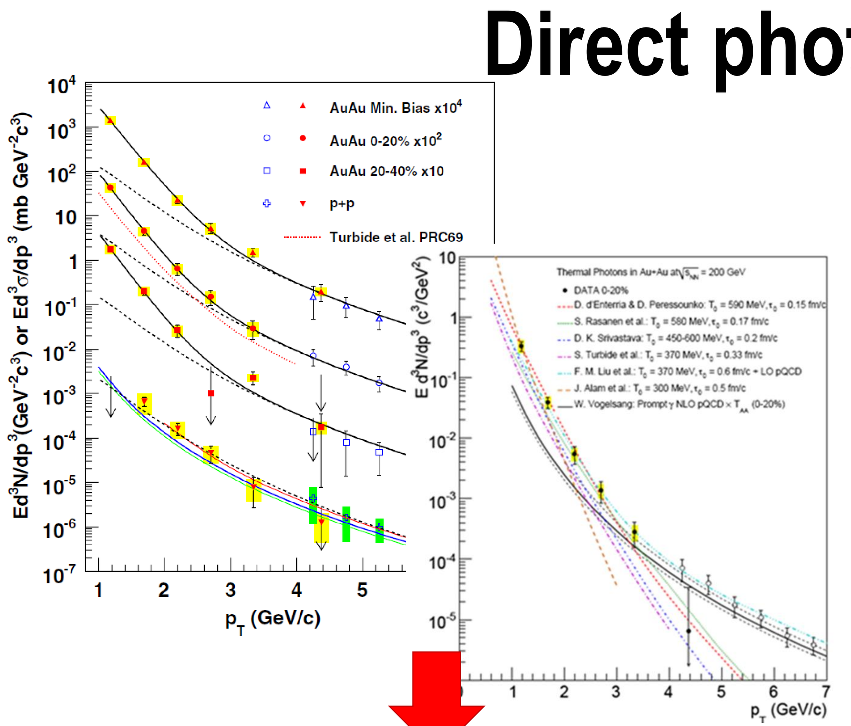
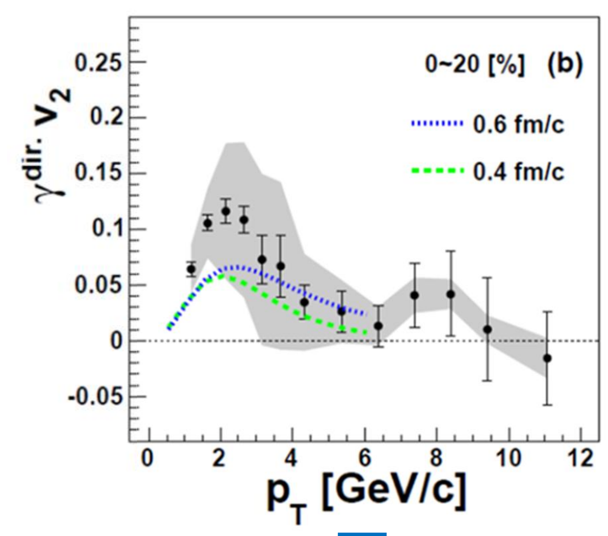
Soft direct photon v_2 and n_q-scaling

