# Search of the Chiral Magnetic Wave with Anisotropic Flow of Identified Particles at RHIC

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2018 Quark Matter Venezia

SINAP

STAR

BROOKHAVEN NATIONAL LABORATORY

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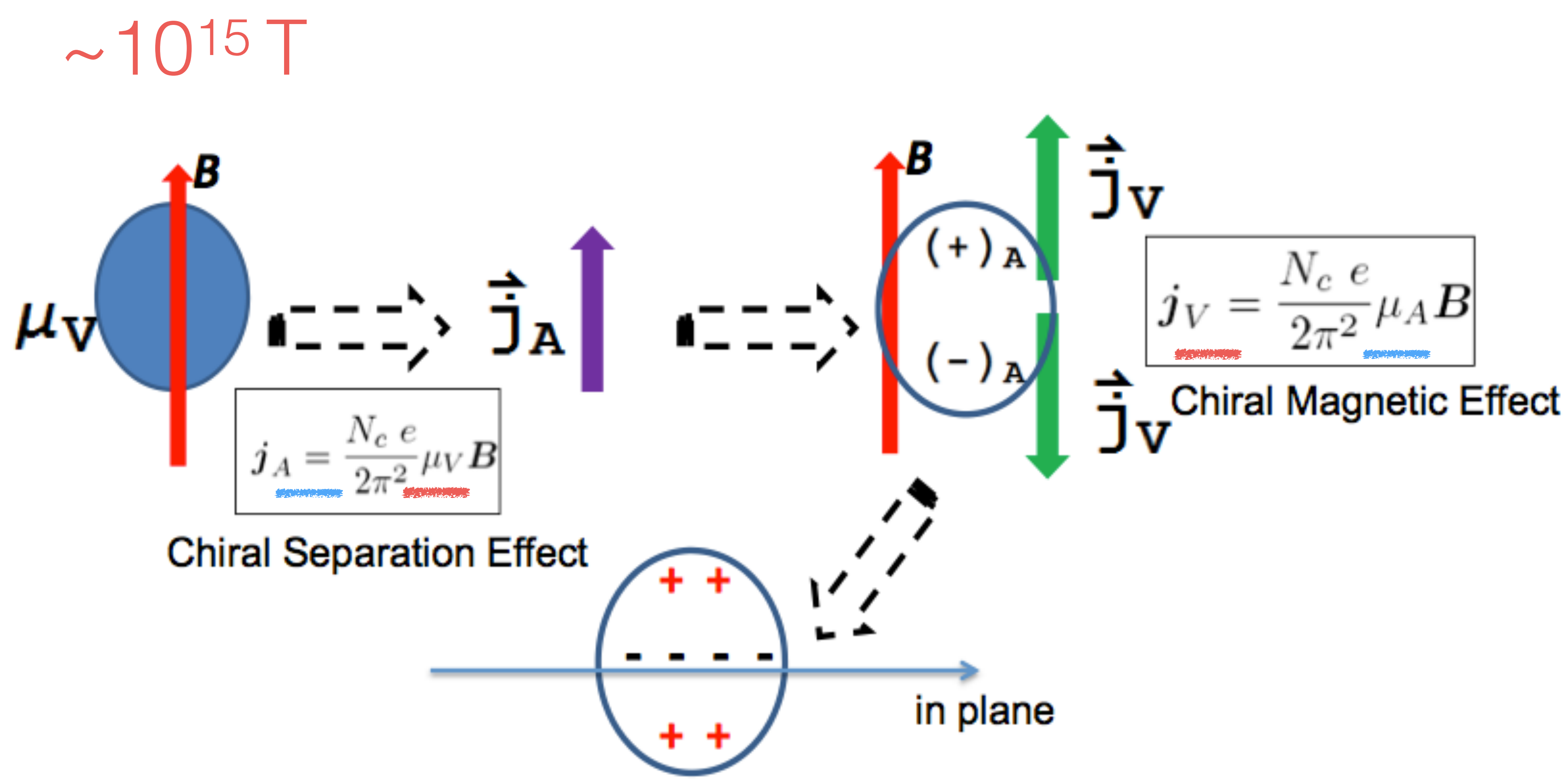
# Chiral Magnetic Wave

Y. Burnier, D. E. Kharzeev, J. Liao, and H.-U. Yee, Phys. Rev. Lett. 107, 52303 (2011)




Asymmetry in the azimuthal distributions of h+ and h-

$$N_+(\phi) - N_-(\phi) = (\bar{N}_+ - \bar{N}_-)[1 - r\cos(2\phi)]$$

monopole, non-zero net charge density

$$q_e = \int RdRd\phi \cos(2\phi)[j_e^0(R,\phi) - j_{e,B=0}^0(R,\phi)]$$

$$r \equiv \frac{2q_e}{\bar{\rho}_e}$$

quadrupole, CMW contribution

$$\bar{\rho}_e = \int RdRd\phi\, j_{e,B=0}^0(R,\phi)$$

$$\frac{dN_\pm}{d\phi} = N_\pm[1 + 2v_2\cos(2\phi)]$$

$$\approx \bar{N}_\pm[1 + 2v_2\cos(2\phi) \mp A_{ch}\, r\cos(2\phi)]$$

$$A_{ch} \equiv (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-)$$

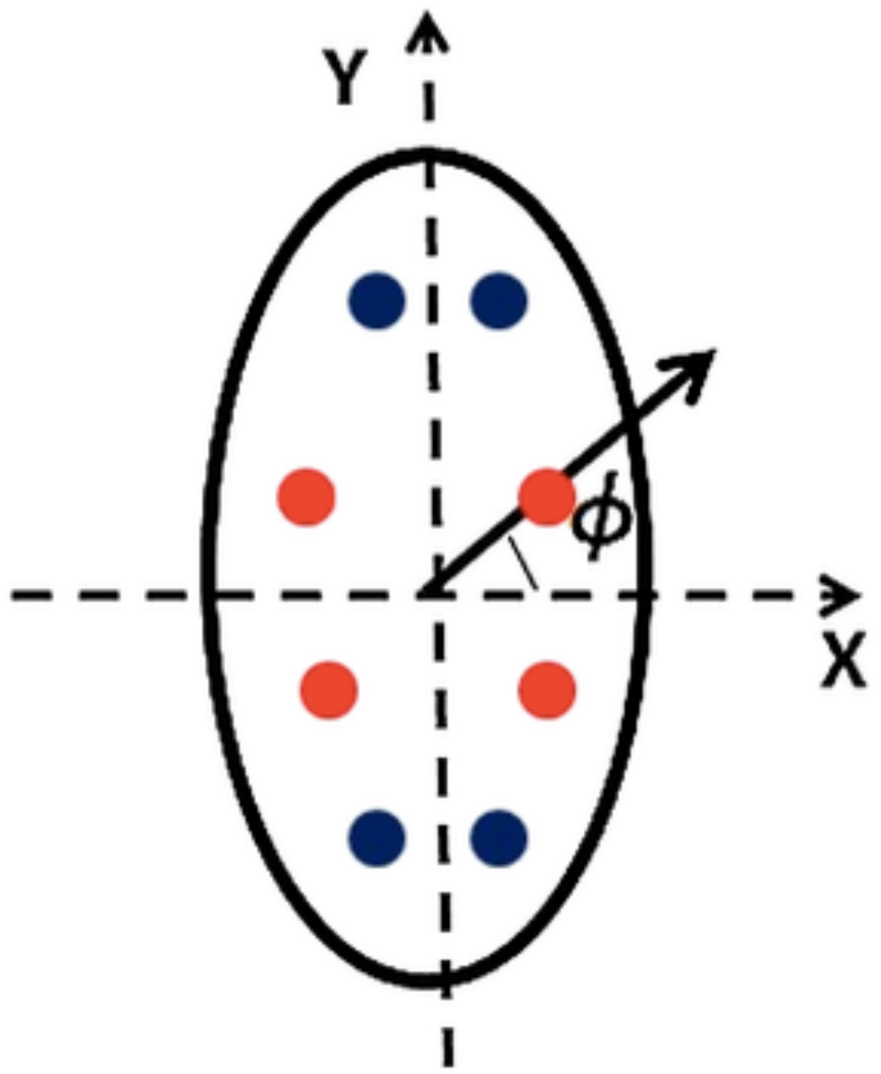
$$\Delta v_2 = v_2^- - v_2^+ \approx r\, A_{ch}$$

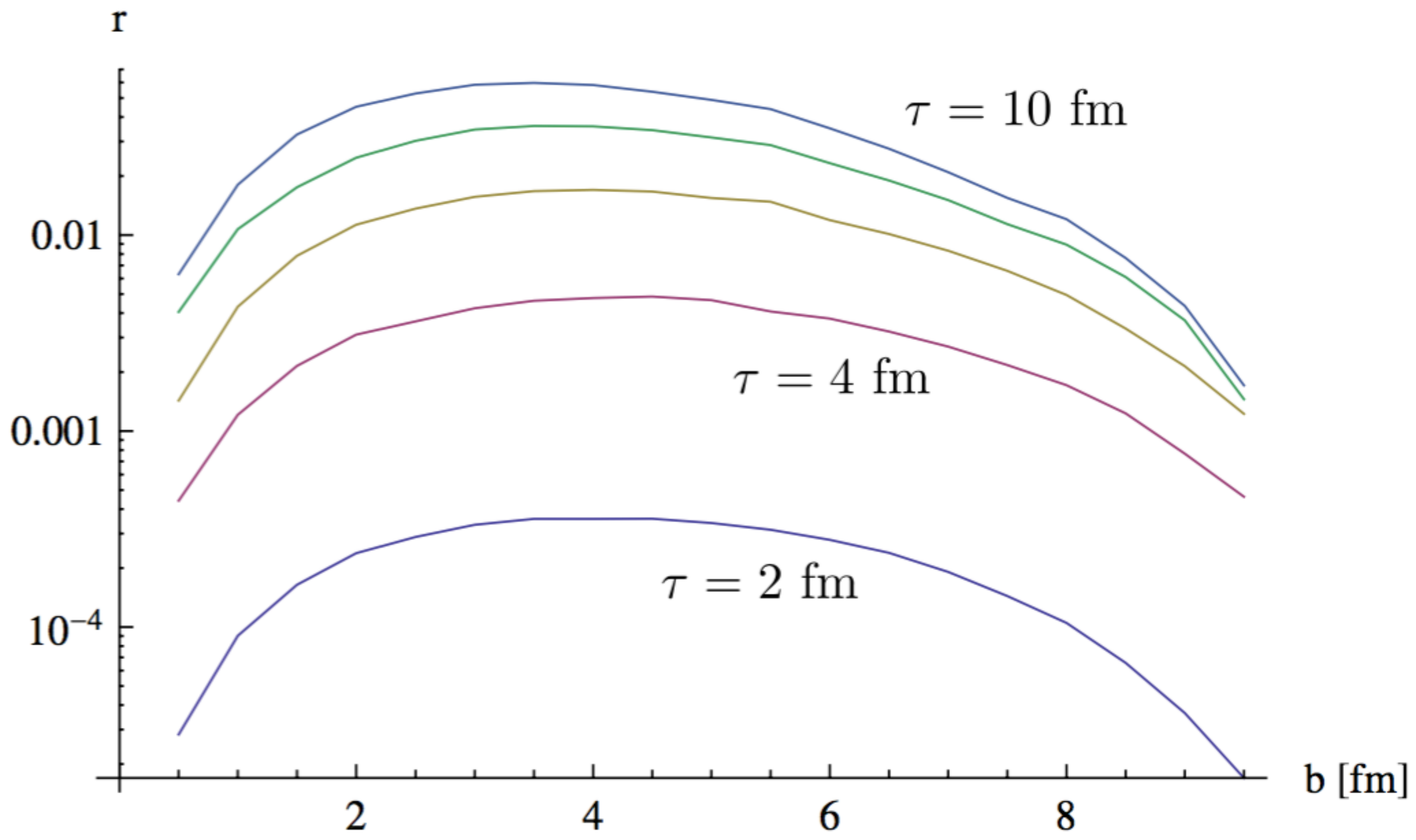
$$v_2^\pm = v_2 \mp \frac{r\, A_{ch}}{2}$$

**Observables: $\Delta v_2$, $A_{ch}$**

# Chiral Magnetic Wave

Y. Burnier, D. E. Kharzeev, J. Liao, and H.-U. Yee, Phys. Rev. Lett. 107, 52303 (2011)

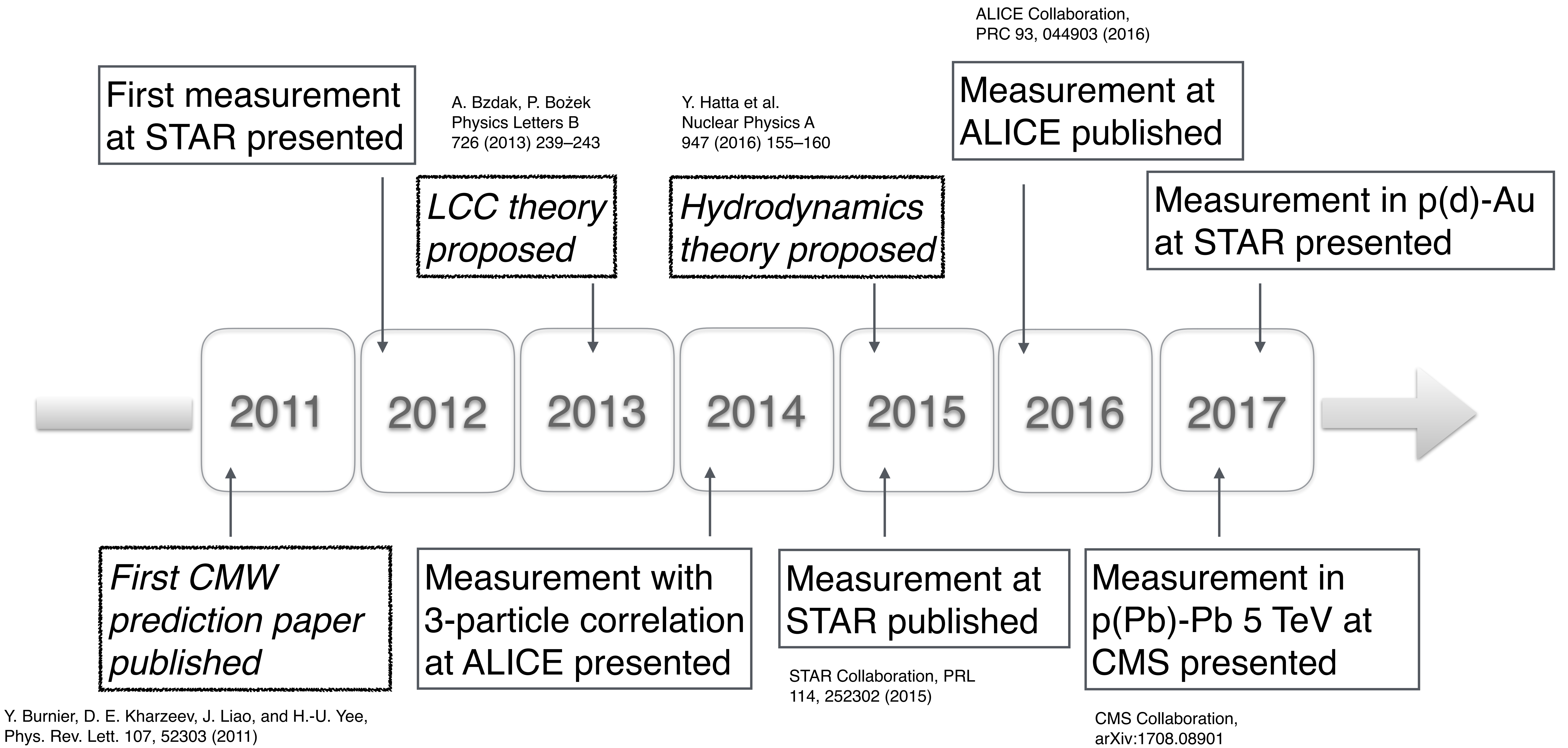



- Possible best probe: **negative and positive pions** due to the small difference in the absorption cross sections

- For **negative and positive kaons** and **antiprotons and protons**, the large differences in the absorption cross sections could **mask or reverse** the potential signal

# Brief history of CMW



# Brief history of CMW

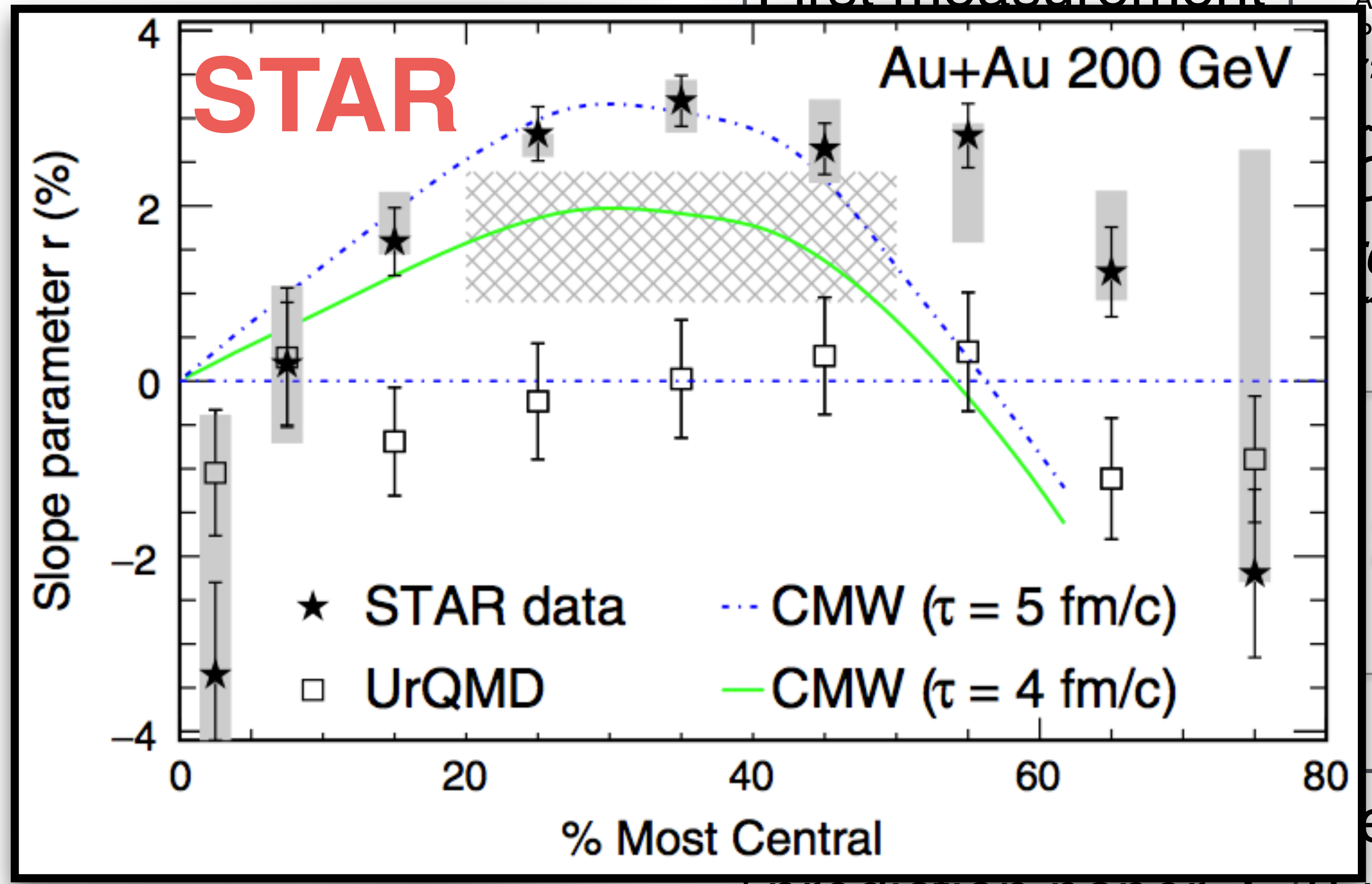
ALICE Collaboration,
PRC 93, 044903 (2016)

