Is the QGP produced at the LHC more opaque than that produced at RHIC

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Essential question

Do recent flow and jet quenching measurements at RHIC and the LHC give new constraints for characterization of the Quark Gluon Plasma (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**

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

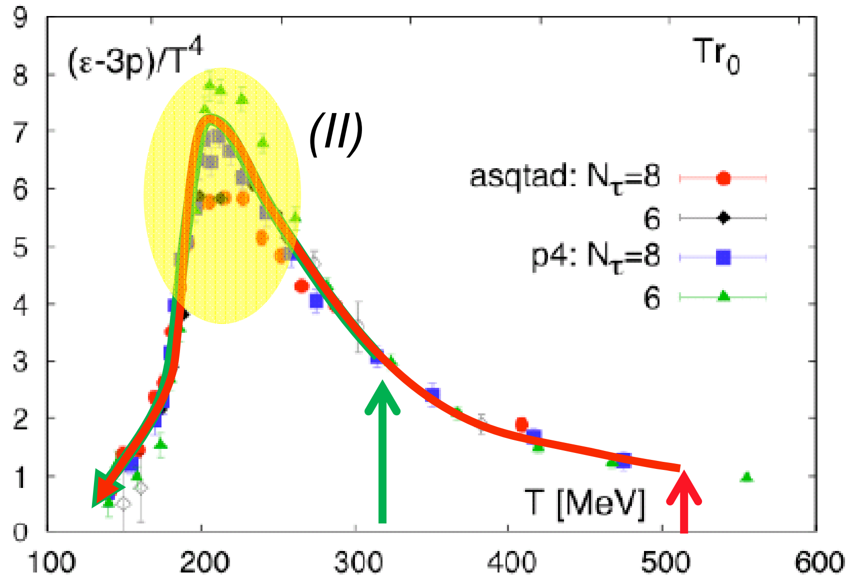
II. **Development of quantitative model descriptions of these properties**

Experimental Access:

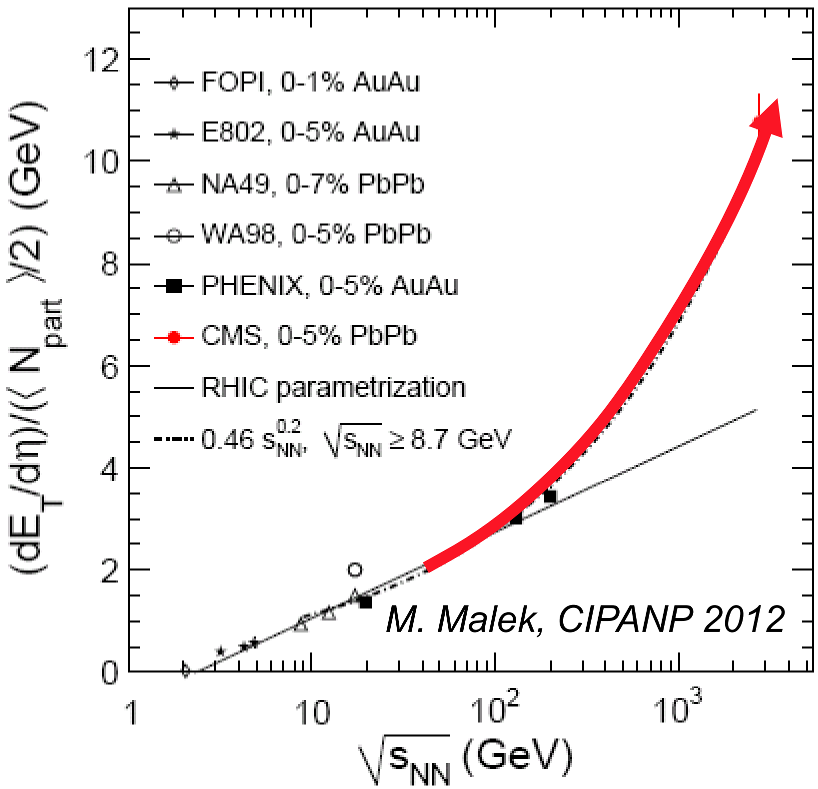
✓ **Temp/time-averaged constraints as a function of $\sqrt{s_{NN}}$**
(with similar expansion dynamics)

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

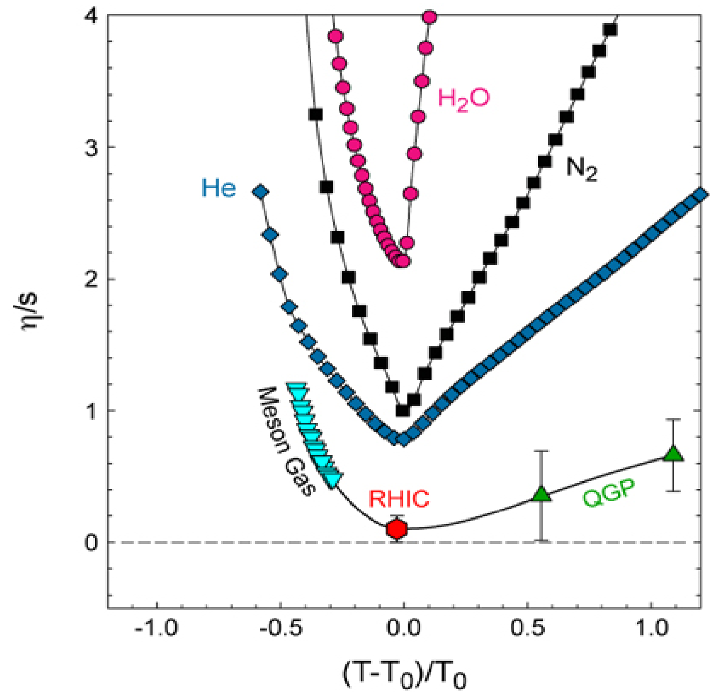
(I) Expect space-time averages to evolve with $\sqrt{s_{NN}}$



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:

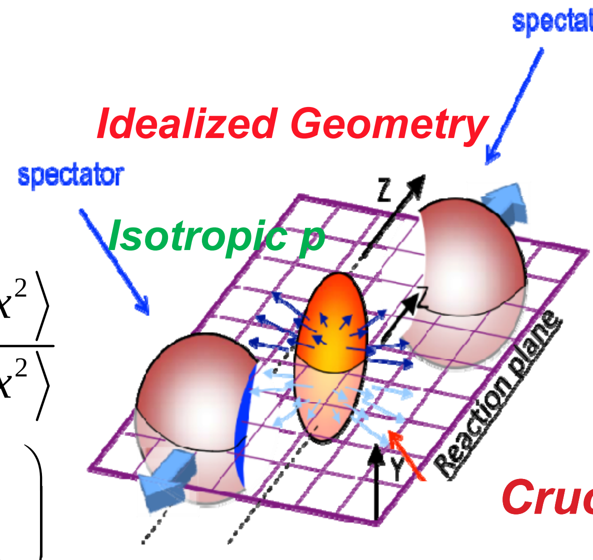
- ***How do the transport coefficients*** $\langle c_s\rangle, \left\langle \frac{\eta}{s} \right\rangle, \langle \hat{q}\rangle, \langle \alpha_s\rangle$ ***evolve with T?***
- ***Any indication for a change in coupling close to*** T_o***?***

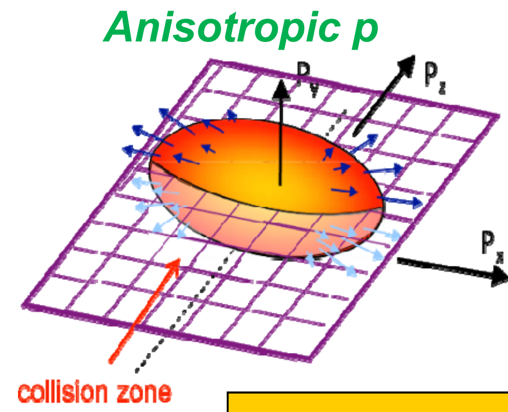
The Flow Probe

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

$$\sim 5 - 45\ \frac{GeV}{fm^3} \qquad \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

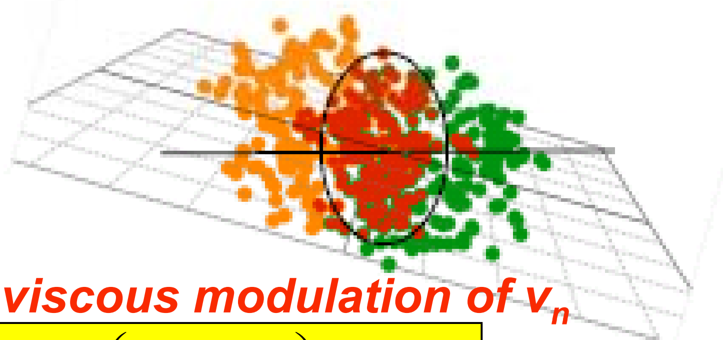
$$\left(P = \rho^2 \cdot \left(\partial \varepsilon_{Bj} / \partial \rho \right) \Big|_{s/\rho} \right)$$



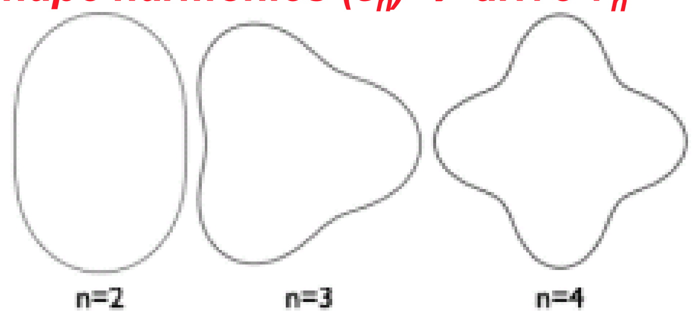


Crucial parameters $\varepsilon,\ c_s,\ \frac{\eta}{s},\ \delta f,\ T_f$

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**

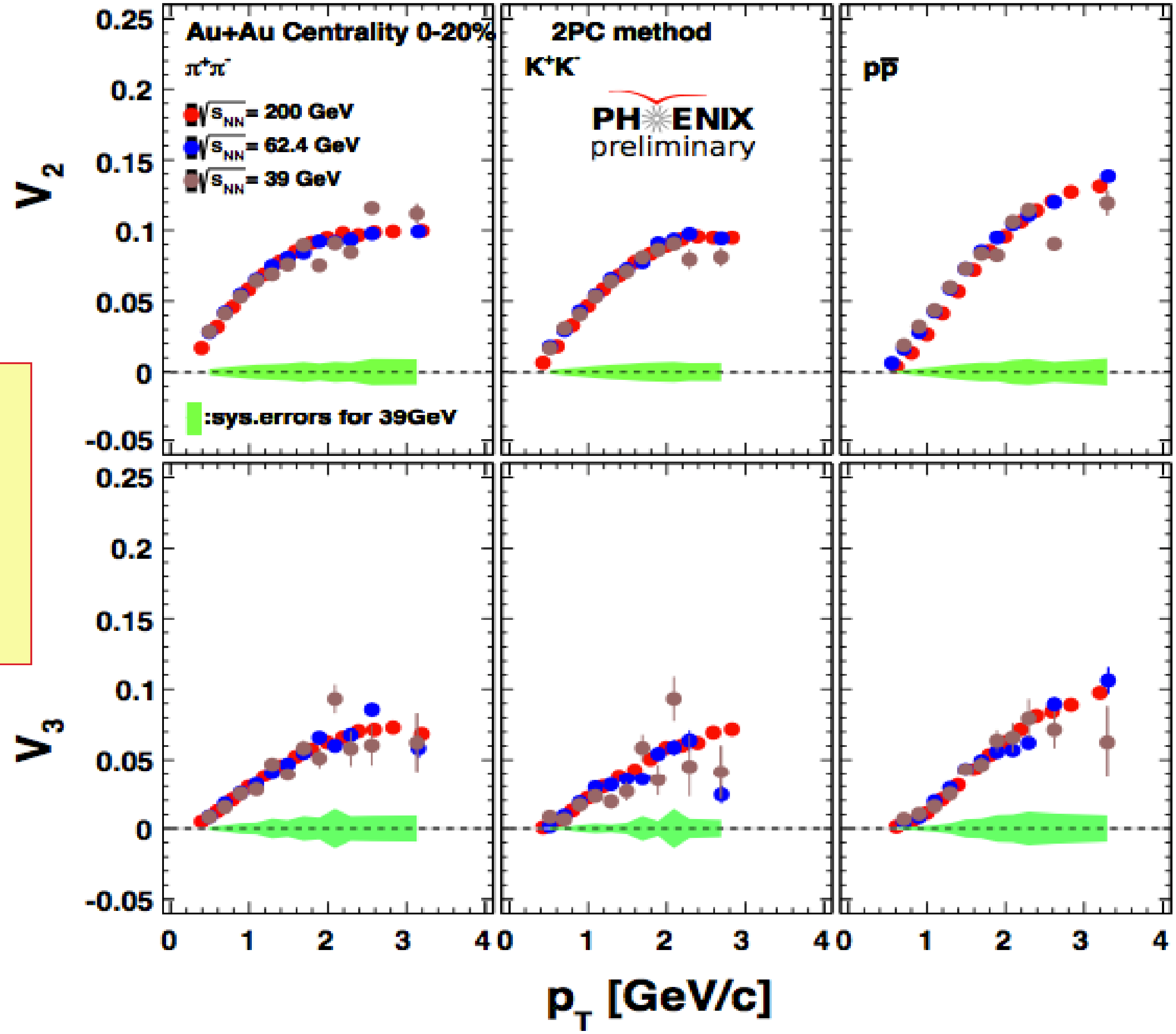
$$\varepsilon_n = \frac{\langle r^n \cos(n\varphi_{part}) \rangle^2 + \langle r^n \sin(n\varphi_{part}) \rangle^2}{\langle r^n \rangle^2}$$

