# Investigating the NCQ scaling of elliptic flow at LHC with AMPT

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Eur. Phys. J. A53, 124, (2017) LZ, Hui Li, Hong Qin, Qi-Ye Shou and Zhong-Bao Yin

# Outline

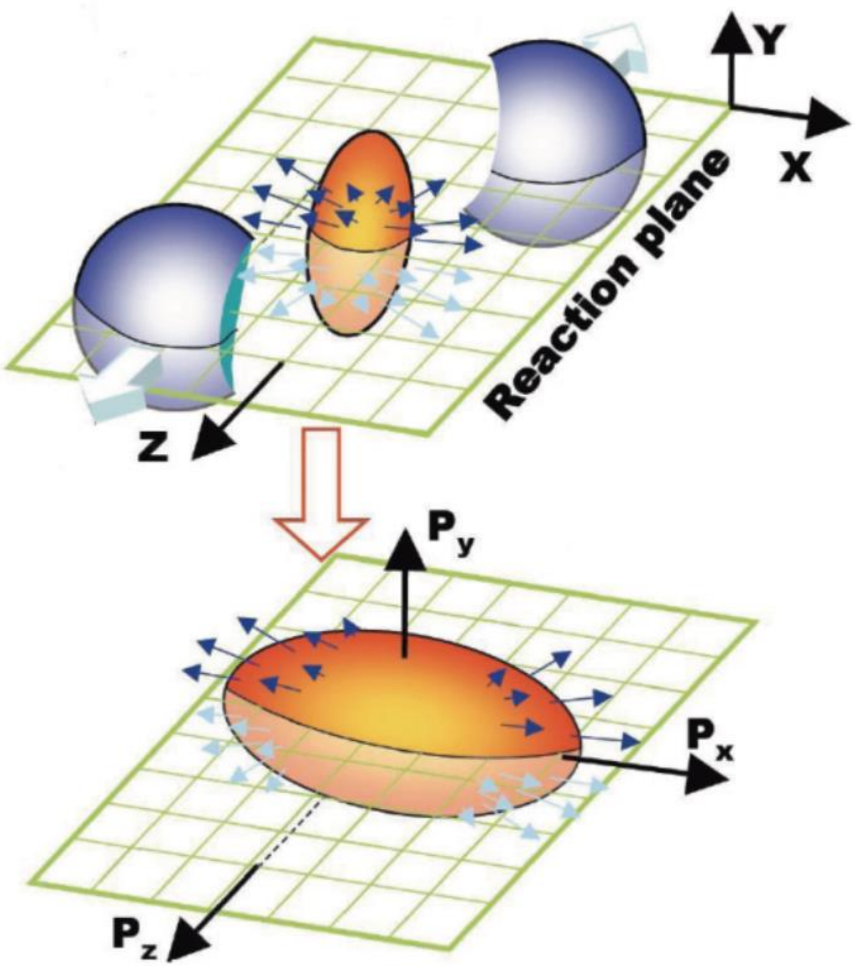
- Elliptic flow and quark number scaling
- Quark coalescence model
- Insights to $v_2$ NCQ scaling from AMPT
- Outlook and Summary

# Elliptic flow in heavy ion collisions

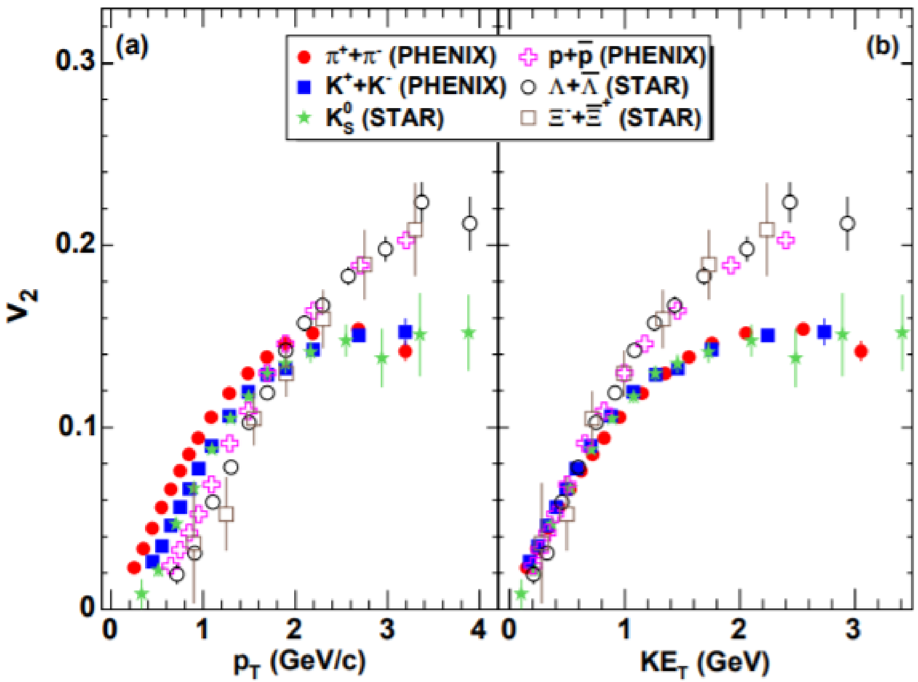
- Elliptic flow: Momentum space anisotropy of particle production

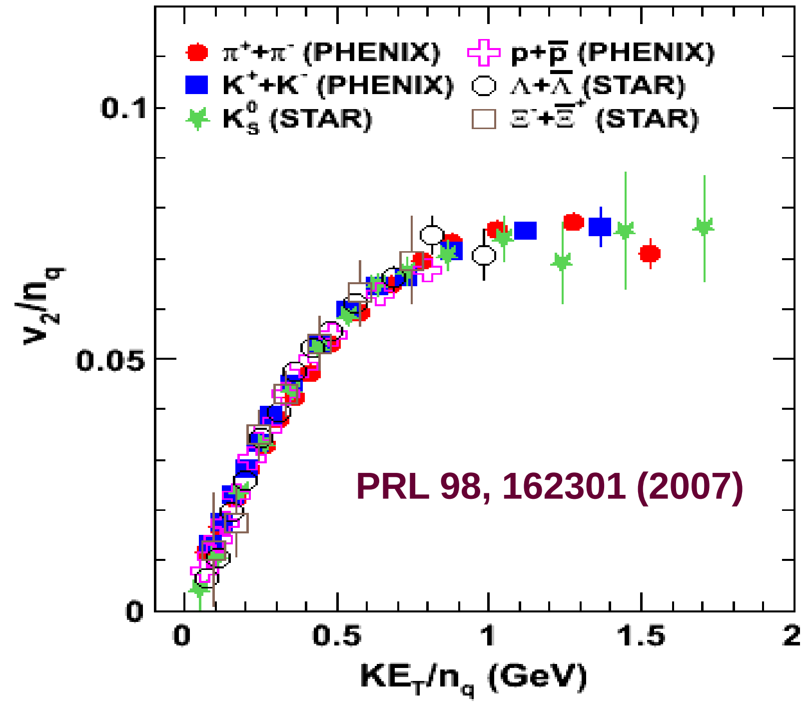
$$v_2 = \langle \cos(2(\phi - \Psi)) \rangle$$

- Arising due to coordinate space anisotropy (b>0) and interactions among medium constituents
- Why do we care:
  - Sensitive to the properties of QGP medium, e.g. shear viscosity
  - Provide information on the initial state of the collisions



# $v_2$ and quark number scaling

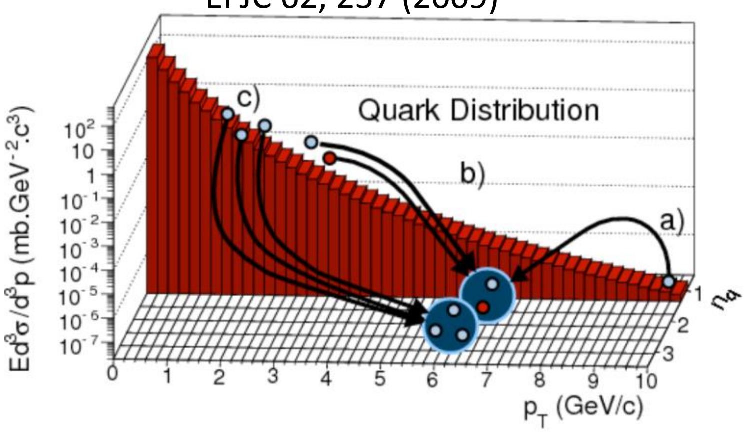



- Mass ordering at low $p_T$ driven by the hydrodynamic pressure gradient.
- Baryon meson ordering in the high $p_T$ region.
- NCQ scaling observed in a wide range of $KE_T$ indicates the dominance of partonic degrees of freedom.

