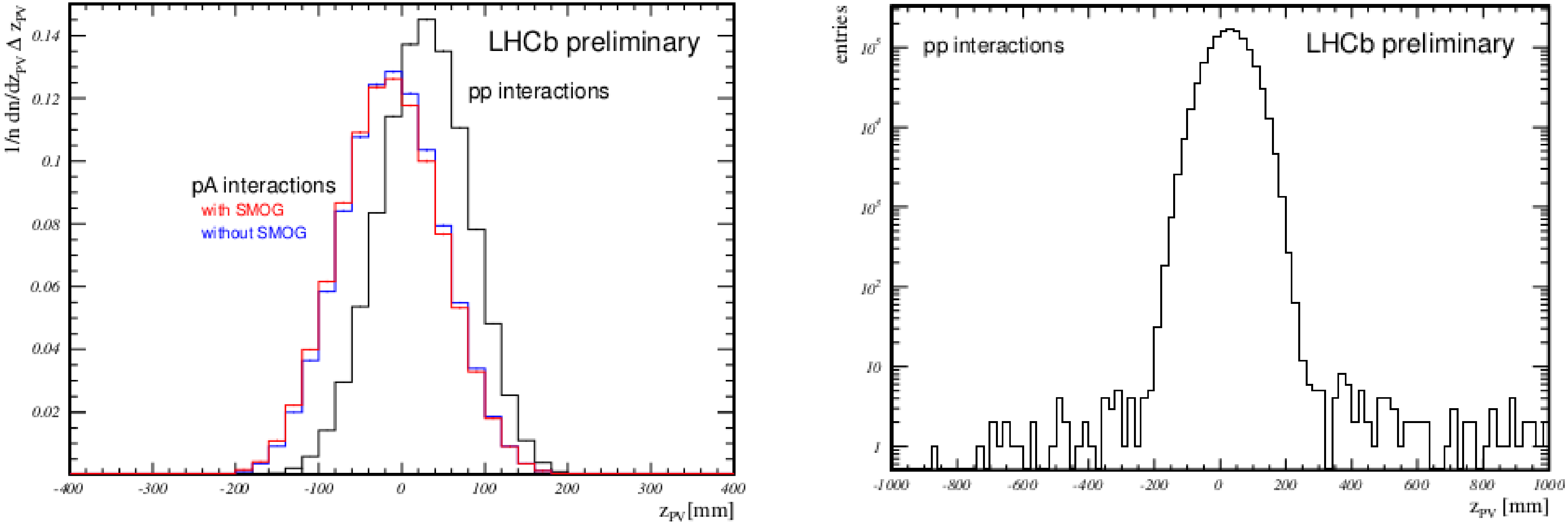
LHCb, CERN-LHCb-CONF-2012-034



LHCb: Beam gas subtraction

LHCb, CERN-LHCb-CONF-2012-034

z-vertex positions of primary vertices in pPb and pp



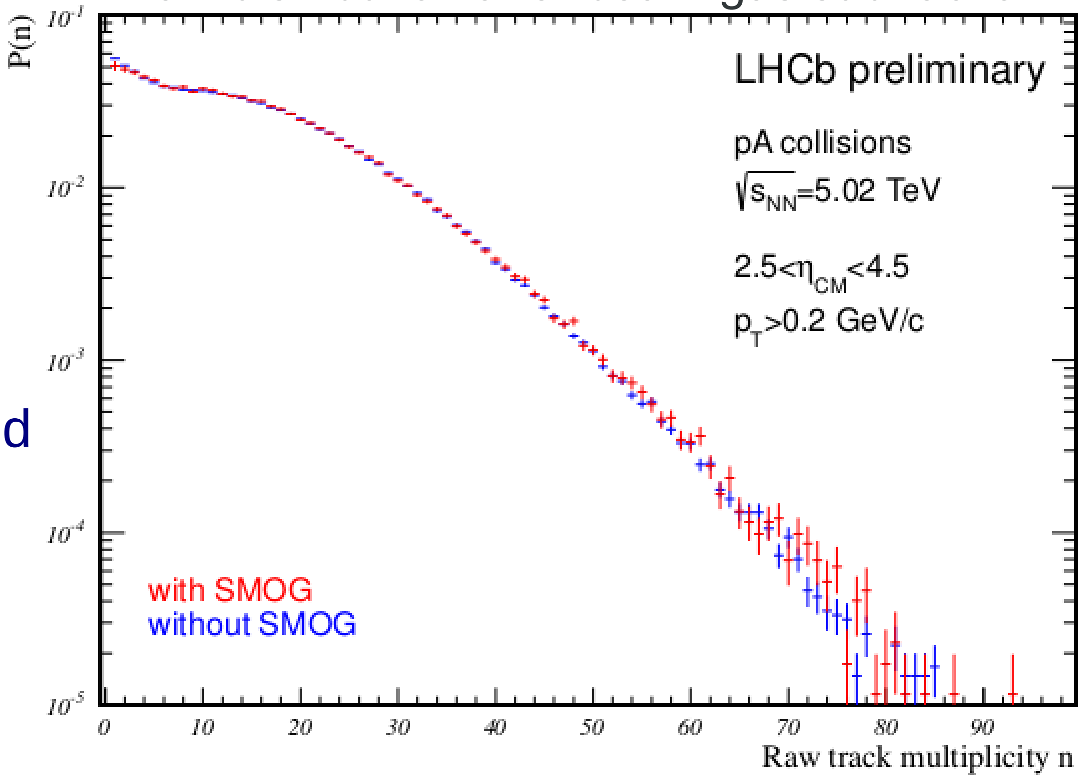
- After beam-gas subtraction vertex distributions in pPb are very similar for collisions taken with and without SMOG
- Differences in luminous region between pPb and pp
- Luminous region in $|z_{PV}|<200$mm for pPb and pp

Inelastic pPb cross section

- Count collisions which produce at least one track in $2.5<\eta<4.5$ (proton side) with $p_T>0.2$ GeV/c
    - In HIJING/DPMJET only 1-2% events without a charged particle
- Analysis steps
    - Beam gas subtraction
    - Pileup below permille level ignored
    - Trigger efficiency 100% ±1%
    - Correction for finite single track finding efficiency: 98% ± 2%
    - Convert using integrated luminosity measured with SMOG
    - Systematic uncertainty dominated by 5.2% error on luminosity

LHCb, CERN-LHCb-CONF-2012-034

Raw distribution after beam-gas subtraction



$$\sigma_{inel}(2.5<\eta_{cm}<4.5,\ p_T>0.2\,\mathrm{GeV}/c)=2.09\pm0.12\,\mathrm{b}$$

(consistent with HIJING, DPMJET and Glauber with σ_{NN}=70mb)

NSD pPb normalization

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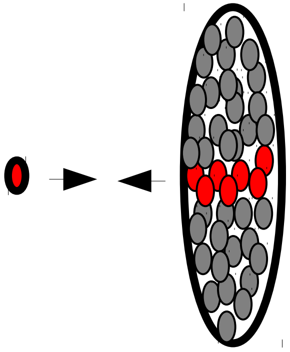
- Event selection
  - VZERO-A ($2.8<\eta<5.1$) and VZERO-C ($-3.7<\eta<-1.7$) incl. time cuts
  - Systematic variation using ZDC on nucleus side (ZNA)
- Resulting event sample



  - Non single-diffractive (NSD)
    - At least one binary N+N interaction is NSD (Glauber picture)
    - Inspired from DPMJET, which includes incoherent SD of the projectile with target nucleons that are mainly concentrated on the surface of the nucleus
    - SD about 4% from HIJING, DPMJET or standalone Glauber
  - Negligible contamination from SD and EM processes
- Validated with a cocktail of generators
  - DPMJET for NSD (2b)
  - PHOJET + Glauber for incoherent SD part (0.1b)
    - SD/INEL = 0.2 in pp at 7 TeV (arXiv:1208.4968)
  - EM with STARLIGHT (0.1-0.2b)

Pseudorapidity density

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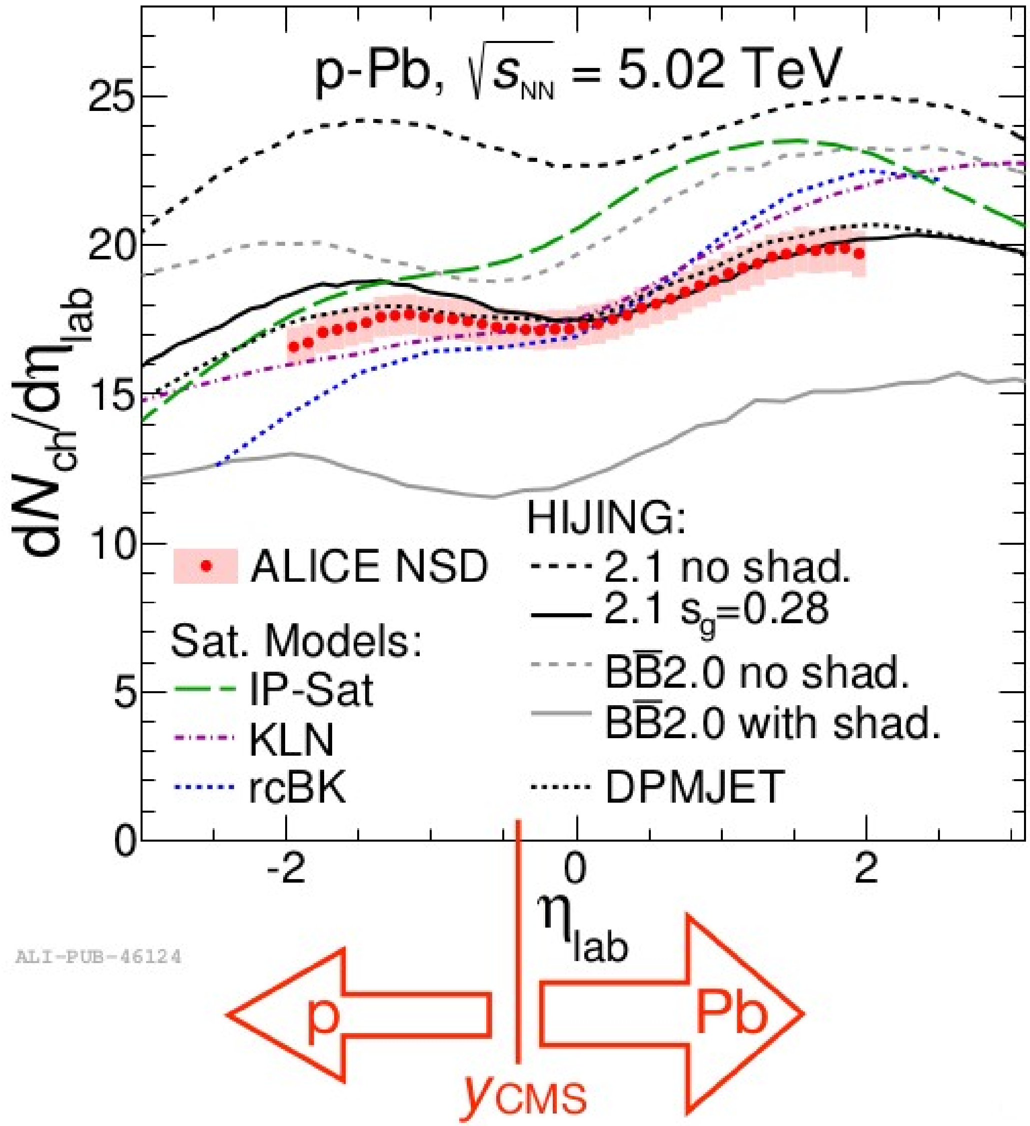
- Tracklet analysis using SPD hits
  - Dominant systematic uncertainty from NSD normalization of 3.1%
- Reach of SPD extended to |η|<2 by extending the z-vertex range
- Results in ALICE laboratory system
  - $y_{cms} = -0.465$
- Comparison
  - Most models within 20%
  - Saturation models have to steep rise between p and Pb region



NB: HJING calculations for NSD expected to increase by ~4%

Pseudorapidity density at midrapidity

- Measurement (tracklet based)
    - $dN/d\eta = 16.81 \pm 0.71$ (syst)
    - Converted into centre-of-mass system using HIJING
    - Dominant uncertainty from NSD normalization of 3.1%
- Glauber model for pPb
    - With $\sigma_{INEL} = 70 \pm 5$ mb
    - $\langle N_{part} \rangle = 7.9 \pm 0.6$ (syst)
- Participant scaled value
    - $(dN/d\eta)/\langle N_{part} \rangle = 2.14 \pm 0.17$ (syst)
    - About 15% below NSD pp
    - Similar to pp INEL
- Inelastic pPb would be 4% lower (estimate from models)

