Di-hadron correlations with event shape engineering in Au+Au collisions at the STAR experiment

Ryo Aoyama, for the STAR Collaboration
University of Tsukuba, TCHoU
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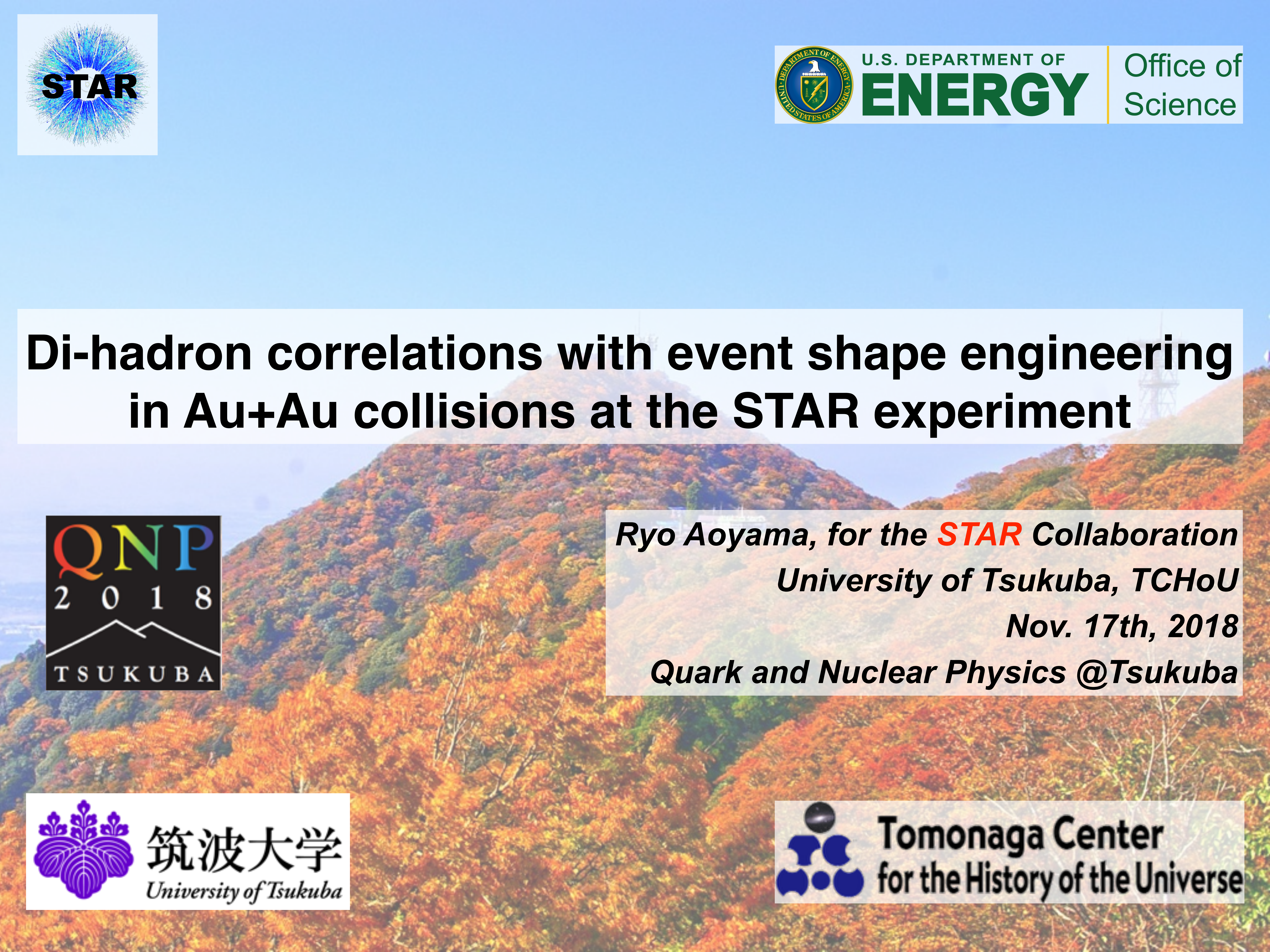
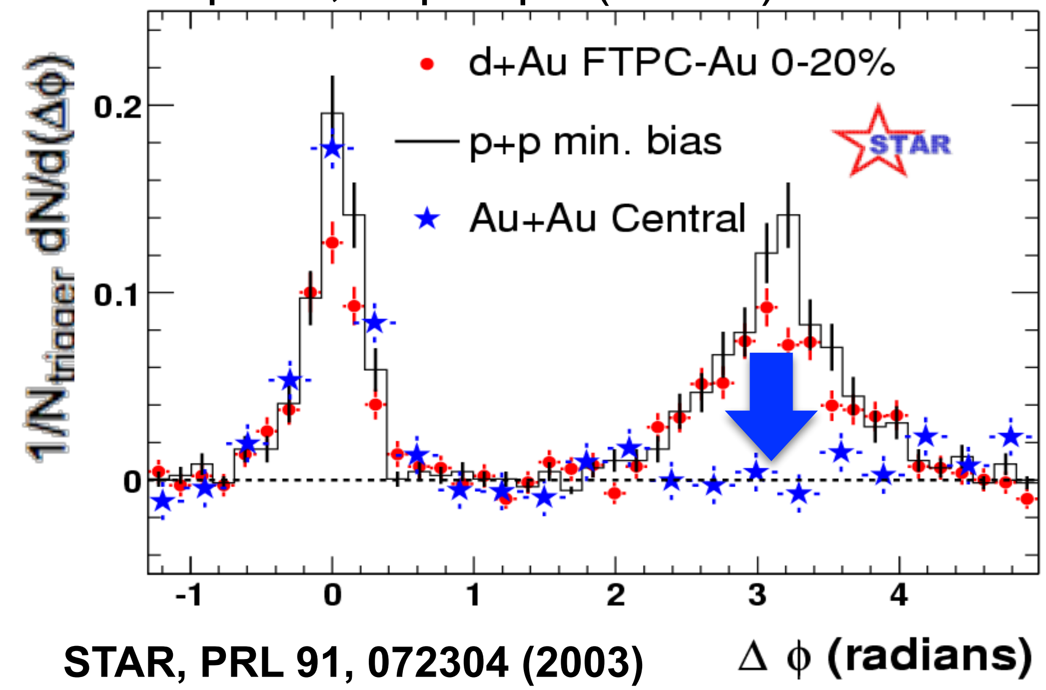
Quark and Nuclear Physics @Tsukuba



Jets with di-hadron correlations in heavy-ion collisions

- ✦ Jets interact with colored matter and lose their energy : jet quenching
  - ‣ probe energy loss mechanisms in the QGP
- ✦ **high-p_T** : disappearance of back-to-back jet-like peak in central Au+Au collisions
  - ‣ jet suppression in the QGP

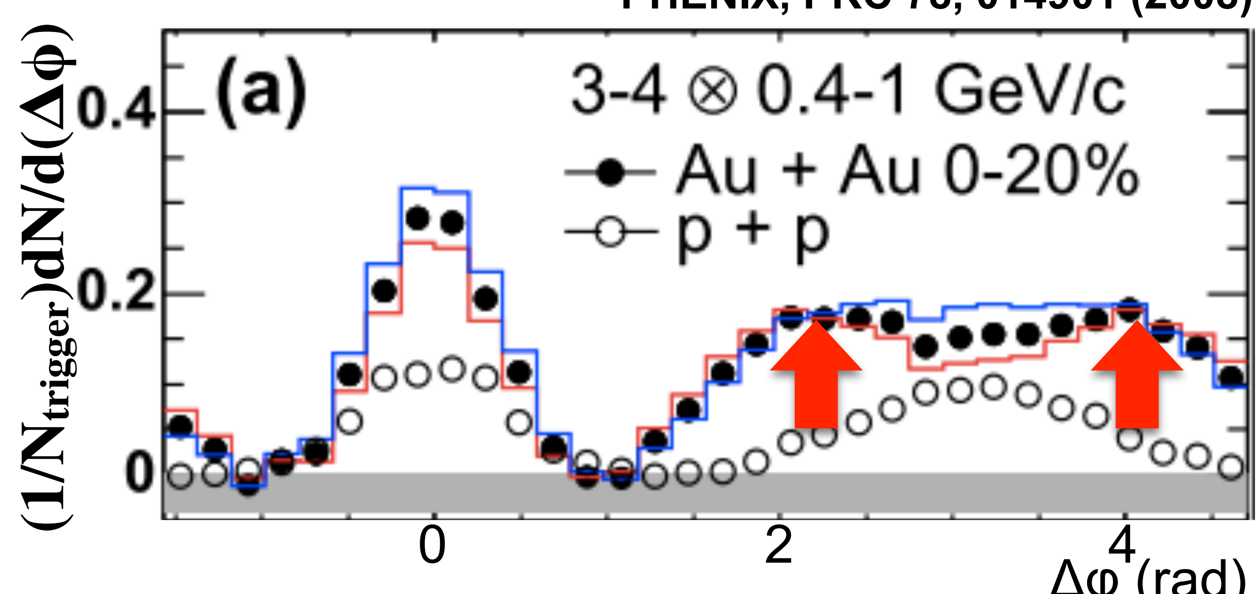


STAR, PRL 91, 072304 (2003)

only v_2 subtraction

- ✦ **low-p_T** : enhanced yield on both near and away side compared to p+p collisions
  - ‣ re-distribution of deposited energy

PHENIX, PRC 78, 014901 (2008)



only v_2 subtraction

Event plane and higher order flow harmonics

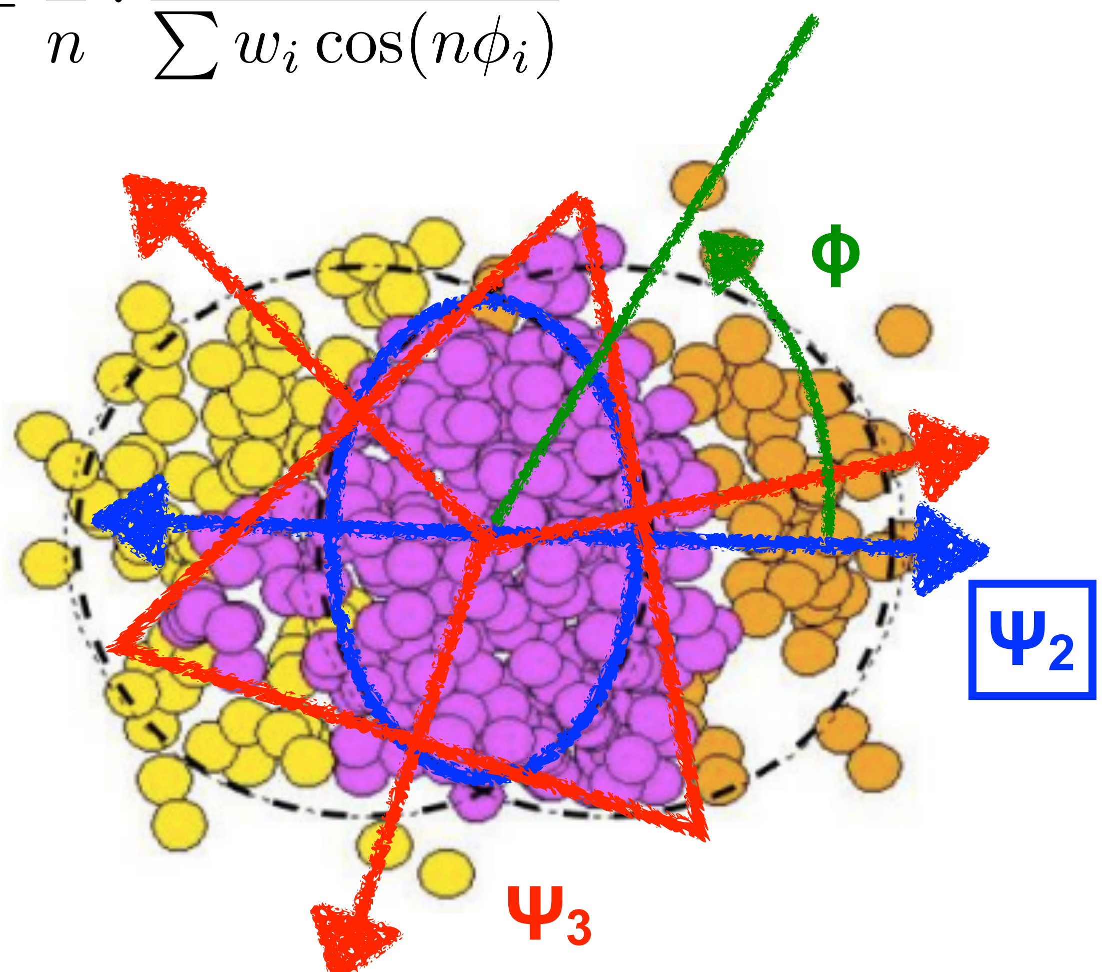
✦ Spatial anisotropy due to **almond-like shape** and **event-by-event fluctuations** of overlapping region of nuclei in non-central heavy-ion collisions

✦ Deformation converted into momentum space by **collective motion** (**flow**)

- azimuthal anisotropy

azimuthal distribution : $\frac{dN}{d\phi} \propto 1 + \sum_i 2v_n \cos n(\phi - \Psi_n)$

n-th order event plane : $\Psi_n = \frac{1}{n} \cdot \frac{\sum w_i \sin(n\phi_i)}{\sum w_i \cos(n\phi_i)}$

