Near-side jet peak broadening in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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on behalf of the ALICE Collaboration

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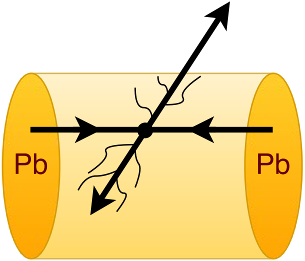
arXiv:1609.06643
arXiv:1609.06667

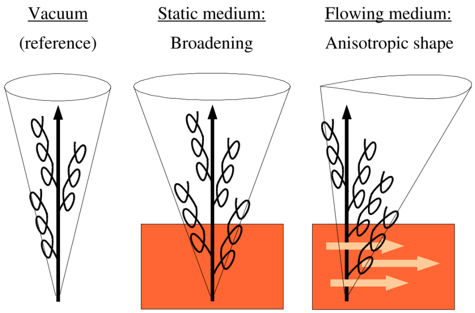
Physics motivation

- Goal: study interaction of jets with the medium
- Angular correlation measurements
  - Analysis done on a statistical basis
  - Subtraction of large fluctuating background possible
  - Low p_{T} measurement possible
  - Complementary tool to jet reconstruction
- Interactions would appear as modification of the near-side peak
- Modification of the jet-peak has been seen by STAR
  STAR Collaboration, Phys. Rev. C85 (2012) 014903



Theoretical aspects

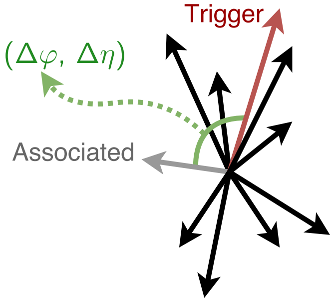
- Larger width in $\Delta\eta$ than in $\Delta\varphi$
  - Interaction with longitudinal flowing medium
    Romatschke, Phys. Rev. C75 (2007) 014901
    Armesto, Salgado, Wiedemann, Phys. Rev. C72 (2005) 064910
    Armesto, Salgado, Wiedemann, PRL 93,242301 (2004)

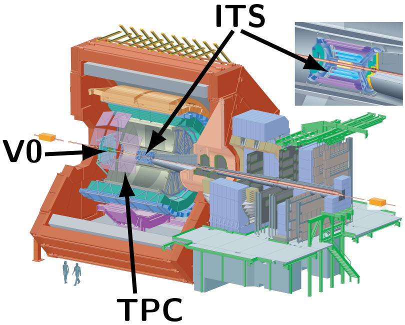


  - Interaction with turbulent color fields
    Majumder, Muller, Bass, Phys. Rev. Lett. 99 (2007) 042301
- Double hump-shape in the energy distribution of the jet
  Armesto, Salgado, Wiedemann – PRL 93,242301 (2004)

- Pb–Pb and pp data at $\sqrt{s_{NN}} = 2.76$ TeV
- Trigger and associated particle taken in certain p_{T} window
- Associated yield per trigger:

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





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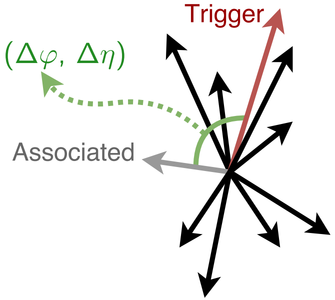
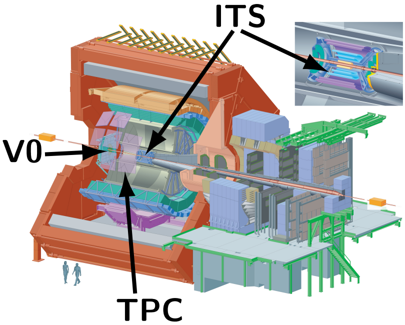
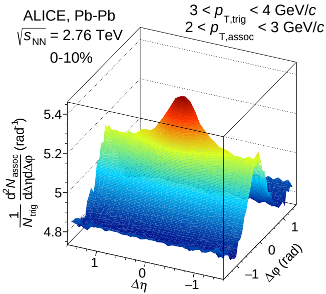
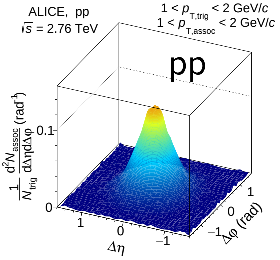
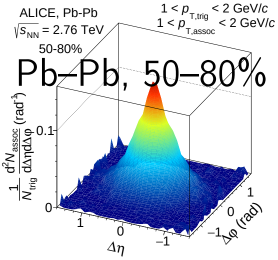




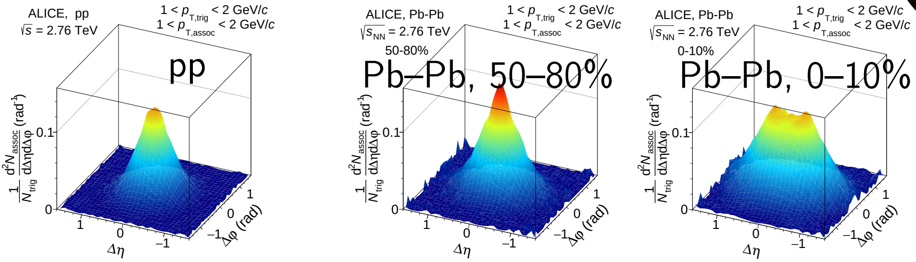


Evolution of the near-side peak shape



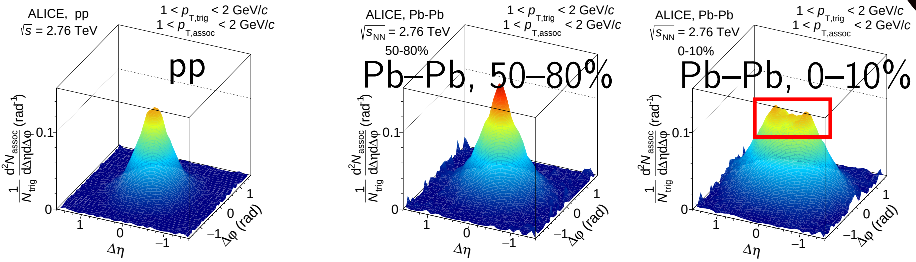


- Histograms background subtracted for illustration
- Shape is similar in pp and peripheral collisions