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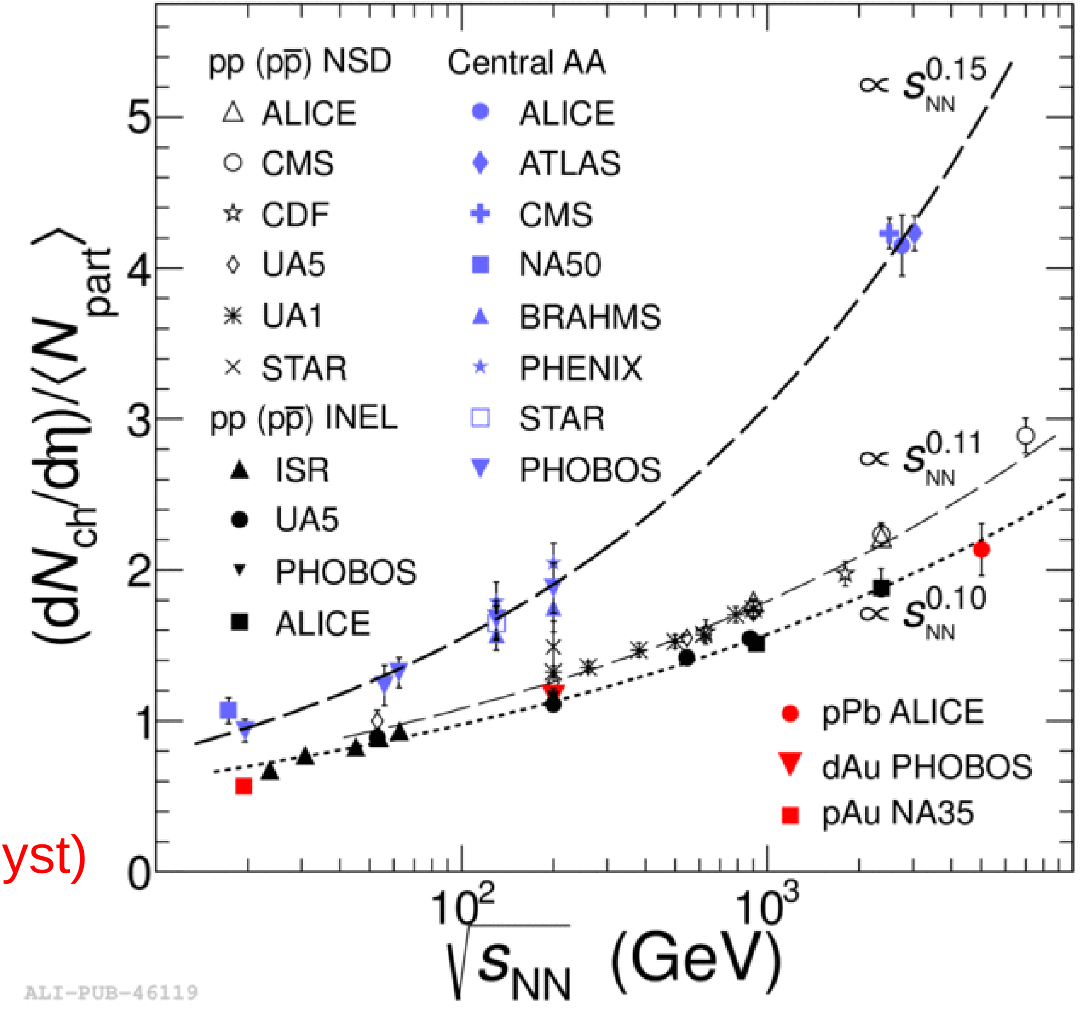
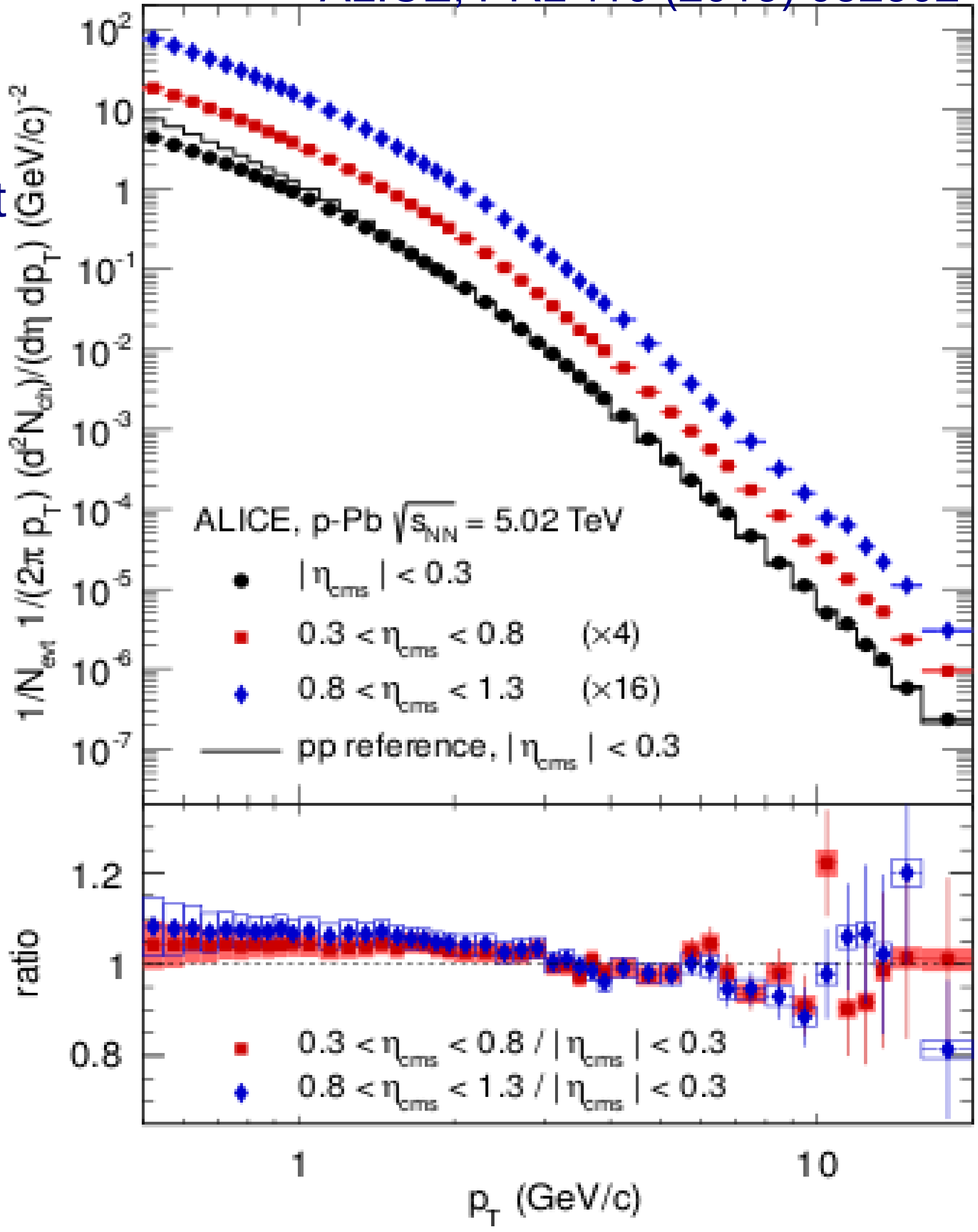


Charged particle spectrum

- Primary charged tracks (3 η bins)
  - Reconstructed in ITS+TPC (|η|<0.8)
  - Assume $\eta_{cms} = \eta_{lab} - y_{cms}$, then correct
  - Systematic uncertainty: 5.2-7.1%
  - NSD normalization: 3.1 %
- Hint for slightly softer spectrum at higher η (Pb side)?
- Reference constructed from pp (INEL) data at 2.76 and 7 TeV
  - Interpolation below 5 GeV/c, and above scaled by factor obtained from NLO calculation
    - Systematic uncertainty: 8%
    - Normalization uncertainty: 3.6%
  - $\langle T_{pPb} \rangle = 0.0983 \pm 0.0035\ \mathrm{mb}^{-1}$ from Glauber model

ALICE, PRL 110 (2013) 082302



Nuclear modification factor

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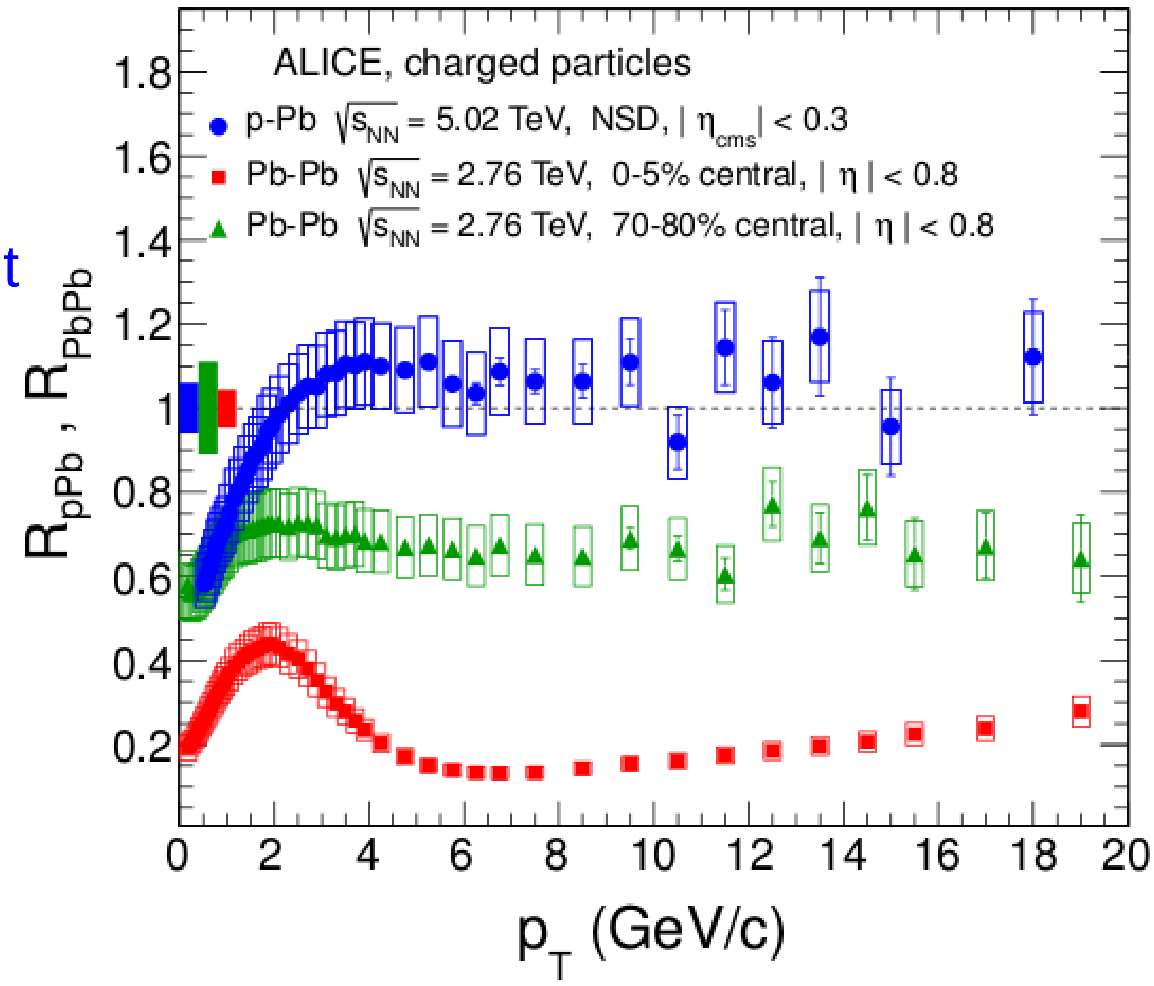
$$R_{AB} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- R_{pPb} (at mid-rapidity) consistent with unity for $p_T > 2$ GeV/c
- High-p_T charged particles exhibit binary scaling
- Unlike in PbPb, no suppression is observed
- Suppression in PbPb is not an initial state effect

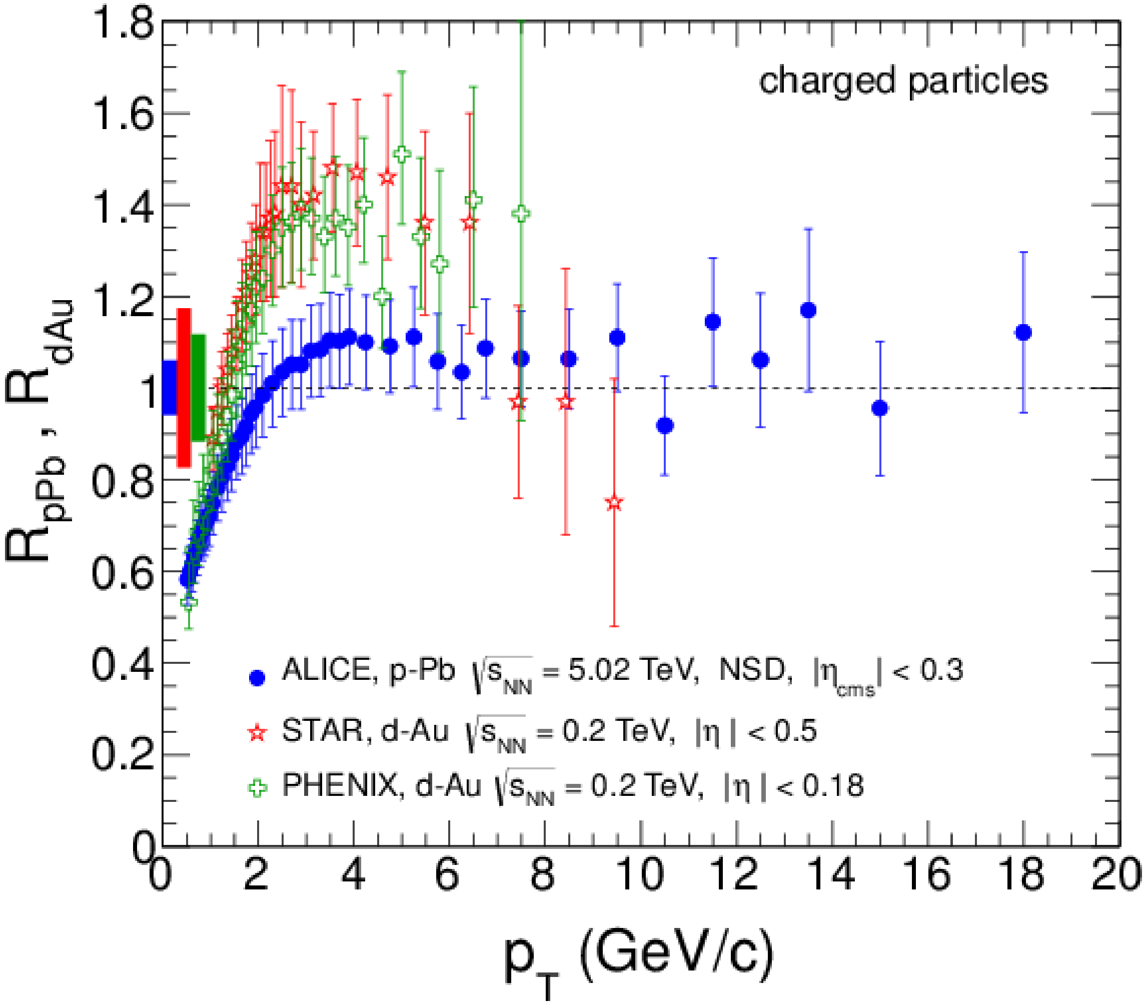


Cronin effect at RHIC and LHC

ALICE, PRL 110 (2013) 082302
STAR, PRL 91 (2003) 072304
PHENIX, PRL 91 (2003) 072030

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

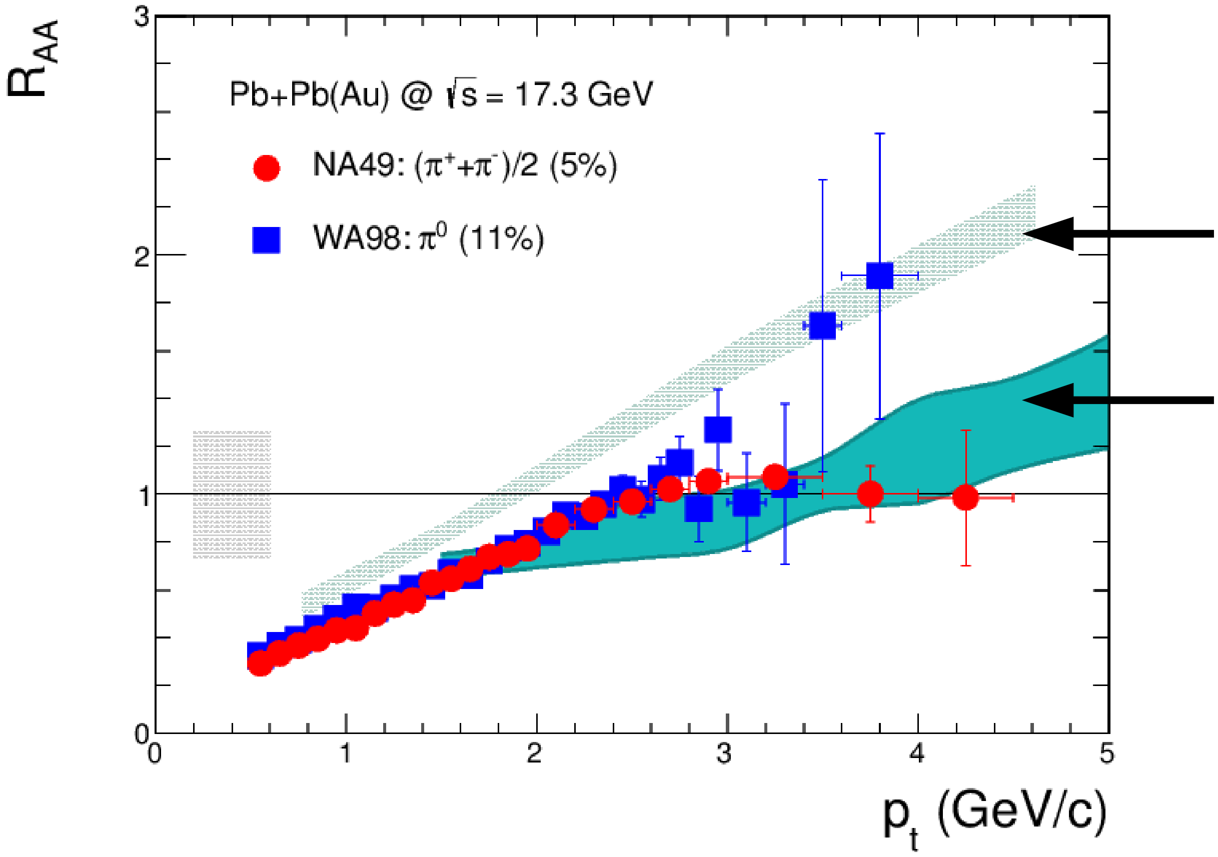
- $R_{AB} > 1$ at intermediate p_T observed in dAu collisions at RHIC typically attributed to Cronin effect
- No enhancement seen in pPb at the LHC
- No Cronin effect?



