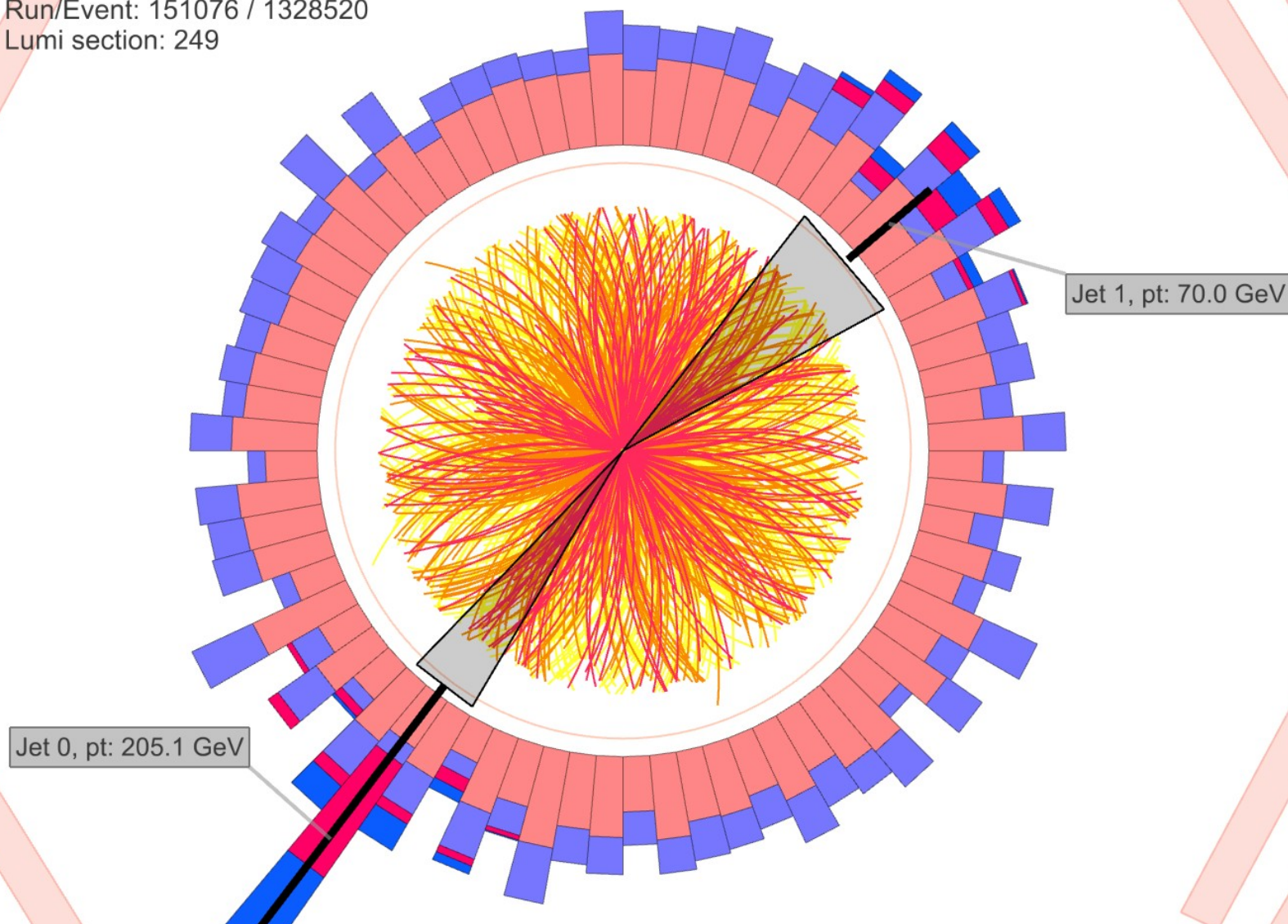


CMS Experiment at LHC, CERN  
Data recorded: Sun Nov 14 19:31:39 2010 CEST  
Run/Event: 151076 / 1328520  
Lumi section: 249

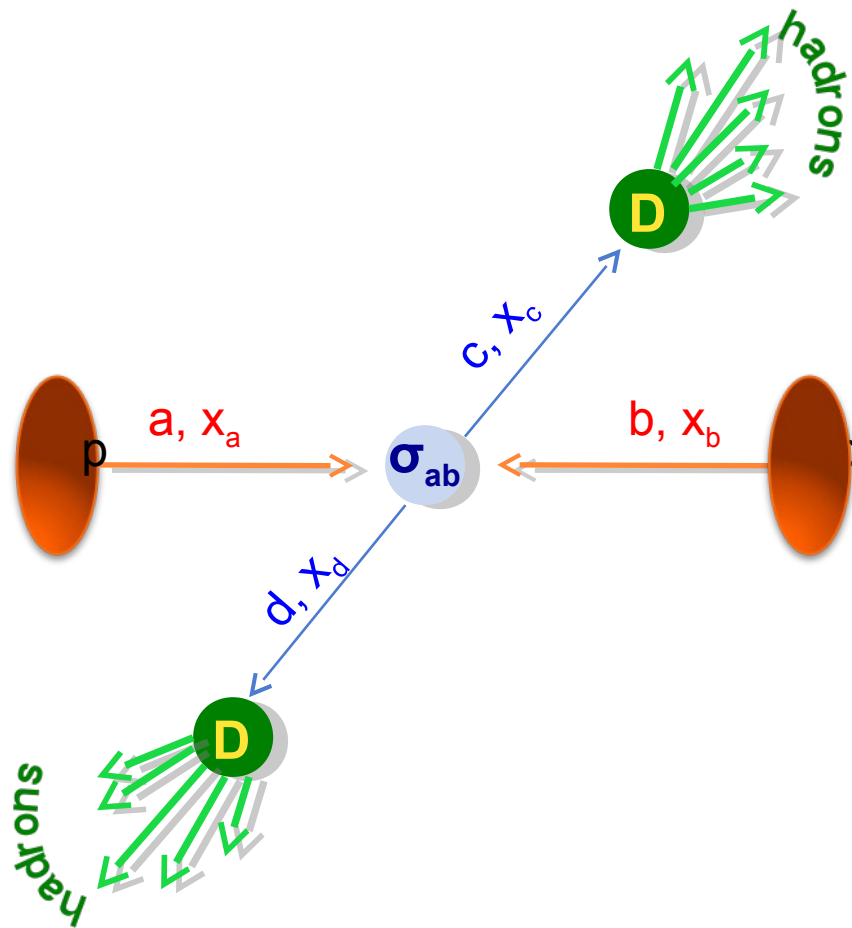


# Precision background subtraction in dihadron and jet-hadron correlations

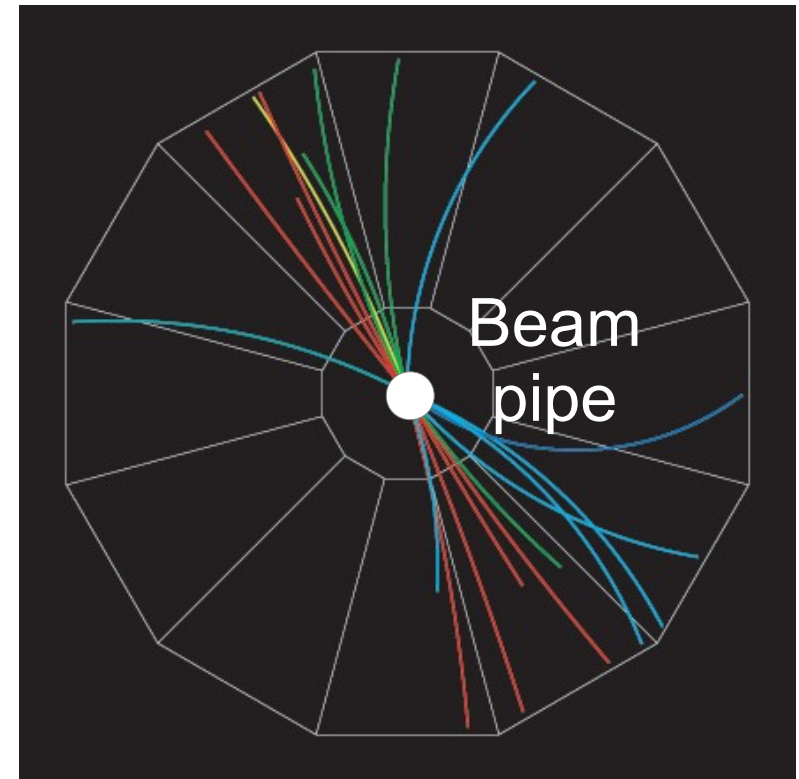
Based on nucl-ex/1509.04732 submitted to PRC

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

# Jets



**p+p → dijet**



**Jets** – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

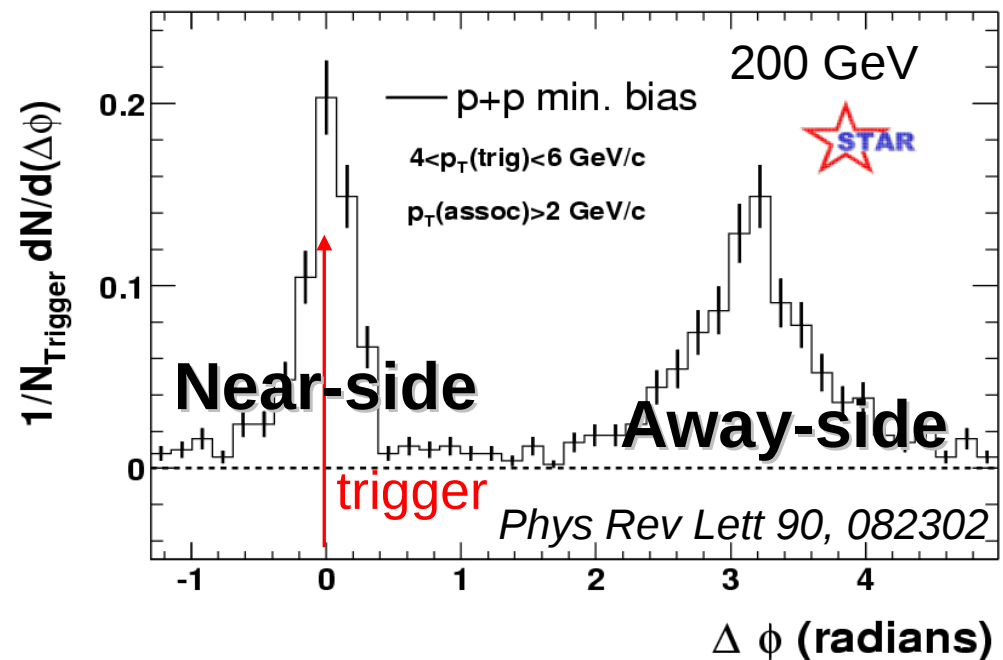
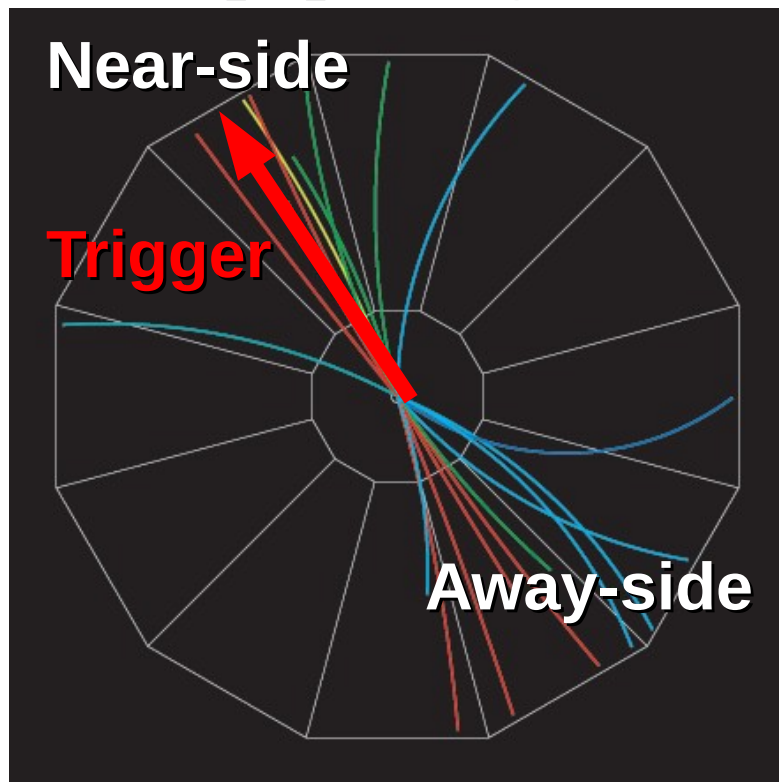
# Azimuthal correlations

