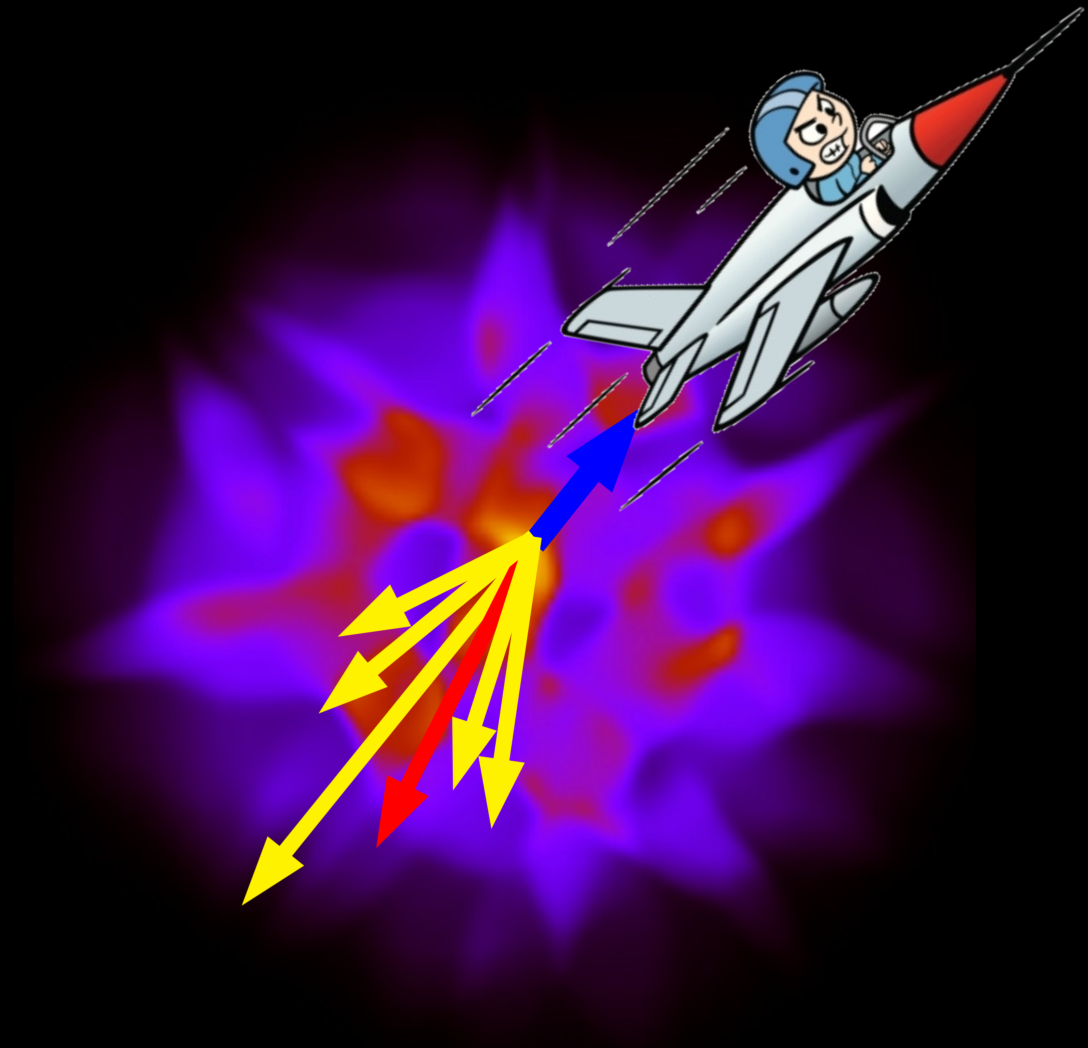
Jet-hadron correlations



Christine Nattrass
University of Tennessee, Knoxville

Hydro simulation of a single Au+Au collision

Shown is the energy density in the transverse plane. For more

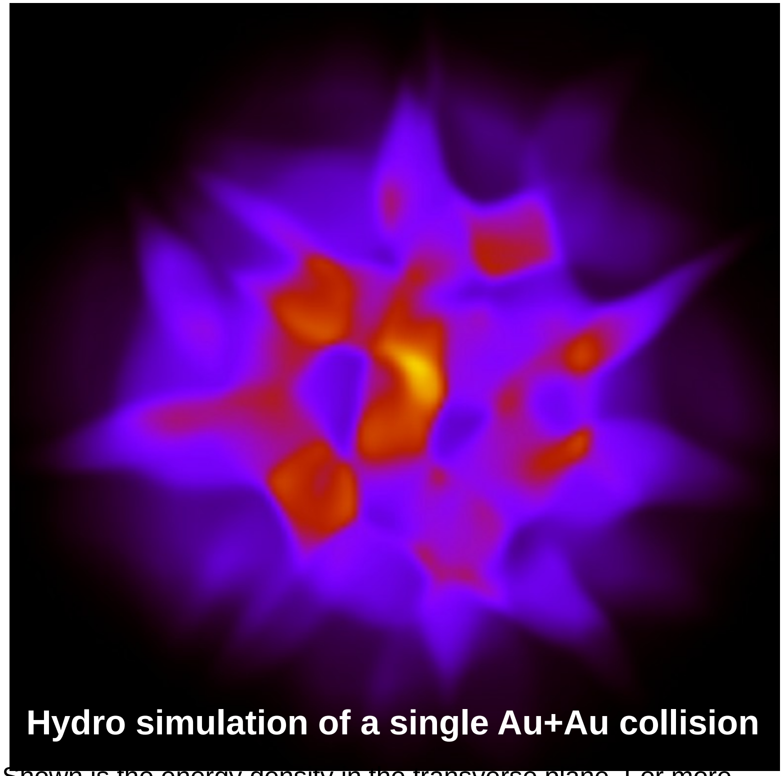
Why measure jet-hadron correlations?

Because we understand the background

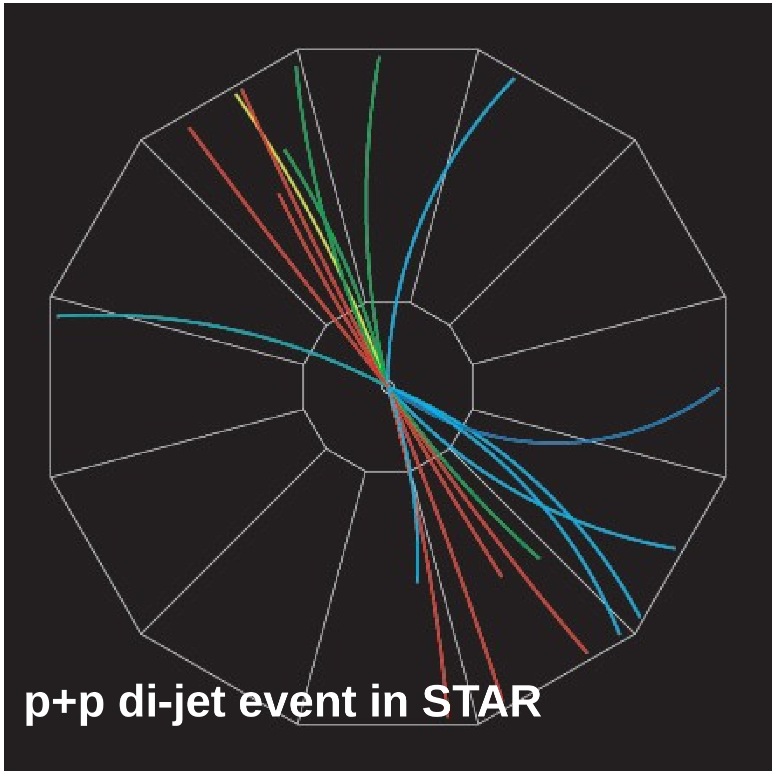
So we can study the away side

What is measured

Jets and flow



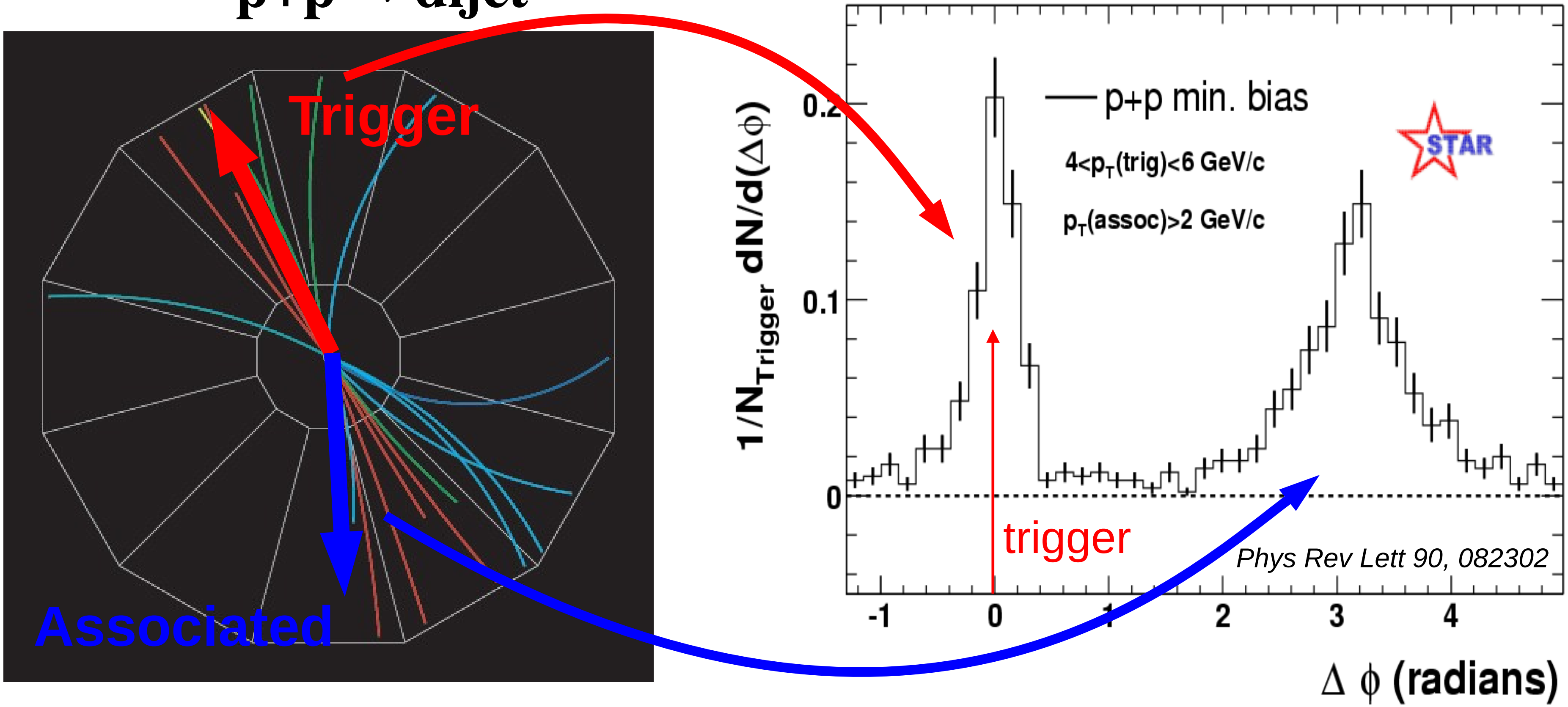
Shown is the energy density in the transverse plane. For more information on the simulation refer to arXiv:1009.3244.



- Both lead to azimuthal correlations
- Jets → background for flow
- Flow → background for jets

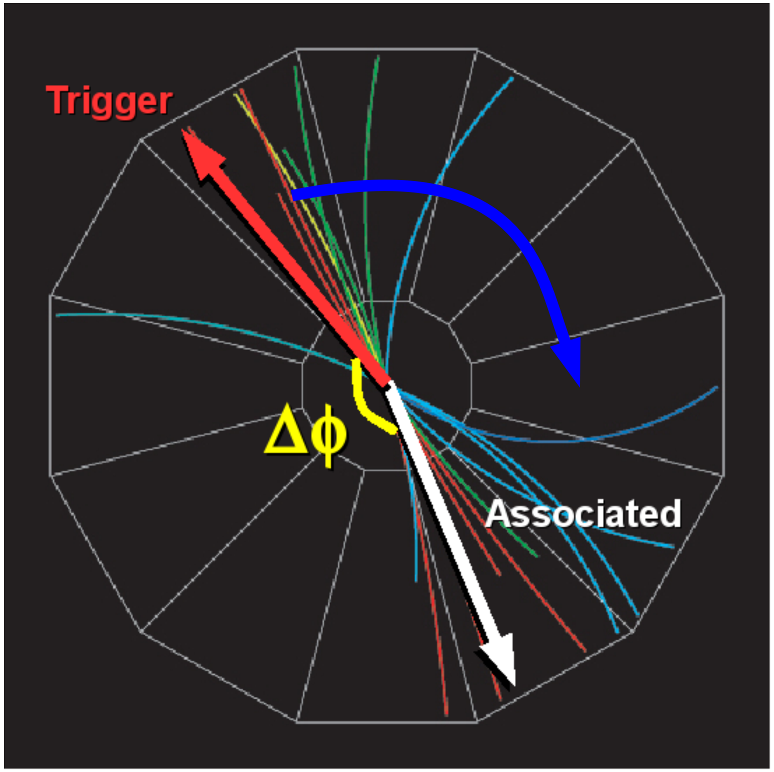
Jets – azimuthal correlations

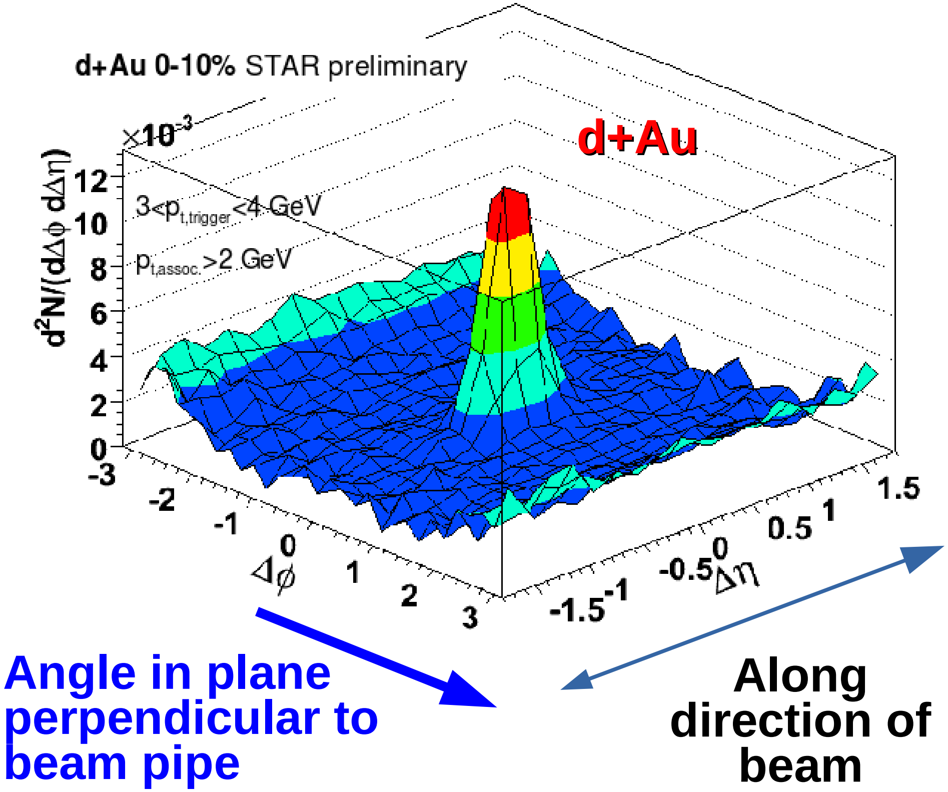
p+p → dijet



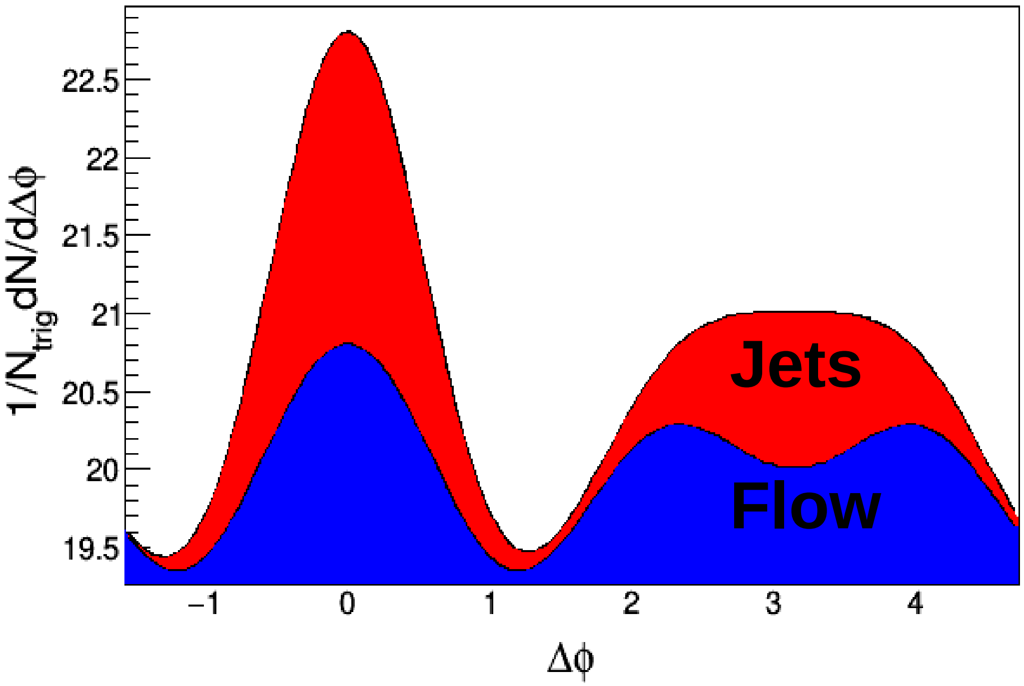
Select high momentum particles → biased towards jets

