New Constraints for the Transport Coefficients of the Quark Gluon Plasma (QGP)

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Essential Question

- ***Do recent measurements at RHIC & the LHC, give new insights for characterization of the QGP?***

QGP Characterization?

Characterization of the QGP produced in RHIC and LHC collisions requires

I. Development of experimental constraints to map the topological, thermodynamic and transport coefficients

$$T(\tau),\ c_s(T),\ \eta(T),\ \zeta(T),\ \alpha_s(T),\ \hat{q}(T),\ \pm_{sep}(\tau), \text{etc ?}$$

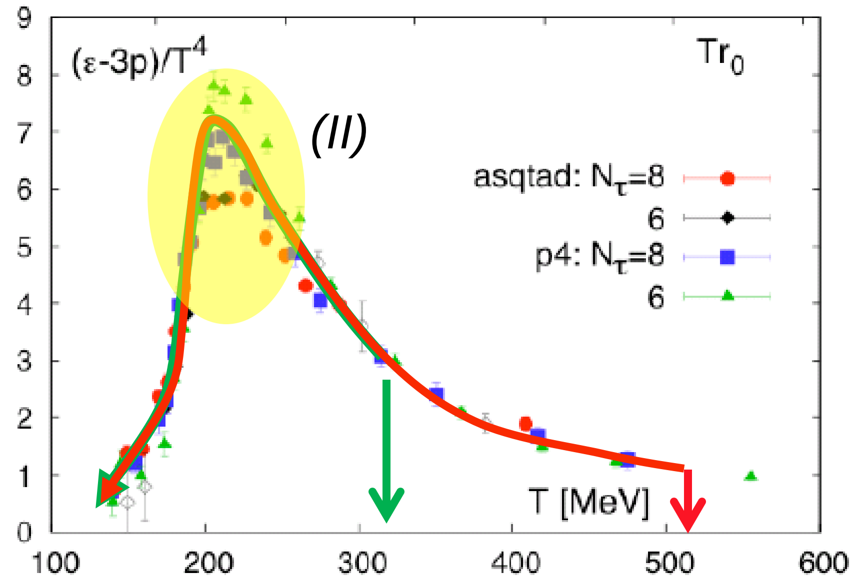
II. Development of quantitative model descriptions of these properties

Experimental Access:

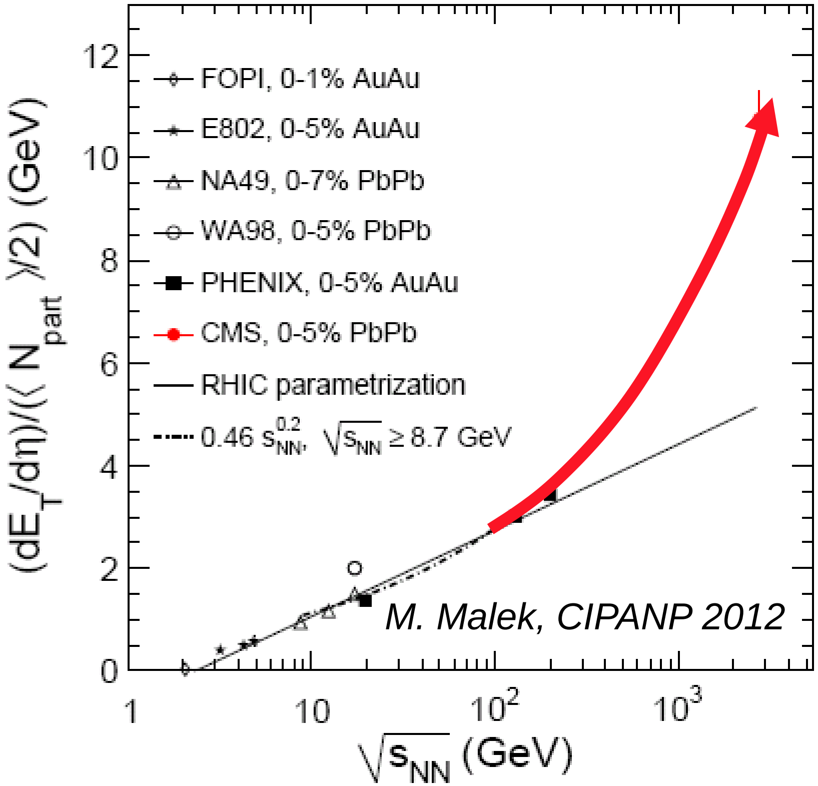
✓ **Temp/time-averaged constraints as a function of $\sqrt{s_{NN}}$**
(with similar expansion dynamics)

$$\langle T\rangle, \langle c_s\rangle, \left\langle \frac{\eta}{s}\right\rangle, \left\langle \frac{\zeta}{s}\right\rangle, \langle \hat{q}\rangle, \langle \alpha_s\rangle, \text{etc ?}$$

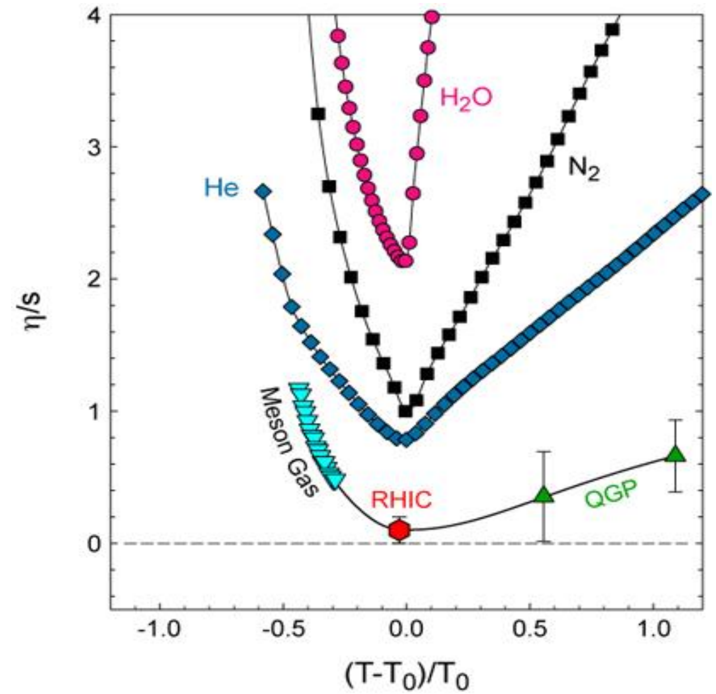
(I) Expect space-time averages to evolve with $\sqrt{s_{NN}}$



The LHC energy density lever arm



Lacey et. al, Phys.Rev.Lett.98:092301,2007



RHIC (0.2 TeV) → LHC (2.76 TeV)

- *Power law dependence (n ~ 0.2)*
- $(dE_T/d\eta)/(\langle N_{part}\rangle/2)$ *increase ~ 3.3*
- *Multiplicity density increase ~ 2.3*
- *→ <Temp> increase ~ 30%*

Essential questions:

- ***How do the transport coefficients*** $\langle c_s\rangle, \left\langle \frac{\eta}{s}\right\rangle, \langle\hat{q}\rangle, \langle\alpha_s\rangle$ ***evolve with T?***
- ***Any indications for sizeable changes close to T_o?***

Take home message:

The scaling properties of flow and Jet quenching measurements give crucial new insights

The Flow Probe

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

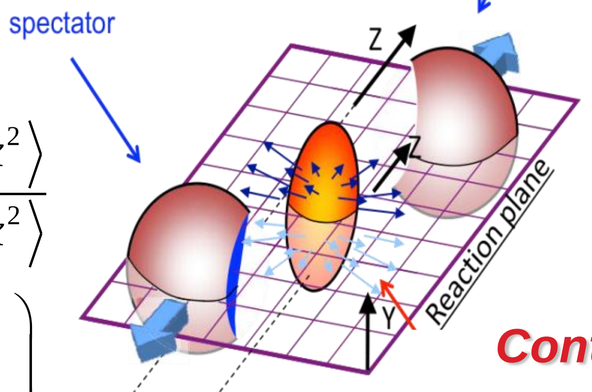
$$\sim 5-15\ \frac{GeV}{fm^3} \qquad \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

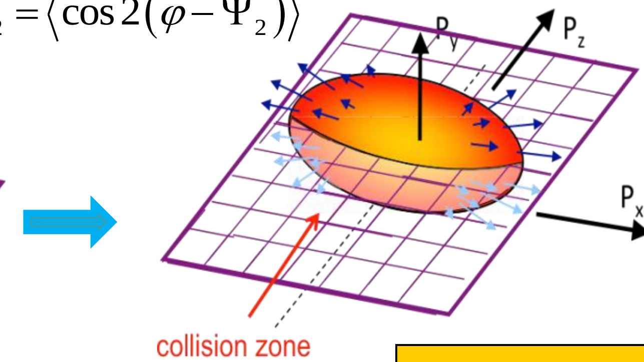
$$\left(P = \rho^2 \cdot \left(\partial\varepsilon_{Bj} \big/ \partial\rho \right)\Big|_{s/\rho} \right)$$

Idealized Geometry

spectator

$$v_2 = \langle \cos 2(\varphi - \Psi_2) \rangle$$

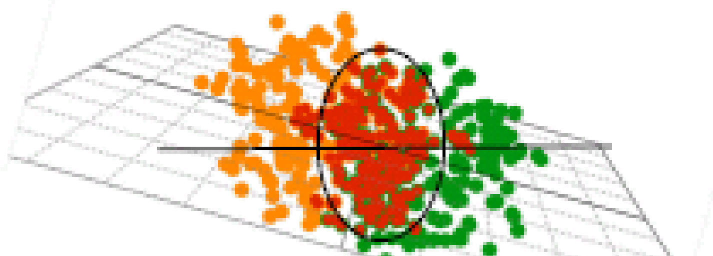




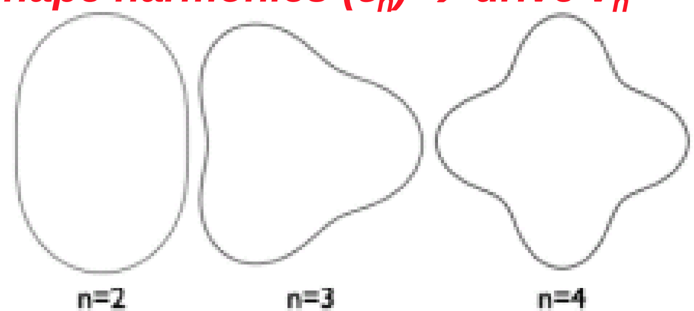
Control parameters

$$\varepsilon,\ c_s,\ \frac{\eta}{s}, \frac{\zeta}{s},\ T$$

Actual collision profiles are not smooth, due to fluctuations!



Initial Geometry characterized by many shape harmonics (ε_n) → drive v_n



Acoustic viscous modulation of v_n

$$\delta T_{\mu\nu}(t,k) = \exp\left(\frac{2}{3}\frac{\eta}{s} k^2 \frac{t}{T} \right) \delta T_{\mu\nu}(0)$$

Staig & Shuryak **arXiv:1008.3139**

$$\varepsilon_n = \frac{\langle r^n \cos(n\varphi_{part}) \rangle^2 + \langle r^n \sin(n\varphi_{part}) \rangle^2}{\langle r^n \rangle^2}$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific scaling properties

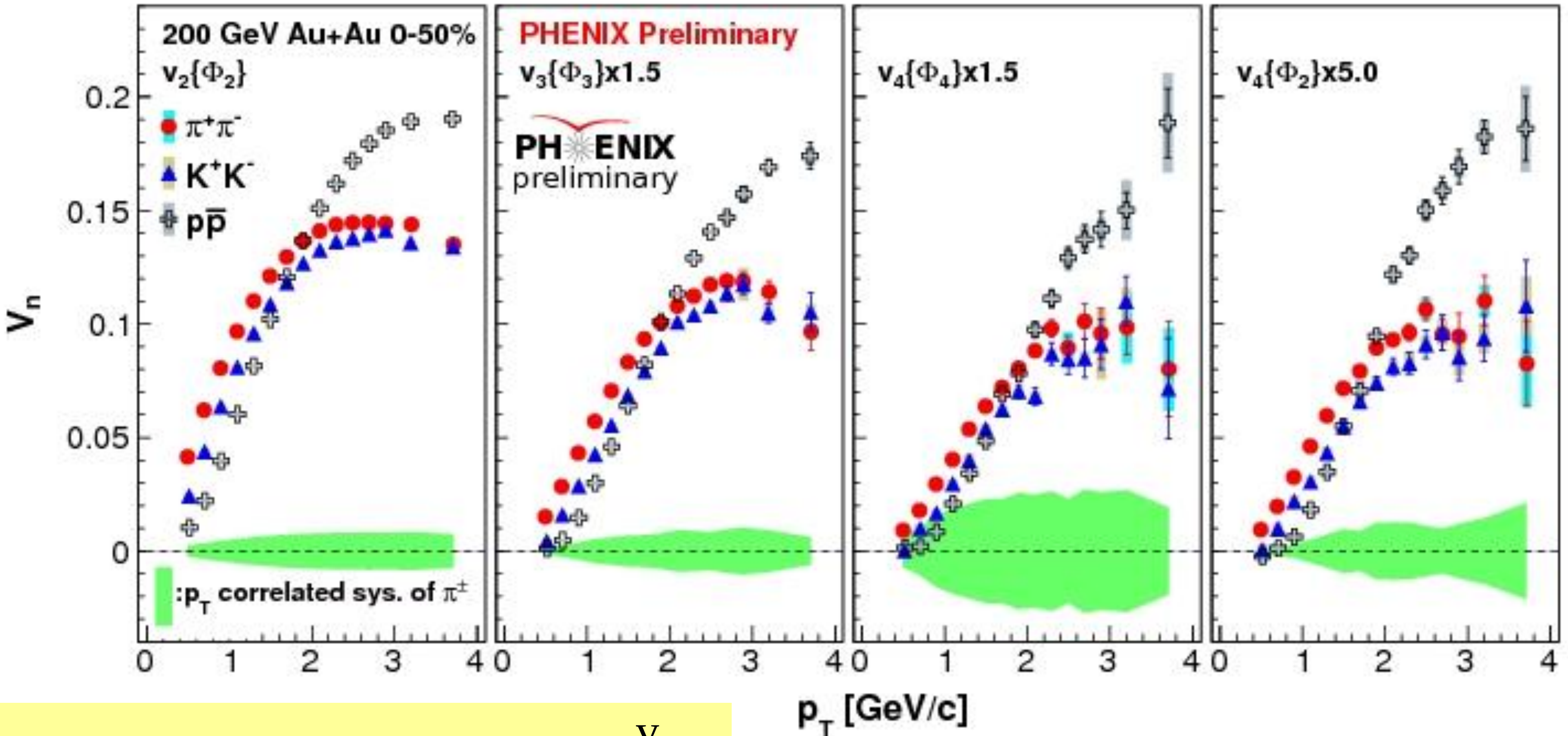
A few insights from the scaling patterns of flow

