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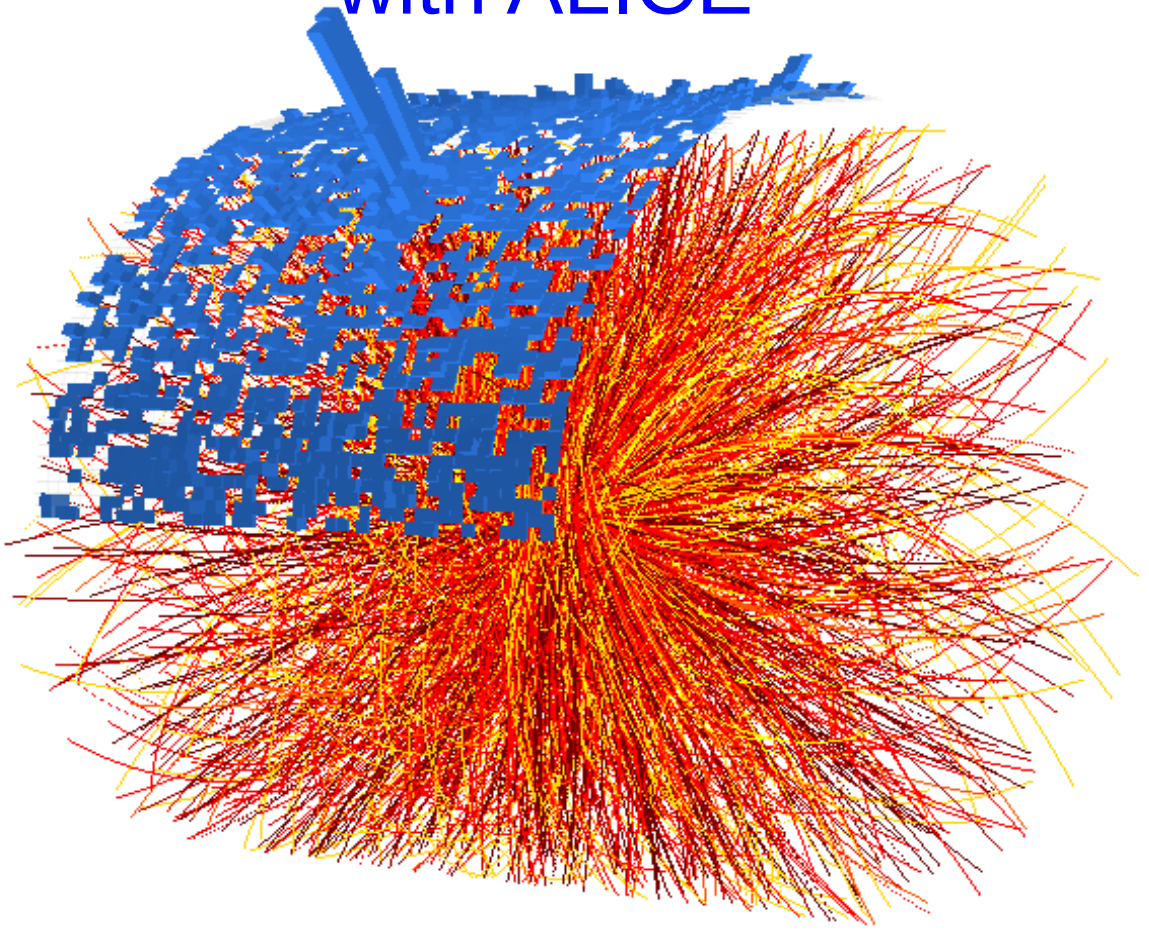
Exploring Jet-Hadron Correlations at the LHC with ALICE



On behalf of the ALICE collaboration

Hot Quarks: September 12th -17th 2016

ALICE

ALICE

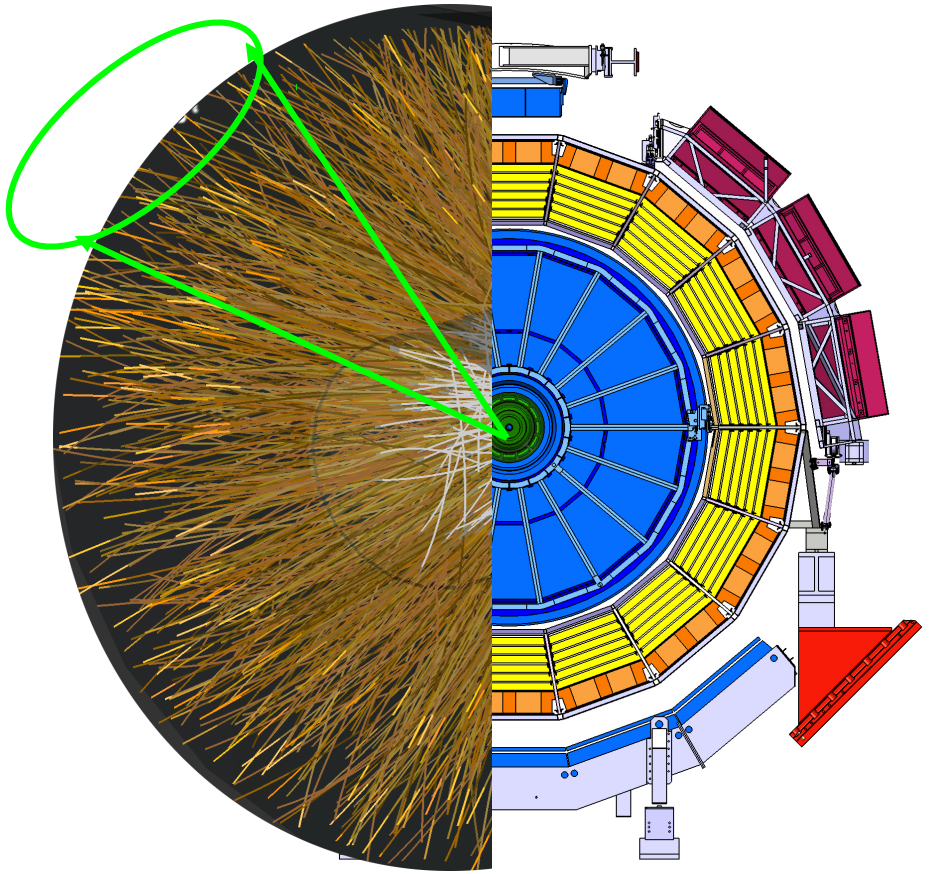
Outline

- Jets
- Jet-hadron motivations
- General analysis steps
- Event plane resolution
- Background subtraction methods
- Angular correlations
- Yields

Jets as probes in heavy-ion collisions

QGP is short lived → need a probe created in the collisions
Jets probe →modifications of jets provide a tool to study the hot and dense medium

- Suppression of the number of jets (compared to p+p or p+A)
  R_{AA} measurements
- Modification of the p_T or angular distributions of jet fragments
  Correlation measurements



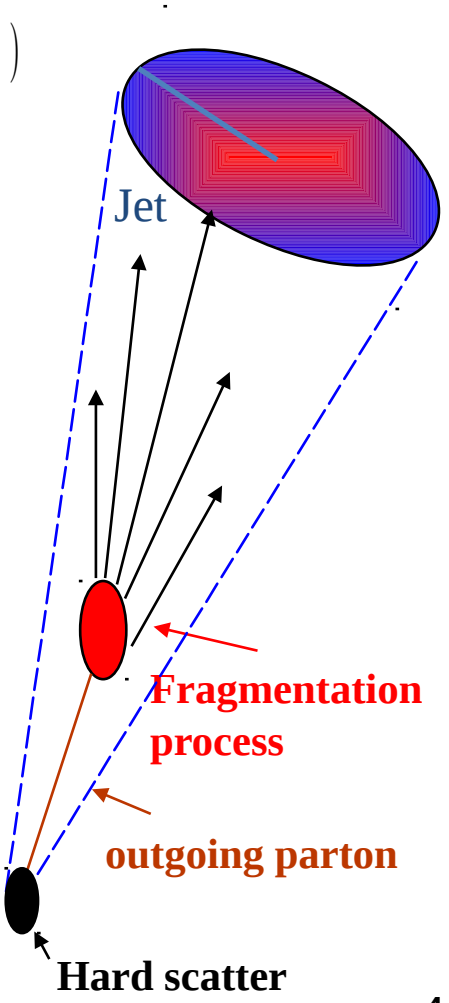
Jet definition

What are jets??

In theory (pQCD): "calculate" the jet from outgoing partons

In experiment: "measure" the jet

- remnants of quarks and gluons (fragments seen as tracks + clusters)
- reflect the kinematics and "topology" of partons (p_T, η, ϕ)



There is no unambiguous definition of what a jet is!

How do we make quantitative measurements?

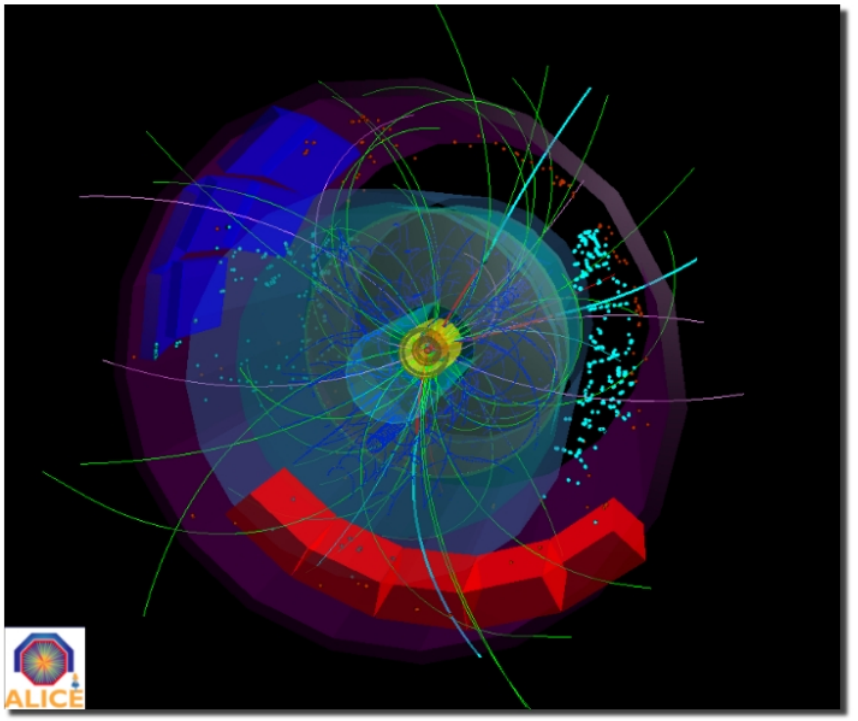
Need general definition to apply to theory calculations and experimental data: jet finding algorithm, its parameters, and a recombination scheme

Jet reconstruction

Jets reconstructed using FastJet package

arXiv:0802.1189v2

Jet algorithm: defines how tracks and clusters in detector (experiment) or partons (theory) are grouped into jets



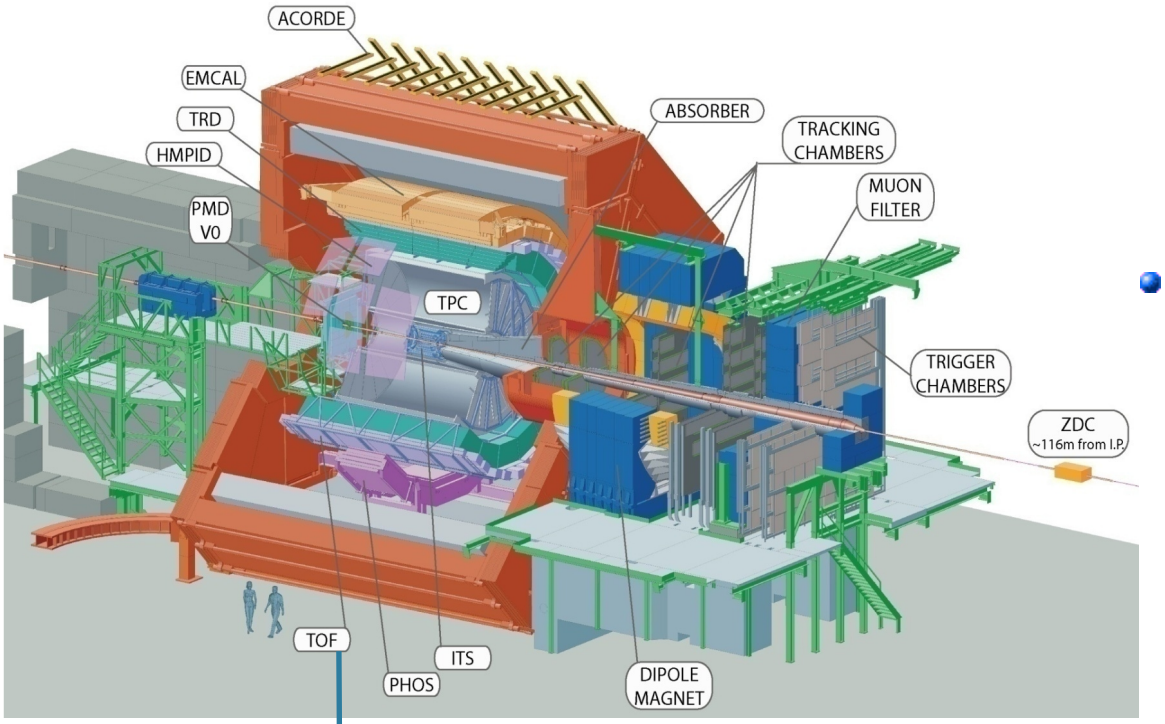
Two types:

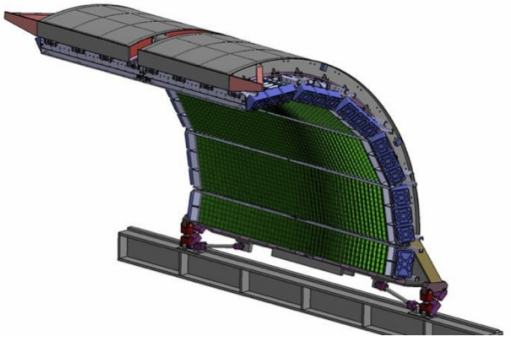
1) Cone
2) Sequential Recombination
[PLB 641 (2006) 57]

Sequential Recombination
k_T: (soft particles merged first)
Anti-k_T: (hard particles merged first)

- Pair-wise group together nearby objects until ALL particles are clustered into jet candidates
- R is resolution parameter → characteristic jet radius

Jets in ALICE





- EMCal is a Pb-scintillator sampling calorimeter which covers:
  - $|\eta| < 0.7$, $|\Delta\phi| = 107°$
  - tower $\Delta\eta \sim 0.014$, $\Delta\phi \sim 0.014$

Remove contamination from charged particles

- Tracking: $|\eta| < 0.9$, $0 < \phi < 2\pi$
  TPC: gas detector
  ITS: silicon detector

Charged constituents (tracks with p_T > 150 MeV/c)

Full JET

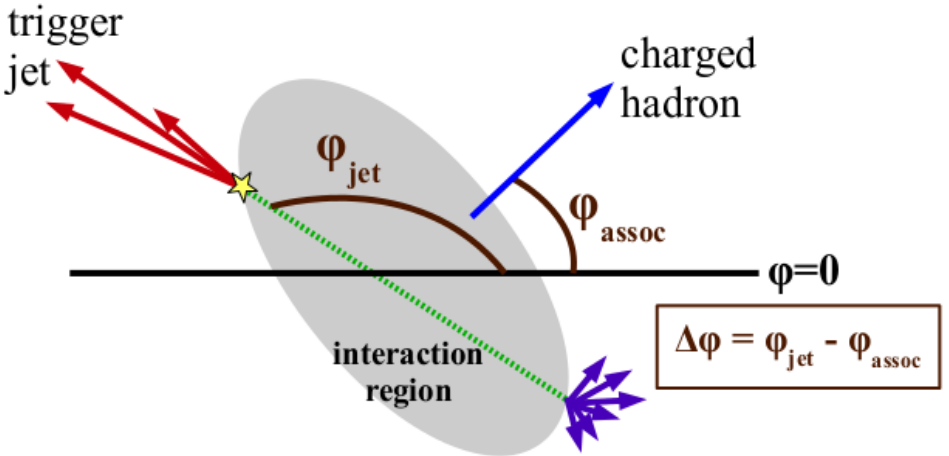
Neutral constituents (EMCal clusters with E_T > 300 MeV)

