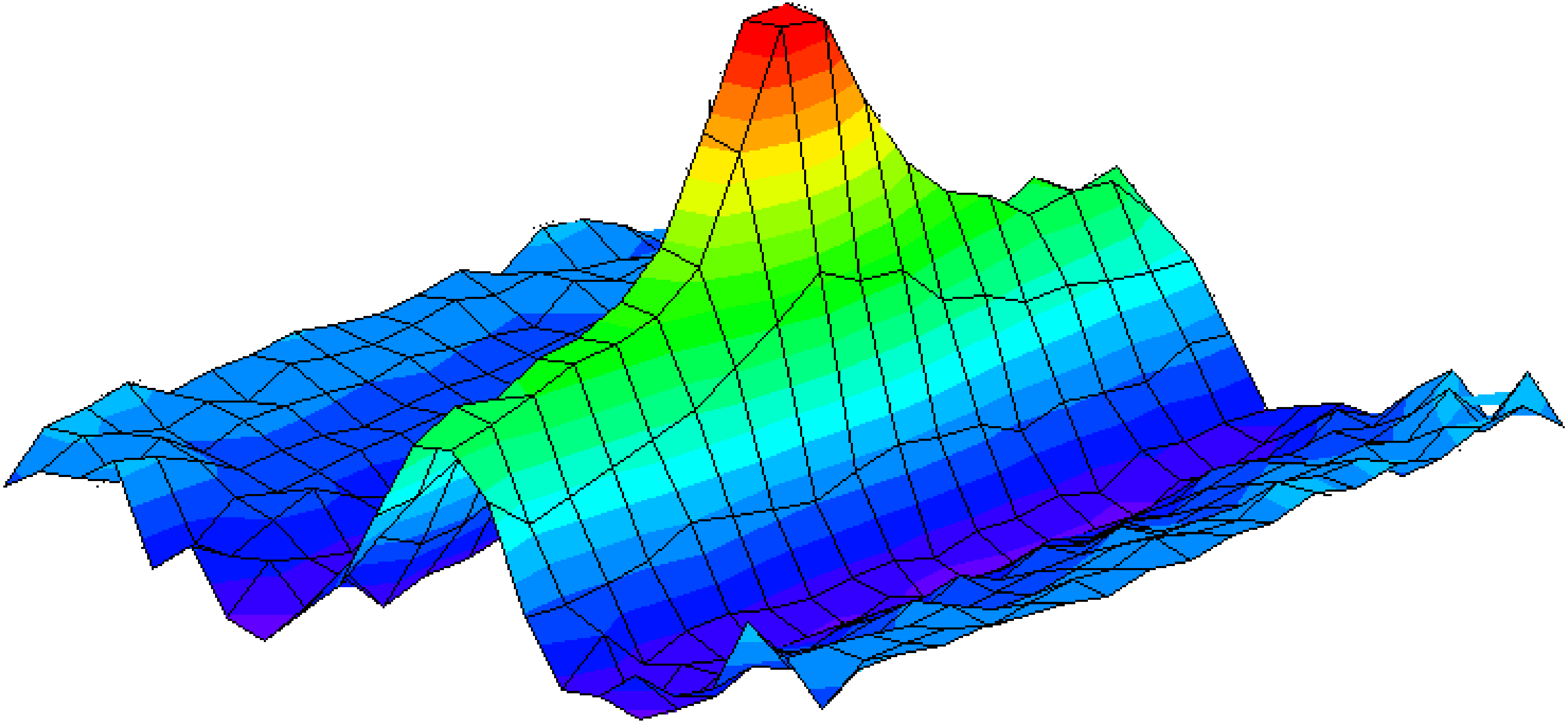
Precision background subtraction in di-hadron and jet-hadron correlations

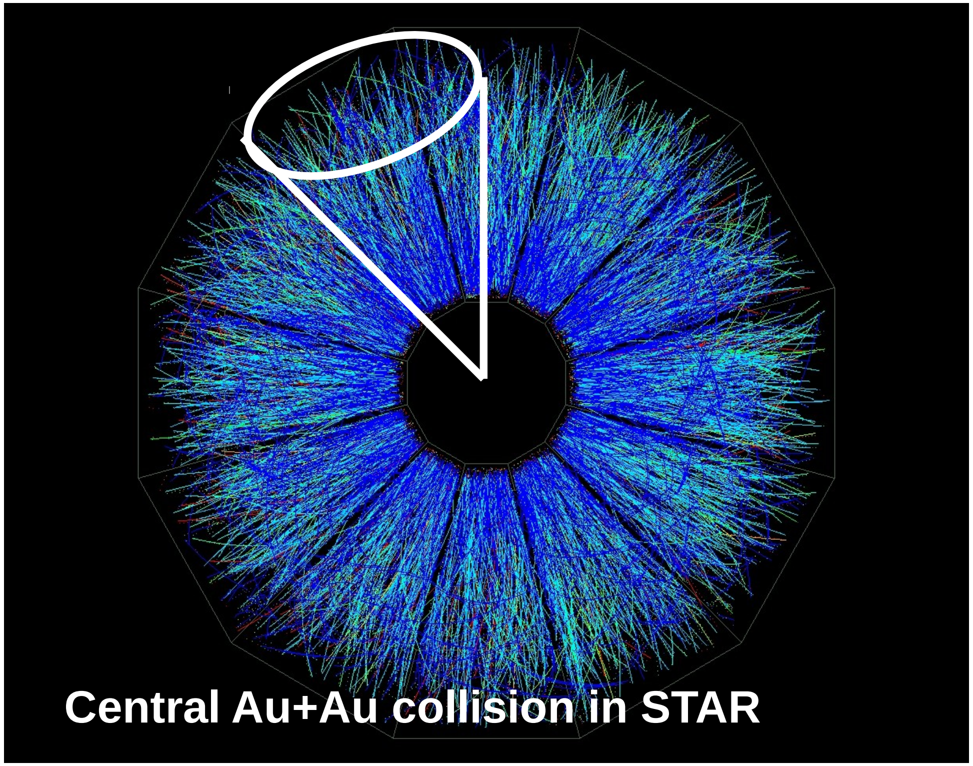
with a re-analysis of STAR results



Based on nucl-ex/1509.04732 accepted to PRC

Contributions from Natasha Sharma, Joel Mazer, Meg Stuart, Aram Bejnood

Background for jet studies



- New method for subtracting combinatorial background from flow (nucl-ex/1509.04732 accepted to PRC)
- Improvements on new method
- Reanalysis of published STAR data (nucl-ex/1010.0690)

Background in correlations

- All reaction plane angles

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

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

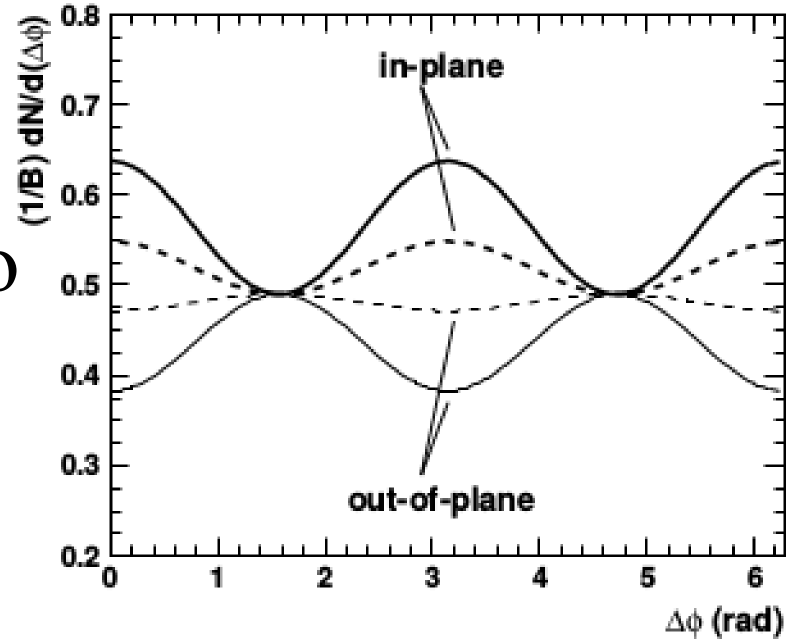
$$B=1+\sum_{k=2}^{\infty} 2 v_k^a v_k^{R,t} \cos(k\varphi_S)\frac{\sin(kc)}{kc} R_n$$

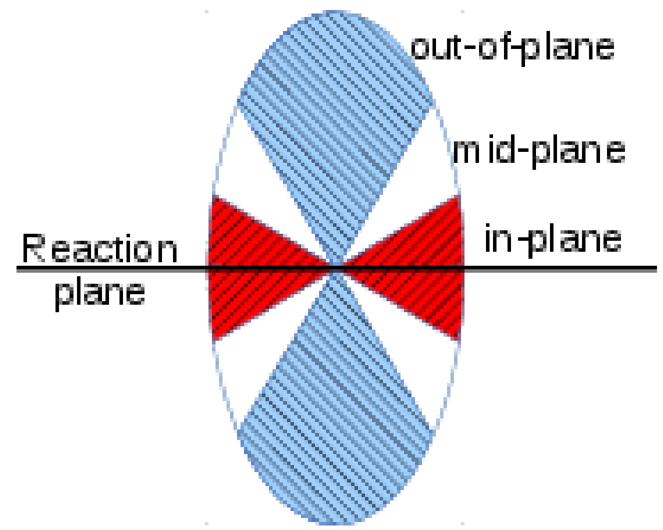
  - Effective v_n modified

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

φ_S is the angular threshold

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





Phys.Rev. C69 (2004) 021901 arXiv:nucl-ex/0311007

Background Subtraction Methods

- **Zero-Yield at Minimum (ZYAM):** Assumes v_n from other studies, assumes region around $\Delta\varphi\approx1$ is background dominated
- **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

