Aspects of Jet physics

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Jet era at the LHC

- The ultimate goal of studying jets in heavy ion collisions is obtaining quantitative information about medium properties (QGP) from the data
- We are in the era of high statistics analysis of fully reconstructed jets in heavy ion collisions at the LHC (at all three experiments ATLAS, CMS and ALICE) *[Next talk by Sidharth Kumar]* and interesting jet results from STAR
- Modification of jet spectra between pp and AA, differential in p_T, centrality, jet radius R
- More discriminatory jet substructure observables
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  1. Analysis of the modification of jet spectra can yield insight about the medium *(work with Sourendu Gupta)*
  2. Examples of the phenomenology of jet substructure observables

Phenomenology of energy loss

Energy loss versus R_{AA}

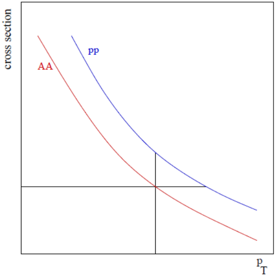
- Very familiar with the modification factor R_{AA}

$$R_{AA} = \frac{d\sigma_{AA}}{dp_T dy} \bigg/ \frac{d\sigma_{pp}}{dp_T dy}, \text{ where } \frac{d\sigma_{AA}}{dp_T dy} = \frac{1}{N_{\mathrm{evt}} T_{AA}} \frac{dN_{\mathrm{jet}}}{dp_T dy}.$$

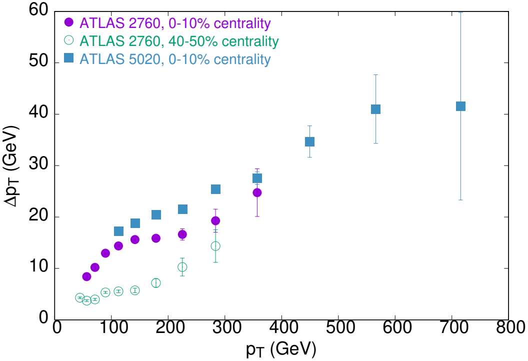
- The same information is encoded differently in the Energy loss or equivalently transverse momentum loss (Δp_T)

$$\left.\frac{d\sigma_{AA}}{dp_T dy}\right|_{p_T} = \left.\frac{d\sigma_{pp}}{dp_T dy}\right|_{p_T + \Delta p_T}$$

- Can be immediately connected with the microscopic details



Δp_T



- Using data from *[ATLAS (2014, 2018)]* we can extract Δp_T. Only statistical errors are shown
- Systematic errors for AA cross-sections are $\sim 15 - 20\%$

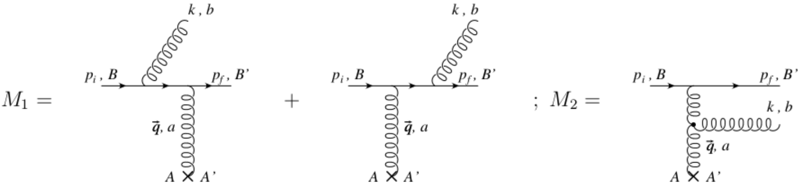
Δp_T versus L

- Δp_T has a direct connection with the path length L from microscopic dynamics
- L is related with centrality
- The relationship between L and Δp_T depends on the medium properties

Weakly coupled medium

- In a weakly coupled quark gluon plasma, famously up to log terms, $\Delta p_T \sim L^2$ (*BDMPS (1993, 1994)*)
- Consequence of coherent addition of amplitudes over the formation time of the emitted gluon in the LPM regime

Single gluon emission



- *[BDMPS (1993, 1994, 1996, 1998), Zakharov (1996, 1997)]*
- Single (transverse) scattering from the medium and resulting induced gluon emission from an energetic parton
- Typical scattering momentum m_D. Mean free path between scatterings λ
- For independent scattering and (Bethe-Heitler)

$$\omega \frac{dI}{d\omega} \sim \frac{\alpha_s}{\pi} N_c$$

Coherent emission

- For independent gluon emission (Bethe-Heitler)

$$\omega \frac{dI}{dz d\omega} \sim \frac{\alpha_s}{\pi} N_c (\frac{1}{\lambda})$$