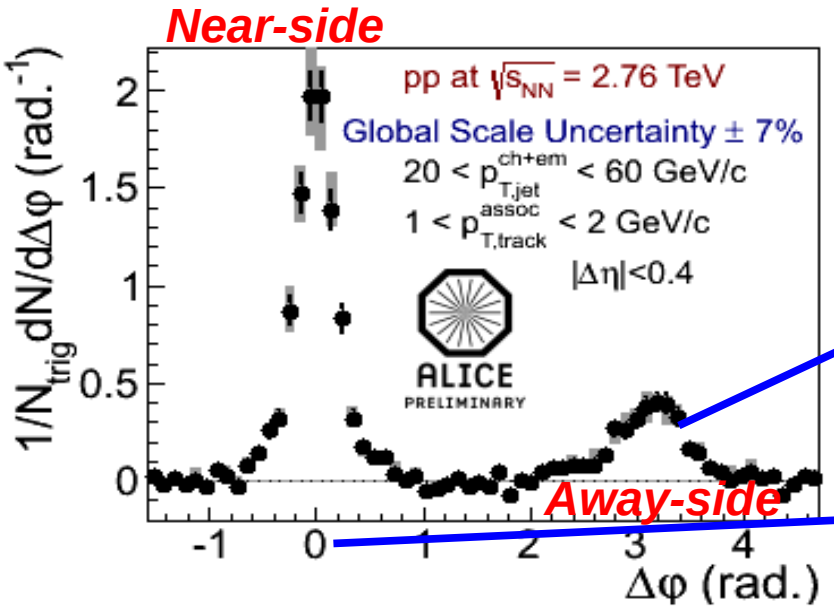
Full jet = charged + neutral

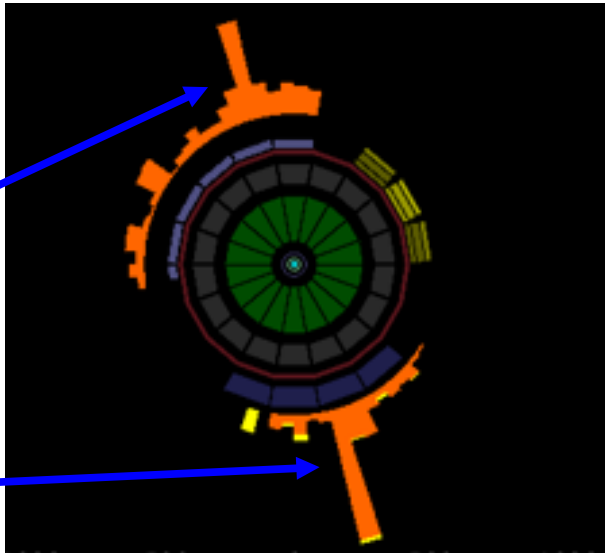
Jet-hadron correlations

Partons lose energy and are scattered as they traverse the medium

Study the azimuthal angular correlations of associated charged particles with respect to the axis of a trigger jet





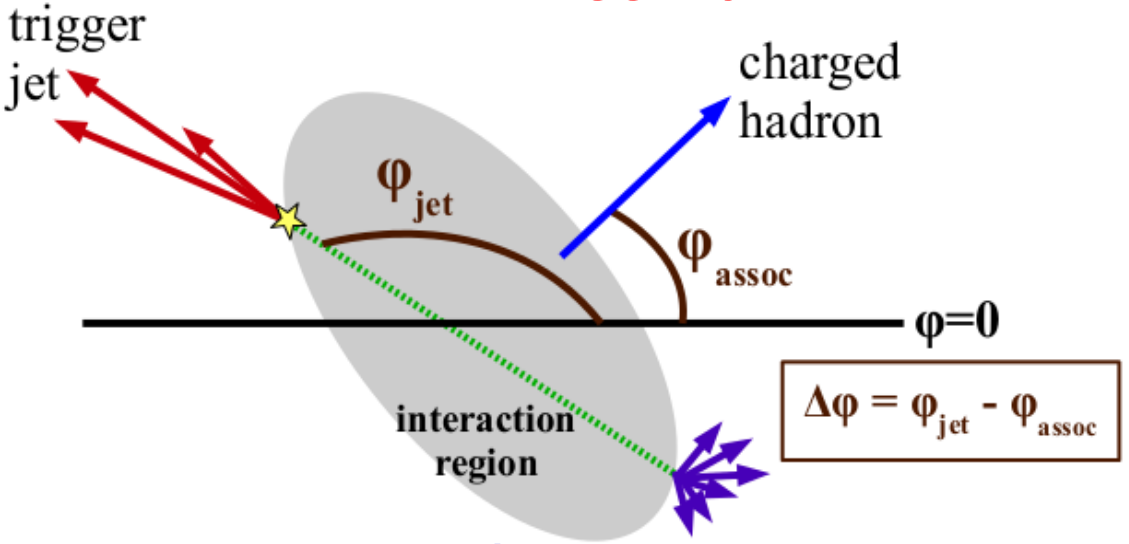


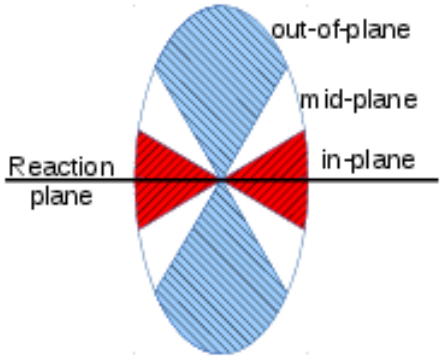
- Enables low p_T part of the jet to be studied
- Subtract background on average

Jet-hadron vs EP correlation motivations

parton energy loss depends on path length through medium
- jets will have a non-trivial correlation to the event plane

Fix trigger jet relative to the event plane





Study 2nd order event plane

Event Plane dependence

IN-plane: $0° < |\varphi_{jet} - \Psi_n| < 30°$

Middle-of-plane: $30° < |\varphi_{jet} - \Psi_n| < 60°$

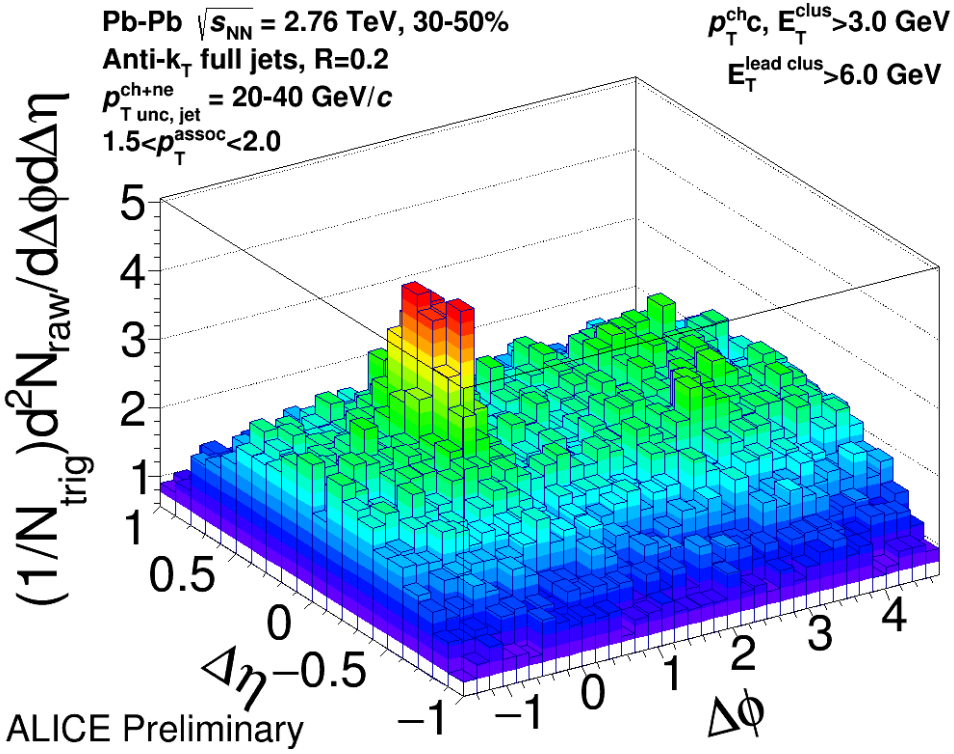
OUT-of-plane: $60° < |\varphi_{jet} - \Psi_n| < 90°$

Jet-Hadron correlations with event plane dependence: constrain path length of jets enabling measurements of lower momenta particles with higher precision

Event plane dependence of medium modifications?

Jet-hadron correlations measurement steps

Jet-hadron correlations analysis steps:



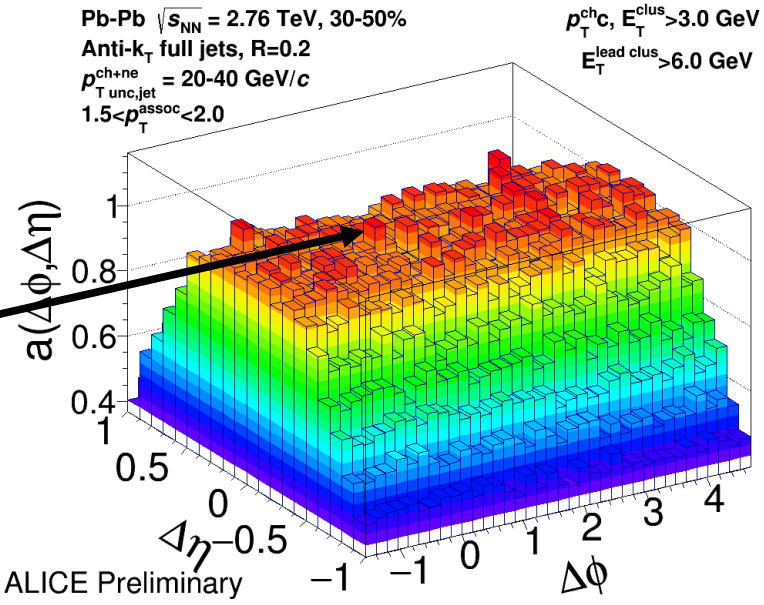
- Signal events: jet-hadron pairs from the same event
  - Generated in Δη and Δφ bins

Single track reconstruction efficiency applied:

$\epsilon(\eta, p_T)$ in centrality bins

Mixed events used for our **acceptance correction:**

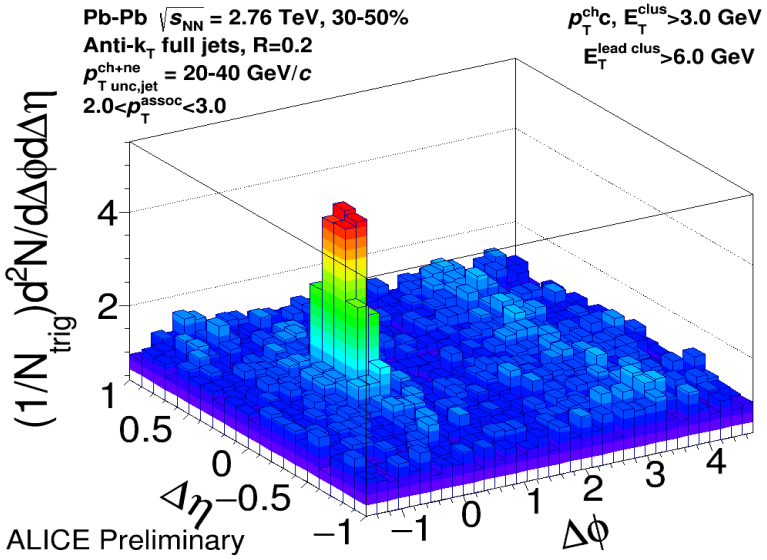
- Jets from triggered events correlated with charged hadrons of different events
- Will serve as correction for limited detector acceptance and efficiency



Normalize mixed events peak region to 1

Jet-hadron correlations analysis steps:

Correct same event pairs by mixed event pairs: (same events) / (mixed events)



- Correlation function = signal (jet) + underlying event
- Underlying event
  - Flat pedestal in pp
  - Flow modulated (initial collision geometry) in Heavy-ion collisions

- Subtract (event plane dependent) background from correlation

of form: $B(1 + 2v_2^{assoc}v_2^{jet}cos(2\Delta\phi) + 2v_3^{assoc}v_3^{jet}cos(3\Delta\phi) + ...)$

  - Shape is dependent on the event plane resolutions: R_n
  - Need to understand how jet v_n (n>2) affect background level

Removing background from correlations

Event plane dependence: background

- Our background shape in the correlations depends on angle relative to the event plane, will need a different formula for each orientation
- All combined reaction plane angles:

$$B\left(1+\sum v_n^t v_n^a \cos\left(n\Delta\phi\right)\right)$$

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

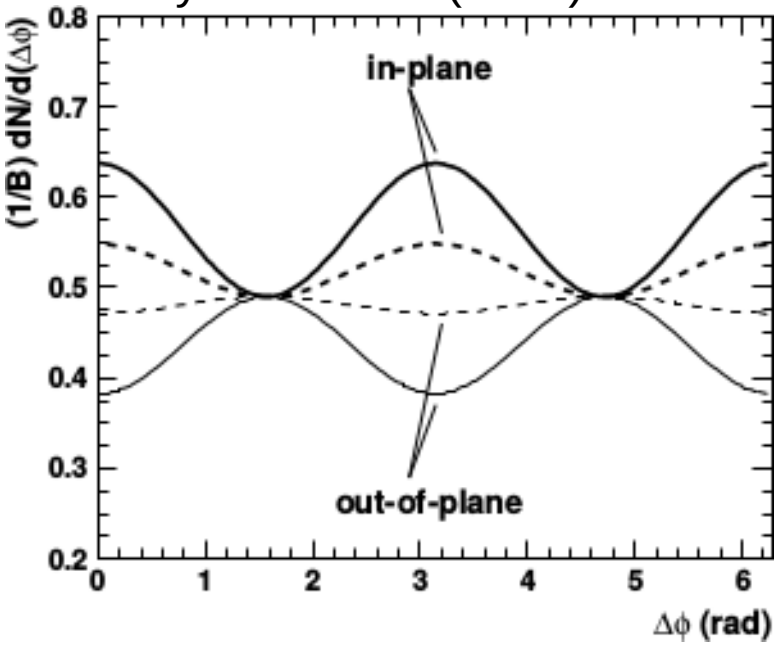
$$B = 1+\sum 2\, v_k^a v_k^{R,t} \cos\left(k\phi_S\right)\frac{\sin\left(kc\right)}{kc}R_n$$

  - Effective v_n modified

$$v_n^{R,t} = \frac{v_n+\cos\left(n\phi_S\right)\frac{\sin\left(nc\right)}{nc}R_n+\sum\left(v_{k+n}+v_{k-n}\right)\cos\left(k\phi_S\right)\frac{\sin\left(kc\right)}{kc}R_n}{1+\sum 2\, v_k \cos\left(k\phi_S\right)\frac{\sin\left(kc\right)}{kc}R_n}, n=even$$

φ_S is the angular threshold

Phys.Rev. C69 (2004) 021901



In-plane and **out-of-plane** correlation functions, ideal EP (FULL Lines) finite EP resolution (<cos(2ΔΨ)> = 0.3) (dashed Lines)

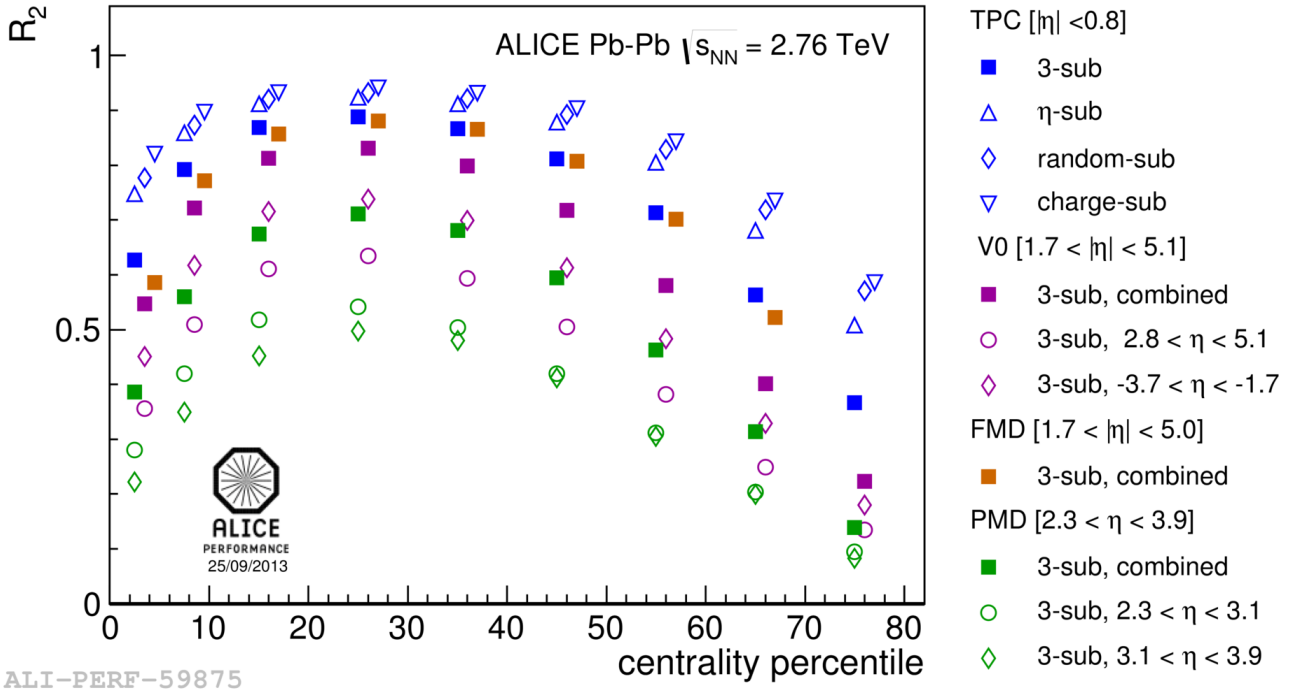
$$R_n = \left\langle \cos\left(n\left(\psi_{true}-\psi_{reco}\right)\right)\right\rangle$$