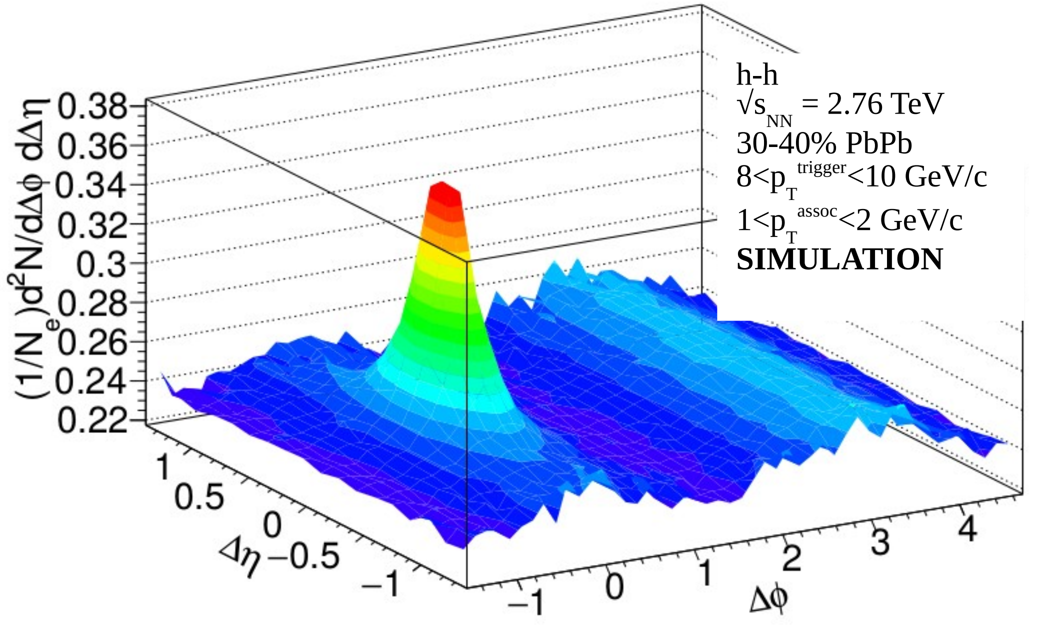
Looking in two dimensions





Two component model



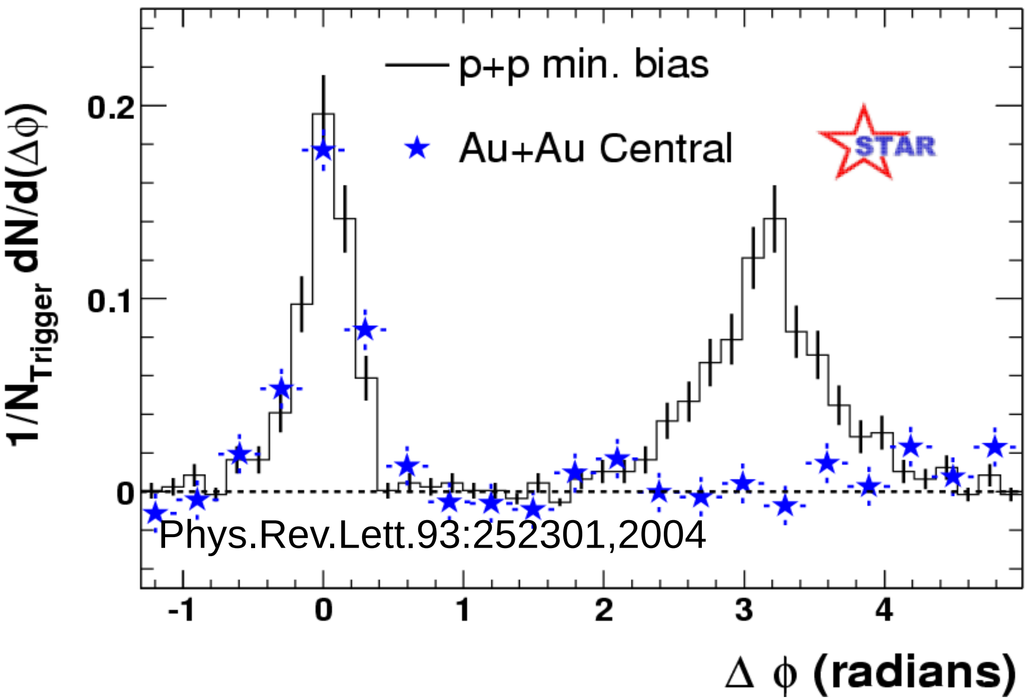


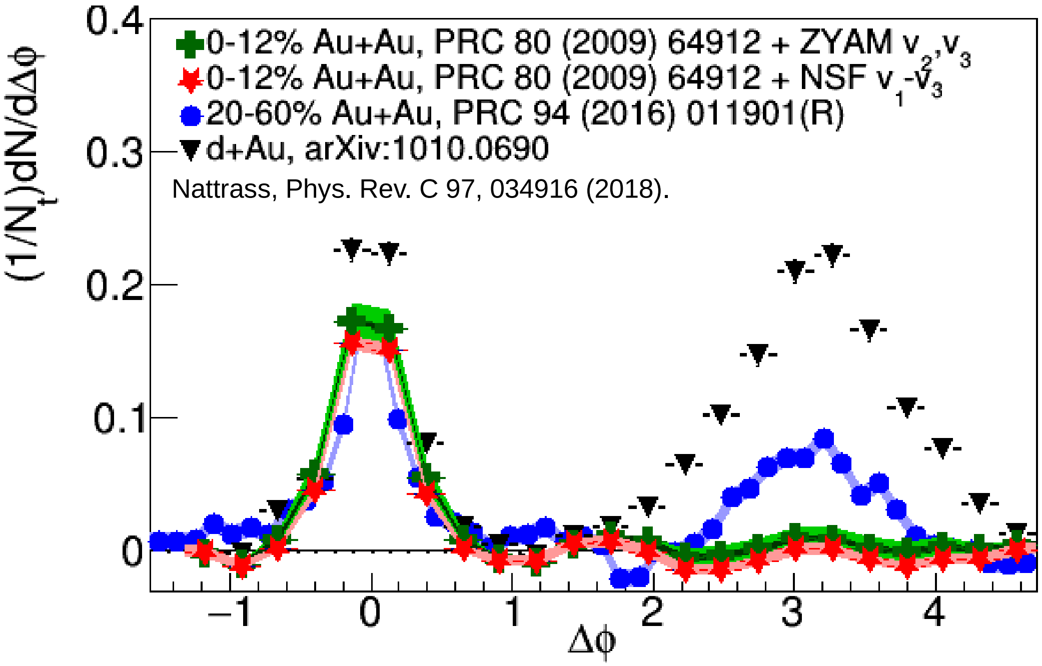
- Two component model
  - Assume contributions can be factorized
  - Alternately, define signal as anything which isn't consistent with separable flow and jet components
  - Assumptions *even embedded in most studies of full jets*
- Flow component given by $B\left(1+\sum_{n=2}^{\infty} \tilde{v}_n^t \tilde{v}_n^a \cos(n\Delta\phi)\right)$

Background Subtraction Methods

- **Zero-Yield at Minimum (ZYAM):** Assumes v_n from other studies, assumes region around $\Delta\varphi\approx1$ is background dominated
- **$\Delta\eta$ Method:** Project near-side signal onto $\Delta\eta$ and subtract constant background. Near-side only
- **$\Delta\eta$ Gap Method:** Use signal at large $\Delta\eta$ to determine background, assuming constant background in $\Delta\eta$. Near-side only
- **Near-Side Fit (NSF):** assumes small $\Delta\varphi$/large $\Delta\eta$ region background dominated, fits v_n and B
- **Reaction Plane Fit (RPF):** assumes small $\Delta\varphi$/large $\Delta\eta$ region background dominated, fits v_n and B using reaction plane dependence
- **Near-Side Subtracted NSF/RPF (NSS NSF/RPF):** fits v_n and B at small small $\Delta\varphi$ using reaction plane dependence after subtracting the near-side with a fit

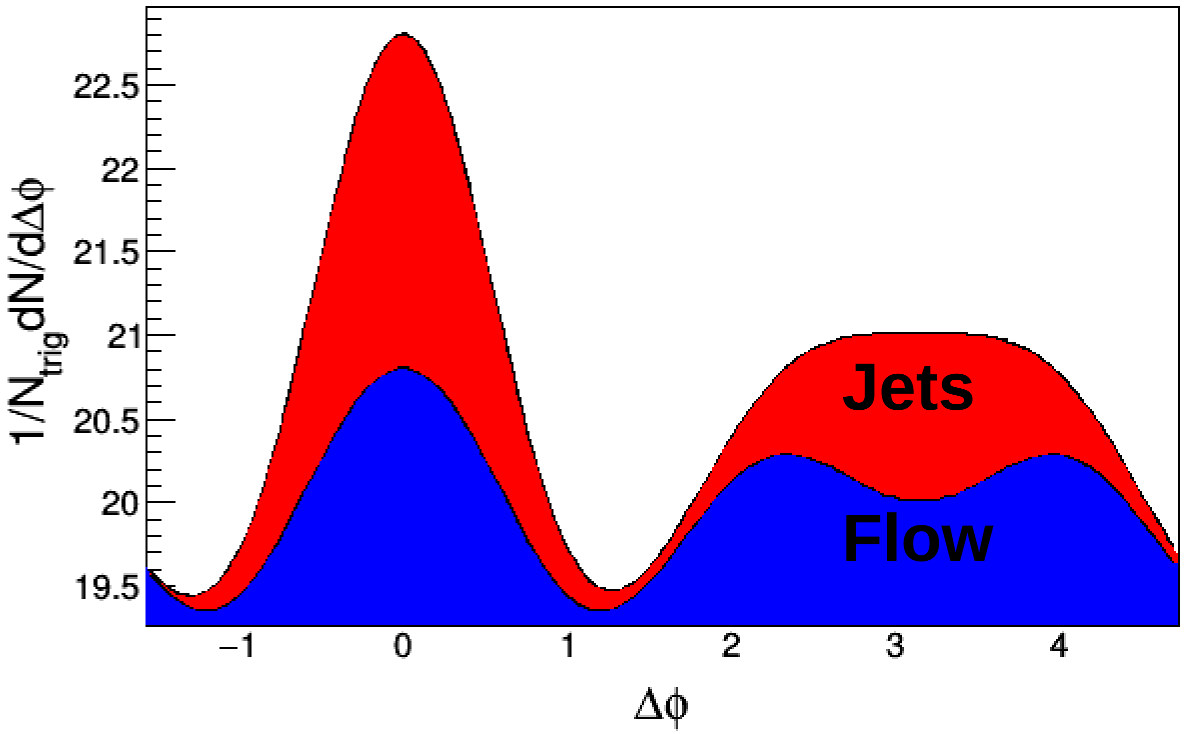
Dihadron correlations with vs without v_3





ZYAM

Zero Yield At Minimum



- Flow component given by

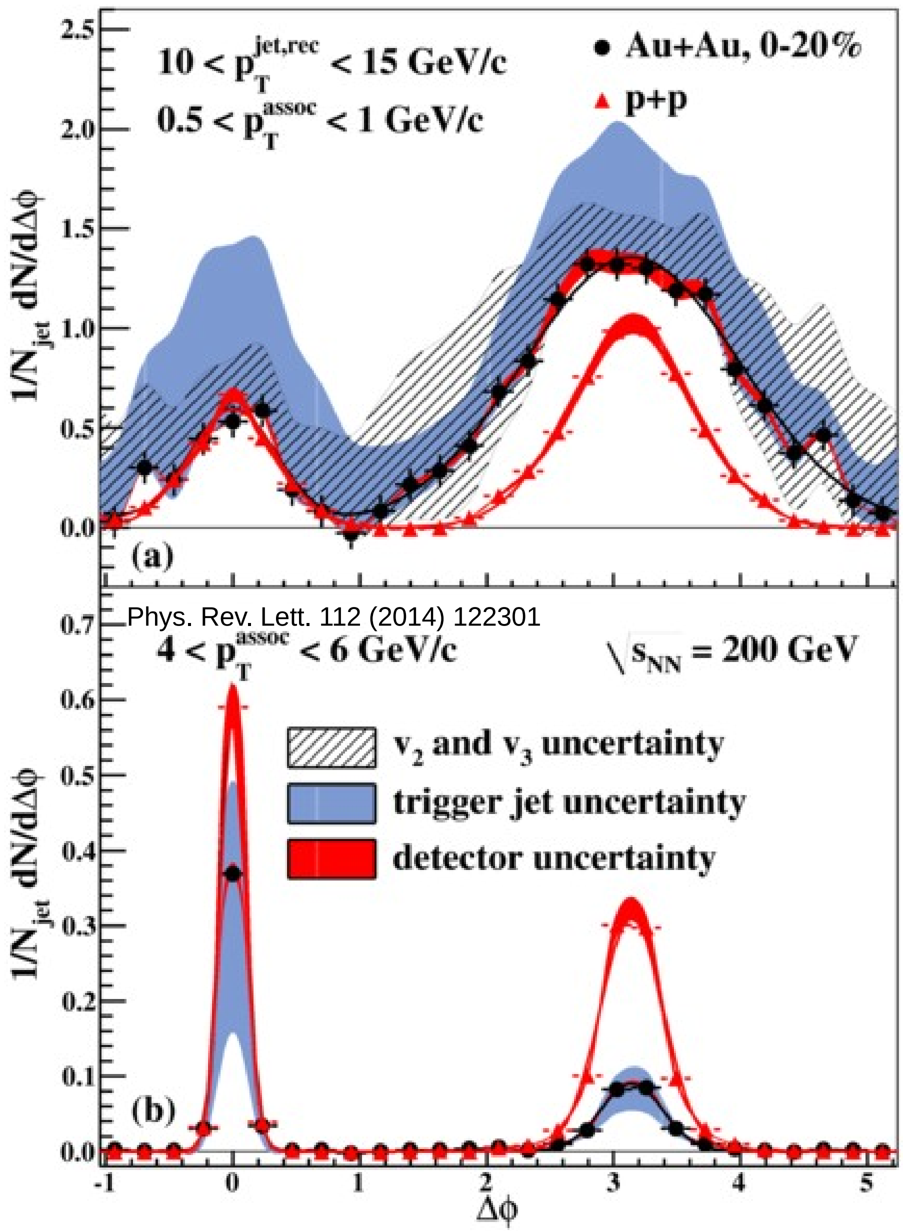
$$B\left(1+\sum_{n=2}^{\infty}\tilde{v}_n^t\tilde{v}_n^a\cos(n\Delta\phi)\right)$$

- Fix background level at minimum
- Use independent measurements of v_n

Issues with ZYAM

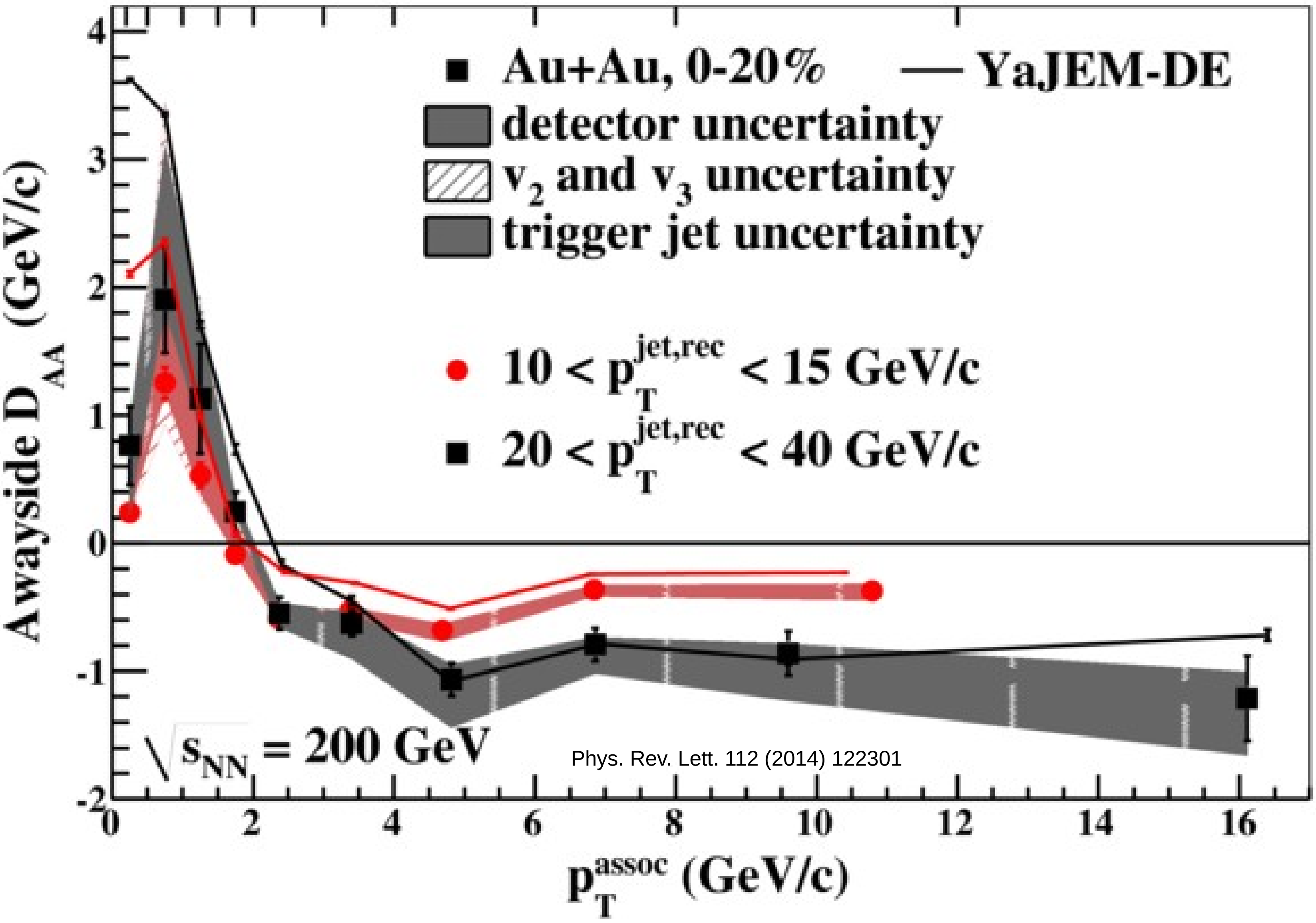
- Tends to underestimate background level
  - Can use fixed point (e.g. $\Delta\varphi=1$) instead
- v_n for background may not be the same as independent measurements
  - Cumulant methods suppress fluctuations $v_n < \tilde{v}_n$
  - Reaction plane measurements may include effects from jets $v_n > \tilde{v}_n$
  - Events with jets may be different $v_n \neq \tilde{v}_n$
  - High and low p_T reaction planes may be different $v_n \neq \tilde{v}_n$
  - Effective v_n are average over particle pairs and includes background from other jets. Measurements of flow are averaged over events and the goal is to suppress contributions from jets. $v_n \neq \tilde{v}_n$
- If jet peak is broadened, may overestimate background (underestimate signal)
- **Only v_2 measured for jets**

STAR



$10 < p_T^{jet,rec} < 15$ GeV/c
$0.5 < p_T^{assoc} < 1$ GeV/c
● Au+Au, 0-20%
▲ p+p
(a)
Phys. Rev. Lett. 112 (2014) 122301
$4 < p_T^{assoc} < 6$ GeV/c
$\sqrt{s_{NN}} = 200$ GeV
v_2 and v_3 uncertainty
trigger jet uncertainty
detector uncertainty
(b)
$1/N_{jet}$ dN/dΔφ
Δφ