Jets are dominantly produced as di-jets

Find high- $p_T$  trigger particle or jet candidate

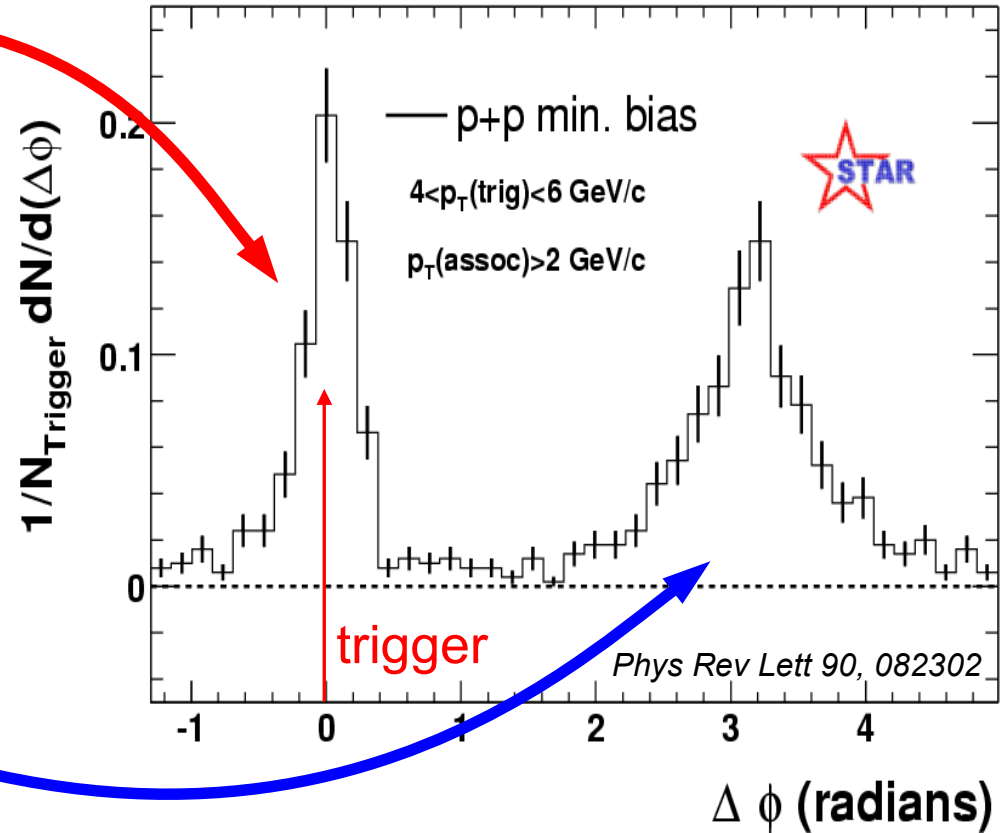
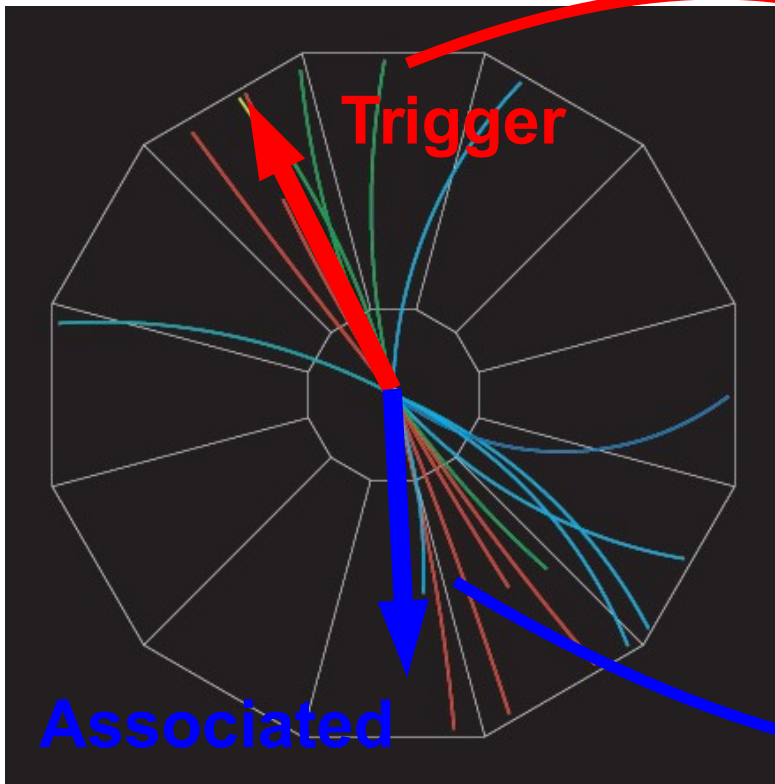
Look at distribution of high- $p_T$  associated particles relative to trigger

**p+p → dijet**



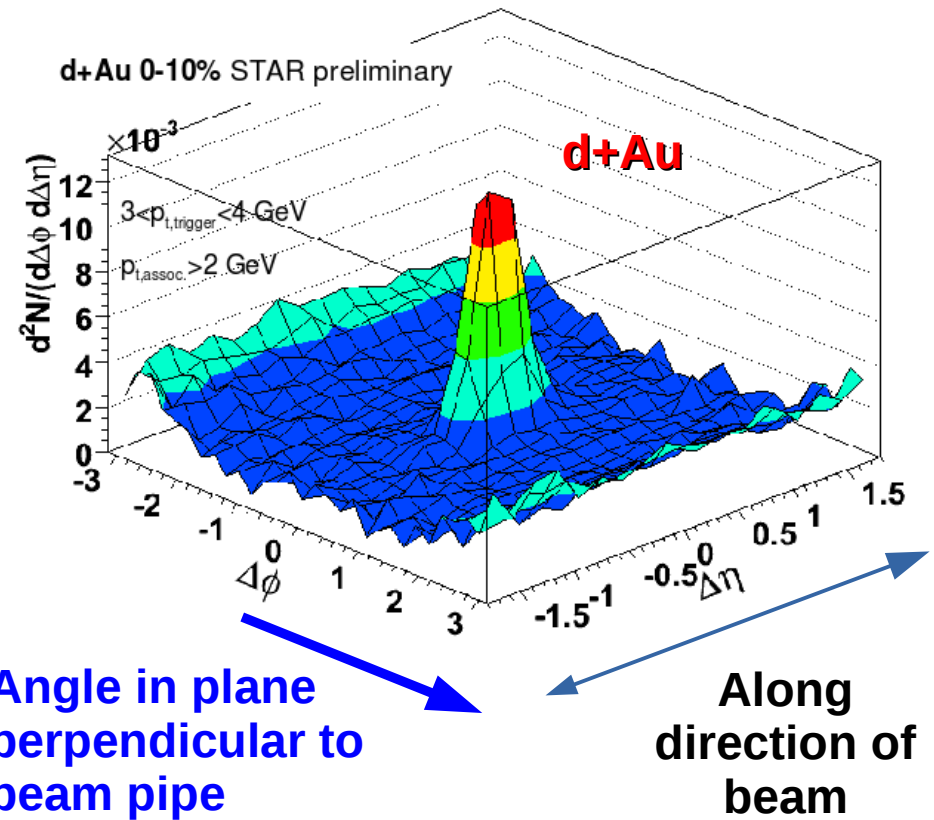
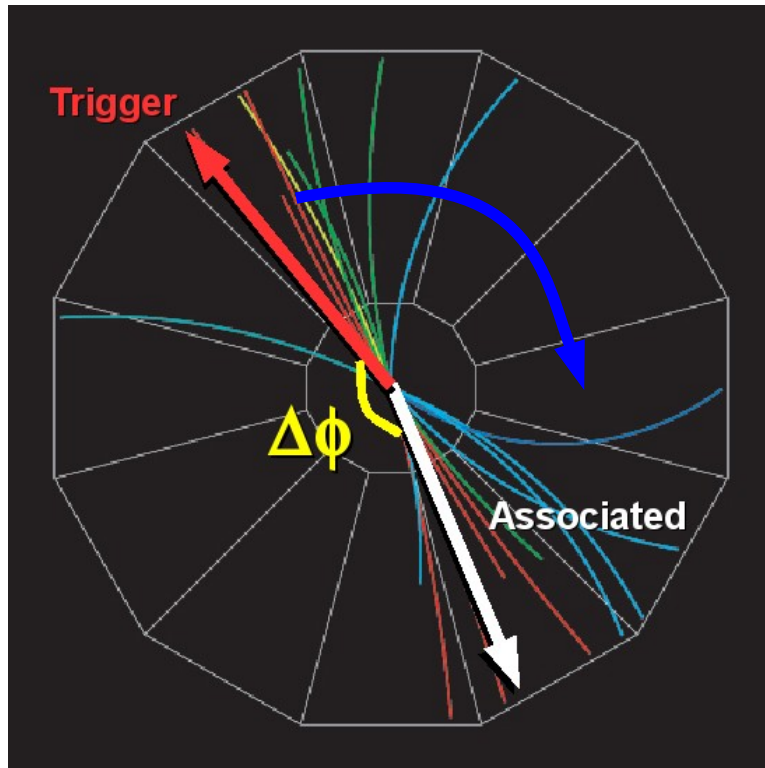
# Jets – azimuthal correlations

