The evolution of the near-side peak in two-particle number and transverse momentum correlations in Pb–Pb collisions from ALICE

Monika Varga-Kofarago
MTA Wigner RCP

on behalf of the ALICE Collaboration

16th May 2018 – Quark Matter 2018

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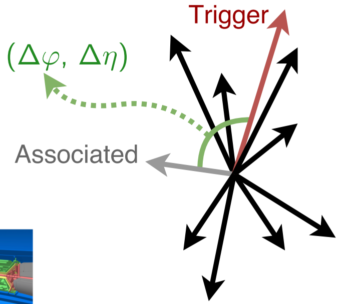
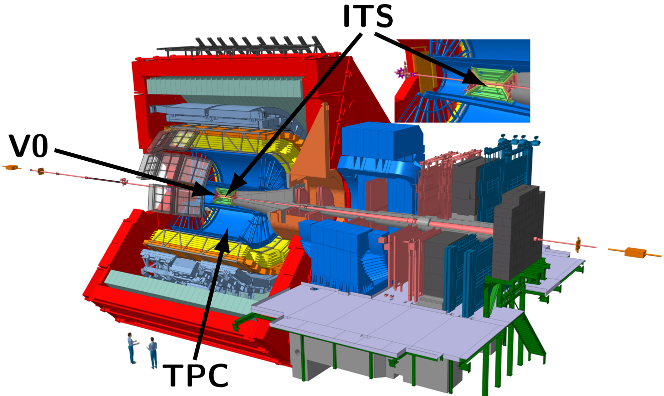
Two-particle correlations – introduction

- Pb–Pb and pp data
- $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV
- Trigger and associated particle
- Number or transverse momentum





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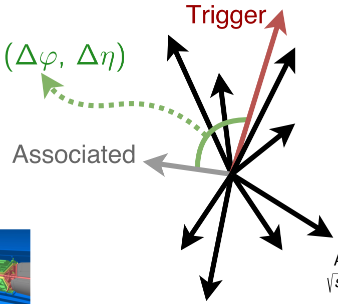

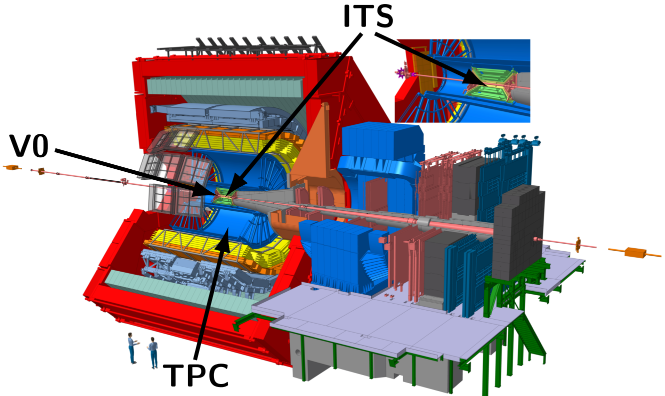

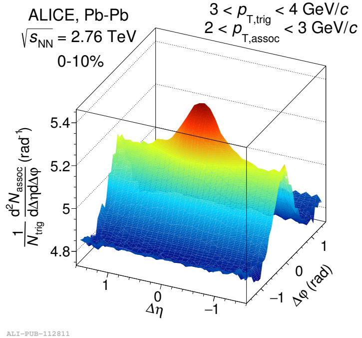

Two-particle correlations – motivation

Number correlations

Momentum correlations

Two-particle correlations – motivation

Number correlations

- Studying interaction of jets with medium
- Analysis done on a statistical basis
- Subtraction of fluctuating background
- Low p_{T} measurement possible
- Complementary tool to jet reconstruction
- Interactions $\Rightarrow$ modification of peak
- Modification has been seen by STAR

  STAR Collaboration, Phys. Rev. C85 (2012) 014903
- Modification of peak yield seen by ALICE

  Phys. Rev. Lett. 108 (2012) 092301

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Momentum correlations

- Studying collision dynamics
- Analysis done on a statistical basis
- Subtraction of fluctuating background
- Sensitive to momentum currents
- Centrality evolution gives information on:
  - System shear viscosity: η/s
  - System relaxation time: τ_π
- STAR: evolution of peak with centrality

  STAR Collaboration, Physics Letters B 704 (2011) 467-473
- Similar recent measurement by ALICE

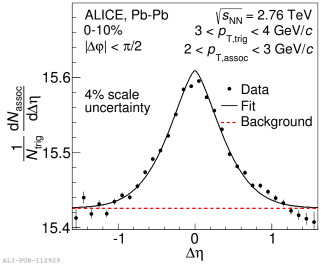
  arXiv:1805.04422

Number correlations

- Per trigger yield:

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

- Acceptance correction by mixed event: $M(\Delta\eta, \Delta\varphi)$
- p_{T} bins between 1 GeV/c and 8 GeV/c
- All charged particles



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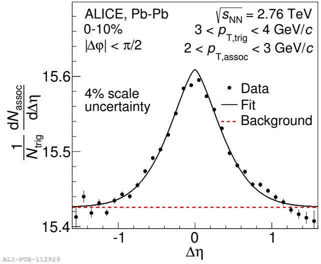


Momentum correlations

- $G_2(\Delta\varphi, \Delta\eta) =$

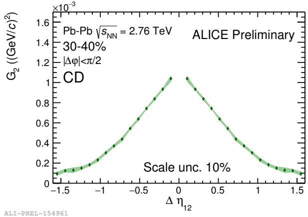
$$= \frac{\left\langle \sum_{i}^{n_{1,1}} \sum_{j\neq i}^{n_{1,2}} p_{\mathrm{T,i}} p_{\mathrm{T,j}} \right\rangle}{\langle n_{1,1}\rangle \langle n_{1,2}\rangle} - \langle p_{\mathrm{T},1}\rangle \langle p_{\mathrm{T},2}\rangle$$

- Accep. corr. to equalize detector response
- Particles with $0.2 < p_{\mathrm{T}} < 2.0$ GeV/c used
- Charge dependent – charge conservation:

CD: $\frac{1}{4}$ $((+-) + (-+) - (++) - (--))$

- Charge independent – collective behavior:

CI: $\frac{1}{4}$ $((+-) + (-+) + (++) + (--))$



Extraction of the near-side peak width

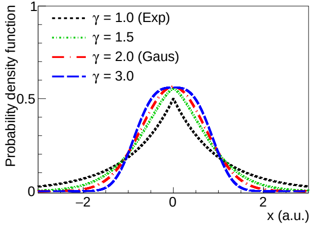
- The near-side is fitted to characterize its shape evolution
- Fit function: background + Generalized Gaussian
  - Background:

$$C_1 + \sum_{n=2}^{N} 2V_n \cos(n\Delta\varphi)$$

  - Generalized Gaussian:

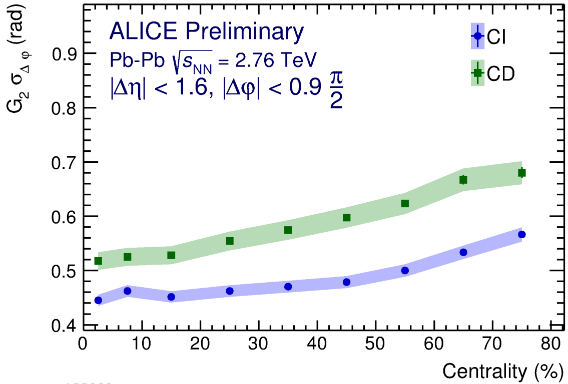
$$N \times e^{-\left|\frac{d\varphi}{w_\varphi}\right|^{\gamma_\varphi} - \left|\frac{d\eta}{w_\eta}\right|^{\gamma_\eta}} \Longrightarrow N = C_2 \times \frac{\gamma_\varphi \gamma_\eta}{4 w_\varphi w_\eta \Gamma\left(\frac{1}{\gamma_\varphi}\right)\Gamma\left(\frac{1}{\gamma_\eta}\right)}$$

$\gamma = 1$: Exponential
$\gamma = 2$: Gaussian



- Characterize peak by variance of generalized Gaussian: $\sigma^2 = \frac{w^2\Gamma(3/\gamma)}{\Gamma(1/\gamma)}$
- No attempt to give physical meaning to parameters of the generalized Gaussian
- Some bins around $(\Delta\varphi, \Delta\eta) = (0, 0)$ are excluded from the fit