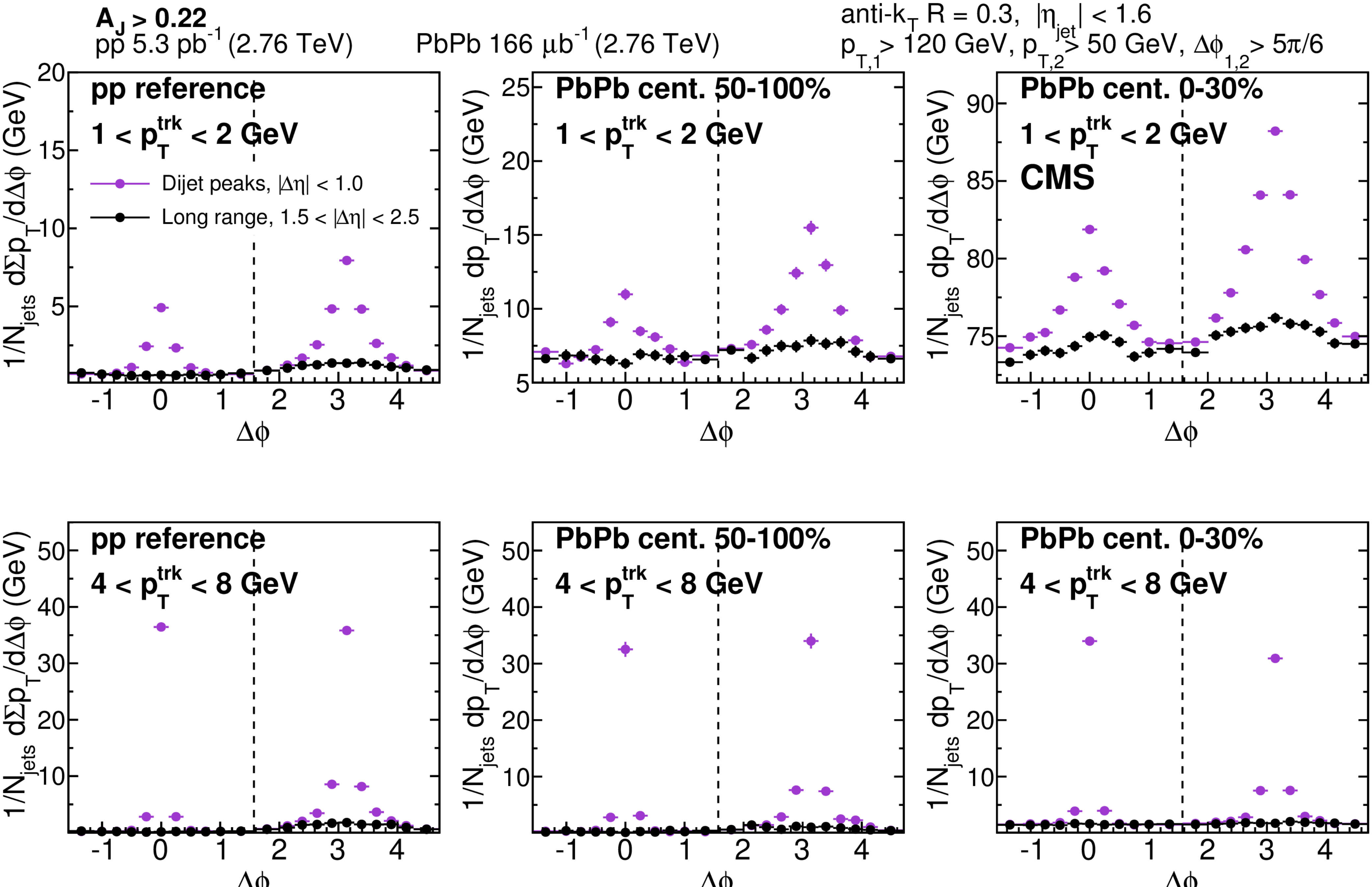
STAR



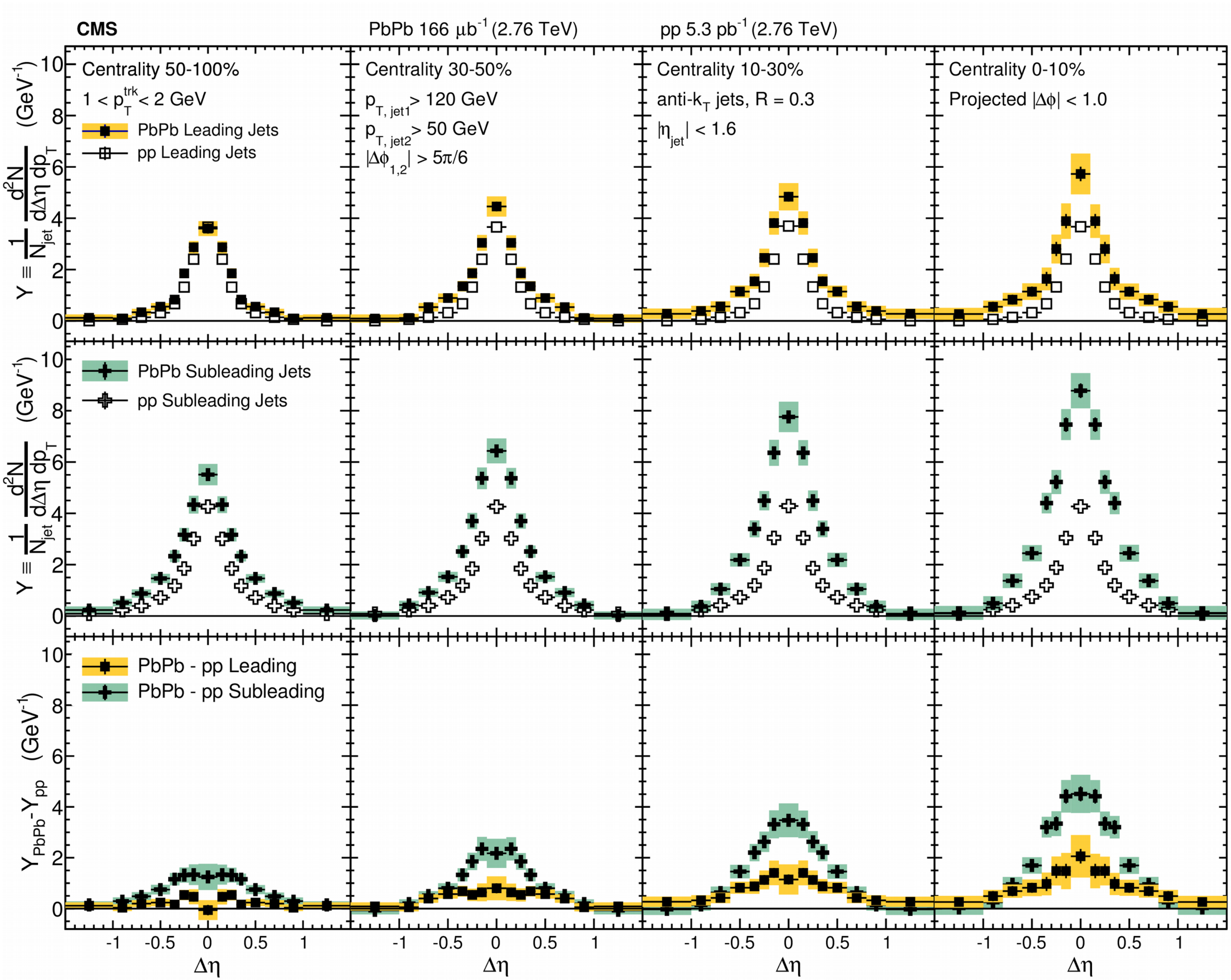
Au+Au, 0-20%
YaJEM-DE
detector uncertainty
v_2 and v_3 uncertainty
trigger jet uncertainty
$10 < p_T^{jet,rec} < 15$ GeV/c
$20 < p_T^{jet,rec} < 40$ GeV/c
$\sqrt{s_{NN}} = 200$ GeV
Phys. Rev. Lett. 112 (2014) 122301
Awayside D_{AA} (GeV/c)
p_T^{assoc} (GeV/c)

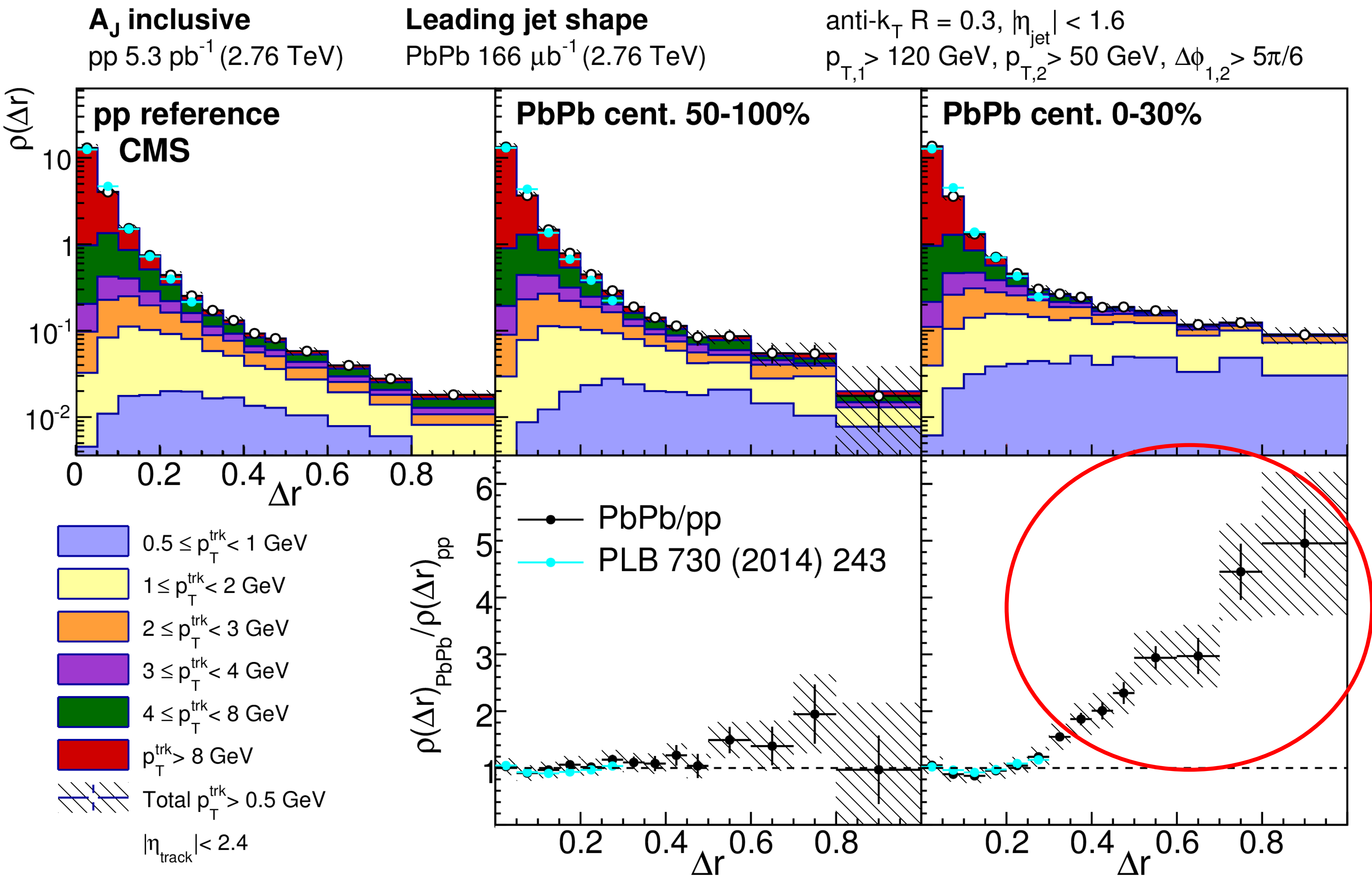
$\Delta\eta$ Method

CMS-HIN-PAS-15-011
JHEP 11 (2016) 055



CMS-HIN-PAS-14-016
JHEP 1602 (2016) 156



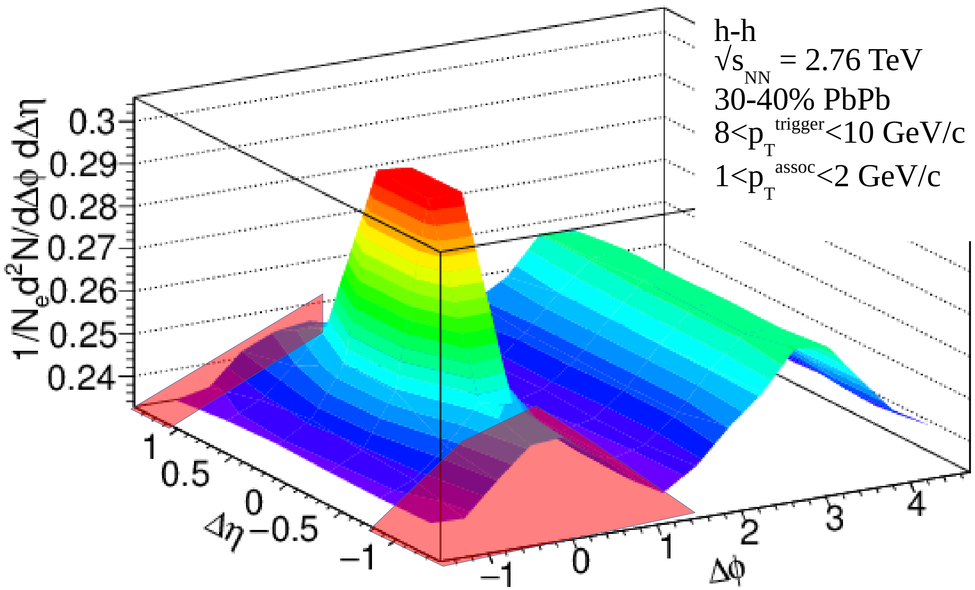

A_J inclusive
pp 5.3 pb^-1 (2.76 TeV)
Leading jet shape
PbPb 166 μb^-1 (2.76 TeV)
anti-k_T R = 0.3, |η_jet| < 1.6
p_T,1 > 120 GeV, p_T,2 > 50 GeV, Δφ_1,2 > 5π/6
pp reference
CMS
PbPb cent. 50-100%
PbPb cent. 0-30%
ρ(Δr)
Δr
ρ(Δr)_PbPb/ρ(Δr)_pp
PbPb/pp
PLB 730 (2014) 243
0.5 ≤ p_T^trk < 1 GeV
1 ≤ p_T^trk < 2 GeV
2 ≤ p_T^trk < 3 GeV
3 ≤ p_T^trk < 4 GeV
4 ≤ p_T^trk < 8 GeV
p_T^trk > 8 GeV
Total p_T^trk > 0.5 GeV
|η_track| < 2.4

Reaction Plane Fit

Based on Phys. Rev. C 93, 044915(2016)

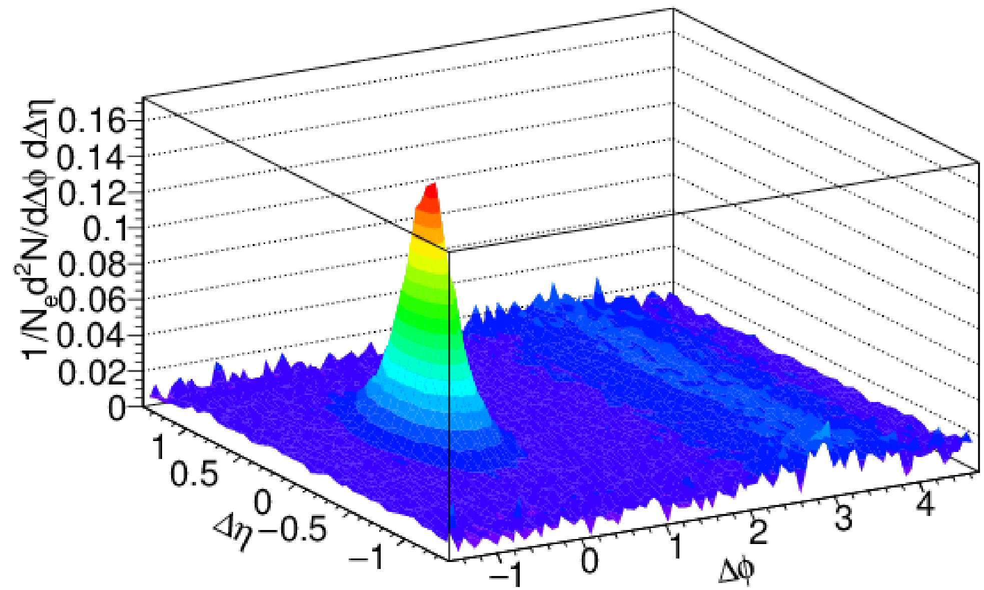
Separating signal+background

Signal+background



Background dominated region

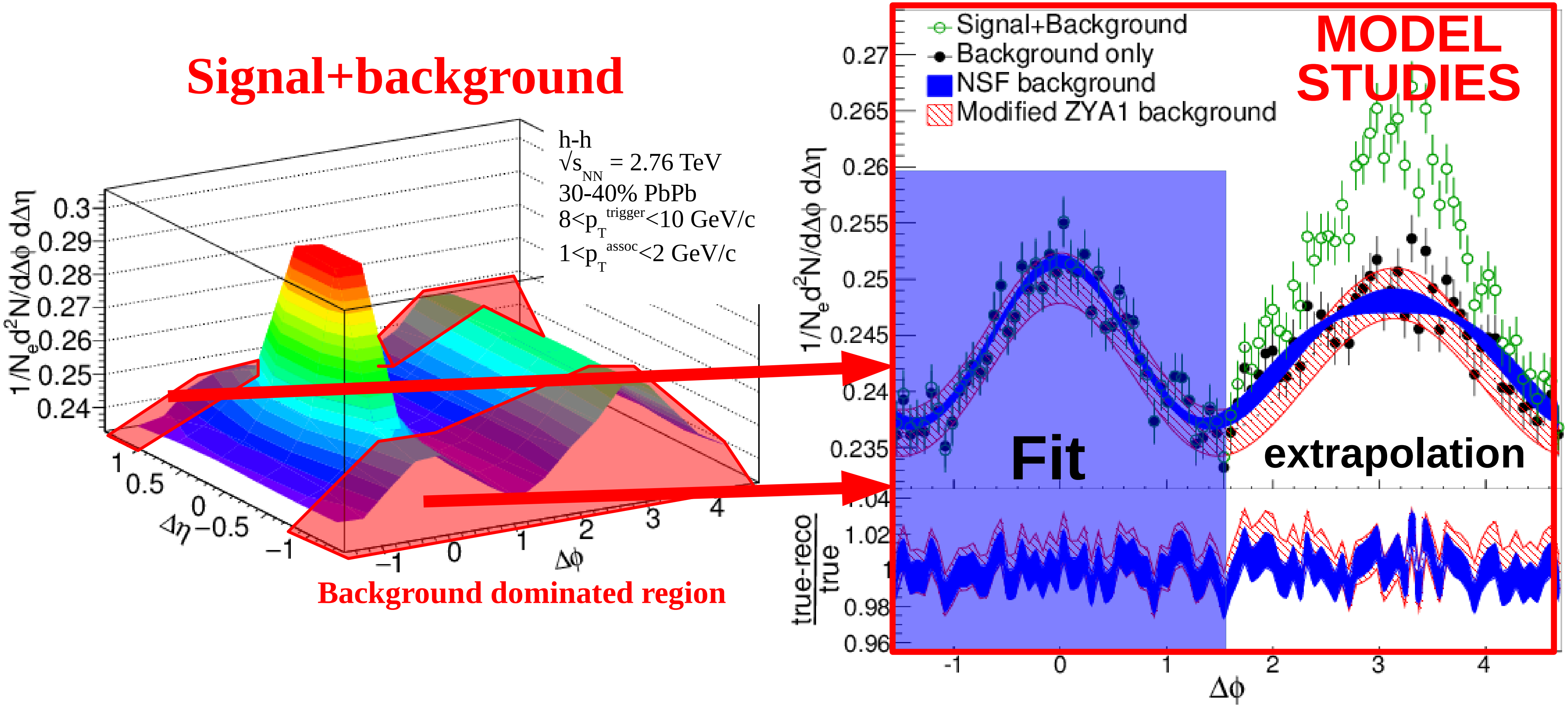
Signal only



MODEL STUDIES

Near-Side Fit (NSF) method

No reaction plane dependence



- Project signal+background over $1.0<|\Delta\eta|<1.4$
- Fit background in $|\Delta\varphi|<\pi/2$