- Formation time of the emitted gluon $l_{coh} = t_f \sim \frac{\omega}{k_\perp^2}$
- When $L > t_f > \lambda$ emission contributions from multiple scatterings add coherently. Effectively only one emission for a coherence length
- The net transverse momentum transferred during this period $k_\perp^2 \sim l_{coh} m_D^2 / \lambda$. Thus $l_{coh} = \sqrt{\frac{m_D^2}{\lambda\, \omega}}$
- Only a single emission per coherence length

$$\omega \frac{dI}{dz d\omega} \sim \frac{\alpha_s}{\pi} N_c (\frac{1}{l_{coh}}) = \frac{\alpha_s}{\pi} N_c \sqrt{\frac{m_D^2}{\lambda\, \omega}}$$

Emission suppressed by $\frac{1}{\sqrt{\omega}}$ (LPM)

Energy loss in a weakly coupled medium

- Integrating over ω to get the net energy loss

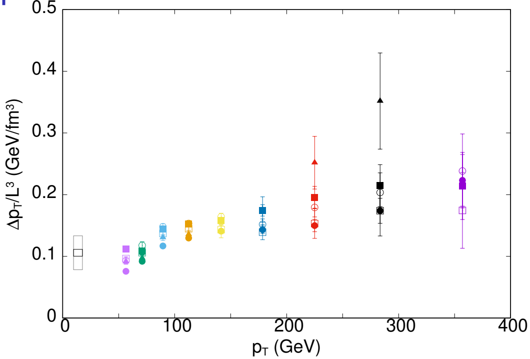
$$\frac{dE}{dz} \sim -\frac{\alpha_s}{\pi} N_c \sqrt{\frac{m_D^2 \omega_{max}}{\lambda}} = -\frac{\alpha_s}{\pi} N_c \frac{m_D^2}{\lambda} L = -\frac{\alpha_s}{\pi} N_c \langle k_\perp^2 \rangle \ .$$

  (Coherence length can't be larger than L)
- $\Delta p_T = \kappa L^2 \log(\frac{p_T}{\Omega^2 L})$ (*Zakharov (2000)*)
- Ω is related to medium scales

Contrast with a strongly coupled medium

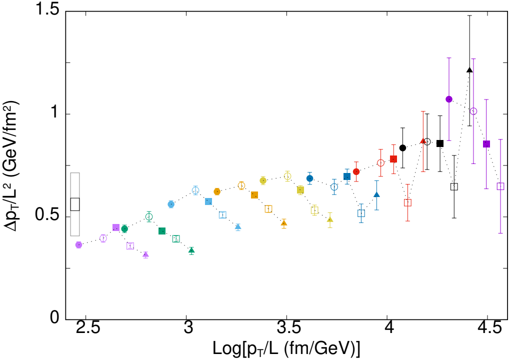
- $\Delta p_T \propto L^3$ *[Marquet, Renk (2009); Chesler, Rajagopal (2014, 2015)]*
- Independence of $\Delta p_T / L^3$ on p_T and centrality would suggest strongly coupled dynamics
- Interestingly, data is consistent with this interpretation

Strongly coupled medium



- Data from *[ATLAS (2014, 2018)]*
- Most central 0-10% of events — filled circles, 10-20% — unfilled circles, 20–30% — filled boxes, 30–40% — unfilled boxes, 40-50% — filled triangles. *[Gupta, Sharma (2022)]*
- For fixed p_T, dependence on centrality is weak
- The gray box at the left is the typical systematic uncertainty

Weakly coupled medium

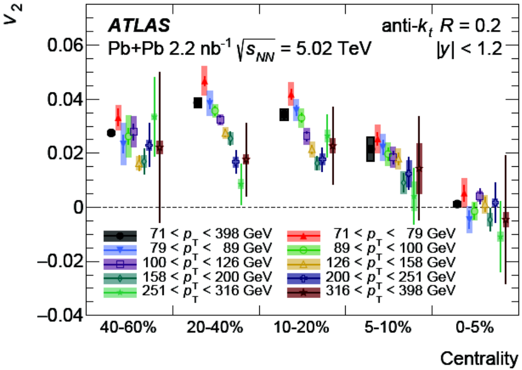


- Points at the same p_T connected with dotted lines (one color)
- Interesting systematic dependence on centrality [from $\log(p_T/L)$] for a fixed p_T. See an increase and then a decrease in $\Delta p_T/L^2$ as we go to more central
- Systematic errors (gray box) substantial. Hence data also consistent with a BDMPS-Z picture