Width of the peak in momentum correlations at $\sqrt{s_{NN}} = 2.76$ TeV



ALI-PREL-155092

- Charge dependent peak is wider than charge independent in $\Delta\varphi$
- Both show narrowing in $\Delta\varphi$ towards central events

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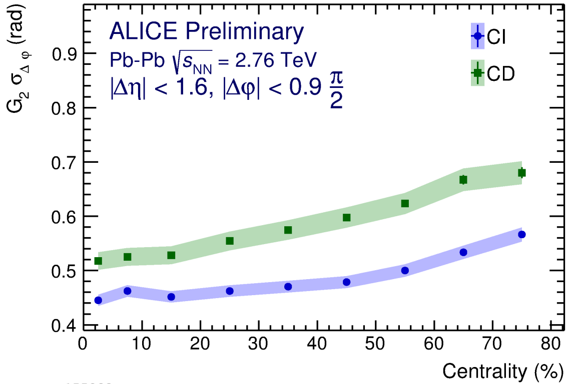

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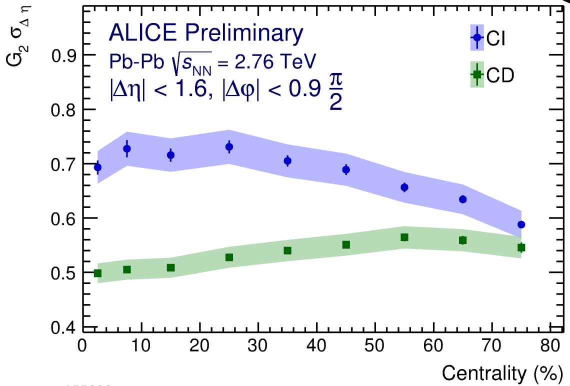
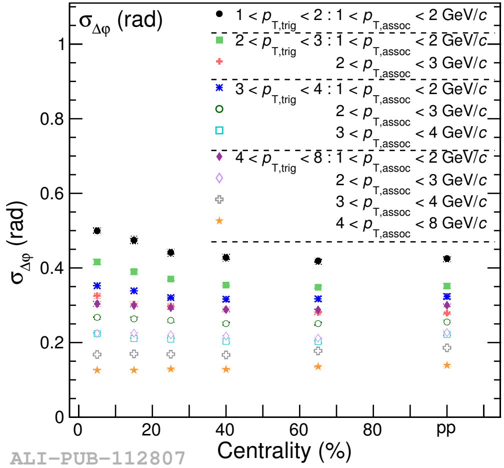


ALI-PREL-155088

- Charge independent peak is wider than charge dependent in $\Delta\eta$
- Charge independent peak is broadening towards central events in $\Delta\eta \rightarrow$ related to η/s
- Charge dependent width is almost flat with centrality in $\Delta\eta$

Width of the peak in number correlations at $\sqrt{s_{NN}} = 2.76$ TeV



- Ordering of the width according to p_T

Phys. Rev. Lett. 119, 102301 (2017)
Phys. Rev. C 96, 034904 (2017)

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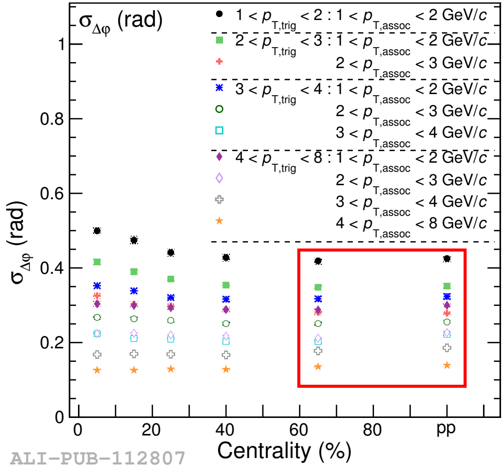

- Ordering of the width according to p_T
- Width in $\Delta\varphi$ in 50–80% is equal to width in pp

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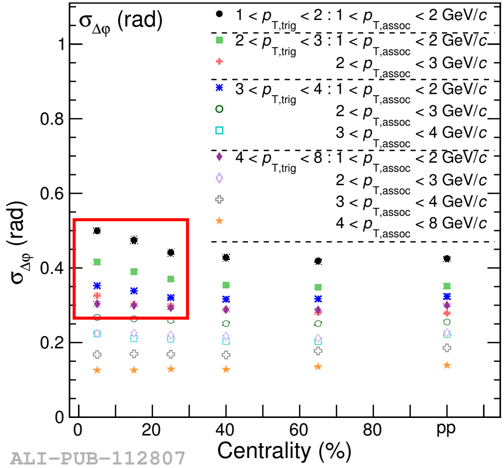

- Ordering of the width according to p_T
- Width in $\Delta\varphi$ in 50–80% is equal to width in pp
- Small increase at low p_T in $\Delta\varphi$ with centrality

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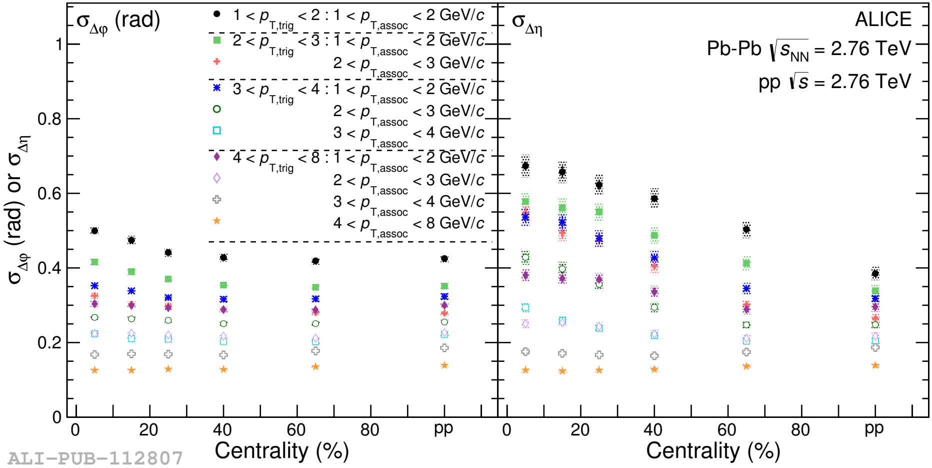
Width of the peak in number correlations at $\sqrt{s_{NN}} = 2.76$ TeV



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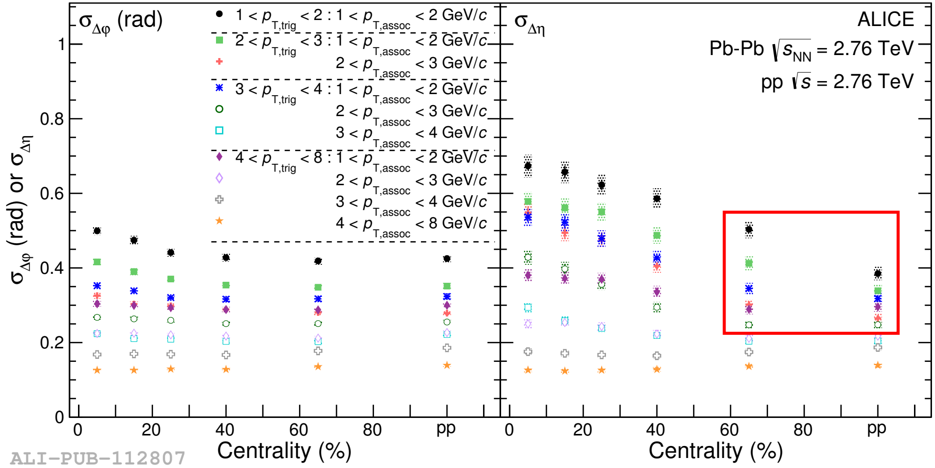

- Ordering of the width according to p_T
- Width in $\Delta\eta$ in 50–80% is already larger than in pp