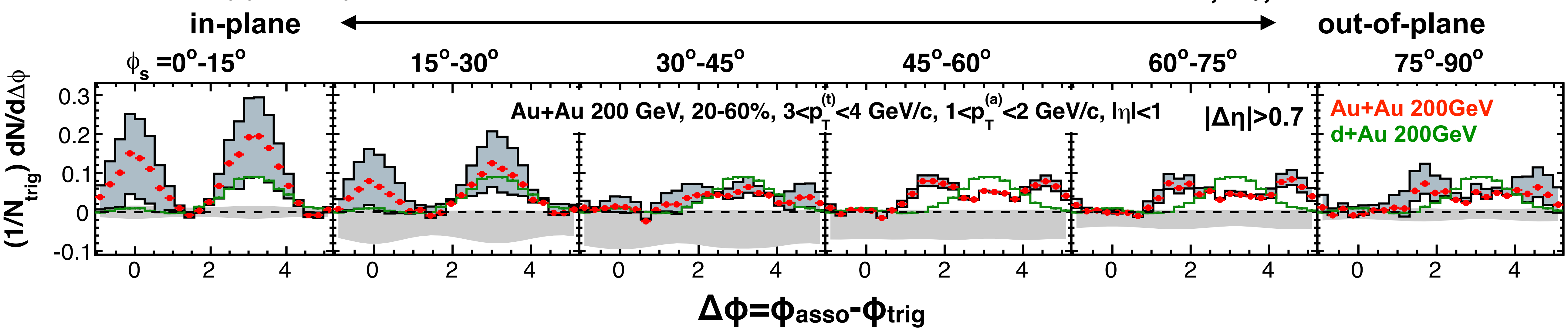


Event plane dependent di-hadron correlations

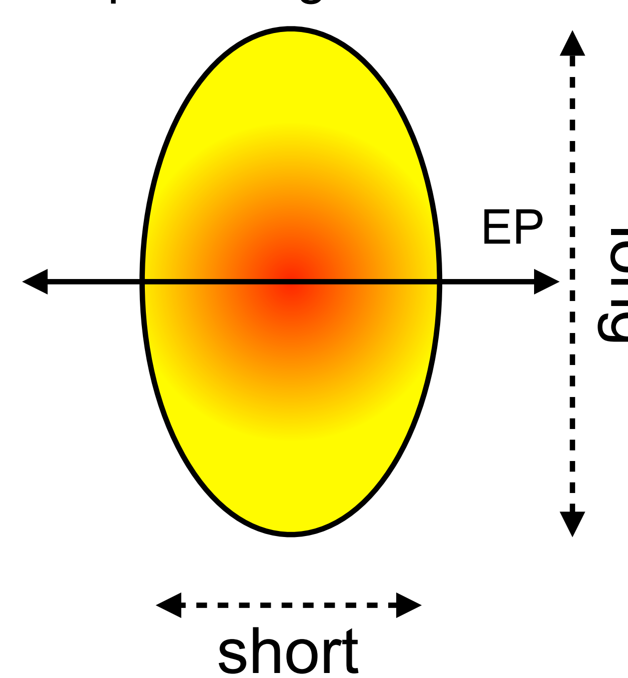
STAR, PRC 89, 041901 (2014)

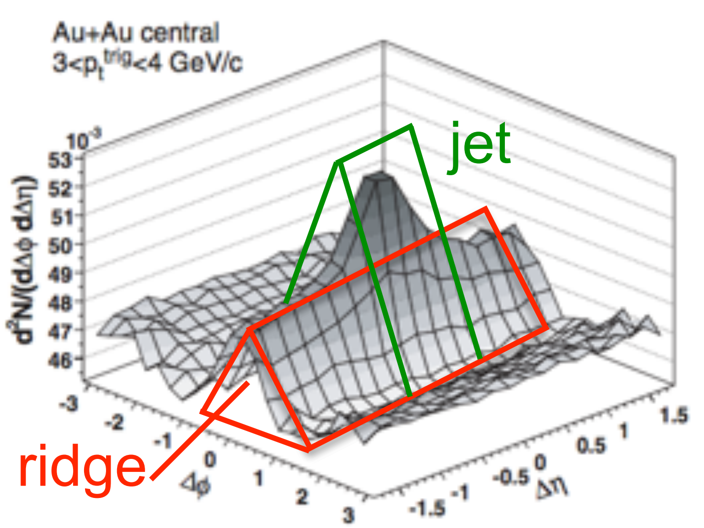
ϕ_s : trigger angle with respect to event plane ($=\phi-\Psi_2$)

v_2, v_3, v_4 subtracted



- ✦ Possibility of control in-medium path length of jets
- ✦ EP dependence of jet-medium interactions
  - Single peak in the away side with the in-plane trigger
  - Away-side peak becomes lower and broadened as trigger direction changes from in-plane to out-of-plane





STAR, PRC 80, 064912 (2009)

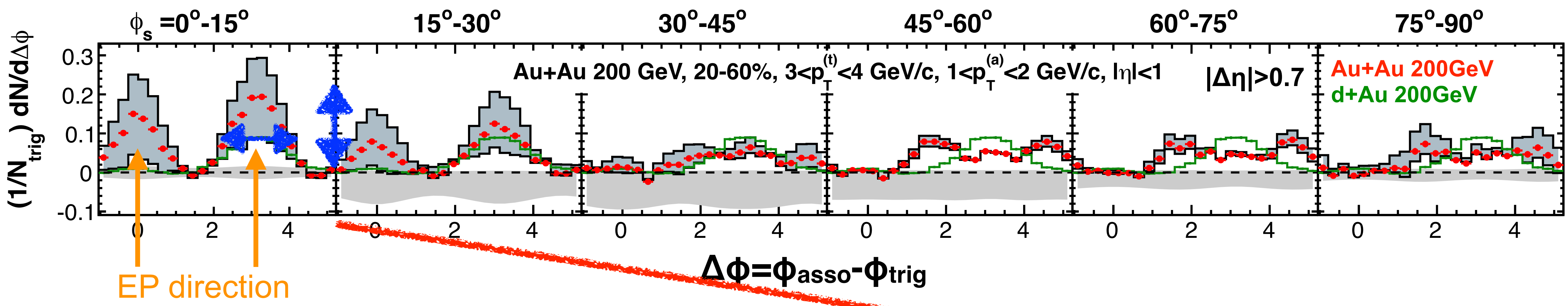
Rest of this talk : **$|\Delta\eta|<1$ ▶** jet cone AND away-side are focused on

Event plane dependent di-hadron correlations

STAR, PRC 89, 041901 (2014)

ϕ_s : trigger angle with respect to event plane (=ϕ-Ψ_2)

v_2, v_3, v_4 subtracted



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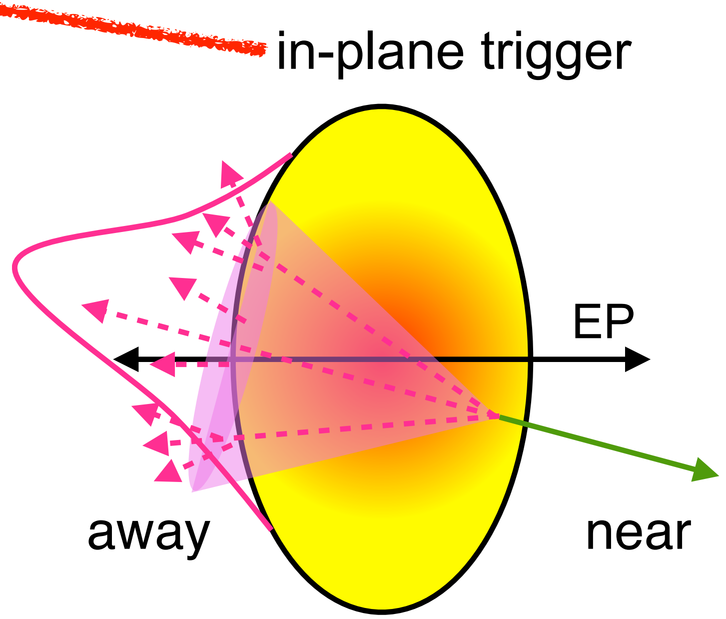

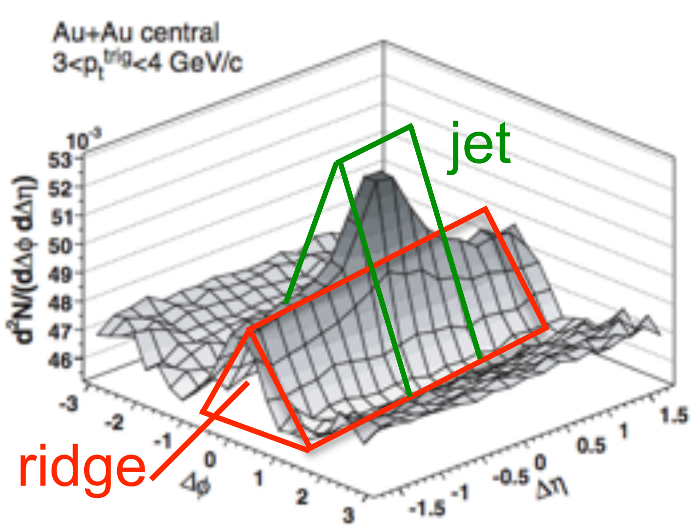

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Event plane dependent di-hadron correlations

STAR, PRC 89, 041901 (2014)

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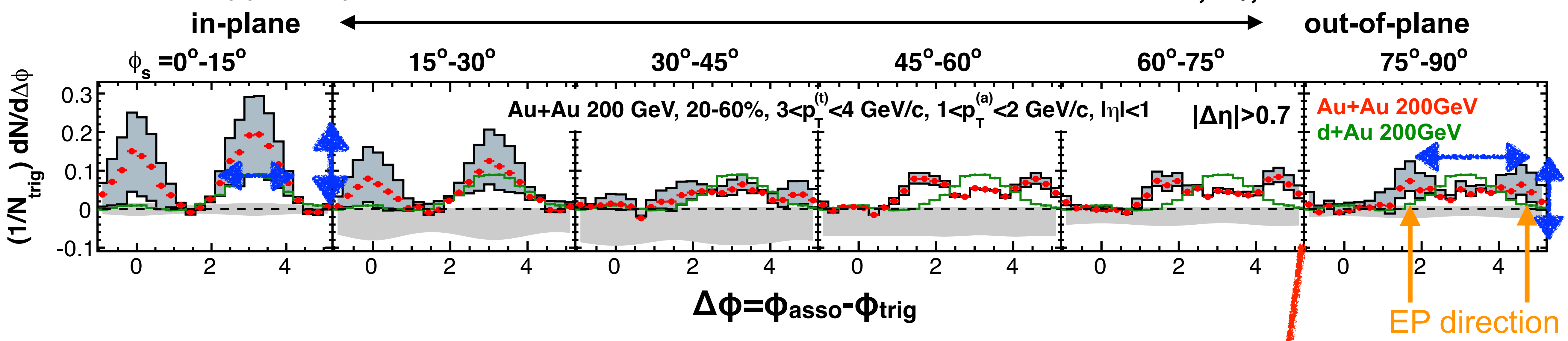
v_2, v_3, v_4 **subtracted**



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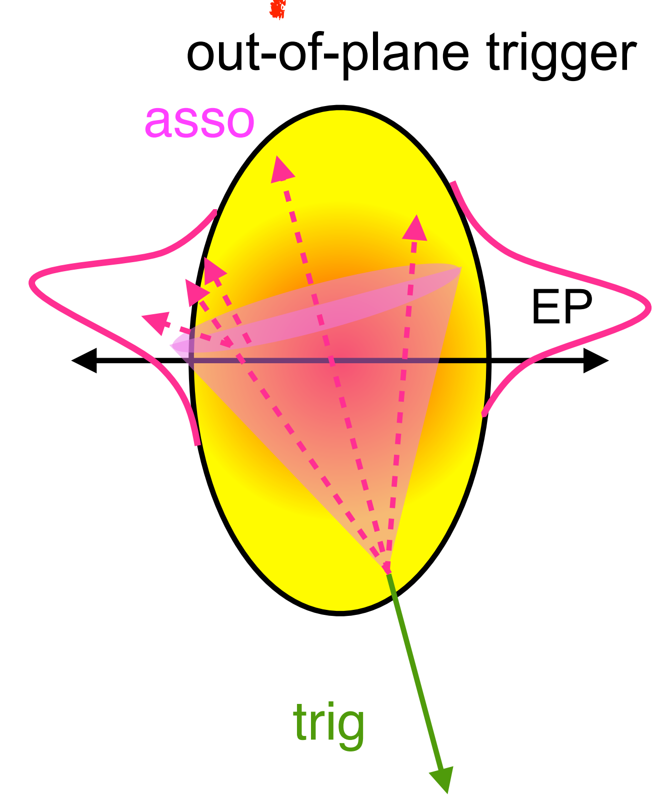

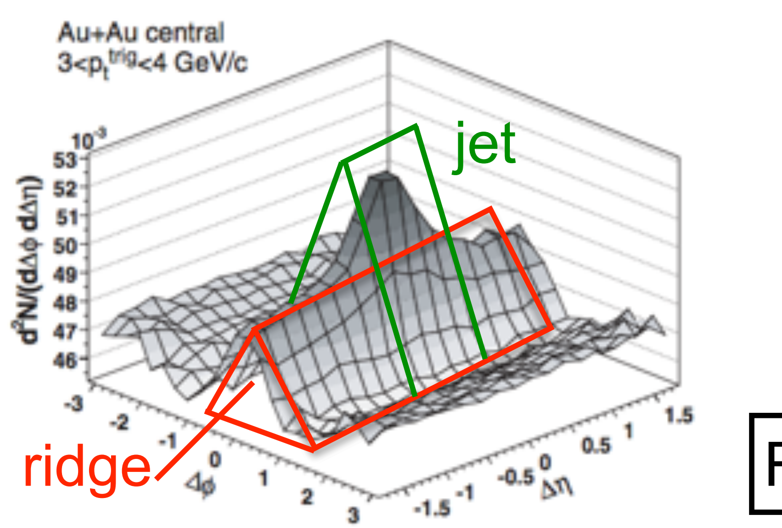

STAR, PRC 80, 064912 (2009)