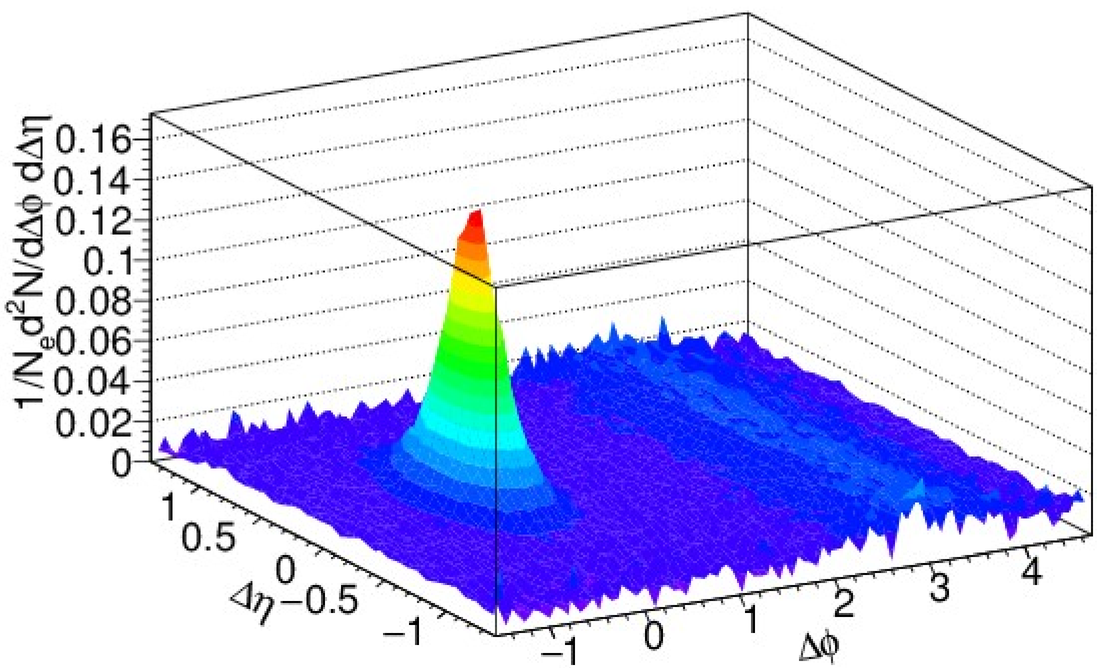
Toy model

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

Model for signal

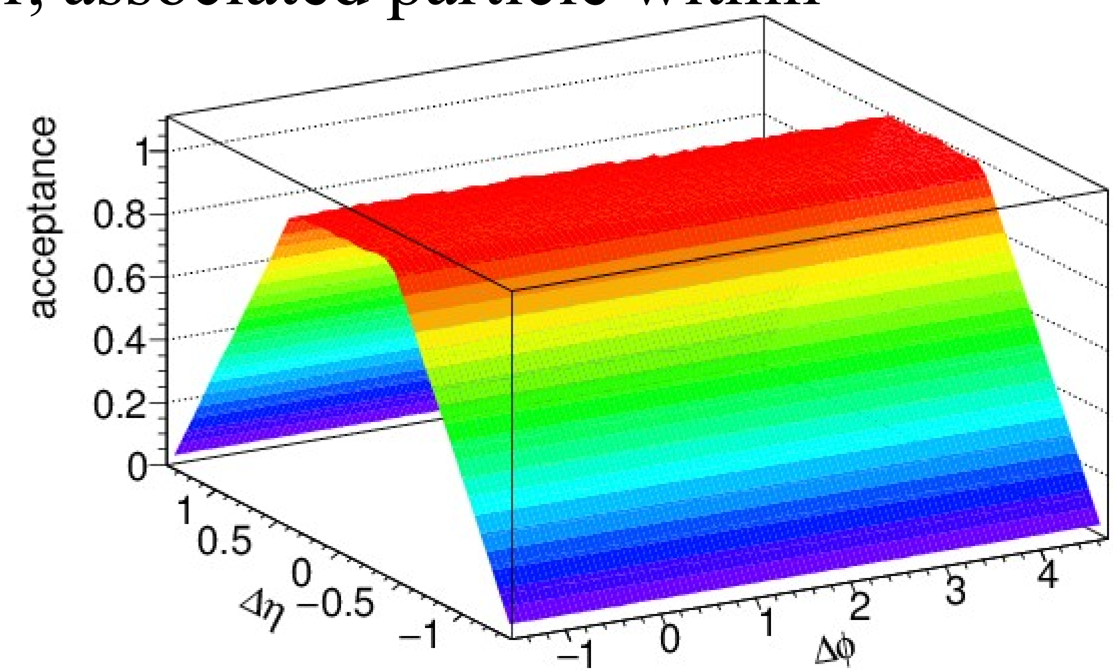
- Use PYTHIA Perugia 2011
- $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$, p for unidentified hadrons
- Quarks and gluons as proxy for reconstructed jets



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

Acceptance correction

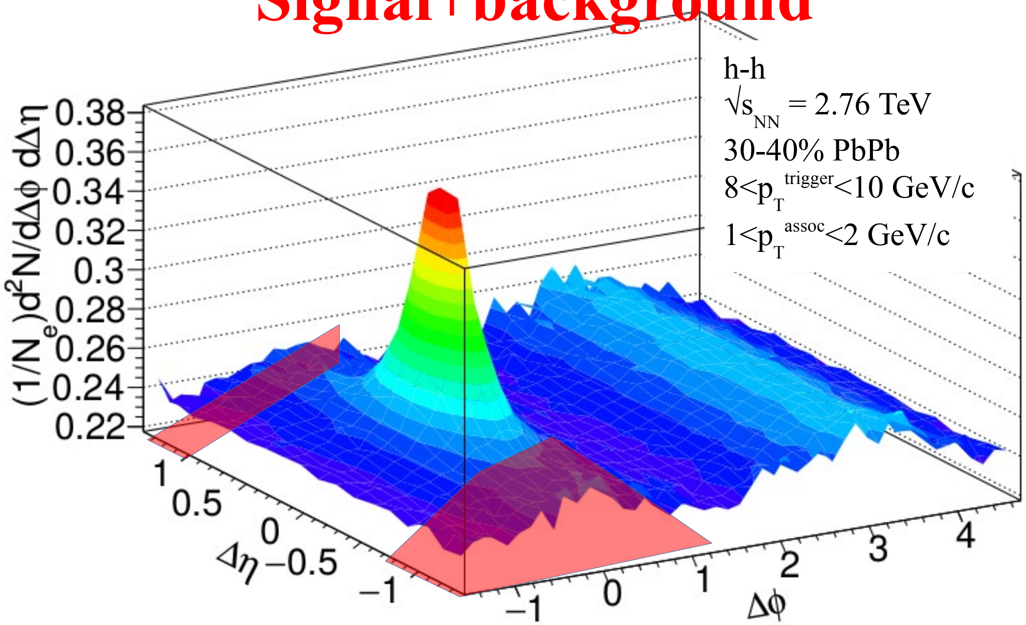
- Fixed acceptance cuts leads to a trivial structure due to acceptance
- This is fixed with a "mixed event" correction
  - Throw random trigger, associated particle within acceptance
  - Calculate Δφ, Δη
  - Use this distribution to correct for acceptance



Separating the signal and the background

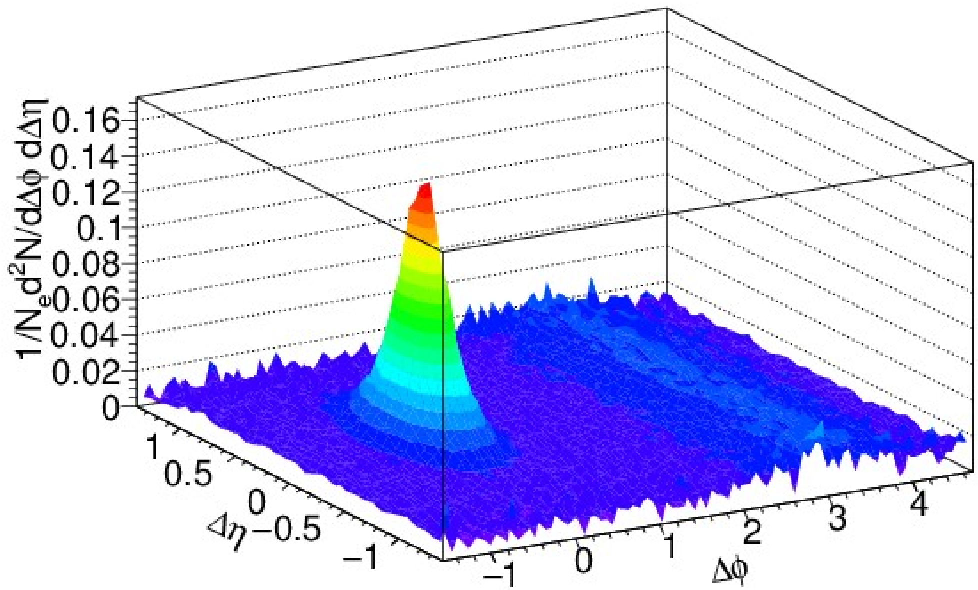
Separating signal+background

Signal+background



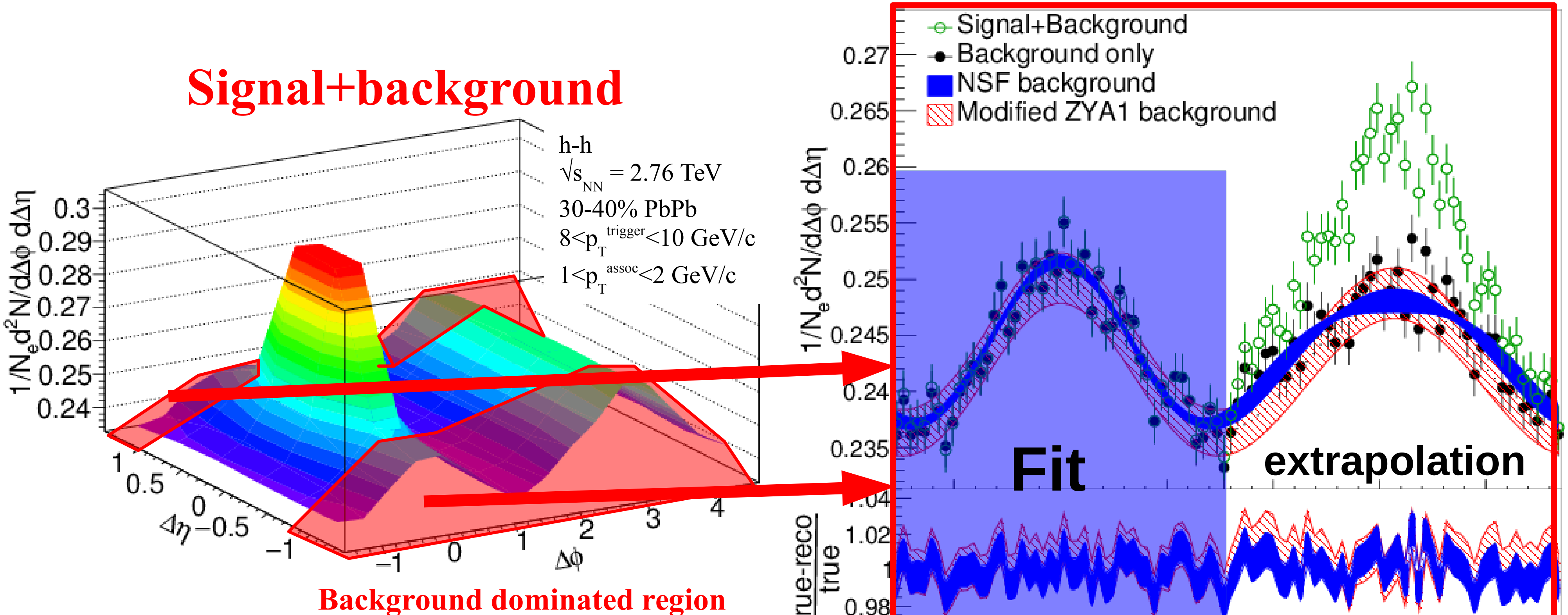
Background dominated region

Signal only



Near-Side Fit (NSF) method

No reaction plane dependence



- Project signal+background over $1.0<|\Delta\eta|<1.4$
- Fit background in $|\Delta\varphi|<\pi/2$ with v_n up to n=4

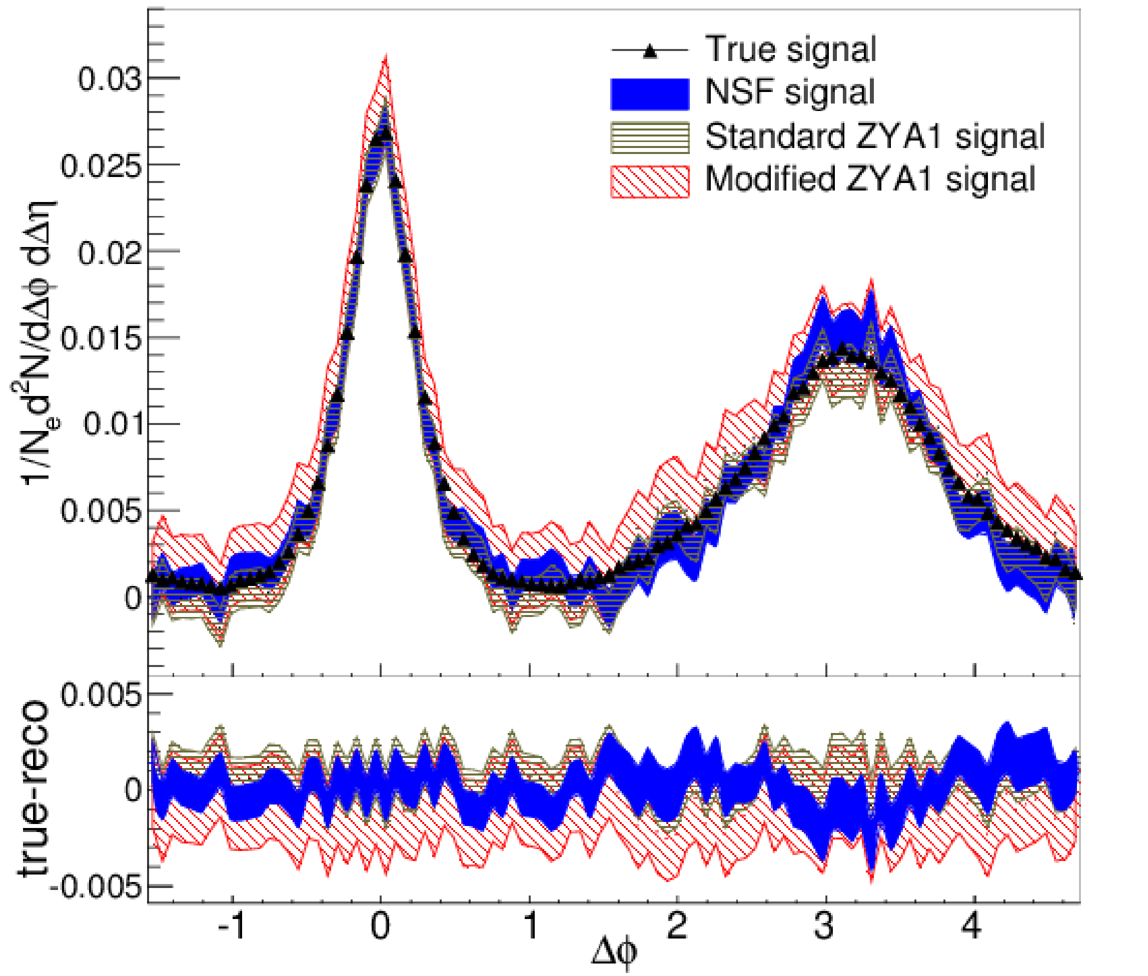
Near-Side Fit (NSF) method

No reaction plane dependence

- Reconstructs signal with less bias and smaller errors than ZYA1 method
- Extract v_n consistent with input