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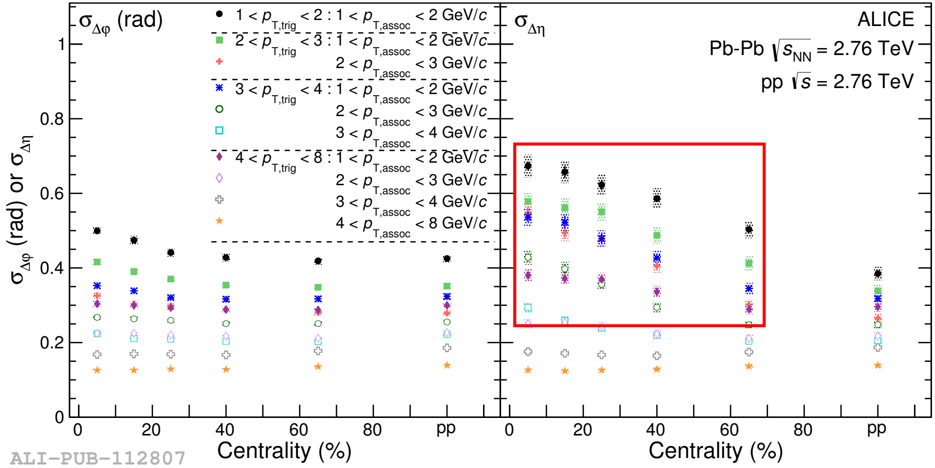
Width of the peak in number correlations at $\sqrt{s_{NN}} = 2.76$ TeV



- Ordering of the width according to p_T
- Width in $\Delta\eta$ in 50–80% is already larger than in pp
- Very pronounced increase at low p_T in $\Delta\eta$

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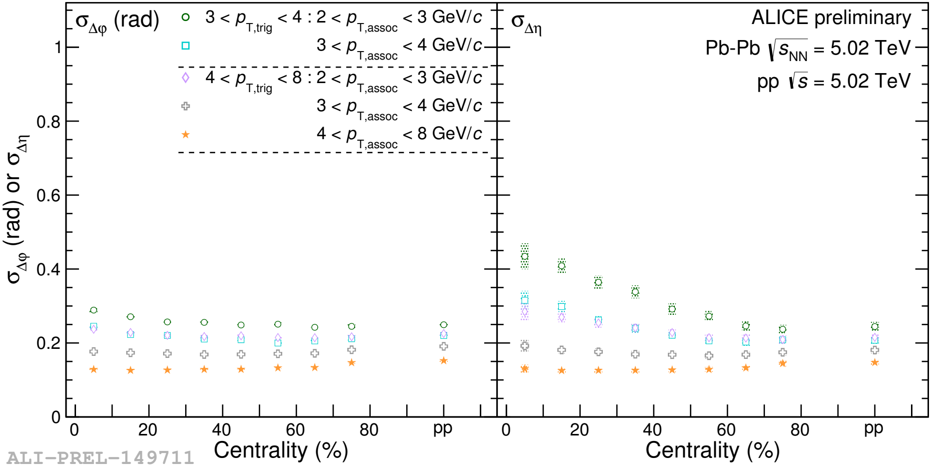
Width of the peak in number correlations at $\sqrt{s_{NN}} = 5.02$ TeV



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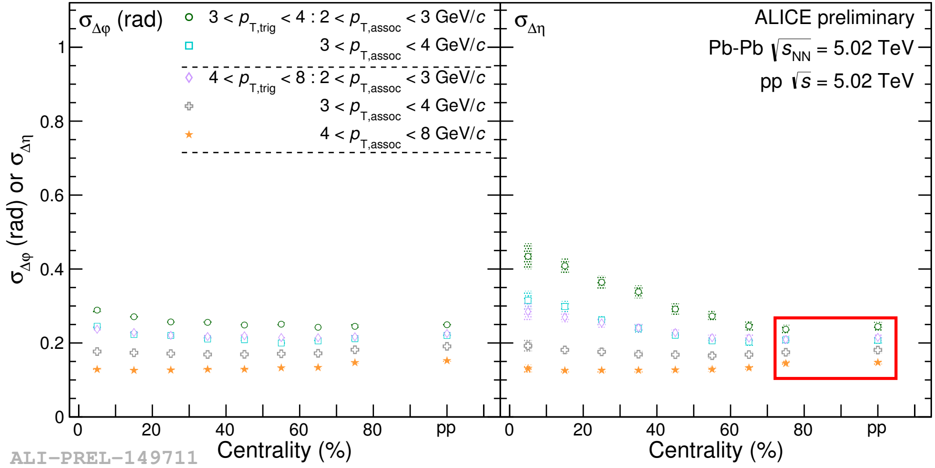

- Peak width in peripheral Pb-Pb equals to width in pp collisions

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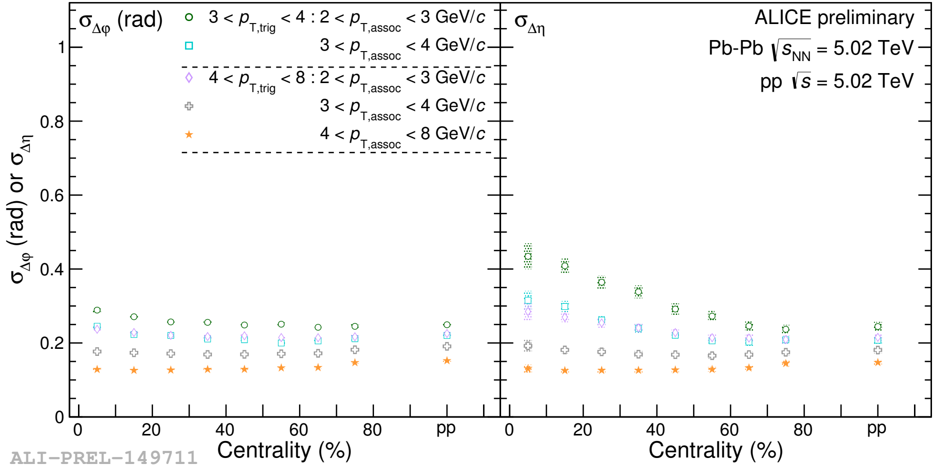

- Peak width in peripheral Pb-Pb equals to width in pp collisions
- Similar broadening towards central events as at $\sqrt{s_{NN}} = 2.76$ TeV

Comparison to models

AMPT (**A** **M**ulti-**P**hase **T**ransport model) [1]

- Addresses non-equilibrium many-body dynamics
- Has collective effects through:
  - Partonic interactions
  - Hadronic interactions

[1] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal, Phys.Rev. C72 (2005) 064901

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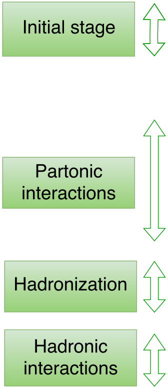

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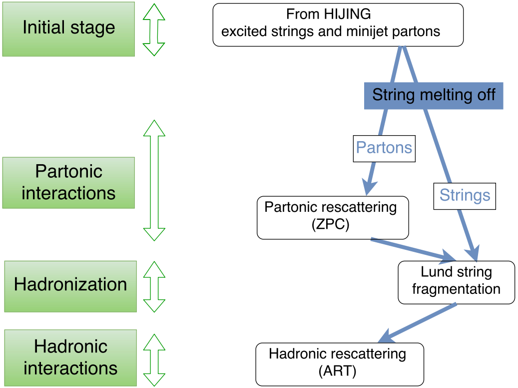

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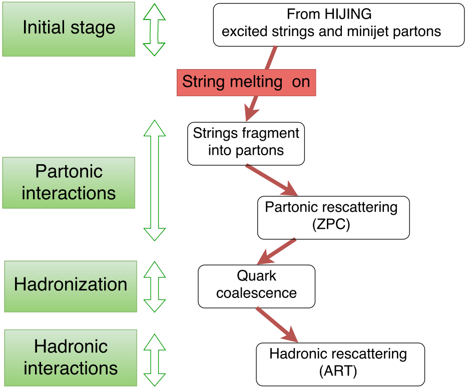

