Recent p-Pb results from ALICE

ALICE

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On behalf of ALICE Collaboration
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CERN PH Seminar

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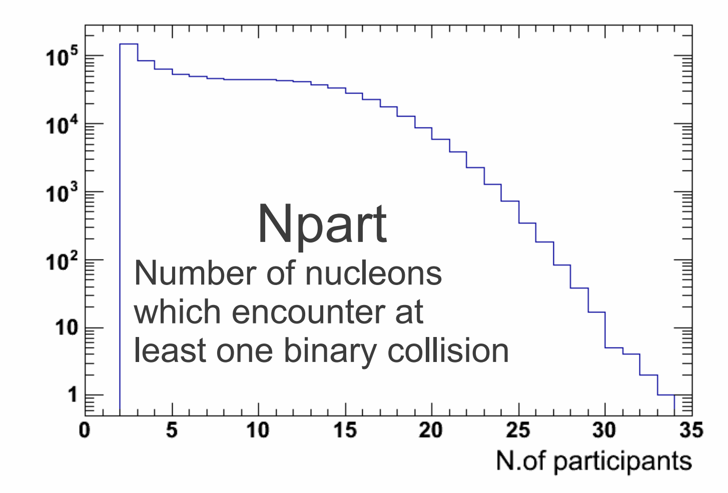
Outline

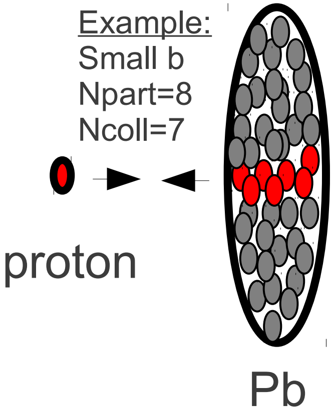
- p-A: Motivation and physics cases
- Pilot p-Pb run on Sep 13, 2012
- First results from ALICE experiment
    - Charged-particle multiplicity density $dN_{ch}/d\eta$ arXiv: 1210.3615
    - Charged-particle p_T spectrum and nuclear modification factor R_{pPb} arXiv: 1210.4520
    - Di-hadron correlations New, submitted ~1h ago
- Conclusions

Motivation

- p-Pb measurements:
    - Major benchmark for Pb-Pb as they address cold nuclear matter effects
    - Probe nucleus structure at unprecedented QCD regime of very small-x

p-A collision geometry and extraction of <Npart>,<Ncoll>, T_{pPb} with Glauber MC

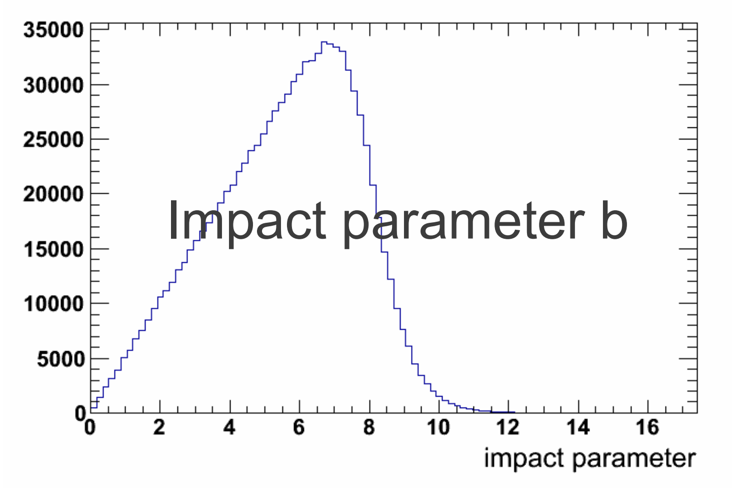




- Nuclear density profile: Woods−Saxon
- σ_{NN}=70 ± 5 mb

<b>,fm	RMS_b,fm	<Npart>	RMS_{Npart}	$<T_{pPb}>$,mb^{-1}	RMS_{TpPb},mb^{-1}
5.56	2.07	7.9	5.1	0.0983	0.0728

In p-A Npart = Ncoll + 1



$<Npart> = 7.9 \pm 0.6_{syst}$

$<T_{pPb}> = 0.0983 \pm 0.0035_{syst}$ mb^{-1}

Nuclear modification factor R_{pPb} defined as:

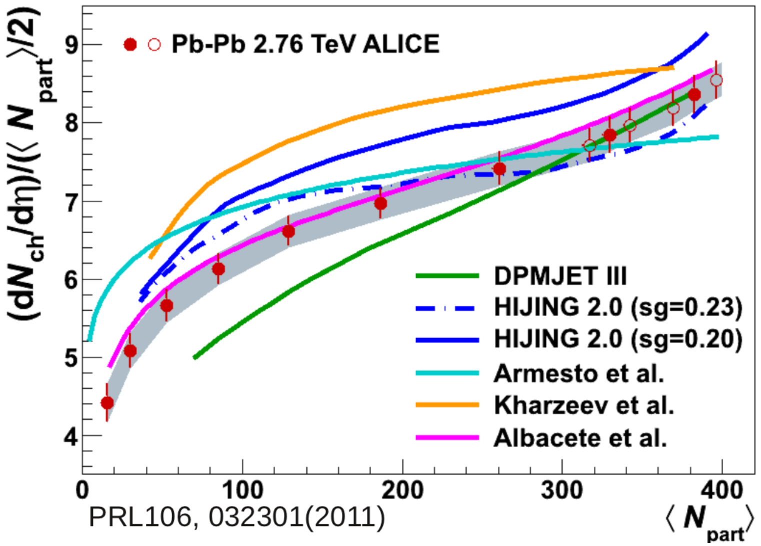
$$R_{pPb}(p_T)=\frac{d^2N_{ch}^{pPb}/d\eta dp_T}{<Ncoll>d^2N_{ch}^{pp}/d\eta dp_T}=\frac{d^2N_{ch}^{pPb}/d\eta dp_T}{<T_{pPb}>d^2\sigma_{ch}^{pp}/d\eta dp_T}$$

$dN_{ch}/d\eta$

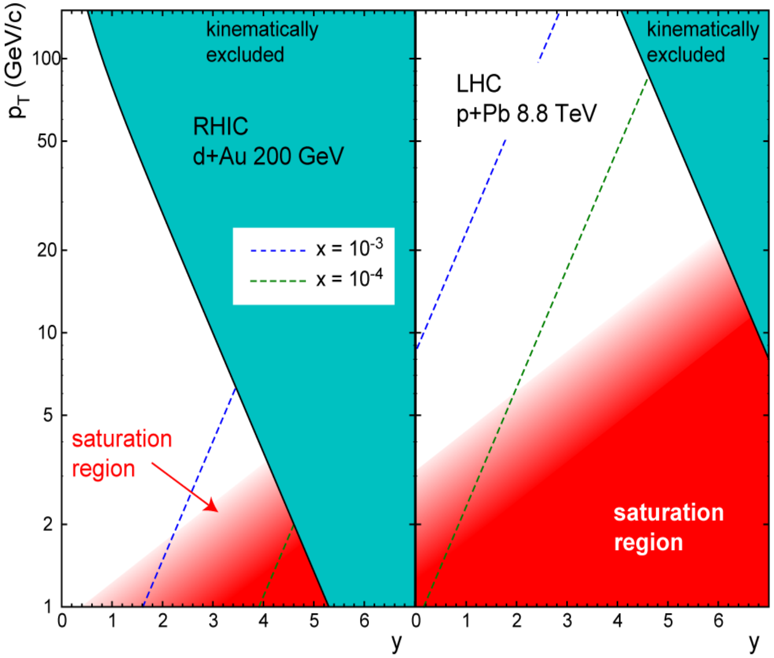
- $dN_{ch}/d\eta$ measurement crucial for understanding the bulk particle production mechanisms

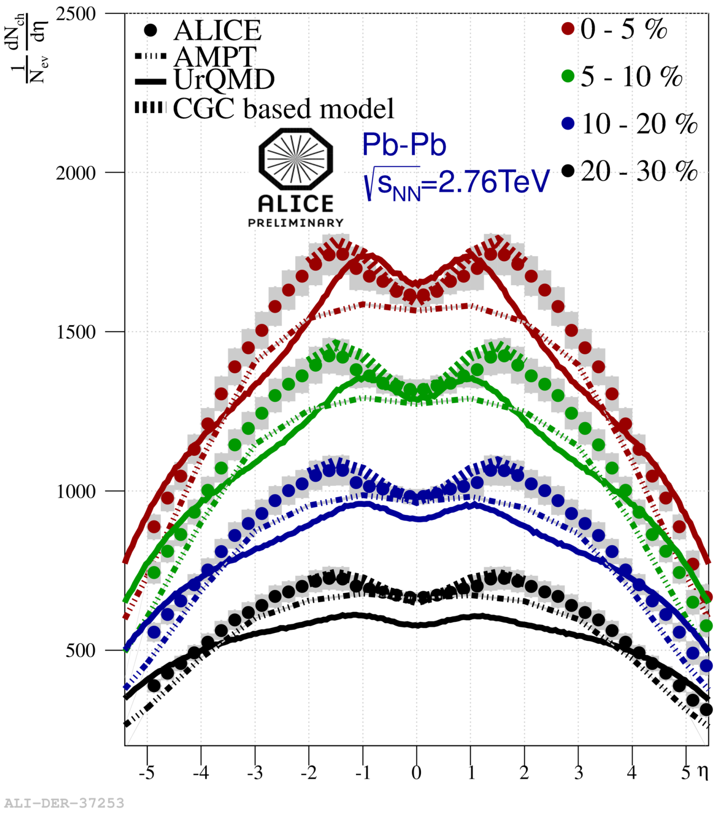
- Two-component models (HIJING, DPMJET, AMPT)
  - Hard component ~Ncoll + underlying soft component ~Npart
  - Stronger centrality dependence moderated by gluon shadowing

- Saturation models - Color Glass Condensate (CGC)
  - High parton density at low x → parton recombination → non-linear evolution → saturation
  - In p-Pb collisions @ LHC:
    - Perturbative regime due to higher saturation scale
    - Lower x at same rapidity
    - Kinematic limit is farther away



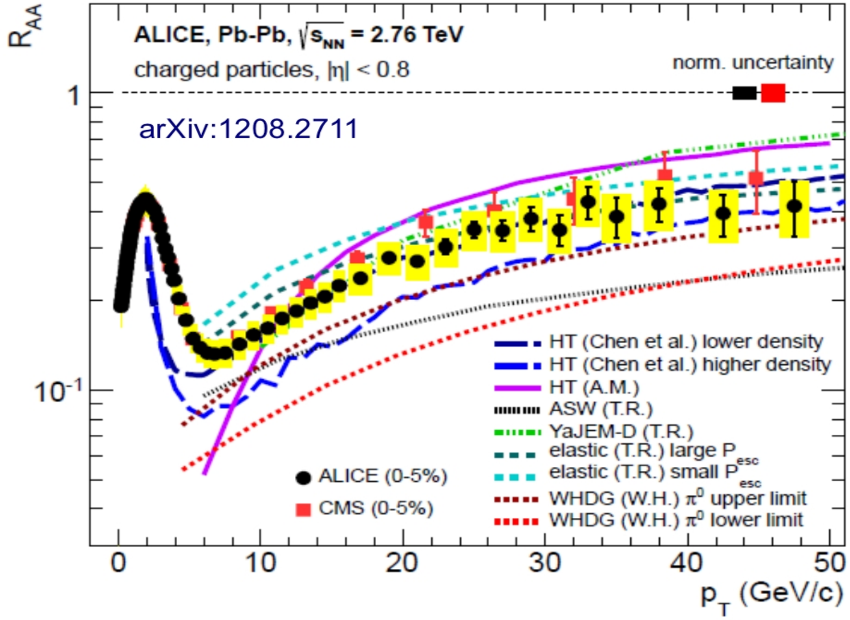
PRL106, 032301(2011)

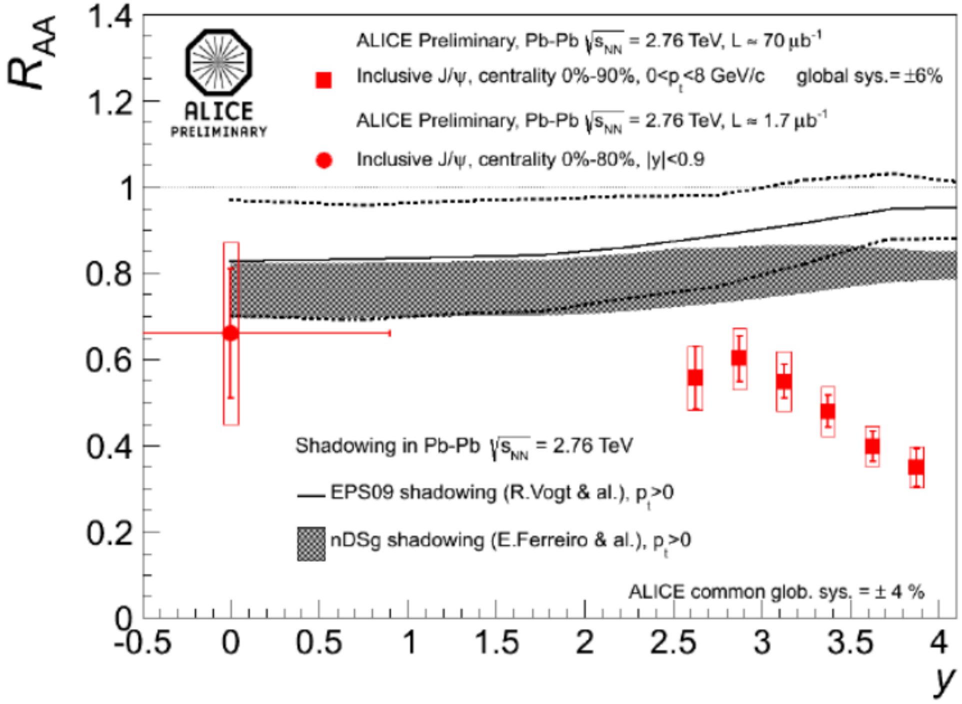


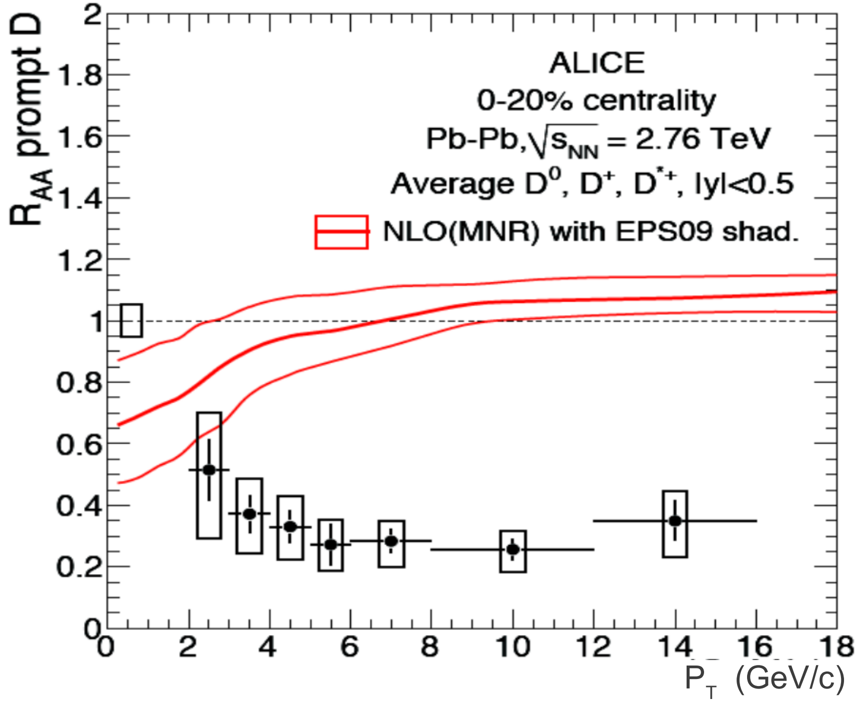


High-p_T hadrons suppression in A-A

- Important to isolate the cold nuclear matter effect
- Significant differences in the model predictions
- **Measurement of Pt spectra and nuclear modification factor in p-A is indispensable**