<u>Flow</u>

- ✓ **is dominantly partonic,**
- ✓ **is sensitive to the harder EOS sampled in LHC collisions**
- ✓ **is acoustic**
  - ➢ **viscous damping follows dispersion relation for sound propagation → important constraint for <η/s> and its Temp. dependence**

→ ***These reflect characteristic scaling patterns which <u>are</u> experimentally validated***

Is flow partonic?

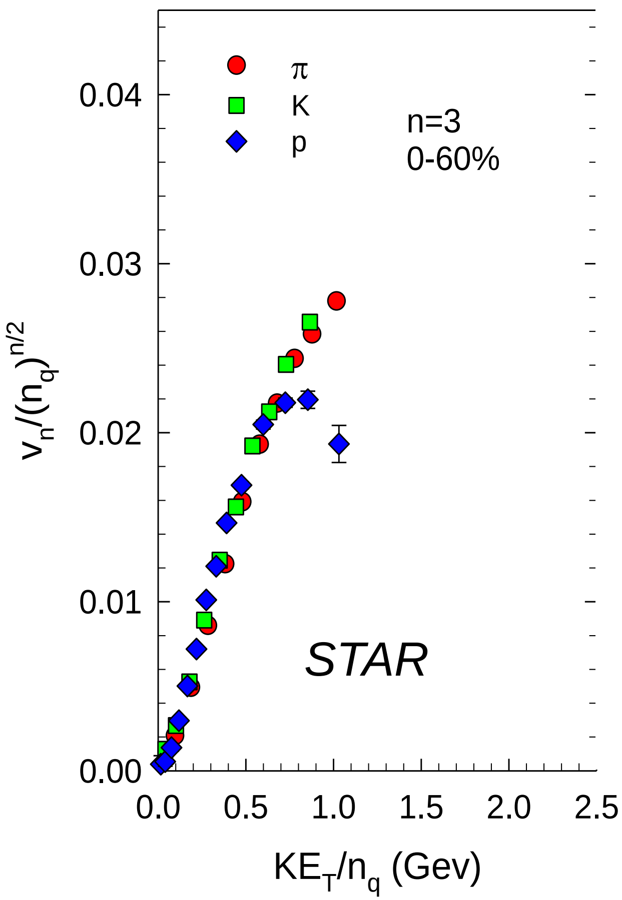


Expectation: $v_n(KE_T) \sim v_2^{n/2}$ or $\frac{v_n}{(n_q)^{n/2}}$

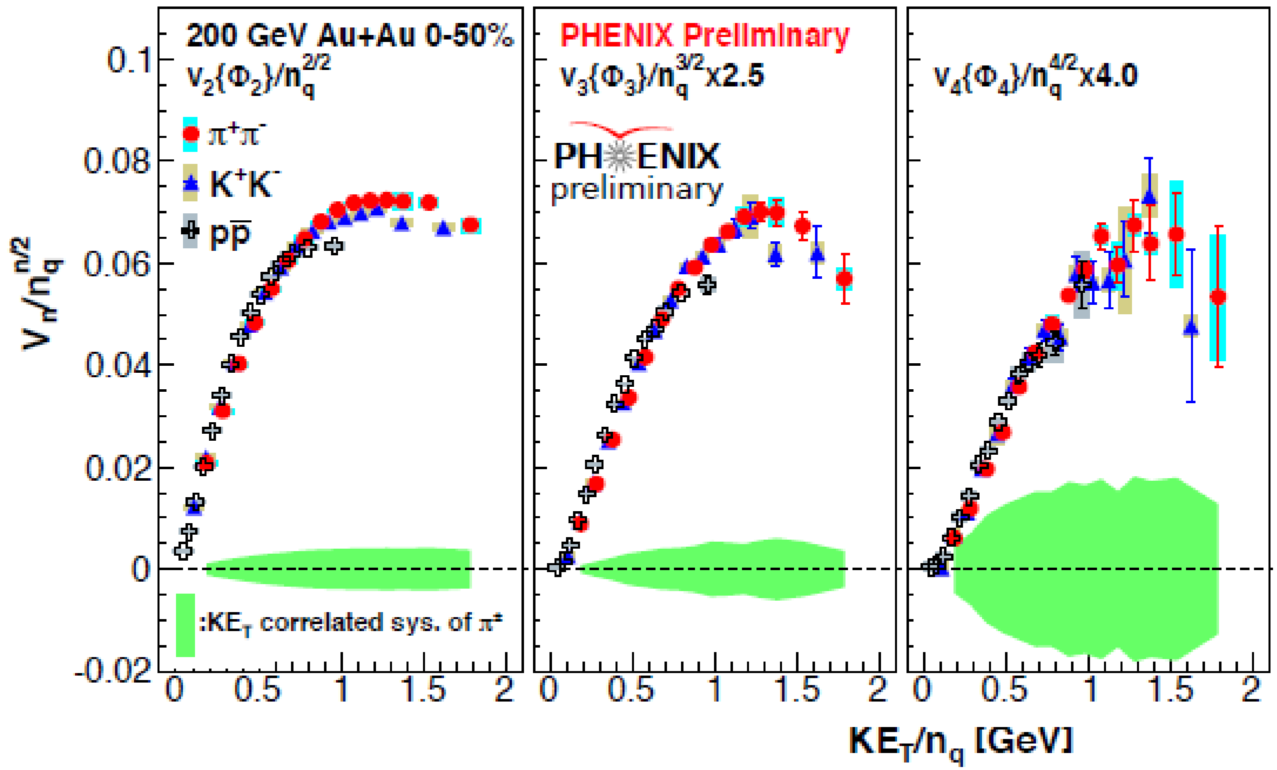
Note species dependence for all v_n

For partonic flow, quark number scaling expected
→ single curve for identified particle species v_n

Flow is partonic @ RHIC

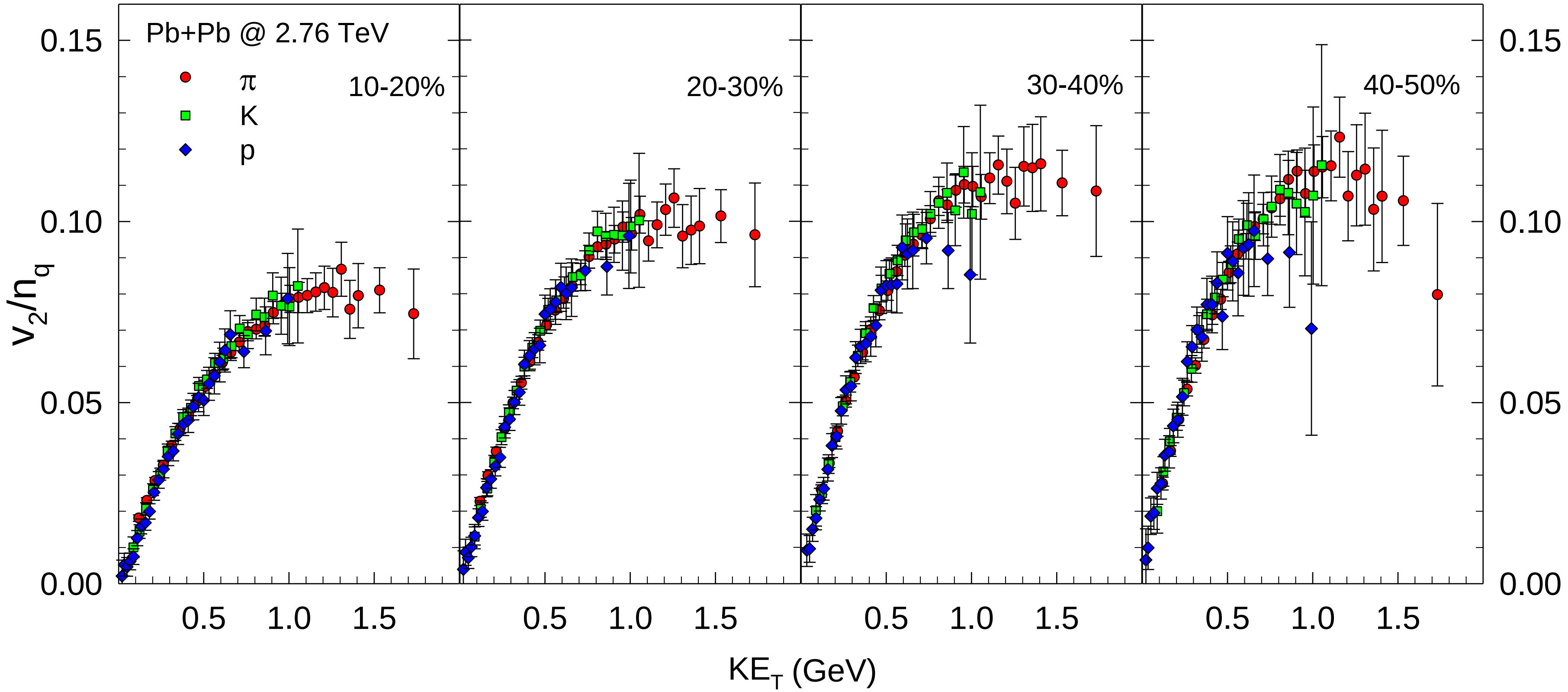


v_n PID scaling



KE_T & $(n_q)^{n/2}$ scaling validated for v_n
→ **Partonic flow**

Flow is partonic @ the LHC

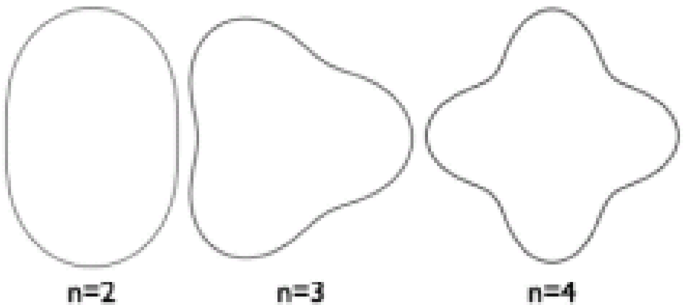


Scaling for partonic flow validated after accounting for proton blueshift

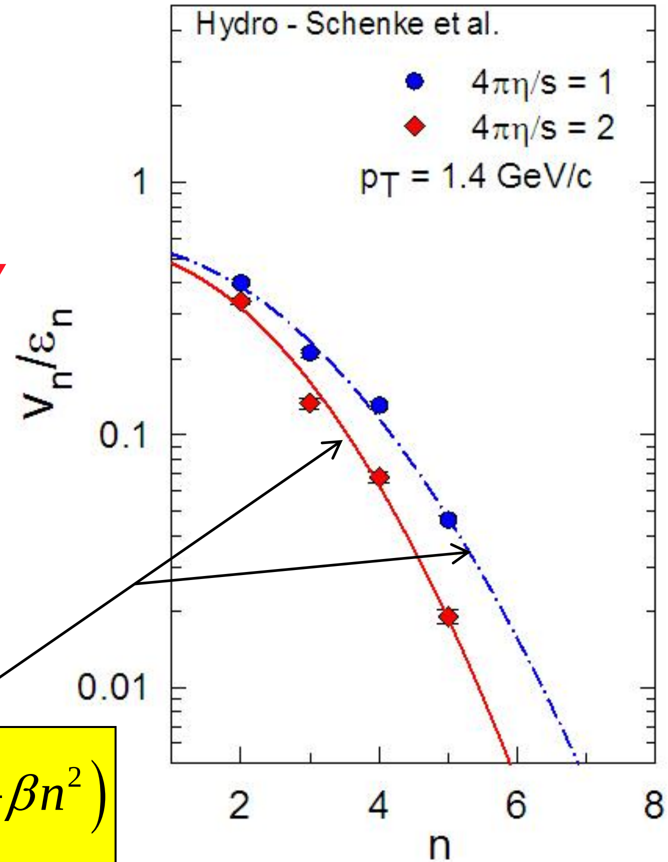
- ***Proton flow blueshifted [hydrodynamic prediction]***
  - ✓ ***Sensitivity to harder EOS***
  - ✓ ***Role of radial flow***
  - ✓ ***Role of hadronic re-scattering?***

Is hydrodynamic flow acoustic?