Cronin effect at SPS

- Reminder from SPS energies: RAB ≈ 1 does not necessarily imply absence of effects

NA49, NPA 783 (2007) 65
WA98, PRL 89 (2002) 252301



Calculation
taking into account:

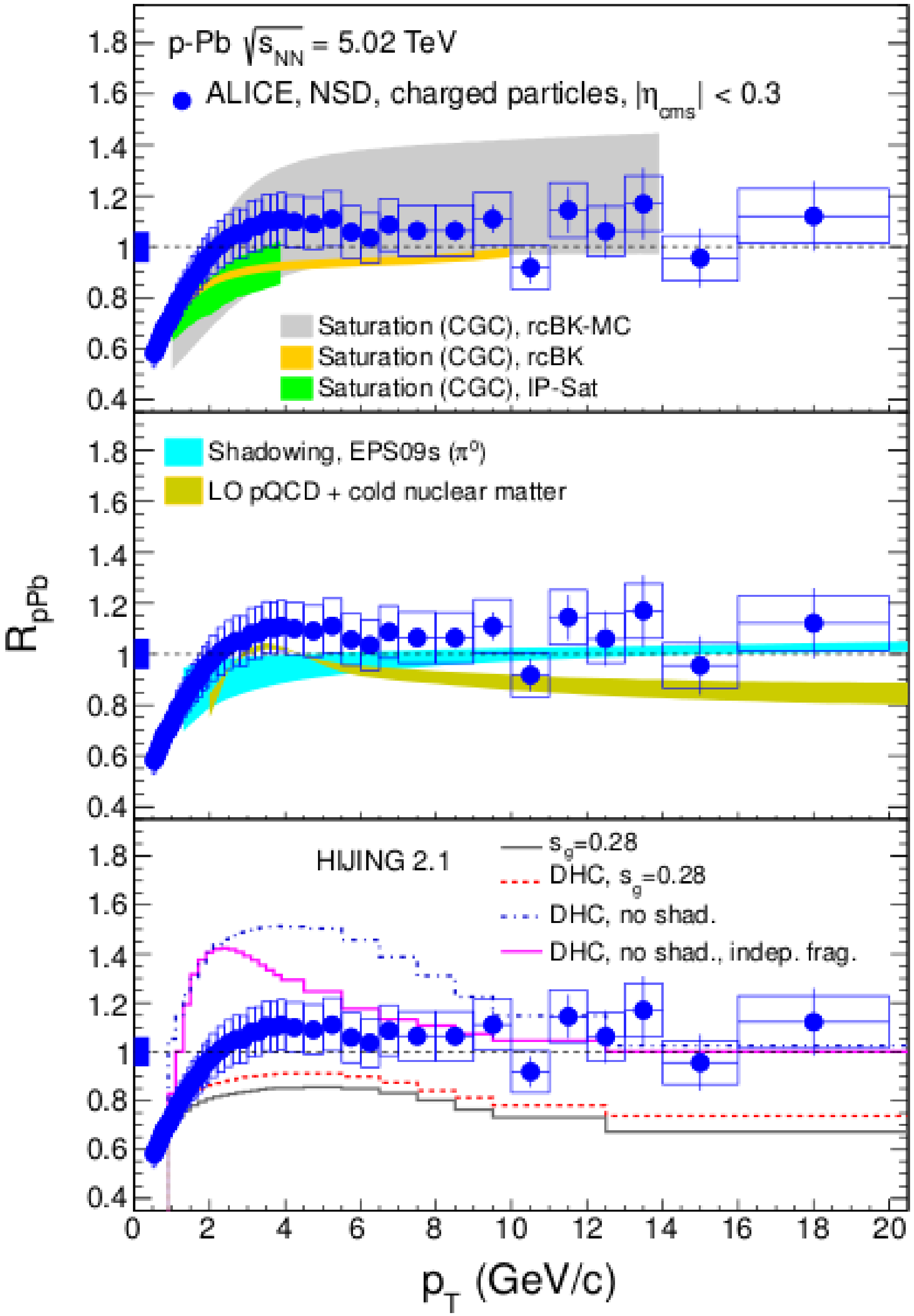
Cronin effect + shadowing

Cronin effect, shadowing plus partonic energy loss

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

Nuclear modification factor vs models

- Saturation (CGC) models:
  - Consistent with the data
  - Large uncertainties
- pQCD models with shadowing
  - Consistent at low p_T
  - Discrepancies at high p_T
- HIJING
  - With shadowing describes η and low p_T better
  - No shadowing better at high p_T
- Spectrum on its own interesting
  - Neither HIJING nor DPMJET do describe the p-Pb p_T spectra

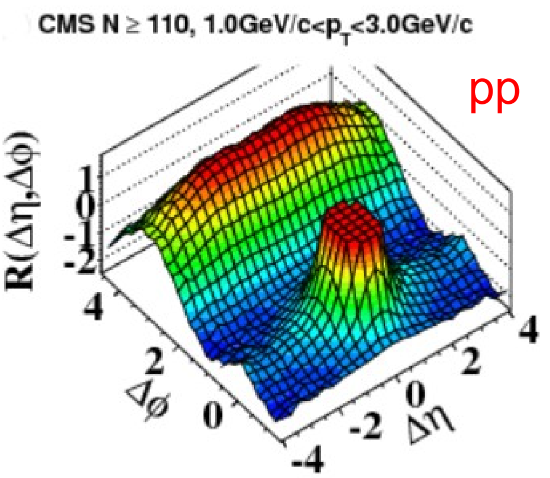


NB: HJING calculations for NSD expected to increase by ~4%

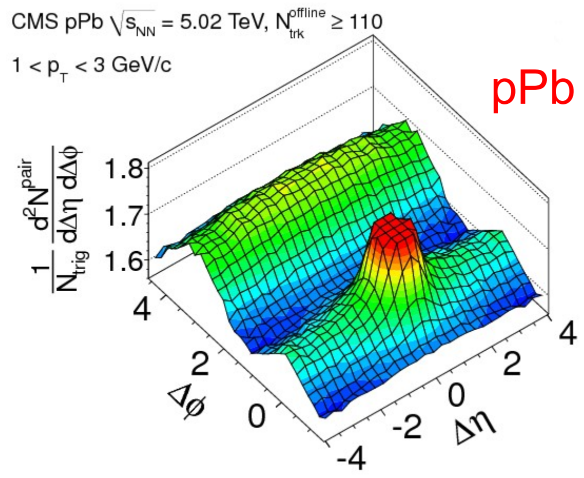
Di-Hadron Correlations (DHC)

- CMS: pp, pPb at LHC
  - Long-range near-side correlations (ridge) appear at high-multiplicity
    - Collective effects in pp and pPb?
    - CGC initial state effects?

CMS, JHEP 1009 (2010) 91

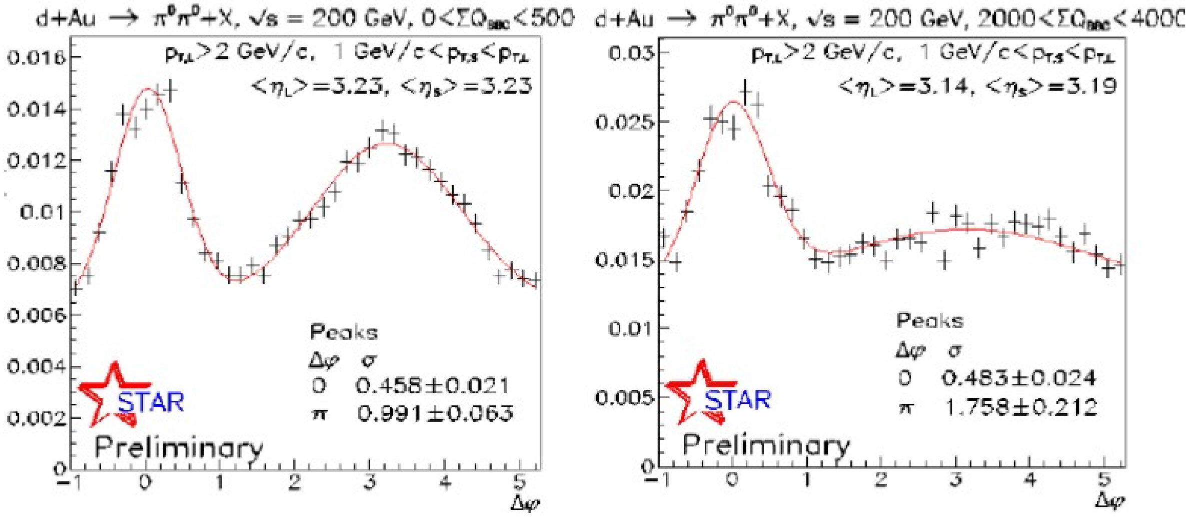


CMS, PLB 718 (2012) 795



- STAR: dAu at RHIC
  - Back-to-back (jet-like) correlations in forward π^0 correlations disappear in high-multiplicity events
    - Compatible with CGC predictions
- LHC mid- and RHIC forward-η probe a similar x regime

STAR, arXiv:1005.2378

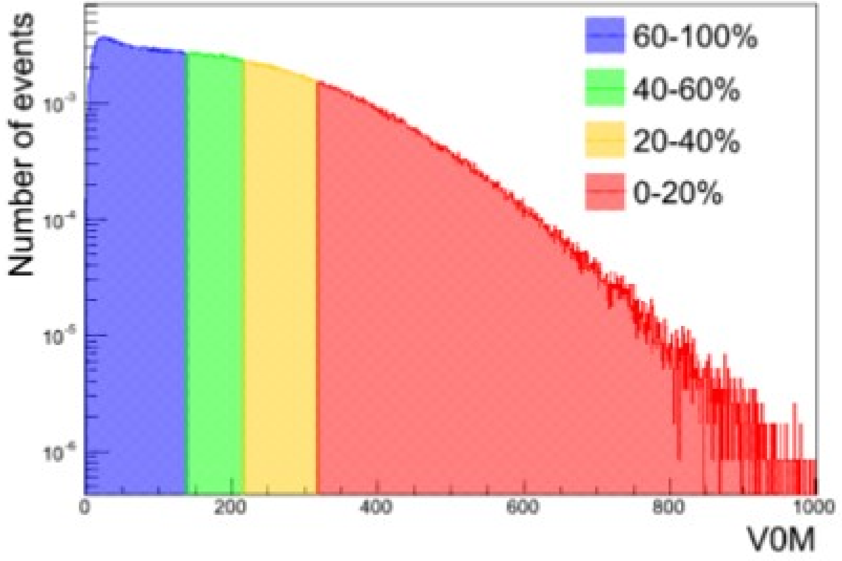


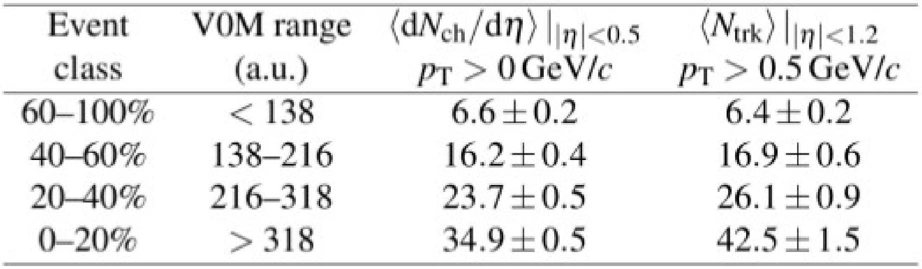
Peripheral Central

DHC: Multiplicity classes

ALICE, PLB 719 (2013) 29

- Correlation between geometry and multiplicity in pA is not as strong as in AA
  - System also shows features of biased pp (NN) collisions in the low and high multiplicity tails
- Define multiplicity classes
  - Use charge in VZERO to avoid correlation with tracks in barrel
  - V0M: sum of amplitudes from
    - VZERO-A ($2.8<\eta<5.1$)
    - VZERO-C ($-3.7<\eta<-1.7$)
- Systematic checks using
  - SPD ($|\eta|<1.4$)
  - ZNA (beam neutron on Pb side)





Event class	V0M range (a.u.)	$\langle dN_{ch}/d\eta \rangle \|_{\|\eta\|<0.5}$ $p_T > 0\,\mathrm{GeV}/c$	$\langle N_{trk} \rangle \|_{\|\eta\|<1.2}$ $p_T > 0.5\,\mathrm{GeV}/c$
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

DHC: Correlation measure

ALICE, PLB 719 (2013) 29

- Associated yield per trigger particle (with $p_T^{trig} > p_T^{assoc}$)

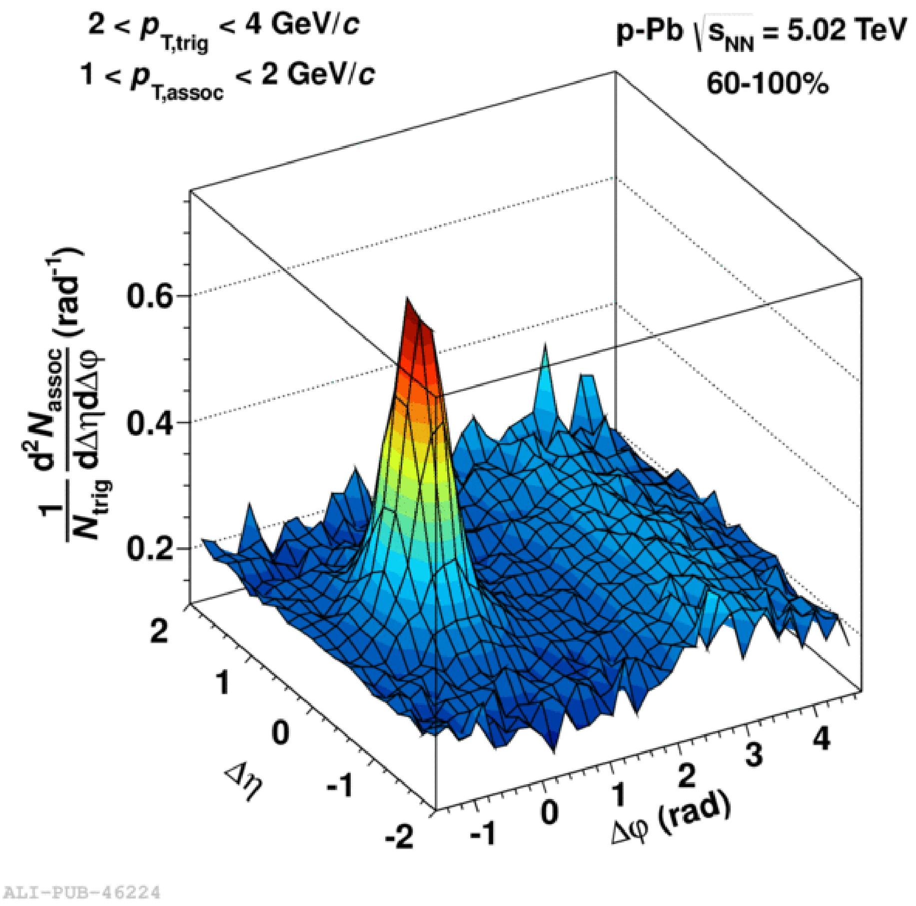
$$\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{assoc}}}{\mathrm{d}\Delta\eta\, \mathrm{d}\Delta\varphi} = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$$

