Two-particle angular correlations in Pb–Pb collisions from ALICE

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on behalf of the ALICE Collaboration

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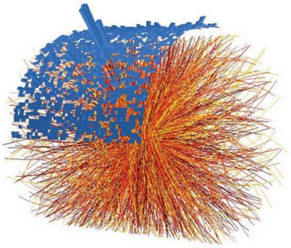
Physics motivation

- In heavy-ion collisions high p_T partons are produced
- They propagate through the medium and lose energy
- They hadronize into jets
- Goal: study interaction of jets with medium
- Angular correlation measurements
  - Analysis done on a statistical basis
  - Subtraction of large fluctuating background possible
  - Lower p_T measurements possible
  - Complementary tool to jet reconstruction

ALICE event display with jet



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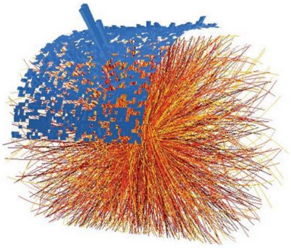
  - Analysis done on a statistical basis
  - Subtraction of large fluctuating background possible
  - Lower p_T measurements possible
  - Complementary tool to jet reconstruction
- Interactions can change the jet fragmentation pattern
  - The p_T distribution of fragments
  - Their angular distribution
- Modification of the jet-peak has been seen by STAR

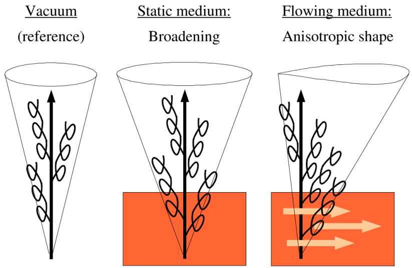
STAR Collaboration, Phys. Rev. C85 (2012) 014903

ALICE event display with jet



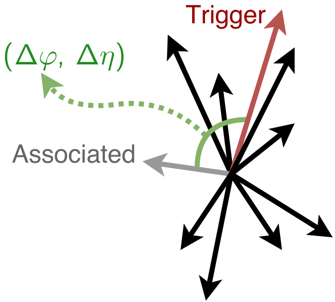
Theoretical aspects

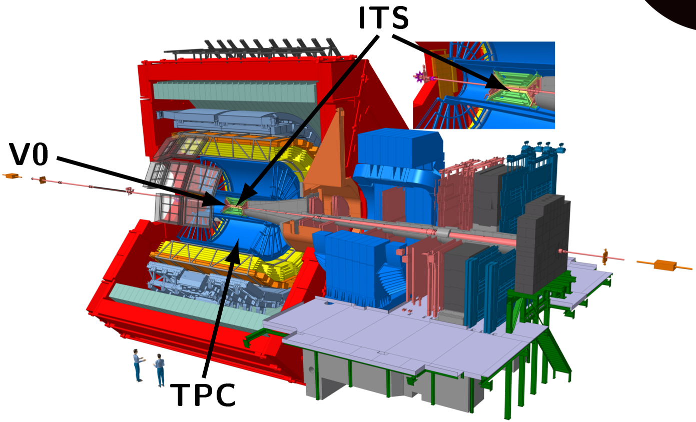
- Larger width in $\Delta\eta$ than in $\Delta\varphi$
  - Interaction with longitudinal flowing medium
    Romatschke, Phys. Rev. C75 (2007) 014901
    Armesto, Salgado, Wiedemann, Phys. Rev. C72 (2005) 064910
    Armesto, Salgado, Wiedemann, PRL 93,242301 (2004)



  - Interaction with turbulent color fields
    Majumder, Muller, Bass, Phys. Rev. Lett. 99 (2007) 042301
- Double hump-shape in the energy distribution of the jet
  Armesto, Salgado, Wiedemann – PRL 93,242301 (2004)

- Pb–Pb and pp data
- $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and 5.02 TeV
- Trigger and associated particle
- Azimuthal ($\Delta\varphi$) difference
- Pseudorapidity ($\Delta\eta$) difference



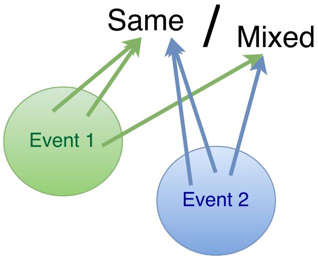


Two-particle correlations – definitions

- 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:
  - $M(\Delta\eta,\Delta\varphi)$
  - Correlation histogram is calculated in both same and mixed event
  - Division of the two removes detector effects and inefficiencies
- p_{T} bins between 1 GeV/c and 8 GeV/c
- All charged particles



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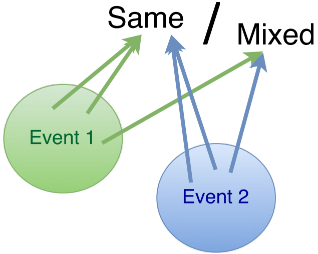
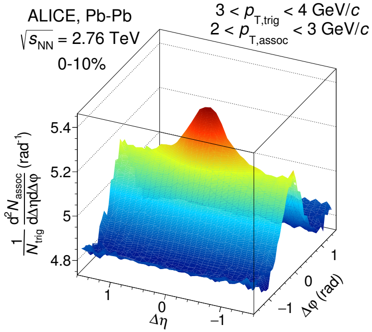
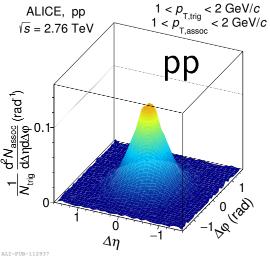
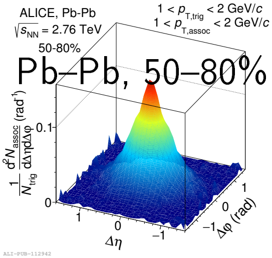




Evolution of the near-side peak shape





- Histograms background subtracted for illustration
- Shape is similar in pp and peripheral collisions

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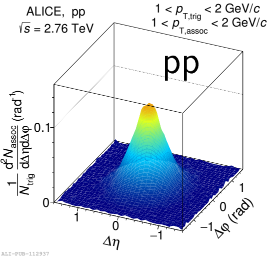

