Seminar

ExtreMe Matter Institute EMMI
GSI, Darmstadt, Germany

Dynamics of heavy flavour in hadronic collisions

An insight from azimuthal angular correlations

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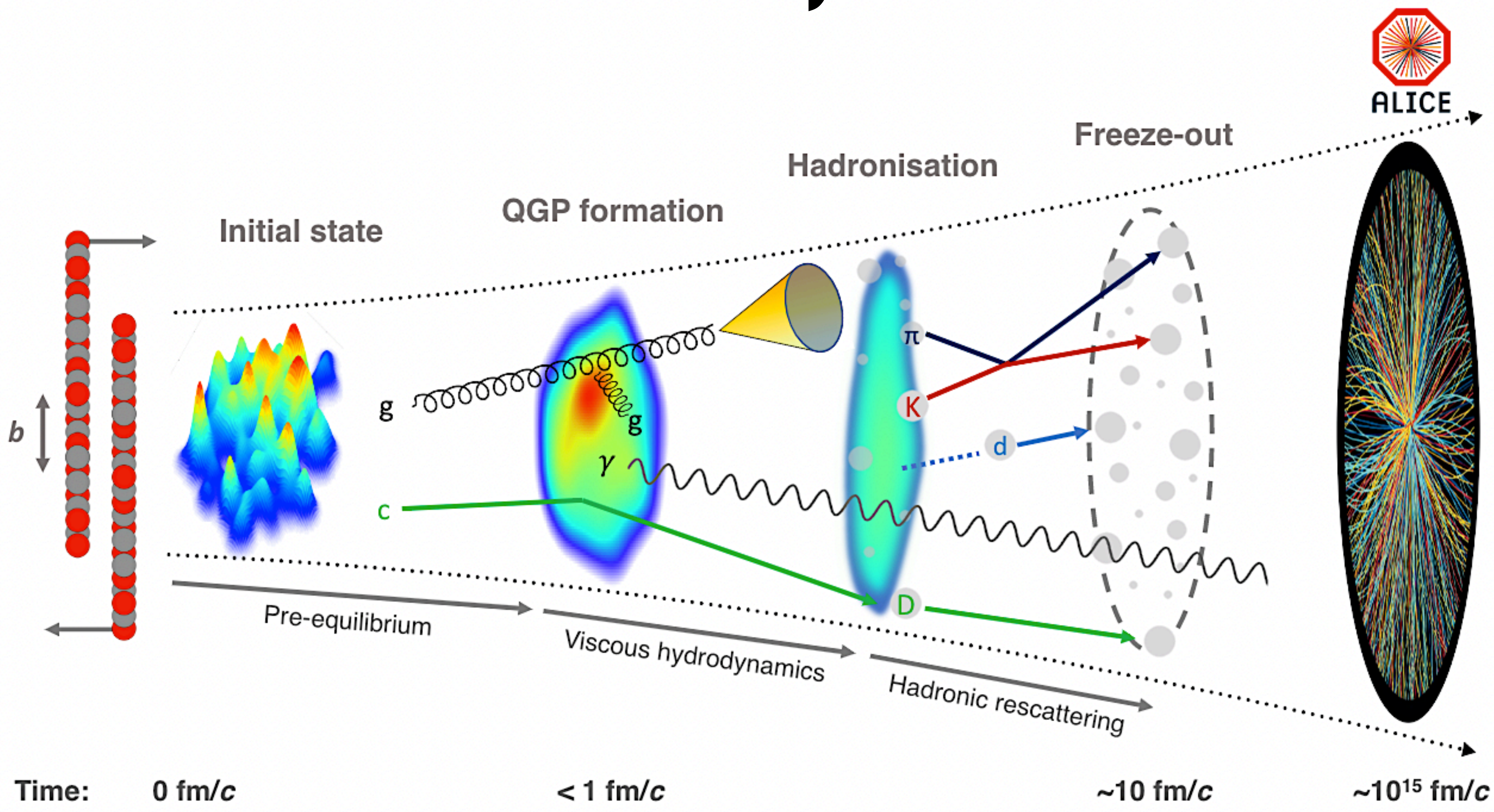
Overview

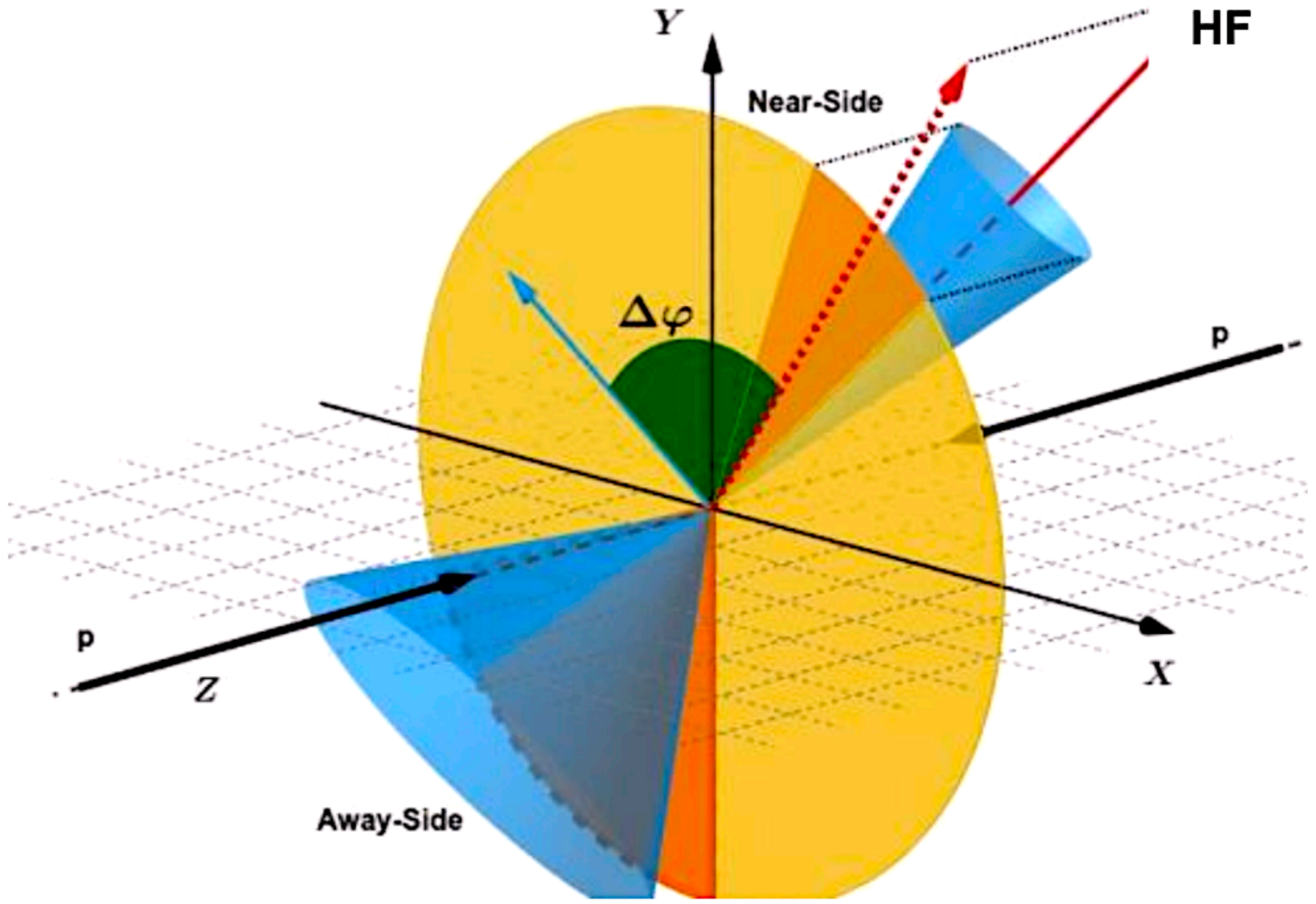
- Introduction: Evolution of heavy ion collisions
- Physics Motivation : Azimuthal angular correlation
- Data Analysis
  - ALICE detector
  - D^0-hadron correlation
- Phenomenology
  - Study of D^0 jet fragmentation
  - Effects of nuclear parton distribution function on azimuthal angular correlations
- Summary & Outlook

Evolution of heavy ion collisions



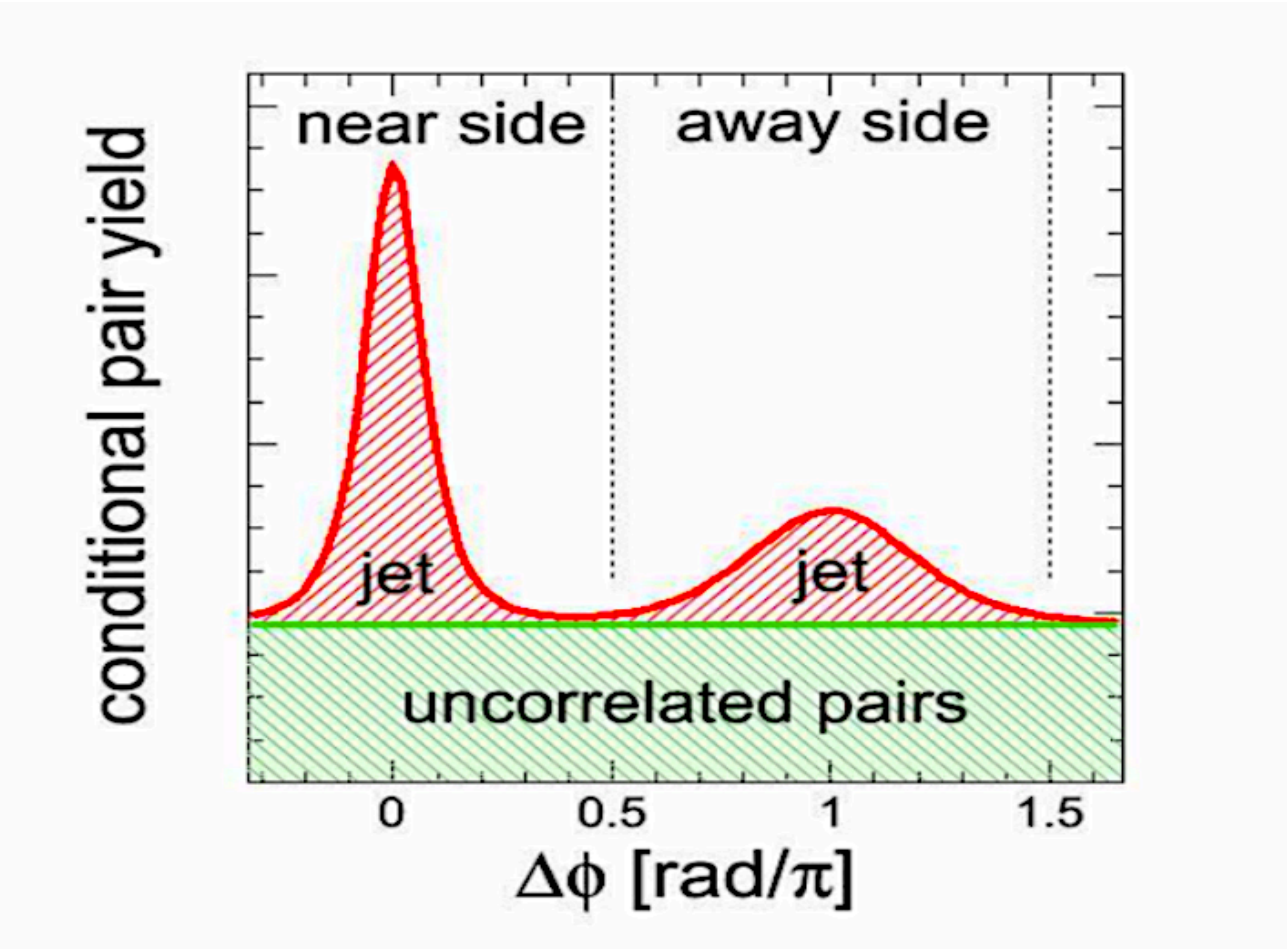
Physics Motivation

- Heavy flavours (HF) are produced via initial hard scattering processes
- High p_T heavy quarks created in these collisions form jets, which are directed sprays of particles
- Open heavy flavour: $D^0(c\bar{u}), D^+(c\bar{d}), D_s^+(c\bar{s})$
- Closed heavy flavour: $J/\psi\,(c\bar{c})$, $\Upsilon\,(b\bar{b})$



HF azimuthal correlation is an excellent observable to study

- Heavy quark production
- Initial state effects
- Quark gluon plasma
- Fragmentation and Hadronization of HF