$p+p \rightarrow \text{dijet}$

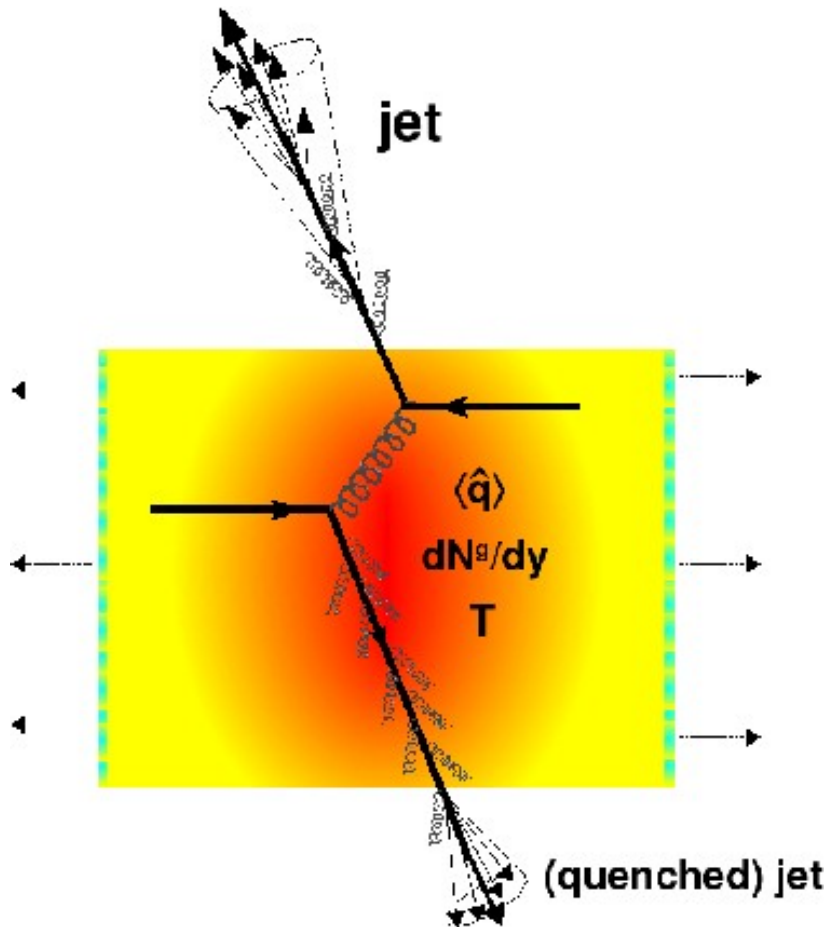


Select high momentum particles → biased towards jets

# Looking in two dimensions

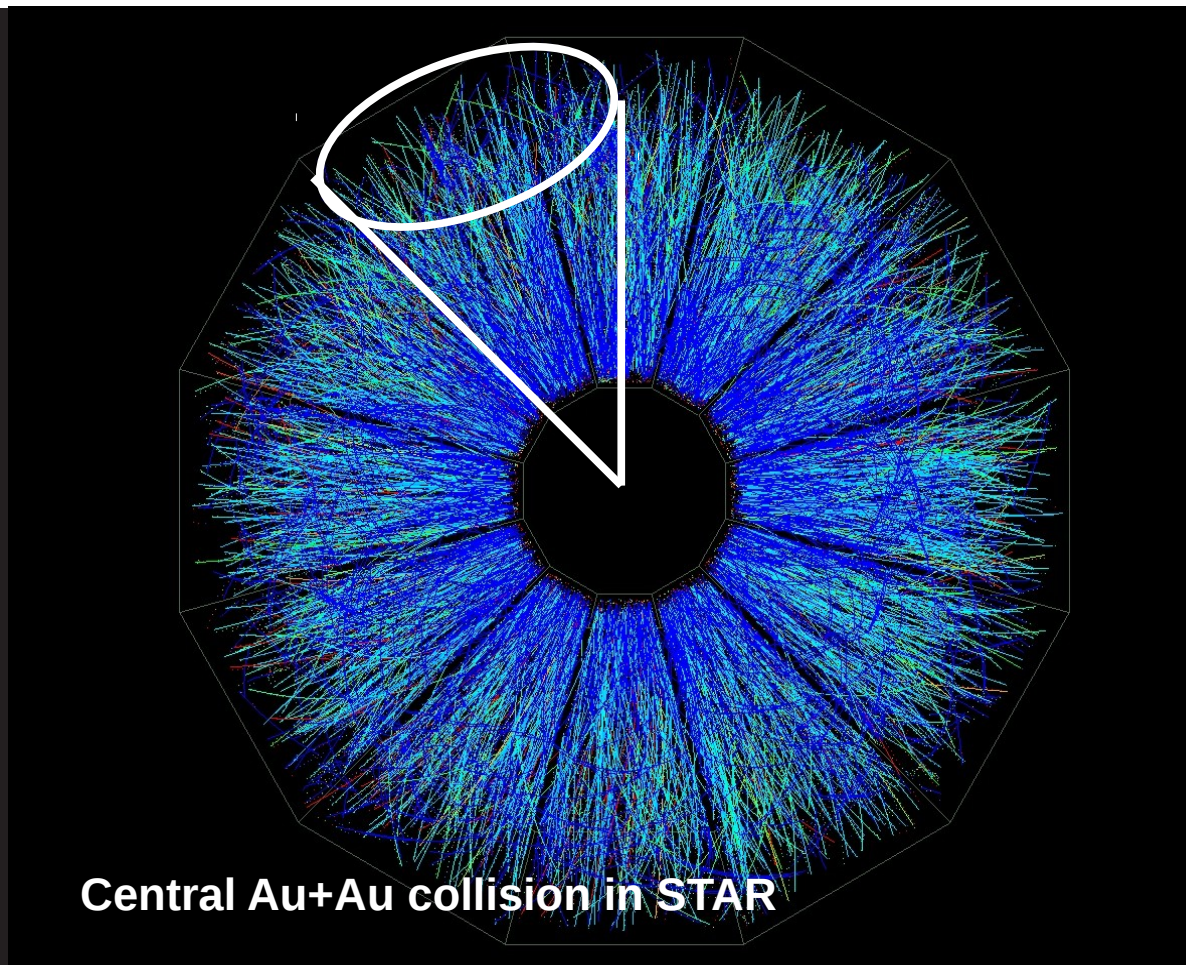
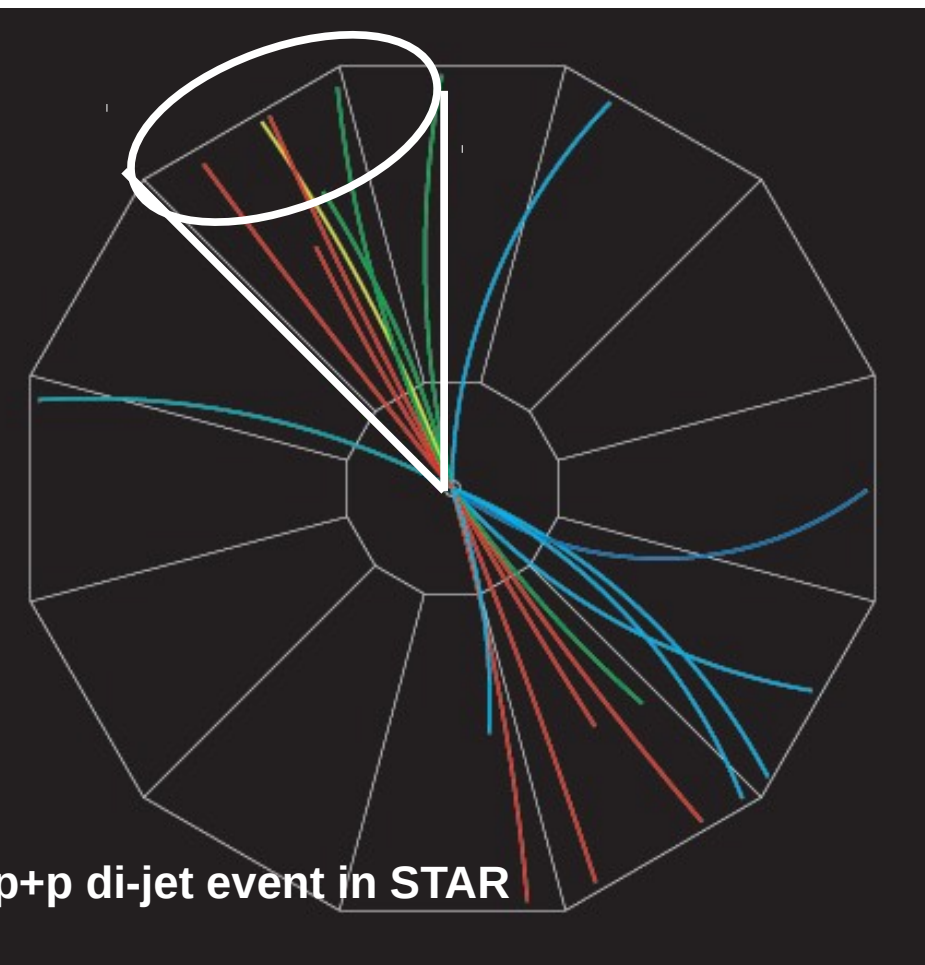


# Jet quenching



- Quenched jet
  - Softer constituents
  - Broader radius
- → Looks more like background

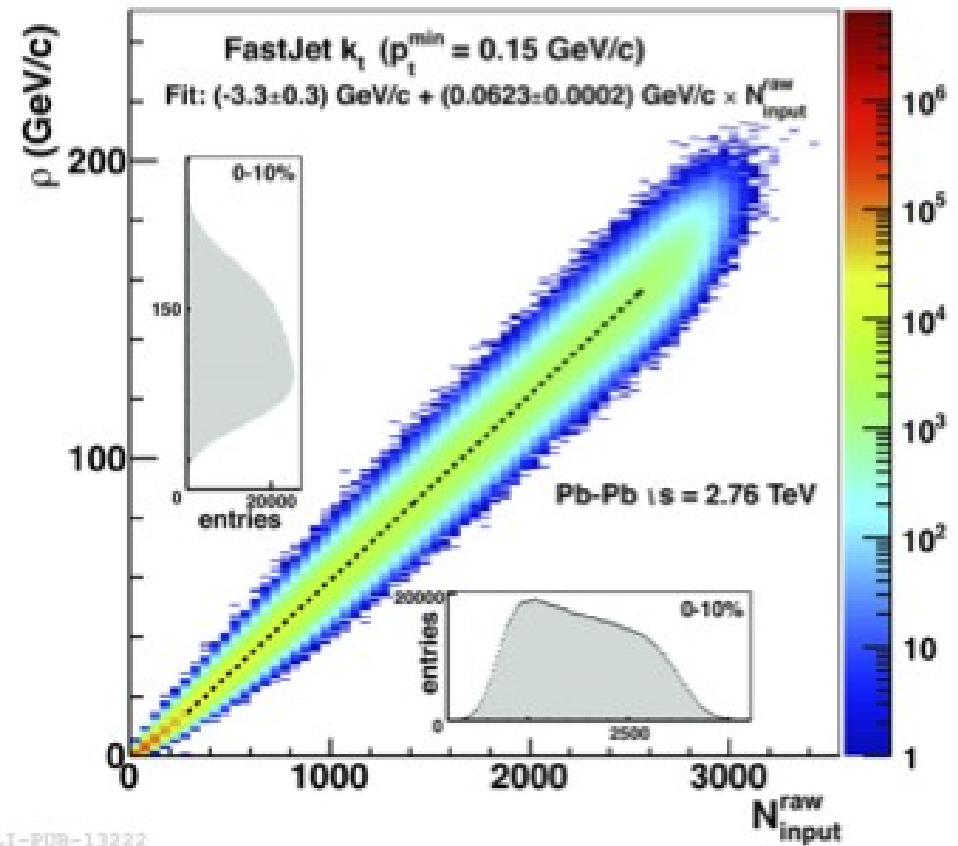
# Large combinatorial background in heavy ion collisions



# Background in heavy ion collisions

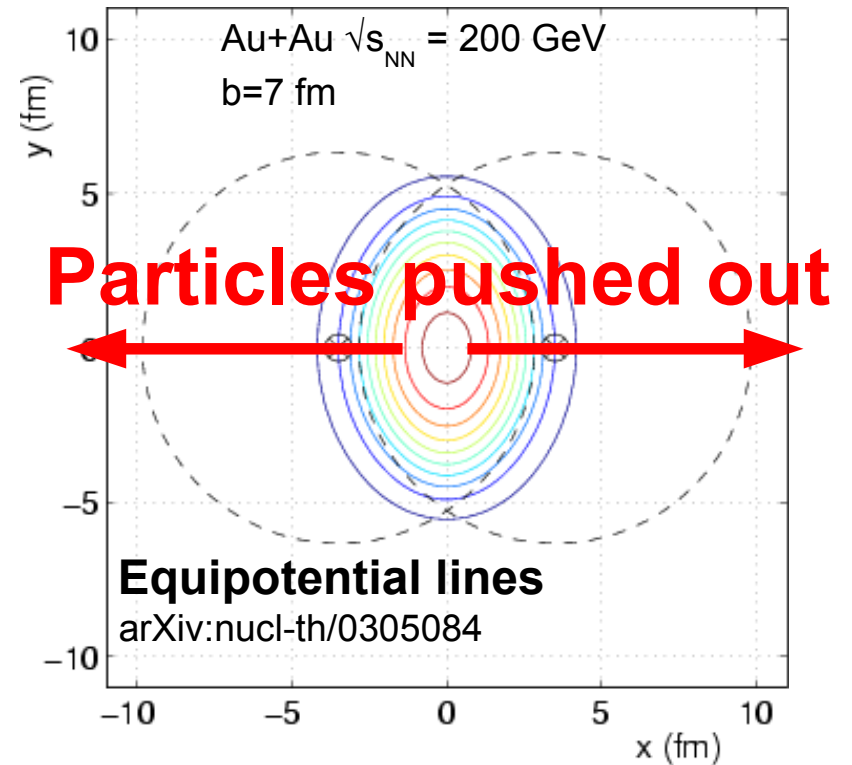
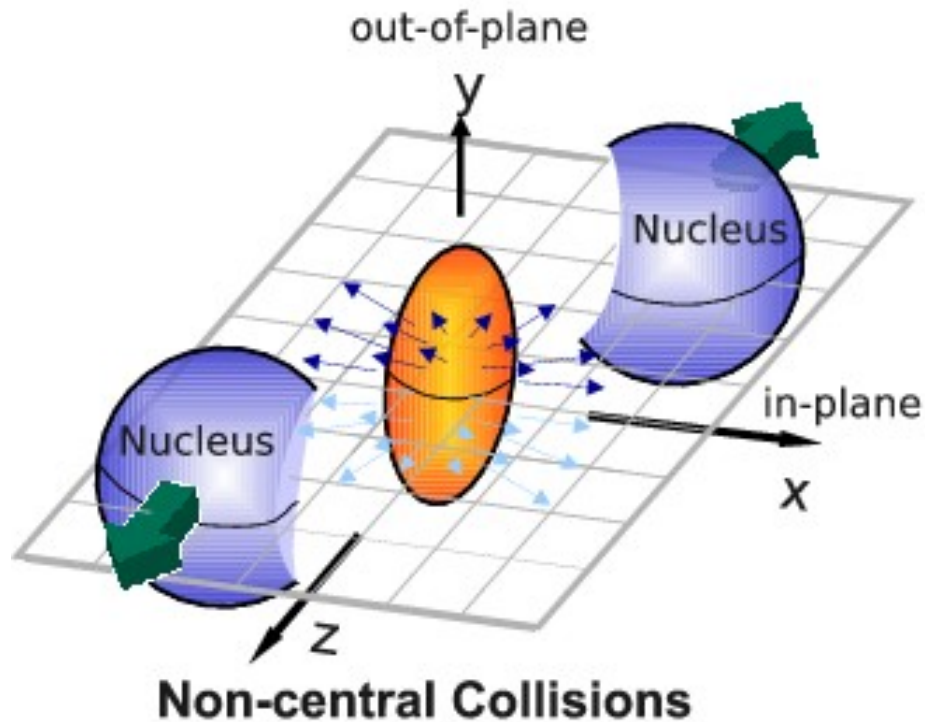
- Increase signal/background by
  - Increasing  $p_{T}^{\min}$  threshold for jet finding
  - Increase jet energy
  - Require high  $p_T$  constituent
  - Restrict angular size of jet  $R = \sqrt{(\Delta\eta^2 + \Delta\Phi^2)}$
- → Bias measurement towards unmodified jets