- Signal (same event) pair yield

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

  - Definition as ratio of sums is multiplicity independent

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

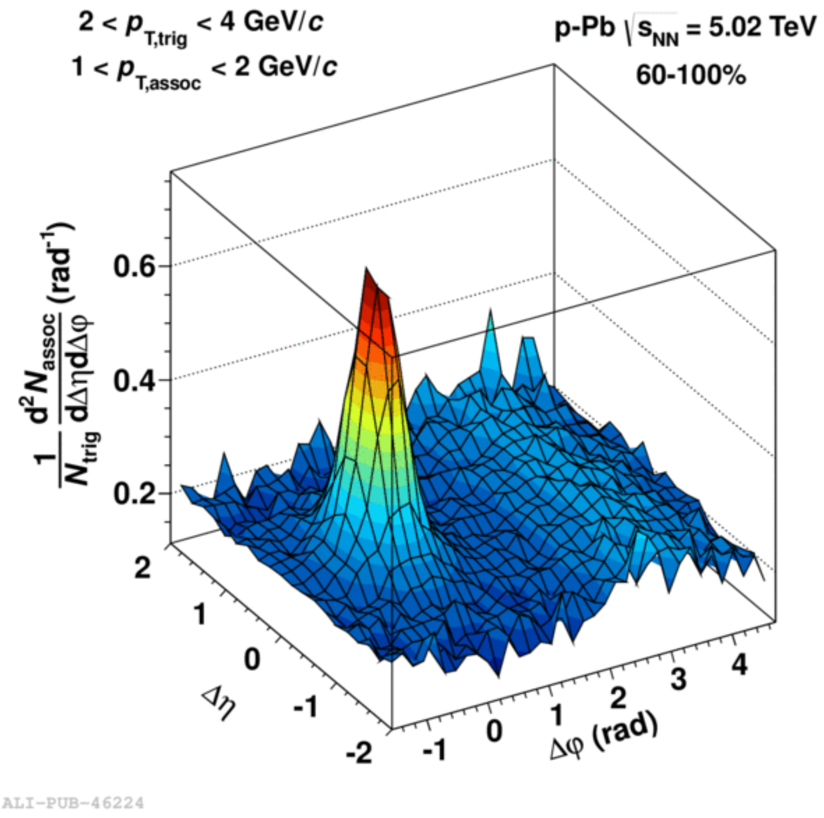


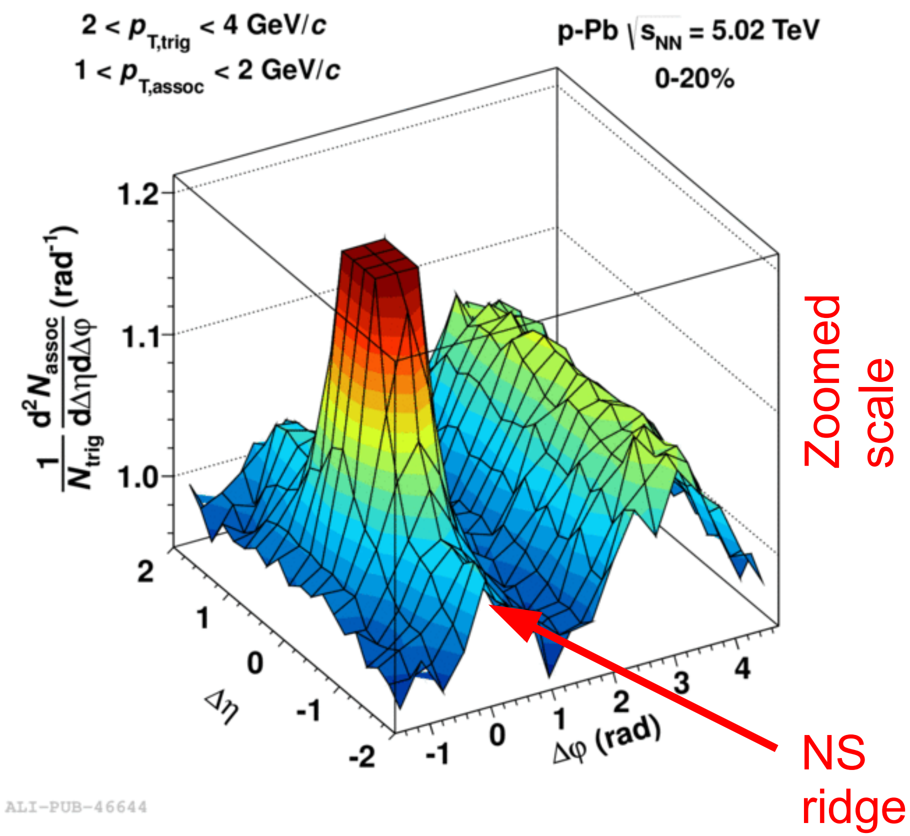
- Background (mixed event) pair yield

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

DHC: Multiplicity dependence

ALICE, PLB 719 (2013) 29





Zoomed scale

NS ridge

- Low-multiplicity p-Pb (60-100%)
  - pp-like (jet-like) correlation structures
- High-multiplicity p-Pb (0-20%)
  - Near-side ridge appears (first seen in CMS)
  - Higher yields on near- and away-side

DHC: Multiplicity dependence

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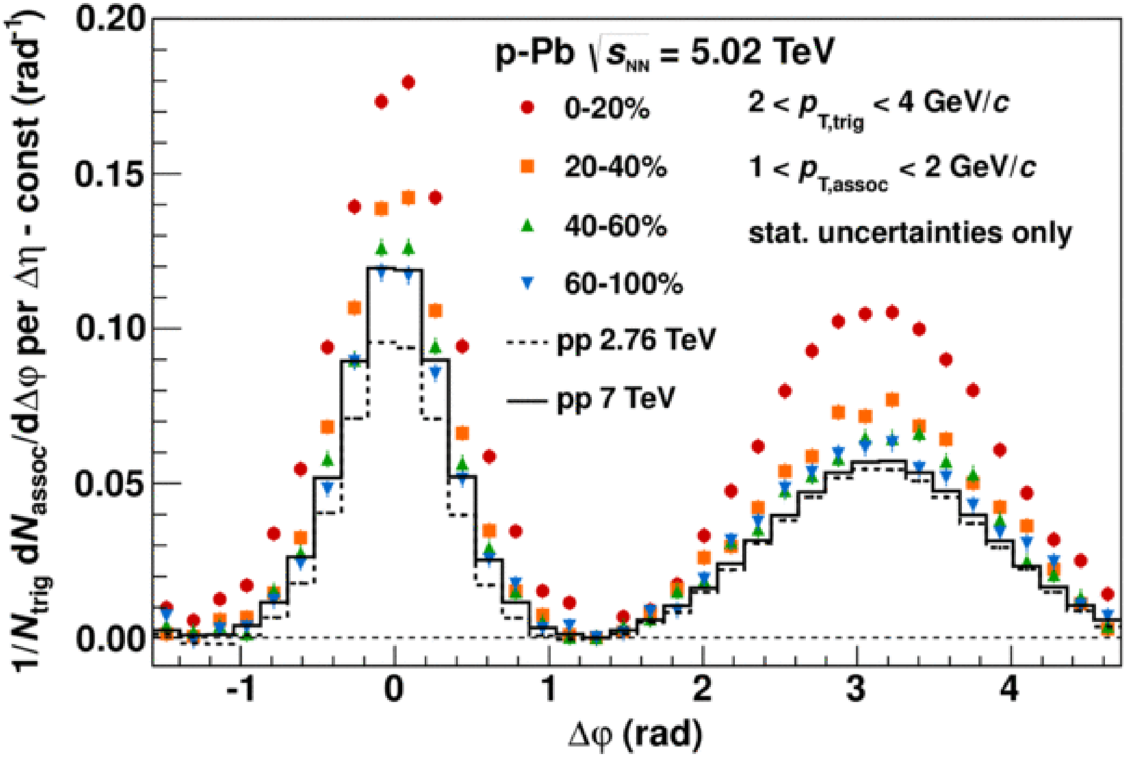
- Compare associated yield in pPb multiplicity classes and pp
  - Project to Δφ over |Δη|<1.8
  - Subtract baseline at Δφ~1.3
- Low multiplicity pPb is similar to pp (at 7 TeV)
- Yield rises on near and away side with increasing multiplicity
- In contrast with away-side suppression observed in dAu at RHIC at forward η (similar x)



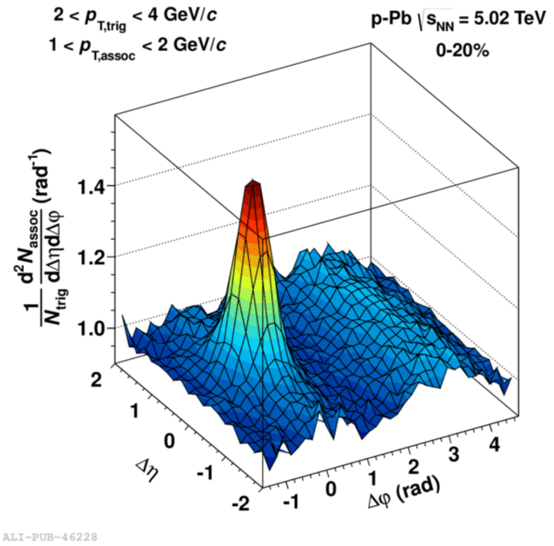
ALI-PUB-46238

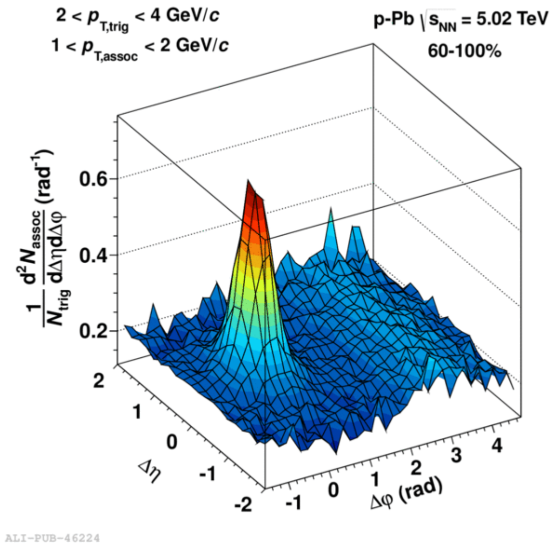
DHC: Two ridges

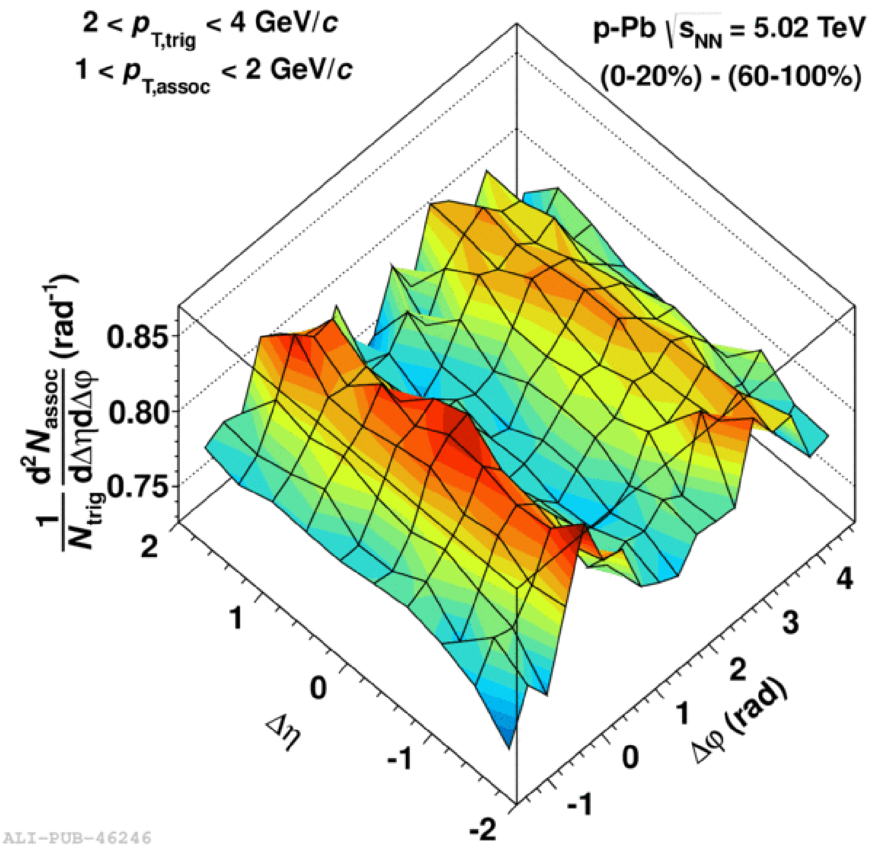
ALICE, PLB 719 (2013) 29

- Quantify the excess in high-multiplicity pPb by subtracting the jet-like correlations:

0-20% minus 60-100% =







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

DHC: Two ridges

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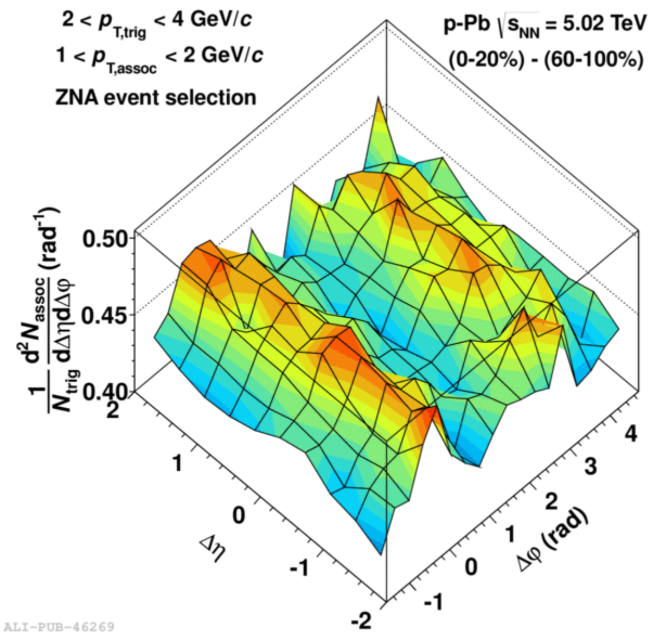
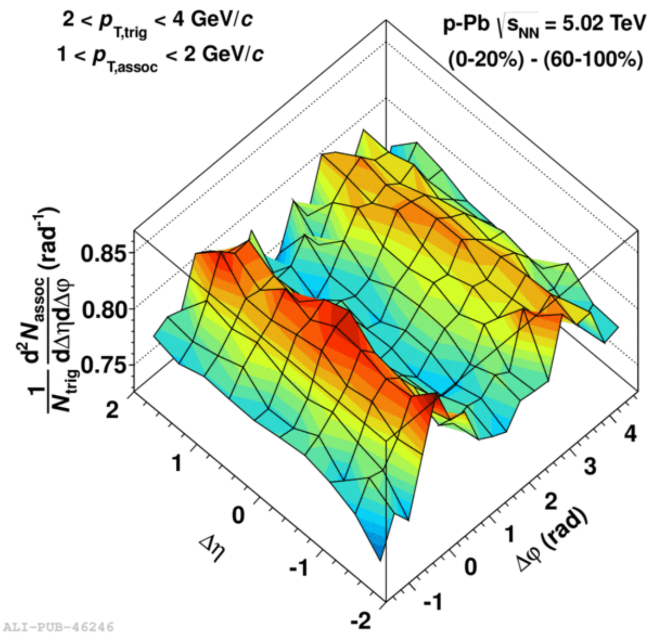
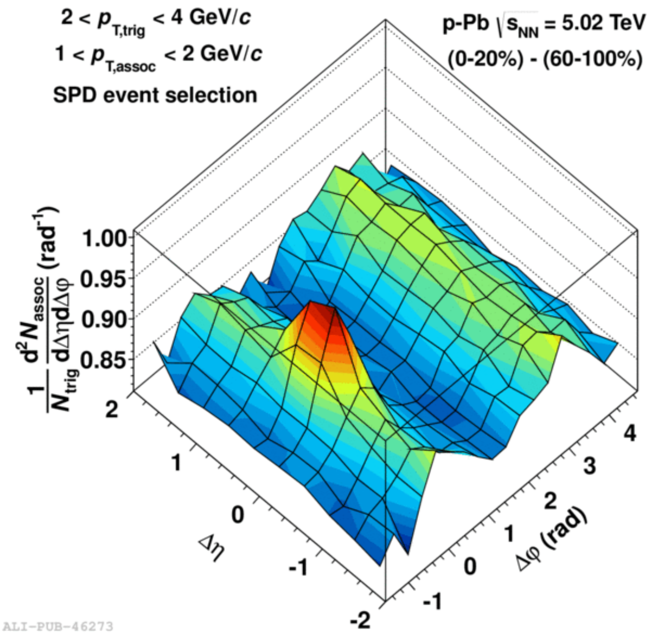
- A residual jet peak at (0,0) remains even after subtraction of 60-100% from the 0-20% multiplicity class
- Compare effects using different event class definition