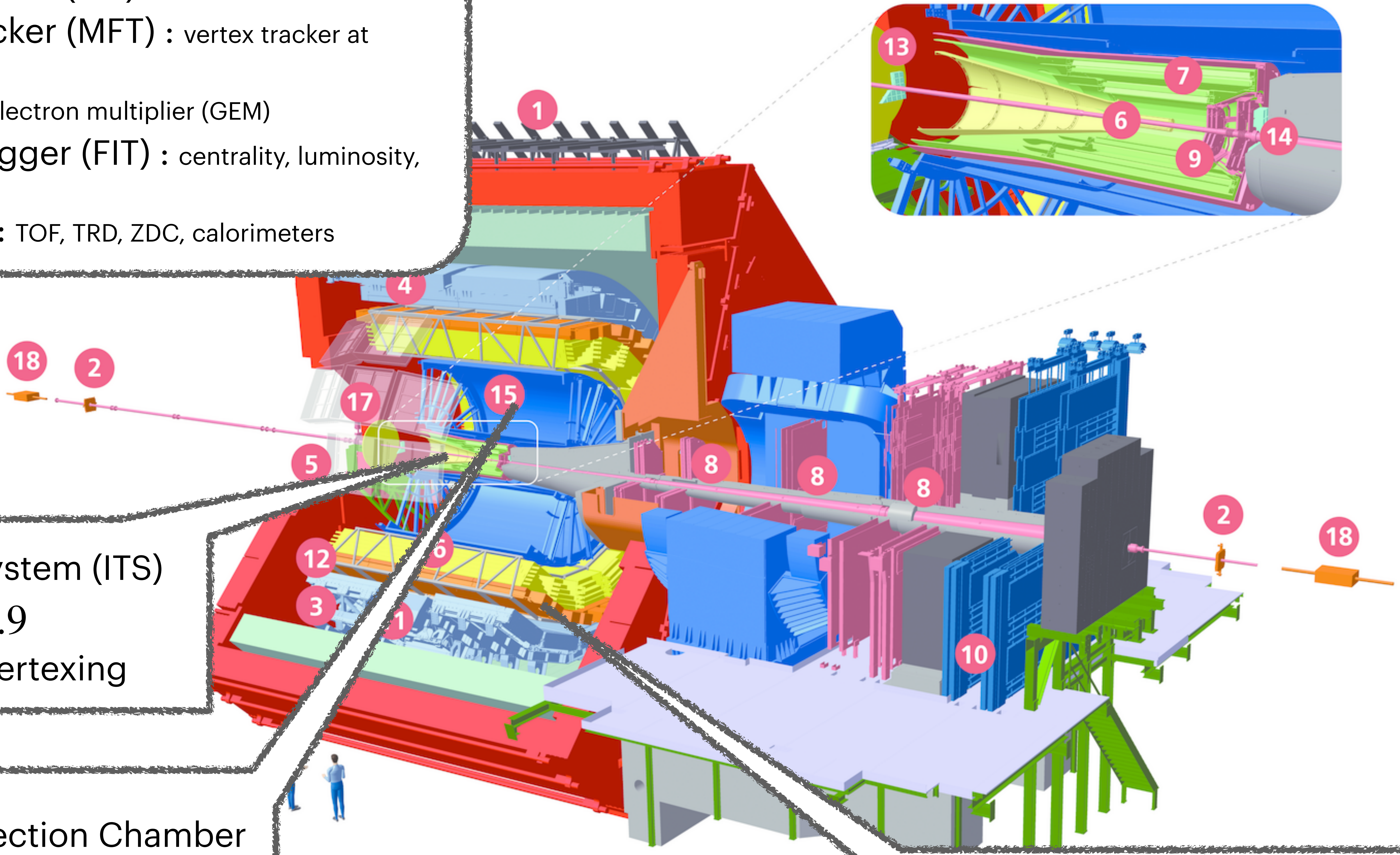
- Azimuthal angular correlation is obtained by measuring azimuthal angular difference between trigger particle and associate particles

$$\Delta\phi = \phi_{trig} - \phi_{asso}$$

The ALICE Detector

RUN 3 Upgrade

- Inner Tracking System (ITS)
- Muon Forward Tracker (MFT) : vertex tracker at forward rapidity
- TPC Readout : Gas electron multiplier (GEM)
- Fast Interaction Trigger (FIT) : centrality, luminosity, event plane
- Readout upgrade : TOF, TRD, ZDC, calorimeters



Inner Tracking System (ITS)

$|\eta| < 0.9$

Tracking and vertexing

Time Projection Chamber (TPC)

$|\eta| < 0.9$

Tracking and charged PID

Time of Flight (TOF)

$|\eta| < 0.9$

Charged PID

1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

D^0-hadron correlation analysis

1. D^0 selection and signal extraction
   1. Reconstruction of D^0 candidates using decay daughters $D^0 \rightarrow K^-\pi^+$
   2. TPC and TOF are used for kaon and pion identification
2. Correlation of D^0 candidates with associated tracks
   1. Correlation with all primary charged particles
   2. Removal daughter tracks
   3. Soft pion contribution from $D^{*+} \rightarrow D^0 + \pi^+$
3. Removal of secondary track contamination
   1. Tracks from long lived strange decays or from interaction of particles with detector material
   2. DCA to primary vertex cut
4. Background subtraction

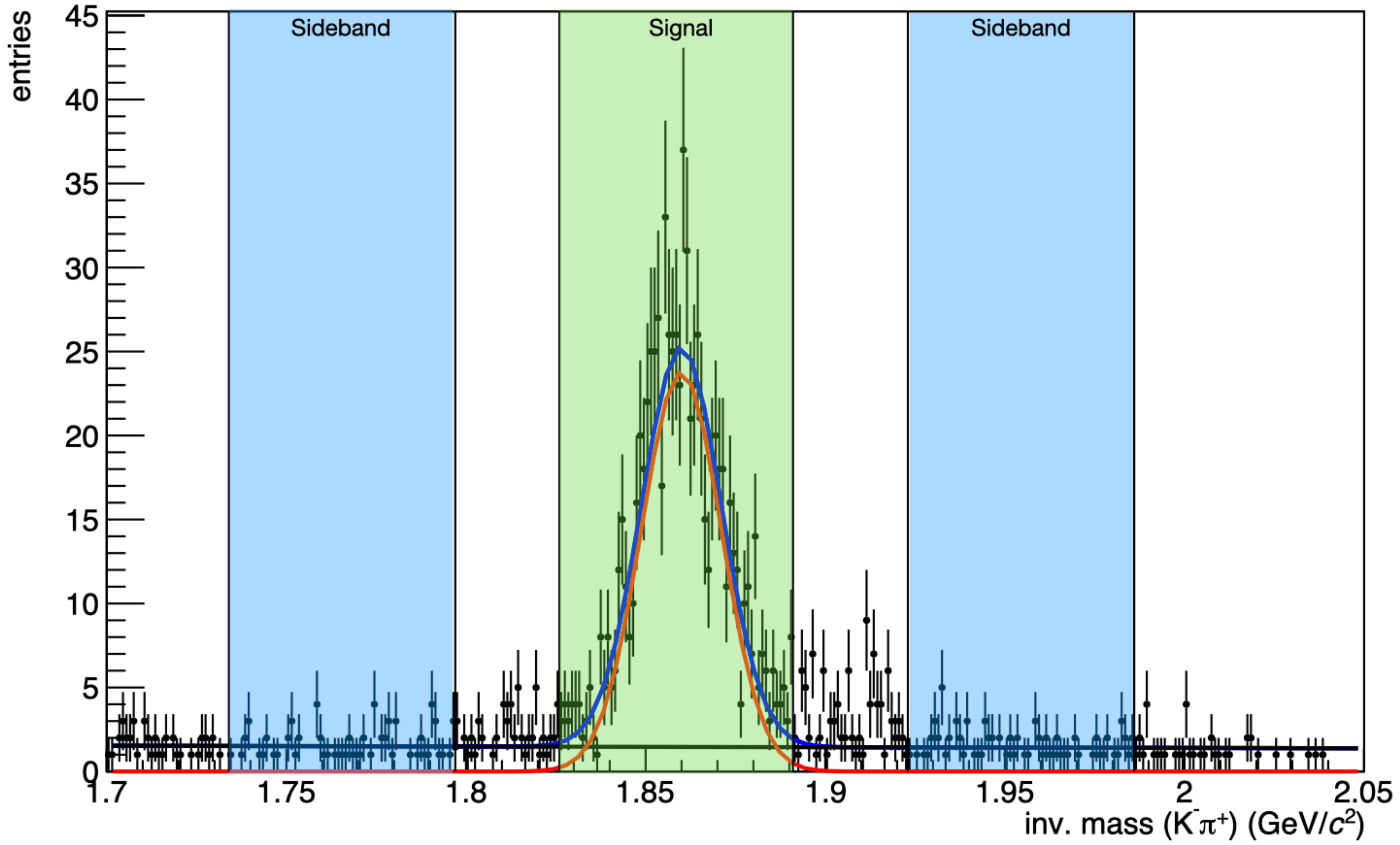
1. Event mixing
   1. To remove background due to detector inhomogeneities
2. Correction for D-meson efficiency and associated tracks
   1. Corrections for D^0 and tracks which are not properly reconstructed

Extraction Task

1. Feed-down corrections
   1. Corrections to remove D^0 coming from b-hadron decays
2. Study of correlation properties
   1. Extraction of correlation parameters by using two Gaussian functions for near and away side

D^0-hadron correlation analysis

- Sideband subtraction : To remove correlations due to background in signal region
  - Signal region: $|m - m_{pdg}| < 2\sigma$
  - Sideband region: $|4\sigma| < m - m_{pdg} < |8\sigma|$

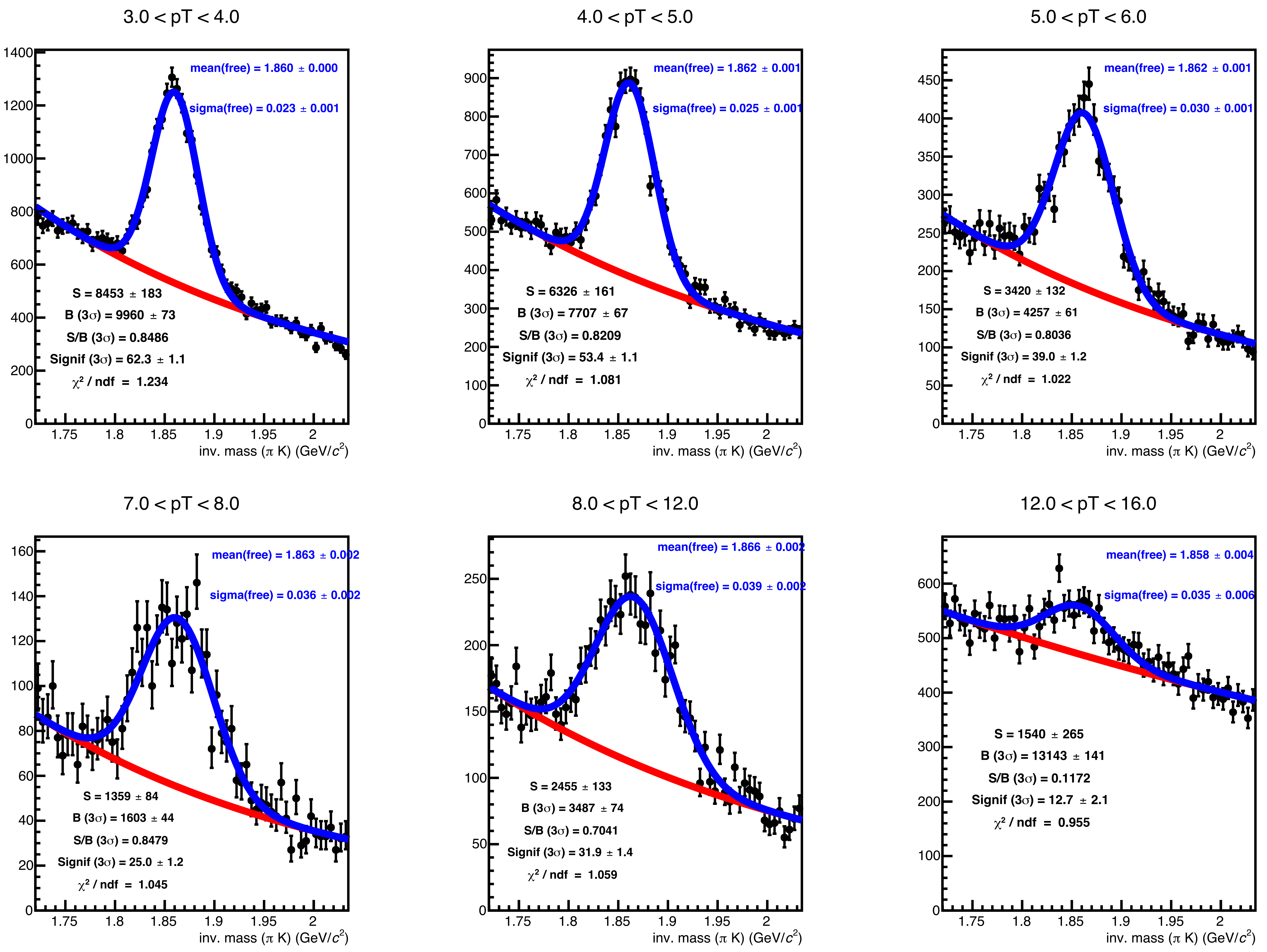


- Mixed event correction : To remove background due to detector inhomogeneity

$$C_{inc}(\Delta\eta, \Delta\phi) = \frac{1}{S_{peak}} \left(\left. \frac{C(\Delta\eta, \Delta\phi)}{ME(\Delta\eta, \Delta\phi)} \right|_{signal} - \left. \frac{B_{peak}}{B_{sideb}} \frac{C(\Delta\eta, \Delta\phi)}{ME(\Delta\eta, \Delta\phi)} \right|_{sideband} \right)$$

- S_{peak} : D^0 in signal region
- B_{peak} : Background in signal region
- $B_{sideband}$: Background in sideband region

Invariant Mass Spectra

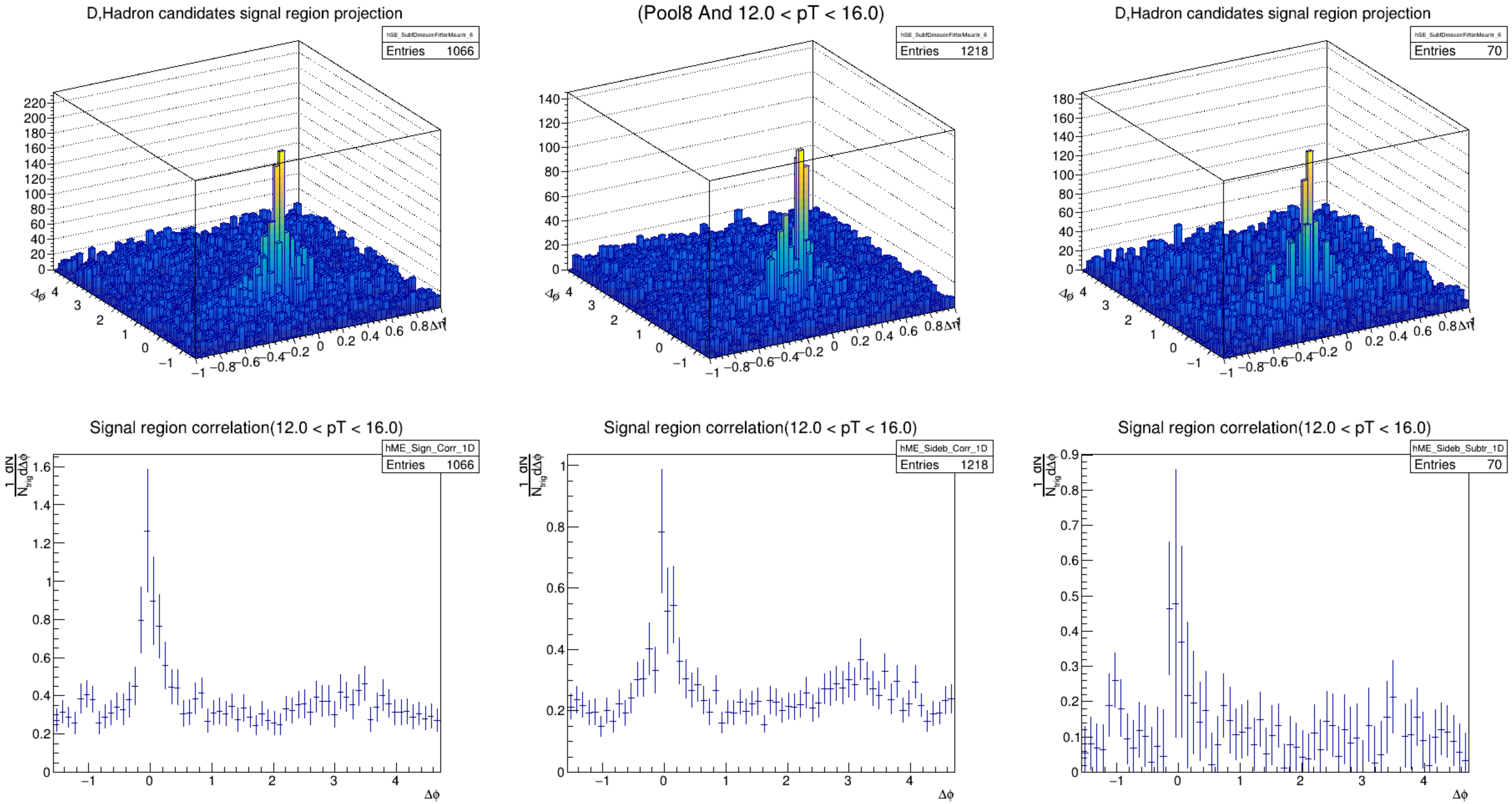


- System: pp, $\sqrt{s}$ = 13.6 TeV
- Statistics: 2B
- Sample: LHC22o_pass4_small
- Fitting function