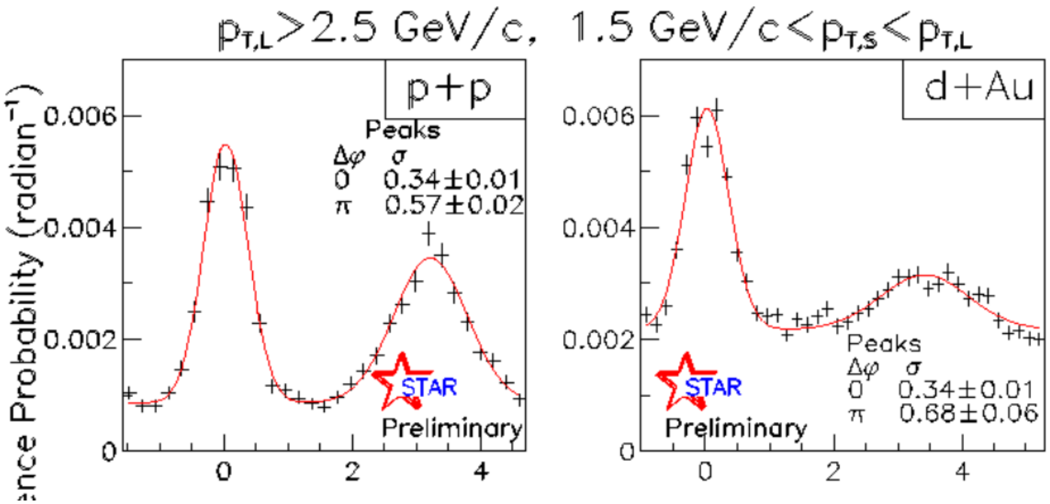


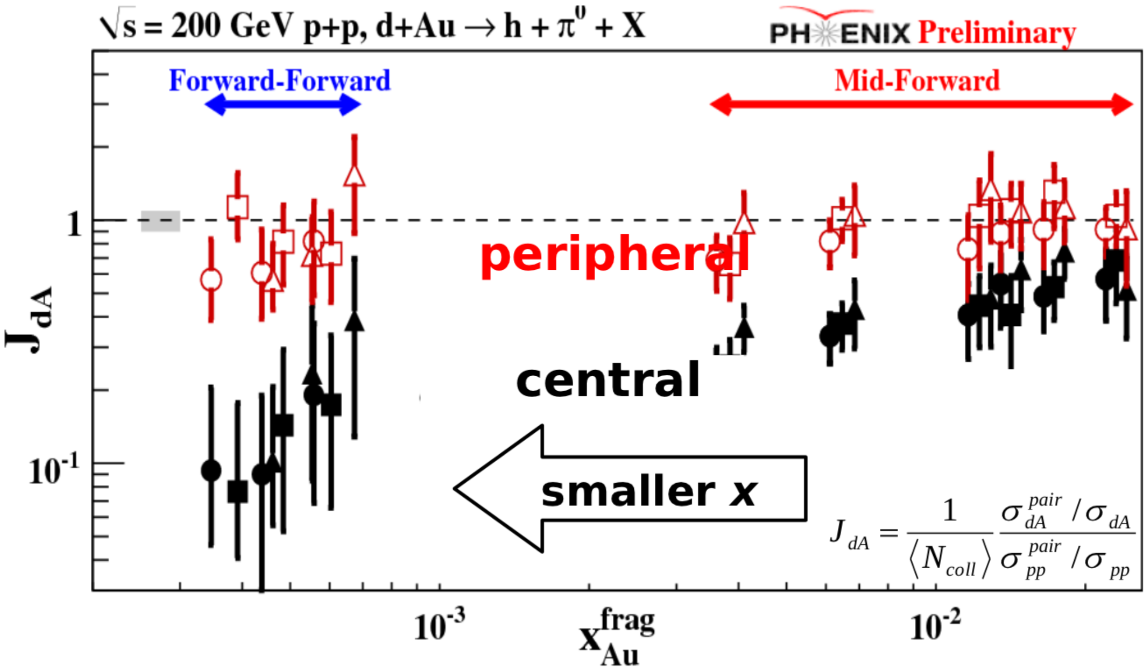




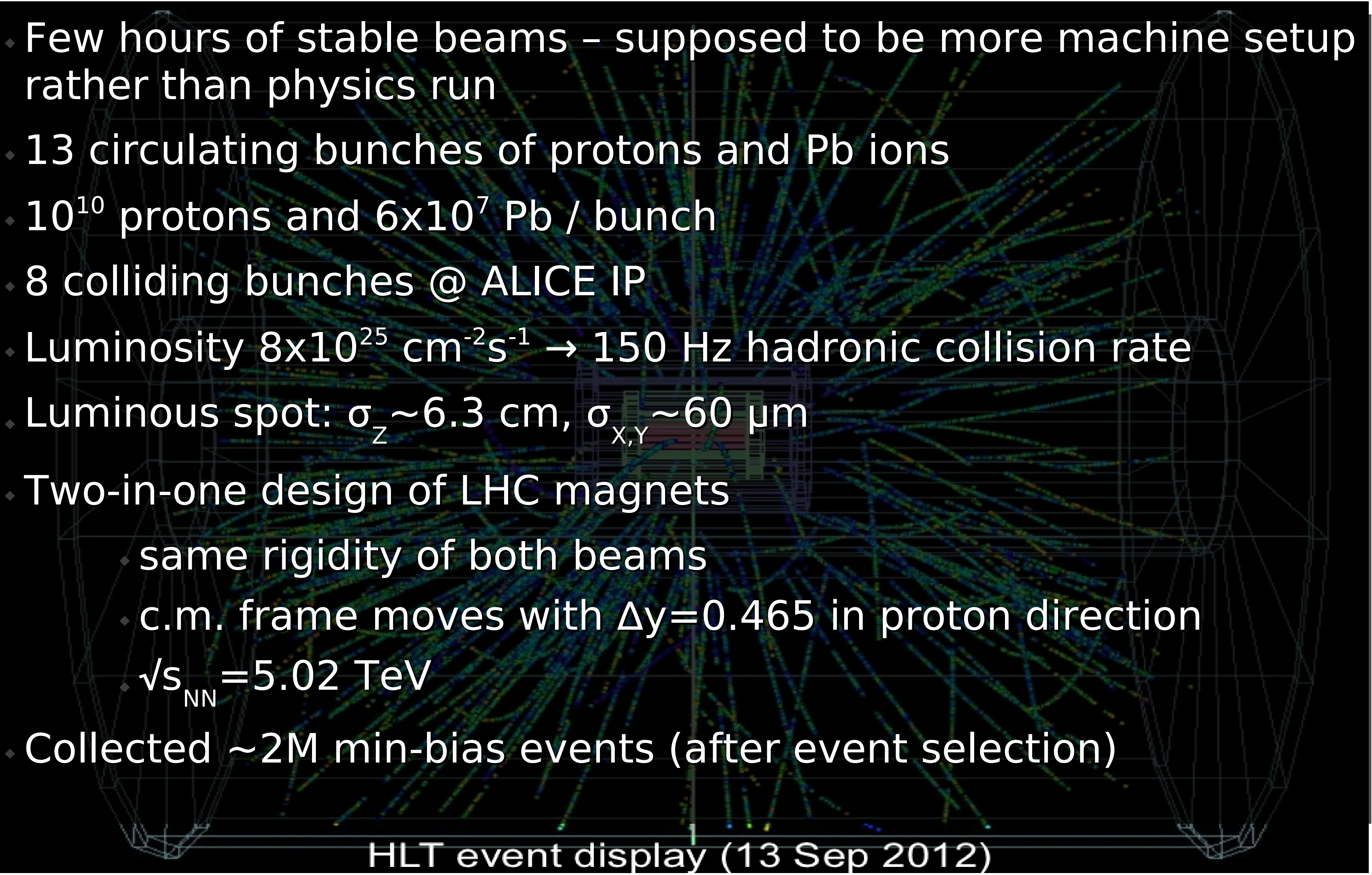
Di-hadron correlations

- Suppression at forward rapidity at RHIC
  - Interpreted within CGC model as suppression of initial-state low-x gluon
- Data @ LHC should allow to:
  - Check for similar suppression at similar x-values
  - Constrain the model





Pilot p-Pb run



- Few hours of stable beams – supposed to be more machine setup rather than physics run
- 13 circulating bunches of protons and Pb ions
- 10^{10} protons and $6x10^{7}$ Pb / bunch
- 8 colliding bunches @ ALICE IP
- Luminosity $8x10^{25}$ $cm^{-2}s^{-1}$ → 150 Hz hadronic collision rate
- Luminous spot: σ_Z~6.3 cm, $\sigma_{X,Y}$~60 μm
- Two-in-one design of LHC magnets
  - same rigidity of both beams
  - c.m. frame moves with Δy=0.465 in proton direction
  - $\sqrt{s_{NN}}$=5.02 TeV
- Collected ~2M min-bias events (after event selection)

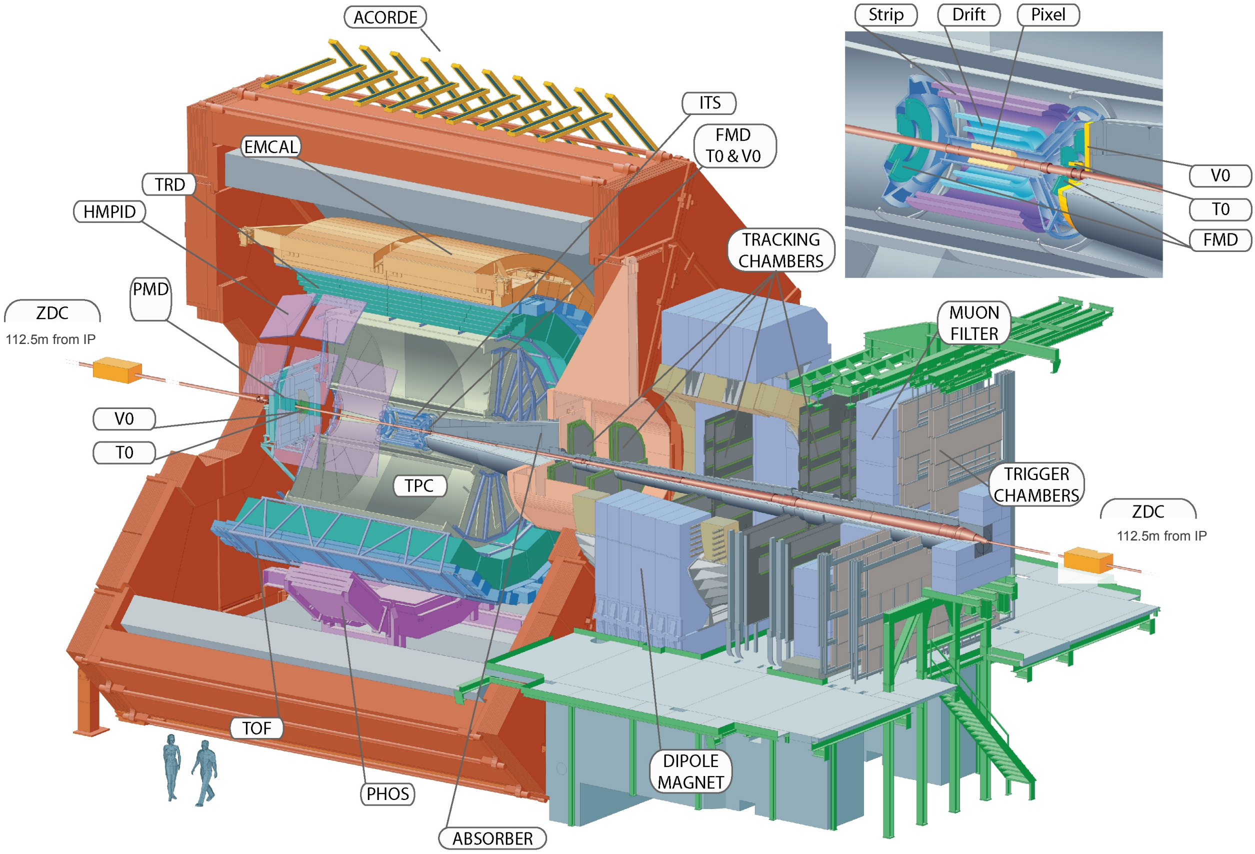
HLT event display (13 Sep 2012)

Pilot p-Pb run

- Trigger & Event selection
    - VZERO-A ($2.8<\eta_{lab}<5.1$) or
      VZERO-C ($-3.7<\eta_{lab}<-1.7$)
    - Beam-induced background removal with VZERO and 2 neutron zero-degree calorimeters (ZDC) ZNA@+112.5m / ZNC@-112.5
    - Control trigger: ZNA or ZNC

- Vertex and charged-particle multiplicity
    - Silicon Pixel Detector (SPD) - two innermost layers of ITS
        - Acceptance $|\eta|<1.4$
        - 93.5% active modules

- Vertex and track reconstruction
    - ITS
        - 2 layers of SPD
        - 2 layers of Silicon Drift Detector (SDD)
        - 2 layers of Silicon Strip Detector (SSD)
    - TPC, acceptance $|\eta|<0.9$ → 1.5



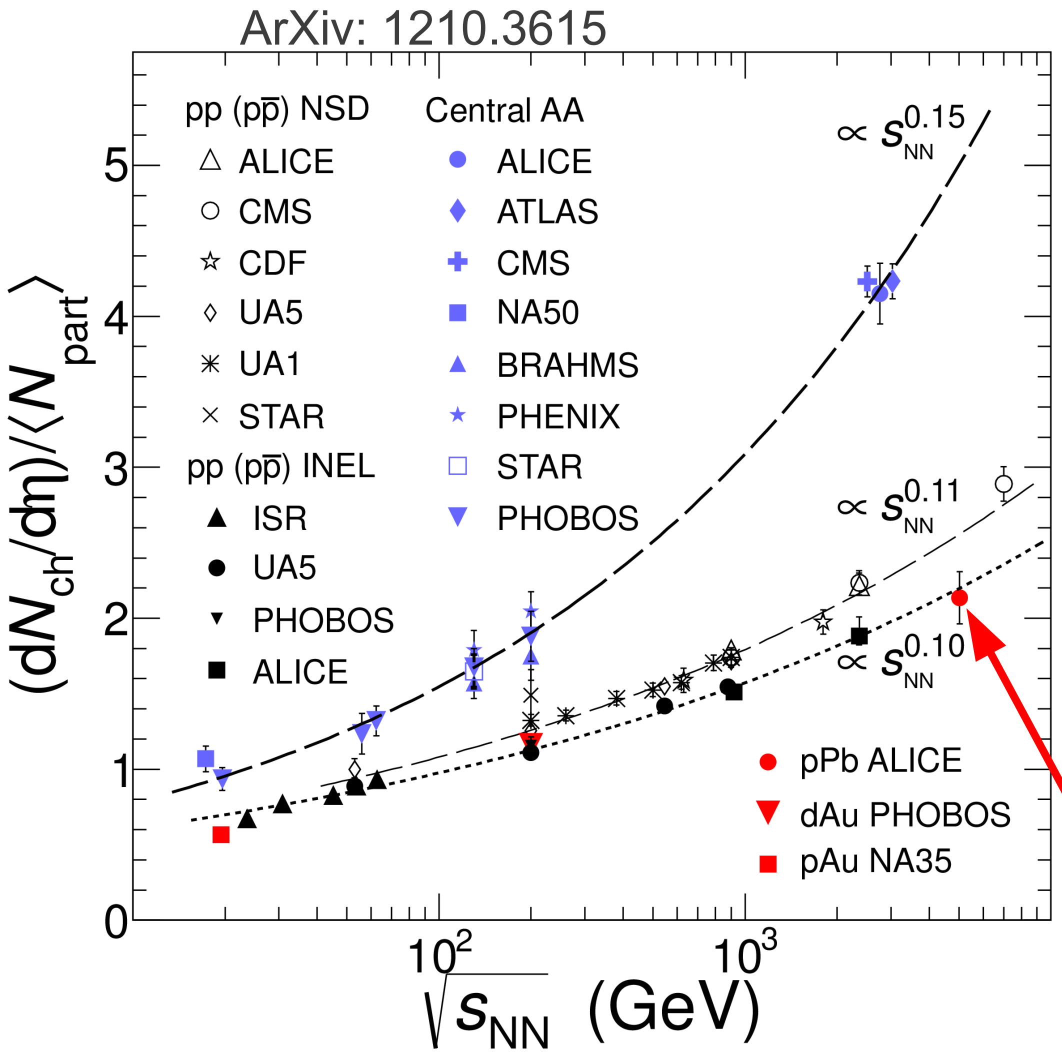
Event selection

- Multiplicity measurement → need a well-defined event class for which it is measured:
    - High efficiency, but close to minimum bias
        - Minimize dependence on MC model (DPMJET, HIJING, ...)
    - Low contamination from 'background' processes
        - Diminish dependence on simulation of so far unmeasured 'background' processes