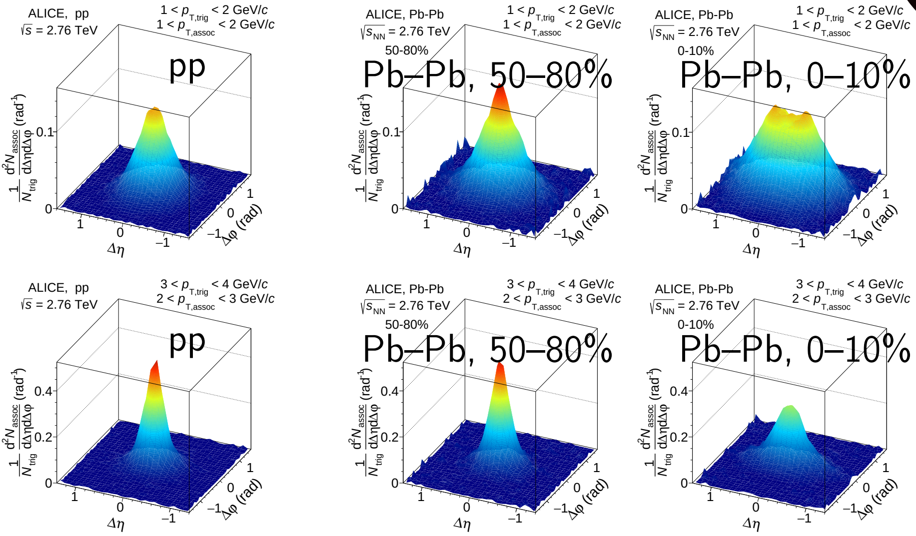
- Histograms background subtracted for illustration
- Peak: broader and asymmetric in central collisions

Evolution of the near-side peak shape



- 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

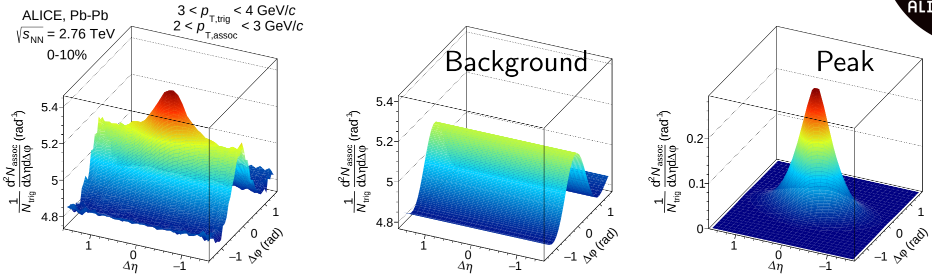


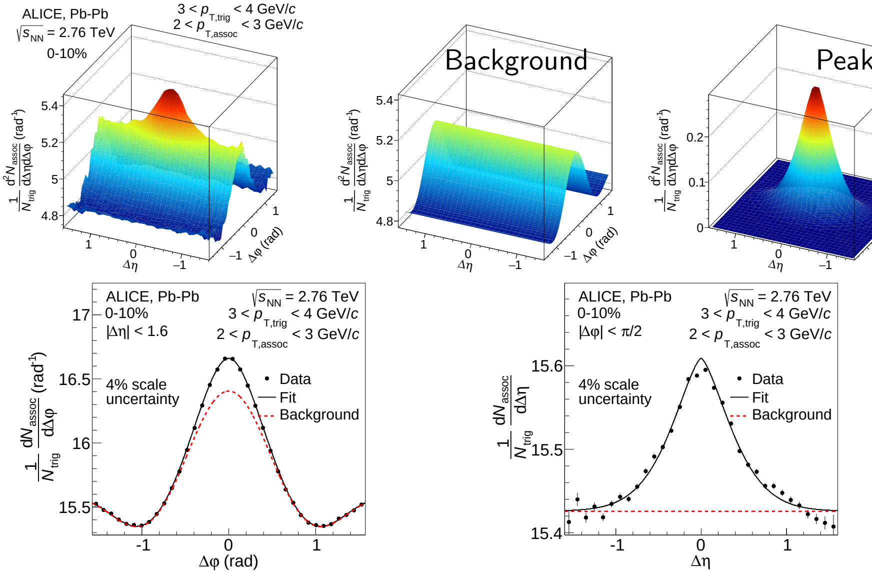
- Histograms background subtracted for illustration
- Peak is narrower at high p_T

Fitting technique

- The near-side is fitted to characterize its shape evolution
- Fit function: background + Generalized Gaussian
  - Background:
    $C_1 + \sum_{n=2}^{4} 2V_n \cos(n\Delta\varphi)$
  - Generalized Gaussian:
    $$N \times e^{-\left|\frac{d\varphi}{w_\varphi}\right|^{\gamma_\varphi} - \left|\frac{d\eta}{w_\eta}\right|^{\gamma_\eta}} \quad \Longrightarrow N = C_2 \times \frac{\gamma_\varphi \gamma_\eta}{4 w_\varphi w_\eta \Gamma\left(\frac{1}{\gamma_\varphi}\right)\Gamma\left(\frac{1}{\gamma_\eta}\right)}$$
    $\gamma = 1$: 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