# Quark coalescence model

EPJC 62, 237 (2009)




Freeze-out hypersurface

Hadron wave-function

$$E\frac{dN_M(\vec{p})}{d^3p} = \int d\sigma^\mu p_\mu \int d^3q |\psi_{\vec{p}}(\vec{q})|^2 f_\alpha(\vec{p_\alpha}, x) f_\beta(\vec{p_\beta}, x)$$

$$E\frac{dN_B(\vec{p})}{d^3p} = \int d\sigma^\mu p_\mu \int d^3q_1 d^3q_2 |\psi_{\vec{p}}(\vec{q_1}, \vec{q_2})|^2 f_\alpha(\vec{p_\alpha}, x) f_\beta(\vec{p_\beta}, x) f_\gamma(\vec{p_\gamma}, x)$$

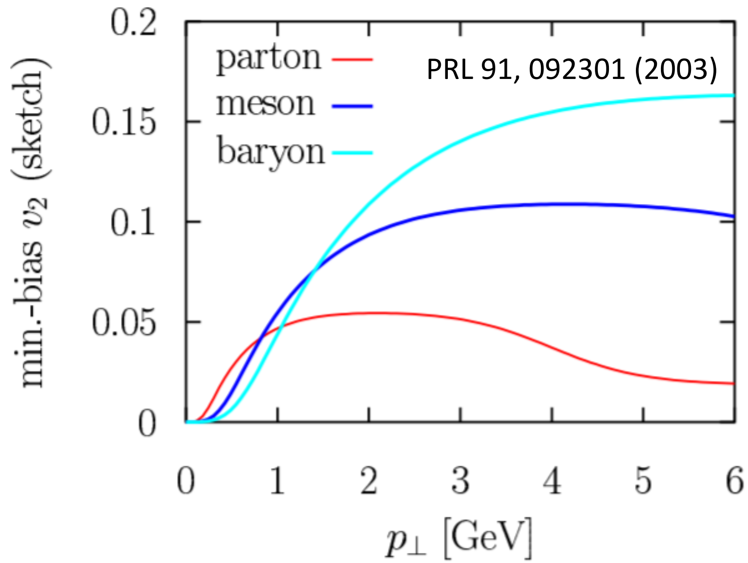
Quark phase space density

Assume quark momentum distribution:

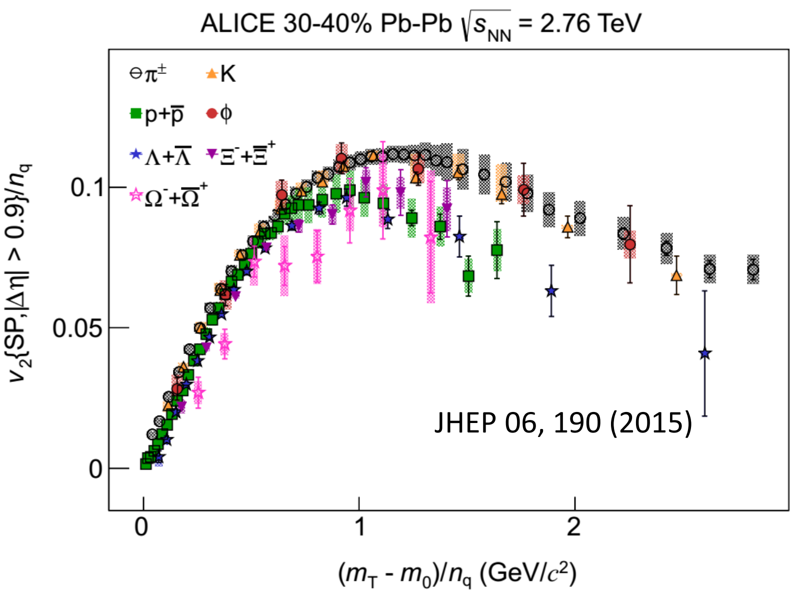
$$f_i(\vec{p_\perp}) \equiv \frac{dN}{d^3p} = g_i(p_\perp)\left[1 + 2v_{2,i}(p_\perp)\cos(2\phi)\right]$$

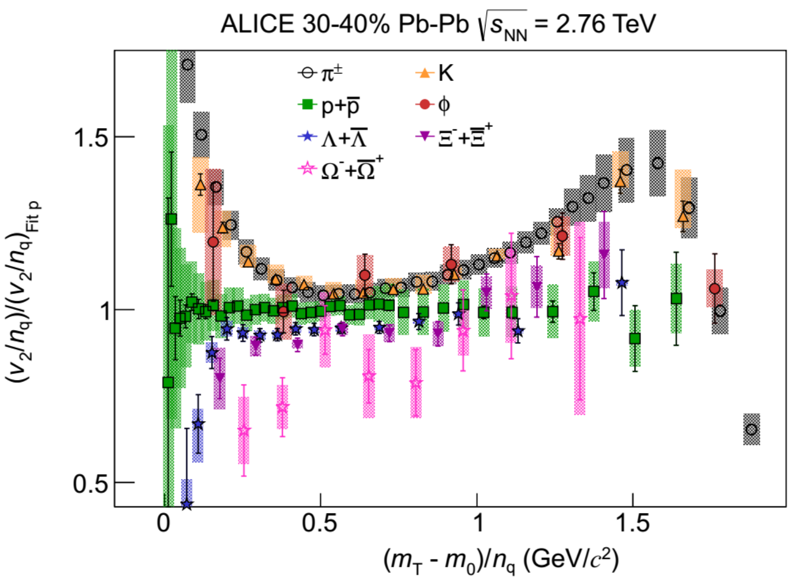
Yield simple relations of quark and hadron flow:

$$v_{2,M}(p_\perp) \approx 2v_{2,q}\left(\frac{p_\perp}{2}\right) \qquad v_{2,B}(p_\perp) \approx 3v_{2,q}\left(\frac{p_\perp}{3}\right)$$



# Violation to NCQ scaling



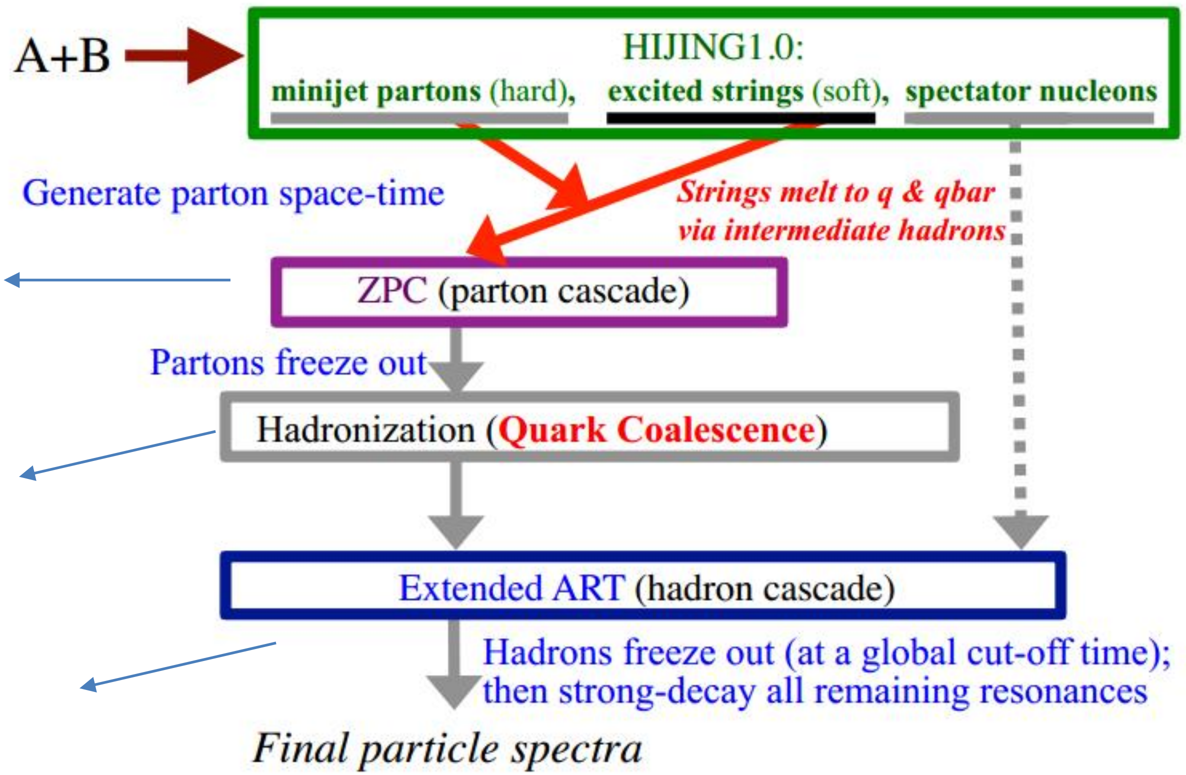

- Deviations from the NCQ scaling at the level of 20% observed in LHC data
- Possible reasons:
  - Narrow wave function width, Resonance decay, Space-Momentum correlations at freeze-out, Phase-space density

# The paradigm in AMPT

Space-momentum correlation at parton stage

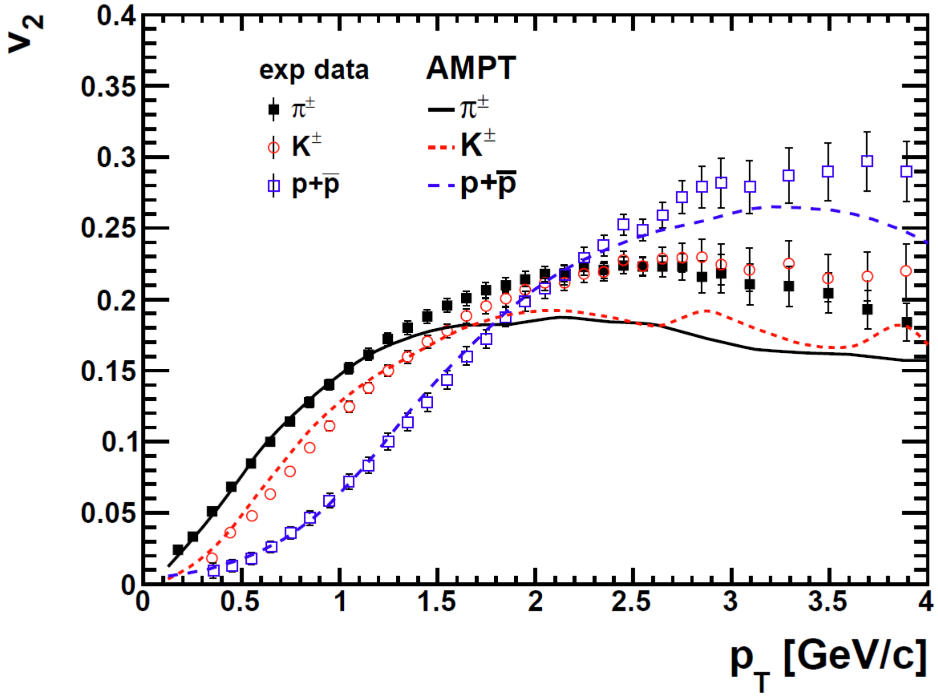
Coalescence mechanism

Hadron rescattering, resonance decay



# Identified particle $v_2$ in AMPT

PbPb 2.76 TeV 30-40%




$v_2$ obtained with event plane method.