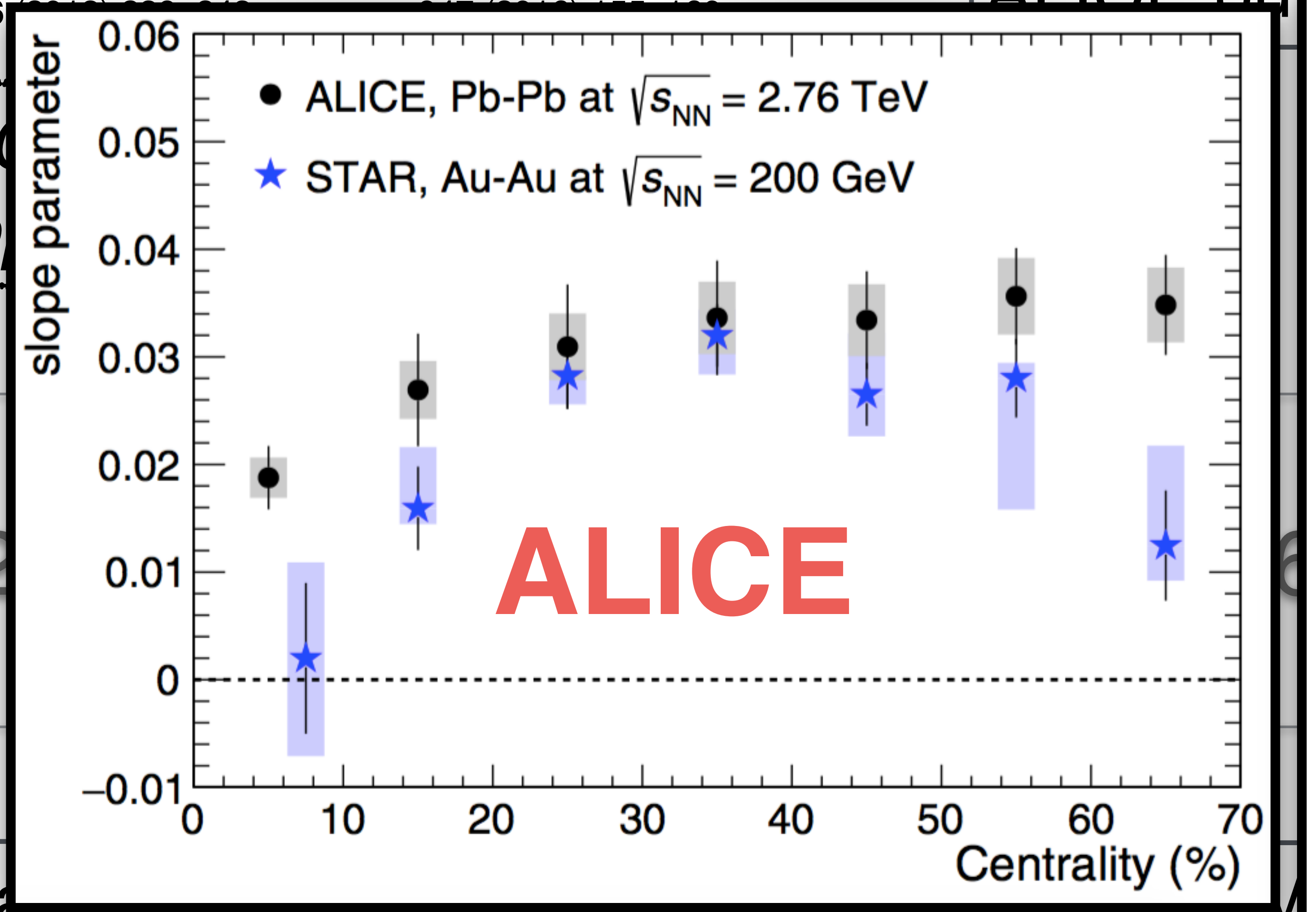
First measurement

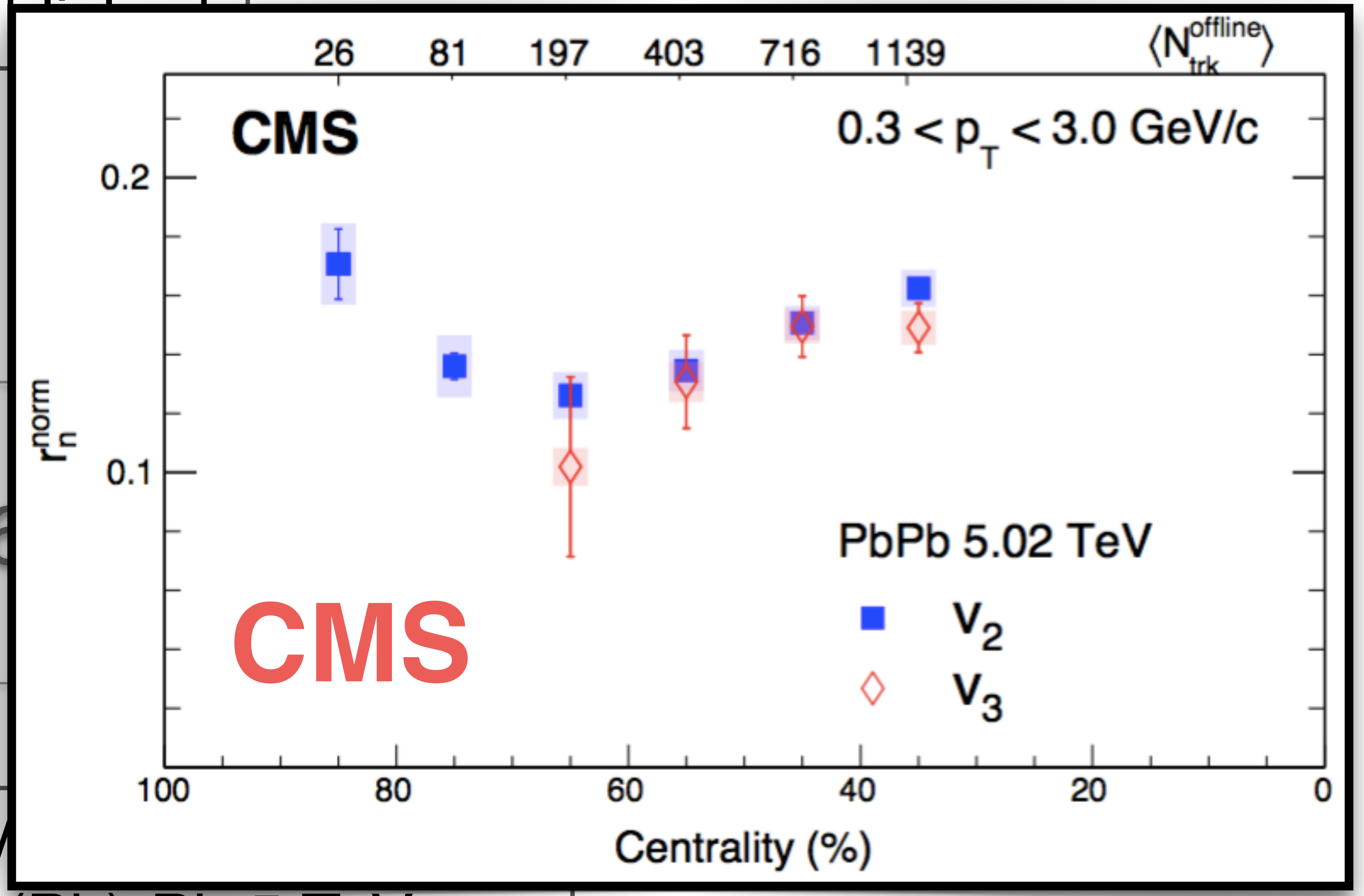
Measurement at
ALICE publi...

A. Bzdak, P. Bożek
Physics Letters B
726 ...

Y. Hatta et al.
Nuclear Physics A
...




*prediction paper published*

3-particle correlation at ALICE presented

STAR published

p(Pb)-Pb 5 TeV at CMS presented

Y. Burnier, D. E. Kharzeev, J. Liao, and H.-U. Yee,
Phys. Rev. Lett. 107, 52303 (2011).

STAR Collaboration, PRL
114, 252302 (2015)

CMS Collaboration,
arXiv:1708.08901

CMS results show the consistency between p+Pb and Pb+Pb, and between $v_2$ and $v_3$, what about RHIC?

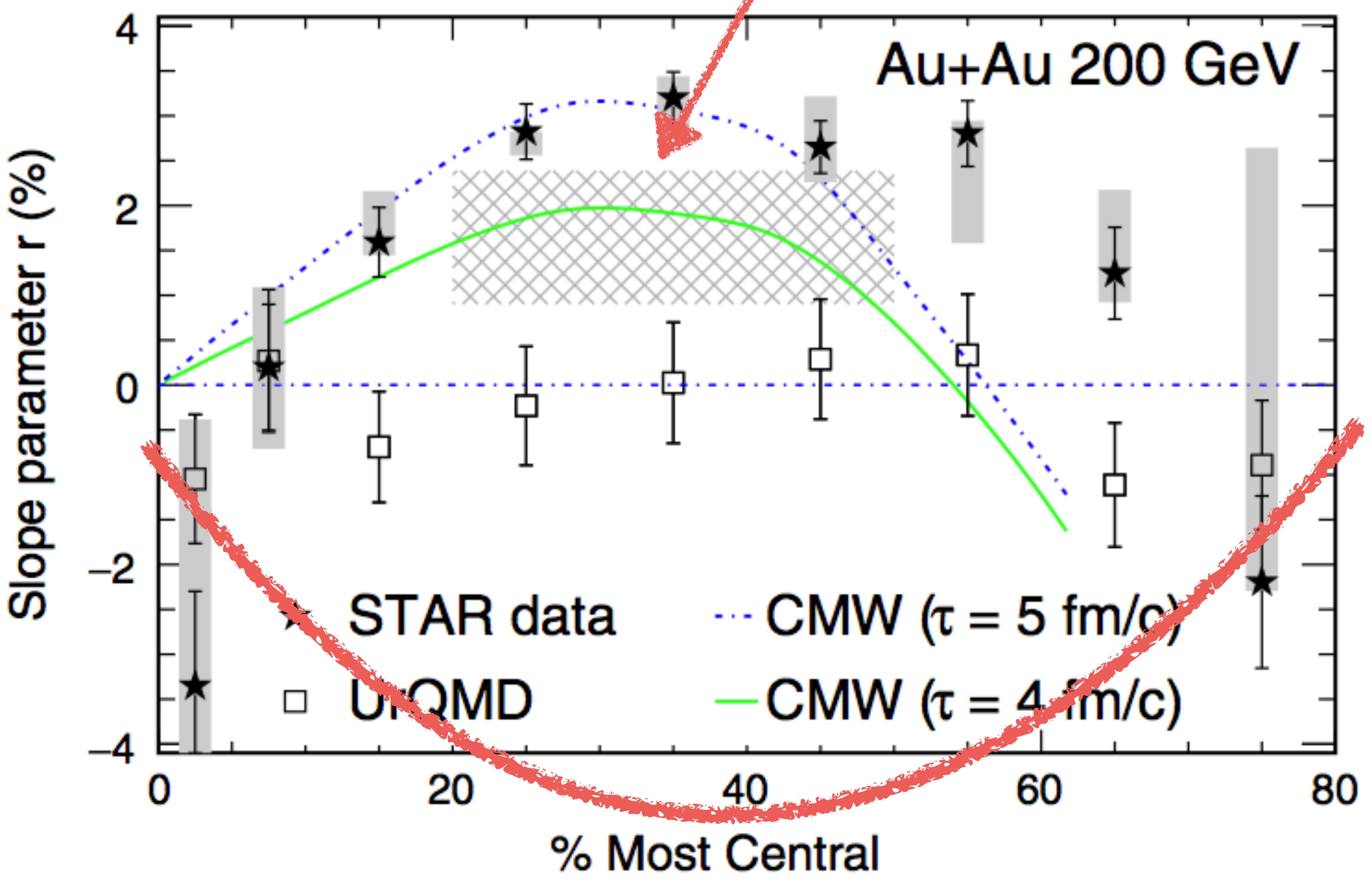
# Possible background — Hydrodynamics with isospin chemical potential ($\mu_I$)

Y. Hatta et al. Nuclear Physics A 947 (2016) 155–160

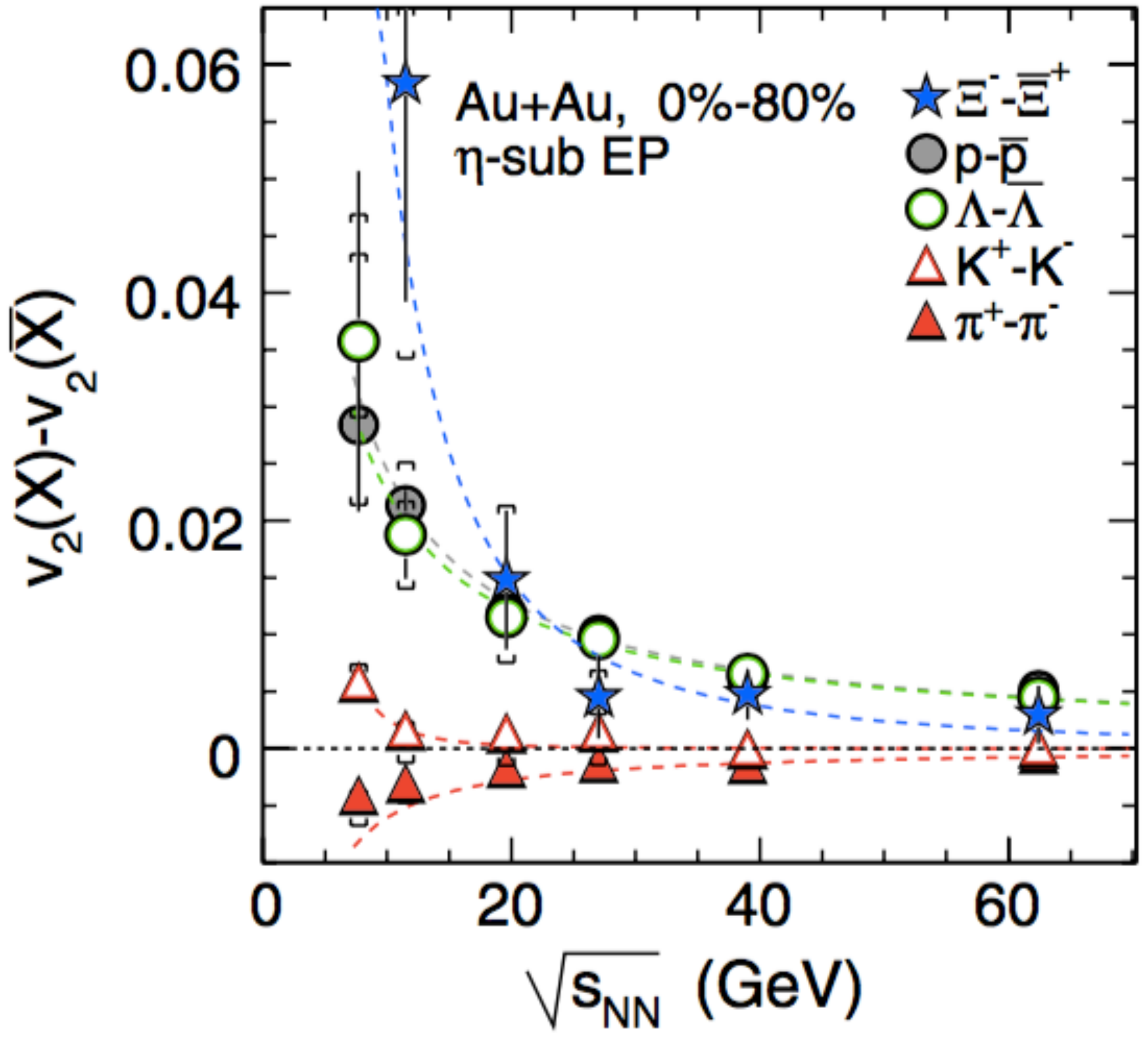
*"… the STAR results can be understood within the standard viscous hydrodynamics without invoking the CMW…"*

$\Delta v_2 \propto -\mu_I$; $A_{ch} \propto -\mu_I$ (assumed); $\rightarrow \Delta v_2 \propto A_{ch}$

*"… the slope r for the kaons should be negative, in contrast to the pion case, and the magnitude is expected to be larger… (in wider $p_T$ coverage)"*




STAR Collaboration, Phys. Rev. Lett. 110, 142301 (2013)

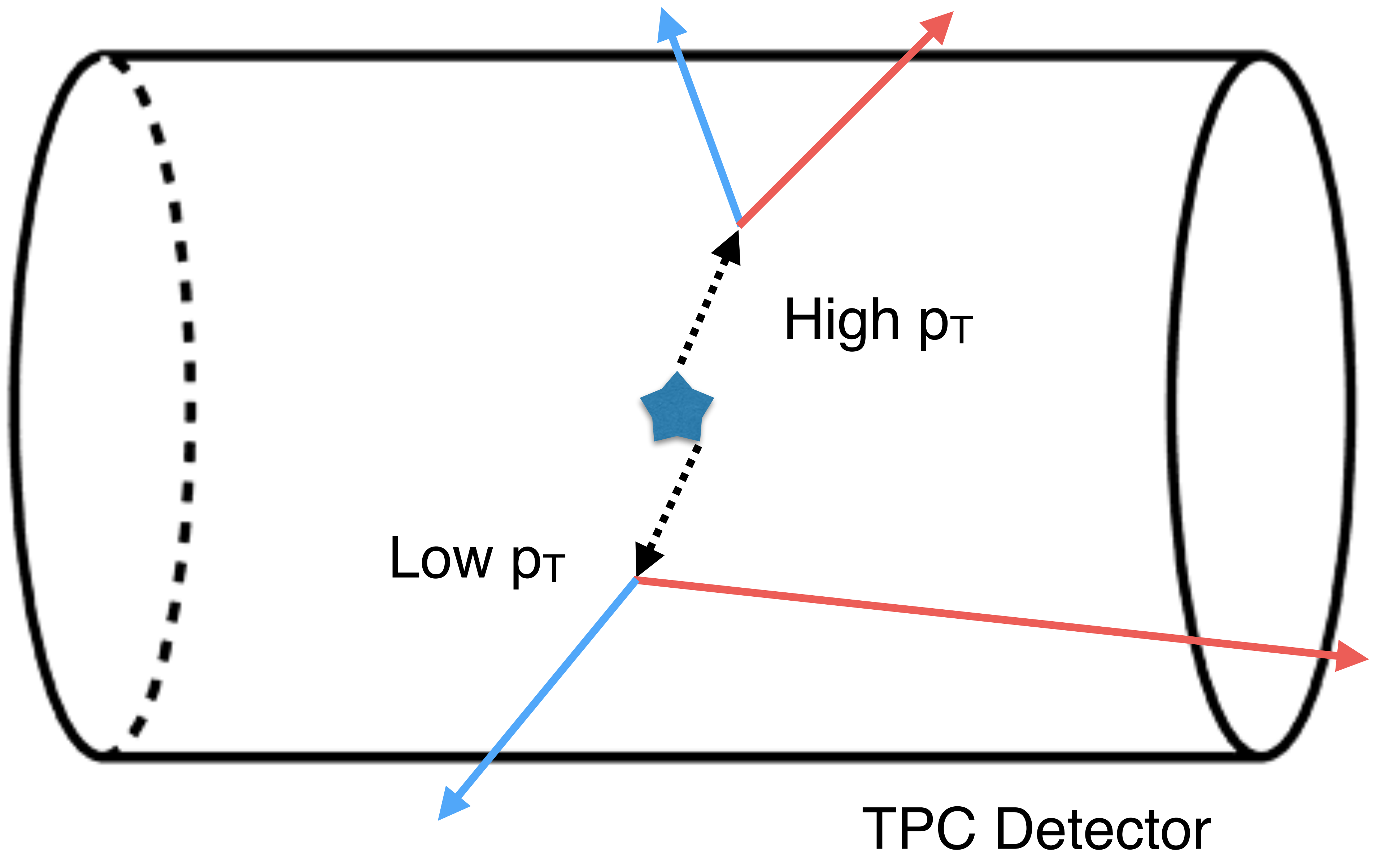



$v_2(\pi^+) < v_2(\pi^-)$
$v_2(K^+) > v_2(K^-)$

# Possible background — Local Charge Conservation

A. Bzdak, P. Bożek, Physics Letters B 726 (2013) 239–243

Multi-particle emission from "clusters"
(resonance decays, strongly flowing fluid elements)