- Event selection: VZERO-A and VZERO-C, i.e. on both sides of IP
- **Event class definition: NSD (defined in Glauber terminology as interactions in which at least one of the binary nucleon-nucleon collisions is NSD)**
  In DPMJET, SD collisions are concentrated mainly on the surface of the nucleus

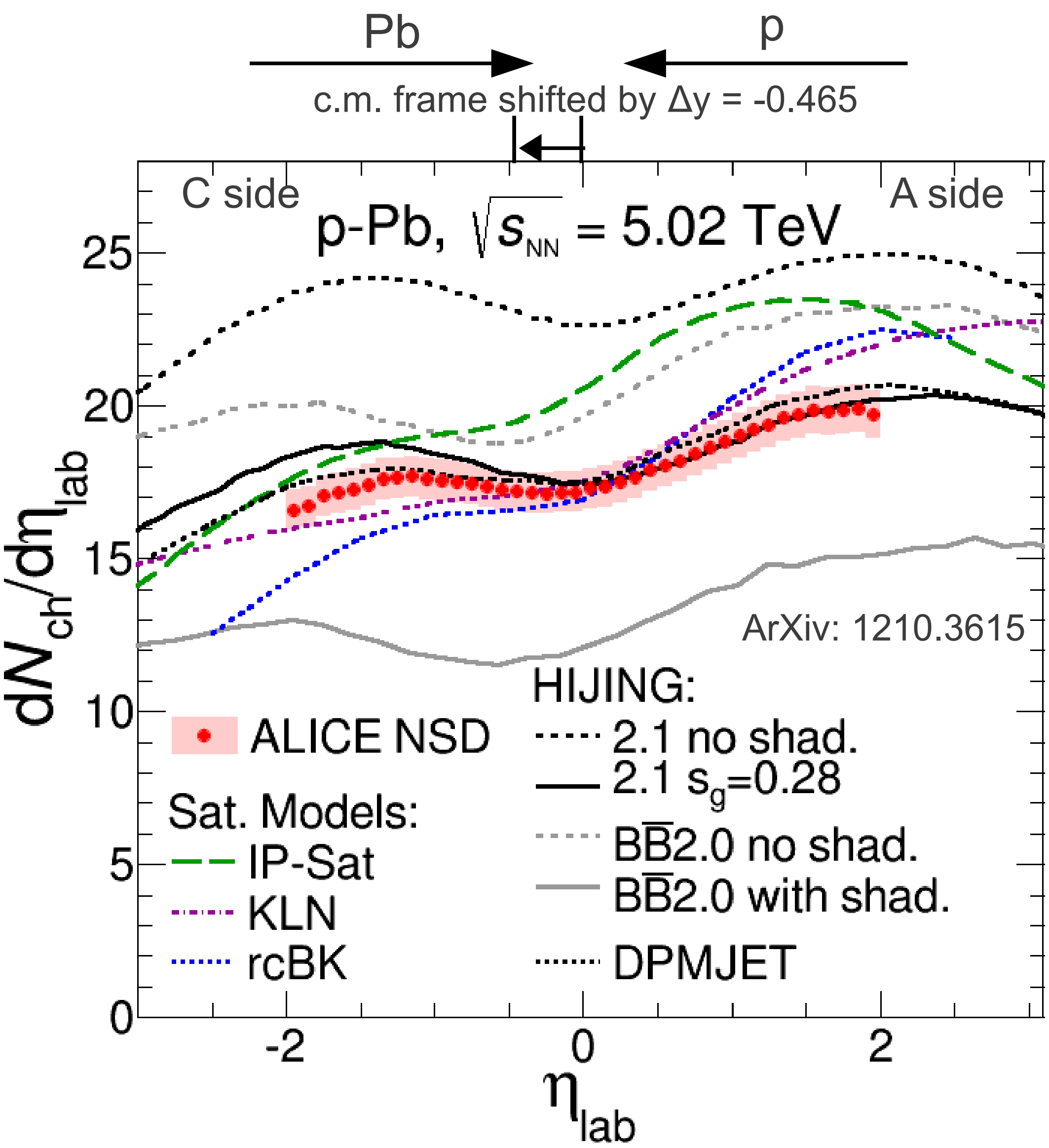
- 99.2% efficiency (DPMJET)
- Negligible contamination from:
    - SD ← p-p PHOJET tuned to 2.76 and 7 TeV and coupled to Glauber MC
    - EM (proton excitation in Pb field) ← STARLIGHT MC
    - Residual beam-induced background ← non-colliding bunches

$dN_{ch}/d\eta$ @ midrapidity – Energy dependence



- $dN_{ch}/d\eta_{lab}$=**$17.35\pm0.01_{stat}\pm0.67_{syst}$** $(|\eta_{lab}|<0.5)$
- $dN_{ch}/d\eta_{cms}$ = **$16.81 \pm 0.71_{syst}$** $(-0.965<\eta_{lab}<0.035$, corrected for Δy using HIJING)
- Participant scaled value: $(dN_{ch}/d\eta_{cms})/\langle Npart\rangle$= **$2.14\pm0.17_{syst}$**
- Main systematic error from normalization: 3.1%
- **About 15% below NSD pp**
- **Similar to INEL pp**

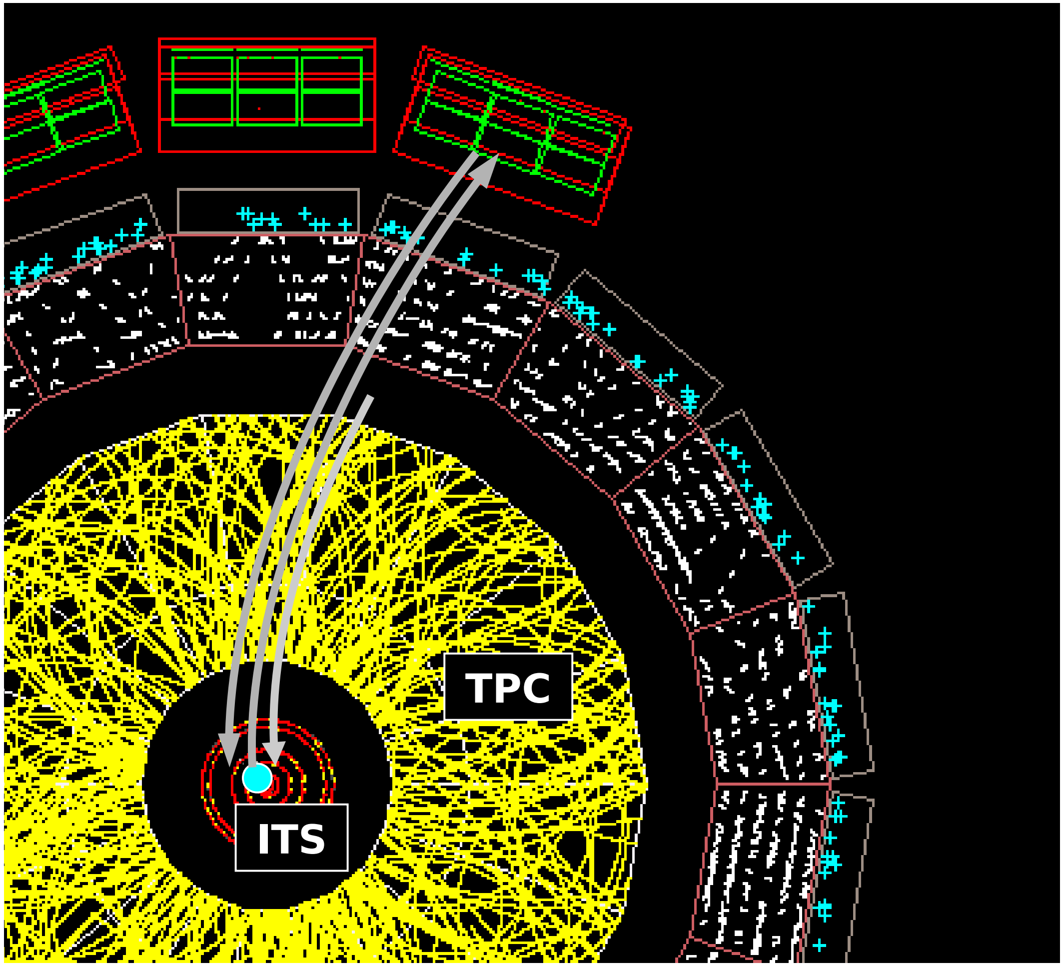
$dN_{ch}/d\eta$ vs η



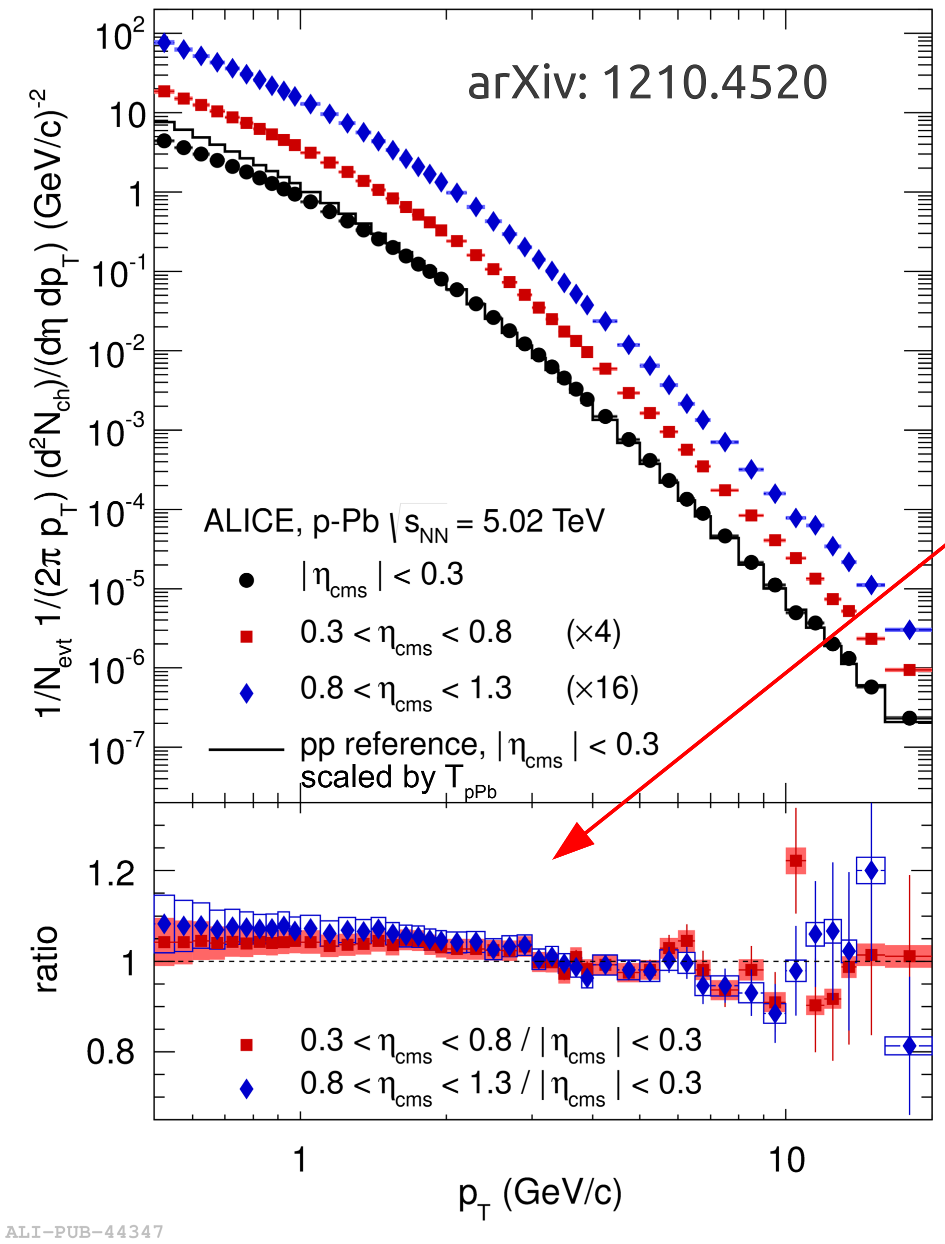
- Data favors models that incorporate shadowing
- Saturation models predict much steeper η-dependence which is not seen with the data
- Note: Result would decrease by ~4% going from NSD → INEL (HIJING)

Pt Spectra – reconstruction and analysis technique

- Track reconstruction using ITS and TPC
- ALICE standard primary track selection
  - Cuts on DCA to primary vertex, track-fit quality and number of space-points
- Primary vertex reconstructed from tracks

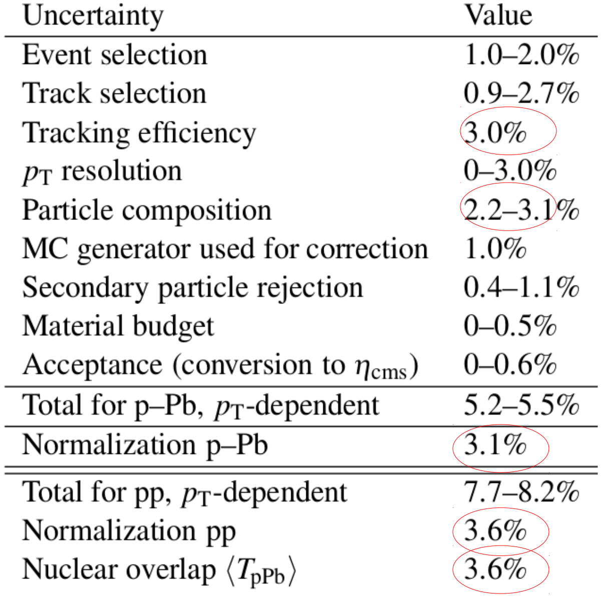


p_T Spectra



- Reference p-p spectrum obtained from data @ 2.76 and 7 TeV:
  - <5 GeV/c by interpolation assuming power law dependence on √s
  - >5 GeV/c by scaling with factor from NLO calculations
- Spectra slightly softens at higher pseudorapidity?