Ampt-v1.26t5-v2.26t5

a=0.3, b=0.15 GeV$^{-2}$

μ =2.3 fm$^{-1}$, $\alpha_s$=0.33, $\sigma_{parton}$=3 mb

PRC 90, 014904 (2014)

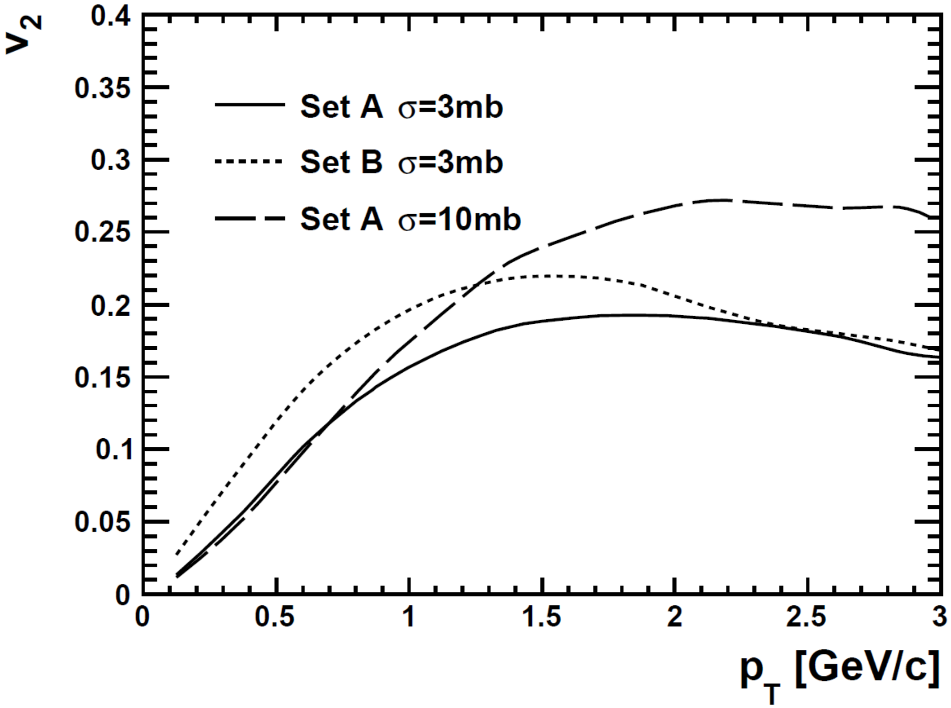
$$f(z) \propto z^{-1}(1-z)^a \exp(-b\, m_\perp^2/z)$$

$$\sigma_{PP} \approx \frac{9\pi\alpha_s^2}{2\mu^2}$$

Identified particle $v_2$ within |η|<0.8 agree with data except in the high $p_T$ region, where model results are systematically smaller than data.

# Charged particle $v_2$ with different initial and final state conditions

PbPb 2.76 TeV 30-40%, charged pion




Right after coalescence

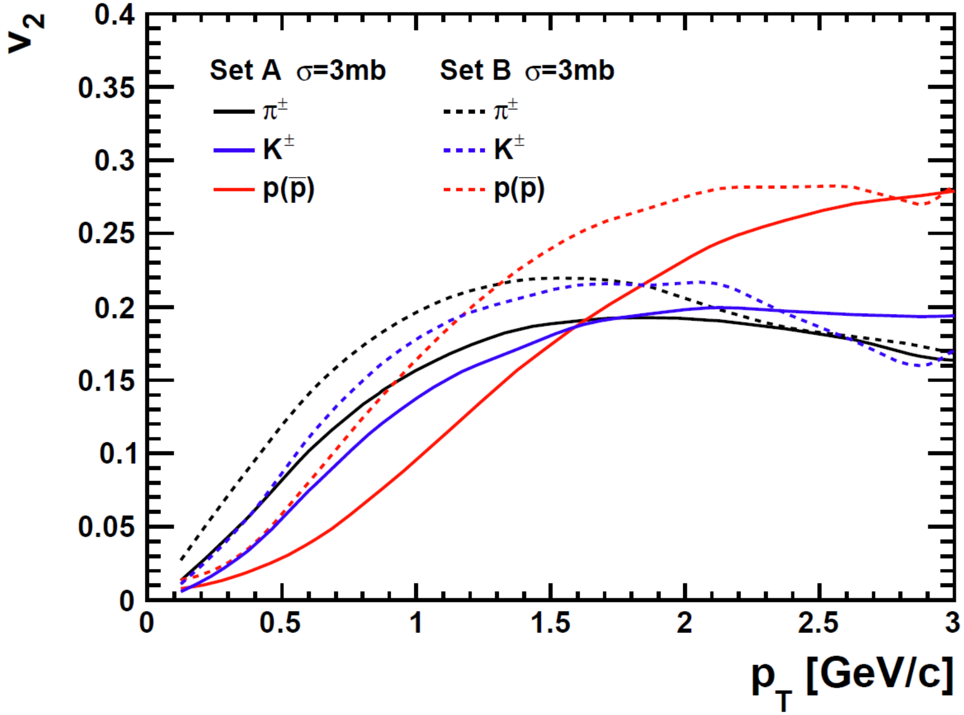
| | a | b ($GeV^{-2}$) |
|---|---|---|
| Set A | 0.3 | 0.15 |
| Set B | 0.5 | 0.9 |

$$\kappa \propto 1/[b(2+a)]$$
$$\kappa_B \approx 1/6\kappa_A$$

- Small string tension leads to large low $p_T$ $v_2$
- Large parton-parton scattering cross section generates stronger high $p_T$ $v_2$.

# $v_2$ with different initial conditions

PbPb 2.76 TeV 30-40%

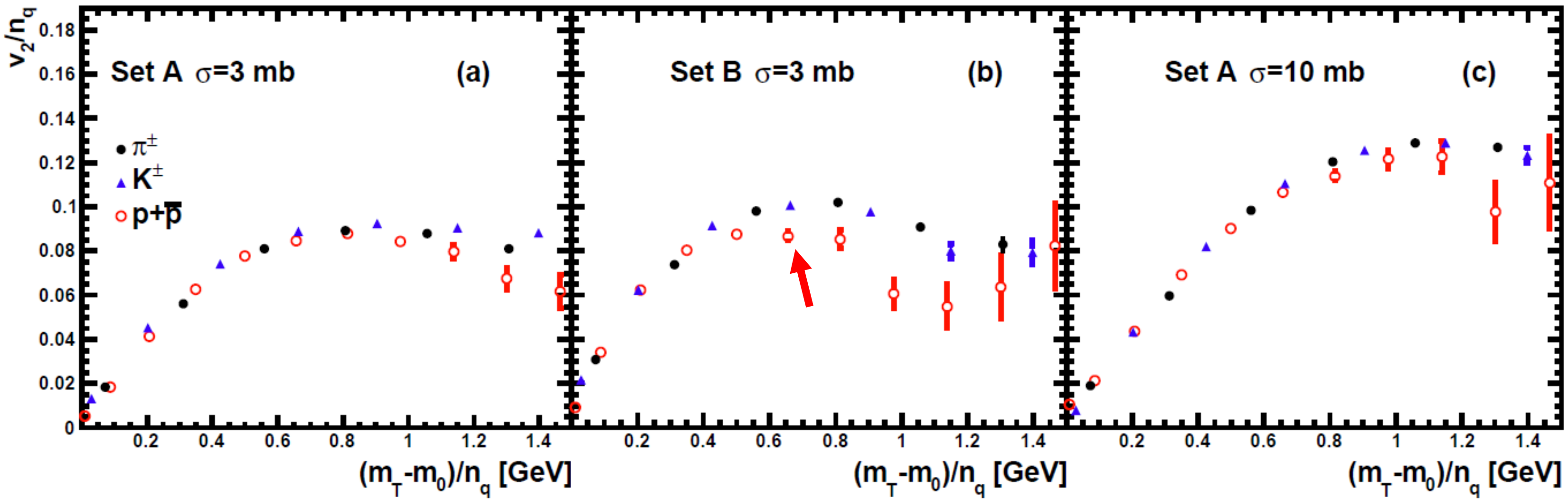



Right after coalescence

- $v_2$ from different initial conditions converge at high $p_T$.
- Mass ordering exists in both two sets, while the magnitude of the mass splitting changes a little.