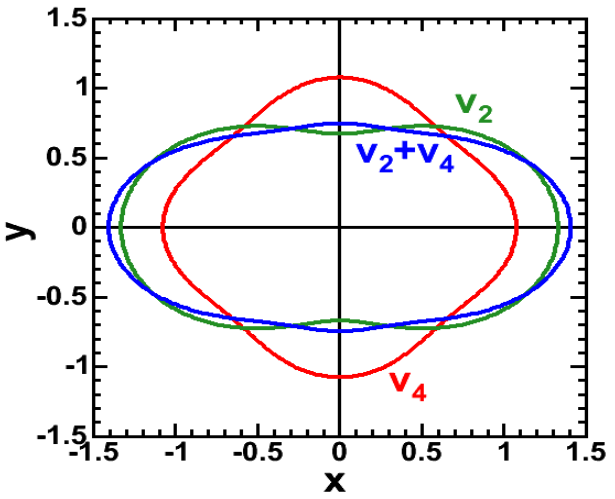
Reaction plane resolution

- Due to finite multiplicity of each event, there will be difference between reconstructed event plane and underlying symmetry plane: ψ_n
- Need to correct for this via event plane resolution R:

$$R = < \cos\left(n\left[\Psi_{EP} - \Psi_n\right]\right) >$$

- Used 3 sub-event method





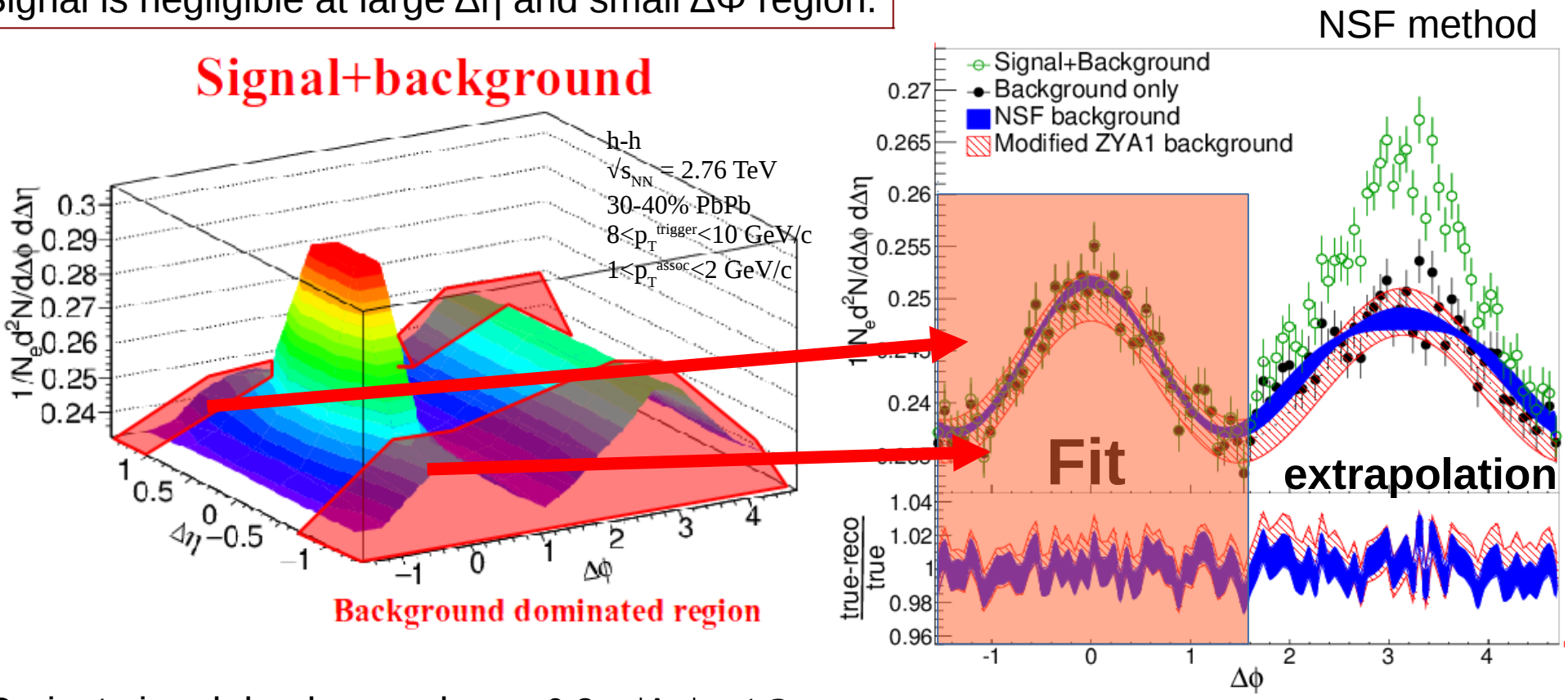
- R_2, R_4 correction to 2nd order EP needed

ALI-PERF-59875

Reaction plane fit (RPF) method

TOY MODEL

- Signal is negligible at large Δη and small ΔΦ region.



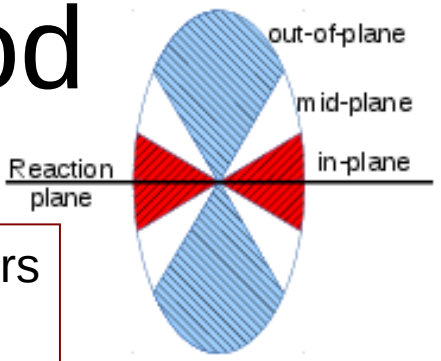
- Project signal+background over $0.8 < |\Delta\eta| < 1.2$
- Fit background in $|\Delta\varphi| < \pi/2$
- Fitting till 4th order v_n term, total 6 fit parameters: B, v_2^{assoc}, v_2^{trig}, $v_3^{assoc} \times v_3^{trig}$, v_4^{assoc}, and v_4^{trig}

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

Nattrass, Sharma, Mazer, Stuart, and Bejnood: (Phys. Rev. C 94, 011901(R) 2016)

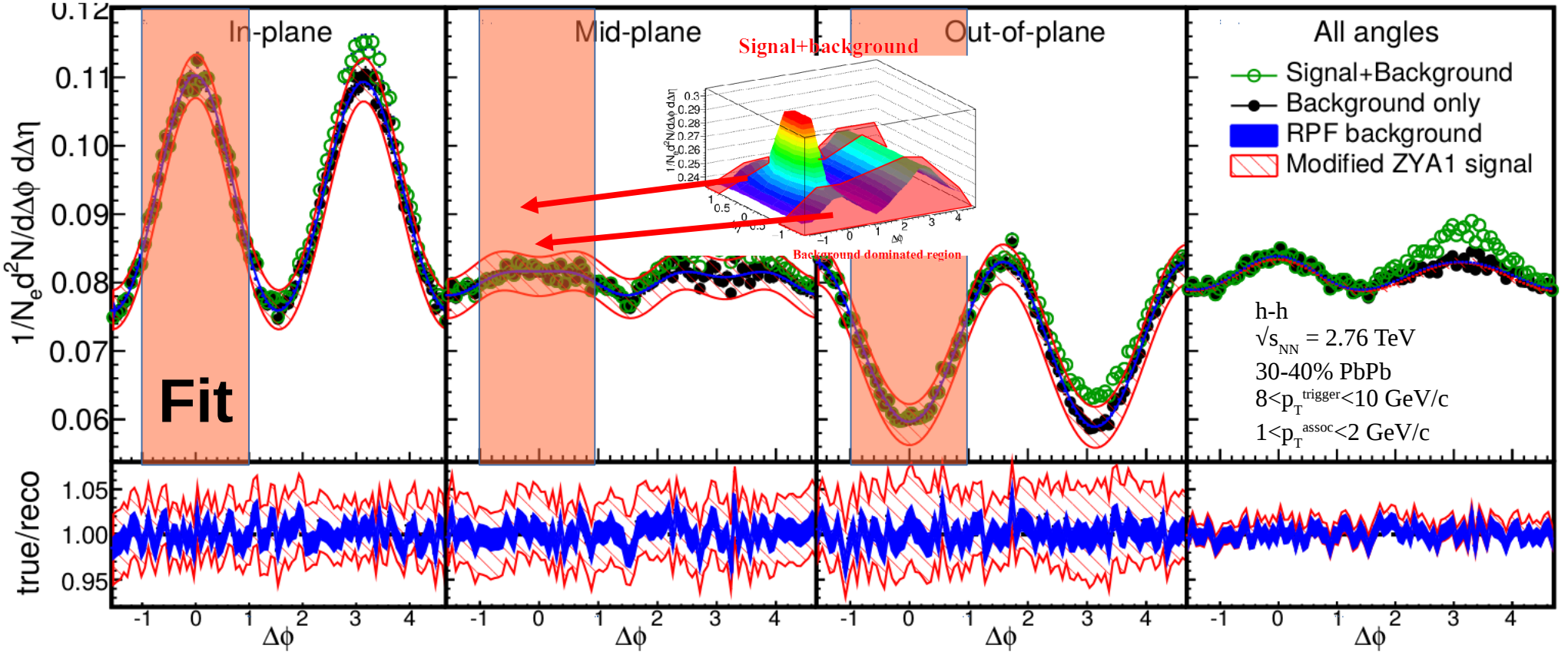
Reaction plane fit (RPF) method

30-40% central (simulation) TOY MODEL



- Each orientation has different functional form, but require same parameters
- More robust method, now have a higher constrained background

with more information going into fit



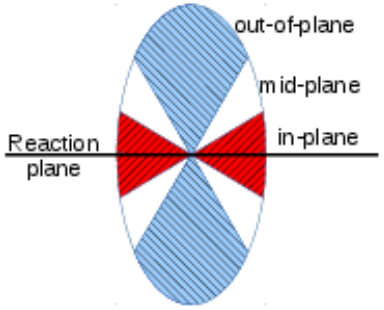
Project signal+background over $0.8<|\Delta\eta|<1.2$

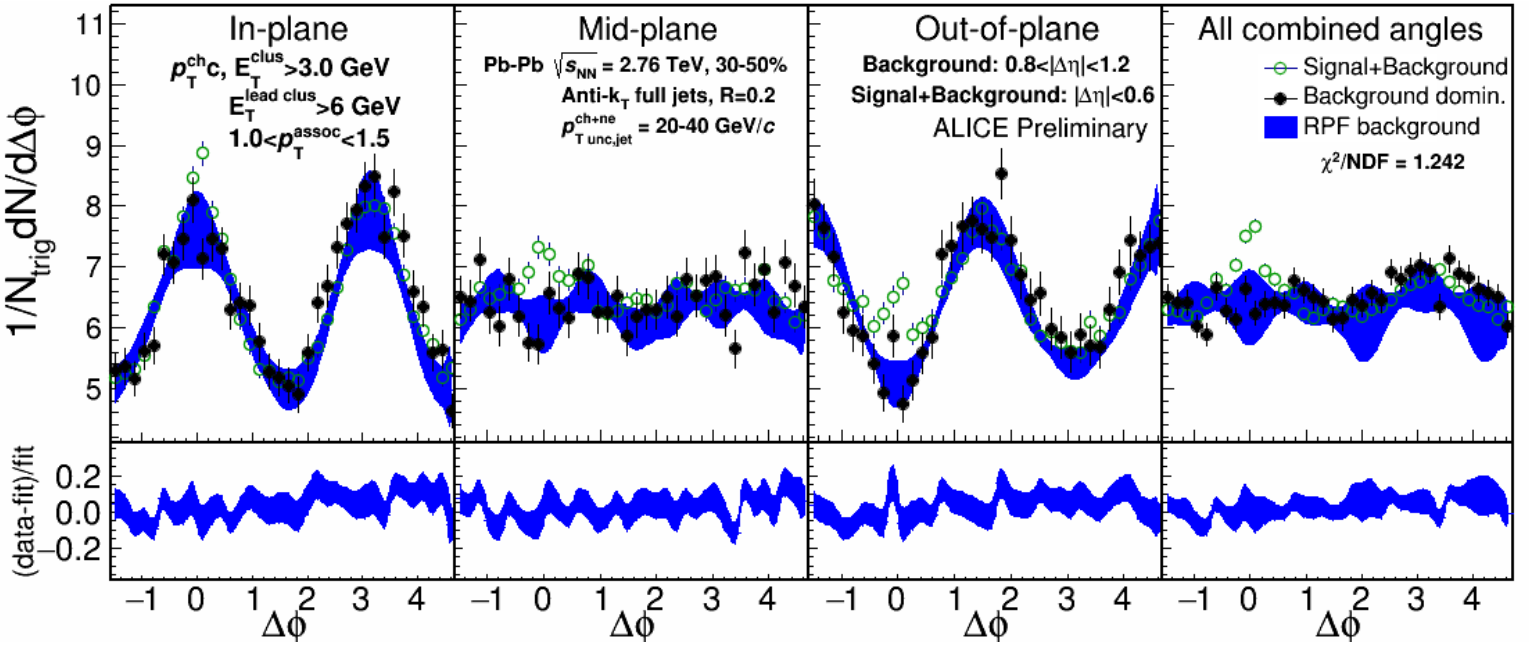
- v_n and B extracted
- Fewer assumptions and bias than ZYAM while having much smaller errors

Correlation Results

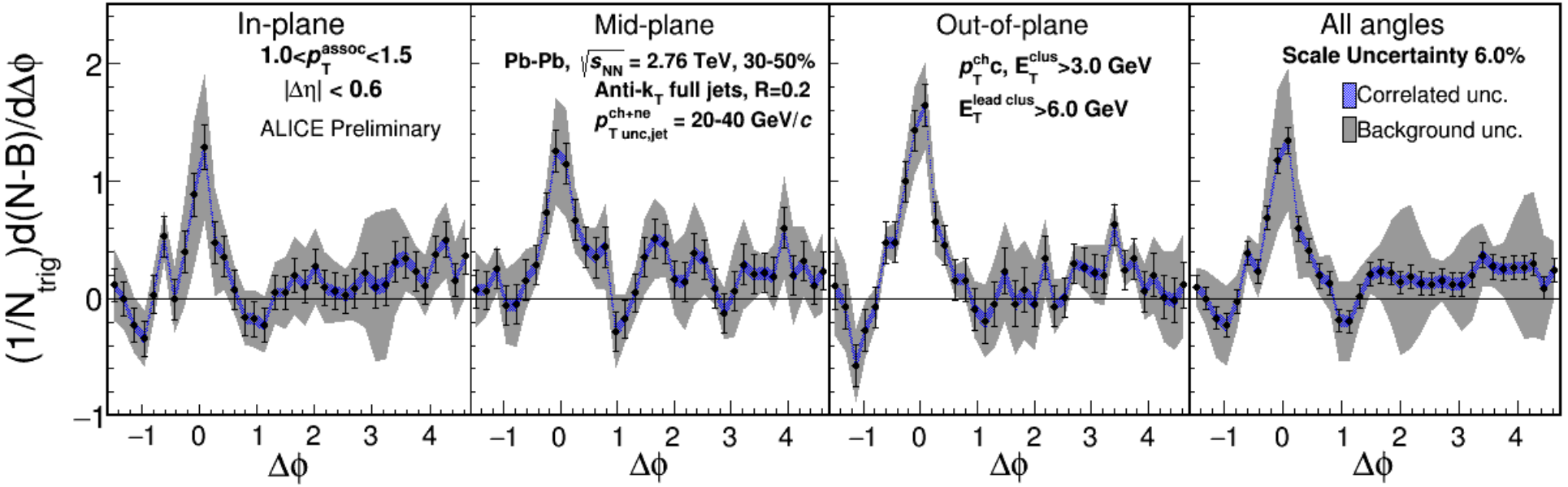
1.0-1.5 GeV/c p_T^{assoc}

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





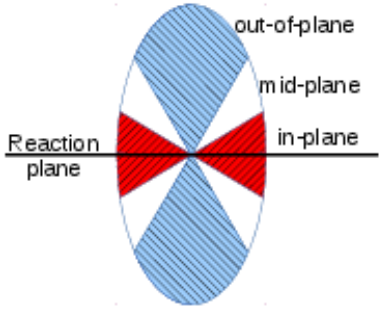
[Correlation function]