Sample		Yield ($Y \times 10^{-3}$) near-side	Yield ($Y \times 10^{-3}$) away-side
30-40% h-h	True	$17.1 \pm 0.1 \pm 0.2$	$19.9 \pm 0.1 \pm 0.2$
	Mod. ZYA1	$18.9 \pm 4.2 \pm 1.2$	$21.9 \pm 4.2 \pm 1.2$
	Std. ZYA1	$15.7 \pm 1.6 \pm 1.2$	$18.7 \pm 1.6 \pm 1.2$
	NSF	17.14 ± 1.1	20.14 ± 1.11

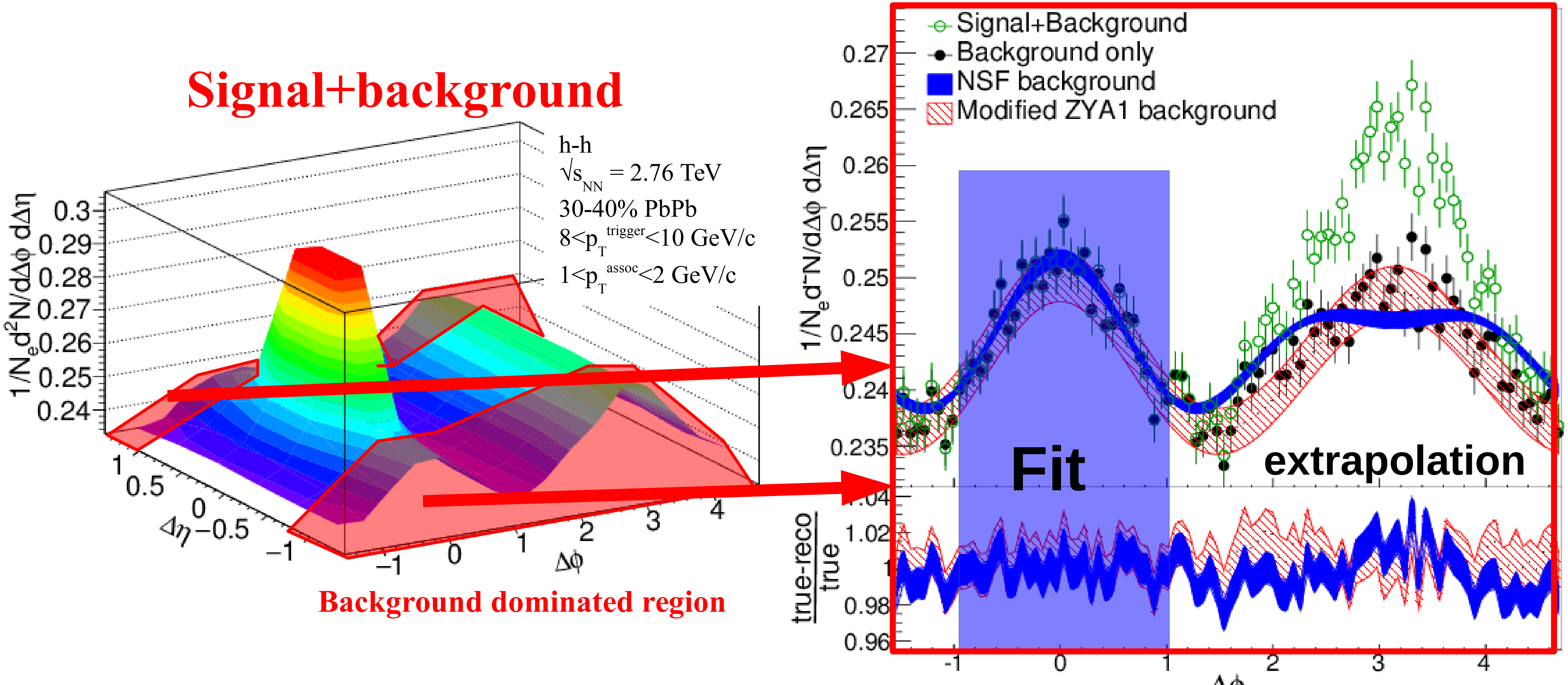
h-h
$\sqrt{s_{NN}} = 2.76$ TeV
30-40% PbPb
$8 < p_T^{trigger} < 10$ GeV/c
$1 < p_T^{assoc} < 2$ GeV/c



Standard ZYA1 = Zero Yield at $\Delta\Phi$=1
Modified ZYA1 = Zero Yield at $\Delta\Phi$=1 for $1.0<|\Delta\eta|<1.4$

Near-Side Fit (NSF) method

No reaction plane dependence

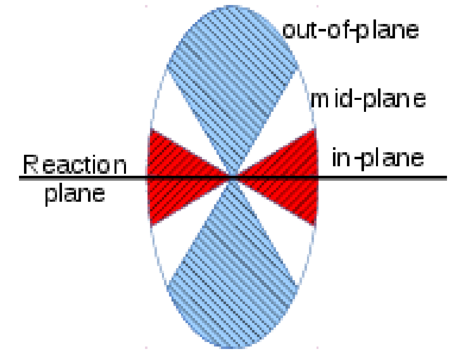


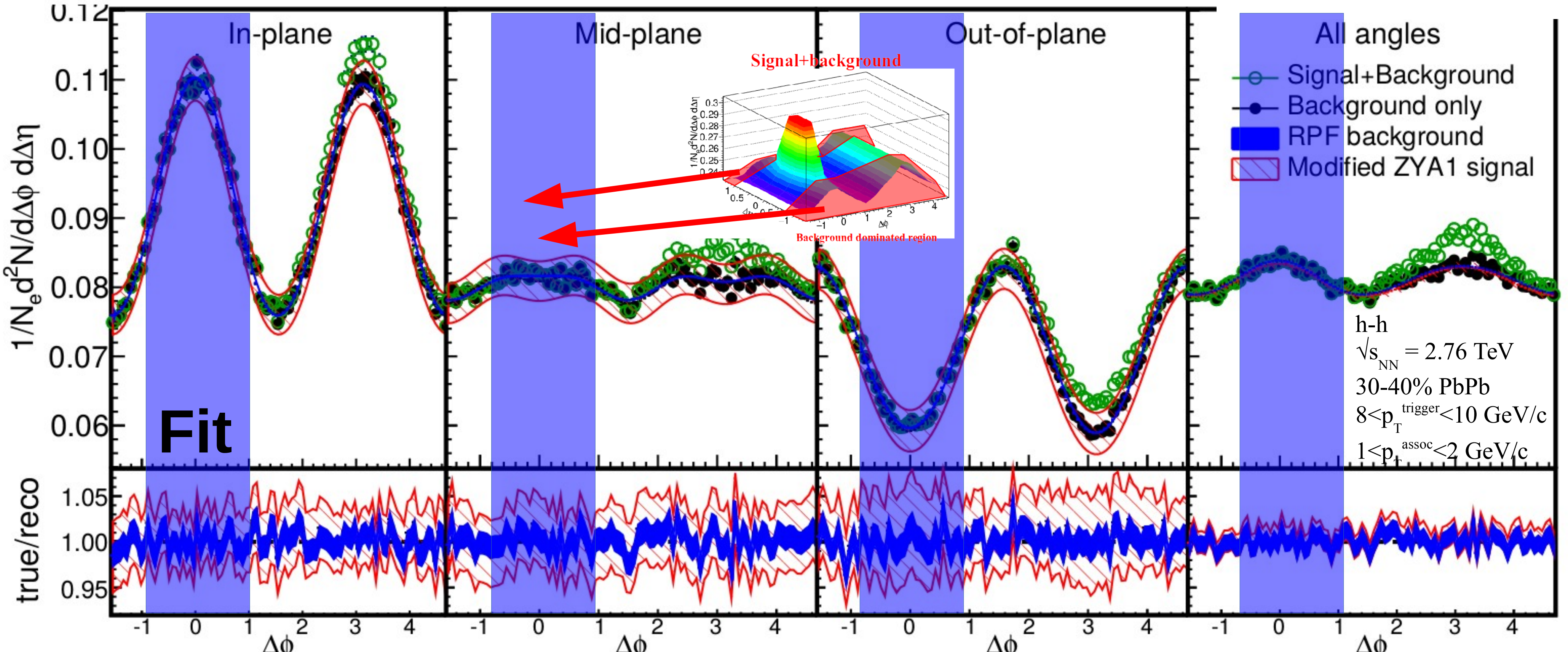
- Project signal+background over $1.0<|\Delta\eta|<1.4$
- Fit background in **$|\Delta\phi|<1$**
- **Not reliable over narrower $\Delta\phi$ region**

Adding reaction plane dependence

Reaction Plane Fit (RPF) method

30-40% central

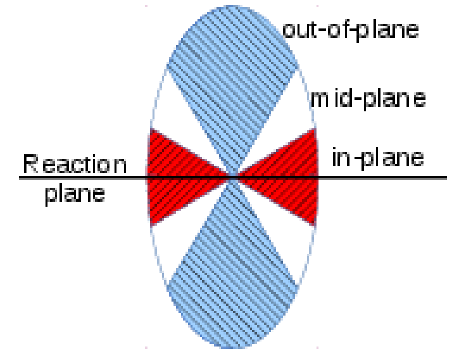


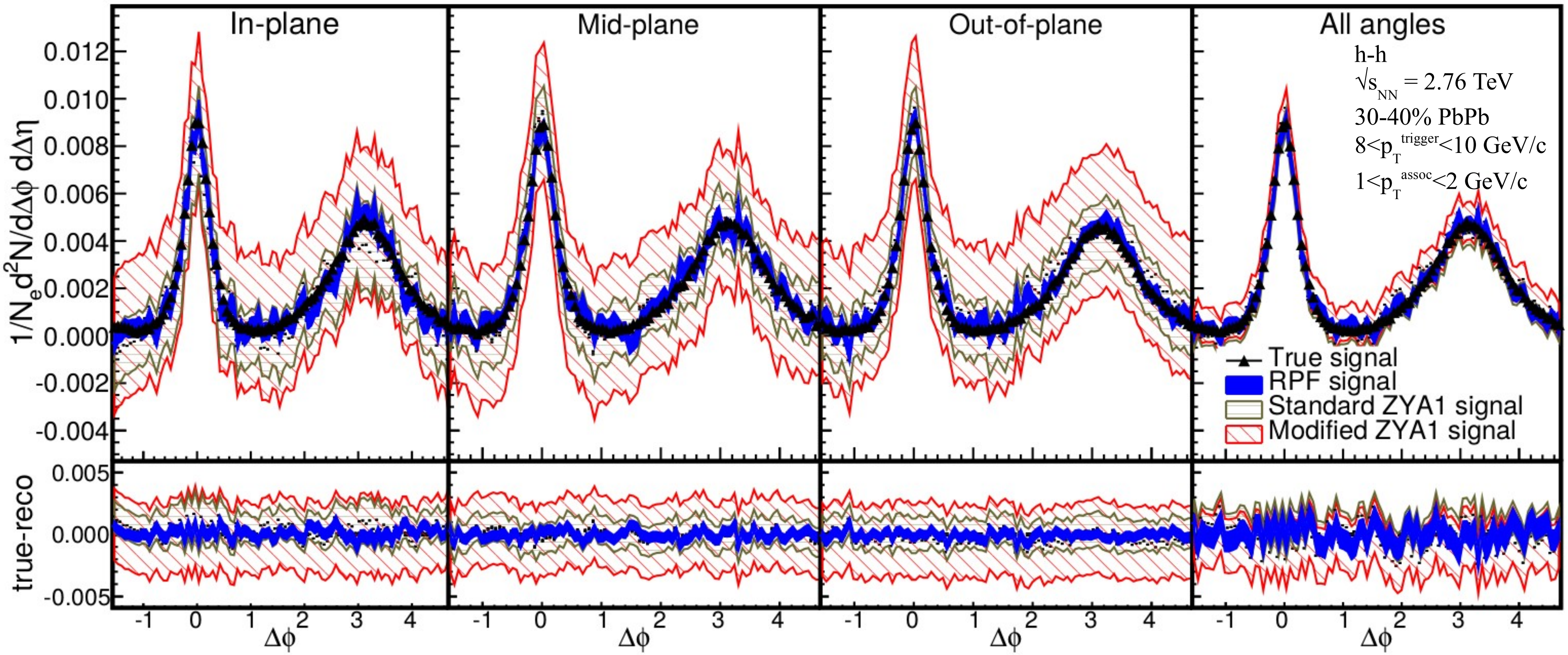


- Project signal+background over $1.0<|\Delta\eta|<1.4$
- Fit background in $|\Delta\varphi|<1$ including reaction plane dependence
- v_n and B extracted with v_n up to n=4