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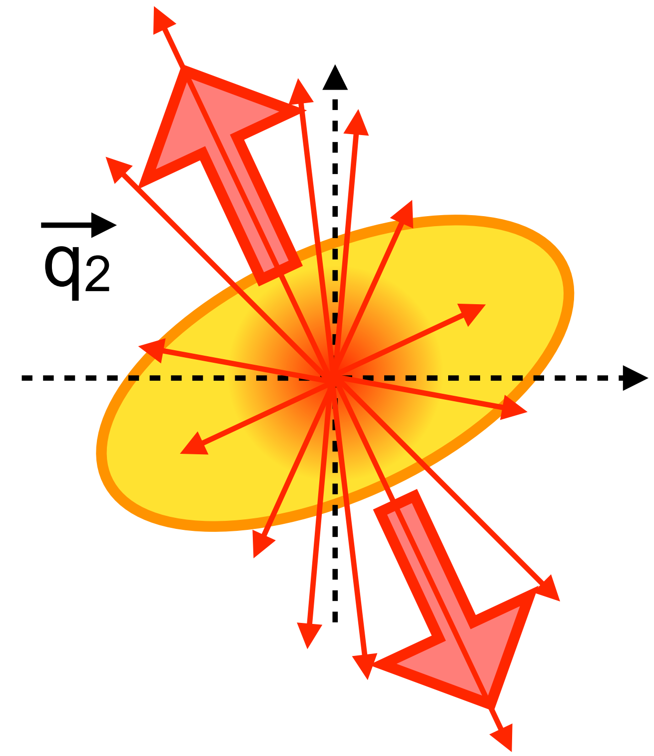
Event shape engineering (ESE)

- Selection of event-by-event flow amplitude
  - event-by-event v_2 largely fluctuates in a fixed centrality bin
  - control fluctuating v_2 by selecting the magnitude of flow vector q_2
  - Possibility to control the initial geometry

J.Schukraft, A.Timmins and S.A.Voloshin, PLB 719 (2013), 394-398



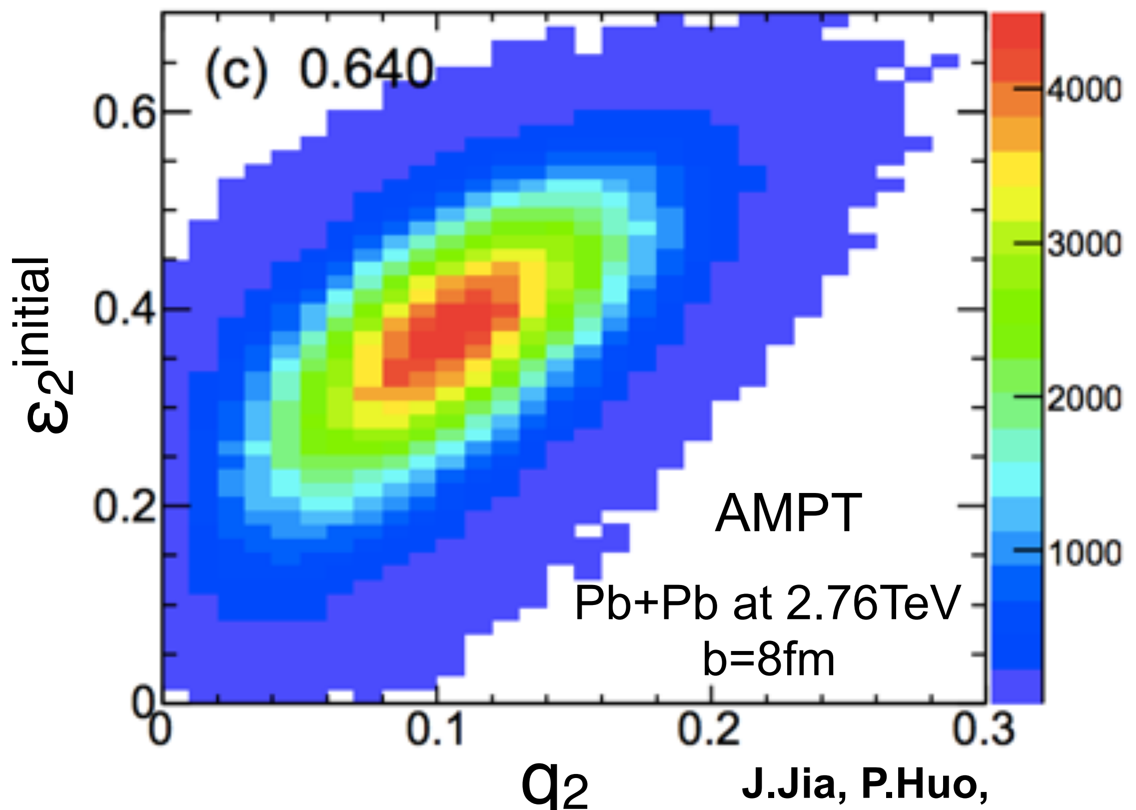
$$Q_{2,x} = \sum w_i \cos(2\phi_i)/\sqrt{\sum w_i}$$
$$Q_{2,y} = \sum w_i \sin(2\phi_i)/\sqrt{\sum w_i}$$
$$q_2 = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}$$

w_i : weighting factor

A.M.Poskanzer, S.A.Voloshin, PRC 58 (1998), 1671-1678

initial eccentricity $\varepsilon_2 = \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$

correlation between q_2 and ε_2



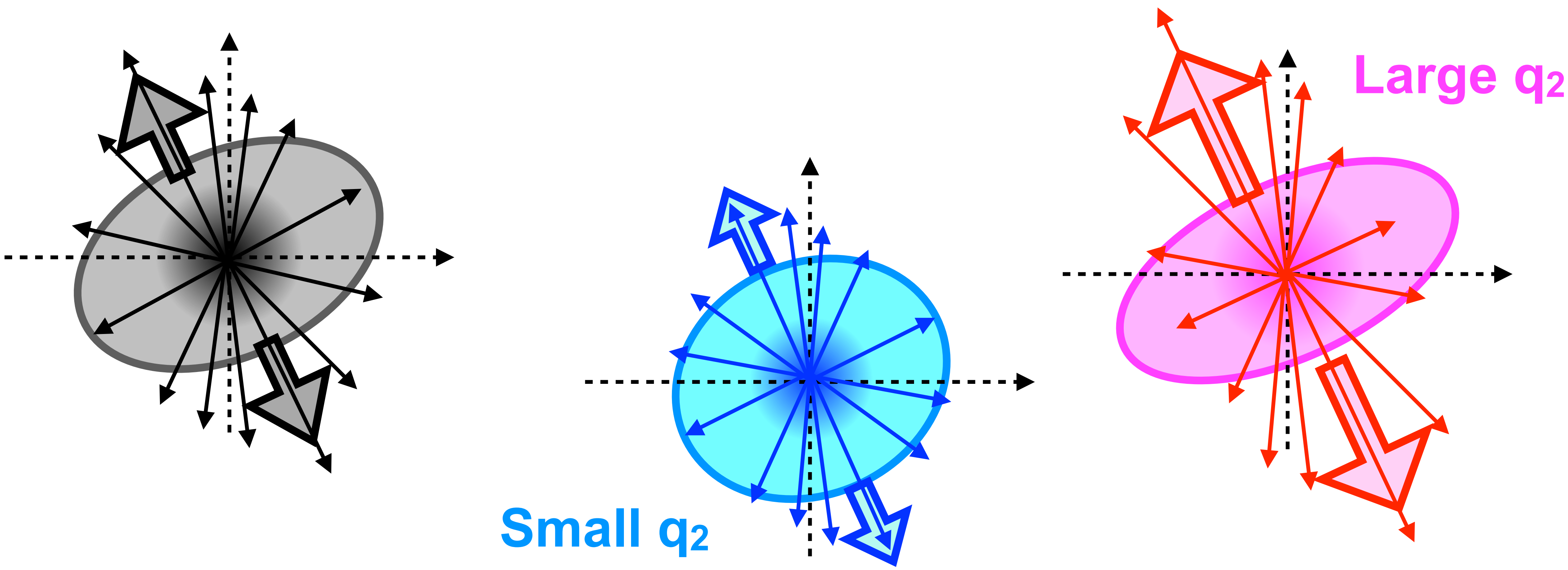
J.Jia, P.Huo, PRC 90 (2014), 034915

Separation of volume effect and geometry effect could be allowed

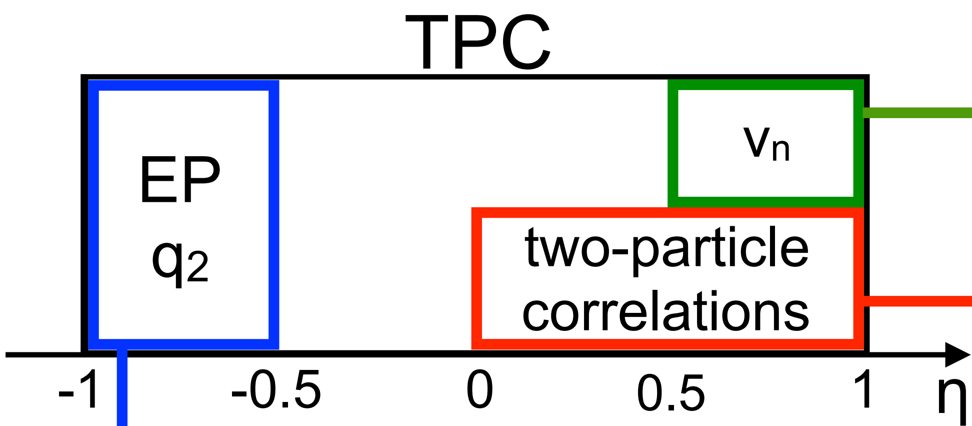
Motivation

- ✦ Combination of centrality selection and event shape engineering allows control of the initial geometry while keeping the average energy density (multiplicity) fixed
  - **Study difference of jet modification in medium expansion**
- ✦ Di-hadron correlations with event shape engineering allow new differential insight into energy loss mechanisms as a function of initial energy and shape
  - **Detailed information which was previously averaged out**

- ✦ **Analysis with minimum-bias Au+Au at $\sqrt{s_{NN}}$ = 200 GeV data collected by STAR in 2011**



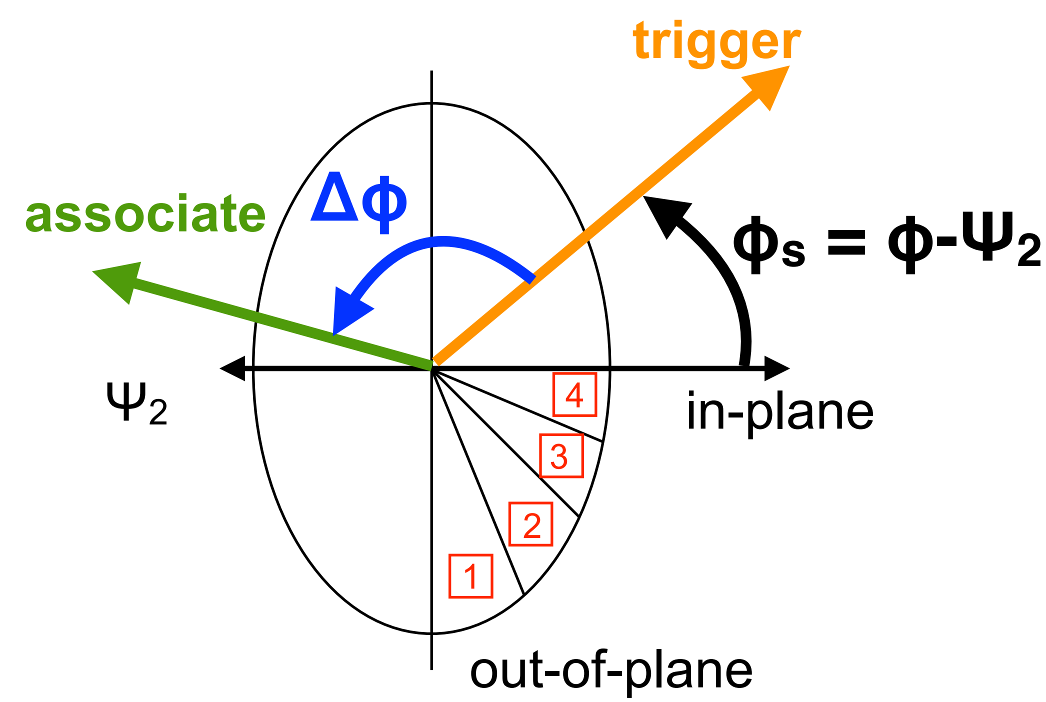
Data analysis



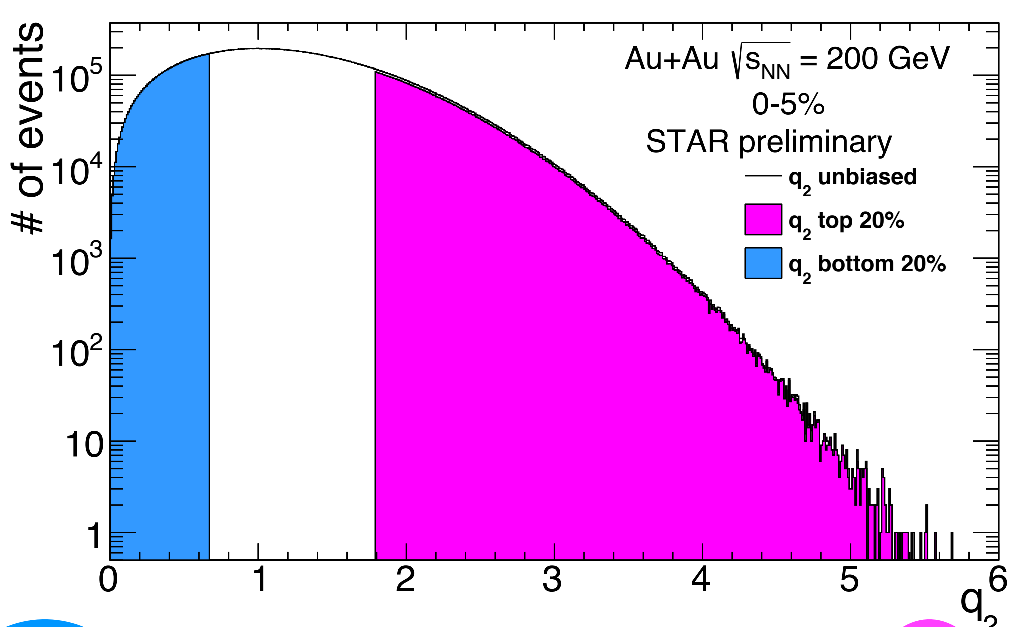
- ✦ **v_n measurement via EP method**
- ✦ **Two-particle correlations**