Background in correlations

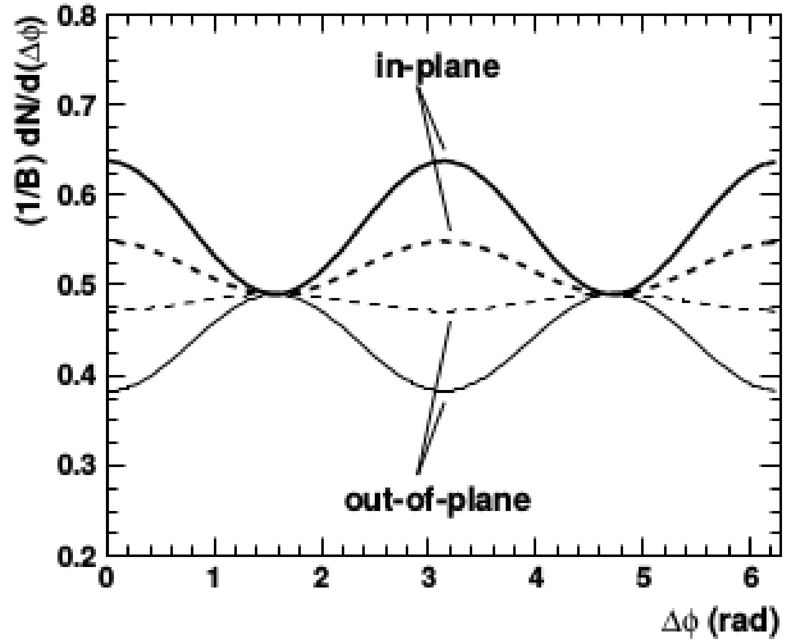
- All reaction plane angles

$$B\left(1+\sum_{n=2}^{\infty} v_n^t v_n^a \cos(n\Delta\phi)\right)$$

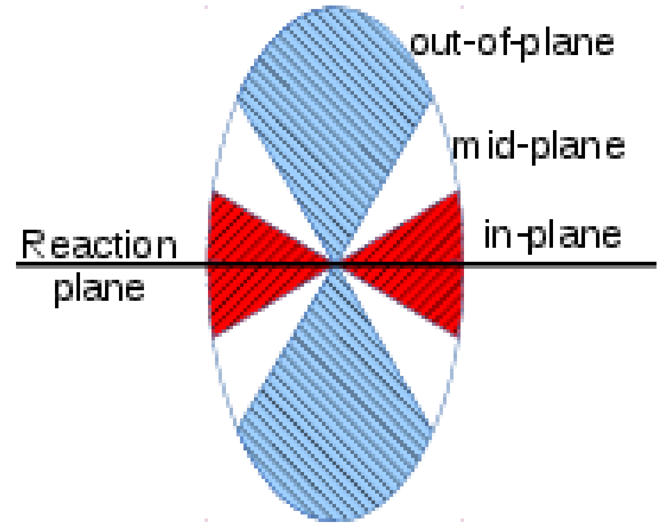
- *When trigger is restricted relative to reaction plane*
  - **Background level modified**

$$B=1+\sum_{k=2}^{\infty} 2 v_k^{R,t} \cos(k\phi_S)\frac{\sin(kc)}{kc}R_n$$

  - **Effective v_n modified**



$$v_n^{R,t}=\frac{v_n+\cos(n\%8_S)\frac{\sin(nc)}{nc}R_n+\sum_{k=2,4,6...}^{\infty}(v_{k+n}+v_{k-n})\cos(k\phi_S)\frac{\sin(kc)}{kc}R_n}{1+\sum_{k=2,4,6...}^{\infty}2v_k\cos(k\phi_S)\frac{\sin(kc)}{kc}R_n}, n=even$$



φ_S is the angular threshold

$$R_n=\langle\cos(n(\psi_{true}-\psi_{reco}))\rangle$$

Bielcikova et al, Phys.Rev. C69 (2004) 021901

Background in correlations

- All reaction plane angles

$$B\left(1+\sum_{n=2}^{\infty} v_n^t v_n^a \cos(n\Delta\phi)\right)$$

- *When trigger is restricted relative to reaction plane*
  - **Background level modified**

$$B=1+\sum_{k=1}^{\infty} 2 v_{jk}^{R,t} \cos(jk\phi_S)\frac{\sin(jkc)}{jkc} R_{j,n} C_{jk,0,j}$$

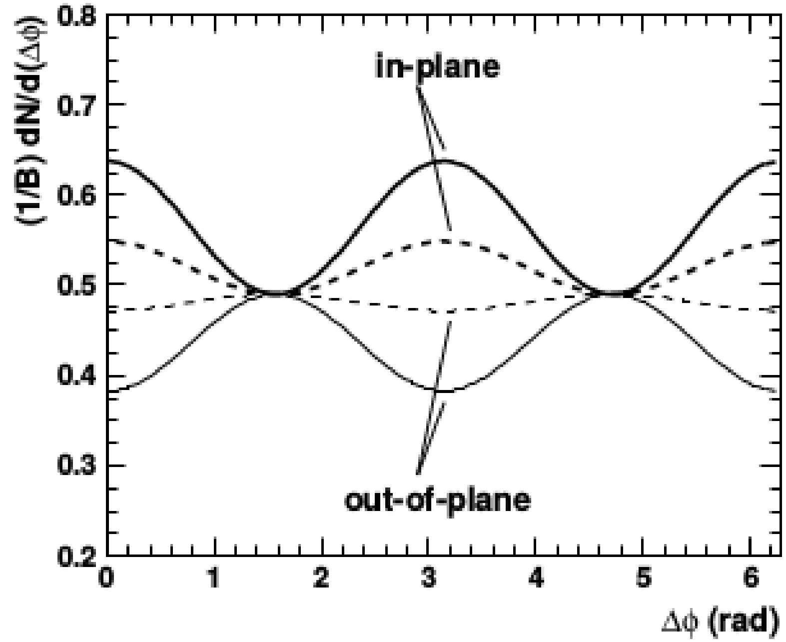
  - **Effective v_n modified**

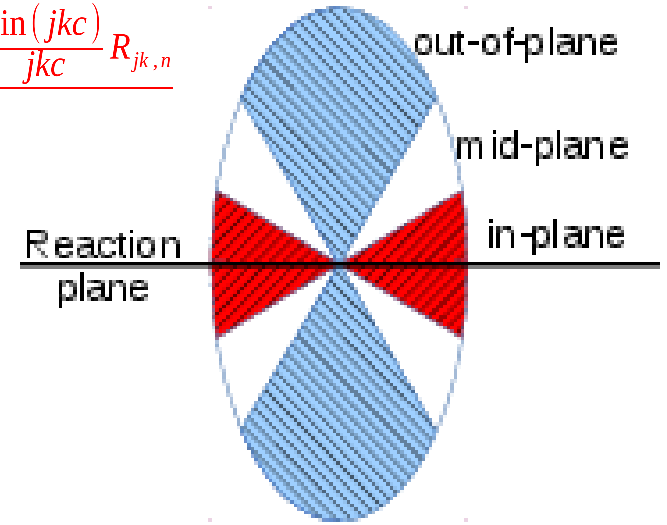
$$v_n^{R,t}=\frac{v_n+\delta_{n,mult\,j}\cos(n\phi_S)\frac{\sin(nc)}{nc}R_{j,n}C_{n,0,j}+\sum_{k=1,2,3...}^{\infty}\left(v_{jk+n}C_{¿jk+n\vee,n,j}+v_{jk-n}C_{¿jk-n\vee,n,j}\right)\cos(jk\phi_S)\frac{\sin(jkc)}{jkc}R_{jk,n}}{1+\sum_{k=1,2,3...}^{\infty}2v_{jk}\cos(jk\phi_S)\frac{\sin(jkc)}{jkc}R_{j,jk}C_{jk,0,j}}$$

φ_S is the angular threshold

$$C_{n,m,j}=\langle\cos(n\psi_n+m\psi_m-(n+m)\psi_j)\rangle$$

$$R_{n,j}=\langle\cos(n(\psi_{true,j}-\psi_{reco,j}))\rangle$$

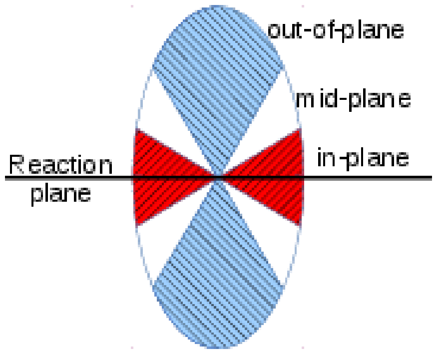


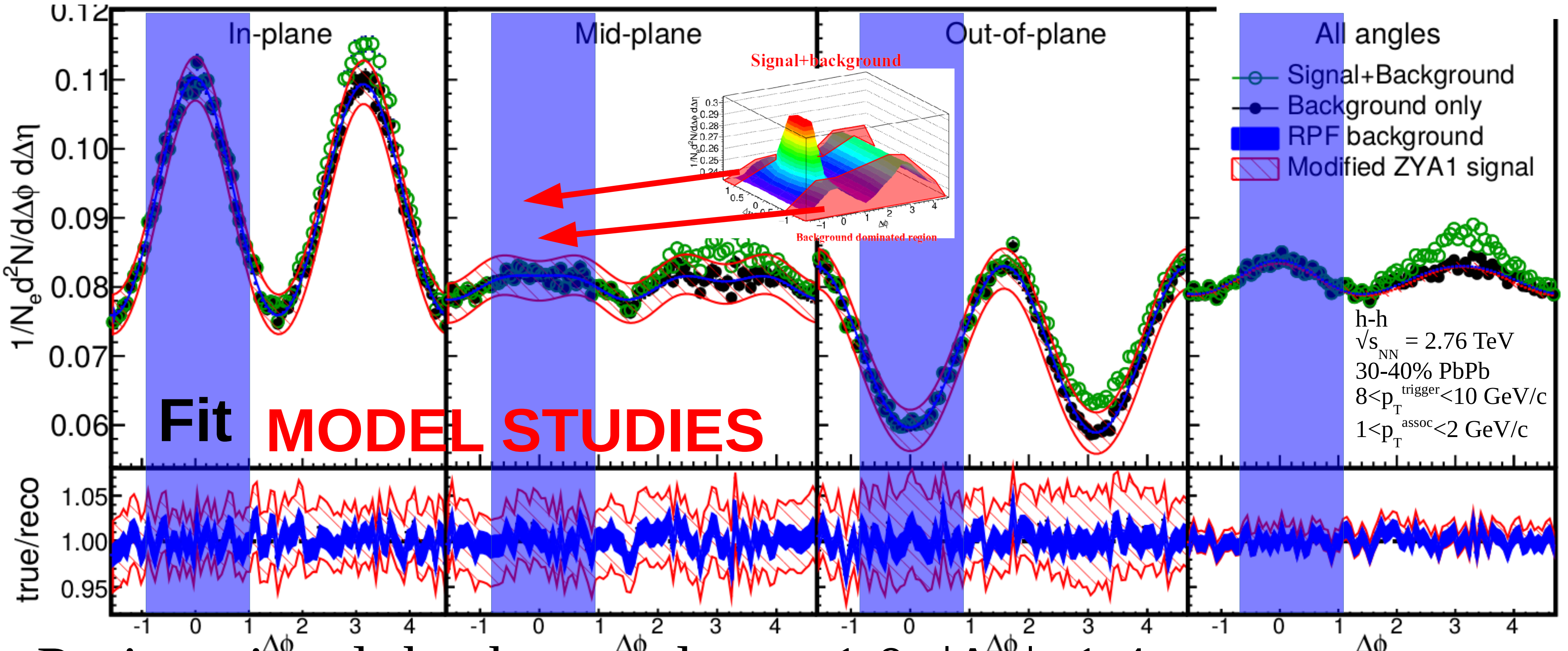


Nattrass & Todoroki, Phys. Rev. C 97, 054911 (2018).
Bielcikova et al, Phys.Rev. C69 (2004) 021901

Reaction Plane Fit (RPF) method

30-40% central

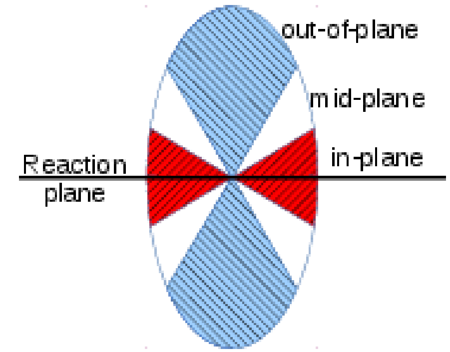


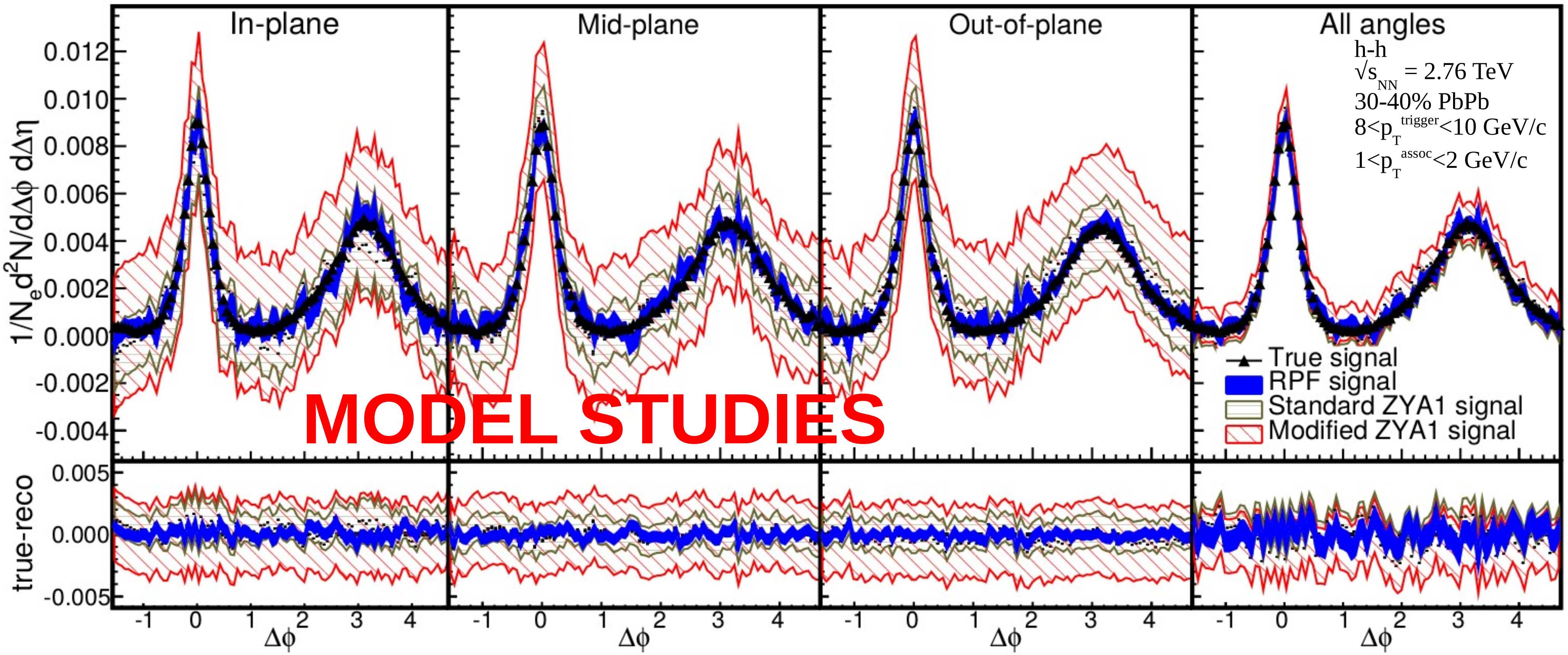


- Project signal+background over $1.0<|\Delta\eta|<1.4$
- Fit background in $|\Delta\varphi|<1$ including reaction plane dependence
- v_n and B extracted with v_n up to n=4

Reaction Plane Fit (RPF) method

30-40% central



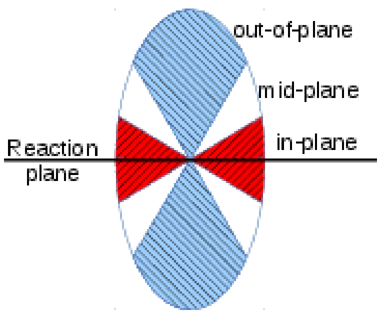


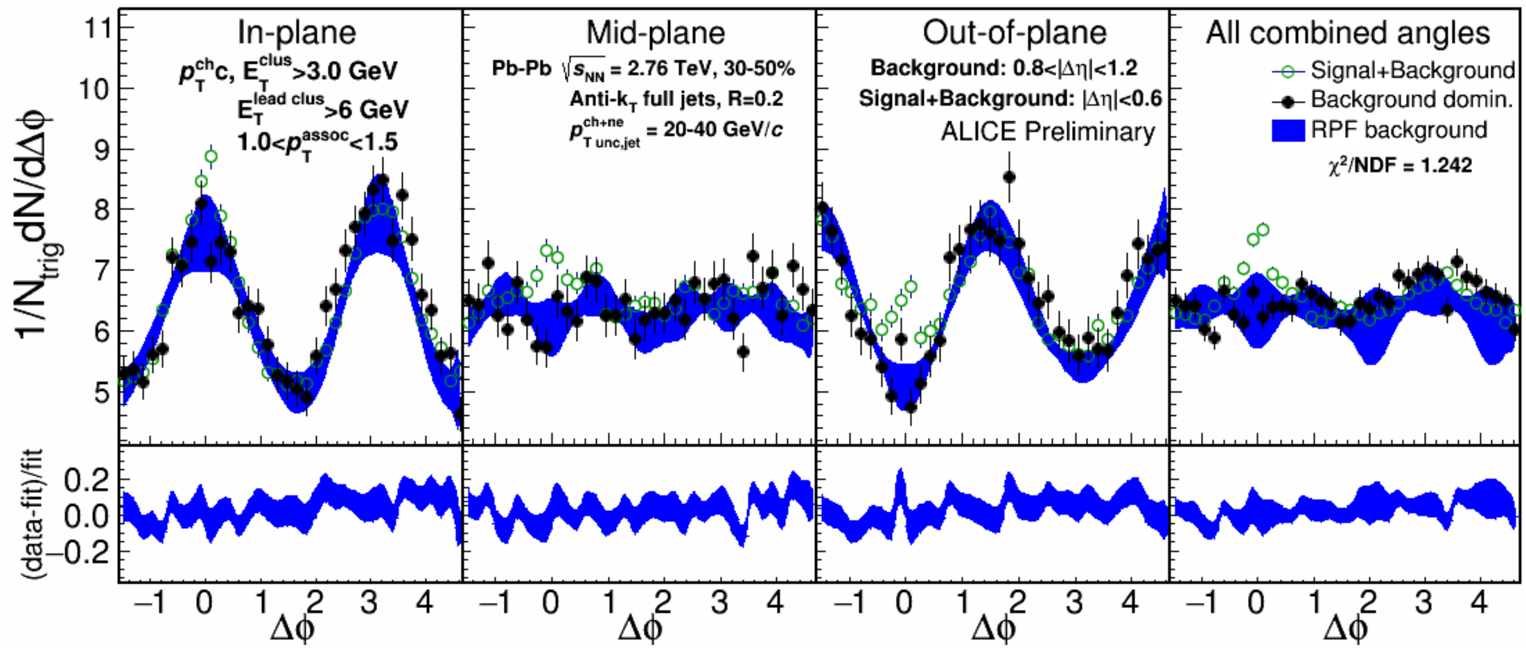
	near-side $Y \times 10^{-3}$				away-side $Y \times 10^{-3}$			
	in-plane	mid-plane	out-of-plane	All	in-plane	mid-plane	out-of-plane	All
True	$5.78 \pm 0.03 \pm 0.13$	$5.77 \pm 0.03 \pm 0.14$	$5.65 \pm 0.03 \pm 0.13$	$17.1 \pm 0.1 \pm 0.2$	$6.74 \pm 0.03 \pm 0.13$	$6.72 \pm 0.03 \pm 0.14$	$6.52 \pm 0.03 \pm 0.13$	$19.9 \pm 0.1 \pm 0.2$
Mod. ZYA1	$6.3 \pm 5.9 \pm 1.7$	$5.7 \pm 6.0 \pm 0.3$	$6.8 \pm 6.1 \pm 0.9$	$18.9 \pm 4.2 \pm 1.2$	$7.3 \pm 5.9 \pm 1.7$	$6.8 \pm 6.0 \pm 0.3$	$7.7 \pm 6.1 \pm 0.9$	$21.9 \pm 4.2 \pm 1.2$
Std. ZYA1	$4.5 \pm 2.3 \pm 1.7$	$5.5 \pm 2.3 \pm 0.3$	$5.6 \pm 2.3 \pm 0.9$	$15.7 \pm 1.6 \pm 1.2$	$5.5 \pm 2.3 \pm 1.7$	$6.5 \pm 2.3 \pm 0.3$	$6.5 \pm 2.3 \pm 0.9$	$18.7 \pm 1.6 \pm 1.2$
RPF ($\lvert\Delta\phi\rvert < \pi/2$)	5.5 ± 0.4	5.7 ± 0.3	5.9 ± 0.3	17.0 ± 0.7	6.6 ± 0.4	6.8 ± 0.3	6.8 ± 0.3	20.1 ± 0.7
RPF ($\lvert\Delta\phi\rvert < 1$)	5.7 ± 0.4	5.8 ± 0.4	5.9 ± 0.3	17.4 ± 0.7	6.8 ± 0.4	6.8 ± 0.4	6.8 ± 0.3	20.4 ± 0.7