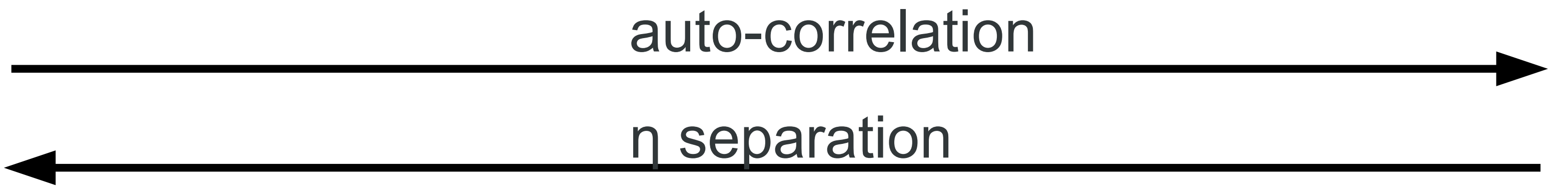
ZNA



VZERO



SPD

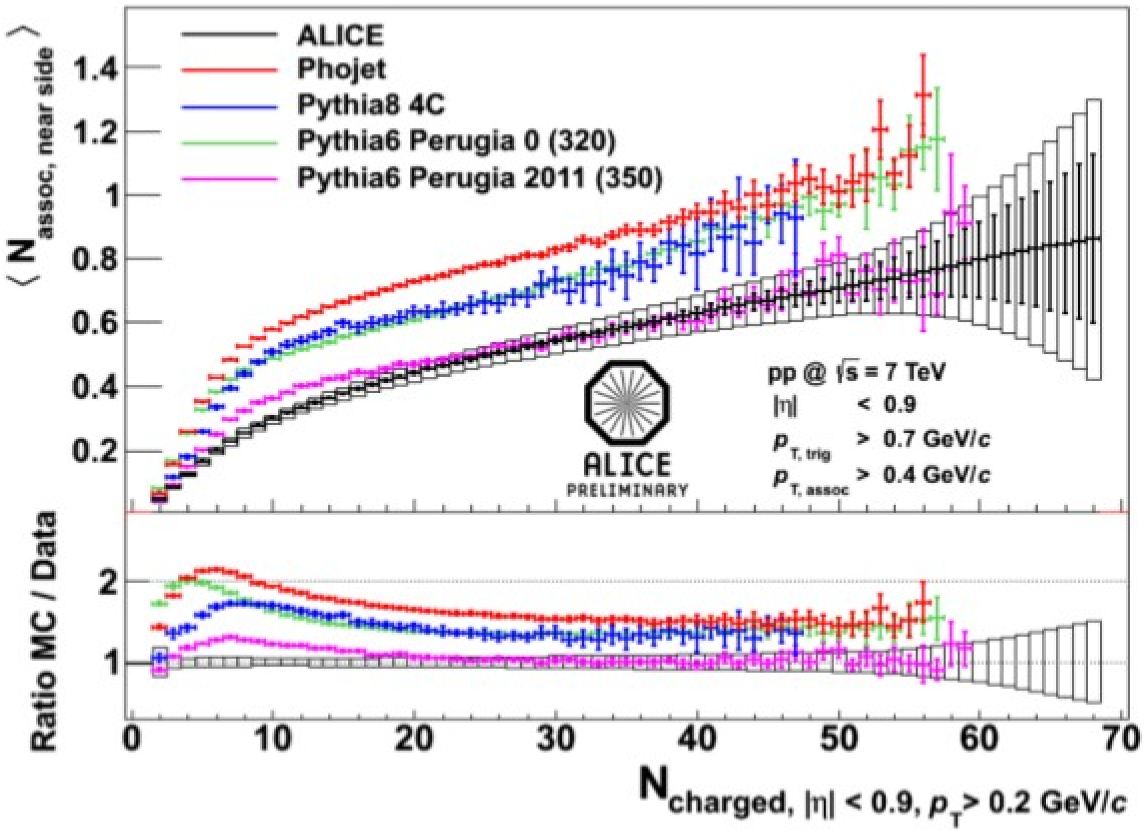


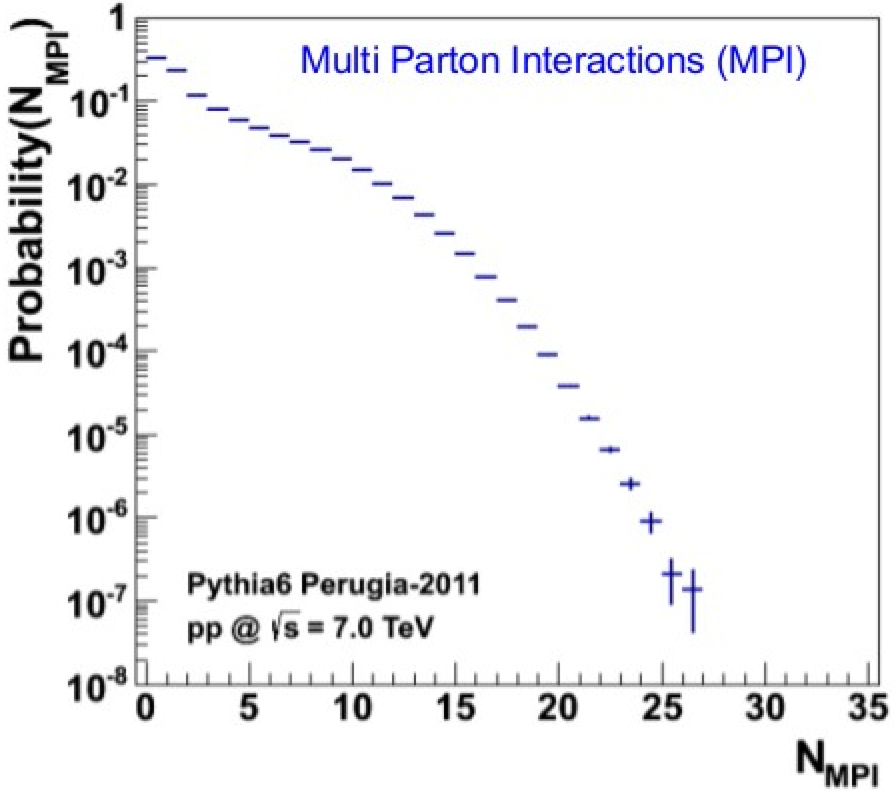
auto-correlation

η separation

DHC: Selection bias on fragmentation (pp)

Per trigger near-side pair yield in pp



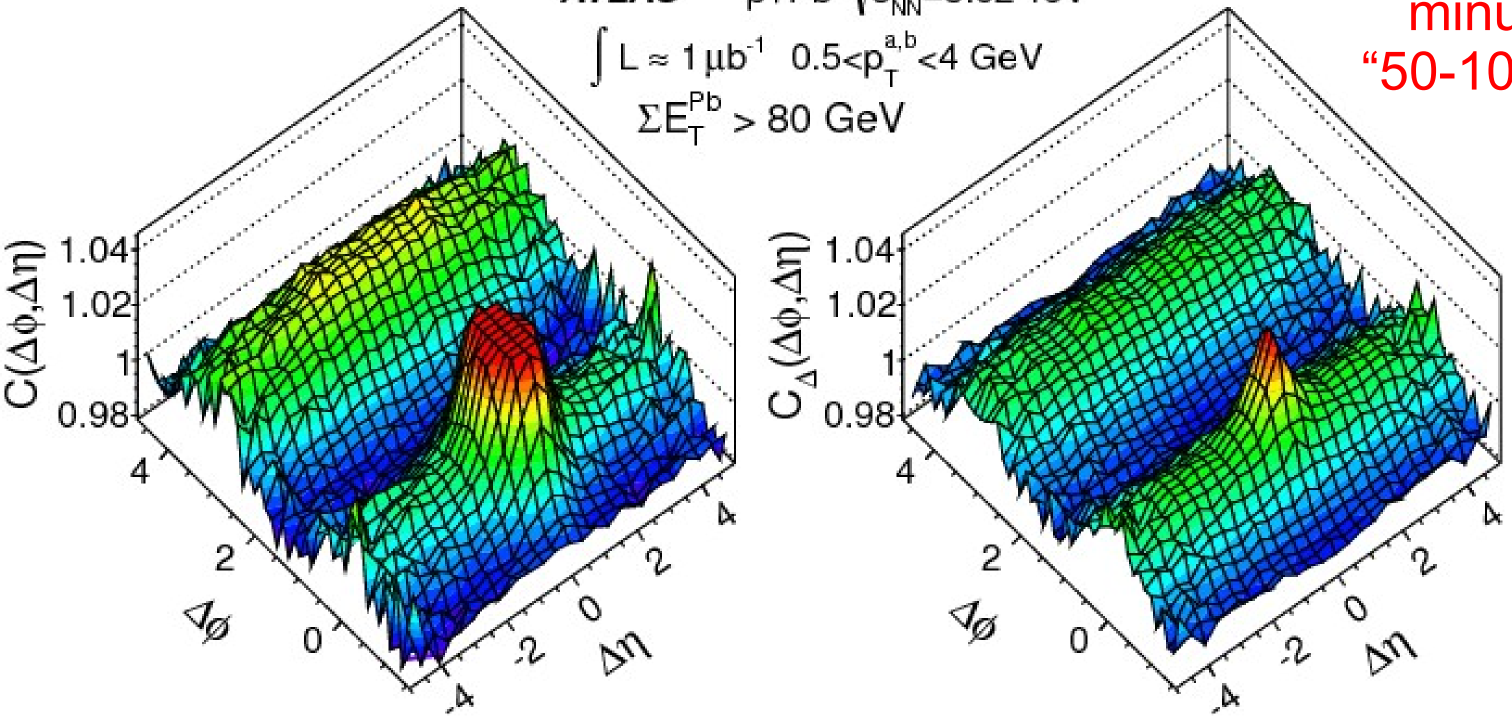


- By selecting on multiplicity, jet fragmentation is biased towards higher number of fragmenting products
- Competition between higher number of MPI and fragmentation

DHC: Two ridges (ATLAS)

ATLAS, arXiv:1212.5198

- Similar two ridge structures also observed by ATLAS
  - Event multiplicity classes defined by sum of transverse energy ($3.1<\eta<4.9$) on the Pb nucleus side
  - Also here, the jet peak at (0,0) remains even after subtraction of 50-100% from the 0-2% multiplicity class



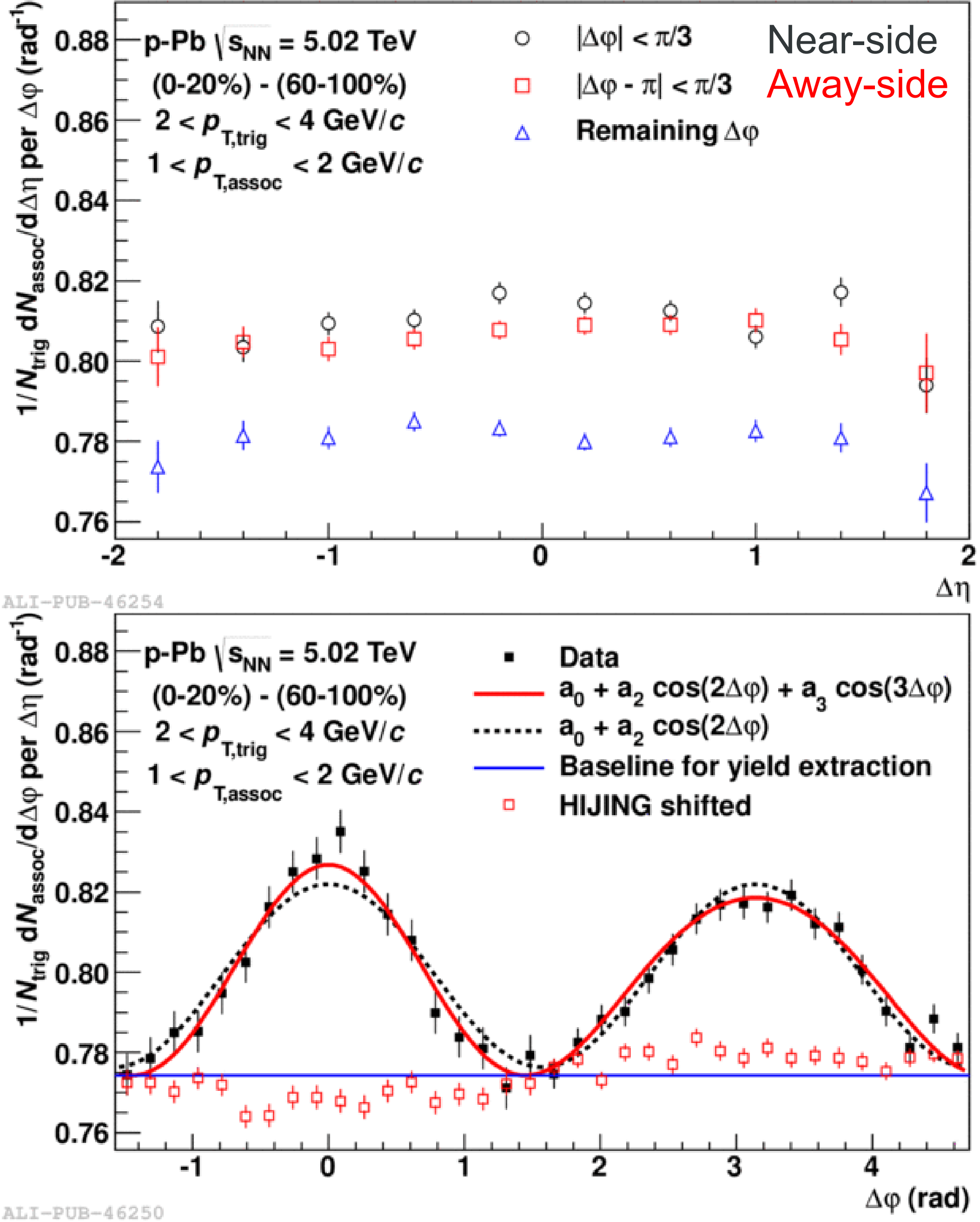
"0-2%"