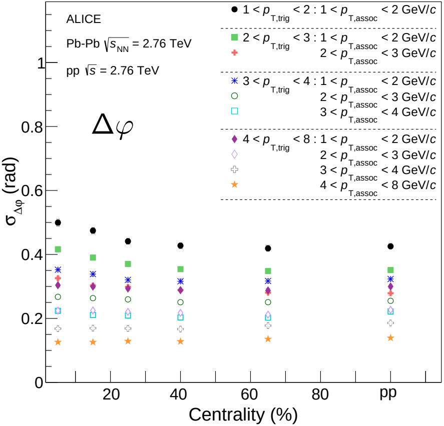




- Small signal over background ratio
- Fit describes the data very well

Width of the near-side peak

- Characterize peak by the variance of the fit: $\sigma^2 = \frac{w^2\Gamma(3/\gamma)}{\Gamma(1/\gamma)}$



- Ordering of the width according to p_{T}

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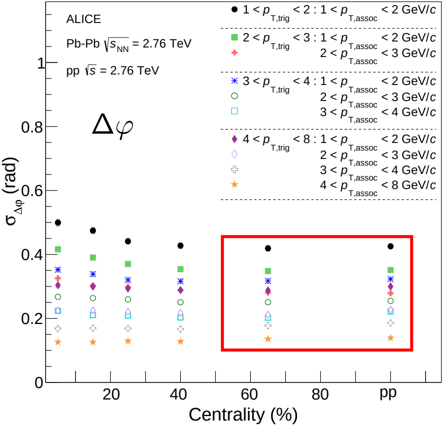

- Ordering of the width according to p_{T}
- Width in $\Delta\varphi$ in 50–80% is equal to width in pp

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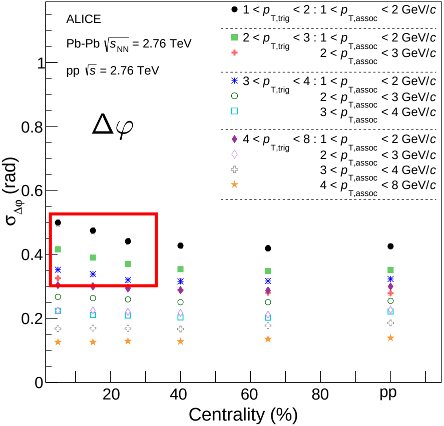

- Ordering of the width according to p_{T}
- Width in $\Delta\varphi$ in 50–80% is equal to width in pp
- Small increase at low p_{T} in $\Delta\varphi$ with centrality

Width of the near-side peak

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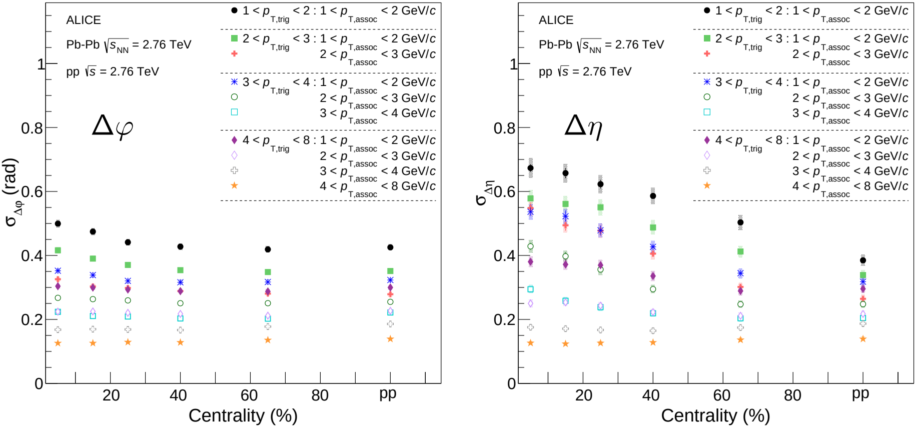

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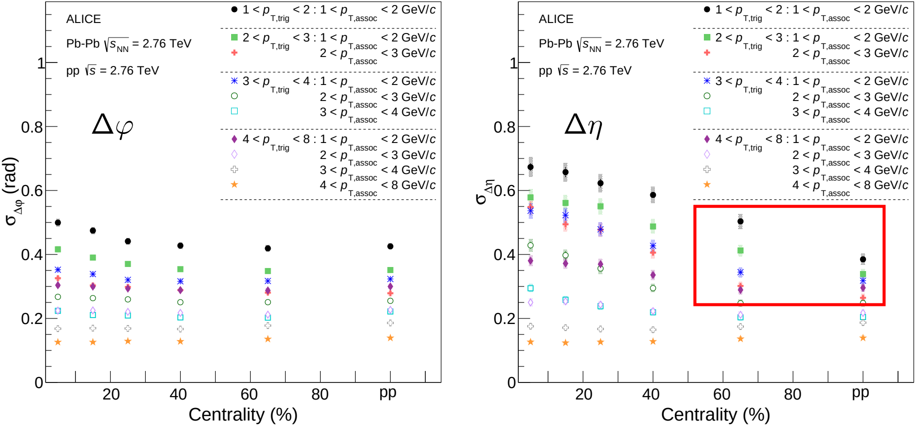

- Ordering of the width according to p_T
- Width in $\Delta\eta$ in 50–80% is already larger than in pp