ALICE jet-hadron correlations

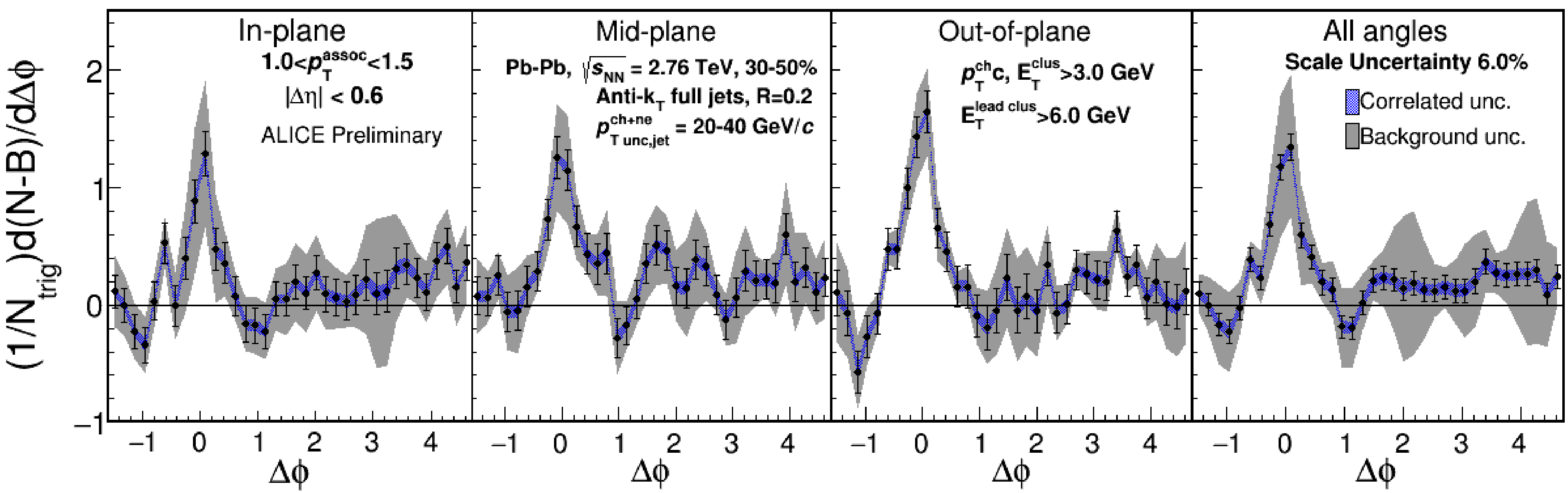
1.0-1.5 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit





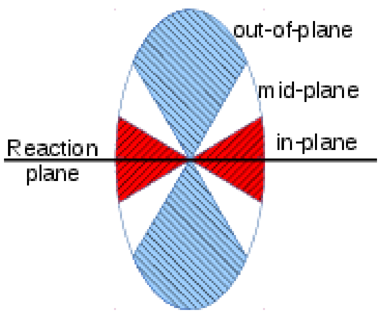
[Correlation function](#)

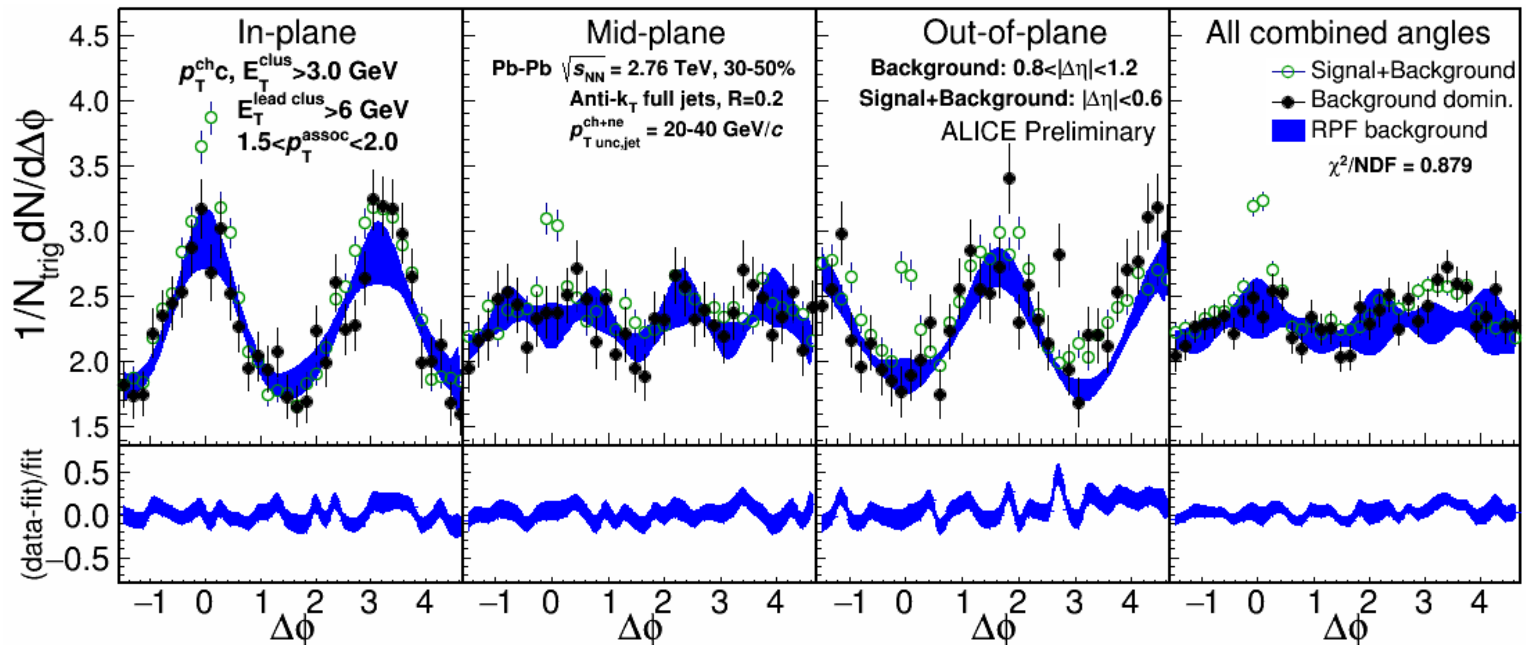


- Uncertainties dominated by statistics
- Background uncertainty is non-trivially correlated point-to-point

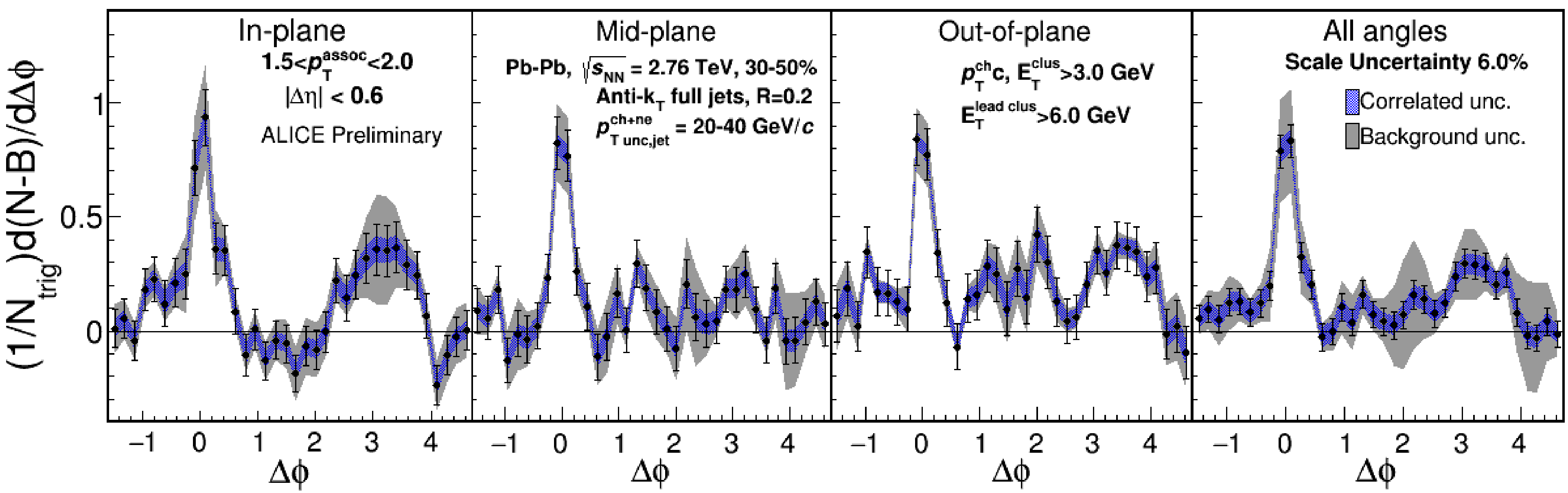
1.5-2.0 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit





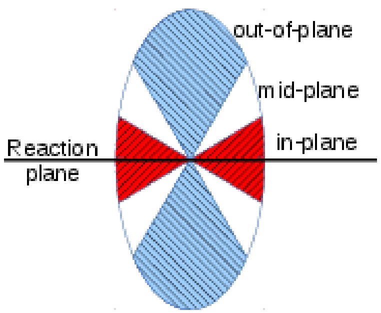
Correlation function

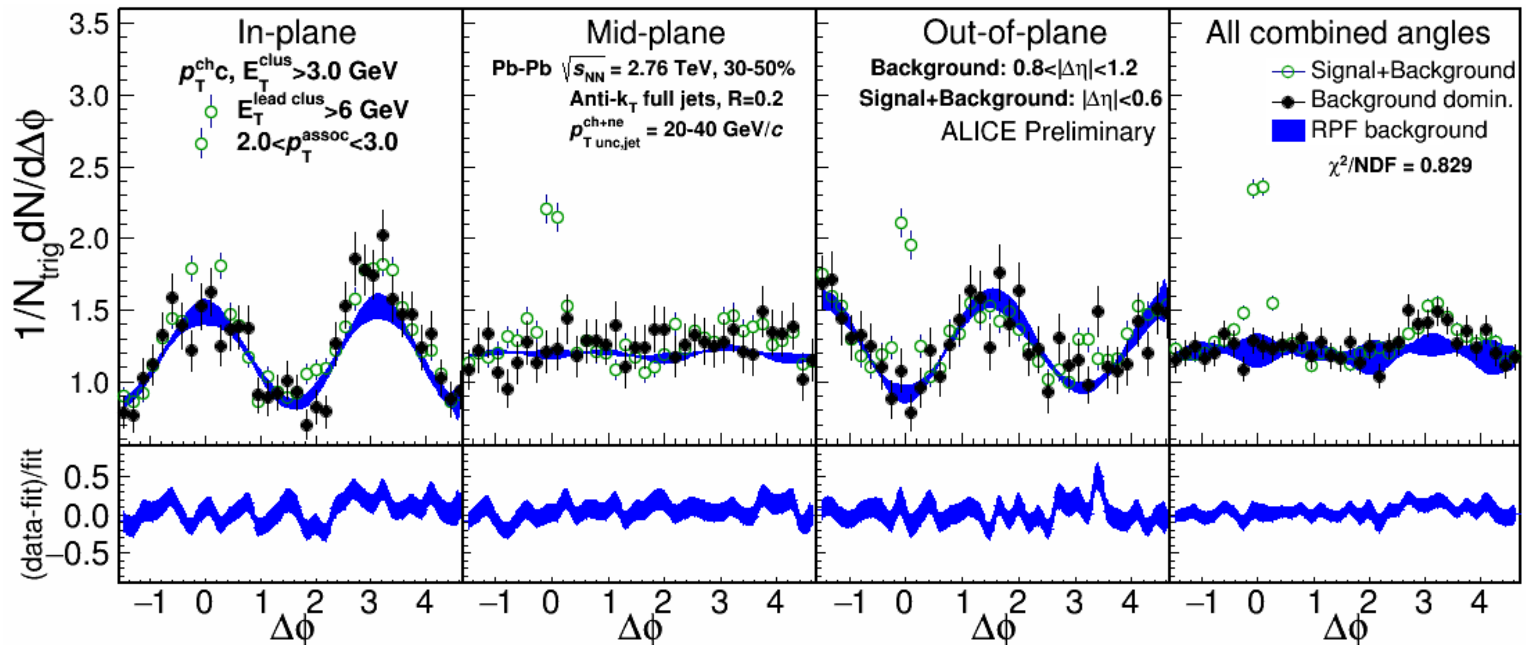


- v_3 and v_4 components important
- Background uncertainty is non-trivially correlated point-to-point

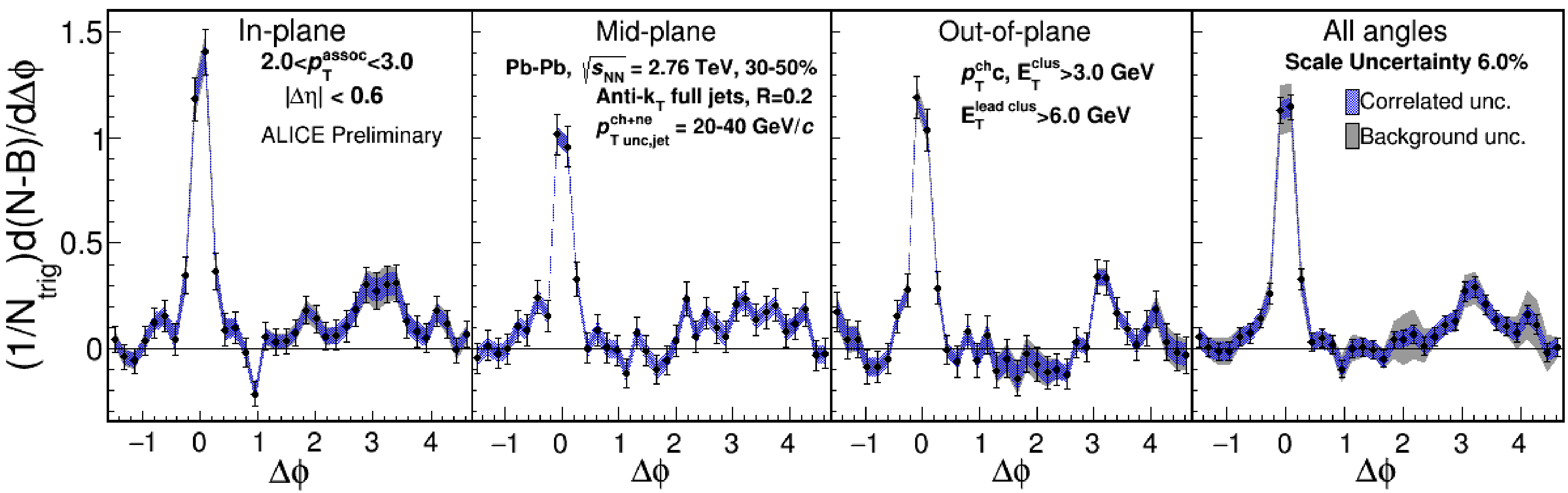
2.0-3.0 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit





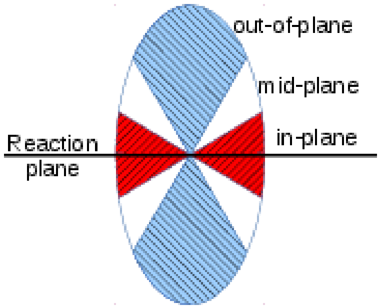
[Correlation function]

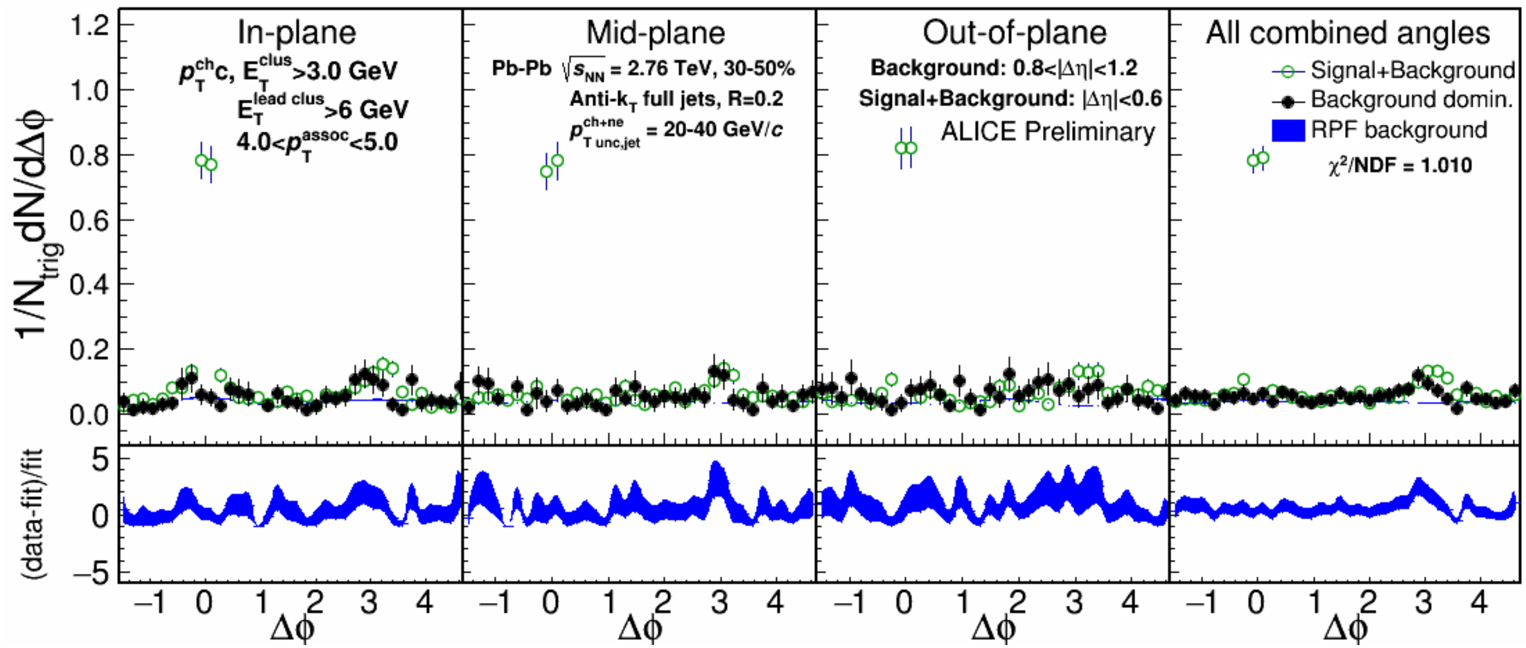


- Away side clearly there and suppressed

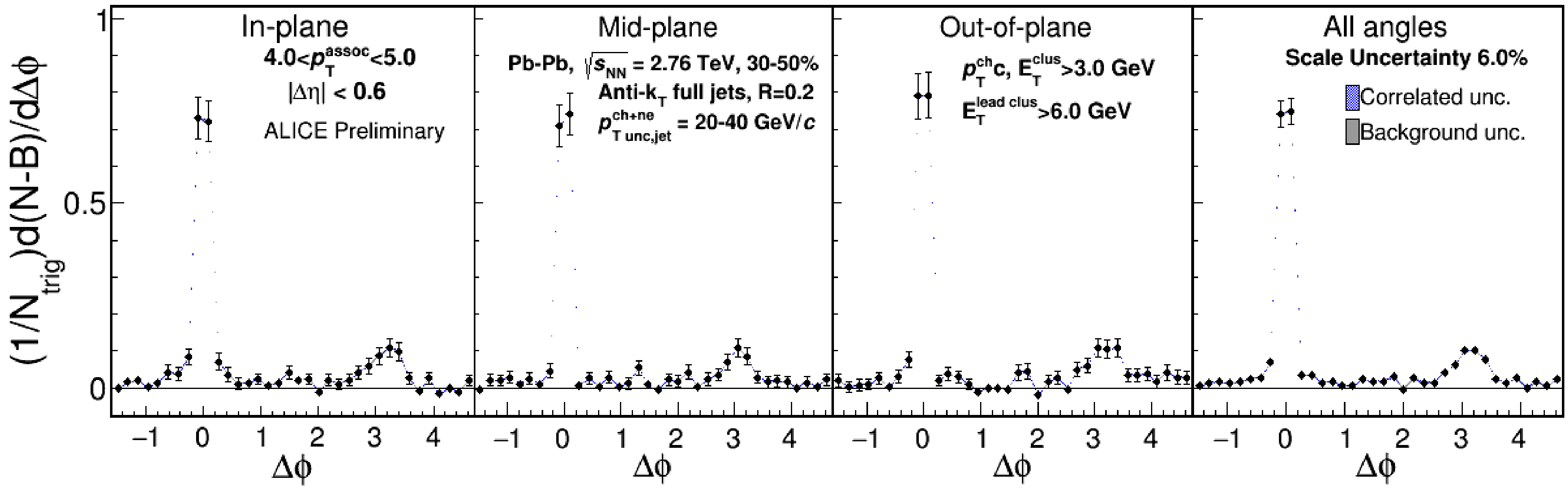
4.0-5.0 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit