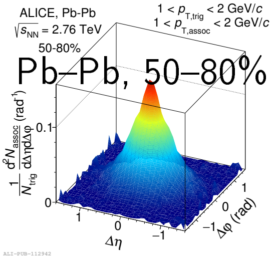

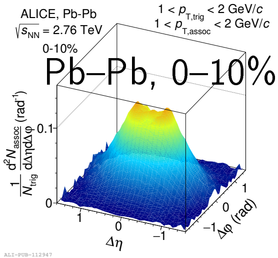

- Histograms background subtracted for illustration
- Peak: broader and asymmetric in central collisions

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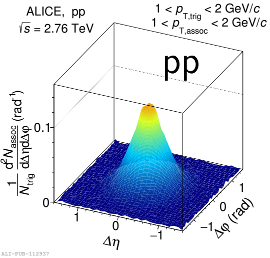
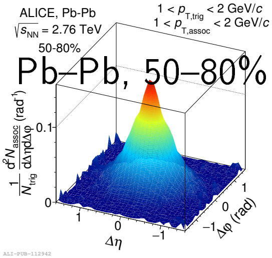
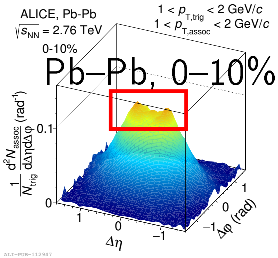
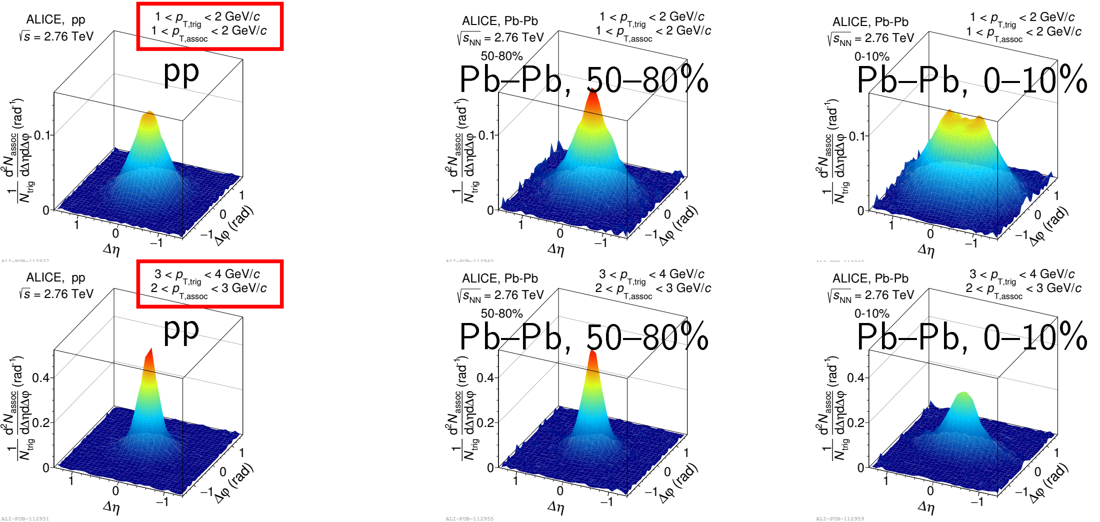






- Histograms background subtracted for illustration
- Depletion around $(\Delta\varphi, \Delta\eta) = (0, 0)$ in central collisions at low p_{T}

Evolution of the near-side peak shape



- Histograms background subtracted for illustration
- Peak is narrower at high p_{T}

Extraction of the near-side peak width

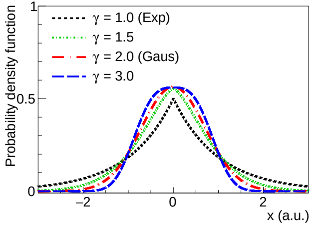
- The near-side is fitted to characterize its shape evolution
- Fit function: background + Generalized Gaussian
  - Background:

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

  - Generalized Gaussian:

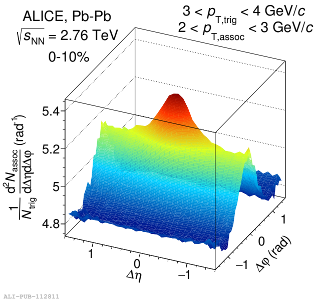
$$N \times e^{-\left|\frac{d\varphi}{w_\varphi}\right|^{\gamma_\varphi} - \left|\frac{d\eta}{w_\eta}\right|^{\gamma_\eta}} \qquad \Longrightarrow N = C_2 \times \frac{\gamma_\varphi \gamma_\eta}{4 w_\varphi w_\eta \Gamma\left(\frac{1}{\gamma_\varphi}\right)\Gamma\left(\frac{1}{\gamma_\eta}\right)}$$

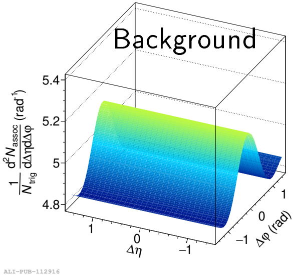
$\gamma = 1$: Exponential
$\gamma = 2$: Gaussian

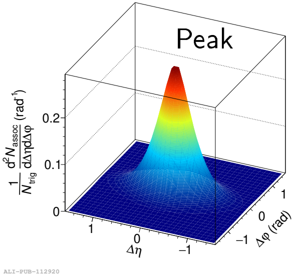


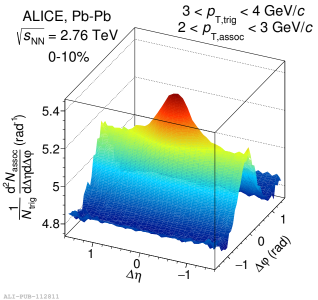
- Characterize peak by variance of generalized Gaussian: $\sigma^2 = \frac{w^2\Gamma(3/\gamma)}{\Gamma(1/\gamma)}$
- No attempt to give physical meaning to parameters of the generalized Gaussian
- Some bins around $(\Delta\varphi, \Delta\eta) = (0, 0)$ are excluded from the fit