Reaction Plane Fit (RPF) method

30-40% central

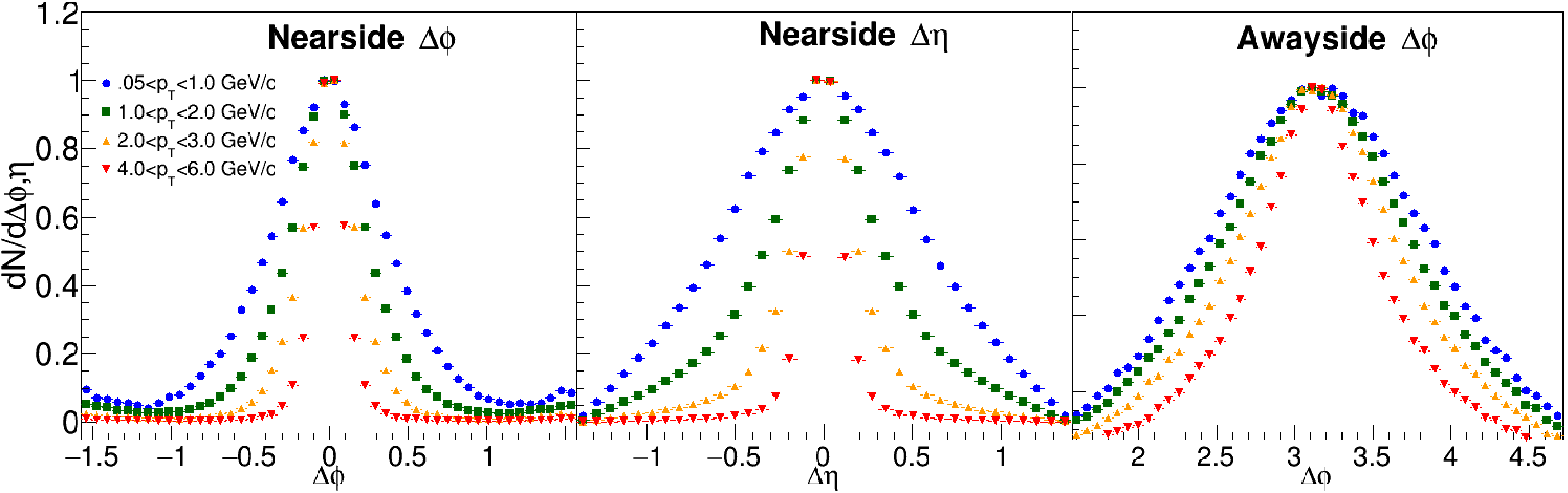




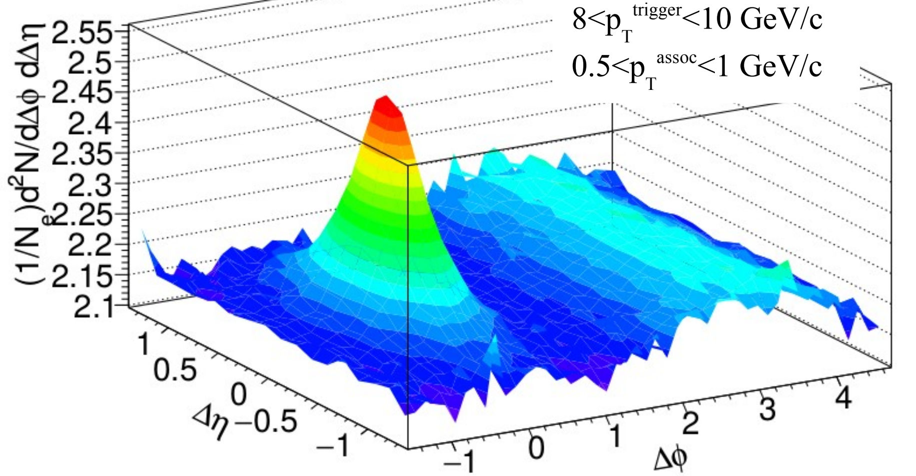
	near-side $Y \times 10^{-3}$				away-side $Y \times 10^{-3}$			
	in-plane	mid-plane	out-of-plane	All	in-plane	mid-plane	out-of-plane	All
True	5.78 ± 0.03 ± 0.13	5.77 ± 0.03 ± 0.14	5.65 ± 0.03 ± 0.13	17.1 ± 0.1 ± 0.2	6.74 ± 0.03 ± 0.13	6.72 ± 0.03 ± 0.14	6.52 ± 0.03 ± 0.13	19.9 ± 0.1 ± 0.2
Mod. ZYA1	6.3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

Going to lower momenta

Low momenta

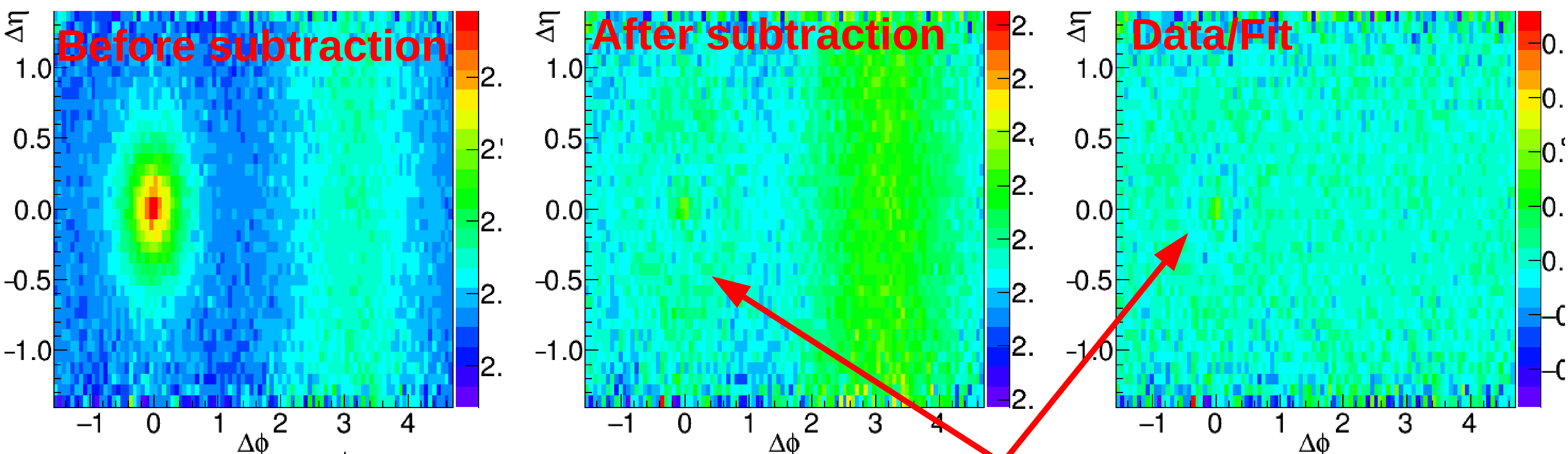


- ZYAM assumptions break down at low p_T
- If method doesn't work on PYTHIA, it can't be trusted on data!
- But low p_T is interesting!



Going to lower momenta, medium modifications

- Peak gets broader
- Fit near-side peak and subtract it
- Increase $\Delta\eta$ range available for background subtraction



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

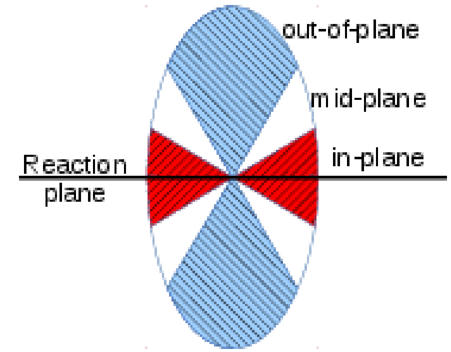
$8<p_T^{trigger}<10$ GeV/c

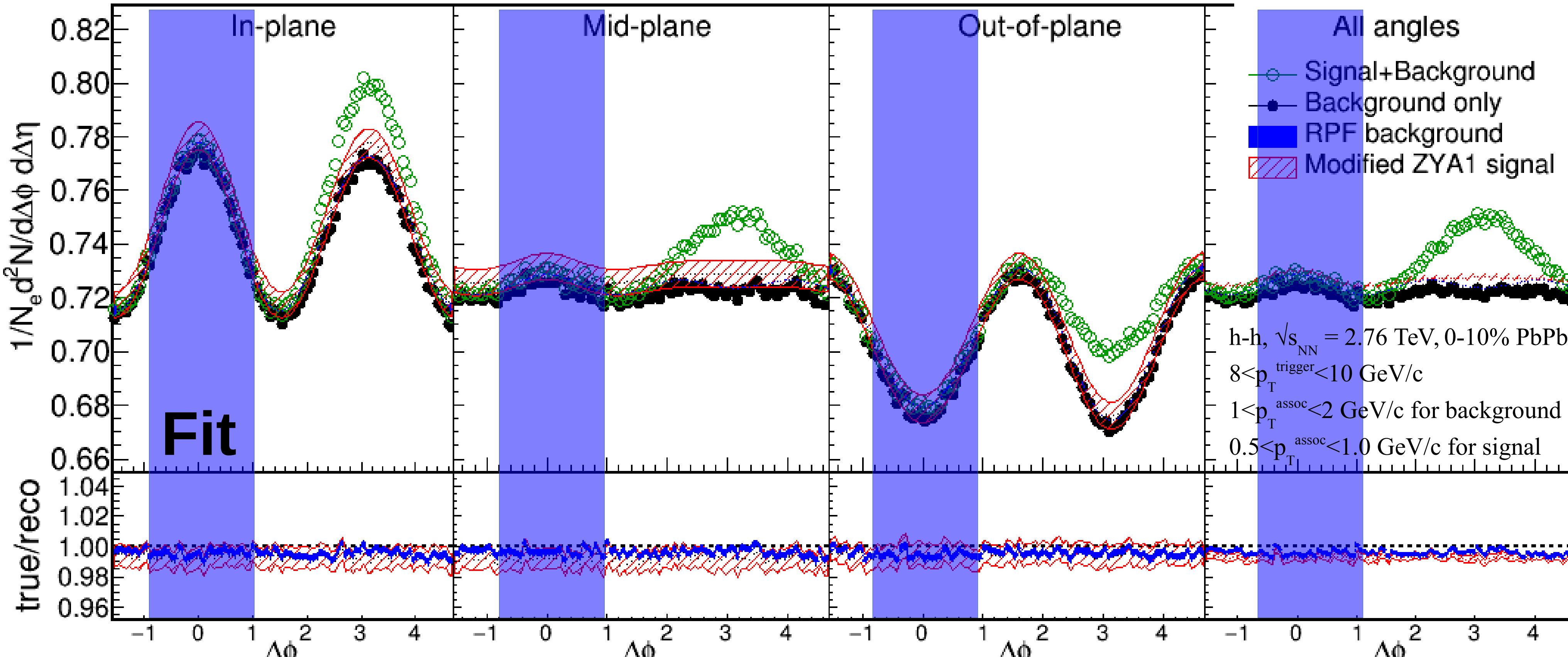
$1<p_T^{assoc}<2$ GeV/c for background, $0.5<p_T^{assoc}<1.0$ GeV/c for signal