Sarah Campbell
Department of Physics and Astronomy
Iowa State University

Direct photon puzzle

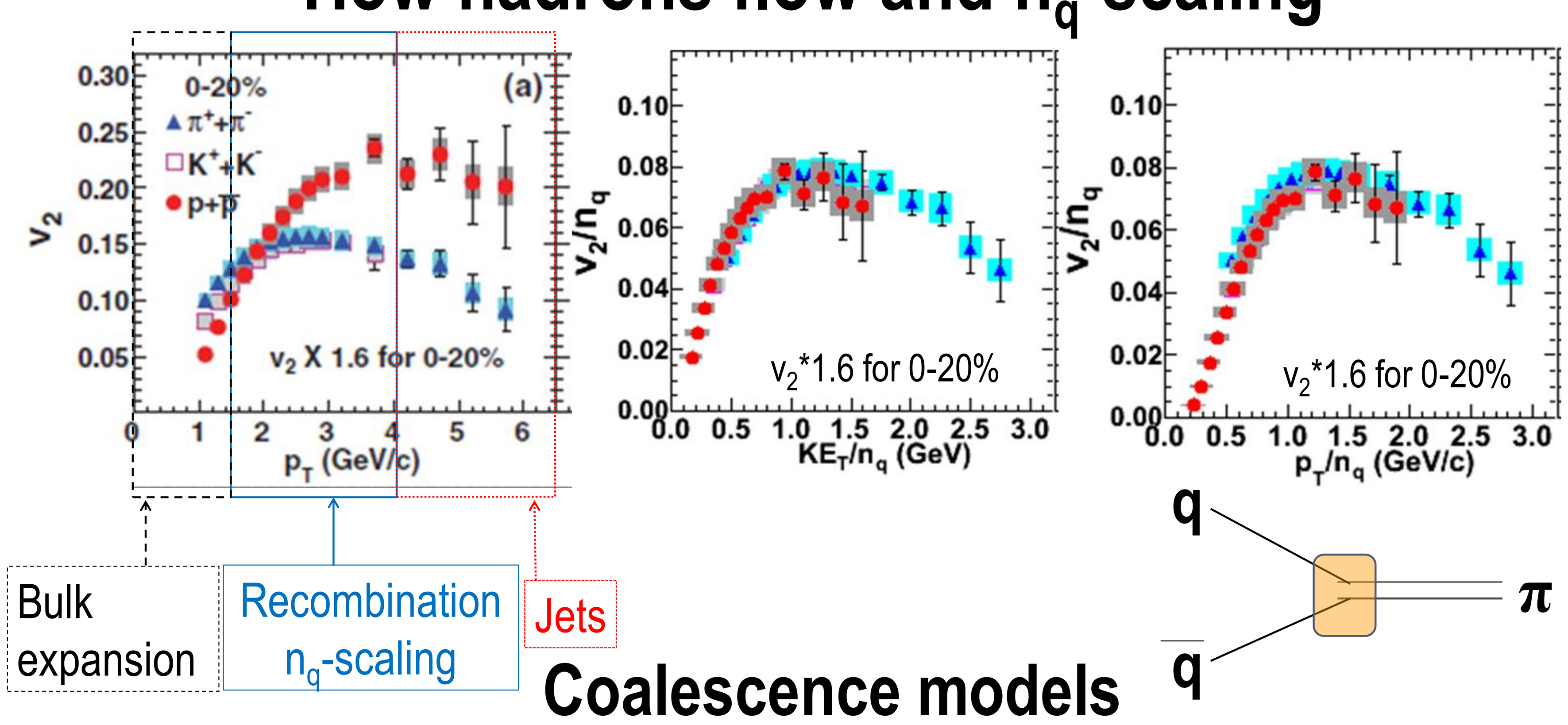




Early-stage partonic emission
T_{init} ~ 300 to 600 MeV
τ_0 ~ 0.15 - 0.5 fm/c

Late-stage hadronic emission
γ^{dir} $v_2 \approx \pi$ v_2

How hadrons flow and n_q-scaling



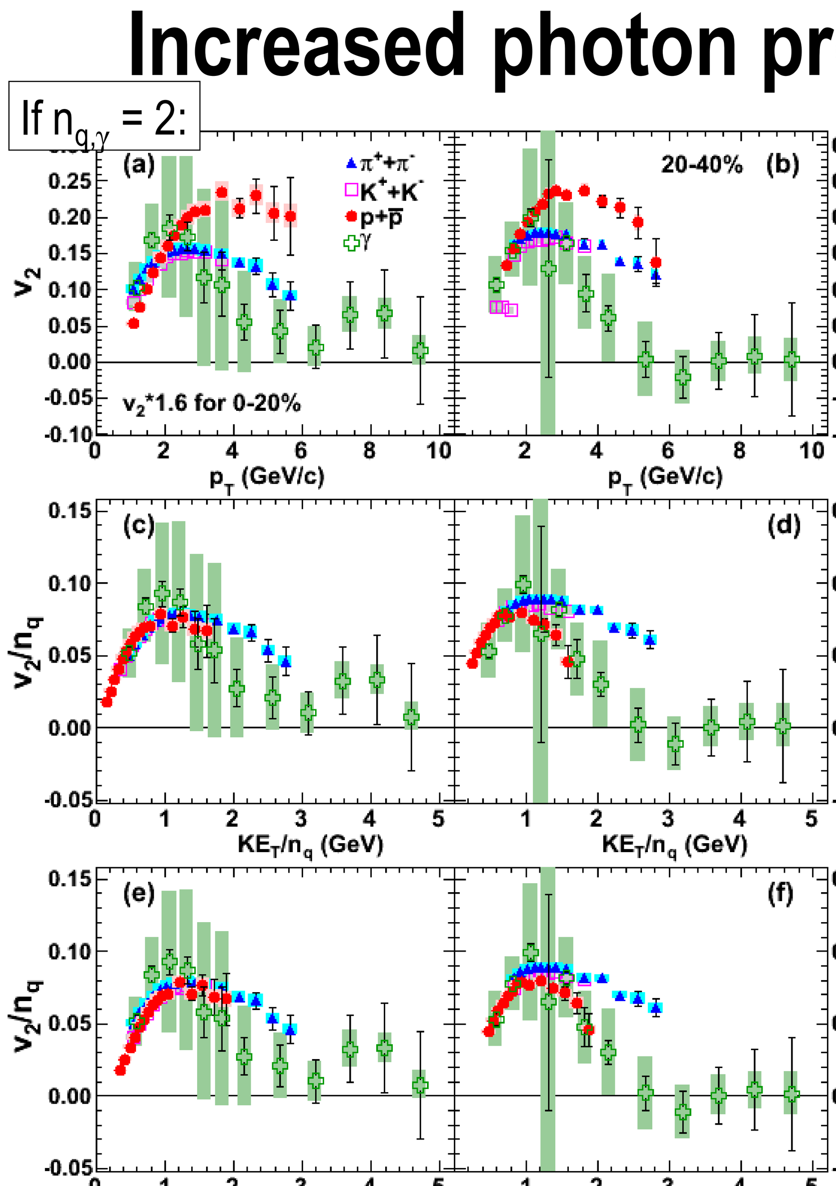
Coalescence models

Quark number scaling is modeled using a coalescence framework. A simple coalescence model assumes thermalized co-moving flowing quarks of the same momentum will form into mesons and baryons and the p_T and v_2 of the produced hadrons scale with the number of quarks.

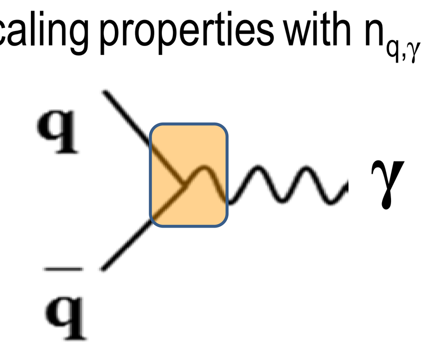
- Quarks: $\frac{dN}{d\phi} \approx 1 + 2v_{2,q}(p_{T,q})\cos(2\phi)$
- Mesons: $p_{T,M} \rightarrow 2p_{T,q}$ and $v_{2,M}(p_{T,M}) \rightarrow 2v_{2,q}(p_{T,M}/2)$
- Baryons: $p_{T,B} \rightarrow 3p_{T,q}$ and $v_{2,B}(p_{T,B}) \rightarrow 3v_{2,q}(p_{T,B}/3)$

Within the coalescence model, momentum conservation is maintained by the mean field interaction resulting in soft gluon interactions with the medium.