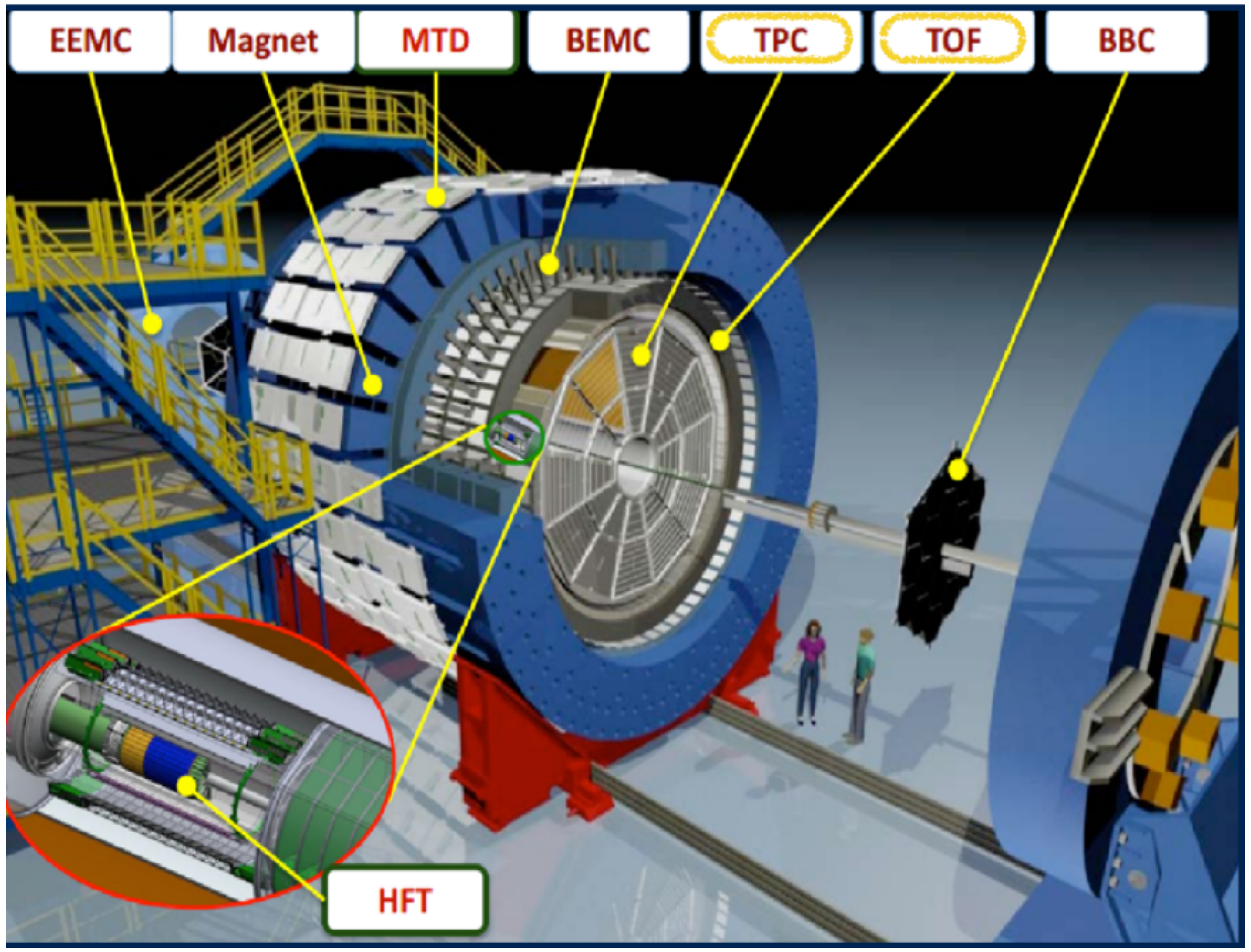



Low $p_T$ clusters
-> larger opening angles in the lab
-> more likely to miss one particle

If such a lost particle is:
positive:
$A_{ch}$ decreases; mean $p_T(-)$ < mean $p_T(+)$; $v_2(-) < v_2(+)$
negative:
$A_{ch}$ increases; mean $p_T(-)$ > mean $p_T(+)$; $v_2(-) > v_2(+)$

Same relationship is also valid for $v_3$

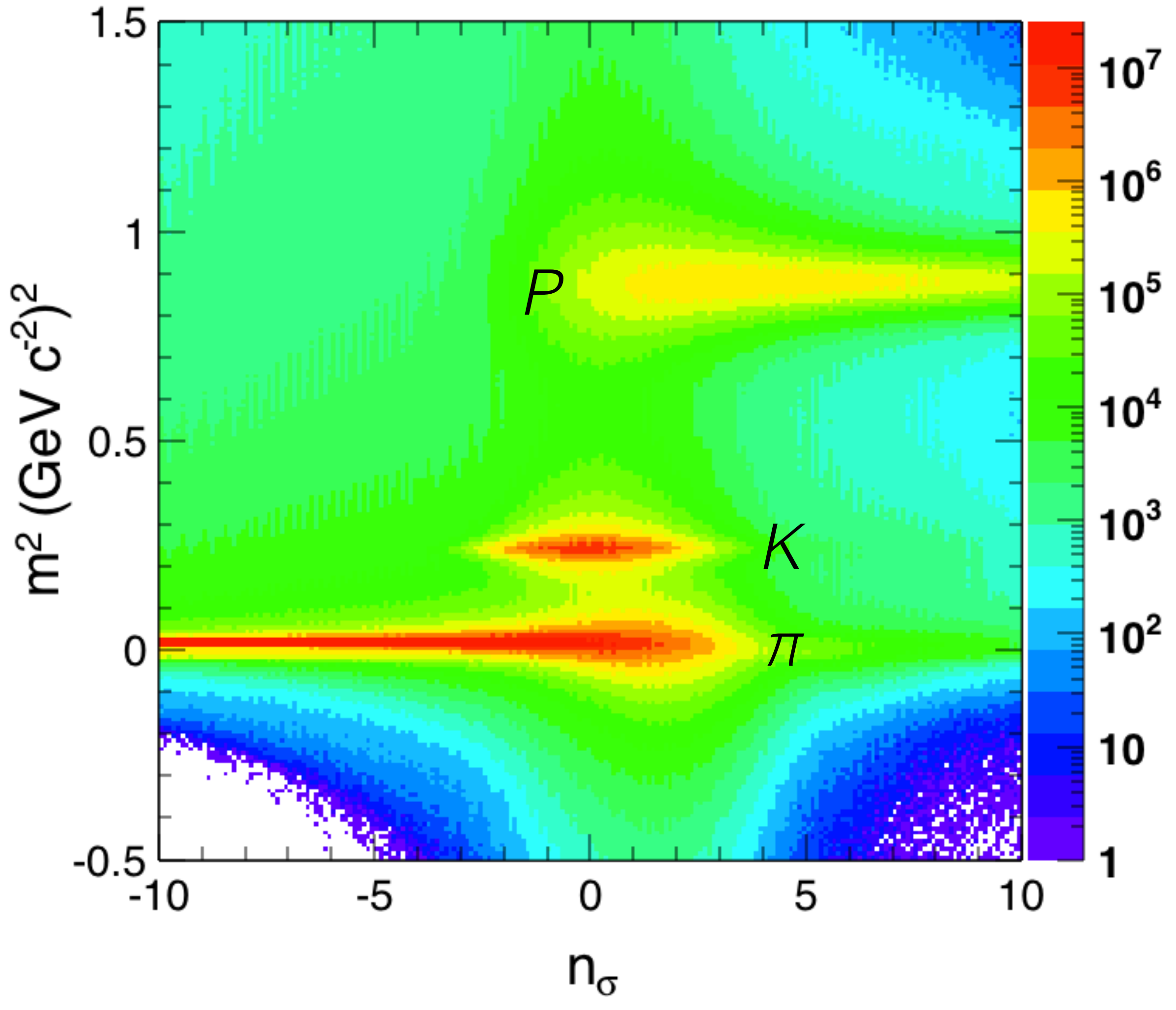
# The STAR experiment at RHIC and analysis method




- Event selection
  Min. bias, $|V_z| < 30$ cm, $|V_r| < 2$ cm

- Charge asymmetry ($A_{ch}$)
  $|\eta| < 1$, DCA (Distance at Closest Approach) < 1 cm
  All charged particles excluding (anti)proton with $p_T < 0.4$ GeV/c

- Particle identification
  Primary tracks with DCA < 1 cm
  $\pi$: $|n\sigma_\pi| < 2$, $0<m^2<0.1$ $(GeV/c^2)^2$
  K: $|n\sigma_K| < 2$, $0.15<m^2<0.35$ $(GeV/c^2)^2$

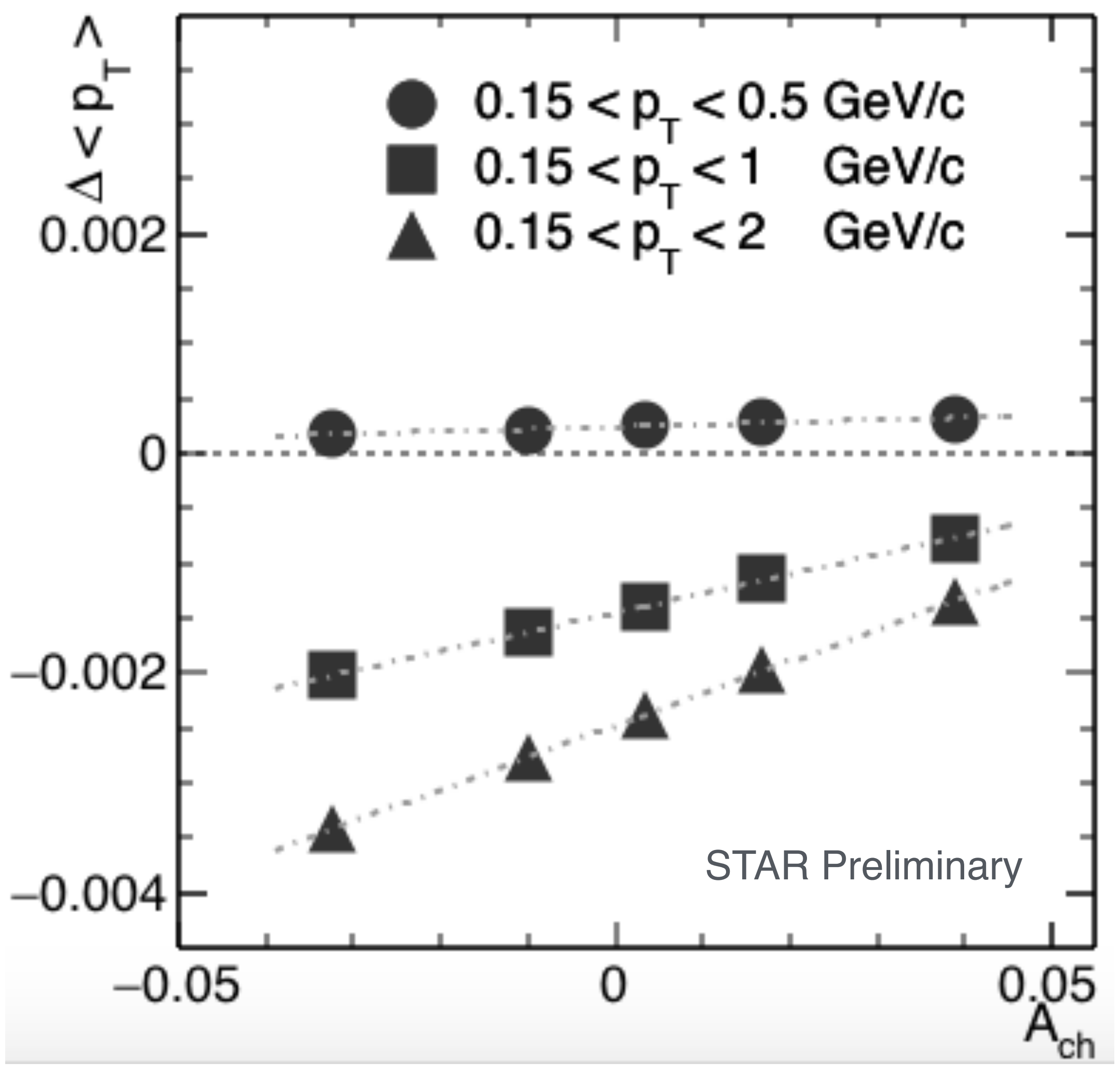


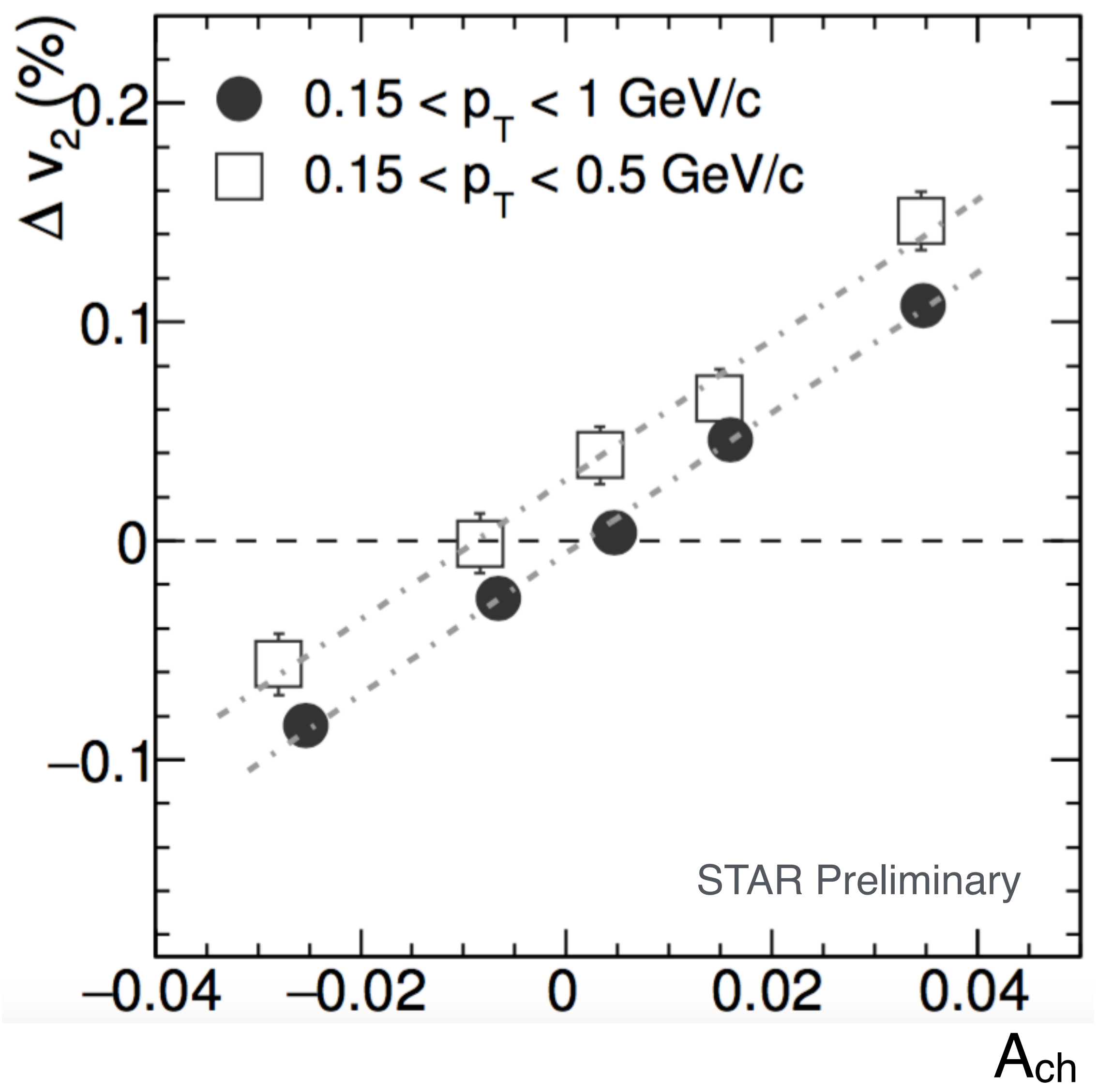

$|n\sigma|<2$: within $2\sigma$ window of theoretical dE/dx (tracks' average energy loss per unit length) curves

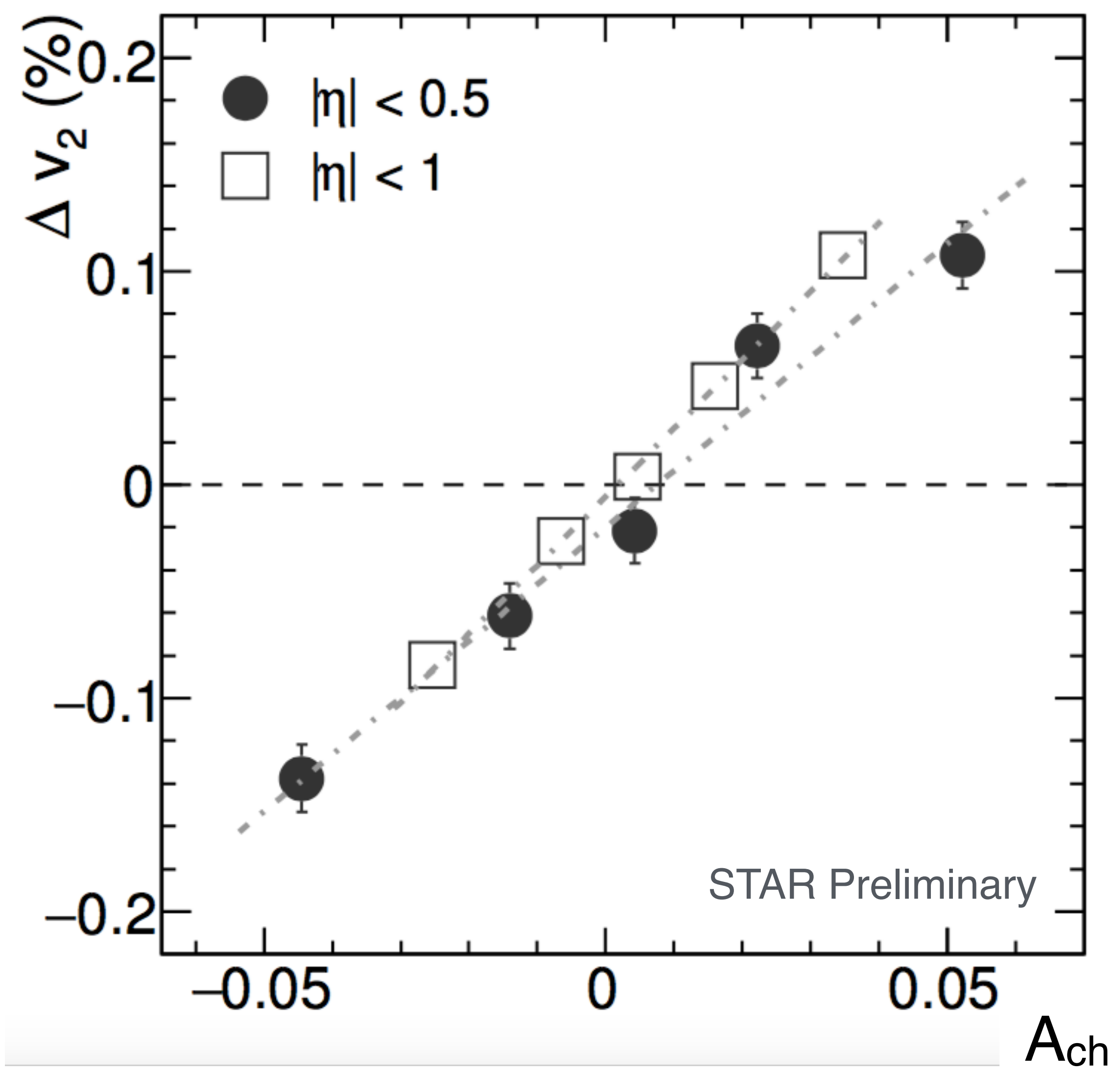
- Flow calculation
  2-particle Q-Cumulants method
  2 subevents with 0.3 $\eta$ gap to reduce non-flow