Width of the near-side peak

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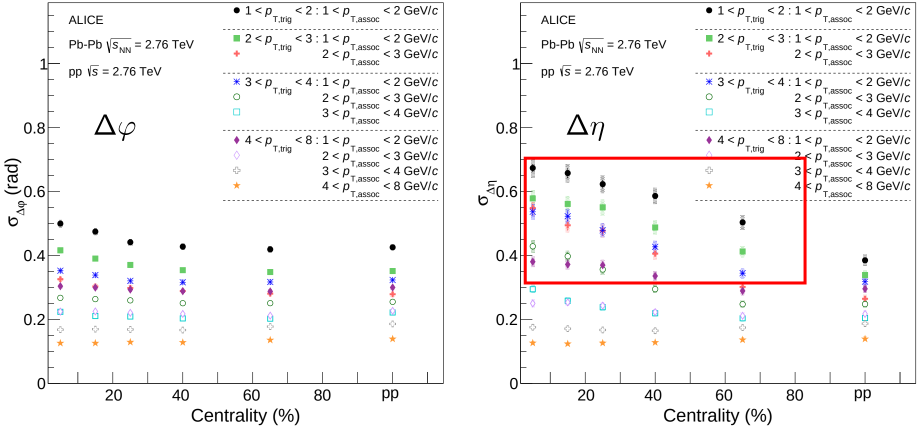

- Ordering of the width according to p_T
- Width in $\Delta\eta$ in 50–80% is already larger than in pp
- Very pronounced increase at low p_T in $\Delta\eta$

Comparison to models

- Study if interplay of flow and jets could cause the observed effects
- AMPT (**A** **M**ulti-**P**hase **T**ransport model) [1]
  - Addresses non-equilibrium many-body dynamics
  - Has collective effects through partonic and hadronic interactions
  - Large longitudinal flow in AMPT $\Rightarrow$ longitudinal broadening [2]
  - Different settings available to study the origin and the effect of flow

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

[2] G. L. Ma, S. Zhang, Y. G. Ma, X. Z. Cai, J. H. Chen, and C. Zhong, Eur. Phys. J. C57 (2008) 589–593

AMPT

Settings:

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

Initial stage

Partonic interactions

Hadronization

Hadronic interactions

AMPT

Settings:

- string melting off, hadronic rescattering on
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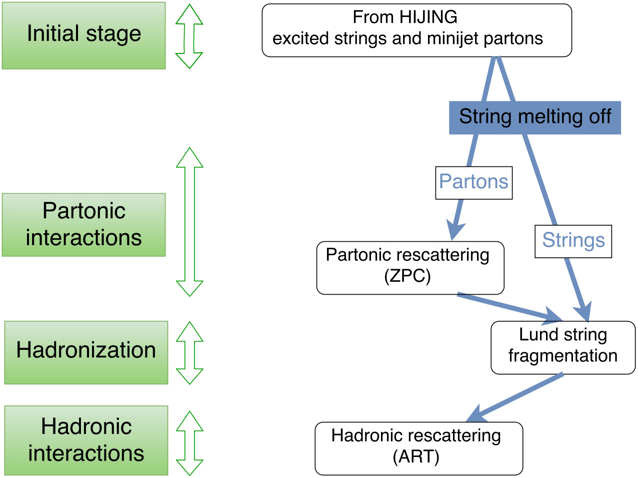

AMPT

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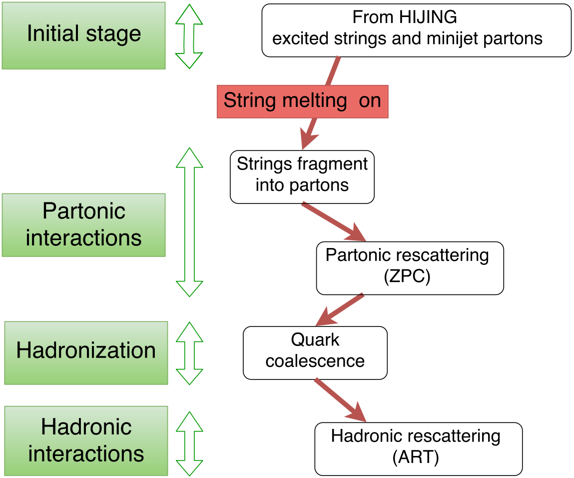

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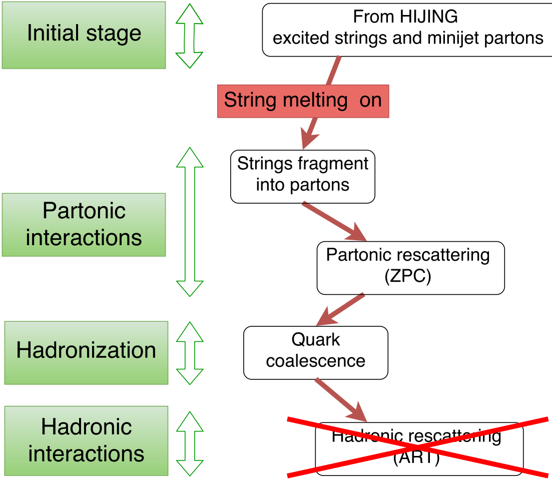
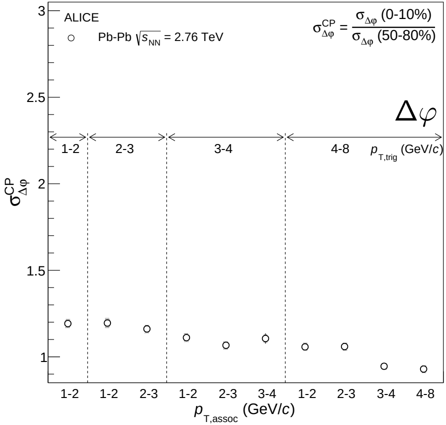


- Ratio of width in central over peripheral:

$$\sigma_{CP,\Delta\varphi} = \frac{\sigma_{\Delta\varphi}(0-10\%)}{\sigma_{\Delta\varphi}(50-80\%)},\ \sigma_{CP,\Delta\eta} = \frac{\sigma_{\Delta\eta}(0-10\%)}{\sigma_{\Delta\eta}(50-80\%)}$$