Increased photon production at confinement?

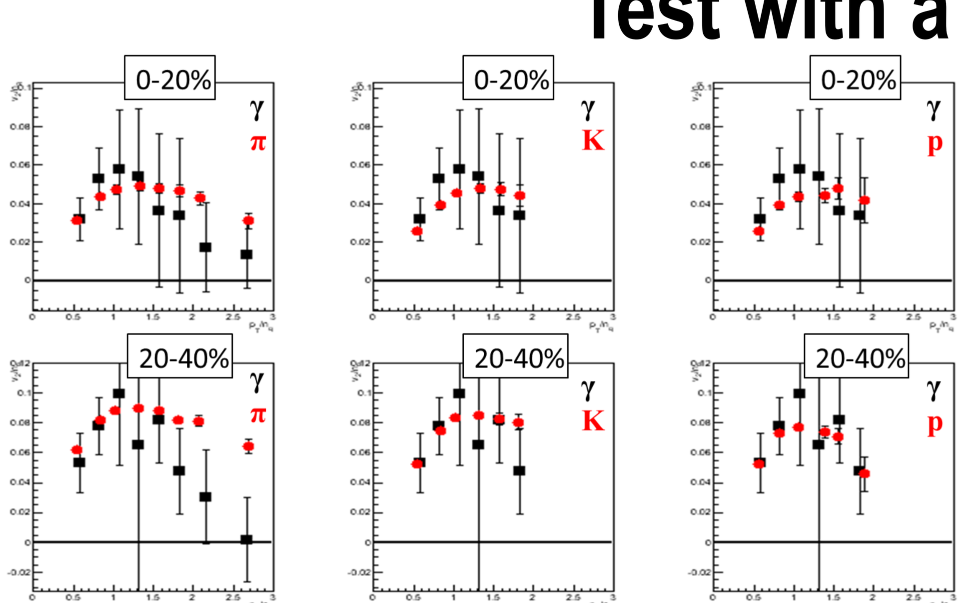


Could similar mean field or soft gluon interactions lead to an increase in the quark-anti-quark annihilation as the system moves toward confinement? This could result in increased thermal photon production from partonic processes late in the medium's evolution when quarks are flowing. These thermal photons would then show similar n_q-scaling properties with $n_{q,\gamma}$ = 2.



Assuming $n_{q,\gamma}$ = 2, the n_q-scaled direct photon v_2 follows a similar trend as the nq-scaled pion, kaon and proton v_2 for both p_T- and KE_T-scaling.

Test with a χ^2 analysis



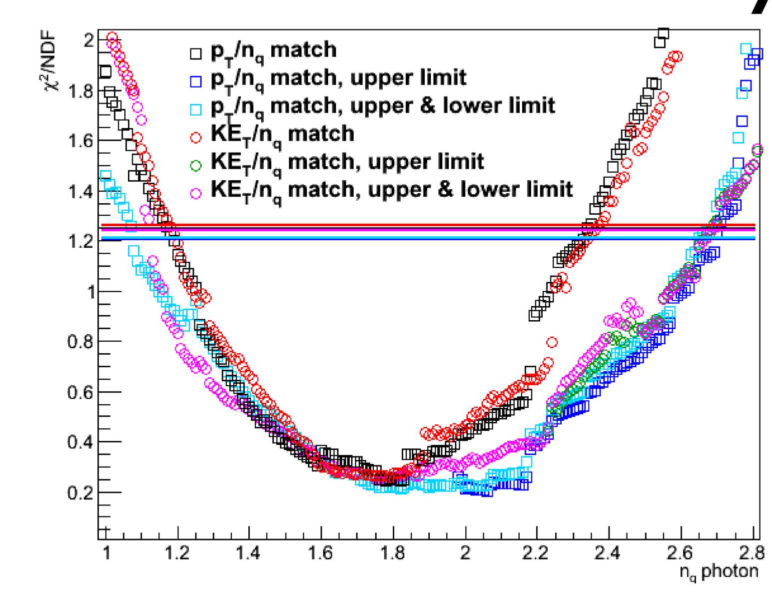
For $n_{q,\gamma}$ = 2: χ^2 = 16.74
NDF = 39
χ^2/NDF = 0.43

