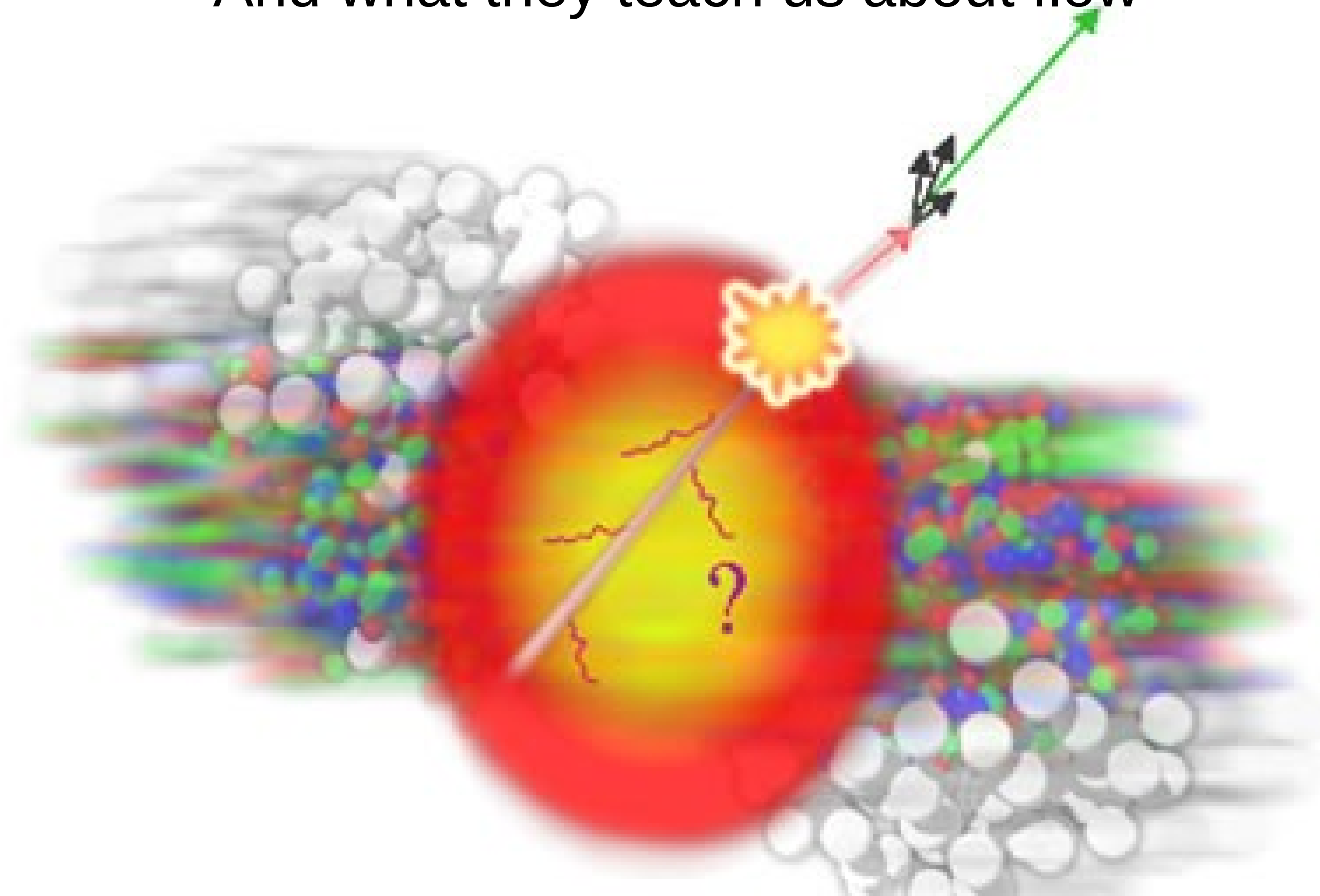
Precision measurements of jet-like correlations

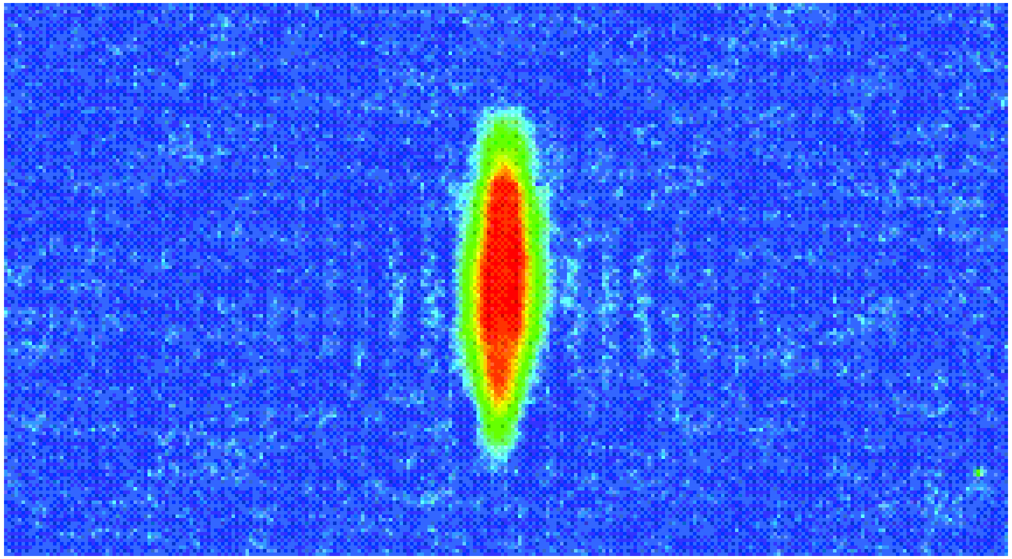
And what they teach us about flow



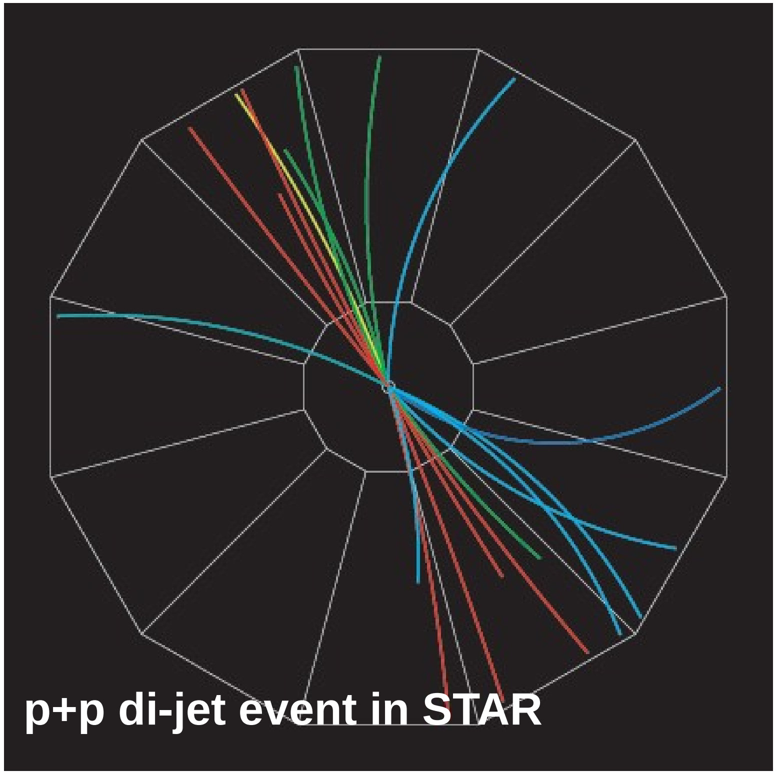
Christine Nattrass

Based on Phys. Rev. C 93, 044915(2016) & Phys.Rev. C94 011901(2016)
Contributions from Natasha Sharma, Joel Mazer, Meg Stuart, Aram Bejnood

Jets and flow



K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas **Science** 298 **2179 (2002)**



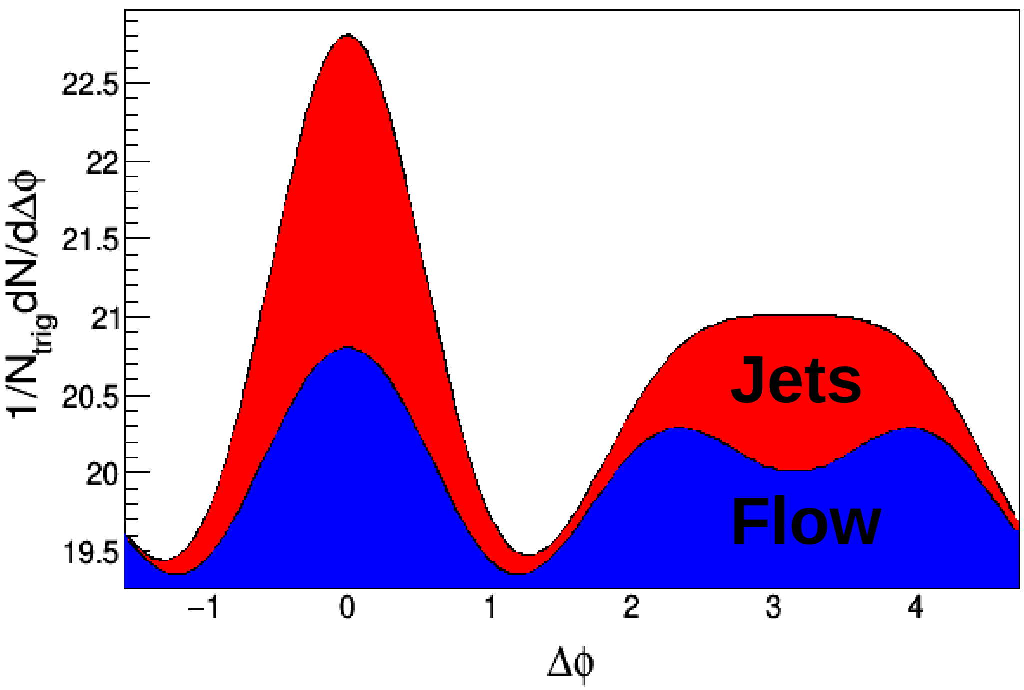
- Both lead to azimuthal correlations
- Jets → background for flow
- Flow → background for jets

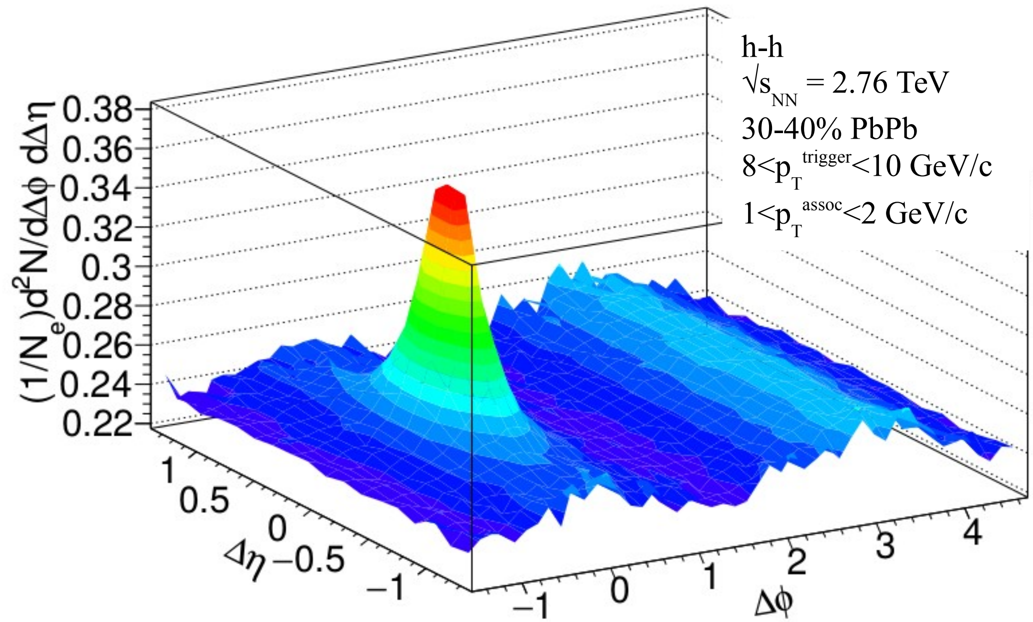
Overview

- New method for separating jets from flow
- Apply it to data
  - Di-hadron correlations
  - Jet-hadron correlations
- And what we learn about flow from jet-like correlations

Methods

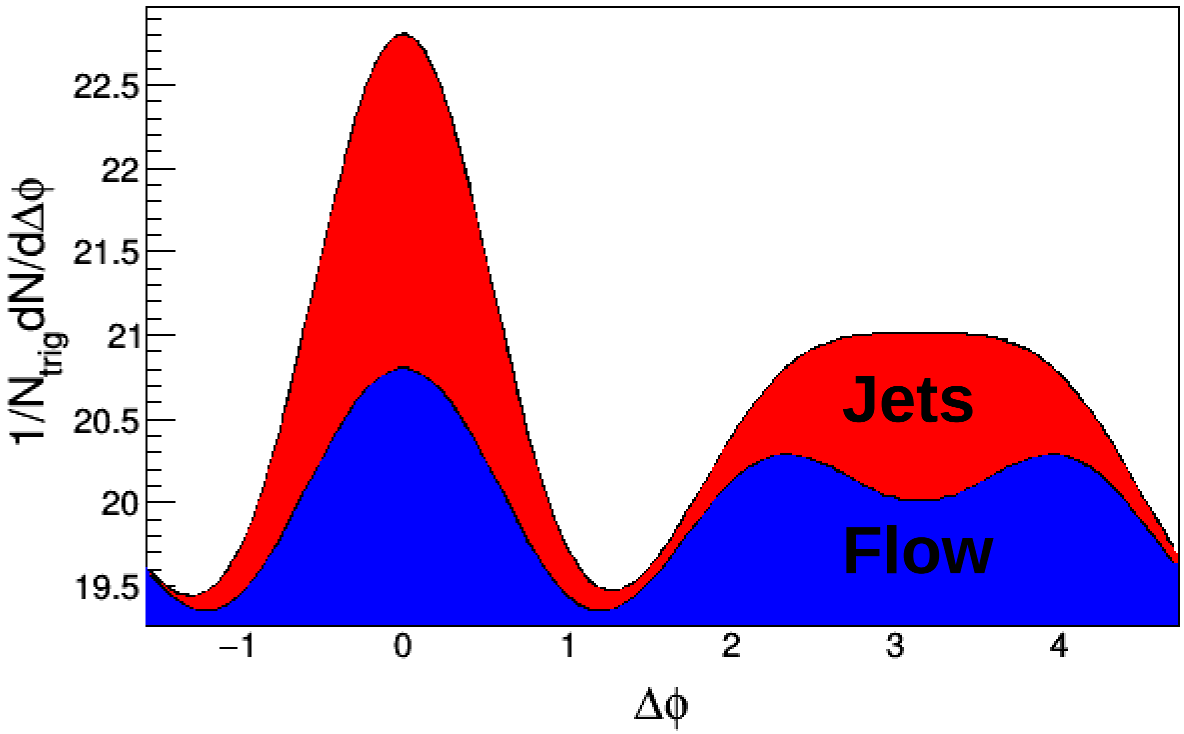
Two component model





- 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 studies of full jets*

Zero Yield At Minimum

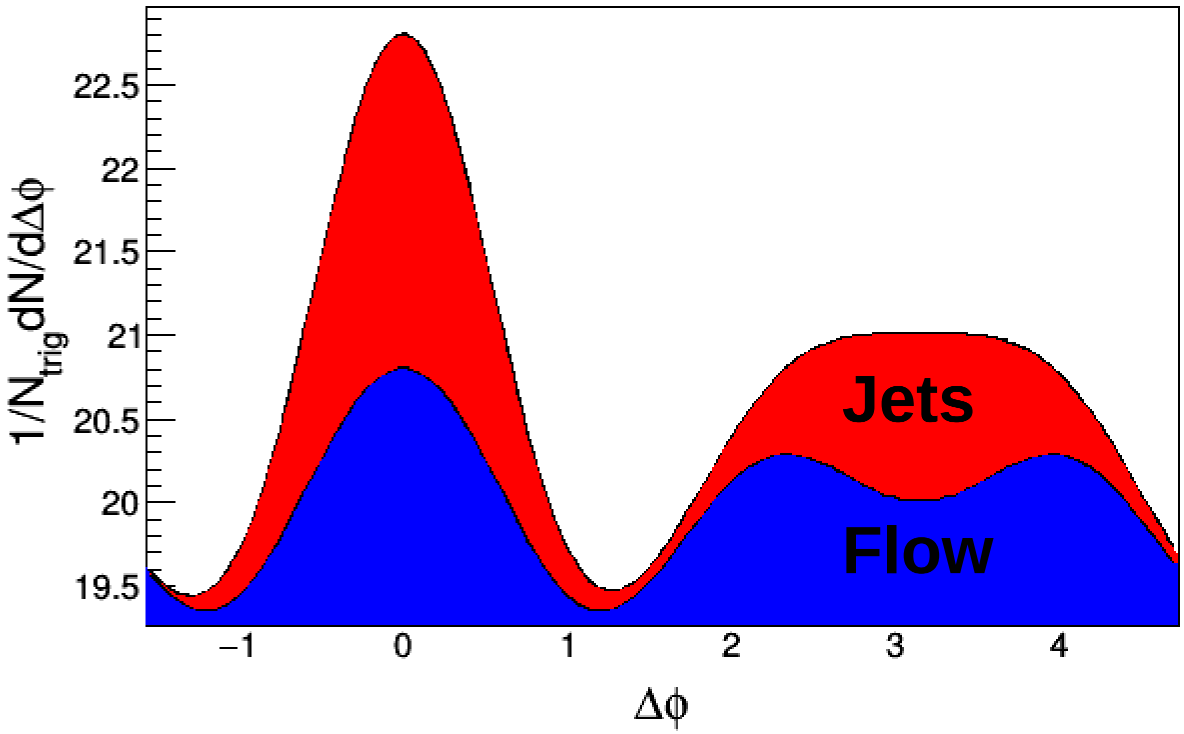


- Flow component given by

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

- 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. Δφ=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 $v_n \neq \tilde{v}_n$
- If jet peak is broadened, may overestimate background (underestimate signal)

Background Subtraction Methods

- **Δη Method:** Project near-side signal onto Δη and subtract constant background. Near-side only
- **Δη Gap Method:** Use signal at large Δη to determine background, assuming constant background in Δη. Near-side only
- **Zero-Yield at Minimum (ZYAM):** Assumes v_n from other studies, assumes region around $\Delta\varphi \approx 1$ is background dominated

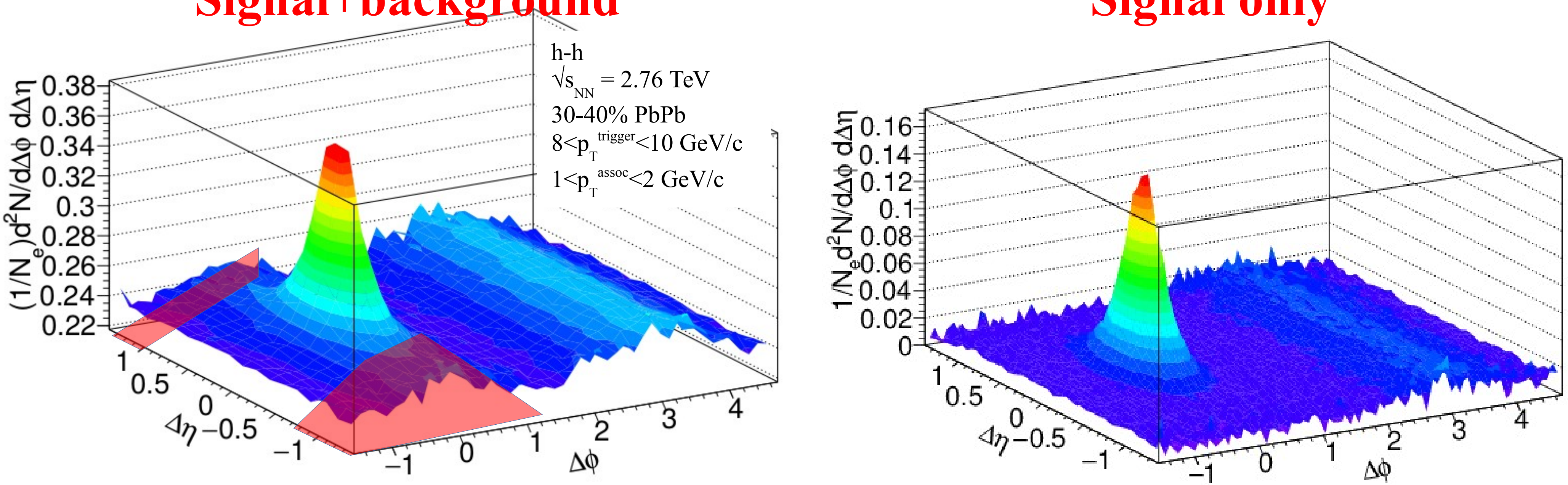
Separating the signal and the background

Toy model:

- Signal: PYTHIA
- Background: thrown to v_n = 10 to match data
- Details in backup and paper