"0-2%" minus "50-100%"

DHC: Two ridges

- A closer look at the two ridges: the near- and away-side ridges
    - Are essentially flat in Δη
        - Slight excess on near side due to small residual jet peak
    - Have the same magnitude
- Projection to Δφ
    - Exclude residual peak (|Δη<0.8| on near-side) exhibits a modulation
    - In HIJING, the correlation shows no qualitative changes with multiplicity
    - Quantify the ridges
        - Ridge yields
        - Fourier coefficients

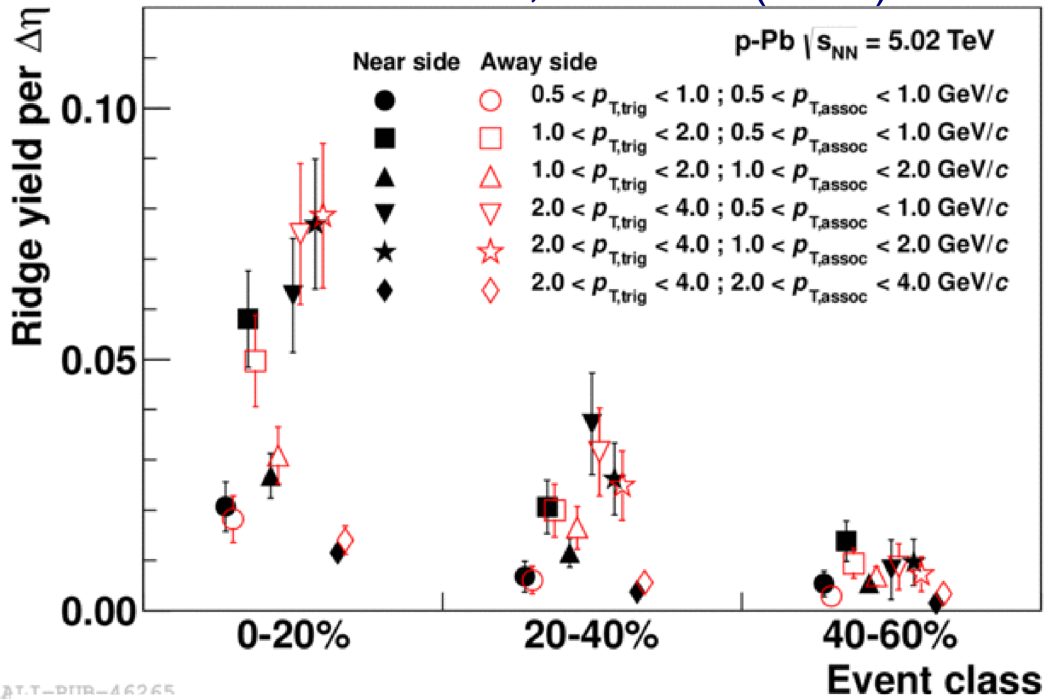
ALICE, PLB 719 (2013) 29



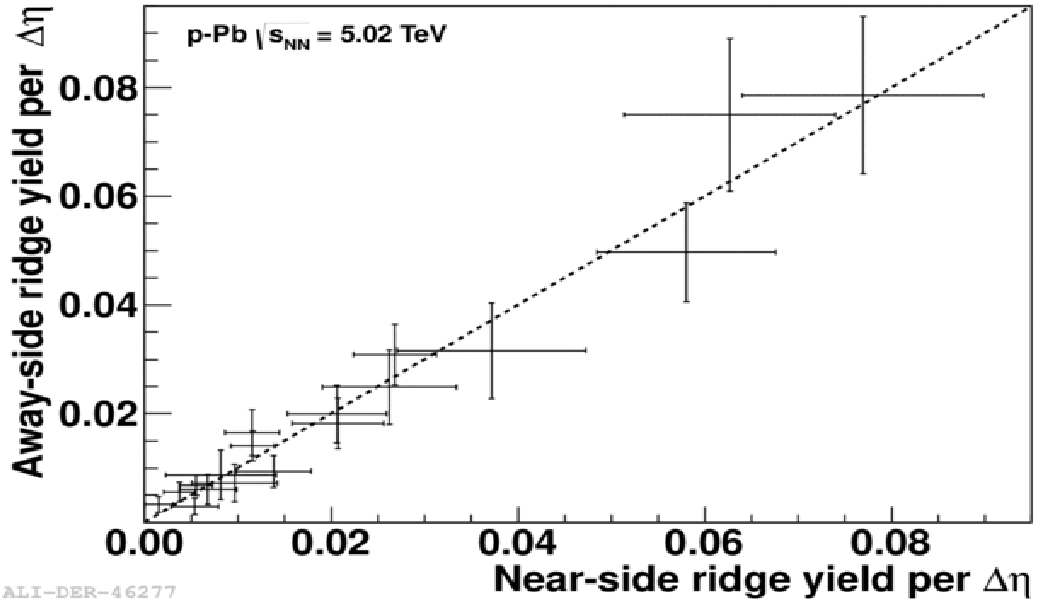
DHC: Ridge yields

- Integrate two ridges above baseline on the
    - Near side (|Δ|<π/2)
    - Away side (π/2<|Δ|<3π/2)
- Near and away-side ridge yields
    - Change significantly
    - Agree for all p_T and multiplicity ranges
    - Increase with trigger p_T and multiplicity
    - Widths are approximately the same (not shown)
- The correlation between near- and away-side yields suggests a common underlying origin

ALICE, PLB 719 (2013) 29



ALI-PUB-46265

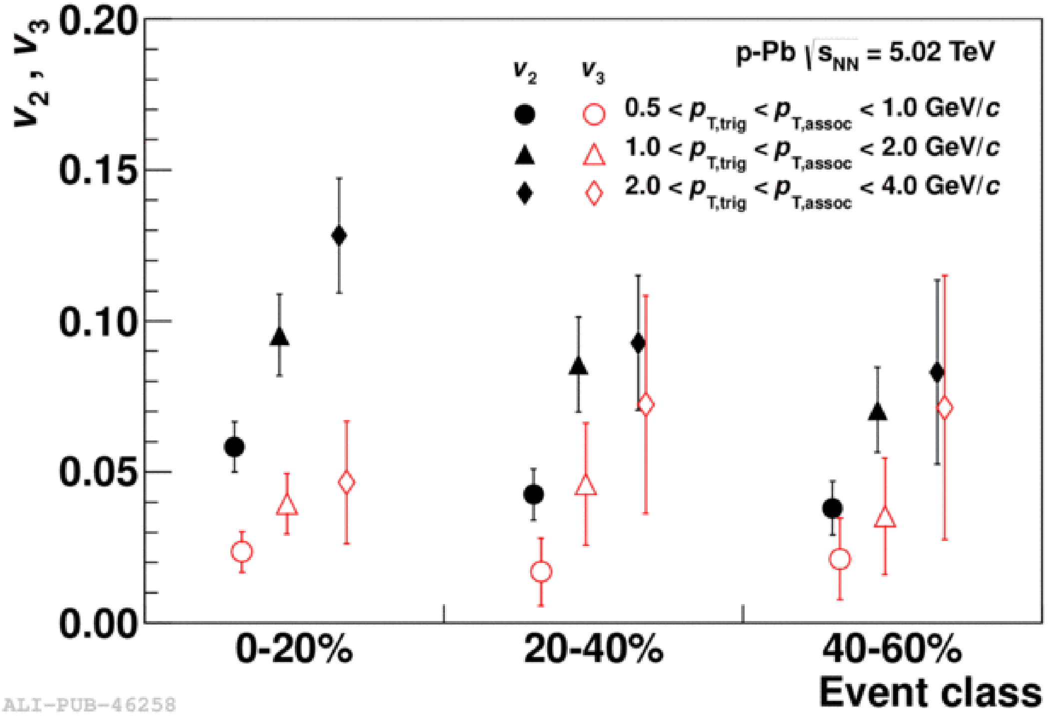


ALI-DER-46277

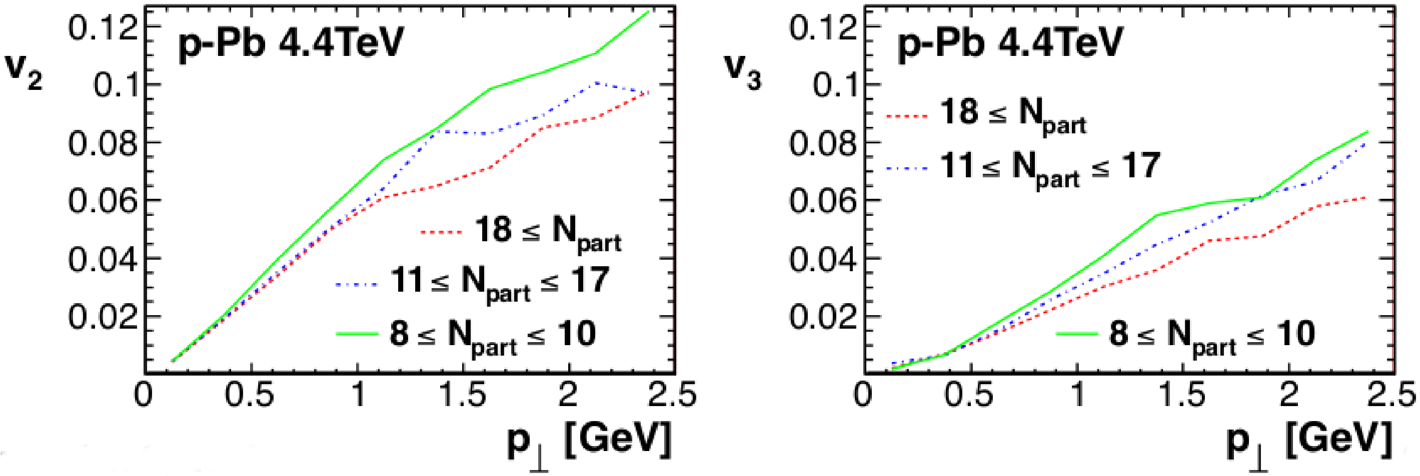
DHC: Ridge modulation

- Obtain $v_n = \sqrt{(a_n/b)}$ from $a_0+2a_2\cos(2\Delta\varphi)+2a_3\cos(3\Delta\varphi)$ fit where b is baseline in higher multiplicity class
    - v_2 increases strongly with p_T and mildly with multiplicity
    - v_3 increases with p_T within large uncertainties
    - These trends are in qualitative agreement with expectations from viscous hydrodynamical predictions