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

PID flow excitation function @ RHIC

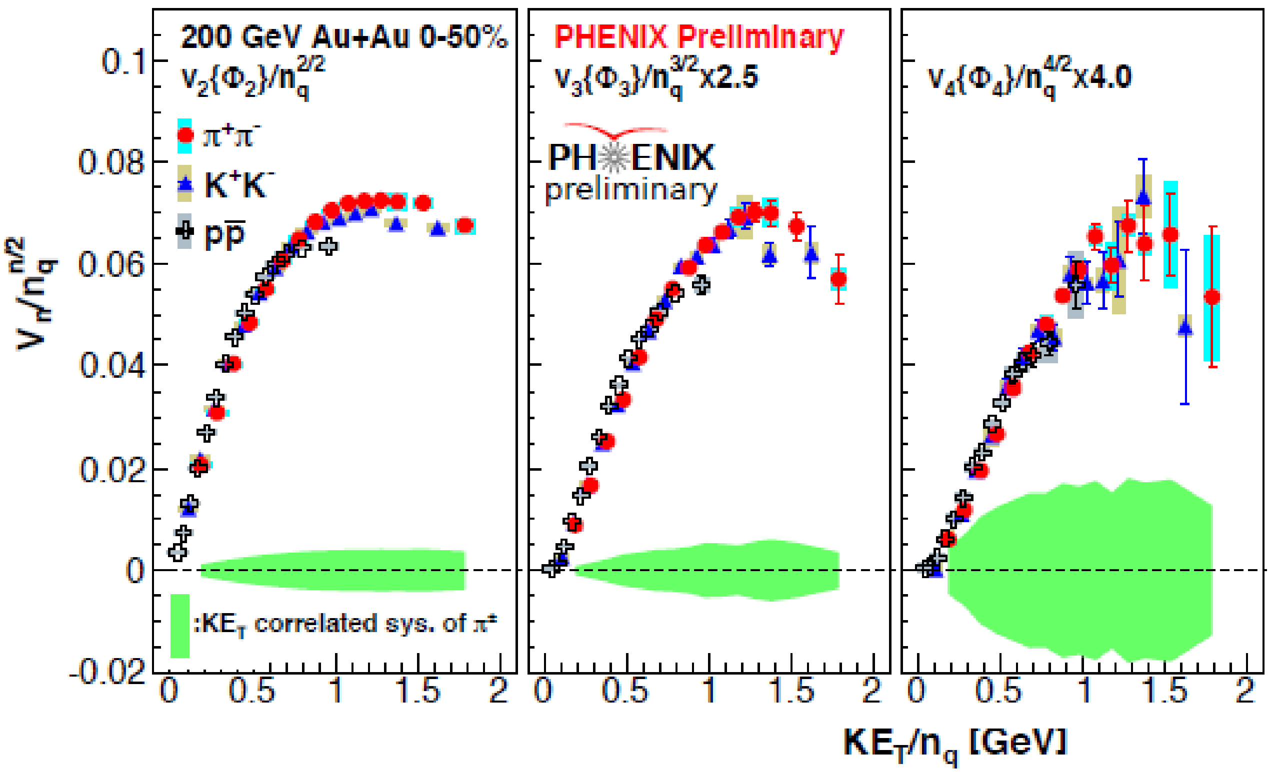
Flow saturates for
$\sqrt{s_{NN}}$ = 39-200 GeV

Soft region of EOS?



Flow is partonic @ RHIC

v_n PID scaling

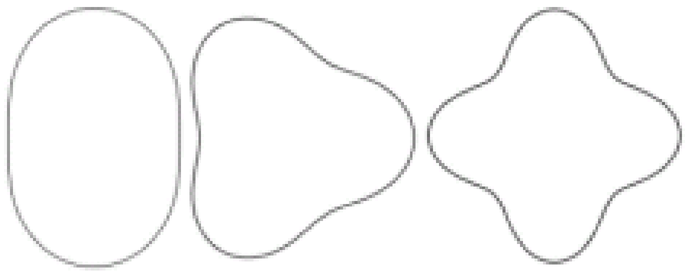


KE_T & $\left(n_q\right)^{n/2}$ scaling validated for v_n
→ **Partonic flow**

arXiv:1105.3782

Acoustic Constraint

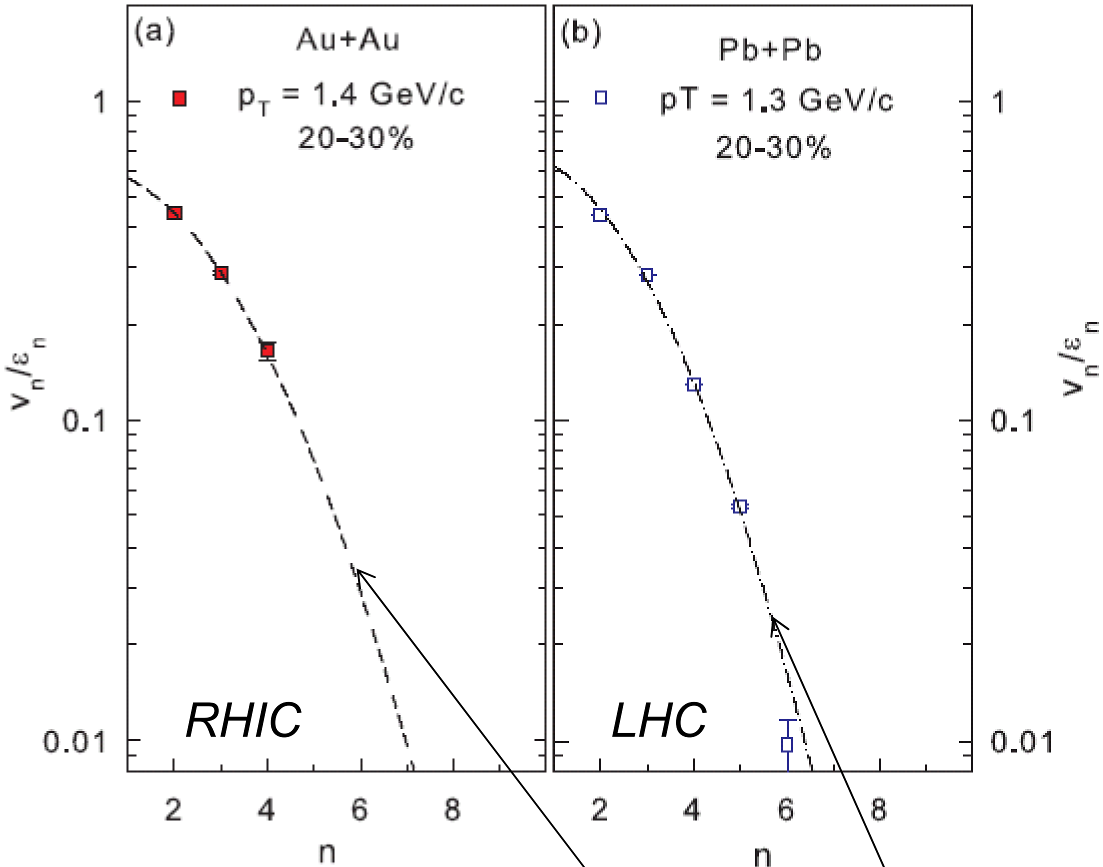
$$\delta T_{\mu\nu}(t,k) = \exp\left(\frac{2}{3}\frac{\eta}{s}k^2\frac{t}{T}\right)\delta T_{\mu\nu}(0)$$



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

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

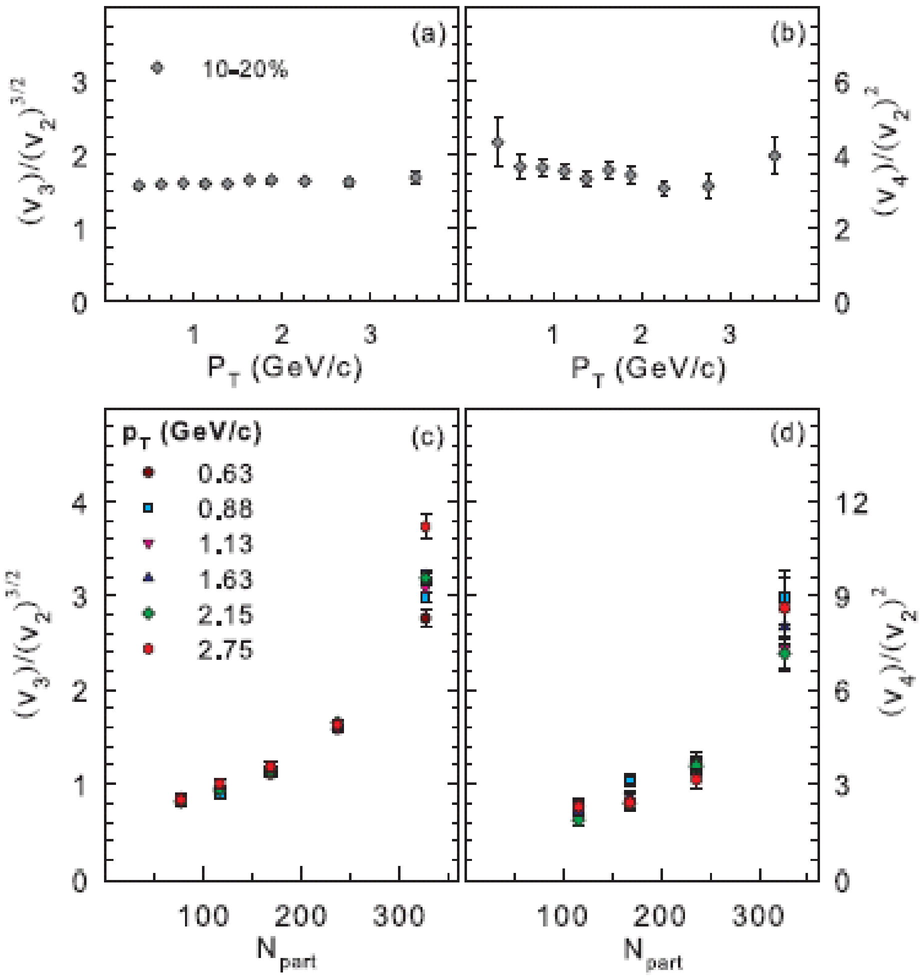
Characteristic viscous damping of the harmonics validated →Important constraint



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

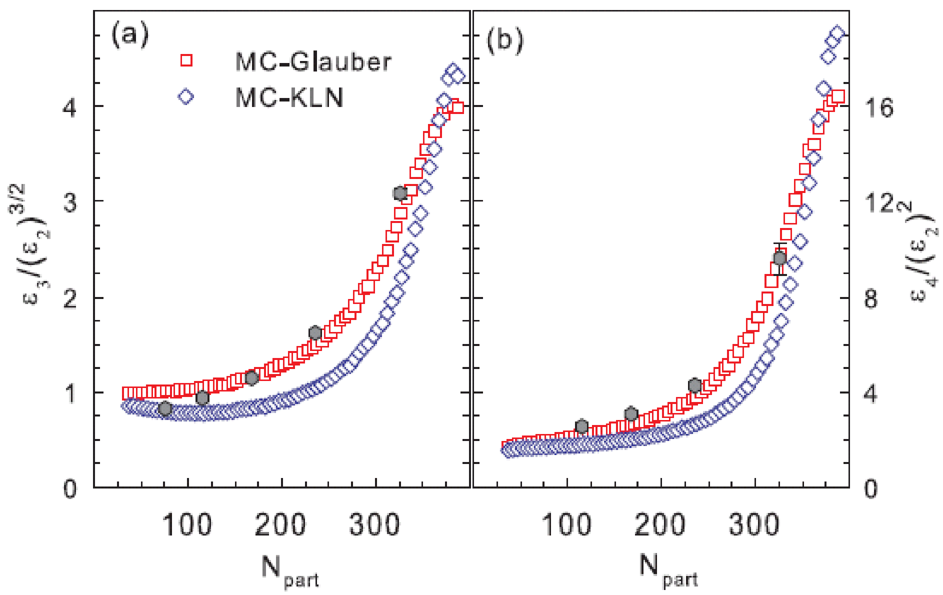
$$\frac{\eta}{s} \sim \frac{1}{4\pi}$$

Eccentricity Constraint



$$v_n(p_T) \propto (v_2)^{n/2}$$

arXiv:1105.3782

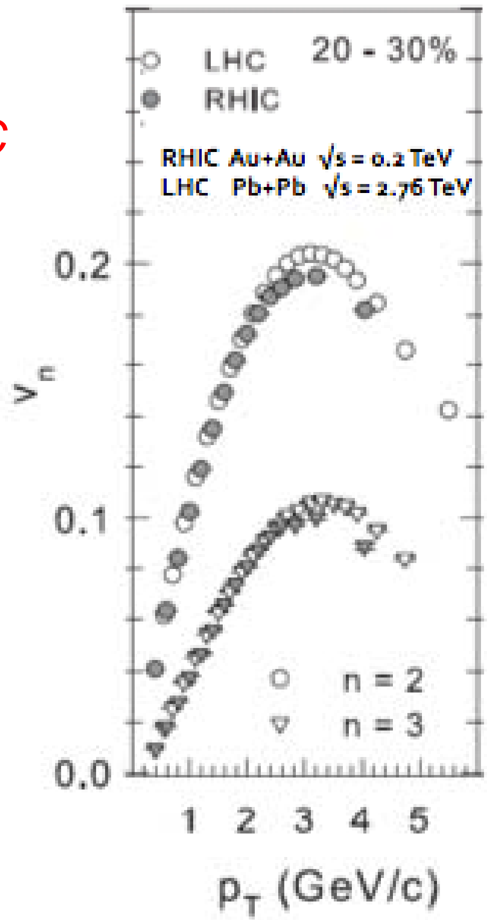


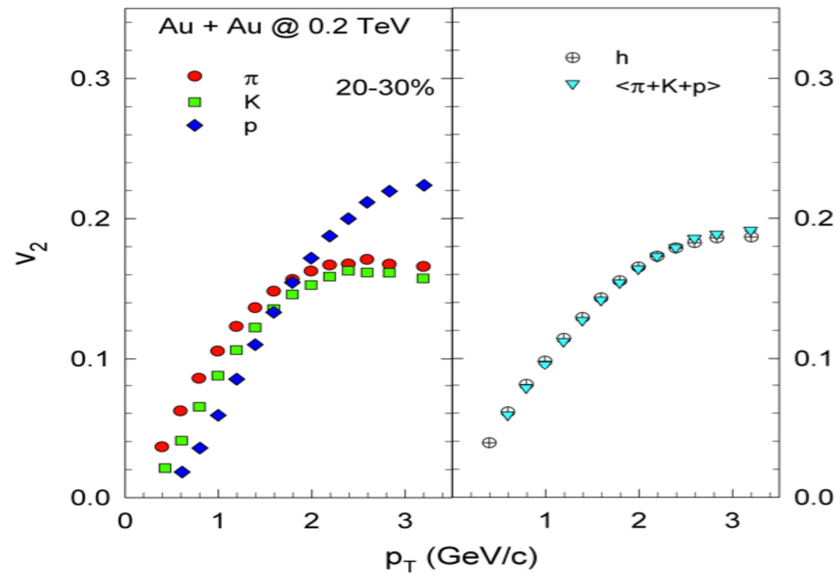
- ✓*Scaling validated for v_n*
- ✓ *Similar scaling at LHC*
- ✓*Centrality dependence reflect eccentricity ratio*
  - ✓*Constraints for ε_n*