Signal vs background

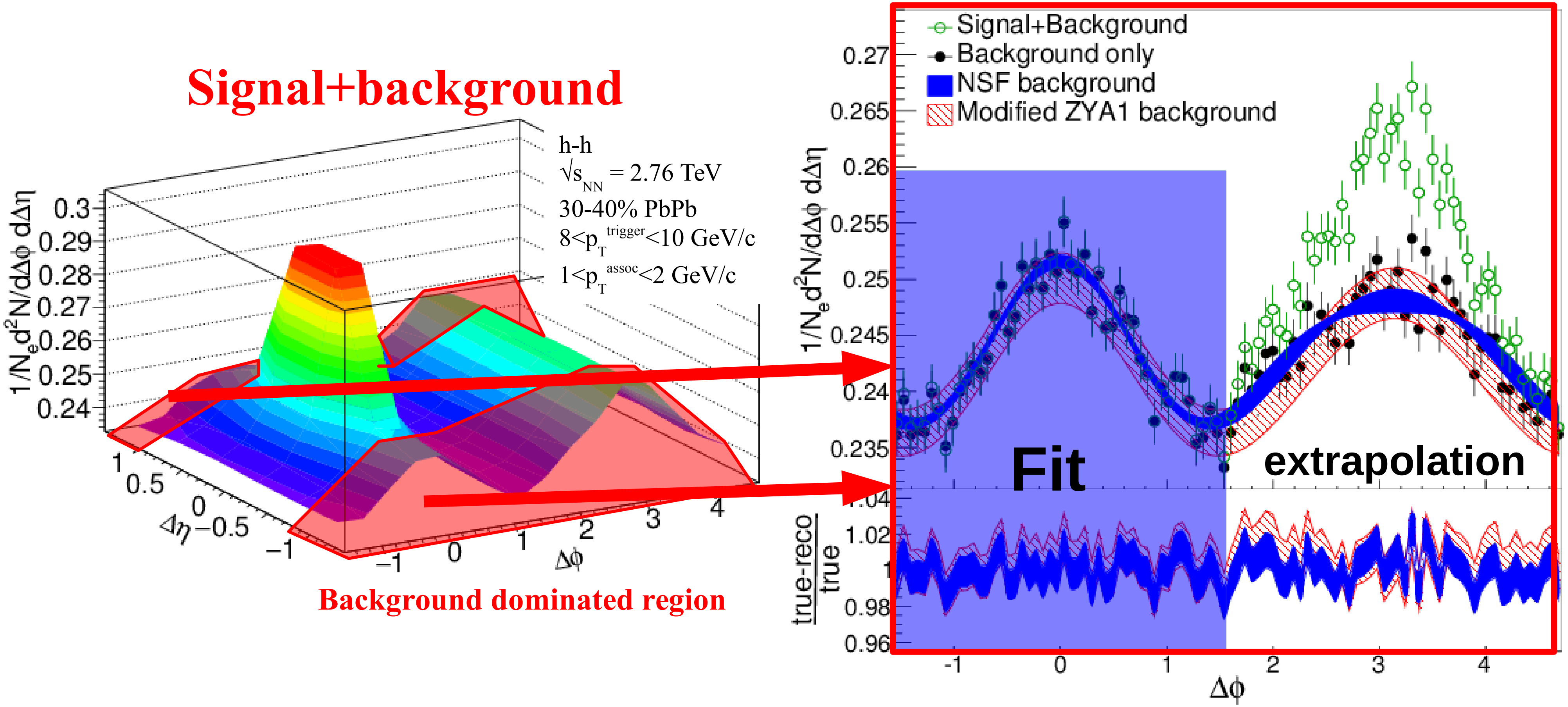
Signal+background **Signal only**



Background dominated region

Near-Side Fit (NSF) method

No reaction plane dependence



- Project signal+background over 1.0<|Δη|<1.4
- Fit background in |Δφ|<π/2 with v_n up to n=4

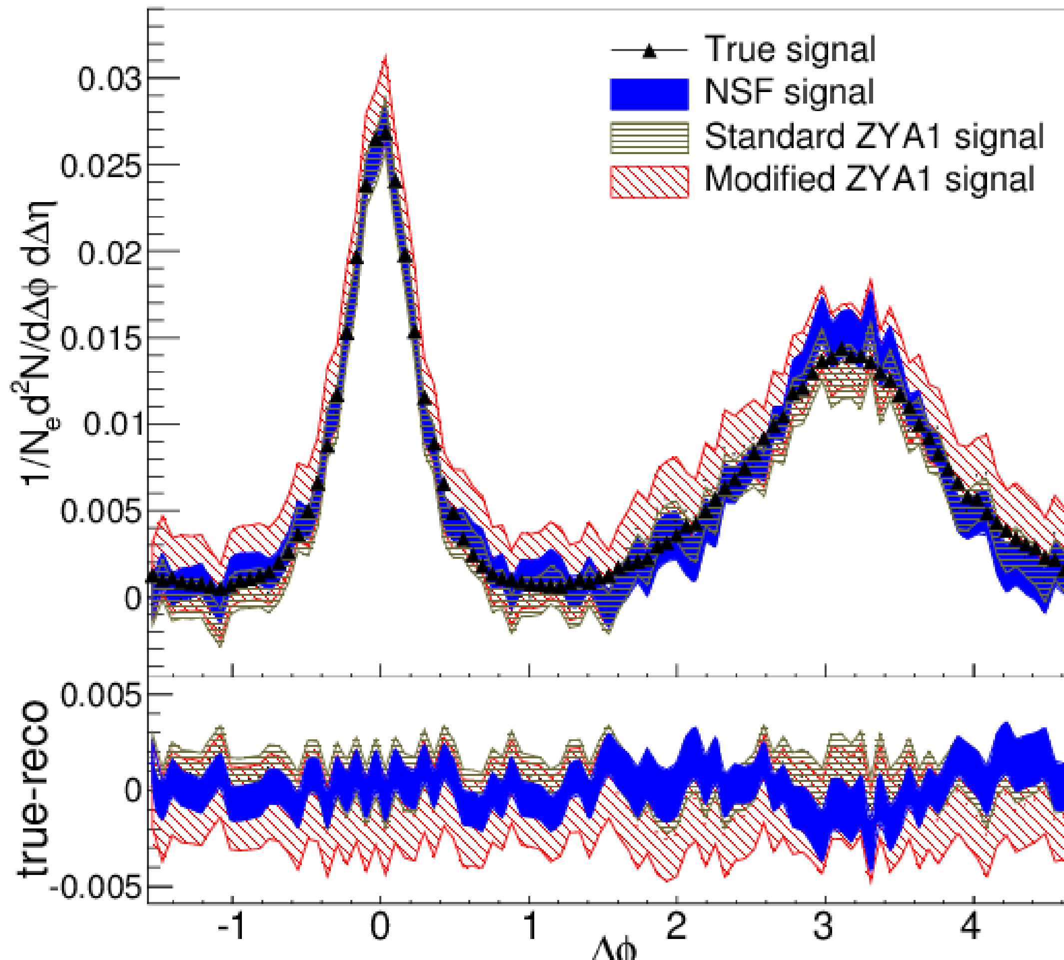
Near-Side Fit (NSF) method

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	away-side
30-40% h-h	True	17.1 ± 0.1 ± 0.2	19.9 ± 0.1 ± 0.2
	Mod. ZYA1	18.9 ± 4.2 ± 1.2	21.9 ± 4.2 ± 1.2
	Std. ZYA1	15.7 ± 1.6 ± 1.2	18.7 ± 1.6 ± 1.2
	NSF	17.14 ± 1.1	20.14 ± 1.11

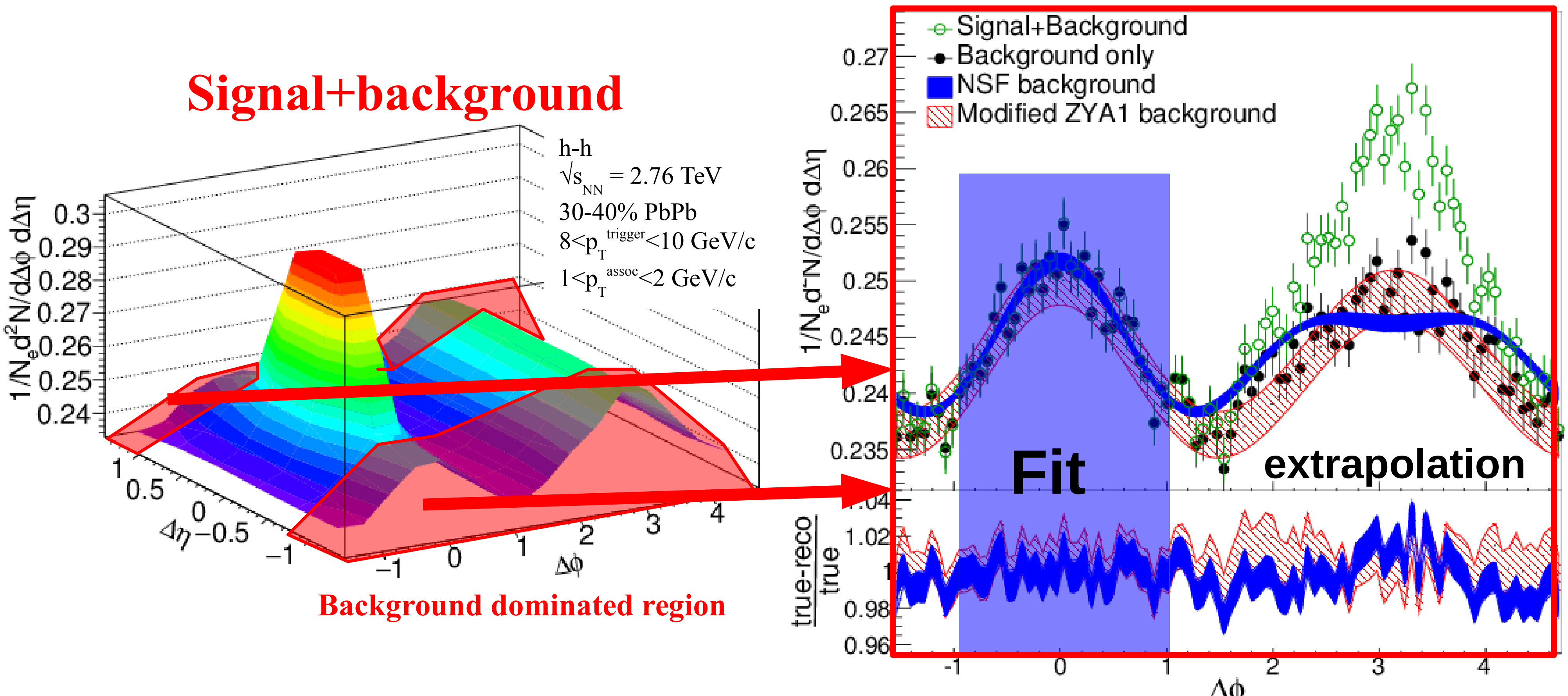
h-h
$\sqrt{s_{NN}}$ = 2.76 TeV
30-40% PbPb
8<$p_T^{trigger}$<10 GeV/c
1<p_T^{assoc}<2 GeV/c



Standard ZYA1 = Zero Yield at ΔΦ=1
Modified ZYA1 = Zero Yield at ΔΦ=1 for 1.0<|Δη|<1.4

Near-Side Fit (NSF) method

No reaction plane dependence



- Project signal+background over 1.0<|Δη|<1.4
- Fit background in **|Δφ|<1**
- **Not reliable over narrower Δφ region**

Background Subtraction Methods

- **Δη Method:** Project near-side signal onto Δη and subtract constant background. Near-side only
- **Δη Gap Method:** Use signal at large Δη to determine background, assuming constant background in Δη. Near-side only
- **Zero-Yield at Minimum (ZYAM):** Assumes v_n from other studies, assumes region around Δφ≈1 is background dominated
- **Near-Side Fit (NSF):** assumes small Δφ/large Δη region background dominated, fits v_n and B

Adding reaction plane dependence

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**

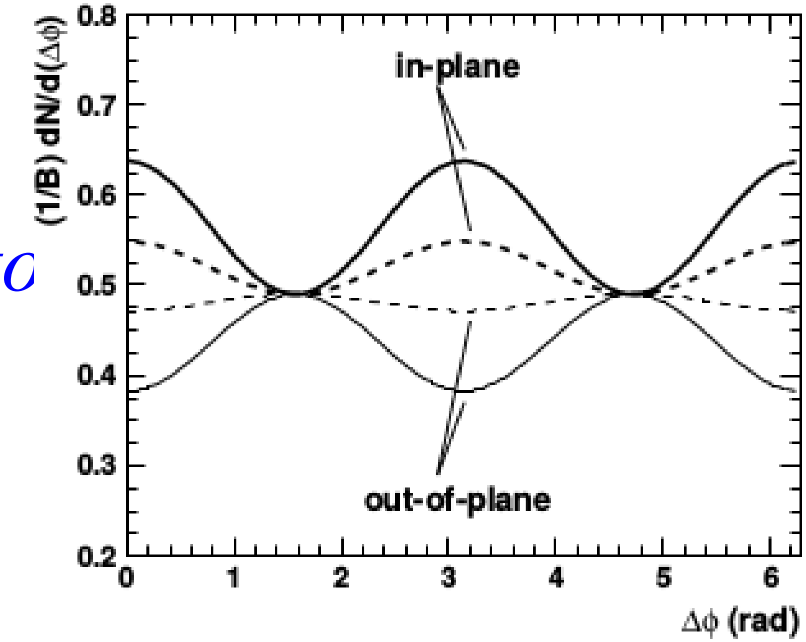
$$B=1+\sum_{k=2}^{\infty} 2 v_k^a v_k^{R,t} \cos(k\phi_S)\frac{\sin(kc)}{kc}R_n$$

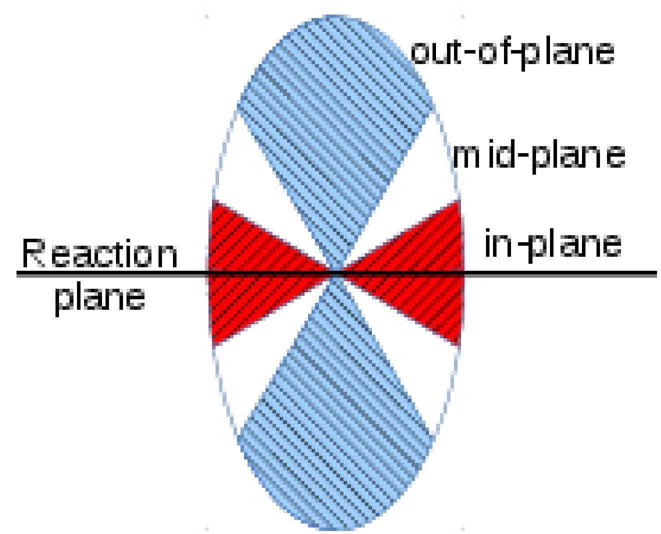
  - **Effective v_n modified**

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

φ_S is the angular threshold

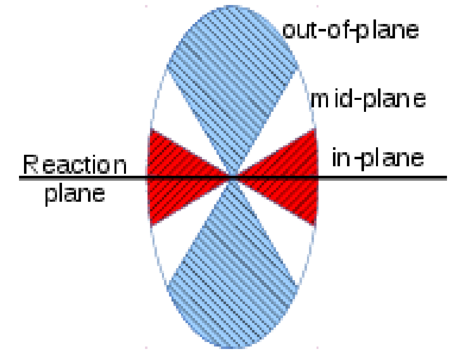
$$R_n=\langle\cos(n(\psi_{true}-\psi_{reco}))\rangle$$



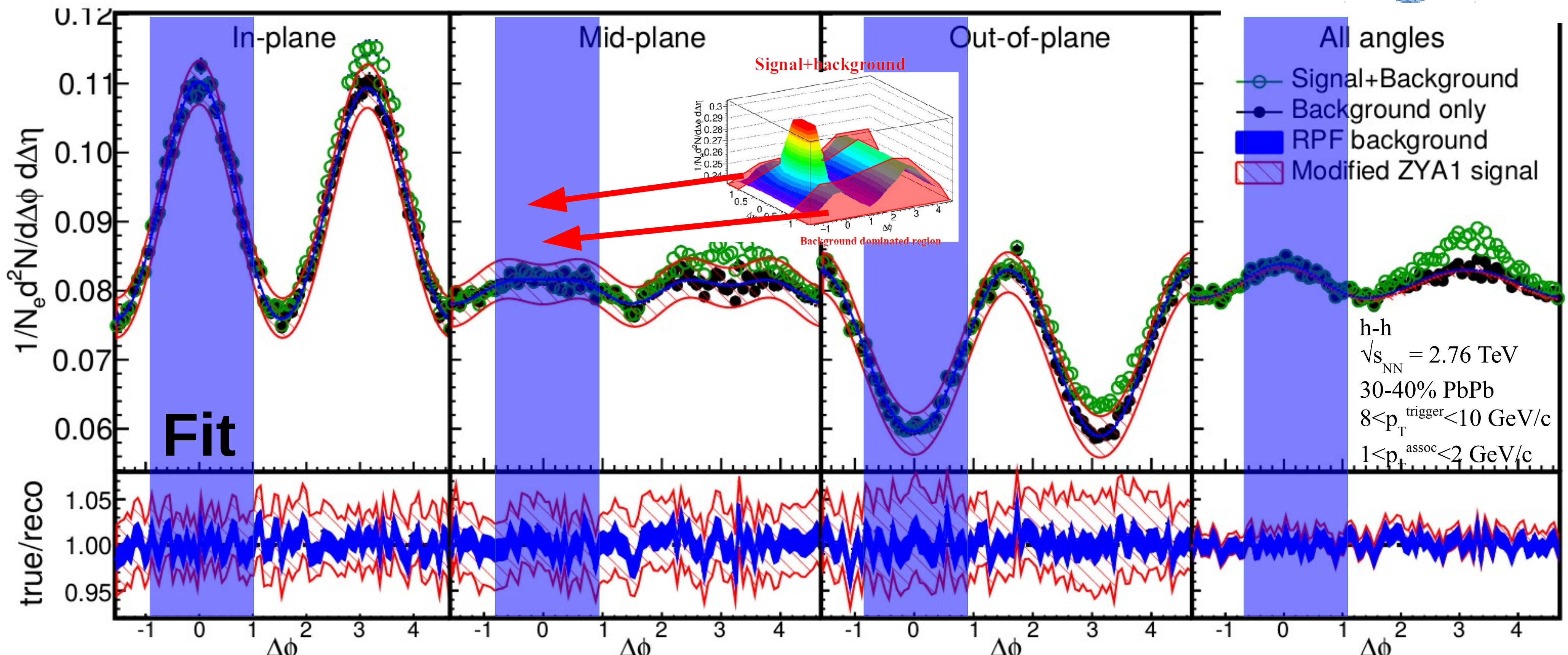


Phys.Rev. C69 (2004) 021901 arXiv:nucl-ex/0311007

Reaction Plane Fit (RPF) method



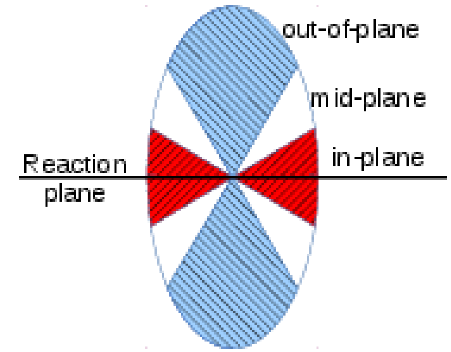
30-40% central

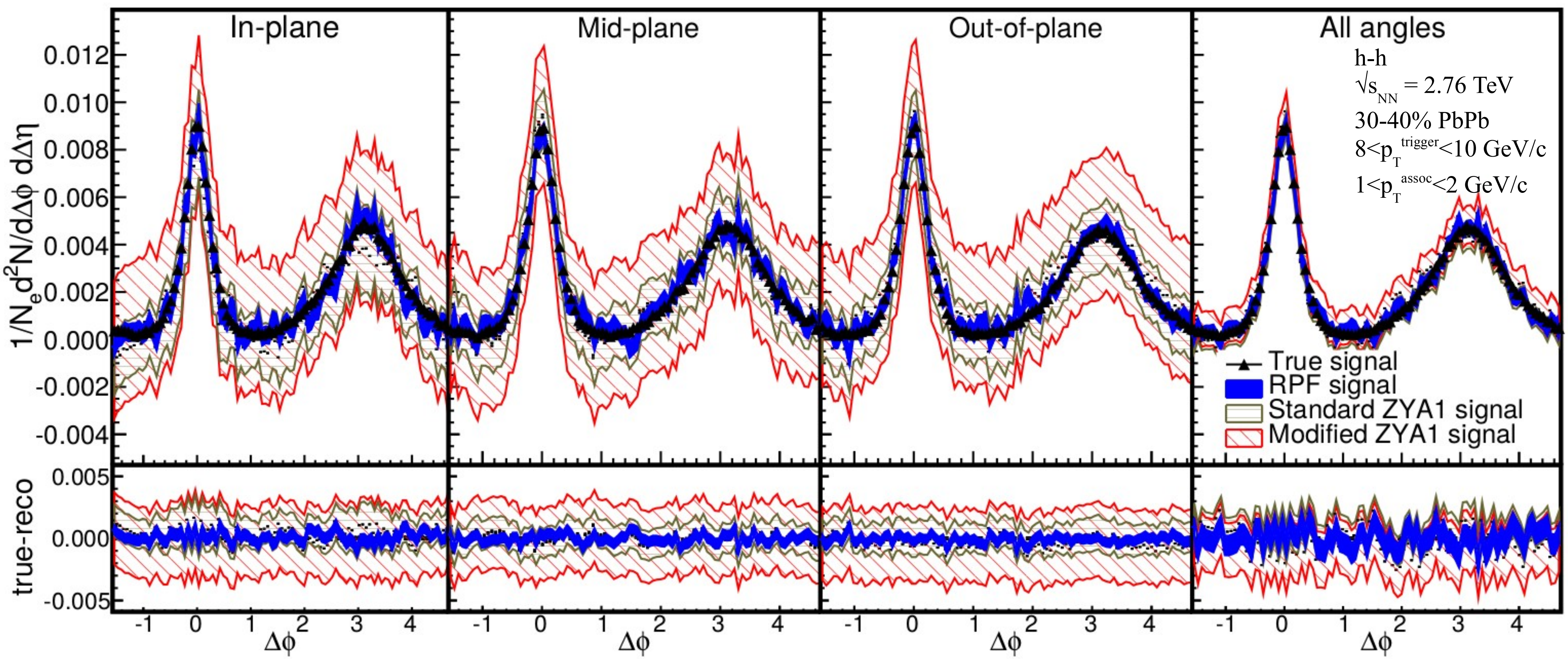


- Project signal+background over $1.0<|\Delta\eta|<1.4$
- Fit background in $|\Delta\varphi|<1$ including reaction plane dependence
- v_n and B extracted with v_n up to n=4