A. Bilandzic, R. Snellings and S. Voloshin, Phys. Rev. C 83, 044913 (2011)

# Dependence of $\Delta\langle p_T\rangle$ and $\Delta v_2$ on $A_{ch}$ for pions in different kinematic windows



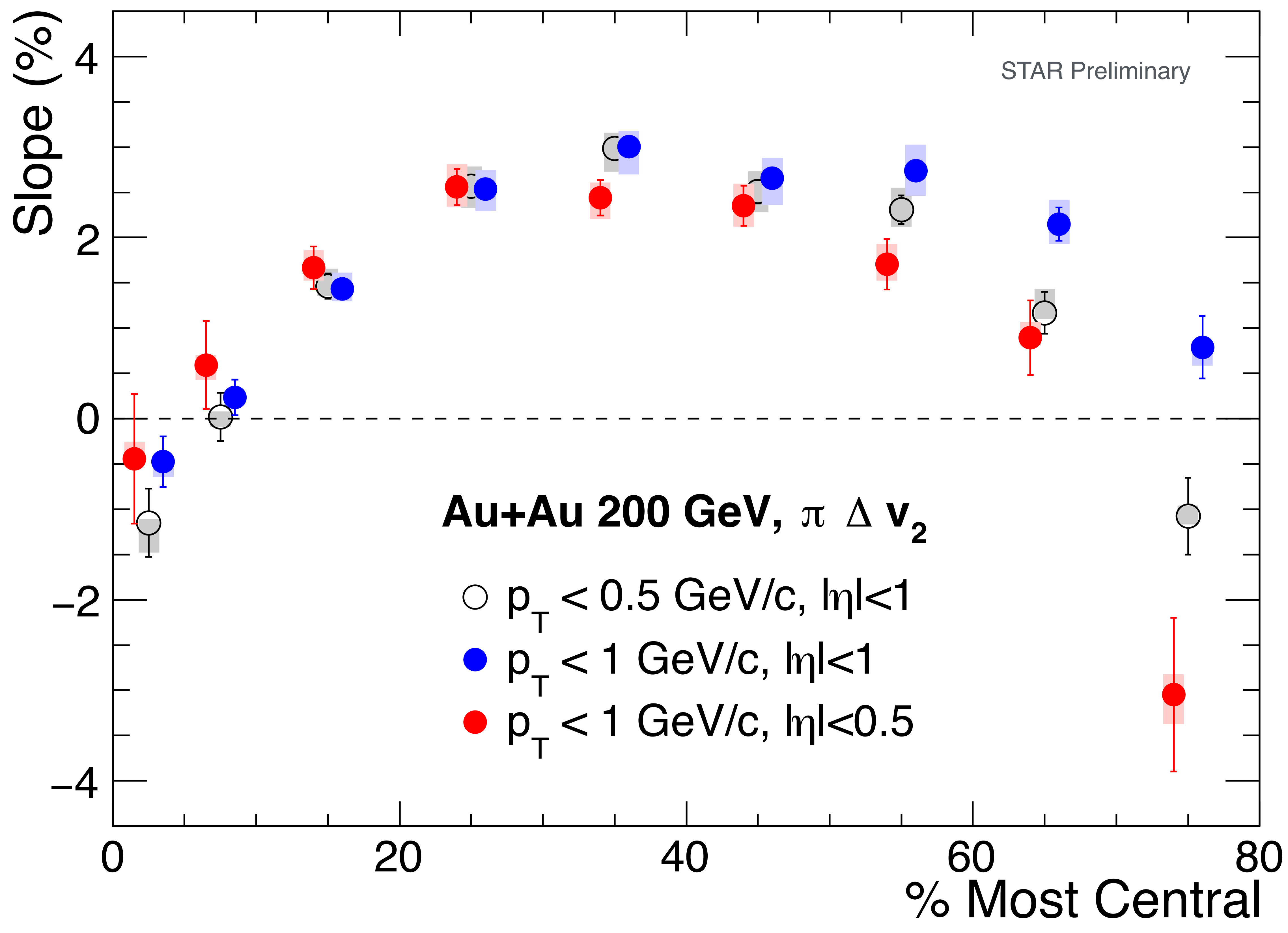




- $\langle p_T\rangle$ and $v_2$ differences of π+ and π- are tested as functions of $A_{ch}$
- The relative variation of $\langle p_T\rangle$ (~0.1%) is typically smaller than the relative variation of $v_2$ (~1%) by an order of magnitude.
- A wider $p_T$ range enhances particle yields -> important for analyses involving K and p.

- η coverage is reduced to half

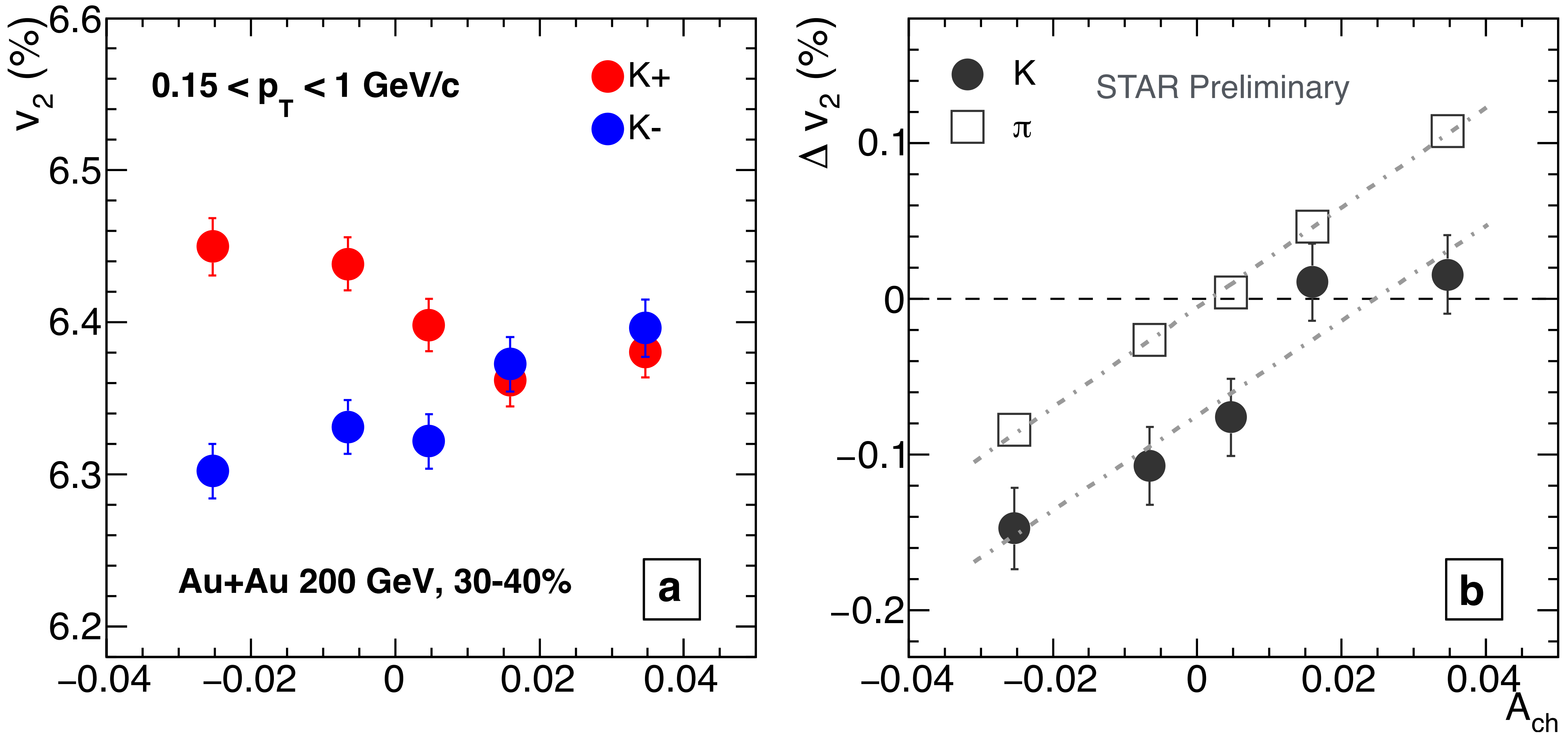
*Δ $v_2(A_{ch})$ slope does not display a significant variation, suggesting the smallness of the LCC effect in the data.*

# Dependence of $\langle p_T \rangle$ and $v_2$ on $A_{ch}$ for pions in different kinematic windows



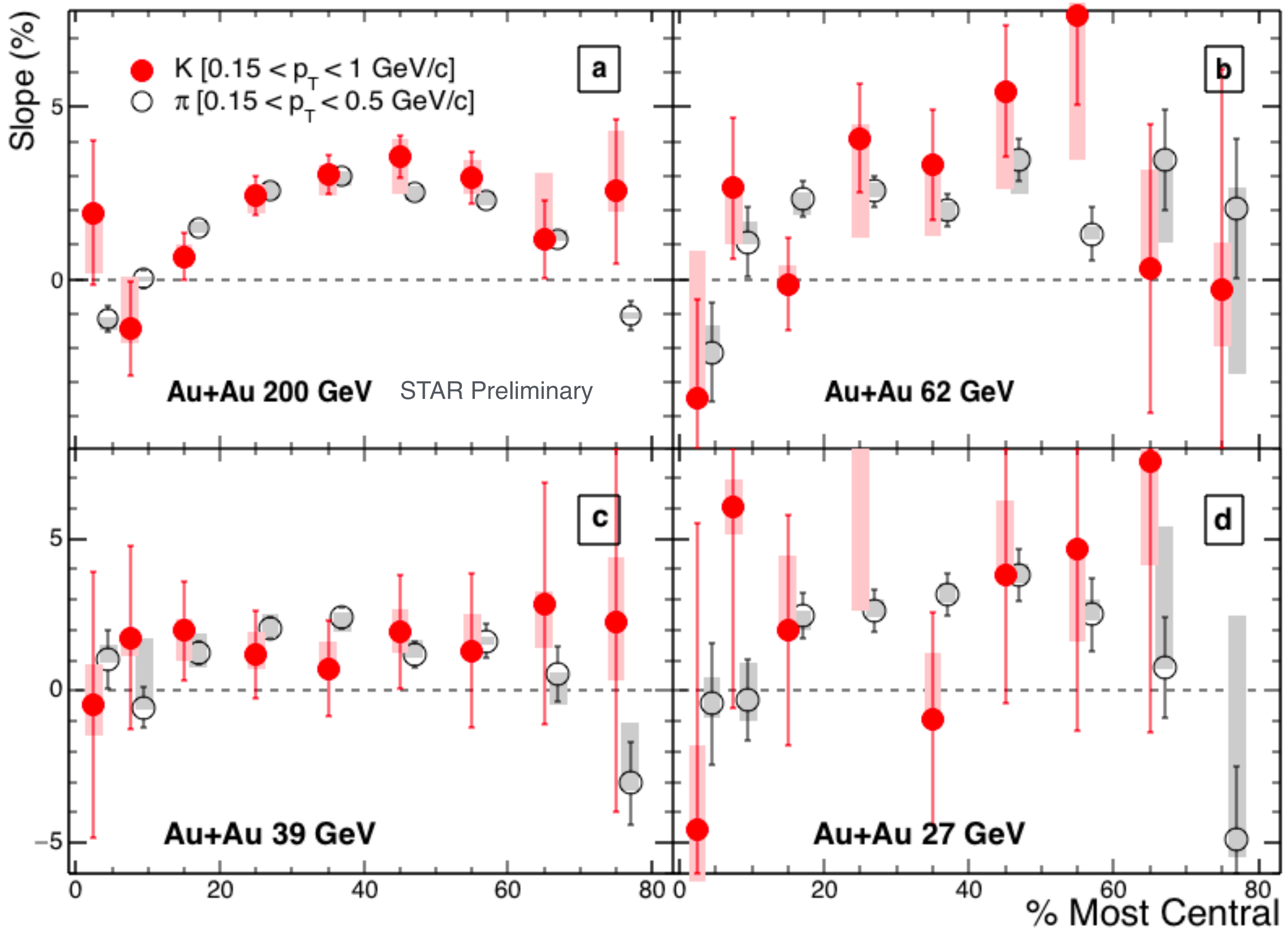

The slope parameters obtained with different phase space selections show similar trends and values

# Dependence of the $\Delta v_2(A_{ch})$ slope on centrality and collision energy for K

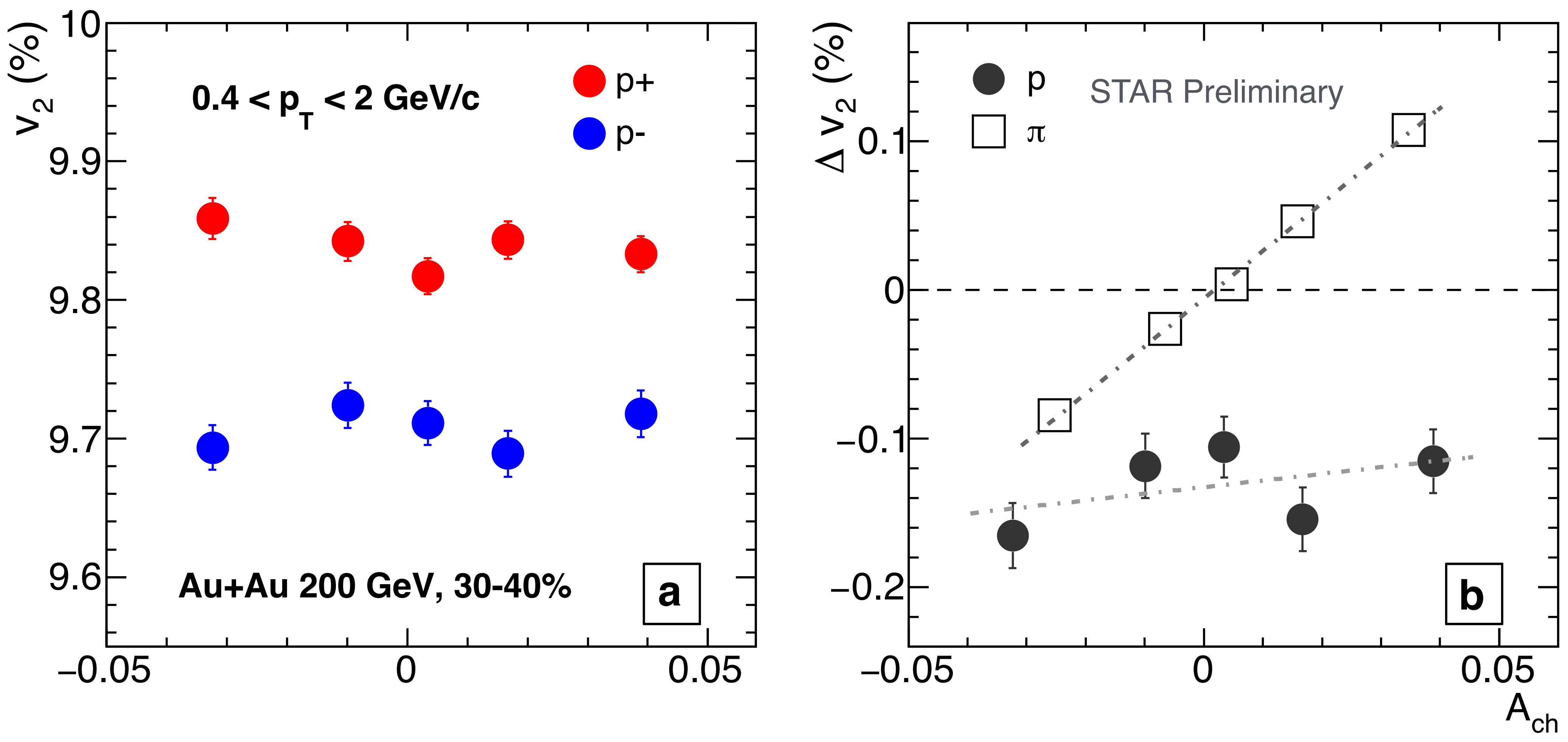



- $\Delta v_2(A_{ch})$ slope for K is positive and close to the π slope
- Contradicts the prediction of the viscous hydrodynamics model with $\mu_I$
  (Note that the intercept for kaons is negative)

- Centrality dependence of slopes for K behave similarly to that of π
- No significant absorption effect (see slide 4)
- Hydrodynamics with $\mu_I$ cannot be the dominant mechanism