Medium parameters

- We can extract κ and Ω, and then $\hat{q}$ from the data
- $\kappa = C\alpha_s\frac{\hat{q}}{4}$
- $C = C_F$ for quark jets and $C = C_A$ for gluon jets
- Using the fraction of gluon and quark initiated jets from perturbative QCD estimates, we get a weighted κ
- Using $\kappa = C\alpha_s\frac{\hat{q}}{4}$, $C \simeq 2.3 - 2.4$, $\alpha_s \simeq 0.15 - 0.25$
- Obtain $\hat{q} = 1.2 - 5.4\text{GeV}/\text{fm}^2$ which is consistent with other results from the literature *JET Collaboration (2013); Yacine Mehtar-Tani et. al. (2021); JETSCAPE Collaboration (2021).*

Jet v_2 with centrality



- Additional interesting data that can test the L dependence *[ATLAS (2021)]*
- γ or Z tagged jets can be also used to measure Δp_T *[Brewer, Milhano, Thaler (2019)]* but have lower statistics

Jet substructure phenomenology

Jet substructure

- Going beyond yields in *pp* versus *AA*, look at substructures of jets
- Jets specified by a "radius" $R \sim \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
- Jet substructure observables measure how energy and (longitudinal and transverse to the jet axis) momentum is distributed in the jet radius and it is natural to ask how these are different in *pp* and *AA*
- May have the power to distinguish between models of parton energy loss which . Eg. "zeal" *[Jain, Gavai, Sharma (2015)]* showed promise in distinguishing between models featuring multiple gluon emissions carrying a small fraction of the leading parton energy and models which featuring few gluon emissions carrying a larger fraction
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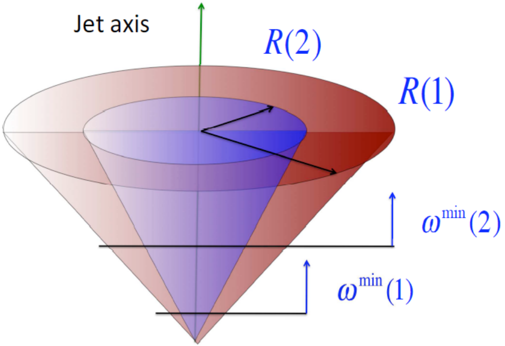
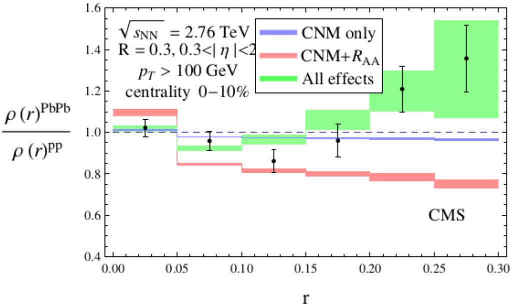
    1. Jet shapes
    2. Jet angularities