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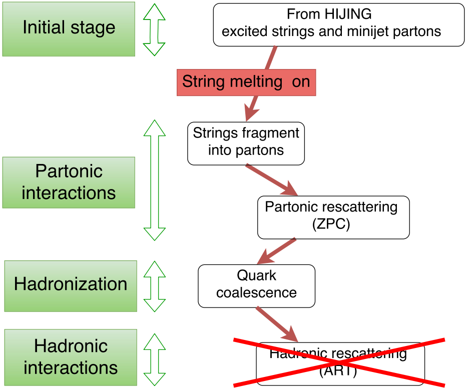

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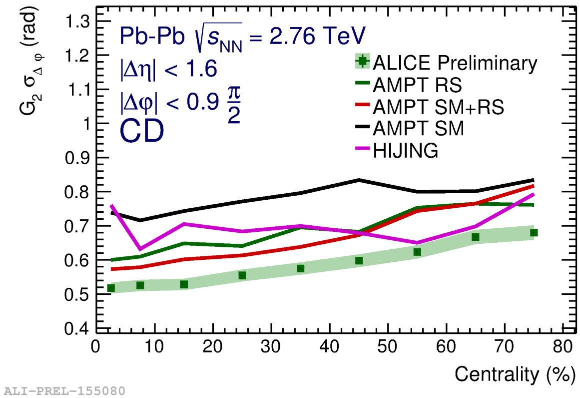
Width in momentum correlations – charge dependent



- None of the models describe the absolute width in $\Delta\varphi$
- All AMPT settings describe the trend in $\Delta\varphi$

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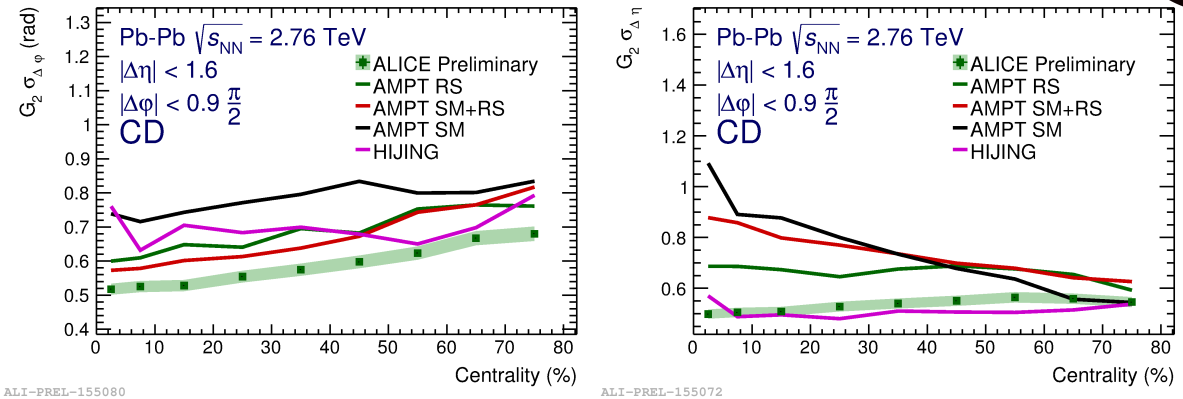
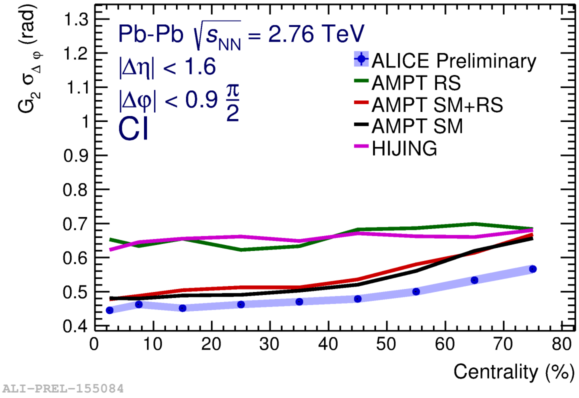


- HIJING describes the centrality evolution in $\Delta\eta$
- All settings of AMPT give opposite trend in $\Delta\eta$

Width in momentum correlations – charge independent



- Only AMPT with string melting on describes the centrality evolution in $\Delta\varphi$

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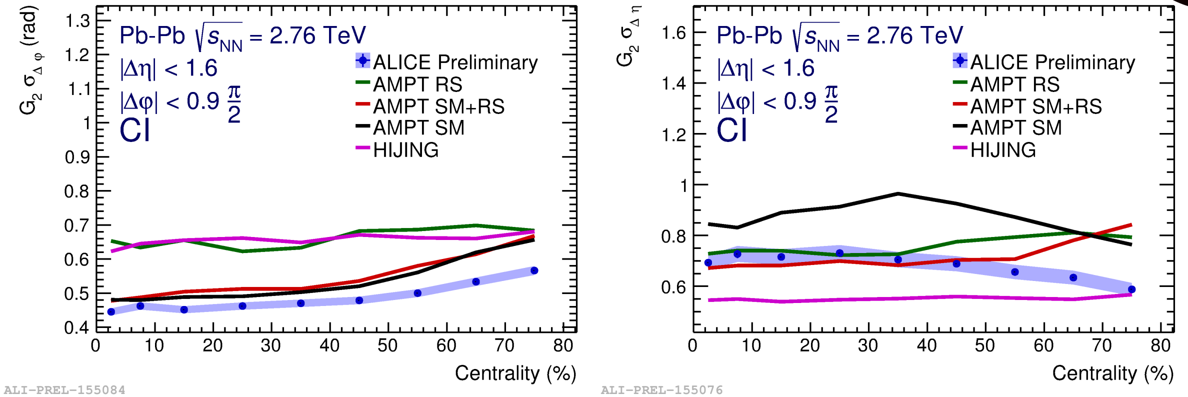

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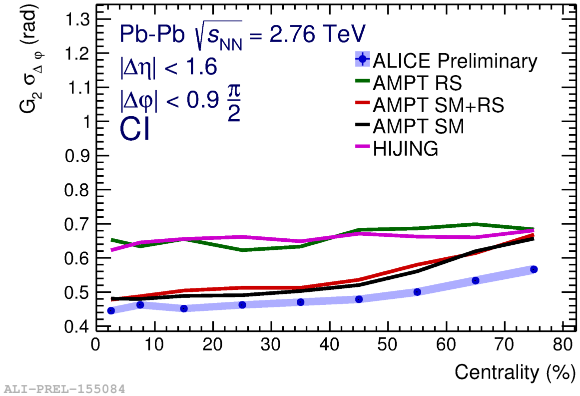
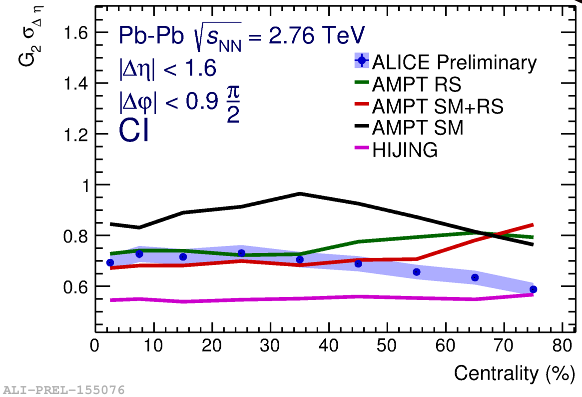
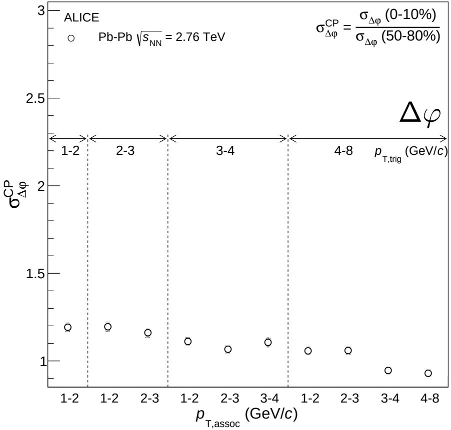




- None of the models describe the trend in $\Delta\eta$
- Further details of this analysis can be found in Victor Gonzalez's poster (COR-11)

Broadening in number correlations

- Ratio of width in central over peripheral: $\sigma^{CP}_{\Delta\varphi} = \frac{\sigma_{\Delta\varphi}(0-10\%)}{\sigma_{\Delta\varphi}(50-80\%)}$, $\sigma^{CP}_{\Delta\eta} = \frac{\sigma_{\Delta\eta}(0-10\%)}{\sigma_{\Delta\eta}(50-80\%)}$