ALICE, PLB 719 (2013) 29

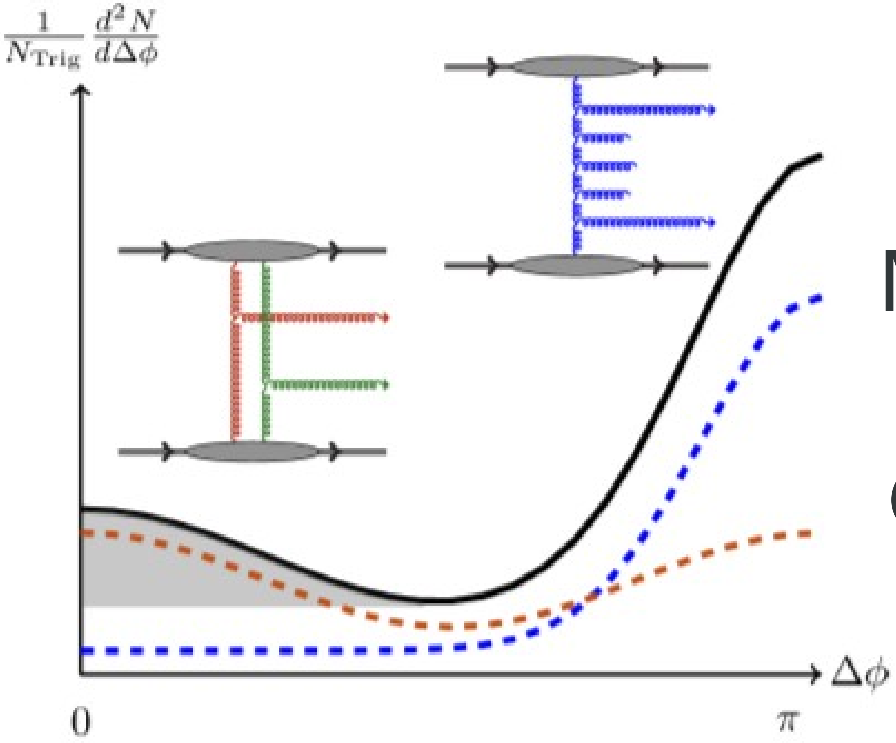


Bozek, PRC 85 (2012) 014911



DHC: Ridge modulation

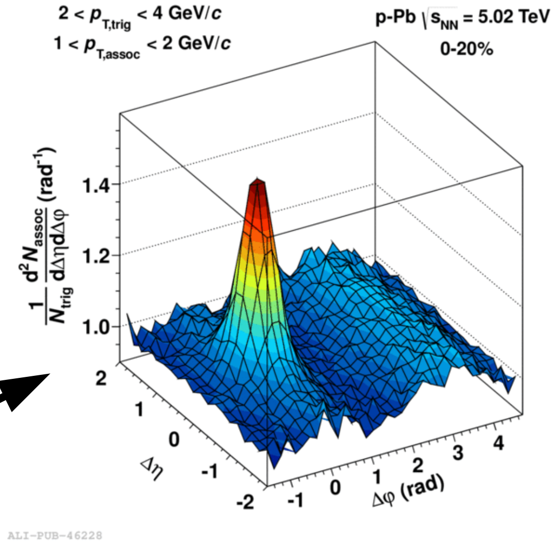
- Two ridges are also predicted by CGC

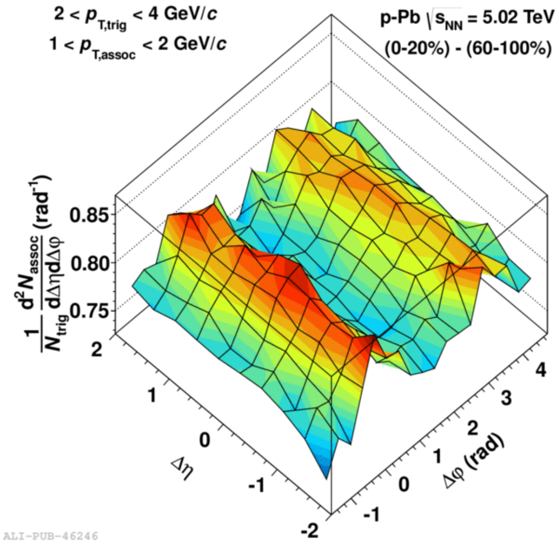


Dusling and Venugopalan, arXiv:1302.7018

Minijets

Glasma

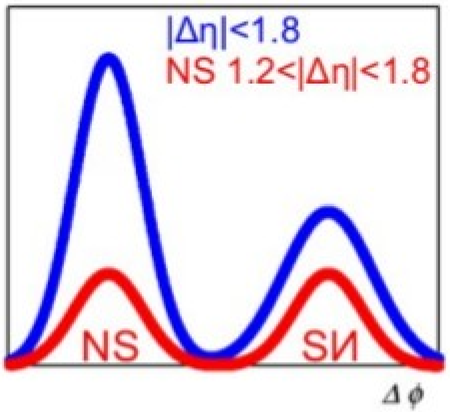


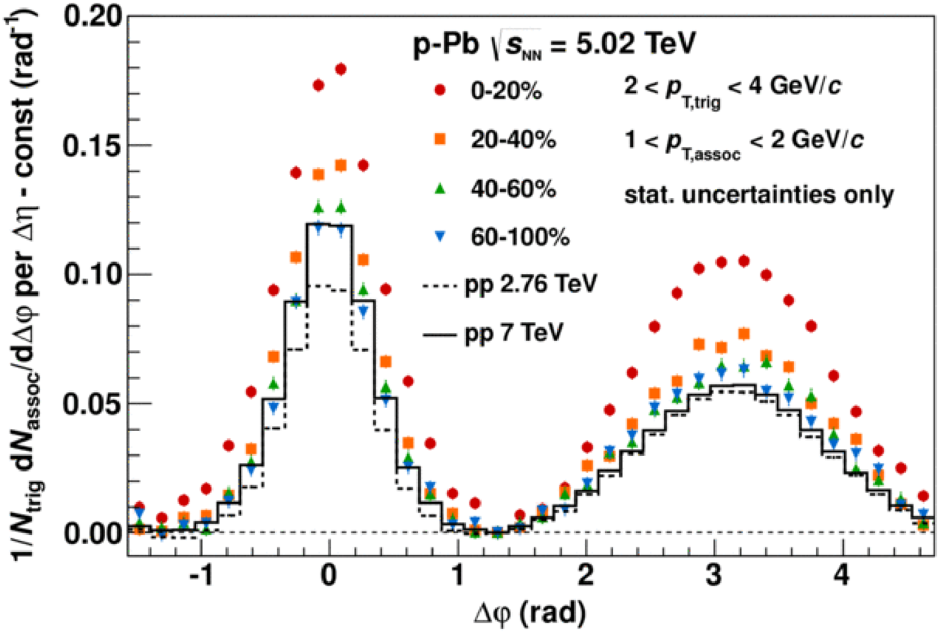


DHC: Symmetric ridge

ALICE, PLB 719 (2013) 29

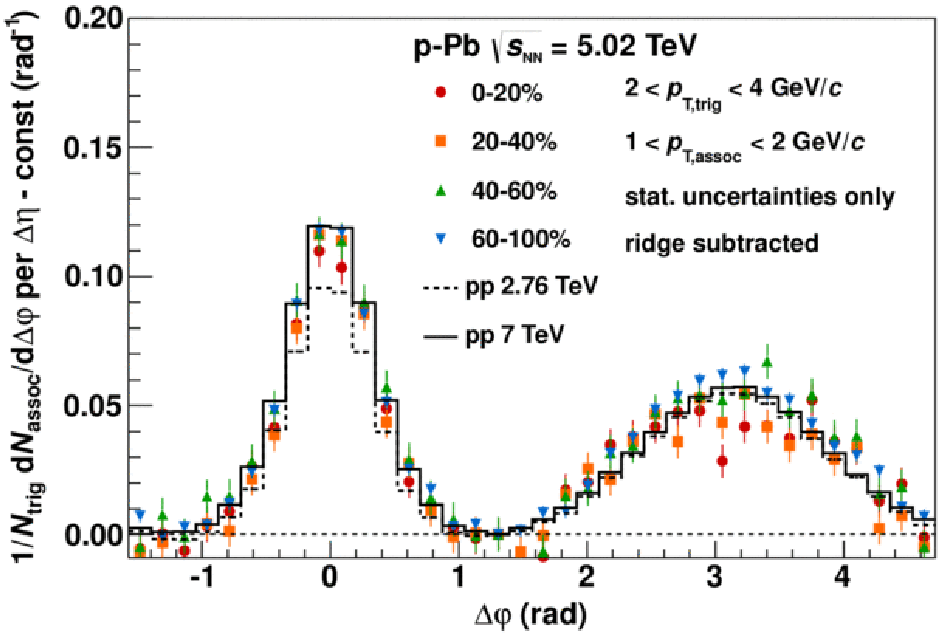
- What would the assumption of a symmetric ridge give?
  - Determine the near-side ridge in 1.2 < |Δη| < 1.8
  - Mirror to away-side and subtract





ALI-PUB-46238

Subtract



ALI-PUB-46242

- No significant other multiplicity dependent structures left over

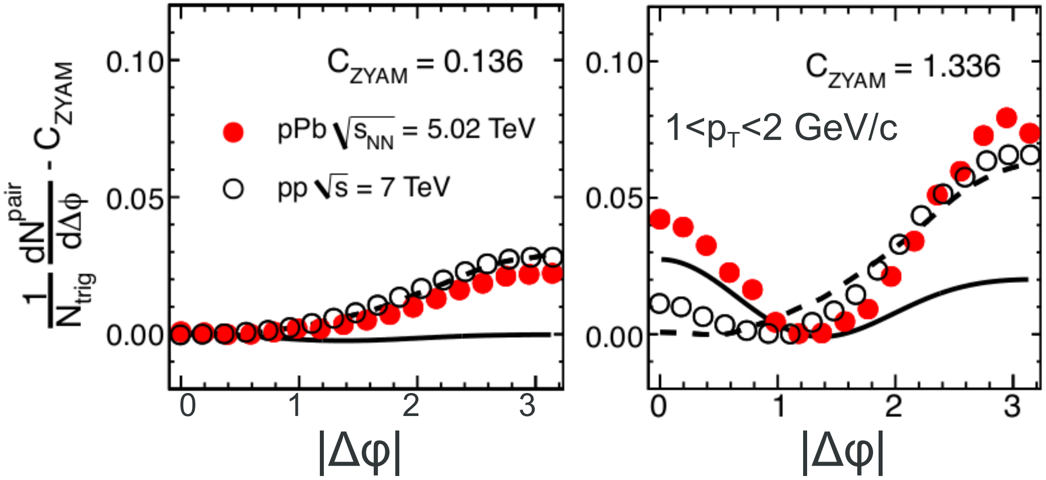
DHC: CMS and ATLAS

- CMS
    - Reported near-side ridge
- ATLAS
    - Confirms two-ridge structure
        - Larger acceptance
        - More p_T and multiplicity bins
- Results by the 3 collaborations are qualitatively similar
    - Differences in event selection, normalization, acceptance and p_T ranges, as well as in the per-trigger yield definition make direct comparisons difficult
    - A few cases were checked “together” and found to be consistent
    - See appendix: arXiv:1302.7018

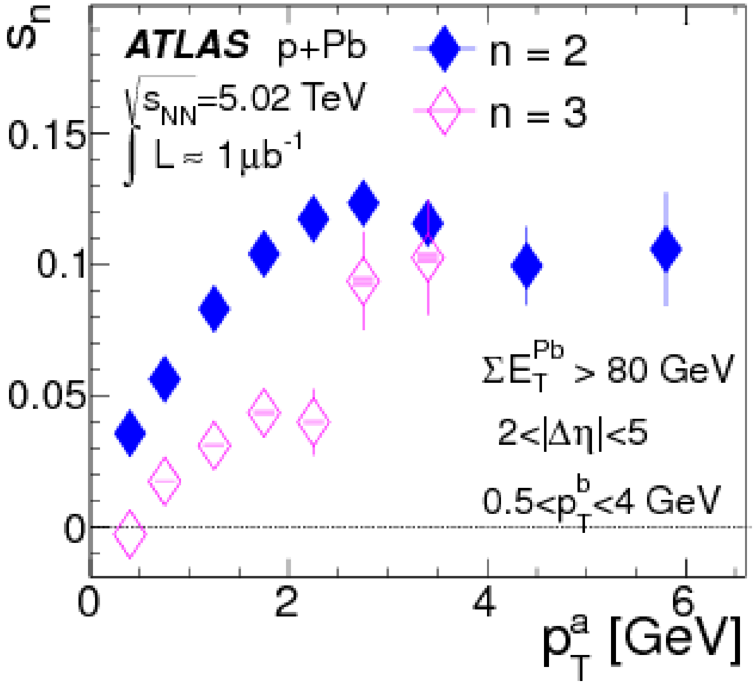
CMS, PLB 718 (2012) 795

Low mult. (Ntrack<35)

High mult. (Ntrack≥110)

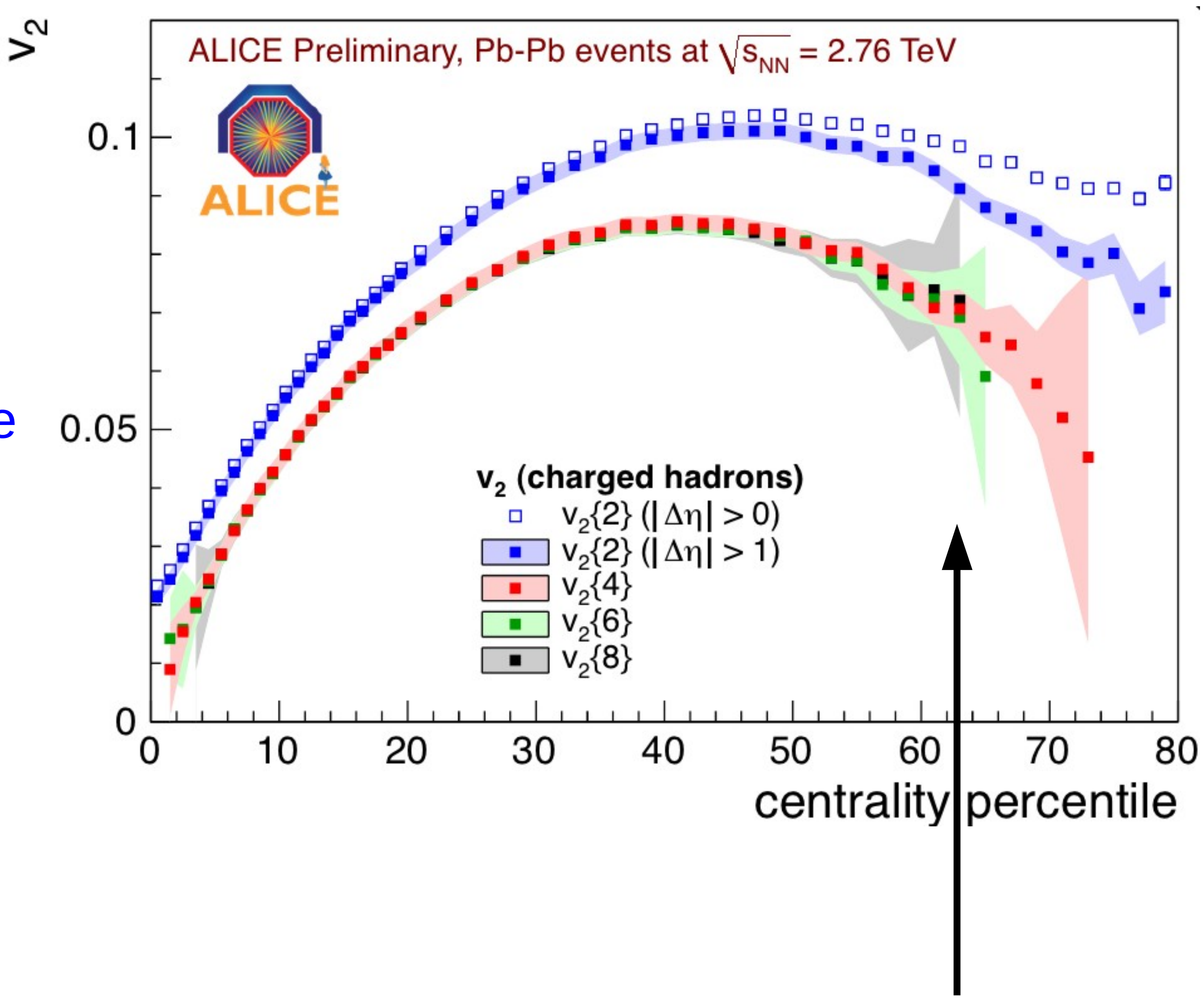


ATLAS, arXiv:1212.5198



Multi-particle correlations in PbPb

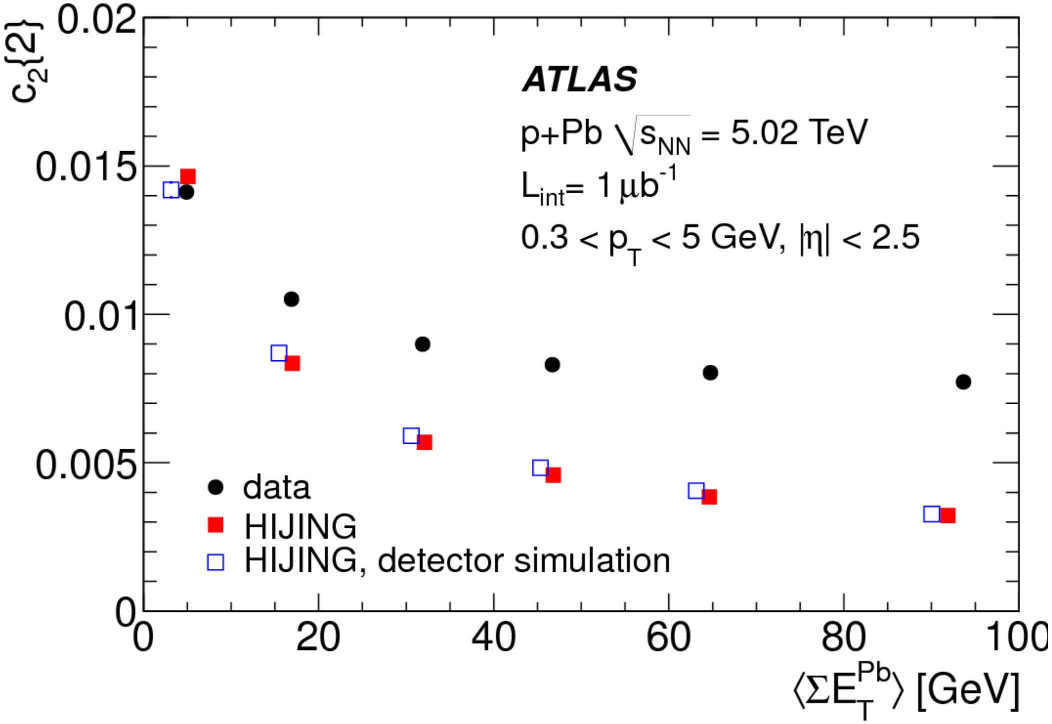
- Cumulants to extract genuine k-particle correlations excluding those from k-1 particles
- Higher order cumulant nicely work out in PbPb, where multiplicity is large
- Definitions
  - $v_2\{2\}^2 = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta$
    $v_2 \gg 1/\sqrt{M}$
  - $v_2\{4\}^2 = \langle v_2 \rangle^2 - \sigma_{v_2}^2$
    $v_2 \gg 1/M^{3/4}$
    - eg. M=100, v_2>>0.03
  - Care is needed when averaging over M, as cumulants are also sensitive to multiplicity fluctuations