Jet shape



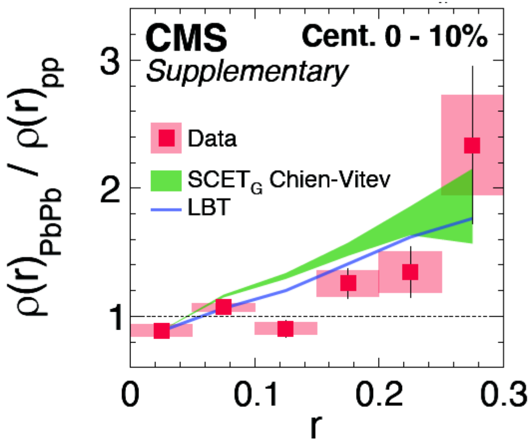
- *[Vitev, Wicks, Zhang (2008]*

Jet shape



- *[Y-T Chien, Vitev (2015); CMS (2013)]*

Photon tagged jet shapes



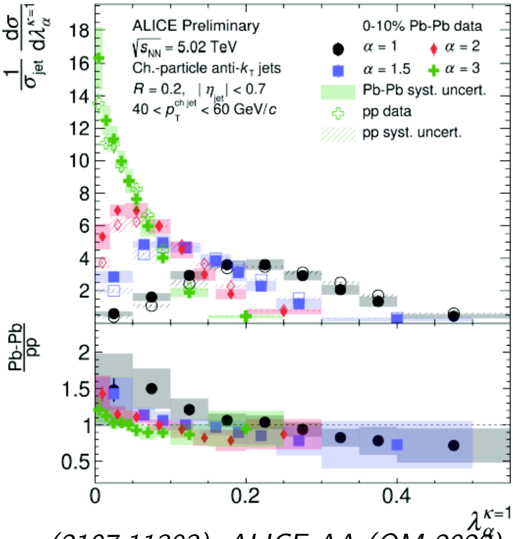
- *[Y-T Chien, Vitev (2015); CMS (2019)]*

Jet angularities

- $$\tau_a = \sum_{i \in jet} z_i \theta_i^{2-a}$$
- $$z_i = \frac{p_{T,i}}{p_{T,jet}}, \quad \theta_i = \frac{\Delta R_{i,jet}}{R}$$
- For infrared safety $a < 2$
- $\alpha = 2 - a$

Angularities

Ungroomed

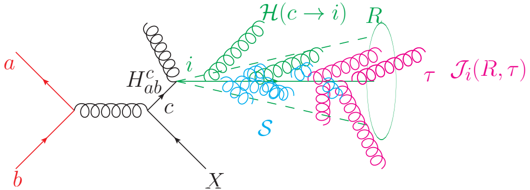


- *[ALICE pp (2107.11303); ALICE AA (QM 2022).]* Calculations from Monte-Carlo studies (JEWEL, JETSCAPE, H-T, Hybrid)

Factorization formula

- For $a < 1$ angularities and $\tau_a^{\frac{1}{2-a}} \ll R$,

$$\frac{d\sigma^{AA\to(jet[R,\tau_a])X}}{d\tau_a dp_T d\eta} = \sum_{abc}\sum_{i} f_a(x_a,\mu)\otimes f_b(x_b,\mu)$$
$$\otimes H_{ab}^c(x_a,x_b,\eta,p_T/z,\mu)\times \mathcal{H}_{c\to i}(z,p_T R,\mu)$$
$$\otimes \mathcal{J}(\tau_a^c,p_T,R,\mu)\otimes \mathcal{S}(\tau_a^s,p_T,R,\mu)$$



Medium effect on angularities

- The medium effects show up (see Ankita Budhraja's talk on Tuesday, 5:15 for more details) in angularity-jet function $\mathcal{J}(\tau_a^c, p_T, R, \mu)$. The natural scale for $\mathcal{J}$ is

$$p_T \times (\tau_a)^{\frac{1}{2-a}}$$

- $\mathcal{J} = \mathcal{J}^{vac} + \mathcal{J}^{med}$
-

$$\mathcal{J}^{med}_{i\to jk}(..) \sim \sum_{jk} \int d\phi dx \frac{d^2 k_\perp}{(2\pi)^2} P^{med}_{i\to jk}(k_\perp, x) \delta(\tau_a - \hat{\tau}_a)$$

Medium effect on angularities

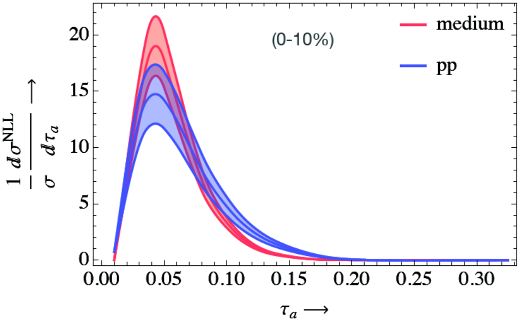
- Medium splitting kernels derived using $SCET_G$ in *[Vitev, Ovanesyan (2011, 2012, 2013]*. For eg, in the small x limit,

$$x\frac{dN^{med}_{q\to qg}}{dxd^2k_\perp} = \alpha_s\int_0^L d\Delta z d^2q_\perp \frac{1}{\sigma}\frac{d^2\sigma}{dq_\perp^2}\frac{2k_\perp q_\perp}{k_\perp^2(q_\perp - k_\perp)^2} \times \left[1-\cos\left(\frac{(q_\perp-k_\perp)^2\Delta z}{x\omega}\right)\right]$$