Structure from imperfect fit

Near-Side Subtracted RPF method

30-40% central

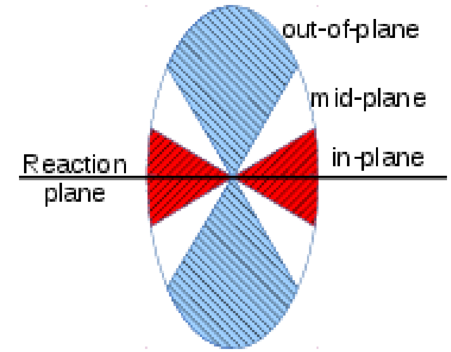


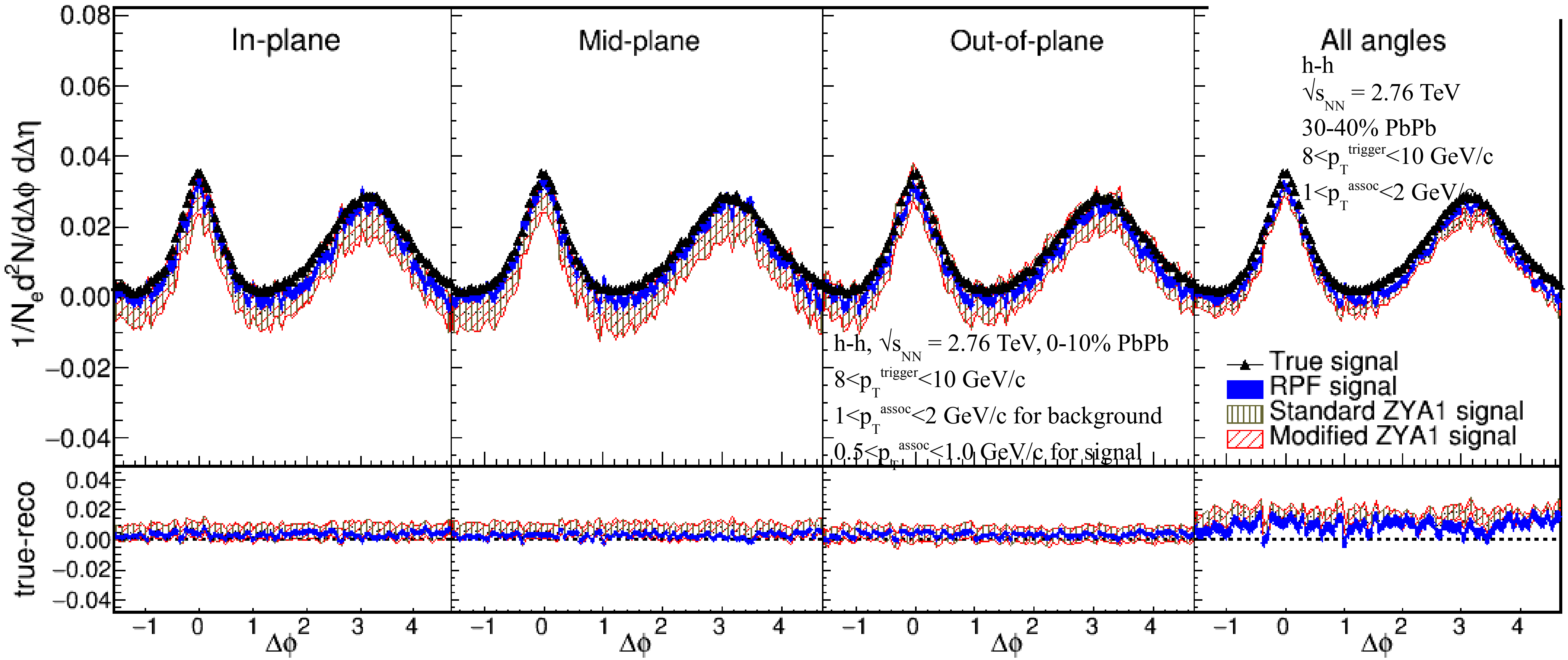


- Project signal+background over **0.0**<|Δη|<1.4
- Fit background in |Δφ|<1 including reaction plane dependence
- v_n and B extracted with v_n up to n=4

Reaction Plane Fit (RPF) method

30-40% central



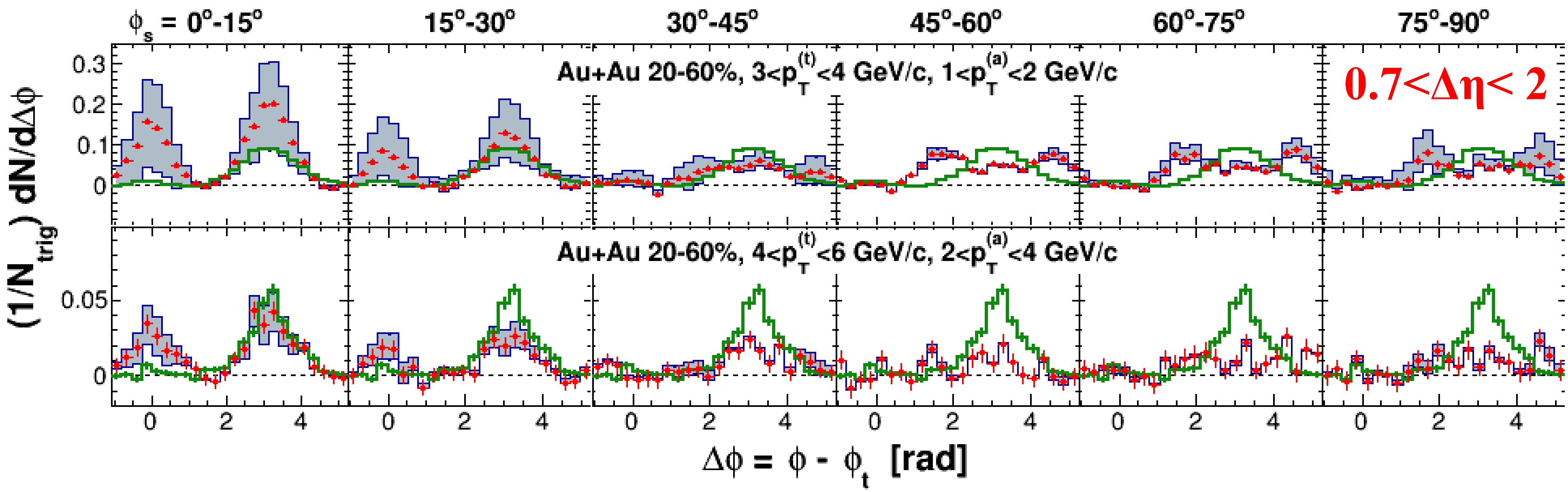


- **Works beautifully!**

STAR data

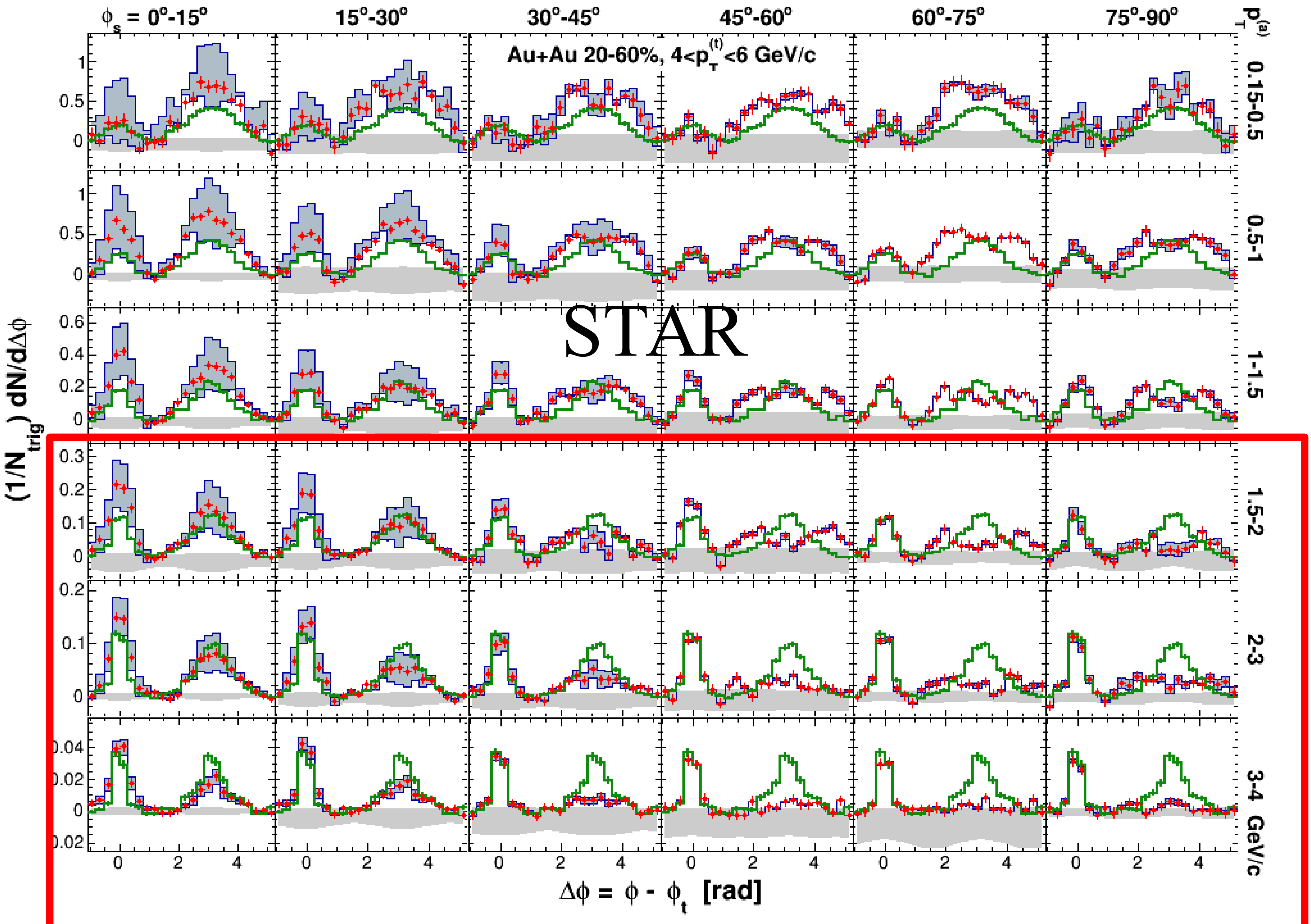
STAR measurements of dihadron correlations relative to reaction plane

- 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 Δη> 0.7
  - RPF method assumes no signal at Δη> 0.7