JHEP 1203:053, 2012  
(arxiv:1201.2423)



# Background in heavy ion collisions

# If we have a fluid...



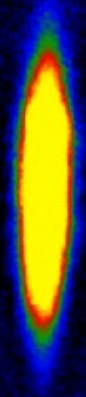
- Initial overlap asymmetric  $\rightarrow$  pressure gradients
- Momentum anisotropy  $\rightarrow$  Fourier decomposition:

$$\frac{d^2 N}{dp_T d\varphi} \approx 1 + 2v_1 \cos(d\varphi) + 2v_2 \cos(2d\varphi) + 2v_3 \cos(3d\varphi) + 2v_4 \cos(4d\varphi) + 2v_5 \cos(5d\varphi) + \dots$$

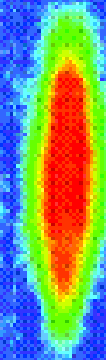
# What does this mean?

- Same phenomena observed in gases of strongly interacting atoms
  - K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas *Science* 298 2179 (2002)

High viscosity

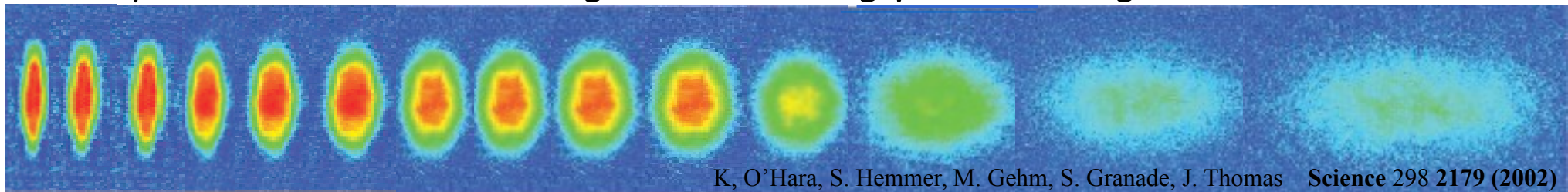


Low viscosity



# What does it mean?

Same phenomena observed in gases of strongly interacting atoms



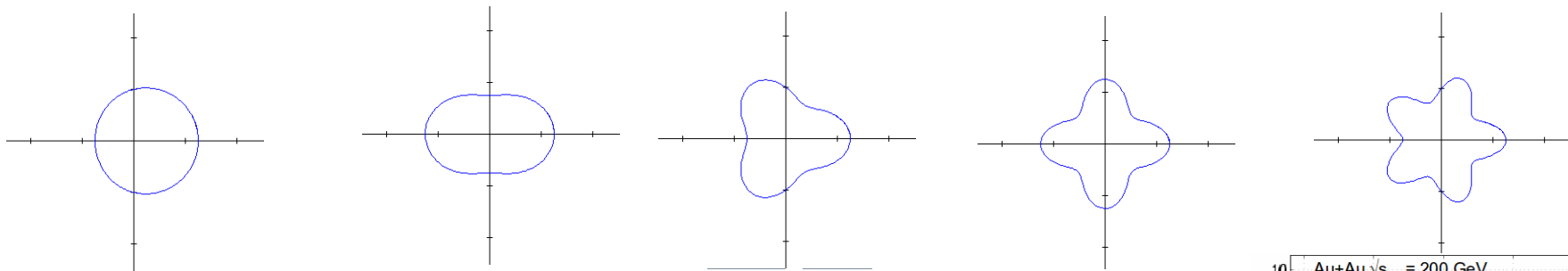
K, O'Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas *Science* 298 2179 (2002)

Time  $\longrightarrow$

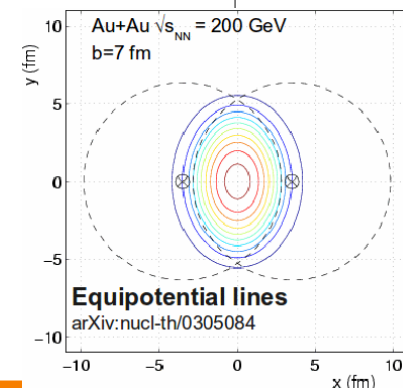
**Initial state anisotropies converted to final state anisotropies**

Fourier decomposition:

$$\frac{d^2 N}{dp_T d\varphi} \approx 1 + 2 v_1 \cos(d\varphi) + 2 v_2 \cos(2d\varphi) + 2 v_3 \cos(3d\varphi) + 2 v_4 \cos(4d\varphi) + 2 v_5 \cos(5d\varphi) + \dots$$



Offset  
measured



# Background in correlations

- All reaction plane angles

$$B(1 + \sum_{n=2}^{\infty} \cos(n \Delta \varphi))$$

- When trigger is restricted relative to reaction plane

- Background level modified

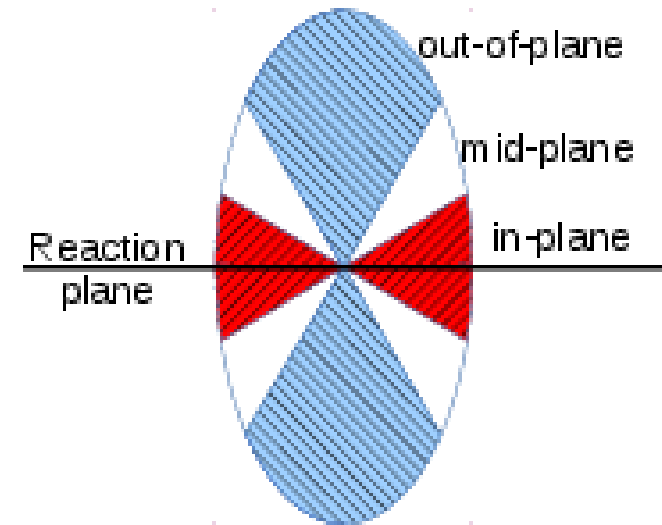
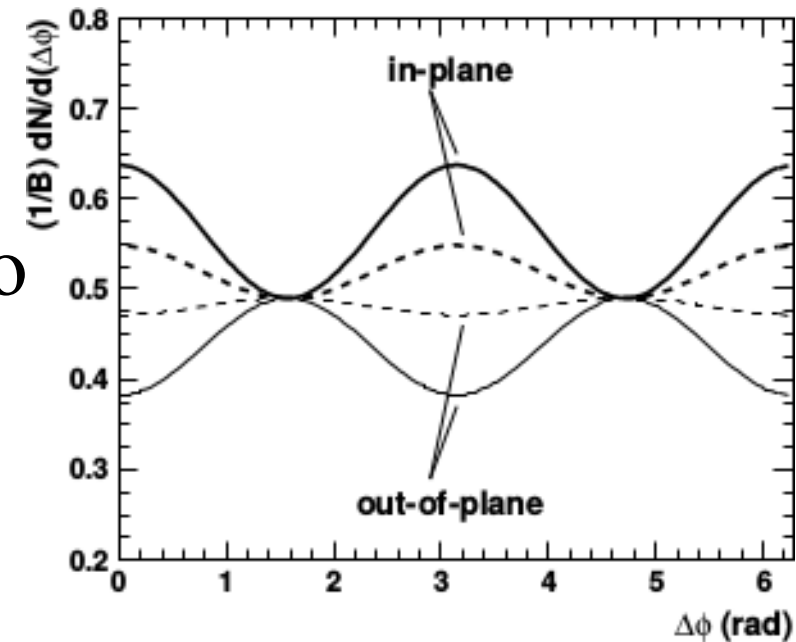
$$B = 1 + \sum_{k=2,4,6\dots}^{\infty} 2 v_k \cos(k \varphi_S) \frac{\sin(kc)}{kc} R_n$$

- Effective  $v_n$  modified

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

$\varphi_S$  is the angular threshold

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



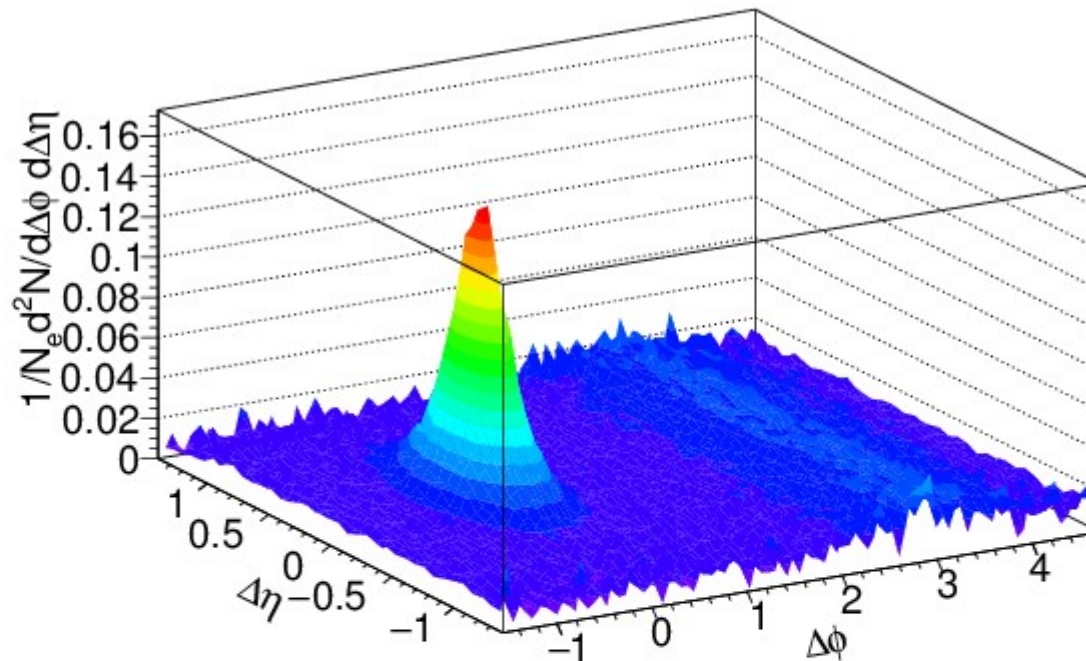
# Toy model

# Model for background

- True reaction plane angle is always at  $\varphi=0$  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