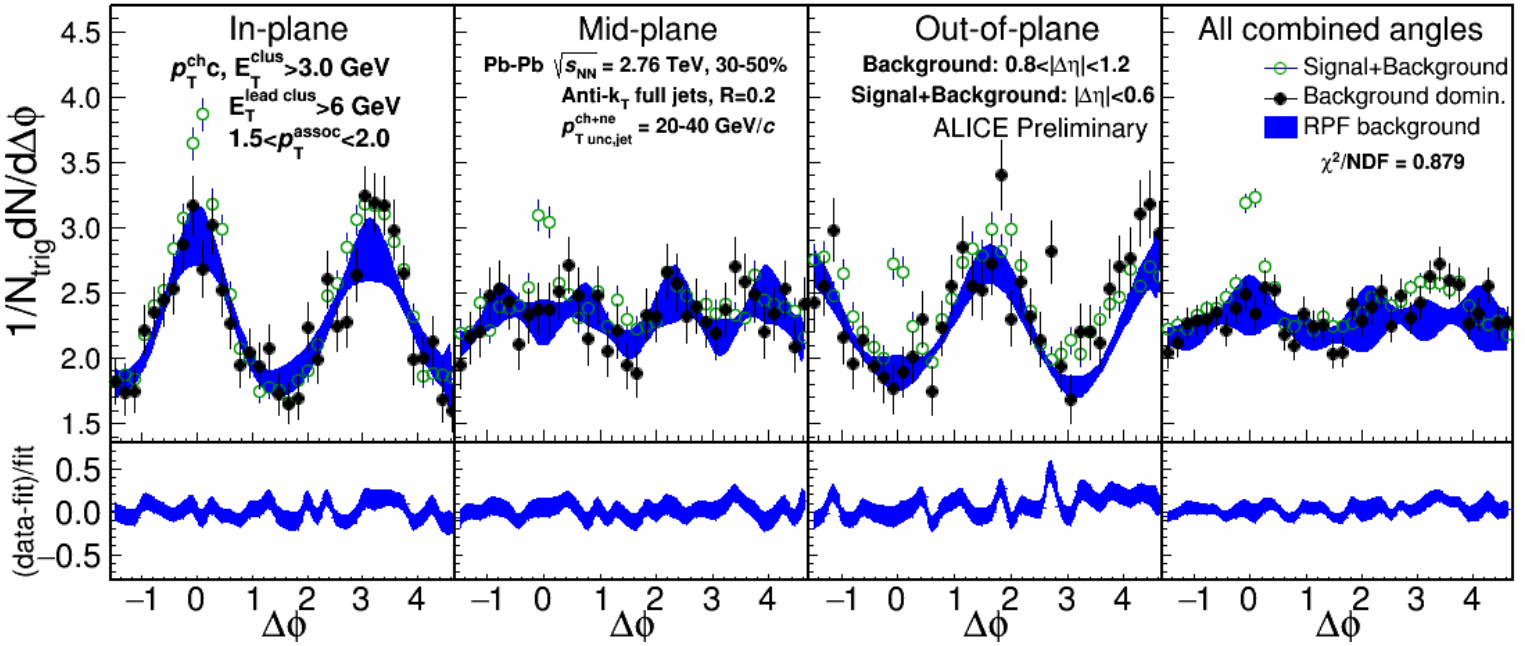


- Uncertainties dominated by statistics
- Background uncertainty is non-trivially correlated point-to-point

1.5-2.0 GeV/c p_T^{assoc}

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





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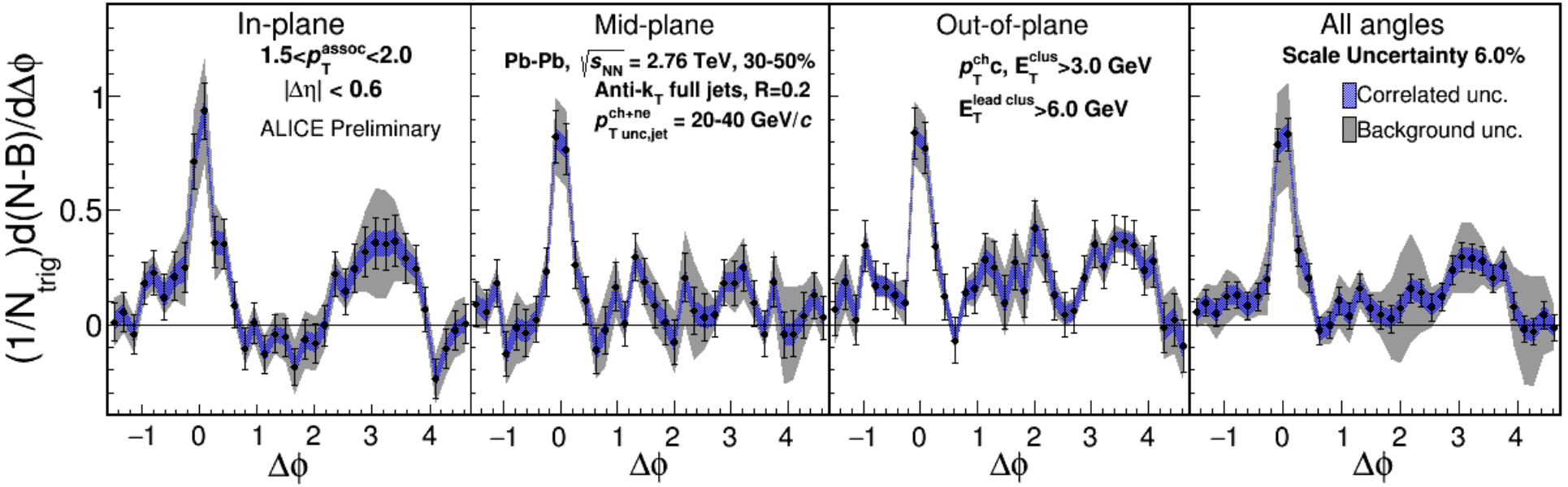
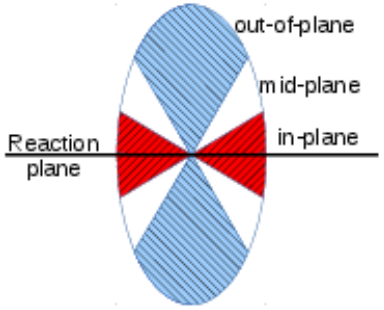
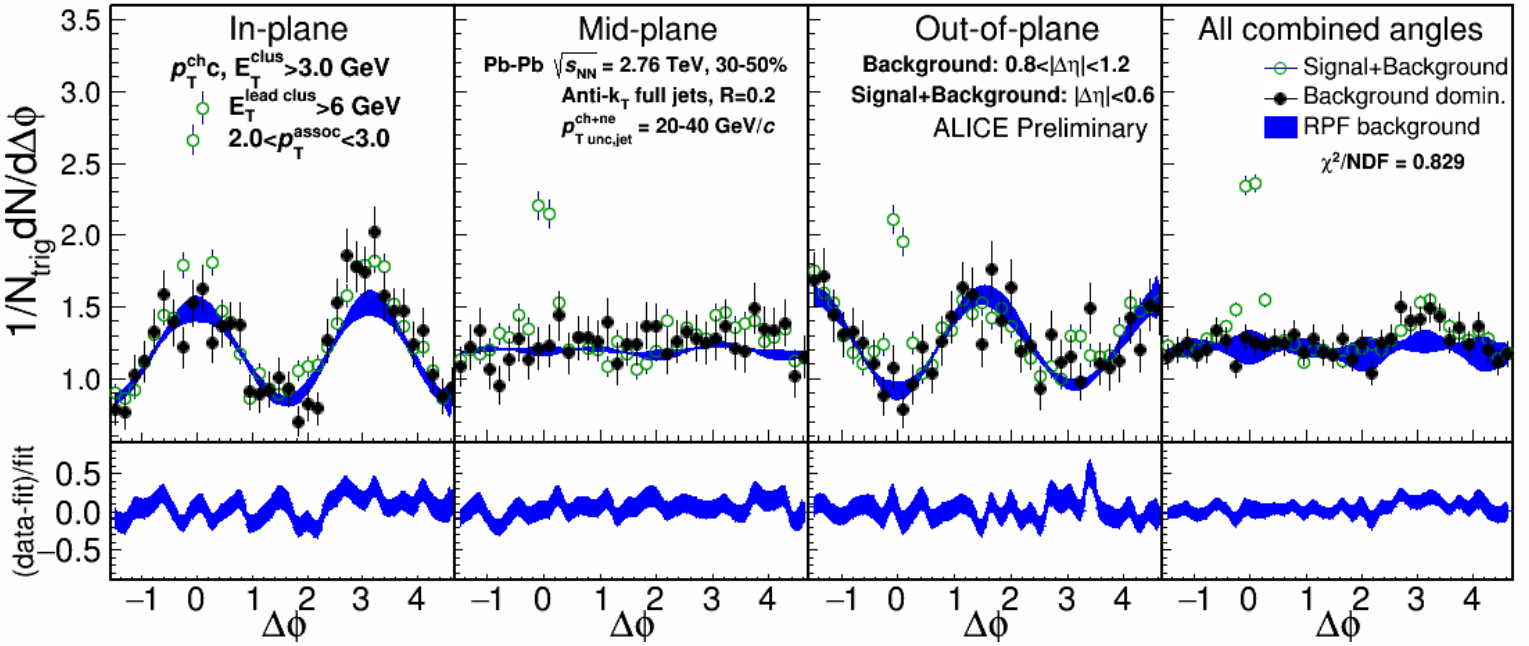


- v_3 and v_4 components important
- Background uncertainty is non-trivially correlated point-to-point

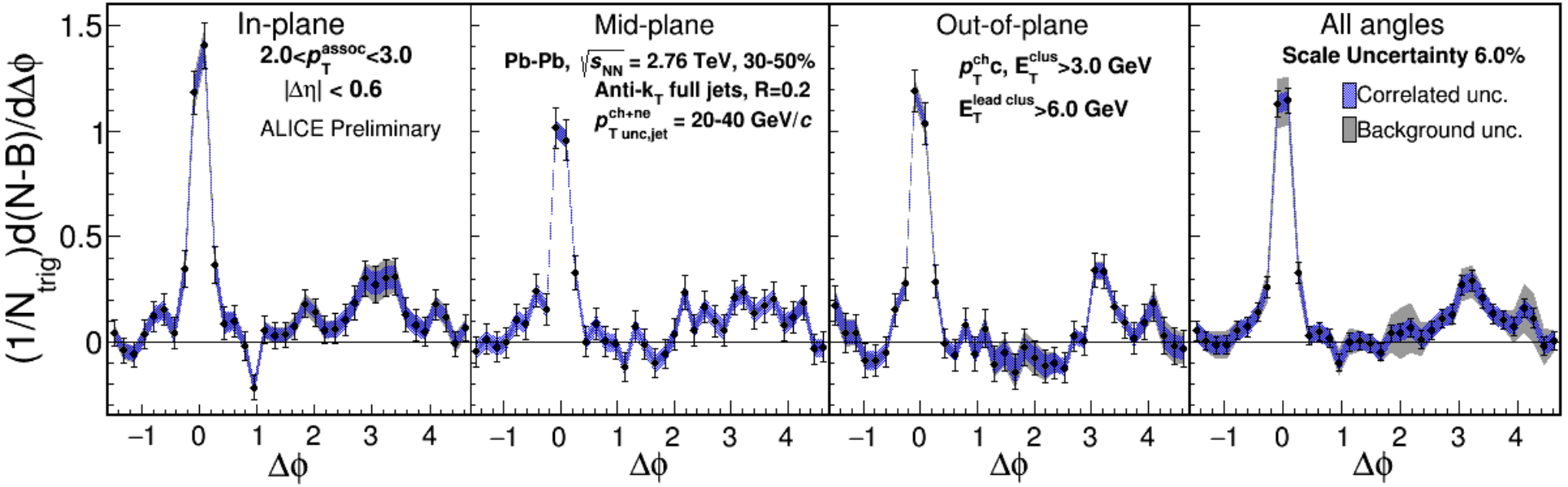
2.0-3.0 GeV/c p_T^{assoc}

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





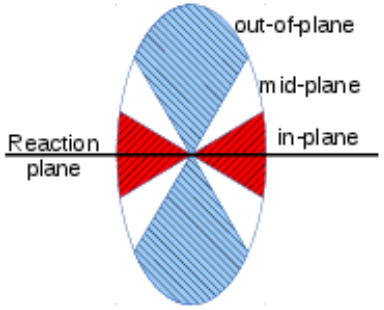
[Correlation function]