  Signal: Gaussian

  Background: Exponential

Results

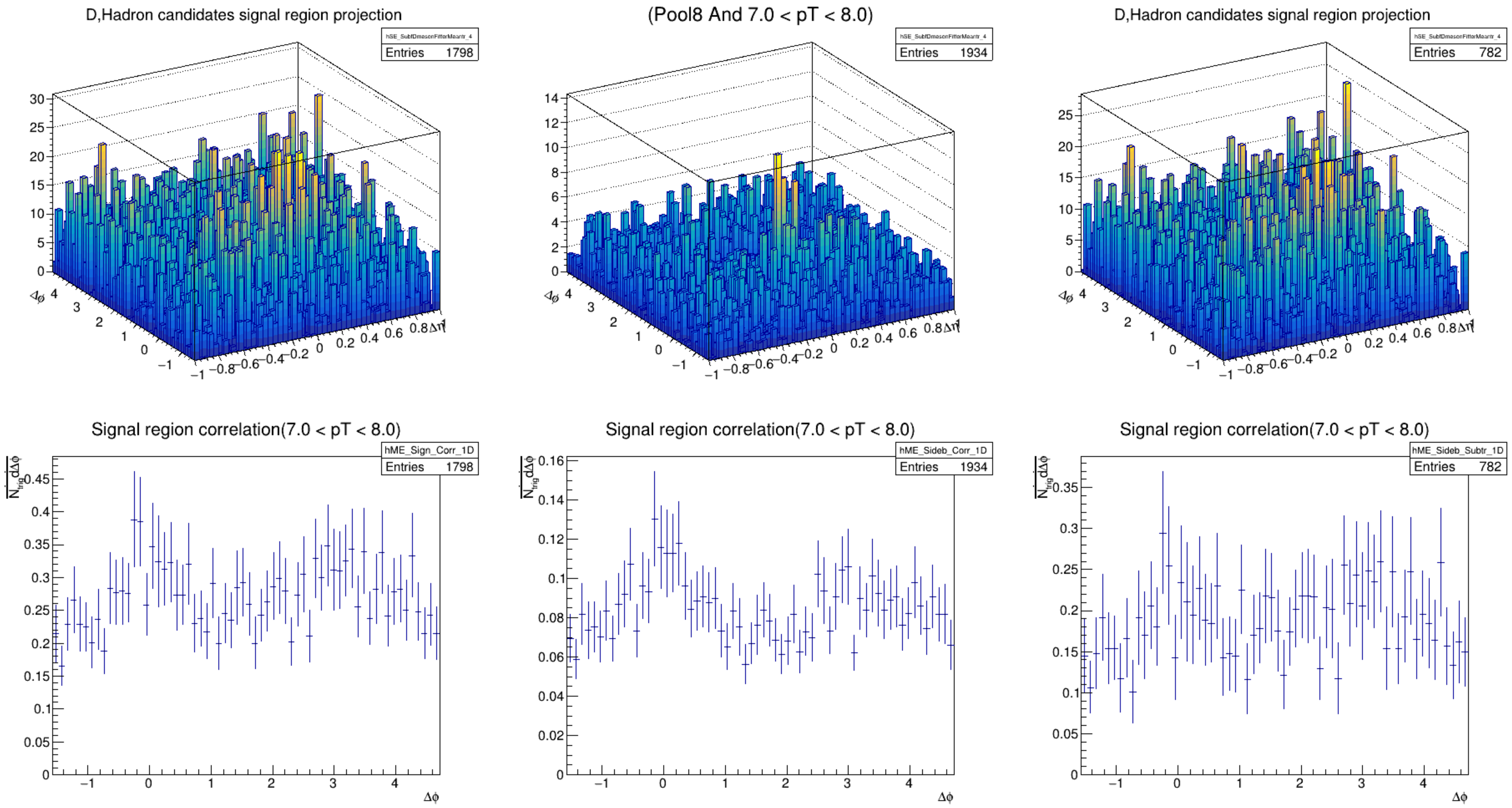


SE(signal)/ME(signal)

SE(side-band)/ME(side-band)

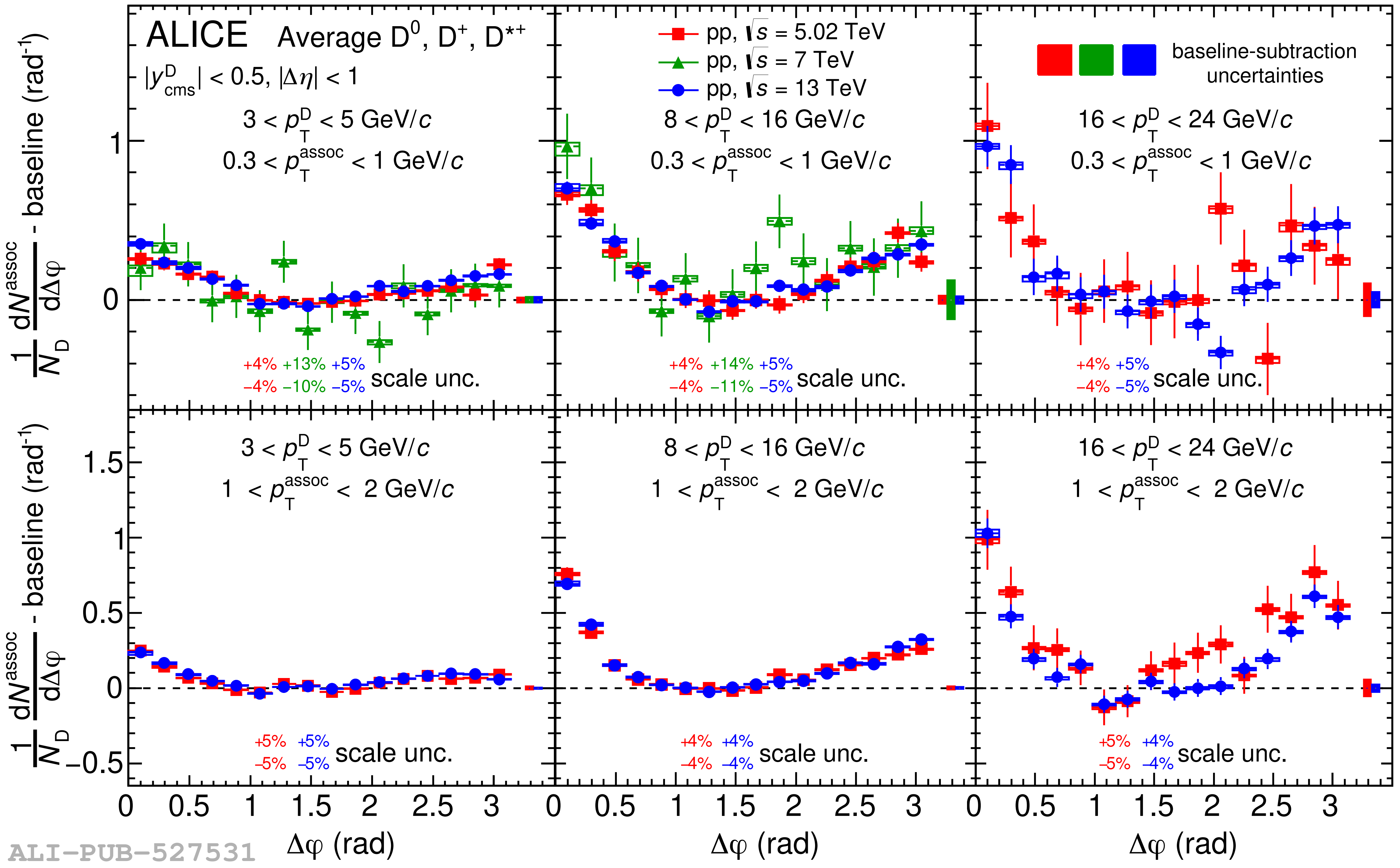
ME and Sideband corrected

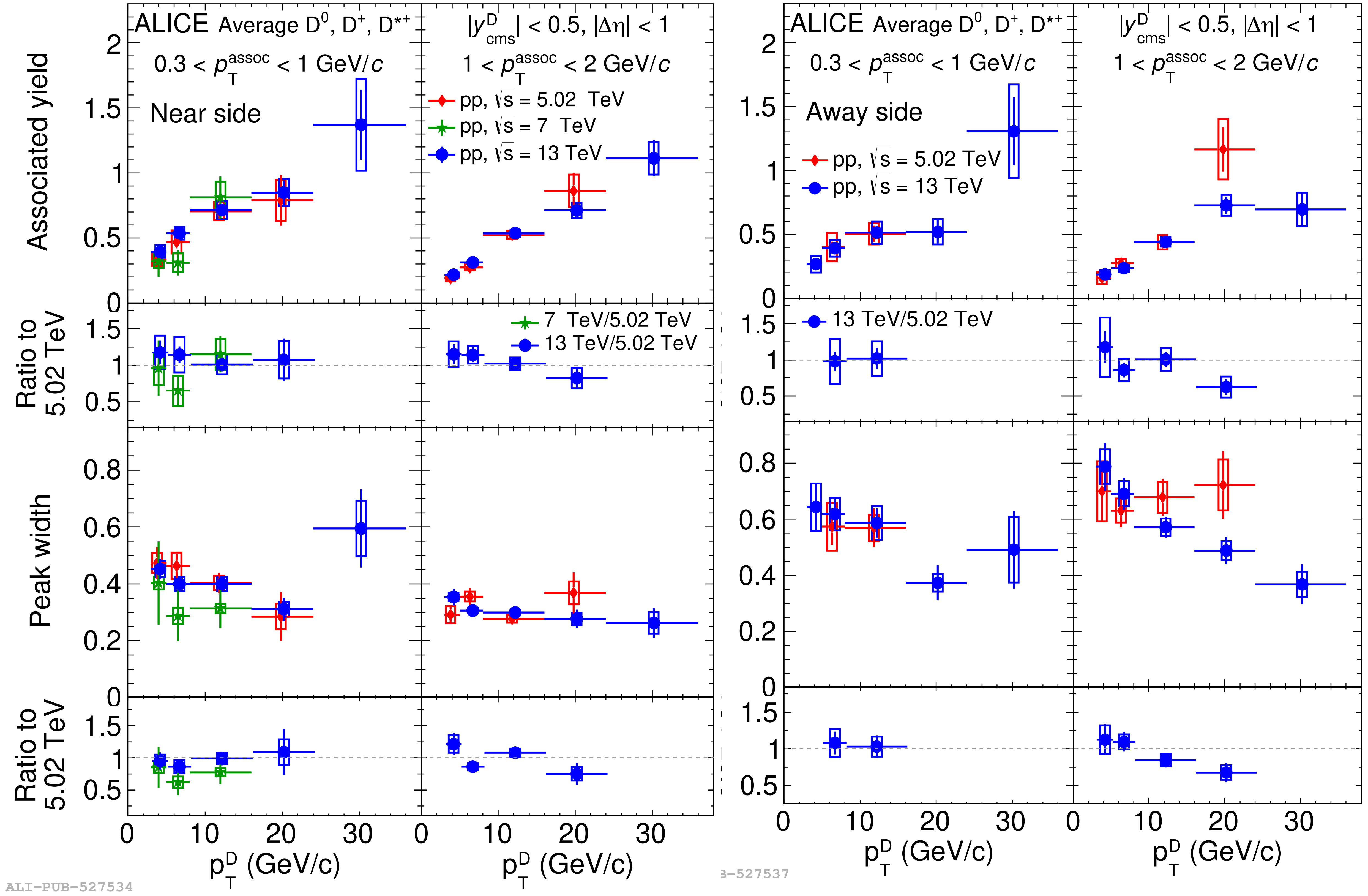
Results



- Correlation is narrower for high p_T^{trig} as compare to low p_T^{trig}.
- Further corrections and fitting procedures are required for qualitative and quantitative comparison between different p_T ranges