- Moderate broadening in $\Delta\varphi$

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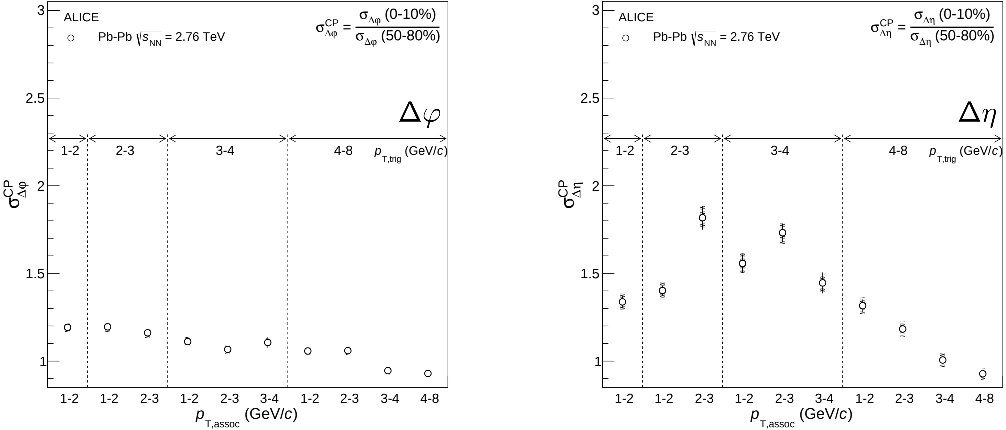

- Moderate broadening in $\Delta\varphi$
- Much larger broadening in $\Delta\eta$

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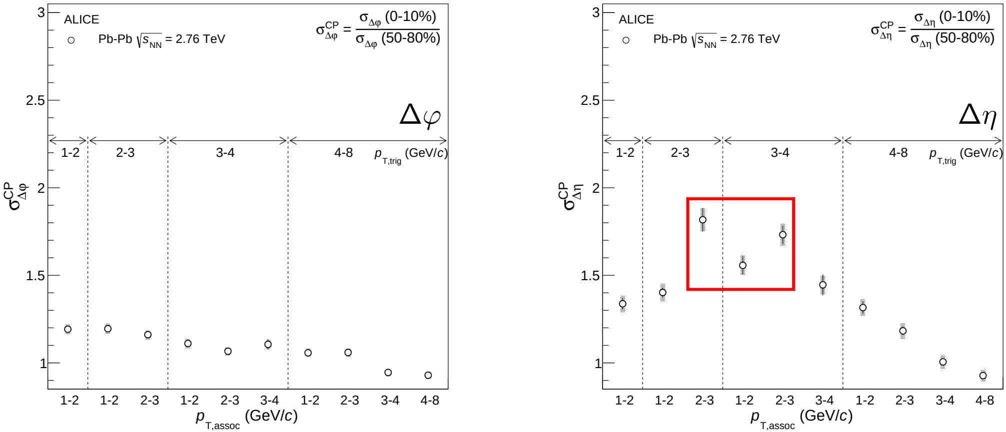

- Moderate broadening in $\Delta\varphi$
- Much larger broadening in $\Delta\eta$
- Broadening most significant at intermediate p_{T}

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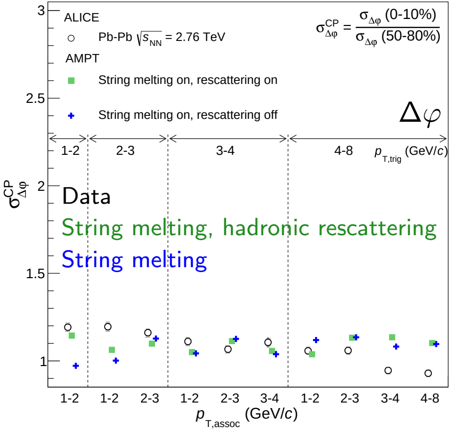

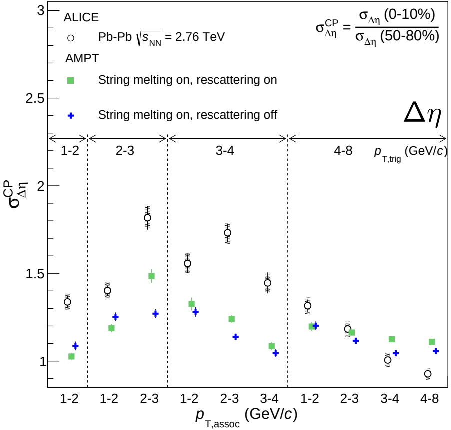

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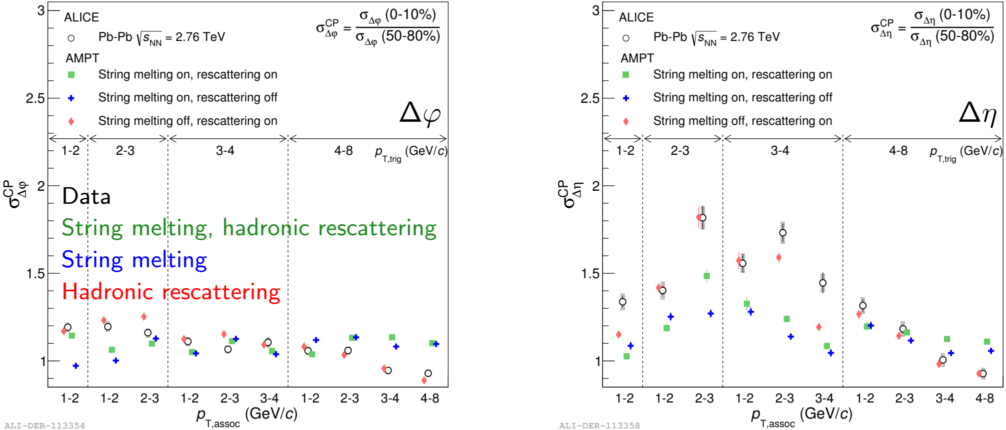

- Small difference between models in $\Delta\varphi$, $\Delta\eta$ more constraining
- String melting off, hadronic rescattering on describes data best

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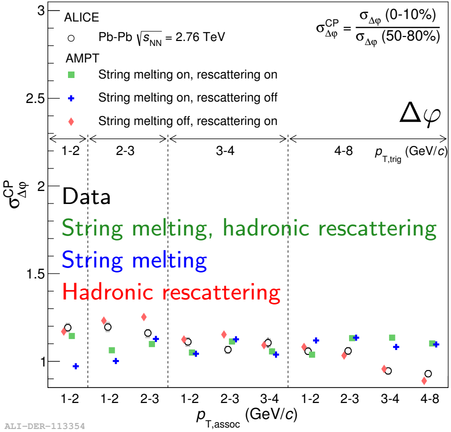

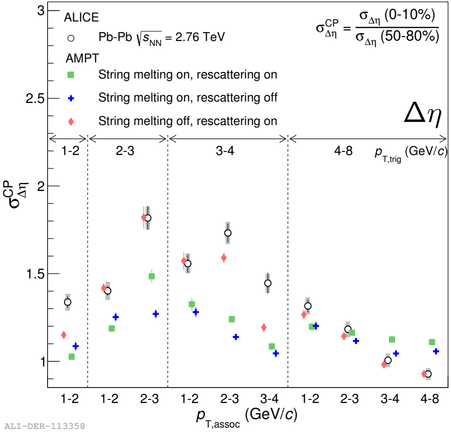

- Small difference between models in $\Delta\varphi$, $\Delta\eta$ more constraining
- String melting off, hadronic rescattering on describes data best
- Note: none of AMPT settings describe absolute width better than 10% (see backup)

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Near-side depletion in number correlations