# Model for signal

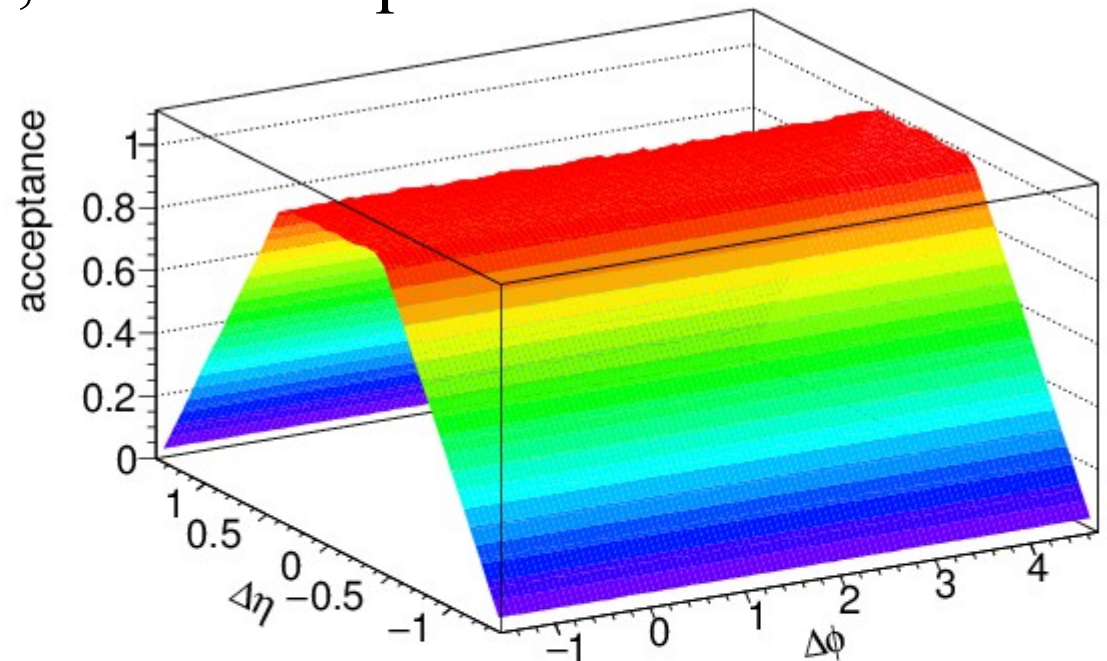
- Use PYTHIA Perugia 2011
- $\pi^\pm$ ,  $K^\pm$ ,  $\bar{p}$ ,  $p$  for unidentified hadrons
- Quarks and gluons as proxy for reconstructed jets



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

# Acceptance correction

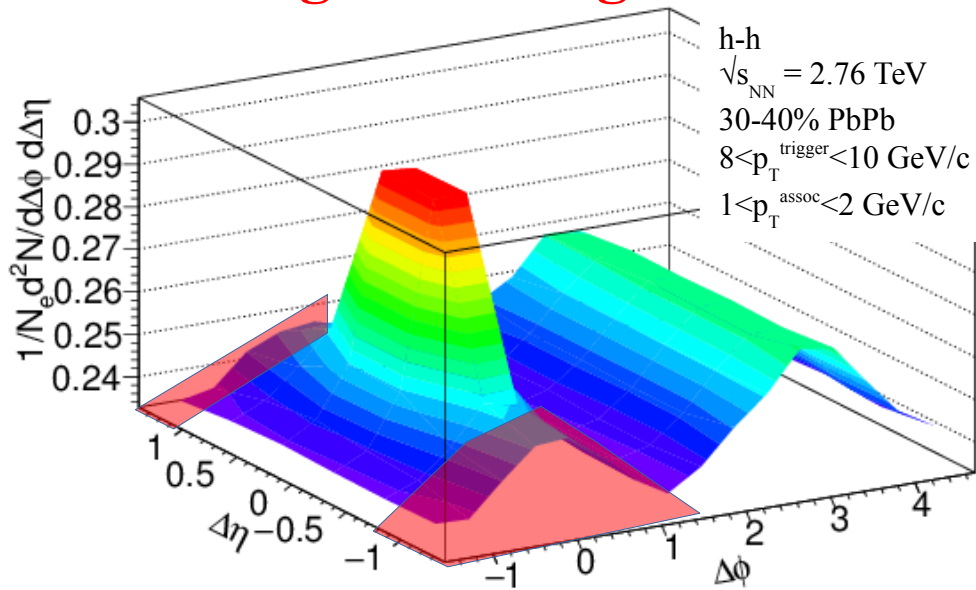
- Fixed acceptance cuts leads to a trivial structure due to acceptance
- This is fixed with a “mixed event” correction
  - Throw random trigger, associated particle within acceptance
  - Calculate  $\Delta\phi$ ,  $\Delta\eta$
  - Use this distribution to correct for acceptance



# Separating the signal and the background

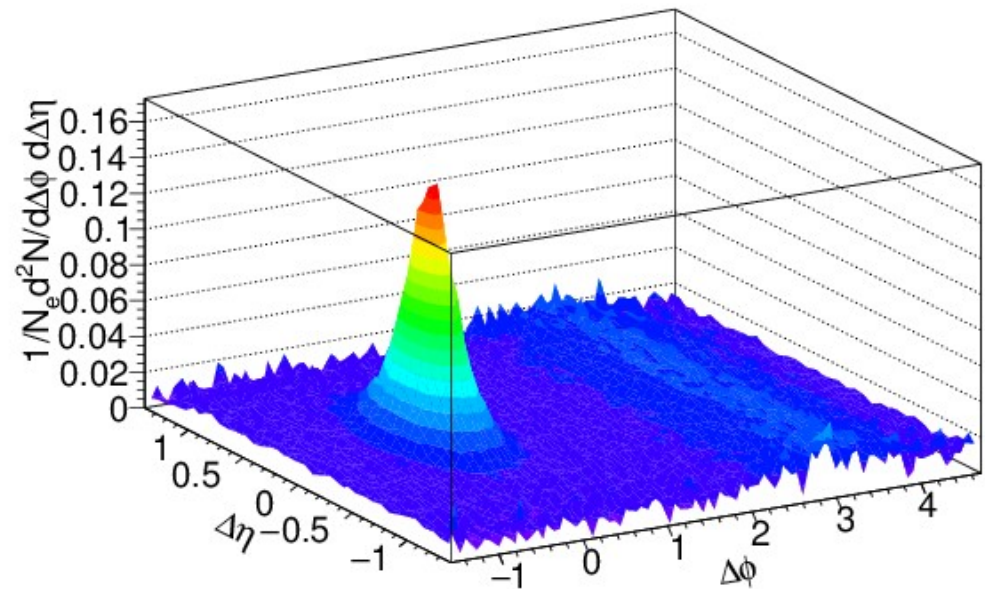
# Separating signal+background

**Signal+background**



**Background dominated region**

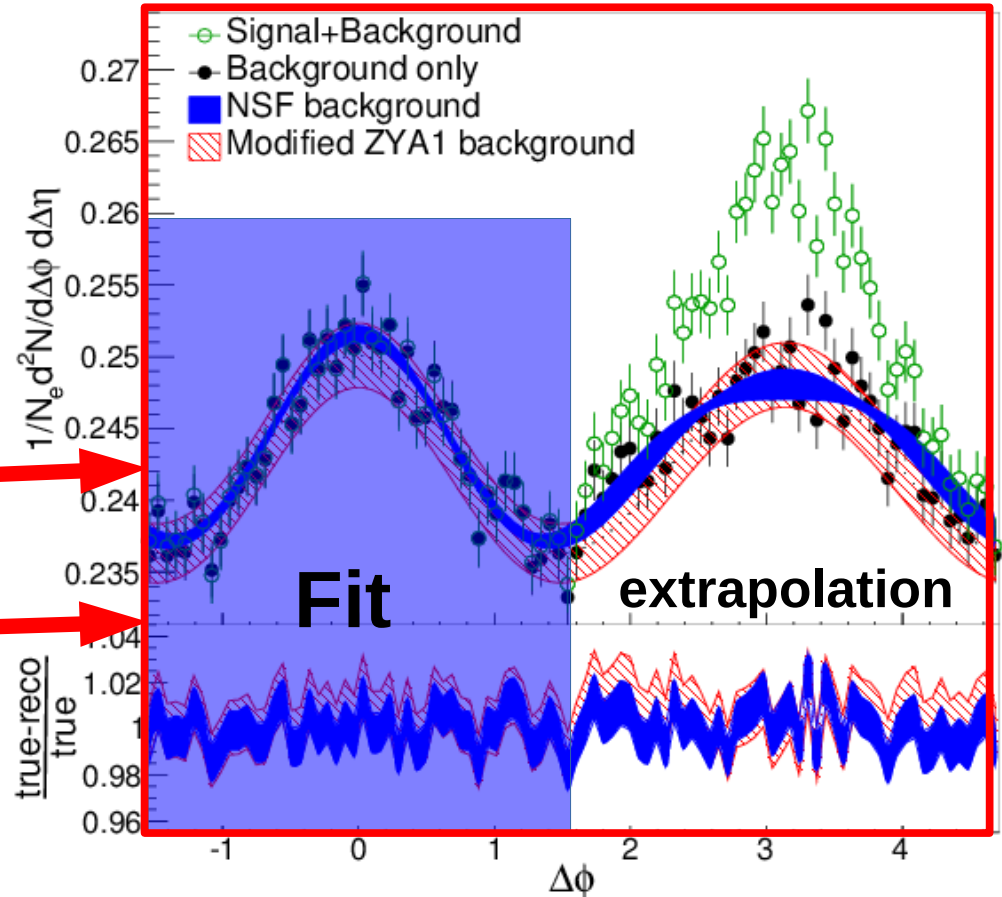
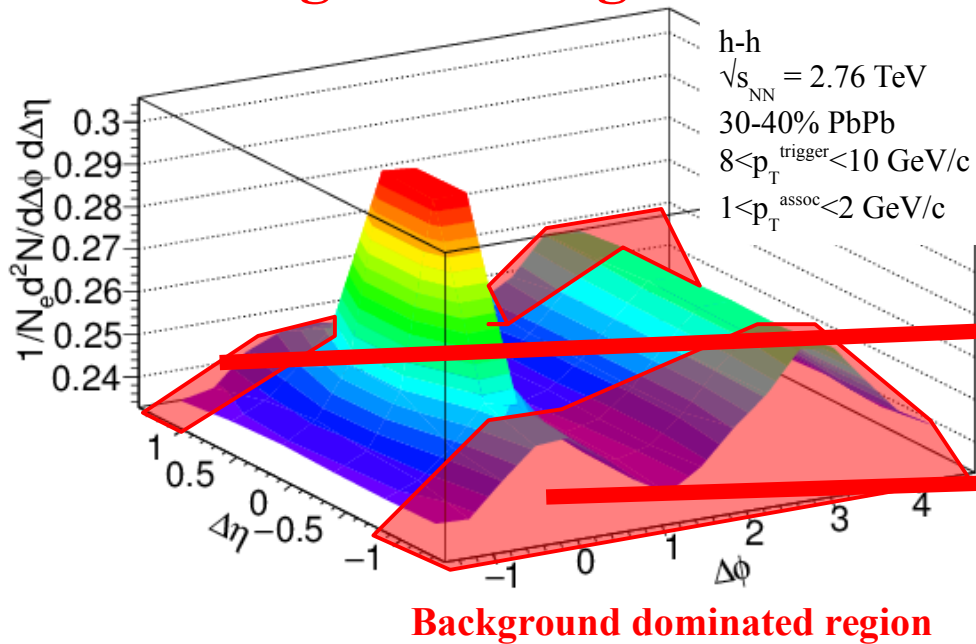
**Signal only**



# Near-Side Fit (NSF) method

No reaction plane dependence

**Signal+background**



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

# 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	$17.1 \pm 0.1 \pm 0.2$	$19.9 \pm 0.1 \pm 0.2$
	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	$17.14 \pm 1.1$	$20.14 \pm 1.11$