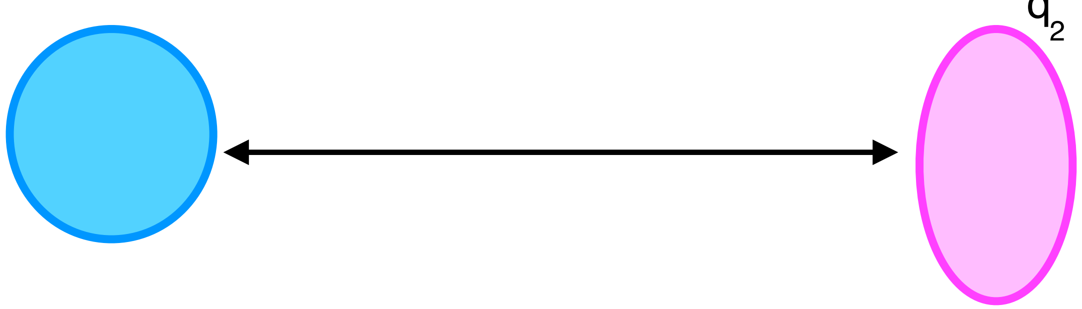
$$C(\Delta\phi) \propto \frac{N^{real}_{pair}(\Delta\phi)}{N^{mix}_{pair}(\Delta\phi)}$$

trigger angle selection w.r.t. EP



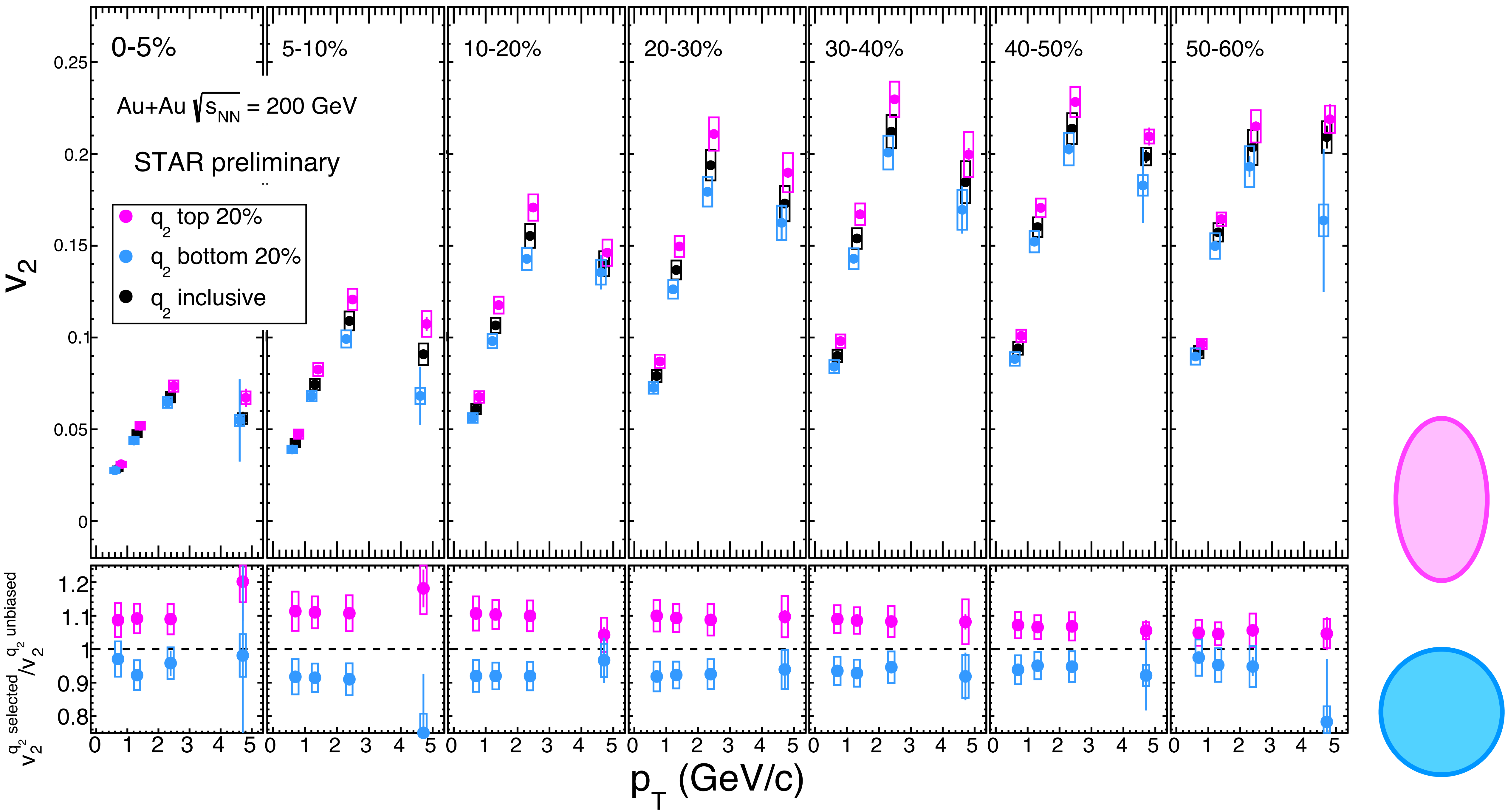
- ✦ **Event Plane Ψ_n**
- ✦ **q_2 selection**
  - bottom 20% and top 20%





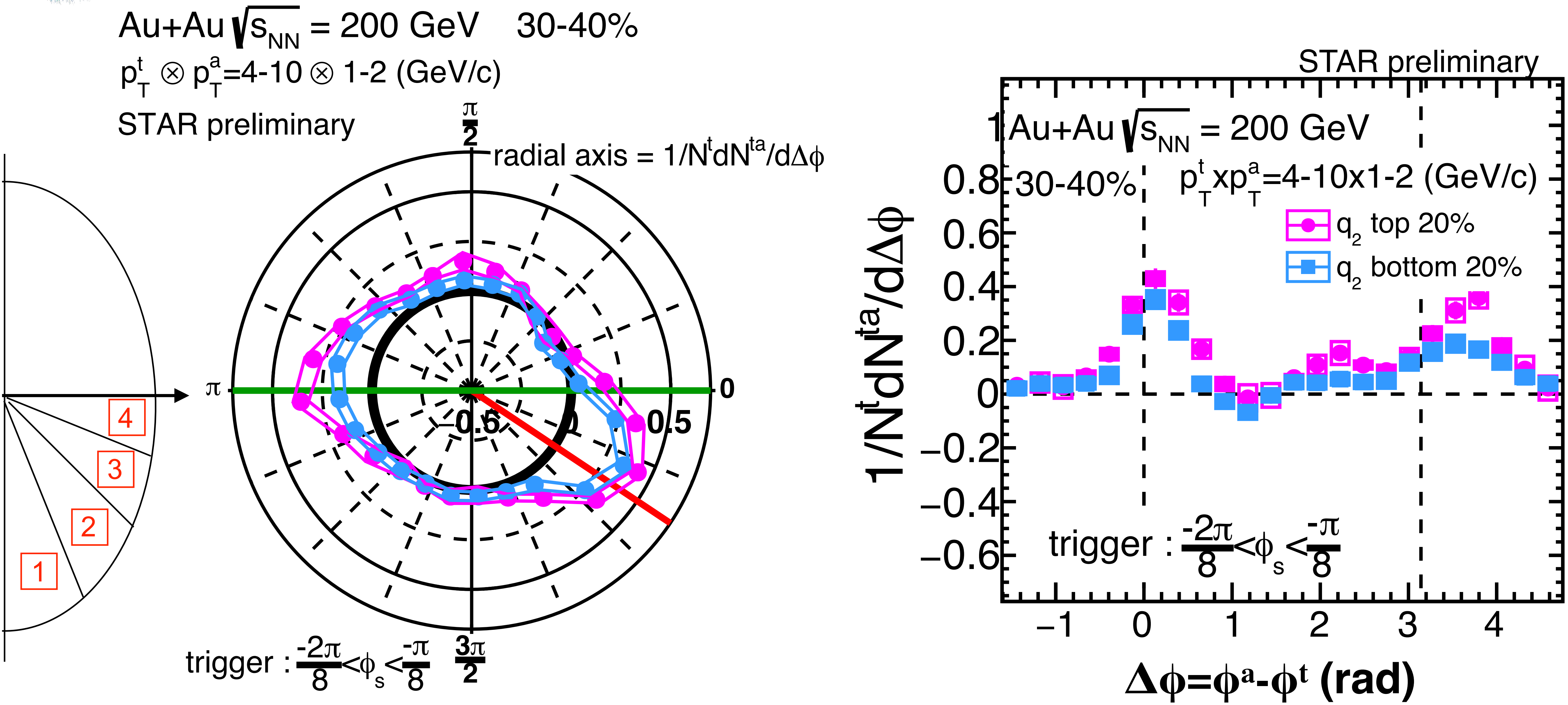
Background subtraction :
assuming ZYAM with inclusive-triggered correlations and subtract v_2, v_3 and v_4 contributions

v_2 with ESE



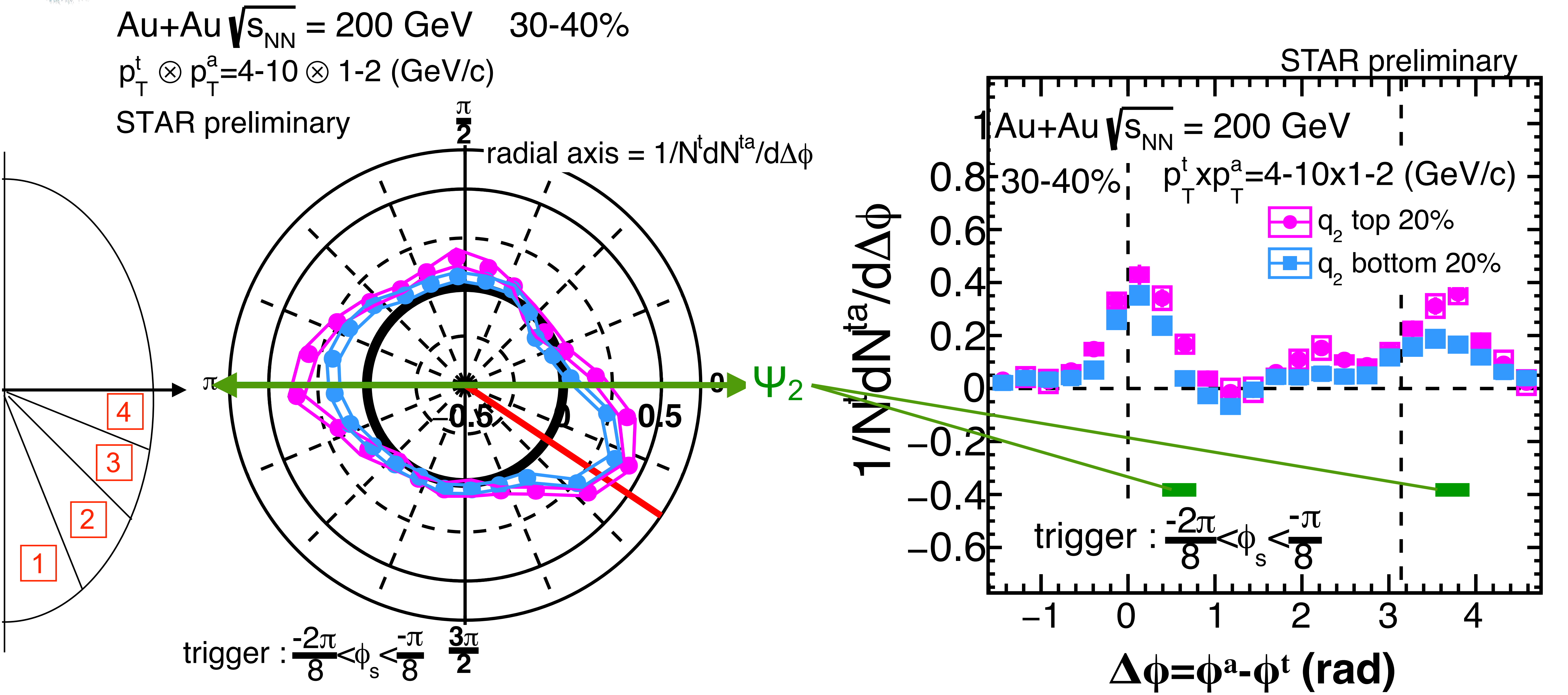
- ✦ v_2 is measured via event plane method with TPC-EP with taking 1.0 η gap
- ✦ 20% largest and smallest q_2 vectors are selected with the same region as TPC-EP
- ✦ Top 20% q_2 selection leads to **~10% larger v_2 events**
- ✦ Bottom 20% q_2 selection leads to **~8% smaller v_2 events**

Polar representation of correlated yield



- ✦ Two axes should be considered : **back-to-back trigger axis** and **EP axis**
  - Polar representations are displayed so that the correlation shapes are visually clear
- ✦ Relative angle Δϕ starts from red line and rotate toward counter-clockwise direction
- ✦ The amplitudes of correlated yield correspond to the radius