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

Background Subtraction Methods

- **$\Delta\eta$ 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
- **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

Background Subtraction Methods

- **$\Delta\eta$ 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
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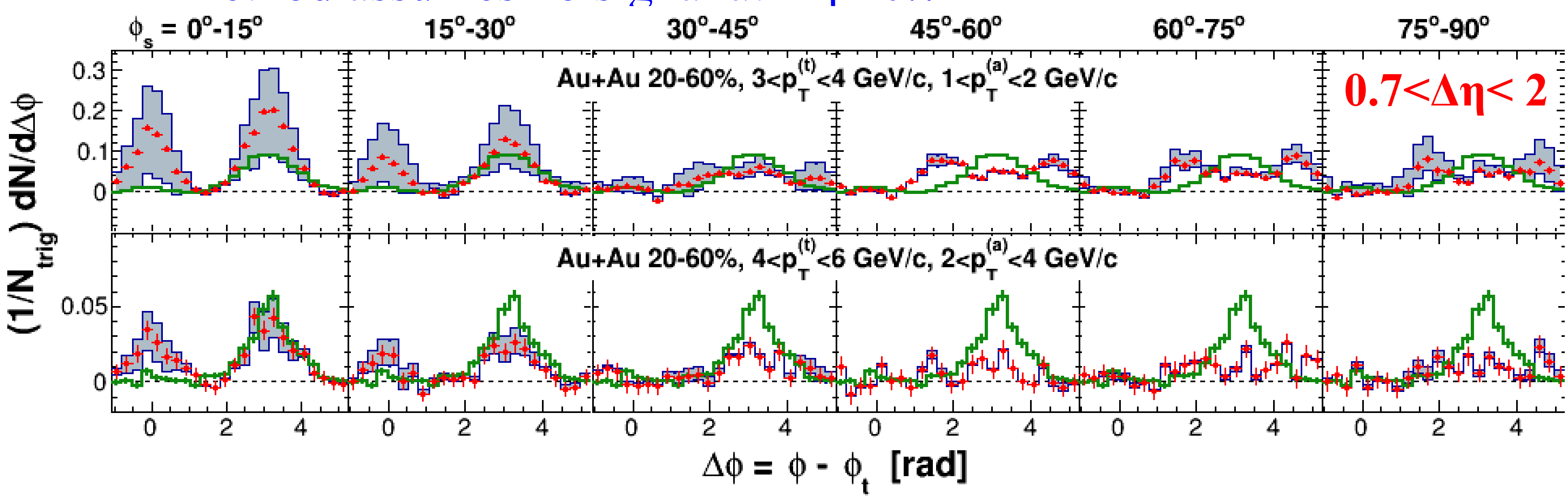
- **Reaction Plane Fit (RPF):** assumes small $\Delta\varphi$/large $\Delta\eta$ region background dominated, fits v_n and B using reaction plane dependence
- **Near-Side Subtracted NSF/RPF (NSS NSF/RPF):** fits v_n and B at small small $\Delta\varphi$ using reaction plane dependence after subtracting the near-side with a fit

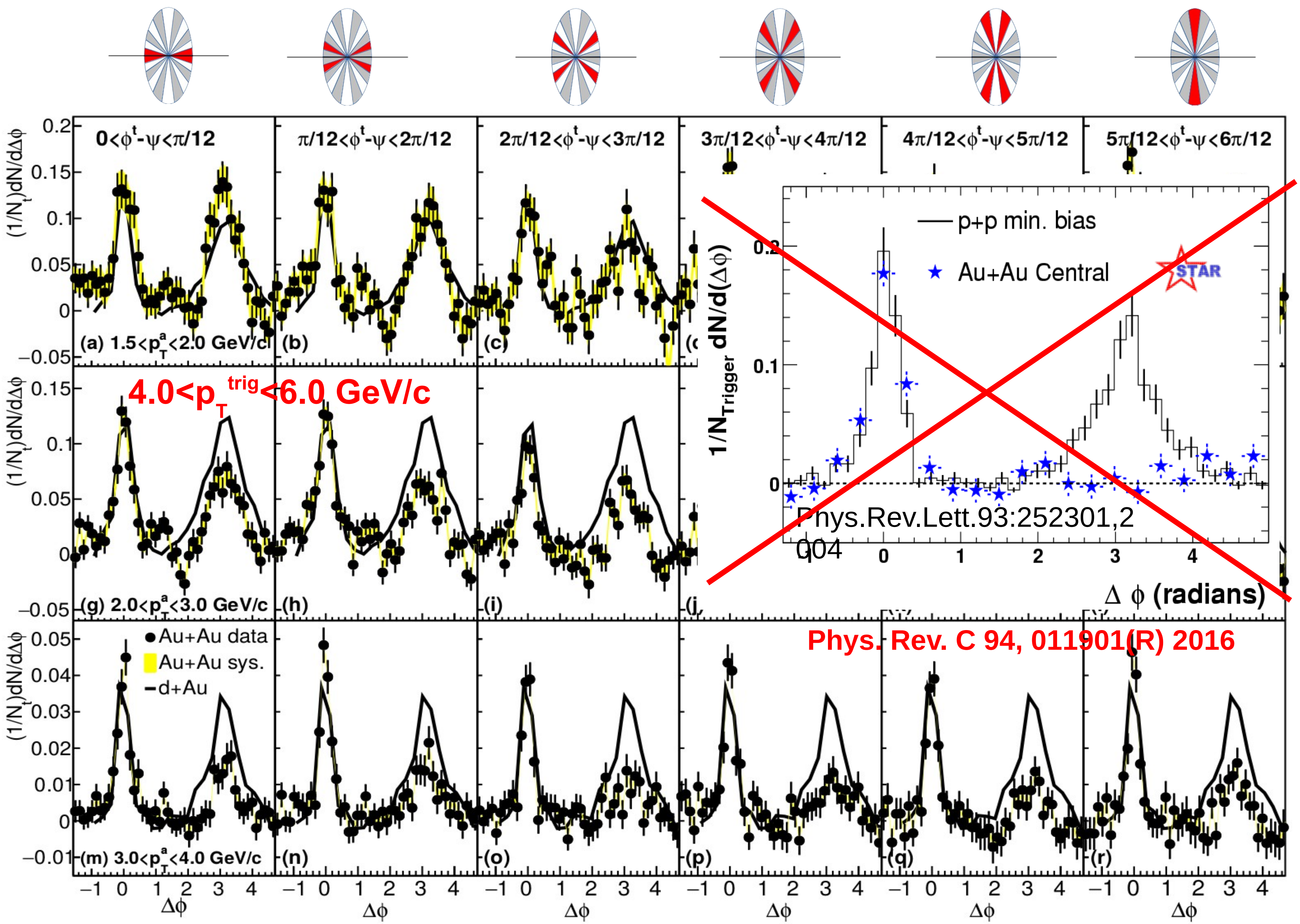
STAR data

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 $\Delta\eta > 0.7$
  - RPF method assumes no signal at $\Delta\eta > 0.7$



Dihadron correlations

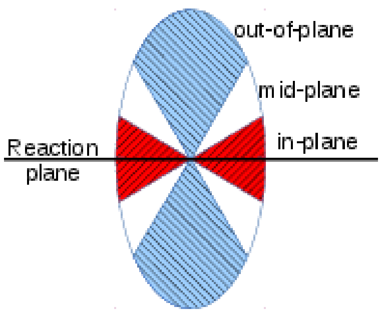


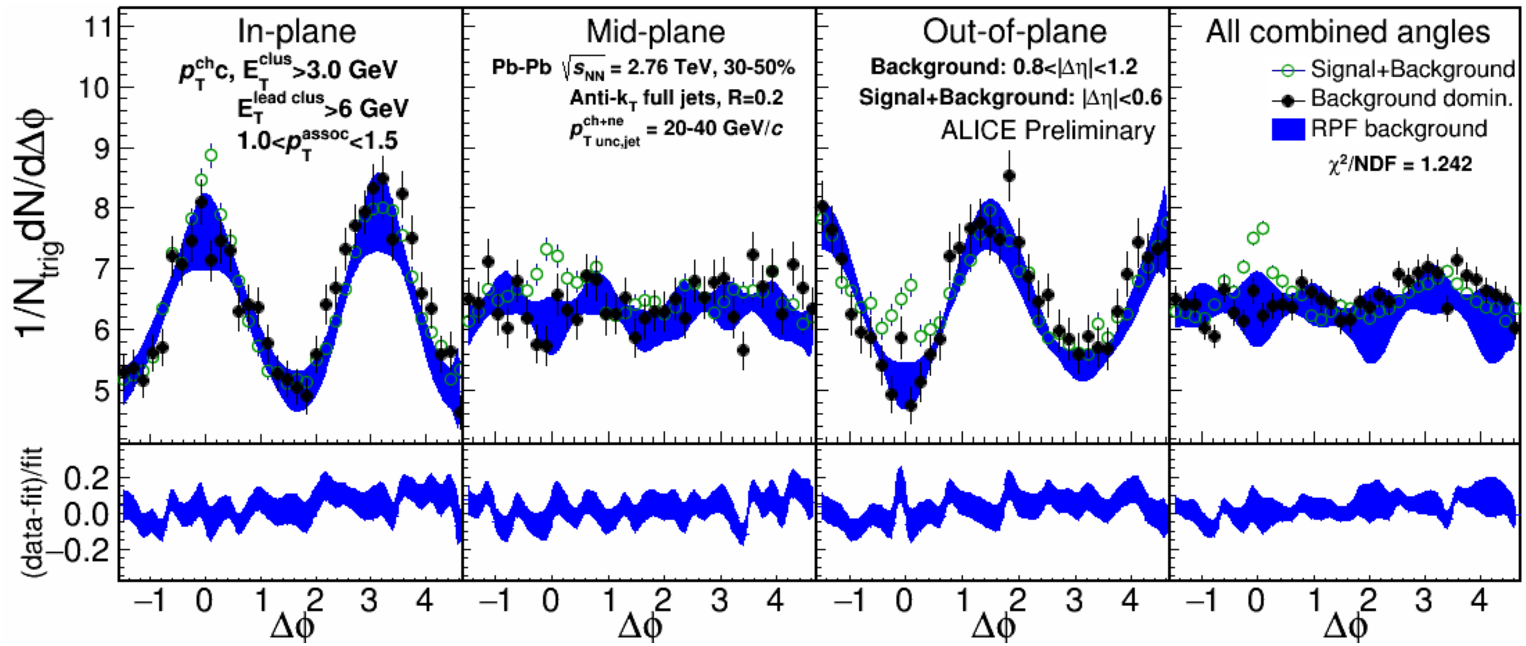
ALICE data

Joel Mazer: Hot Quarks 2016, Quark Matter 2017

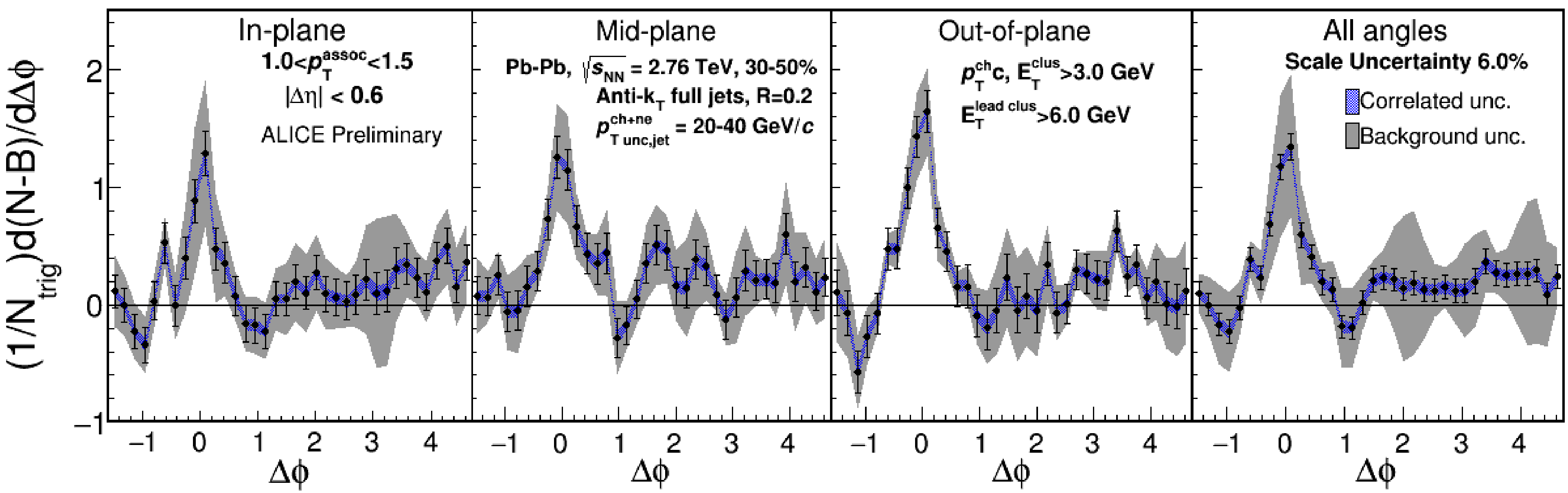
1.0-1.5 GeV/c p_T^{assoc}

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





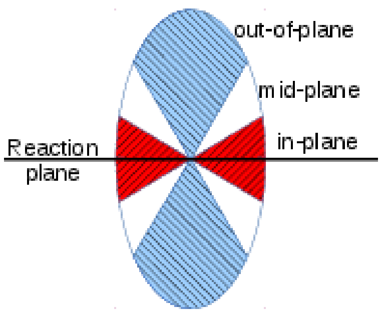
Correlation function

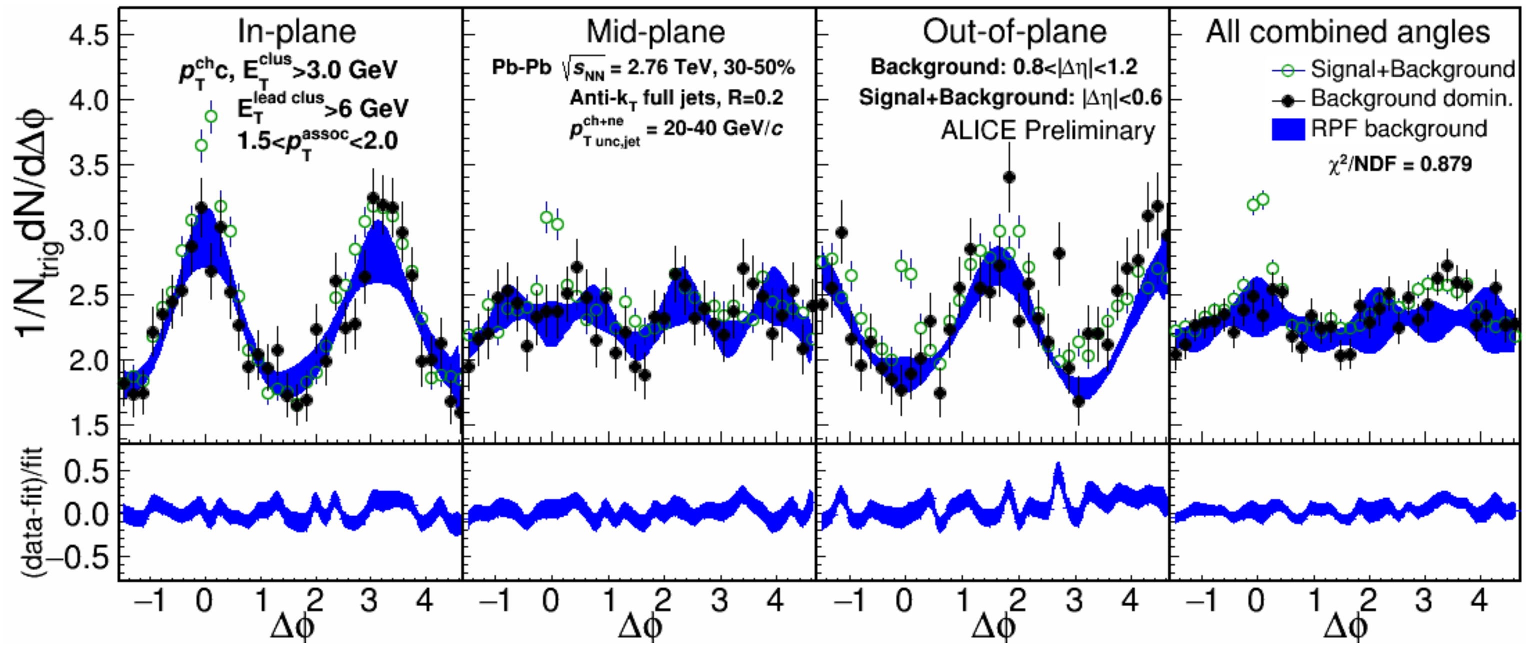


- Uncertainties dominated by statistics
- Background uncertainty is non-trivially correlated point-to-point