- *[Gyulassy, Wang (1994)]*

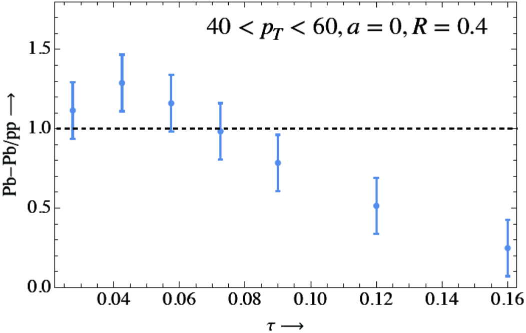
$$\frac{1}{\sigma}\frac{d^2\sigma}{dq_\perp^2} = \frac{m_D^2}{\pi(q_\perp^2+m_D^2)^2}$$

Angularities comparison



- For *pp* also see *[Kang, Lee, Ringer (2018)]*. *[Budharaja, Singh, Sharma (preliminary)]*

Angularities ratio

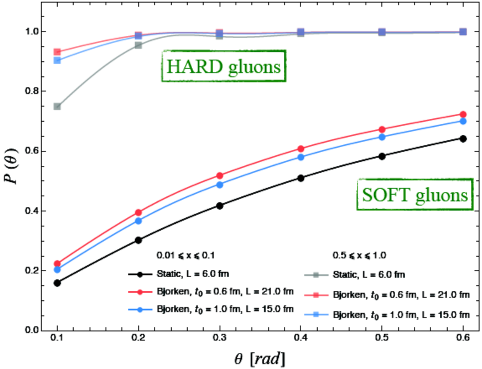


- *[Budharaja, Singh, Sharma (preliminary)]*

Selected interesting developments

- Tagged jet a-coplanarity as a probe of quasi particles in the medium. (See Nihar's talk on Tuesday for details of the measurements)
  1. *[D' Eramo, Lekaveckas, Liu, Rajagopal (2013)]*
  2. *[D' Eramo, Rajagopal, Yin (2019)]*
  3. *[Barata, Mehtar-Tani, Alba Soto-Ontoso, Konrad Tywoniuk (2021)]*
- Improved in-medium splitting kernals
  1. *[Barata, Mehtar-Tani (2020)]*
  2. *[Caucal, Iancu, Soyez (2021)]*
  3. *[Mehtar-Tani, Pablos, Tywoniuk (2021)]*
  4. *[Adhya, Kutak, Placzek, Rohrmoser, Tywoniuk (2022)]* (Talk by Adhya, Tuesday, 5:30)

Effect of Bjorken flow



- *[Adhya, Kutak, Placzek, Rohrmoser, Tywoniuk (2022)]*

Advertisements

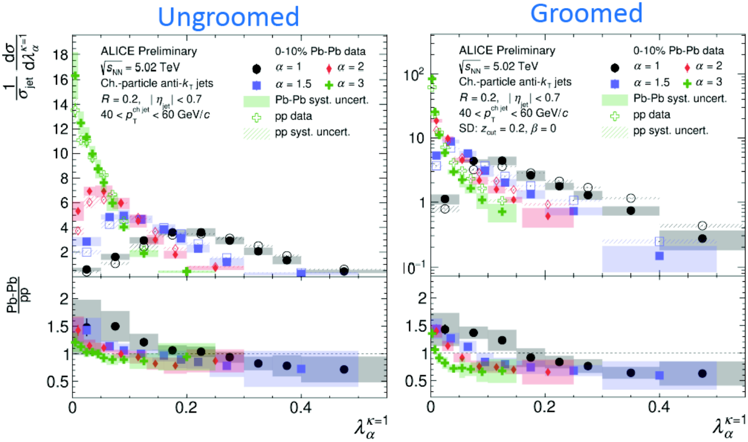
- Talk by Balbeer Singh on “Quarkonium dynamics in the non static limit”, Friday, 3:15
- India+ lectures on Heavy Ion Collision experiments. Online talks every Thursday at 6:30 pm (IST). (Organizers) Sandeep Chatterjee, Sourendu Gupta, Subhash Singha, Rishi Sharma.
    1. Particle ID
    2. Global analysis
    3. Flow and its fluctuations
        - 3.1 Sergei Voloshin (STAR)
        - 3.2 Jiangyoung Jia (ATLAS)[Feb 16]
        - 3.3 Shengquan Tuo (CMS) [Feb 23]
    4. Fluctuations of conserved quantities
    5. Quarkonia
    6. Open heavy flavor