# Test of scaling properties

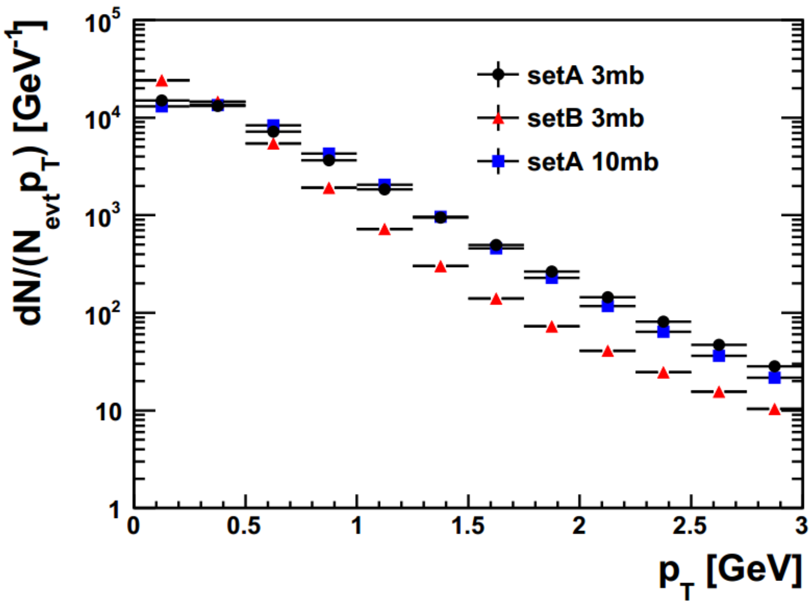
PbPb 2.76 TeV 30-40%, hadron formed right after coalescence

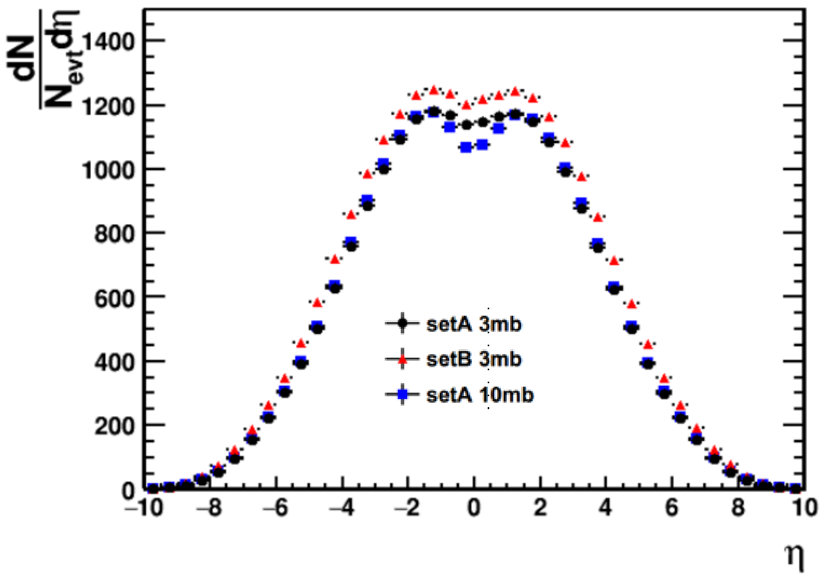



- NCQ scaling behavior relies on the initial conditions even within the quark coalescence context.
- Violation to the NCQ scaling observed in the case generated with smaller string tension.
- The final state parton scattering effect is less important in the formation of NCQ scaling phenomenon.

# Parton distribution before coalescence

Quark distribution before hadronization in PbPb 2.76 TeV 30-40%

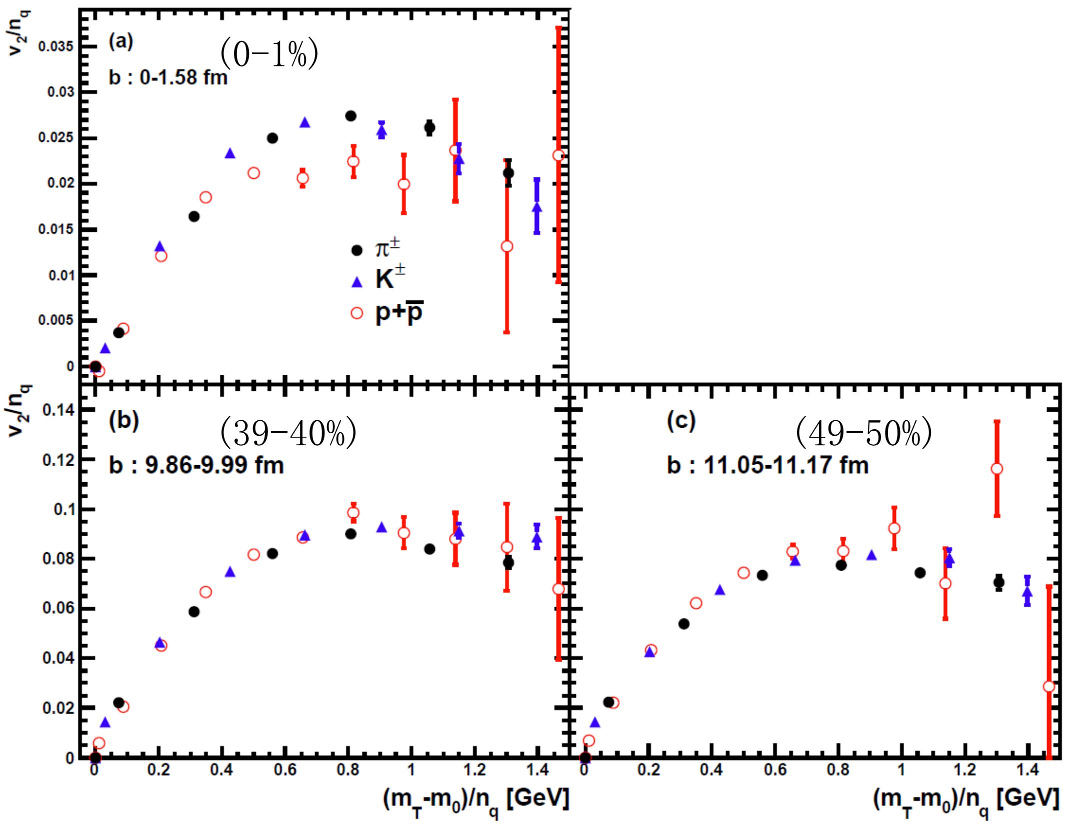



- Quark number densities are quite similar in all cases.
- Smaller string tension generates softer initial parton spectrum.
- The violation to NCQ scaling may arise from the higher parton-parton interaction rate in the overlap region.

# $v_2$ NCQ scaling varying with collision centrality

PbPb 2.76 TeV

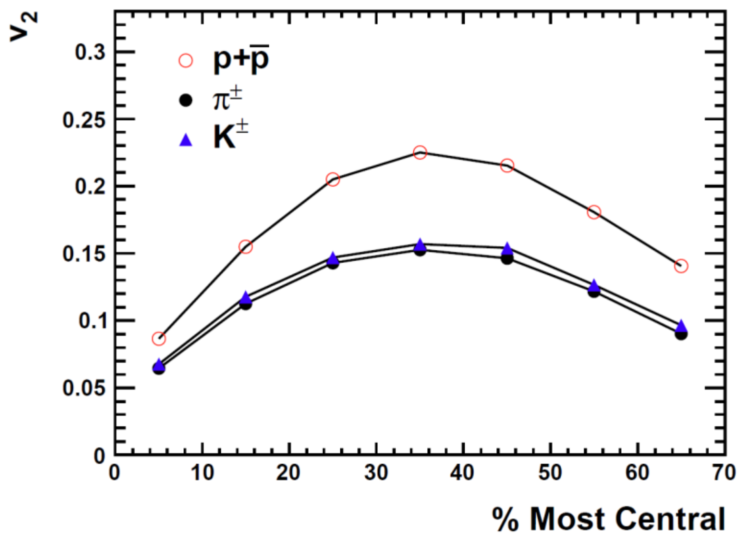


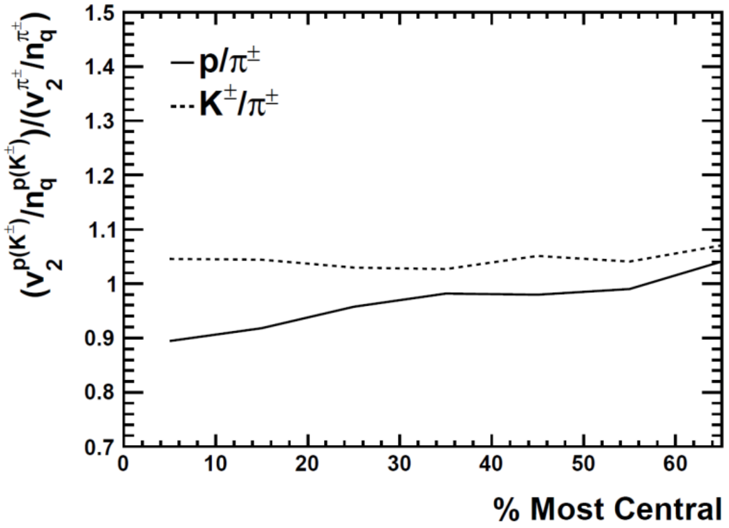

Right after coalescence

- NCQ scaling violated in central collisions and restored in peripheral collisions.
- Similar trend can be extracted from the measured data.