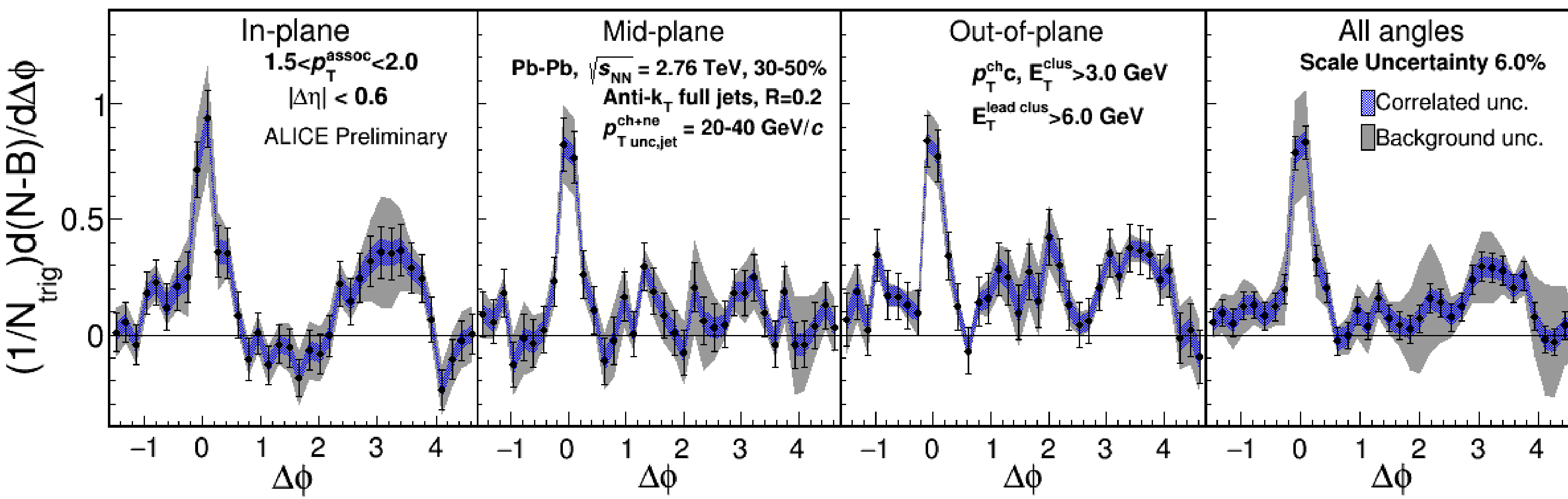
1.5-2.0 GeV/c p_T^{assoc}

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

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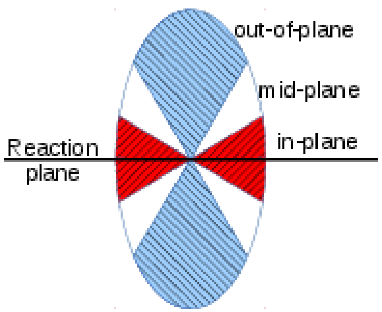
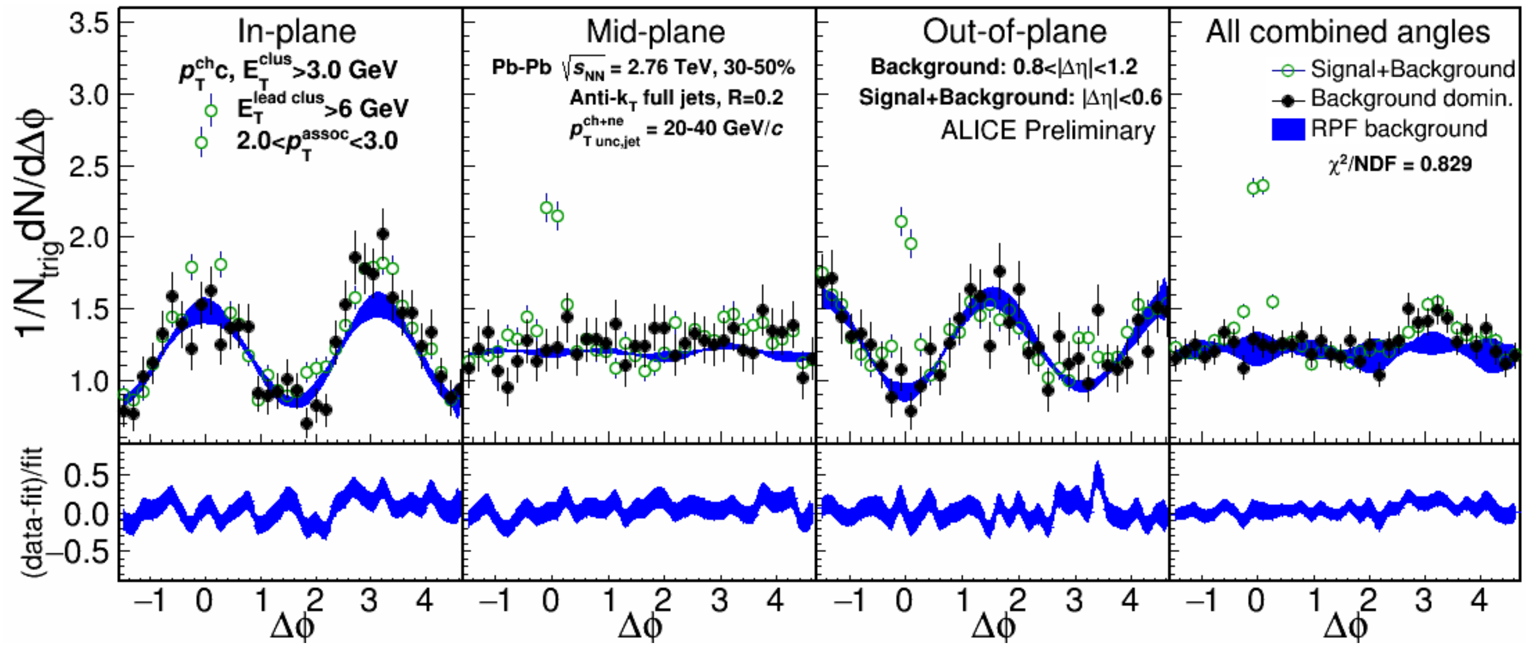
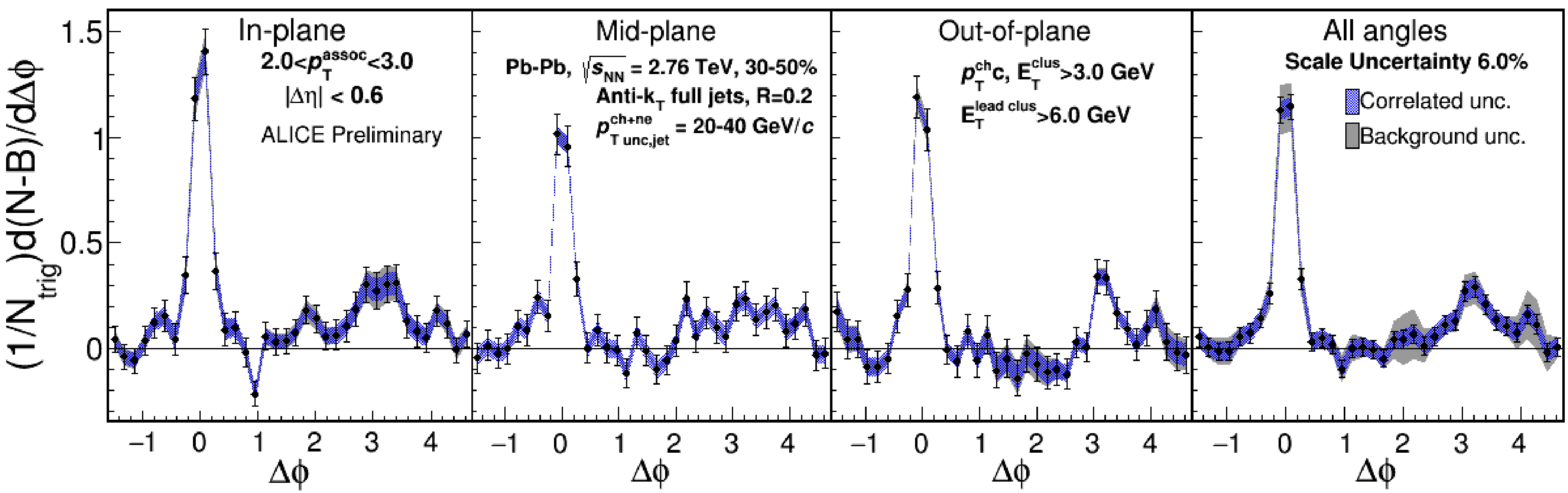
2.0-3.0 GeV/c p_T^{assoc}

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





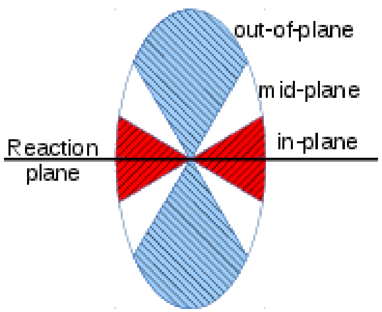
[Correlation function](#)

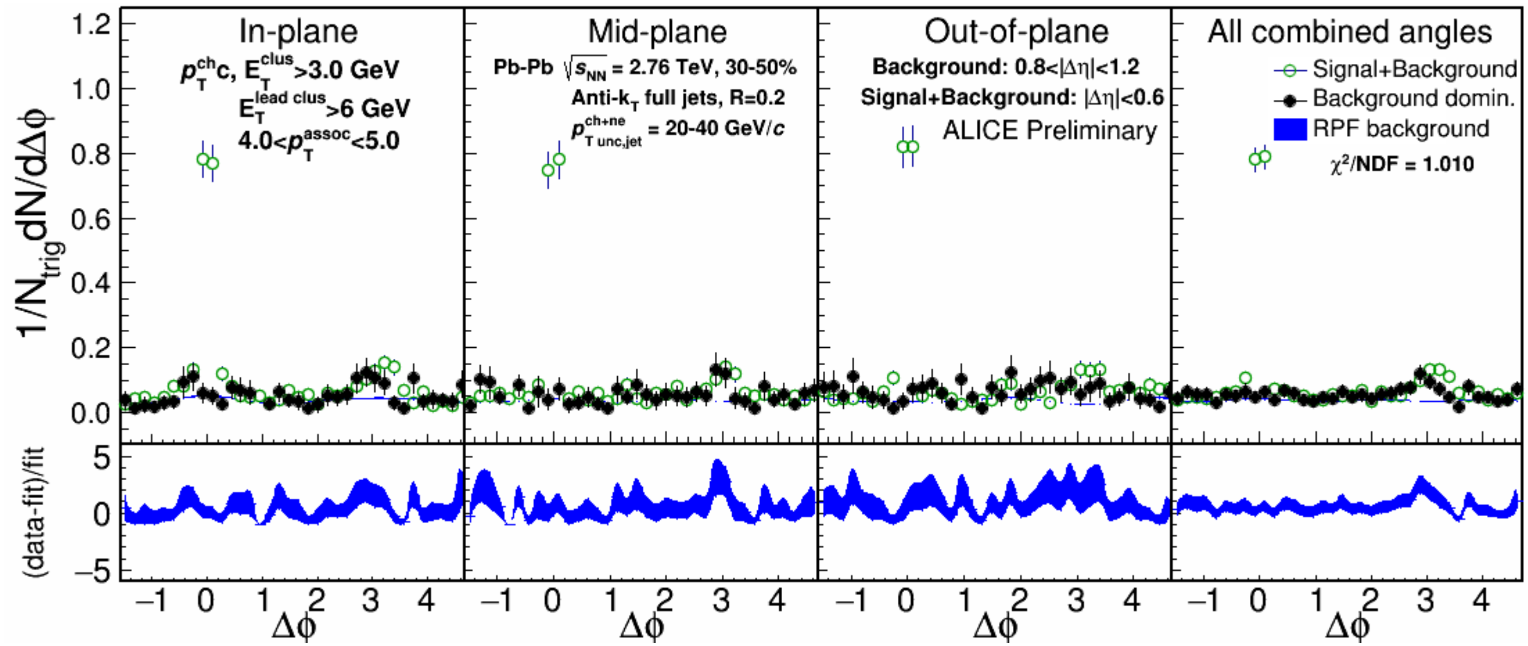


- Away side clearly there and suppressed

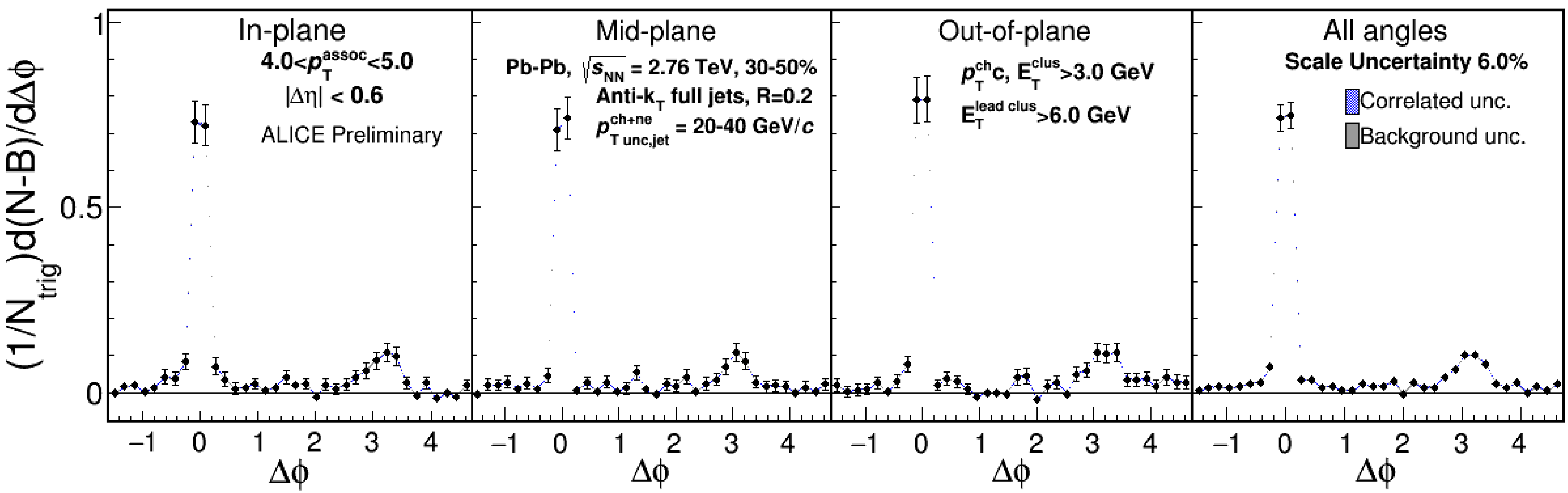
4.0-5.0 GeV/c p_T^{assoc}

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





Correlation function



- Background level negligible

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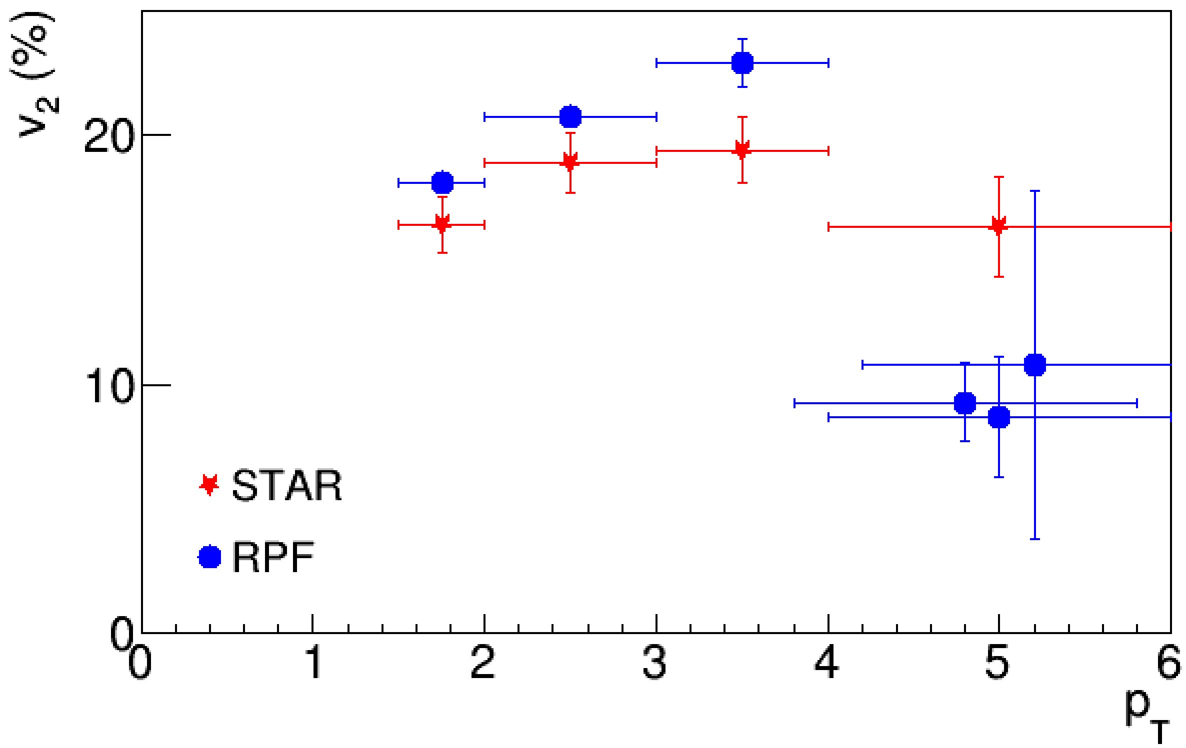
What about flow?

v_n from RPF method



- Different v_n from RPF method for h-h correlations
- Same v_n as inclusive studies from RPF for jet-h correlations

One of the following must be true:

- $v_n^{jet} \neq v_n^{bkgd}$
  - Dihadron correlations:
    - Background: J-B, B-J, B-B
    - Signal: J-J
  - Jet-hadron correlations: fake jets negligible
    - Background: J-B
    - Signal: J-J
- Hard and soft rxn planes decorrelated
  - Soft rxn plane reconstructed

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

- Reaction plane measurements may include effects from jets
- Events with jets have different flow

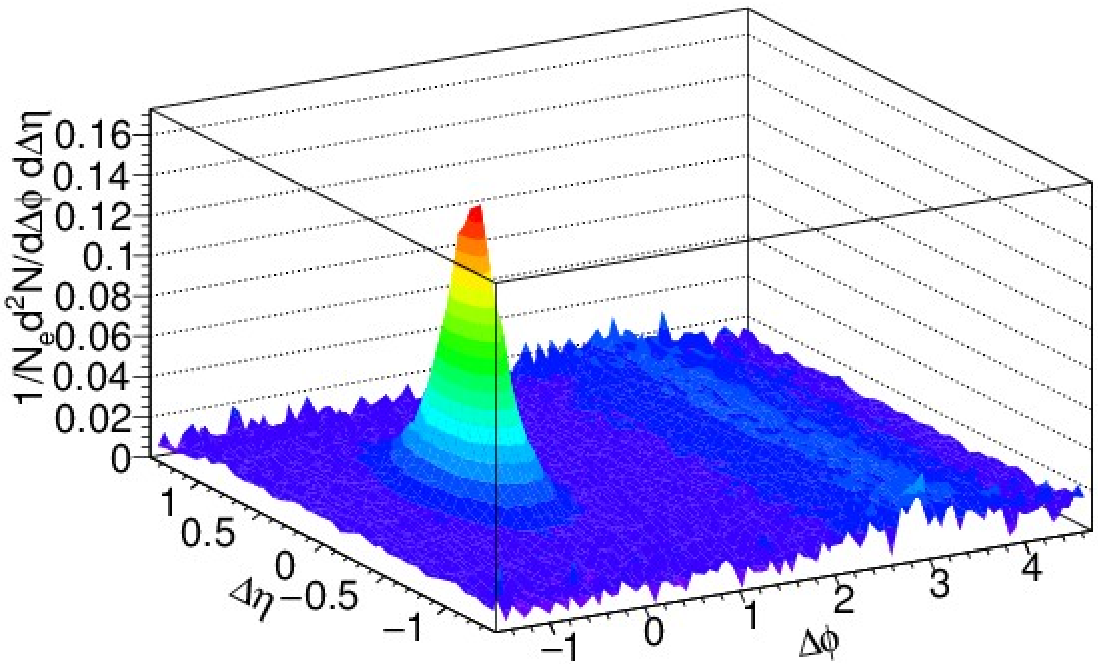
Conclusions

- RPF method is robust
  - Allows studies of away side
  - Move beyond ZYAM.
- Precision correlation studies possible
  - No more Mach cone!
- Jets exhibit little/no reaction plane dependence
- Something interesting is going on with flow

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



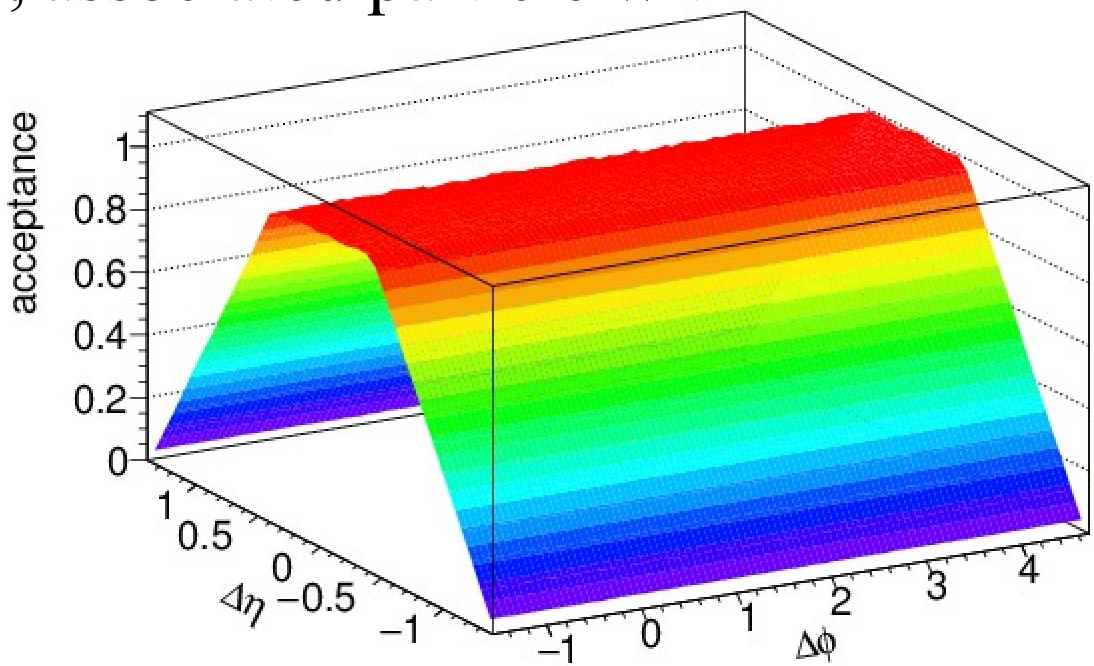
h-h
$\sqrt{s}$ = 2.76 TeV
pp collisions
$8 < p_T^{trigger} < 10$ GeV/c
$1 < p_T^{assoc} < 2$ GeV/c