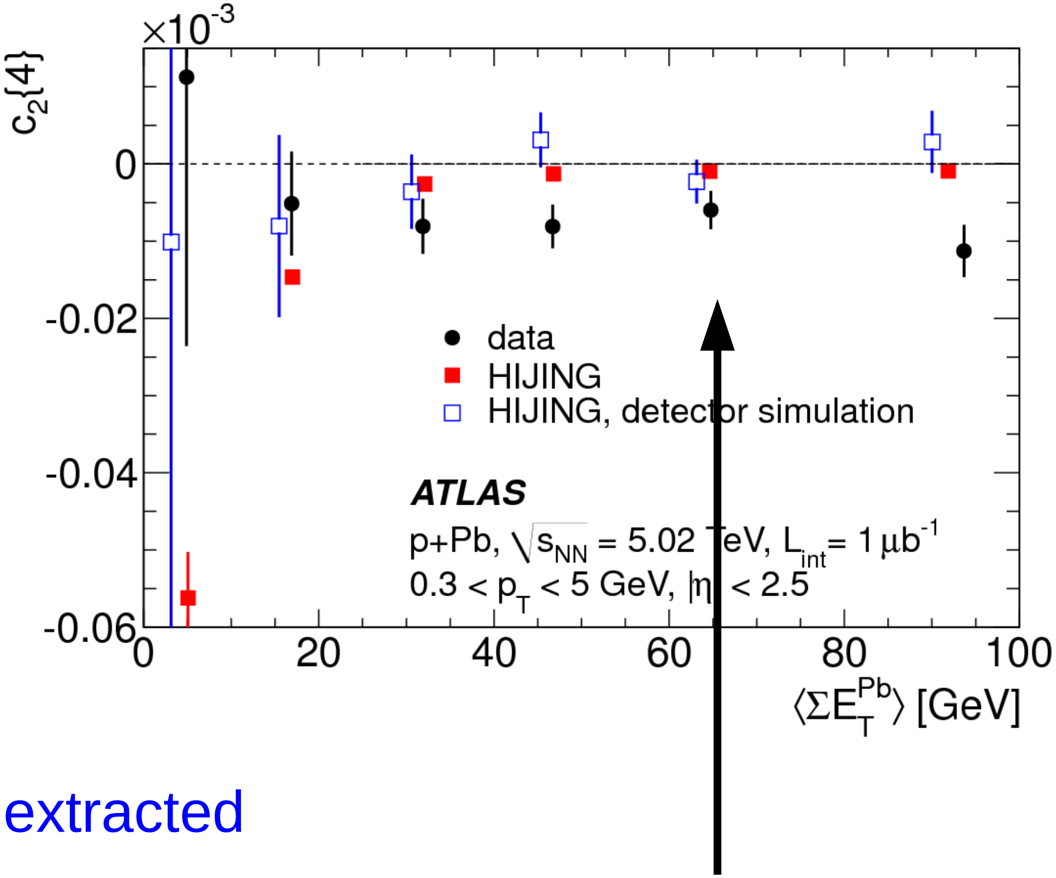


$\langle N_{ch} \rangle \approx 100$

Multi-particle correlations in pPb

ATLAS, arXiv:1303.2084





$<N_{ch}>\approx 100$

- Second and fourth order cumulant extracted
  - Second order above HIJING as expected if additional correlations present
  - Fourth order has different trend than HIJING
    - In high-multiplicity region there are four or higher particle correlations not present in HIJING

Integrated v_2 for pPb

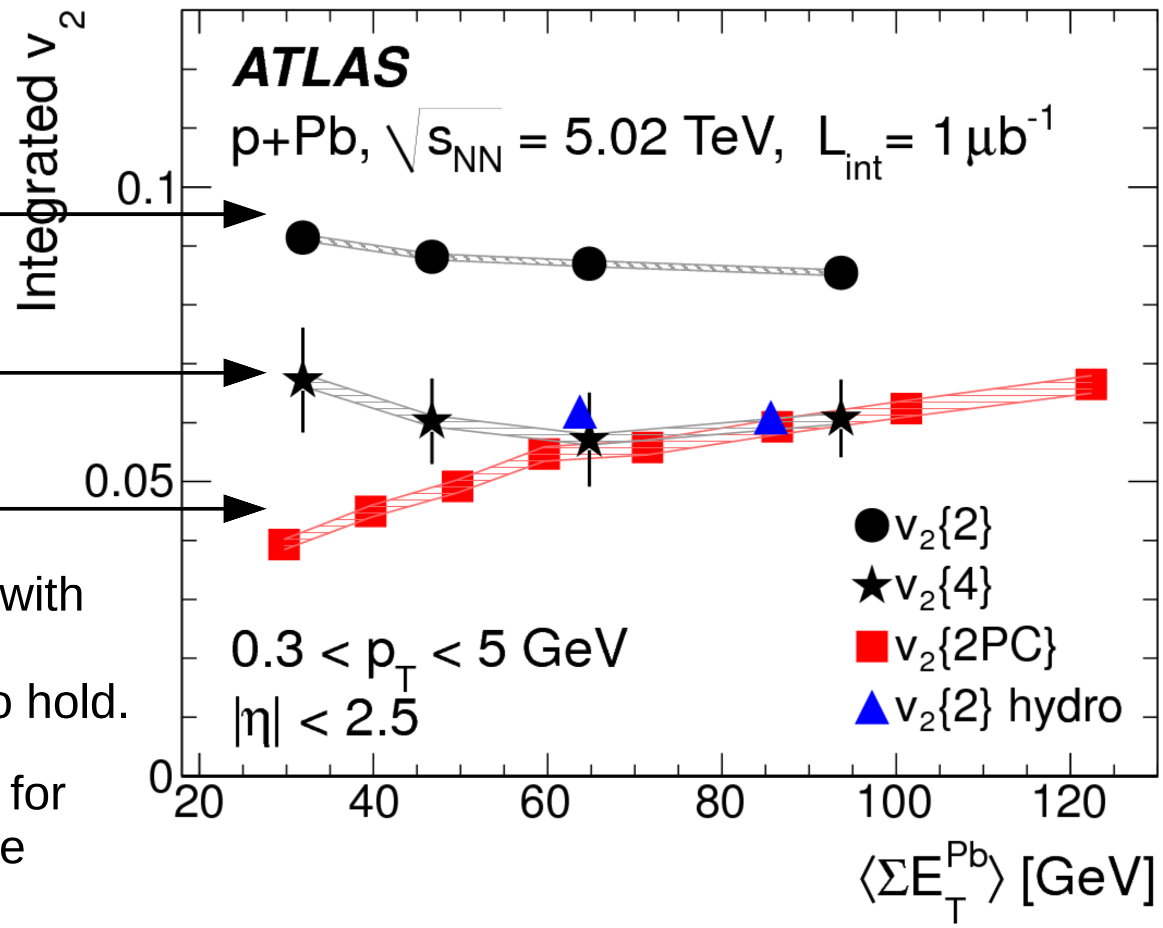
ATLAS, arXiv:1303.2084

In PbPb one would expect

$$v_2\{2\}^2 = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta$$

$$v_2\{4\}^2 = \langle v_2 \rangle^2 - \sigma_{v_2}^2$$

$$v_2\{2PC\}^2 = \langle v_2 \rangle^2 + \sigma_{v_2}^2$$

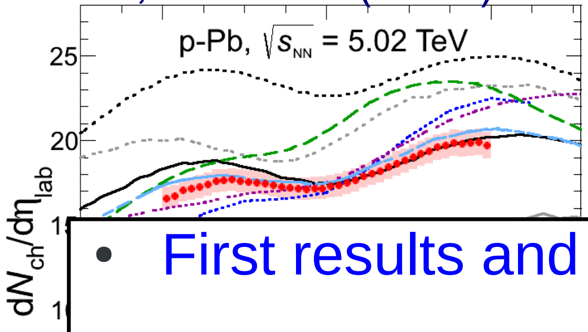


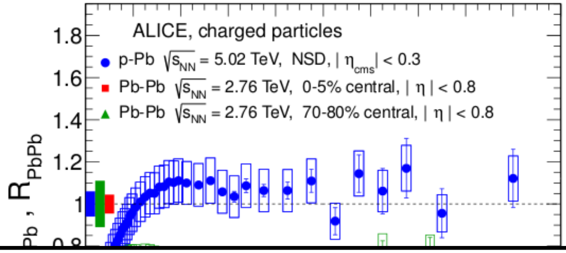
- Equations derived for heavy-ions with guidance from Bessel-Gauss and eccentricity studies do not need to hold.
- Nevertheless taken at face value, for high multiplicity events, compatible solution can exist within errors.

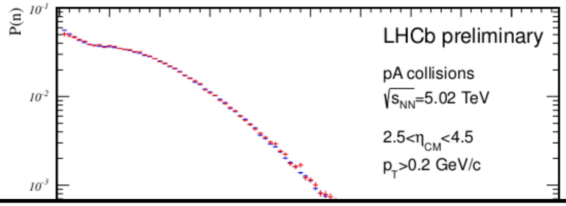
$v_2\{4\}$ compatible with $v_2\{PC\}$ supports the importance of final state effects, even in pPb. Or else, are there other Glasma contributions (or different theory) which predict four azimuthally correlated particles?

Summary

ALICE, PRL 110 (2013) 032301







- First results and surprises already from the pilot run in 2012
  - First measurements (pPb cross section, dN/dη and dN/dp$_T$ spectra)
  - More fundamental work needed (diffraction, fluctuations and centrality)
  - Ridge and higher cumulant results lead to interesting debate of the role of initial and final state effects in pPb
- Thanks to successful LHC operations in 2013, there are soon many more results to come

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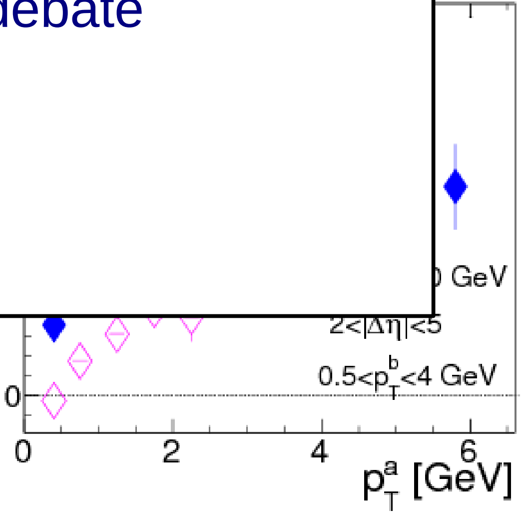
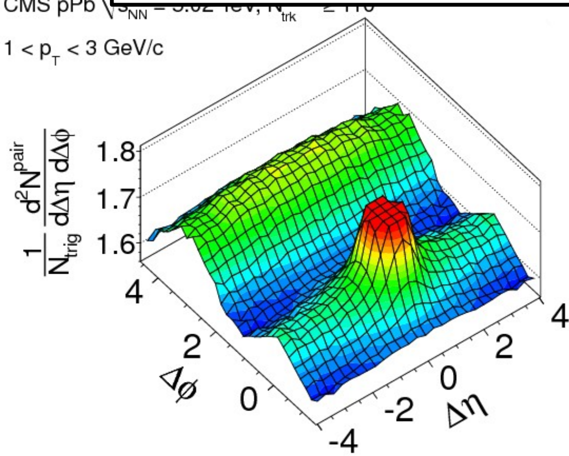
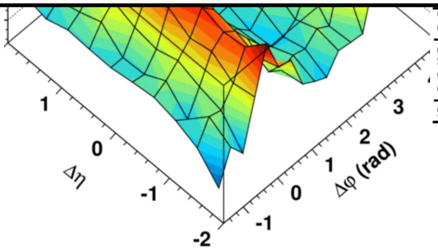
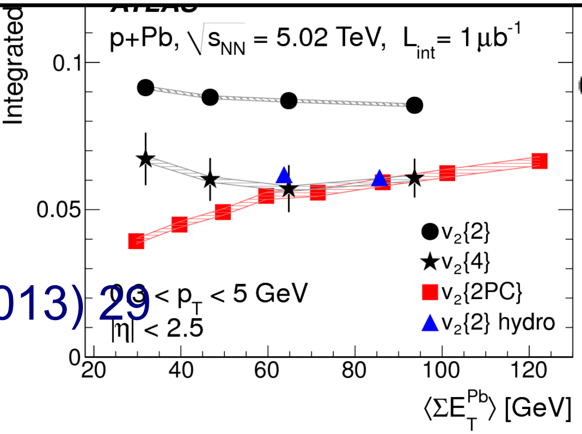


CMS





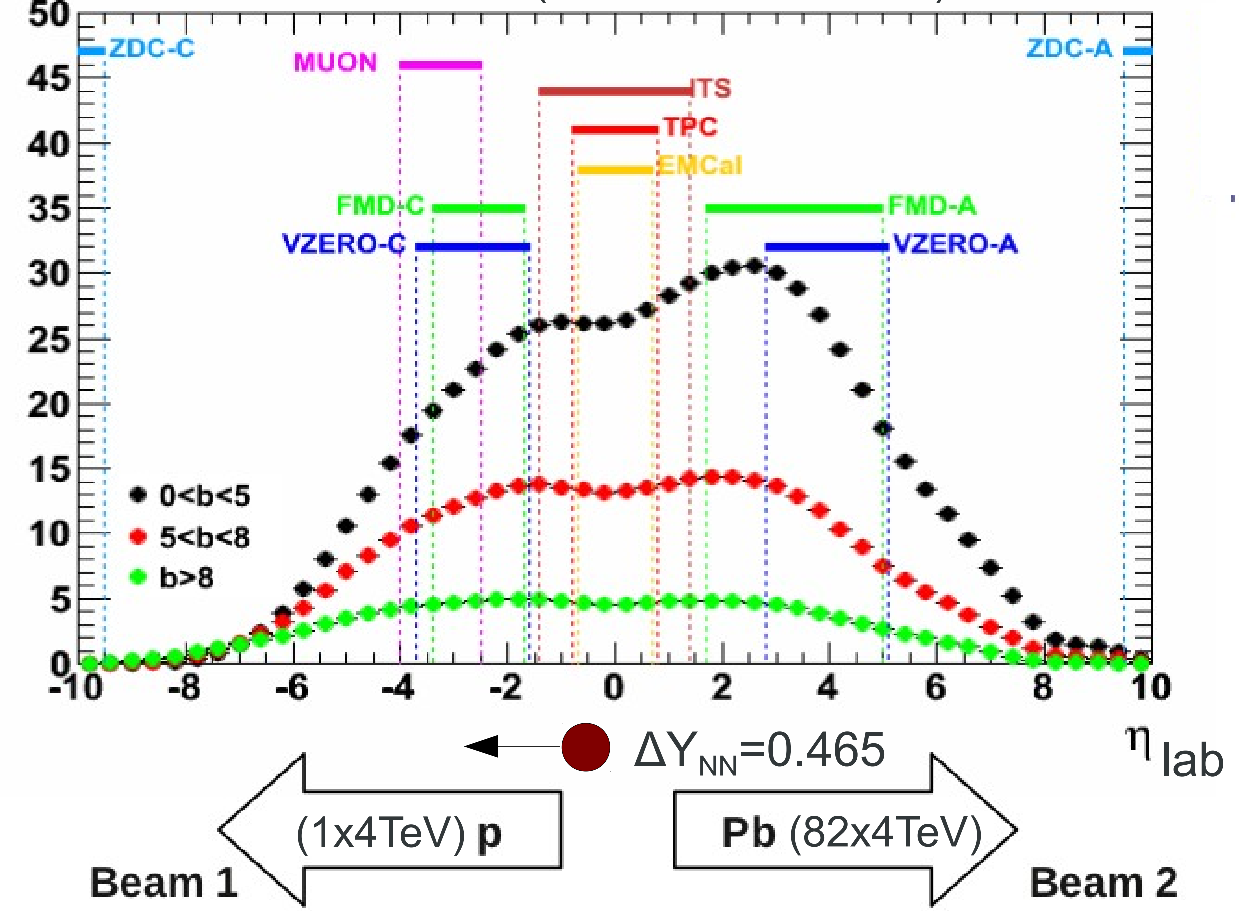
ALICE, PLB 719 (2013) 29



Extra

ALICE configuration (pilot run)

Illustration (HIJING at 4.4 TeV)



- Trigger
  - VZERO-A or C
  - ZDC-A or ZDC-C
- Dataset
  - One fill (a few millions triggers)
  - A part with displaced vertex to have ITS coverage over 6 units in η

Nuclear modification factor