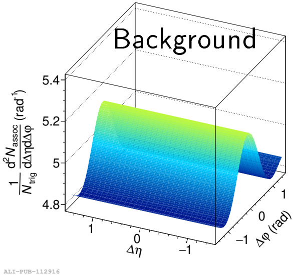
Fitting illustration

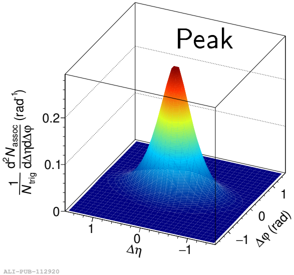


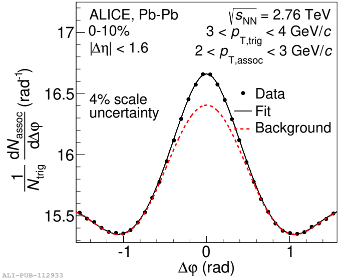


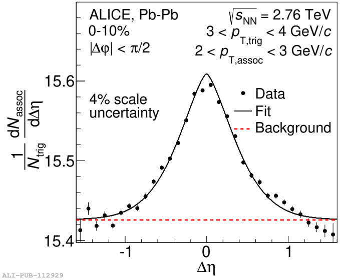




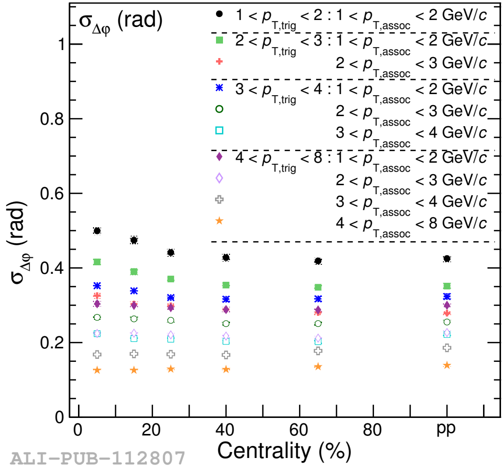








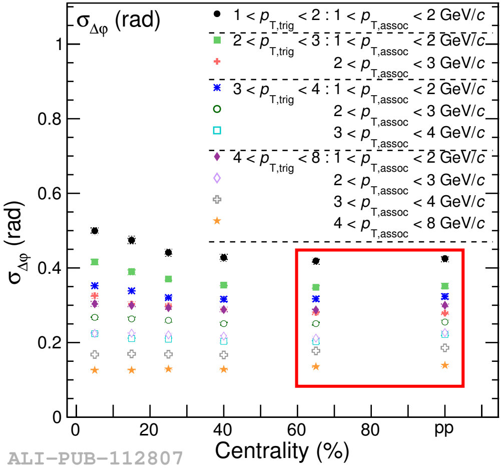
- Small signal over background ratio
- Fit describes the data very well



- Ordering of the width according to p_T

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

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



- 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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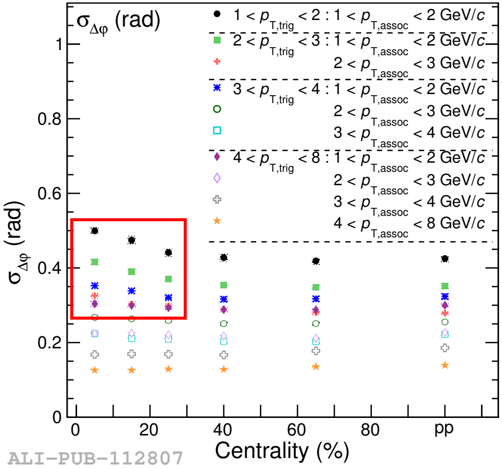

- Ordering of the width according to p_{T}
- Width in $\Delta\varphi$ in 50–80% is equal to width in pp
- Small increase at low p_{T} in $\Delta\varphi$ with centrality

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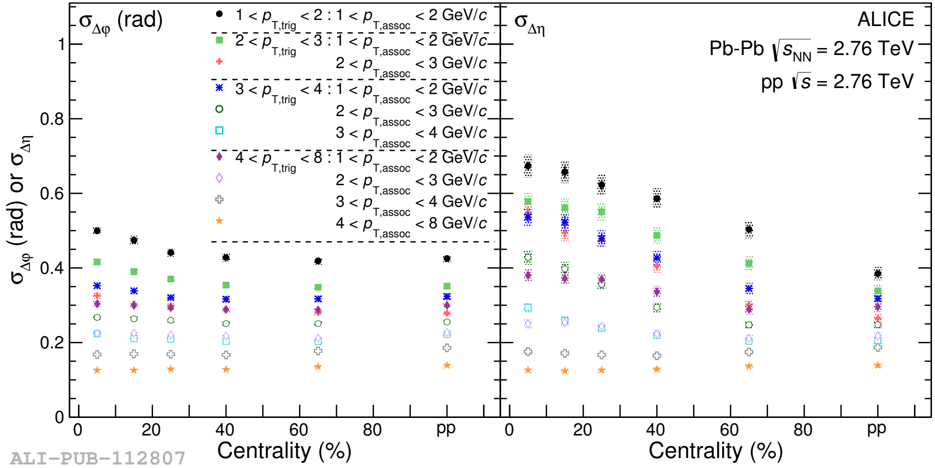

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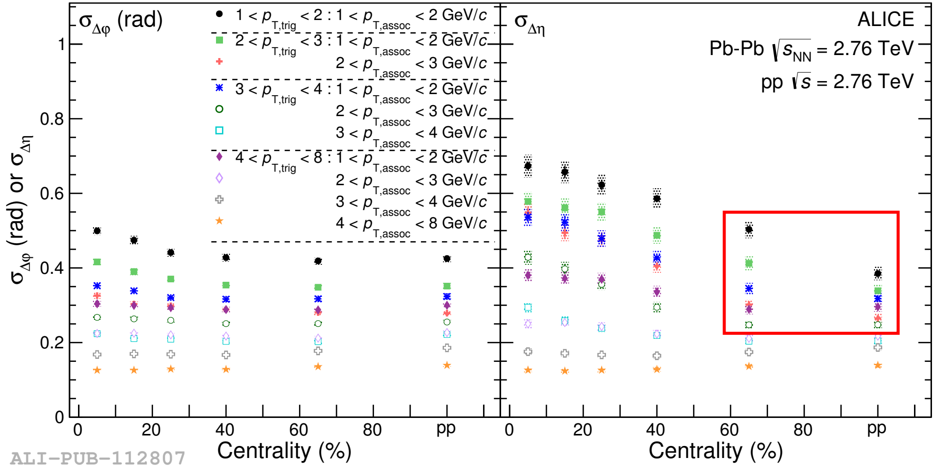

- Ordering of the width according to p_T
- Width in $\Delta\eta$ in 50–80% is already larger than in pp