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

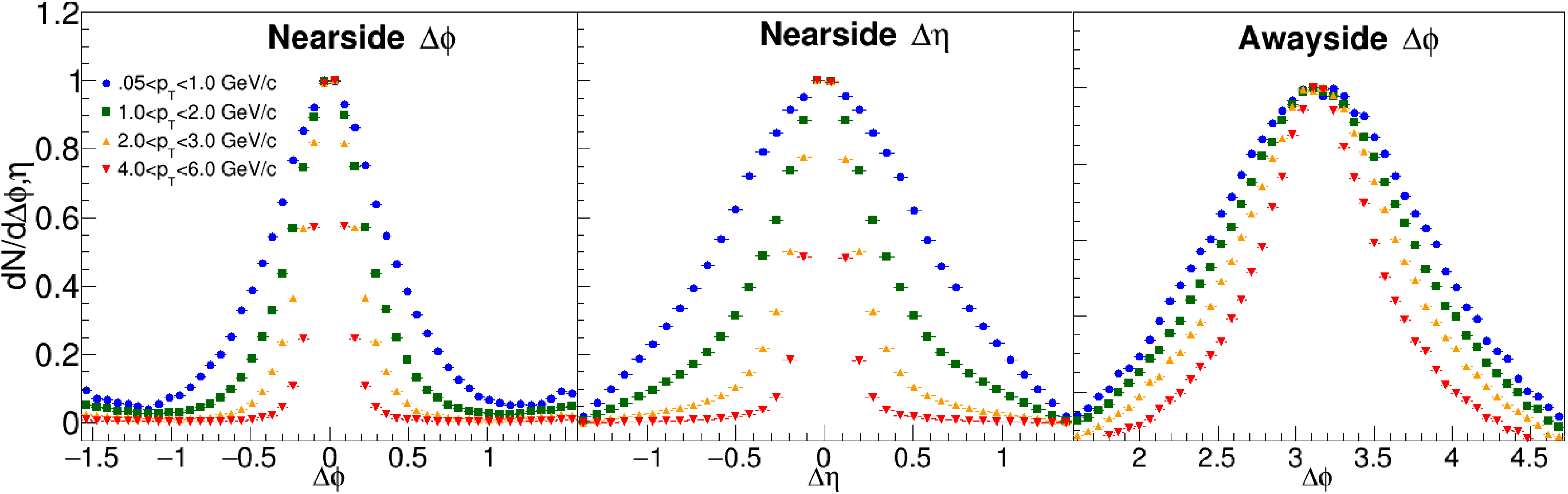
Acceptance correction

- 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

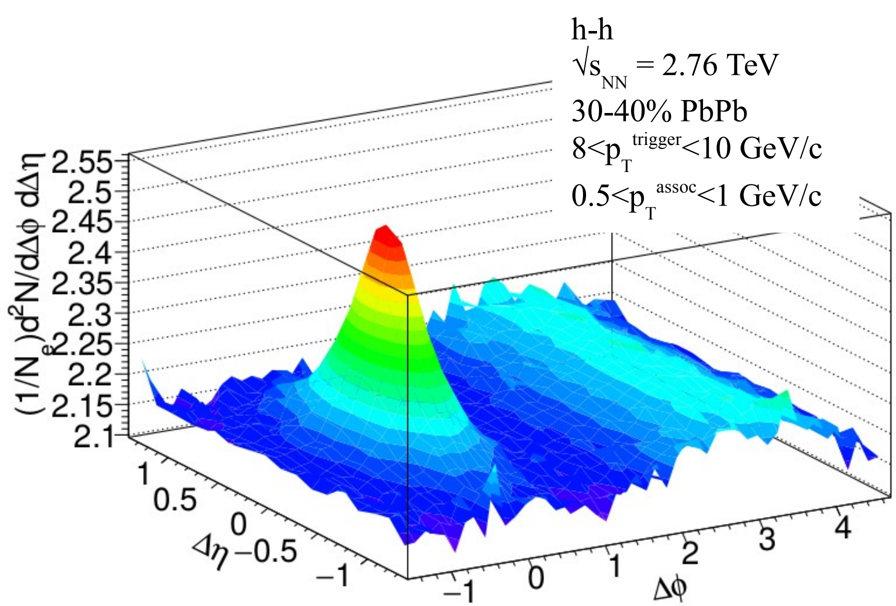


Going to lower momenta

Low momenta

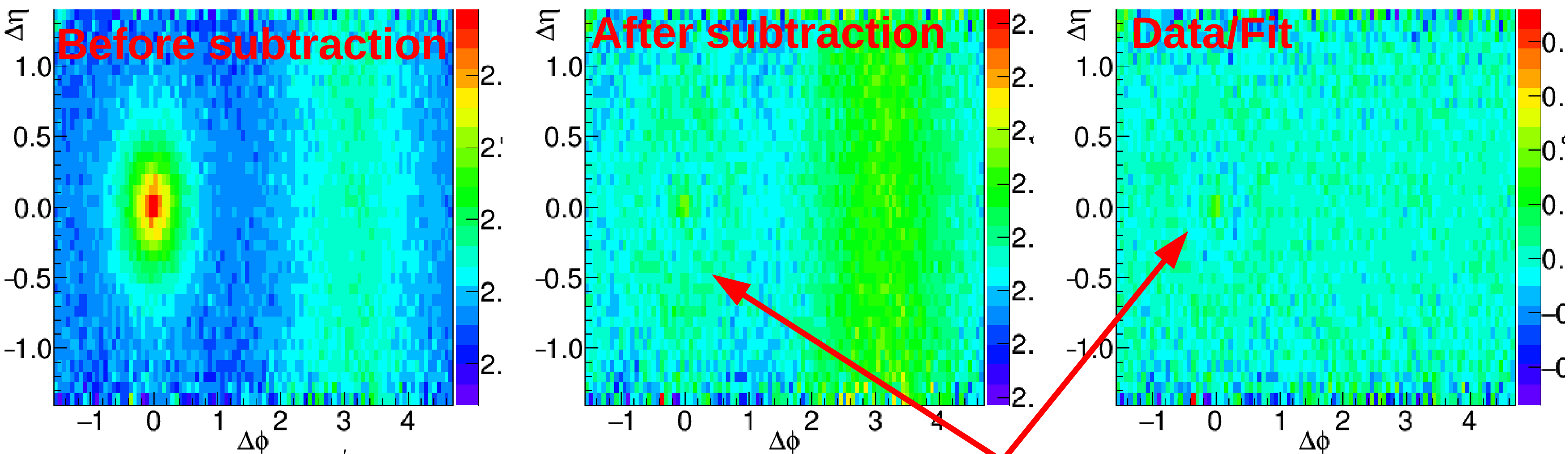


- ZYAM assumptions break down at low p_T
- If method doesn't work on PYTHIA, it can't be trusted on data!
- But low p_T is interesting!



Going to lower momenta, medium modifications

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



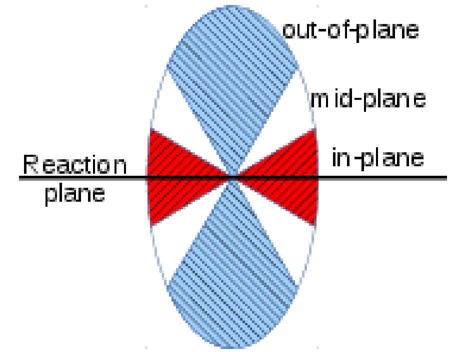
h-h, $\sqrt{s_{NN}}$ = 2.76 TeV, 0-10% PbPb

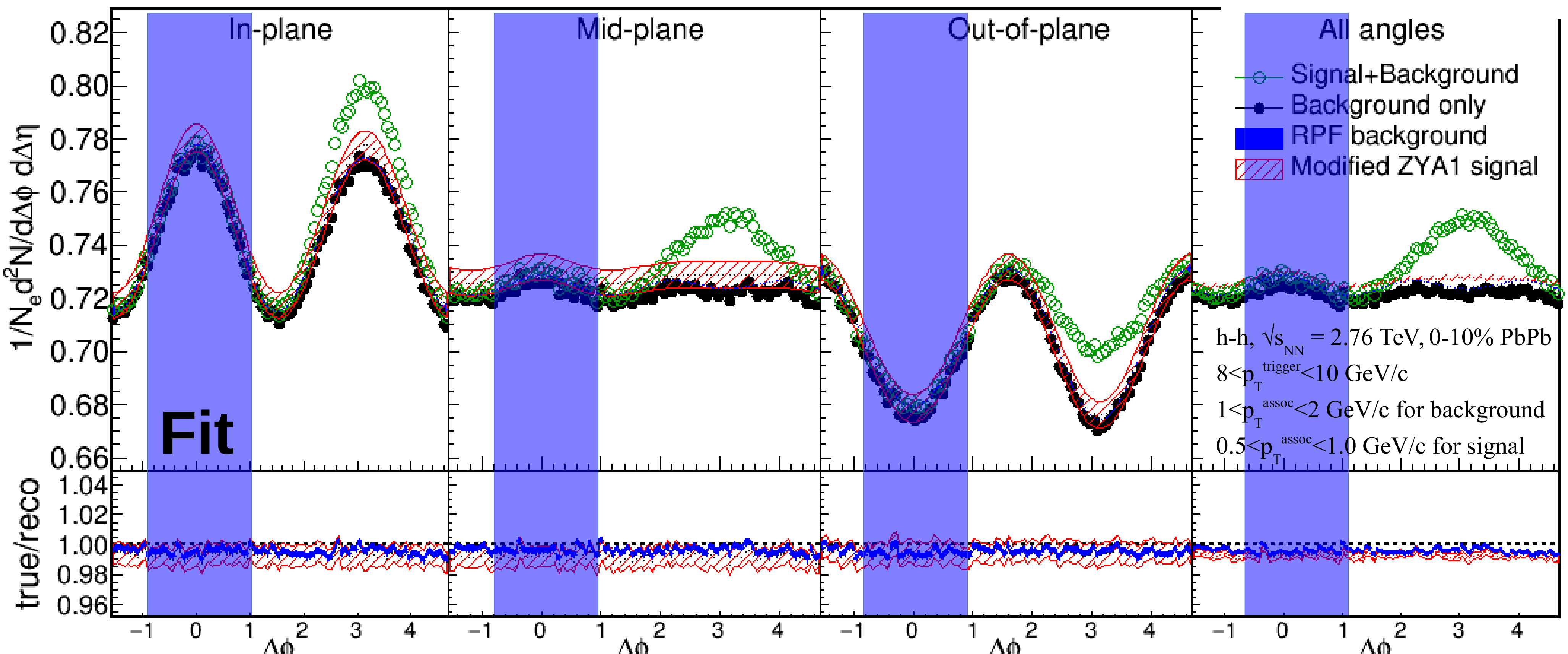
$8<p_T^{trigger}<10$ GeV/c

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

Near-Side Subtracted RPF method

30-40% central

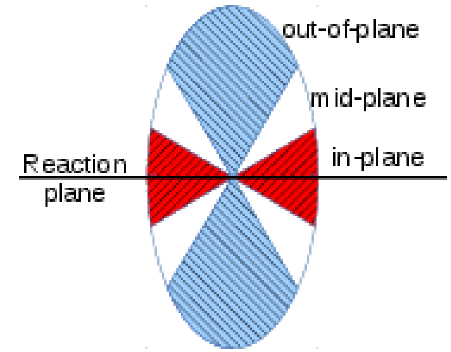


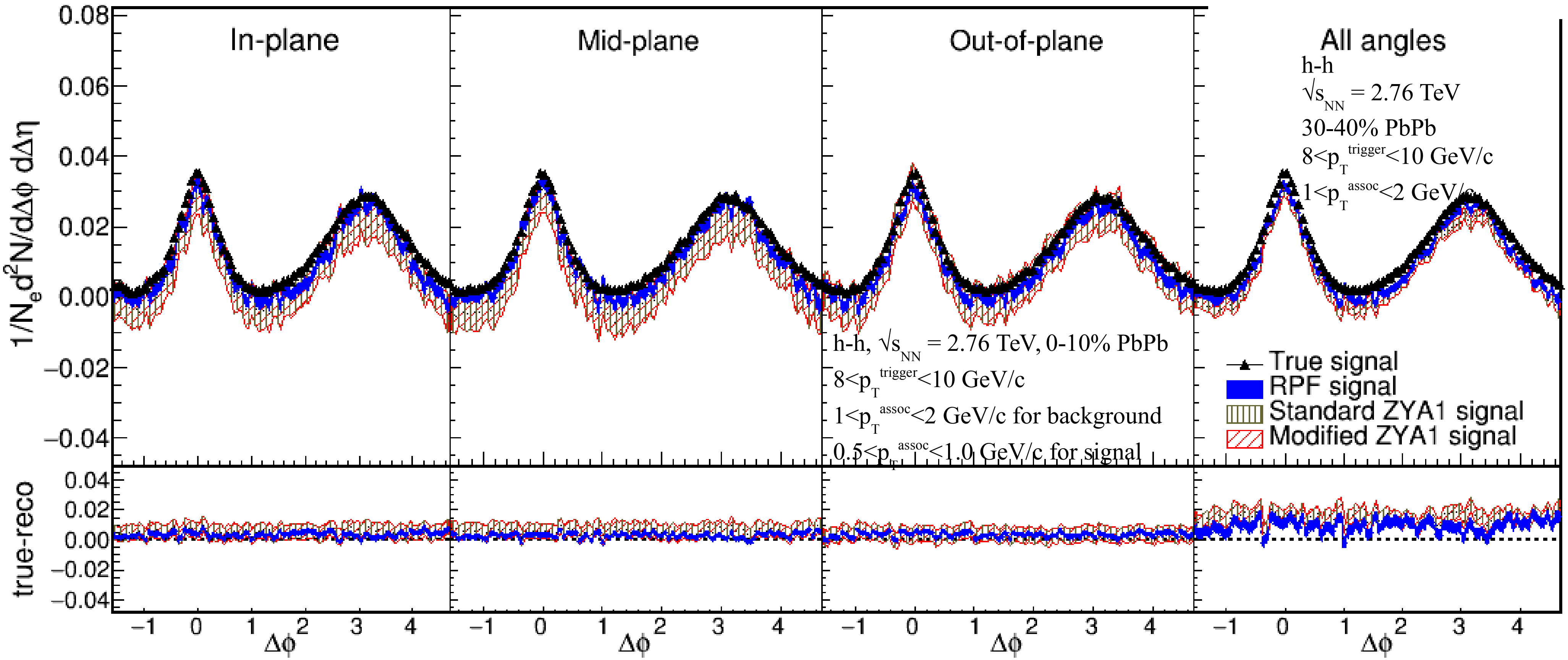


- Project signal+background over **0.0**<|Δη|<1.4
- Fit background in |Δφ|<1 including reaction plane dependence
- v_n and B extracted with v_n up to n=4