- Moderate broadening in $\Delta\varphi$

Quantification of the broadening

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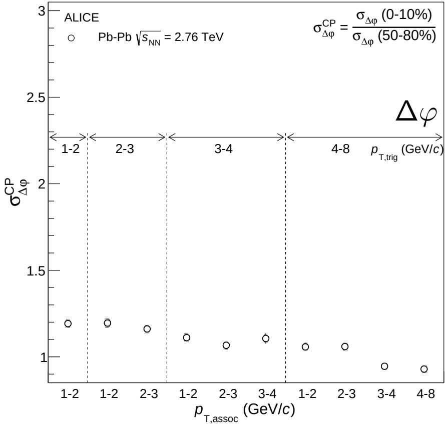
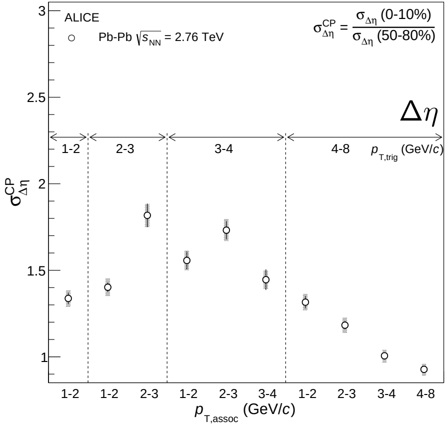
$$\sigma_{CP,\Delta\varphi} = \frac{\sigma_{\Delta\varphi}(0-10\%)}{\sigma_{\Delta\varphi}(50-80\%)}, \ \sigma_{CP,\Delta\eta} = \frac{\sigma_{\Delta\eta}(0-10\%)}{\sigma_{\Delta\eta}(50-80\%)}$$





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

- Ratio of width in central over peripheral:

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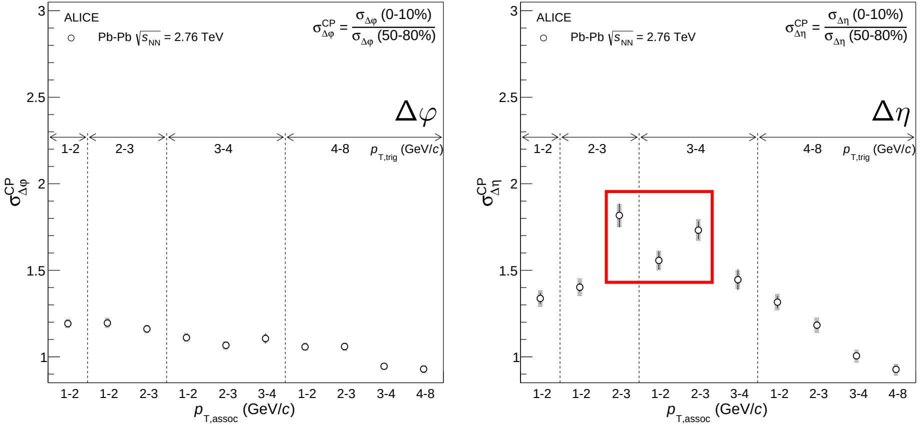

- Moderate broadening in $\Delta\varphi$
- Much larger broadening in $\Delta\eta$
- Broadening most significant at intermediate p_T

- Ratio of width in central over peripheral:

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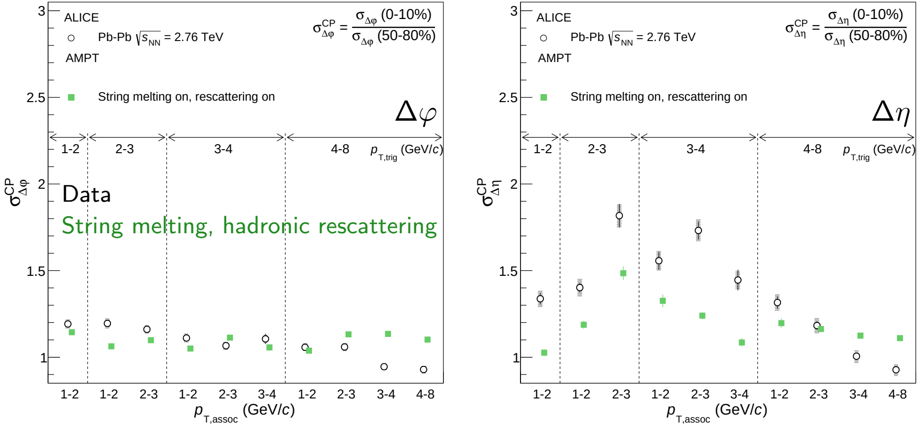

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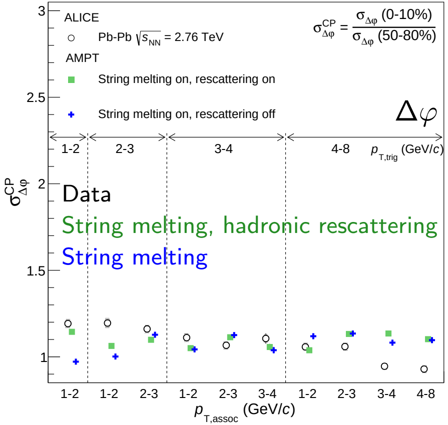