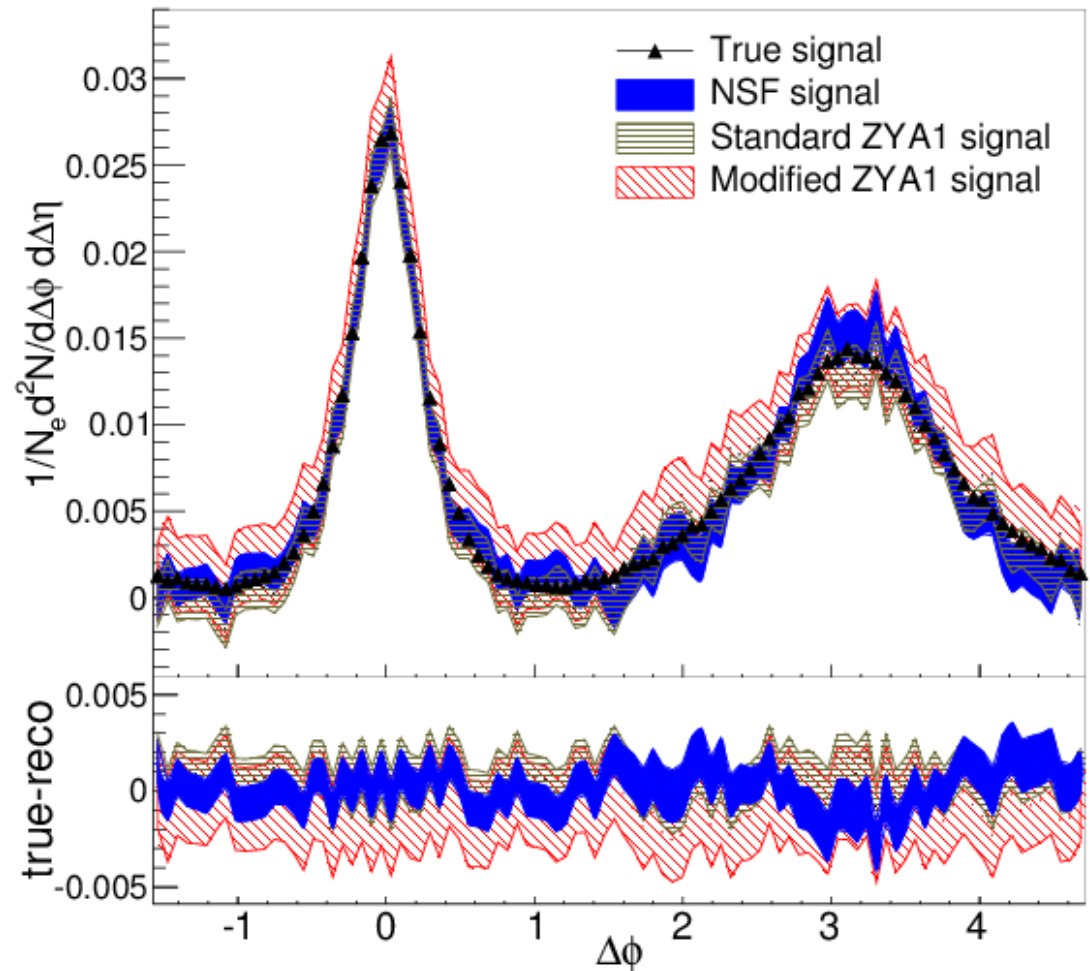
h-h

$\sqrt{s_{NN}} = 2.76$  TeV

30-40% PbPb

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

$1 < p_T^{\text{assoc}} < 2$  GeV/c



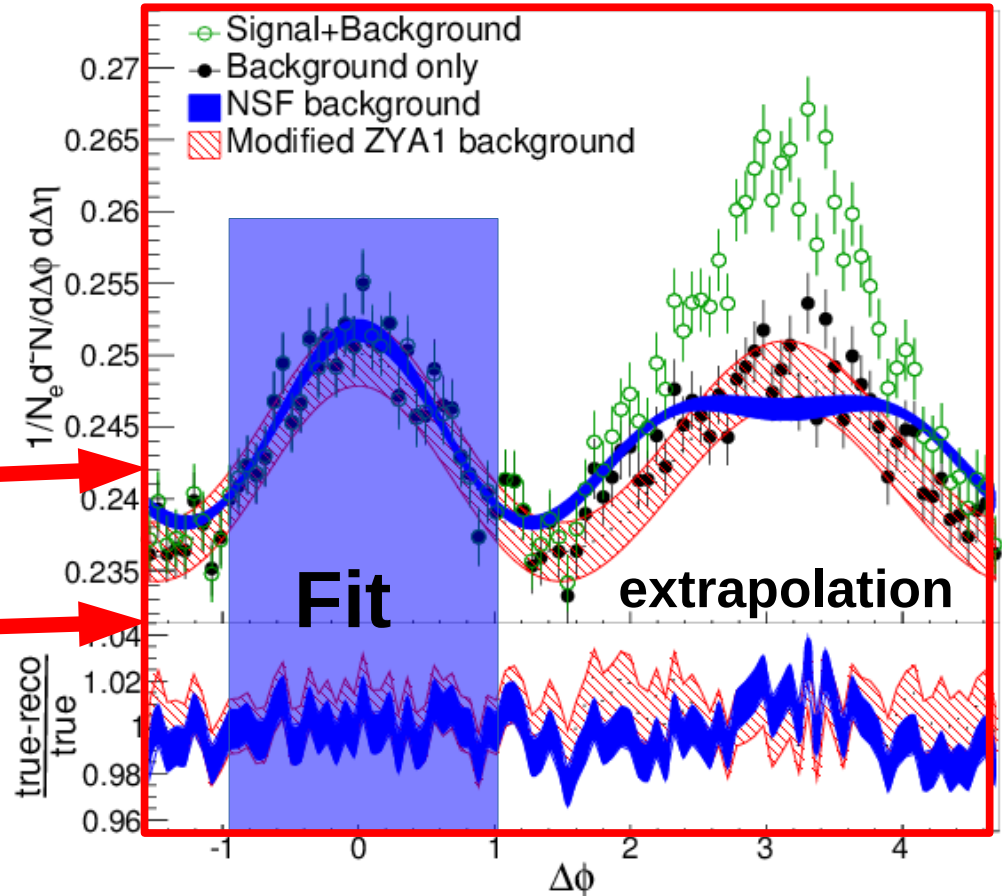
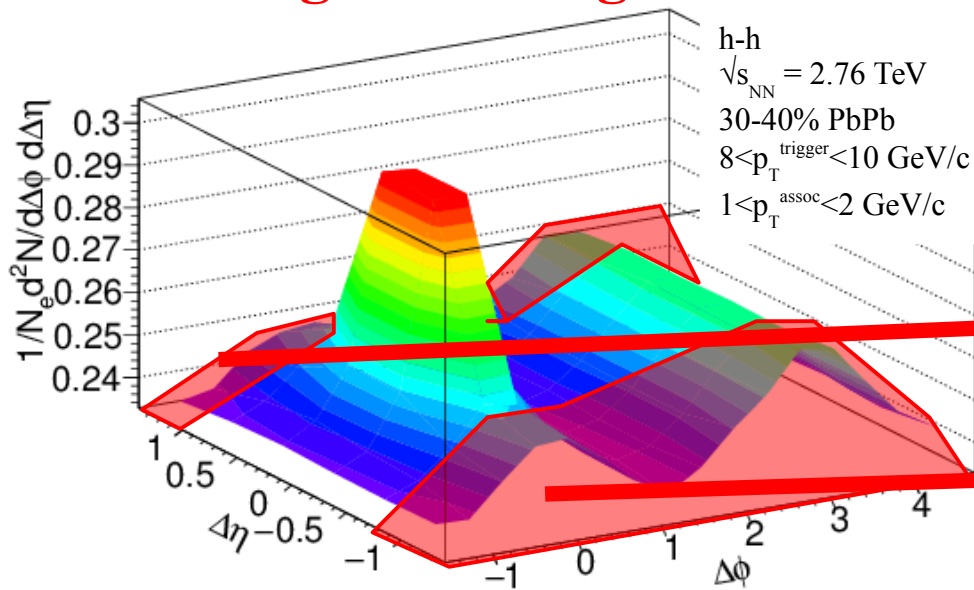
Standard ZYA1 = Zero Yield at  $\Delta\Phi=1$

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

# Near-Side Fit (NSF) method

No reaction plane dependence

Signal+background

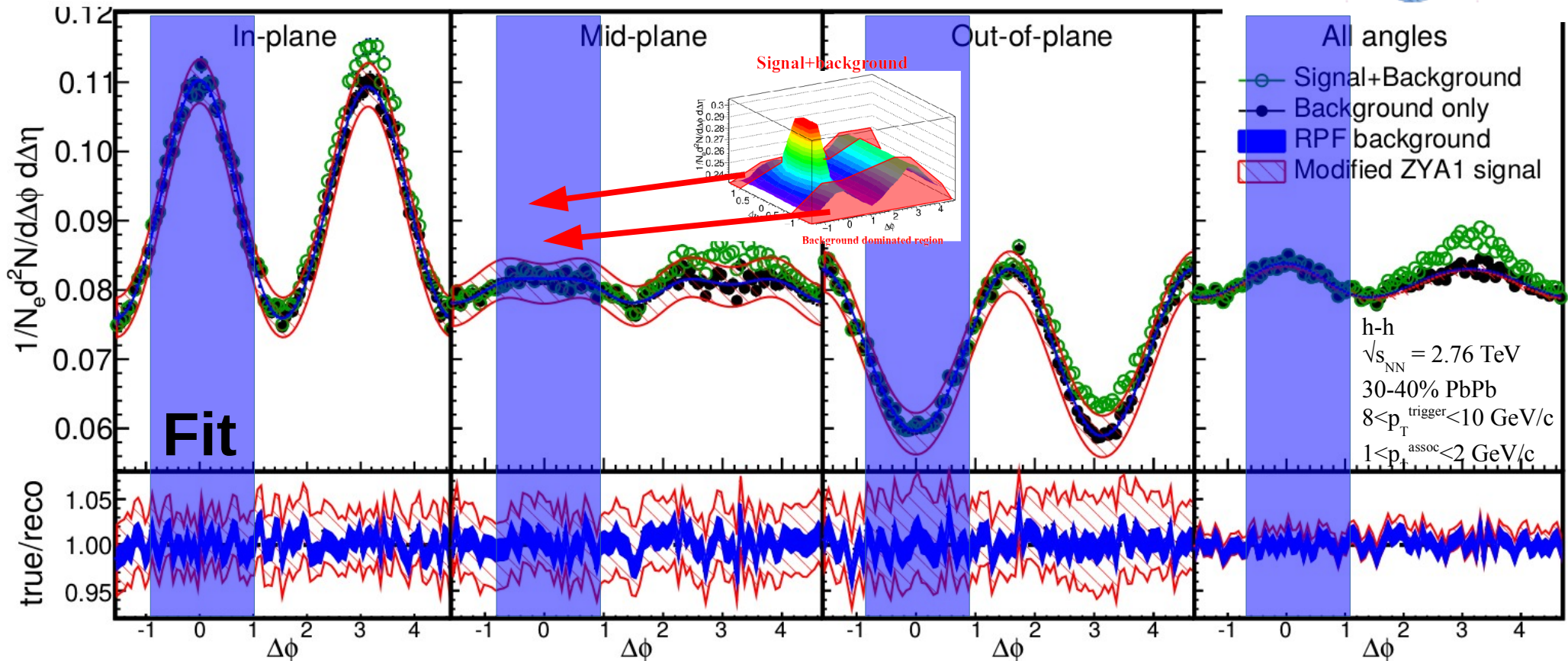
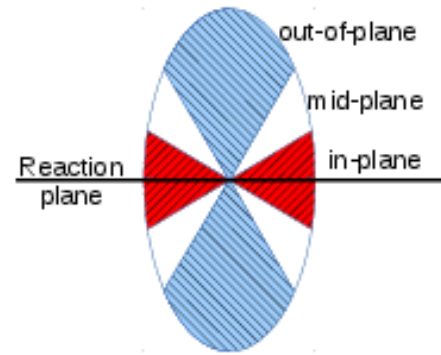