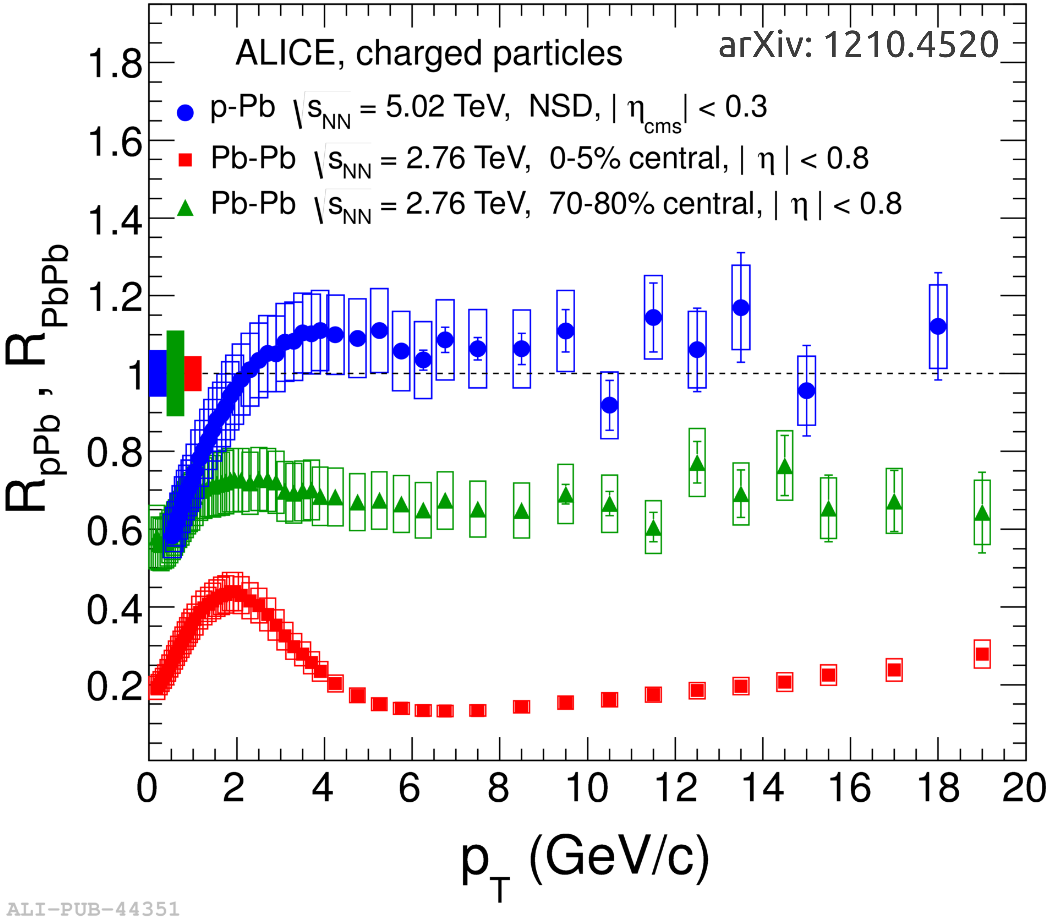
Systematic uncertainties



Uncertainty	Value
Event selection	1.0–2.0%
Track selection	0.9–2.7%
Tracking efficiency	3.0%
p_T resolution	0–3.0%
Particle composition	2.2–3.1%
MC generator used for correction	1.0%
Secondary particle rejection	0.4–1.1%
Material budget	0–0.5%
Acceptance (conversion to η_{cms})	0–0.6%
Total for p–Pb, p_T-dependent	5.2–5.5%
Normalization p–Pb	3.1%
Total for pp, p_T-dependent	7.7–8.2%
Normalization pp	3.6%
Nuclear overlap $\langle T_{pPb} \rangle$	3.6%

Nuclear modification factor $R_{pPb}(p_T)$

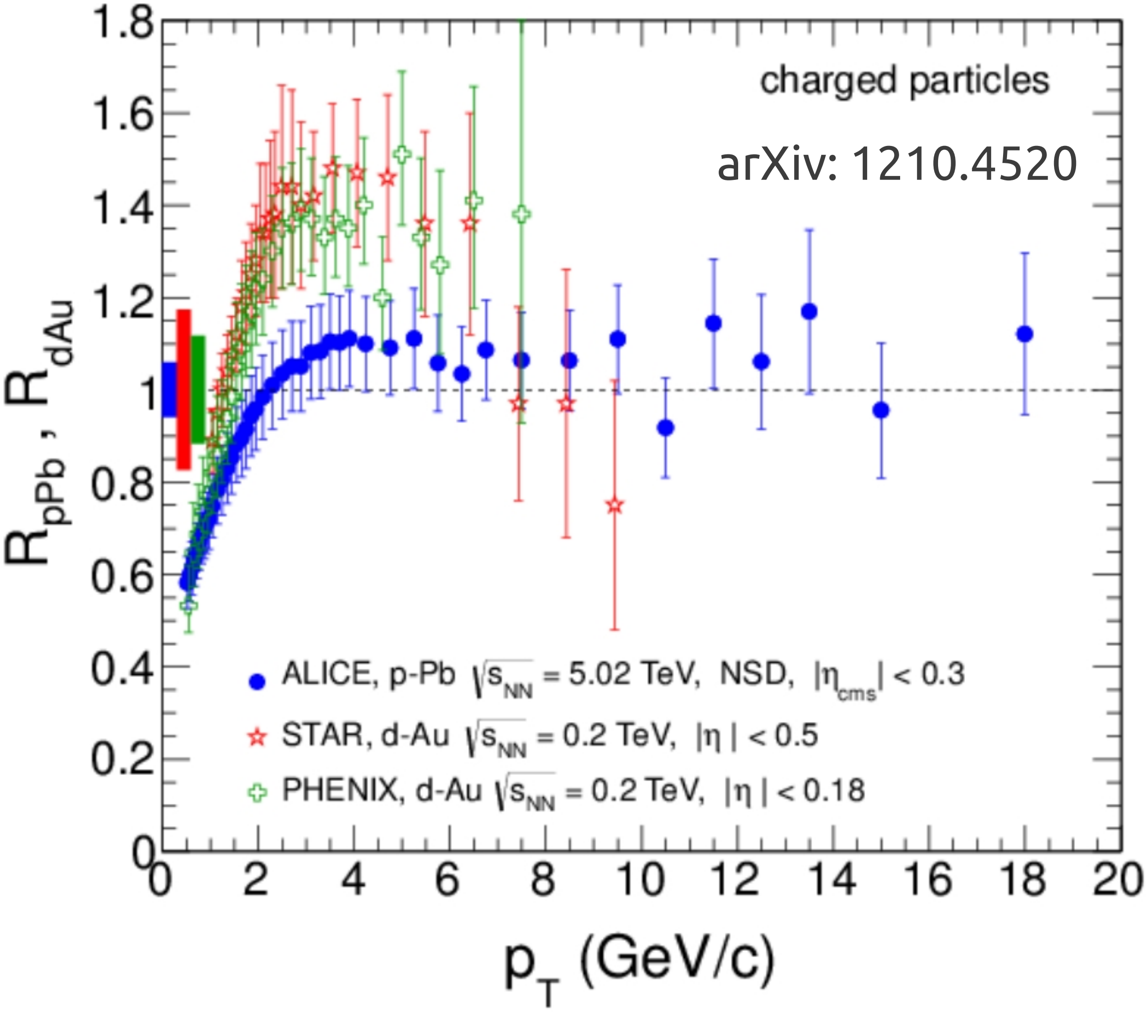
$$R_{pPb}(p_T)=\frac{d^2N_{ch}^{pPb}/d\eta dp_T}{<Ncoll>d^2N_{ch}^{pp}/d\eta dp_T}=\frac{d^2N_{ch}^{pPb}/d\eta dp_T}{<T_{pPb}>d^2\sigma_{ch}^{pp}/d\eta dp_T}$$



- Compatible with 1 above 2-3 GeV/c
  → binary scaling is preserved, no evidence of initial state effects

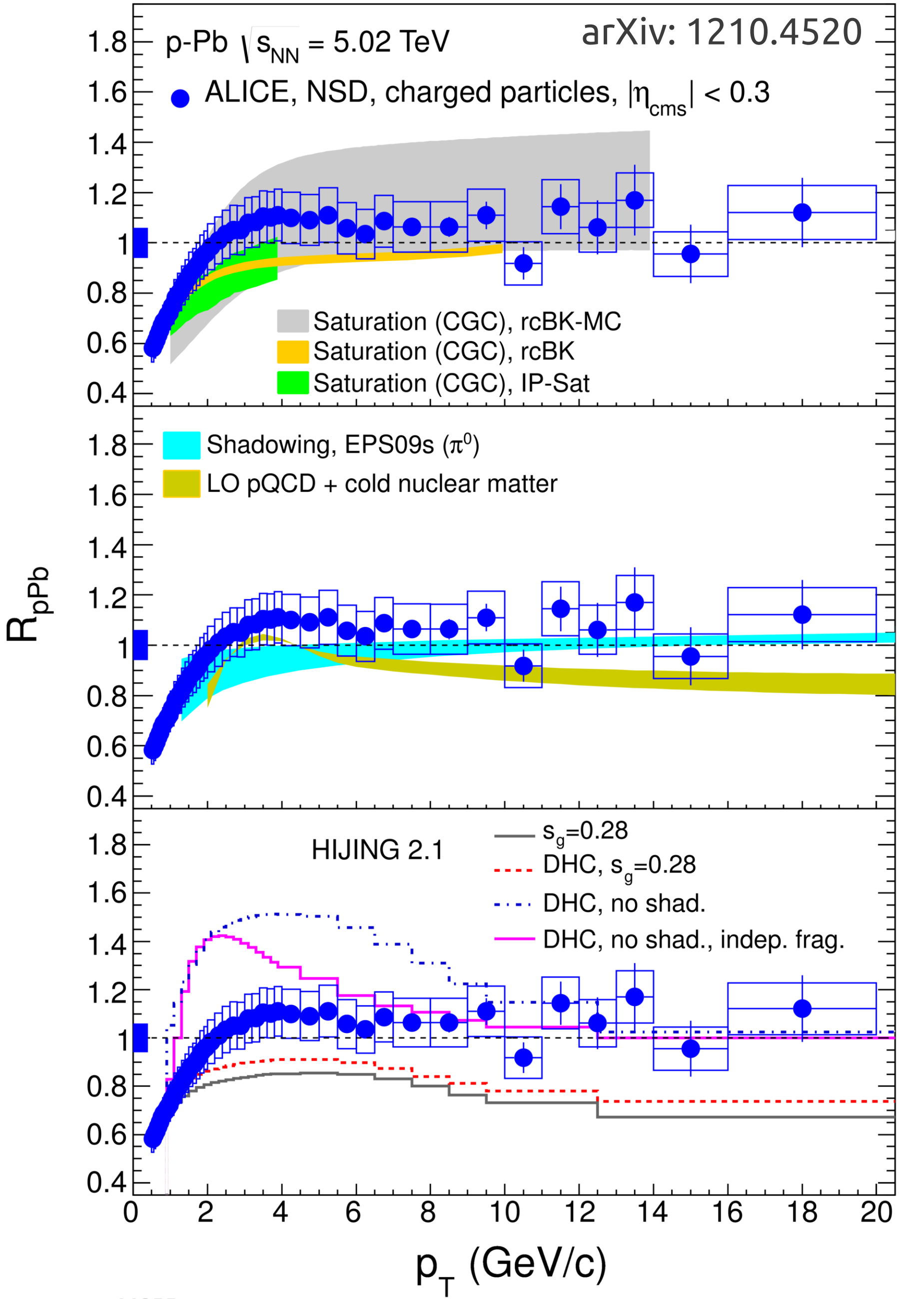
- Note: R_{pPb} would decrease by ~4% going from NSD → INEL (HIJING)

RHIC(d-Au) vs LHC(p-Pb)



- Enhancement at intermediate p_T, so called Cronin effect, was observed at lower energies
- <u>Our data show no strong signs of Cronin effect in contrast to RHIC results</u> (obtained at higher x-value)

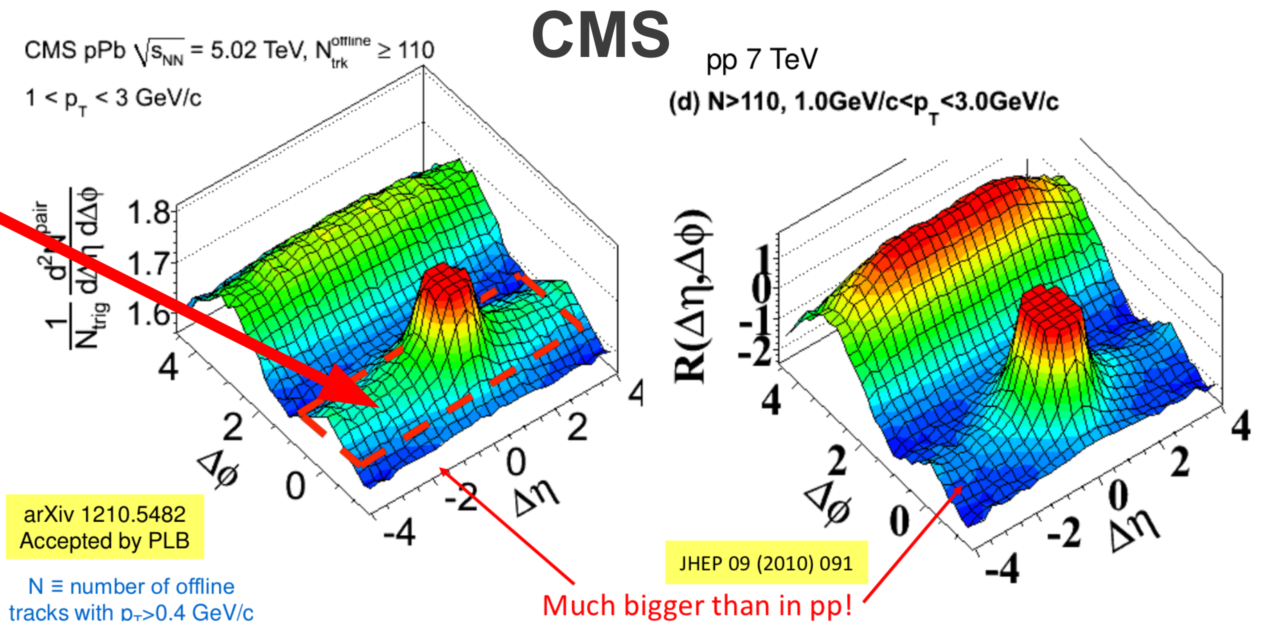
R_{pPb} – comparison to model predictions



- Saturation models consistent within the uncertainties
- Models incorporating shadowing also consistent with the data, some discrepancies at high p_T
- Neither HIJING nor DPMJET are able to describe simultaneously $N_{ch}/d\eta$ and p_T spectrum
- HIJING w/o shadowing higher at low p_T
- HIJING with shadowing too low at high p_T

Di-hadron correlations

- Near-side (NS) ridge observed by CMS



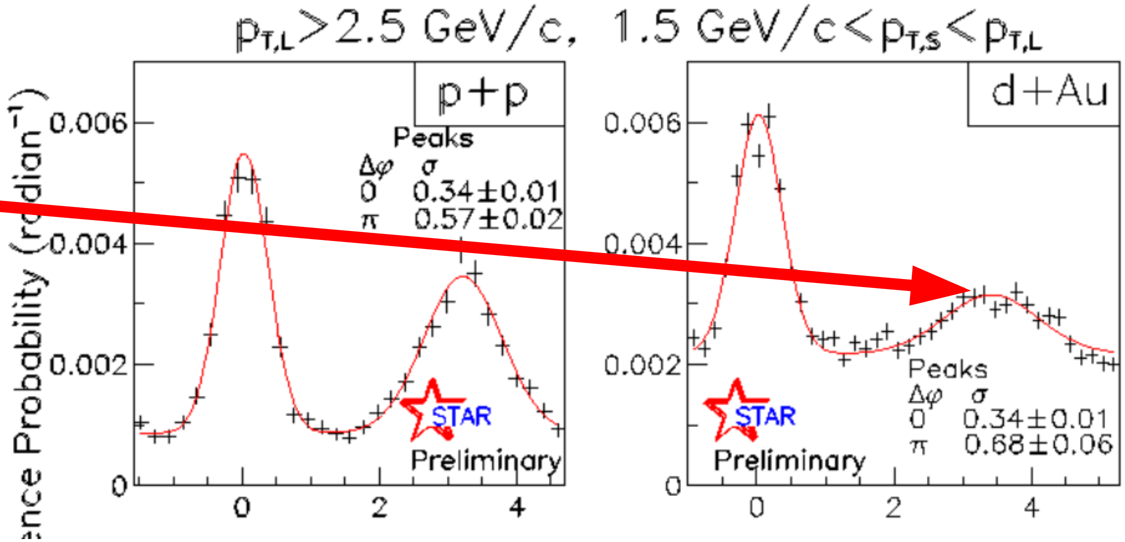
arXiv 1210.5482
Accepted by PLB

N ≡ number of offline tracks with p_T>0.4 GeV/c

JHEP 09 (2010) 091

Much bigger than in pp!