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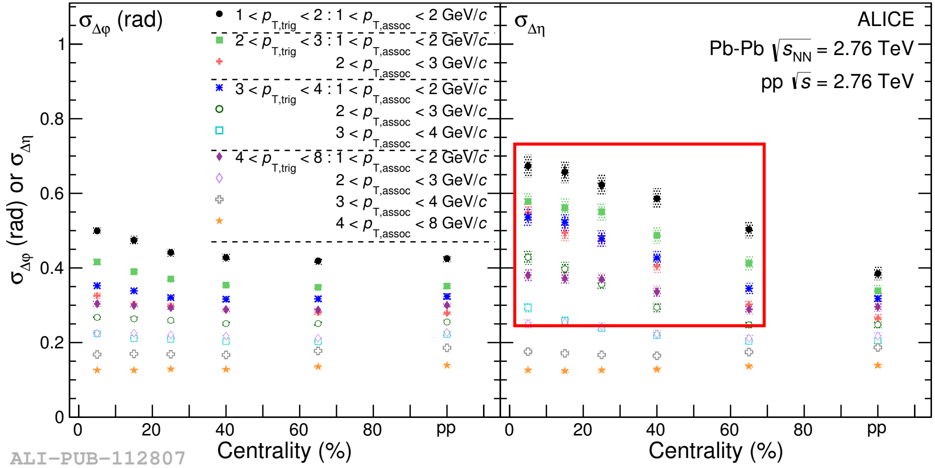

- Ordering of the width according to p_T
- Width in $\Delta\eta$ in 50–80% is already larger than in pp
- Very pronounced increase at low p_T in $\Delta\eta$

Phys. Rev. Lett. 119, 102301 (2017)
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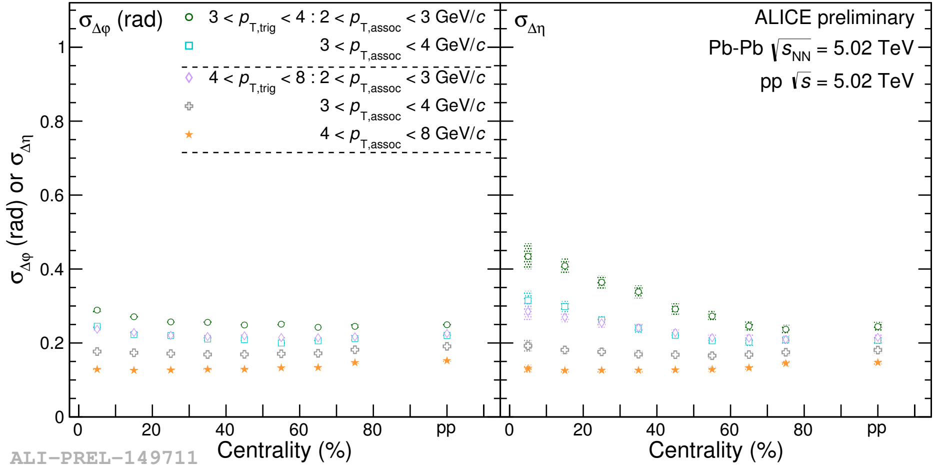
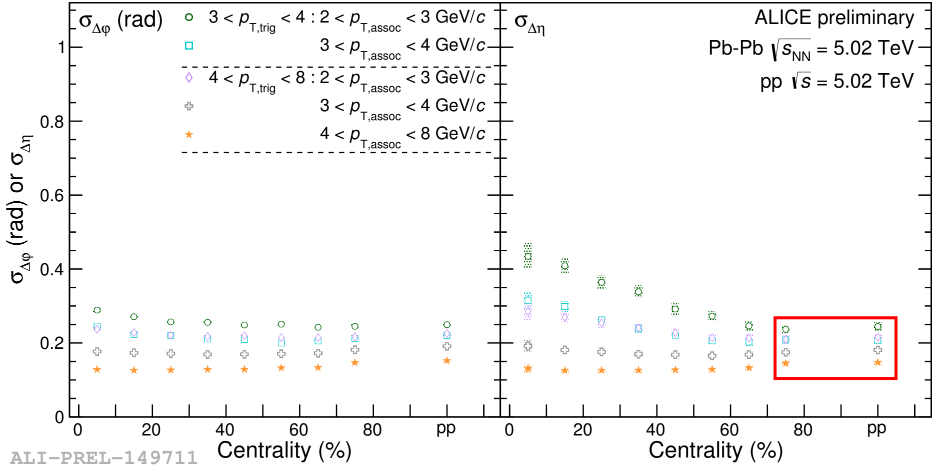
Width of the peak at $\sqrt{s_{NN}} = 5.02$ TeV





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

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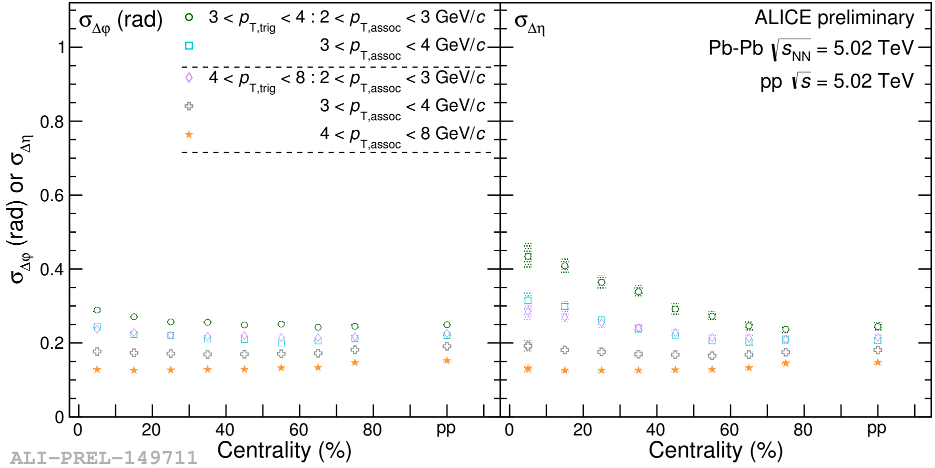
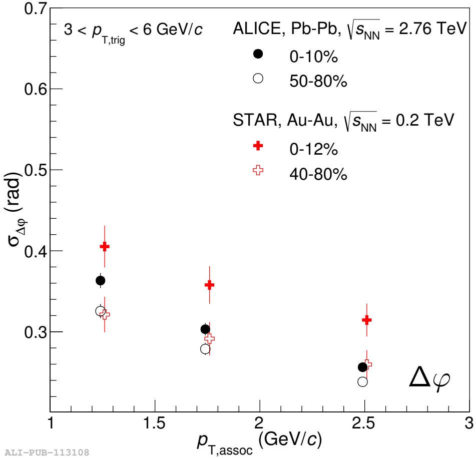
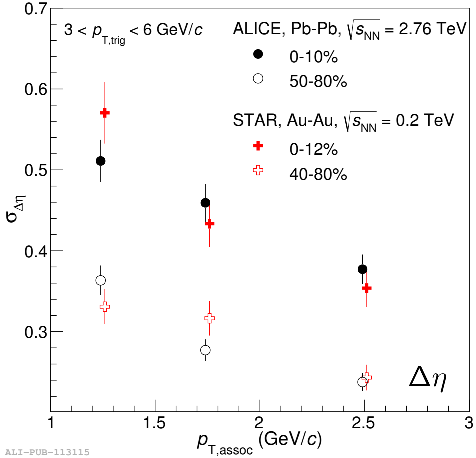