ε_n drive momentum anisotropy v_n with modulation



Initial Geometry characterized by many shape harmonics (ε_n) → drive v_n



Modulation → Acoustic

$$\delta T_{\mu\nu}(t,k) = \exp\left(\frac{2}{3}\frac{\eta}{s}k^2\frac{t}{T}\right)\delta T_{\mu\nu}(0)$$

$$2\pi\bar{R} = n\lambda_g$$

$$k = \frac{n}{\bar{R}}$$

$$\frac{v_n}{\varepsilon_n} = \alpha \cdot \exp\left(-\beta n^2\right)$$

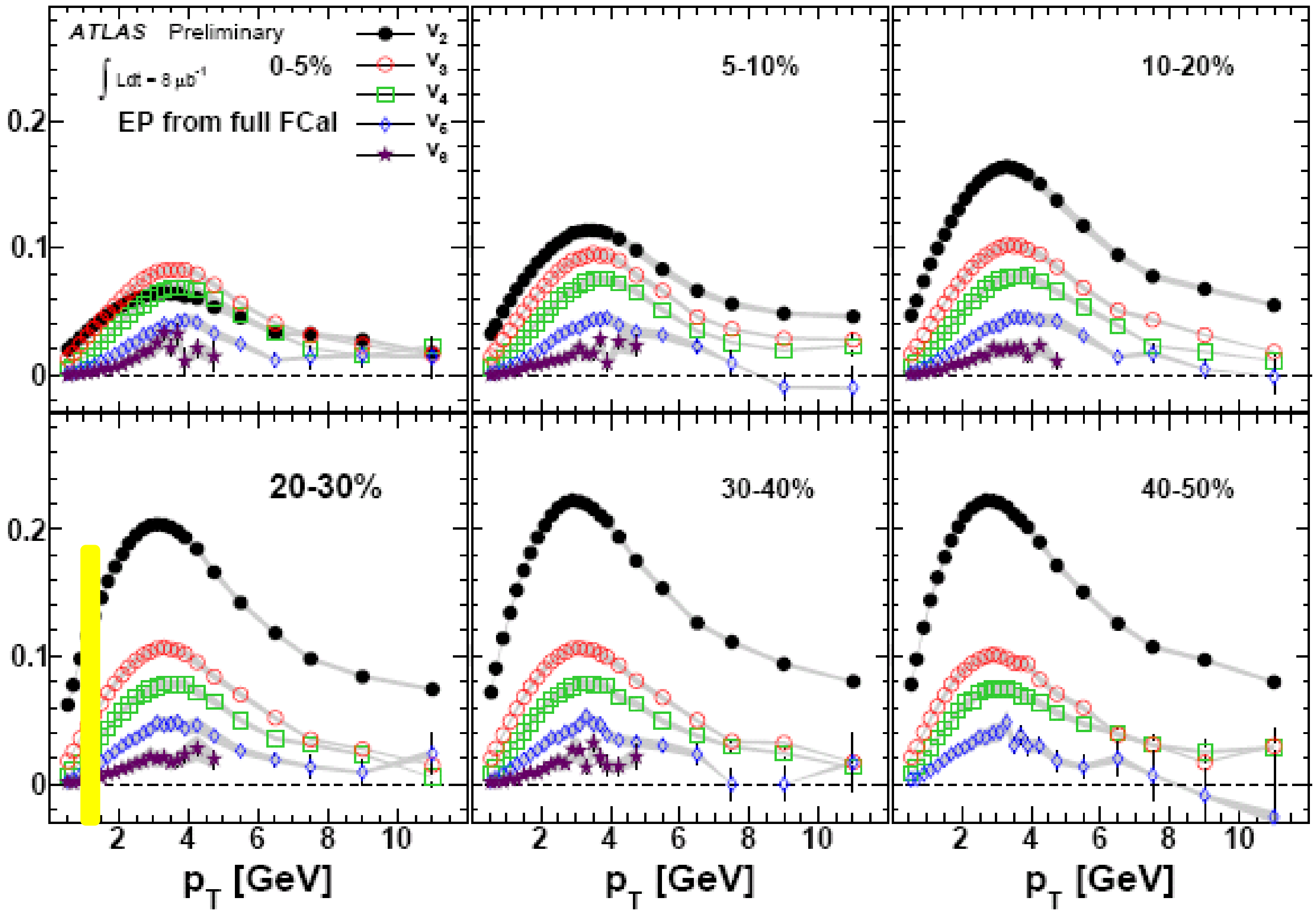
Note: the hydrodynamic response to the initial geometry [alone] is included

$$\frac{v_n}{\varepsilon_n} = \alpha \cdot \exp\left(-\beta n^2\right)$$

Characteristic n^2 viscous damping for harmonics → Crucial constraint for η/s

$v_n(\psi_n)$ Measurements - ATLAS

ATLAS-CONF-2011-074

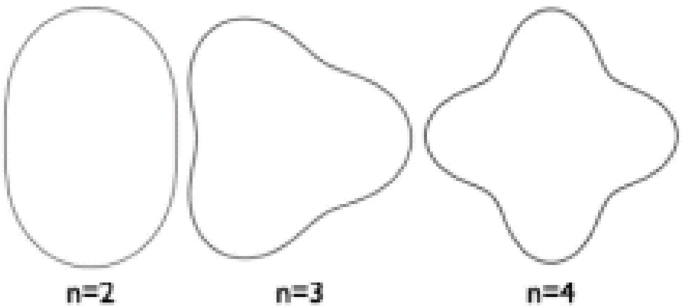


High precision double differential Measurements are pervasive

Do they scale?

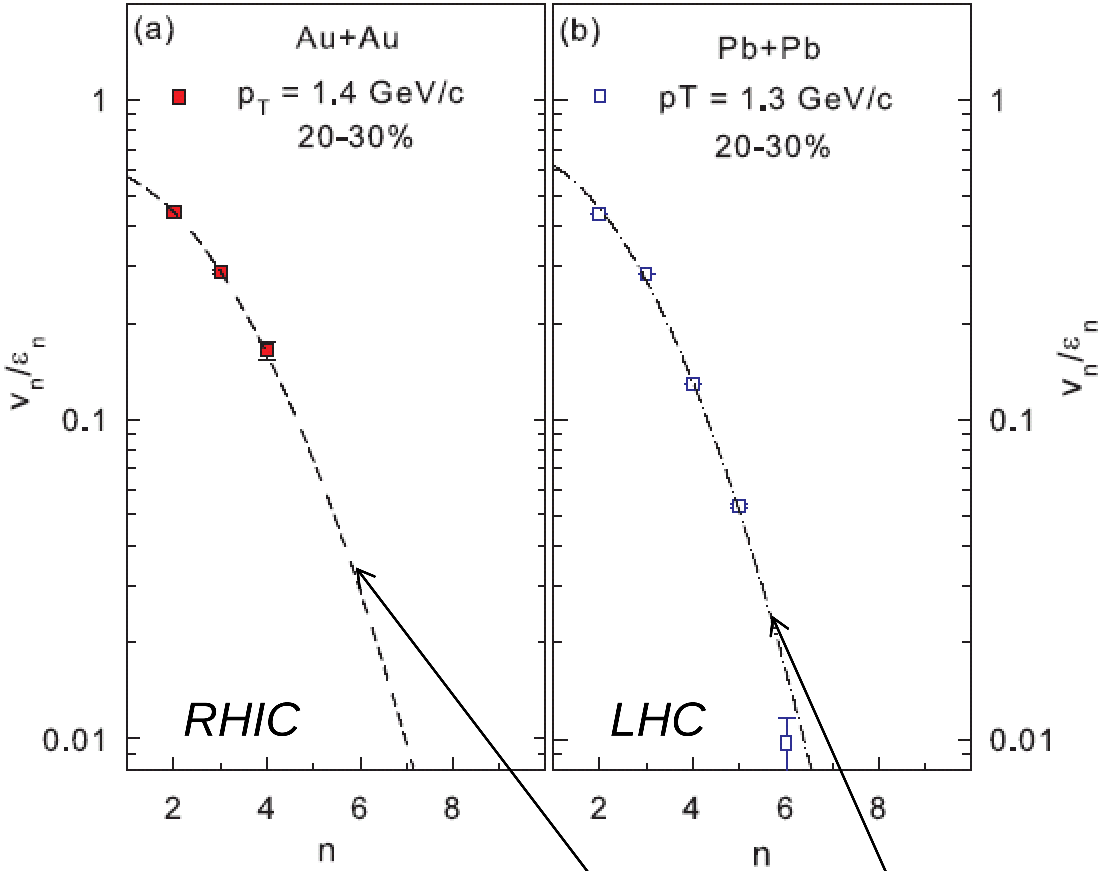
Flow is acoustic

$$\delta T_{\mu\nu}(t,k) = \exp\left(\frac{2}{3}\frac{\eta}{s}k^2\frac{t}{T}\right)\delta T_{\mu\nu}(0)$$



$$2\pi\bar{R} = n\lambda_g$$

Deformation $\quad k = \frac{n}{\bar{R}}$



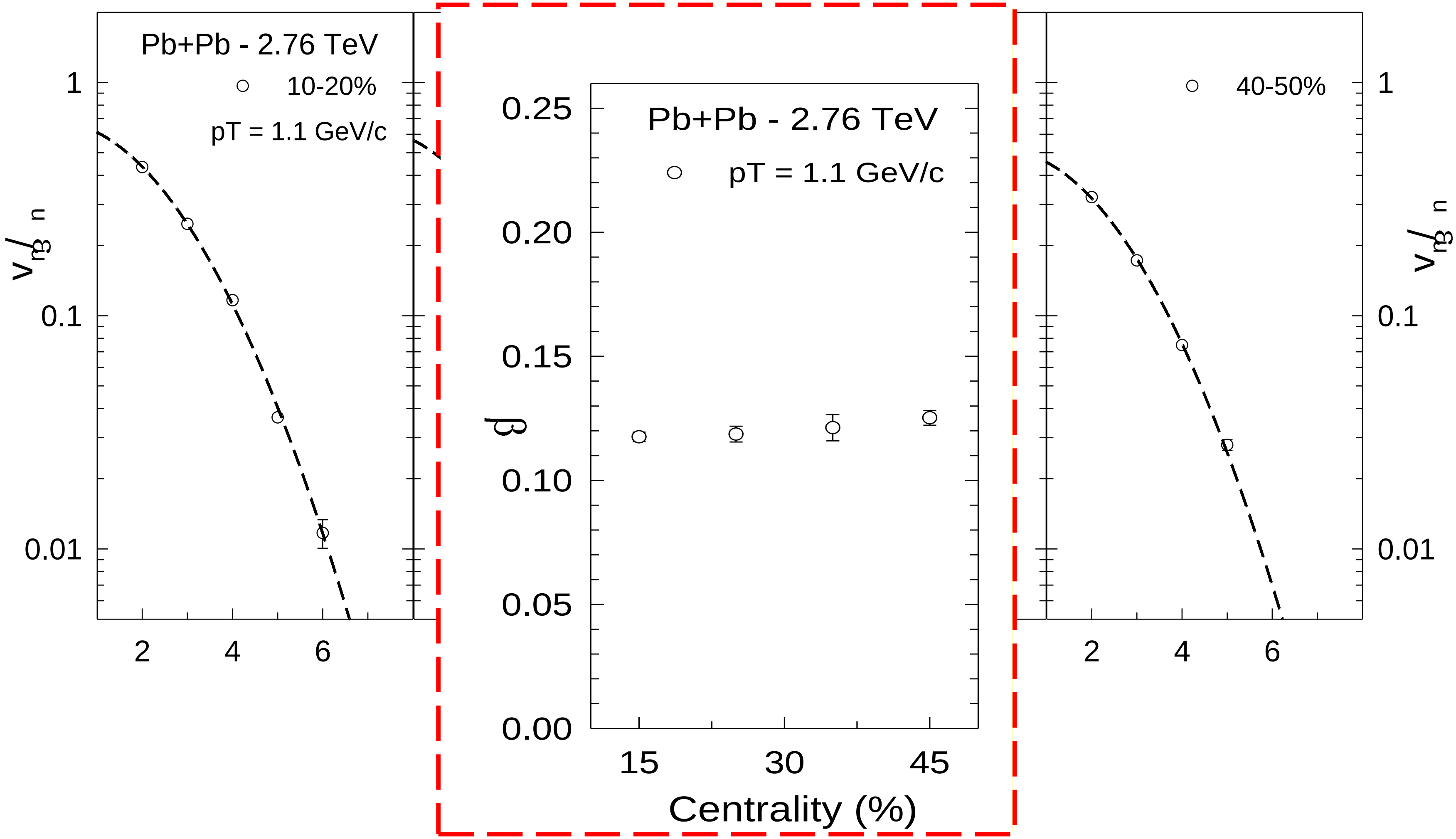
$$\frac{v_n}{\varepsilon_n} = \alpha \cdot \exp\left(-\beta n^2\right)$$