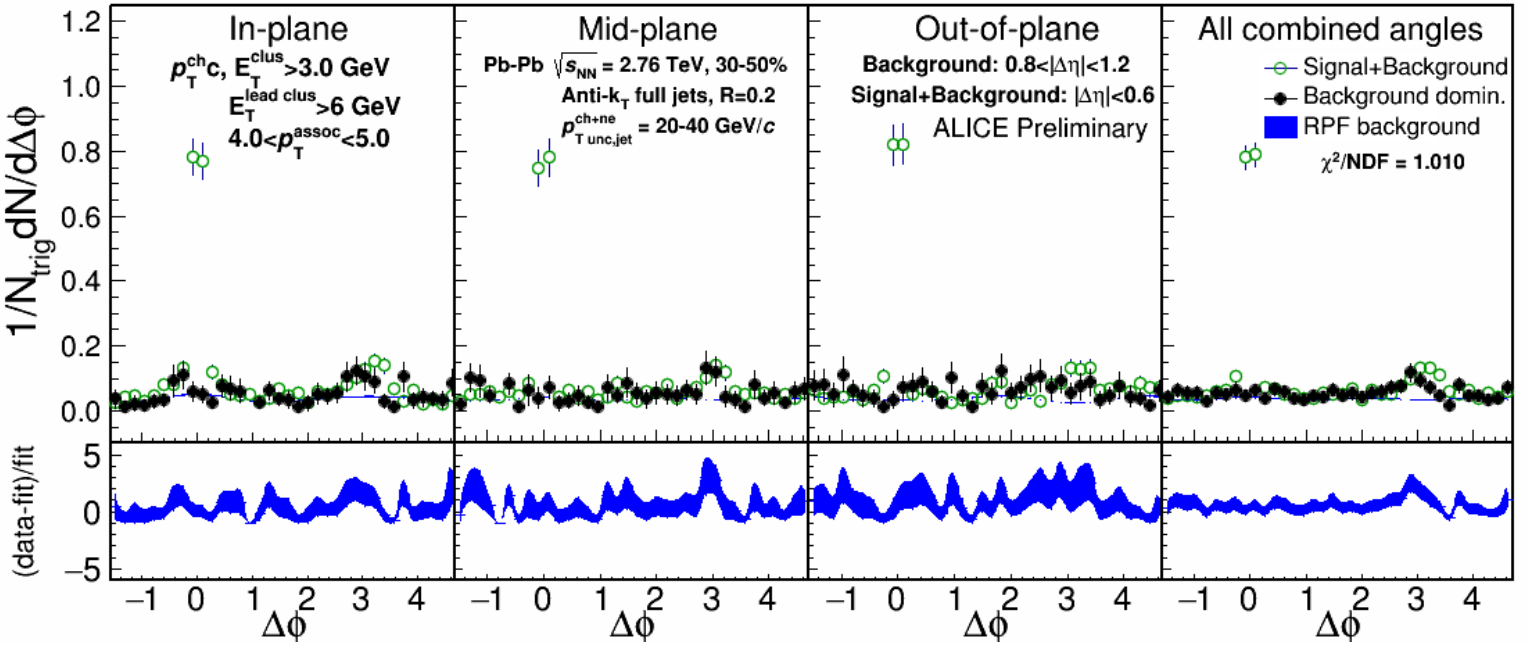


- Away side clearly there and suppressed

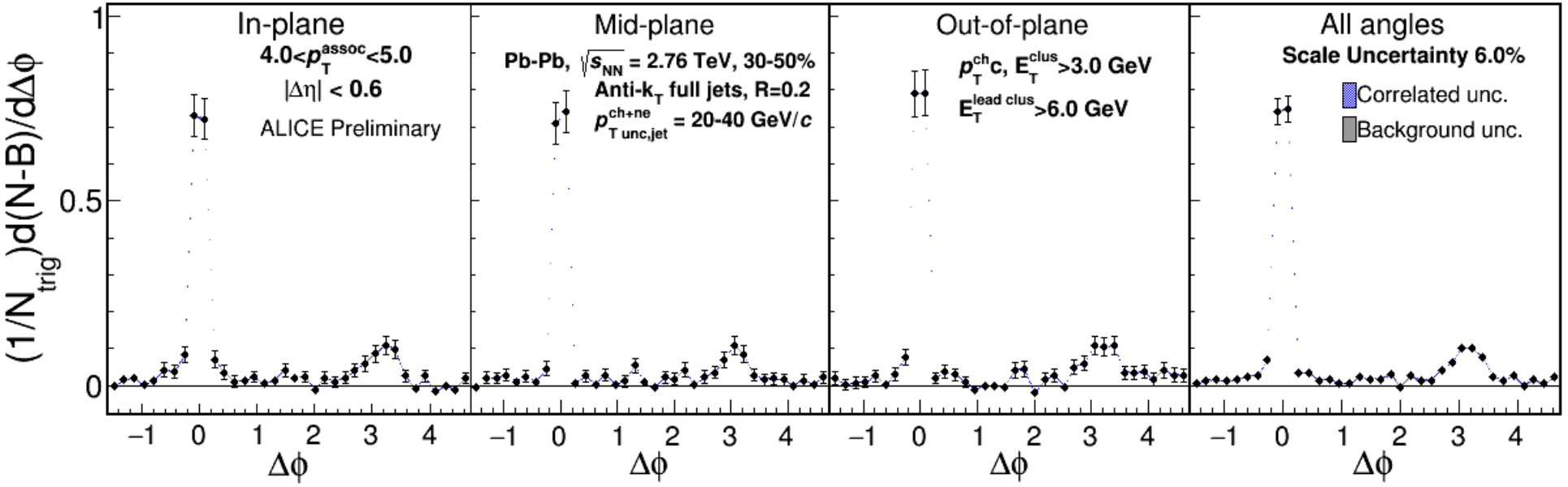
4.0-5.0 GeV/c p_T^{assoc}

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





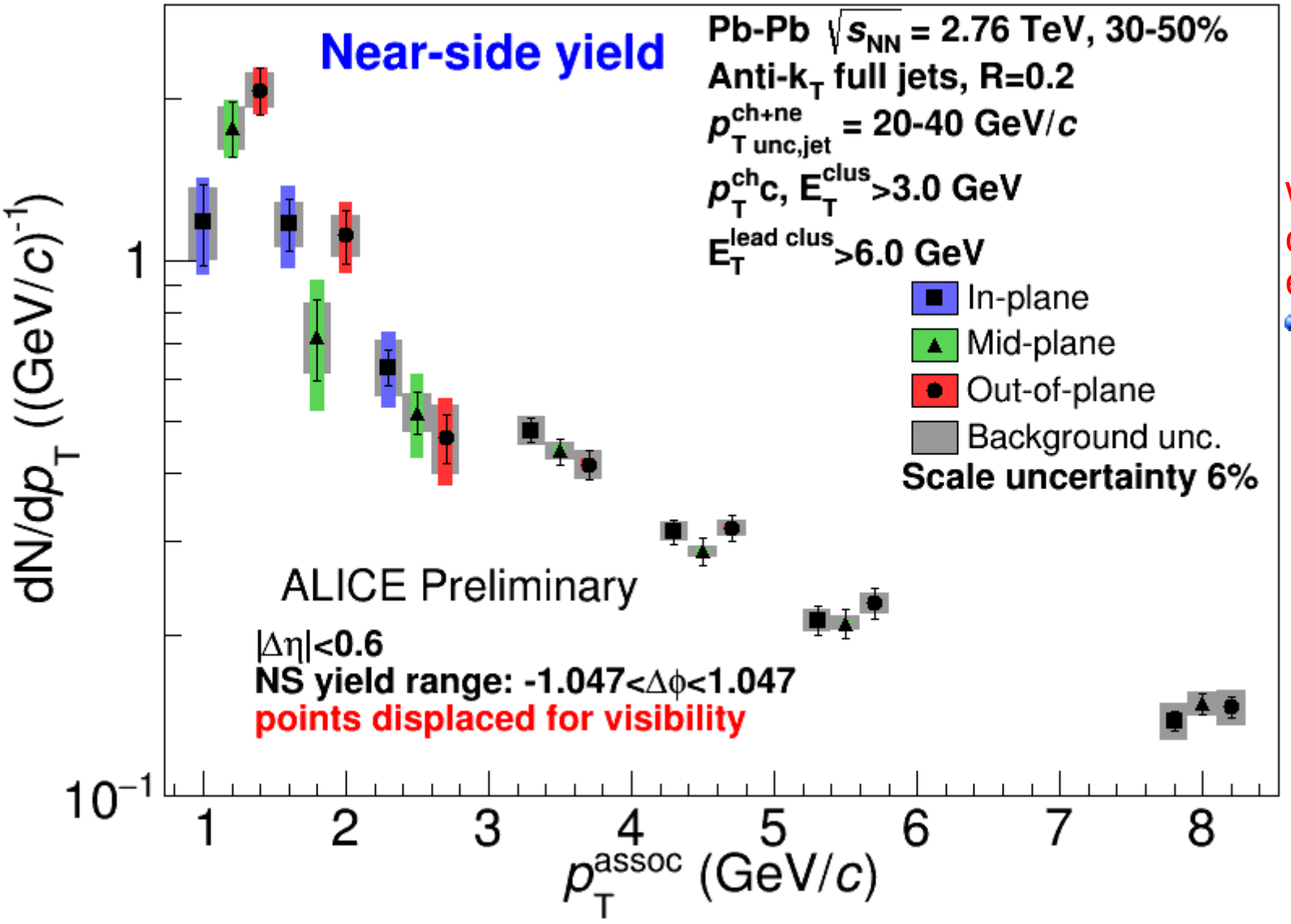
Correlation function



- Background level negligible

Near-side jet yields vs EP

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



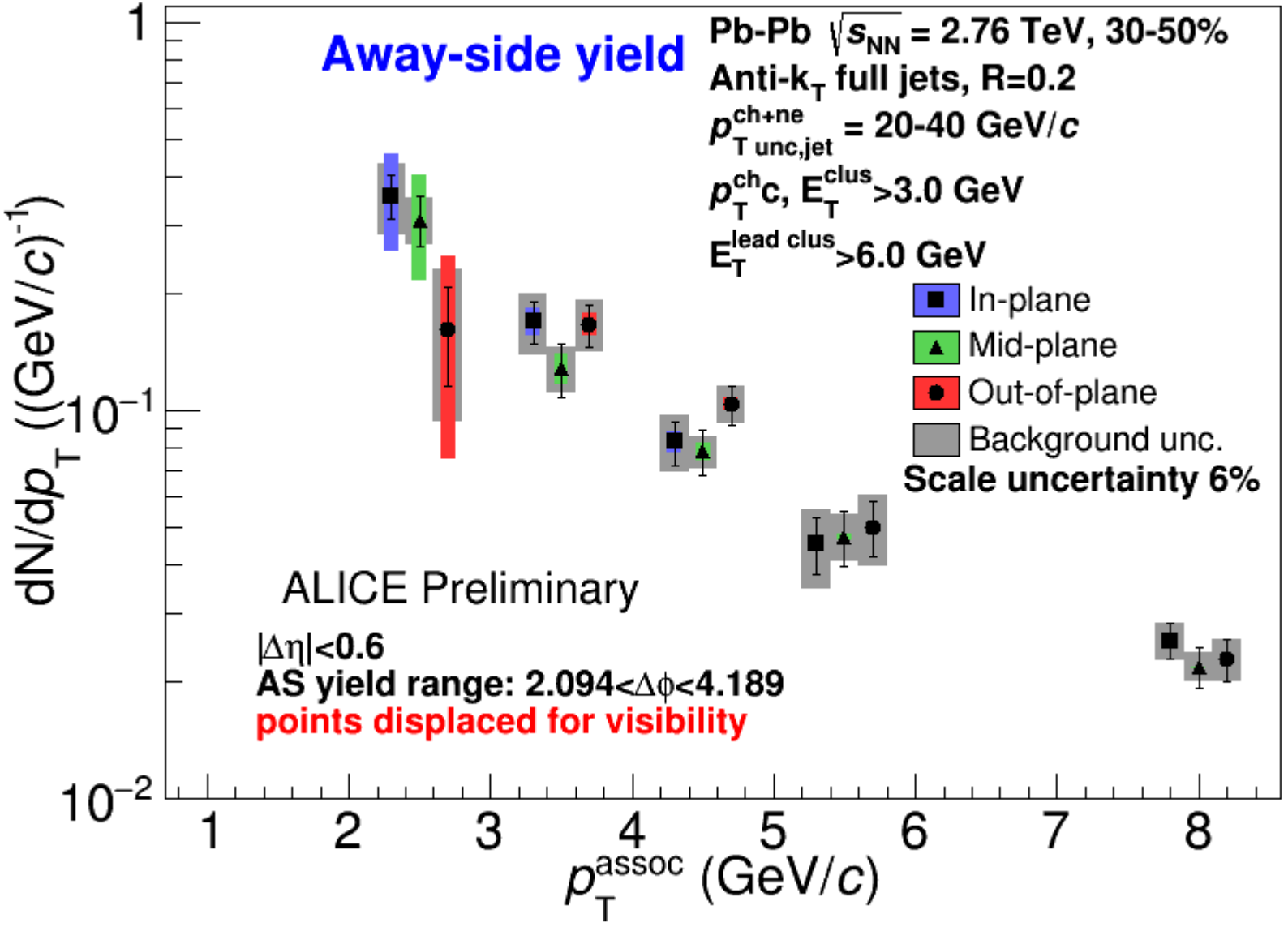
Within uncertainties of current statistics, no event plane ordering

- Different effects in different p_T associated bins

Competing effects
1) Quenching
2) Bremsstrahlung
3) etc

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

Conclusions

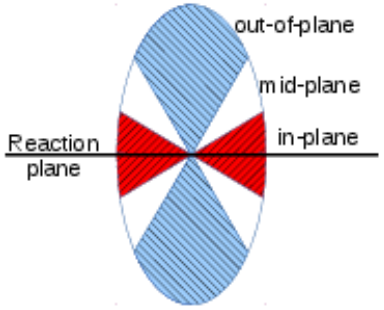
- Event plane dependence of jet-hadron correlations
  - Another tool for exploring modification to jets in medium
- Reaction plane fit (RPF) method for jet-hadron correlations applied to data
  - Robust, uses information from each event plane orientation
  - Does not require independent measurements of v_n
- No significant event plane dependence seen within our uncertainties
- Consistent with re-analysis of STAR data:

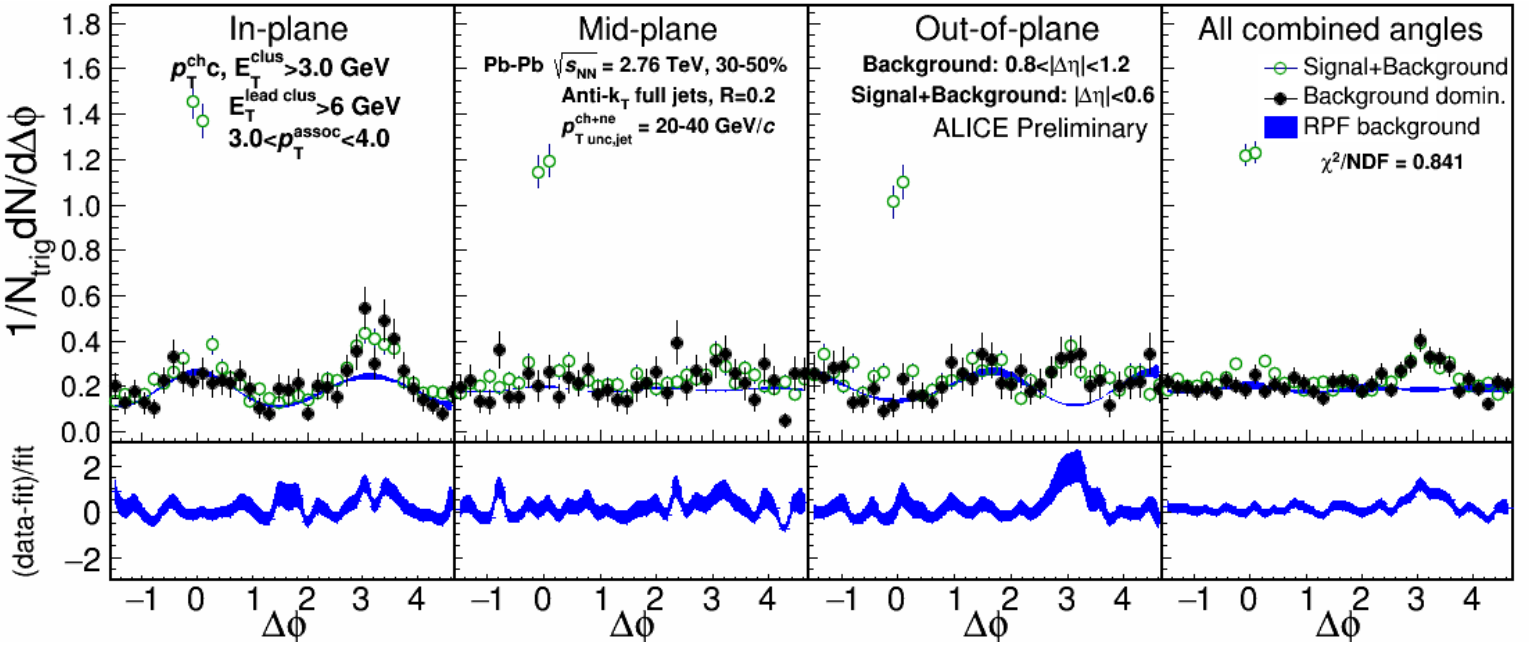
Nattrass, Sharma, Mazer, Stuart, and Bejnood (Phys. Rev. C 94, 011901(R) 2016)

Backup

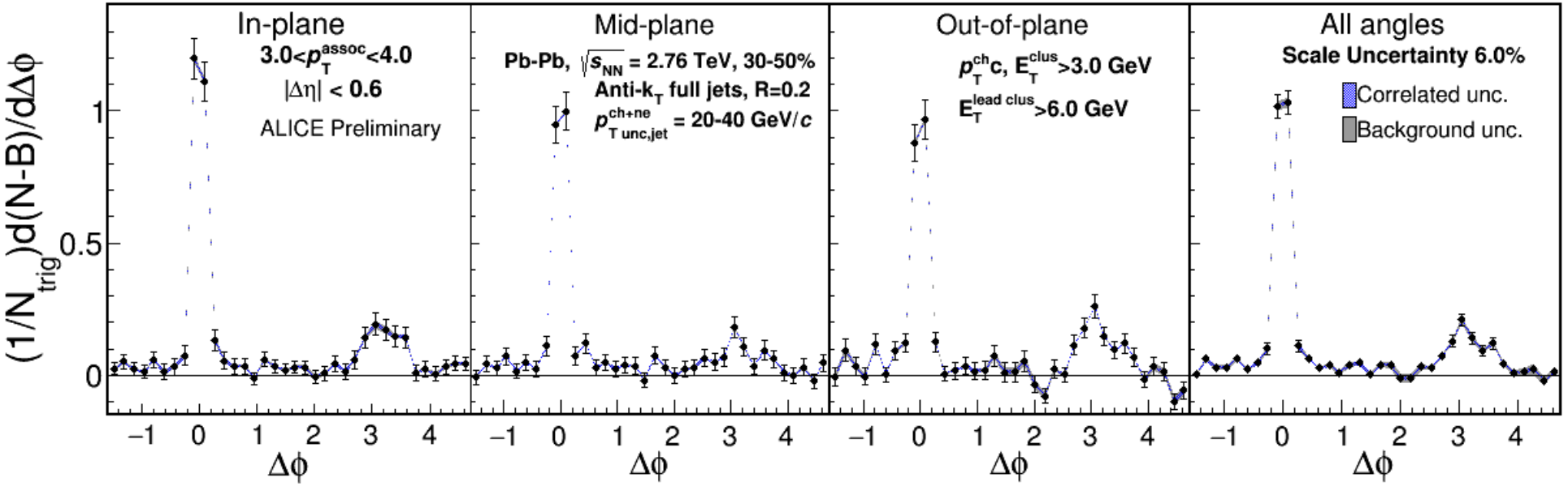
3.0-4.0 GeV/c p_T^{assoc}

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





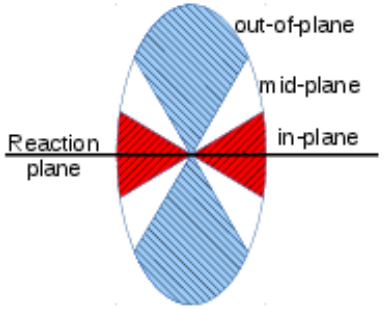
[Correlation function]