- Project signal+background over  $1.0 < |\Delta\eta| < 1.4$
- Fit background in  $|\Delta\phi| < 1$
- **Not reliable over narrower  $\Delta\phi$  region**

# Adding reaction plane dependence

# Reaction Plane Fit (RPF) method

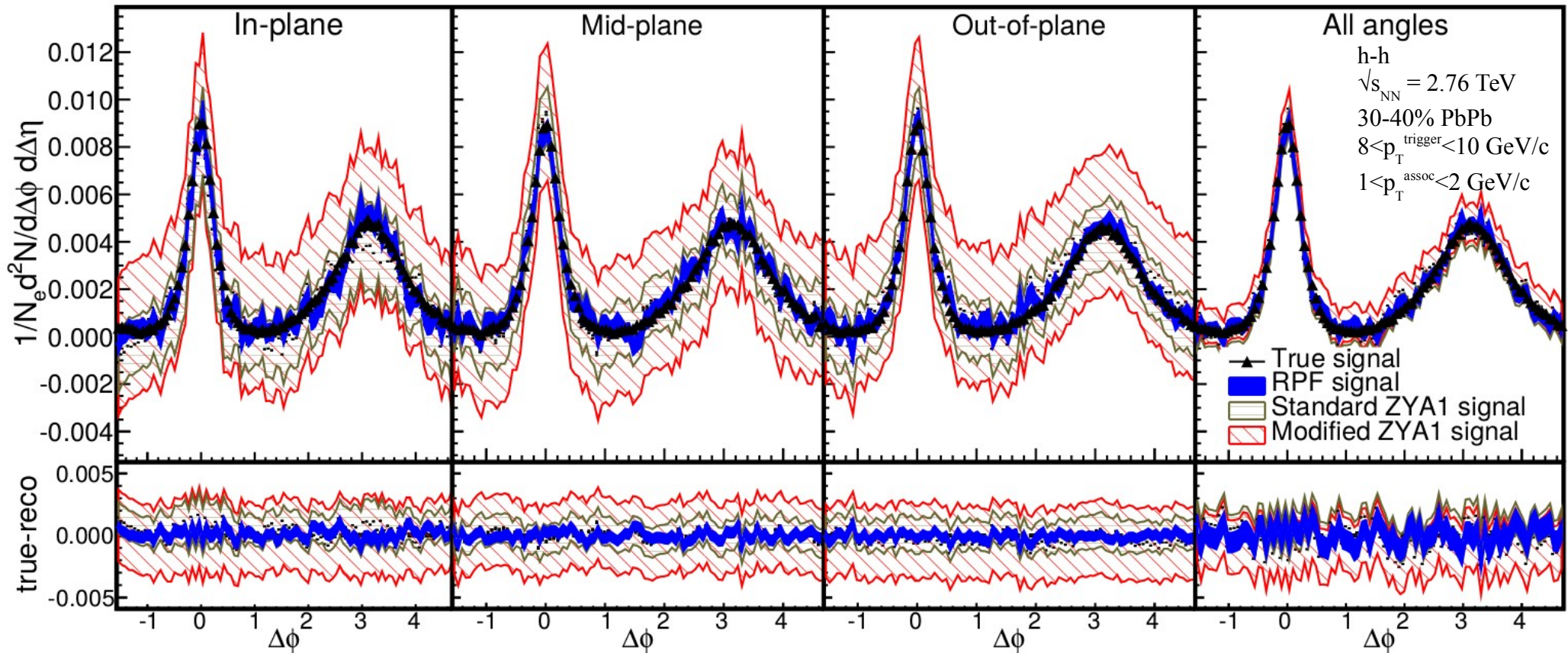
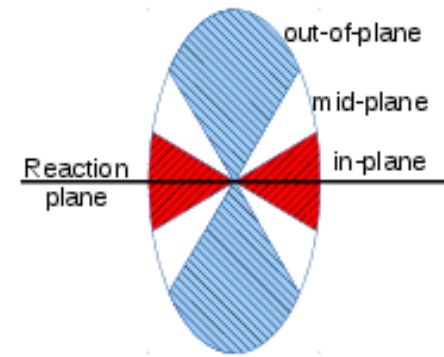
30-40% central



- Project signal+background over  $1.0 < |\Delta\eta| < 1.4$
- Fit background in  $|\Delta\phi| < 1$  including reaction plane dependence
- $v_n$  and  $B$  extracted

# Reaction Plane Fit (RPF) method

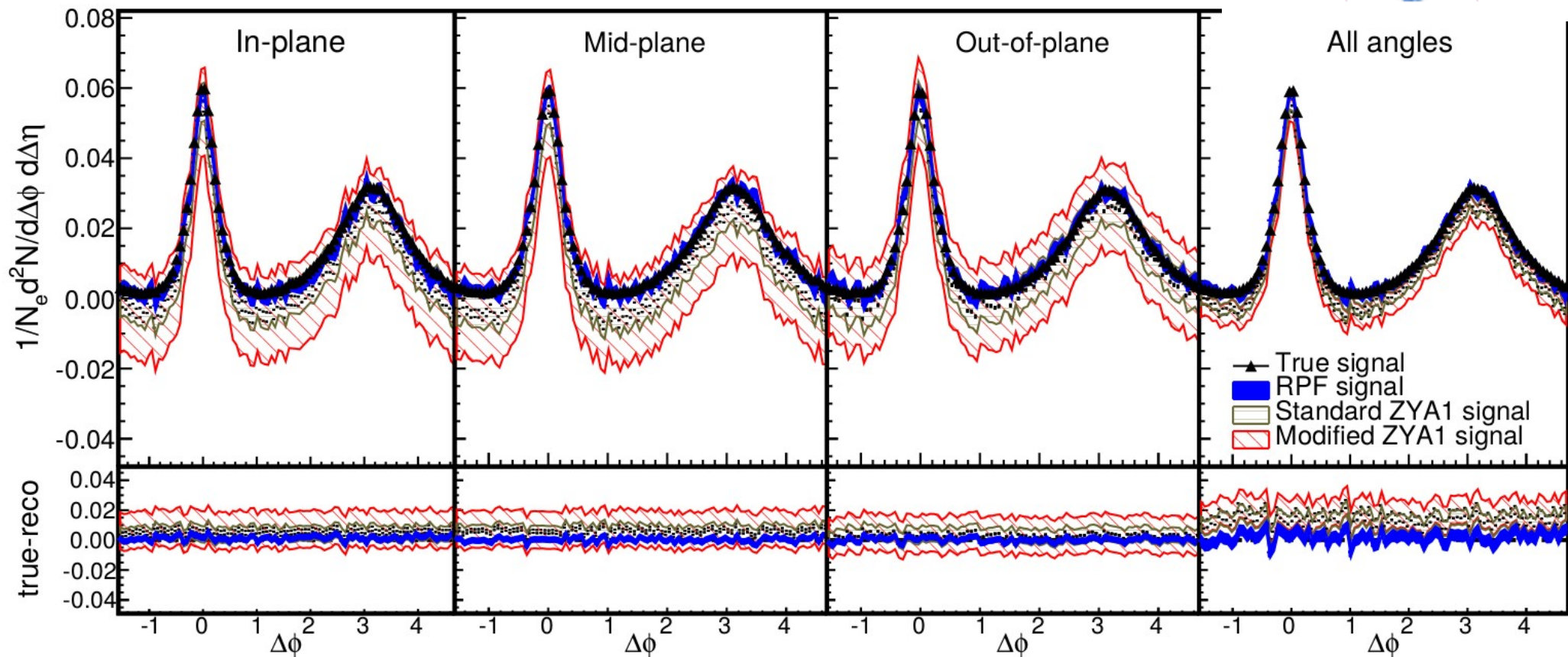
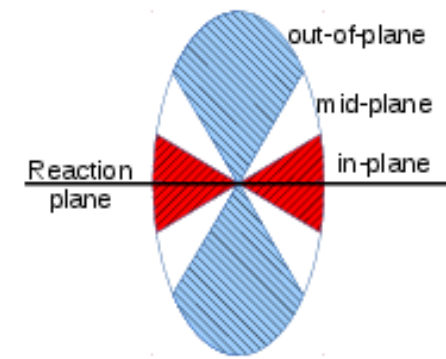
30-40% central



	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 ( $ \Delta\phi  < \pi/2$ )	$5.5 \pm 0.4$	$5.7 \pm 0.3$	$5.9 \pm 0.3$	$17.0 \pm 0.7$	$6.6 \pm 0.4$	$6.8 \pm 0.3$	$6.8 \pm 0.3$	$20.1 \pm 0.7$
RPF ( $ \Delta\phi  < 1$ )	$5.7 \pm 0.4$	$5.8 \pm 0.4$	$5.9 \pm 0.3$	$17.4 \pm 0.7$	$6.8 \pm 0.4$	$6.8 \pm 0.4$	$6.8 \pm 0.3$	$20.4 \pm 0.7$

# Reaction Plane Fit (RPF) method

0-10% central



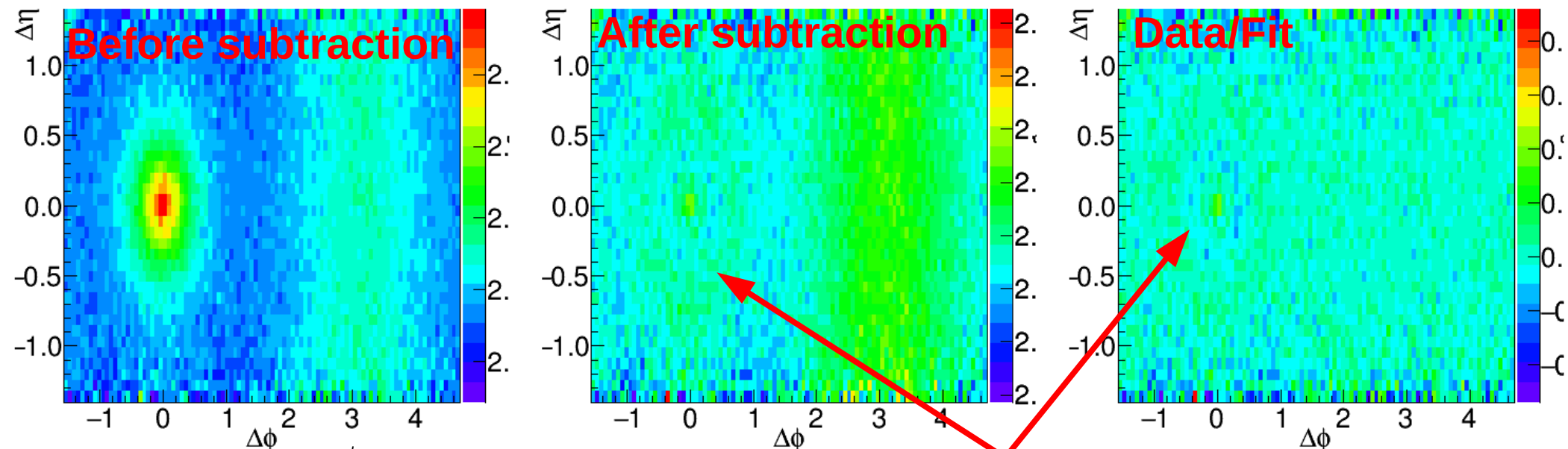
- Also works for central collisions even though reaction plane resolution is not great

h-h  
 $\sqrt{s_{NN}} = 2.76$  TeV  
0-10% PbPb  
 $8 < p_T^{\text{trigger}} < 10$  GeV/c  
 $1 < p_T^{\text{assoc}} < 2$  GeV/c

Next steps...