Summary

1.
    - R_{AA} and Δp_T two different ways of looking at the AA jet spectrum and comparing it to the spectrum in pp
    - Δp_T directly connects to the microscopic details of the energy loss
    - Taking systematic errors into account in the simplest manner (quadrature) we find that both weak coupling and strong coupling dynamics of jets is consistent with the present data, with a minor preference for strong coupling
    - Taking into account correlations in the errors might help in making a more discriminatory deduction
2. Jet substructure can help us pin down the microscopic details of the jet evolution. Clear evidence of increase in distribution of constituents at wider angles (jet shapes), suppression of wider angled jets (angularities)
3. These observables have the power to distinguish between models of jet quenching. May also help us understand the medium response (jet-cone wakes ..)

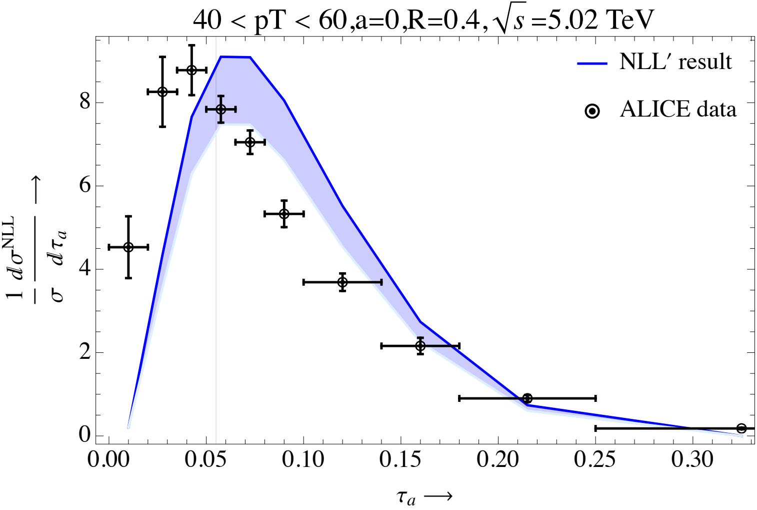
Backup slides

Angularities



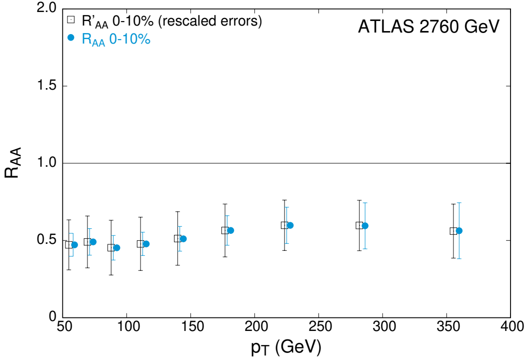
- *[ALICE (2107.11303)]*

Angularities



- *[ALICE pp (2107.11303); ALICE AA (QM 2022).]*

R_{AA}

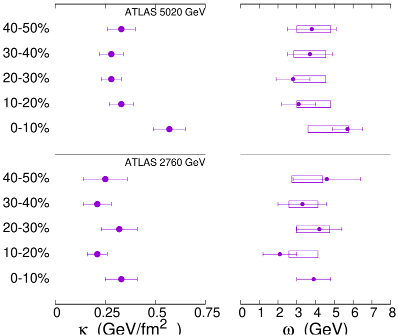


- *[ATLAS (2014)]* (Cyan points)
- Black points *[Gupta, Sharma (2022)]*

$$R'_{AA}(p_T) = \left.\frac{d\sigma_{pp}}{dp_T dy}\right|_{p_T+\Delta p_T} \Bigg/ \left.\frac{d\sigma_{pp}}{dp_T dy}\right|_{p_T}$$

  Provide a consistency check. Errors added in quadrature and the net error divided by 5 for comparison
- Note experimental errors are much smaller than a naïve estimate

Medium parameters



- We can extract κ and ω, and then $\hat{q}$ from the data
- Error bars include systematic and statistical uncertainties

Centrality versus *L*

- *L* is related with centrality (for simplicity using the Glauber model)

Centrality	0–10%	10–20%	20–30%	30–40%	40–50%
L/R	0.50	0.47	0.44	0.41	0.38