Polar representation of correlated yield



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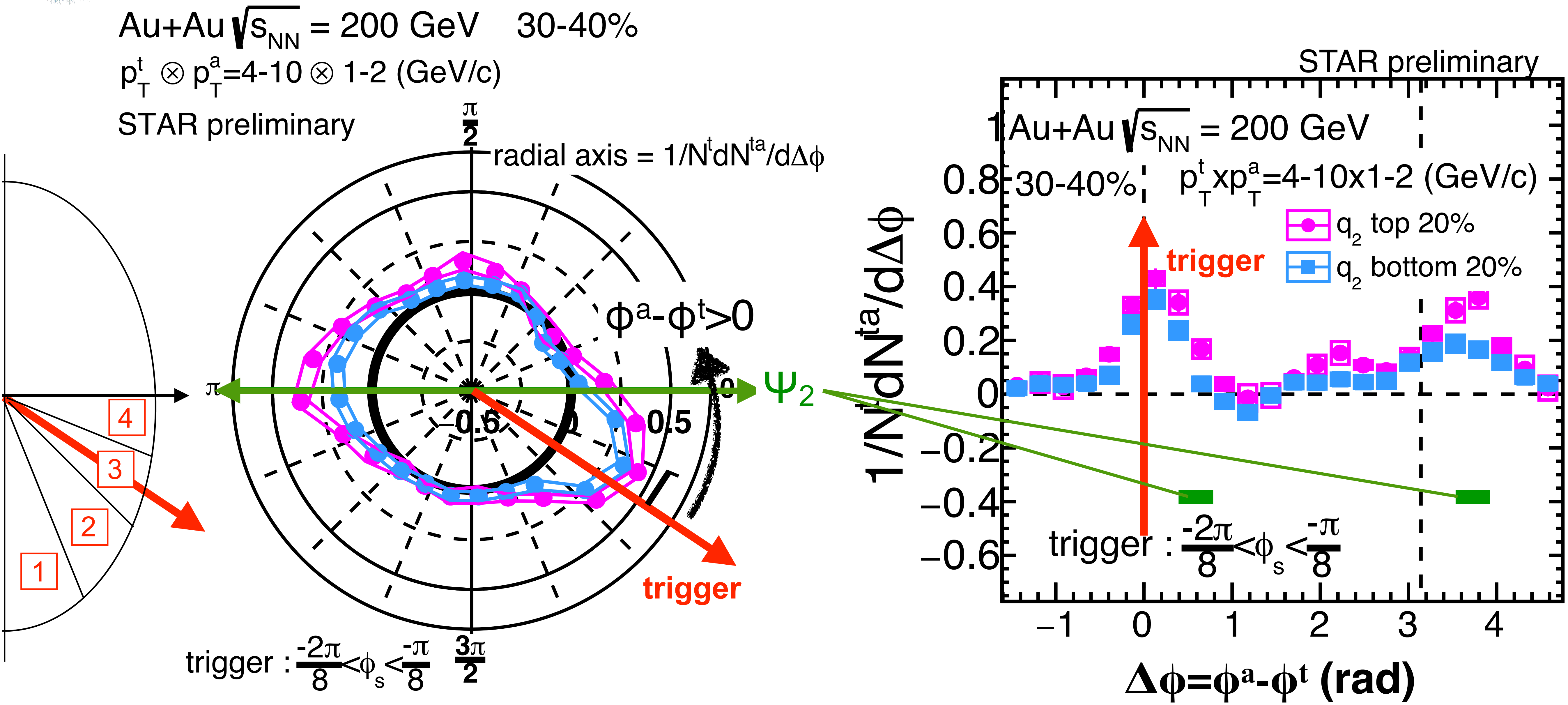

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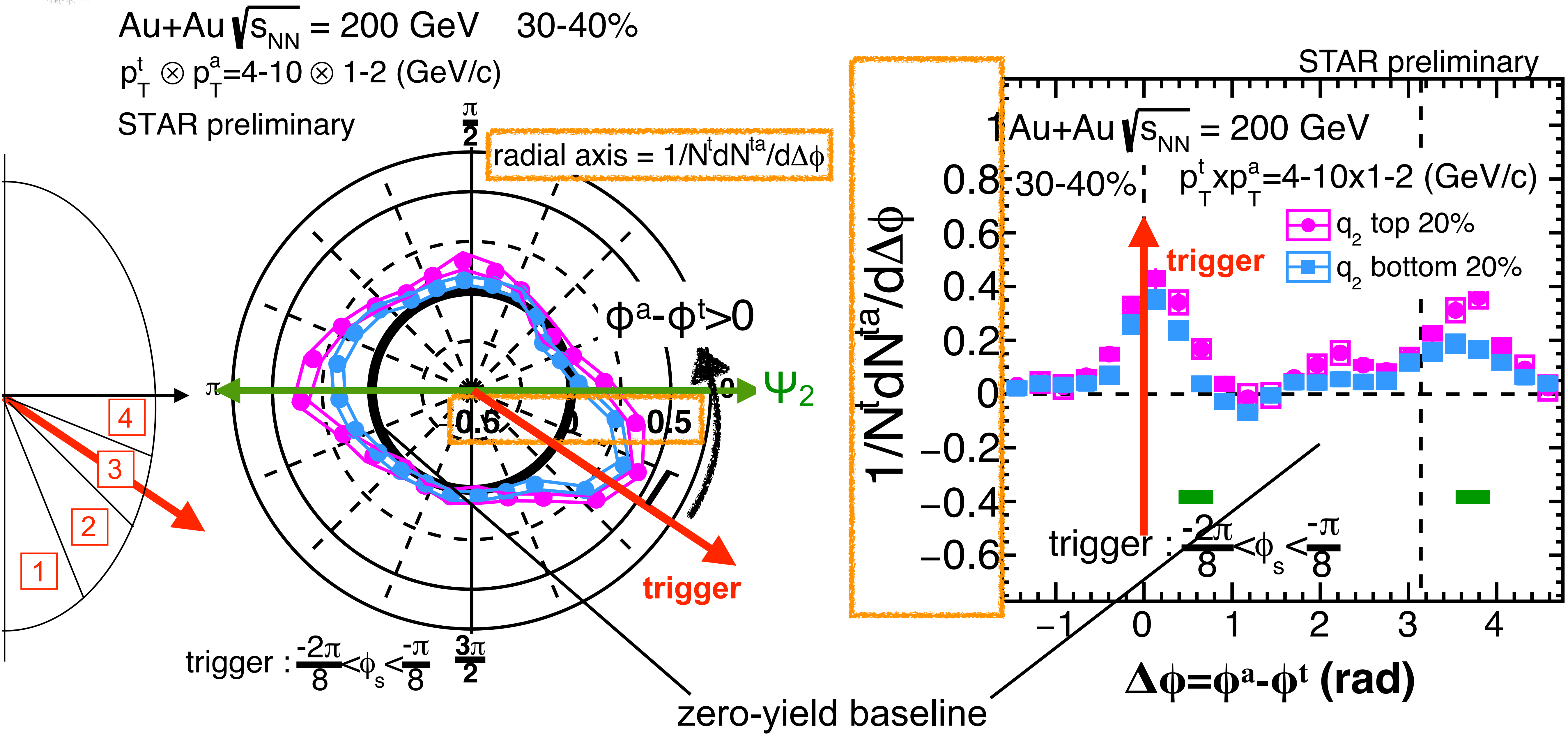

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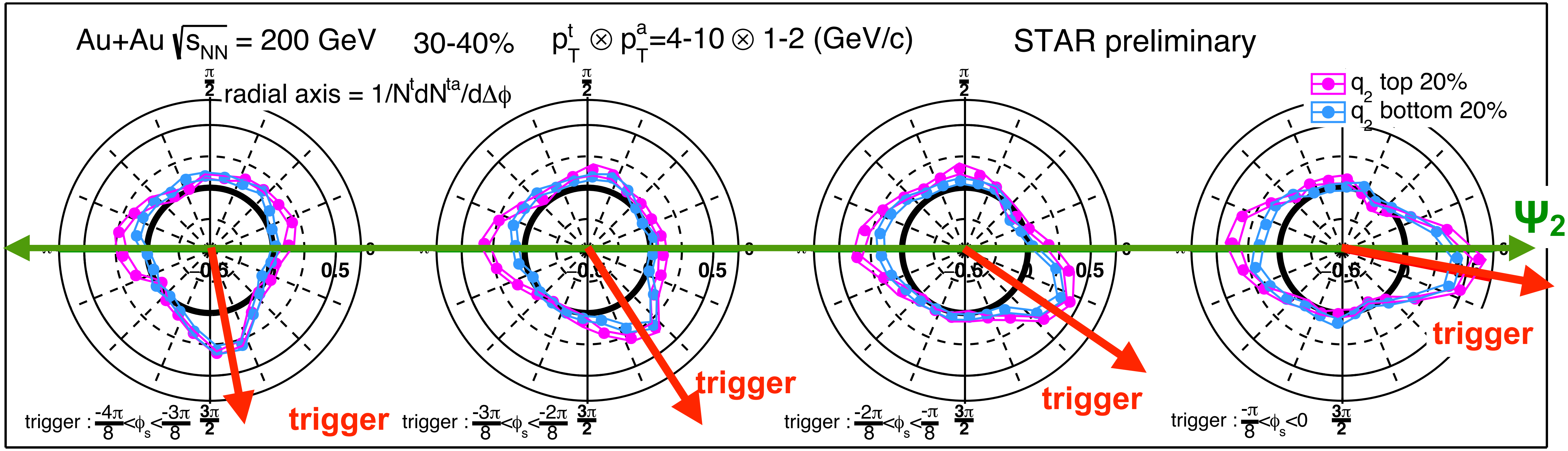
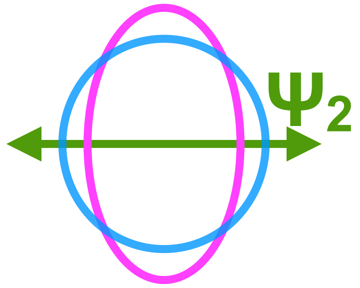
Trigger angle dependence



out-of-plane trigger ⟷ in-plane trigger

✦ **Near side**

- No difference between large-q_2 and small-q_2 events with trigger out-of-plane
- Peak height is enhanced with going to in-plane trigger
  - The enhancement is larger in large-q_2 events

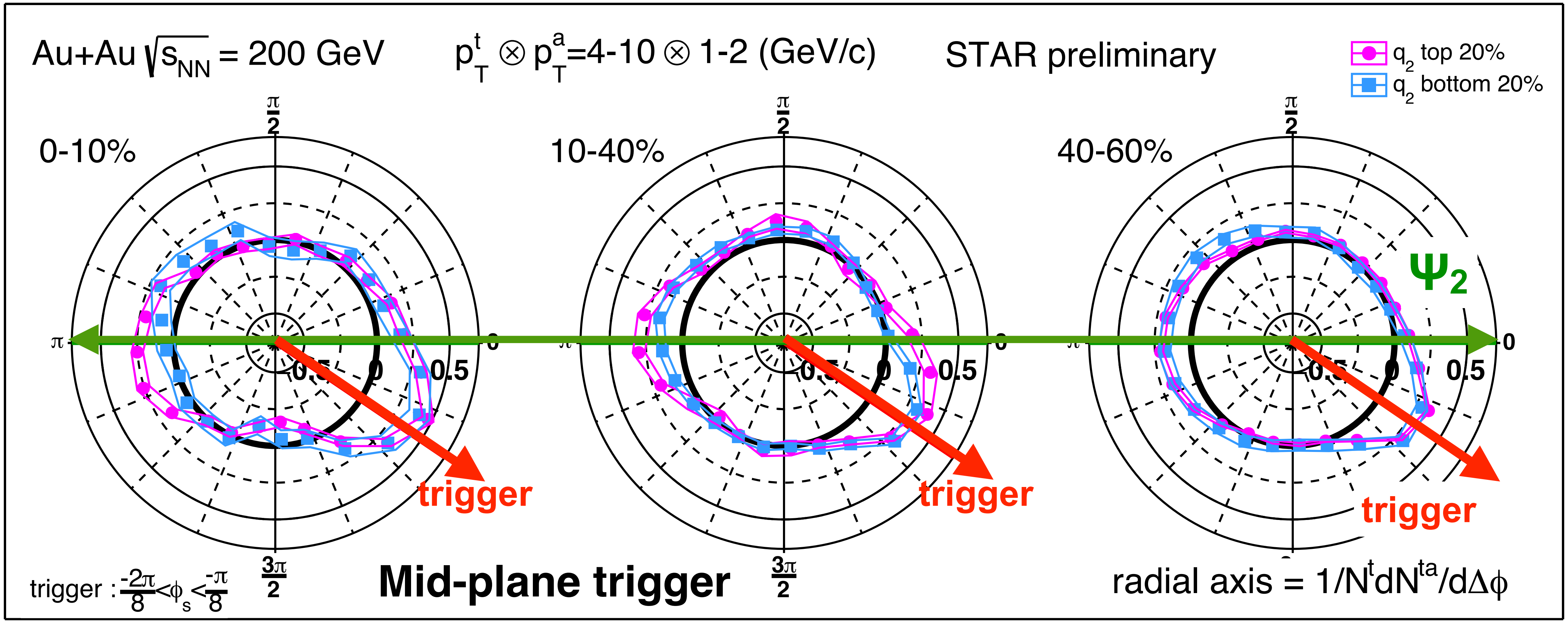


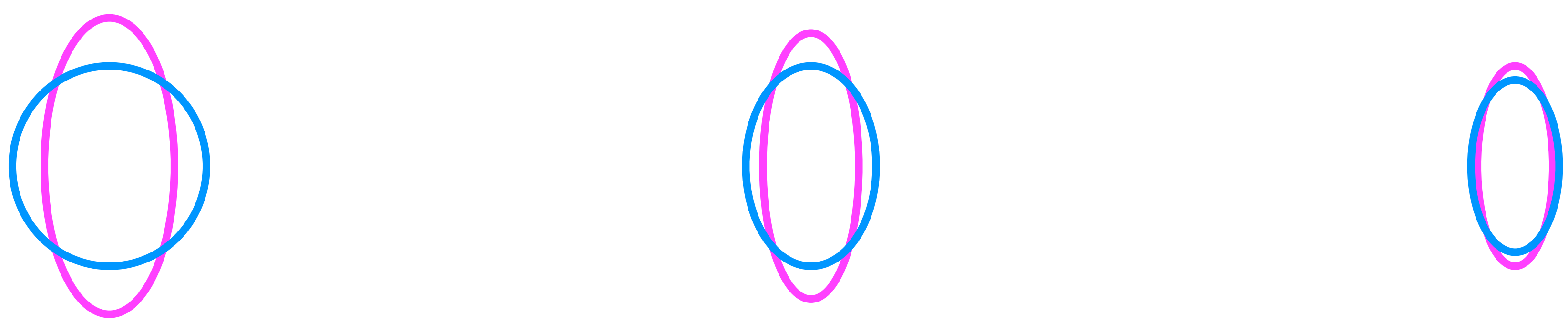
✦ **Away side**

- Peak is almost fully suppressed with trigger out-of-plane both in large-q_2 and small-q_2 events and remnant yield in the EP direction has q_2 dependence
- Peak height is enhanced with going to in-plane trigger

➡ **Low-p_T particles preferentially escape toward in-plane direction?**

Centrality dependence



central

peripheral

✦ See how shifting of away-side peak depends on centrality and q_2

✦ Larger shift in large q_2 events

✦ q_2 dependence is stronger in central events

✦ No q_2 dependence in peripheral events

➡ Related to path-length or initial eccentricity?