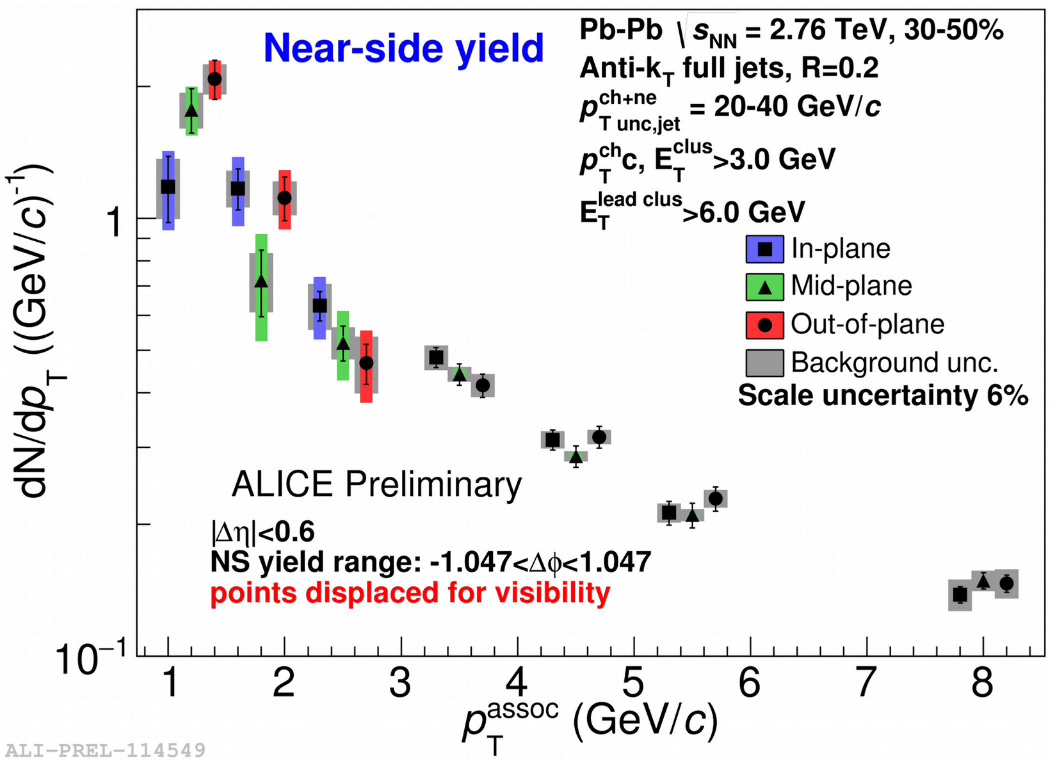


Correlation function

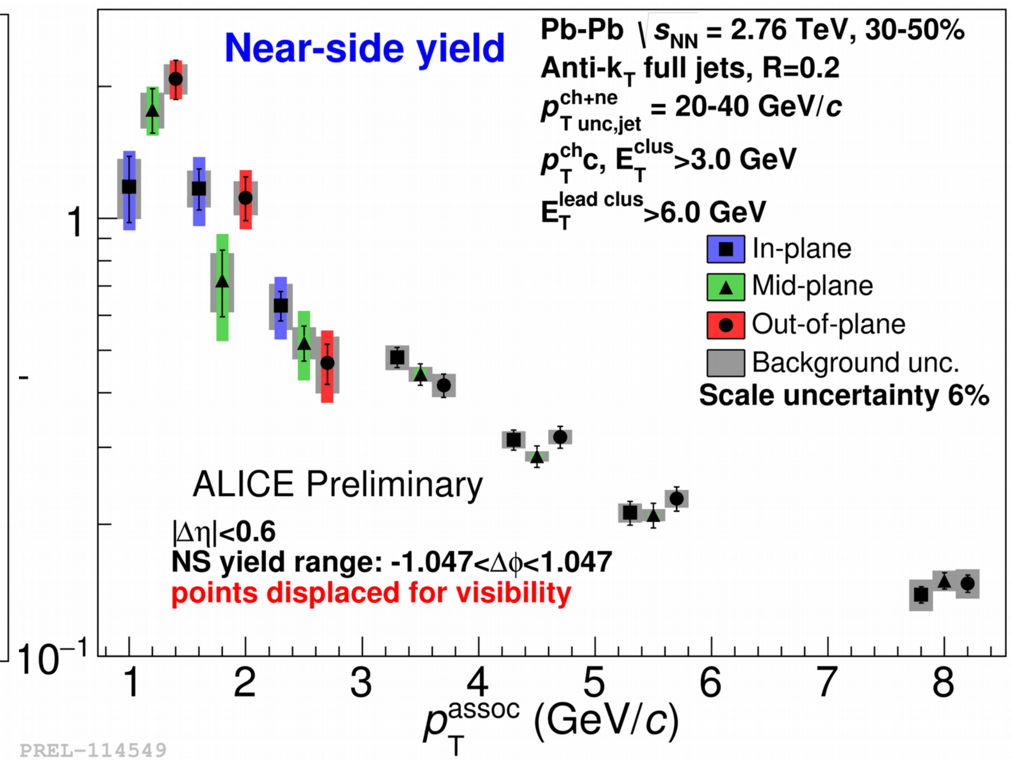


- Background level negligible

Yields



Near-side yield
Pb-Pb √sNN = 2.76 TeV, 30-50%
Anti-kT full jets, R=0.2
pT unc,jet ch+ne = 20-40 GeV/c
pT ch c, ET clus >3.0 GeV
ET lead clus >6.0 GeV
In-plane
Mid-plane
Out-of-plane
Background unc.
Scale uncertainty 6%
ALICE Preliminary
|Δη|<0.6
NS yield range: -1.047<Δφ<1.047
points displaced for visibility
dN/dpT ((GeV/c)-1)
pT assoc (GeV/c)
ALI-PREL-114549



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In-plane
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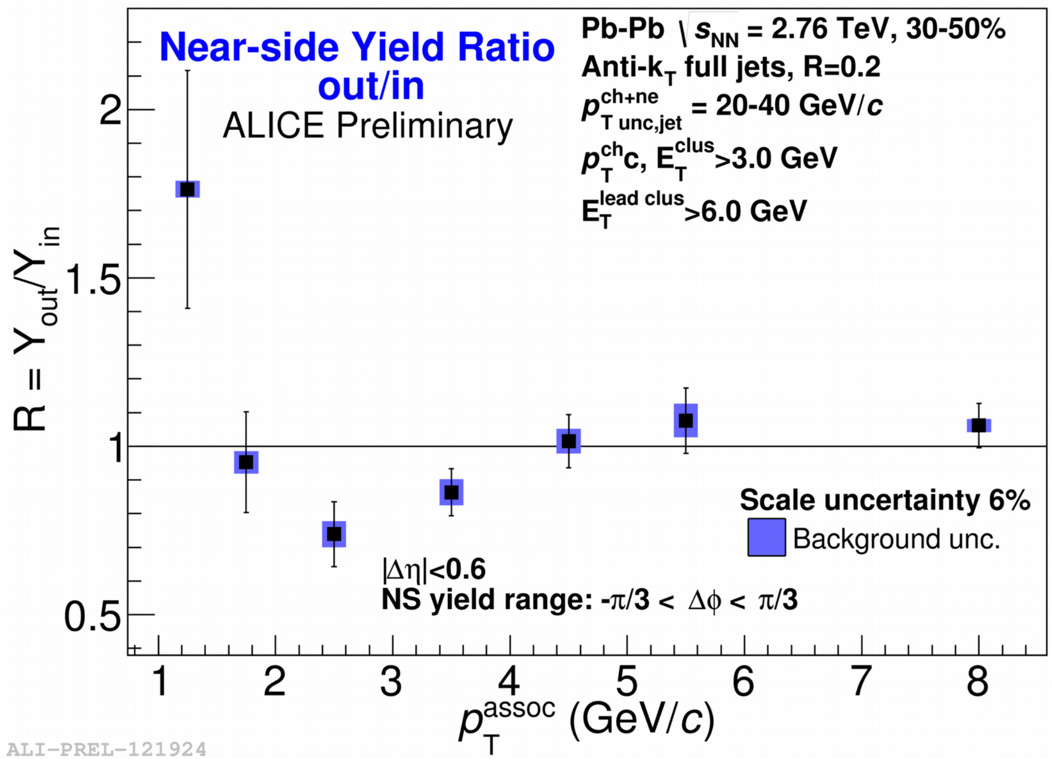
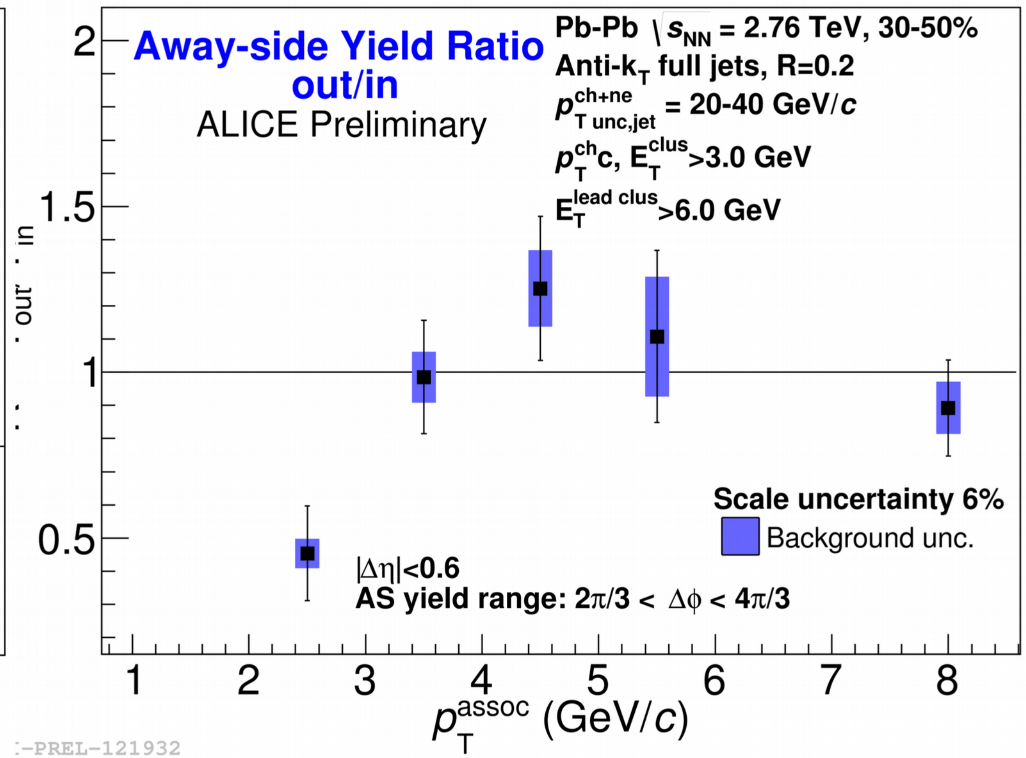
Background unc.
Scale uncertainty 6%
ALICE Preliminary
|Δη|<0.6
NS yield range: -1.047<Δφ<1.047
points displaced for visibility
pT assoc (GeV/c)
PREL-114549

Yield Ratios



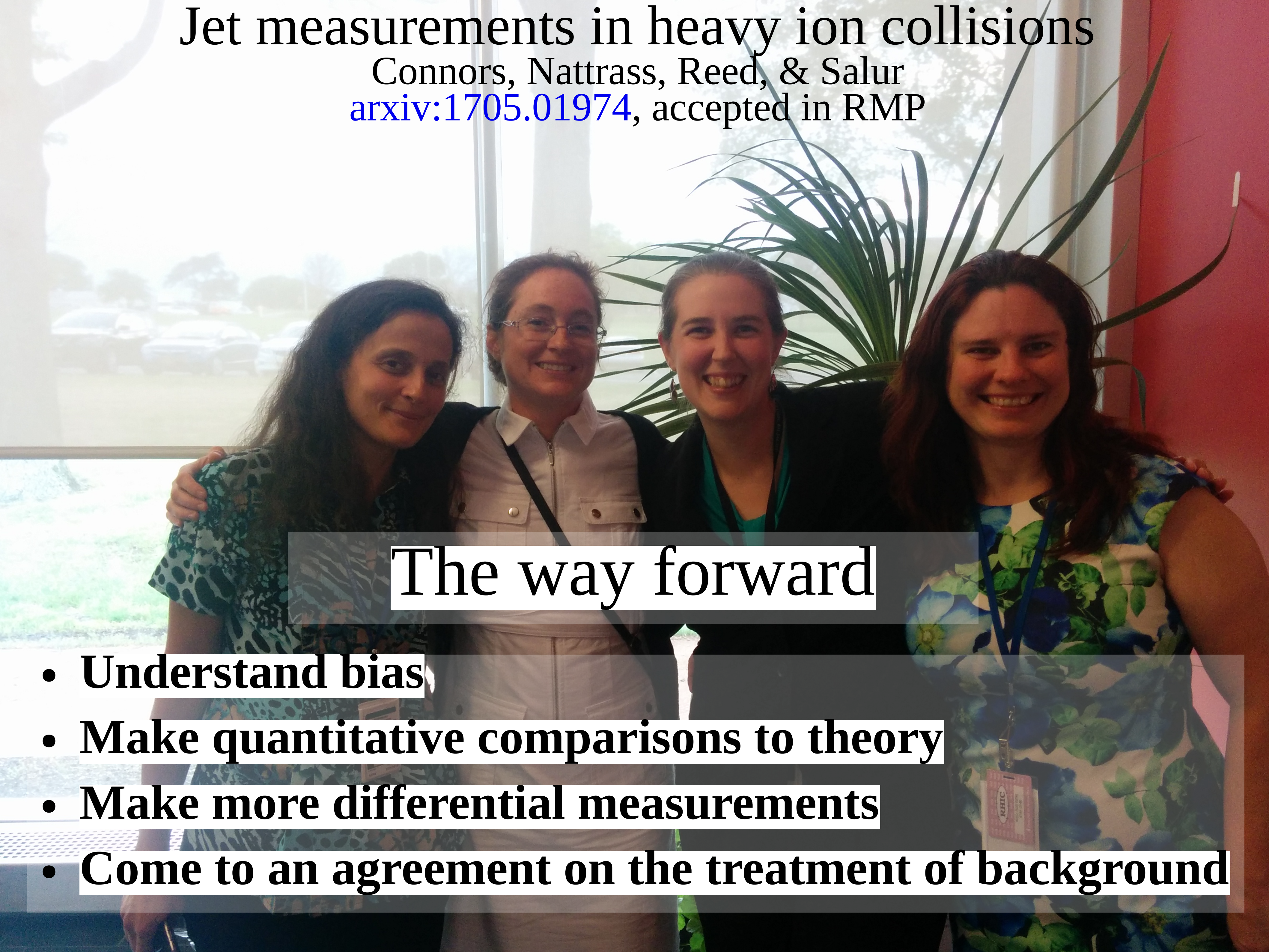


Conclusions

- Jet-hadron correlations allow precise measurements
  - Show broadening, softening of fragmentation
- RPF method is robust
  - Allows studies of away side
  - Move beyond ZYAM.
- Jets exhibit little/no reaction plane dependence
  - Consistent with expectations from energy loss?
  - Indicative of importance of fluctuations?
  - Not yet sensitive?

Jet measurements in heavy ion collisions

Connors, Nattrass, Reed, & Salur
arxiv:1705.01974, accepted in RMP



The way forward

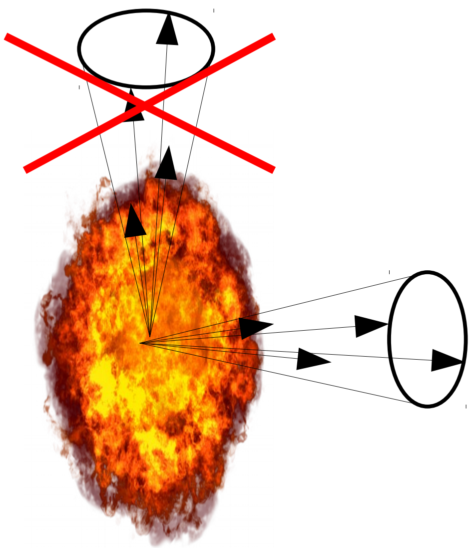
- **Understand bias**
- **Make quantitative comparisons to theory**
- **Make more differential measurements**
- **Come to an agreement on the treatment of background**

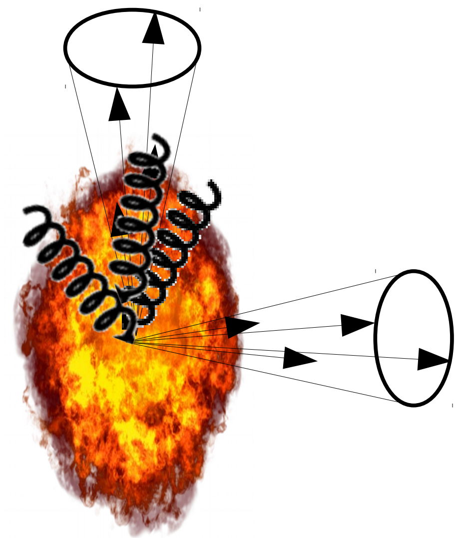
Workshop on the Definition of Jets in a Large Background

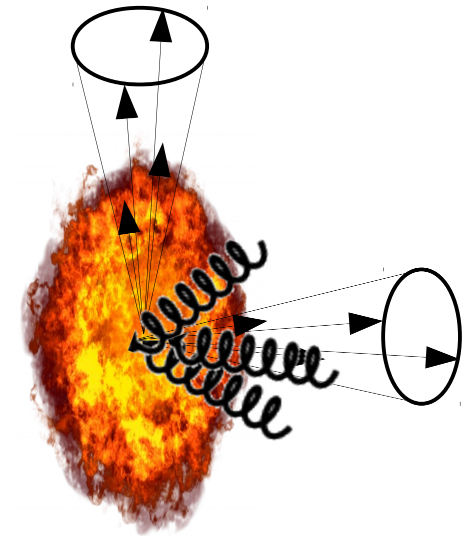
https://www.bnl.gov/jets18/index.php

June 25-27

Competing effects







Quenching
Fewer jets, lower yield out of plane

Bremsstrahlung
Softer, higher yield out of plane

Fluctuations
Individual jets' energy loss may vary

Little/no path length dependence?