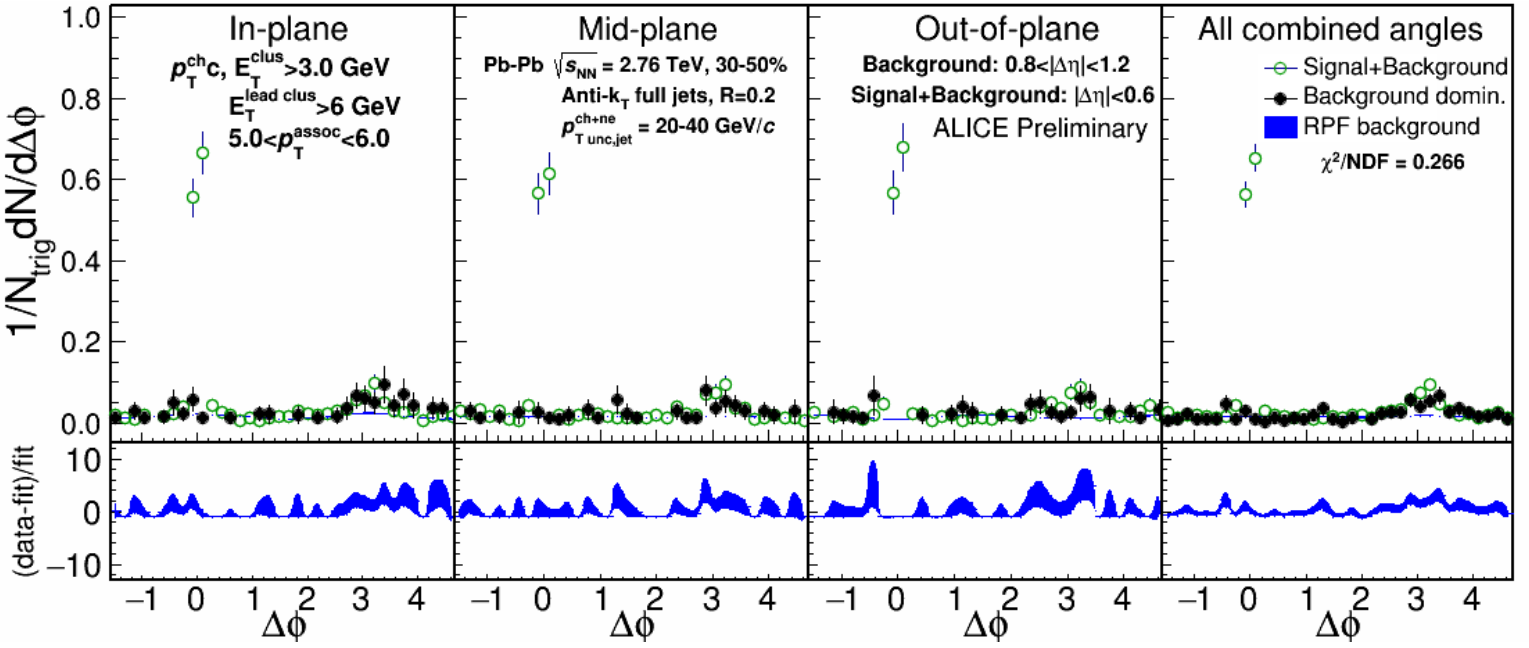


- Background level beginning to fade out

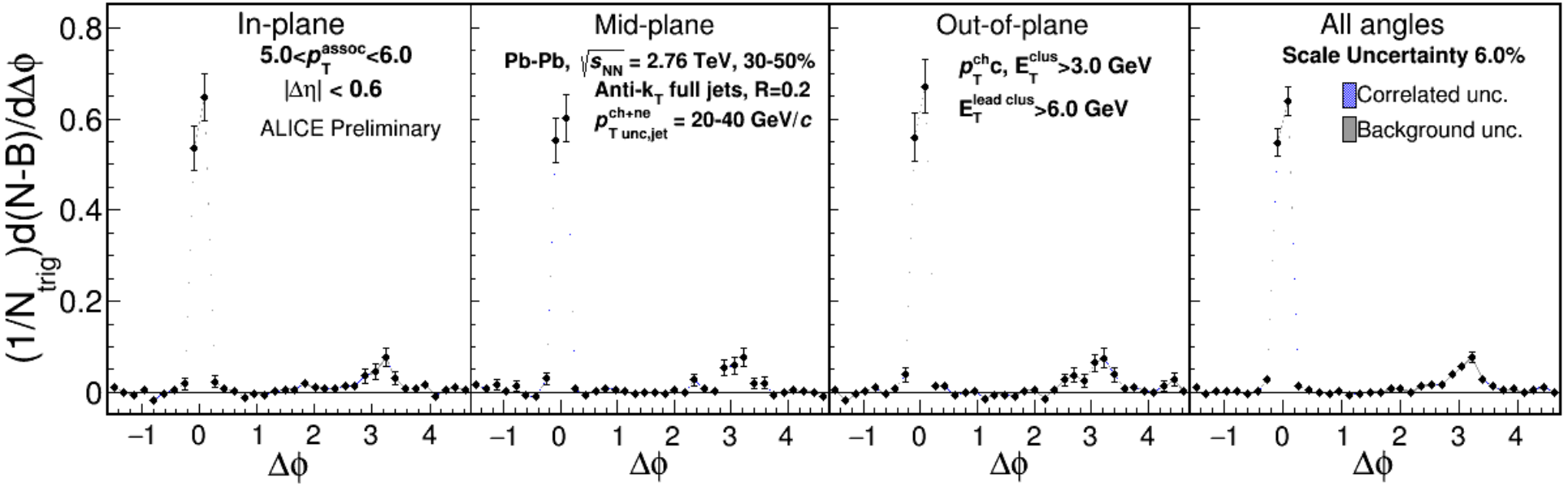
5.0-6.0 GeV/c p_T^{assoc}

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





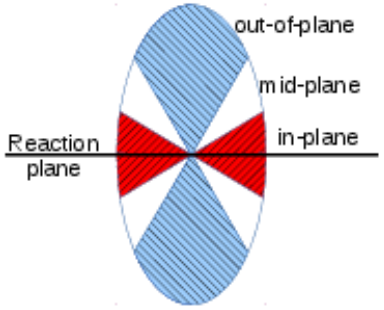
[Correlation function]



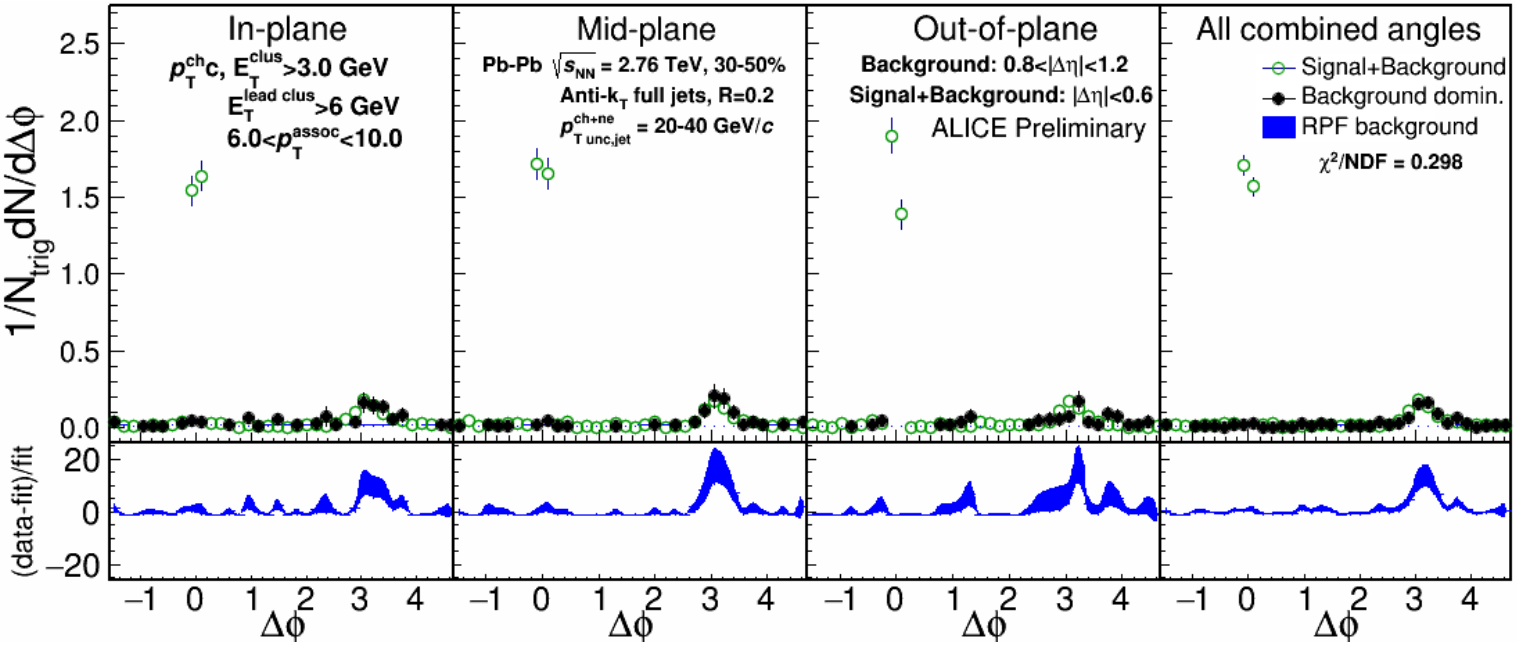
- Background level beginning to fade out

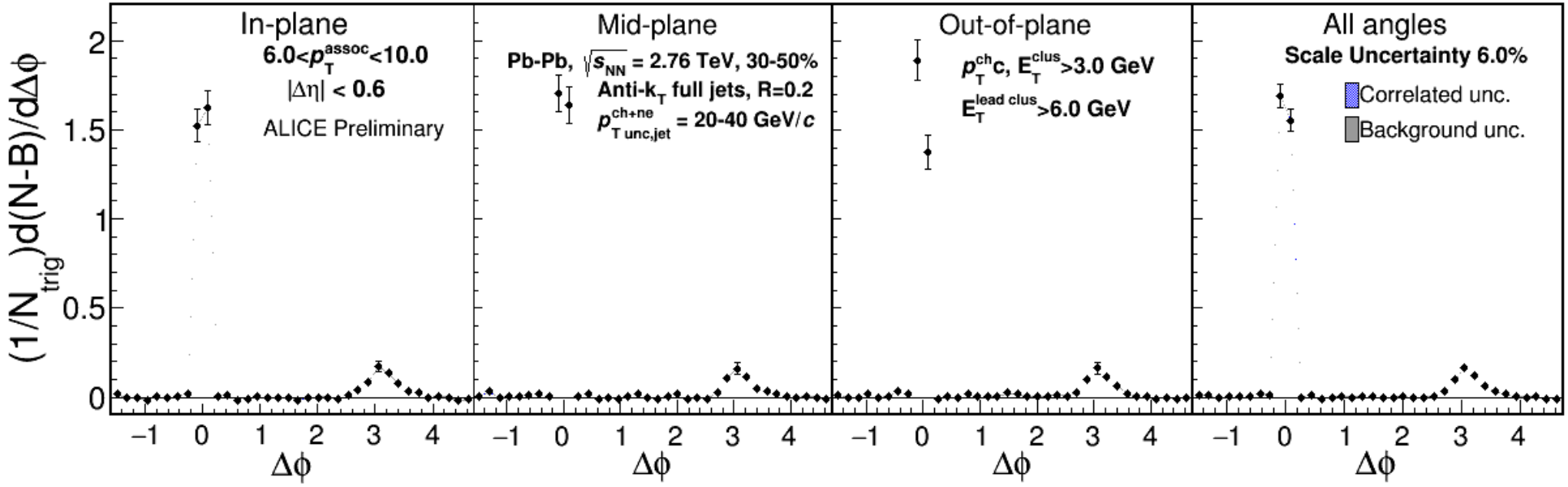
6.0-10.0 GeV/c p_T^{assoc}

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



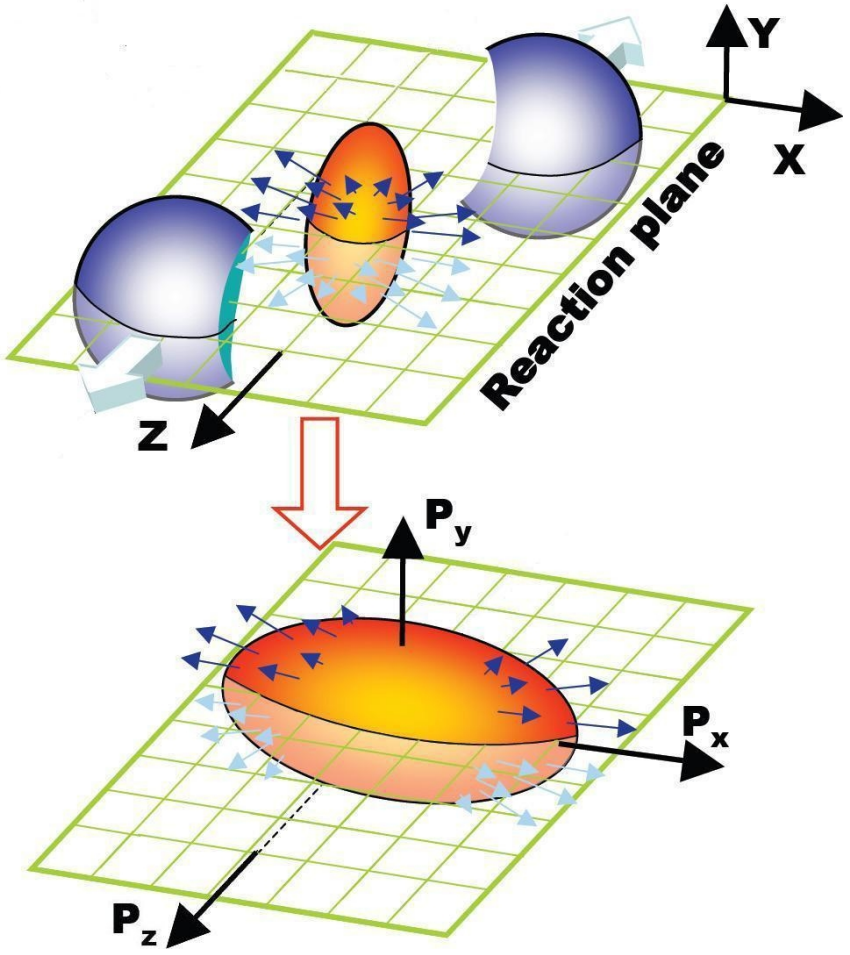
[Correlation function]

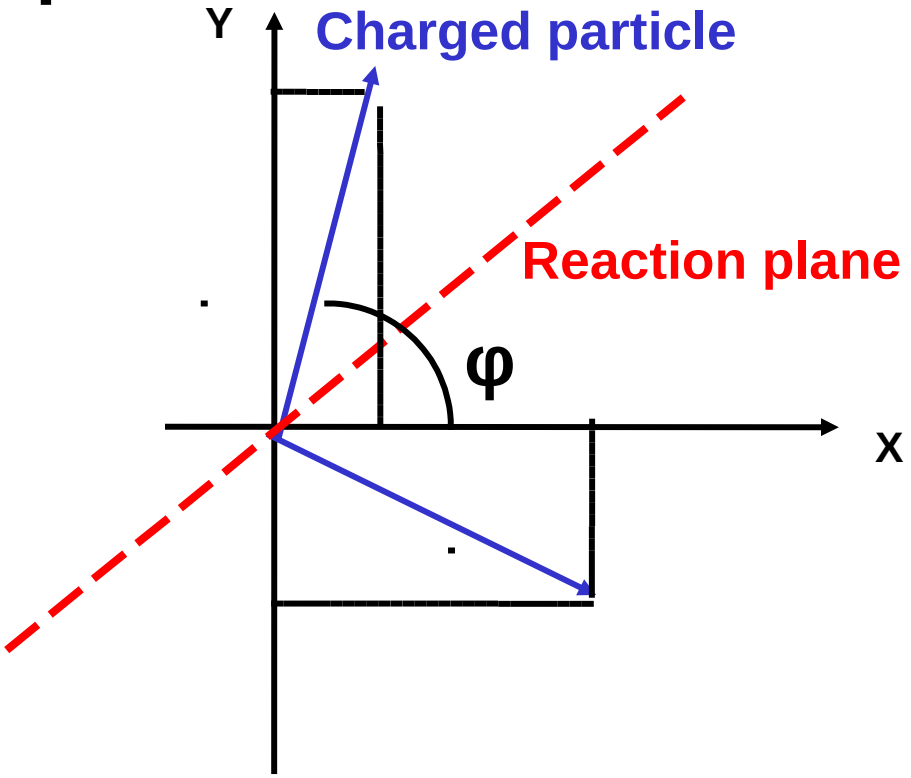




- Can extend analysis up to 6-10 GeV/c bin

Reaction plane





Measure the azimuthal angle of charged particle with respect to the reaction plane

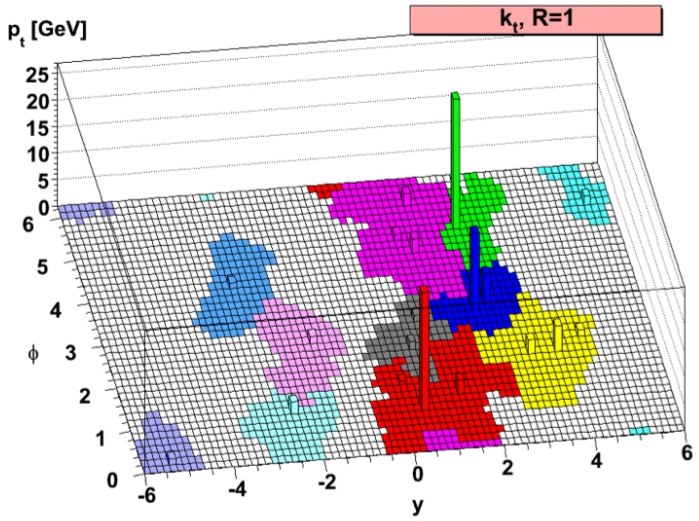
$$\Psi_n = \left(\tan^{-1} \frac{\sum_i w_i \sin(n\varphi_i)}{\sum_i w_i \cos(n\varphi_i)} \right) / n$$

Study n=2 event plane

Jet finding algorithms

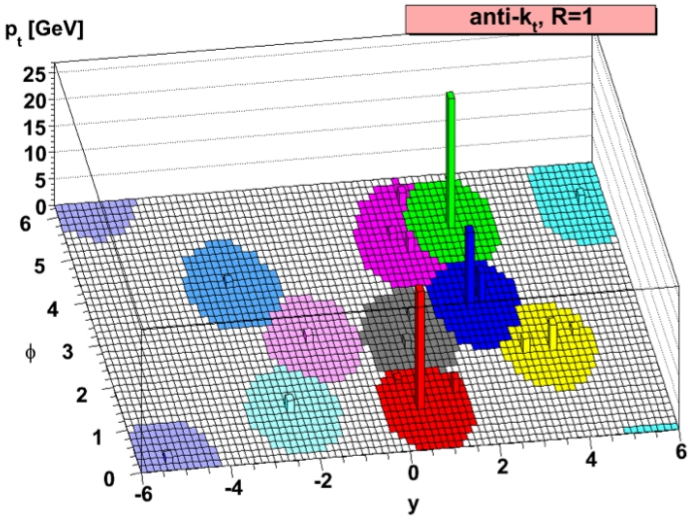
Jets reconstructed using FastJet package

arXiv:0802.1189v2



Background

Not dependent on hardest particles – samples background



Signal

Creates circular jets around the hardest particles!