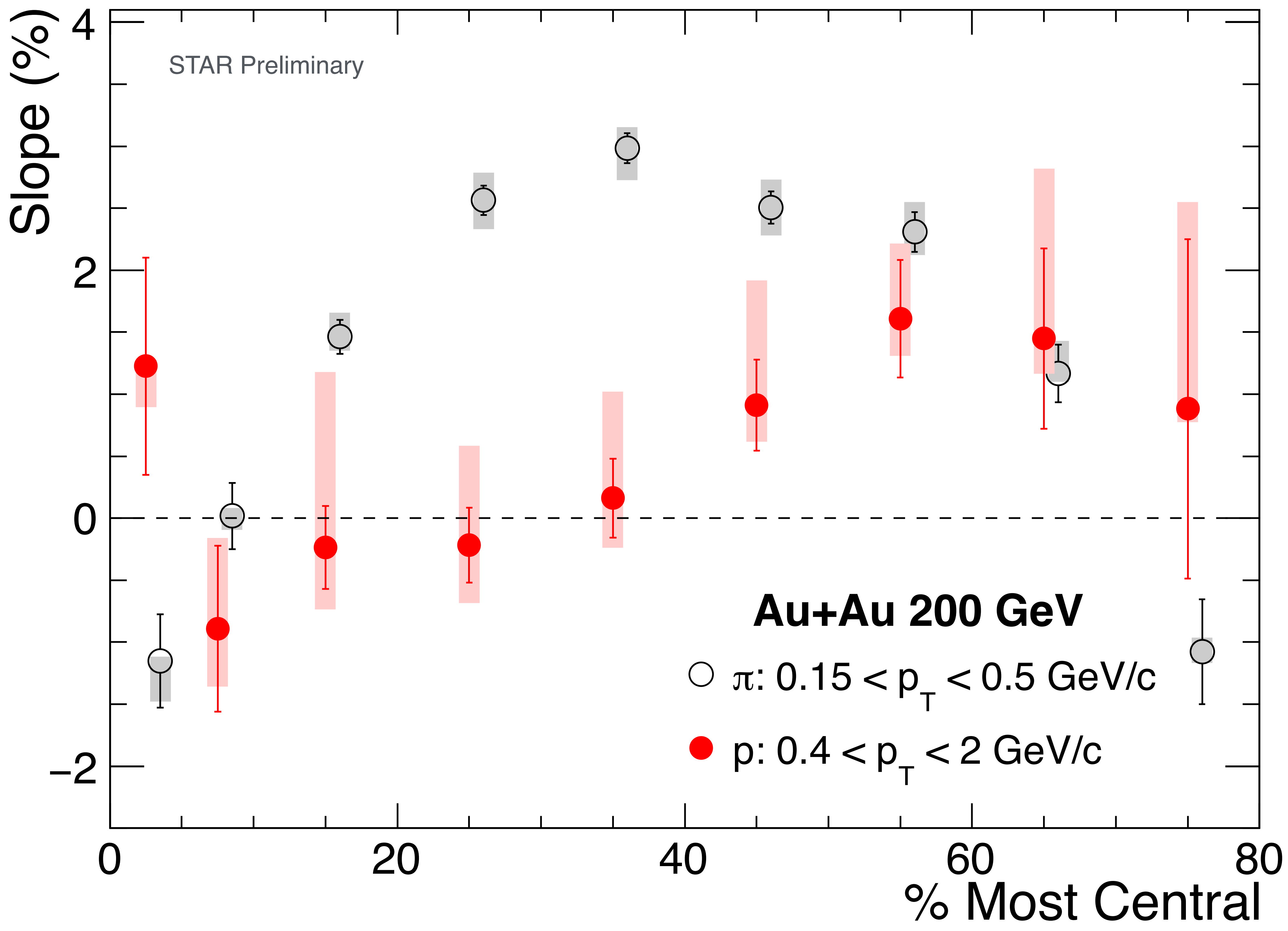


# Dependence of the $\Delta v_2(A_{ch})$ slope on centrality and collision energy for p

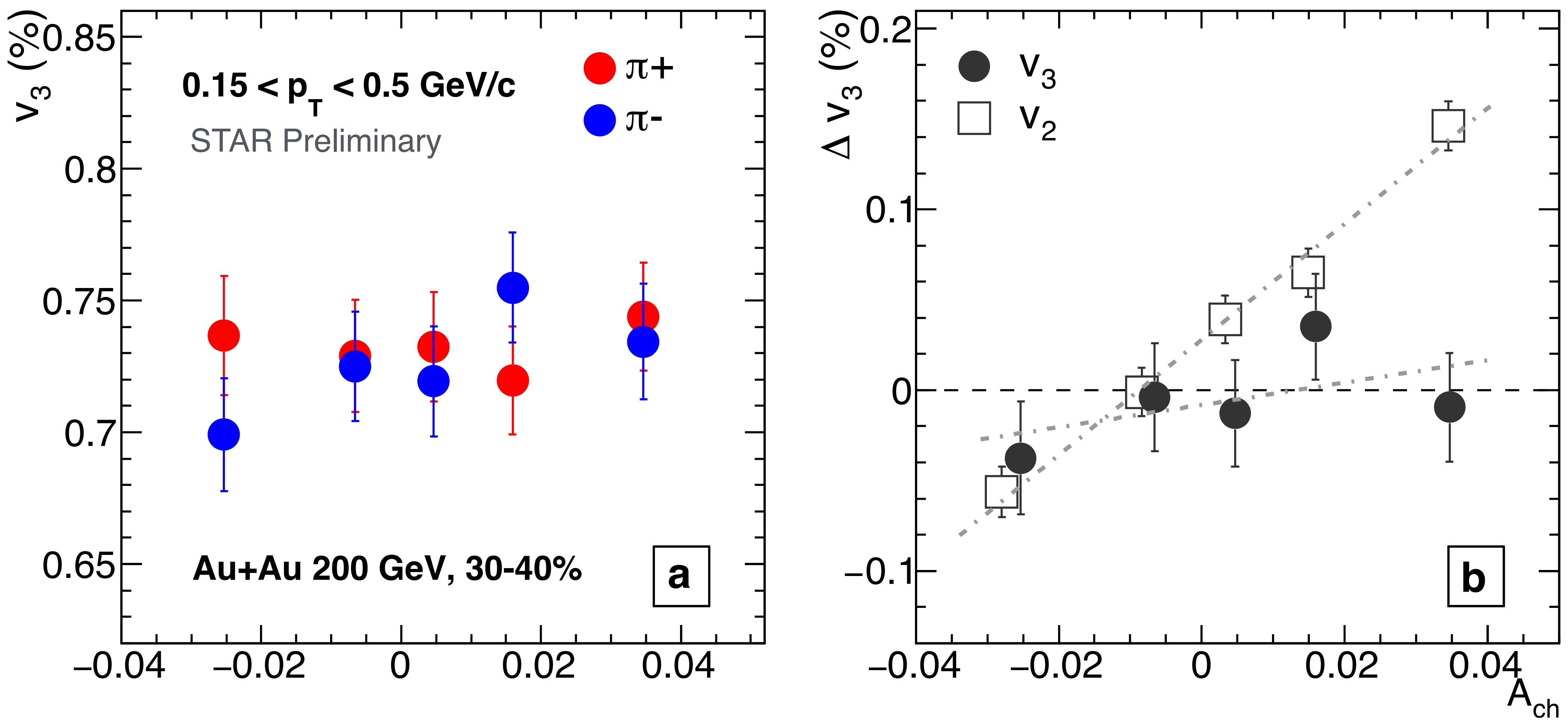



- $\Delta v_2(A_{ch})$ slopes for (anti-)protons are typically much smaller than those for π and K

- The proton slopes are close to zero except for the positive values in 40 – 70% collisions.



# Dependence of the $\Delta v_3(A_{ch})$ slope on centrality for π in Au+Au collisions




- In contrast with CMS results, π $v_3$ at RHIC depends weakly on $A_{ch}$, and the $\Delta v_3(A_{ch})$ slope is much smaller than the $\Delta v_2(A_{ch})$ slope.

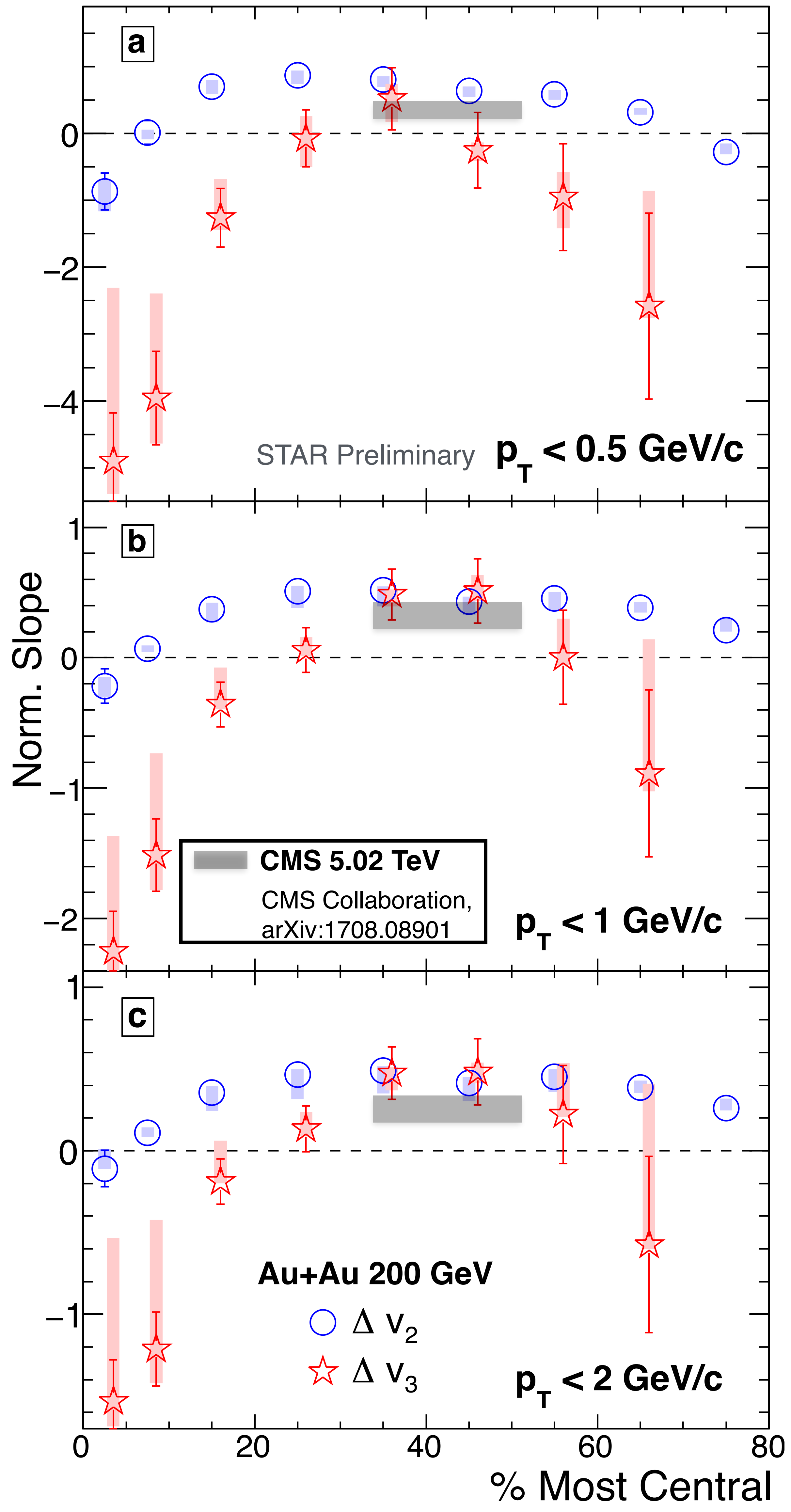
$$\mathrm{Norm.}\Delta v_n = 2\frac{v_n^- - v_n^+}{v_n^- + v_n^+}$$

- 0.15 < $p_T$ < 0.5 GeV/c,

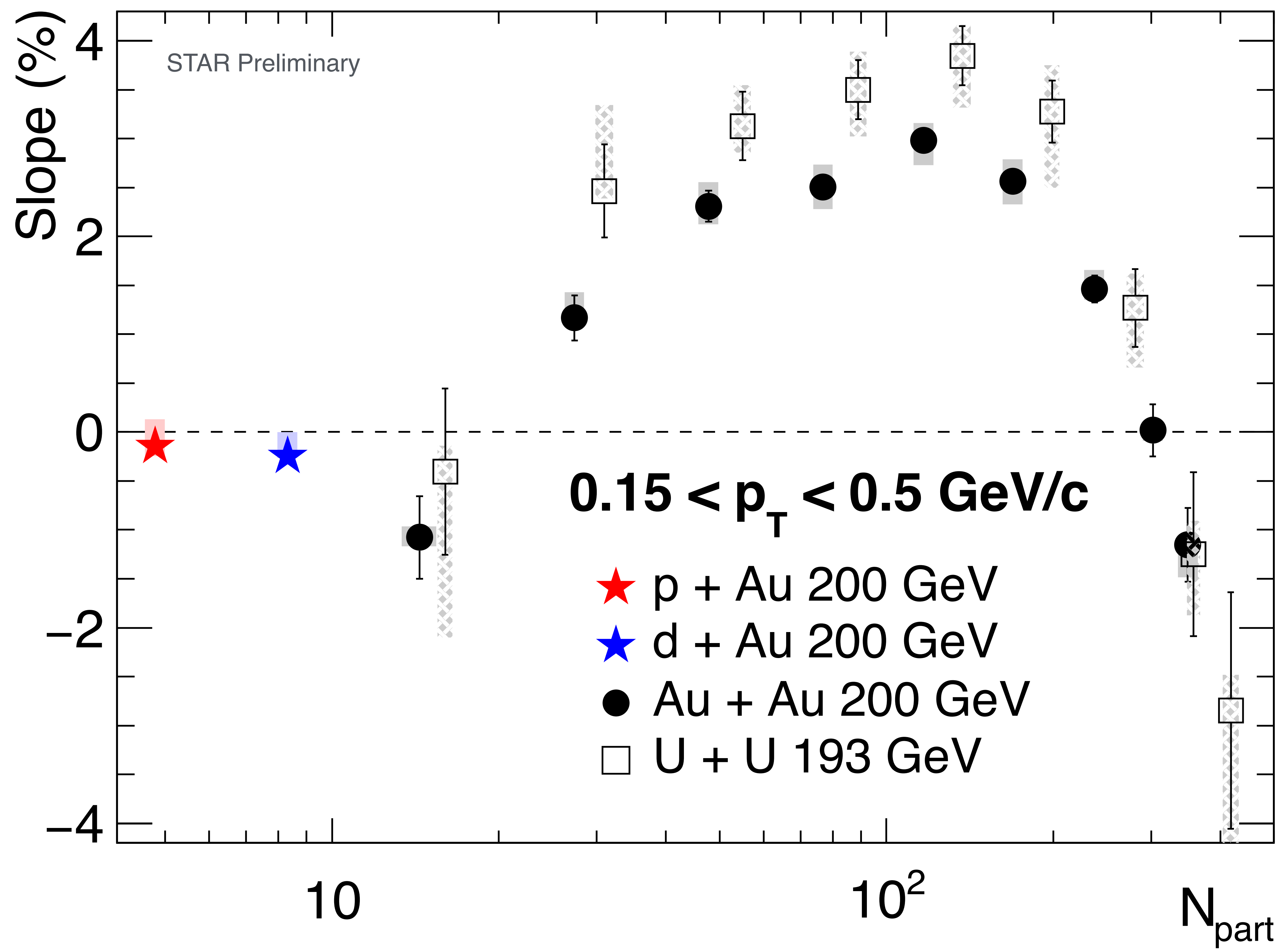
  *the norm. $\Delta v_3(A_{ch})$ slopes are lower than or consistent with zero for all centrality intervals*

- $p_T$ upper bound is increased to 1 or 2 GeV/c,

  *the norm. $\Delta v_3(A_{ch})$ slopes gradually approach the Norm. $\Delta v_2(A_{ch})$ slopes.*



# The $\Delta v_2(A_{ch})$ slopes for π in p+Au, d+Au and U+U collisions




- The CMW signals are expected to disappear in the small systems

  *The orientation decoupling between the magnetic field and the 2nd-order event plane*

- The $\Delta v_2(A_{ch})$ slopes in both p+Au and d+Au (analyzed with the 2nd-order event plane from TPC) are consistent with zero

  *Demonstrates the smallness of the possible background in small systems.*

- The $\Delta v_2(A_{ch})$ slopes in U+U collisions are systematically higher than the results in Au+Au collisions.

  *A uranium nucleus has more protons than a gold nucleus, leading to a stronger magnetic field?*

# Conclusion

- **The ⟨$p_T$⟩ dependence on $A_{ch}$** exists but is **insignificant**. However, one should still try to keep the $p_T$ upper limit as low as possible.

- The **similarity between pion and kaon slopes** suggests that the **hydrodynamics is not the dominant contribution** to the pion or kaon slopes. The isospin effect, however, remains a potential contributor to the proton slopes in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

- The **difference between the normalized $v_2$ and $v_3$ slopes** for pions at various $p_T$, centrality intervals suggests that the **CMW picture remains a viable interpretation** at RHIC.

- The measured slopes are **consistent with zero in p+Au and d+Au collisions** demonstrating the smallness of the possible background in the small systems.

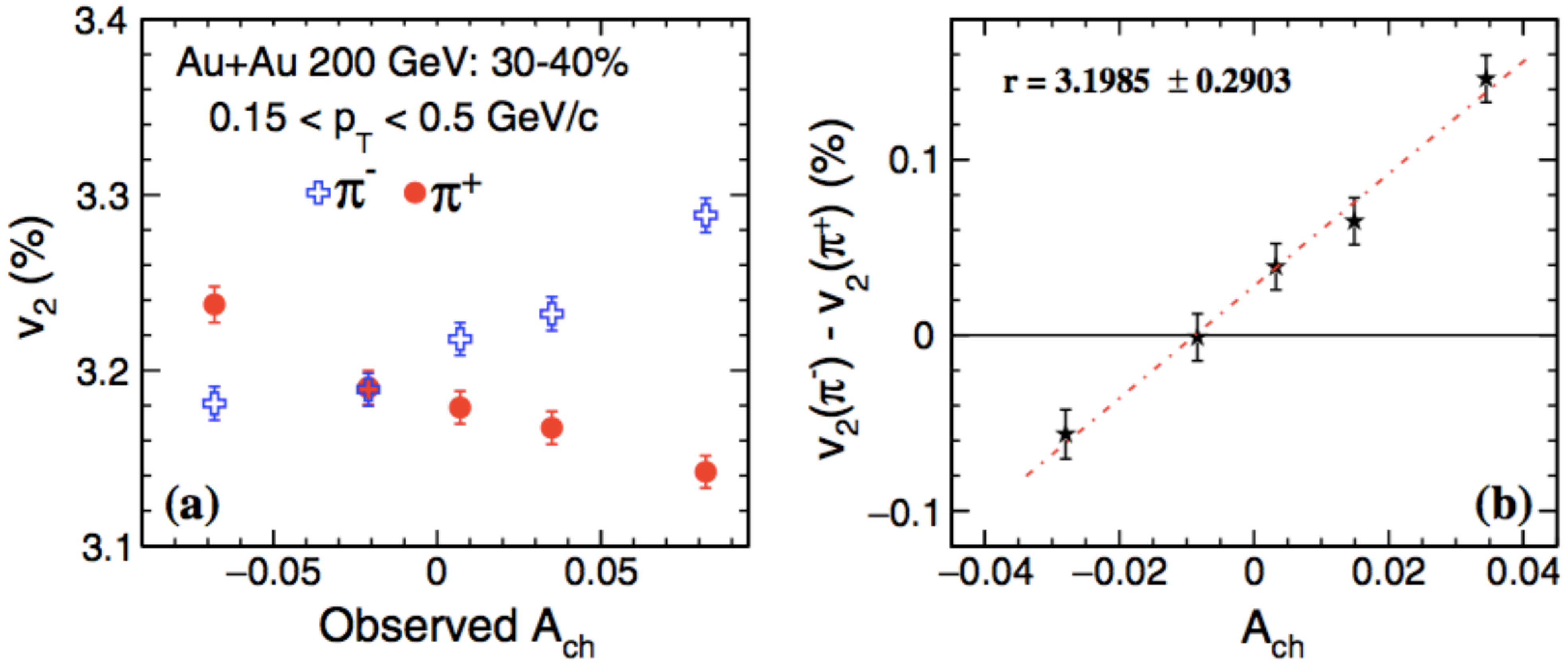
- The difference in the pion $\Delta v_2(A_{ch})$ slope between Au+Au and U+U is consistent with the expectation from the CMW picture.