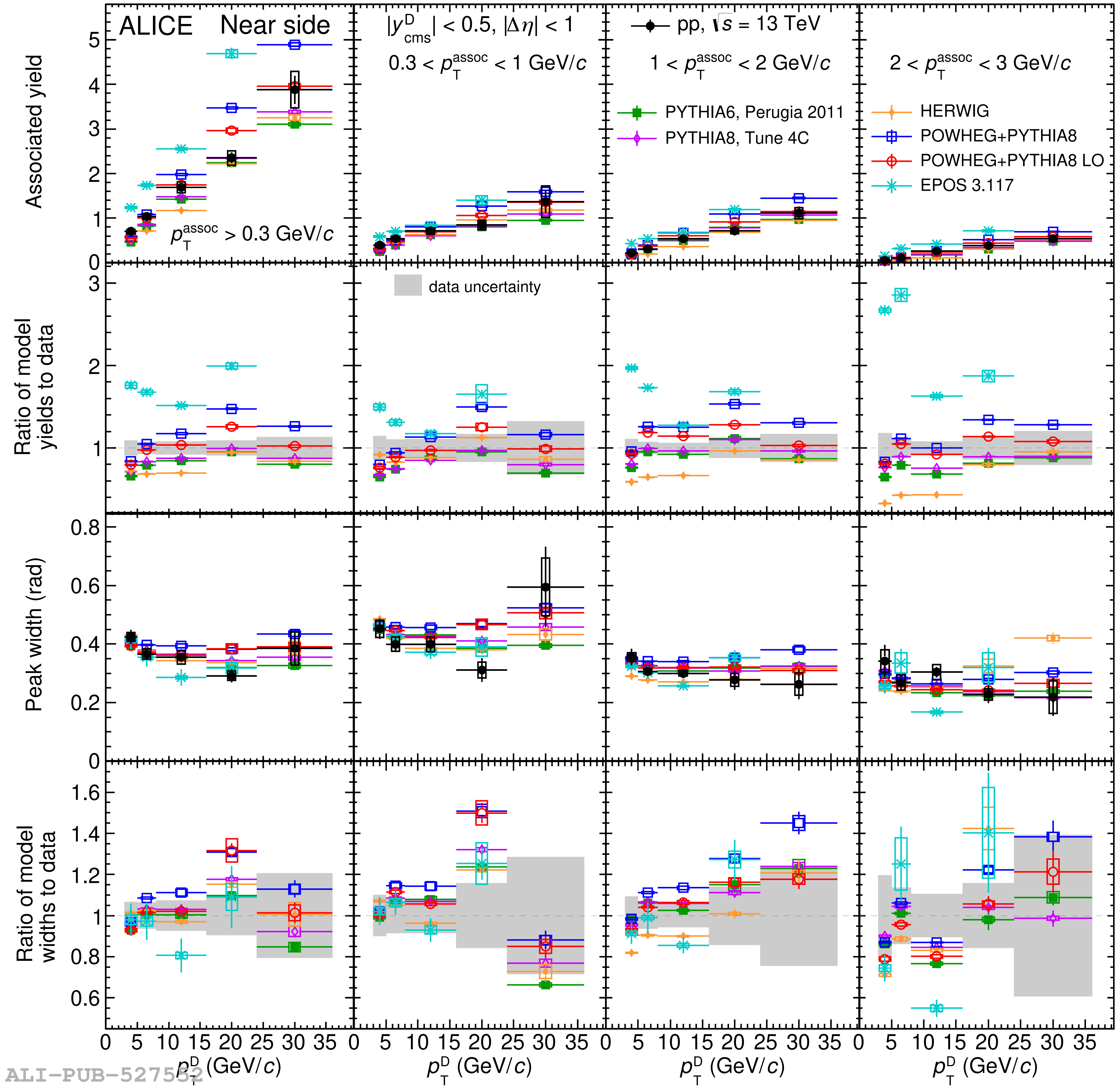
D-h Azimuthal Angular Correlation: Run 2





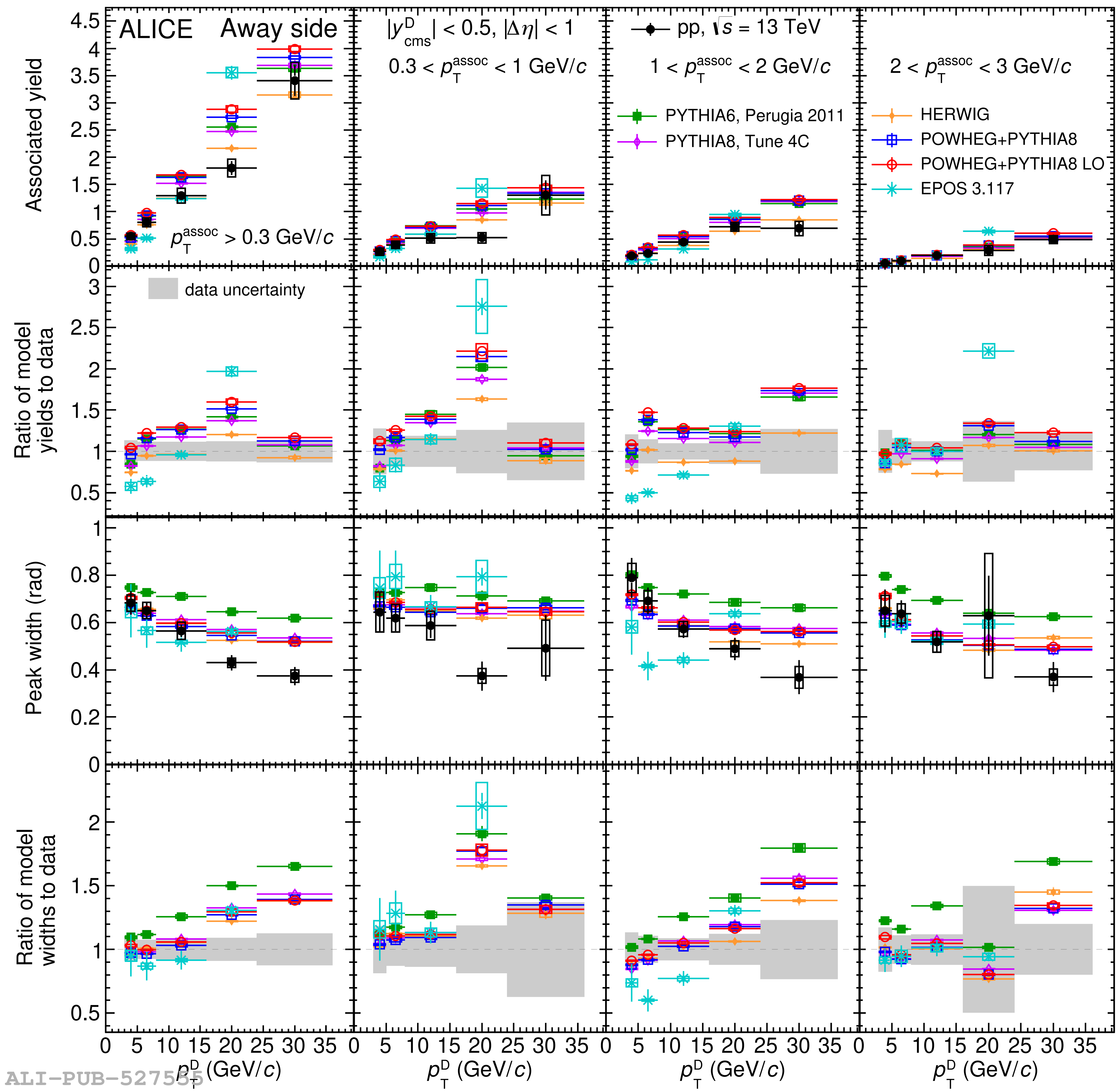
- Parameters of correlation distributions are obtained by fitting two generalised gaussian
- No energy dependence of azimuthal angular correlation is observed.
- Increase in associate yield as a function of trigger pt due to larger available phase space.
- Decrease in width as a function of p_T^D due to larger boost of fragmenting parton.

D-h Azimuthal Angular Correlation : Model Comparison



- Near Side:
  - Best description of data is given by POWHEG+PYTHIA8 and PYTHIA8(4C).
  - EPOS3 and HERWIG respectively overestimates and underestimates NS yield
  - Hints of sharpening of NS correlation with increasing p_T^D is observed in data but absent in models
  - Widths are reproduced by all the models within uncertainty
  - Measurements with better uncertainties are needed distinguish between various models descriptions.

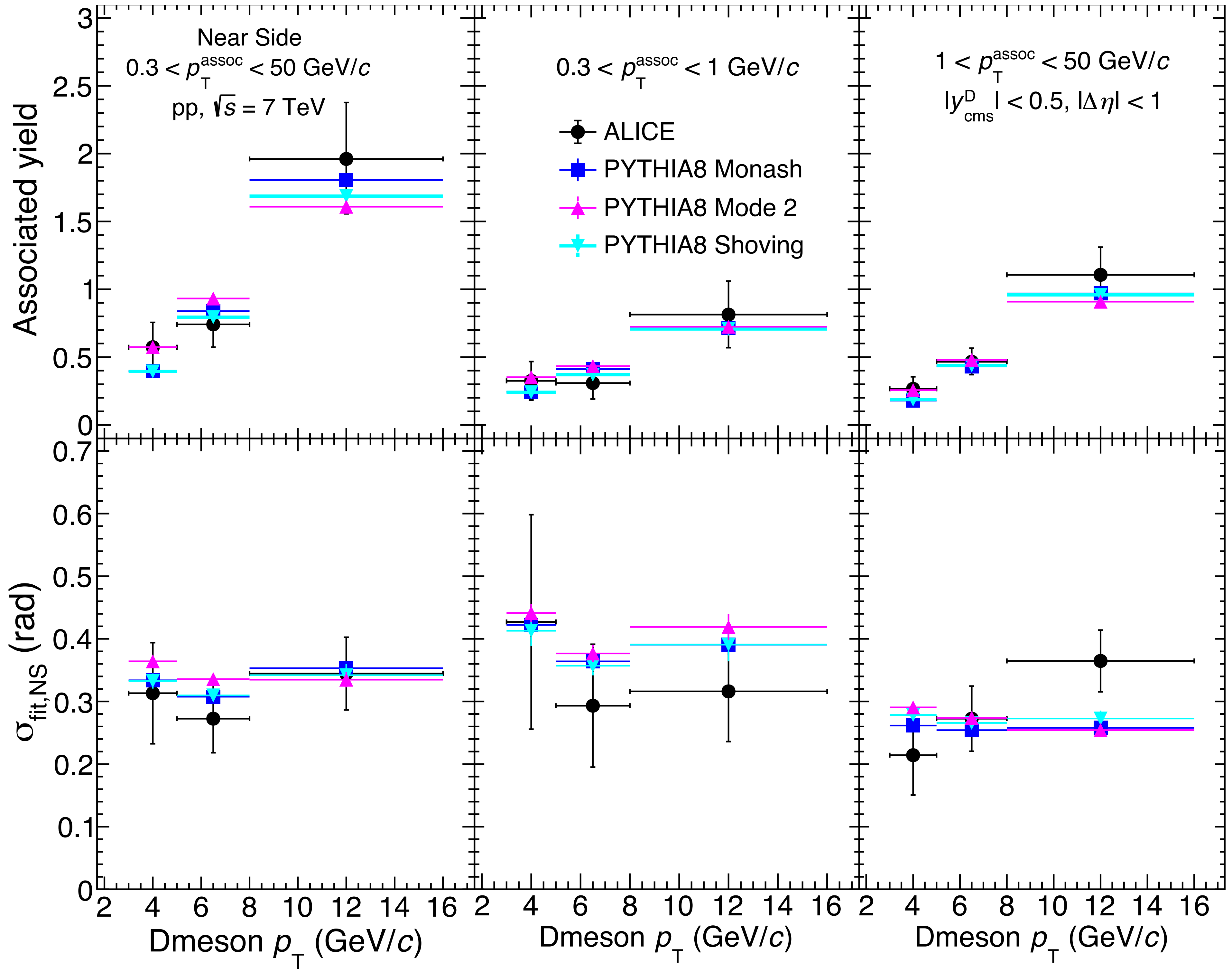
D-h Azimuthal Angular Correlation : Model Comparison

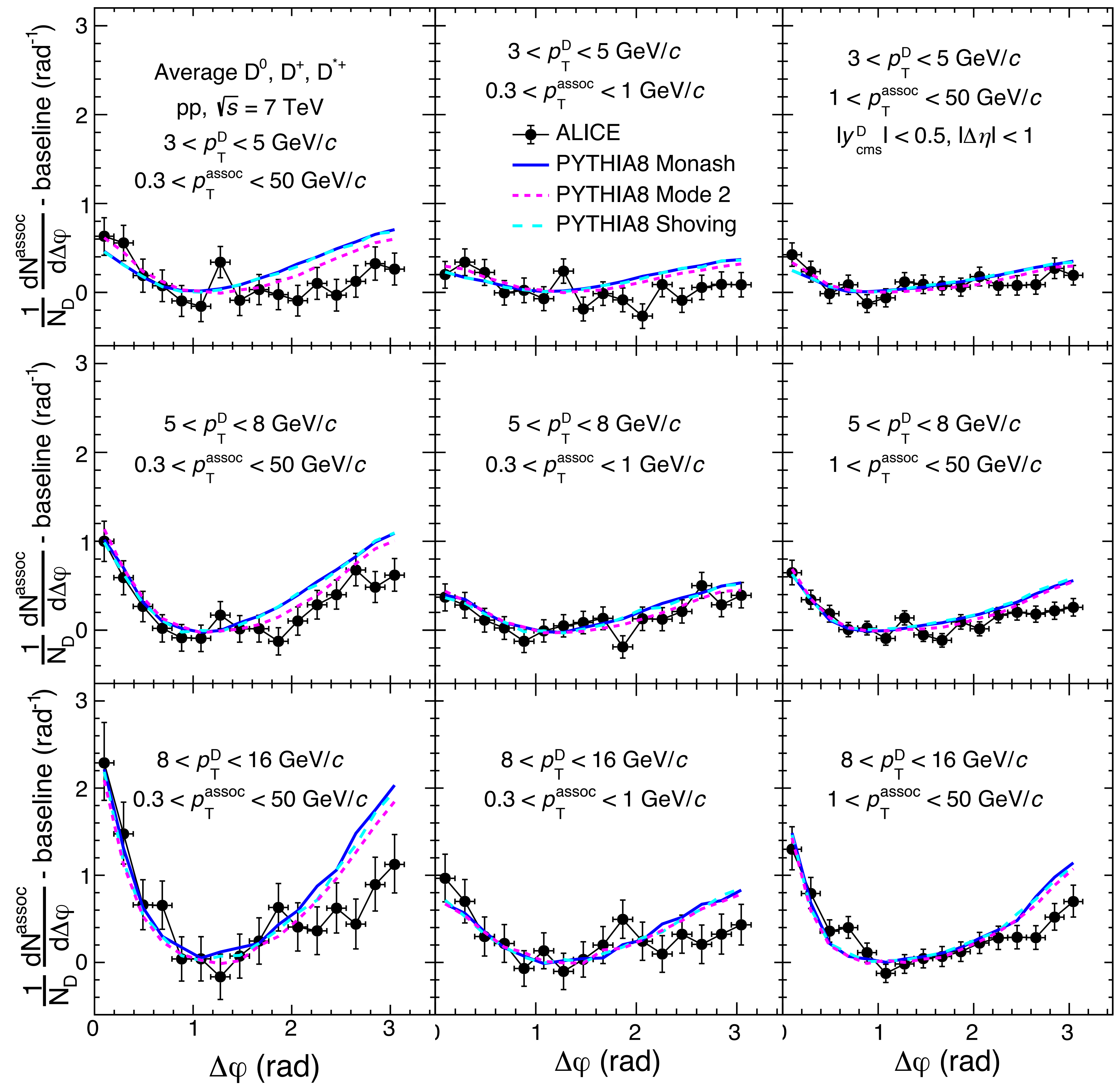


- Away Side:
  - Best description is obtained by PYTHIA8 and HERWIG
  - POWHEG+PYTHIA8 overestimates AS yield while for p_T^D< 5 GeV/c EPOS3 underestimates the yield.
  - Clear trend of decreasing width with increasing p_T^D.
  - All models reproduce width within the uncertainties except for PYTHIA6
  - Better description of away side fragmentation is needed at high associate as well as trigger p_T.