Characteristic viscous damping of the harmonics validated
→Constraint for β → η/s estimates at RHIC & LHC

$$\frac{\eta}{s} \sim \frac{1}{4\pi}$$

Acoustic Scaling

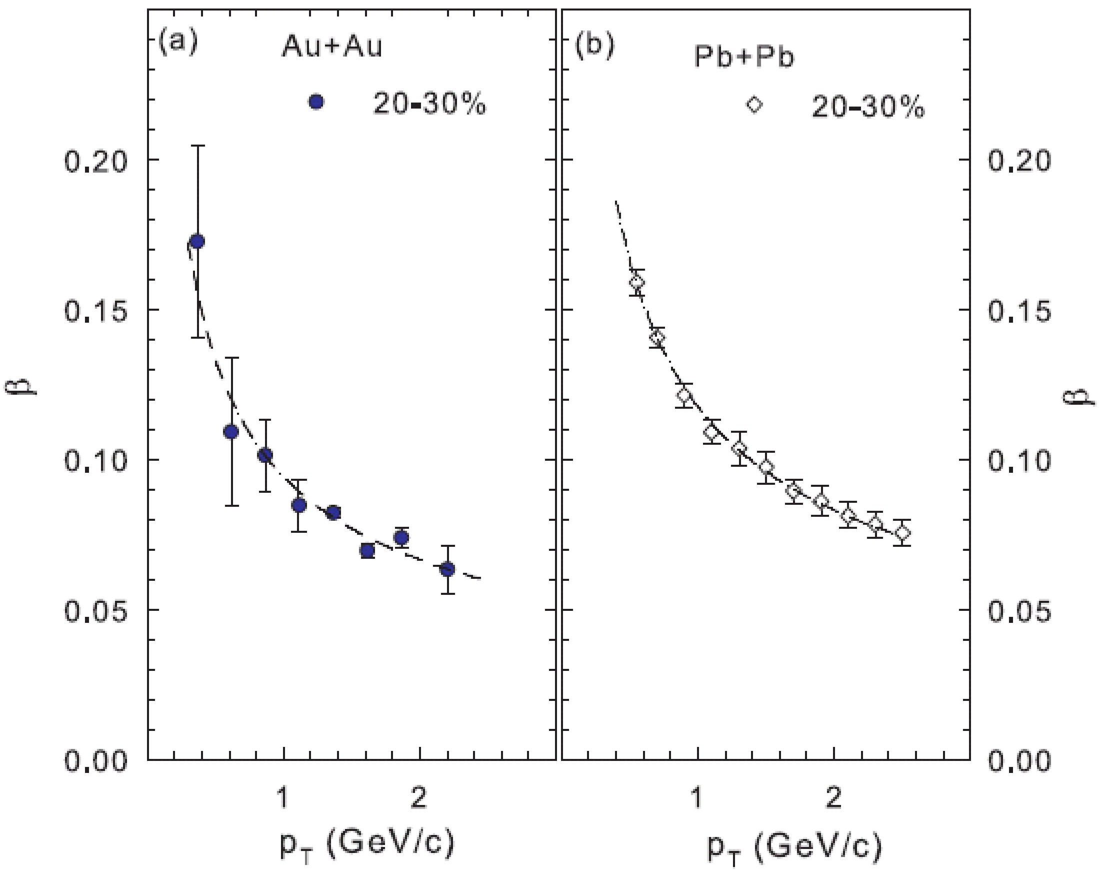
$$\frac{v_n}{\varepsilon_n} = \alpha \cdot \exp\left(-\beta n^2\right)$$

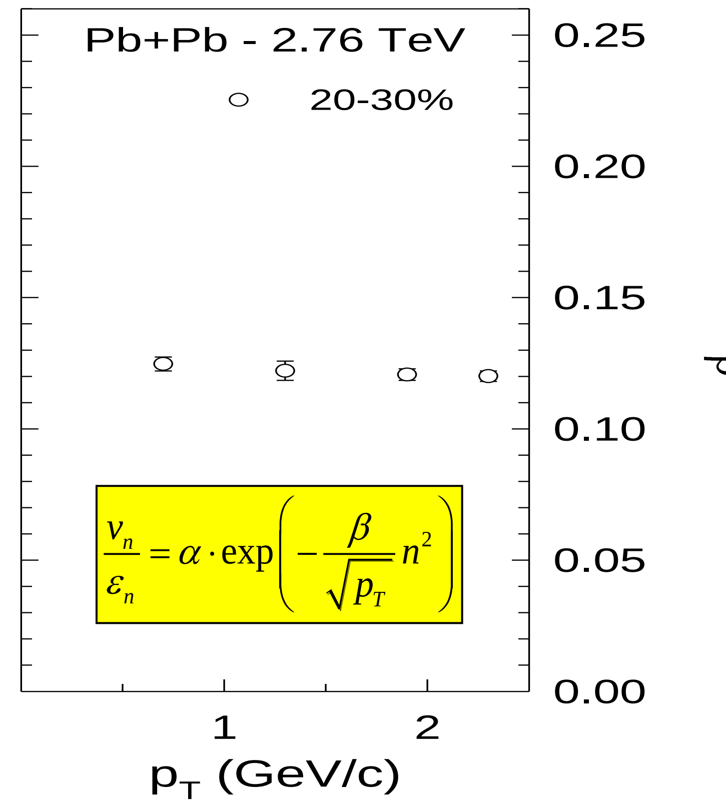


β is essentially independent of centrality for a broad centrality range

Acoustic Scaling

$$\frac{v_n}{\varepsilon_n} = \alpha \cdot \exp\left(-\beta n^2\right)$$

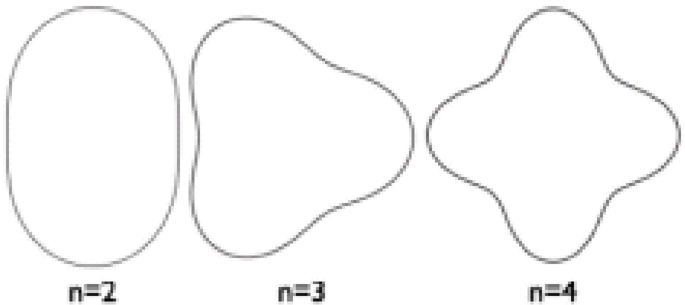




β scales as 1/√p_T

✓single universal curve for v_n

Constraint for η/s & δf

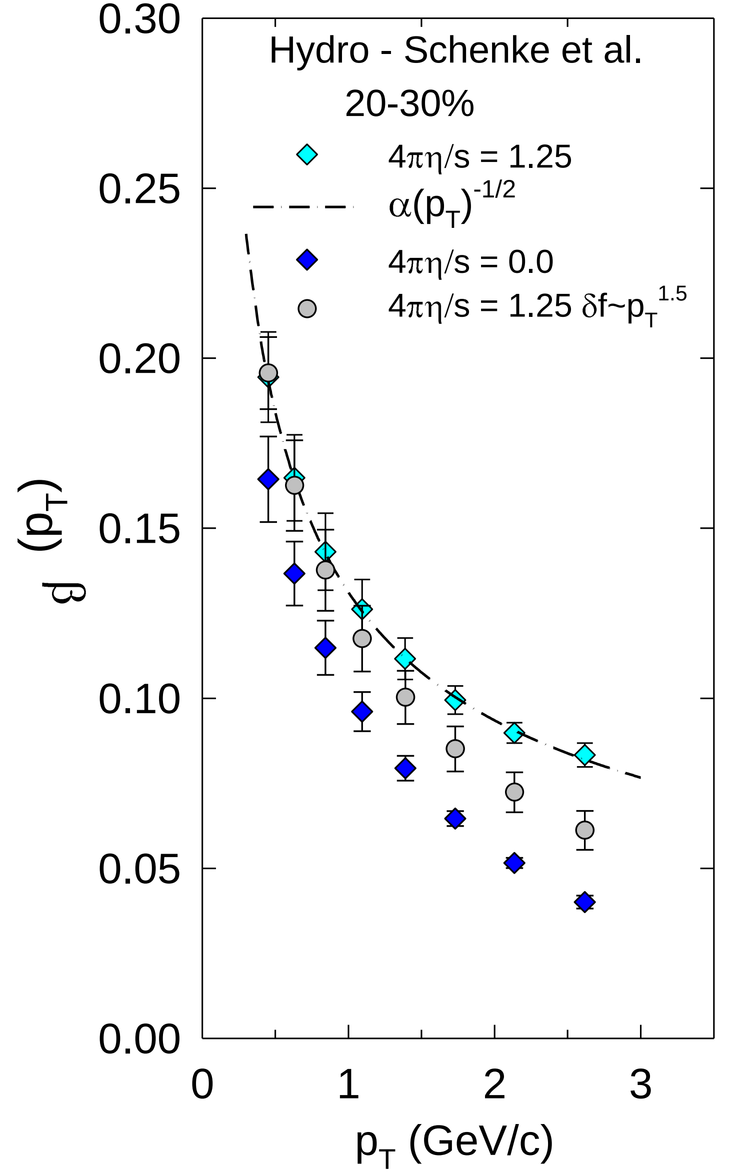


Deformation $k = \frac{n}{\bar{R}}$

$$\delta T_{\mu\nu}(t,k) = \exp\left(\beta n^2\right)\delta T_{\mu\nu}(0)$$

Particle Dist. $f = f_0 + \delta f(p_T)$

$$\delta f(p_T) \sim \frac{p_T^{2-\alpha}}{T_f}$$

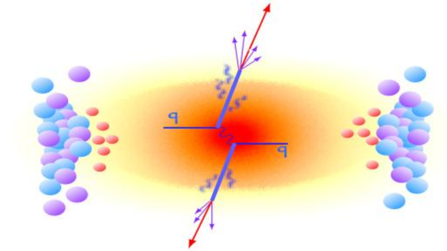


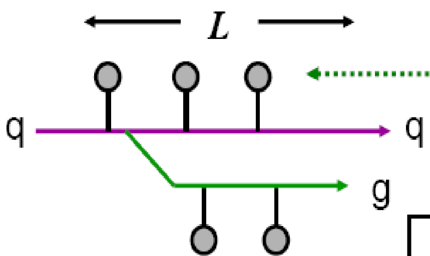
Characteristic p_T dependence of β
→ Additional constraint for δf and η/s

✓ <η/s> comparable at LHC and RHIC

Scaling properties of Jet Quenching

Jet quenching Probe





Radiative:

$$\frac{dE}{dx} \sim \sigma\rho L \left\langle k_T^2 \right\rangle$$

Color charge scattering centers

Range of Color Force

$$\hat{q} \sim \rho\sigma \left\langle k_T^2 \right\rangle \sim \frac{\mu^2}{\lambda}$$

Scattering Power Of Medium

Density of Scattering centers

Obtain ρ and $\hat{q}$ **via R_{AA} measurements**

Gyulassy, Wang, Müller, …

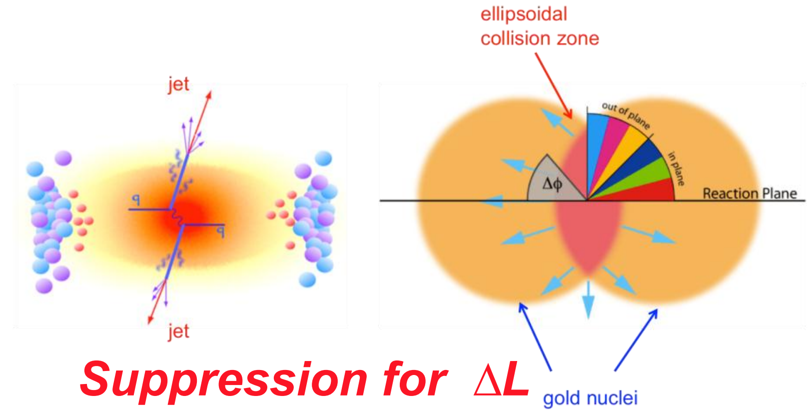
$$R_{AA} = \frac{\text{Yield}_{AA}}{\langle N_{binary} \rangle_{AA} \text{Yield}_{pp}}$$

$$R^{l}_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q} \frac{\mathcal{L}_l}{p_T}} \right]$$

Radiativ E-loss

Dokshitzer and D. E. Kharzeev

Control parameters $\alpha_s, p_T, L, \hat{q}$



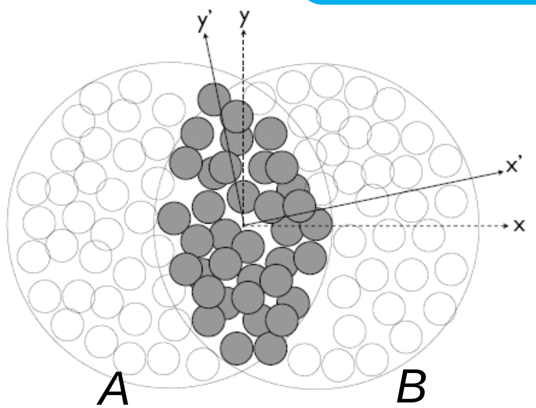
Suppression for ΔL

$$N(\Delta\phi, p_T) \propto [1 + 2v_2(p_T)\cos(2\Delta\phi)]$$

$$R_{v_2}(p_T, \Delta L) = \frac{R_{AA}(90^o, p_T)}{R_{AA}(0^0, p_T)} = \frac{1 - 2v_2(p_T)}{1 + 2v_2(p_T)}$$