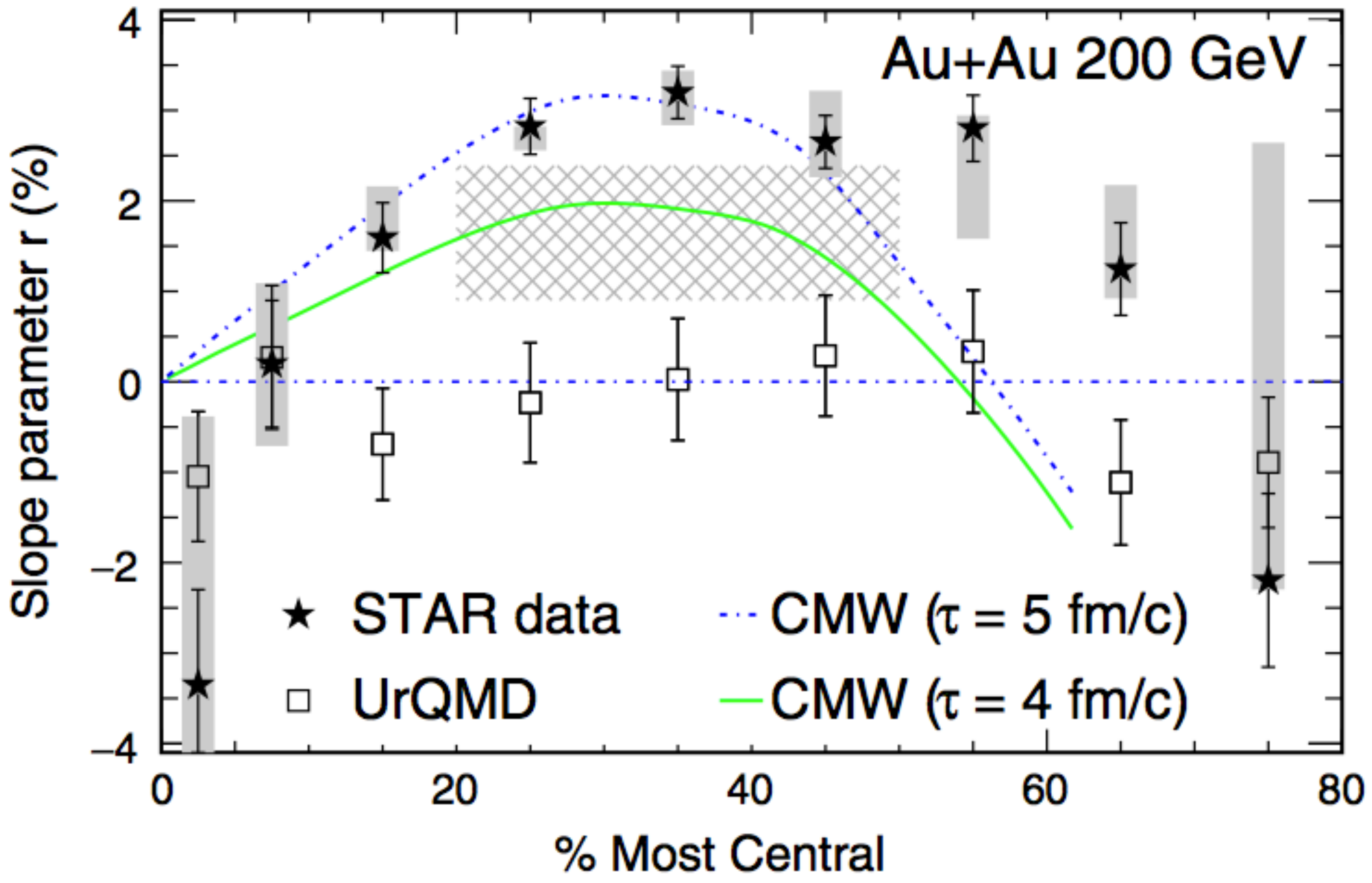
Thanks for your attention!

# Backup

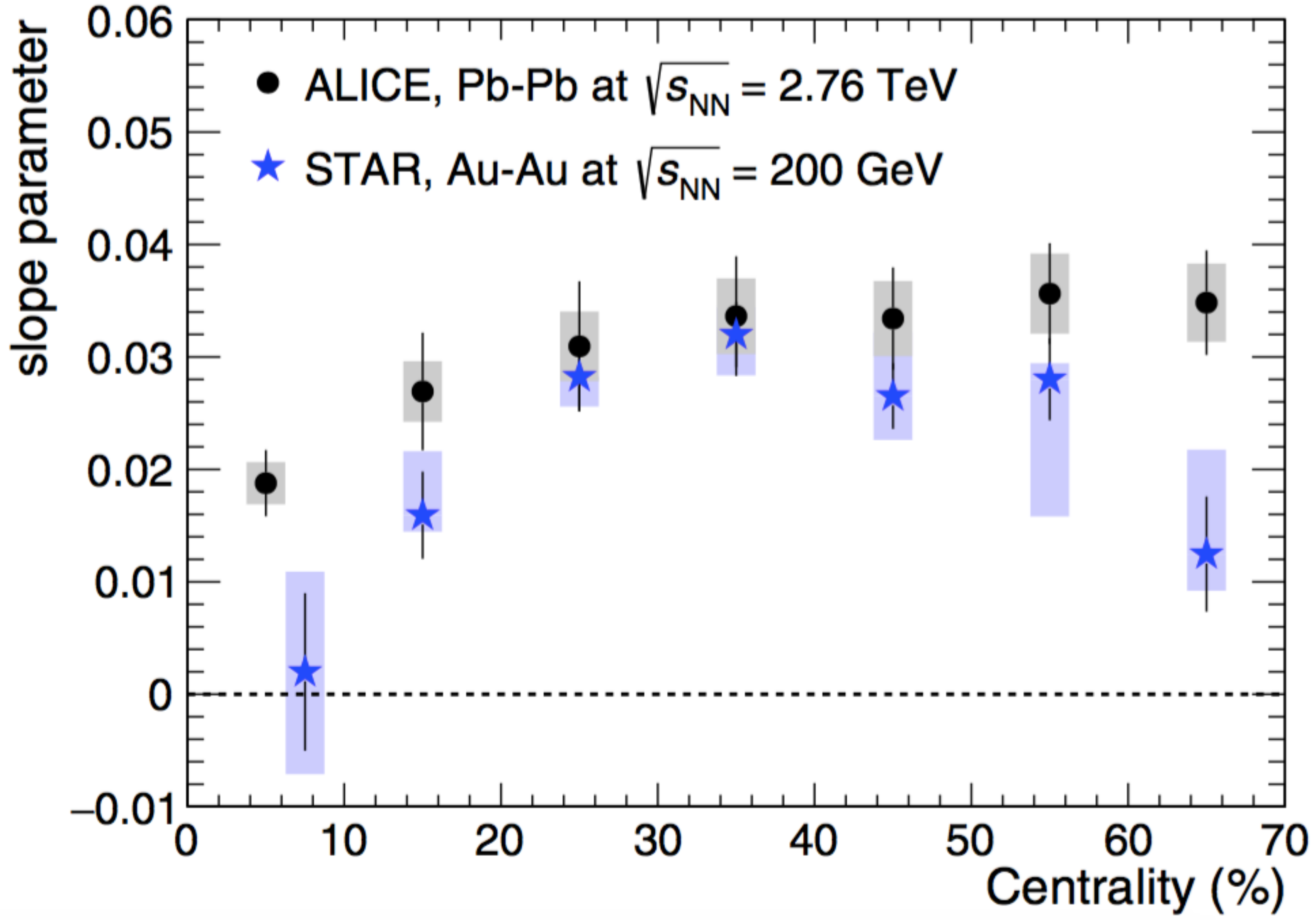
# Previous experimental results from RHIC and LHC

STAR Collaboration, PRL 114, 252302 (2015)



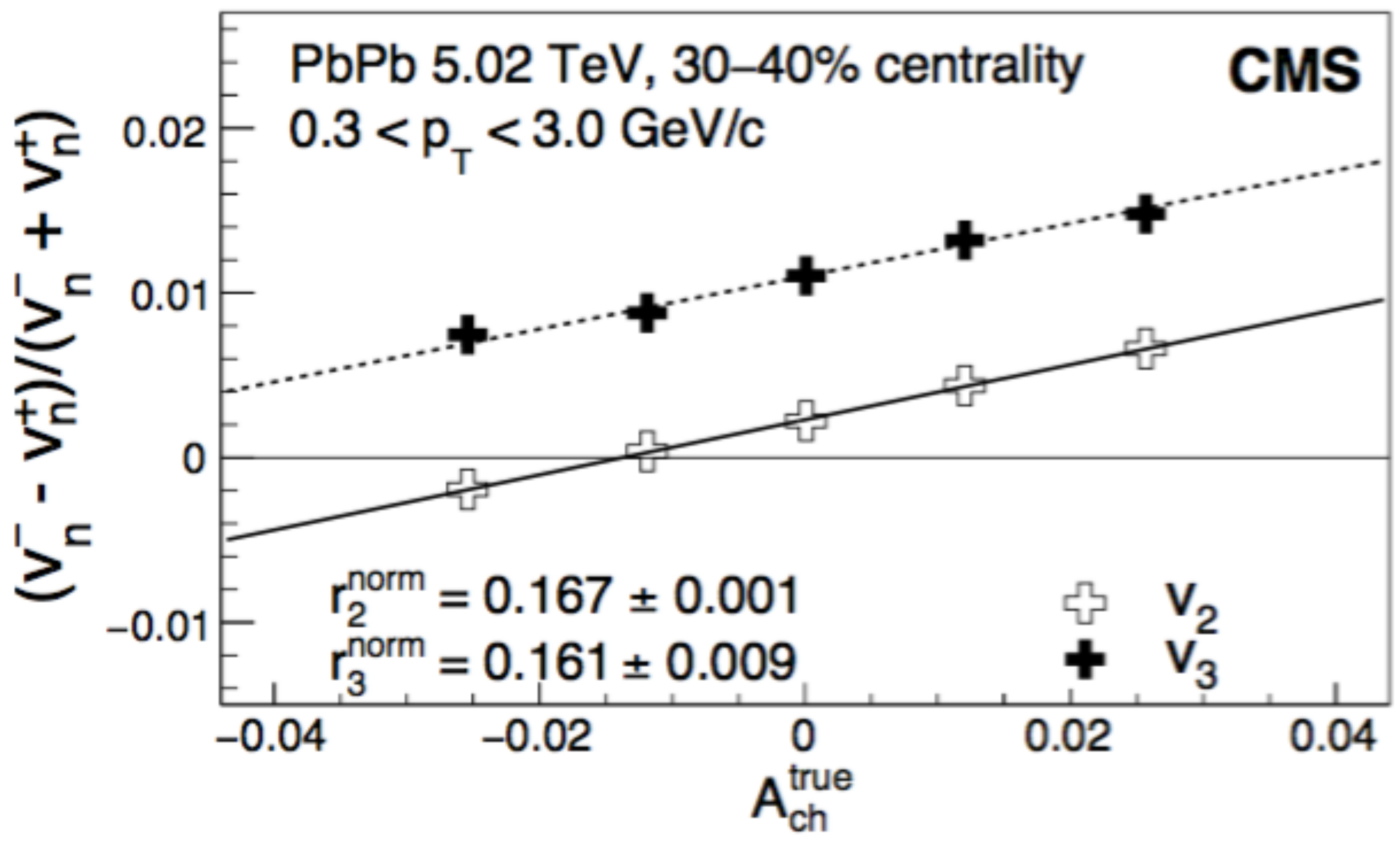

ALICE Collaboration, PRC 93, 044903 (2016)

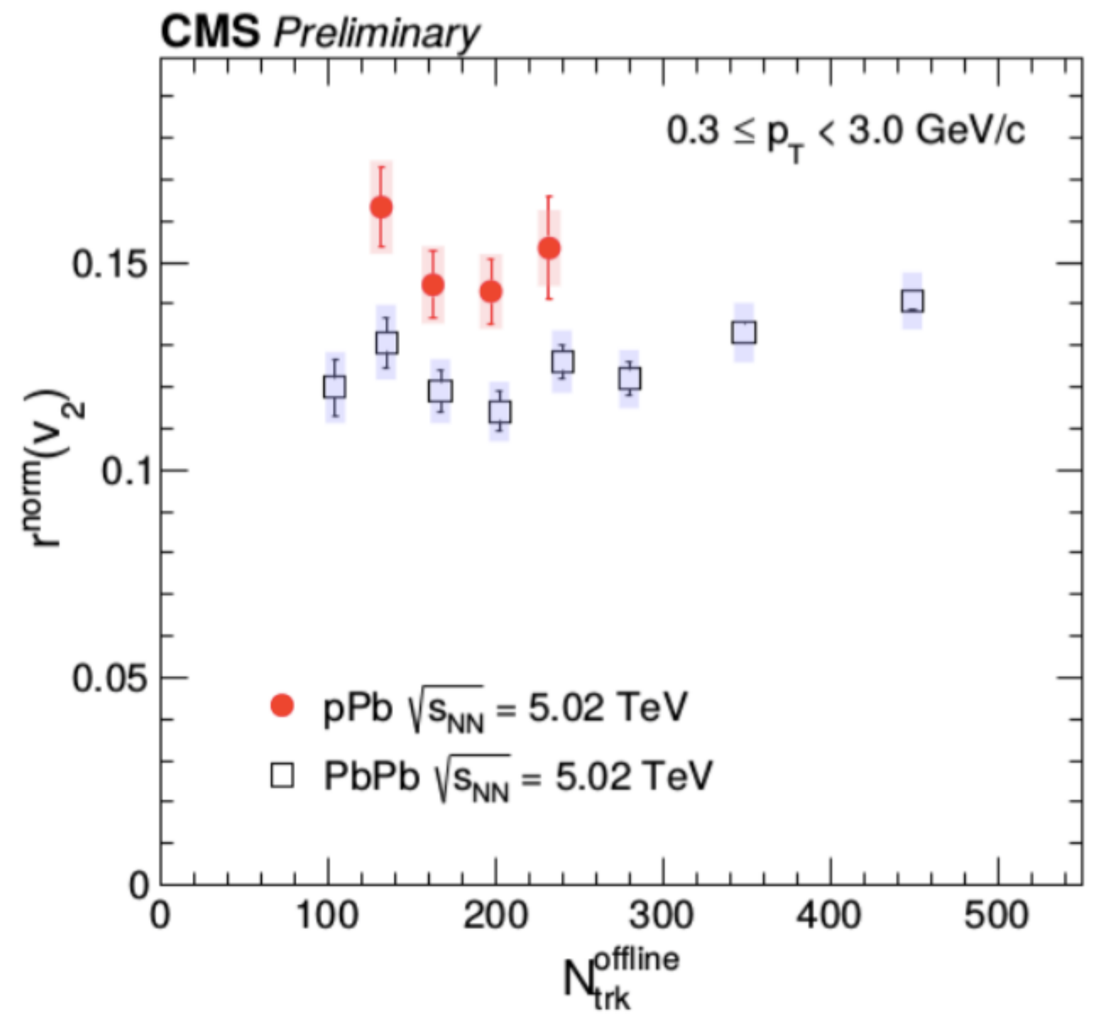


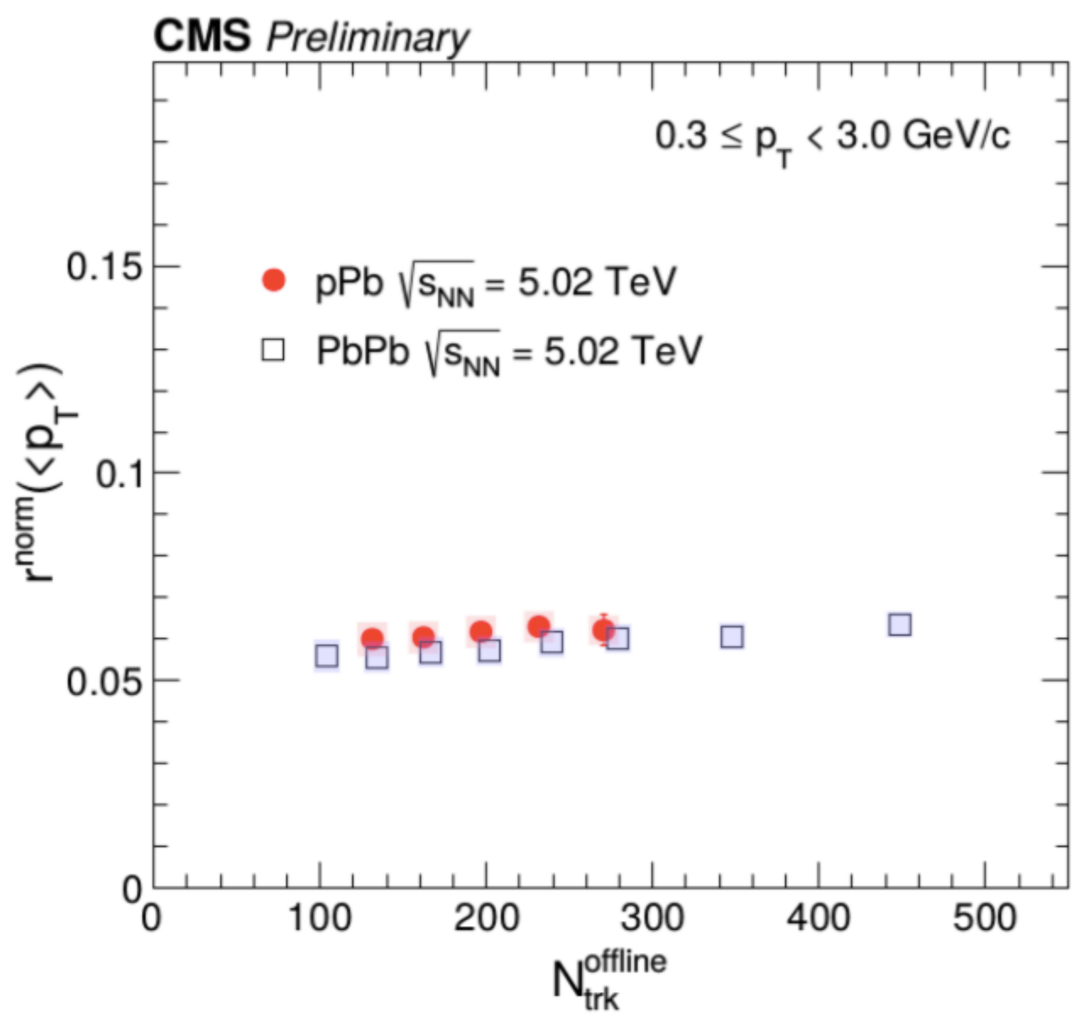

- The linear dependence between (Δ)$v_2$ and $A_{ch}$ is observed at RHIC-STAR and LHC-ALICE. The extracted slopes are within the expectation of CMW theory.
- Note that ALICE data show weak centrality dependence comparing to STAR data, indicating the possible difference (magnetic field, collectivity…) between two collision energies.