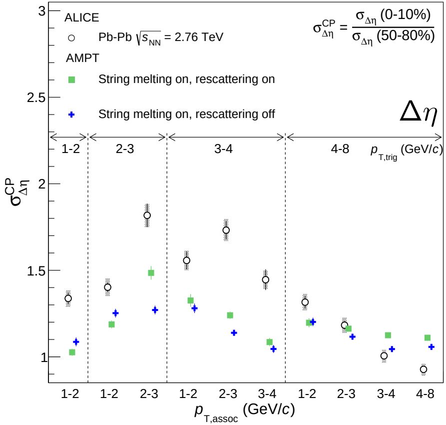

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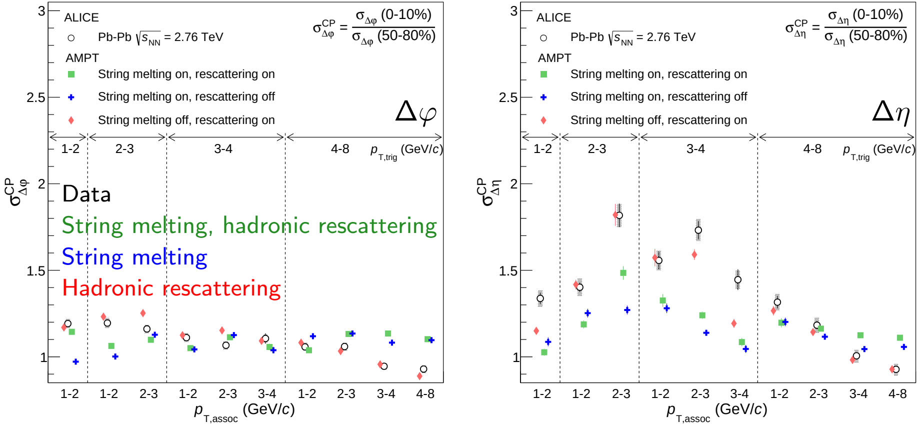

- Small difference between models in $\Delta\varphi$, $\Delta\eta$ more constraining
- String melting off, hadr. rescattering on describes data best

Quantification of the broadening

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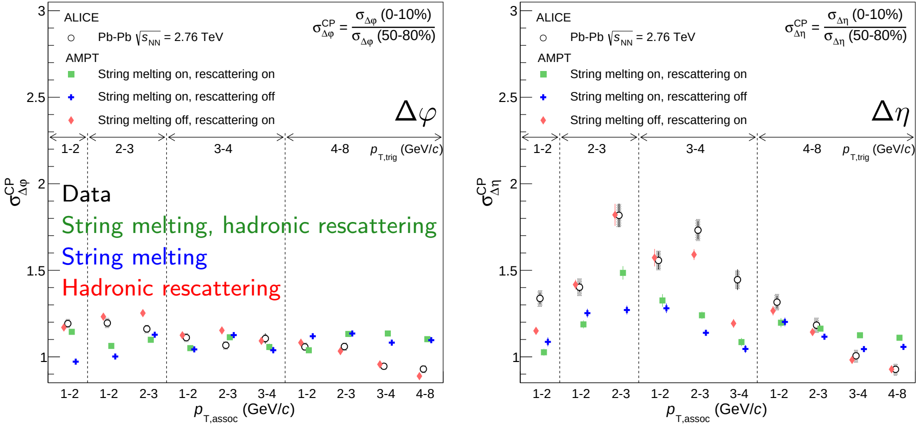
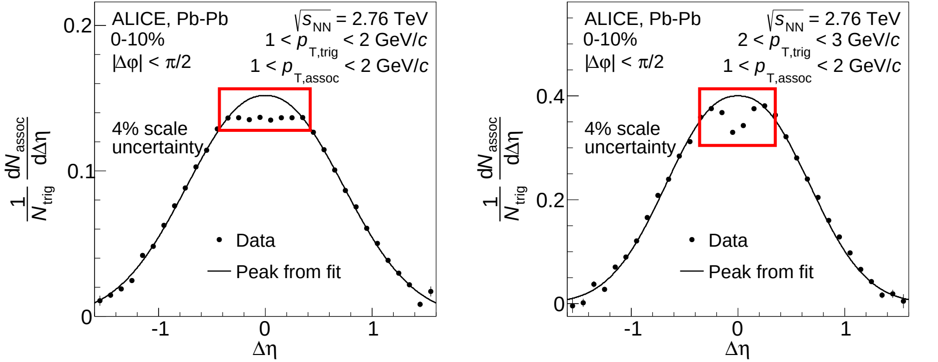


- Small difference between models in $\Delta\varphi$, $\Delta\eta$ more constraining
- String melting off, hadr. rescattering on describes data best
- Note: none of AMPT settings describe absolute width better than 10% (see backup)

Near-side depletion

- 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



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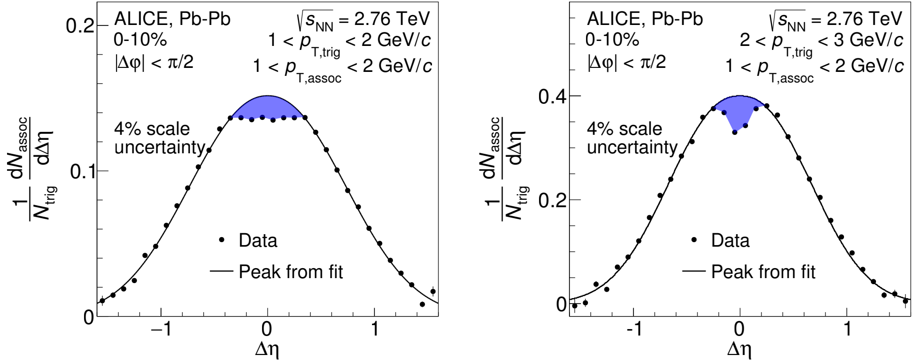
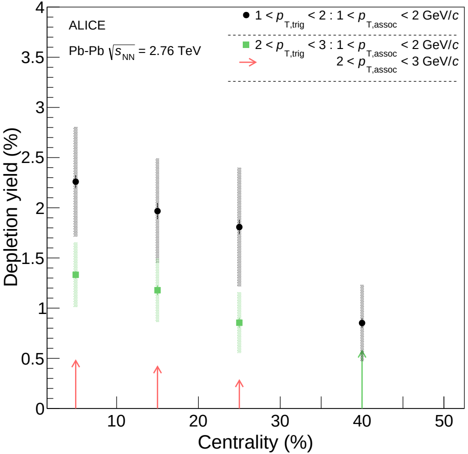
- Per trigger yield is corrected for two-track inefficiencies
- The area of the depletion is excluded from the fit
- Characterized by $\frac{\text{Fit-Data}}{\text{Total yield}}$ in %