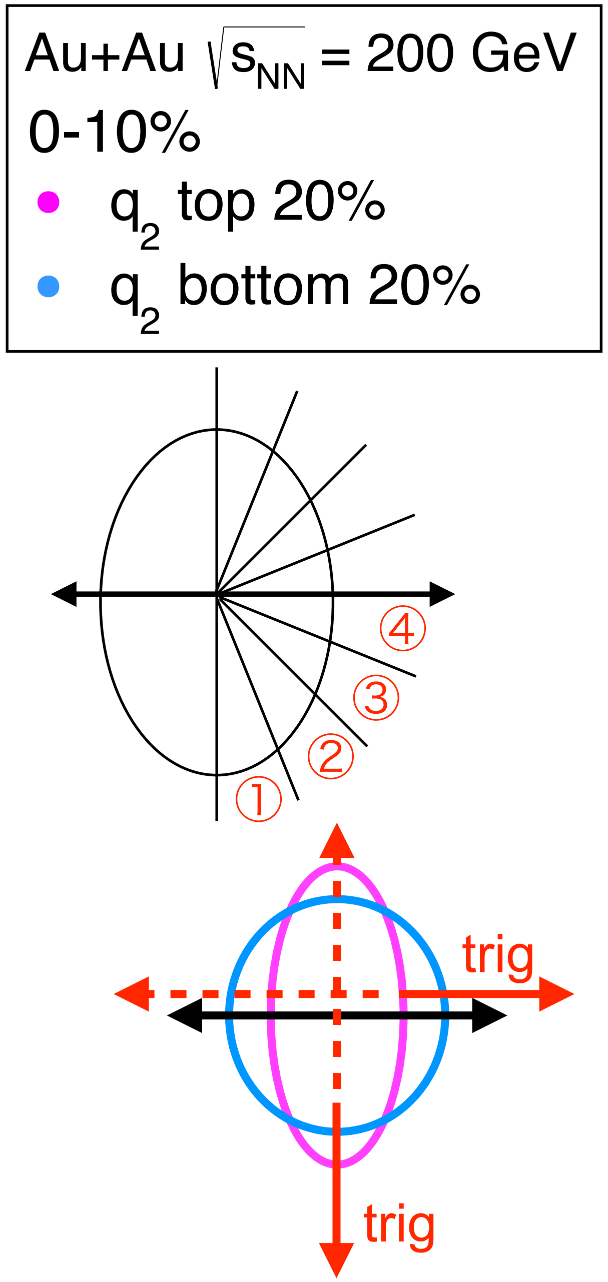
Summary

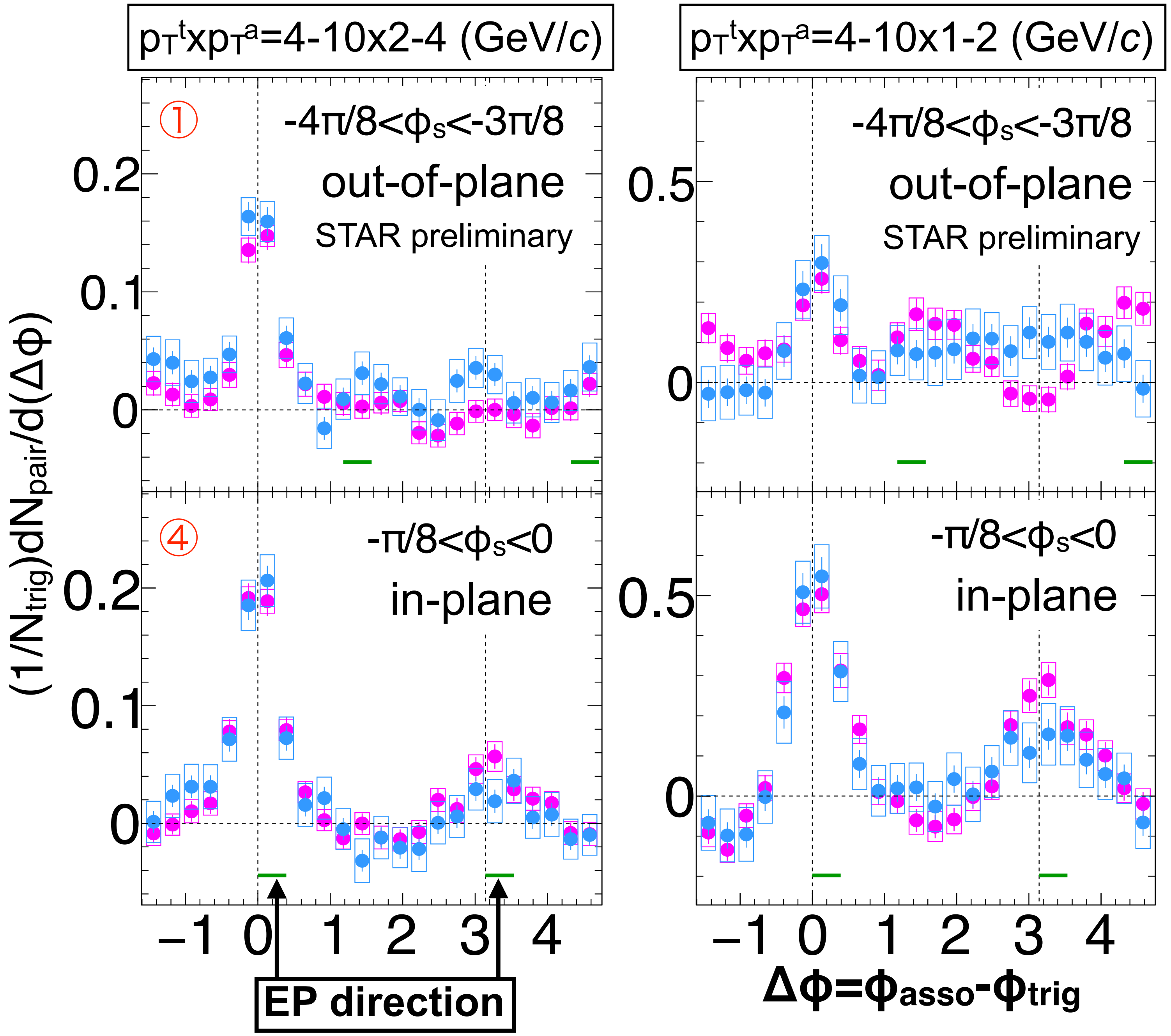
- **Di-hadron correlations with respect to the event plane with event shape engineering at the STAR experiment**
  - Separation between large-q_2 and small-q_2 events enhances difference of correlation shape while preserving average multiplicity in central and mid-central collisions
    ➡ new handle to differentially study partonic energy loss mechanisms

- **Future work**
  - Near- and away-side structure will be quantitatively discussed
  - Experimental results will be compared with some models

Back up

Correlations with q_2 selection

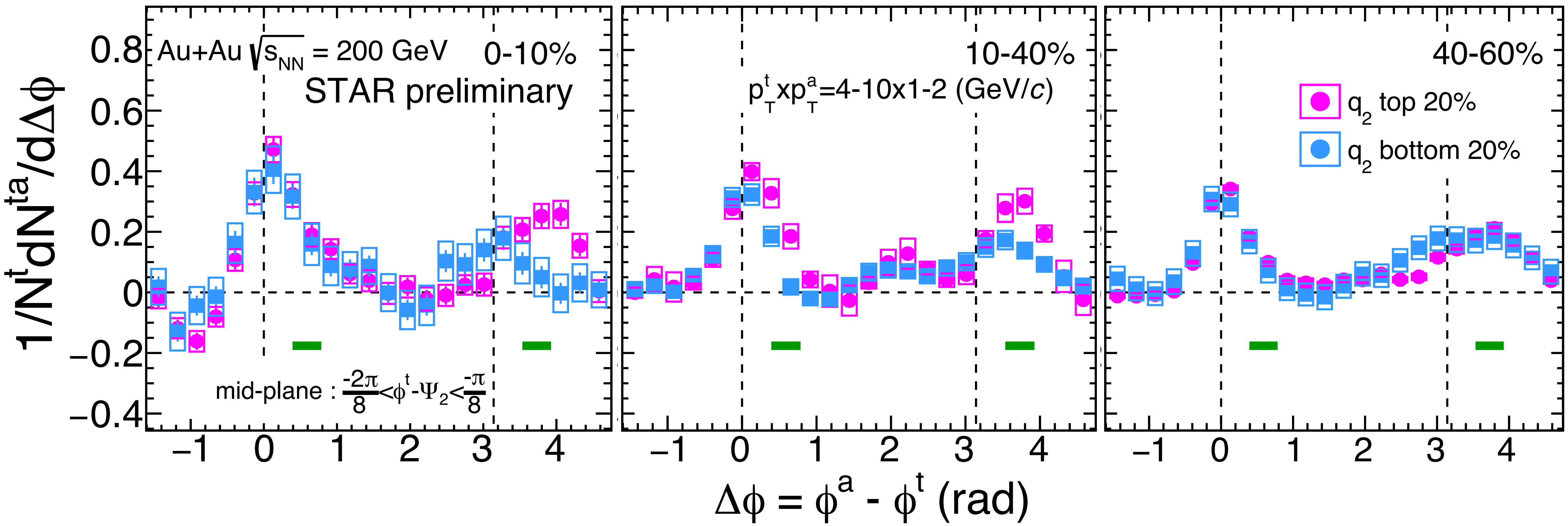


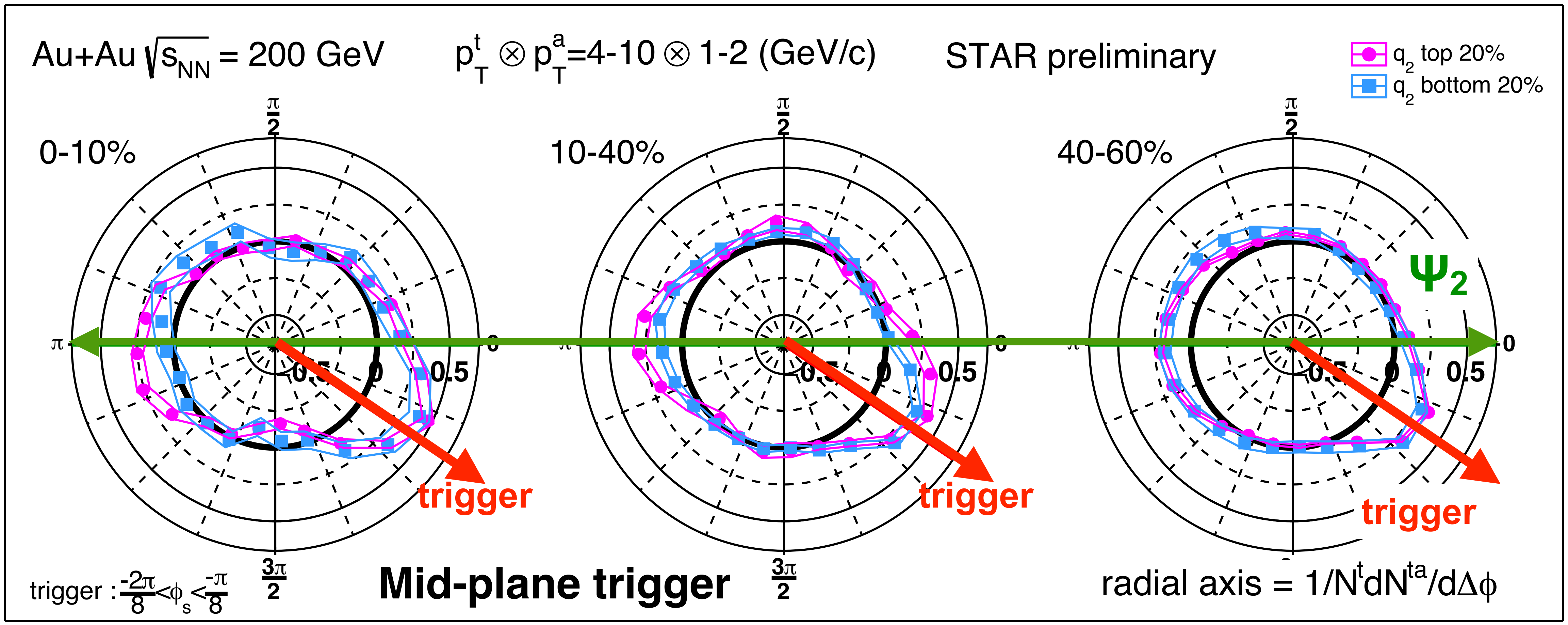


- ✦ High-p_T particles penetrate more with short path length
- ✦ Low-p_T particles are pushed toward in-plane direction and this effect is stronger in large q_2