- Away-side (AS) suppression observed at forward rapidities @ RHIC



Di-hadron correlations – analysis technique

- ALICE standard ITS/TPC track reconstruction/selection
    - + ≥ 1 hit in SPD otherwise constrained to primary vertex → uniform azimuthal acceptance

- Correlations for pairs of trigger and associated particles, $p_{T,trig} > p_{T,assoc}$, as f(Δφ,Δη), defined as associated yield per trigger particle:

Note: η denotes η_{lab}

Ratio of sums over triggers →

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

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N_{same\ event}}{d\Delta\eta\, d\Delta\phi}, \qquad B(\Delta\eta, \Delta\phi) = \alpha \frac{d^2 N_{mixed\ event}}{d\Delta\eta\, d\Delta\phi}, \alpha = \frac{1}{B(0,0)}$$

N_{trig} – total number of trigger particles in event sample

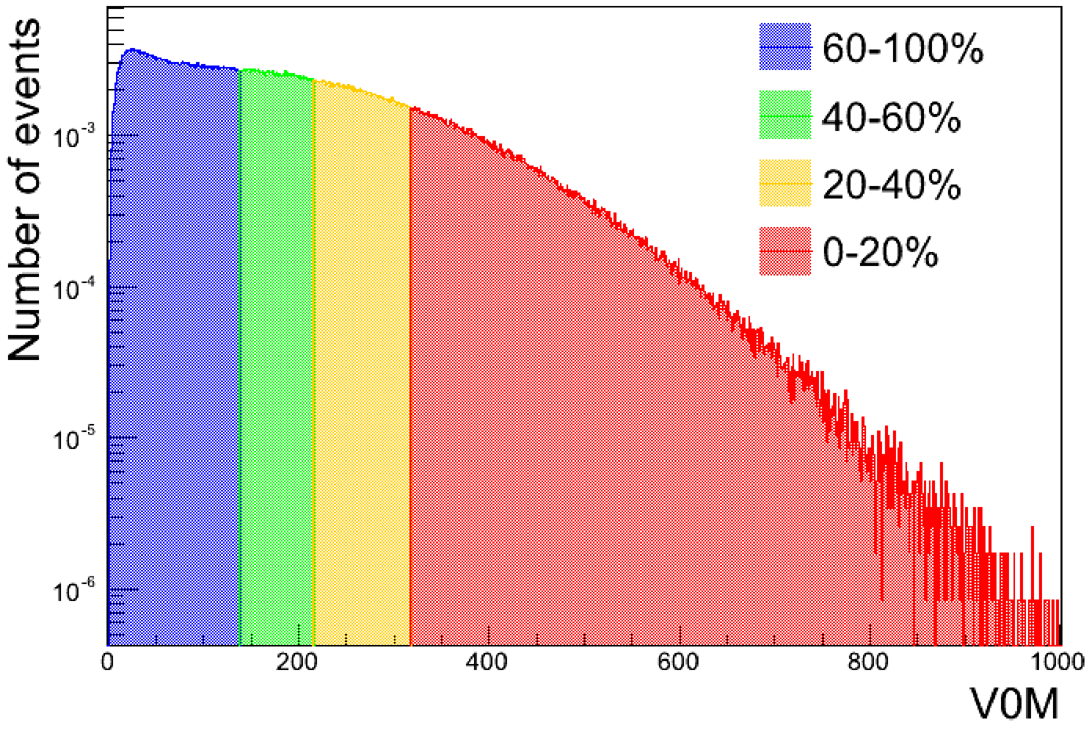
B accounts for pair acceptance/efficiency and $dN_{ch}(\eta)/d\eta$

- Computed separately for different $p_{T,trig}$ and $p_{T,assoc}$ ranges

Multiplcity event classes

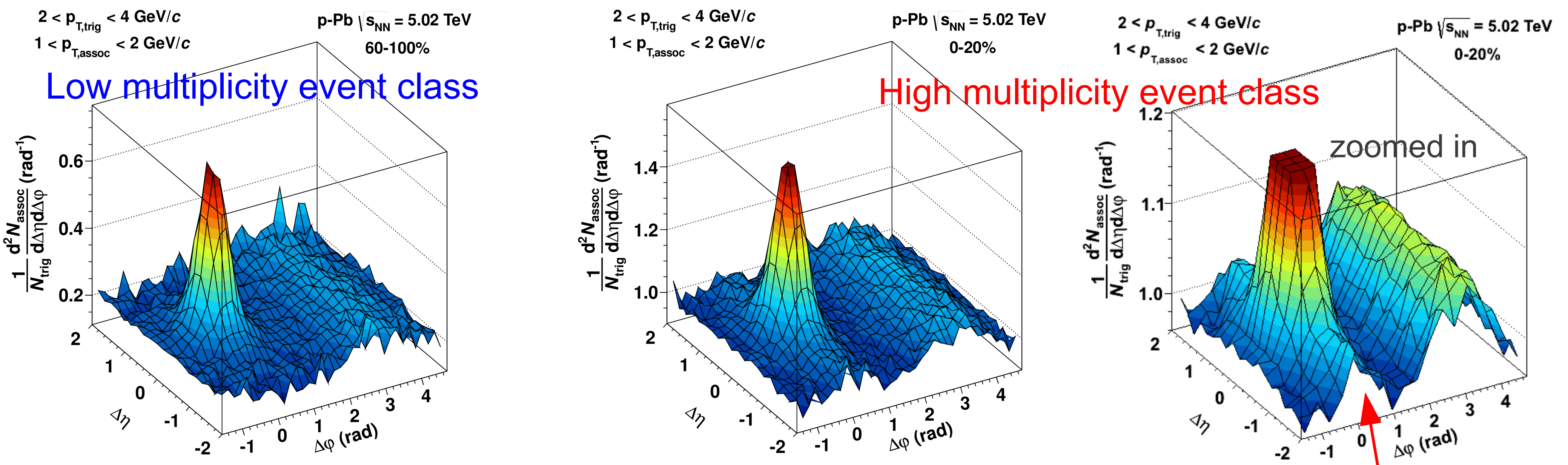
Analysis in multiplicity classes defined by the total charge in VZERO (V0M)

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



Note: We used also alternative event selections based on energy in ZNA and number of SPD hits

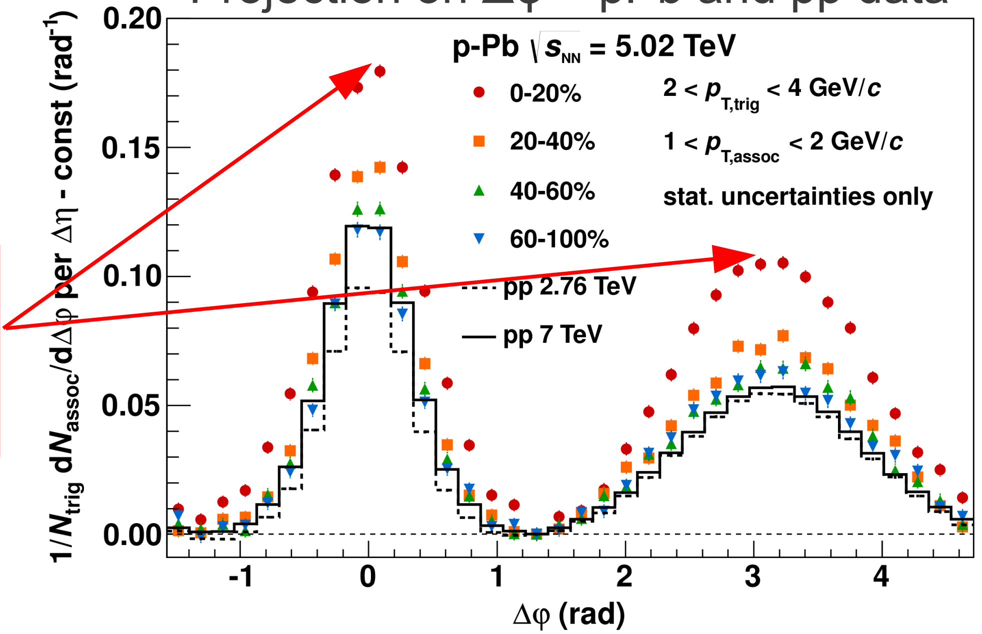
Correlations, results



Low multiplicity event class

High multiplicity event class

Projection on Δφ – pPb and pp data

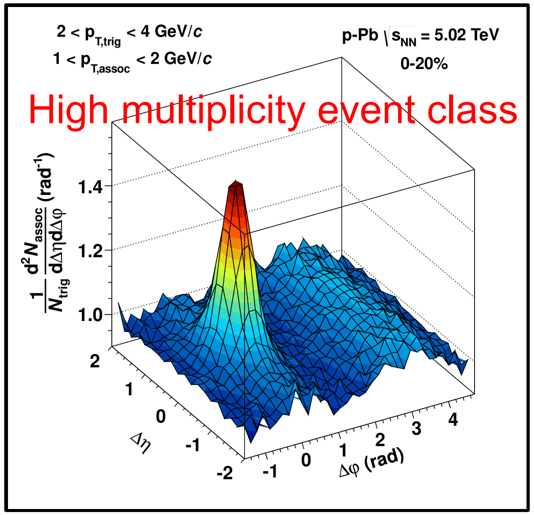


Qualitatively similar to CMS ridge

Excess on both near-side (NS) and away-side (AS) going from p-p/low multiplicity -> high multiplicity events

What remains if one subtracts per-trigger yield in 0-20% and 60-100%?

In our definition of the per trigger yield the subtraction gives the change/excess in the correlation yield between multiplicity event classes


High multiplicity event class

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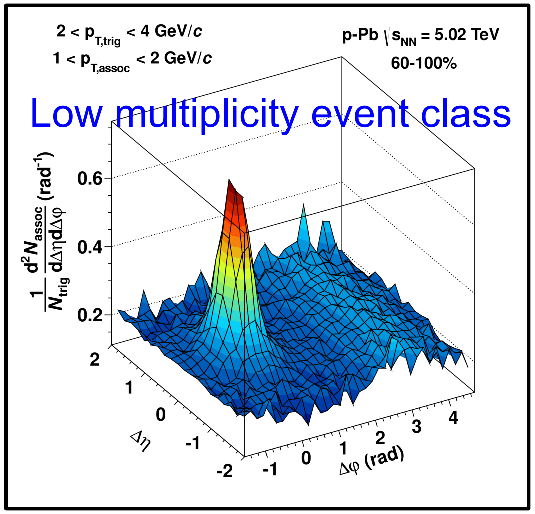
Low multiplicity event class

= ?

Note: Subtraction of p-p from 60-100% event class shows only a change in the baseline due to different combinatorial background

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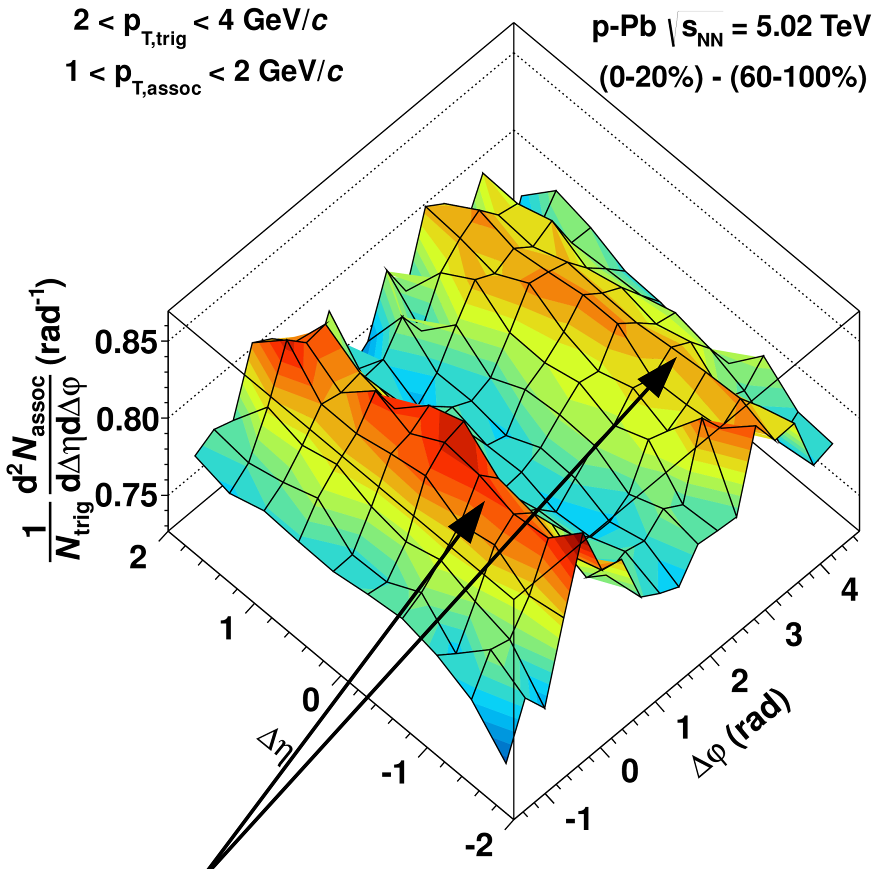

Double-ridge structure

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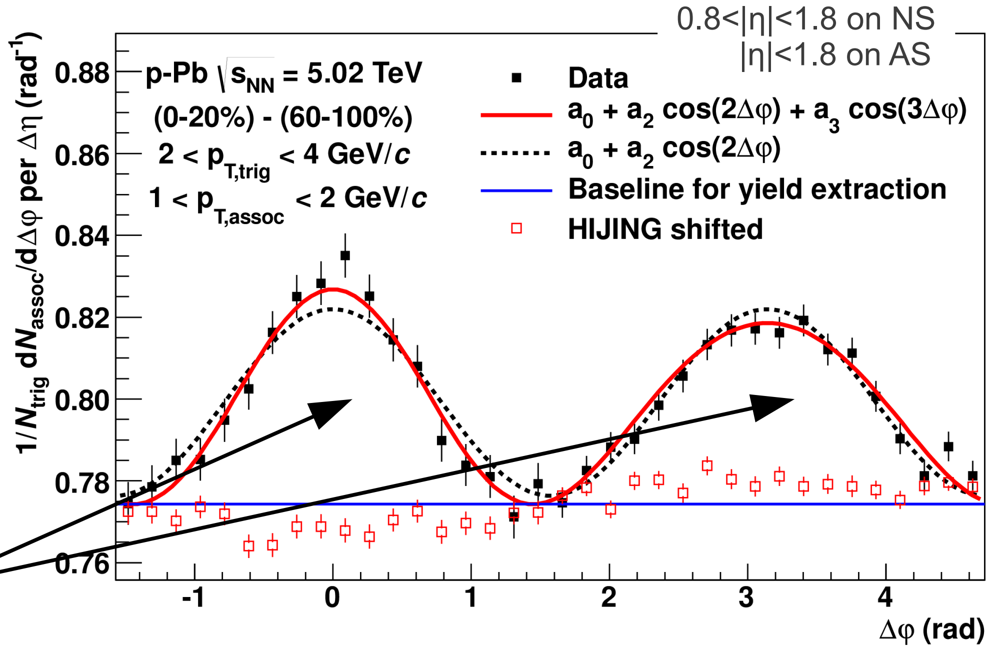