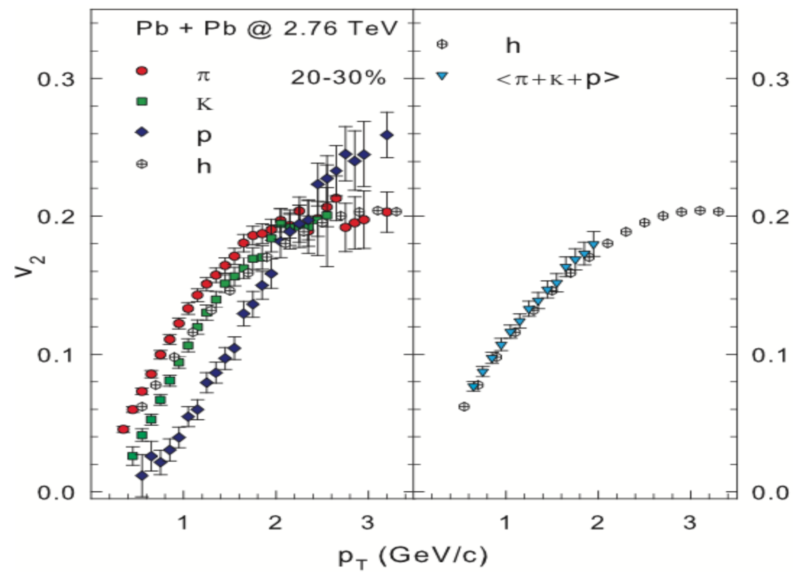
Flow @ RHIC and the LHC

- *Charge hadron flow similar @ RHIC & LHC*

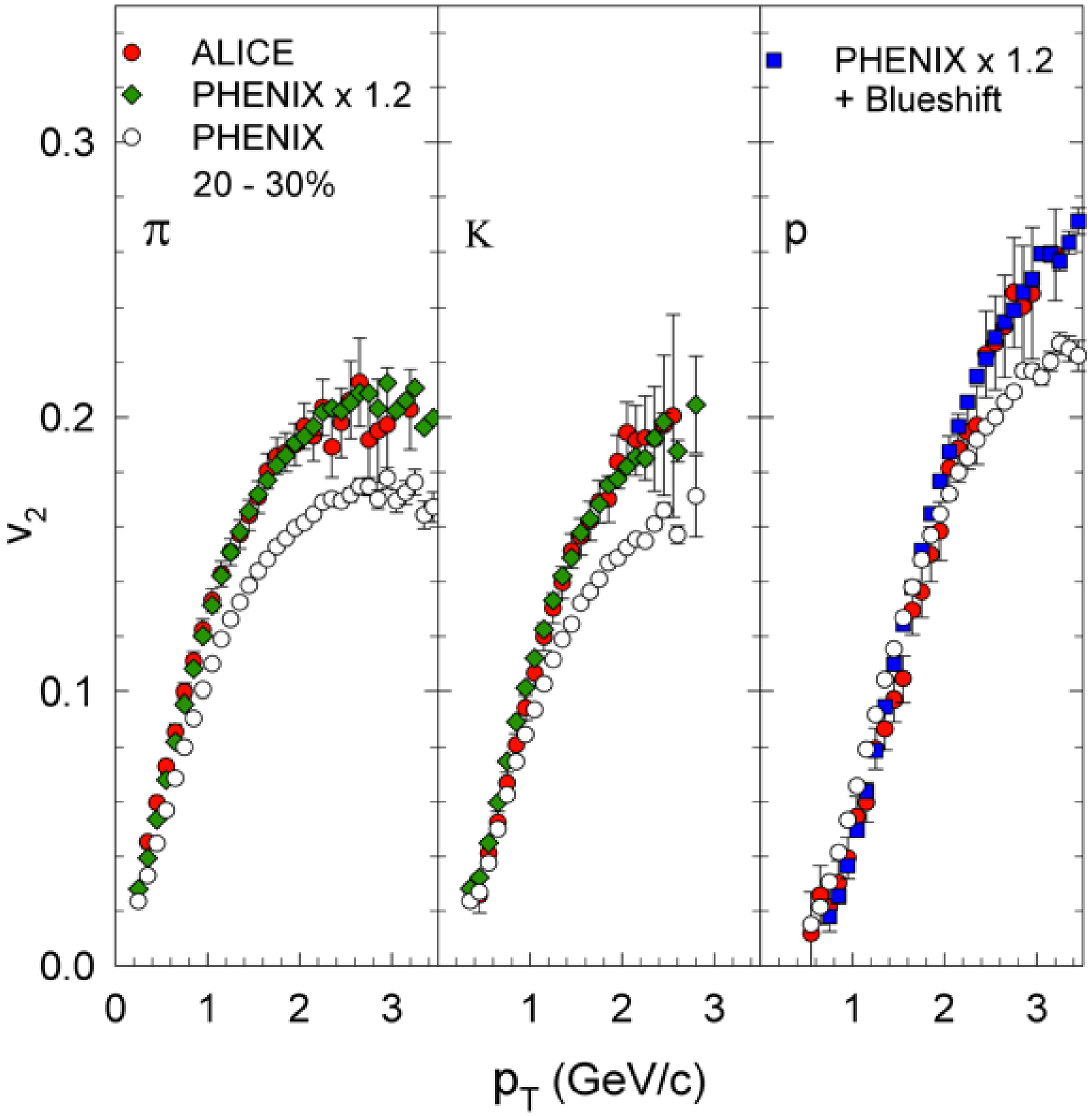
- *Particle ratio-weighted PIDed flow results reproduce inclusive charged hadron flow results at RHIC and LHC respectively*





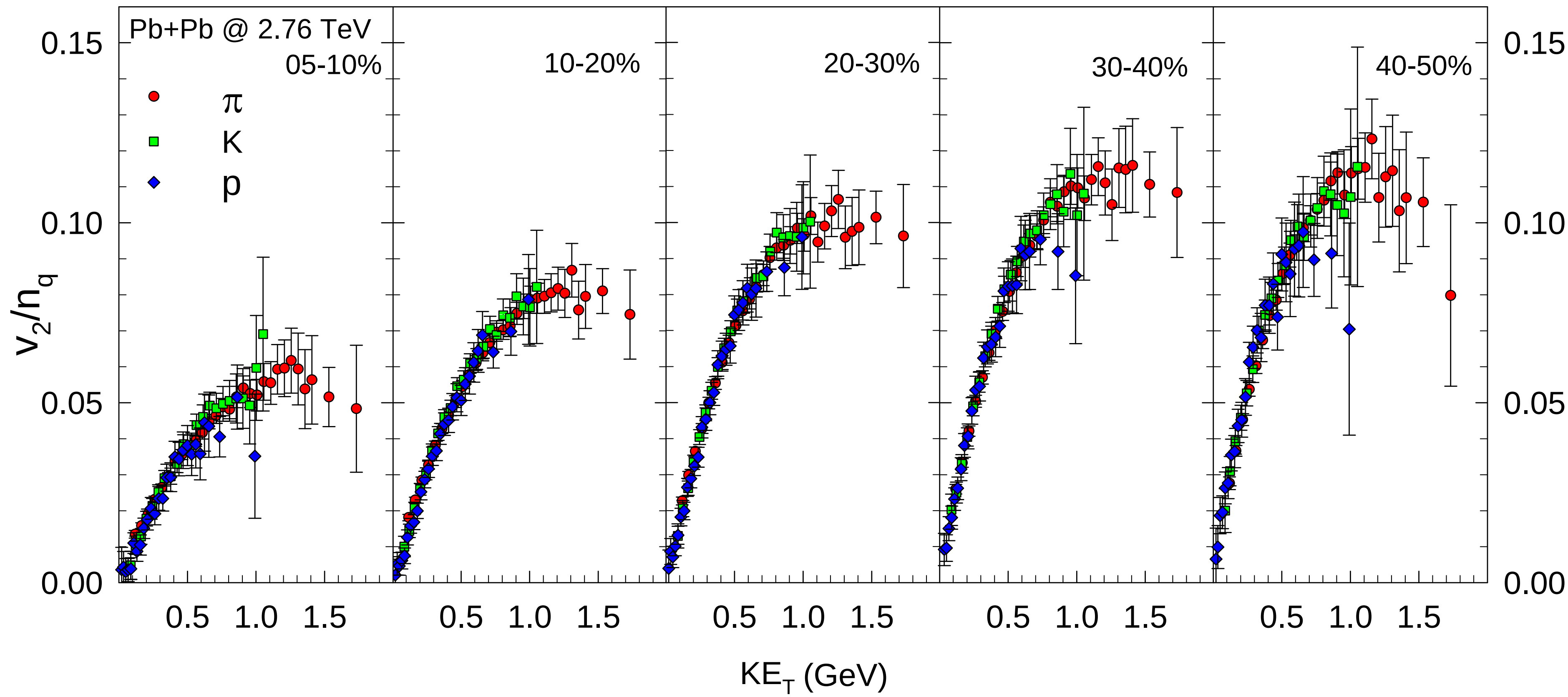


Flow increases from RHIC to LHC



- ***Flow increases from RHIC to LHC***
  - ✓ ***Sensitivity to EOS***
  - ✓ ***increase in <c_s>***
- ***Proton flow blueshifted [hydro prediction]***
  - ✓ ***Role of radial flow***
  - ✓***Role of hadronic re-scattering?***