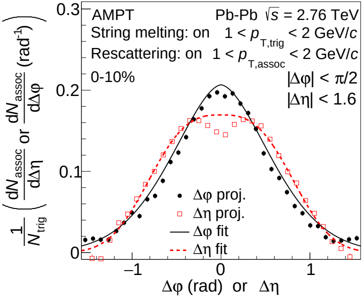
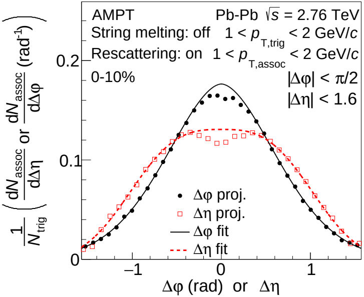
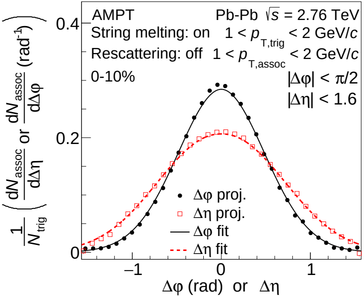
Near-side depletion

- Depletion yield $= \frac{\text{Fit}-\text{Data}}{\text{Total yield}}$ in %



- No depletion in higher p_{T}, peripheral or pp

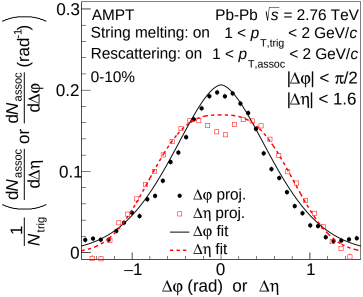
Near-side depletion in AMPT

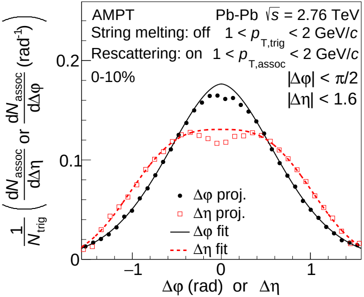
	String melting on	String melting off
Hadronic rescattering on		
Hadronic rescattering off		

- Generator level

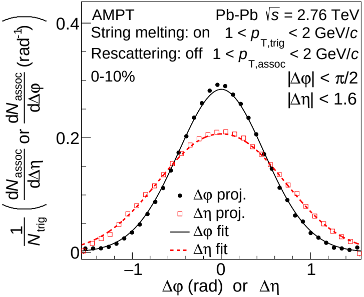
String melting on | String melting off

Hadronic rescattering on





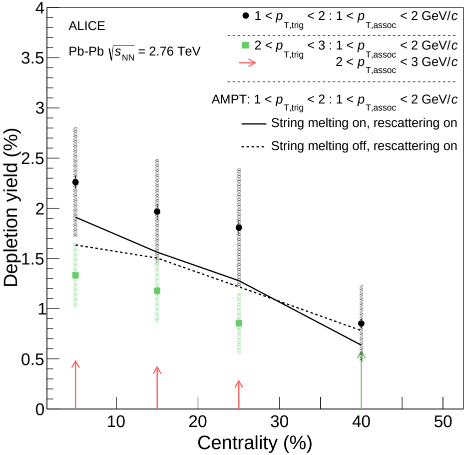
Hadronic rescattering off



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

Comparison to AMPT – near-side depletion

- Depletion yield $= \frac{\text{Fit}-\text{Data}}{\text{Total yield}}$ in %



- Depletion yield in AMPT almost independent of string melting
- AMPT is in agreement with the data at the lowest p_{T}
- At higher p_{T} none of the AMPT versions show depletion

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 $< p_{\mathrm{T}} <$ 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

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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 hadr. rescattering describes $v_2\{2\}$
- β_{T} is lower for all AMPT cases than for data

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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

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)
- $v_2\{2\}$ was extracted with 0.2 $< p_\mathrm{T} <$ 5 GeV/c

Sample	β_T	$v_2\{2\}$
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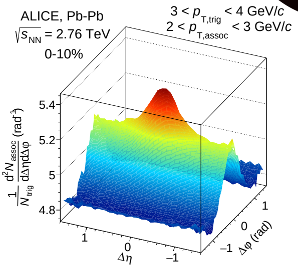
$\Downarrow$

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

Summary



- Evolution of near-side peak shape towards low p_{T} and high centrality:
  - 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 hadr. 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

- 39 million Pb–Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
- 30 million 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$/c^2$ or $|m_{\mathrm{inv}} - m(K_s^0)| < 5$ MeV$/c^2$
- Selection criteria to remove two-track inefficiencies: $|\Delta\eta| > 0.02$ and $|\Delta\varphi^*| > 0.02$ rad
- Correction is done to remove distortion arising from a dependence on η