➡ path-length dependent yield on the away side

Comparison of polar and traditional distributions





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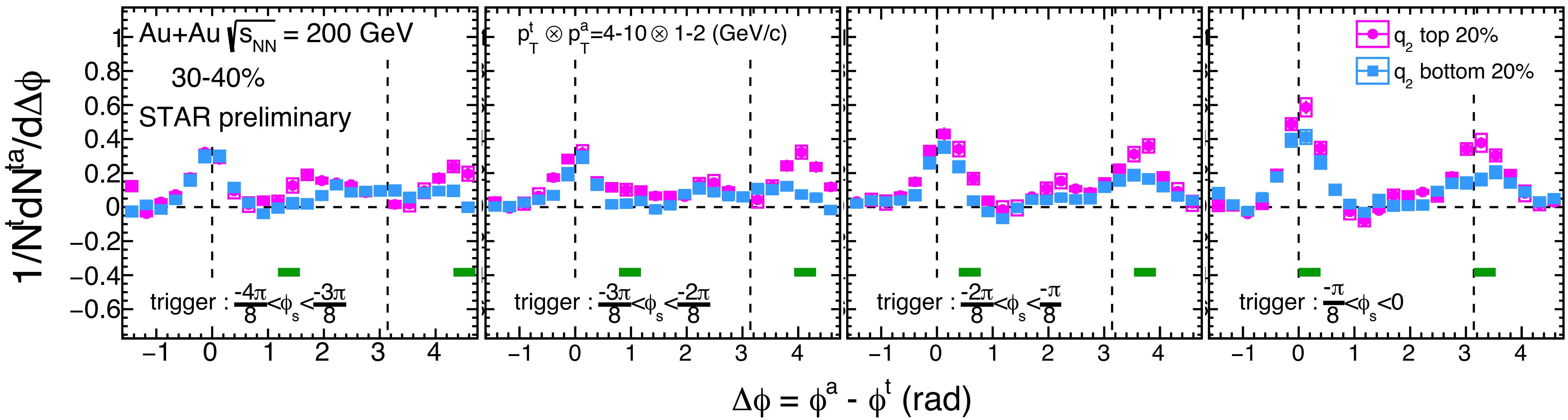
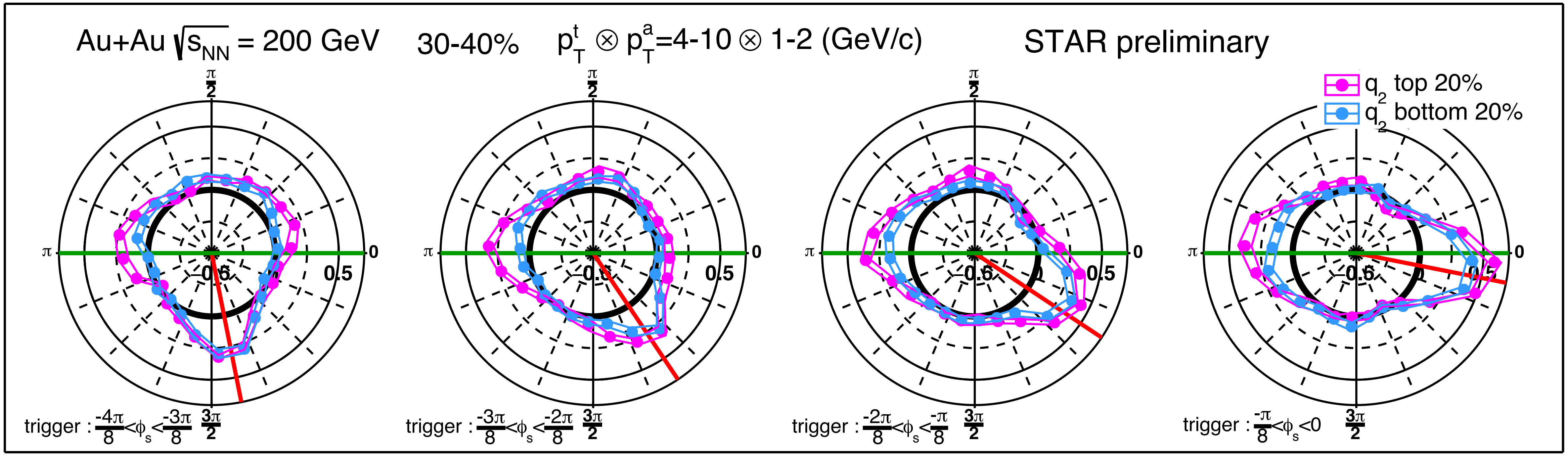
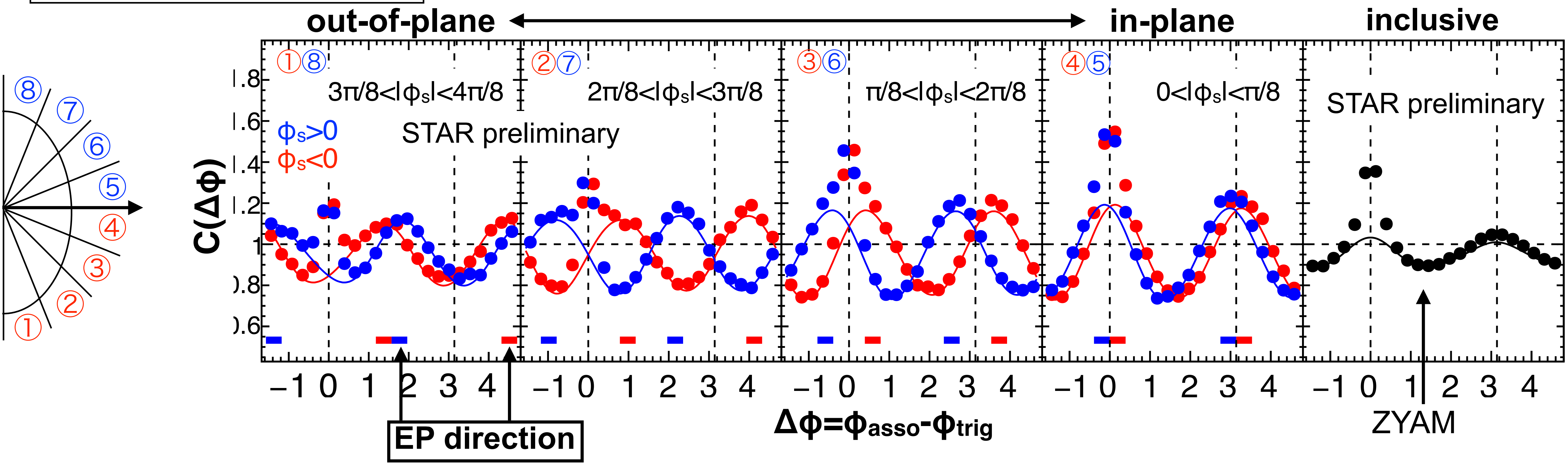




Correlations before flow subtraction and EP correction

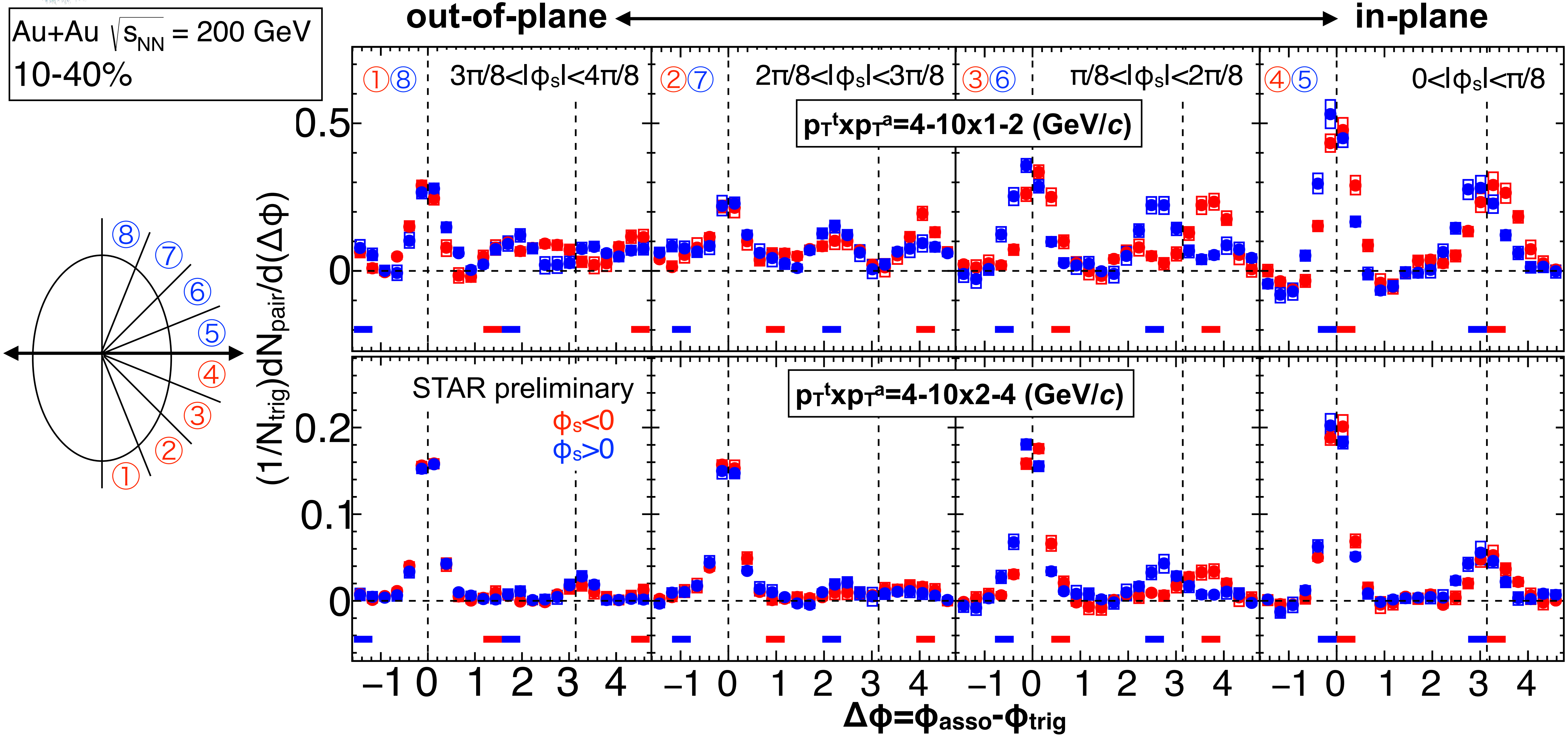
Au+Au $\sqrt{s_{NN}}$ = 200 GeV
20-30%, w/o q_2 selection
$p_T^t \times p_T^a$=4-10x2-4 (GeV/c)

● raw data
– background function ($v_2 \oplus v_3 \oplus v_4$)

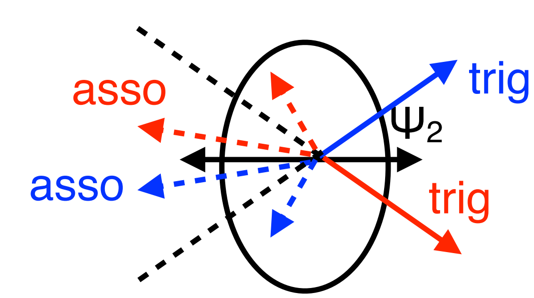


- ✦ Correlation shape
  - Left/Right mirror symmetric trigger selection w.r.t. EP leads to **mirror-imaged distributions** on the away side
- ✦ Flow background subtraction
  - Background **shape** is determined by data-driven simulation
  - Background **level** is determined by inclusive trigger data with ZYAM assumption
- ✦ Correction of trigger smearing effect
  - Smearing of trigger particle's angle due to limited EP resolution is corrected with unfolding method after flow subtraction

Correlations after flow subtraction and EP correction



- ✦ Amplitudes increase as going to in-plane trigger on both near and away side
- ✦ Left/Right separation leads to asymmetric path length
  - averaged out in the previous measurement
- ✦ Away-side particles pushed toward in-plane direction



➡ path-length dependent jet modification

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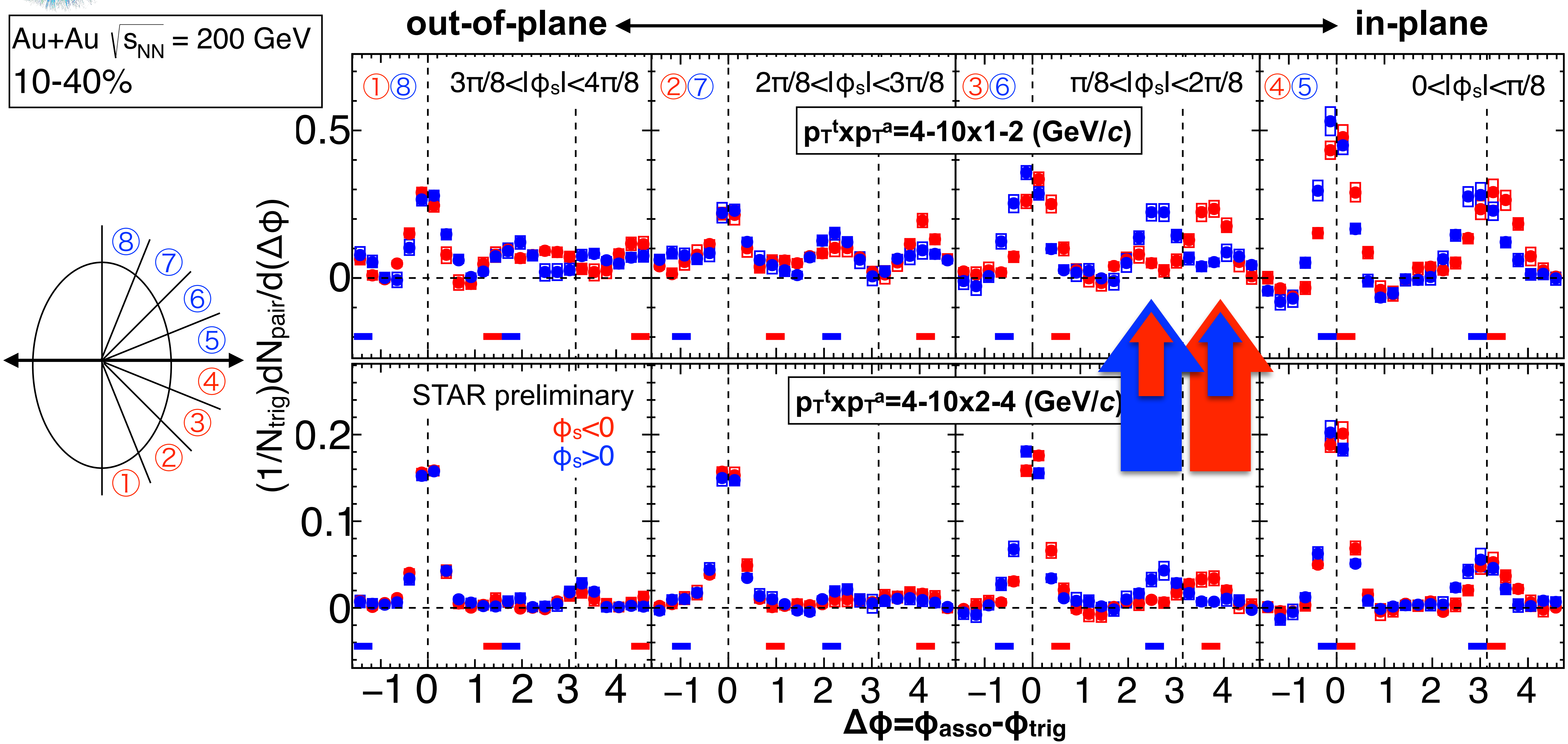