Reaction Plane Fit (RPF) method

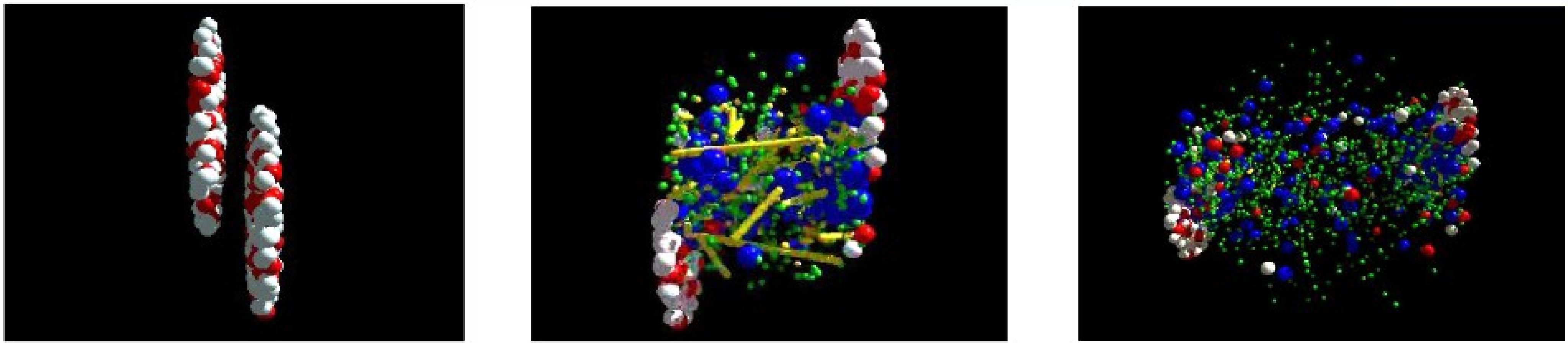
30-40% central

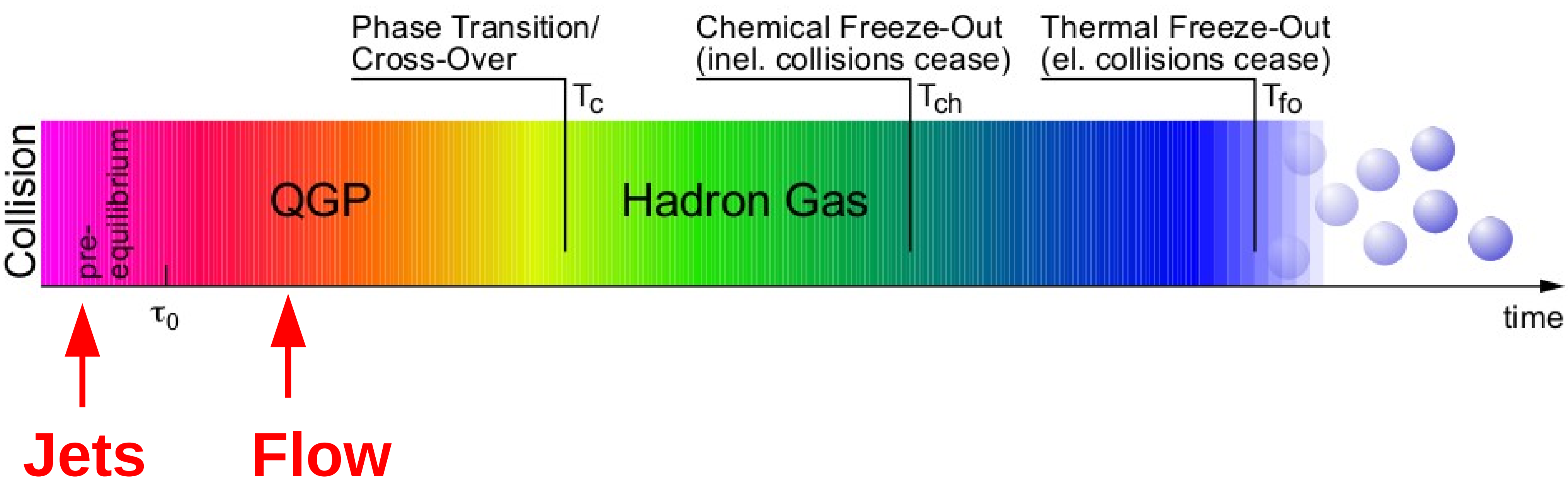




- **Works beautifully!**

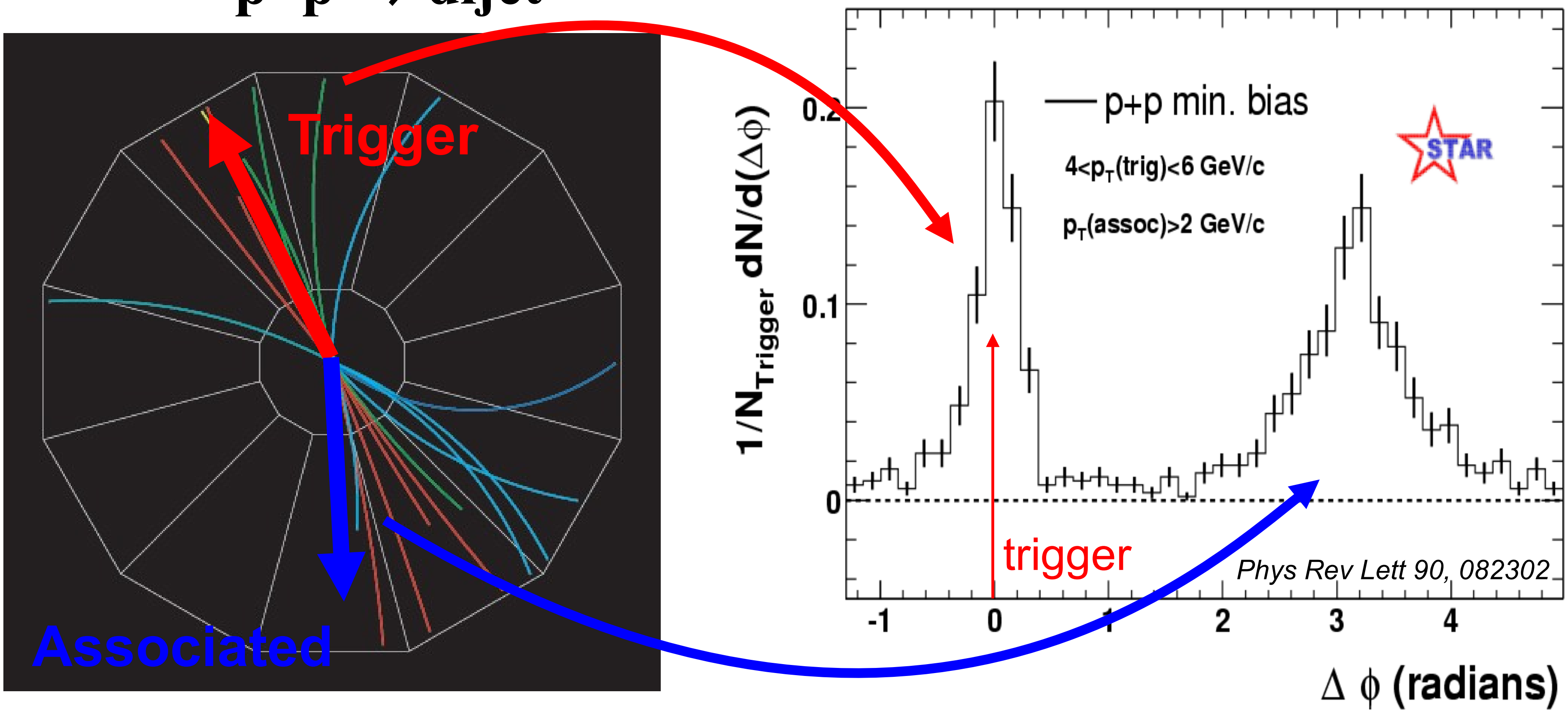
Stages of a heavy ion collision





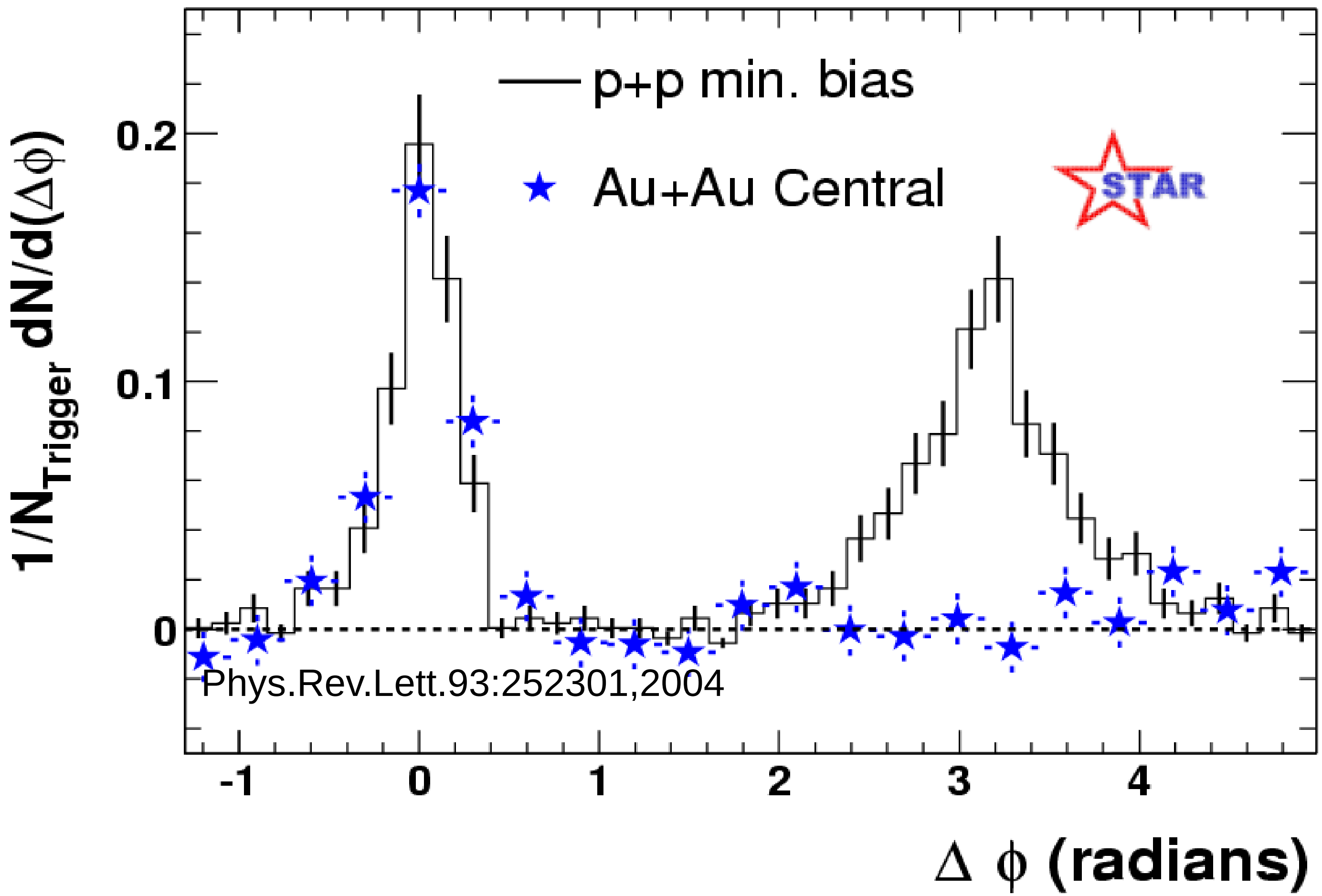
Jets – azimuthal correlations

p+p → dijet

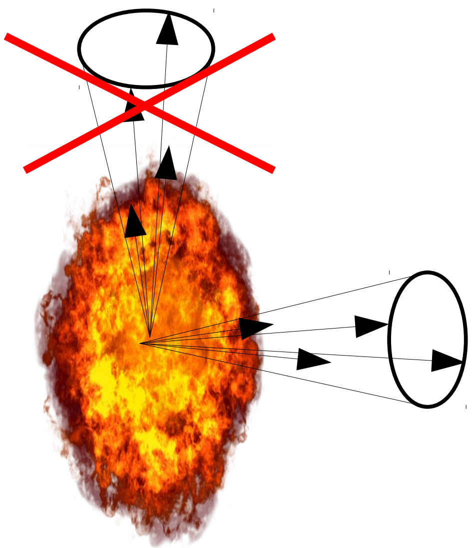


Select high momentum particles → biased towards jets

Azimuthal correlations

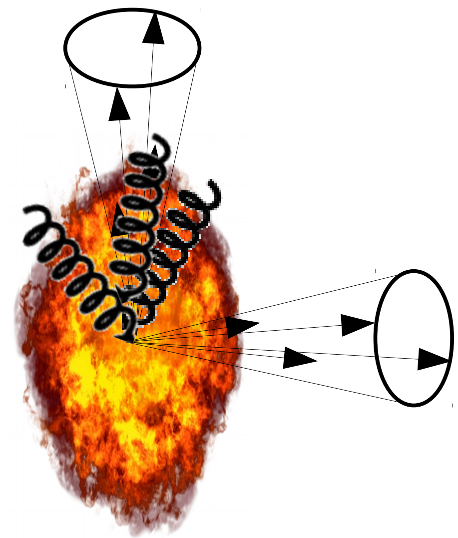


Competing effects



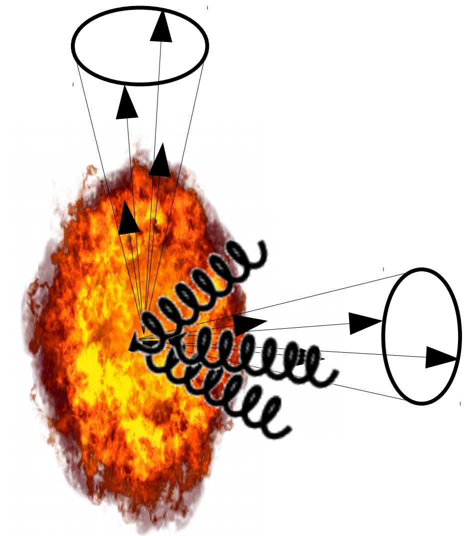
Quenching

Fewer jets, lower yield out of plane



Bremsstrahlung

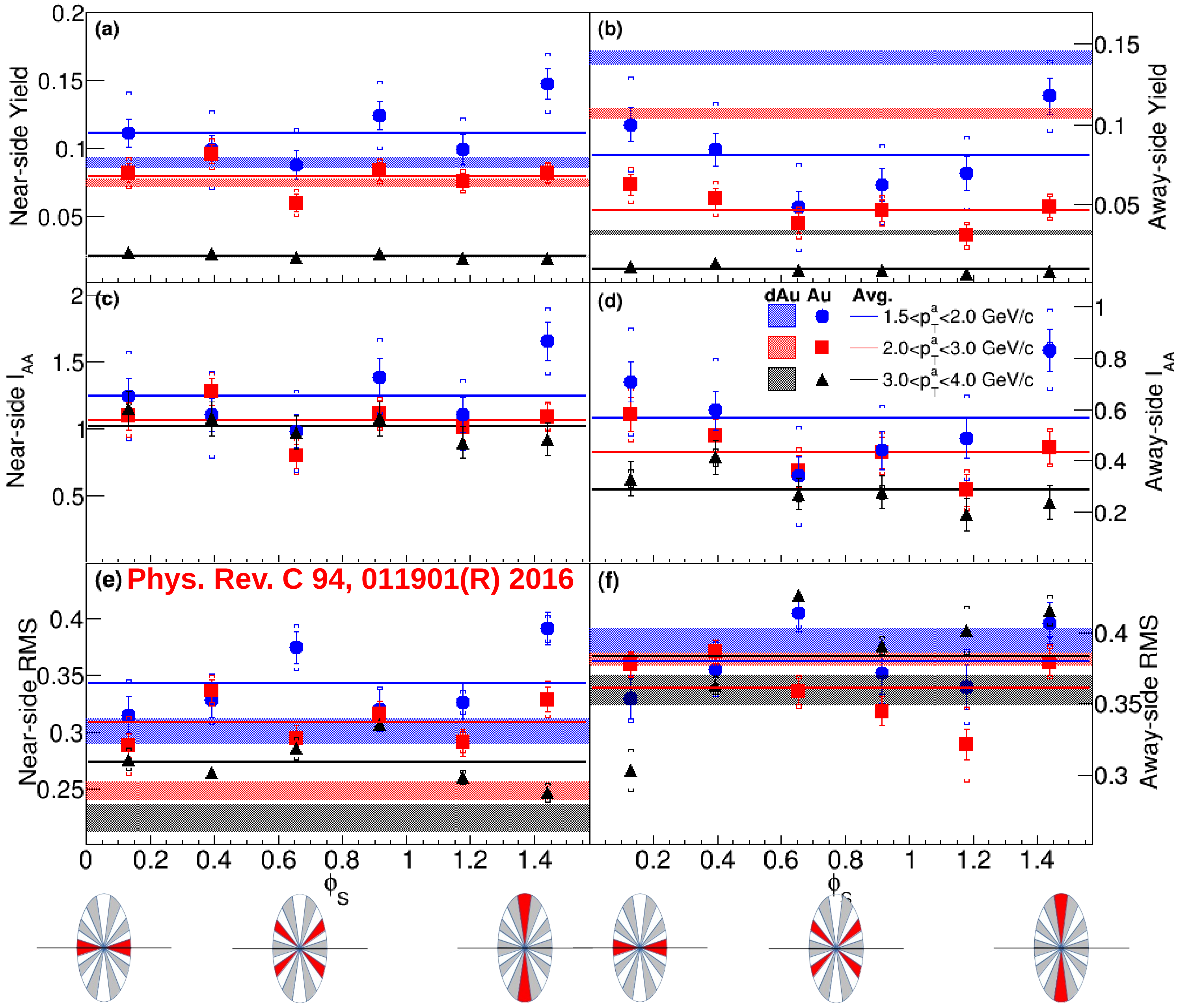
Softer, higher yield out of plane



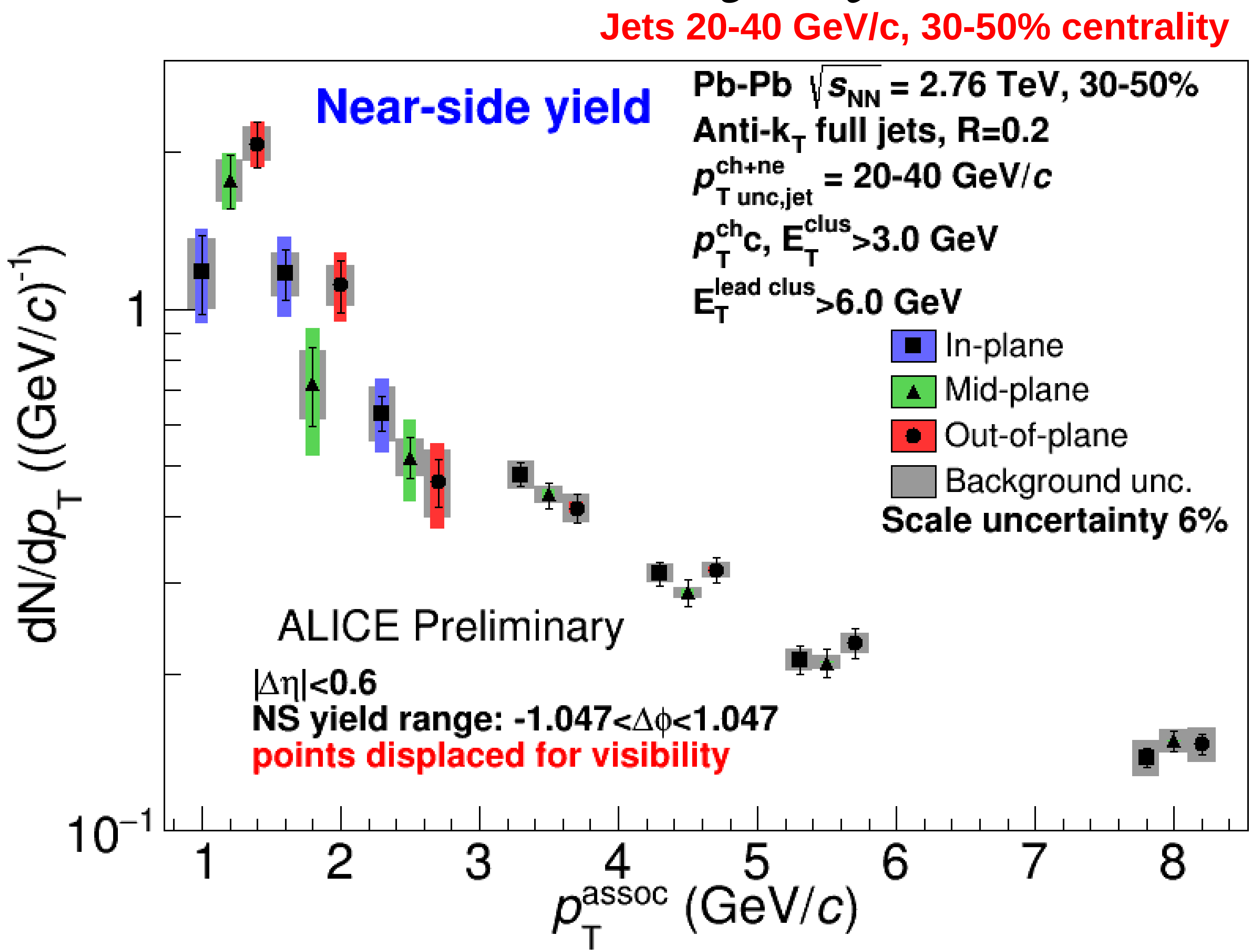
Fluctuations

Individual jets' energy loss may vary

Dihadron correlations



Near-side jet yields vs EP



Within uncertainties of current statistics, no event plane ordering

- Different effects in different p_T associated bins

Competing effects
1) Quenching
2) Bremsstrahlung
3) etc

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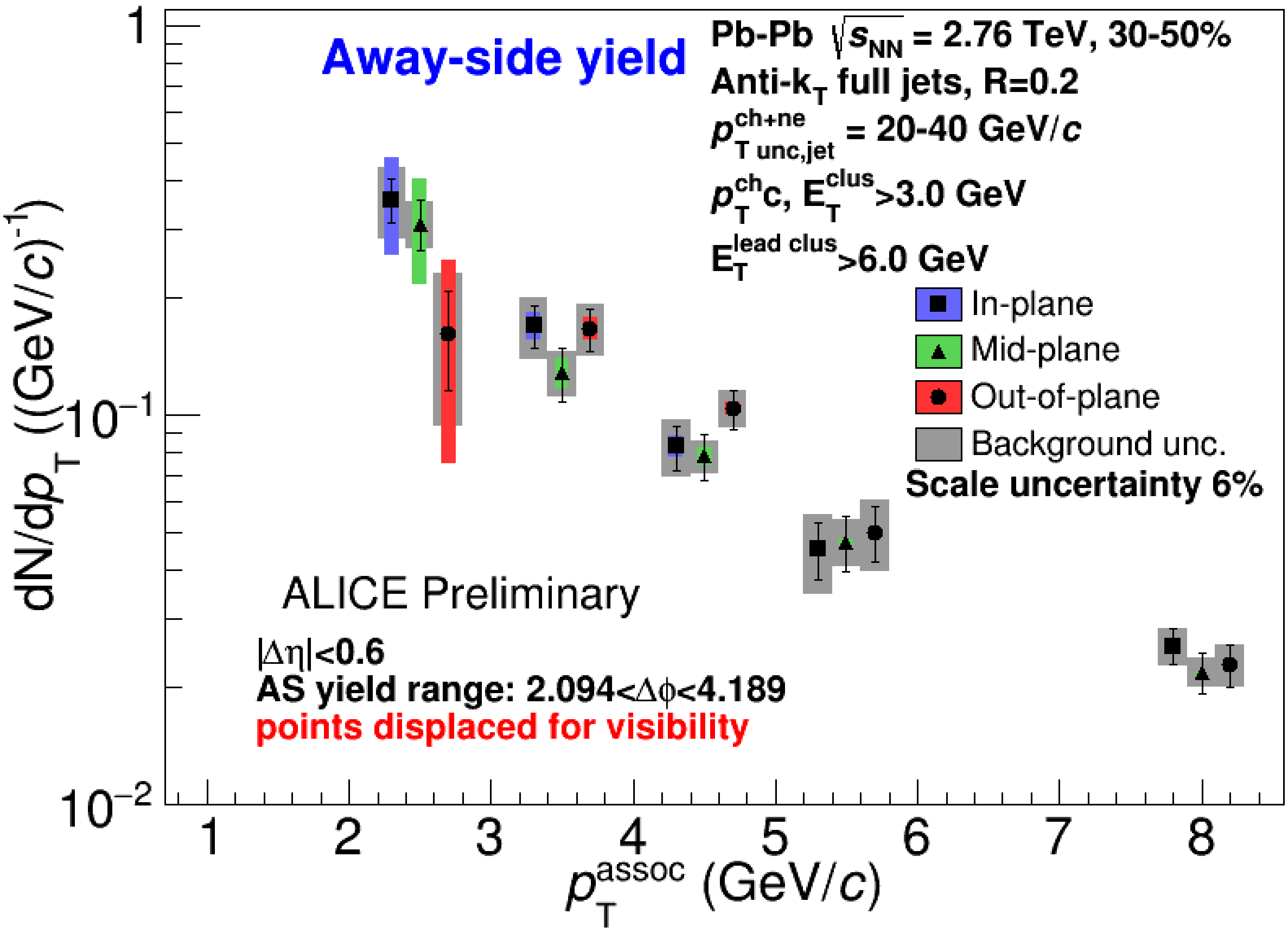
Away-side jet yields vs EP

Jets 20-40 GeV/c, 30-50% centrality

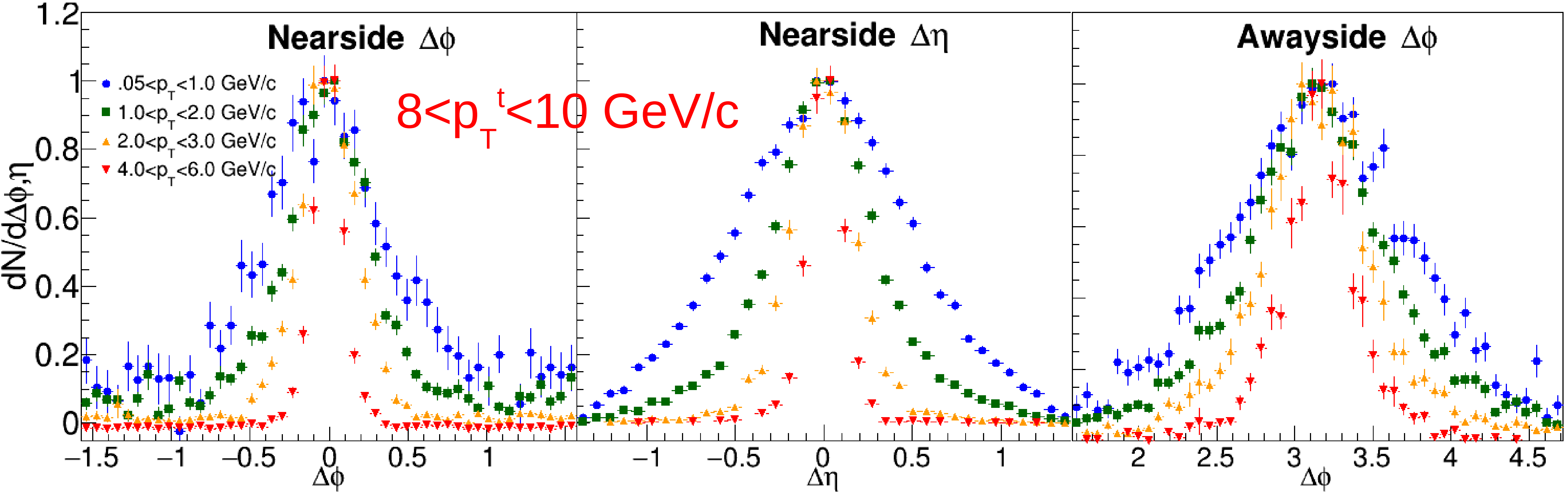


Within uncertainties of current statistics, no event plane ordering

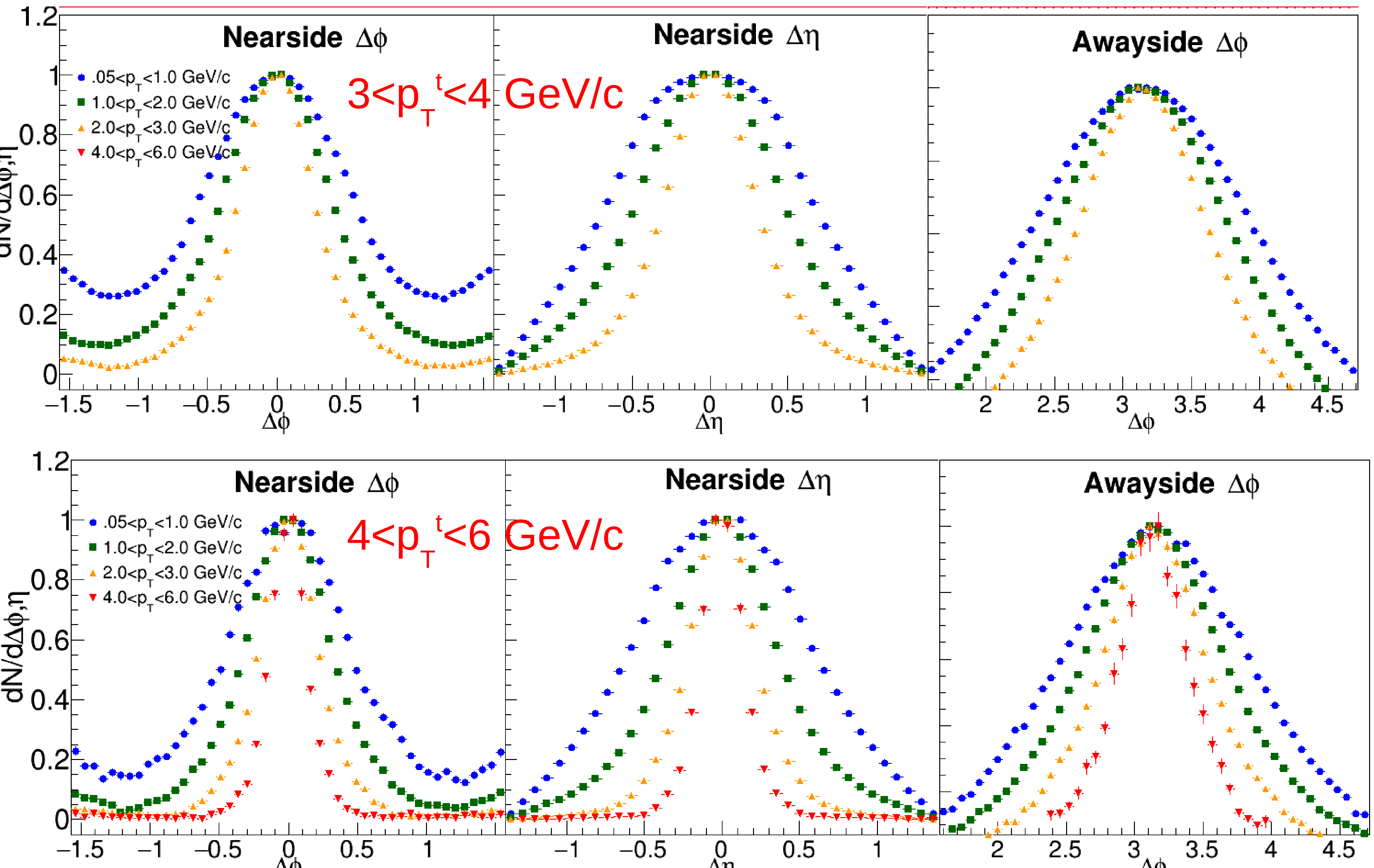
- Different effects in different p_T associated bins