Flow is partonic @ the LHC

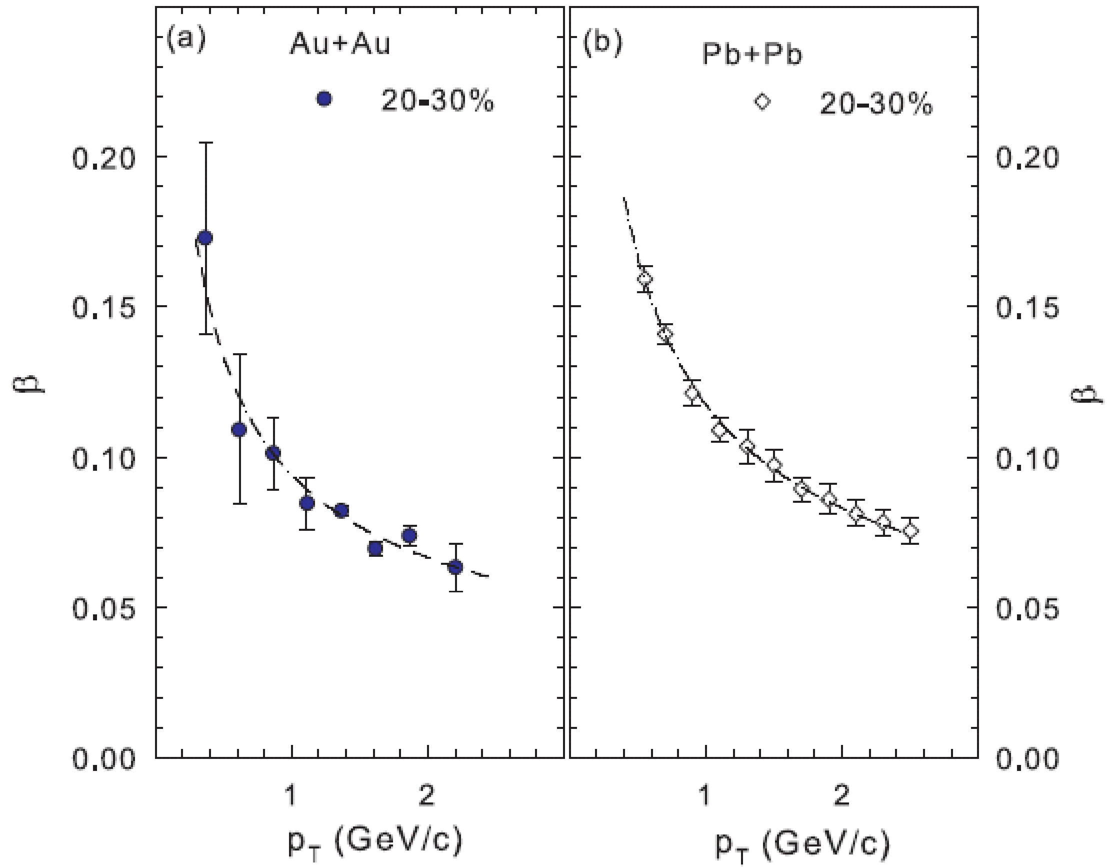


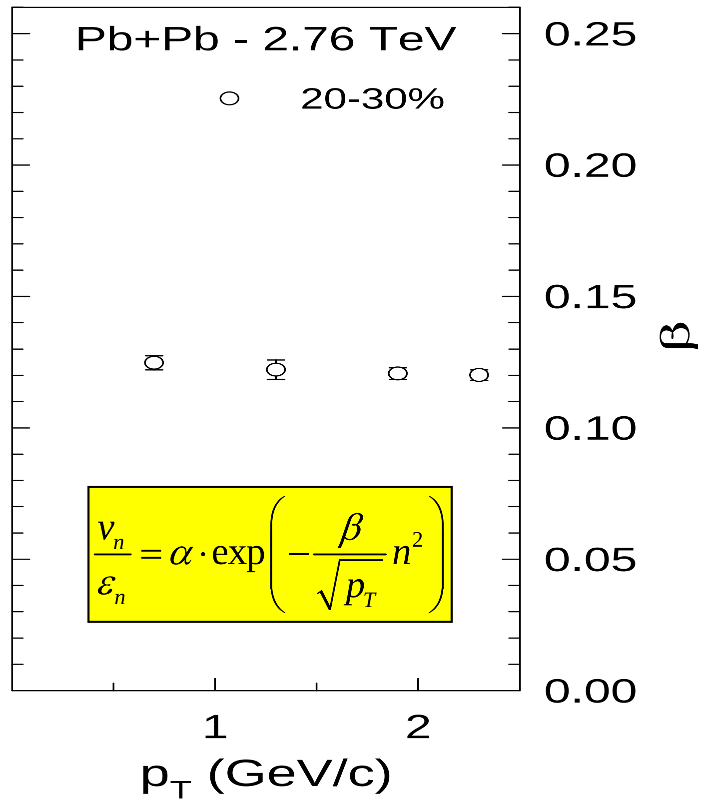
Scaling for partonic flow validated after accounting for proton blueshift

✓ ***Larger partonic flow at the LHC***

Constraint for η/s & δf

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

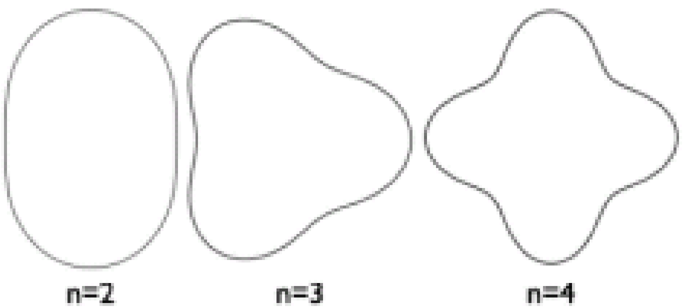




β scales as 1/√p_T

✓Important constraint

Constraint for η/s & δf

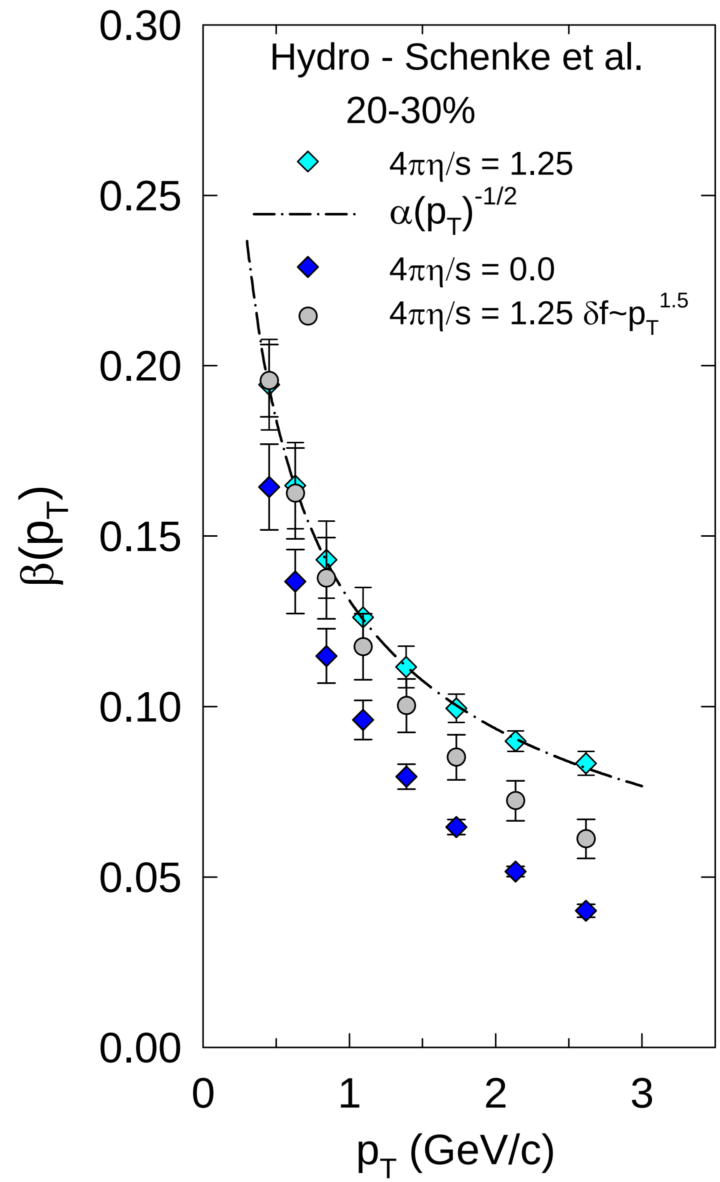


Deformation $k = \frac{n}{\bar{R}}$

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

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

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



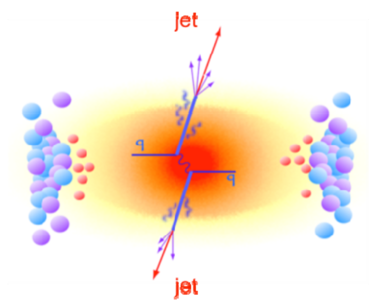
Characteristic p_T dependence of β
→ reflects the influence of δf and η/s

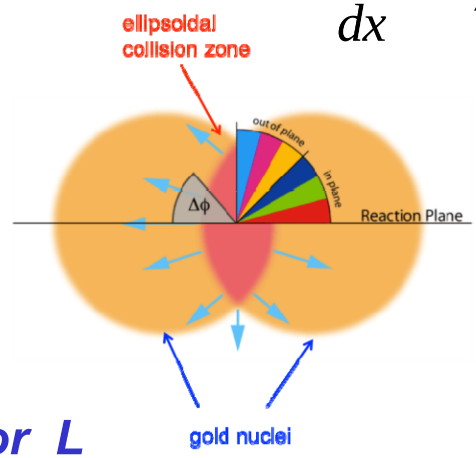
✓ <η/s> similar at LHC and RHIC ~ 1/4π

Jet quenching Probe

Radiative Energy loss:

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





Suppression for ΔL

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

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

Suppression for L

$$\mathrm{R}_{AA}(p_T, L) = \frac{\mathrm{Yield}_{AA}}{\langle \mathrm{N}_{\mathrm{binary}} \rangle_{AA} \mathrm{Yield}_{pp}}$$

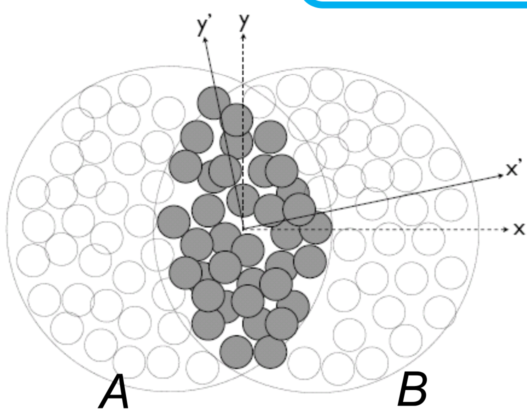
Dokshitzer and D. E. Kharzeev , Phys.Lett.B519:199-206,2001

$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L\sqrt{\hat{q}\frac{\mathcal{L}}{p_\perp}} + \frac{16\alpha_s C_F}{9\sqrt{3}} L\left(\frac{\hat{q}\ M^2}{M^2 + p_\perp^2}\right)^{1/3}\right]$$

$$\mathcal{L} \equiv \frac{d}{d\ln p_\perp} \ln\left[\frac{d\sigma^{vac}}{dp_\perp^2}(p_\perp)\right]$$

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

Geometric Quantities for scaling



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

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

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

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

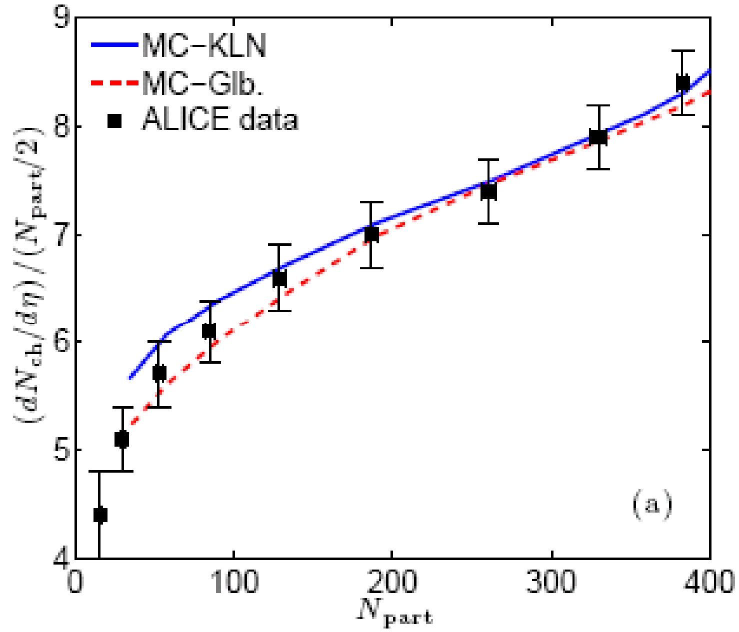
$$\varepsilon_n = \left\langle \cos n\left(\phi - \psi_n^*\right)\right\rangle$$

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

$$L = \bar{R}$$

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

arXiv:1203.3605

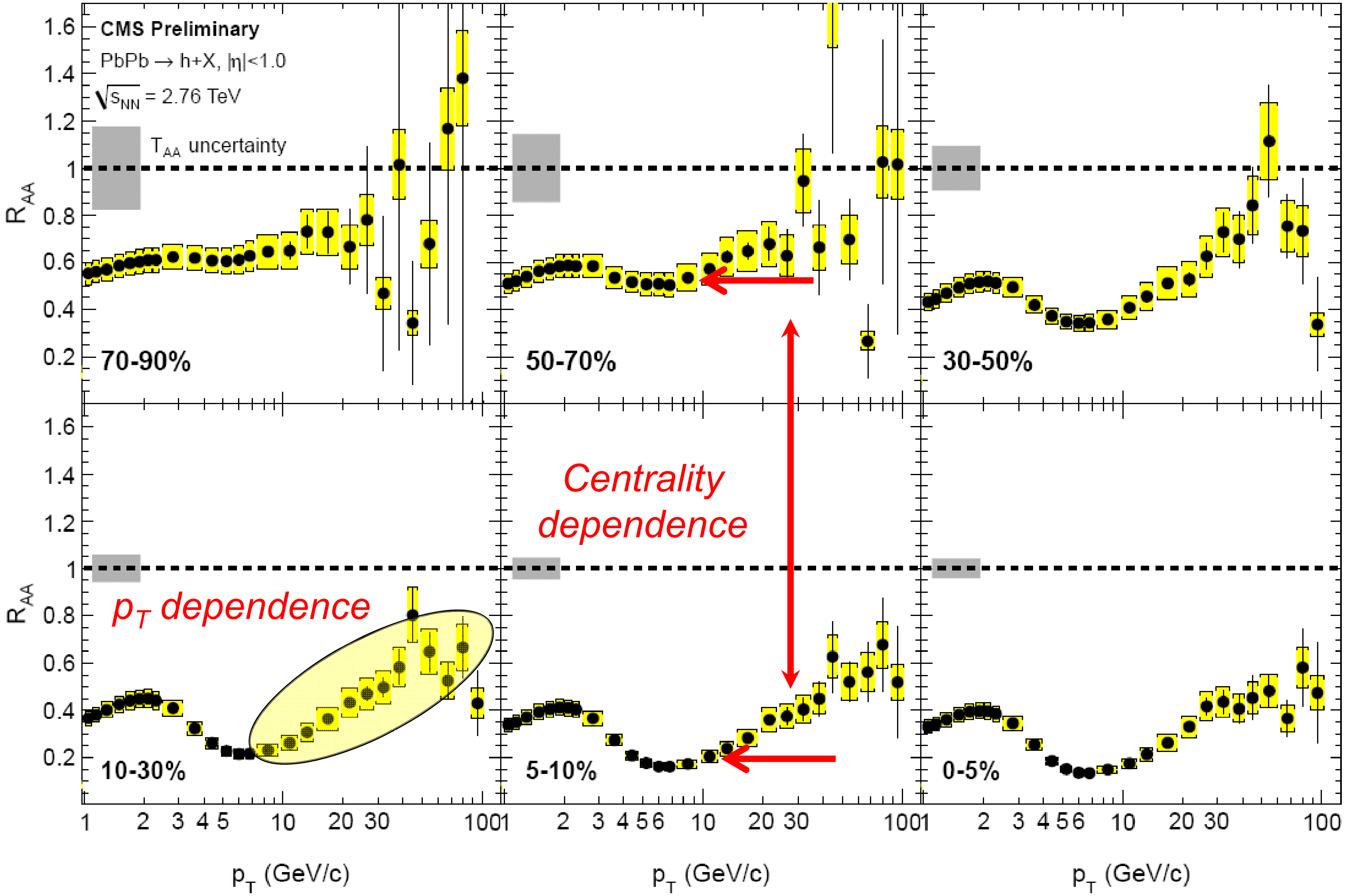


σ_x & σ_y → RMS widths of density distribution

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

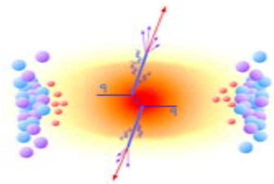
R_{AA} Measurements - CMS

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



Specific p_T and centrality dependencies – Do they scale?