Phys. Rev. Lett. 119, 102301 (2017)
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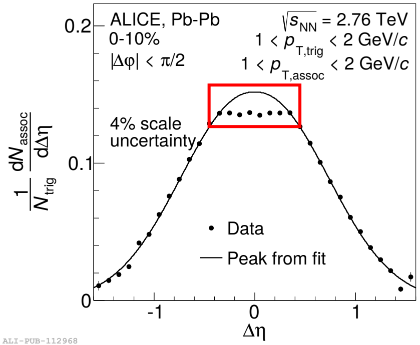
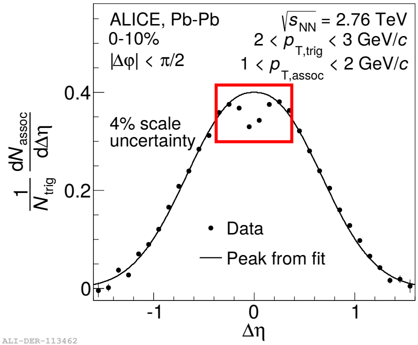
- In central collisions at low p_{T}: depletion around $(\Delta\varphi, \Delta\eta) = (0, 0)$
- Per trigger yield is corrected for two-track inefficiencies
- The area of the depletion is excluded from the fit

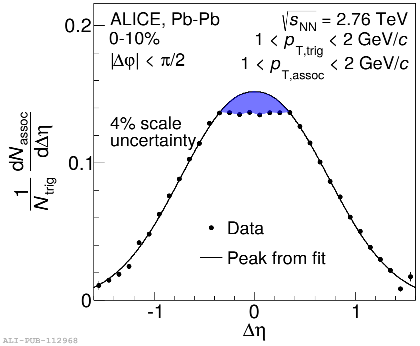


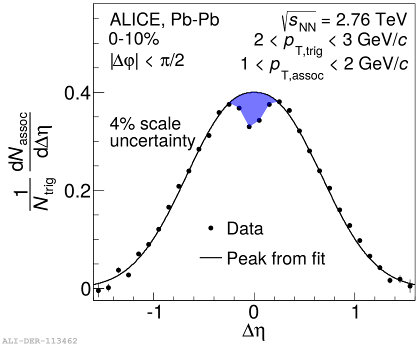


Near-side depletion in number correlations

Phys. Rev. Lett. 119, 102301 (2017)
Phys. Rev. C 96, 034904 (2017)

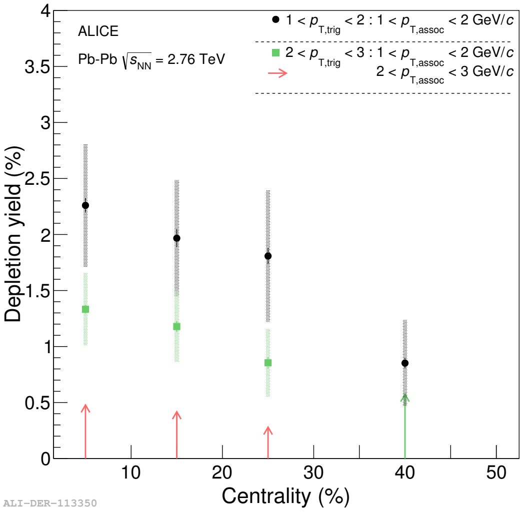
- In central collisions at low p_{T}: depletion around $(\Delta\varphi, \Delta\eta) = (0, 0)$
- Per trigger yield is corrected for two-track inefficiencies
- The area of the depletion is excluded from the fit
- Characterized by $\frac{\text{Fit-Data}}{\text{Total yield}}$ in %





Near-side depletion in number correlations

Phys. Rev. Lett. 119, 102301 (2017)
Phys. Rev. C 96, 034904 (2017)



- Depletion yield $= \frac{\text{Fit}-\text{Data}}{\text{Total yield}}$ in %
- No depletion in higher p_{T}, peripheral or pp

Near-side depletion in number correlations

Phys. Rev. Lett. 119, 102301 (2017)
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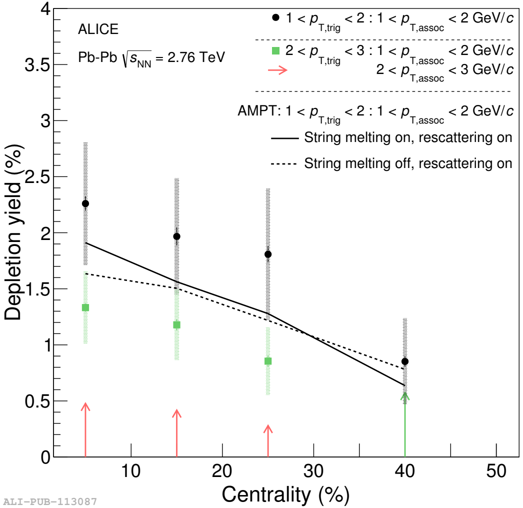

- Depletion yield $= \frac{\text{Fit}-\text{Data}}{\text{Total yield}}$ in %
- No depletion in higher p_T, peripheral or pp
- In AMPT almost independent of string melting
- AMPT is in agreement with data at lowest p_T
- At higher p_T no version shows depletion

Near-side depletion in number correlations

Phys. Rev. Lett. 119, 102301 (2017)
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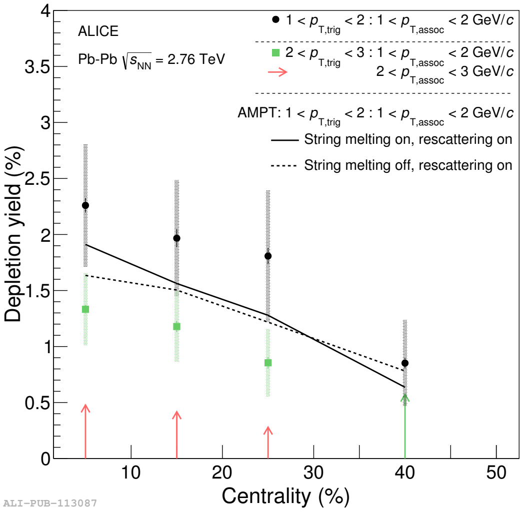
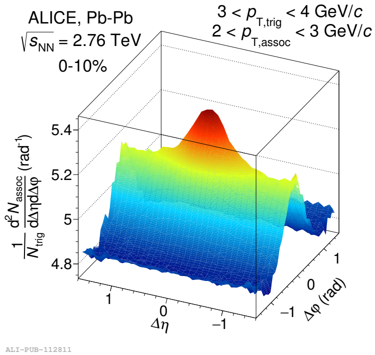


- Depletion yield $= \frac{\text{Fit}-\text{Data}}{\text{Total yield}}$ in %
- No depletion in higher p_{T}, peripheral or pp
- In AMPT almost independent of string melting
- AMPT is in agreement with data at lowest p_{T}
- At higher p_{T} no version shows depletion
- Similar depletion seen at $\sqrt{s_{NN}} = 5.02$ TeV $\rightarrow$ $\rightarrow$ quantification on-going

Summary

- Two-particle angular correlations are sensitive tools to study the QGP:
  - Jet-medium interactions
  - Collision dynamics
  - Shear viscosity
- Evolution of peak in number correlations towards low p_T and central events:
  - Small broadening in $\Delta\varphi$
  - Significant broadening in $\Delta\eta$
  - Depletion around $(\Delta\varphi, \Delta\eta) = (0, 0)$
- Evolution of peak in p_T correlations towards central events:
  - Narrowing in $\Delta\varphi$
  - Broadening of charge independent in $\Delta\eta$
  - Charge dependent in $\Delta\eta$ does not change
- Model comparisons
  - None of the models describe all measured quantities
  - Two-particle correlations are useful to refine the models



Thank you for your attention!