# Integrated $v_2$ varying with collision centrality

PbPb 2.76 TeV, $v_2$ integrated over $0.3<(m_T-m_0)/n_q<1$ GeV

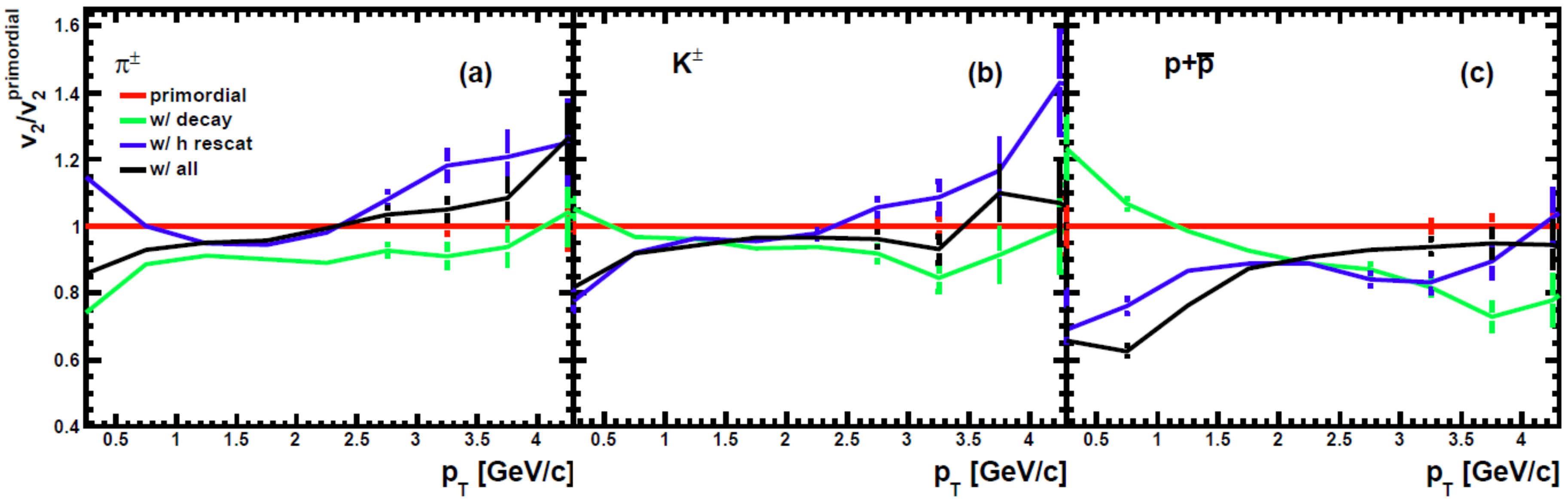



- Integrated flow reaches maximum in semi-central collisions.
- K over π scaled $v_2$ ratio slightly depends on the centrality.
- p over π scaled $v_2$ ratio grows from central to peripheral collisions.

# Hadronic evolution effects

PbPb 2.76 TeV 30-40%




- Primordial v2: formed right after coalescence procedure.
- Resonance decay and hadron rescattering modifies the primordial $v_2$ in opposite way.
- Responses to the modification of hadronic evolution depend on the particle types.

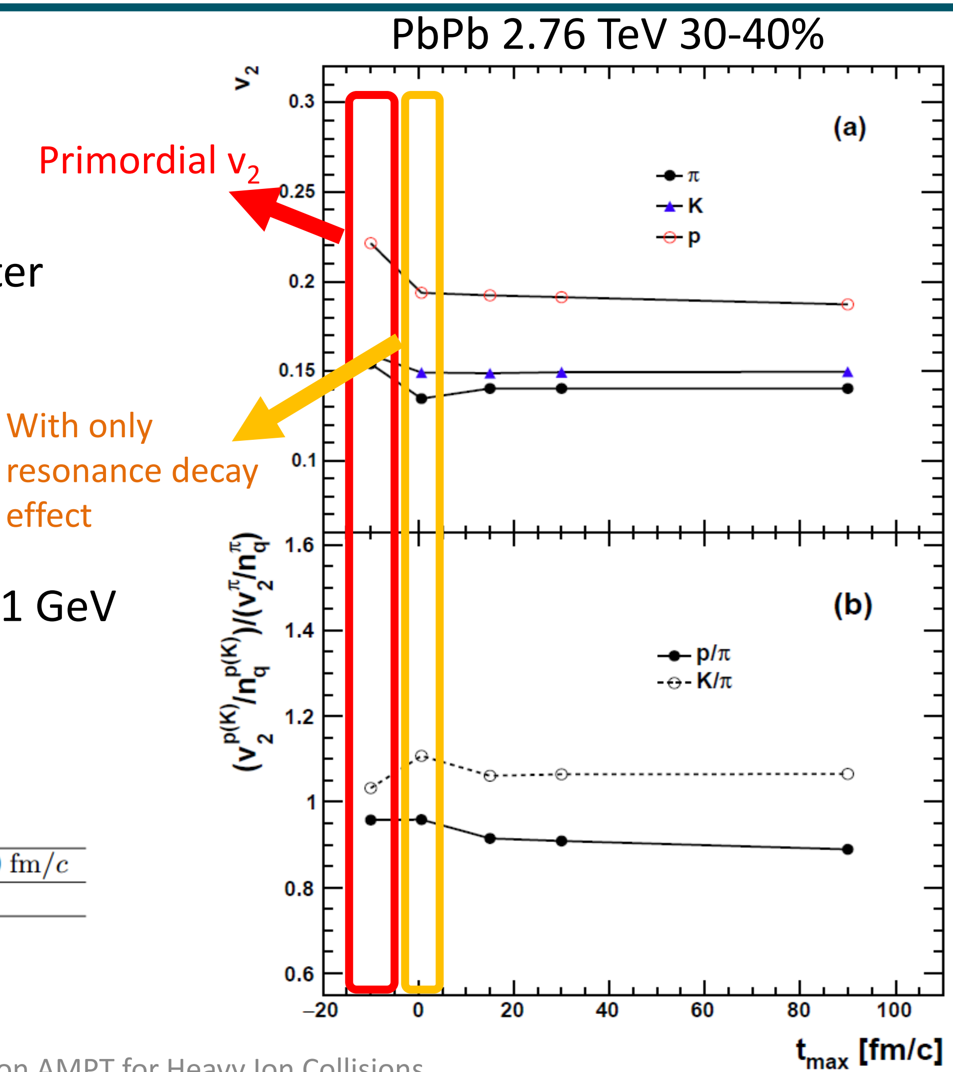
# Impact of hadronic evolution to NCQ scaling

- Hadronic evolution destructs the initial anisotropy formed right after coalescence.
- Larger violation anticipated from stronger hadron rescattering.

$v_2$ integrated over $0.3<(m_T-m_0)/n_q<1$ GeV

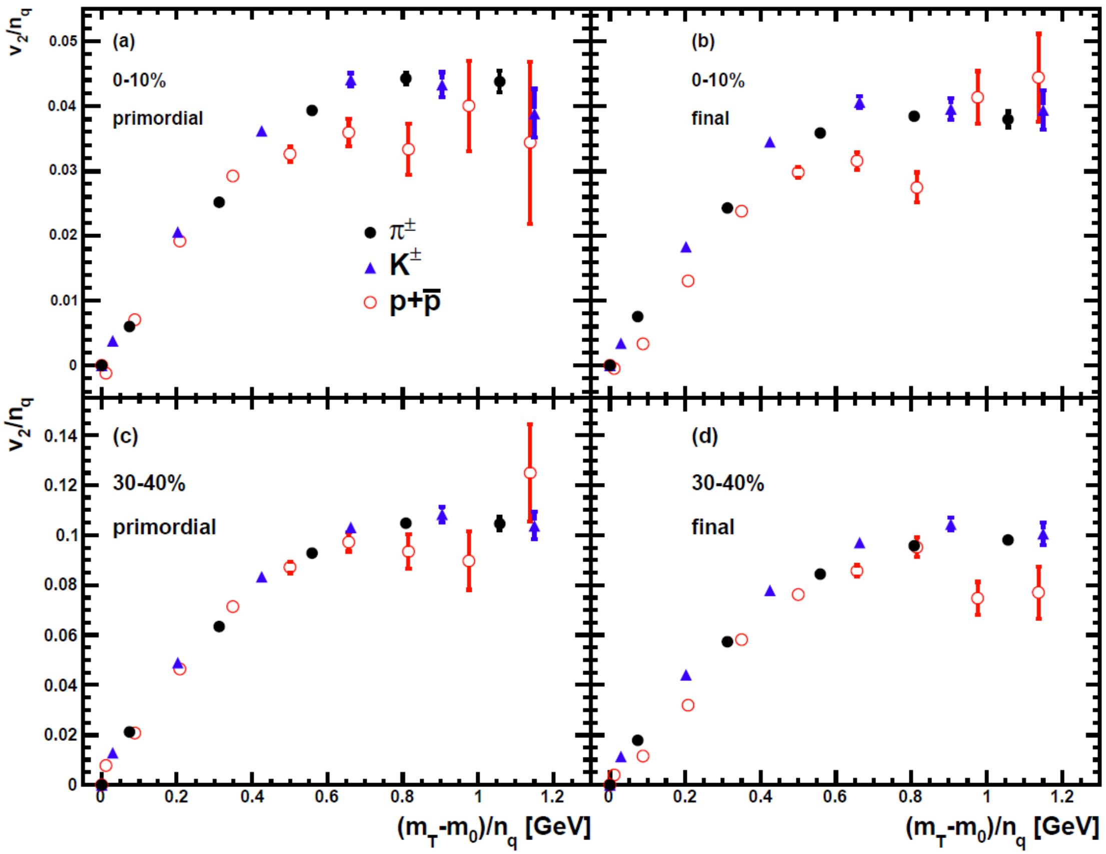
$$\chi = \sqrt{\Sigma_{\pi,K}(\frac{v_2^{\pi,K}/n_q^{\pi,K} - v_2^p/n_q^p}{v_2^p/n_q^p})^2}$$

| | primordial | w/ decay | $t_{max}$=15 fm/$c$ | $t_{max}$=90 fm/$c$ |
|---|---|---|---|---|
| $\chi$ | 0.06 | 0.16 | 0.19 | 0.24 |