Study of jet fragmentation using D^0-hadron correlation

- It is crucial to study jet fragmentation to comprehend how heavy quarks fragment.
- Predictions from different tunes of PYTHIA8 are compared with ALICE data on D^0 hadron correlation.
- Monash, Shoving and Mode2 differ in the treatment of hadronization process.





- All tunes describe near side peak but overestimates away side peak.
- Overestimation of away side peak can be attributed to the fact that in PYTHIA next to leading order processes for heavy quark productions are not taken into account.

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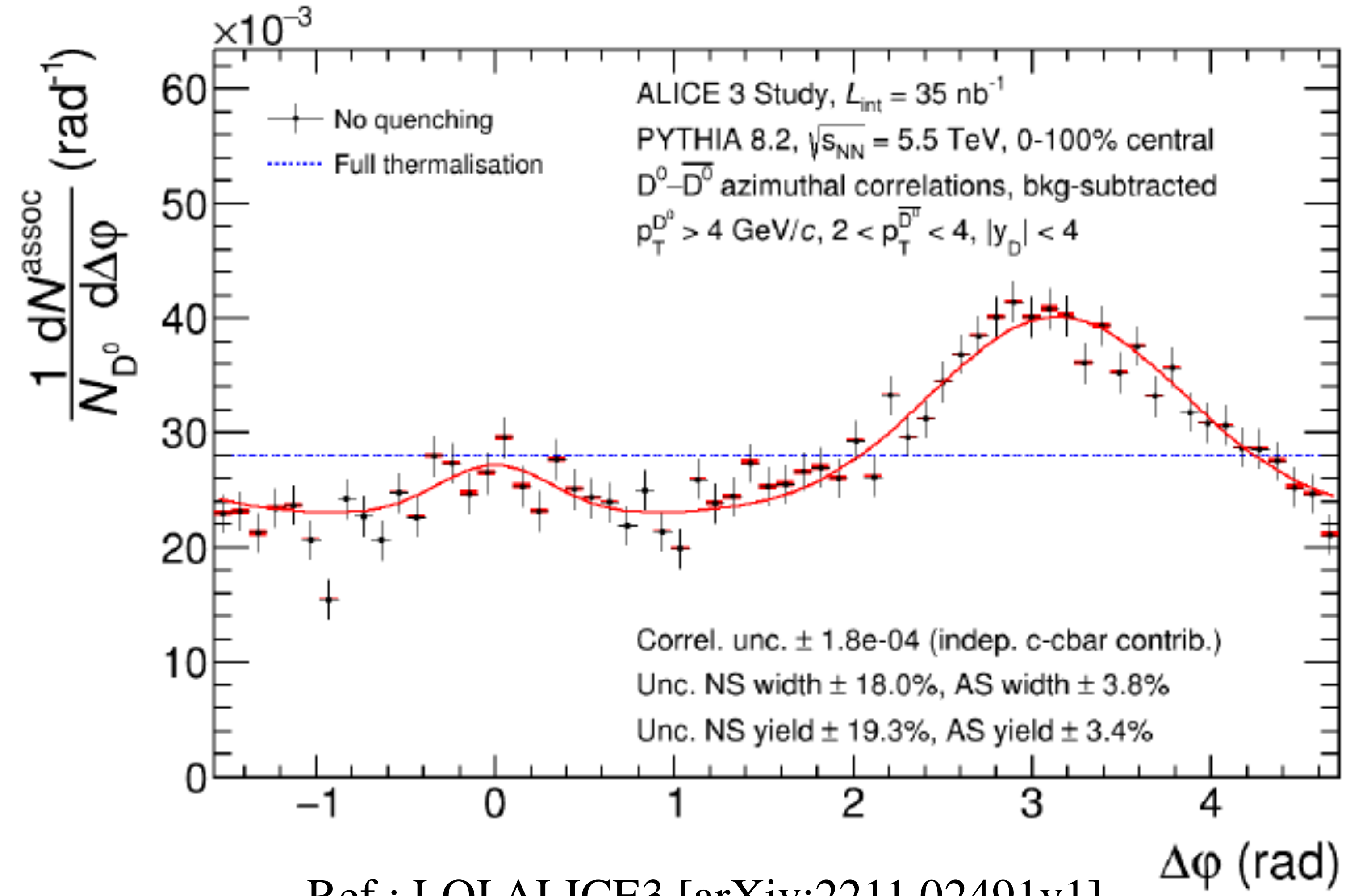
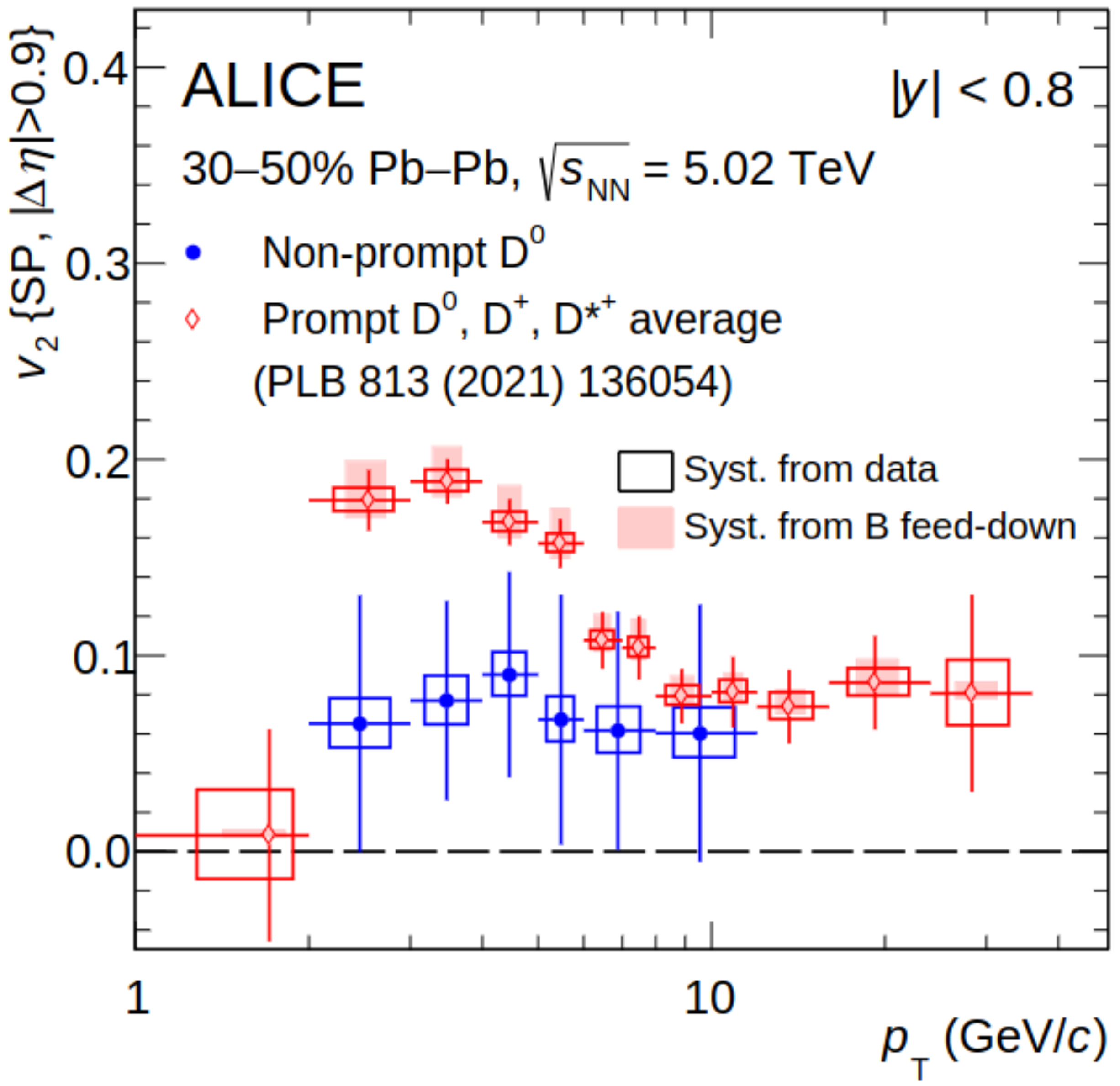
$D^0 - \bar{D}^0$ Azimuthal Angular Correlation

- Azimuthal correlation of $D^0 - \bar{D}^0$ meson
  - Thermalisation of charm quark
  - In medium energy loss
- Full thermalisation → Flat azimuthal angular correlation
- Non- zero elliptic flow (v_2) of prompt D-meson implies charm quark participation in collective motion

- Isolate the effects of different stages of heavy-ion collision on azimuthal angular correlation
- Isolating the initial state using nuclear parton distribution functions

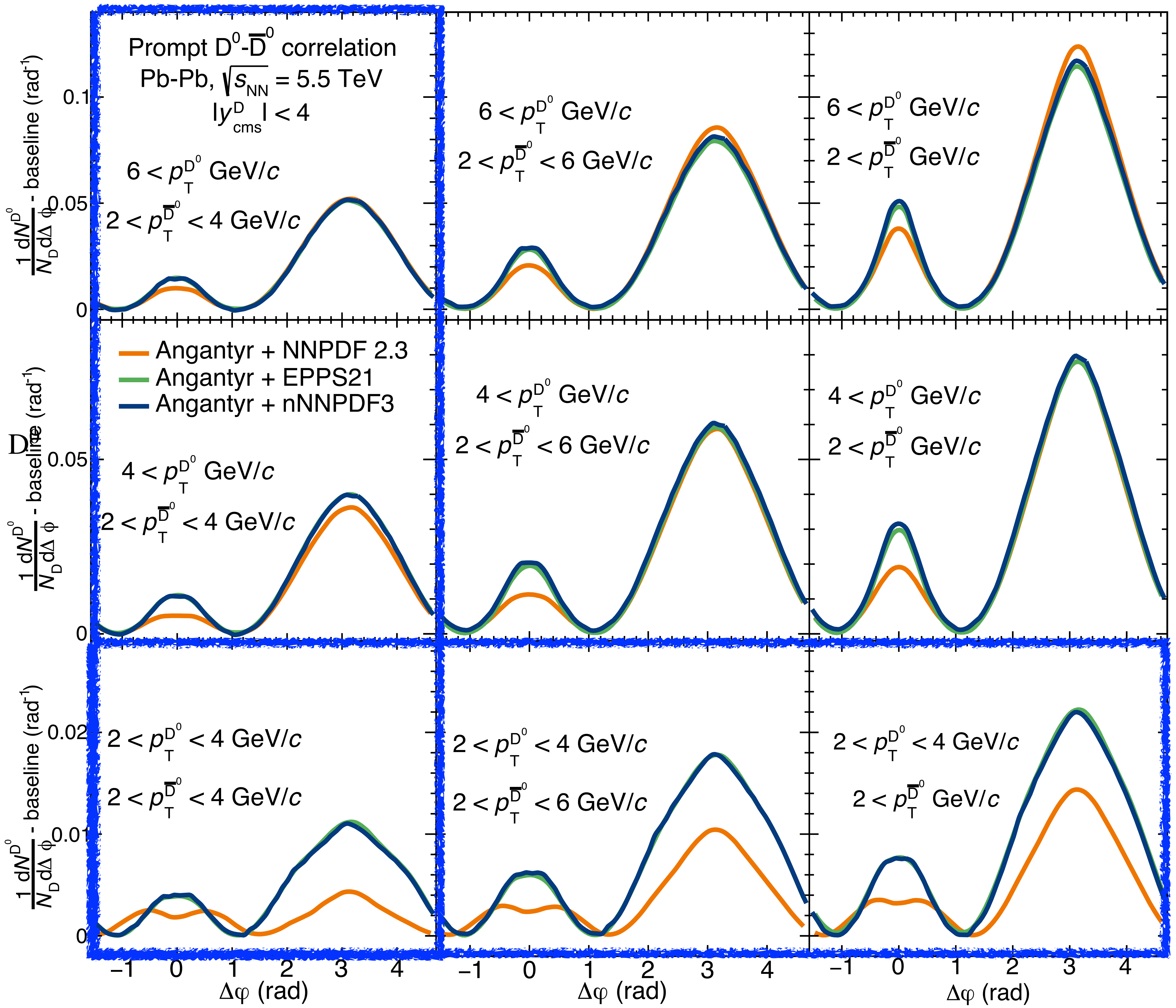


Ref : LOI ALICE3 [arXiv:2211.02491v1]