- Peak width in peripheral Pb-Pb equals to width in pp collisions
- Similar broadening towards central events as at $\sqrt{s_{NN}} = 2.76$ TeV

Comparison to the STAR experiment





- STAR: $\sqrt{s_{NN}} = 200$ GeV, Au–Au collisions
  Taken from Phys.Rev. C85 (2012) 014903
- ALICE: $\sqrt{s_{NN}} = 2.76$ TeV, Pb–Pb collisions

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

Comparison to models

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

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

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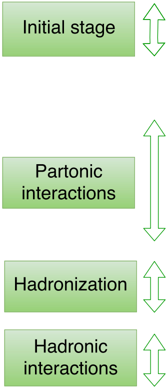

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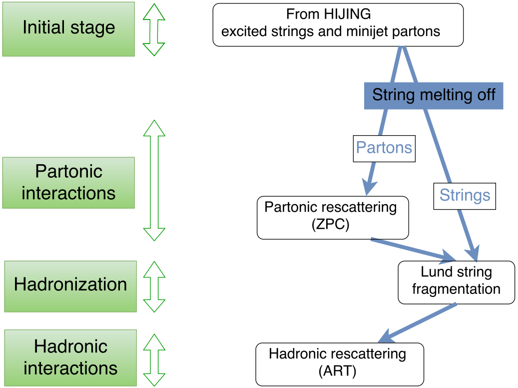

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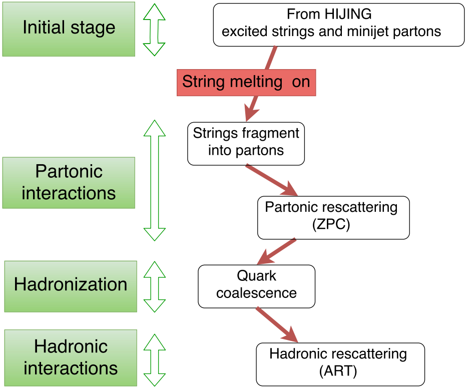

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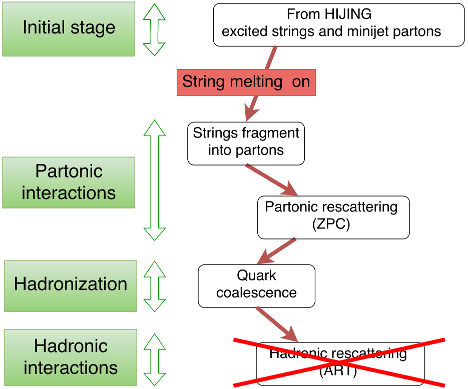

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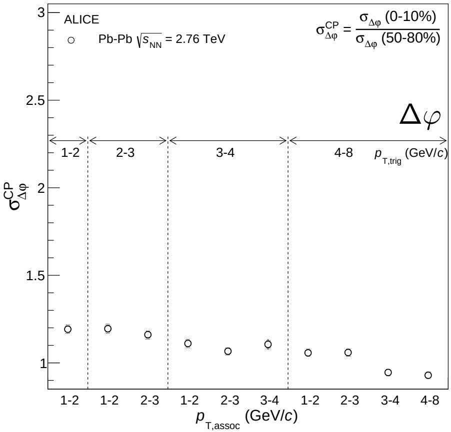
Broadening of the near-side peak

- 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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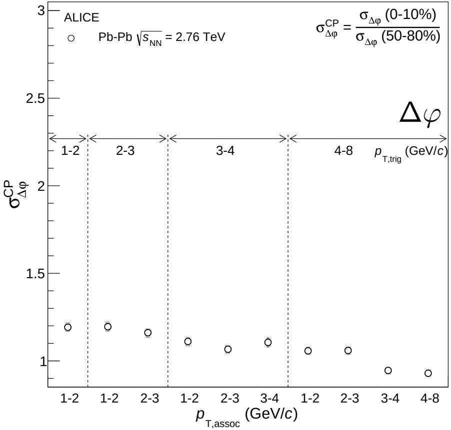

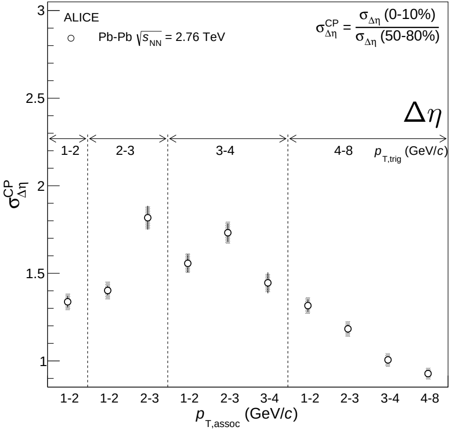

- Moderate broadening in $\Delta\varphi$
- Much larger broadening in $\Delta\eta$

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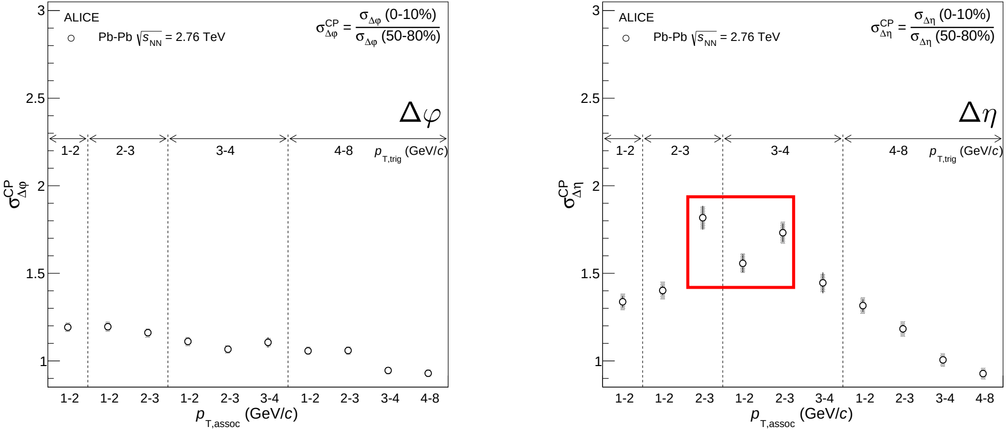