# Previous experimental results from RHIC and LHC

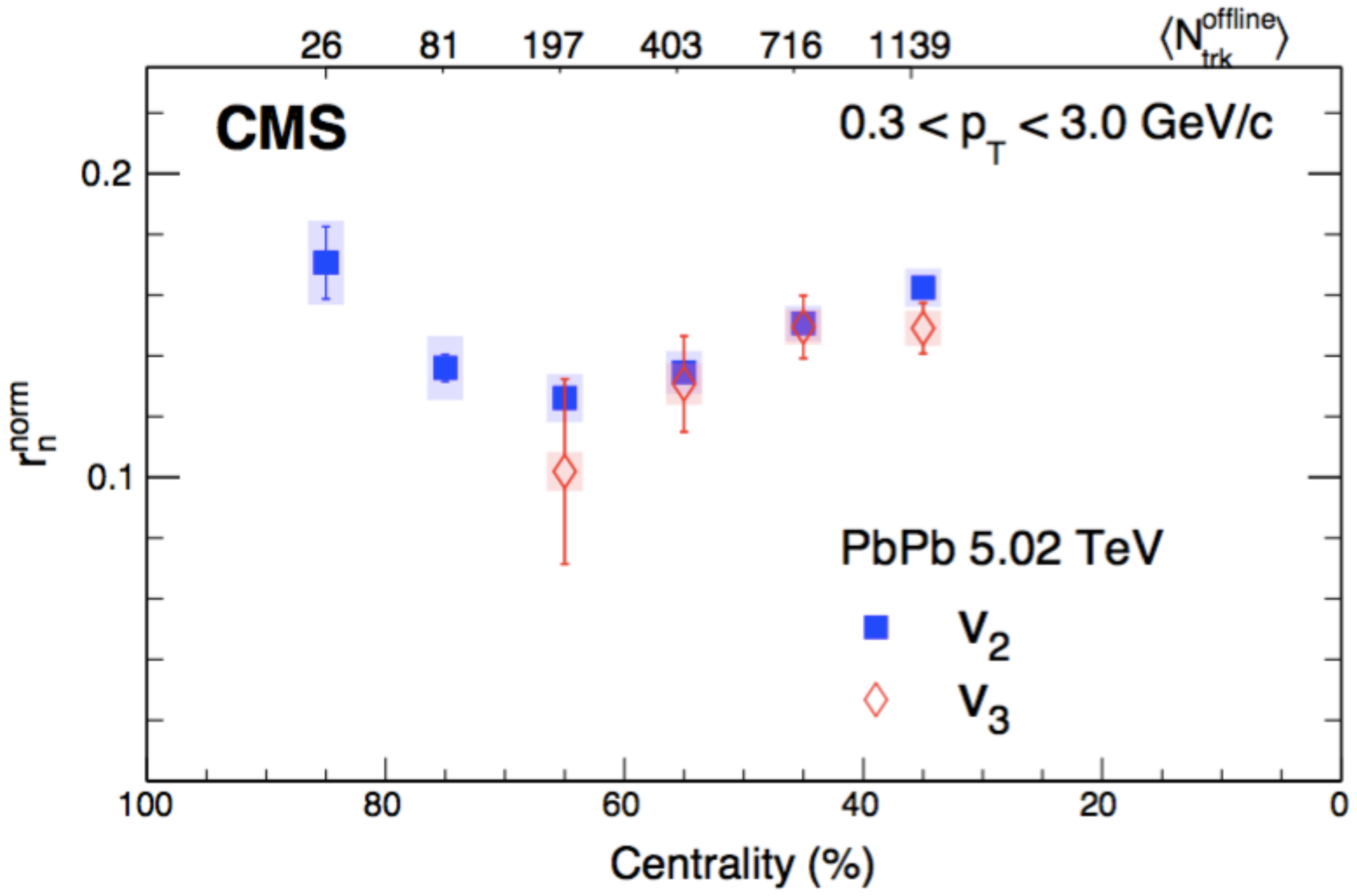
CMS Collaboration, arXiv:1708.08901



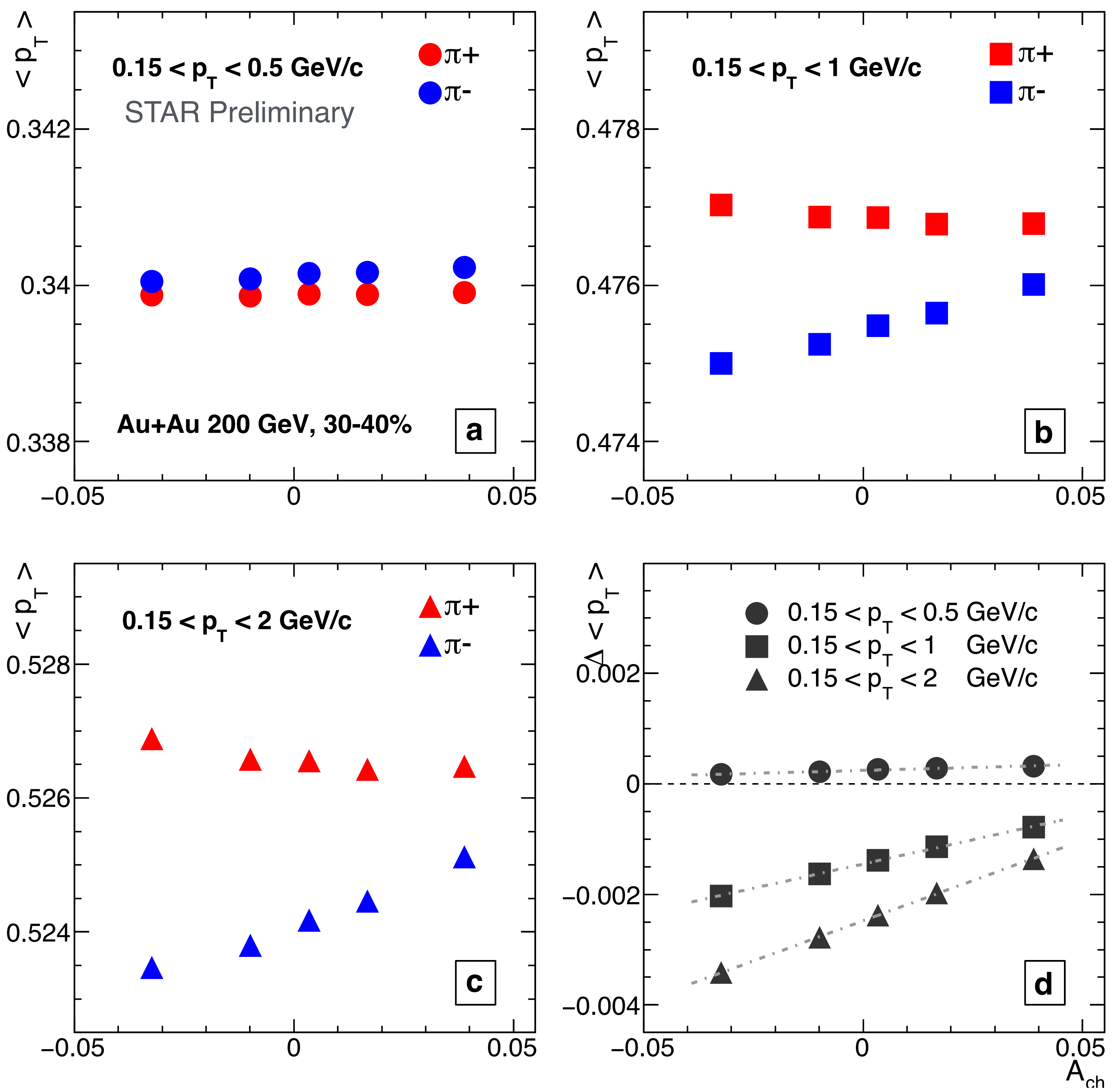



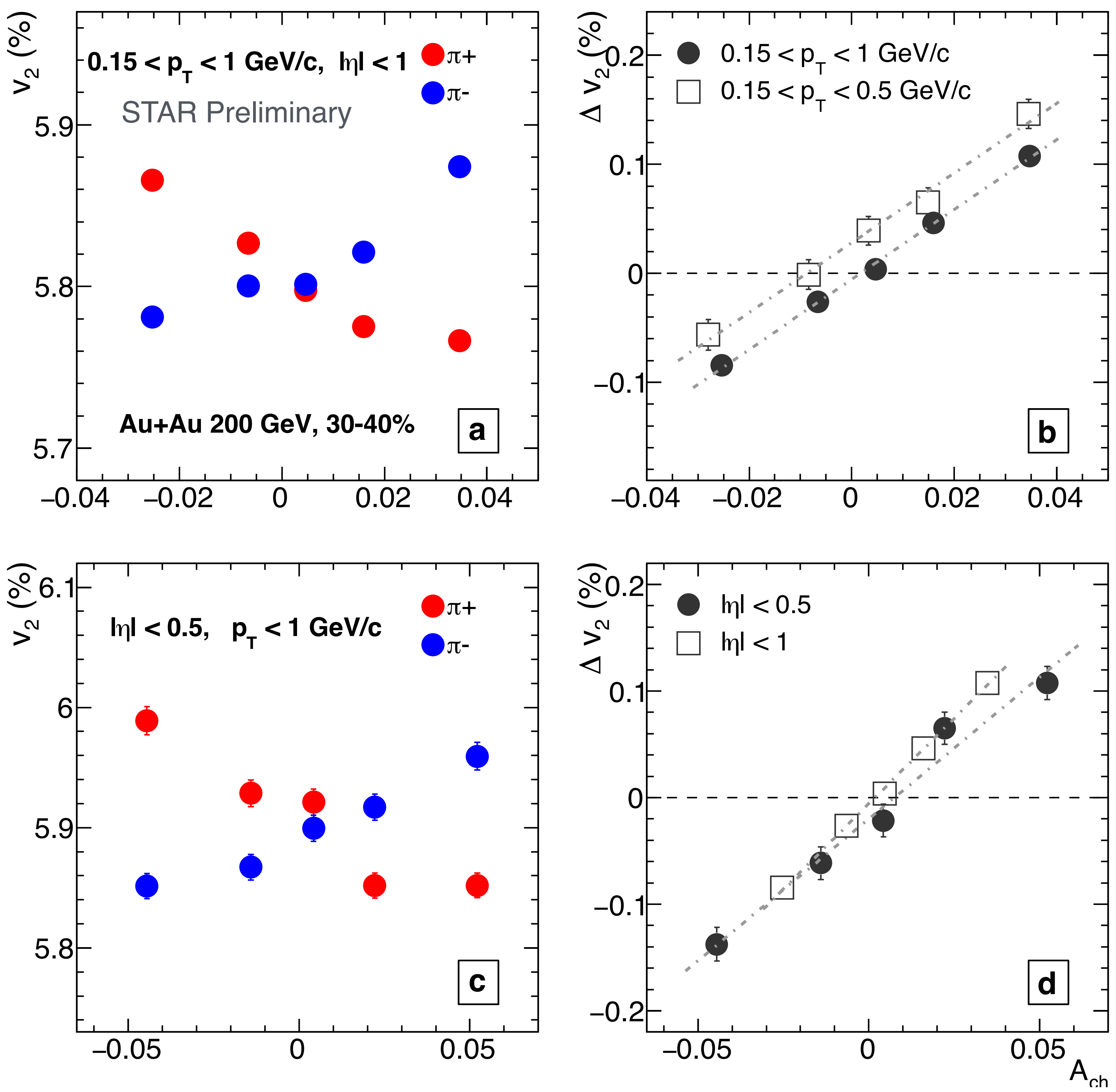

- Significant and similar linear relationships are observed for $v_2$ and $v_3$ at LHC-CMS, which cannot be explained by CMW but is consistent with predictions based on Local Charge Conservation. Similar linear dependences are also found in pPb and PbPb system.
- CMS results challenge CMW, and are in favor of Local Charge Conservation.



# Dependence of $\langle p_T \rangle$ and $v_2$ on $A_{ch}$ for pions in different kinematic windows




- Over the same $A_{ch}$ range, the relative variation of $\langle p_T \rangle$ (~0.1%) is typically smaller than the relative variation of $v_2$ (~1%) by an order of magnitude.
- A wider $p_T$ range enhances particle yields, which is important for analyses involving K and p.



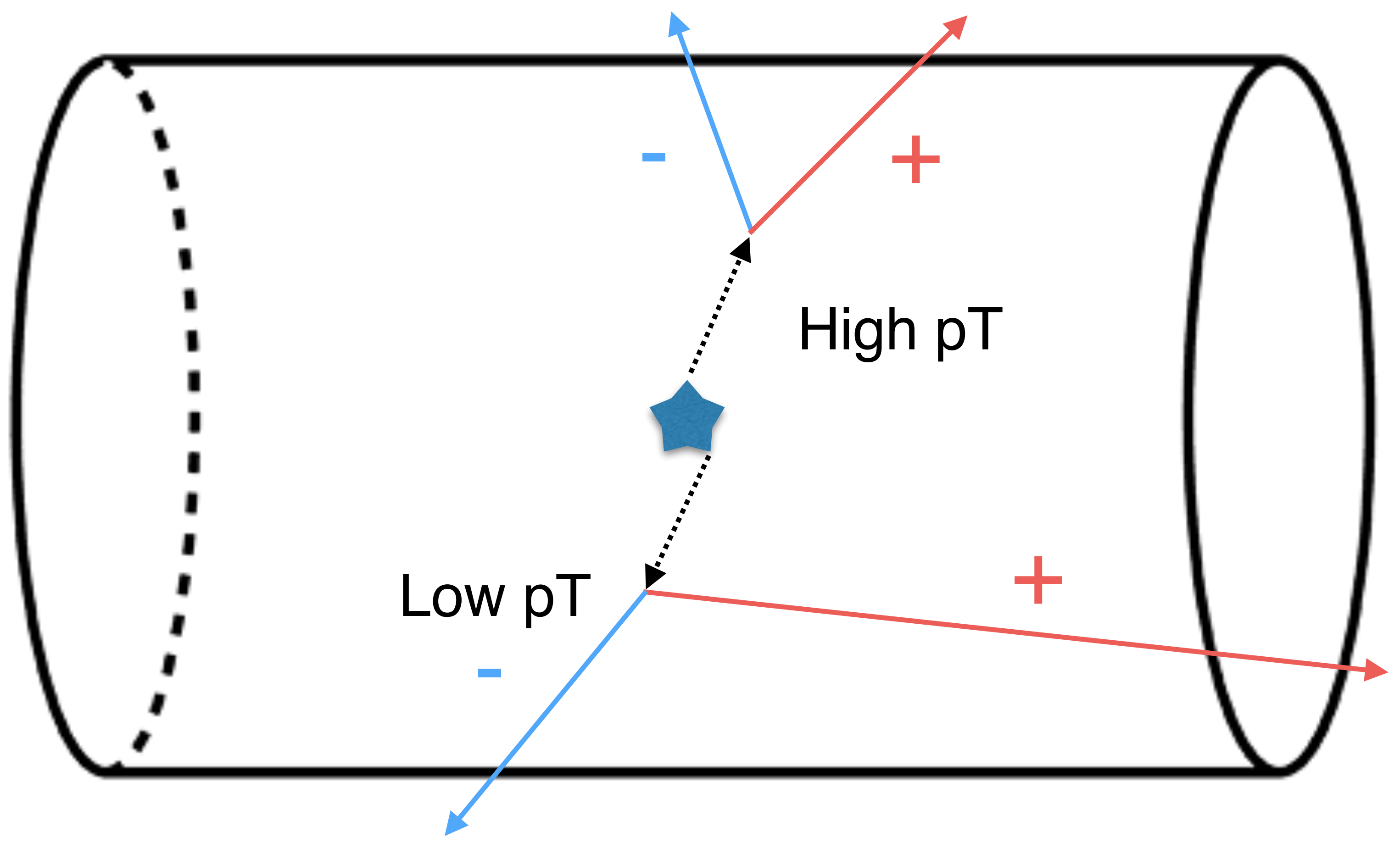

- When the η coverage is reduced to half, the $\Delta v_2(A_{ch})$ slope, does not display a significant variation, suggesting the smallness of the LCC effect in these data.

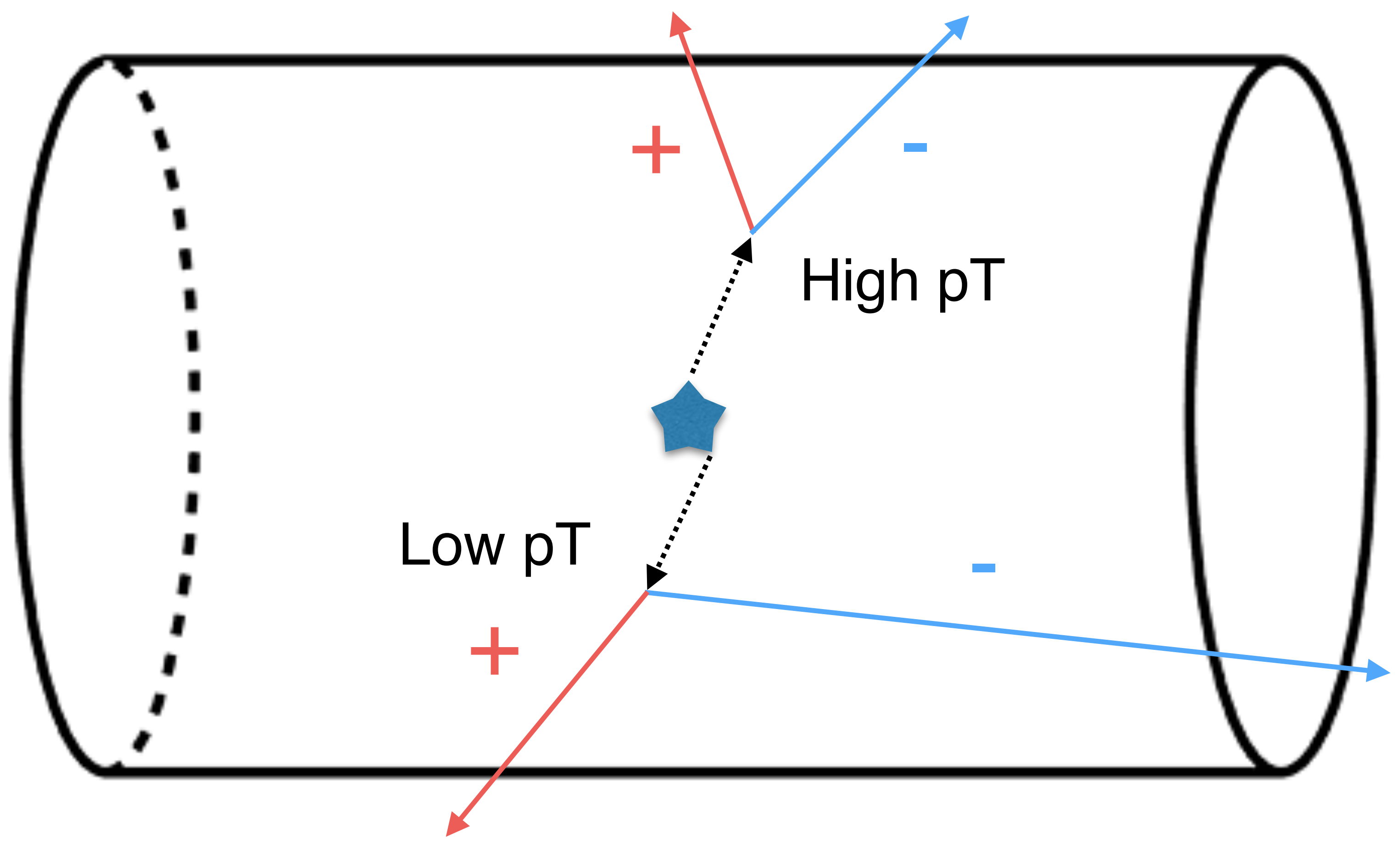
(Some statistical uncertainties are invisible on the current scale)

# Possible background — Local Charge Conservation

A. Bzdak, P. Bożek, Physics Letters B 726 (2013) 239–243

clusters (resonances, fluid elements)