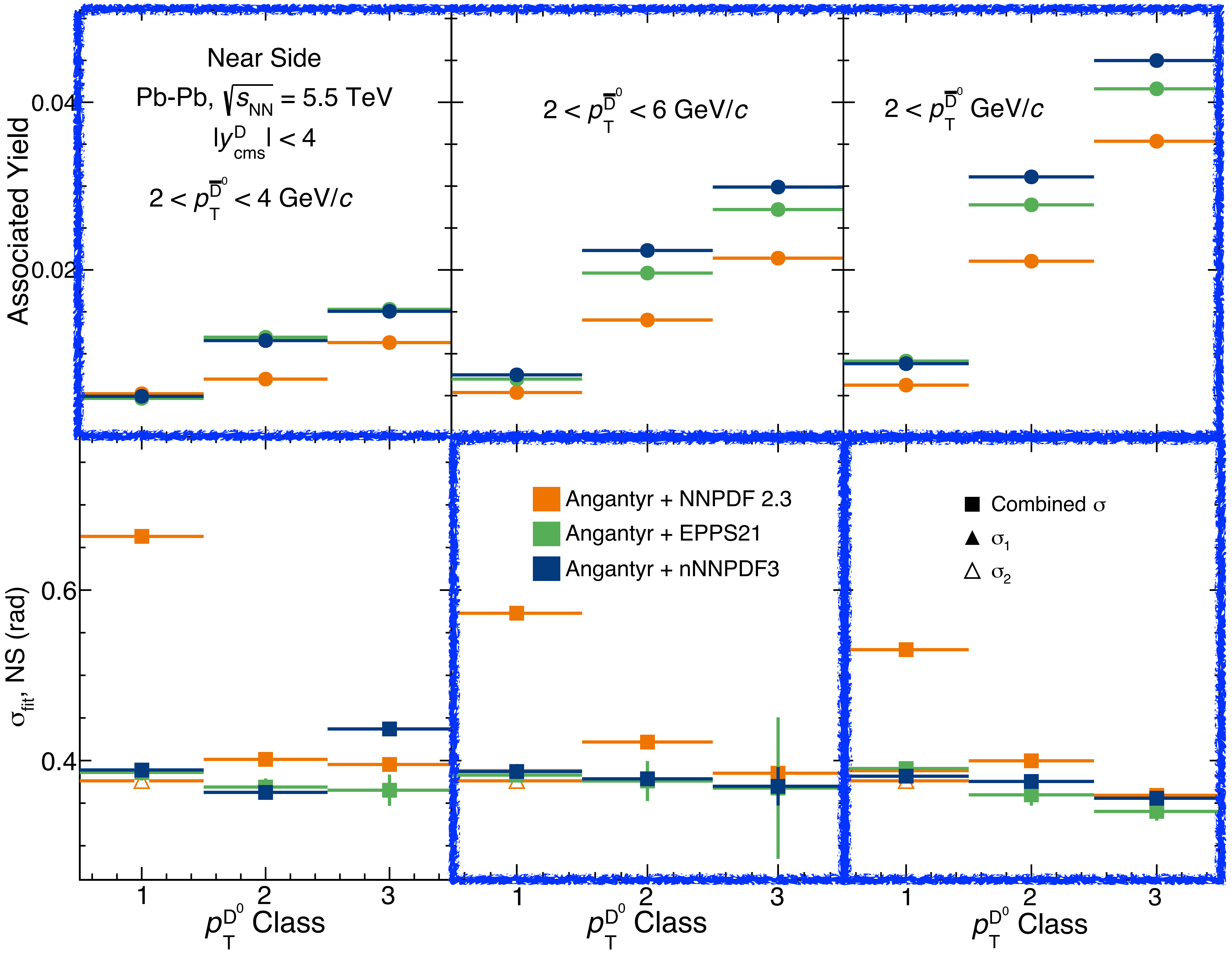
Results: $D^0 - \bar{D}^0$ correlation

- Azimuthal angular correlation between mesons produced in same hard scattering.
- Simulation of Pb—Pb collisions at 5.5 TeV using PYTHIA8 + ANGANTYR model
- Double peak in NS for $2 < p_T^{D^0}(\text{GeV}/c) < 4$
  - Gluon splitting
  - Absence of double peak for nuclear PDFs
- Higher yield from left to right for all PDFs: More associate particle pairs are available
- Increasing yield from low to high $p_T^{D^0}$ for all PDFs
- NS yield is smaller for free proton PDF compare to nuclear PDFs



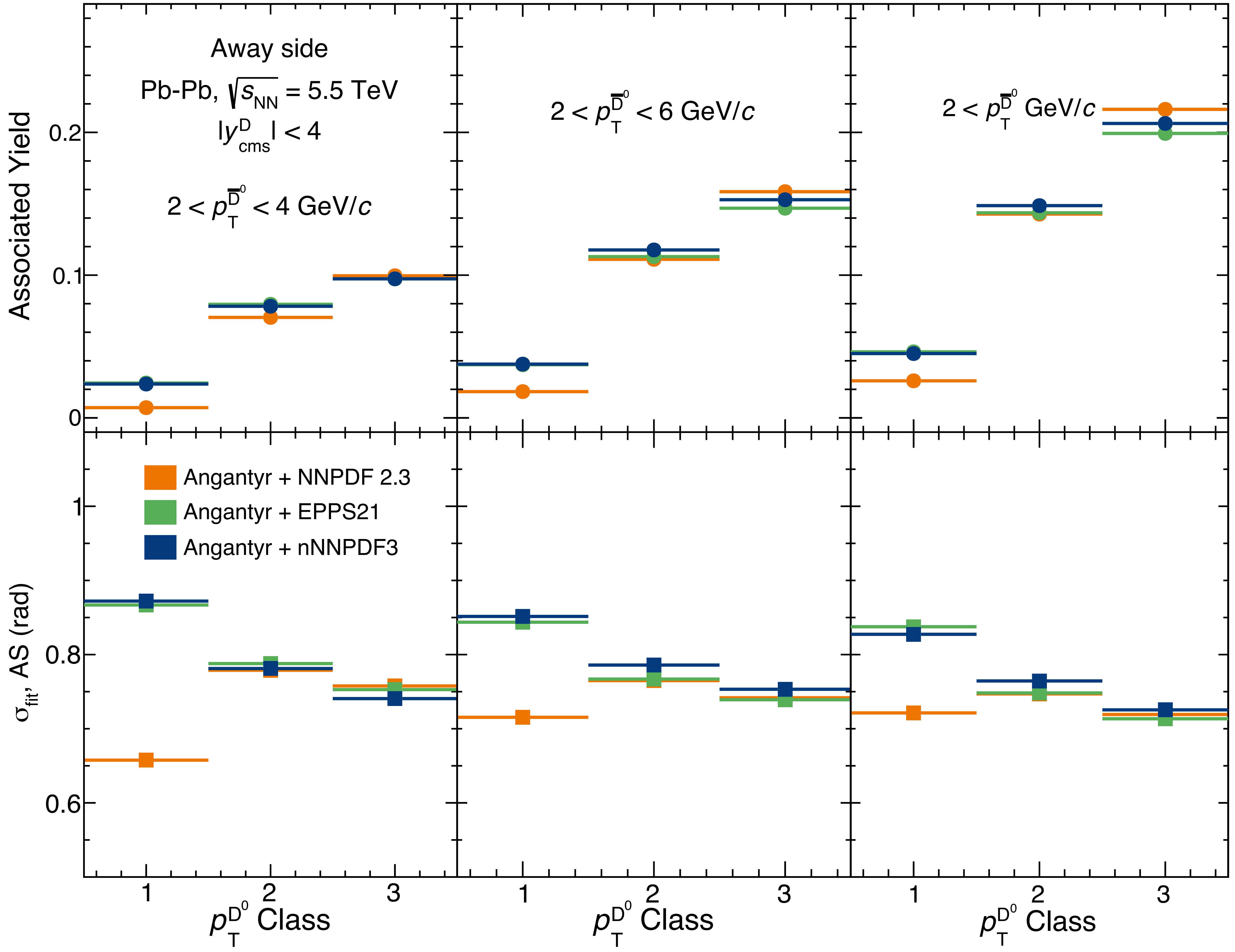
$D^0 - \bar{D}^0$ Correlation Results: Near Side

- Yield increases as a function of $p_T^{D^0}$ and $p_T^{\bar{D}^0}$
- Yield (NNPDF) < Yield (nPDF), can be due to LO and NLO nature of proton and nPDFs
- Combined sigma for $2 < p_T^{D^0} \mathrm{GeV}/c < 4$ is significantly larger.
- Strength of correlation ↑ (width ↓) as $p_T^{D^0}$ ↑ due to high boost $(2 < p_T(\mathrm{GeV}/c))$, nPDFs also shows similar trend
- Strength of correlation is same as $p_T^{D^0}$ ↑ $(2 < p_T(\mathrm{GeV}/c) < 6)$
- Difference nPDFs attributes to different treatment of heavy flavours



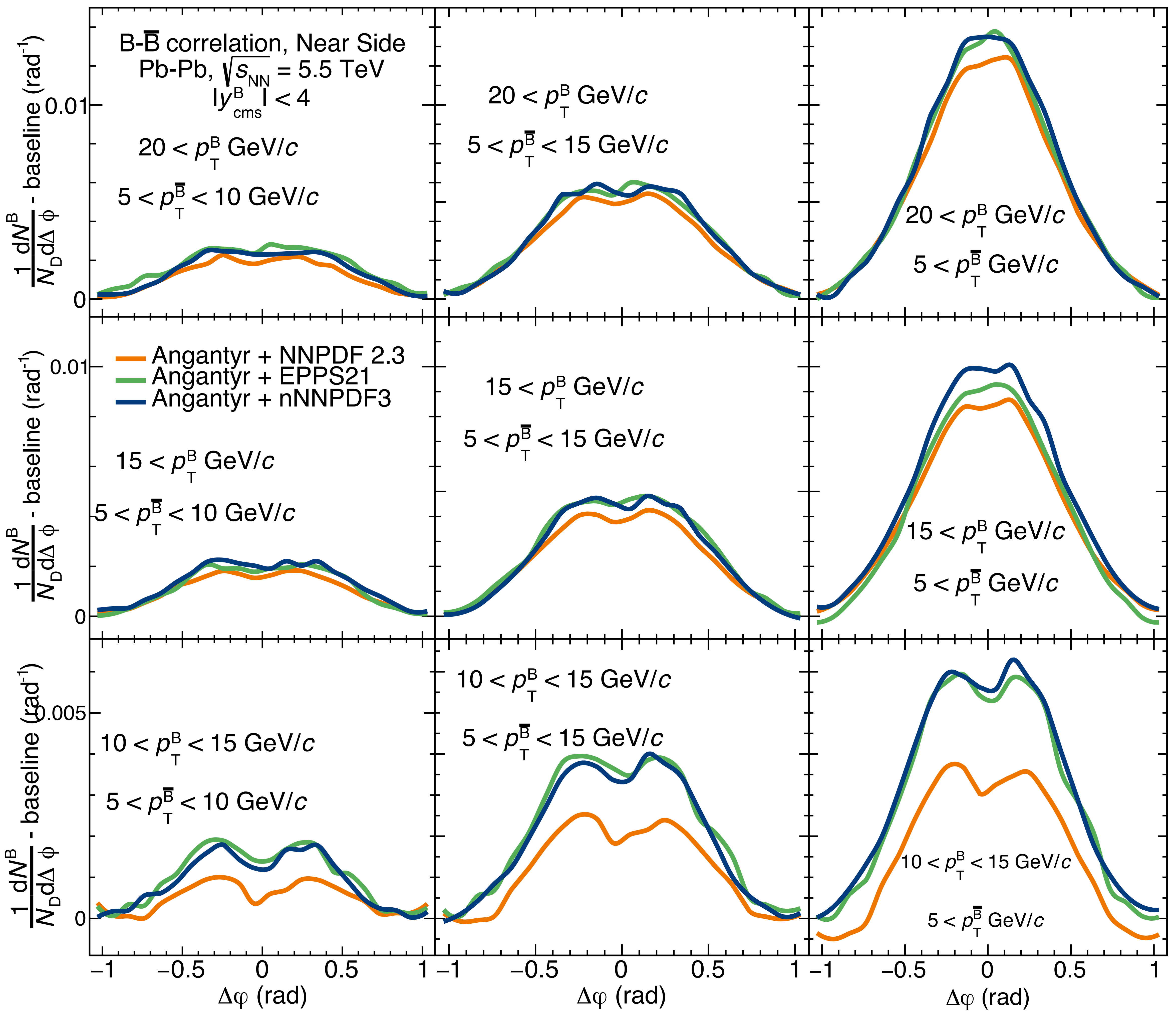
$D^0 - \bar{D}^0$ correlation results: Away side

- Away side yield increases as a function of trigger as well as associate transverse momentum.
- At low $p_T^{D^0}$, associated yield for nPDF and free proton PDF are significantly different as nuclear PDF effects should be visible at low $p_T^{D^0}$.
- At higher p_T^{Trig}, Yield (NNPDF) ~ Yield (nPDFs)
- For $p_T^{D^0}$ $2 < p_T(\mathrm{GeV}/c) < 4$, away side peak is wider for nuclear PDFs.
- Two nuclear PDFs are consistent with each other quantitatively