RPF Method

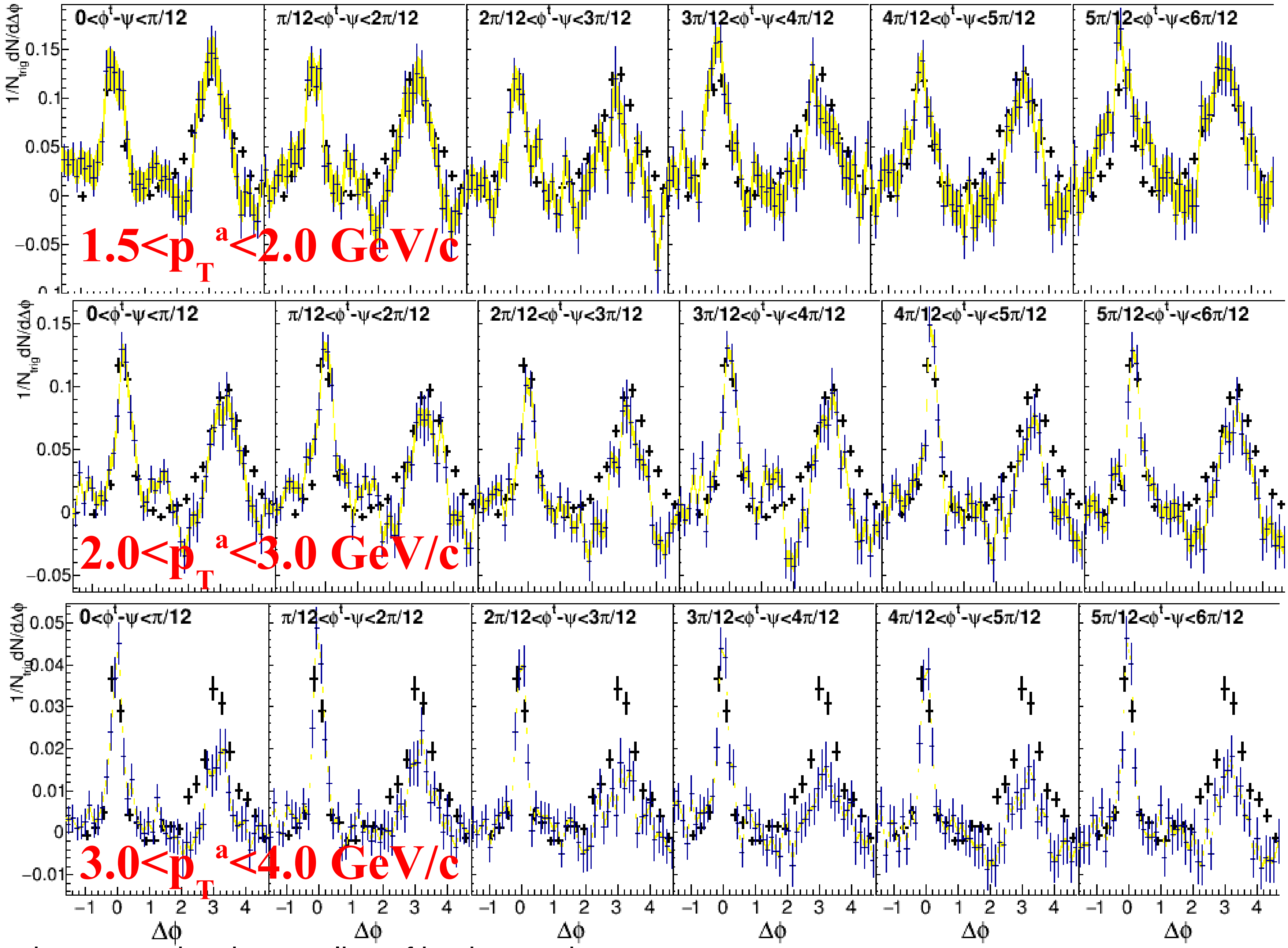
- 6 bins relative to reaction plane
- Background level
  - Normalized per trigger → B same in all bins if v_2^t is the only effect → reduces info for RPF
  - "The background levels can be different for the different φ_s slices because of the net effect of the variations in jet-quenching with φ_s and 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**



ϕ_s = 0°-15°
15°-30°
30°-45°
45°-60°
60°-75°
75°-90°
Au+Au 20-60%, $4<p_T^{(t)}<6$ GeV/c
STAR
$p_T^{(a)}$
0.15-0.5
0.5-1
1-1.5
1.5-2
2-3
3-4 GeV/c
$(1/N_{trig})\ dN/d\Delta\phi$
$\Delta\phi = \phi - \phi_t$ [rad]

Background subtracted correlations $4<p_T^t<6$ GeV/c

Black points: d+Au

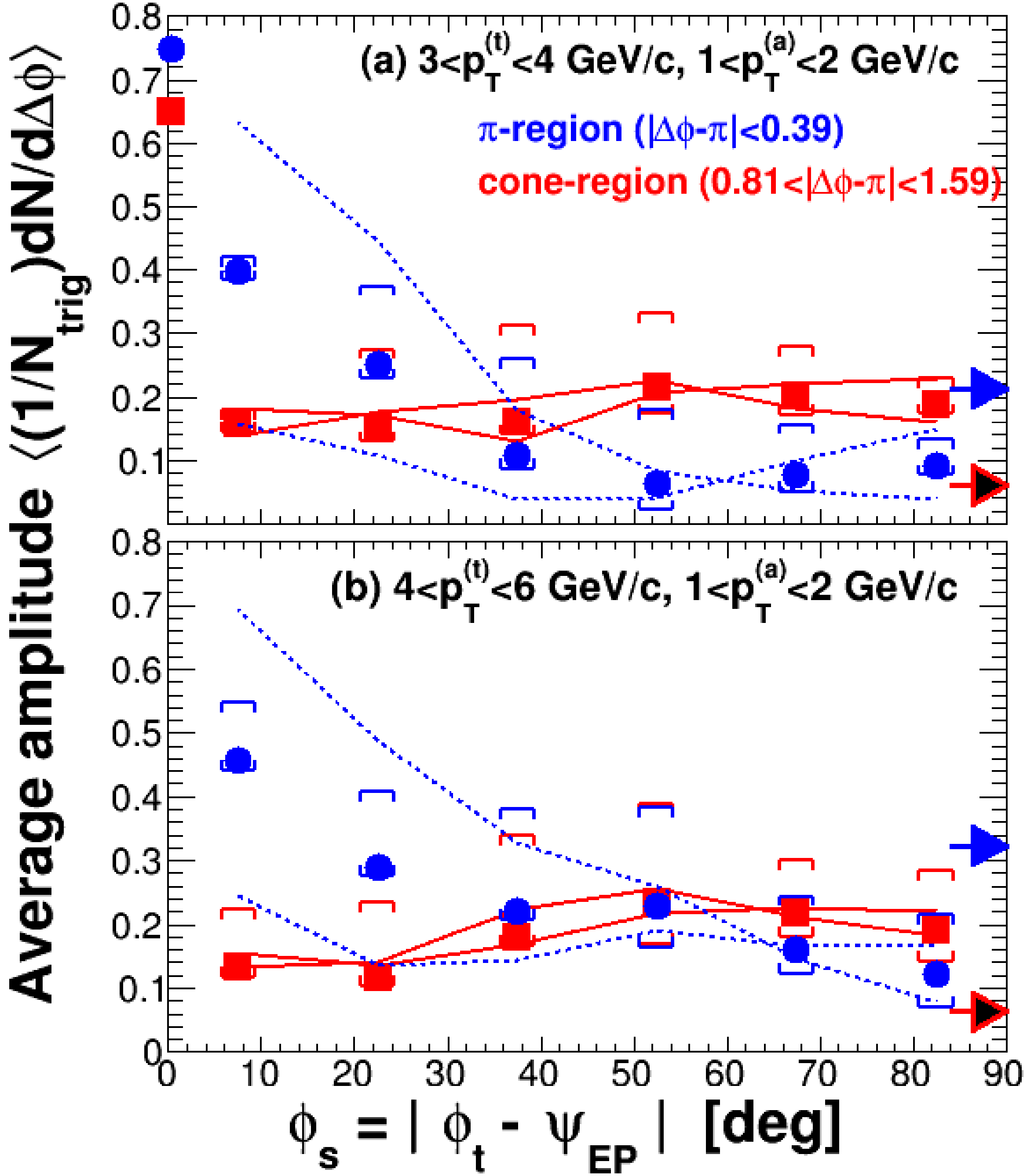


Yellow bands: uncertainty in rescaling of background

Statistical error bars include correlated statistical error on background

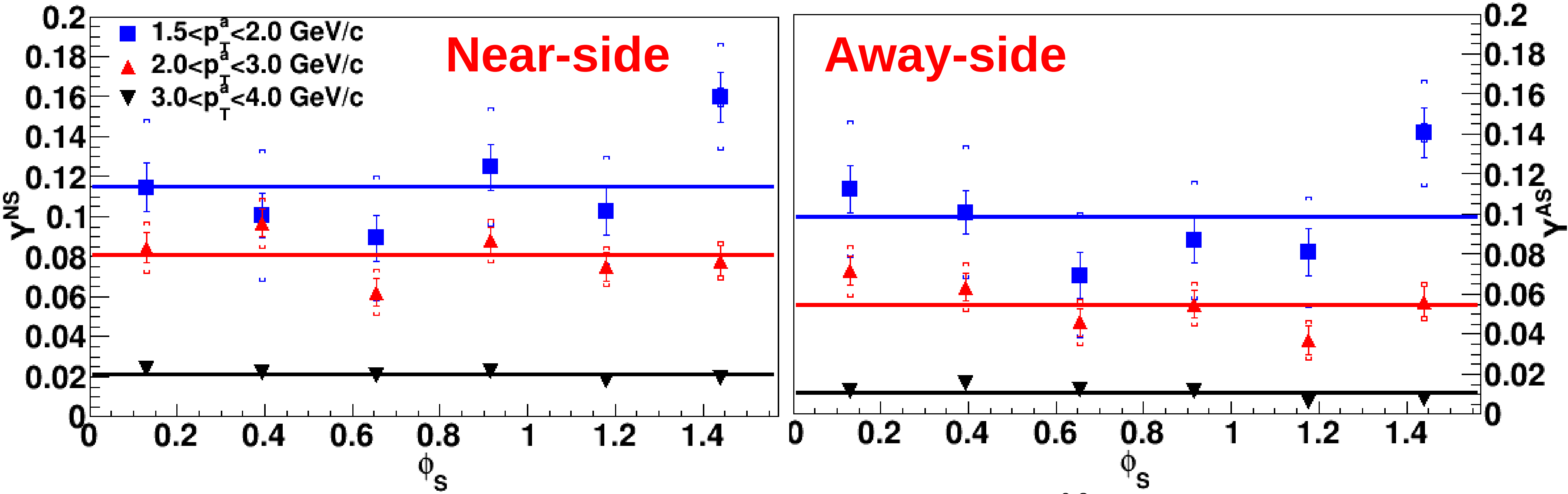
No "Mach Cone"

Yields – STAR



- Large error bars (shown as lines)
- Indications of reaction plane dependence?

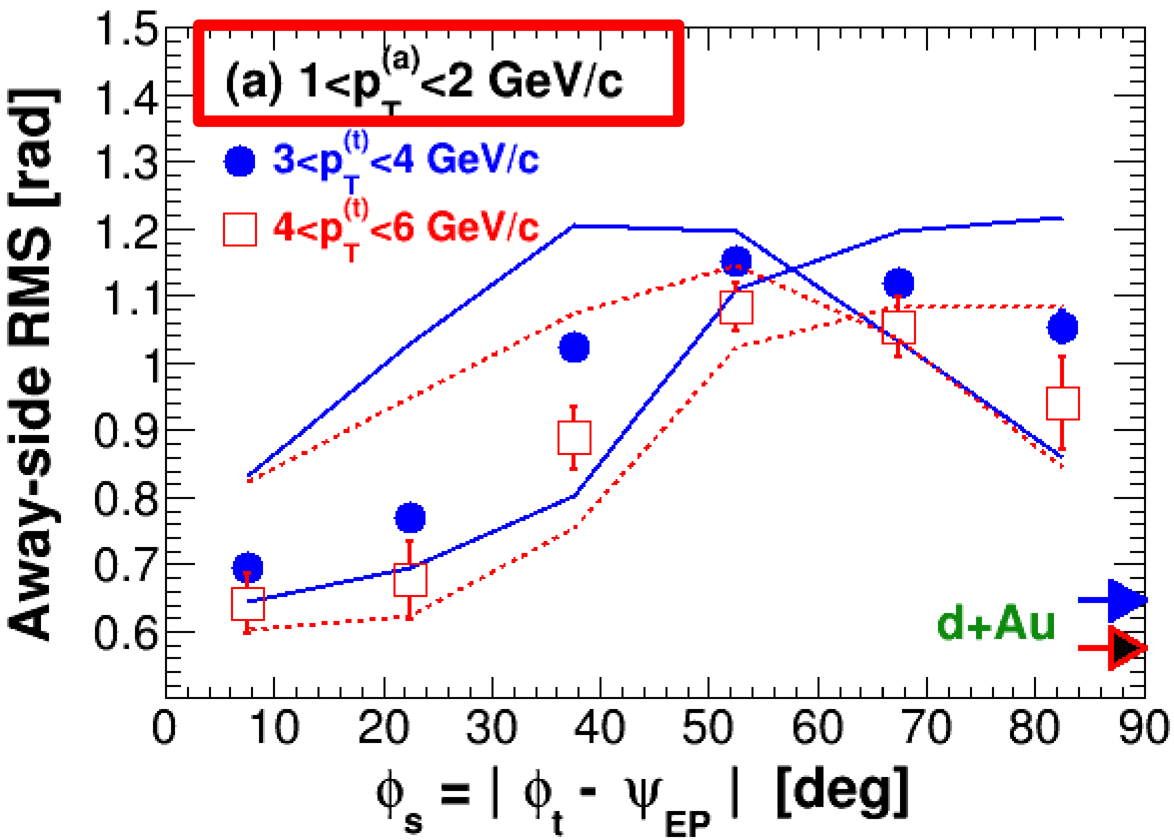
Yields $4<p_T^t<6$ GeV/c



$$Y^{NS} = \int_{-0.8}^{0.8} C(\Delta\varphi)\, d\Delta\varphi \qquad Y^{AS} = \int_{\pi-0.8}^{\pi+0.8} C(\Delta\varphi)\, d\Delta\varphi$$