$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

k_T → not bound to a circular structure

Anti-k_T → circular shape, “cone” radius ~R parameter

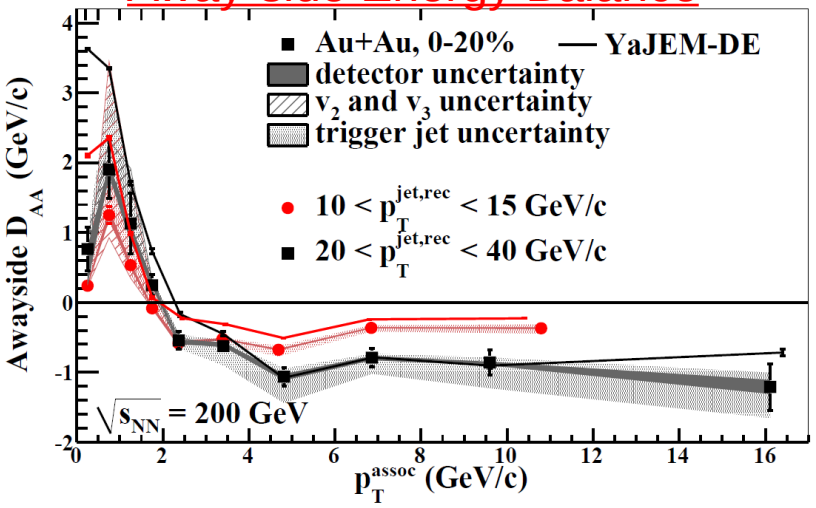
Expected to be less sensitive to background/“back reaction” (it starts from high-p_T particles) → ideal choice in heavy-ion collision

Background subtraction methods

- **Zero-Yield at Minimum (ZYAM):** Assumes v_n from other studies, assumes region around $\Delta\varphi \approx 1$ 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

What we learned at RHIC

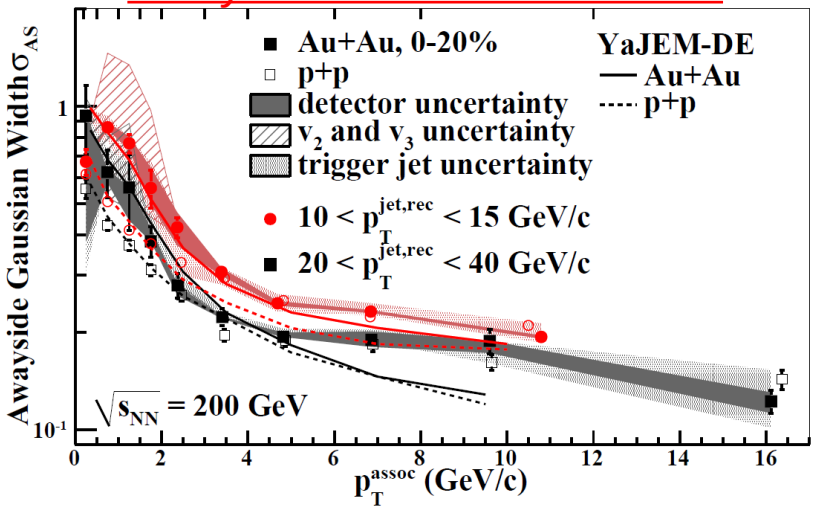
Away-side Energy Balance



$$D_{AA}\left(p_T^{assoc}\right) = Y_{AA}\left(p_T^{assoc}\right)\cdot\langle p_T^{assoc}\rangle_{AA} - Y_{pp}\left(p_T^{assoc}\right)\cdot\langle p_T^{assoc}\rangle_{pp}$$

- Suppression of high-p_T hadron yield on the away side is in large part balanced by enhancement at low-p_T
- Away-side widths suggest jet broadening to large angles at low-p_T

Away-side Gaussian Widths



- Need to understand jet v_n for n > 2?
- Largest uncertainty from v_3 modulation
- LHC can study effect at higher $\sqrt{s_{NN}}$ and access higher parton energies

Implies most modification at low p_T

Our particle identification and reconstruction in ALICE works best here!!

STAR, arXiv:1302.6184 [nucl-ex]
Phys. Rev. Lett. 112, 122301 (2014)

2 GeV/c constituents

EMCal Tower Trigger of 6 GeV

Data Set and cuts

- Dataset: PbPb 2.76 TeV, LHC11h (62 Good TPC runs)
- Jets taken from: EMCAL GA trigger
- R=0.2 Full Jets (charged + neutral tracks)

- Charged hybrid tracks with $p_T > 3.0$ GeV/c
- Cluster energies $E_{cluster} > 3.0$ GeV

Reduces combinatorial background

- Zvtx < | 10 cm |
- Require bias Jet: max cluster $E_T > 6.0$ GeV for 30-50% centrality

cluster constituent is matched to firing EMCAL GA trigger match

Eliminates objects not fired by the trigger patch

Systematic Uncertainties

- Single track reconstruction efficiency
  - 5% overall (scale)
- Contamination
  - considered a 1% error (scale)
- Mixed events – Acceptance (nominal method is not z-vertex weighted) – same ME used for each EP bin, 2-10 GeV bin used for bins above 2 GeV
  - Shape uncertainty on correlation function in $\Delta\Phi$ (variation less than statistical error - negligible)
  - Scale uncertainty on background $\Delta\eta$ (added as band to correlations, Y)
  - Mixed event normalization (scale) (<0.5% in every ptassoc bin)
- Background uncertainty
  - Background fit (shape) (added as band to correlations, Y)
  - Reaction plane resolution R_n (negligible)

Summary of systematics

Source	% Uncertainty
Single particle reconstruction efficiency	5
Contamination	1
Mixed event (shape $\Delta\phi$)	negligible
Mixed event normalization	< 0.5
Event plane resolution	negligible

Source	Result	Orientation	Near-side	Away-side
Mixed event (scale $\Delta\eta$)	Yield	in-plane	0.2-20.4	0.1-33
		mid-plane	0.2-27.4	0.2-50.7
		out-of-plane	0.3-18.7	0.2-53.7
	RMS	in-plane	$^{+0.01}_{-0.01}{}^{-4.7}_{-5.8}$	$^{+0.02}_{-0.03}{}^{-5.2}_{-8.7}$
		mid-plane	$^{+0.01}_{-0.1}{}^{-22.5}_{-11.2}$	$^{+0.07}_{-0.1}{}^{-4.3}_{-5.9}$
		out-of-plane	$^{+0.05}_{-0.07}{}^{-16.8}_{-14.8}$	$^{+0.09}_{-0.4}{}^{-1.9}_{-3.6}$
Background fit	Yield	in-plane	4.4-15.6	11.6-50.4
		mid-plane	2.6-15.3	9.5-56.6
		out-of-plane	3.6-10.9	10.9-35
	RMS	in-plane	3.8-15.8	1.1-9.5
		mid-plane	2.2-10.5	1.1-10.3
		out-of-plane	3.1-13	1.5-12.5

Sequential Recombination

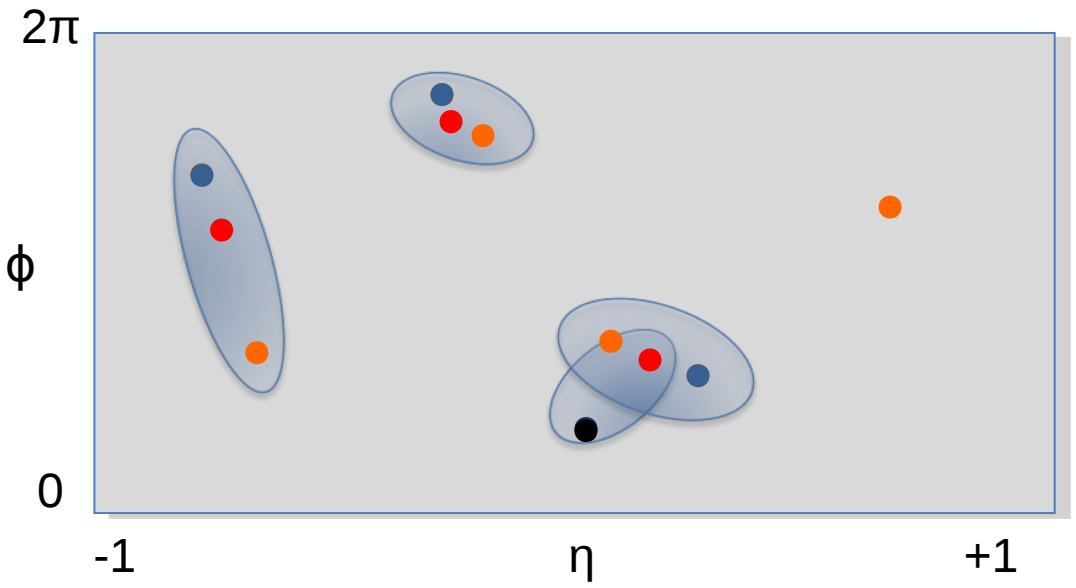
$$d_{ij} = \min\left(k_{Ti^{2p}}, k_{Tj^{2p}}\right)\left(Dy_{ij^2} + Df_{ij^2}\right)/R^2$$

$\mathbf{k_{Ti,j}}$= particle transverse momentum (p_T)

$\mathbf{k_T}$: p>0 (soft particles merged first)

Anti-$\mathbf{k_T}$: p<0 (hard particles merged first)

R=resolution parameter



Example: **Anti-$\mathbf{k_T}$**

Blue = highest p_T particle

If $\boldsymbol{d_{ij} < k_{Ti}^{-2}}$ → merged

If $\boldsymbol{d_{ij} > k_{Ti}^{-2}}$ → not merged → call it a jet

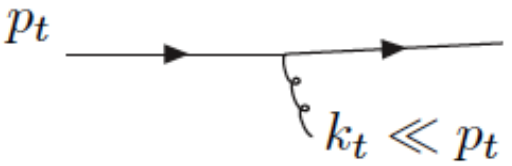
Collinear and Infrared Safety

Collinear safety

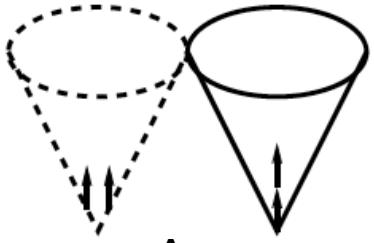
→ replaces one parton by two at the same place

Infrared safety

→ a soft emissions that add very soft gluon



jet-finder should not be sensitive to these issues!!

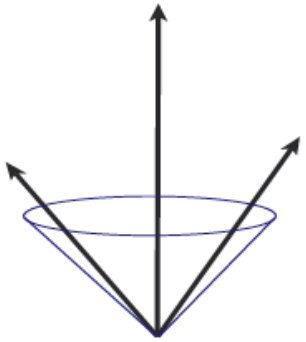


If energy is split among soft particles and each tower is under a threshold, jet is lost

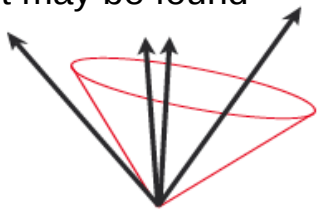
A

collinear

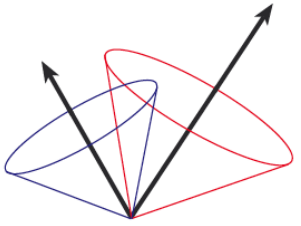
If energy of parton is split in two towers, and algorithm starts with particles with highest E, different jet may be found



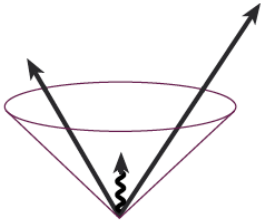
B



Infrared



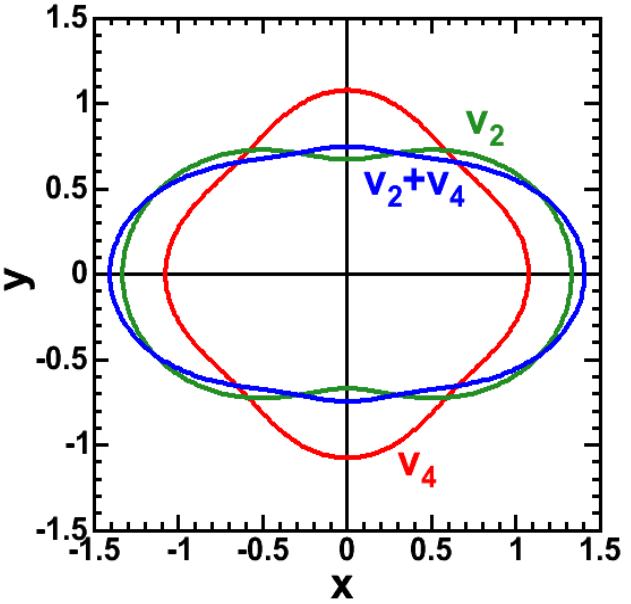
OK



BAD: 2 jets are merged in one

Estimation of reaction plane

- Even v_n :
  - arise from anisotropy of average overlap region of incoming nuclei
  - **correlated with n=2 event plane**
- Odd v_n :
  - arise from fluctuations of individual positions of nucleons within the nucleus
  - **not correlated with n=2 event plane**



- Due to finite multiplicity of each event, there will be difference between reconstructed event plane and underlying symmetry plane: ψ_n
- Need to correct for this via event plane resolution R:

$$R = < \cos\left(n\left[\Psi_{EP} - \Psi_n\right]\right) >$$

want V0 resolution

$$R_n^a = < \cos(n[\Psi_{EP}^a - \Psi_n]) > =$$
$$= \sqrt{\frac{< \cos(n[\Psi_{EP}^a - \Psi_{EP}^b]) >< \cos(n[\Psi_{EP}^a - \Psi_{EP}^c]) >}{< \cos(n[\Psi_{EP}^b - \Psi_{EP}^c]) >}}$$

Fit Function with Rxn Plane dependence

Azimuthal anisotropies of particle pair due to collective flow is:

$$\frac{dN^{pairs}}{\pi d\,\Delta\Phi} = \frac{2c}{\pi} B\left(1+\sum_{k=2,4,6..} 2R_k v_k^{trig}\cos\left(k\phi_S\right)\frac{\sin\left(kc\right)}{kc}\right)\left(1+\sum_{n=1} 2v_n^{effective} v_n^{assoc}\cos\left(n\Delta\phi\right)\right)$$

where,

B : integrated inclusive pair yield; R_k: reaction plane resolution

Φ_S: angle between region center and reaction plane; c: half of the width of region

In-plane: Φ_S=0, c=π/6; Mid-plane: Φ_S=π/4 and 3π/4, c=π/12; Out-plane: Φ_S=π/2, c=π/6;

v_k^{trig}: trigger particle k^{th} order flow component

v_n^{assoc}: associated particle n^{th} order flow component

$$v_{n,odd}^{effective} = v_n^{trig}; v_{n,even}^{effective} = \frac{v_n^{trig} + \delta_{n,even} R_n \cos\left(n\phi_S\right)\frac{\sin\left(nc\right)}{nc} + \sum_{k=2,4,6,..} R_k\left(v_{k+n}^{trig} + v_{|k-n|}^{trig}\right)\cos\left(k\phi_S\right)\frac{\sin\left(kc\right)}{kc}}{1+\sum_{k=2,4,6,..} 2R_k v_k^{trig}\cos\left(k\phi_S\right)\frac{\sin\left(kc\right)}{kc}};$$

Details in: J. Bielcikova et. al., PRC 69, 021901 (2004).