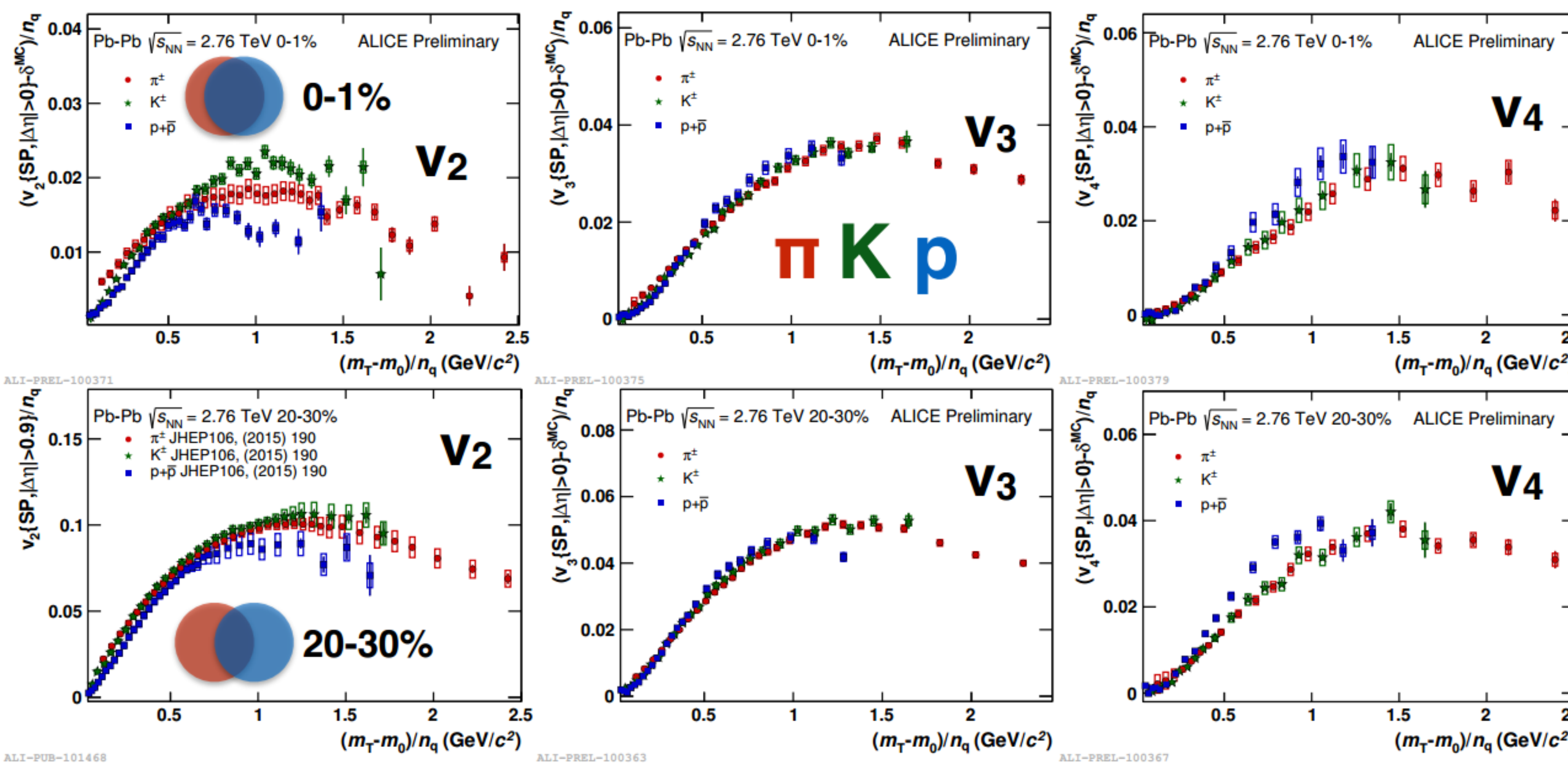
# Energy dependence of NCQ scaling

PbPb 5.02 TeV




- Similar centrality and hadronic evolution impact on NCQ scaling expected with higher collision energy.

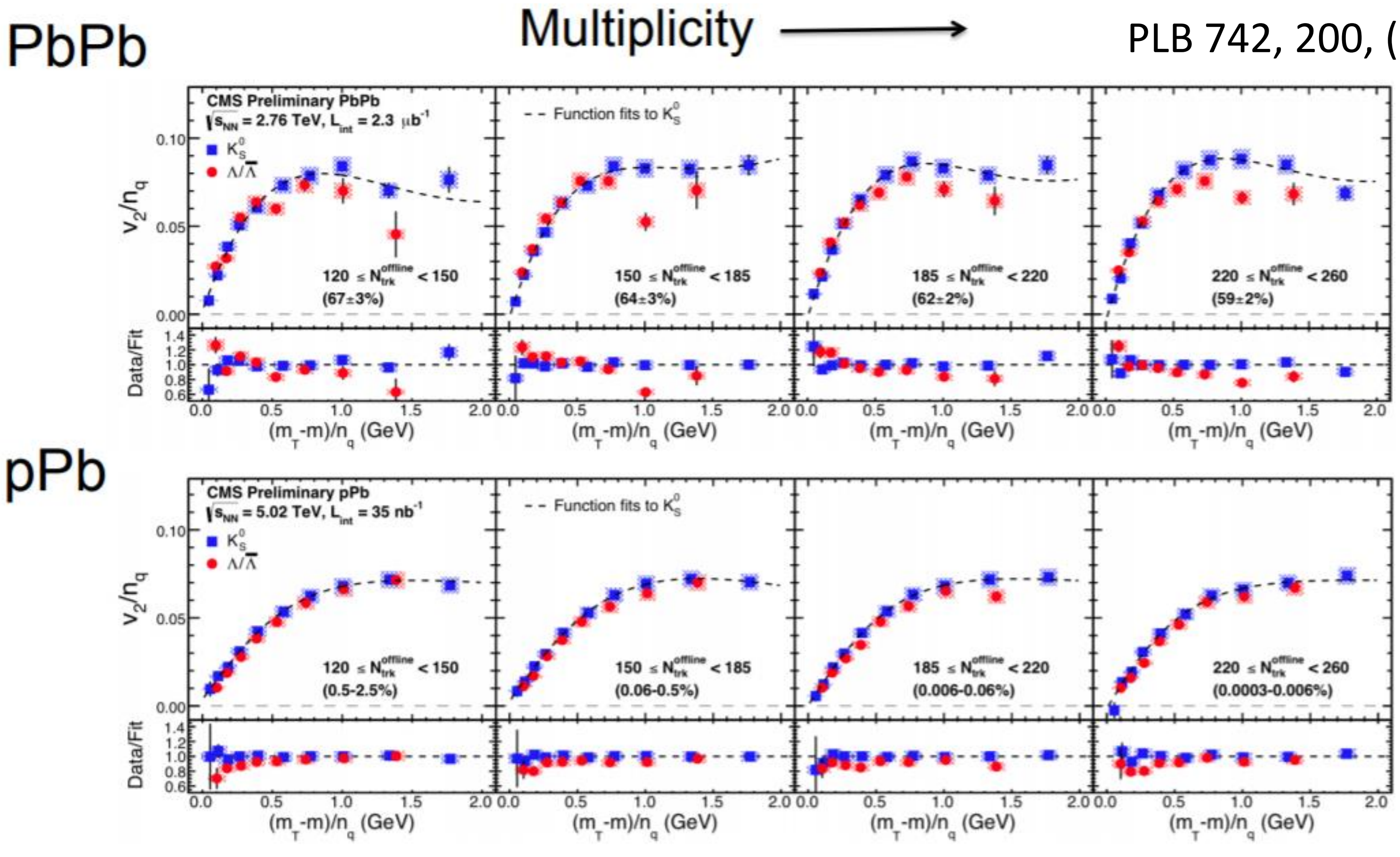
# Outlooks – NCQ scaling in higher order flow




- NCQ scaling seems to work better for $v_3$
- Additional constraint on medium expansion

# Outlooks – NCQ scaling in small systems

PLB 742, 200, (2015)




- NCQ scaling holds better in pPb than in peripheral PbPb

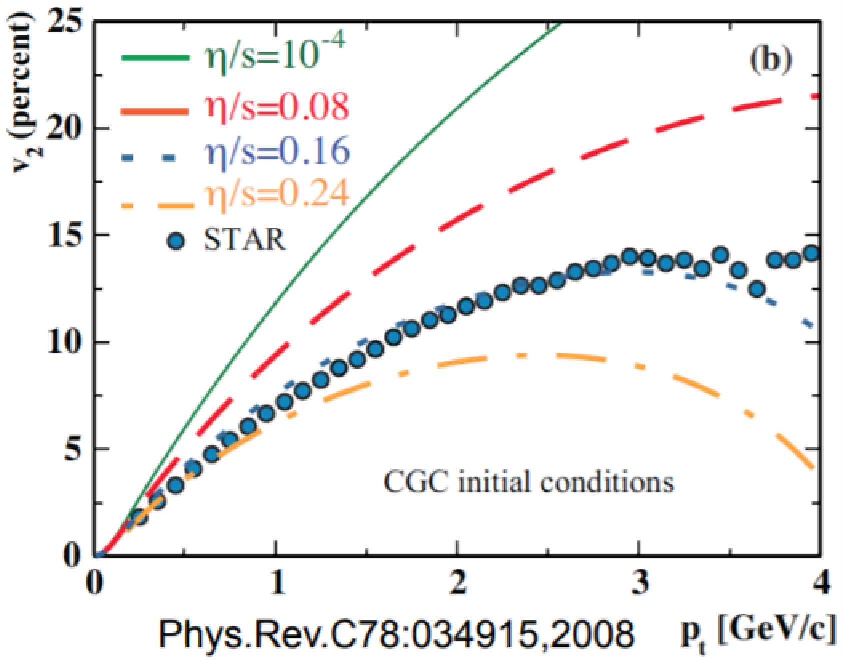
# Summary

- It is shown in the AMPT framework that NCQ scaling structure not only depends on the hadronization procedure but also relies on the parton dynamics at the initial stage.
- A sizable distortion to NCQ scaling arises due to the hadronic interactions.
- The coalescence AMPT coalescence in coordinate space, what if in momentum space?