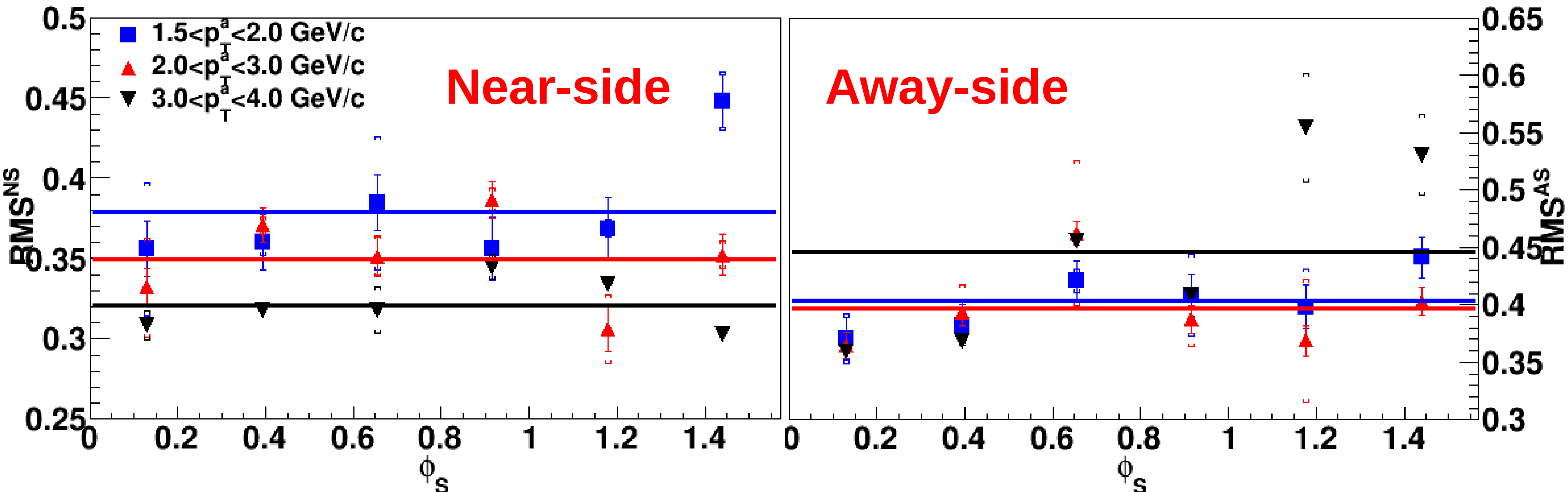
- Lines show averages
- No dependence on $\varphi_S = \varphi^t - \psi$
- Higher precision than public analysis (different p_T)

RMS - STAR



- Large error bars (shown as lines)
- Strong reaction plane dependence

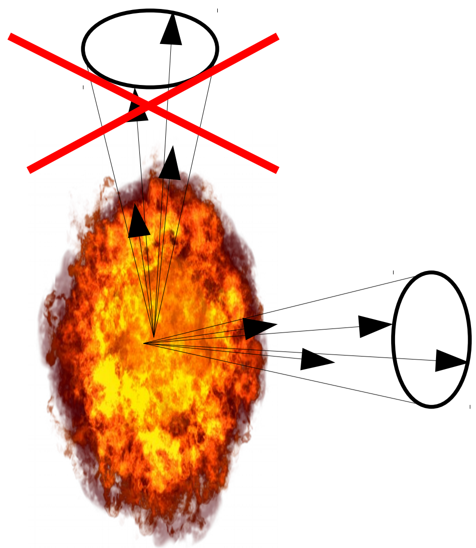
Truncated RMS $4<p_T^t<6$ GeV/c

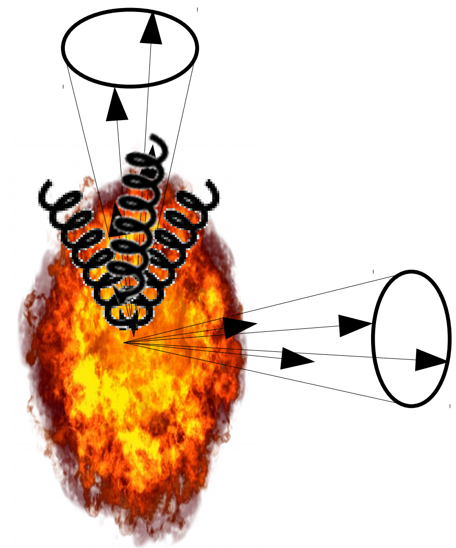


$$RMS_{trunc}^{NS} = \sqrt{\int_{-0.8}^{0.8} \Delta\varphi^2 C(\Delta\varphi)\, d\Delta\varphi} \qquad RMS_{trunc}^{AS} = \sqrt{\int_{\pi-0.8}^{\pi+0.8} (\Delta\varphi-\pi)^2 C(\Delta\varphi)\, d\Delta\varphi}$$

- Lines show averages
- Higher precision than public analysis (different p_T)

Competing effects





Quenching

Fewer jets, lower yield out of plane

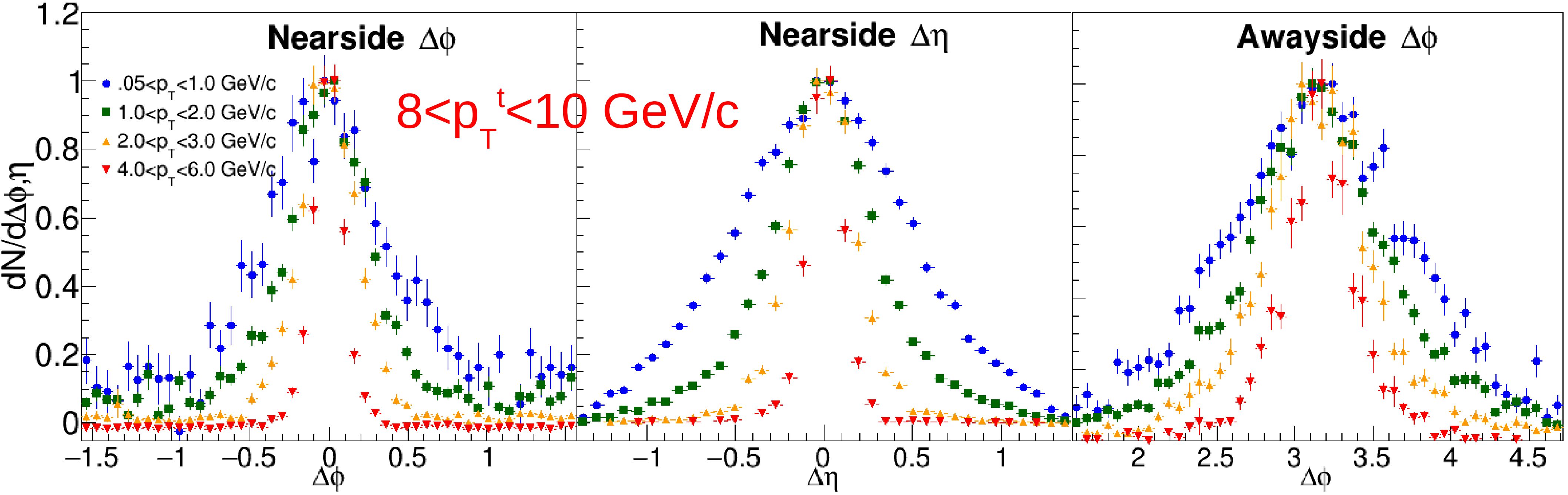
Bremsstrahlung

Softer, higher yield out of plane

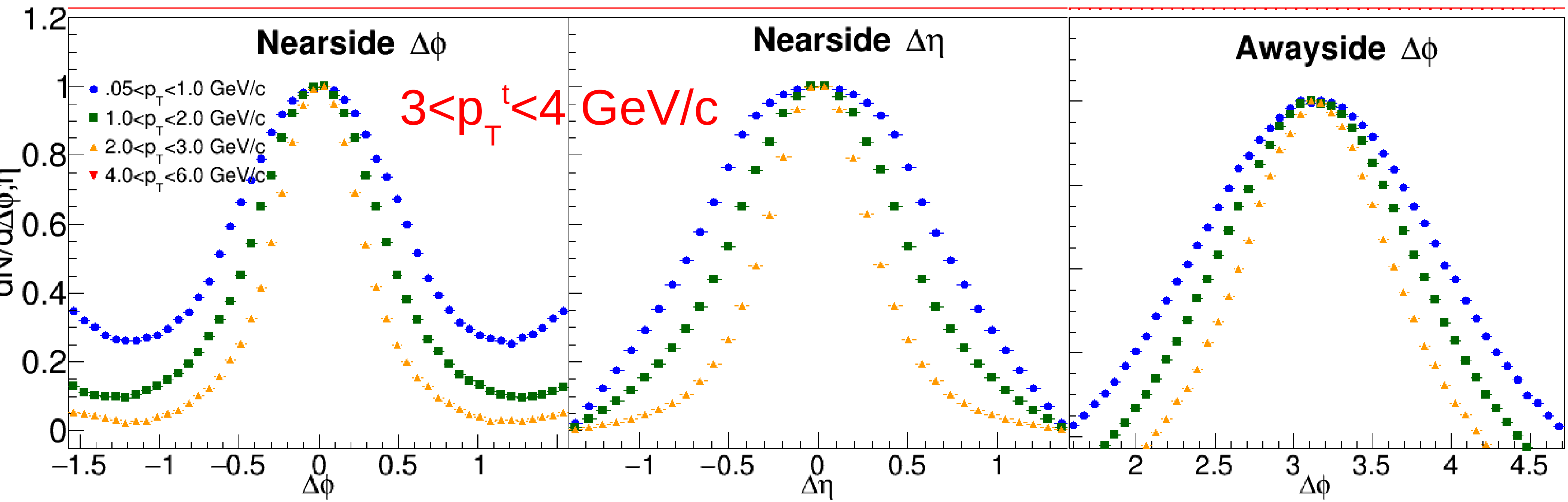
Conclusions

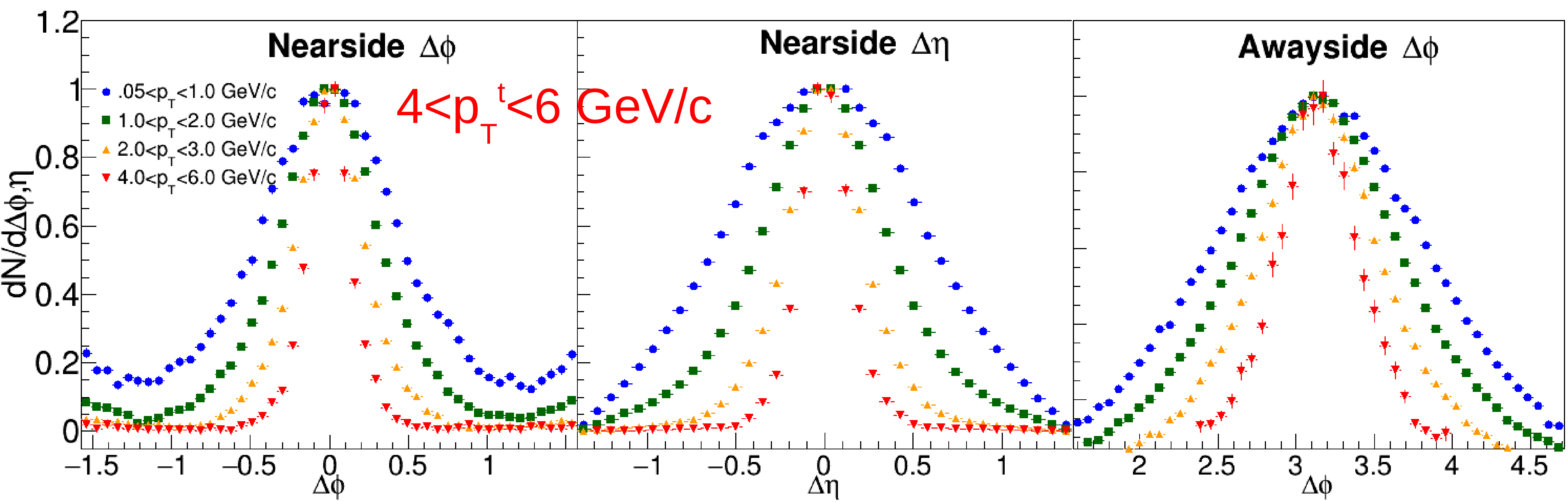
- NSF, RPF, NSS(NSF/RPF) methods work!
  - Much higher precision than ZYAM
  - NSS works to extend analyses to low p_T
- Qualitatively different results from public STAR analysis
  - Little/no reaction plane dependence in yield, RMS at these momenta
  - Away-side does not disappear completely, comparable to d+Au
  - More subtle effects than with ZYAM