- Moderate broadening in $\Delta\varphi$
- Much larger broadening in $\Delta\eta$
- Broadening most significant at intermediate p_{T}

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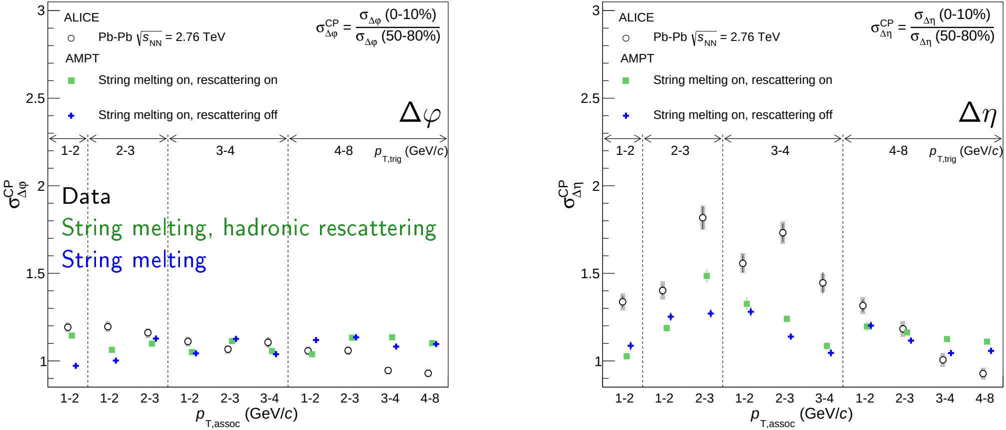

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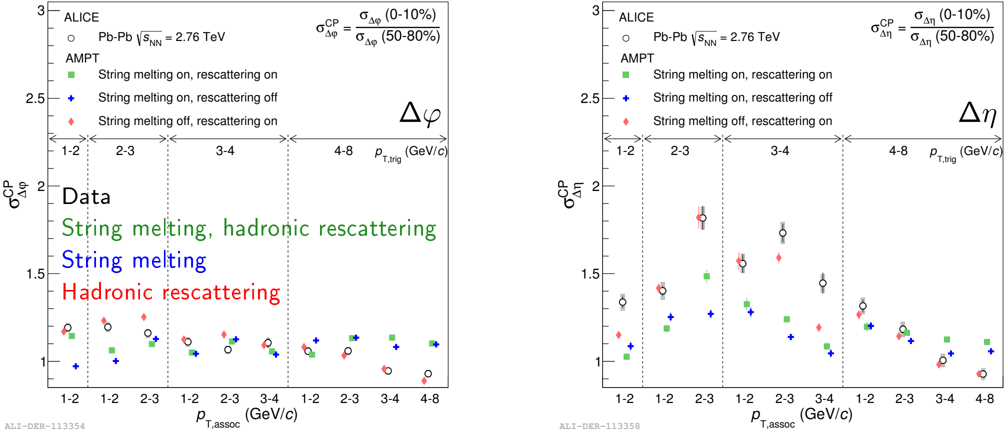

- Small difference between models in $\Delta\varphi$, $\Delta\eta$ more constraining
- String melting off, hadronic rescattering on describes data best

Phys. Rev. Lett. 119, 102301 (2017)
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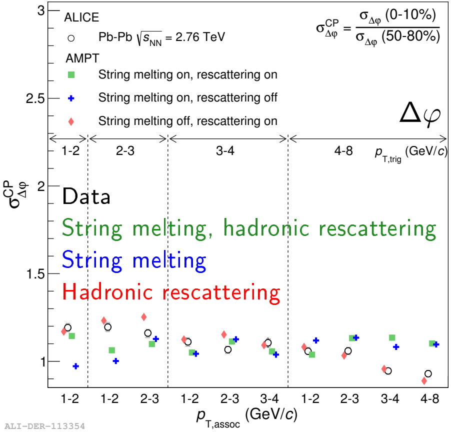
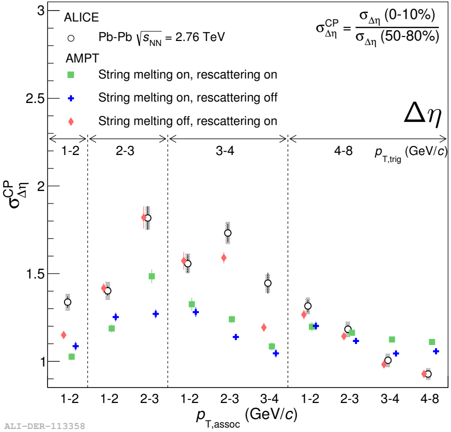
Broadening of the near-side peak

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





- 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)

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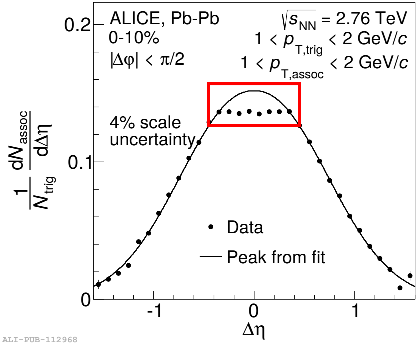
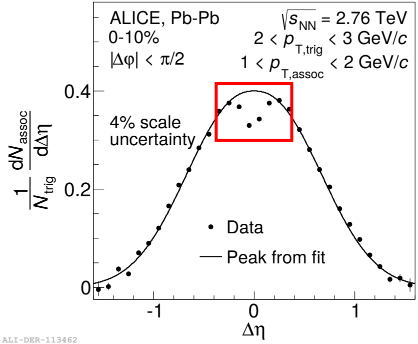
- In central collisions at low p_{T}: depletion around $(\Delta\varphi, \Delta\eta) = (0, 0)$
- Per trigger yield is corrected for two-track inefficiencies
- The area of the depletion is excluded from the fit