STAR measurements of dihadron correlations relative to reaction plane

Phys. Rev. C 94, 011901 2016

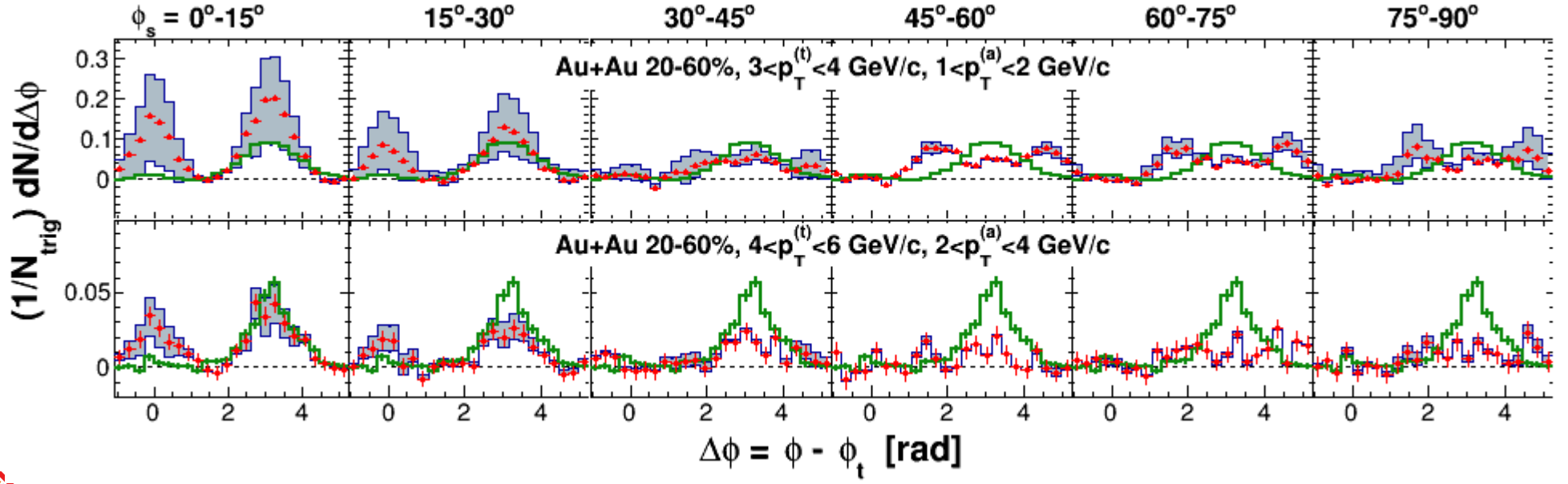
Correlations on arxiv (nucl-ex/1010.0690 v2)

- Published article (Phys. Rev. C 89 (2014) 41901) does not include raw correlations

ZYAM background subtraction

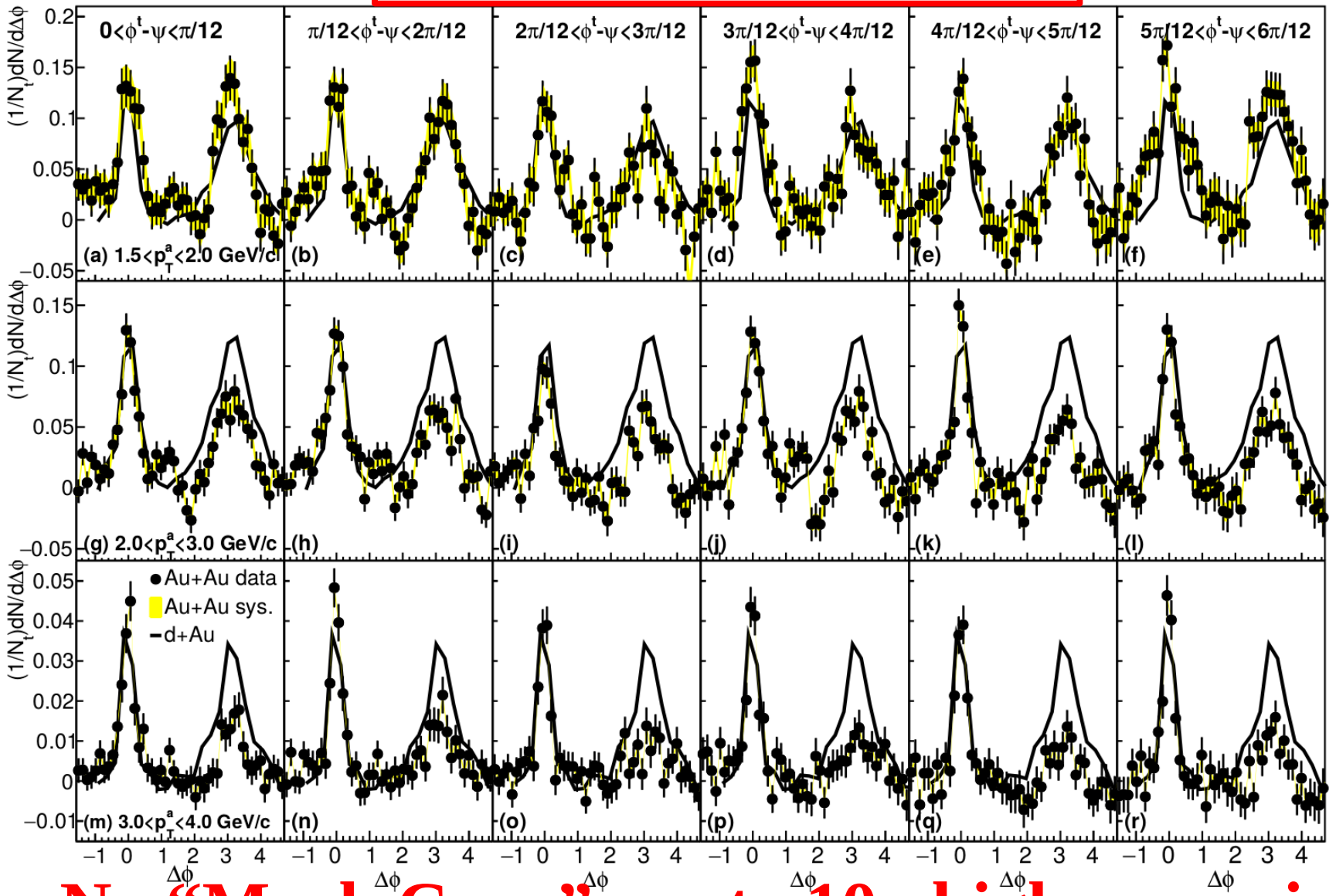
- Reports ridge at $\Delta\eta > 0.7$
- RPF method assumes no signal at $\Delta\eta > 0.7$

$0.7 < \Delta\eta < 2$



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

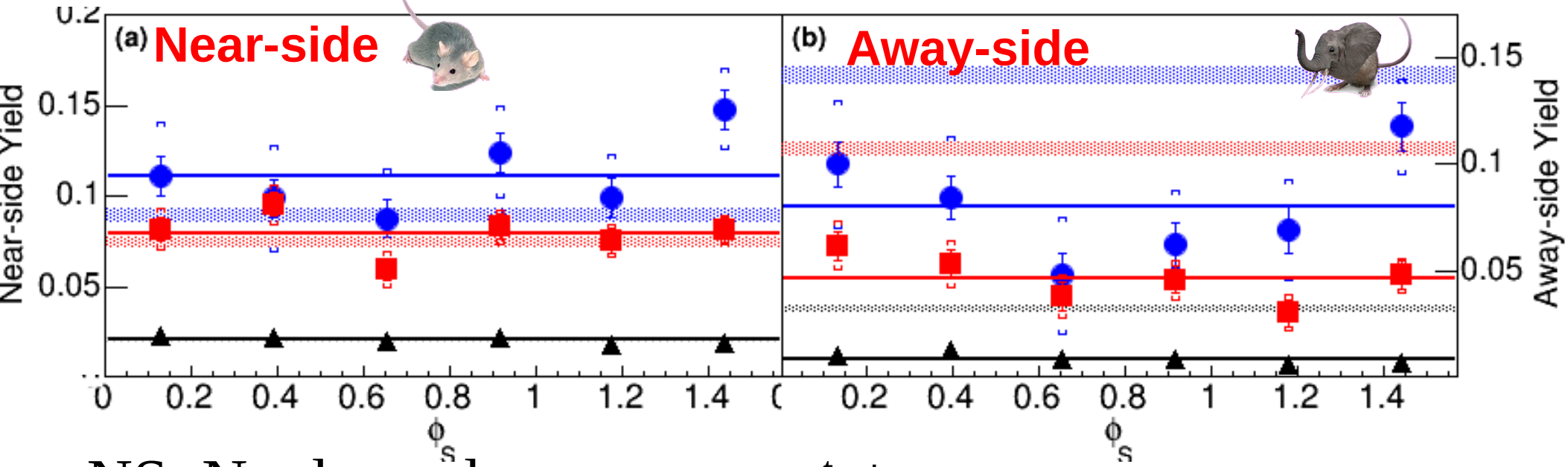
Phys. Rev. C 94, 011901 2016



No "Mach Cone", up to 10x higher precision

Statistical error bars include correlated statistical error on background

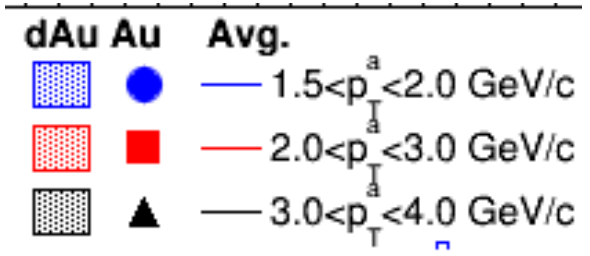
Yields $4<p_T^t<6$ GeV/c



NS: No dependence on $\varphi_S=\varphi^t-\psi$

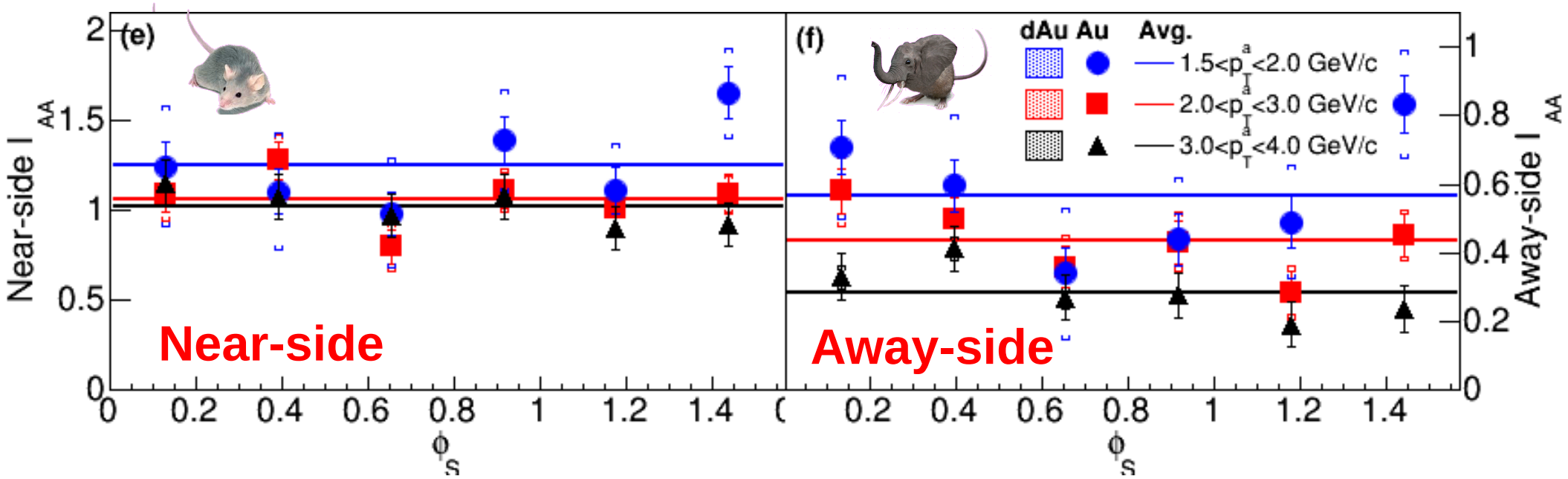
AS: can see φ_S dependence

Higher precision than previous analyses



[Phys. Rev. C 94, 011901 2016]

$$I_{AA} = Y_{AuAu}/Y_{dAu}$$



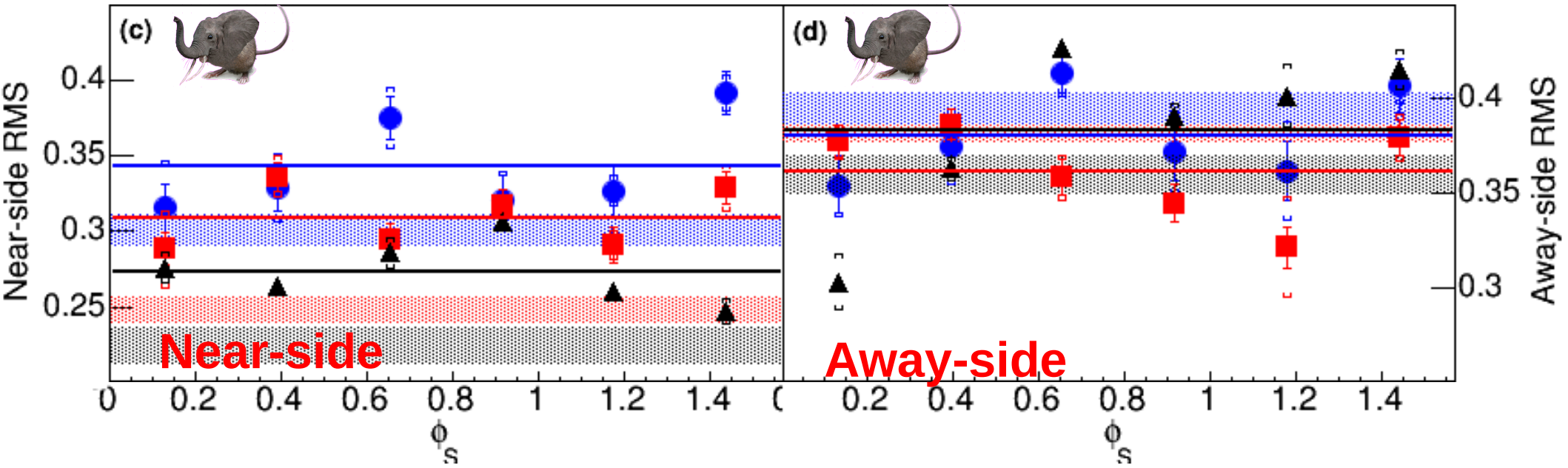
NS: No dependence on $\varphi_S=\varphi^t-\psi$

AS: can see φ_S dependence

Higher precision than previous analyses

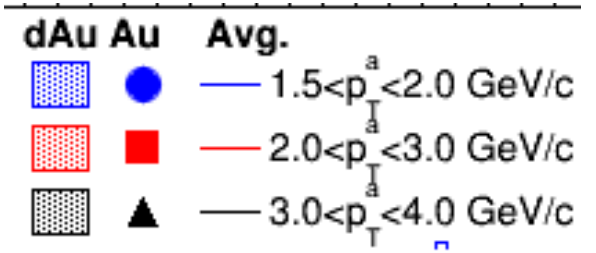
Phys. Rev. C 94, 011901 2016

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



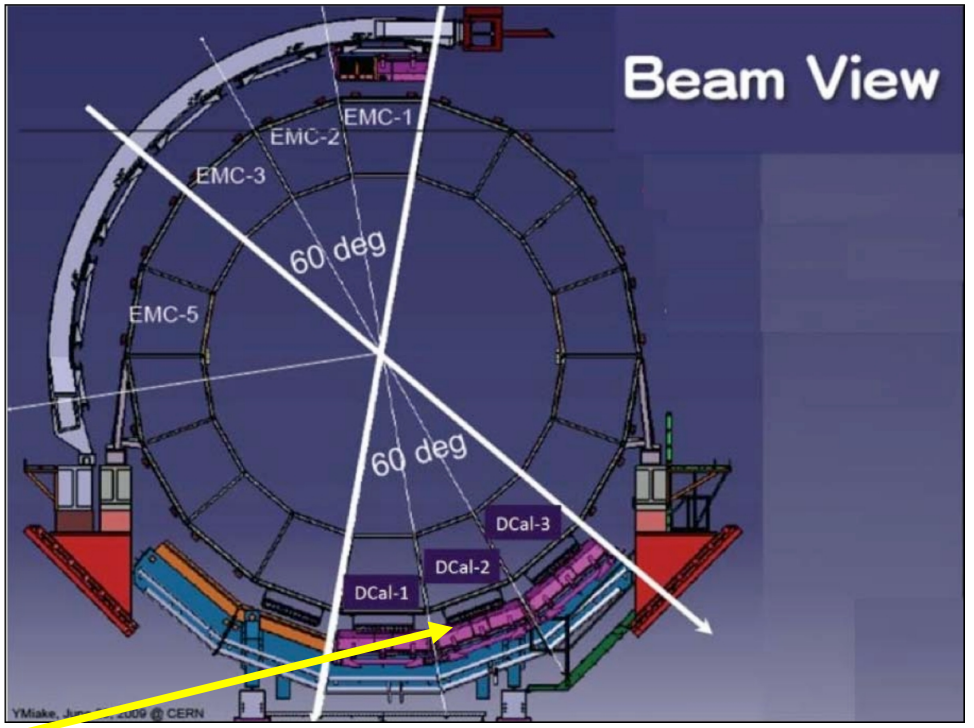
Lines show averages

Higher precision than public analysis (different p_T)

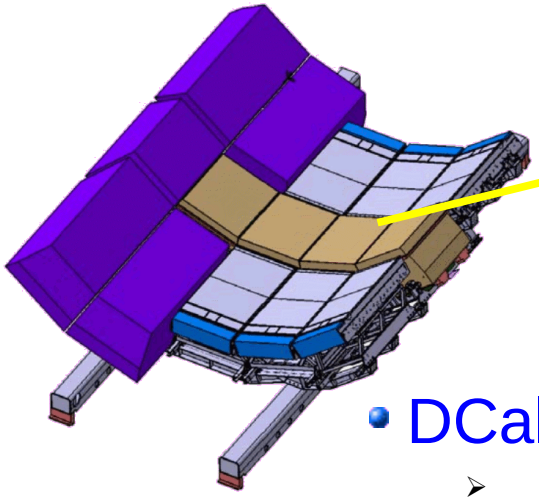


Phys. Rev. C 94, 011901 2016

EMCal & DCal



Installed in Fall 2014
Δη=1.4, Δφ=60º



- Over 20 k towers total
- Each tower Δη X Δφ= 0.014 X 0.014
- σ(E)/E=0.12/√E + 0.02

- DCal: di-jet calorimeter
  - Increased acceptance for full jet reconstruction
  - Di-jet measurements