- Path length dependence naively predicted by every model
  - No path length dependence seen in rxn plane dependent A_j either
- Insufficient sensitivity?
- Statistical variation in energy loss is more important than path length dependence
  - J. G. Milhano and K. C. Zapp, "Origins of the di-jet asymmetry in heavy ion collisions," arXiv:1512.08107
  - F. Senzel, O. Fochler, J. Uphoff, Z. Xu, and C. Greiner, "Influence of multiple in-medium scattering processes on the momentum imbalance of reconstructed di-jets," J. Phys. G42 no. 11, (2015) 115104, arXiv:1309.1657 [hep-ph].

What should we expect?

- From the JET collaboration Phys. Rev. C 90, 014909 (2014)*

  *this is for a 10 GeV parton!

  – RHIC $\hat{q} = Q^2/L = 1.2 \pm 0.3 \quad GeV^2$
  – LHC $\hat{q} = Q^2/L = 1.9 \pm 0.7 \quad GeV^2$

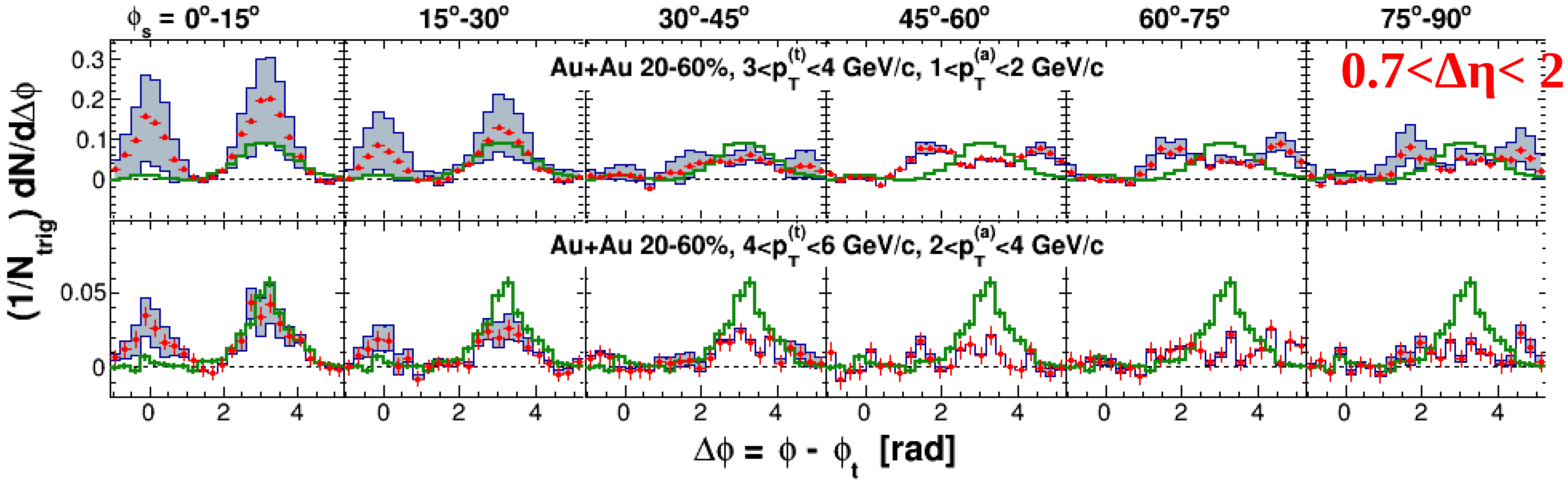
- Use PHENIX paper Phys.Rev.C80:054907(2009) for ballpark estimate of L for 30-40% collisions
  – 4.8 fm in-plane, 6.4 fm out-of-plane
- At RHIC: 2.4 GeV in-plane, 2.8 GeV out-of-plane
- At LHC: 3.0 GeV in-plane, 3.5 GeV out-of-plane

Reanalysis of STAR di-hadron correlations

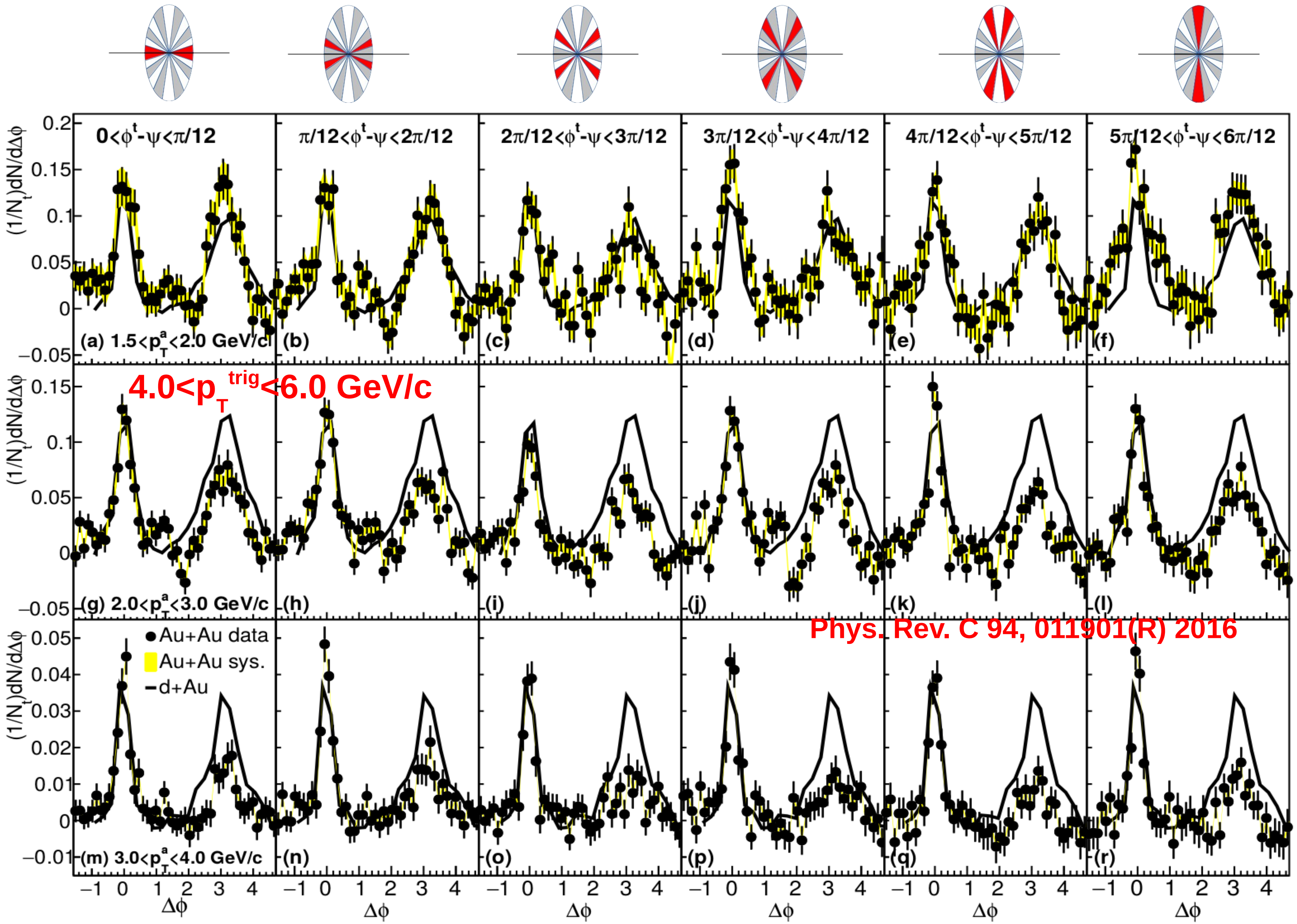
Based on Phys.Rev. C94 011901(2016)

STAR measurements of dihadron correlations relative to reaction plane

- Correlations on arxiv (nucl-ex/1010.0690 v2)
  - Published article (Phys. Rev. C 89 (2014) 41901) does not include raw correlations
- ZYAM background subtraction
  - Reports ridge at $\Delta\eta > 0.7$
  - RPF method assumes no signal at $\Delta\eta > 0.7$

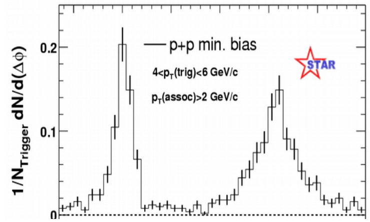


Dihadron correlations

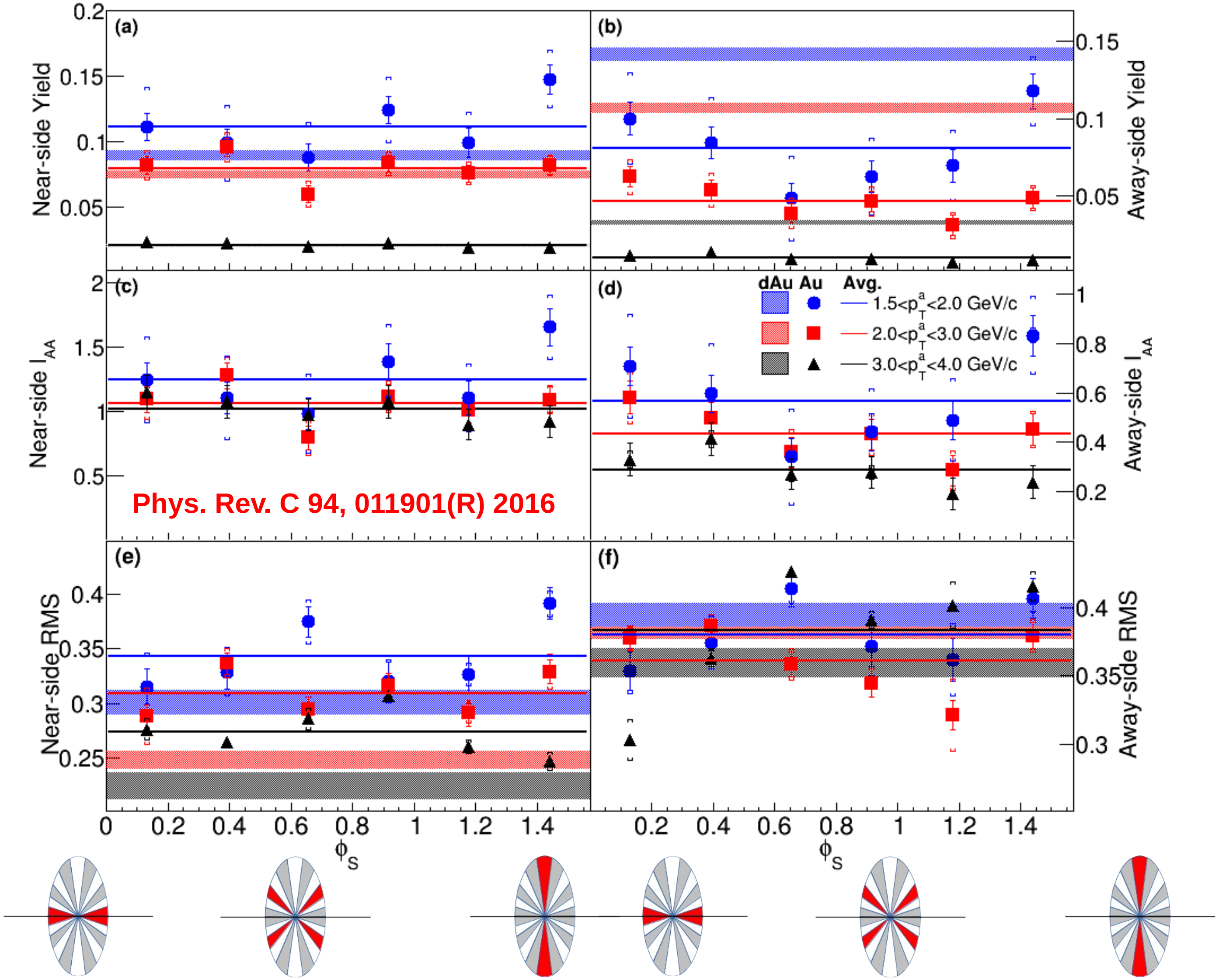


Dihadron correlations

Near side



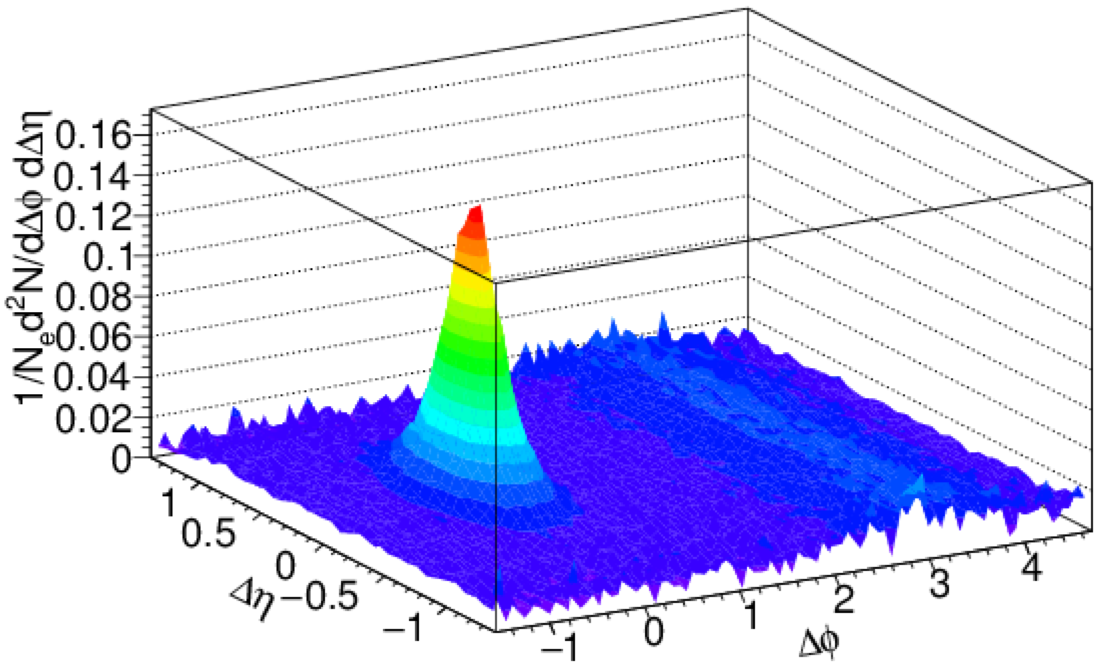
Away side



Toy model

Model for signal

- Use PYTHIA Perugia 2011
- $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$, p for unidentified hadrons
- Quarks and gluons as proxy for reconstructed jets



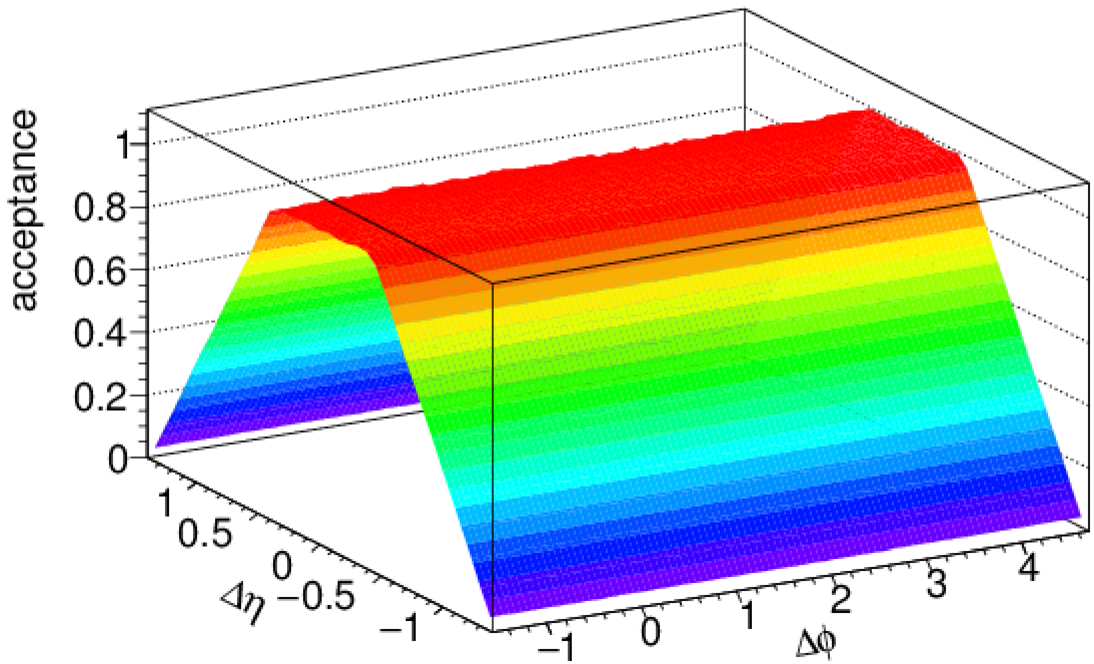
h-h
$\sqrt{s}$ = 2.76 TeV
pp collisions
$8 < p_T^{trigger} < 10$ GeV/c
$1 < p_T^{assoc} < 2$ GeV/c

Model for background

- True reaction plane angle is always at φ=0 in detector coordinates
- Throw random reconstructed reaction plane angle
  - Assume Gaussian reaction plane resolution
  - Selected to approximate data
- Use measured particle yields to calculate how many associated particles would be measured
- Use measured v_n to determine their anisotropy relative to the reaction plane
- Throw associated particles matching distribution observed in data using v_n up to n=10