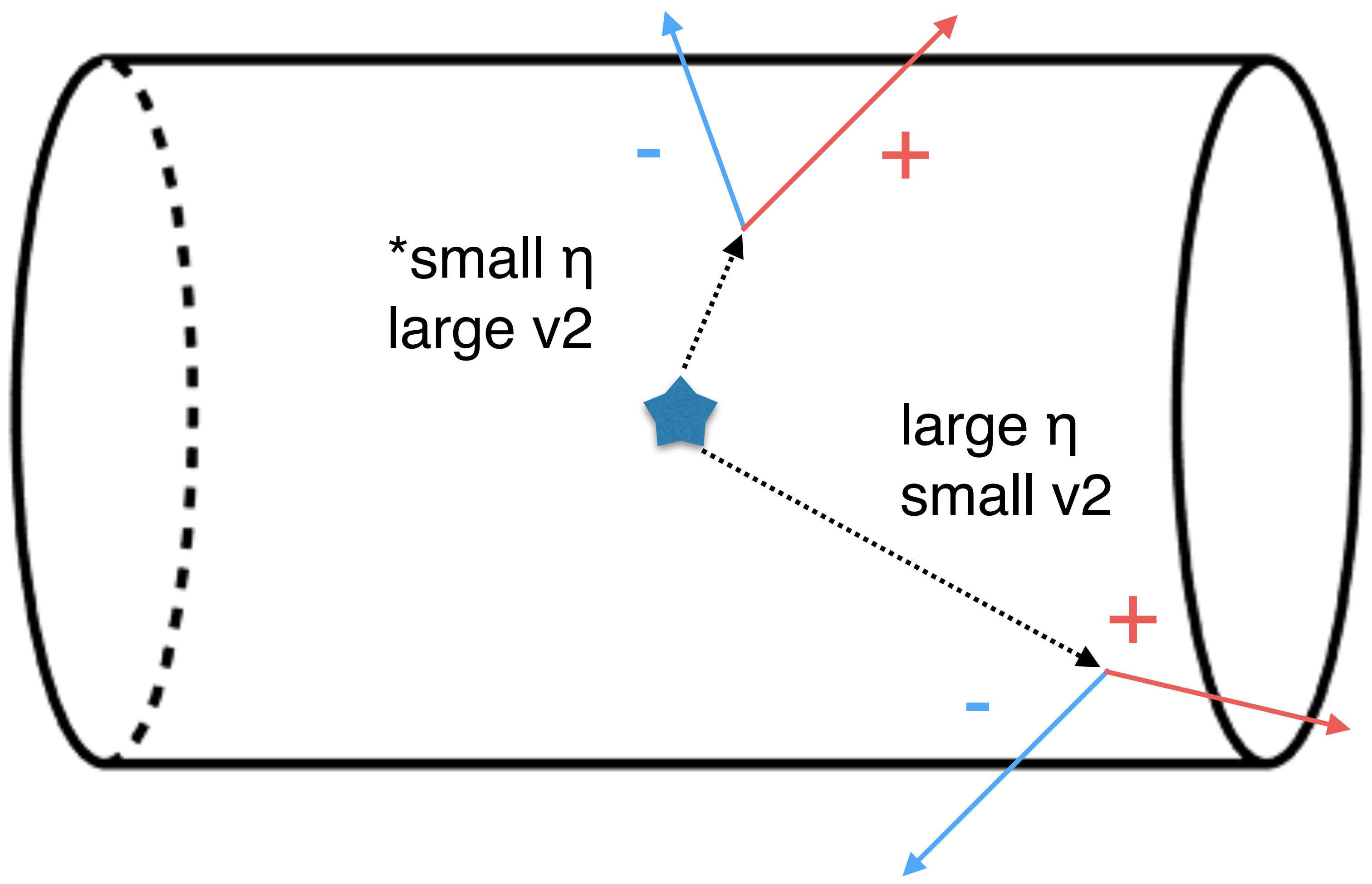

$A_{ch}$ decrease
mean $p_T(-) <$ mean $p_T(+)$
$v_2(-) < v_2(+)$

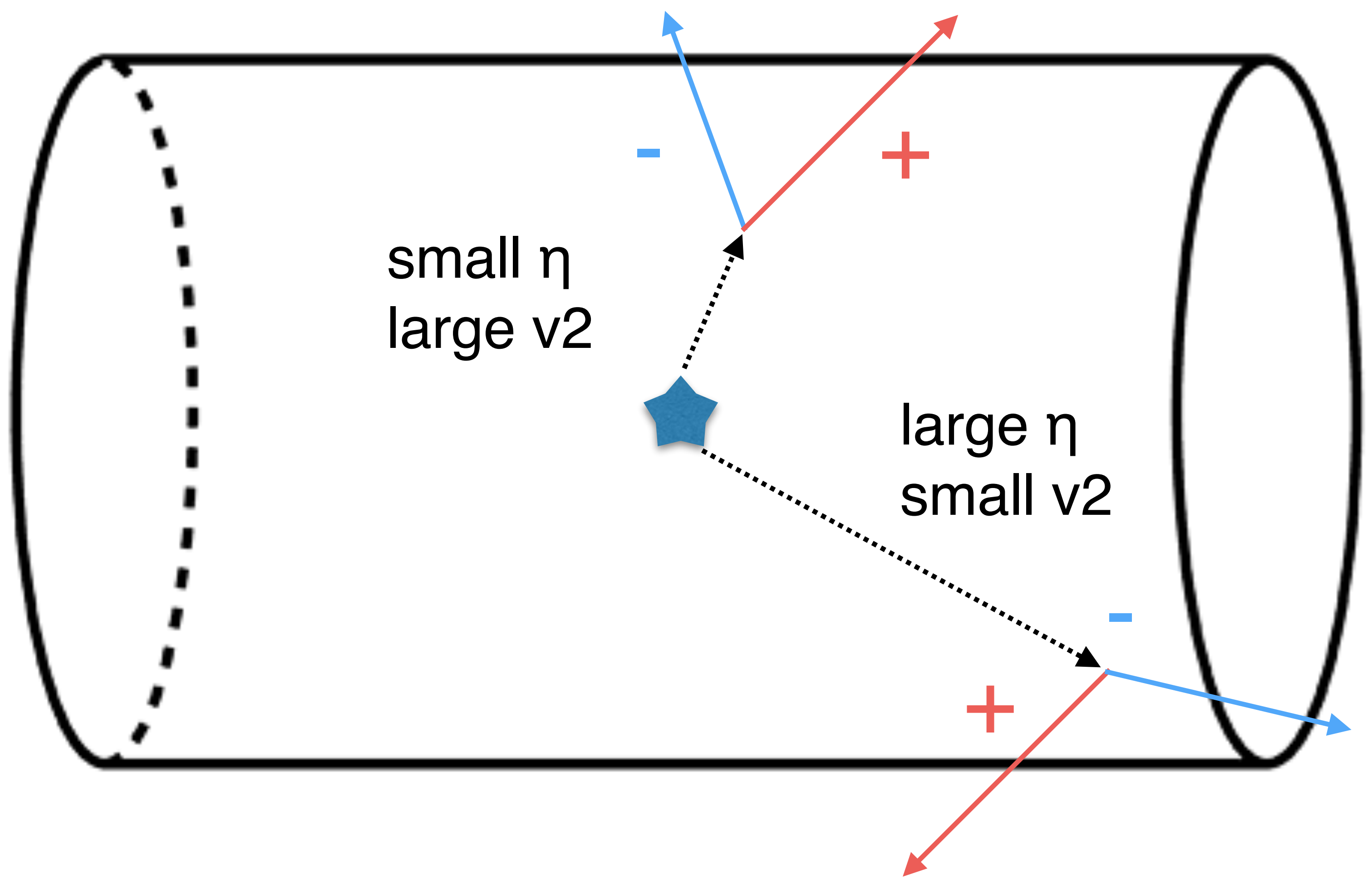
$A_{ch}$ increase
mean $p_T(-) >$ mean $p_T(+)$
$v_2(-) > v_2(+)$

# Possible background — Local Charge Conservation, another mechanism

A. Bzdak, P. Bożek, Physics Letters B 726 (2013) 239–243

clusters (resonances, fluid elements)



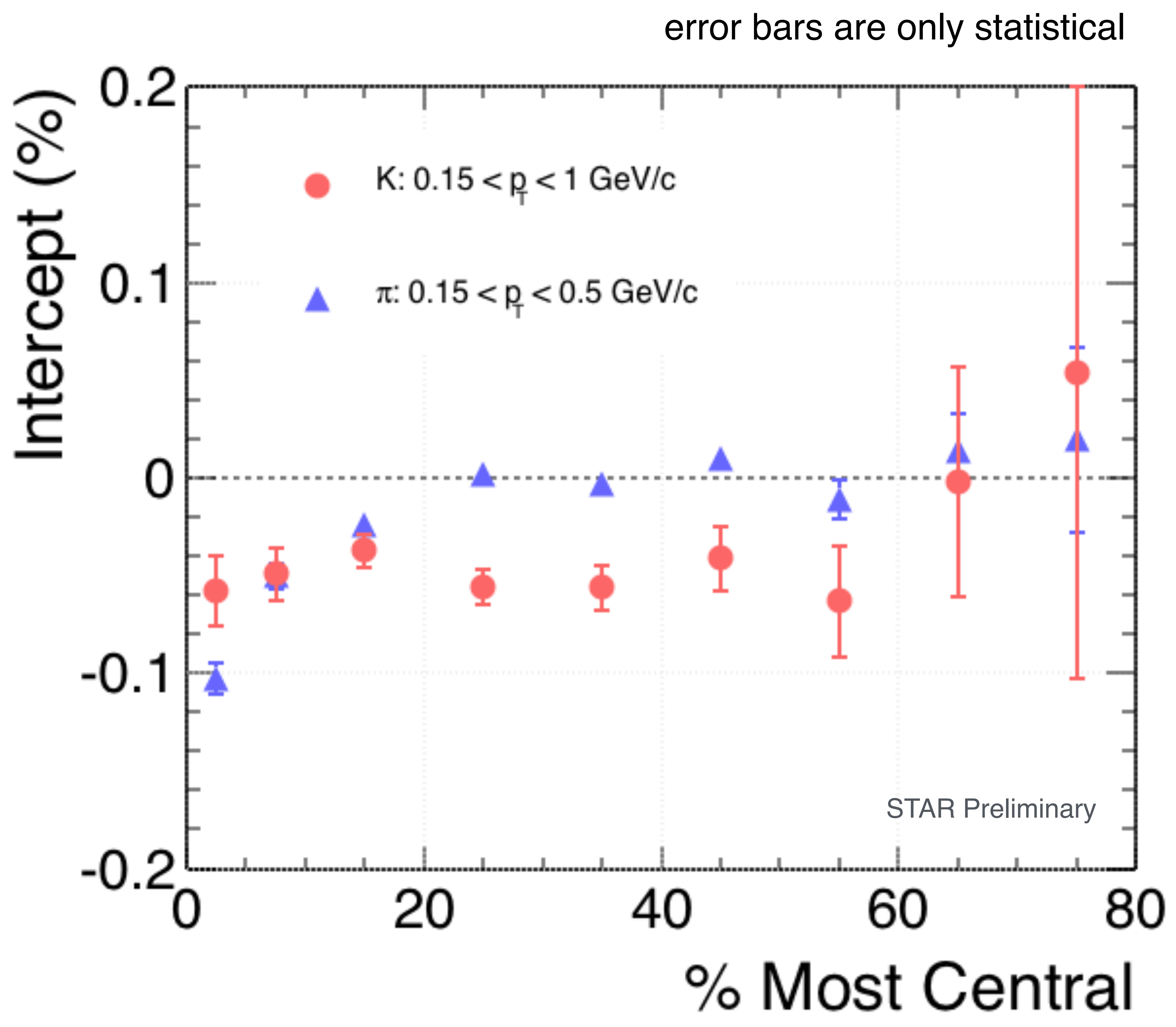




$A_{ch}$ decrease
$v_2(-) < v_2(+)$

$A_{ch}$ increase
$v_2(-) > v_2(+)$

*PHOBOS data

# Intercept(K) in $\sqrt{s_{NN}}$ 200 GeV




We know

$v_2(\pi^-) > v_2(\pi^+)$

$v_2(K^-) < v_2(K^+)$

so both

Slope (>0)

$v_2(\pi^-) - v_2(\pi^+) = v_2^{\pi}(\text{base}) + rA_{ch} > 0$

$v_2(K^-) - v_2(K^+) = v_2^{K}(\text{base}) + rA_{ch} < 0$

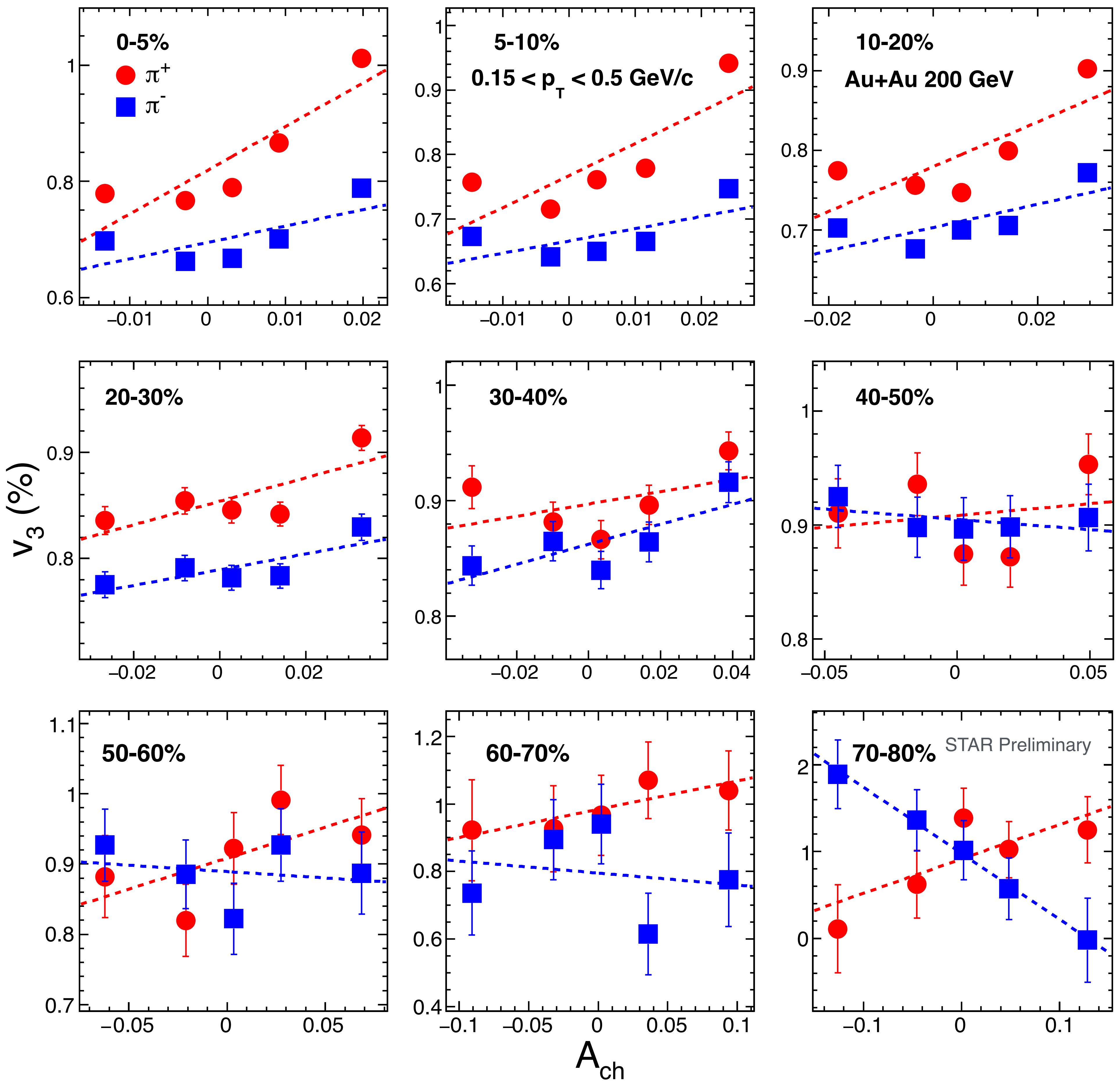
are valid

Intercept

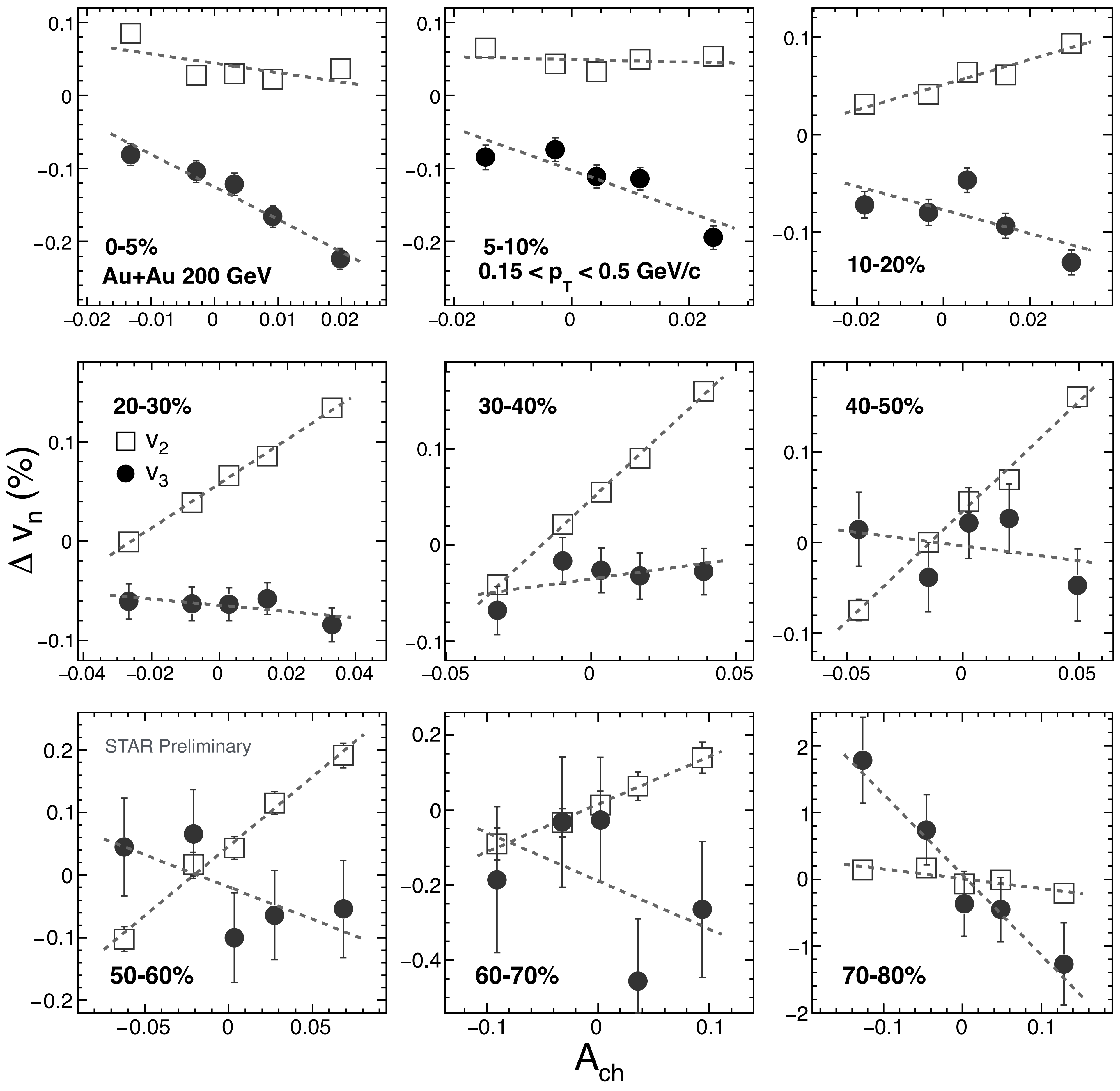
Does this observation conflict with our knowledge of (anti-)particle flow?

No, since the intercepts are negative.

# Dependence of the $\Delta v_3(A_{ch})$ slope on centrality for π in Au+Au collisions




$v_3$ for $\pi^{\pm}$ as functions of $A_{ch}$ in 9 centralities in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV




Comparison of $\Delta v_3$ and $\Delta v_2$ for pions as functions of $A_{ch}$ in 9 centralities in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

# Dependence of the $\Delta v_3(A_{ch})$ slope on centrality for π in Au+Au collisions

$$\sigma_{\mathrm{Norm.}} = \left(\frac{d\mathrm{Norm.}\Delta v_2}{dA_{\mathrm{ch}}} - \frac{d\mathrm{Norm.}\Delta v_3}{dA_{\mathrm{ch}}}\right)/\epsilon$$

ε - combined error of $\Delta v_2$ and $\Delta v_3$ in quadrature

STAR Preliminary

| Centrality | 0-5% | 5-10% | 10-20% | 20-30% | 30-40% | 40-50% | 50-60% | 60-70% | 70-80% |
|---|---|---|---|---|---|---|---|---|---|
| $p_T < 0.5$ GeV/c | 4.2 | 4.1 | 3.9 | 2.4 | 0.7 | 1.3 | 1.9 | 1.4 | 2.2 |
| $p_T < 1$ GeV/c | 5.9 | 4.6 | 3.7 | 2.2 | 0.2 | -0.4 | 0.8 | 1.2 | 2.6 |
| $p_T < 2$ GeV/c | 4.7 | 4.4 | 3.3 | 1.8 | 0.003 | -0.6 | 0.2 | 0.7 | 2.3 |

- These $\sigma_{\mathrm{Norm.}}$ values suggest that the STAR measurements of the $\Delta v_2(A_{ch})$ slopes are different with the CMS measurements.
- It is unlikely that a common background such as LCC could alone explain the data. There could be multiple reasons, particularly at most central and peripheral collisions. CMW picture still remains as a viable interpretation at RHIC.