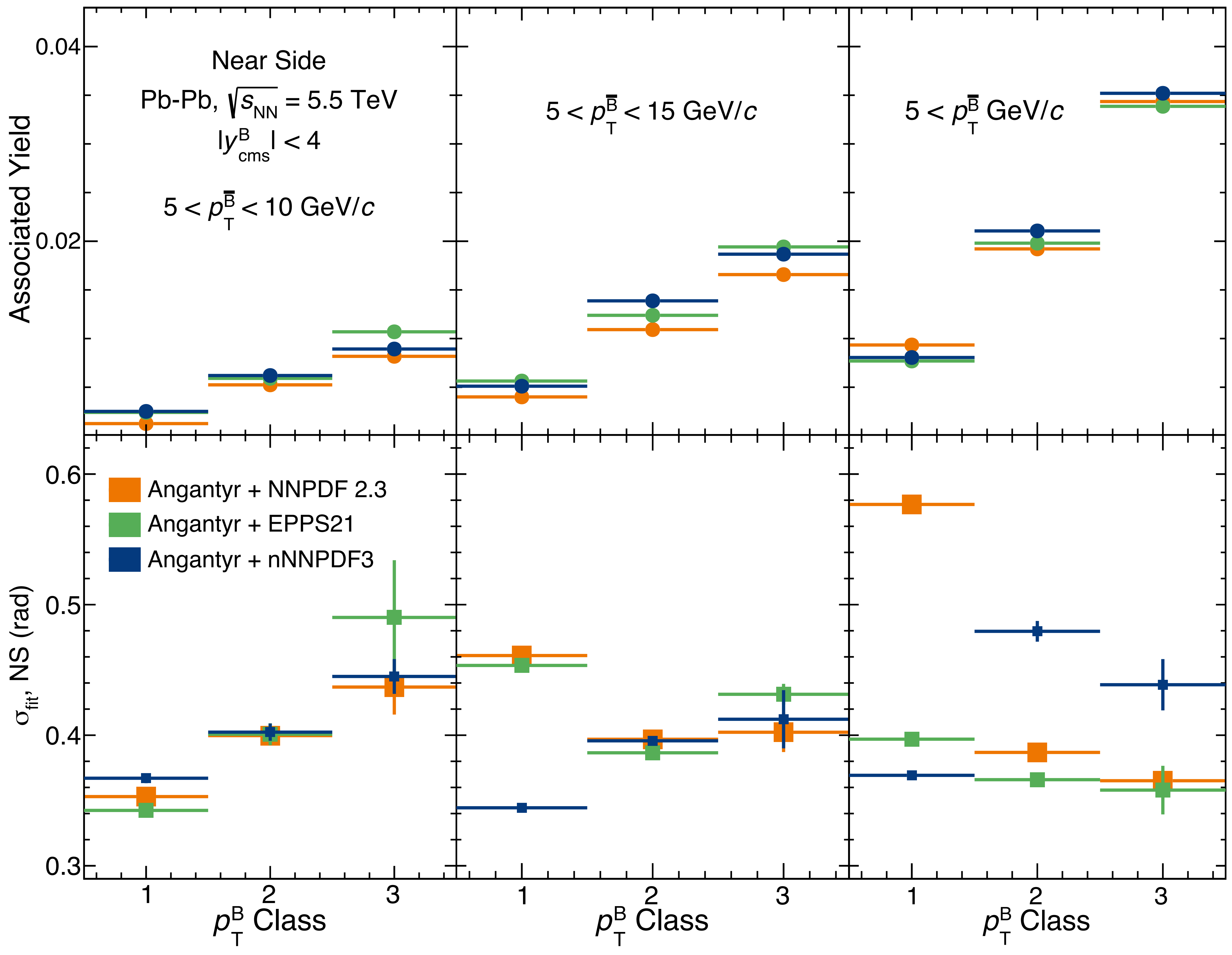


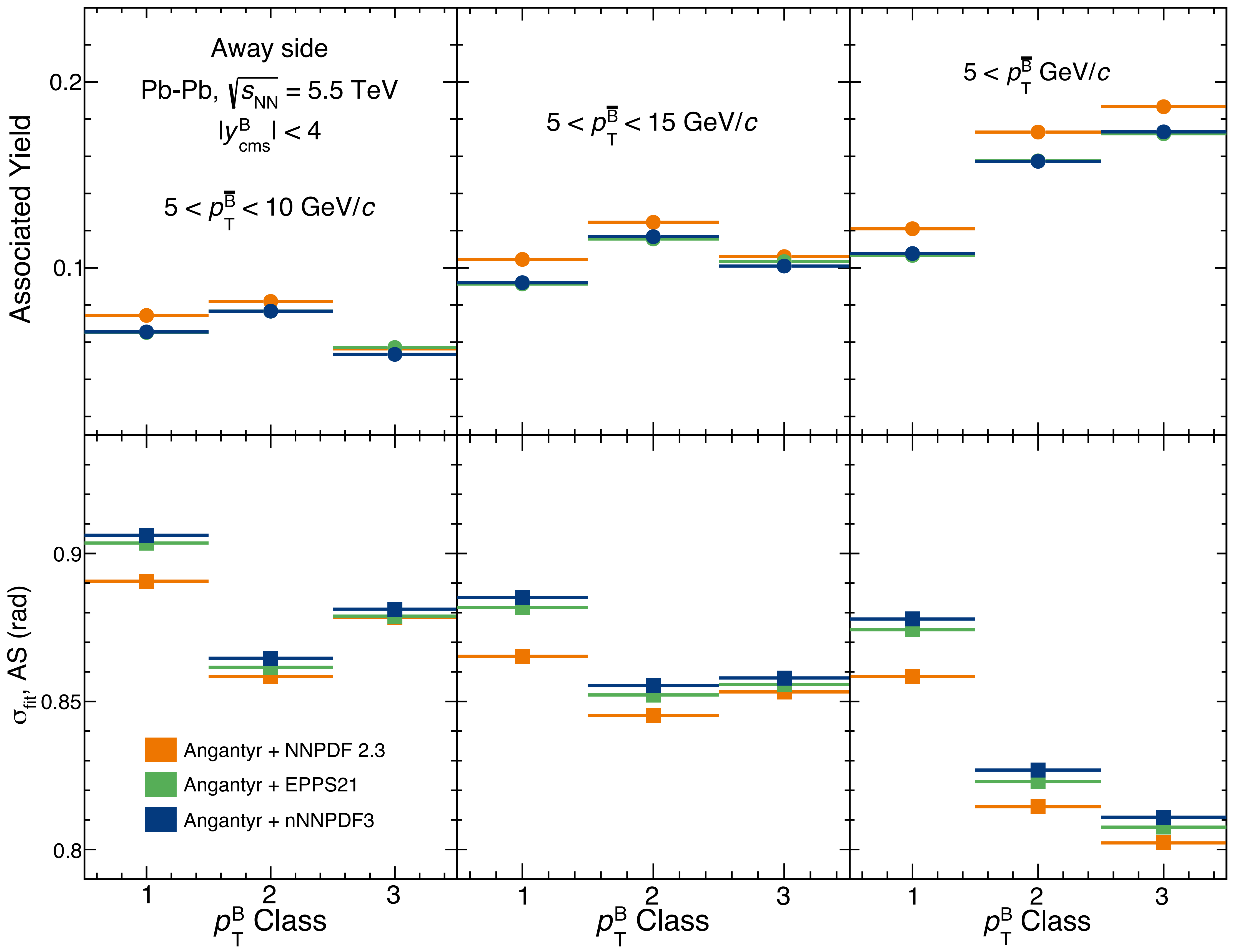
Results: $B - \bar{B}$ correlation

- Trigger and associate p_T ranges are higher than in case of charm mesons.
- Azimuthal distribution is fitted with two generalised Gaussian in near side and Gaussian mutinied by triangular function for away side.
- Except for $10 < p_T^{Trig}$ GeV/c < 15, nuclear and free proton PDF correlations are compatible with each other.
- Double peak at near side observed for nuclear as well as proton PDFs.



$B - \bar{B}$ correlations: Yield and Sigma





- Near side as well as away side yield for nuclear PDFs and proton PDFs are compatible with each other
- Widths are also compatible for all PDFs with exceptions at low p_T

- For away side, Trigger class 3 shows lower yield compared to class 2
- For away side, Trigger class 3 also shows higher width of the distribution than class 2

Summary

- An azimuthal angular correlation of D^0 with other charged particles is an excellent probe of production, fragmentation and hadronization of charm quark as well as various phases of heavy ion collisions.
- In pp collisions, no single model can completely describes the near side as well as away side of azimuthal angular correlations especially at high p_T.
- More precise measurements are needed to better constrain a theoretical models describing production, fragmentation and hadronization of heavy flavours.
- Effects of nuclear PDFs on $D^0 - \bar{D}^0$ azimuthal angular correlation are found to be considerable and should be considered during charm thermalisation measurements with ALICE3.
- Effect of nuclear PDFs is found to be p_T dependent.
- Measurement of $D^0 - \bar{D}^0$ and $B - \bar{B}$ azimuthal correlation can also help to study kinematics of production processes like gluon splitting and pair production in detail.

Outlook

- Finishing D^0- h analysis for pp collision at 13.6 TeV and possibly extending a study in Pb—Pb to better understand the modification due to QGP.
- Extending nuclear PDF study to FoCAL detector which is sensitive to small-x physics.
- Exploring the effects of initial states and energy loss in medium on $D^0 - \bar{D}^0$ azimuthal correlation in heavy-ion collisons using JETSCAPE.

Publications

- Effects of nuclear PDFs on azimuthal angular correlation of open heavy flavours. (By end of June)
- Jet fragmentation via azimuthal angular correlations of heavy flavours in pp collisions at s=7 TeV, R. Singh, **S. Khade**, A.Roy, PRC 107 (2023) 2, 025206

Talks

- ALICE-India collaboration meeting (IIT Bombay)
- ALICE-India collaboration meeting (VECC)

Conferences

- Heavy Flavour Meet 2023: Poster presentation
- Hot QCD, IIT Goa, May 2022
- CETHENP, VECC, December 2022

Thank You

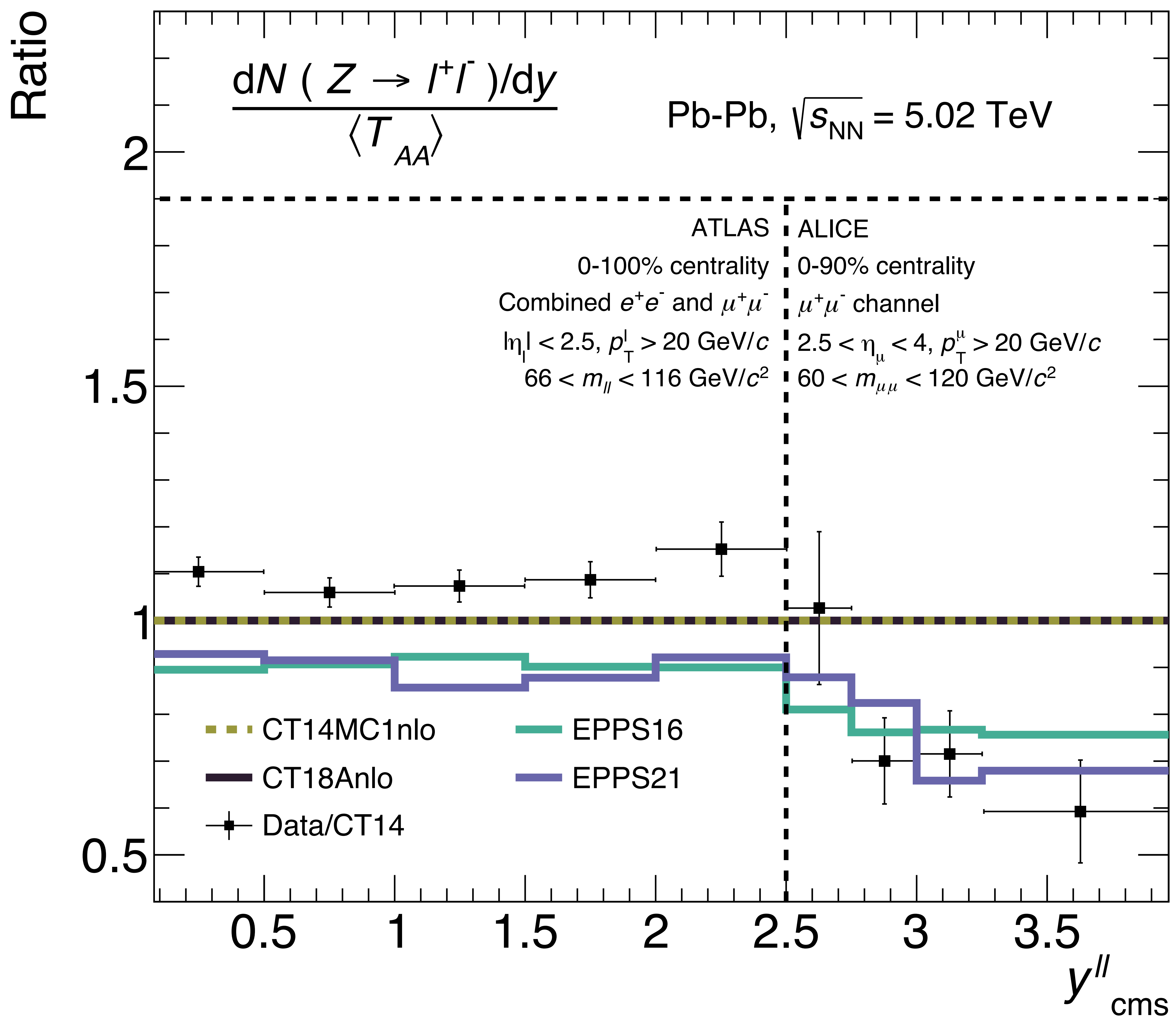
Backup Slides

Results: W/Z boson production

- Weak bosons are excellent probes of PDFs ($Q^2 \approx M_Z \approx 91$ GeV/c^2)
  - Weak interactions with QGP
  - Reconstructed via leptonic decay channel