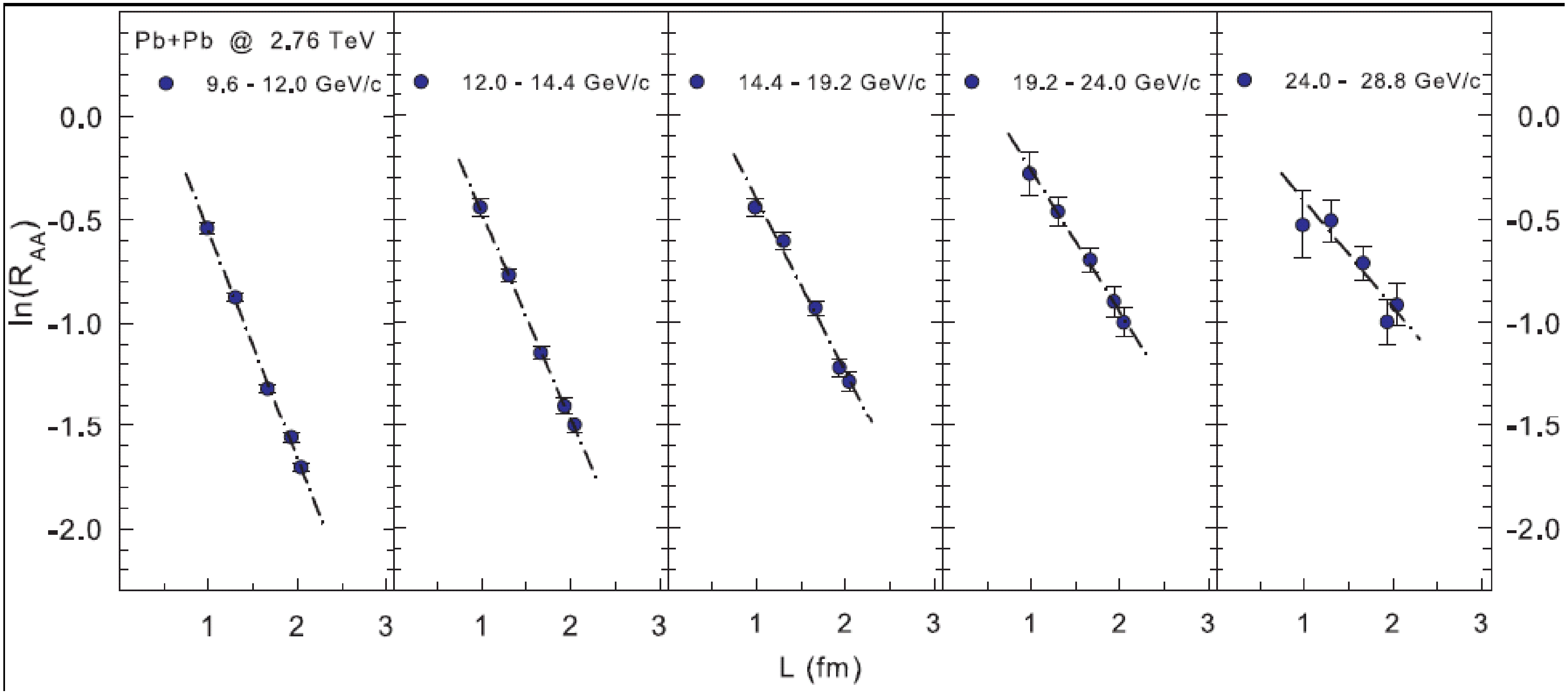
L scaling of Jet Quenching - LHC



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

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

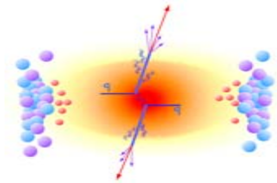
arXiv:1202.5537



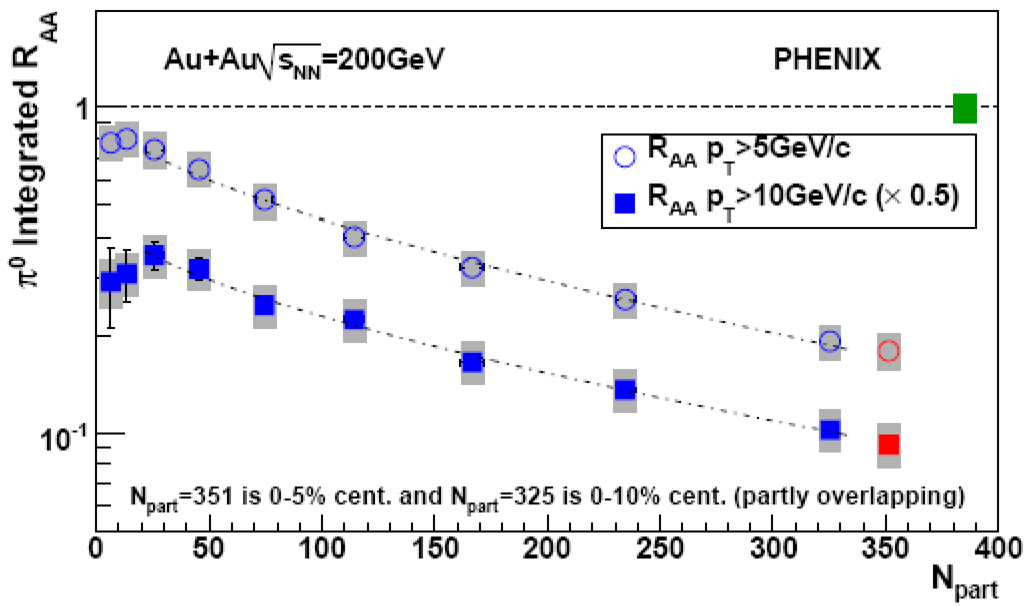
R_{AA} scales with L, slopes (S_L) encodes info on α_s and $\hat{q}$

✓Compatible with the dominance of radiative energy loss

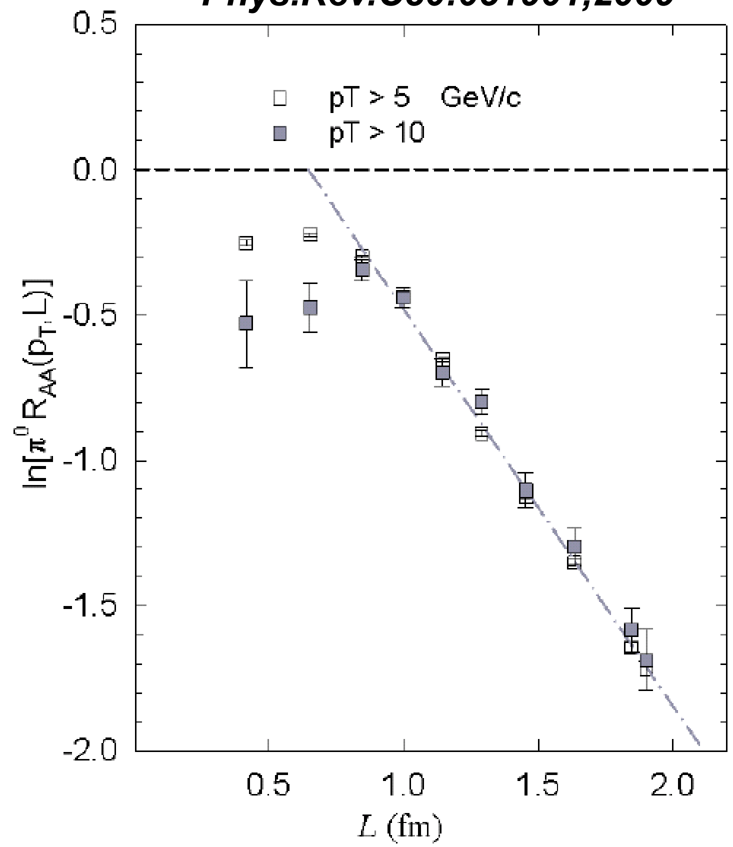
L scaling of Jet Quenching - RHIC



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



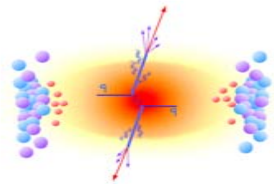
Phys.Rev.C80:051901,2009



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

✓Compatible with the dominance of radiative energy loss

p_T scaling of Jet Quenching



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

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

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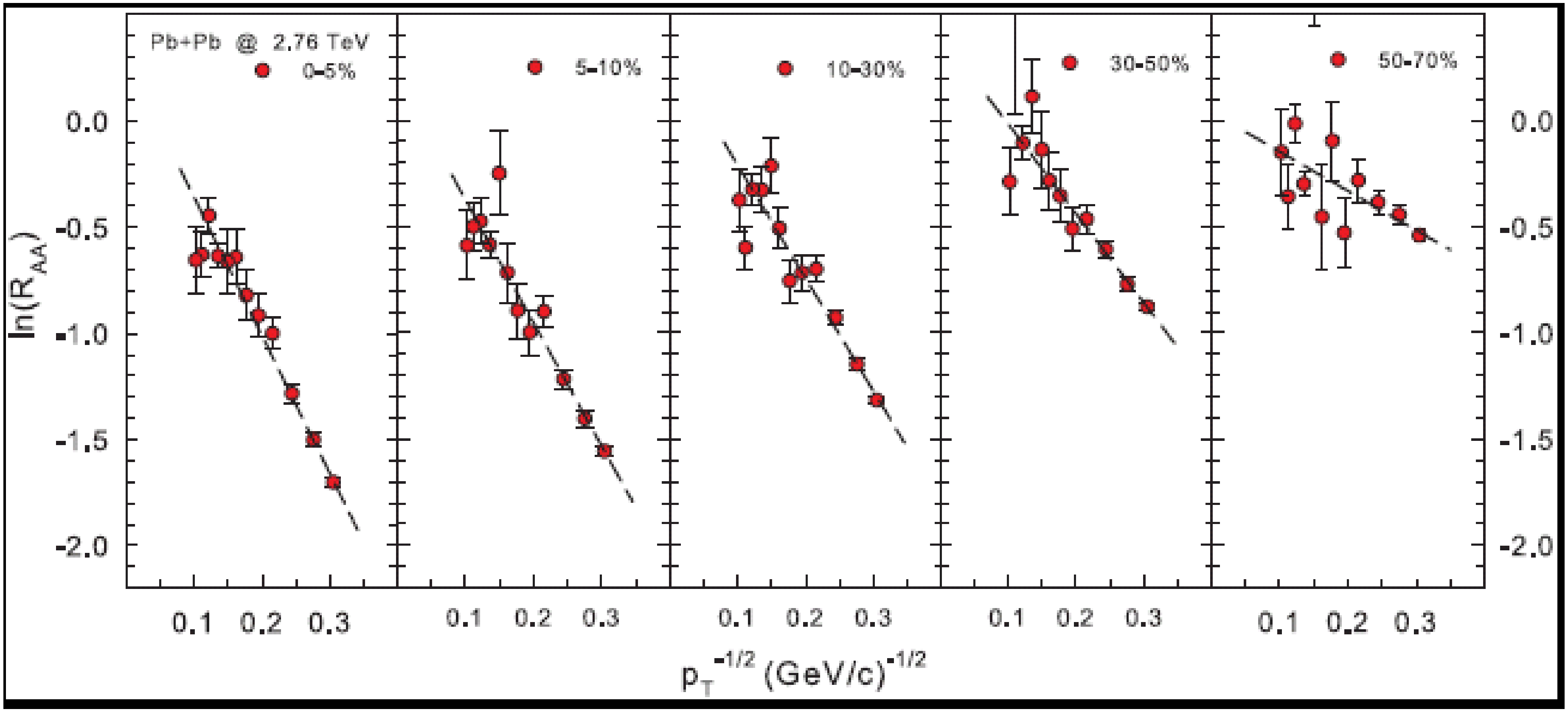
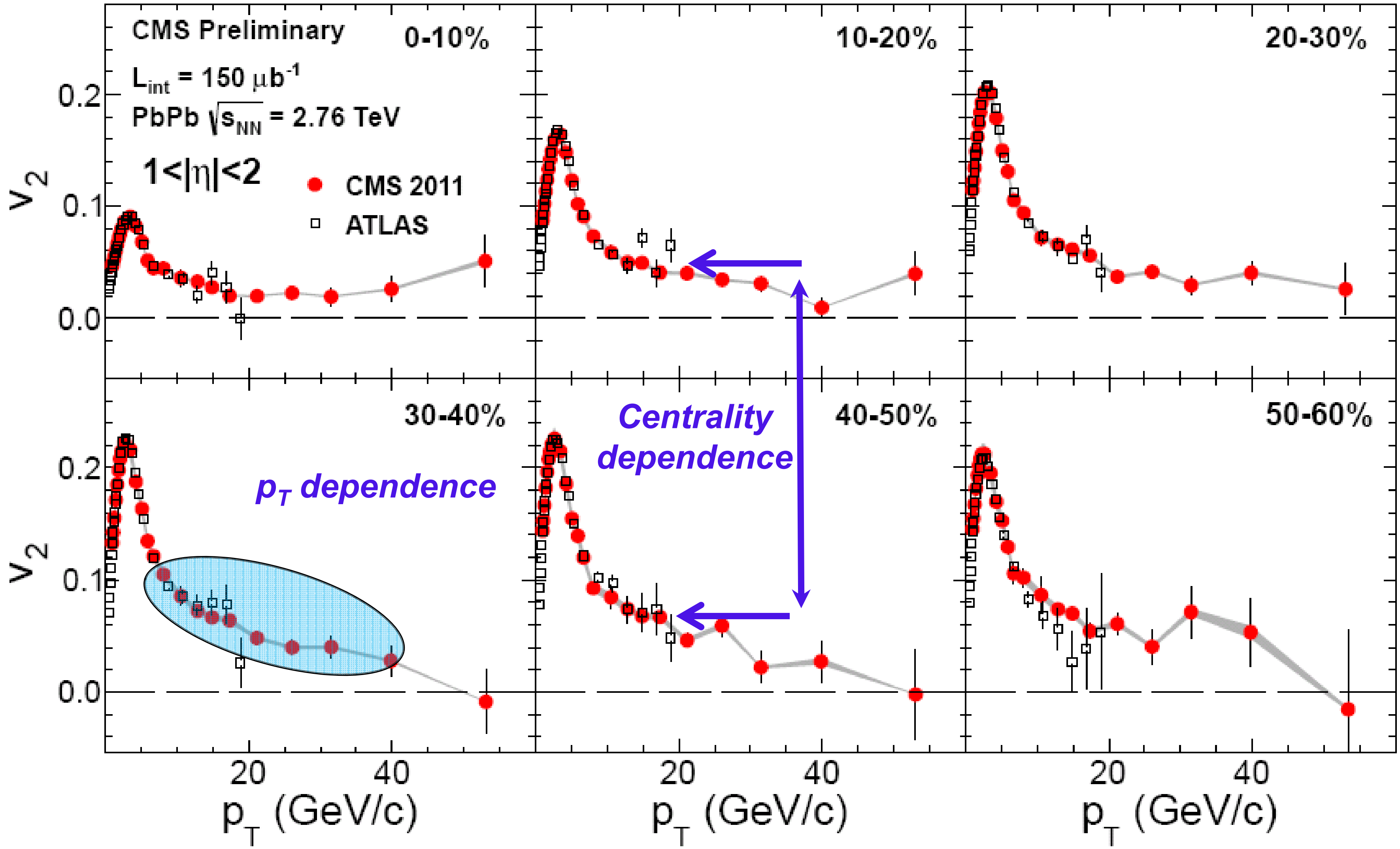