Is $n_{q,\gamma}$ = 2 is the best value for the data? The χ^2-space was scanned comparing the direct photon and hadron data with one free parameter, $n_{q,\gamma}$.

$$\chi^2 = \sum_{Cent,h,p_T/n_q} \frac{\left(v_{2,\gamma}/n_{q,\gamma} - v_{2,h}/n_{q,h}\right)^2}{\left(\sigma_\gamma^2 + \sigma_h^2\right)}$$

The sum is over the charged pion, kaon and proton data in 0-20% and 20-40% centralities. Photon and hadron errors are the quadrature sum of the statistical and systematic errors. To be compared, the photon and hadron point data points must be within 0.1 in p_T/n_q. The number of degrees of freedom varies with $n_{q,\gamma}$. A KE_T-scaling comparison was also performed with a similar method.

χ^2 Results



p_T/n_q range	Min. $n_{q,\gamma}$	Range of $n_{q,\gamma}$
Whole range	1.82	1.17-2.34
Upper limit	2.06	1.07-2.70
Upper & lower limit	1.82	1.06-2.66

KE_T/n_q range	Min. $n_{q,\gamma}$	Range of $n_{q,\gamma}$
Whole range	1.79	1.19-2.38
Upper limit	1.79	1.12-2.68
Upper & lower limit	1.79	1.12-2.69

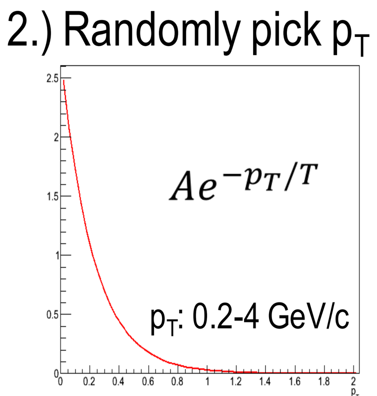
The results are consistent with a late-stage photon production from q-q annihilation hypothesis of $n_{q,\gamma}$ = 2.

Data-driven Monte Carlo

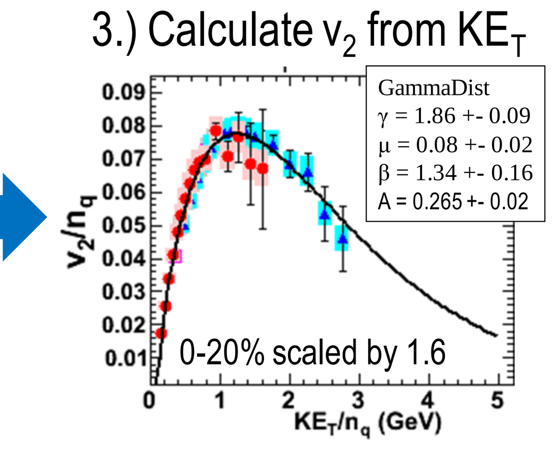
1st quark:

1.) Randomly pick η from a flat distribution

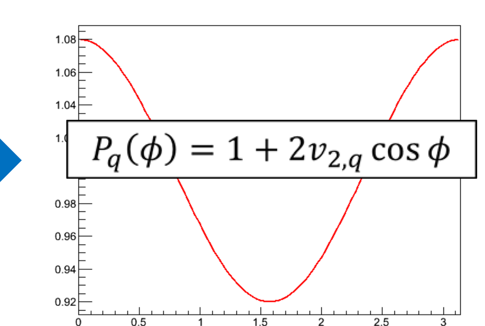
2.) Randomly pick p_T



3.) Calculate v_2 from KE_T



4.) Randomly pick φ



2nd, 3rd quarks:

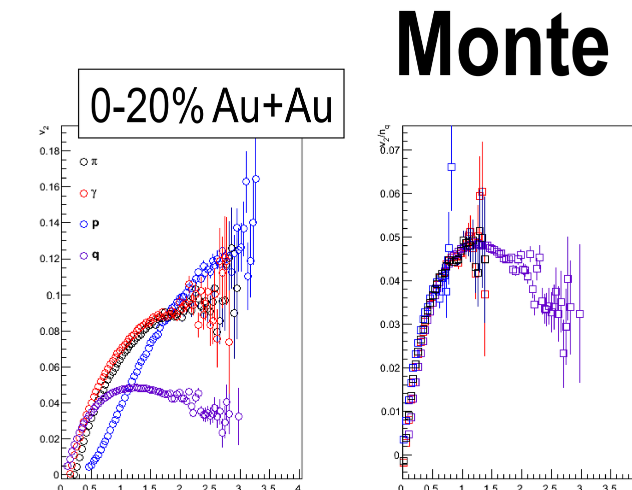
5.) Assume at the same η as 1st quark
6.) Repeat steps 2-4 for 2nd, 3rd quark

Make pairs:

7.) Comoving requirements
for mesons: $|p_1 - p_2| < 2\Delta p_M$
for baryons: $|p_1 - p_2| < \sqrt{2}\Delta p_B$, $|p_1 + p_2 - 2p_3| < \sqrt{6}\Delta p_B$ [4]
8.) For pion, proton and photon: conserve p, E or KE

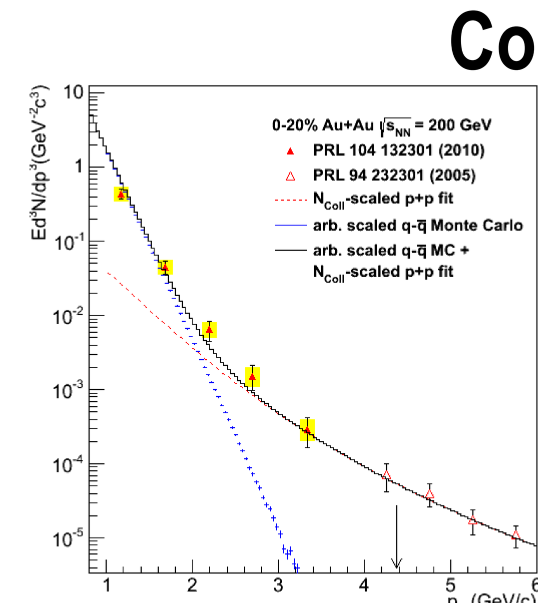
Free parameters:
T = 180 MeV
m_q = 0 MeV
Δp_M = 0.24 [4]
Δp_B = Δp_M

Monte Carlo Results

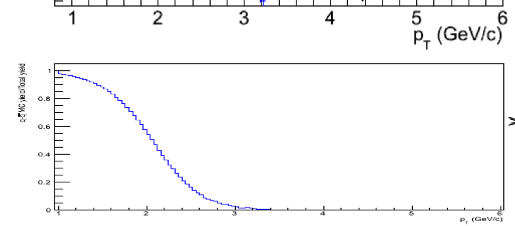


Requiring kinetic energy conservation best reproduced the n_q-scaling seen in the pion and proton data. As expected, the photon v2 is similar to the pion v2.