***Jet quenching drives R_{AA} & high-pT azimuthal anisotropy* with specific scaling properties**

Geometric Quantities for scaling



Phys. Rev. C 81, 061901(R) (2010)

$$S_{nx} \equiv S_n \cos(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\cos(n\phi)$$

$$S_{ny} \equiv S_n \sin(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

$$\Psi_n^* = \frac{1}{n}\tan^{-1}\left(\frac{S_{ny}}{S_{nx}}\right)$$

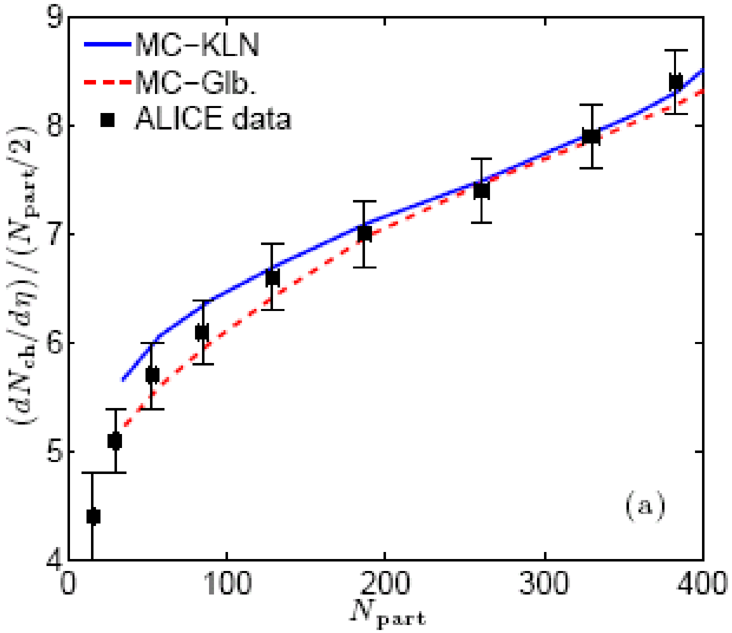
$$\varepsilon_n = \left\langle \cos n\left(\phi - \psi_n^*\right)\right\rangle$$

$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

$$L = \bar{R}$$

$$\Delta L \sim \varepsilon \bar{R}$$

arXiv:1203.3605

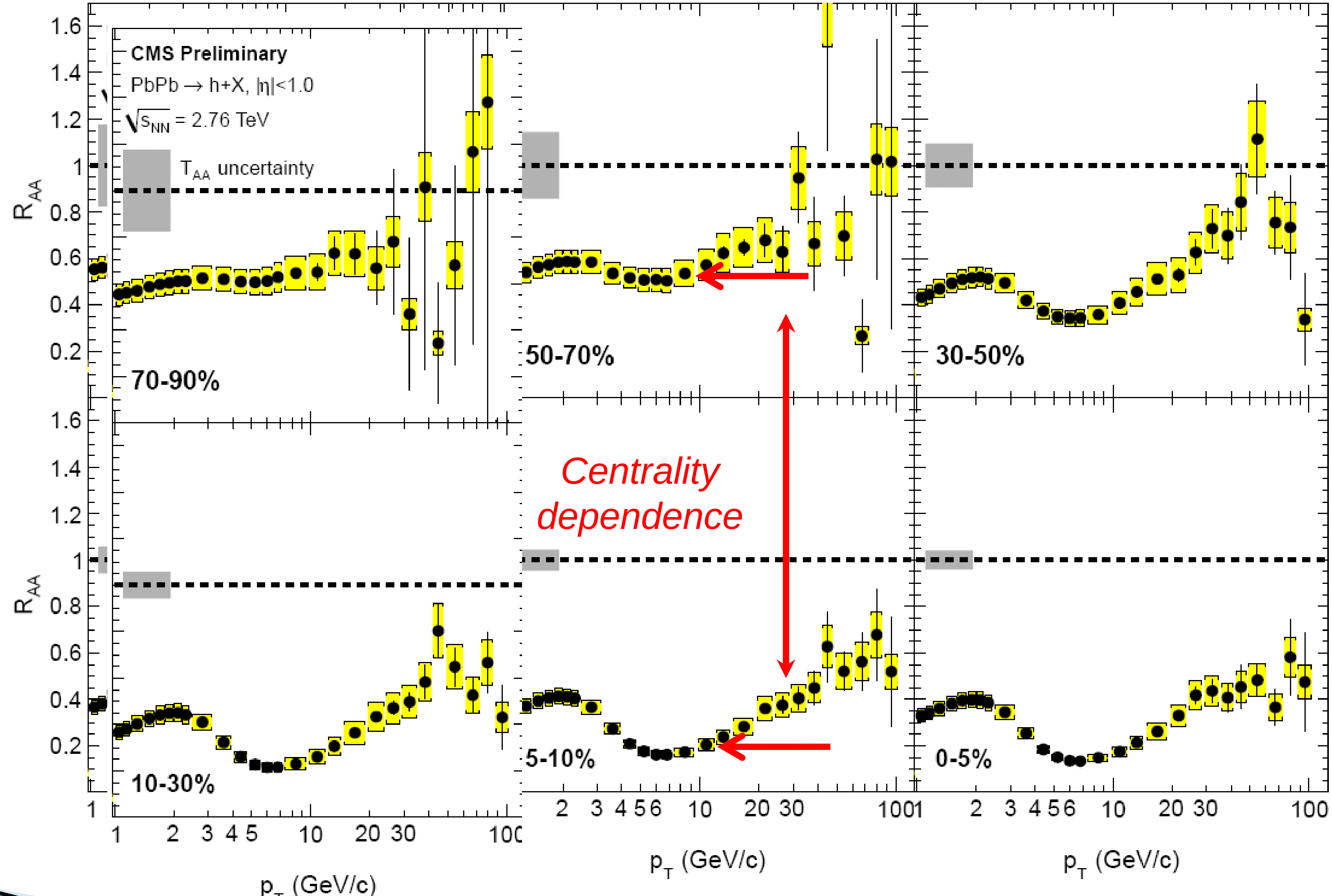


σ_x & σ_y → RMS widths of density distribution

- ***Geometric fluctuations included***
- ***Geometric quantities constrained by multiplicity density.***

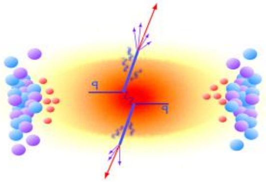
R_{AA} Measurements - CMS

Eur. Phys. J. C (2012) 72:1945
arXiv:1202.2554



Specific p_T and centrality dependencies – Do they scale?

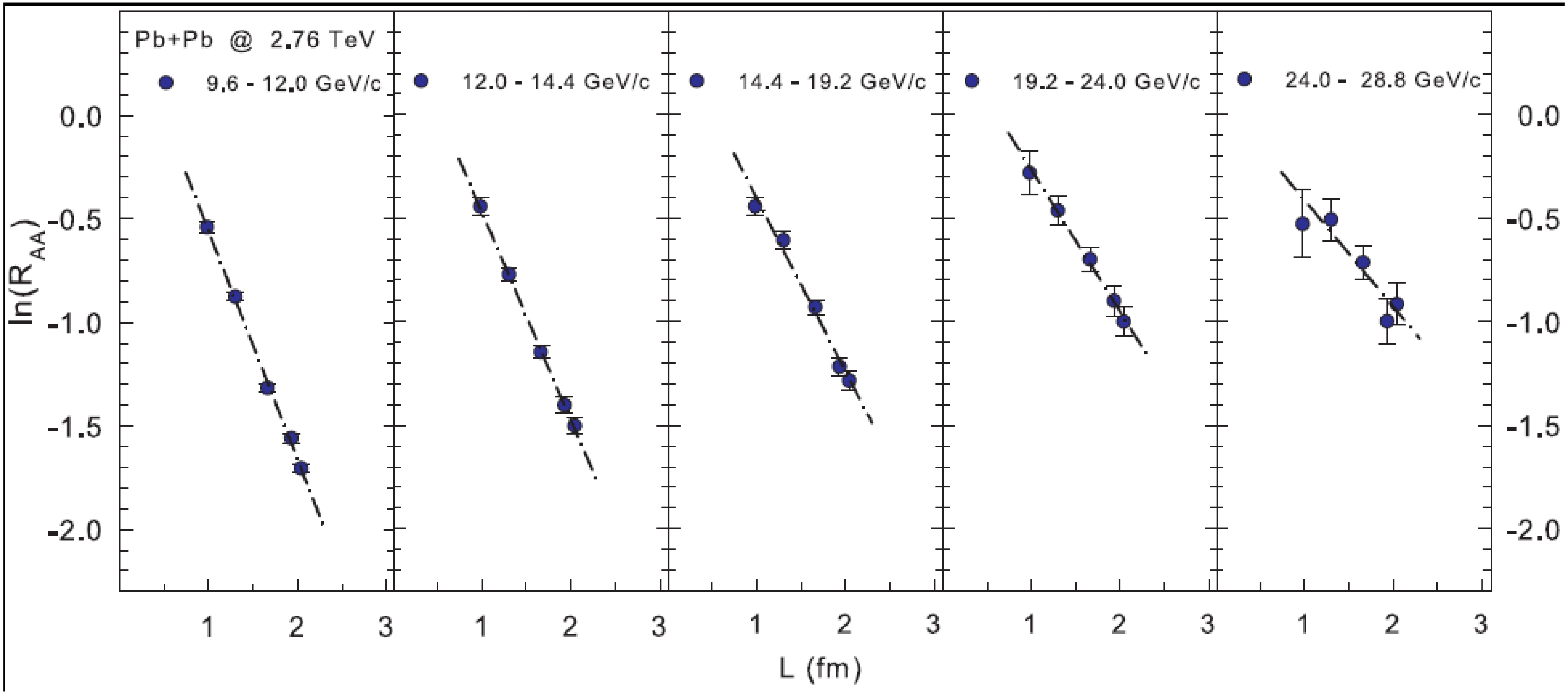
Scaling of Jet Quenching



Dokshitzer and D. E. Kharzeev, Phys.Lett.B519:199-206,2001

$$R^l_{\rm AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\frac{\mathcal{L}_l}{p_T}}\right]$$