Competing effects
1) Quenching
2) Bremsstrahlung
3) etc

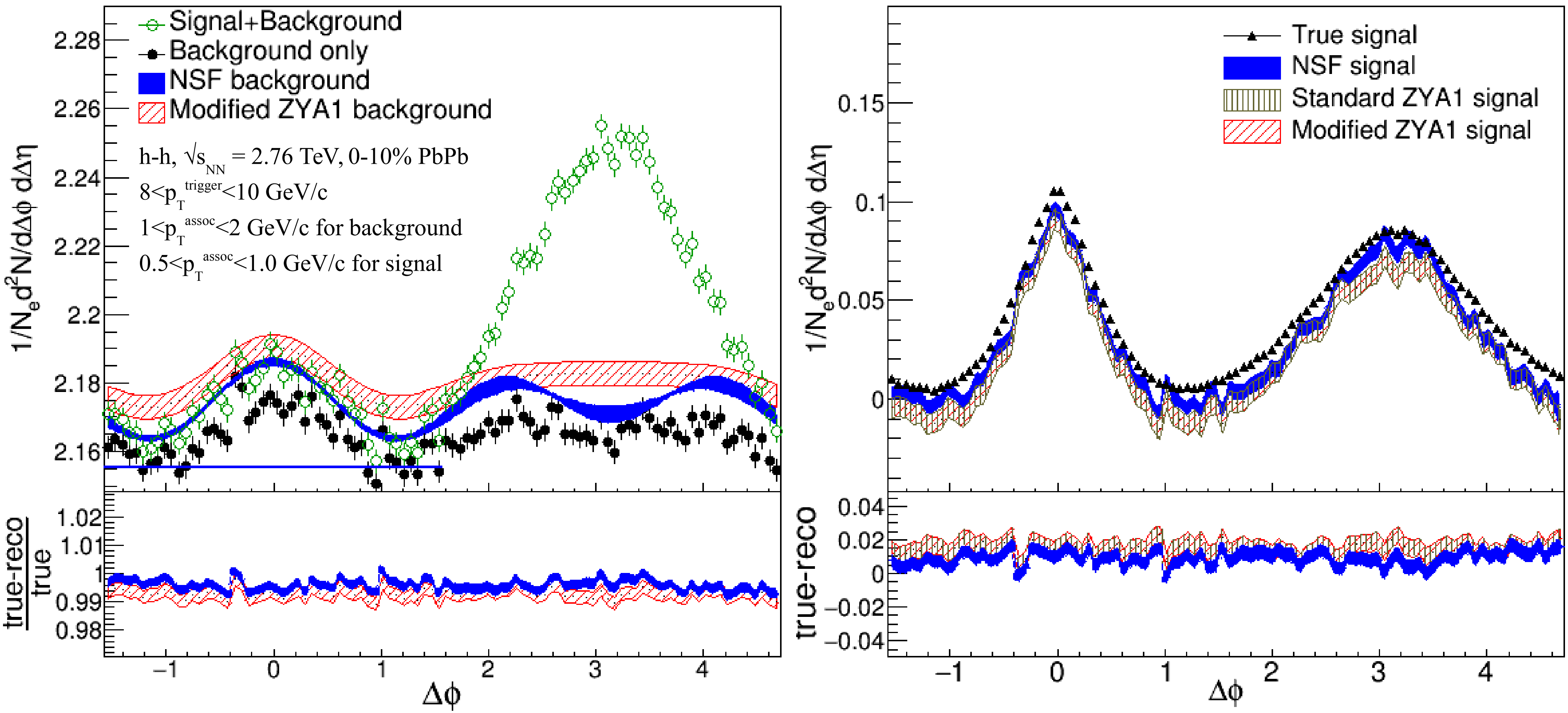
PYTHIA at 200 GeV



PYTHIA at 200 GeV

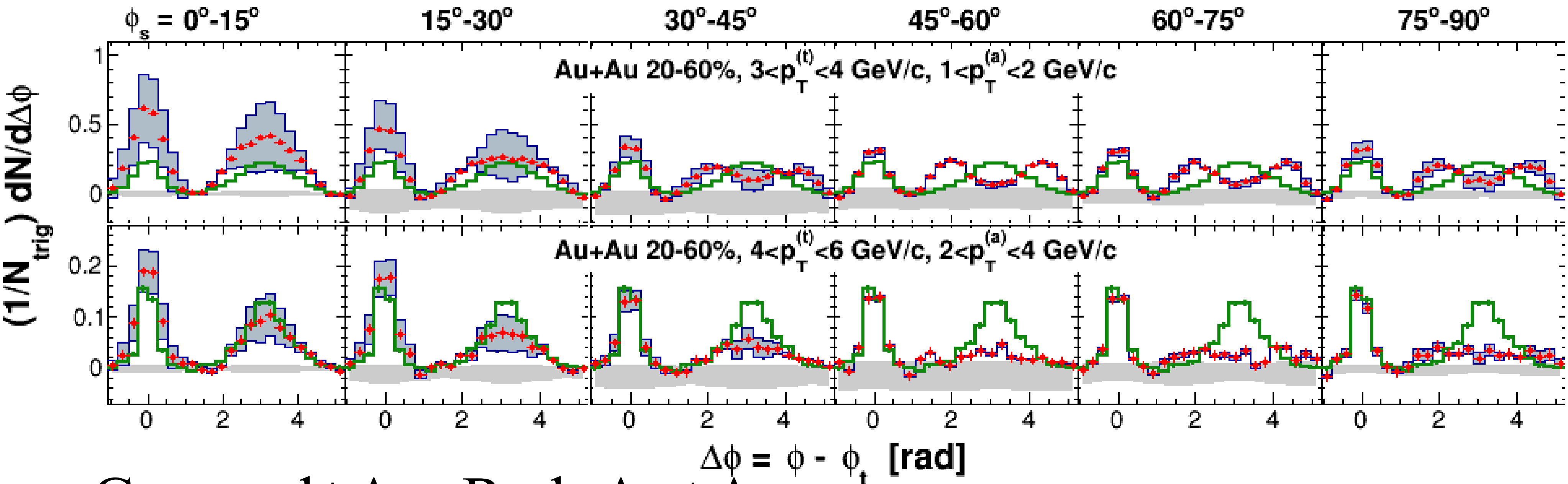


Near-Side Subtracted NSF method



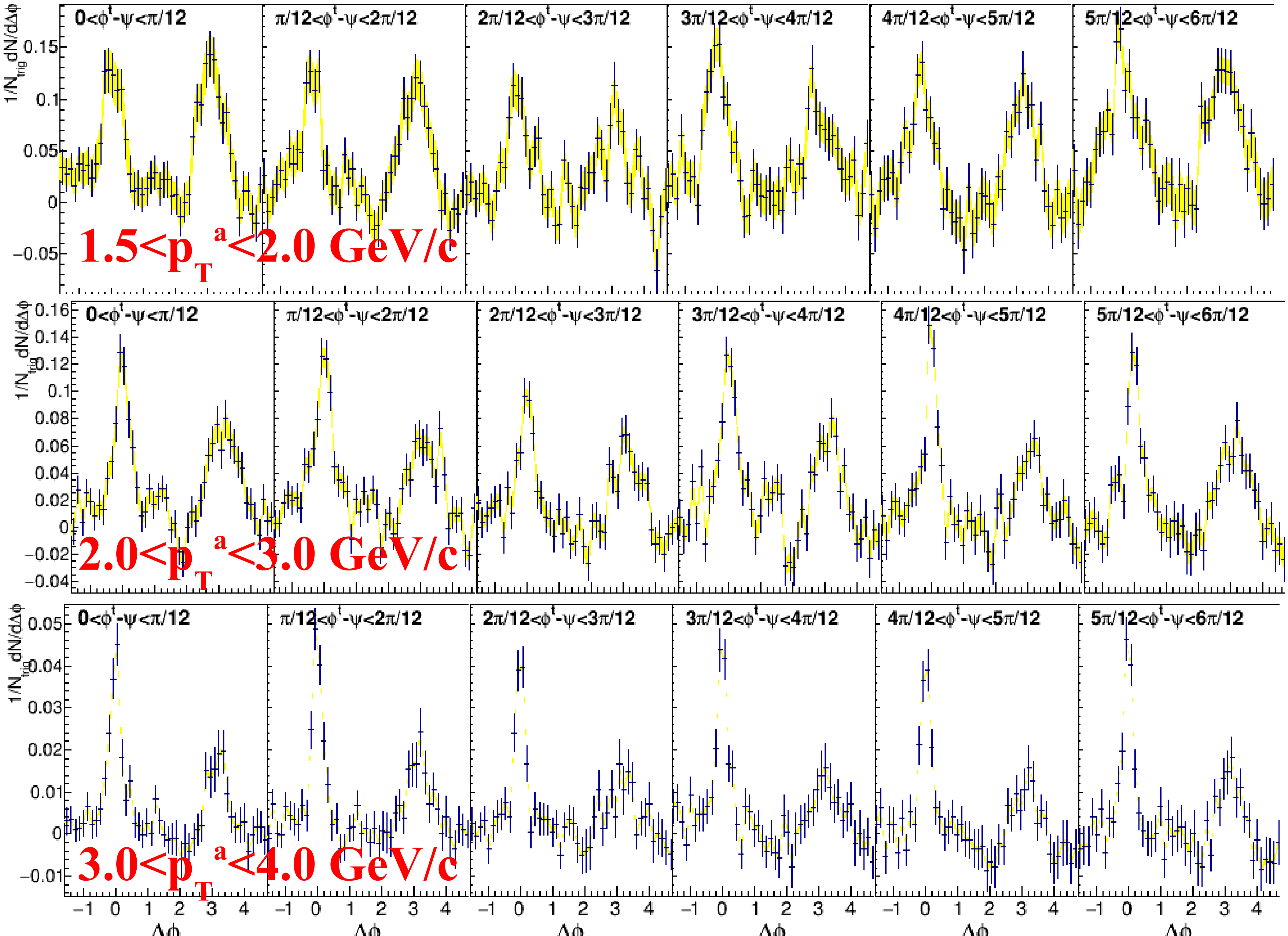
- Project signal+background over **0.0**<|Δη|<1.4
- Fit background in |Δφ|<1 including reaction plane dependence
- Bias from residual contamination by near-side

Correlations - STAR



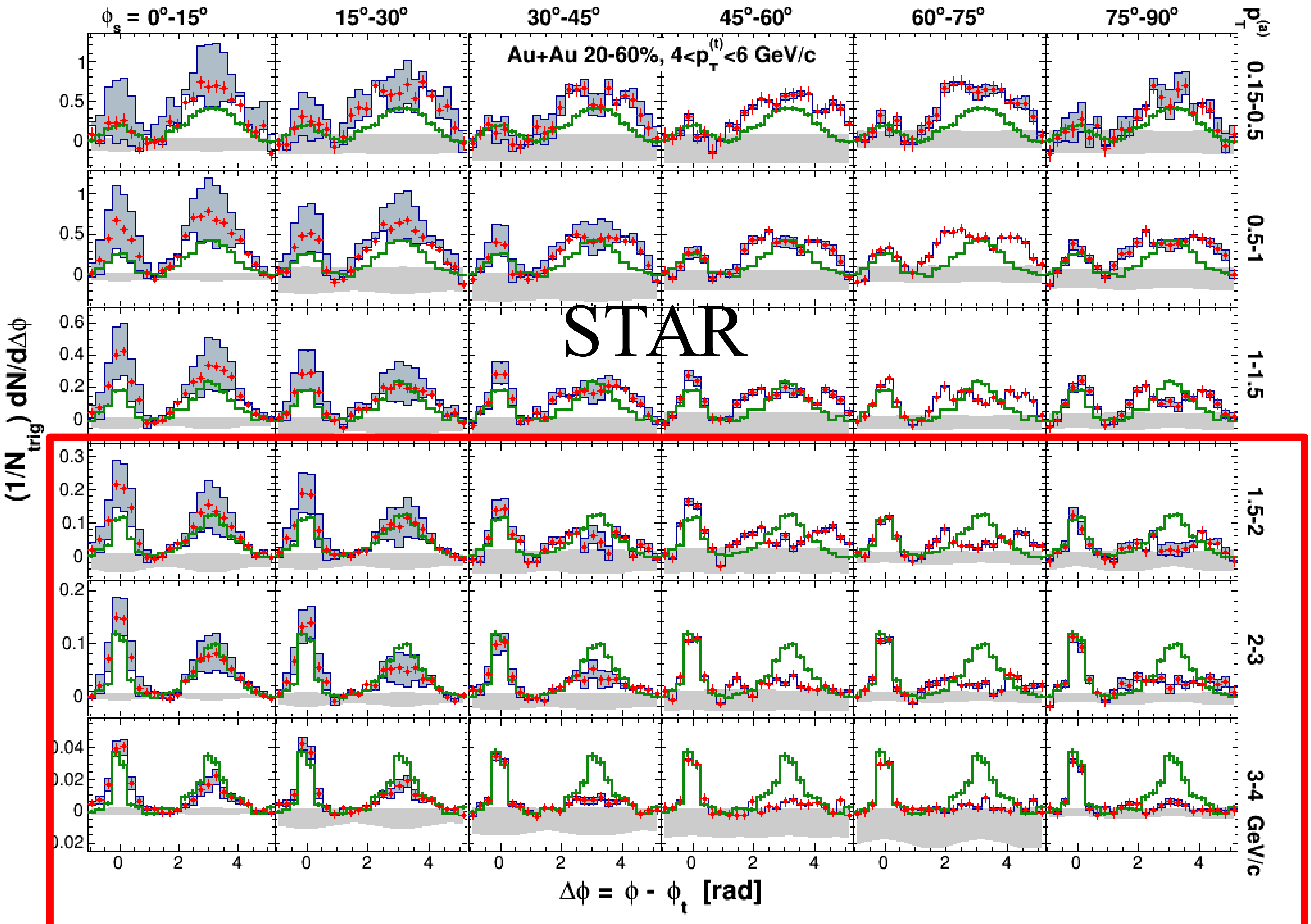
- Green: d+Au, Red: Au+Au
- Large error bars
- "Mach Cone" evident, even decrease in amplitude for higher p_T^t

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"



ϕ_s = 0°-15°
15°-30°
30°-45°
45°-60°
60°-75°
75°-90°
$p_T^{(a)}$
Au+Au 20-60%, 4<$p_T^{(t)}$<6 GeV/c
STAR
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]

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**

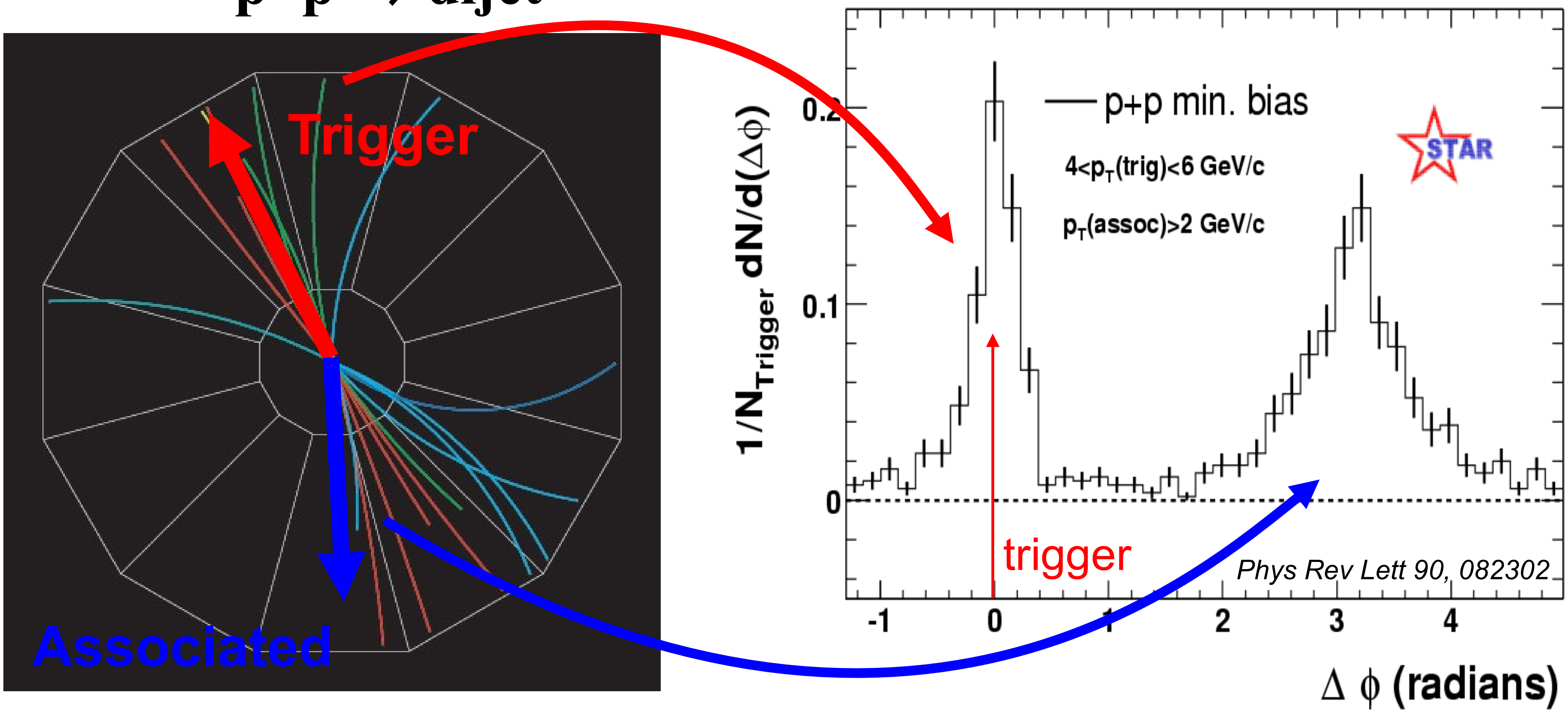
v_2 STAR vs Fit

	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 $N_{trigger}$?