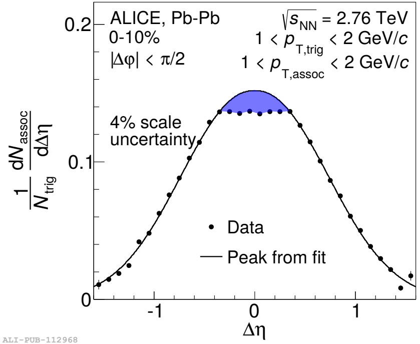


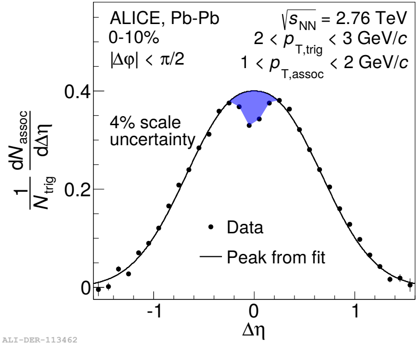


Near-side depletion

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

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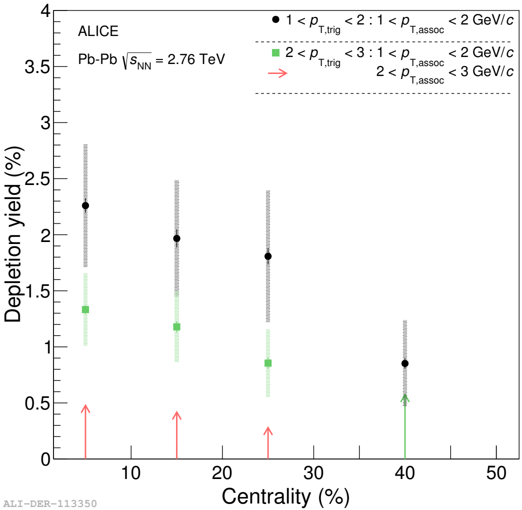

- Depletion yield $= \frac{\text{Fit}-\text{Data}}{\text{Total yield}}$ in %
- No depletion in higher p_{T}, peripheral or pp

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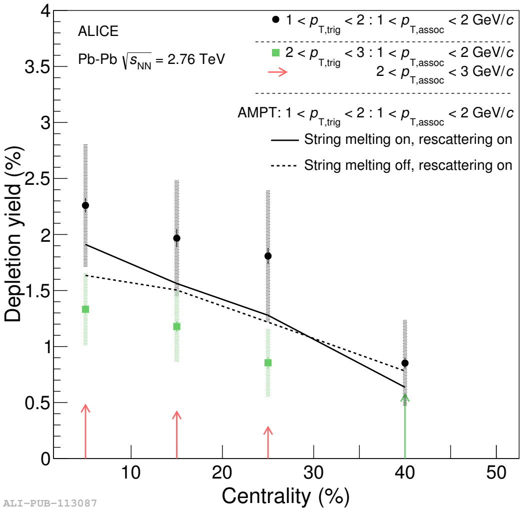
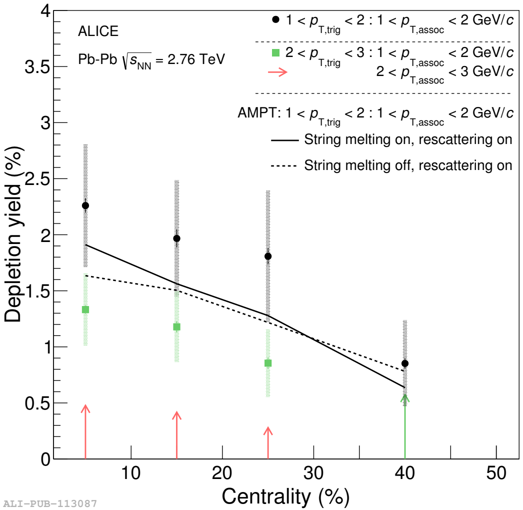


- Depletion yield $= \frac{\text{Fit}-\text{Data}}{\text{Total yield}}$ in %
- No depletion in higher p_{T}, peripheral or pp
- In AMPT almost independent of string melting
- AMPT is in agreement with data at lowest p_{T}
- At higher p_{T} no version shows depletion

Near-side depletion

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



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- 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 of the comparison 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 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: $0.5 < p_T < 1$ GeV/c, K: $0.2 < p_T < 1.5$ GeV/c, p: $0.3 < p_T < 2.0$ GeV/c)
- $v_2\{2\}$ was extracted with $0.2 < p_T < 5$ 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 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)
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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 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)
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Closest β_{T} to data

- Has depletion
- Follows the centrality and p_{T} evolution of relative width

Comparison to AMPT – explanation

- Are observed effects described by elliptic and/or radial flow?
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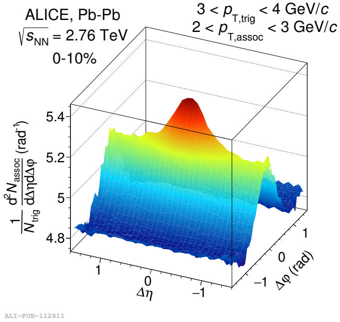
$\Downarrow$

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



- Evolution of near-side peak shape towards low p_T and central collisions:
  - Small broadening in $\Delta\varphi$
  - Significant broadening in $\Delta\eta$
  - Depletion around $(\Delta\varphi, \Delta\eta) = (0, 0)$
- Comparison to AMPT:
  - None of the AMPT settings describe the absolute width
  - With only hadronic rescattering describes the evolution of the peak
  - With hadronic rescattering describes depletion, independent of string melting
- Interpretation:
  - Strong longitudinal flow $\Rightarrow$ longitudinal broadening
  - Driving factor for depletion and broadening is radial flow
  - Depletion and broadening caused by interplay of jets and collective medium

Thank you for your attention!