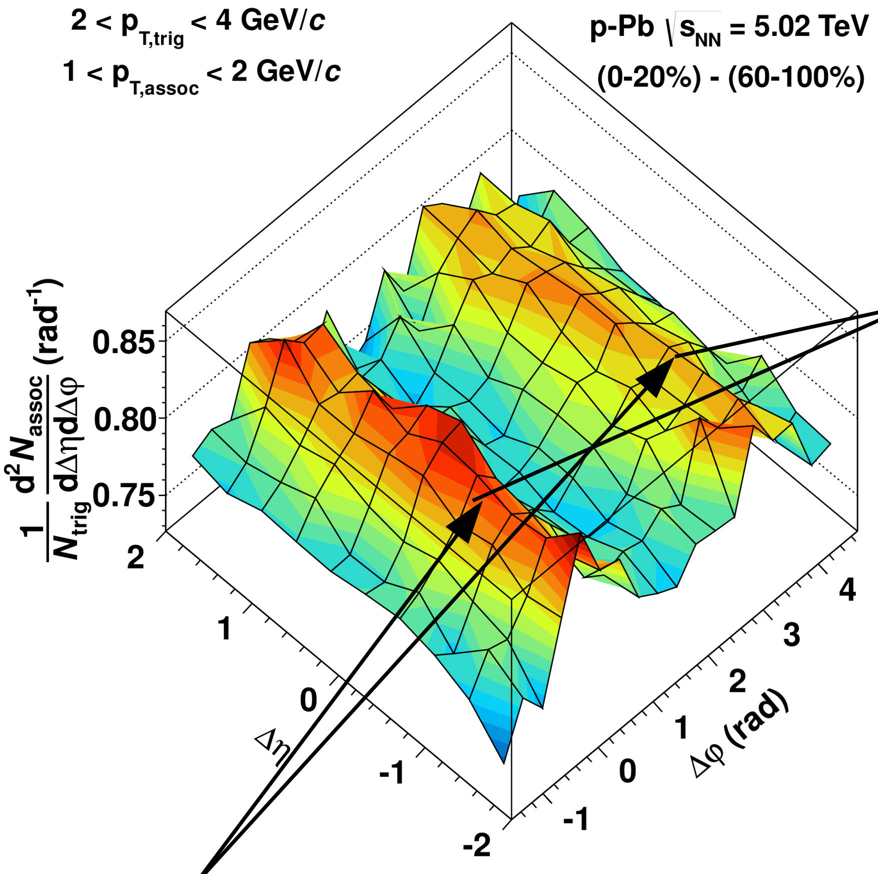

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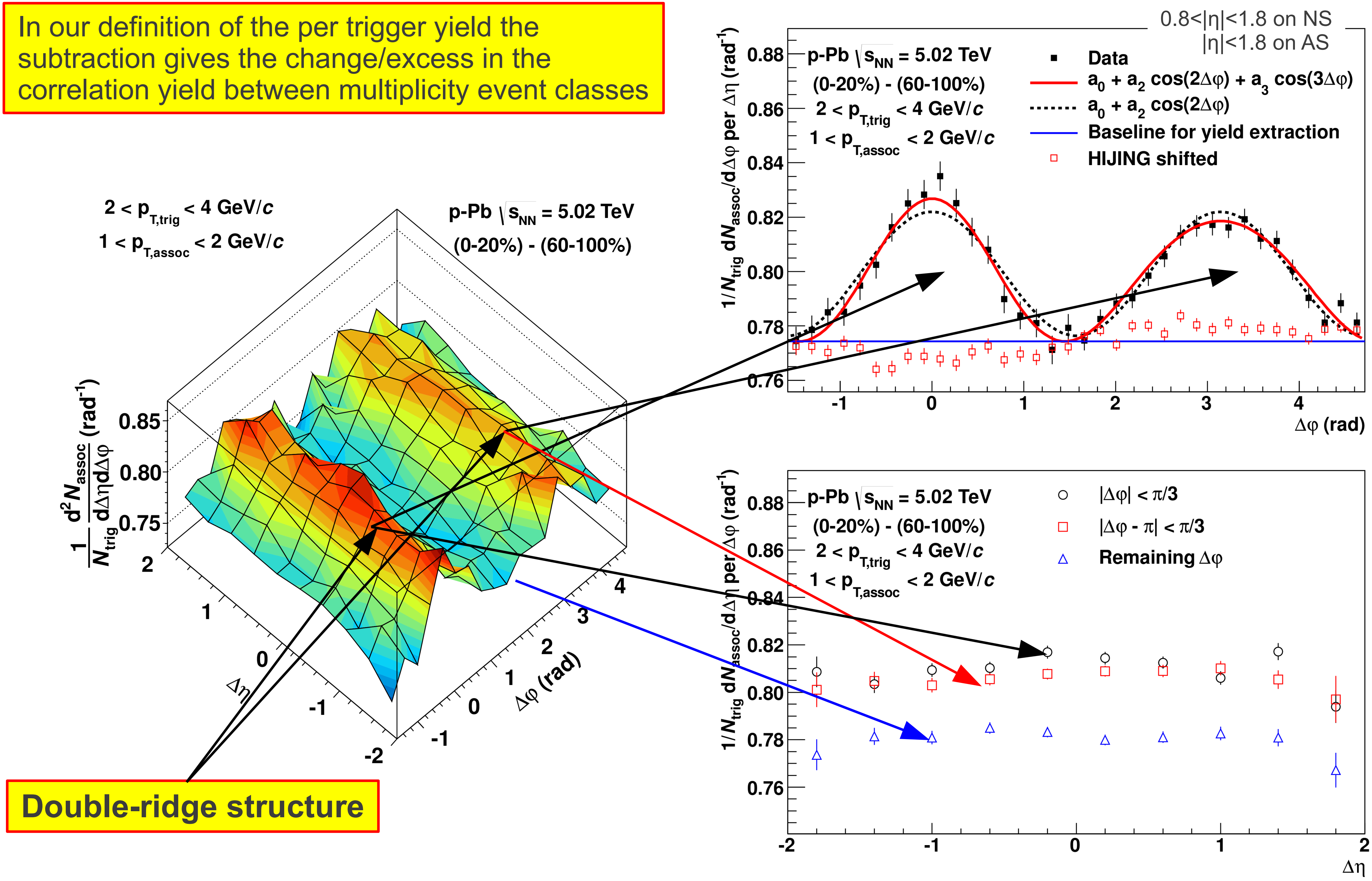
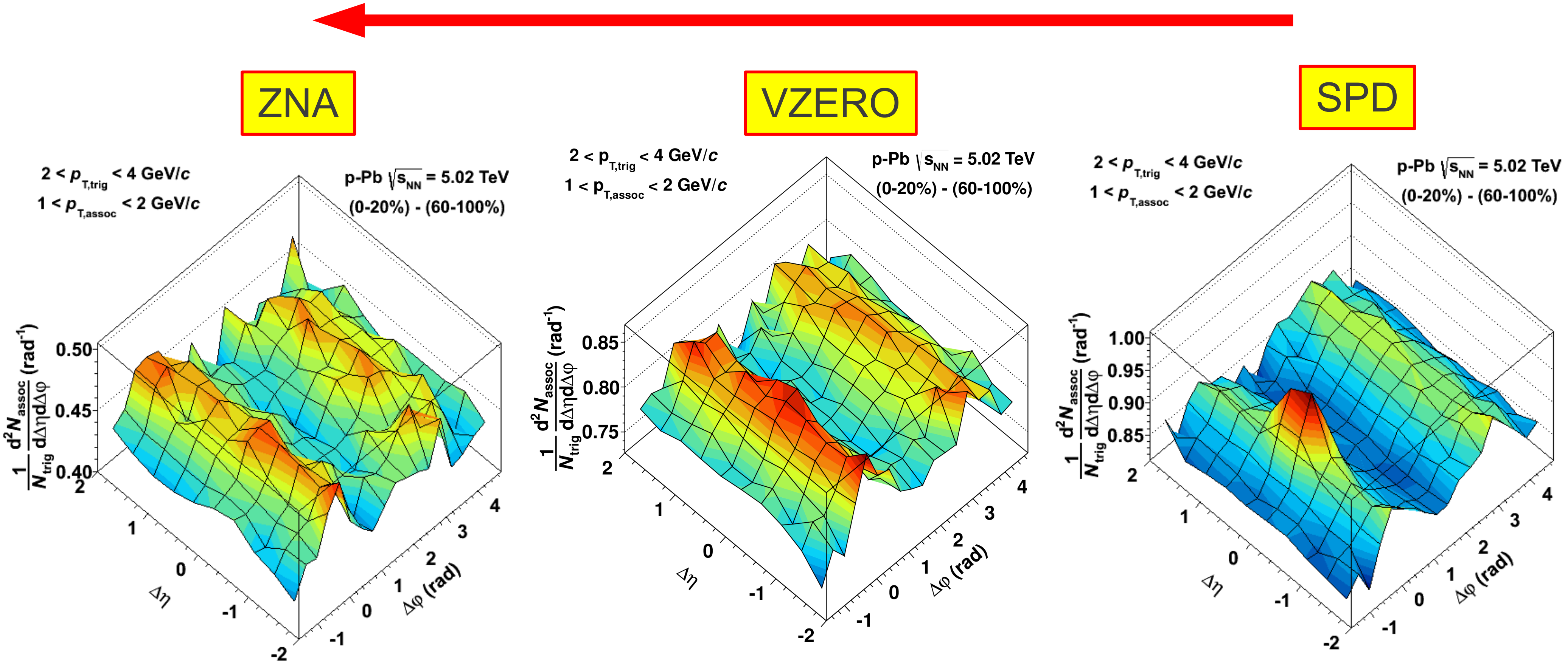


Double-ridge structure

Small residual NS peak

- Possibly related to jet-enhancement bias introduced by the event class selection

Residual NS peak decreases moving away from mid-rapidity event class selection



ZNA

VZERO

SPD

Double-ridge structure - quantified

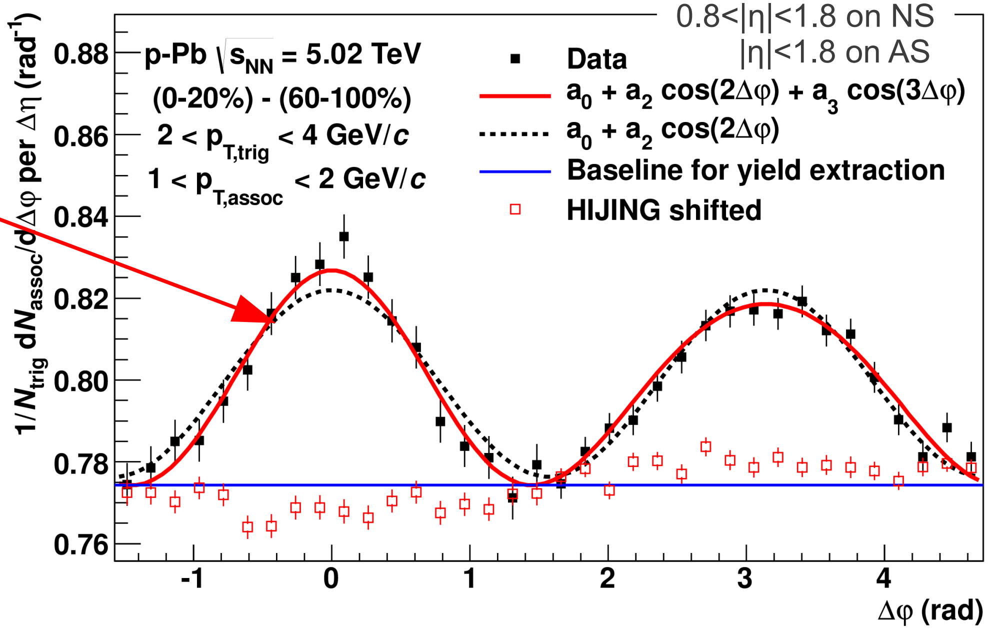
- Fit with:

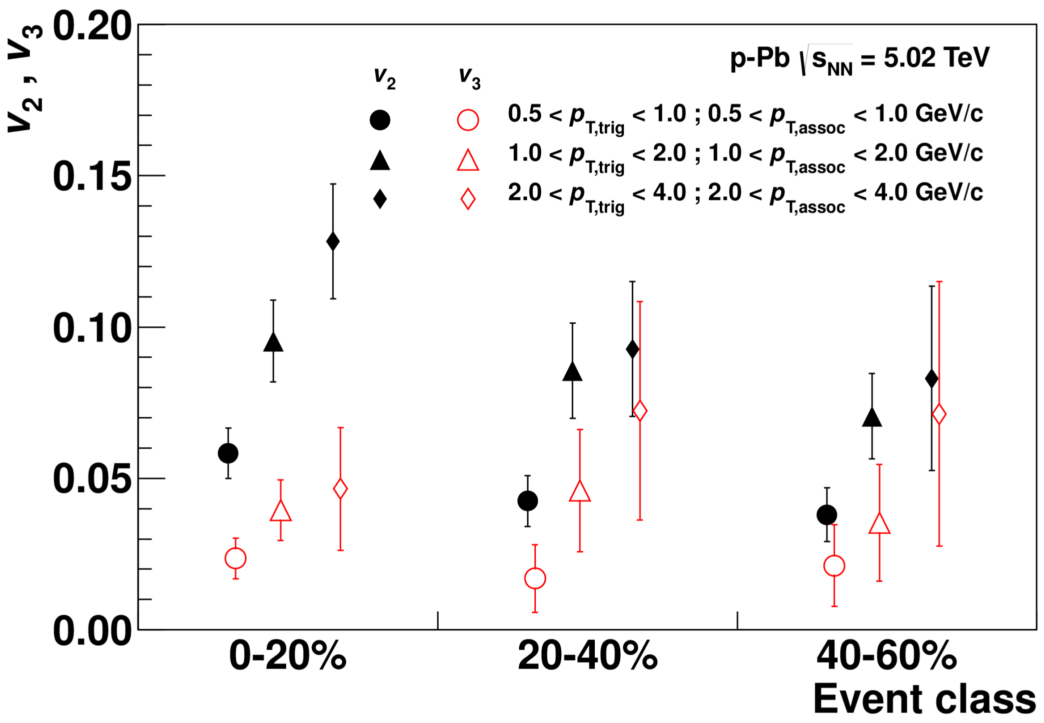
$$\frac{1}{N_{trig}}\frac{dN_{assoc}}{d\Delta\phi}=a_0+2a_2\cos(2\Delta\phi)+2a_3\cos(3\Delta\phi)$$

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

b – baseline in higher multiplicity event class

- $v_{2,3}$ – Fourier coefficients of single-particle azimuthal distribution



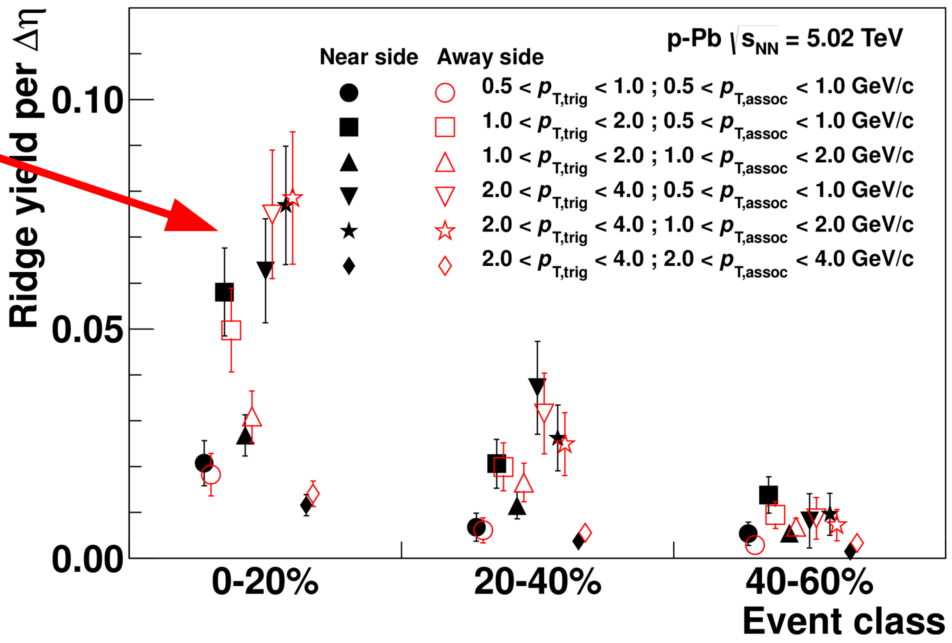


Both v_2 and v_3 are increasing with p_T

v_2 increases with event multiplicity

Double-ridge structure - properties

- NS ≈ AS yields for all Pt bins and event classes
  → Suggest common underlying process