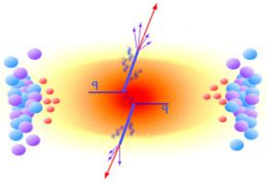
arXiv:1202.5537



R_{AA} scales with L, slopes (S_L) encodes info on α_s and $\hat{q}$

✓Compatible with the dominance of radiative energy loss

Scaling of Jet Quenching



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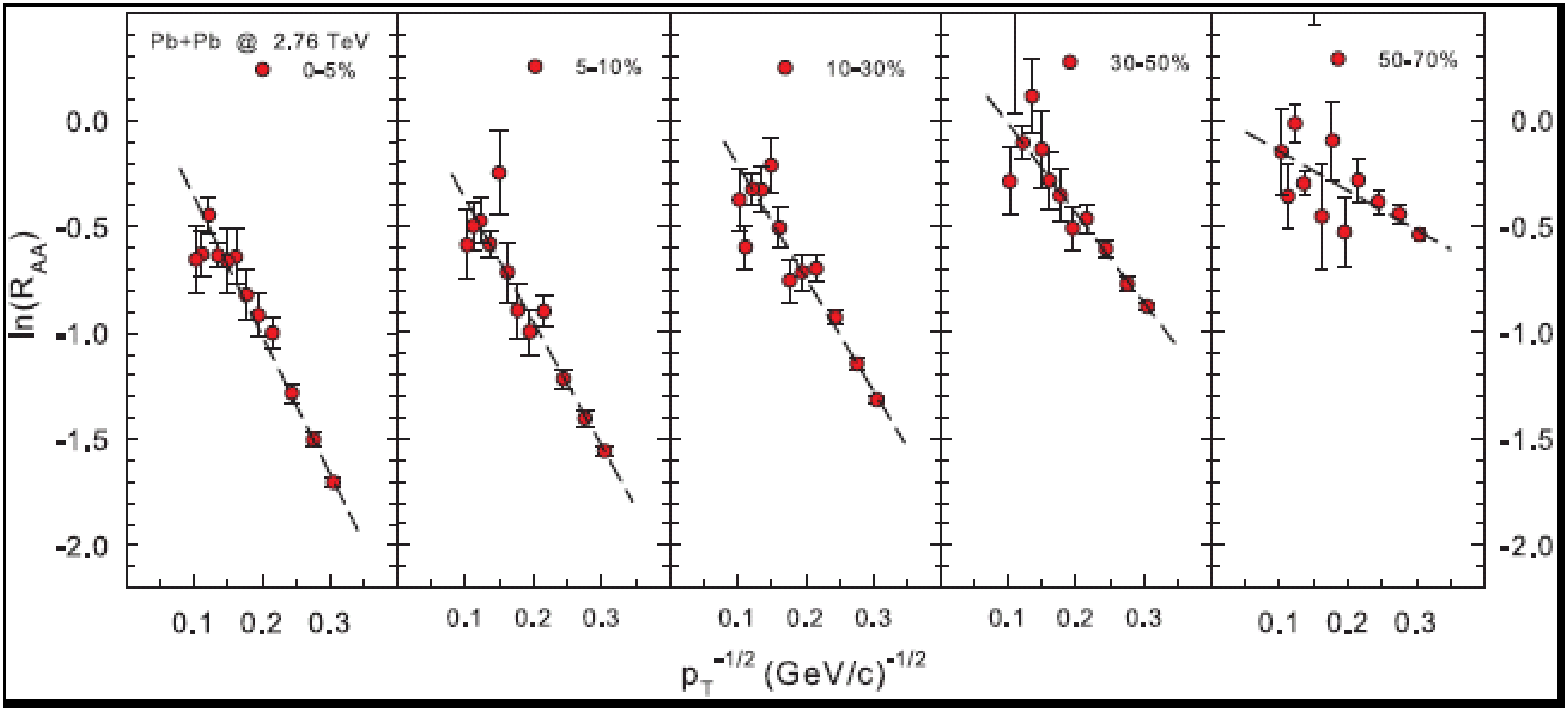
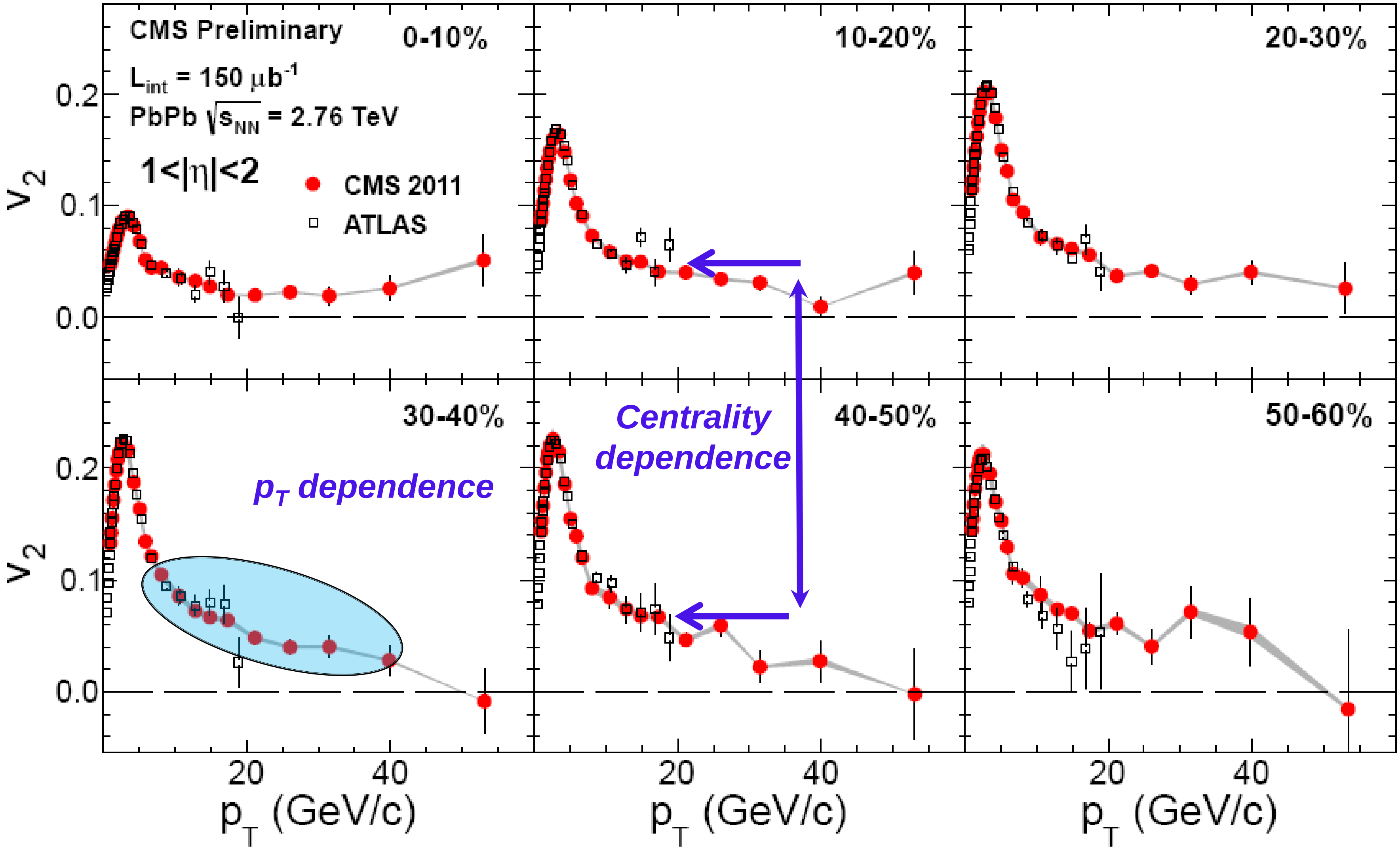


R_{AA} scales as $1/\sqrt{p_T}$; slopes (S_{pT}) encode info on α_s and $\hat{q}$

- ✓ ***L and $1/\sqrt{p_T}$ scaling → single universal curve***
- ✓***Compatible with the dominance of radiative energy loss***

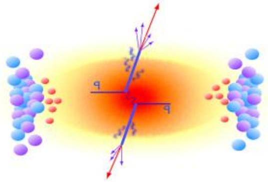
High-pT v_2 measurements - CMS

arXiv:1204.1850



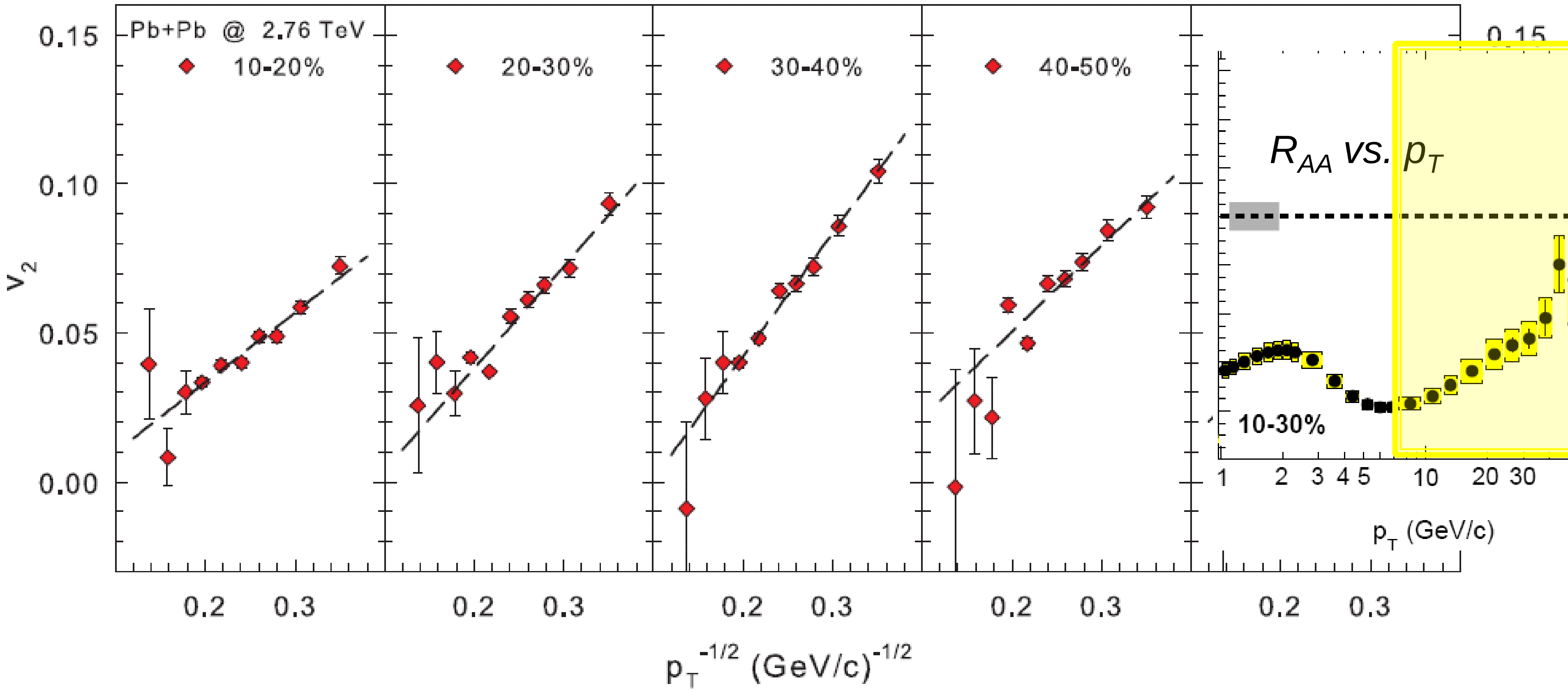
Specific p_T and centrality dependencies – Do they scale?

Scaling of high-pT v_2



$$R^{l}_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\frac{\mathcal{L}_l}{p_T}}\right]$$

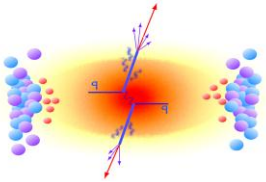
arXiv:1203.3605



v_2 follows the p_T dependence observed for jet quenching

Note the expected inversion of the $1/\sqrt{p_T}$ dependence

ΔL Scaling of high-pT v_2



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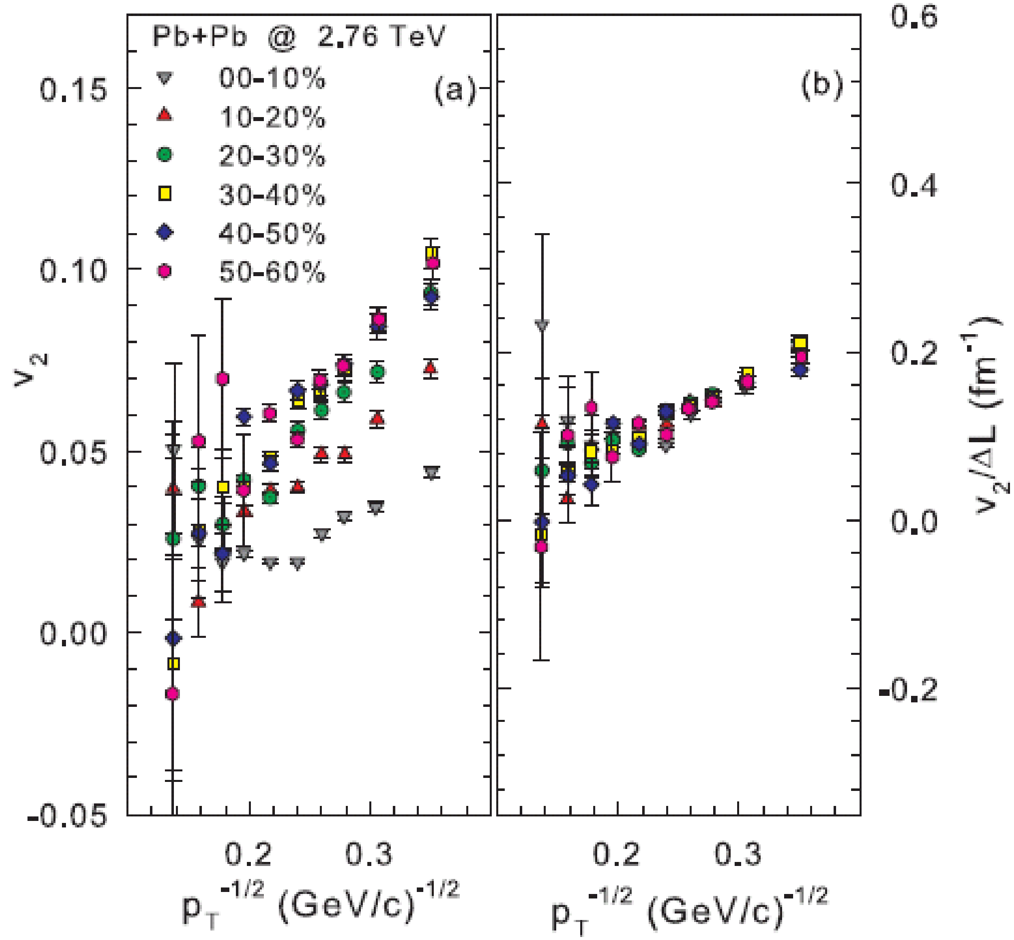
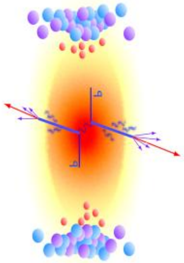