BACKUP

Further details of the analysis

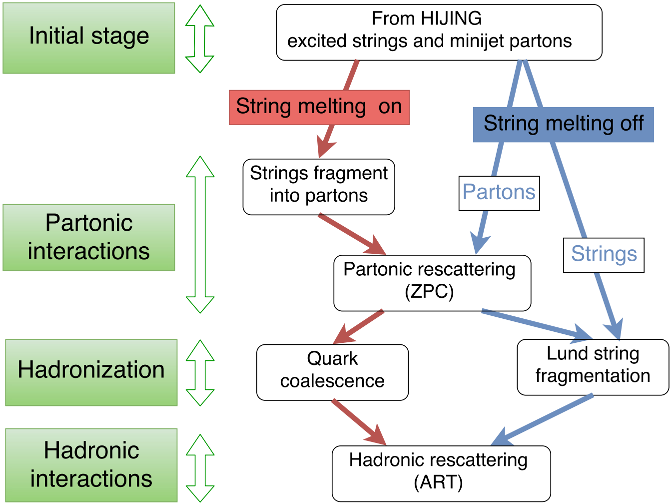
- 39M Pb–Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
- 50M Pb–Pb events at $\sqrt{s_{NN}} = 5.02$ TeV
- 30M pp events at $\sqrt{s} = 2.76$ TeV
- $|\eta| < 0.8$
- $|z_{\mathrm{vtx}}| < 7$ cm
- Selection criteria on decay products: pair excluded if
  - $m_{\mathrm{inv}} < 4$ MeV$/c^2$
  - $|m_{\mathrm{inv}} - m(\Lambda)| < 5$ MeV$/c^2$
  - $|m_{\mathrm{inv}} - m(K^0_s)| < 5$ 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

AMPT settings

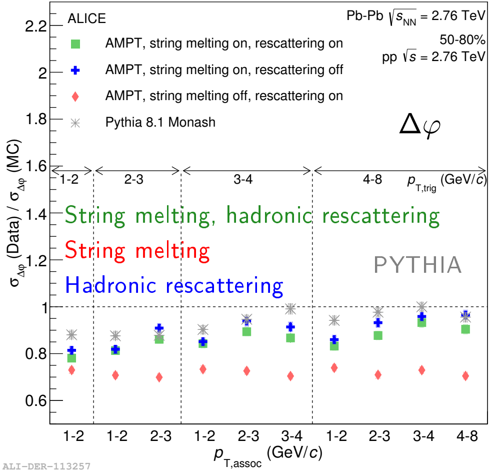
- With string melting and with hadronic rescattering
  - Version v2.25t3
  - Parameter isoft = 4
  - Parameter ntmax = 150
- With string melting and without hadronic rescattering
  - Version v2.25t3
  - Parameter isoft = 4
  - Parameter ntmax = 3
- Without string melting and with hadronic rescattering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

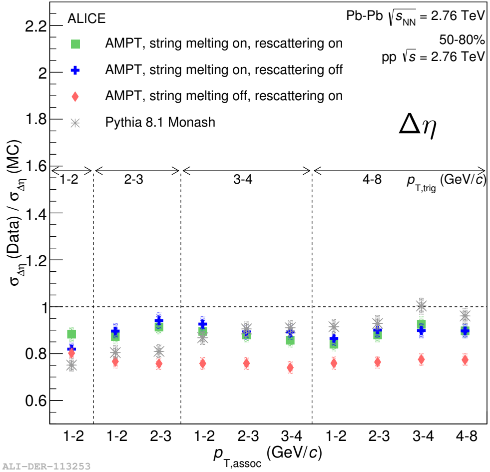
Settings:

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



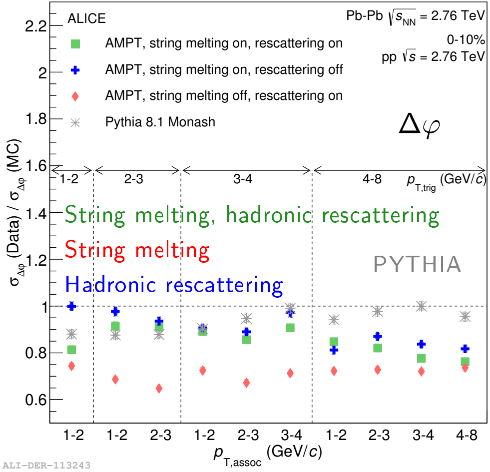
- Absolute width described by $\frac{\sigma_{\Delta\varphi}(\text{Data})}{\sigma_{\Delta\varphi}(\text{MC})}$, $\frac{\sigma_{\Delta\eta}(\text{Data})}{\sigma_{\Delta\eta}(\text{MC})}$

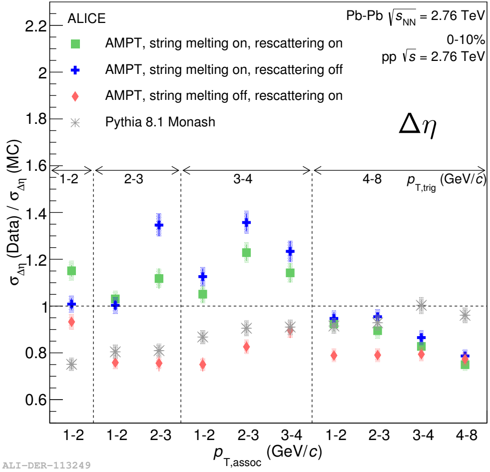




- None of the AMPT settings describe all p_T bins

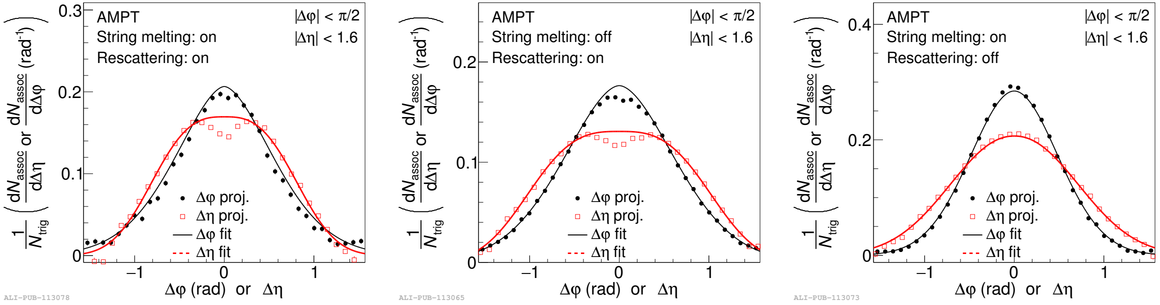
- Absolute width described by $\frac{\sigma_{\Delta\varphi}(\mathrm{Data})}{\sigma_{\Delta\varphi}(\mathrm{MC})}$, $\frac{\sigma_{\Delta\eta}(\mathrm{Data})}{\sigma_{\Delta\eta}(\mathrm{MC})}$





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

Near-side depletion in AMPT



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