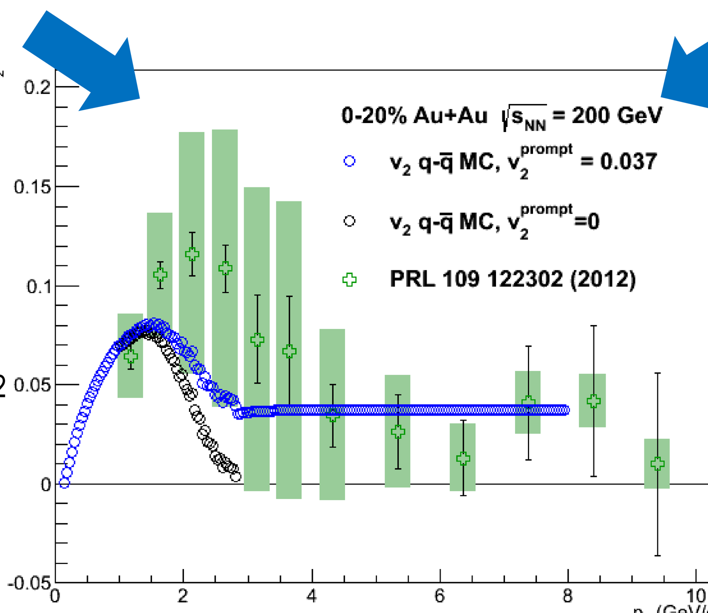
Comparison with measurement

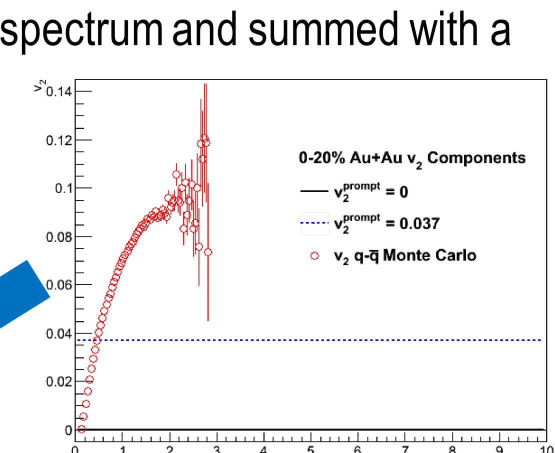


The Monte Carlo provides the p_T shape of the q-q annihilation component. No attempt to reproduce the measured yield is made. A yield calculation would be dependent on the number of quarks and the volume of the QGP. Instead, the Monte Carlo p_T shape is arbitrarily scaled to the measured direct photon p_T spectrum and summed with a N_{coll}-scaled fit to the p+p spectrum.



The total v_2 is determined by the weighted average of the q-q Monte Carlo v_2 and the v_2 of the N_{Coll}-scaled p+p component.





Two prompt v_2 components are examined.

- No prompt v_2
- Constant value of 0.037

The published PHENIX 0-20% Au+Au data are consistent at the lowest p_T values with late-stage partonic production by q-q annihilation within a medium containing soft gluons. When the prompt v_2 is zero, the theory is unable to reproduce the measurement above 2 GeV/c. When the prompt v_2 is a constant value of 0.037, the total v_2 is near the bottom of the measured uncertainties from 2 - 3 GeV/c. Fragmentation photons and thermal-mini-jet pairs may be able to produce a non-zero v_2 above 2 GeV/c. These additional contributions need further study.

This poster presents results for the 0-20% centrality bin only. Calculations for other centralities are ongoing. New measurements extending the direct photon v_n measurements to more centralities and higher orders of n while improving the systematic errors are needed to understand the physics of this observable and determine whether it scales with n_q = 2.

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References

[1] A. Adare et al., PRL 104, 132301 (2010)
[2] A. Adare et al., PRL 109, 122302 (2012)
[3] A. Adare et al., PRC 85, 064914 (2012)
[4] V. Greco, C. M. Ko, P. Levai, PRC 68, 034904 (2003)