BACKUP

Further details of the analyses

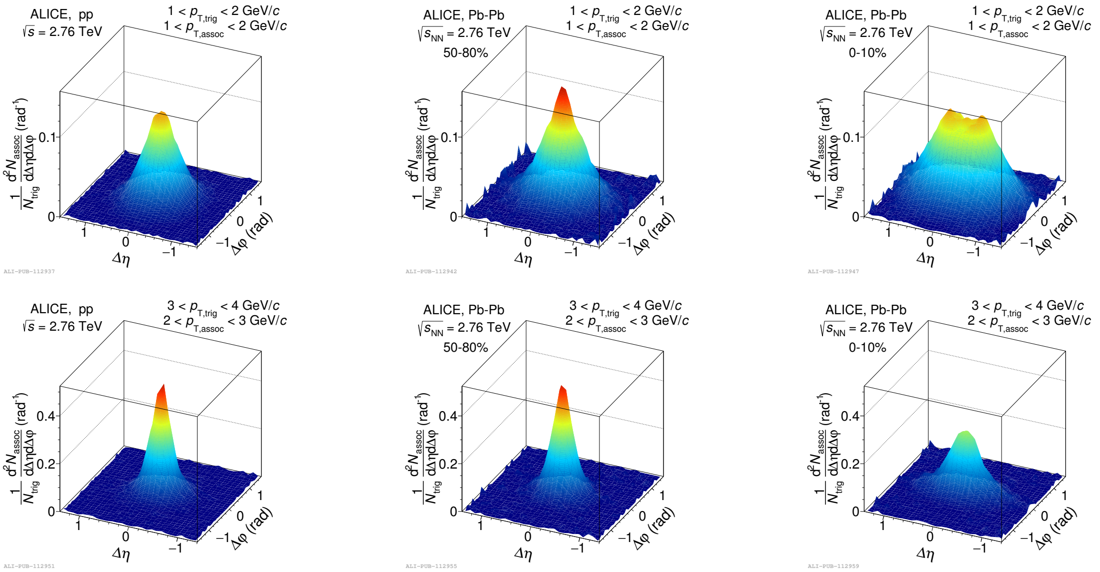
Number correlations

- 39M Pb–Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
- 50M Pb–Pb events at $\sqrt{s_{NN}} = 5.02$ TeV
- 30M pp events at $\sqrt{s} = 2.76$ TeV
- $|\eta| < 0.8$
- $|z_{\mathrm{vtx}}| < 7$ cm
- Selection criteria on decay products: pair excluded if
  - $m_{\mathrm{inv}} < 4$ MeV$/c^2$
  - $|m_{\mathrm{inv}} - m(\Lambda)| < 5$ MeV$/c^2$
  - $|m_{\mathrm{inv}} - m(K_s^0)| < 5$ MeV$/c^2$
- Selection criteria to remove two-track inefficiencies: $|\Delta\eta| > 0.02$ and $|\Delta\varphi^*| > 0.02$ rad
- Correction done to remove distortion arising from a dependence on η

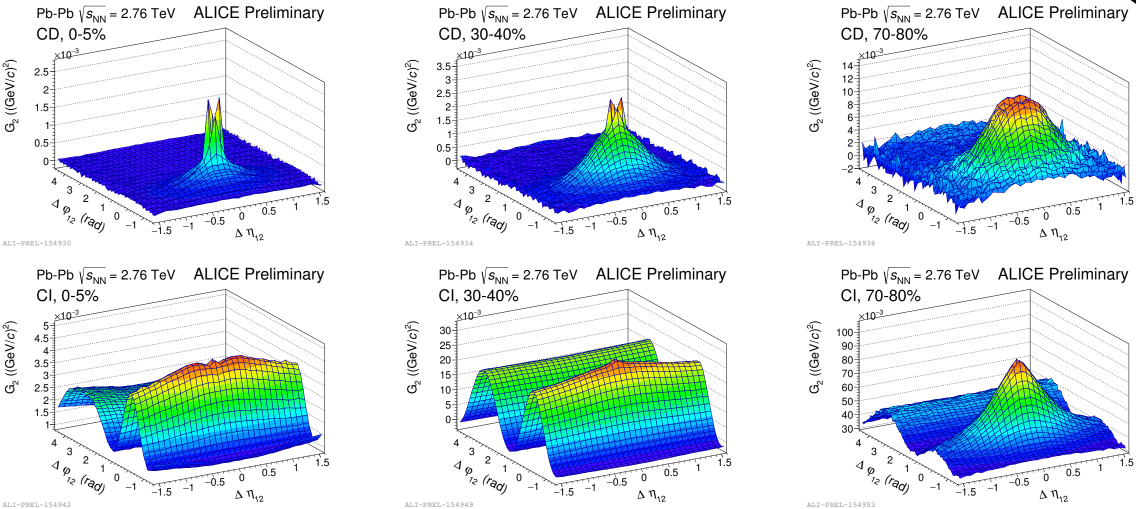
Momentum correlations

- 11M Pb–Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
- $|\eta| < 0.8$
- $|z_{\mathrm{vtx}}| < 7$ cm
- Electrons are rejected based on TPC d$E/$dx
- Statistical uncertainties based on sub-sample method

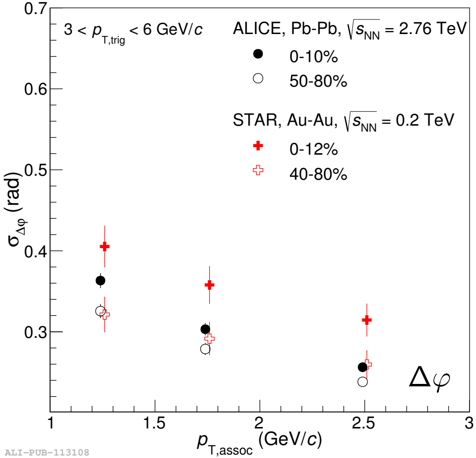
Evolution of the near-side peak shape in number correlations

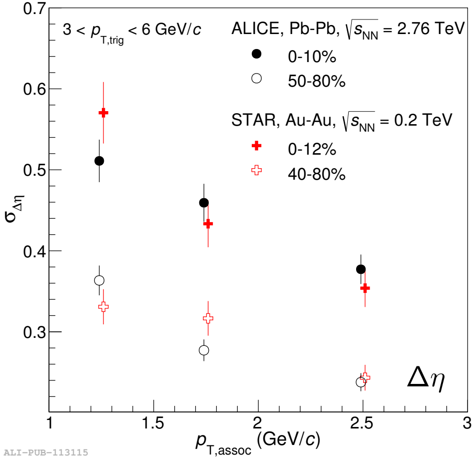


Evolution of the near-side peak shape in momentum correlations



Comparison of number correlations to the STAR experiment



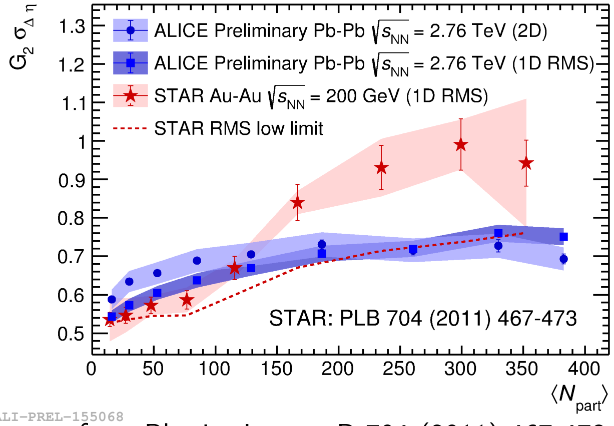


- STAR: $\sqrt{s_{NN}} = 200$ GeV, Au–Au collisions

  Taken from Phys.Rev. C85 (2012) 014903

- Results agree within 2σ in all bins
- Values slightly higher at STAR in the central bins in $\Delta\varphi$

Comparison of momentum correlations to the STAR experiment



- STAR points are from Physics Letters B 704 (2011) 467-473
- Values labeled 1D RMS are extracted with the same method as at STAR
- Different trend, but agree within the lower limit of STAR

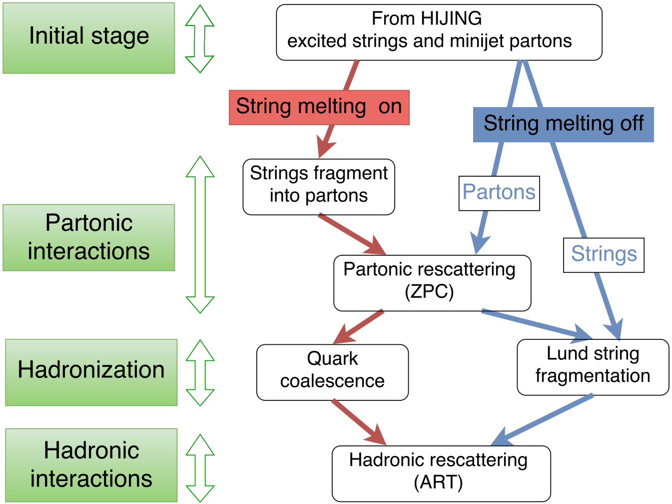
AMPT settings

- With string melting and with hadronic rescattering
  - Version v2.25t3
  - Parameter isoft = 4
  - Parameter ntmax = 150
- With string melting and without hadronic rescattering
  - Version v2.25t3
  - Parameter isoft = 4
  - Parameter ntmax = 3
- Without string melting and with hadronic rescattering
  - Version v1.25t3
  - Parameter isoft = 1
  - Parameter ntmax = 150