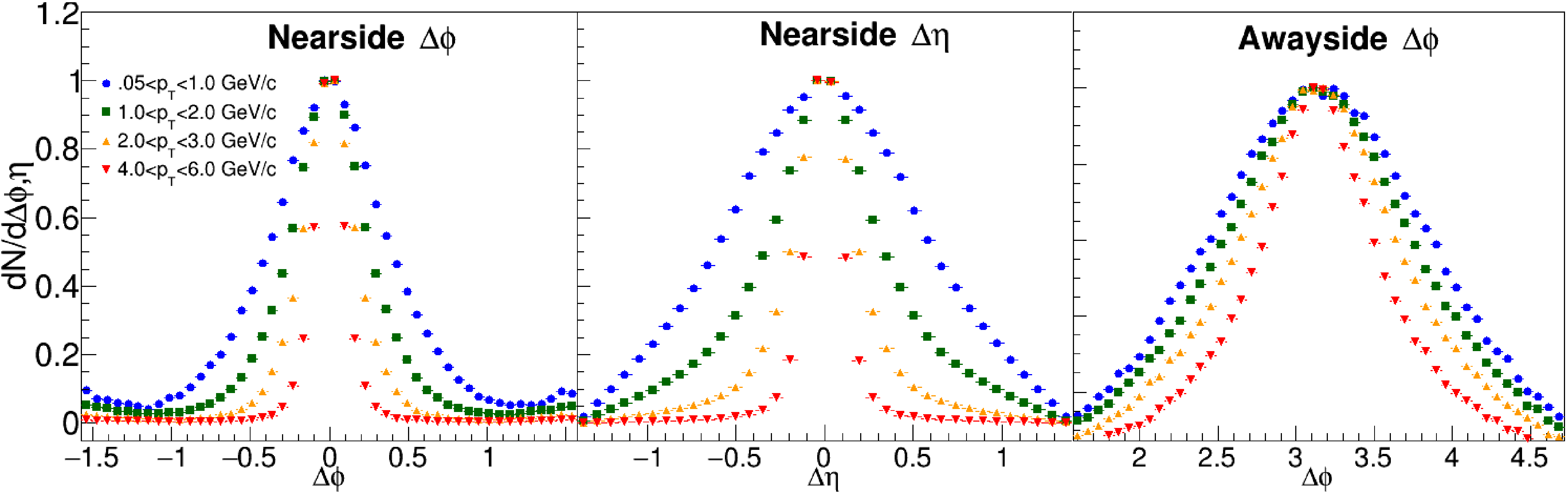
Acceptance correction

- Fixed acceptance cuts leads to a trivial structure due to acceptance
- This is fixed with a “mixed event” correction
  - Throw random trigger, associated particle within acceptance
  - Calculate Δφ, Δη
  - Use this distribution to correct for acceptance

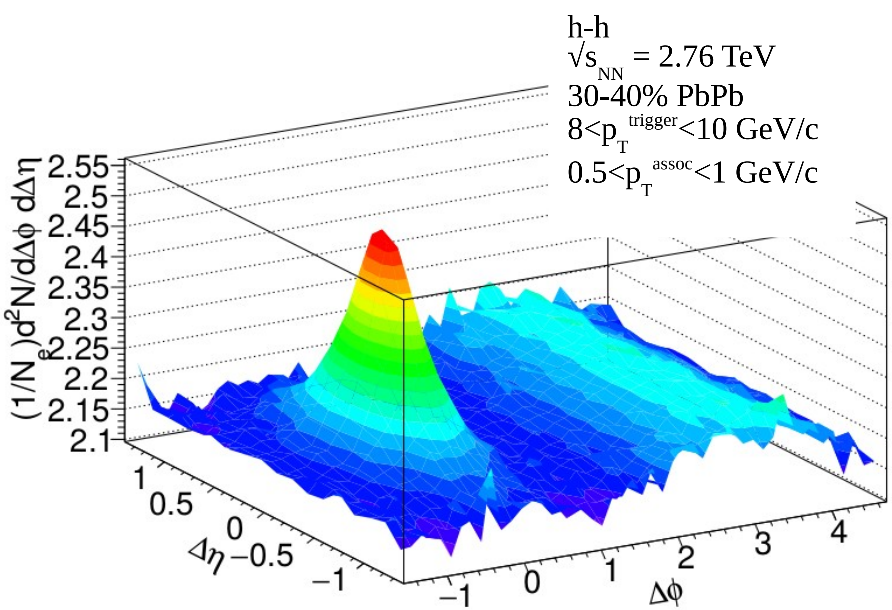


Going to lower momenta

Low momenta

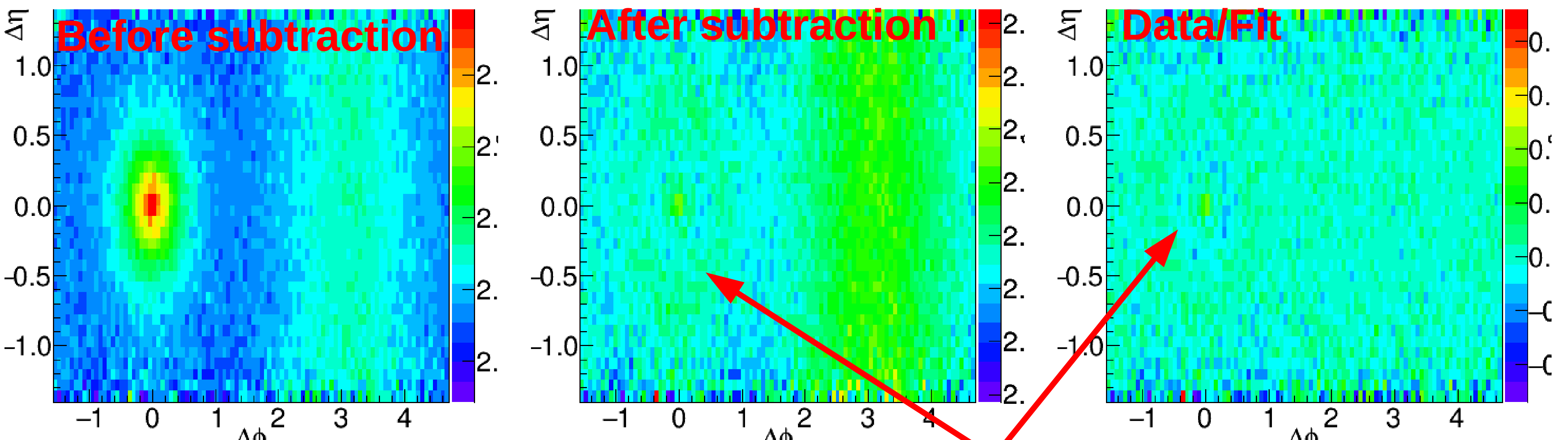


- ZYAM assumptions break down at low p_T
- If method doesn't work on PYTHIA, it can't be trusted on data!
- But low p_T is interesting!



Going to lower momenta, medium modifications

- Peak gets broader
- Fit near-side peak and subtract it
- Increase Δη range available for background subtraction



h-h, $\sqrt{s_{NN}}$ = 2.76 TeV, 0-10% PbPb

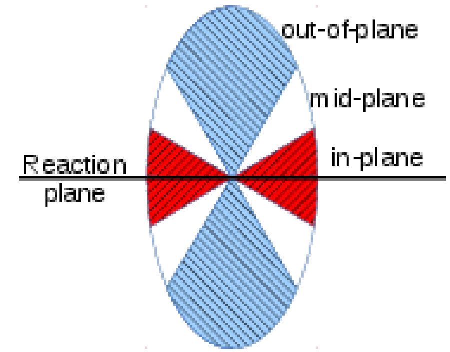
$8<p_T^{trigger}<10$ GeV/c

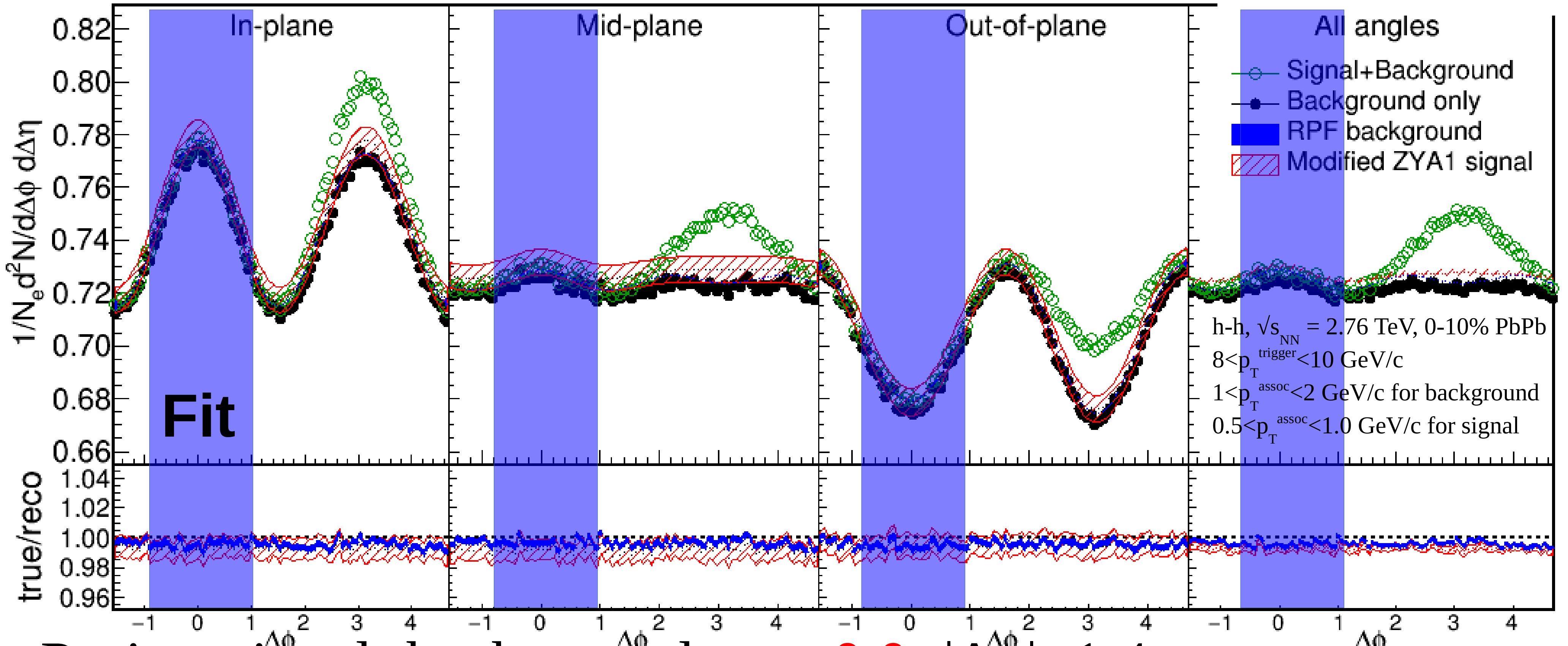
$1<p_T^{assoc}<2$ GeV/c for background, $0.5<p_T^{assoc}<1.0$ GeV/c for signal

Structure from imperfect fit

Near-Side Subtracted RPF method

30-40% central

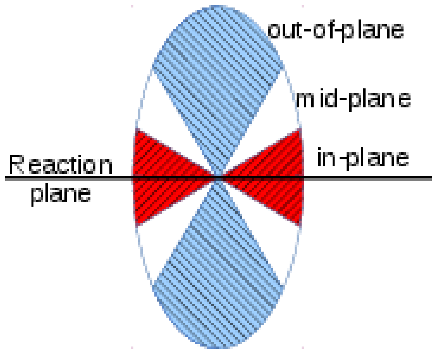


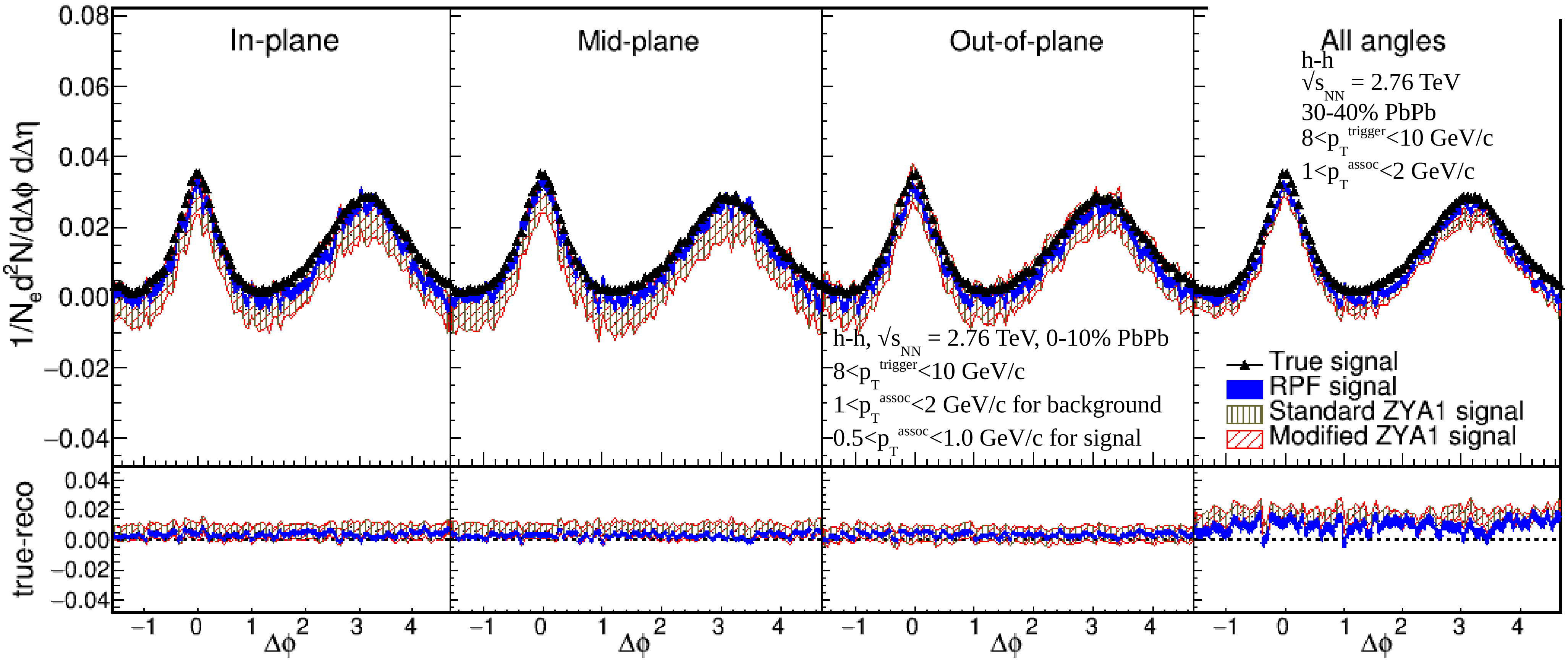


- Project signal+background over **0.0**<|Δη|<1.4
- Fit background in |Δφ|<1 including reaction plane dependence
- v_n and B extracted with v_n up to n=4

Reaction Plane Fit (RPF) method

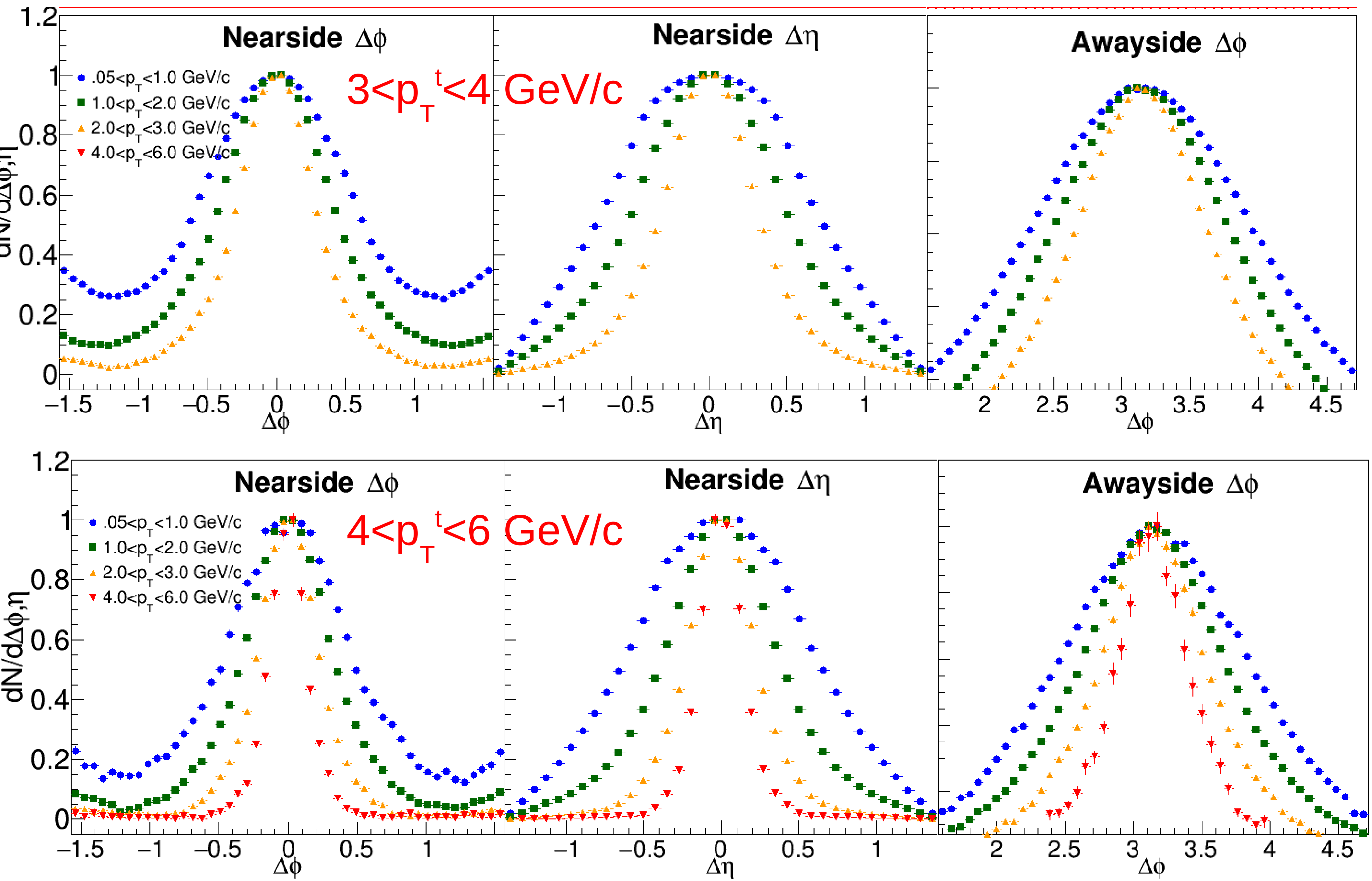
30-40% central





- **Works beautifully!**

PYTHIA at 200 GeV



RPF Method

- 6 bins relative to reaction plane
- Background level
  - Normalized per trigger → B same in all bins if v_2^t is the only effect → reduces info for RPF
  - "The background levels can be different for the different φ_s slices because of the net effect of the variations in jet-quenching with φ_s and the centrality cuts in total charged particle multiplicity in the TPC within $|\eta| < 0.5$." (Pg. 10, arxiv version) → **Not consistent with ZYAM assumptions!**
- Used reaction plane resolution values from paper and their uncertainties
  - Used TPC for reaction plane and analysis – potential autocorrelations
- Data available for $\Delta\eta < 0.7$ (signal+background) and $0.7 < \Delta\eta < 2$ (background dominated)
  - Acceptance correction in not applied → background must be scaled → uncertainty
  - Jet-like correlation not eliminated in $0.7 < \Delta\eta < 2$ for all p_T^t, p_T^a given in paper → **focus on high p_T**

v_2 STAR vs Fit

	v_2 STAR (Table I)	v_2 Fit (stat. errors only)
$1.5<p_T<2.0$ GeV/c	0.164 ± 0.011	0.194 ± 0.008
$2.0<p_T<3.0$ GeV/c	0.189 ± 0.012	0.237 ± 0.010
$3.0<p_T<4.0$ GeV/c	0.194 ± 0.013	0.293 ± 0.058
$4.0<p_T<6.0$ GeV/c	0.163 ± 0.020	0.073 ± 0.025 0.036 ± 0.033 0.033 ± 0.068

- Centrality bin is 20-60% - proper weighting of average?
- Bias in event selection with high p_T trigger?
- Bias in reconstructed reaction plane in the presence of a jet?
- Residual jet-like signal in background dominated region?
- Less information in fit due to normalization by $N_{trigger}$?