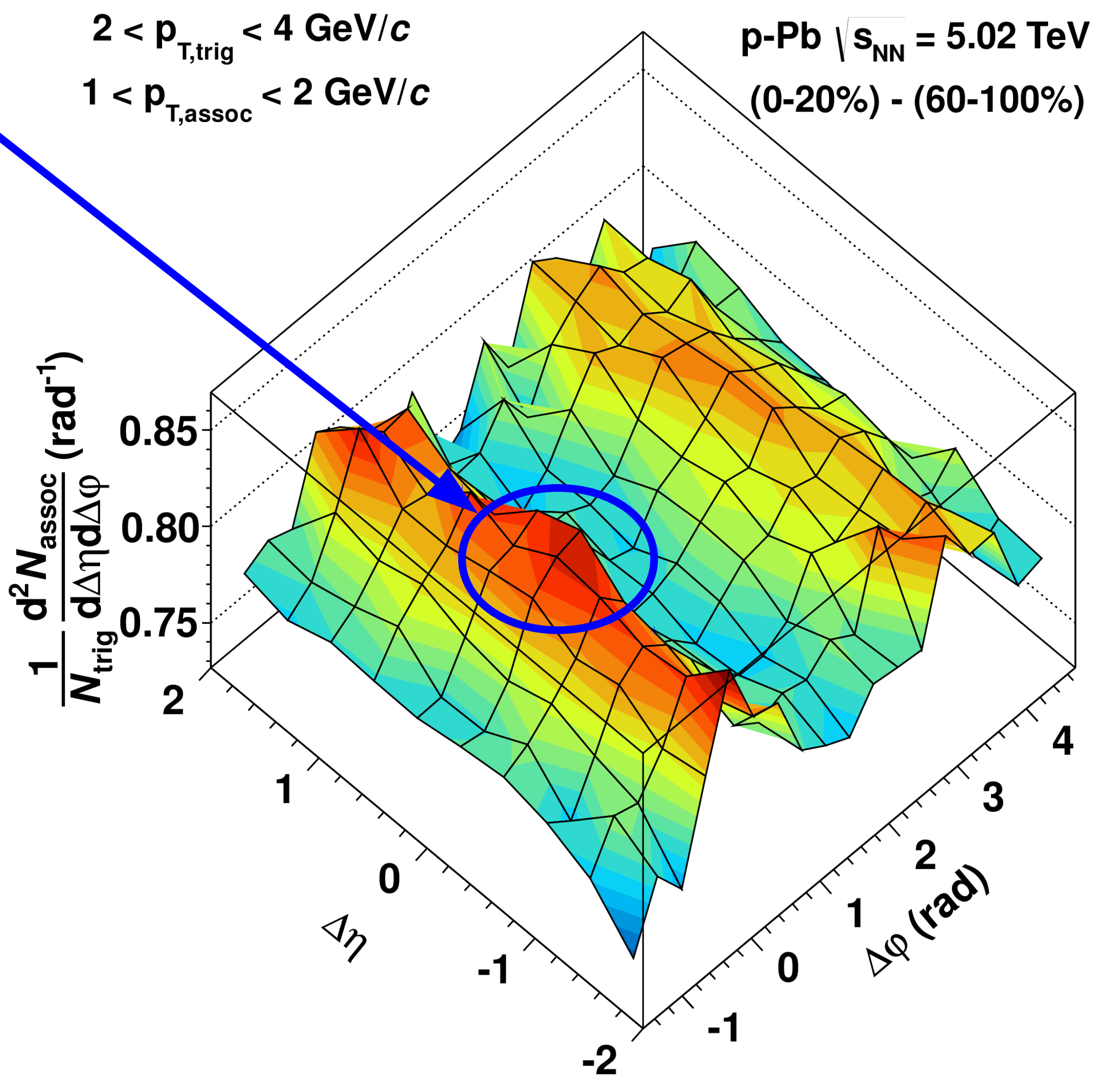


- Width of NS and AS ridges are within 20% and **do not depend on p_T**

- Alternative event selection using E_{ZNA} → weaker correlation with particle production @ η≈0, but also smaller autocorrelations from jets
  - Qualitatively the same picture – equal yields and widths of NS and AS
  - Different $dN_{ch}/d\eta$, ridge yields and v_2,v_3 w.r.t. VZERO selection
  - **However the yields obtained with both VZERO and ZNA selection follow a common trend as a function of $<dN_{ch}/d\eta>$**

Systematic uncertainties

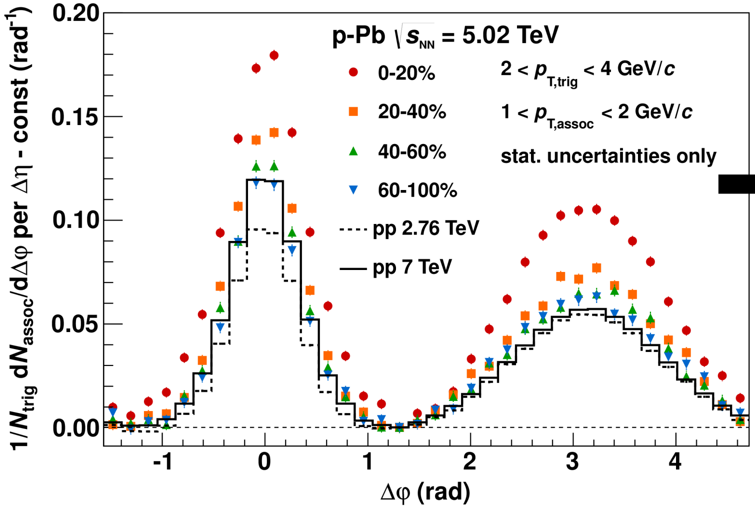
- Small residual NS jet peak → <15% (v_2), <40% in (v_3)
  - NS exclusion |η|>0.8 → 1.2
  - Residual peak subtracted from AS (using NS/AS ratio from low-multiplicity class)
  - Low-multiplicity class scaled and subtracted so that NS peak disappears

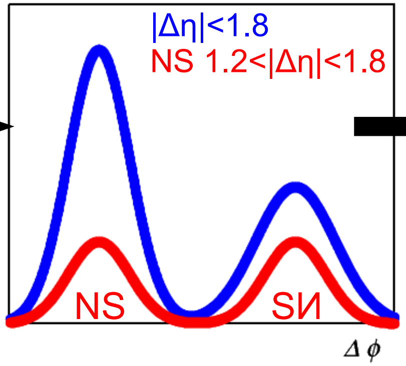


- Other systematic uncertainties:
  - Track acceptance/efficiency → 4% (yields)
    - HIJING corrected with DPMJET
  - Track selection → 5% (yields)
    - Used alternative track selection criteria
  - Baseline extraction → 10% (yields)
    - Minimum of fit function → parabolic function fit in |Δφ-π/2|<1

Further modifications?

Assume 2 ridges are symmetric → mirror NS on AS and subtract →look what is left

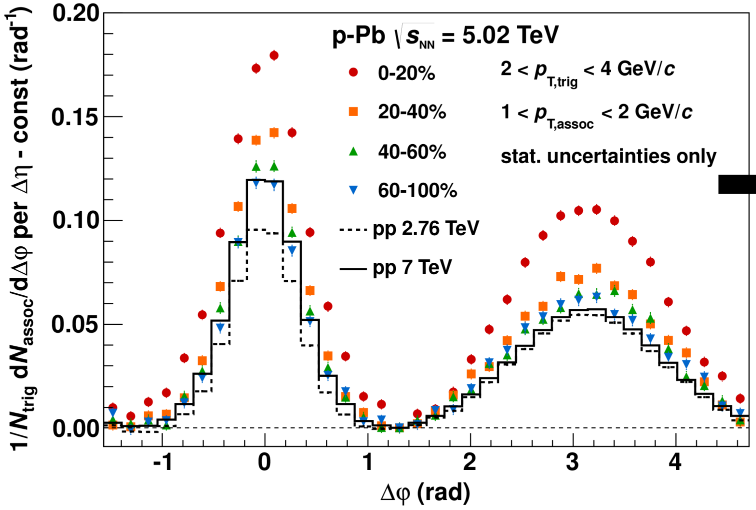


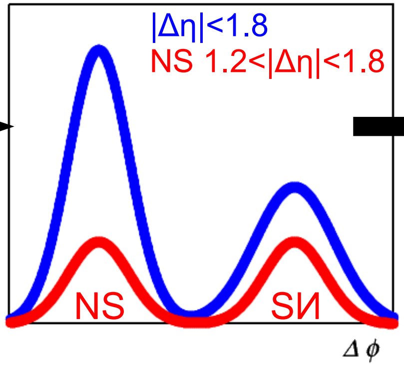


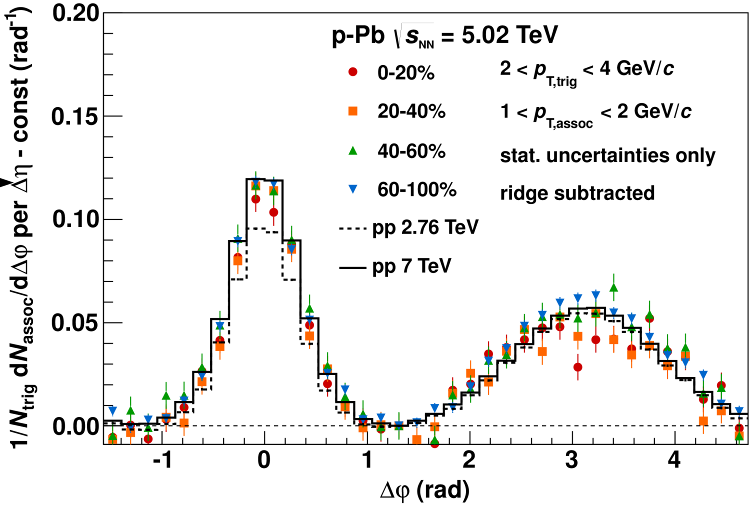
?

Further modifications?

Assume 2 ridges are symmetric → mirror NS on AS and subtract →look what is left







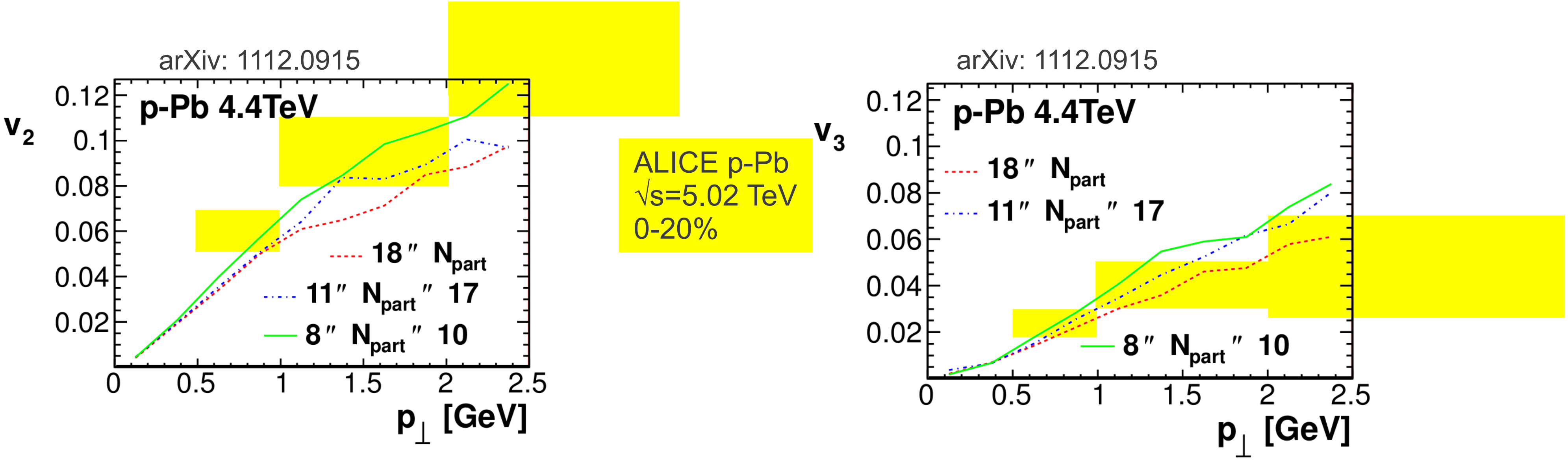
In case of no subtraction - yields increased
In case of subtraction - yields unmodified

→

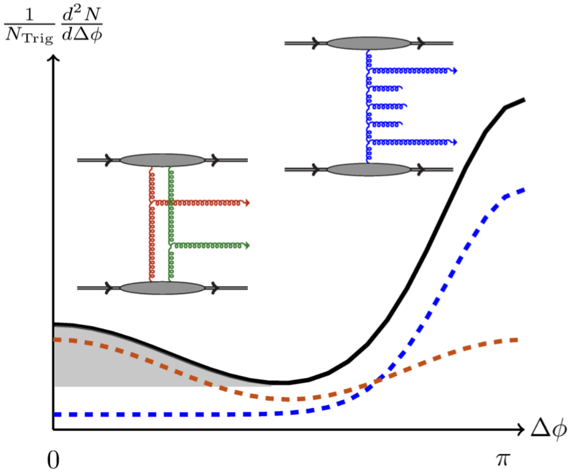
In contrast to the suppression observed at similar x @ RHIC

Double-ridge – Comparison to theory predictions

- 3+1 viscous hydro pPb@4.4 TeV (arXiv: 1112.0915)
  → v2,v3, p_T and multiplicity dependence qualitatively agree with the ALICE measurement



- Another possible explanation within CGC (arXiv: 1211.3701)
- Describes NS ridge observed by CMS
- Quantitative comparison with the ALICE measurement not possible
  - Different definition of correlation function, event selection and acceptance



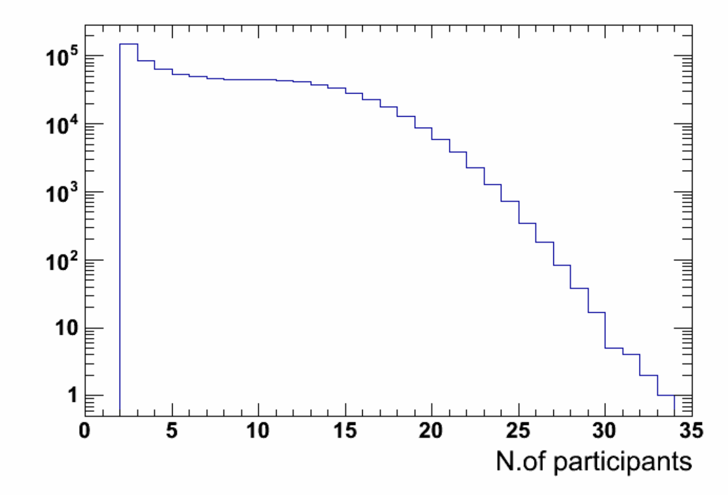
Conclusions

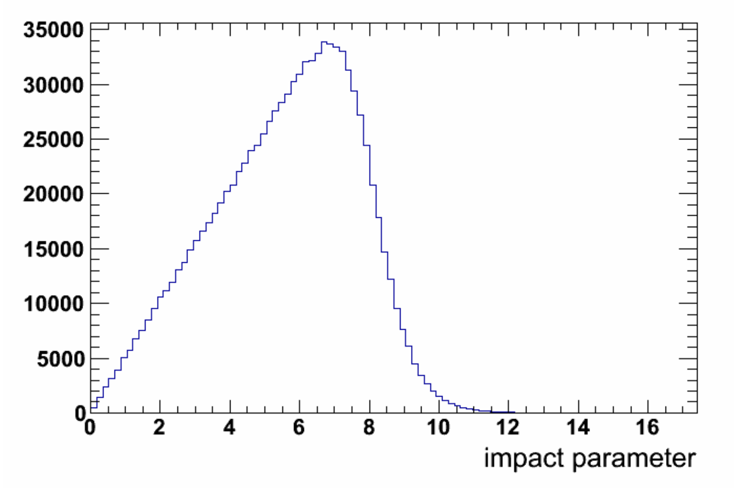
- $dN_{ch}/d\eta$ measurement
  - Available saturation model predictions have too steep η-dependence
- R_{pPb} measurement shows no suppression of high-p_T hadrons
  - High-p_T hadrons and jets suppression in Pb-Pb is not due to initial state effects
- Observation of double-ridge symmetric structure in the di-hadron correlations
  - Origin not yet known
  - No apparent suppression in the di-hadron correlations at mid-rapidity

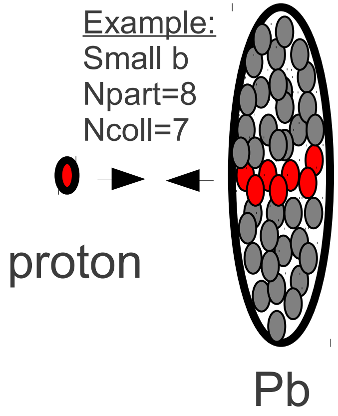
We would like to thank the machine for providing us with these data!