AMPT settings

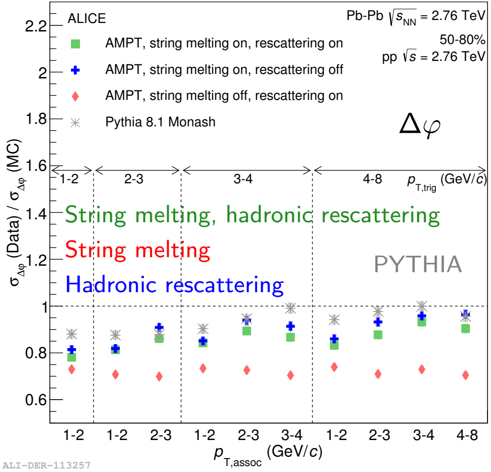
Settings:

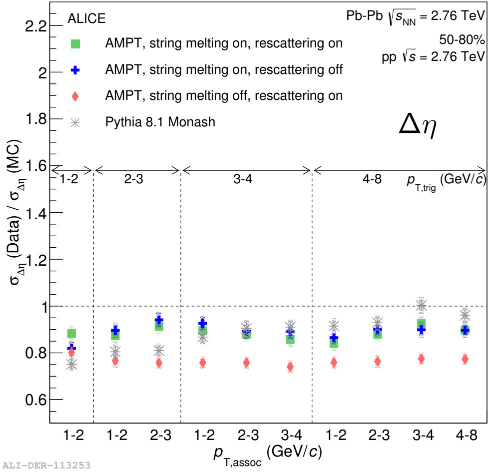
- string melting off, hadronic rescattering on
- string melting on, hadronic rescattering on
- string melting on, hadronic rescattering off



Comparison of number corr. to MC – absolute width in peripheral

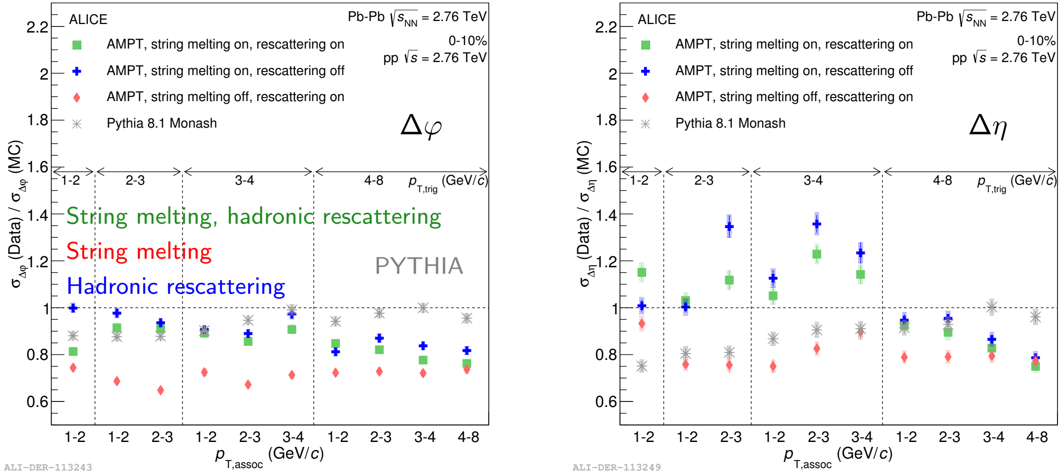
- Absolute width described by $\frac{\sigma_{\Delta\varphi}(\text{Data})}{\sigma_{\Delta\varphi}(\text{MC})}$, $\frac{\sigma_{\Delta\eta}(\text{Data})}{\sigma_{\Delta\eta}(\text{MC})}$





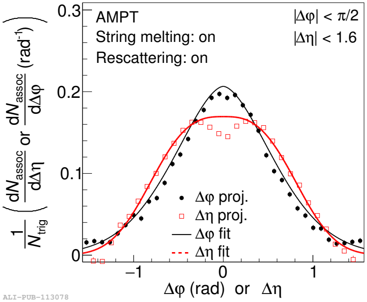
- None of the AMPT settings describe all p_{T} bins

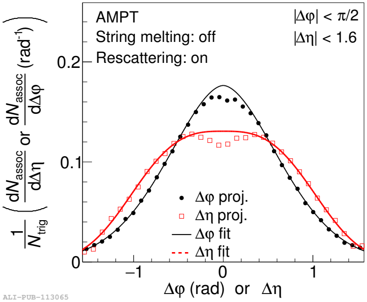
- Absolute width described by $\frac{\sigma_{\Delta\varphi}(\text{Data})}{\sigma_{\Delta\varphi}(\text{MC})}$, $\frac{\sigma_{\Delta\eta}(\text{Data})}{\sigma_{\Delta\eta}(\text{MC})}$

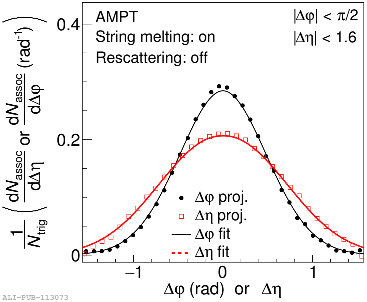


- None of the AMPT settings describe all p_{T} bins

Near-side depletion in number correlations in AMPT







- Generator level
- AMPT with hadronic rescattering on shows depletion independent of string melting

Summary of the comparison of the number correlations to AMPT

AMPT settings / Measurements	String melting & hadronic rescattering	String melting	Hadronic rescattering
Evolution of width	No	No	Yes
Absolute width	10%	10 – 15%	20 – 30%
Depletion	Yes	No	Yes

- With hadronic rescattering describes depletion and shape evolution
- Absolute width is not described better than 10%

Comparison of the number correlations to AMPT – explanation

- Are observed effects described by elliptic and/or radial flow?
- 0–10% fitted with Blast-wave fit to extract expansion velocity
  (π: $0.5 < p_{\mathrm{T}} < 1$ GeV/c, K: $0.2 < p_{\mathrm{T}} < 1.5$ GeV/c, p: $0.3 < p_{\mathrm{T}} < 2.0$ GeV/c)
- $v_2\{2\}$ was extracted with $0.2 < p_{\mathrm{T}} < 5$ GeV/c

Sample	β_{T}	$v_2\{2\}$
AMPT string melting and hadronic rescattering	0.442	0.0412 ± 0.0002
AMPT string melting	0.202	0.0389 ± 0.0002
AMPT hadronic rescattering	0.540	0.0330 ± 0.0002
Data*	0.649 ± 0.022	0.0364 ± 0.0003

* From Phys. Rev. C88 (2013) 044910 and Phys. Rev. Lett. 105 (2010) 252302

- With string melting or with hadronic rescattering describes $v_2\{2\}$
- β_{T} is lower for all AMPT cases than for data

Comparison of the number correlations to AMPT – explanation

- Are observed effects described by elliptic and/or radial flow?
- 0–10% fitted with Blast-wave fit to extract expansion velocity
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Closest $v_2\{2\}$ to data

- Only version with hadronic rescattering
  - has depletion
  - follows the centrality and p_{T} evolution of relative width

Comparison of the number correlations to AMPT – explanation

ALICE

- Are observed effects described by elliptic and/or radial flow?
- 0–10% fitted with Blast-wave fit to extract expansion velocity
  (π: $0.5 < p_{\mathrm{T}} < 1$ GeV/c, K: $0.2 < p_{\mathrm{T}} < 1.5$ GeV/c, p: $0.3 < p_{\mathrm{T}} < 2.0$ GeV/c)
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Closest β_{T} to data

- Has depletion
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$\Downarrow$

- Large β_{T} is needed to describe depletion and evolution
- Likely cause of the effects is radial flow