R_{AA} scales as $1/\sqrt{p_T}$; slopes (S_{pT}) encode info on α_s and $\hat{q}$

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

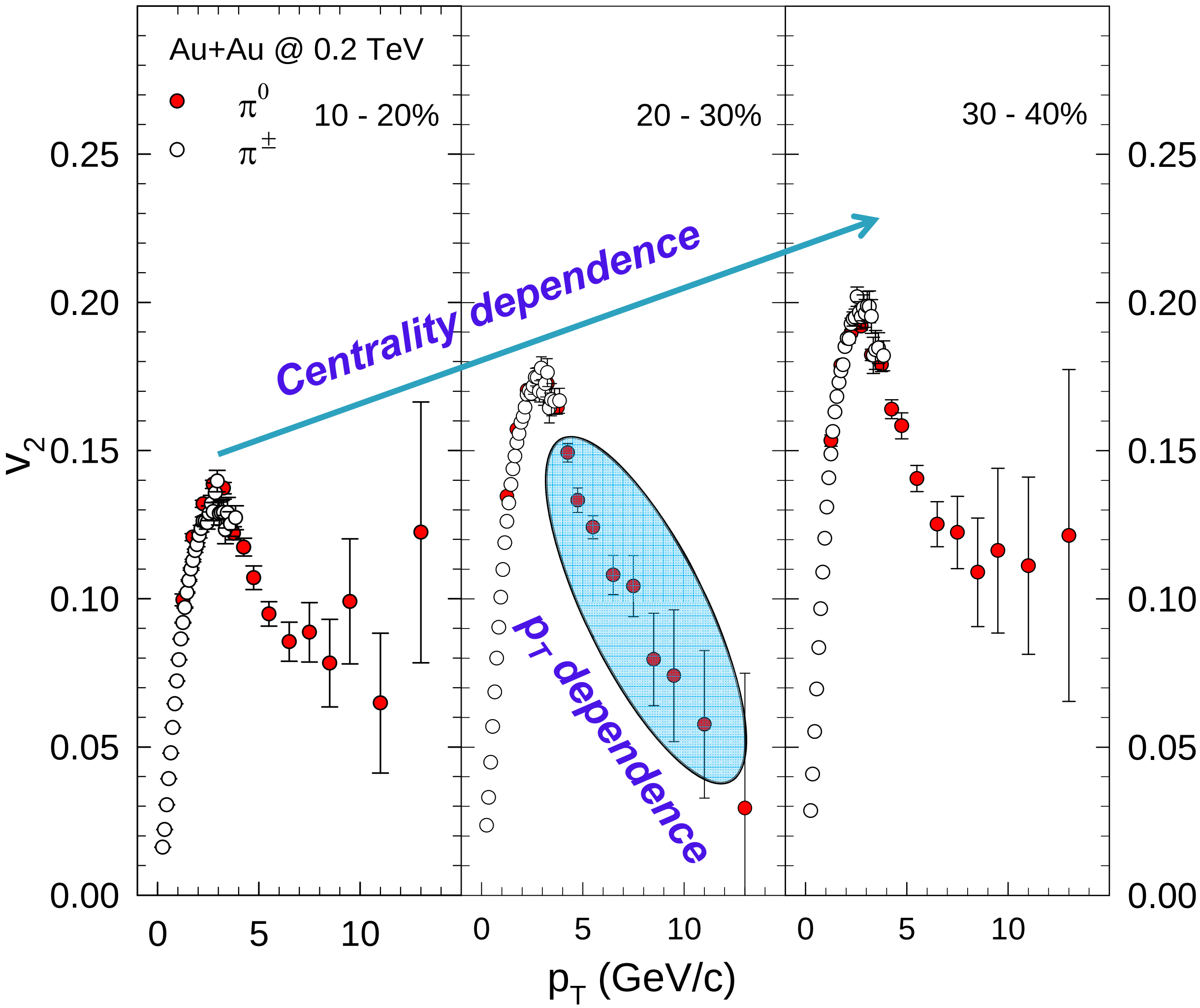
High-pT v_2 measurements - CMS

arXiv:1204.1850



Specific p_T and centrality dependencies – Do they scale?

High-pT v_2 measurements - PHENIX

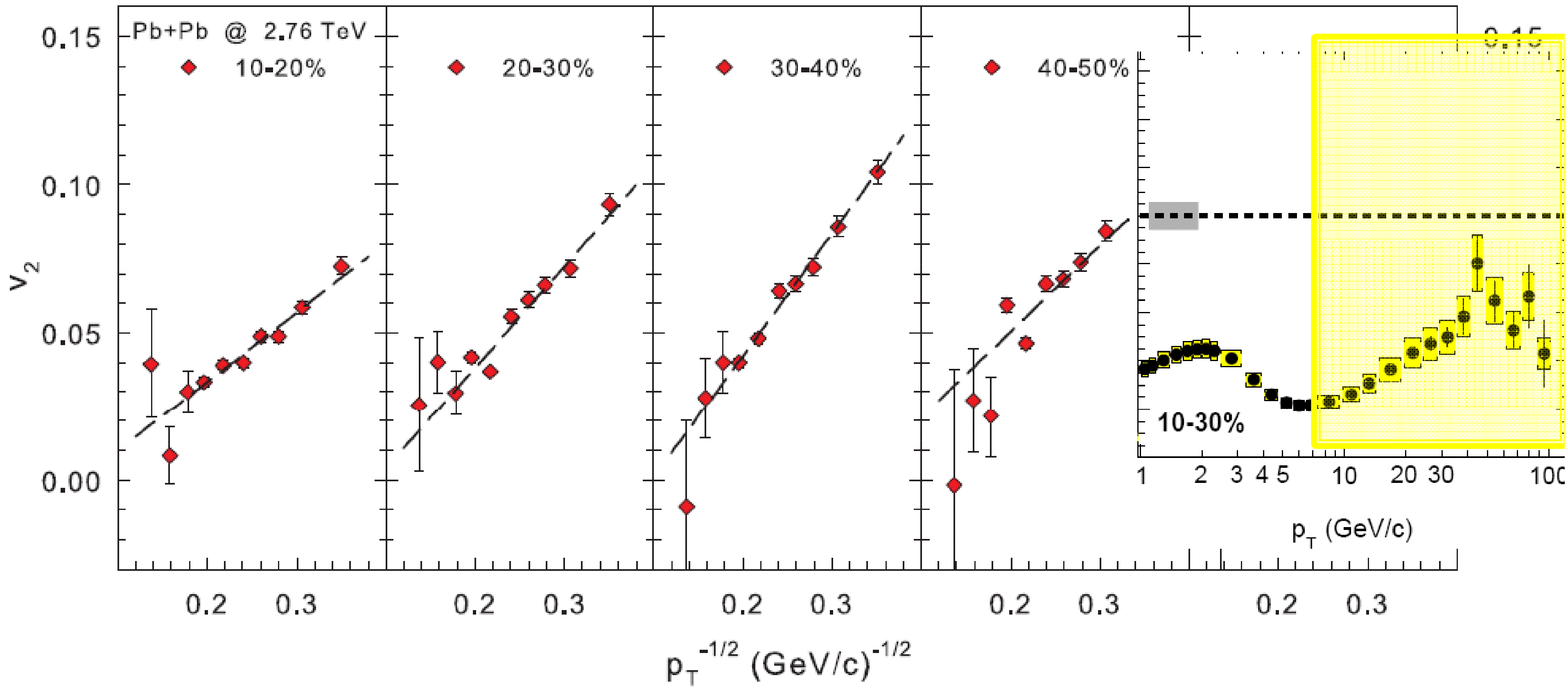


Specific p_T and centrality dependencies – Do they scale?

High-pT v_2 scaling - LHC

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

arXiv:1203.3605

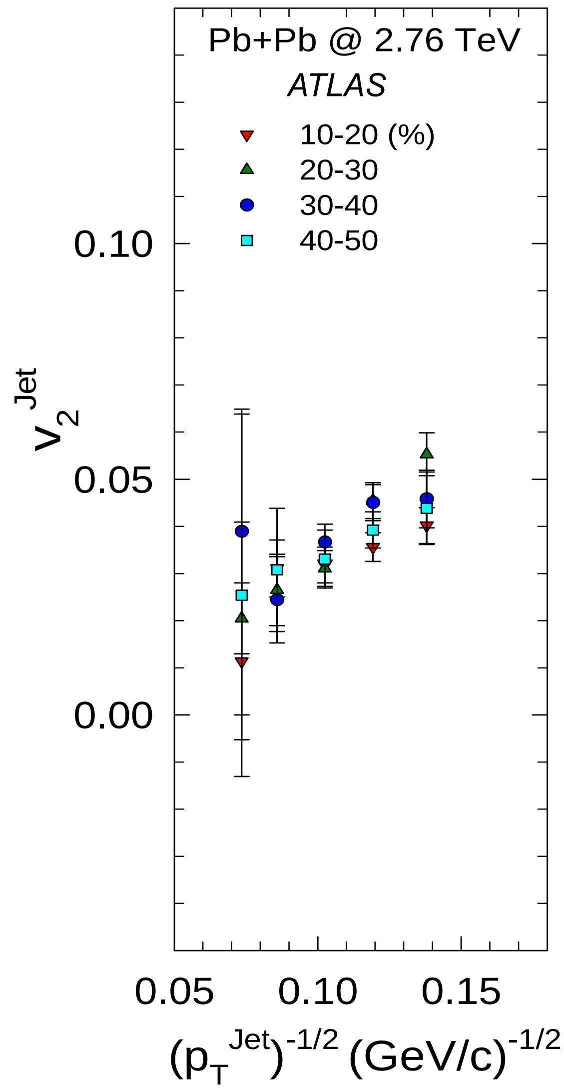


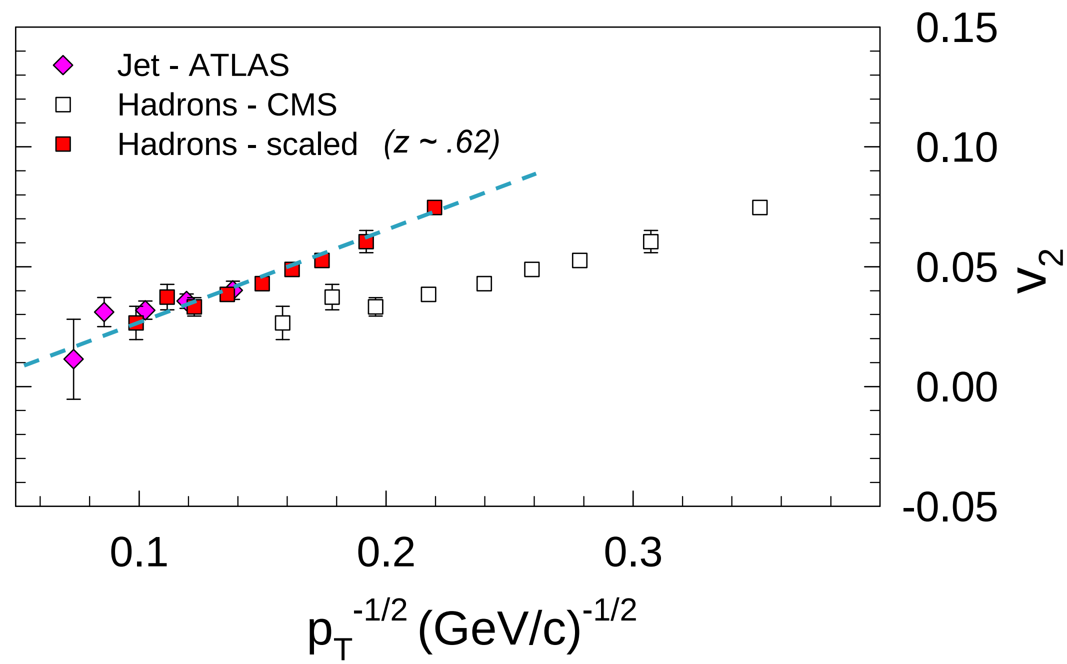
v_2 follows the p_T dependence observed for jet quenching