# Going to lower momenta, medium modifications

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



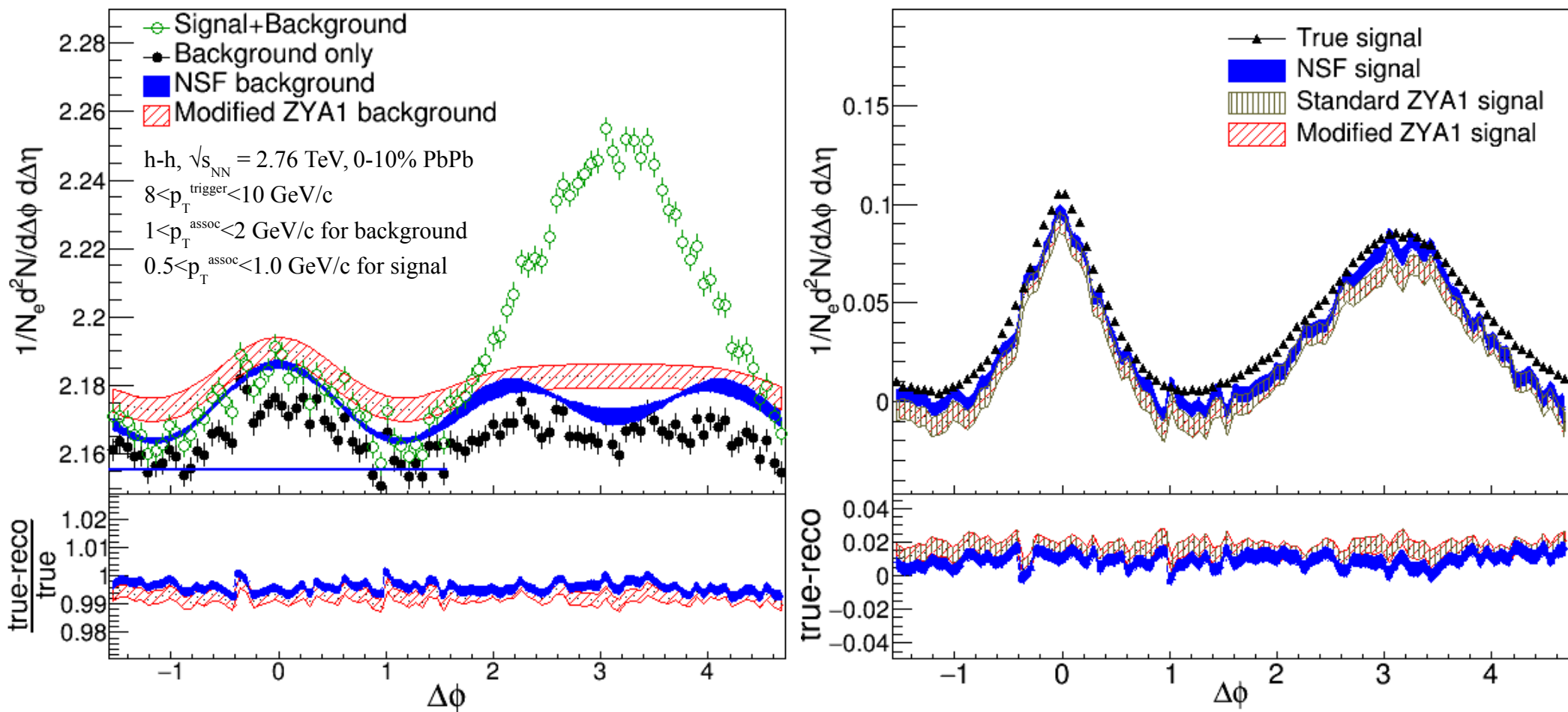
h-h,  $\sqrt{s_{NN}} = 2.76$  TeV, 0-10% PbPb

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

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

**Structure from  
imperfect fit**

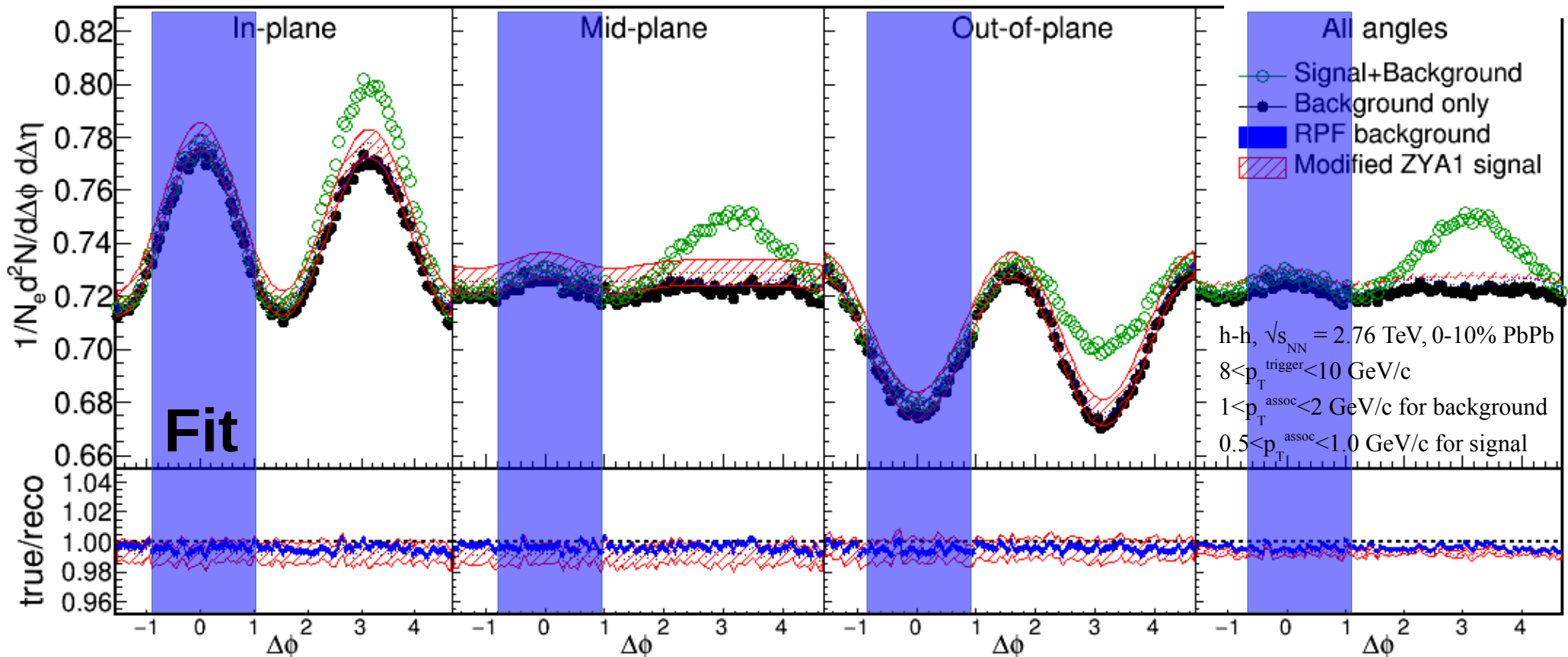
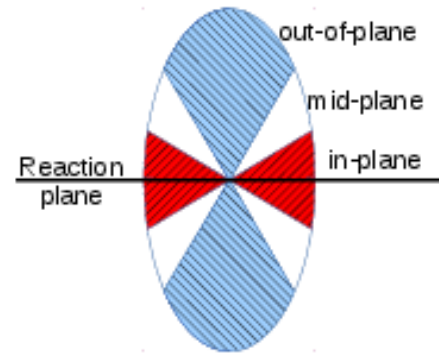
# NSF method



- Project signal+background over  $0.0 < |\Delta\eta| < 1.4$
- Fit background in  $|\Delta\phi| < 1$  including reaction plane dependence
- Bias from residual contamination by near-side

# Reaction Plane Fit (RPF) method

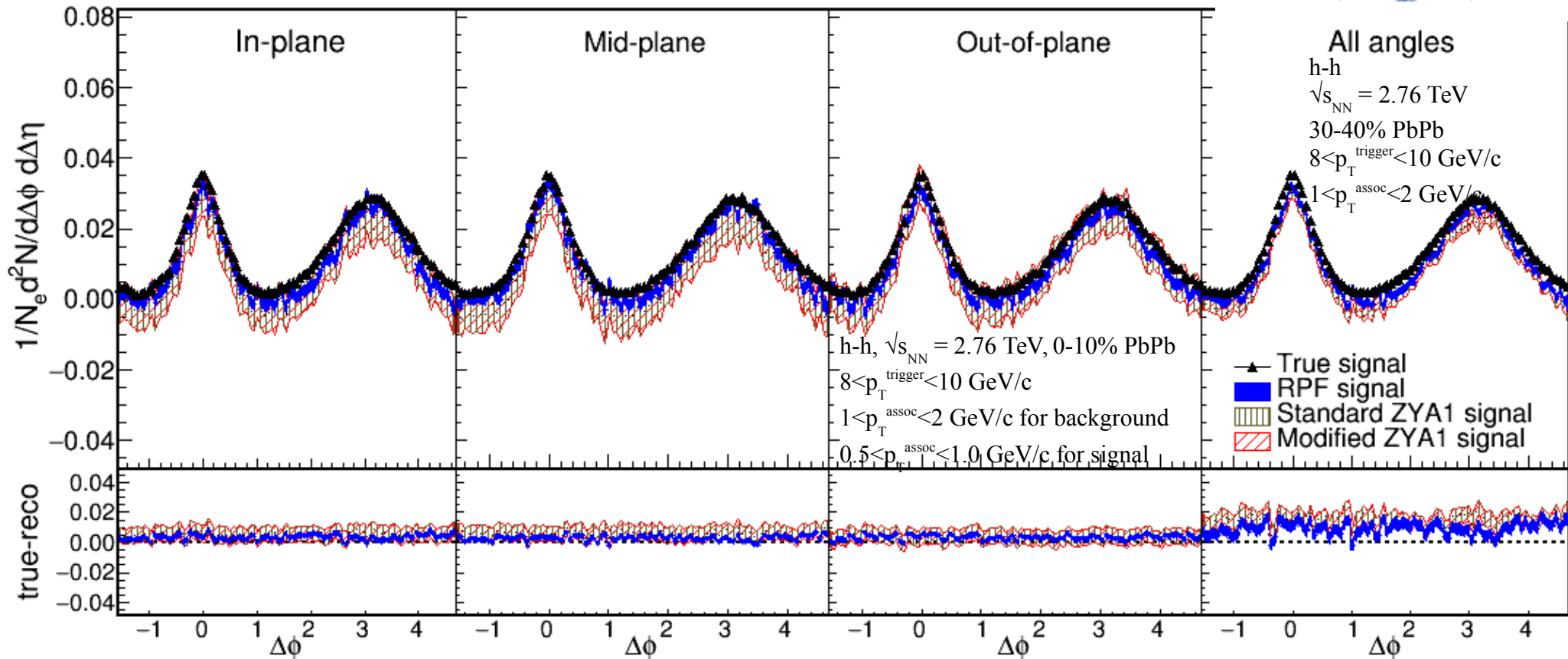
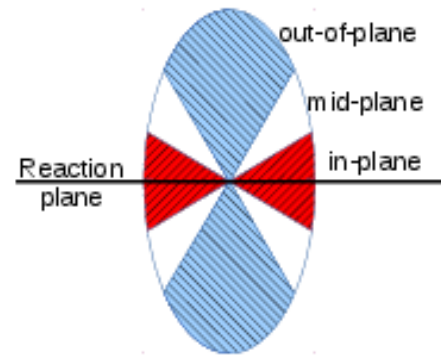
30-40% central



- Project signal+background over  $0.0 < |\Delta\eta| < 1.4$
- Fit background in  $|\Delta\phi| < 1$  including reaction plane dependence
- $v_n$  and B extracted

# Reaction Plane Fit (RPF) method

30-40% central



• **Works beautifully!**

# Remaining work

- Use proper background level
- Study impact of changing  $\Delta\eta_{\min}$ 
  - Background determined from  $\Delta\eta_{\min} < |\Delta\eta| < 1.4$
- Add RMS calculations with error

# Conclusions

- NSF & RPF methods better than ZYAM/ZYA1
- Benefits of RPF & NSF methods
  - Do not require independent measurements of  $v_n$ 
    - $v_n$  could be different for events with jets
      - Sample different events
      - Effective  $v_n$  is a weighted average over  $v_n$  due to jets and due to flow
    - $v_n$  is not available for jets for  $n > 2$
  - ZYAM/ZYA1 biased towards underestimating background
  - Extracts signal with lower error
- Can be extended to low momenta/modified jets!