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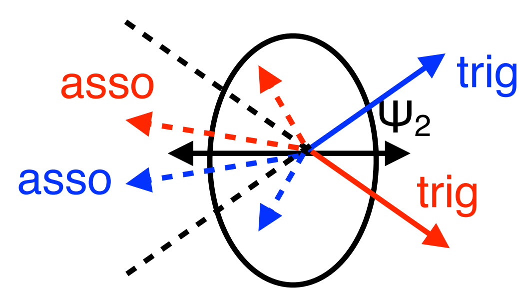
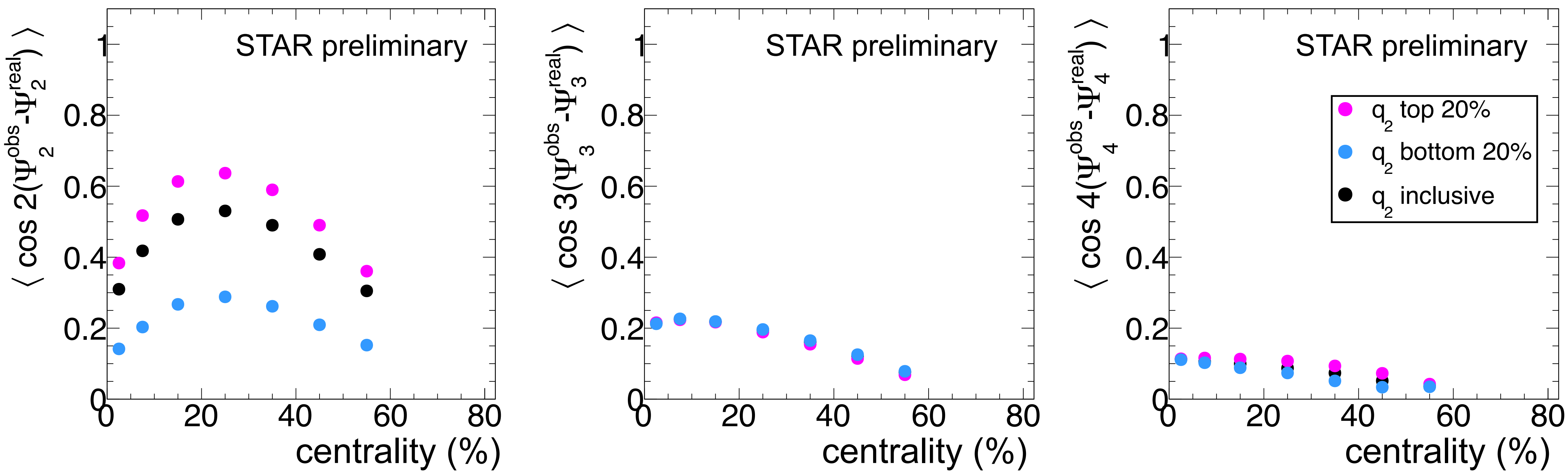
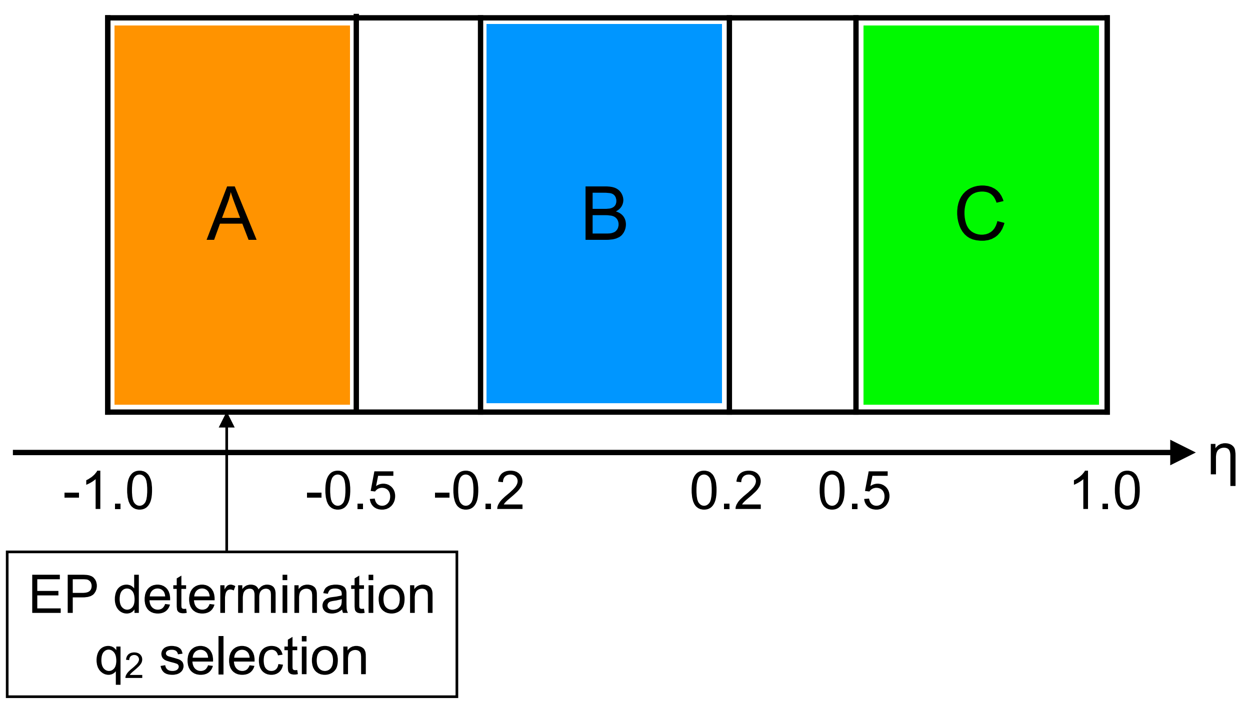


➡ path-length dependent jet modification

Resolution of EP

Au+Au $\sqrt{s_{NN}}$ = 200 GeV





EP resolution via 3 sub-event method

$$\mathrm{Res}\{\Psi_n^A\} = \sqrt{\frac{\langle \cos n(\Psi_n^A - \Psi_n^B)\rangle \langle \cos n(\Psi_n^A - \Psi_n^C)\rangle}{\langle \cos n(\Psi_n^B - \Psi_n^C)\rangle}}$$

Res{Ψ_n^A} is shown in the upper figure

Data-driven flow MC simulation

Reconstruct flow distribution by Monte Carlo simulation

Input parameter : v_2, v_3, v_4, χ_{42}, and Res{Ψ_2}

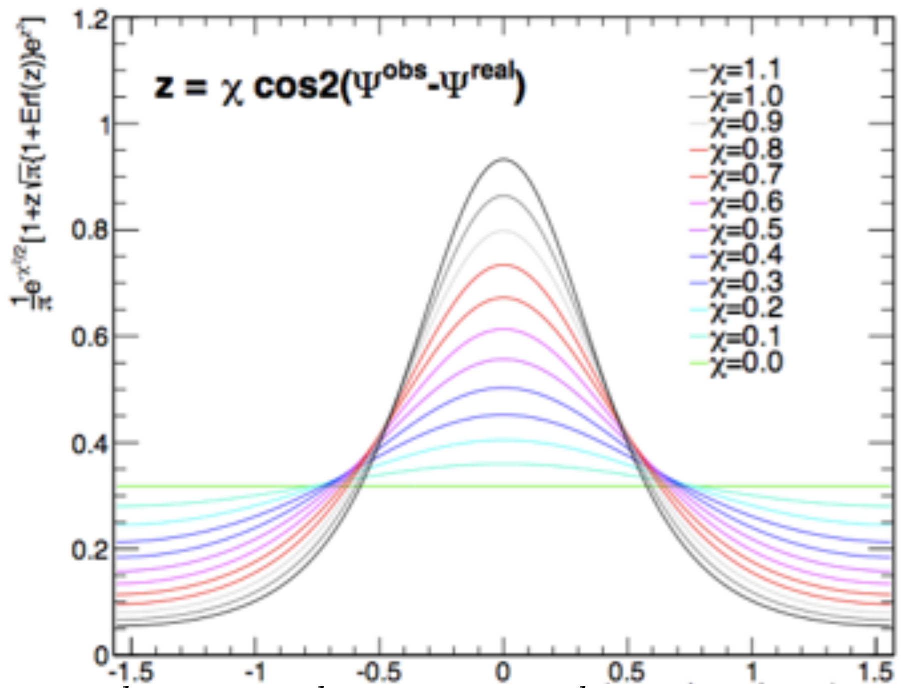
1. generate Ψ_2, Ψ_3 at random and Ψ_4 with considering correlation between Ψ_2 and Ψ_4
2. make flow distribution which reproduce v_n
3. smear trigger particle's angle with probability distribution when selecting trigger particles angle
4. generate particles at random along the flow distribution and calculate $\Delta\phi$

Probability distribution can be written with χ_n which is calculated with following formula :

$$\langle\cos[kn(\Psi_n^{obs} - \Psi_n^{real})]\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_n e^{-\chi_n^2/4}\left[I_{(k-1)/2}\left(\frac{\chi_n^2}{4}\right) + I_{(k-1)/2}\left(\frac{\chi_n^2}{4}\right)\right]$$

Jean-Yves OLLITRAULT, PRD 48 (1993) 1132

example of probability distributions of $\Delta\Psi_2$



$$\Psi_n^{obs} - \Psi_n^{real} = (\phi^t - \Psi_n^{obs}) - (\phi^t - \Psi_n^{real})$$

Trigger smearing correction via fitting method

Assuming the associate-particles yield are distributed with respect to the event plane, we can correct the effect of trigger smearing due to the limited event-plane resolution which is similar to the resolution correction in the flow measurement of the single particles.

$$\frac{dN^{1+PTY}}{d(\phi^a - \Psi_2)} = 1 + Y(\phi_s, \Delta\phi)$$
$$= 1 + 2v_2^Y \cos 2(\phi_s + \Delta\phi) + 2v_4^Y \cos 4(\phi_s + \Delta\phi) \quad ...(1)$$

$$\phi_s + \Delta\phi = (\phi^t - \Psi_2) + (\phi^a - \phi^t) = \phi^a - \Psi_2$$

Applying a Fourier fitting eq.(3) to $1+Y(\phi_s,\Delta\phi)$ as a function of ϕ_s with a phase shift $\Delta\phi$, v_n^Y can be determined and the azimuthal distributions can be corrected with corrected v_n^Y by the event-plane resolution eq.(5).

$$\frac{dN_{cor}^{1+PTY}}{d(\phi^a - \Psi_2)} = 1 + 2\frac{v_2^Y}{\sigma_2} \cos 2(\phi_s + \Delta\phi) + 2\frac{v_4^Y}{\sigma_{42}} \cos 4(\phi_s + \Delta\phi) \quad ...(2)$$

$$F(\phi_s)^{raw} = 1 + 2v_2^{raw} \cos 2(\phi_s + \Delta\phi) + 2v_4^{raw} \cos 4(\phi_s + \Delta\phi) \quad ...(3)$$
$$F(\phi_s)^{cor} = 1 + 2\frac{v_2^{raw}}{\sigma_2} \cos 2(\phi_s + \Delta\phi) + 2\frac{v_4^{raw}}{\sigma_{42}} \cos 4(\phi_s + \Delta\phi) \quad ...(4)$$

$$1 + Y^{cor}(\phi_s, \Delta\phi) = \frac{F(\phi_s)^{cor}}{F(\phi_s)^{raw}} \cdot (1 + Y^{raw}(\phi_s, \Delta\phi)) \quad ...(5)$$

$\sigma_2 = \langle\cos 2(\Psi_2^{obs} - \Psi_2^{real})\rangle$
$\sigma_{42} = \langle\cos 4(\Psi_2^{obs} - \Psi_2^{real})\rangle$

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Trigger smearing correction via iteration method

bin-by-bin iterative unfolding correction method for $Y(\Delta\varphi,\varphi_s)$

Y^{raw} : yield before correction
O : offset
$A^{(n)}$: n-th corrected data
$B^{(n)}$: n-th smeared correlation
$C^{(n)}$: n-th correction function
x,y : index of $\Delta\varphi$ and φ_s
Y^{corr} : yield after correction

input
(raw data) + offset

$A^{(0)} = Y^{raw}+O$

smear (n-1)-th corrected data
for φ_s direction
with using probability distribution (P.21)

$B^{(n)} = SA^{(n-1)}$

make correction function
((n-1)-th corrected data) / (n-th smeared data)

$C^{(n)}(x,y) = A^{(n-1)}(x,y)/B^{(n)}(x,y)$

iteration

smooth correction function
with neighboring bins
with using smoothing parameter

$$C^{(n)}(x,y) = p_{\Delta\varphi}\{C^{(n)}(x-1,y)+C^{(n)}(x+1,y)\} + p_{\varphi s}\{C^{(n)}(x,y-1)+C^{(n)}(x,y+1)\}$$

correction of raw data
with n-th correction function

$A^{(n)}(x,y) = C^{(n)}(x,y)*A^{(0)}(x,y)$

after converge

output
(corrected data) - offset

$Y^{corr} = A^{(n)}-O$

Sources of systematics

- v_2, v_3 and v_4
  - including track cut, EP selection, and difference between v_n\{EP\} and v_n\{2PC\}
- EP resolution
  - difference between East and West for trigger smearing in toy-MC
- EP correlation between different order harmonics
  - only Ψ_2-Ψ_4 correlations
- $\Delta\phi$ range used for determination of zero-yield baseline
  - $\pi/6$ (default), $\pi/12$, $\pi/4$
- Trigger smearing correction
  - range of fitting method and iteration method
  - RMS of various smoothing parameter for ϕ_s and $\Delta\phi$