Combined ΔL and $1/\sqrt{p_T}$ scaling → single universal curve for v_2

Jet suppression from high-pT v_2



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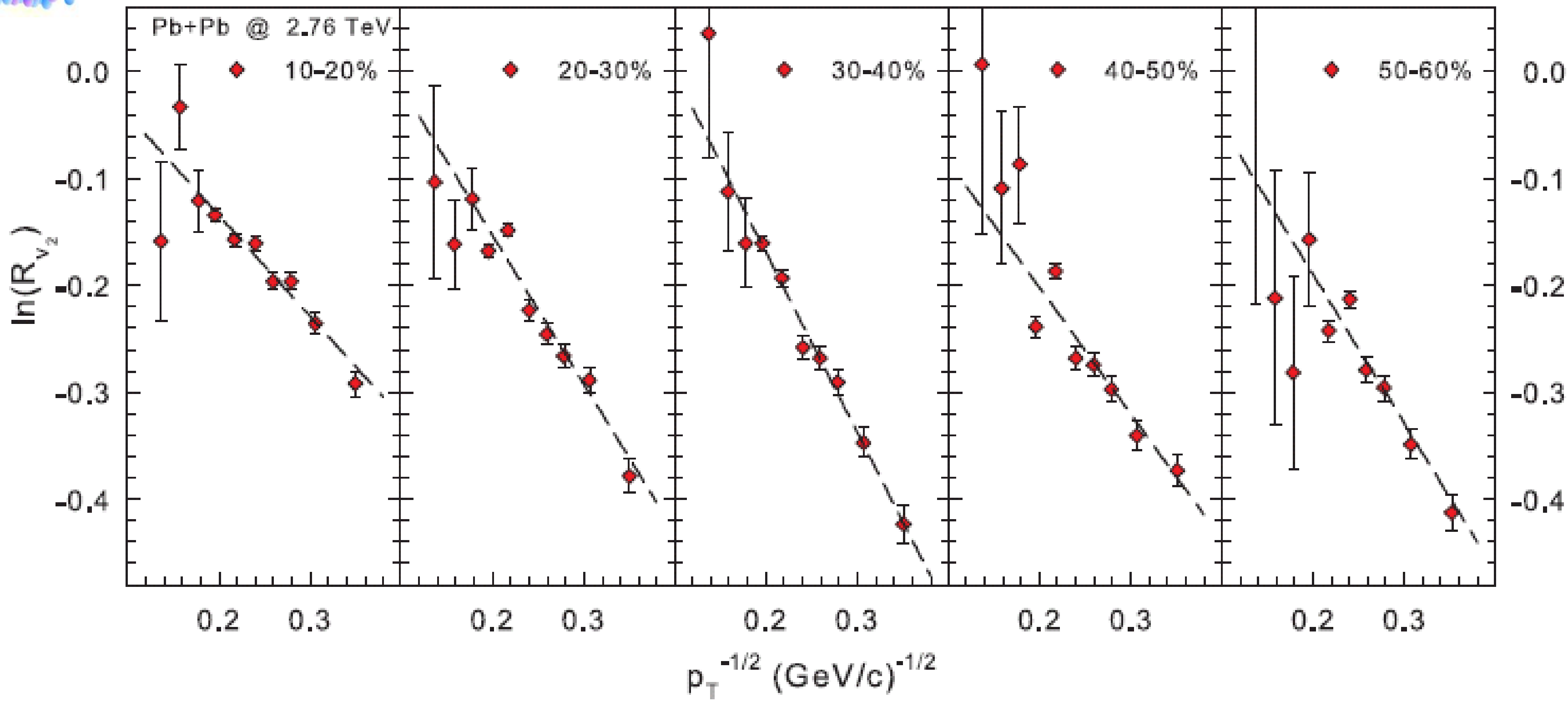
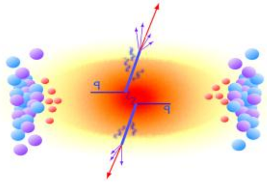


Jet suppression obtained directly from v_2

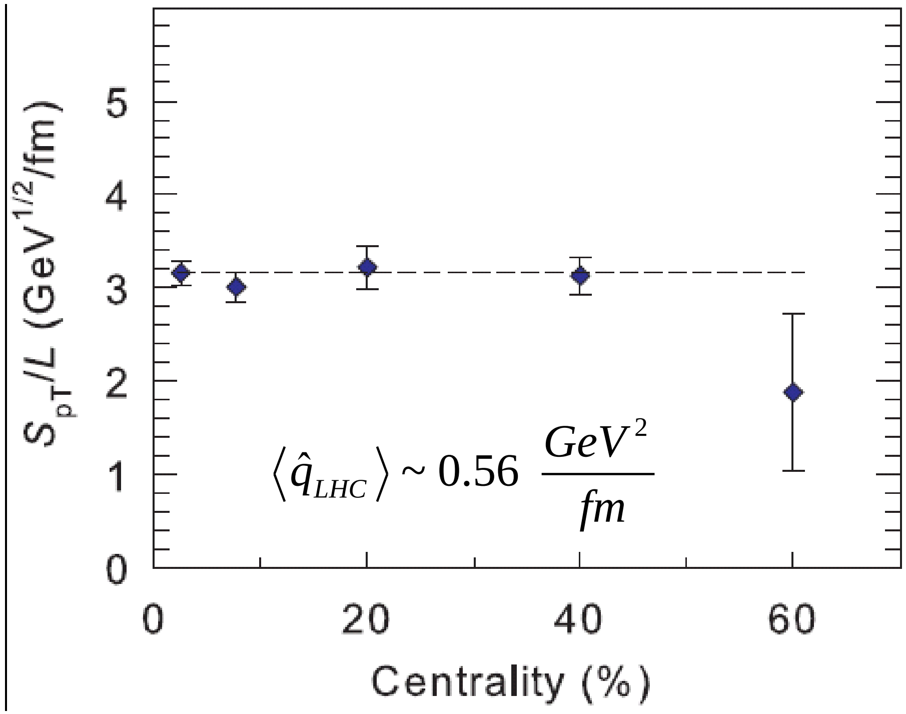
R_{v2} scales as $1/\sqrt{p_T}$, slopes encodes info on α_s and $\hat{q}$

Extracted stopping power

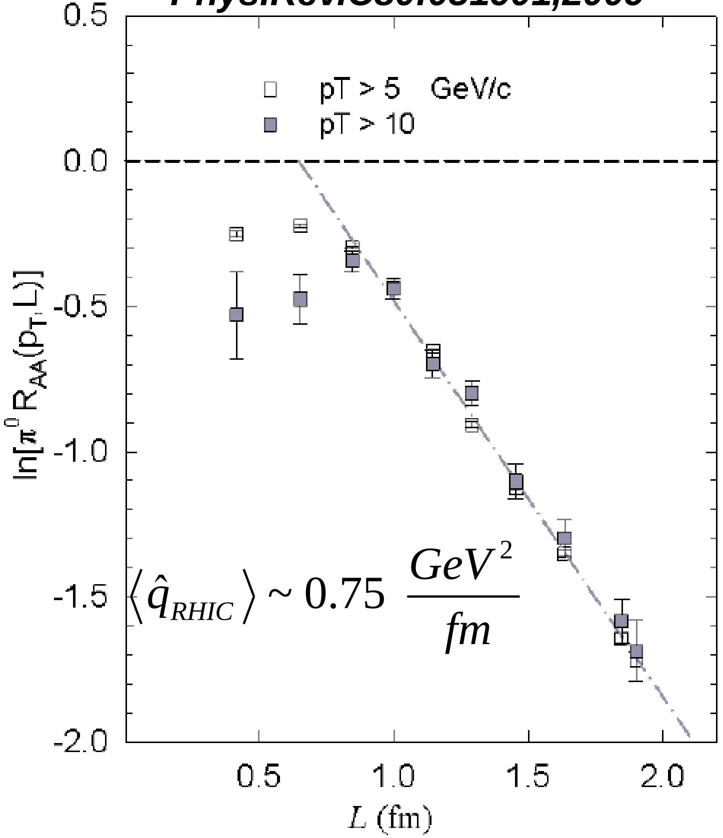


$$R^{l}_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\frac{\mathcal{L}_l}{p_T}}\right]$$

arXiv:1202.5537 **arXiv:1203.3605**



Phys.Rev.C80:051901,2009



- ***$\hat{q}_{LHC}$ obtained from high-pT v_2 and R_{AA} [same α_s] → similar***
- ***$\hat{q}_{RHIC} > q_{LHC}$ - medium produced in LHC collisions less opaque!***

Conclusion similar to those of Liao, Betz, Horowitz,
→ Stronger coupling near T_c?

Summary

Remarkable scaling have been observed for both Flow and Jet Quenching

They lend profound mechanistic insights, as well as New constraints for estimates of the transport and thermodynamic coefficients!

What do we learn?

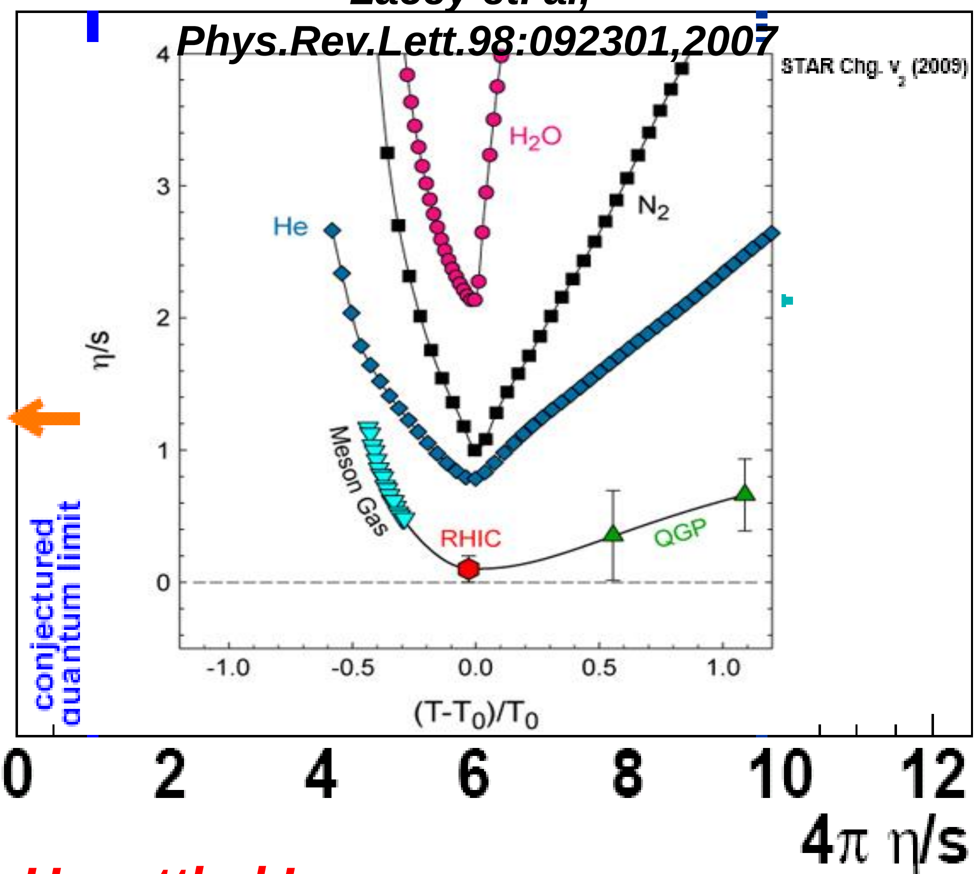
- **R_{AA} and high-pT azimuthal anisotropy stem from the same energy loss mechanism**
- **Energy loss is dominantly radiative**
- **R_{AA} and anisotropy measurements give consistent estimates for $<\hat{q}_{LHC}>$ ~ 0.6 GeV^2/fm**
- **The QGP created in RHIC collisions is less opaque than that produced at the LHC**

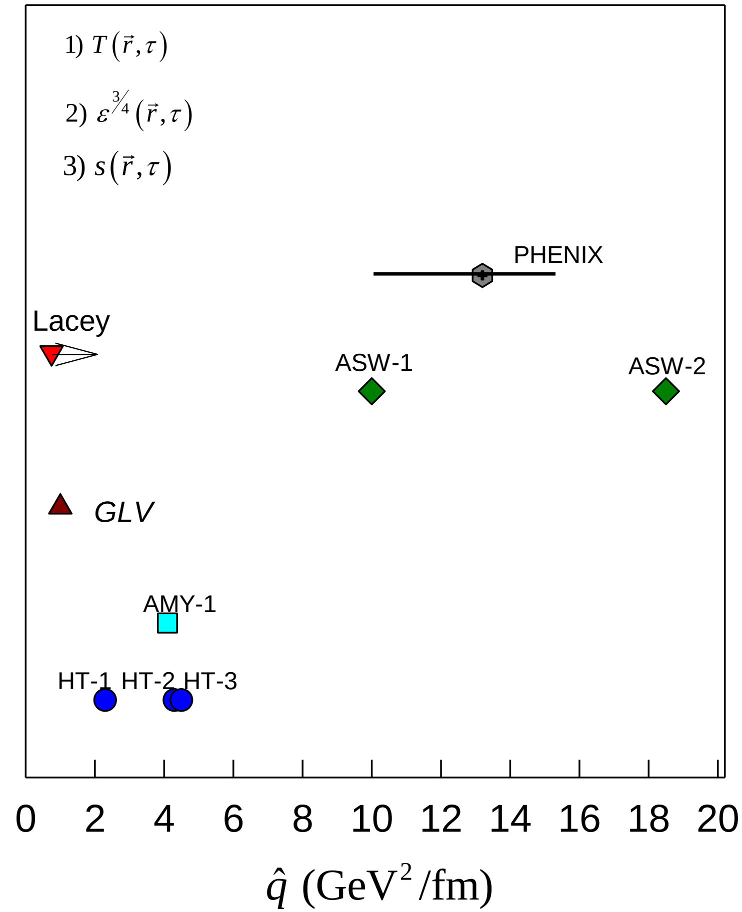
- ***Flow is acoustic***
  - ✓ *Flow is pressure driven*
  - ✓ *Obeys the dispersion relation for sound propagation*
- ***Flow is partonic***
  - ✓ *exhibits scaling* $v_{n,q}(KE_T) \sim v_{2,q}^{n/2}$ or $\frac{v_n}{(n_q)^{n/2}}$
- ***Constraints for:***
  - ✓ *initial geometry*
  - ✓ *<η/s> comparable at LHC and RHIC ~ 1/4π*
  - ✓ *actual temp dependence coming soon*