Systematic Uncertainties

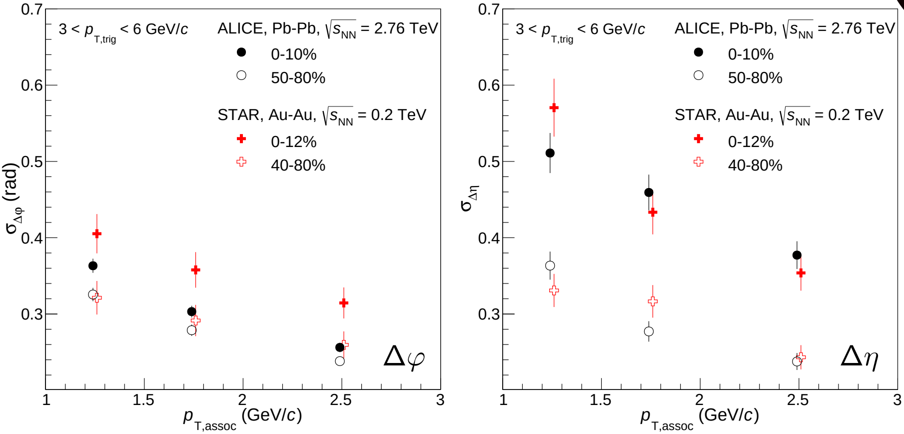
Source	$\sigma_{\Delta\varphi}$	$\sigma_{\Delta\eta}$	$\sigma_{CP,\Delta\varphi}$	$\sigma_{CP,\Delta\eta}$	Depletion yield
Track selection and efficiencies	1.0%		1.3%		20%
Small opening angles cut	0.7%		1.3%		5–10%
Neutral-particle decay cut	0.1%		0.2%		8–20%
Vertex range	1.0%		1.0%		5–10%
Pseudorapidity dependence	1.7%	4.1%	0.6%	2.5%	5–15%
Exclusion region	0.1%	1.0%	0.1%	1.5%	7–28%
Total	2.3%	4.5%	2.2%	3.6%	24-45%

- Ranges indicate p_{T} dependence

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

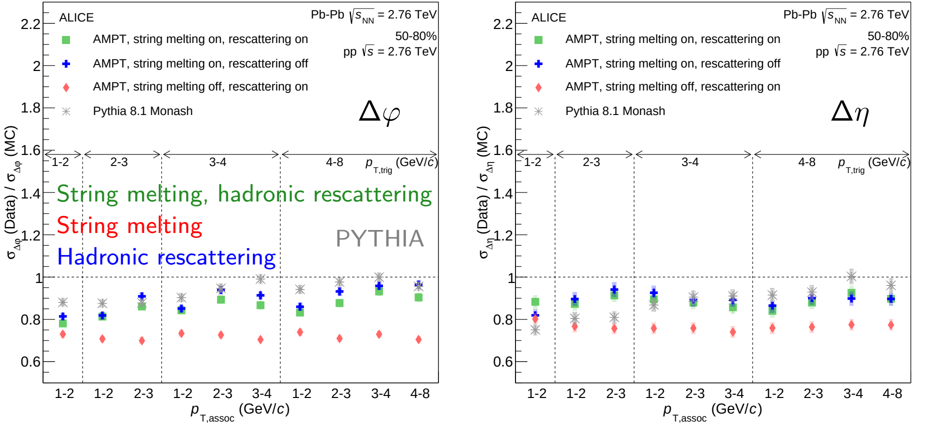
Comparison to the STAR experiment



- 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 $\Delta\varphi$

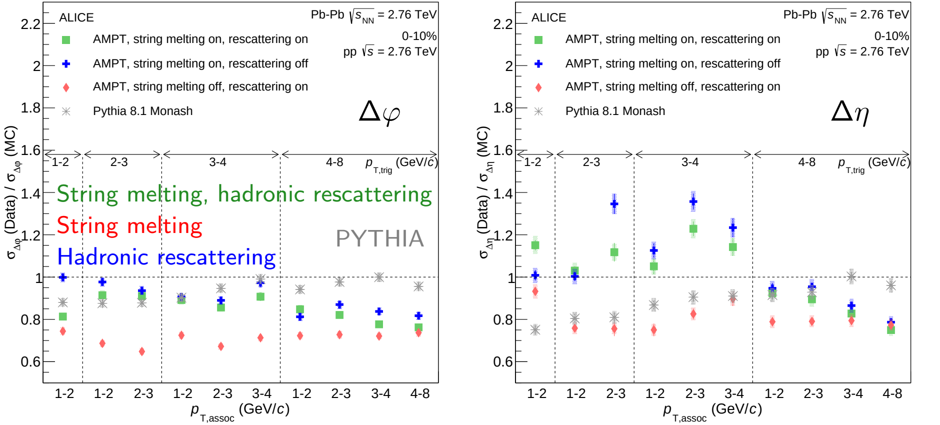
- Absolute width described by $\frac{\sigma_{\Delta\varphi}(\text{Data})}{\sigma_{\Delta\varphi}(\text{MC})}$, $\frac{\sigma_{\Delta\eta}(\text{Data})}{\sigma_{\Delta\eta}(\text{MC})}$



- None of the AMPT settings describe all p_T bins

Comparison to MC – absolute width in central

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



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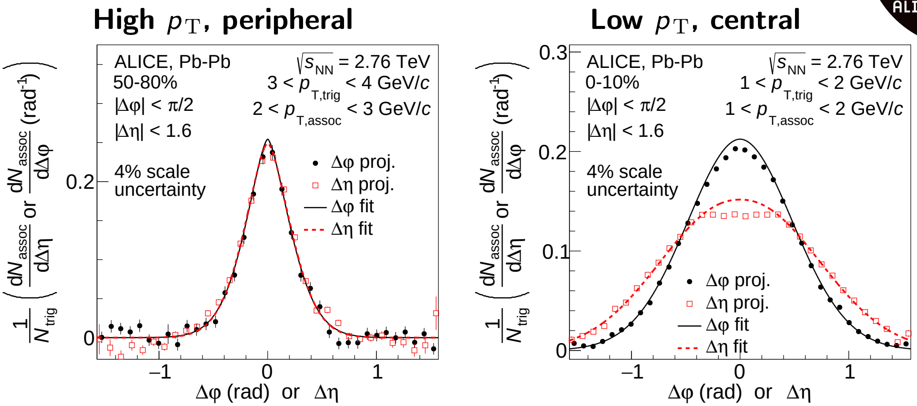
Evolution of the near-side peak shape



Towards central collisions and low p_T:

- Peak broadens
- Peak gets asymmetric ($\Delta\eta > \Delta\varphi$)
- Depletion around $(\Delta\varphi, \Delta\eta) = (0,0)$ develops

Settings:

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