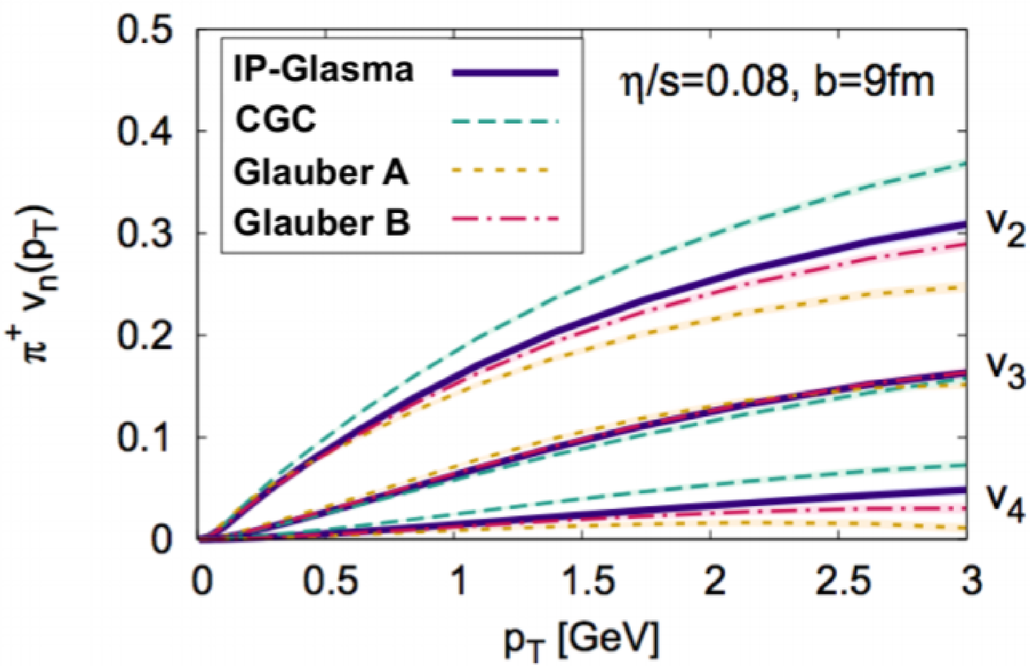
Thank you for your attention!

# Backup

# Why do we care about flow?




Phys.Rev.C78:034915,2008

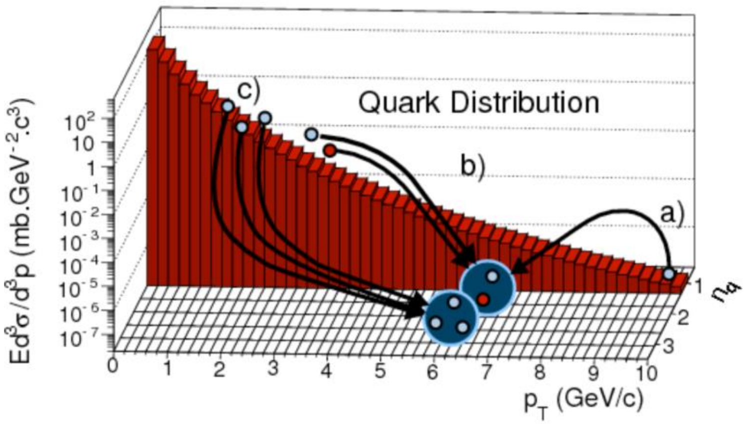



Phys. Rev. Lett. 108, 252301, 2012

- Sensitive to the properties of QGP, e.g.: shear viscosity over entropy density, η/s, of the produced medium
- Provide information on the initial state of the collisions

# Quark coalescence model

EPJC 62, 237 (2009)




Freeze-out hypersurface

Hadron wave-function

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$$E\frac{dN_B(\vec{p})}{d^3p} = \int d\sigma^\mu p_\mu \int d^3q_1 d^3q_2 |\psi_{\vec{p}}(\vec{q_1}, \vec{q_2})|^2 f_\alpha(\vec{p_\alpha}, x) f_\beta(\vec{p_\beta}, x) f_\gamma(\vec{p_\gamma}, x)$$

Quark phase space density

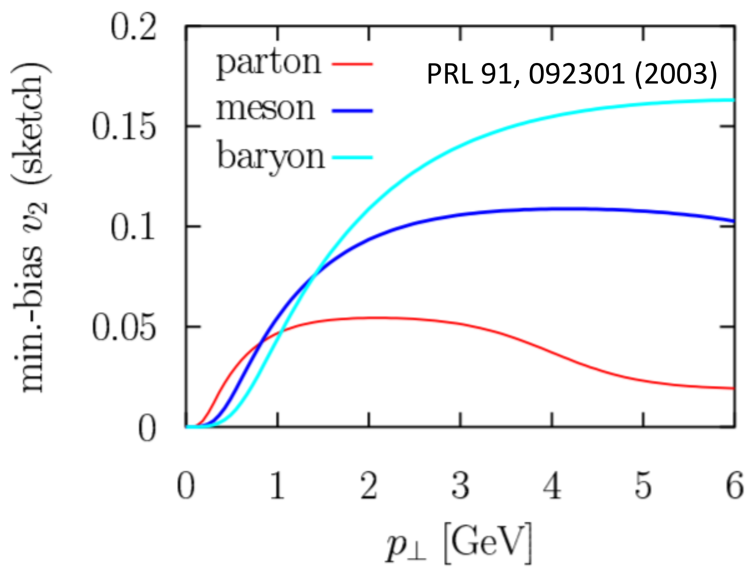
Already assumed: rare process, small binding energy, factorization of 2-parton distribution functions, slowly-varying quark spatial-distributions, same hypersurface

Assume quark momentum distribution:

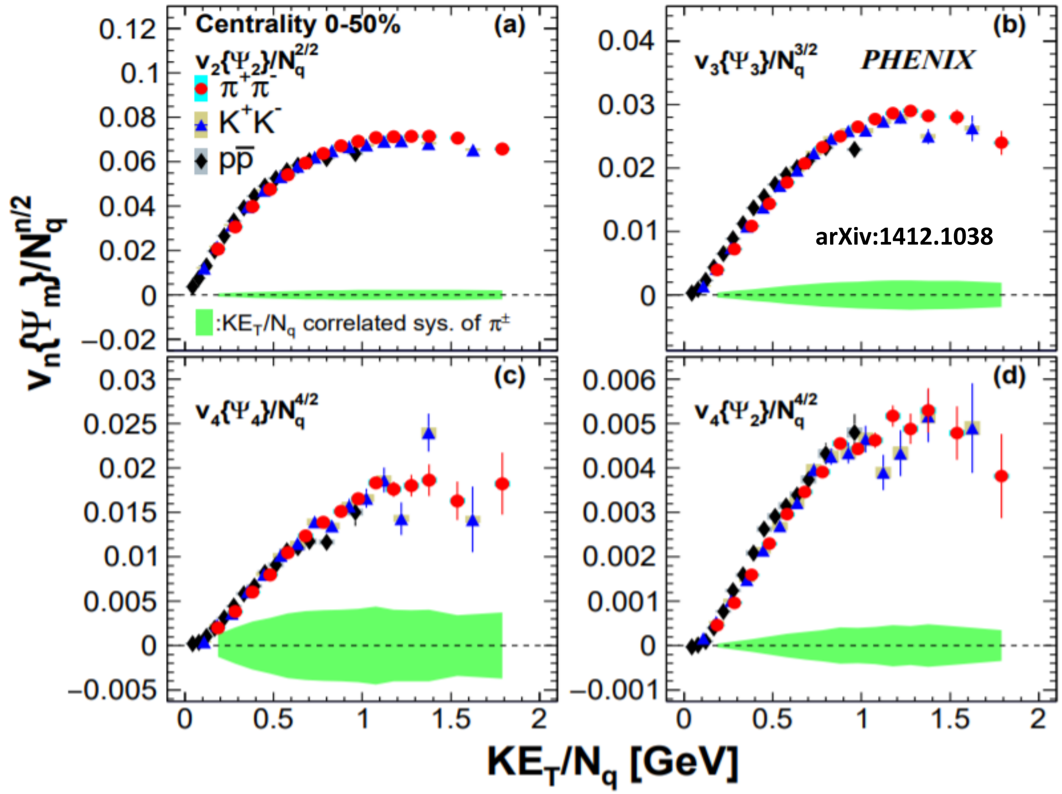
$$f_i(\vec{p_\perp}) \equiv \frac{dN}{d^3p} = g_i(p_\perp)\,[1 + 2v_{2,i}(p_\perp)\cos(2\phi)]$$

Yield simple relations of quark and hadron flow:

$$v_{2,M}(p_\perp) \approx 2v_{2,q}(\frac{p_\perp}{2}) \qquad v_{2,B}(p_\perp) \approx 3v_{2,q}(\frac{p_\perp}{3})$$