End

Transport coefficient estimates – 2009

Lacey et. al, Phys.Rev.Lett.98:092301,2007



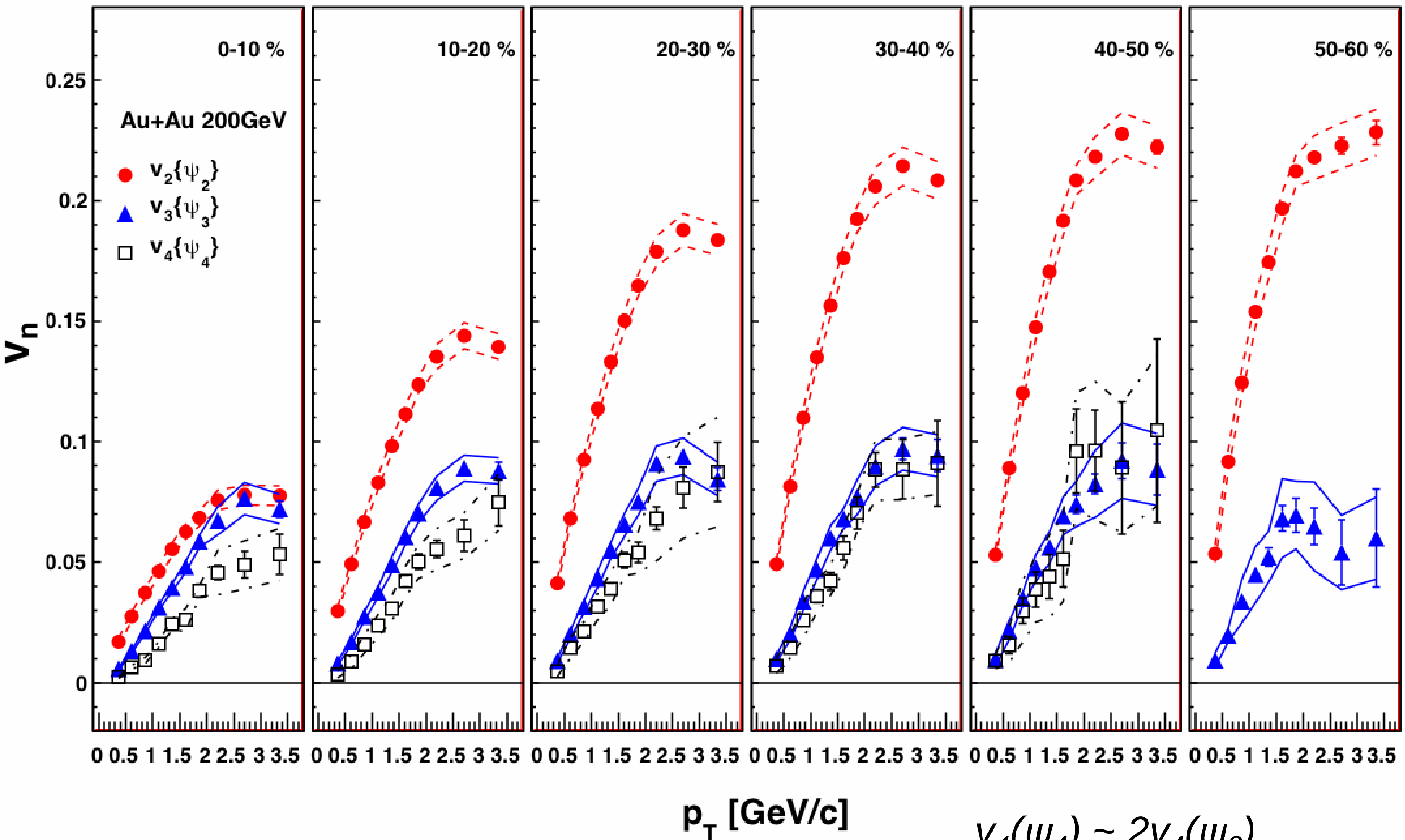


Unsettled Issues

- ***Detailed mechanistic understanding?***
- ***Quantitative values (including T/t dependence)?***
- ***Evidence for change in coupling strength close to T_c?***
- ***ε, α_s, δf, etc.*** ***!!Much work to be done!!***

$v_n(\psi_n)$ Measurements - PHENIX

Phys.Rev.Lett. 107 (2011) 252301 (arXiv:1105.3928)



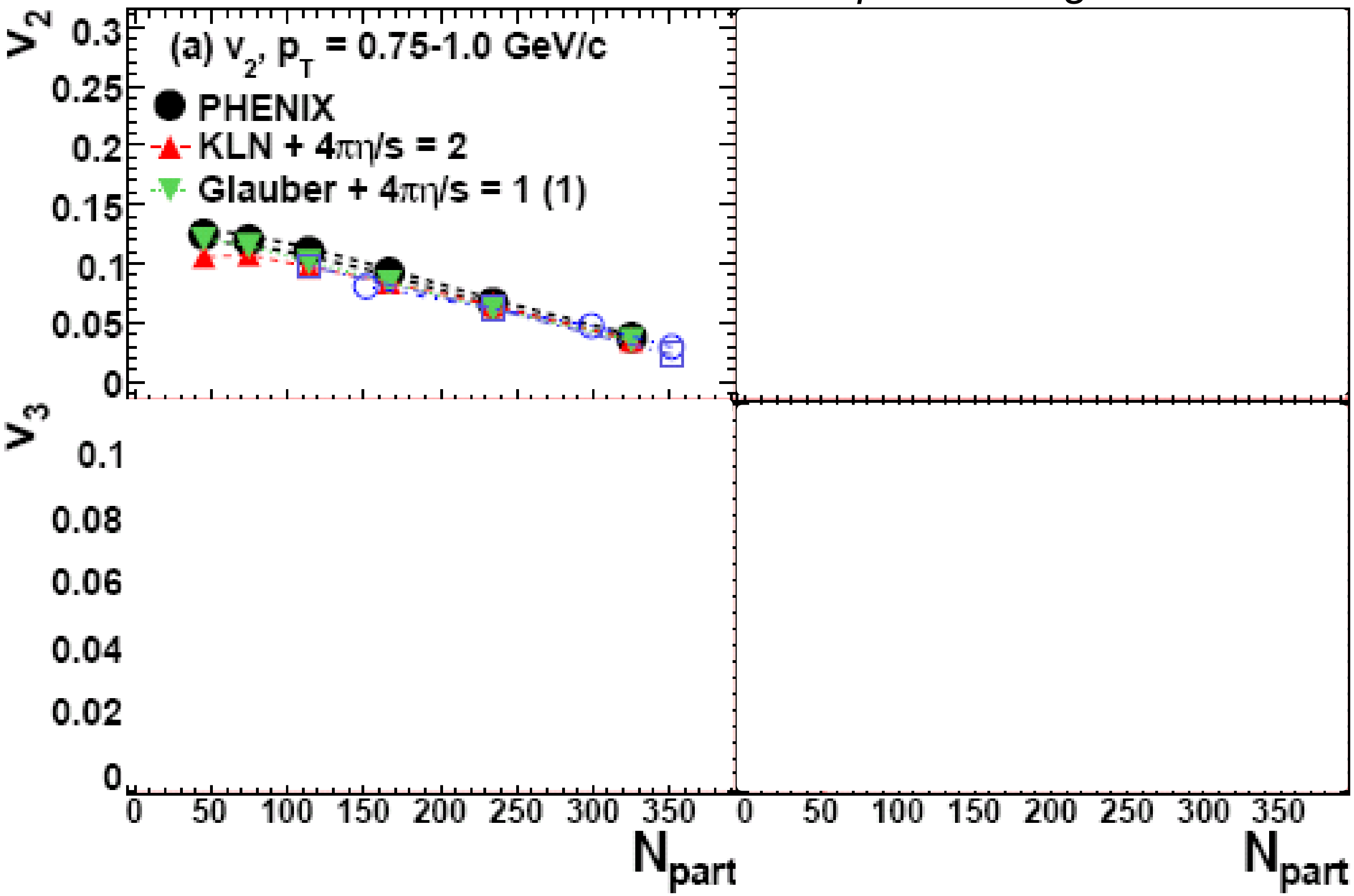
$v_4(\psi_4) \sim 2v_4(\psi_2)$

High precision double differential Measurements are pervasive

Do they scale?

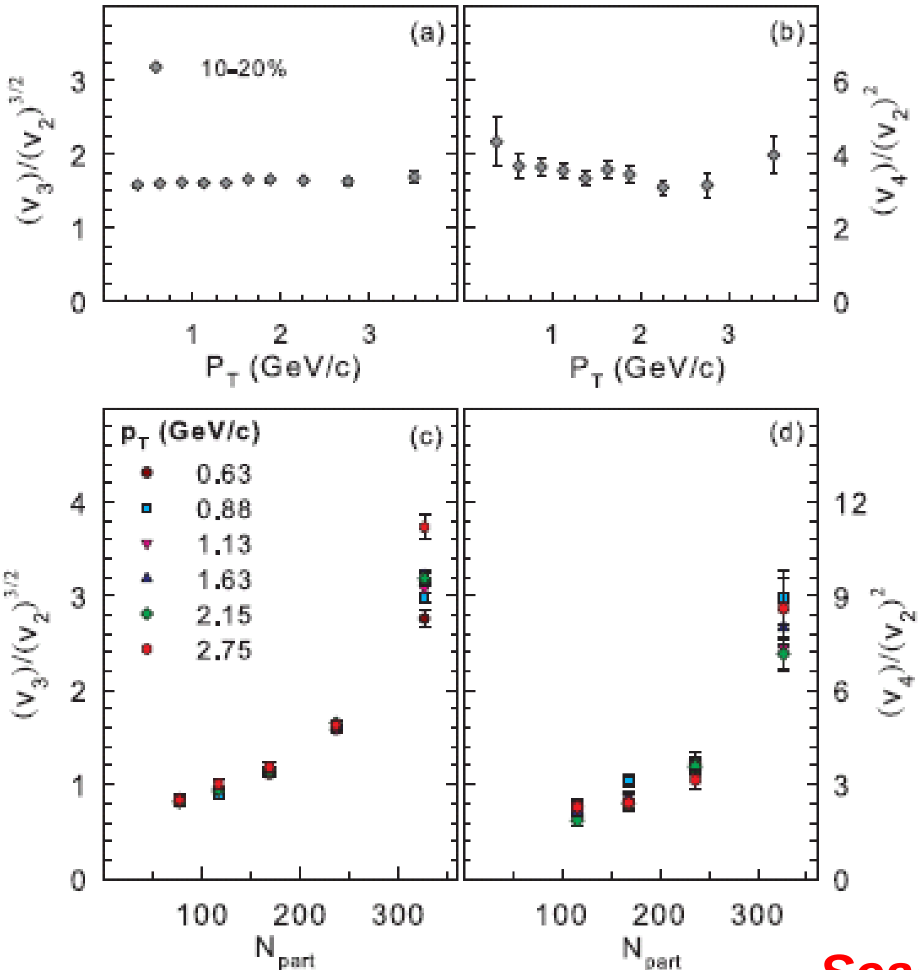
Decoupling the Interplay between ε_n and η/s

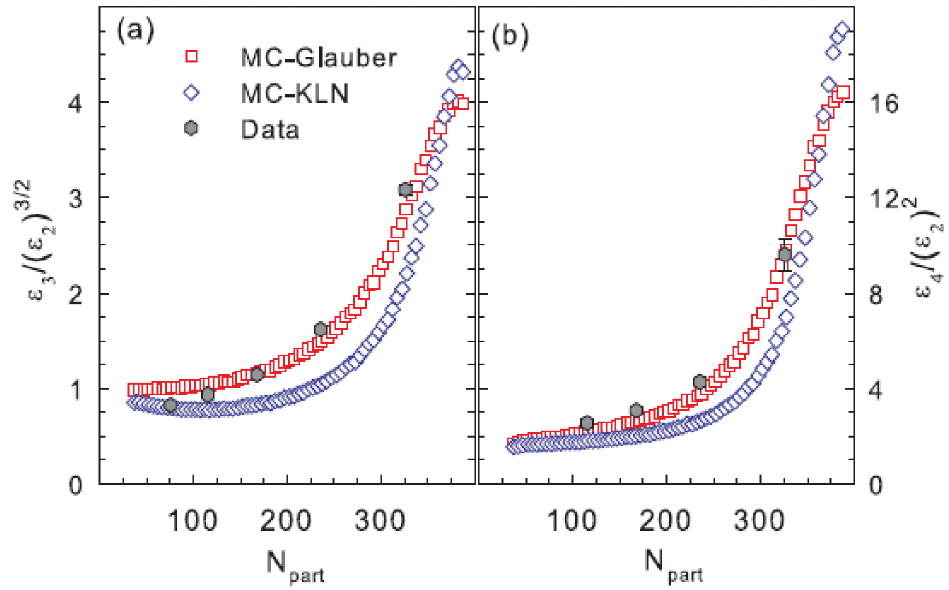
http://arxiv.org/abs/1105.3928



v_3 breaks the ambiguity between MC-KLN vs. MC-Glauber initial conditions and η/s, because of the n^2 dependence of viscous corrections

Flow is partonic





Scaling for partonic flow validated for v_n

- ✓ ***Constraints for ε_n***

Similar scaling observed at the LHC