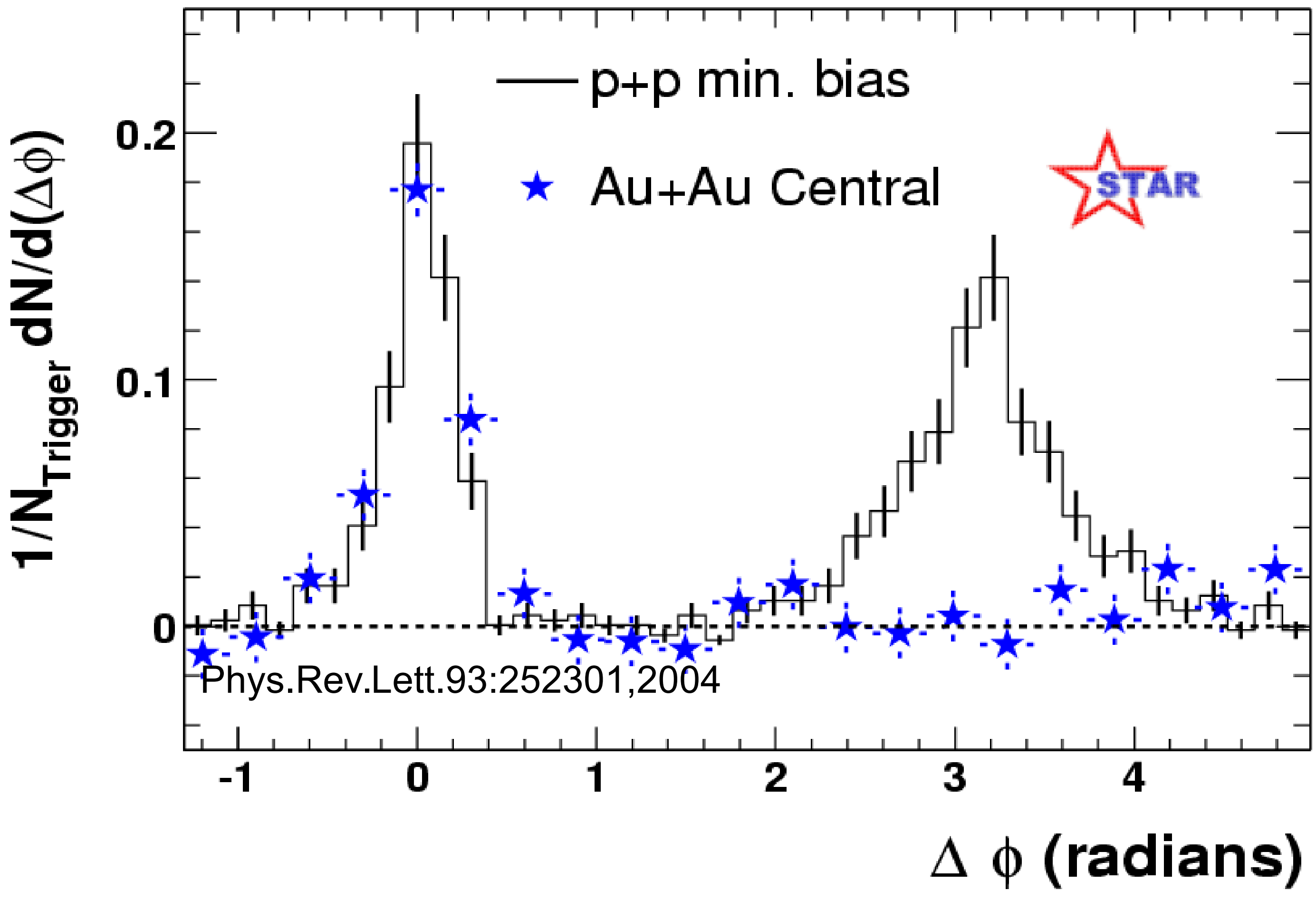
Jets – azimuthal correlations

p+p → dijet

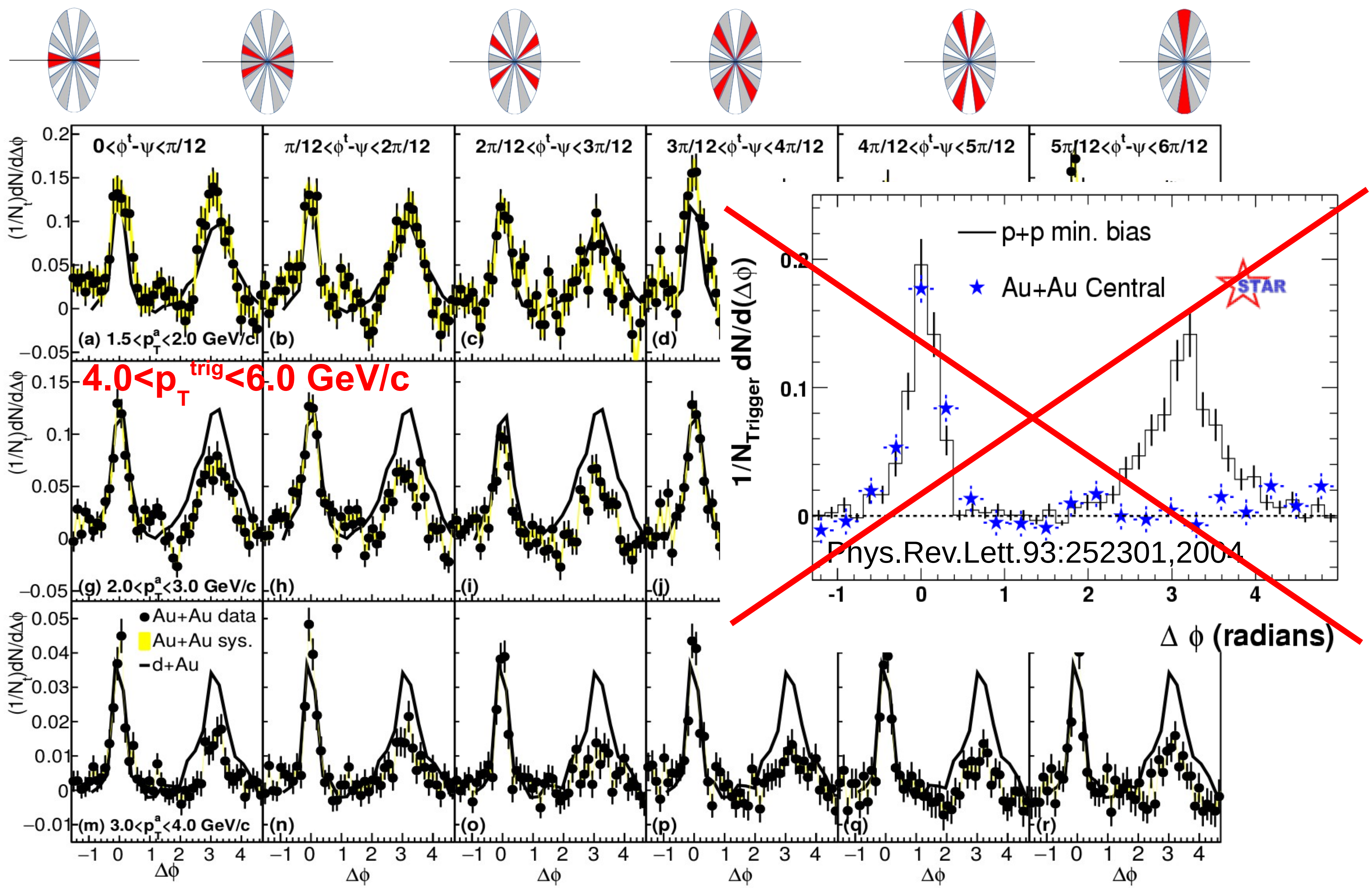


Select high momentum particles → biased towards jets

Azimuthal correlations

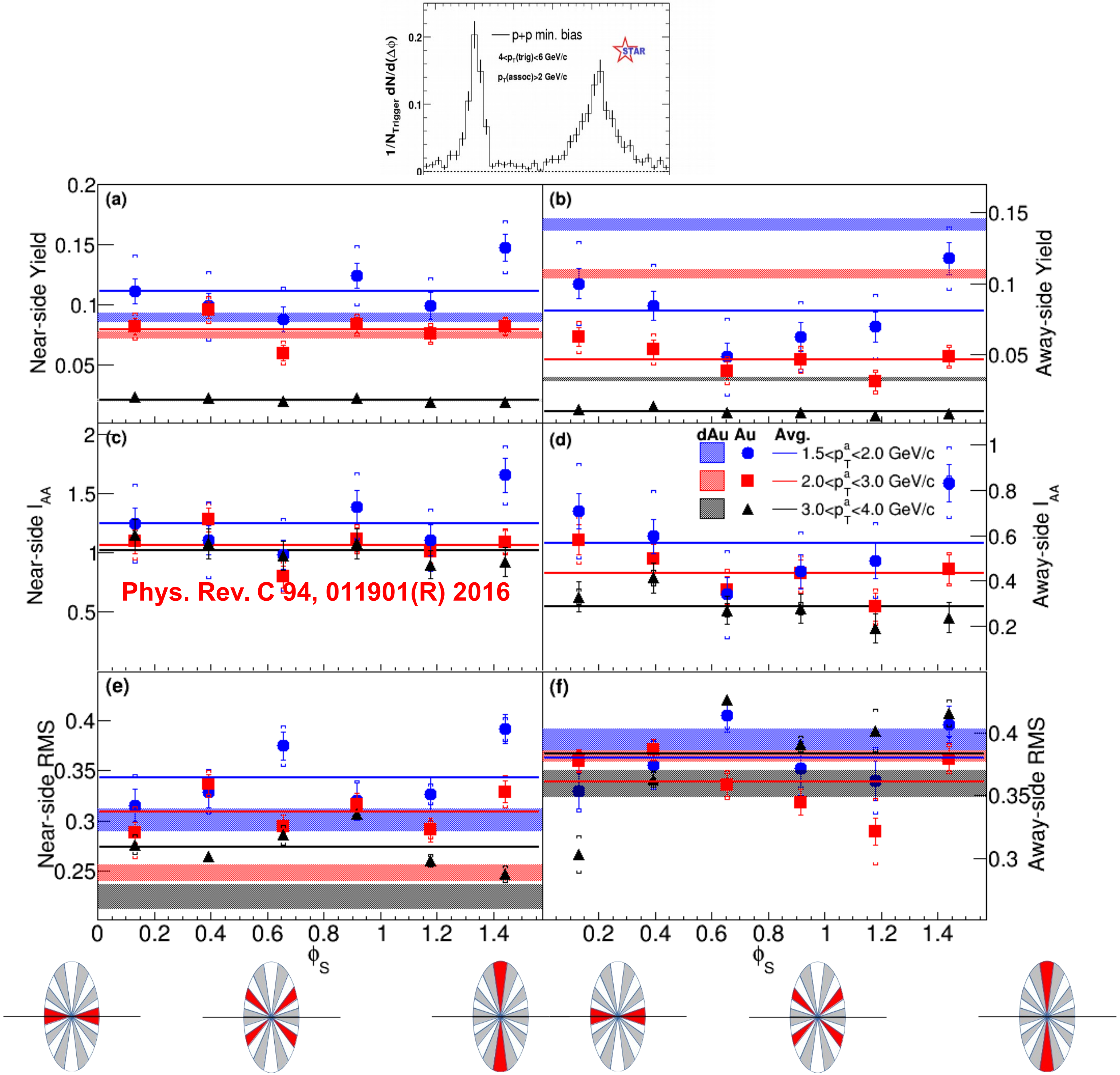


Dihadron correlations



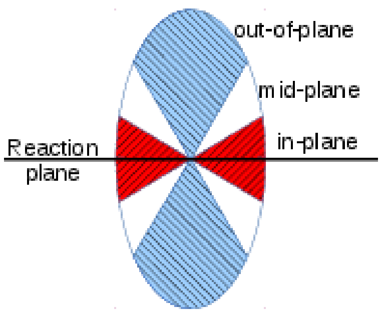
Sharma, Mazer, Stuart, Nattrass: (Phys. Rev. C 93, 044915 2016)

Dihadron correlations

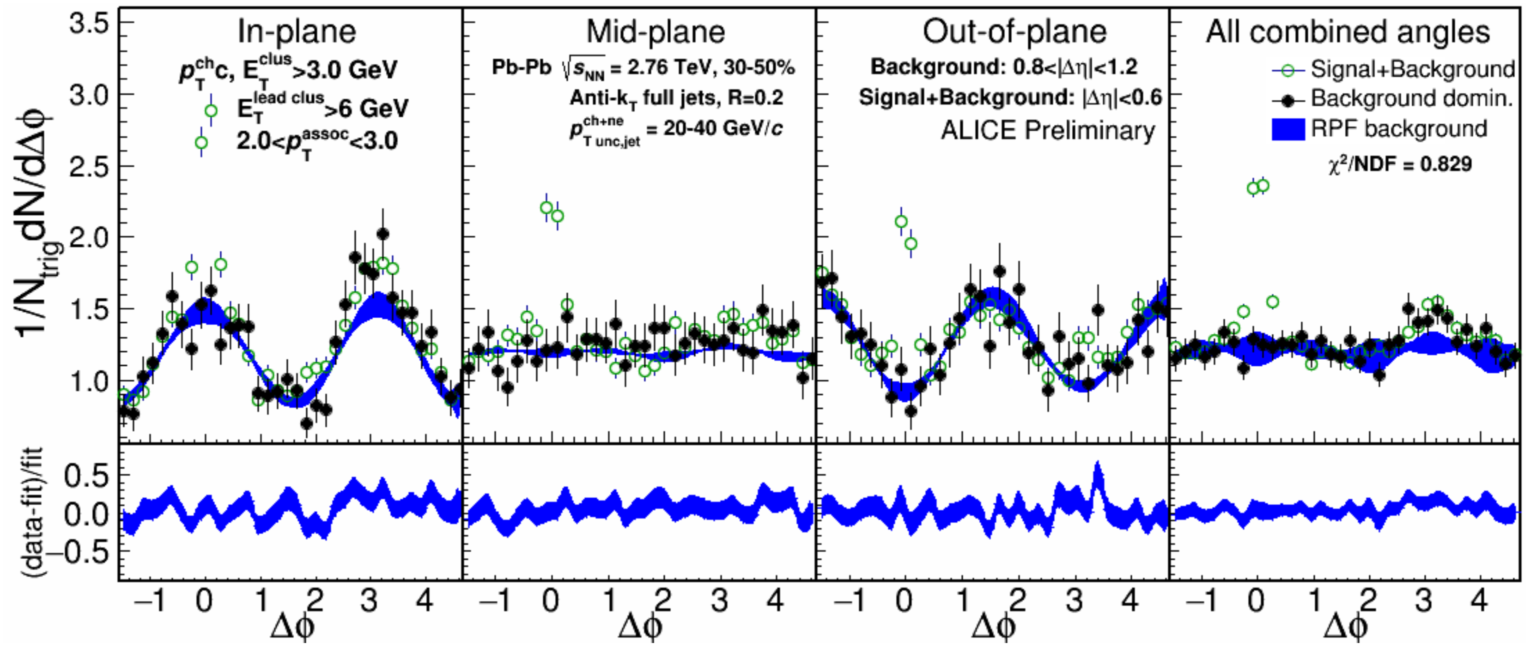


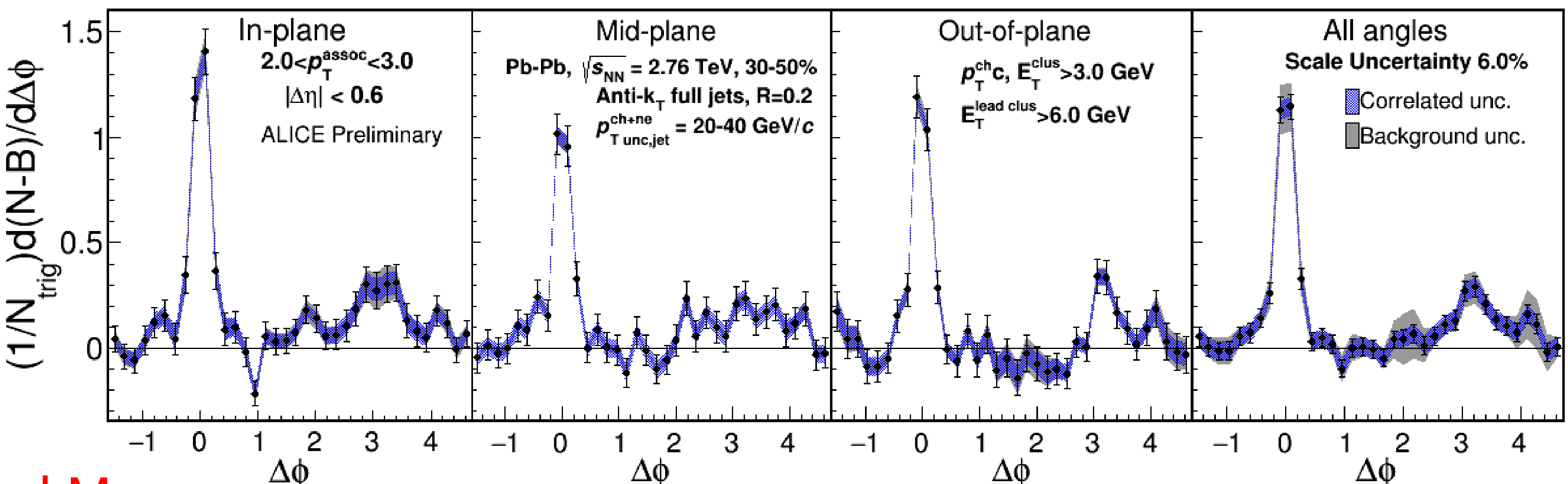
2.0-3.0 GeV/c p_T^{assoc}

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



Correlation function





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- Away side clearly there and suppressed

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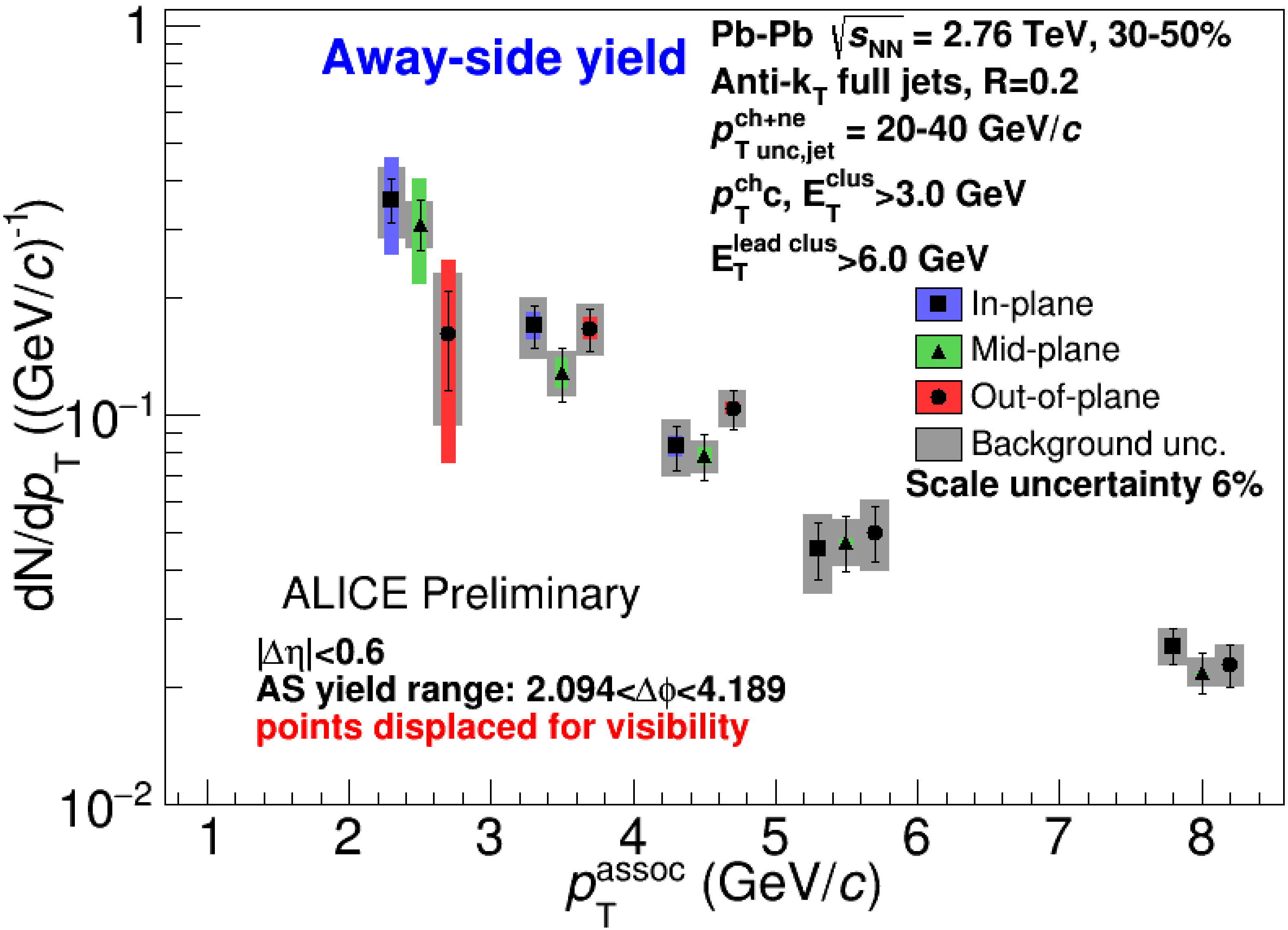
Away-side jet yields vs EP

Jets 20-40 GeV/c, 30-50% centrality



Within uncertainties of current statistics, no event plane ordering

- Different effects in different p_T associated bins

Competing effects
1) Quenching
2) Bremsstrahlung
3) etc

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Hot Quarks 2016

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].

http://www.boredpanda.com/animal-camouflage/

Bias

- **Modified jets probably look more like the medium**
- **Quark jets are narrower, have fewer tracks, fragment harder [Z Phys C 68, 179-201 (1995), Z Phys C 70, 179-196 (1996),]**
- **Gluon jets reconstructed with k_T algorithm have more particles than jets reconstructed with anti-k_T algorithm [Phys. Rev. D 45, 1448 (1992)]**
- **Gluon jets fragment into more baryons [EPJC 8, 241-254, 1998]**

Piet Grobler 2009

http://www.boredpanda.com/animal-camouflage/