PYTHIA at 200 GeV

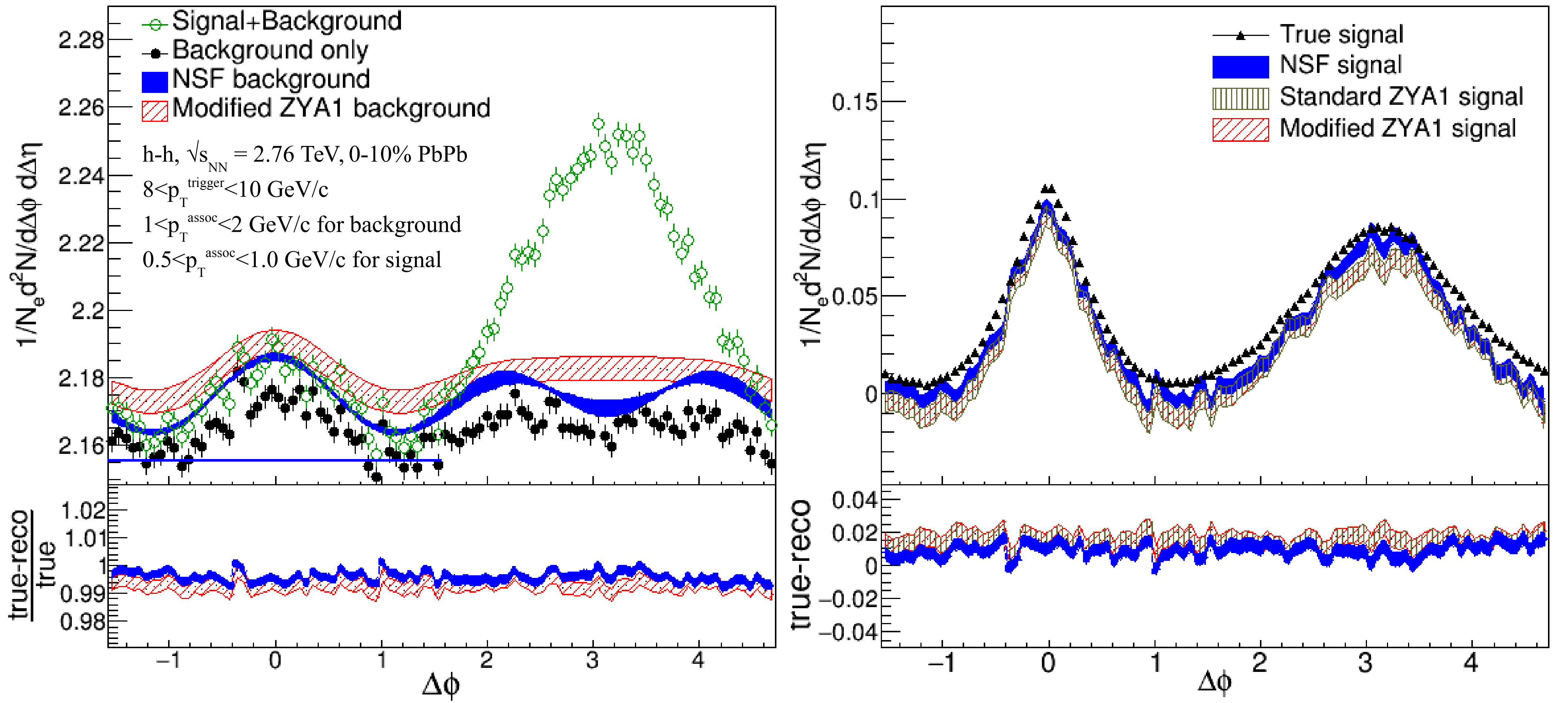


PYTHIA at 200 GeV



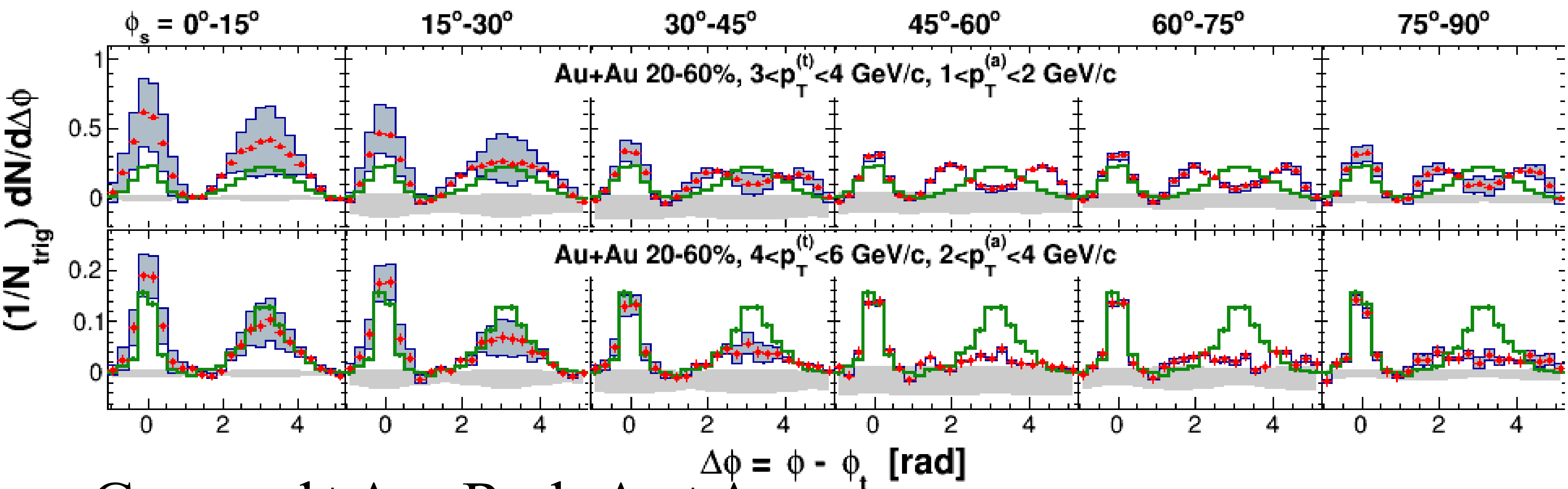


Near-Side Subtracted NSF method



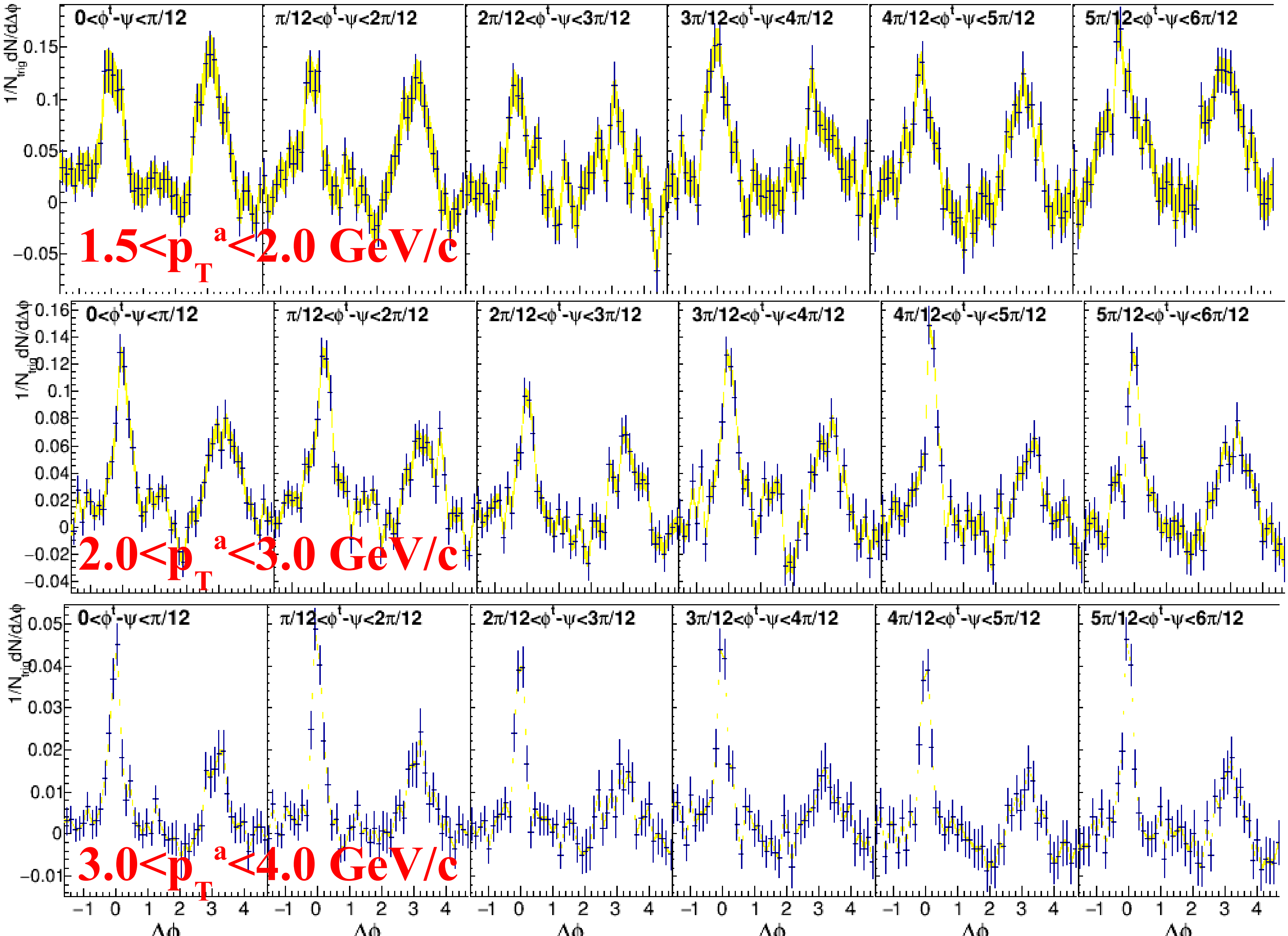
- Project signal+background over **0.0**<|Δη|<1.4
- Fit background in |Δφ|<1 including reaction plane dependence
- Bias from residual contamination by near-side

Correlations - STAR



- Green: d+Au, Red: Au+Au
- Large error bars
- "Mach Cone" evident, even decrease in amplitude for higher p_T^t

Background subtracted correlations $4<p_T^t<6$ GeV/c



Yellow bands: uncertainty in rescaling of background
Statistical error bars include correlated statistical error on background

No "Mach Cone"

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 $N_{trigger}$?