Backup

p-A collision geometry and extraction of <Npart>,<Ncoll>, T_{pPb} with Glauber MC







- Nuclear density profile: Woods−Saxon
  - Radius = 6.62 ± 0.06_{syst} fm
  - Skin depth = 0.546 ± 0.010_{syst} fm
  - Intra-nucleon distance = 0.4 ± 0.4_{syst} fm
- Cross-section σ_{NN}=70 ± 5 mb (interpolated for √s=5.02 TeV)

<b>,fm	RMS_b,fm	<Npart>	RMS_{Npart}	$<T_{pPb}>$,mb^{-1}	RMS_{TpPb},mb^{-1}
5.56	2.07	7.9	5.1	0.0983	0.0728

In p-A   Npart = Ncoll + 1

<Npart> = 7.9 ± 0.6_{syst}

$<T_{pPb}>$ = 0.0983 ± 0.0035_{syst} mb^{-1}

Nuclear modification factor R_{pPb} defined as:

$$R_{pPb}(p_T)=\frac{d^2N_{ch}^{pPb}/d\eta dp_T}{<Ncoll>d^2N_{ch}^{pp}/d\eta dp_T}=\frac{d^2N_{ch}^{pPb}/d\eta dp_T}{<T_{pPb}>d^2\sigma_{ch}^{pp}/d\eta dp_T}$$

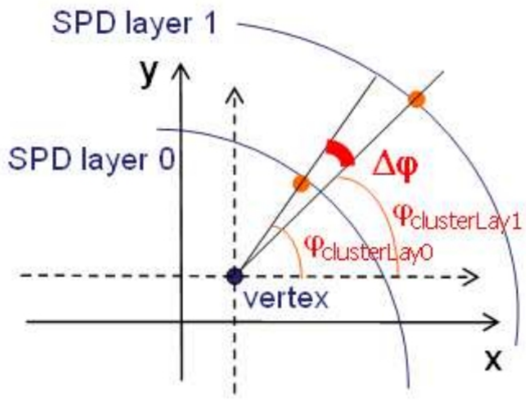
Event selection and reconstruction efficiency

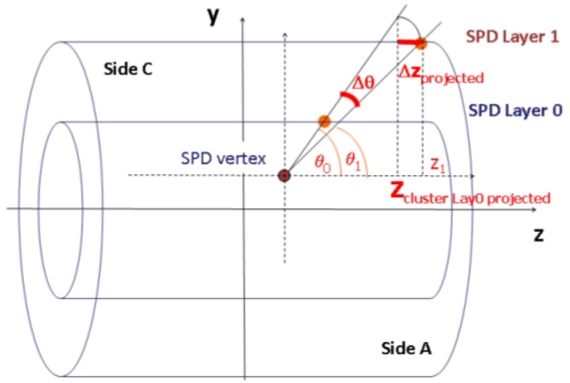
- 98.5% (data) and 99.4% (DPMJET) of selected events have vertex (event w/o vertex = bin0)
- 41% probability to select event w/o vertex (DPMJET)
- Difference in bin0 between data and MC → -2.2% correction on $dN_{ch}/d\eta$
- 96.4% overall selection and reconstruction efficiency

- Cross-check of selection efficiency using ZDC trigger and E_{ZNA} (Pb remnants side) threshold
  - E_{ZNA} > 12 spectator neutrons ← DPMJET + nuclear fragments production
  - Largely suppressed EM dissociation and SD processes
  - 3.1% difference taken as systematic error on $dN_{ch}/d\eta$

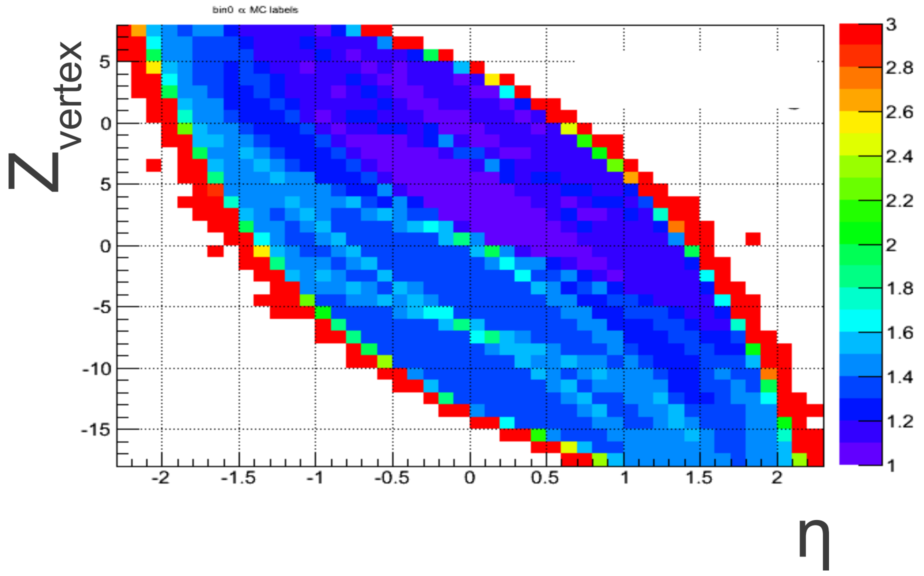
$dN_{ch}/d\eta$ – reconstruction and analysis technique

- Measurement based on tracklets - pairs of hits in the two layers of SPD, constrained to the primary vertex reconstructed with SPD





- Pseudorapidity coverage extended by using wide range of longitudinal primary-vertex position (Z_{vertex})
- Background mainly from secondaries and correlated combinatorials
- Efficiency and acceptance corrections based on MC (DPMJET, cross-checked with HIJING)



dNdEta – Systematic uncertainties

Source	Uncertainty, %	Evaluation method
Detector acceptance	1.5	Variation of Zvertex range
Combinatorial background	0.3	Comparison of tracklets residuals in data and MC
Secondaries (weak decays)	0.8	
Particle composition	1.0	Variation of rel. amount of π/p/K by factor of 2
Extrapolation to 0 Pt	1.0	50% variation of # particles at low Pt
Event selection normalization	3.1	ZNA trigger
Total	3.8	

Pt Spectra and R_{pPb} – systematic uncertainties

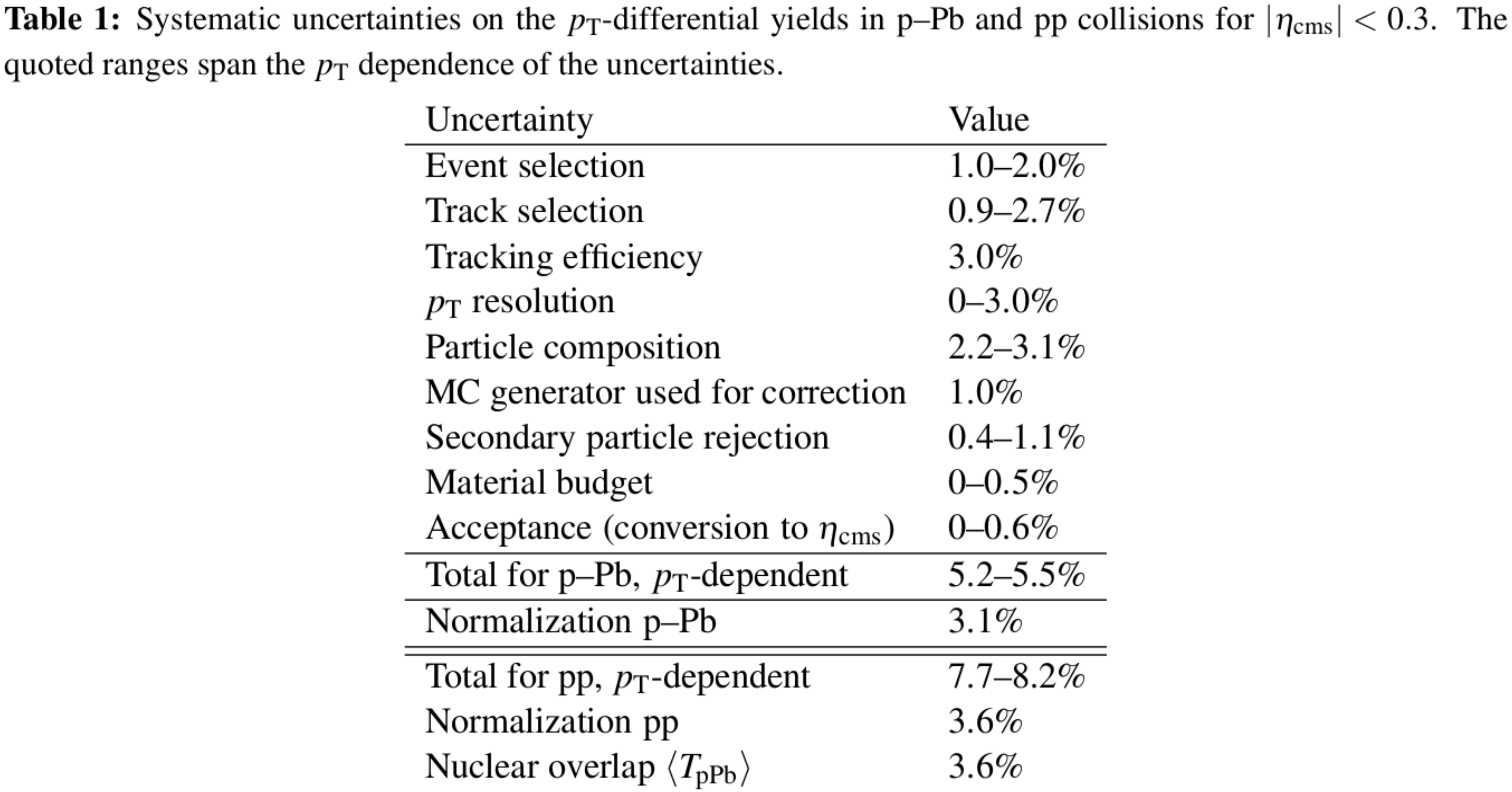


Table 1: Systematic uncertainties on the p_{T}-differential yields in p–Pb and pp collisions for $|\eta_{\mathrm{cms}}| < 0.3$. The quoted ranges span the p_{T} dependence of the uncertainties.

Uncertainty	Value
Event selection	1.0–2.0%
Track selection	0.9–2.7%
Tracking efficiency	3.0%
p_{T} resolution	0–3.0%
Particle composition	2.2–3.1%
MC generator used for correction	1.0%
Secondary particle rejection	0.4–1.1%
Material budget	0–0.5%
Acceptance (conversion to η_{cms})	0–0.6%
Total for p–Pb, p_{T}-dependent	5.2–5.5%
Normalization p–Pb	3.1%
Total for pp, p_{T}-dependent	7.7–8.2%
Normalization pp	3.6%
Nuclear overlap $\langle T_{\mathrm{pPb}} \rangle$	3.6%

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

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

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) $N_{source} = 1$

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

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}

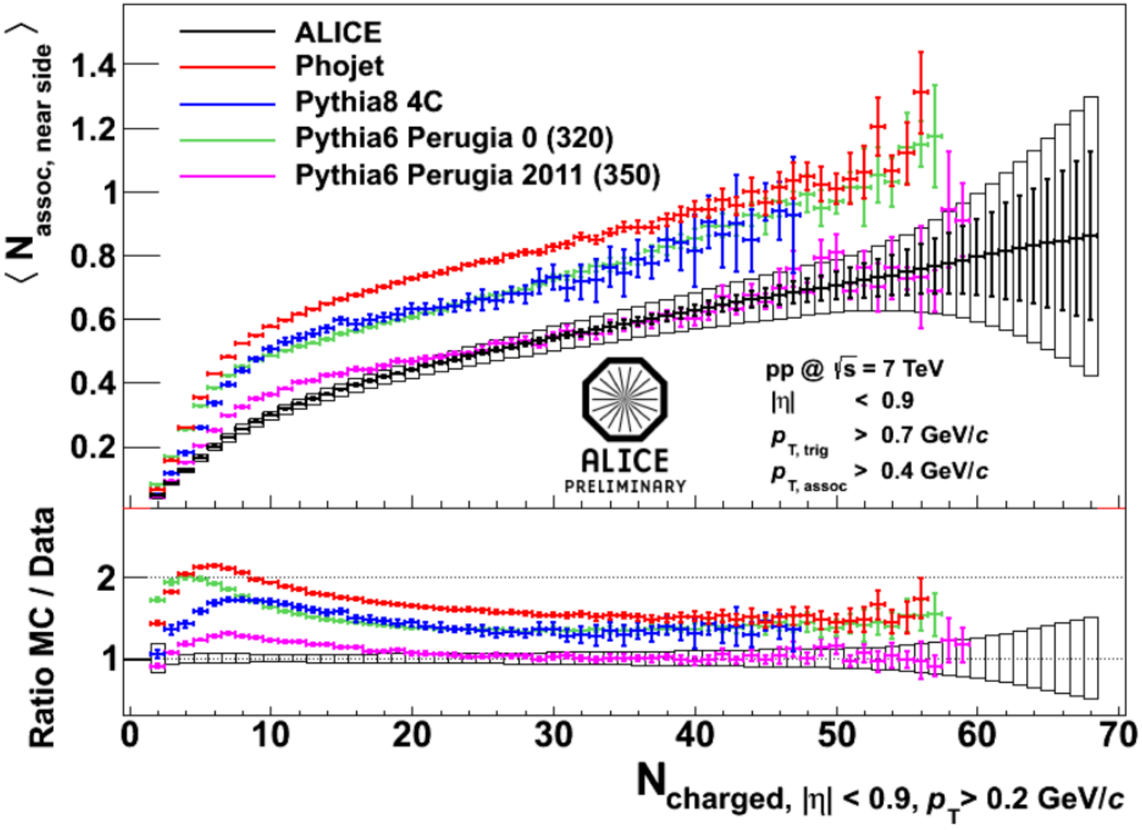
(2) N_{source} **large** In this case the source average and the event average are equal and the average of ratios is equal to the ratio of averages.

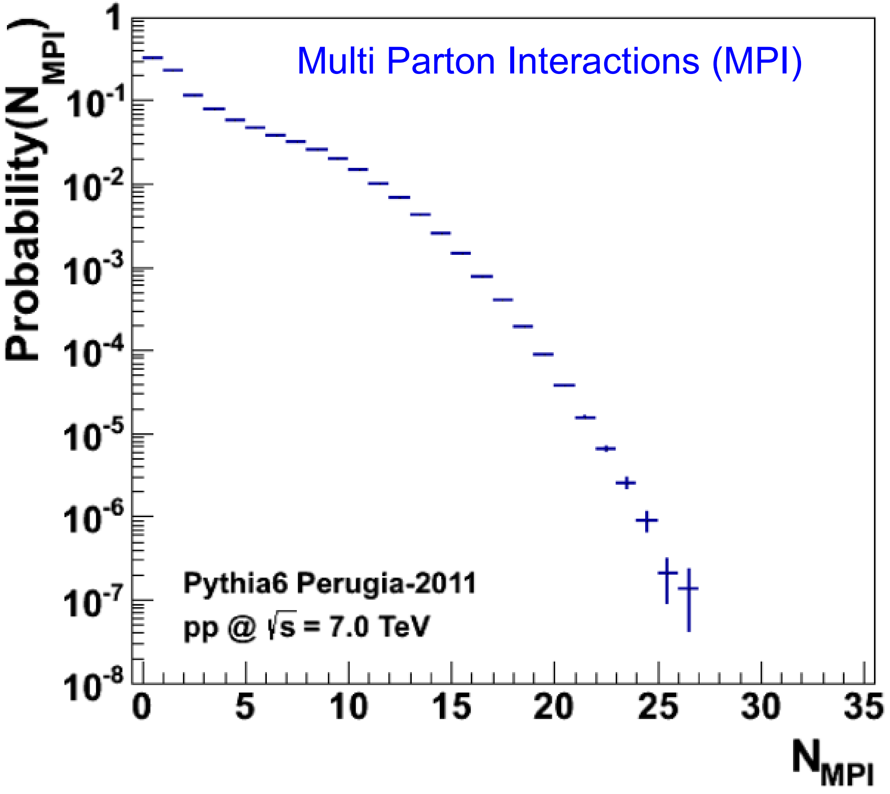
$$\begin{aligned}\frac{N_{pair}}{N_{trig}} &= \frac{1}{N_{evt}} \sum_{i}^{N_{evt}} \frac{\sum_{j=1}^{N^i_{source}} n_{i,j}(n_{ij}-1)}{\sum_{j=1}^{N^i_{source}} n_{i,j}} \\ &= \frac{\langle n(n-1) \rangle}{\langle n \rangle}\end{aligned} \tag{4}$$

multiplicity dependent

Multiplicity selection bias on Fragmentation (pp)

Per trigger near-side pair yield in pp





Jet fragmentation is strongly biased towards higher number of frag. products.
Competition between higher number of MPI and fragmentation.

Why are we able to observe the double-ridge?

- Correlation function defined as associated per trigger yield
  → allowing to subtract low mult from high mult event classes and obtain the change in the correlation yield
- Smaller eta gap, where the shape of dN/dη does not affect the away side (HIJING)
- Smaller eta coverage, where dN/dη is still more or less flat
- Quite different event selections tracks → SPD → VZERO → ZNA (introducing less autocorrelations and bias on jet yields)