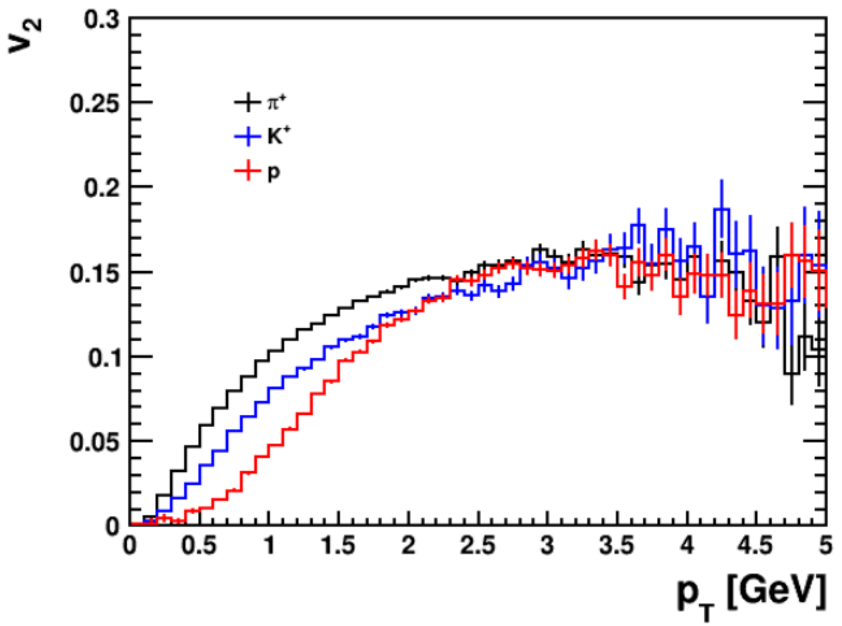
# $v_2$ and quark number scaling

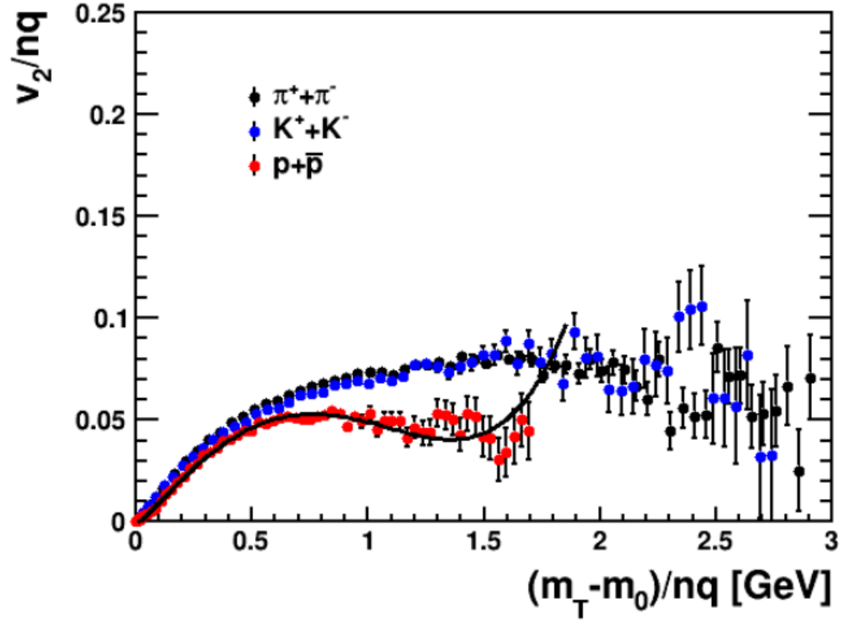



- Mass ordering at low $p_T$ driven by the hydrodynamic pressure gradient.
- Baryon meson ordering in the high $p_T$ region.
- NCQ scaling observed in a wide range of $KE_T$ indicates the dominance of partonic degrees of freedom.

# Elliptic flow in default mode

PbPb 2.76 TeV 30-40%

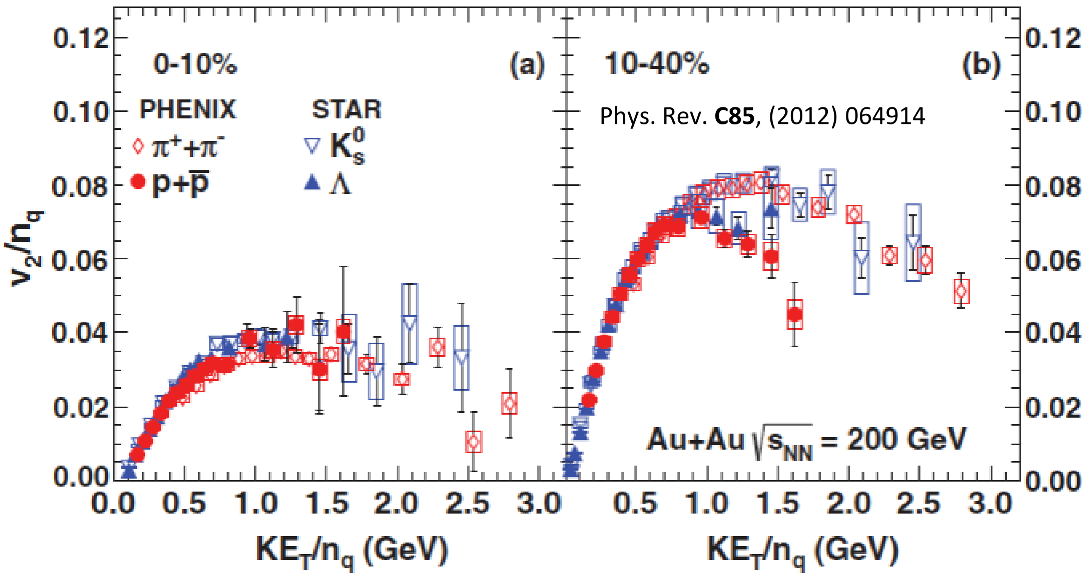



- Mass ordering exists in the low $p_T$ region
- No baryon meson grouping of $v_2$
- NCQ scaling doesn't exist

# Violations to NCQ scaling

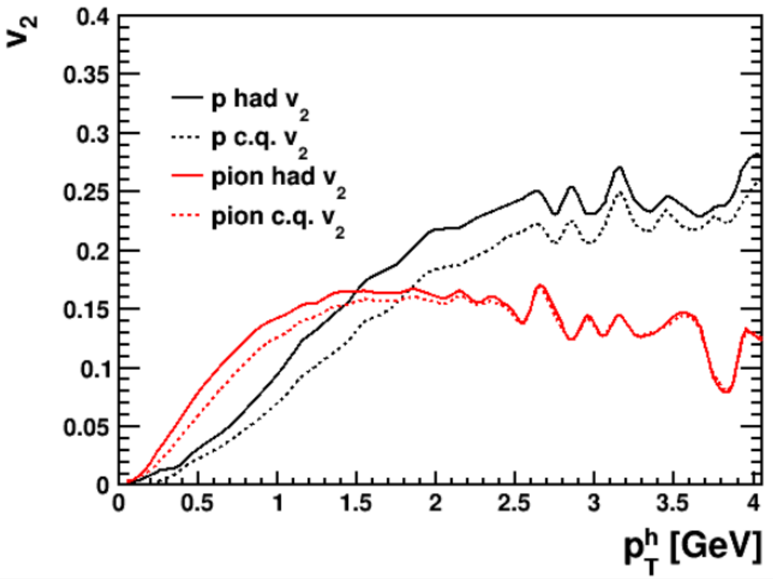
Deviations from NCQ scaling at RHIC depend on centrality

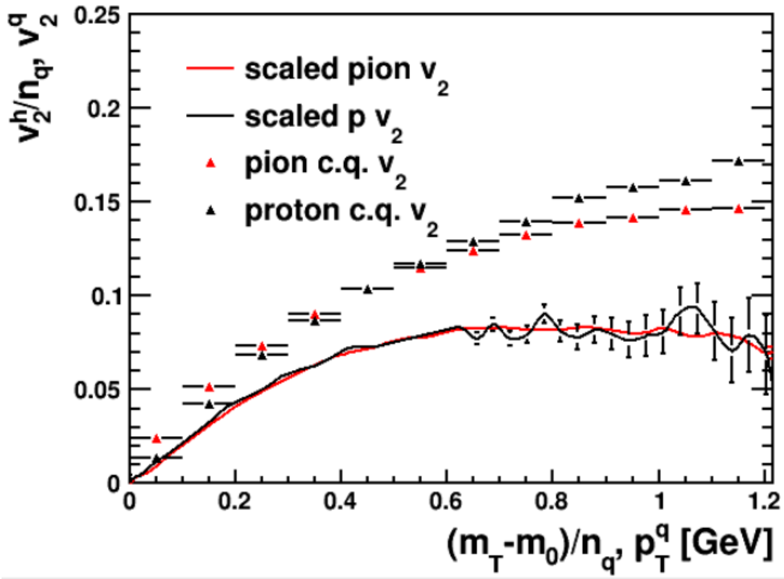



- Possible reasons:
  - Narrow wave function width *Phys. Lett. B* 618:77 (2005)
  - Resonance decay *Phys. Rev. C* 71:041901 (2005)
  - Higher Fock states contribution *J. Phys. G* 32:S135 (2006)
  - Space-Momentum correlations at freeze-out *Nucl. Phys. A* 749:268 (2005) , nucl-th/0408044, nucl-th/0505061, *Phys. Rev. C* 68:034904 (2003) , *Phys. Rev. C* 70:024901 (2004)
  - Phase-space density Phys. Rev. C 93, 034908 (2016)

# Quark hadron flow relations

PbPb 2.76 TeV 30-40%




- Constituent quark flow very close to the formed hadron, different from the amplification behavior expected in coalescence model.
- Hadron flow can not be reverted to the quark flow through simple NCQ rule while NCQ scaling exists!