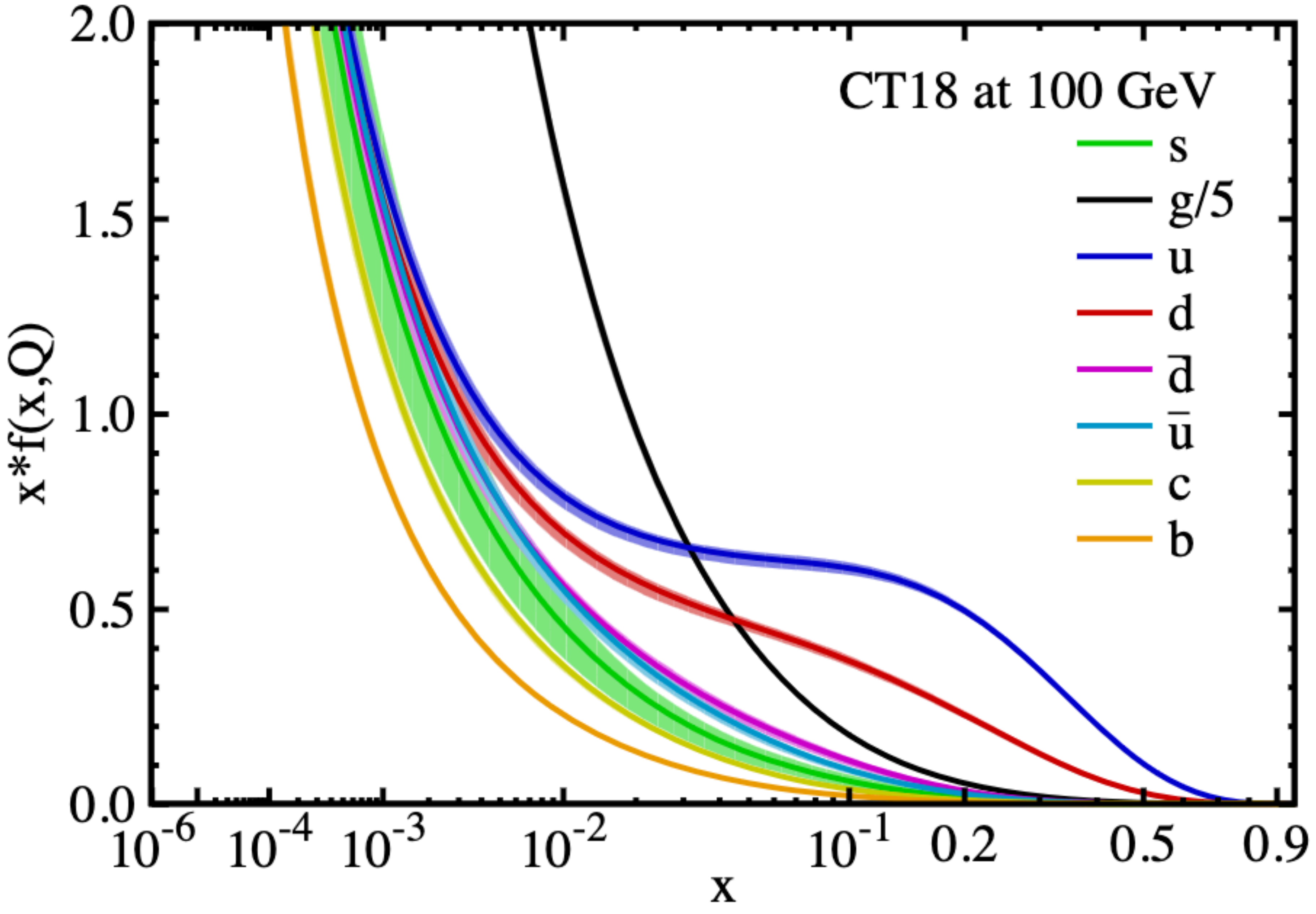
$$x \approx \frac{Q^2}{s} e^{-|y|}$$

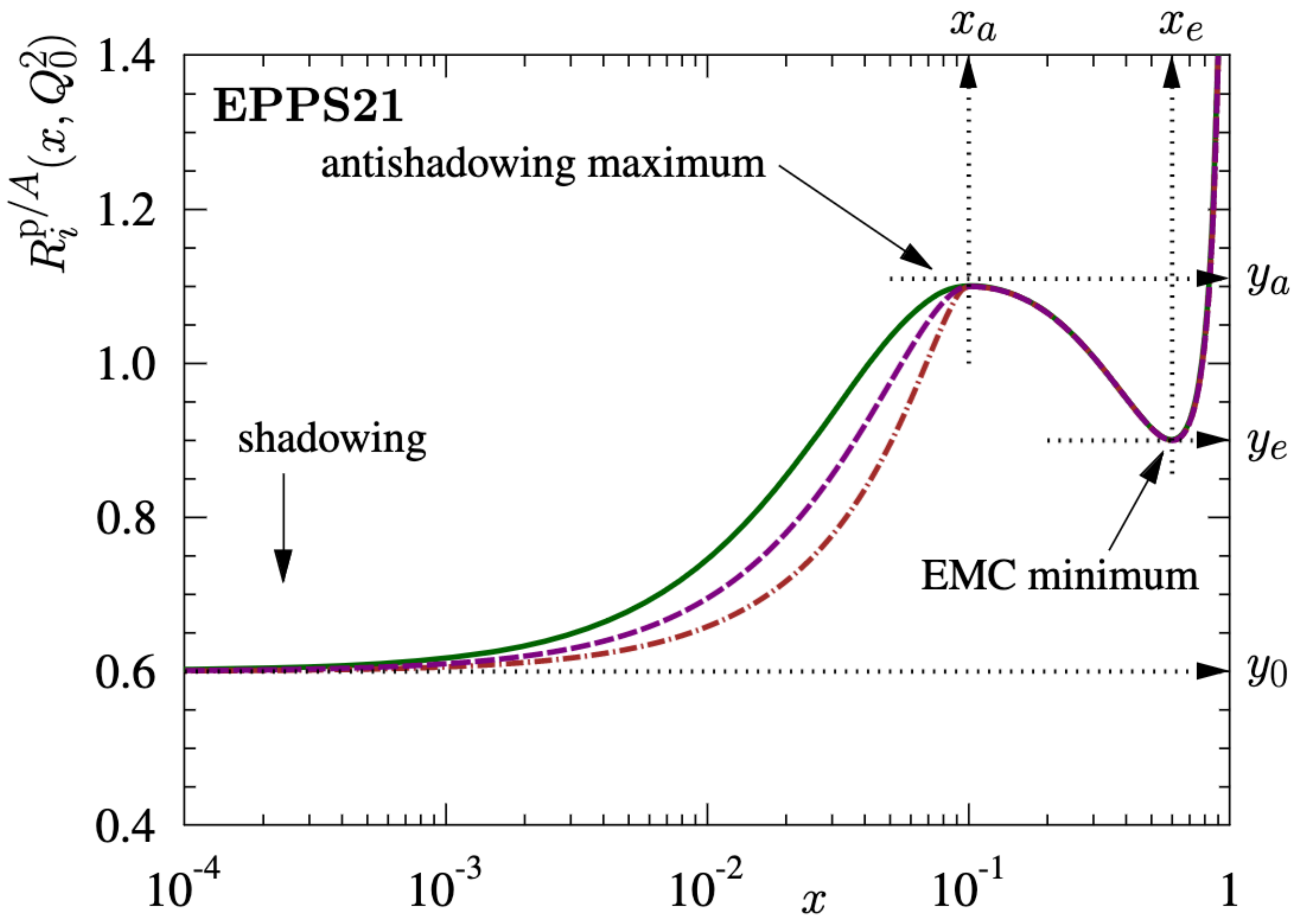
- Simulation of Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using PYTHIA8 + Angantyr (No QGP medium)
- Comparison between free proton PDFs and nuclear PDFs
- At forward rapidities nuclear PDFs are explaining experimental data better than free proton PDFs
- Integrated rapidity yield shows 3.4σ deviation from free proton PDF → Importance of using nuclear PDFs in phenomenological studies



Parton distribution function

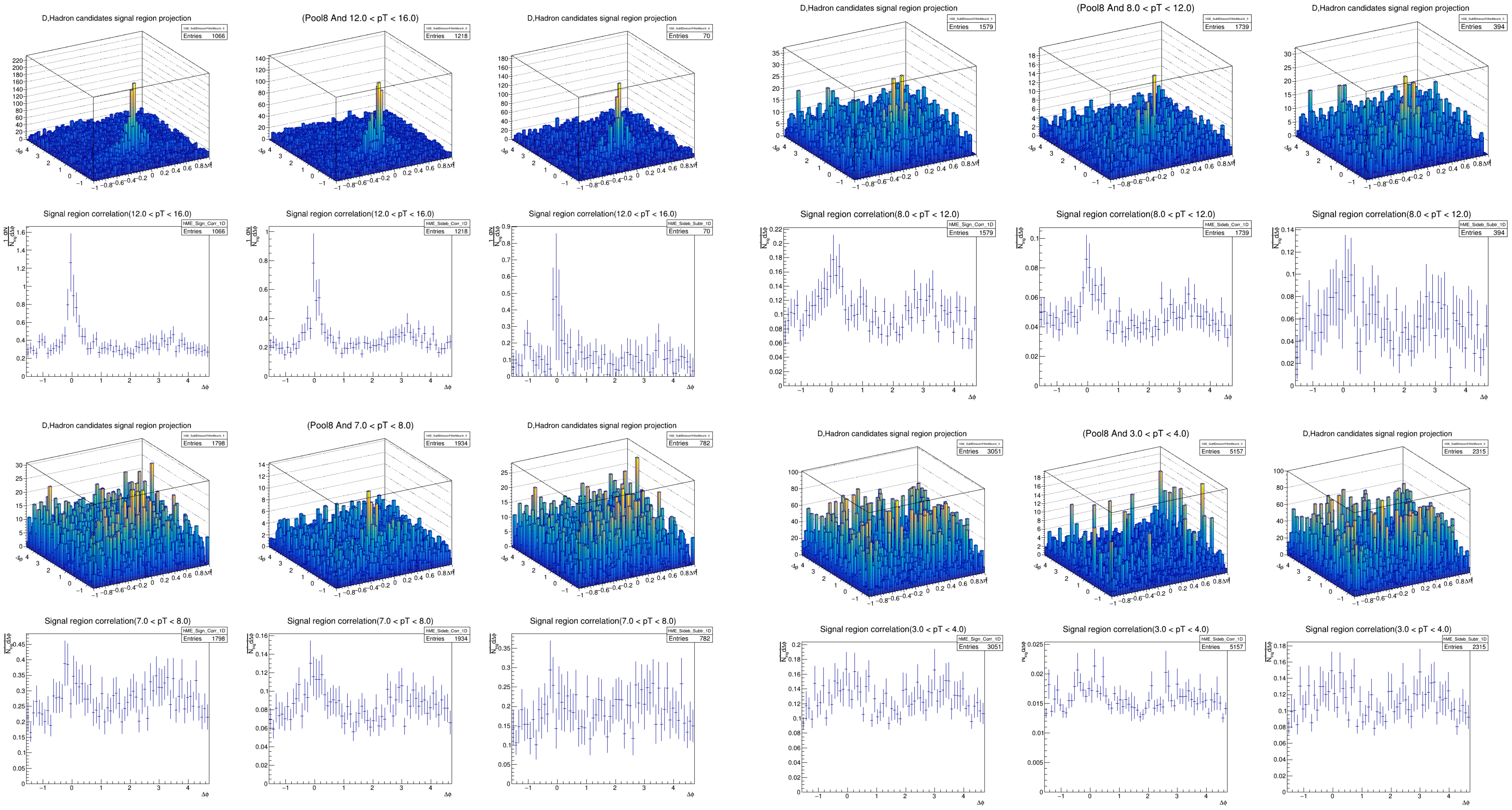
- Parton distribution function (PDF) : probability of finding a parton inside nucleon
- Nuclear PDF (nPDF) : Modified PDF due to nuclear environment
- PDF/nPDFs differ methods of extraction of PDFs from data





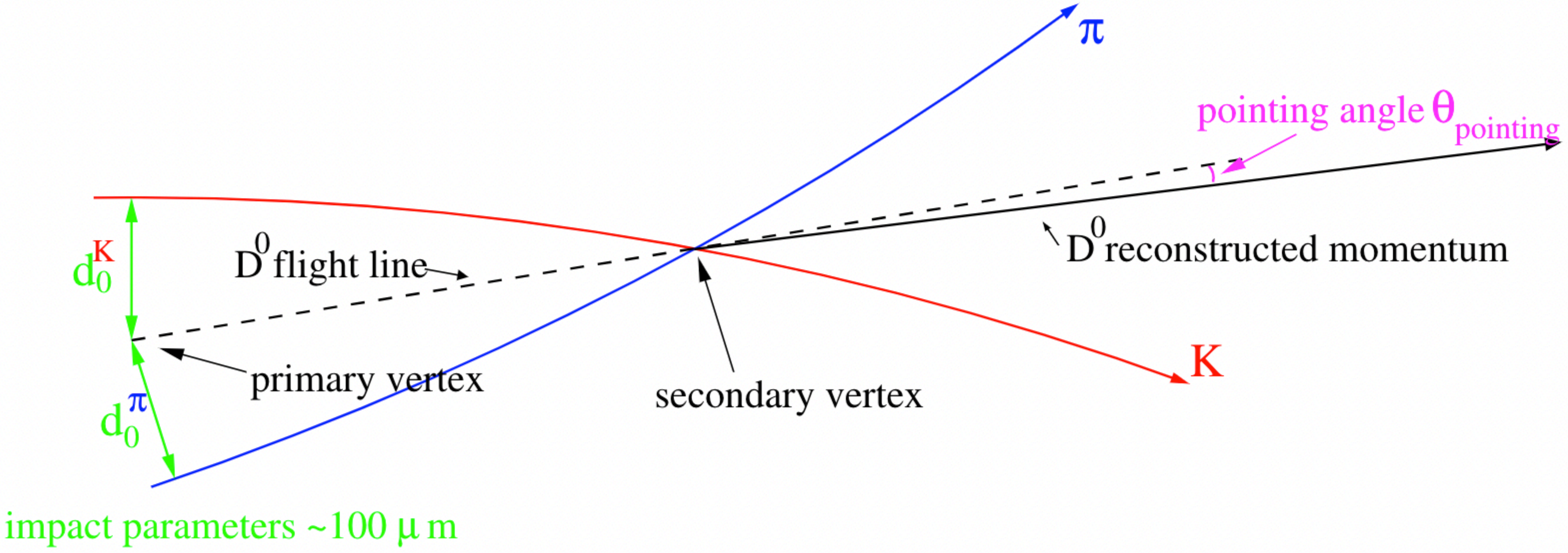
$$f^{p,n/A}(x, Q^2) = R_f^{p/A}(x, Q^2) f^{p,n}(x, Q^2)$$

Extraction Task results : ME corrections (Pool 8)



D^0 selection cuts

- Cuts for D^0 Selection : hf_D^0_candidate selector task



Kinematical / Topological cuts	
Δm	0.4 GeV/c^2
DCA	0.035 cm
$\cos\theta^*$	0.8
pT K^-	0.5 GeV/c
pT π^+	0.5 GeV/c
$\lvert d_0^K \rvert$	1.0 cm
$\lvert d_0^\pi \rvert$	1.0 cm
$d_0^K \times d_0^\pi$	-2E-05 cm^2
$\cos\theta_p$	0.9
$\cos\theta_{pxy}$	0.9
Decay length	10 cm
Decay length XY	10 cm
Minimum decay length	0.06 cm

Detector cuts	
pTCandMin	0 GeV/c
pTCandMax	50 GeV/c
pidTPCMinpT	0.15 GeV/c
pidTPCMaxpT	10 GeV/c
nSigmaTPC	3
nSigmaTPCCombined	5
pidTOFMinpT	0.15 GeV/c
pidTOFMaxpT	10 GeV/c
nSigmaTOF	3
nSigmaTOFCombined	5

D^0-hadron correlation : Physics motivation

- Heavy quarks are produced in initial hard scattering processes.
- High p_T heavy quarks produced in these collisions produce directed spray of particles called as jets.
- D^0-hadron azimuthal correlation is a $\Delta\phi$ distribution of charged particles in heavy ion collisions w.r.t D^0 meson.

$$\Delta\phi = \phi_{trig} - \phi_{asso}$$

D^0-hadron correlation as probe of

- Heavy quark production
- Initial state effects
- Quark gluon plasma
- Fragmentation and Hadronization