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

Jet v_2 scaling - LHC

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

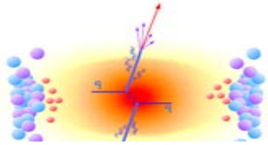




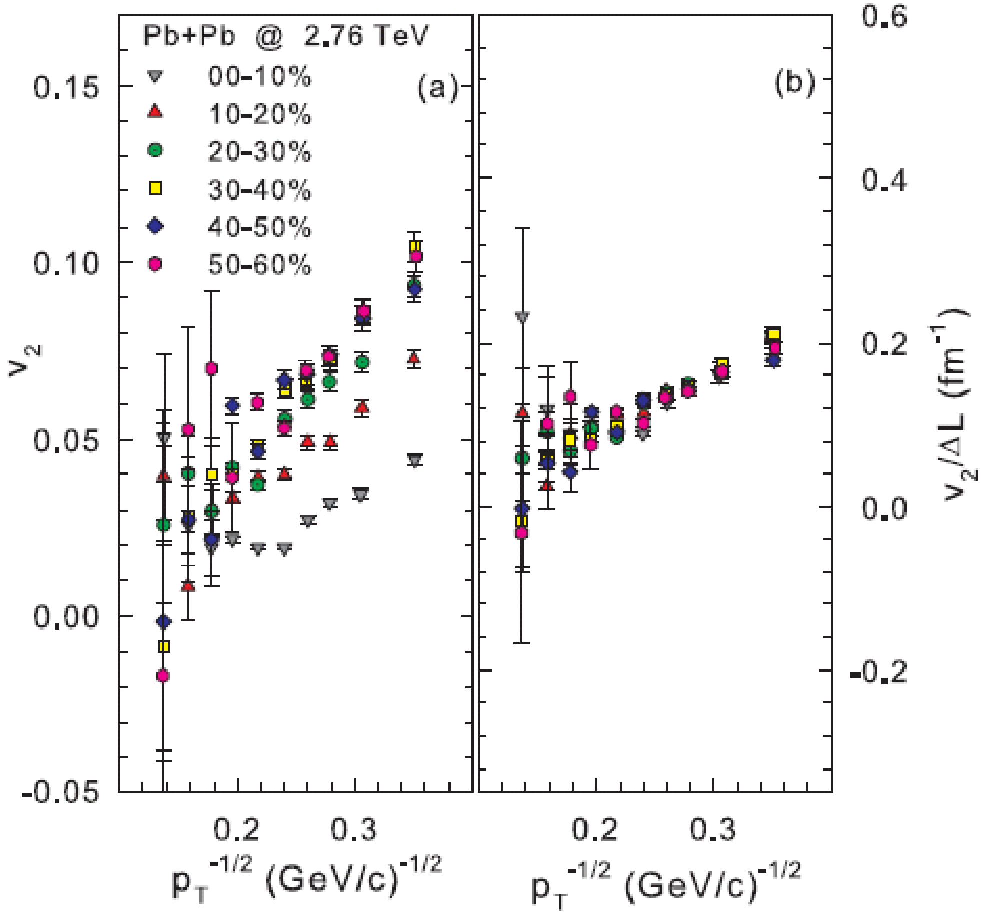
v_2 for Jets follows the p_T dependence for jet quenching

Similar magnitude and trend for Jet and hadron v_2 after scaling

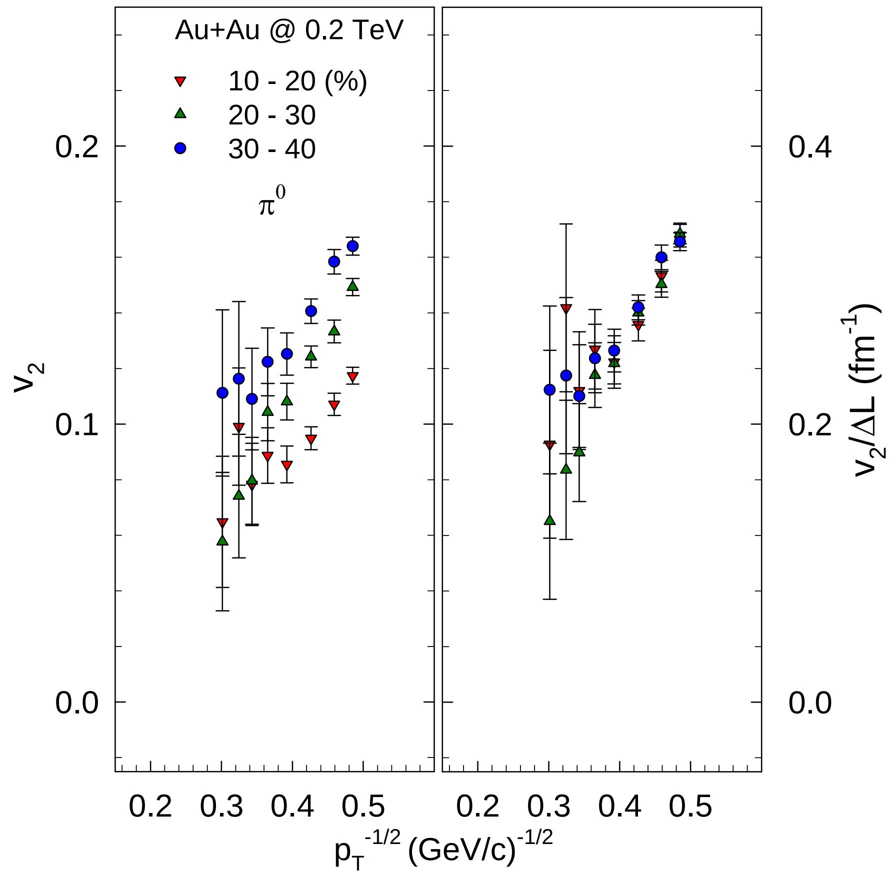
ΔL Scaling of high-pT v_2



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

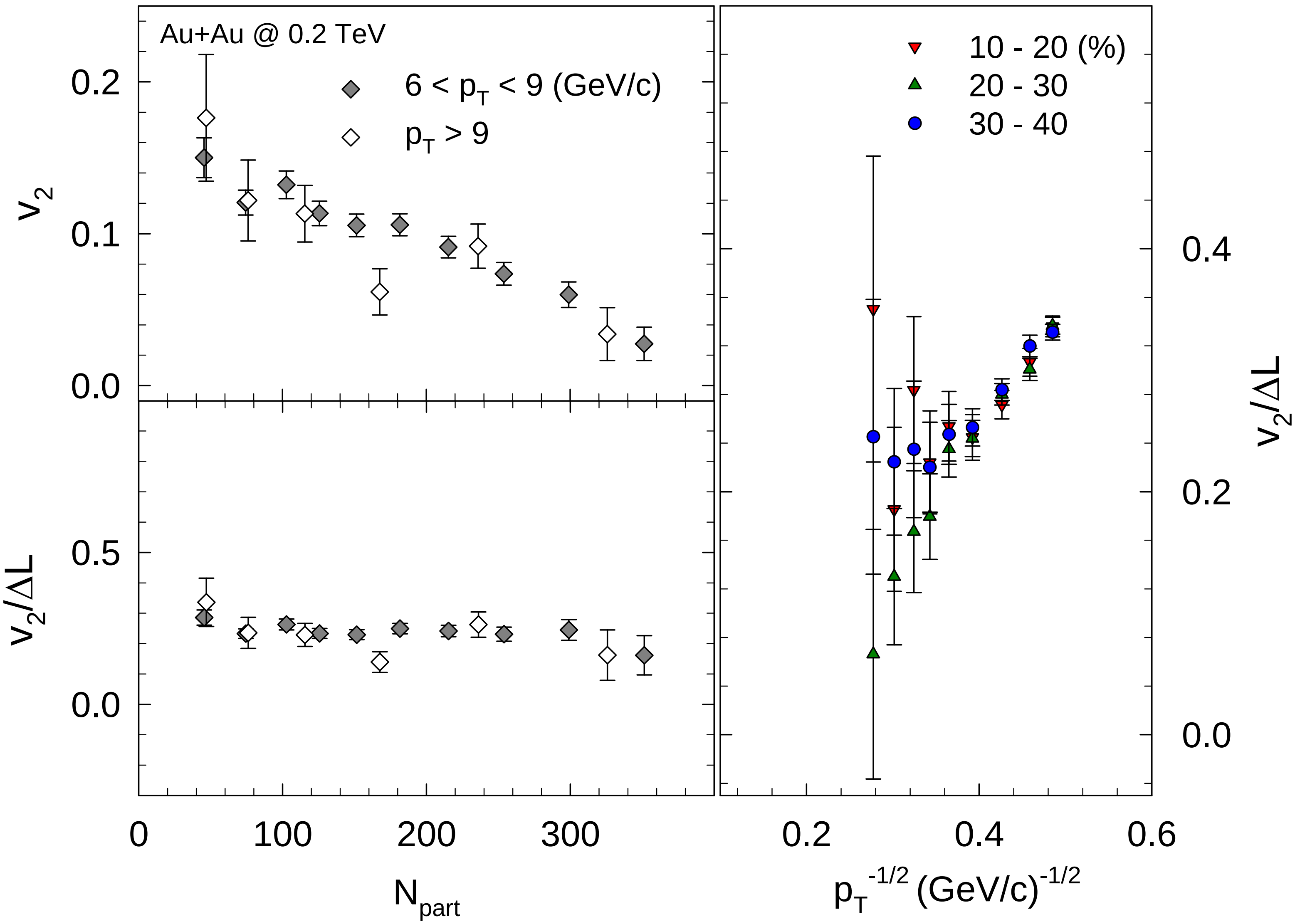


arXiv:1203.3605



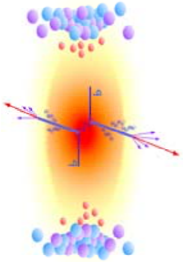
Combined ΔL and $1/\sqrt{p_T}$ scaling → single universal curve for v_2

ΔL Scaling of high-pT v_2



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

Jet suppression from high-pT v_2 - LHC

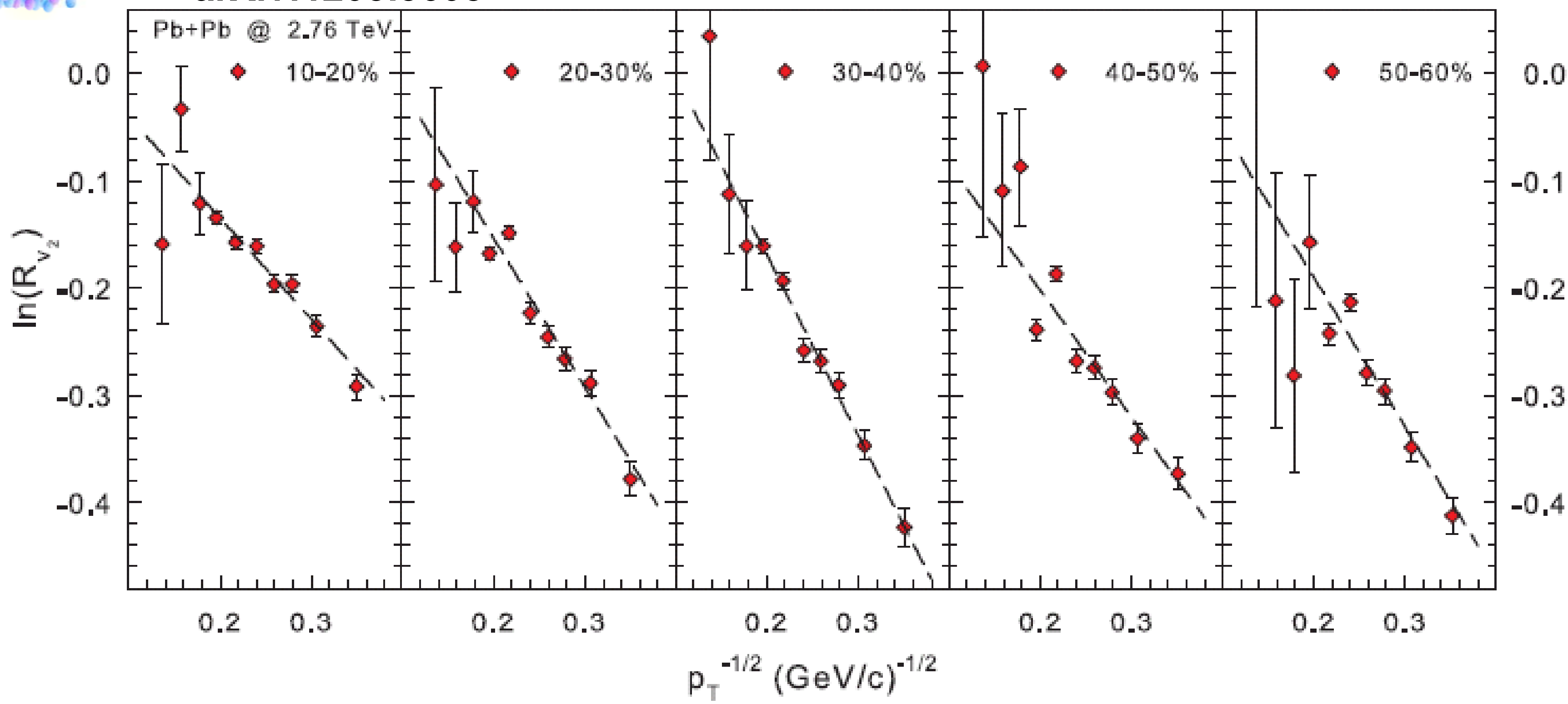


$$N(\Delta\phi, p_T) \propto [1 + 2v_2(p_T)\cos(2\Delta\phi)]$$

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

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

arXiv:1203.3605

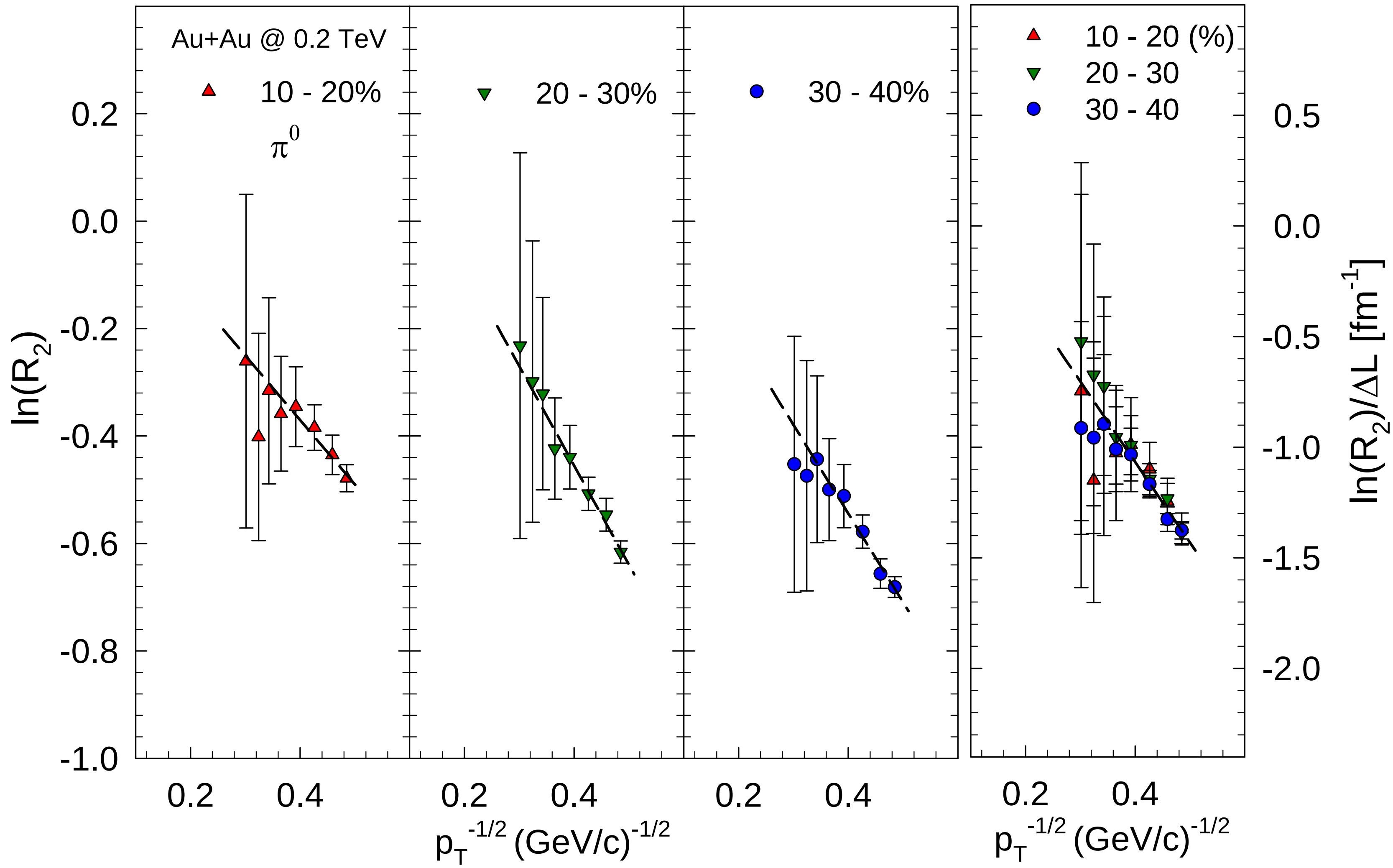


Jet suppression obtained directly from v_2

R_{V2} scales as $1/\sqrt{p_T}$, slopes encodes info on α_s and $\hat{q}$

Jet suppression from high-pT v_2 - RHIC

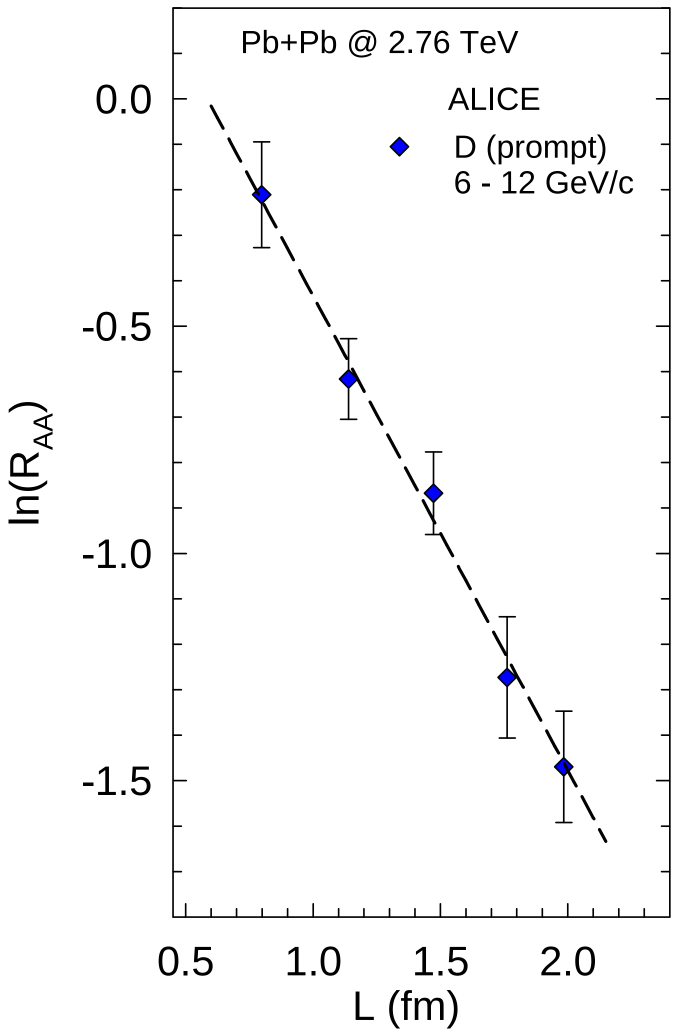
$$R_{v_2}(p_T, \Delta L) = \frac{R_{AA}(90^o, p_T)}{R_{AA}(0^0, p_T)} = \frac{1 - 2v_2(p_T)}{1 + 2v_2(p_T)}$$



Jet suppression obtained directly from v_2

R_{V2} scales as $1/\sqrt{p_T}$, slopes encodes info on α_s and $\hat{q}$

Heavy quark suppression



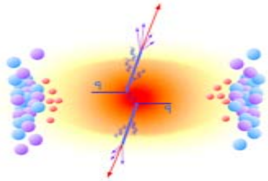
$$R_{\rm AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}}\, L\sqrt{\hat{q}\frac{\mathcal{L}}{p_\perp}} + \cdot\right.$$

$$\left.\frac{16\alpha_s C_F}{9\sqrt{3}} L\left(\frac{\hat{q}\;M^2}{M^2+p_\perp^2}\right)^{1/3}\right]$$

$$\mathcal{L} \equiv \frac{d}{d\ln p_\perp}\ln\left[\frac{d\sigma^{vac}}{dp_\perp^2}(p_\perp)\right]$$

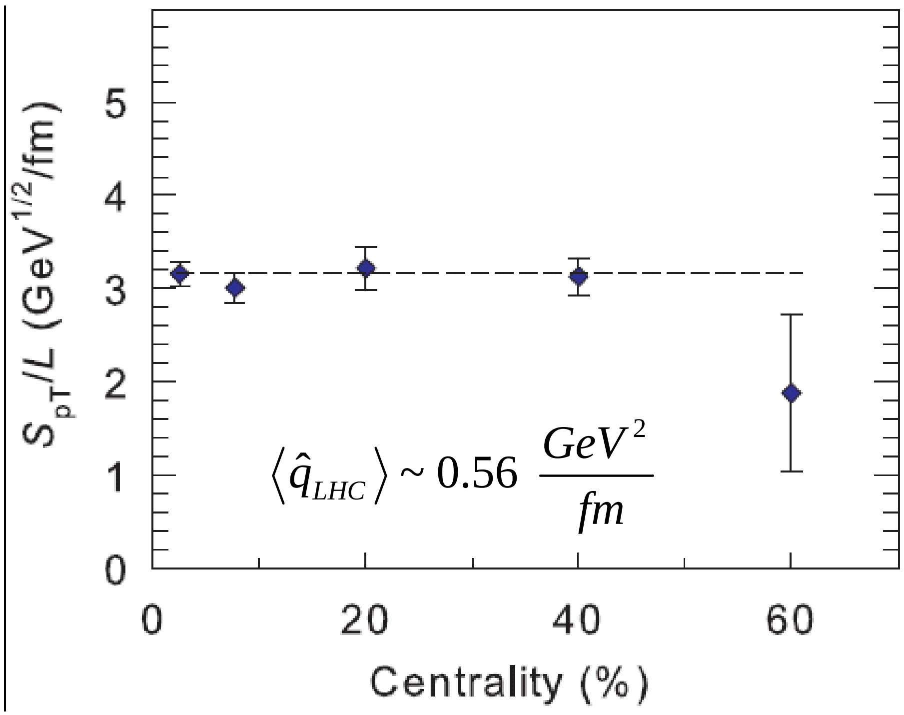
Consistent $\hat{q}_{LHC}$ obtained from D's

Extracted stopping power

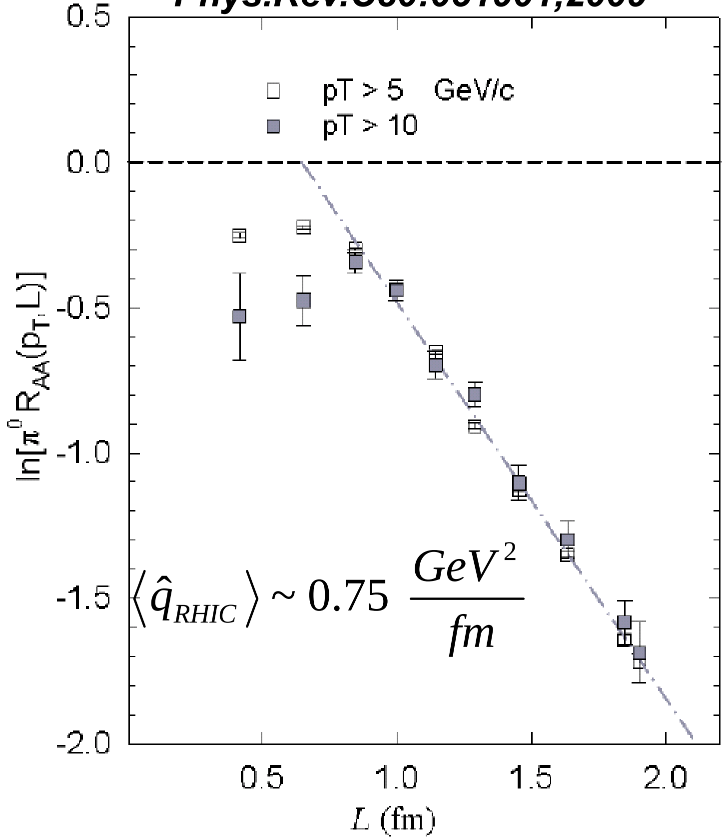


$$R^l_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}}\, L \sqrt{\hat{q}\frac{\mathcal{L}_l}{p_T}}\right]$$

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-p_T azimuthal anisotropy stem from the same energy loss mechanism
- **Energy loss is dominantly radiative**
- R_{AA} and anisotropy measurements give consistent estimates for <ˆq >
- **R_{AA} for D's give consistent estimates for <ˆq >**
- Magnitude and trend of Jet v_2 similar to scaled hadron v_2
- The QGP created in LHC collisions is less opaque than that produced at RHIC

- ***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 similar at LHC and RHIC ~ 1/4π***

End