Direct photon production in heavy ion collisions: Increased $q - \overline{q}$ photon production at hadronization

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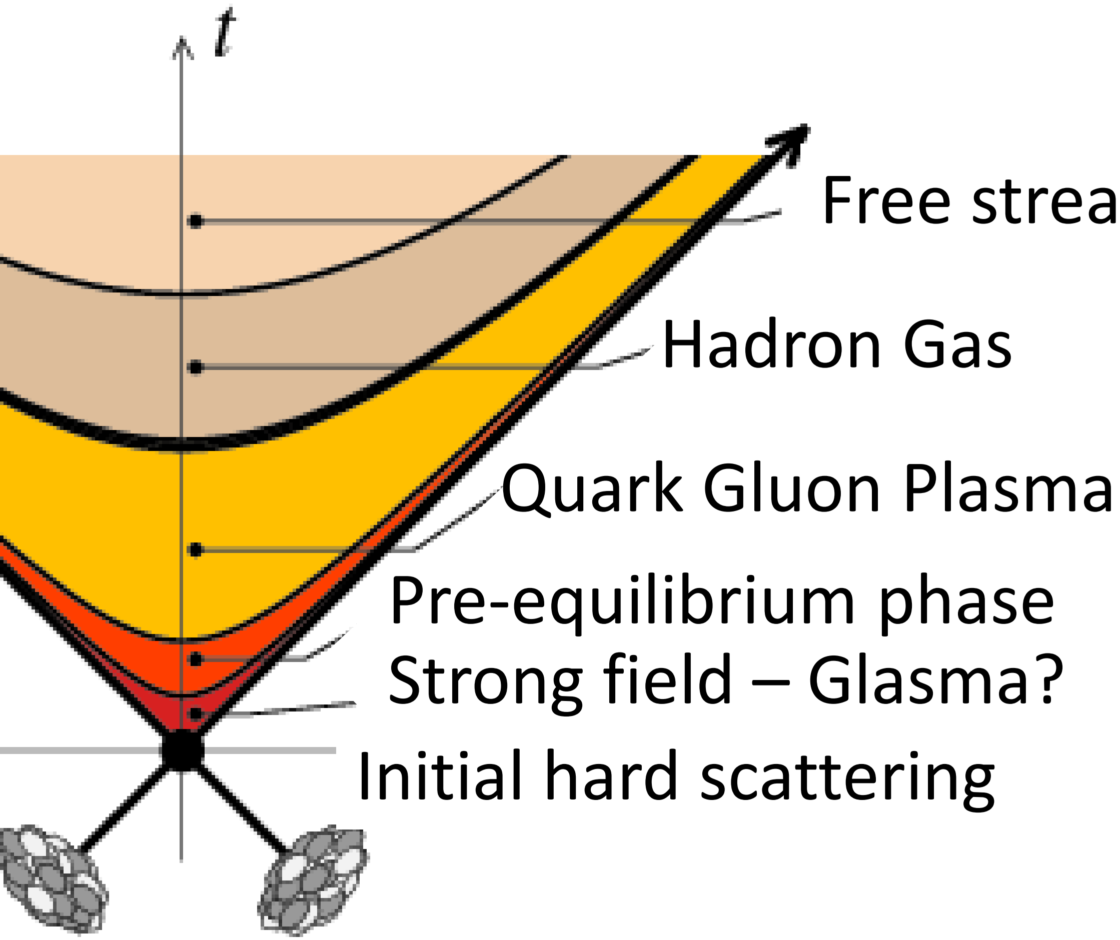
The Erice Center – June 27, 2015

- Photon production and direct photon puzzle
- Increased photon production at confinement
- Conclusions

Direct photon sources

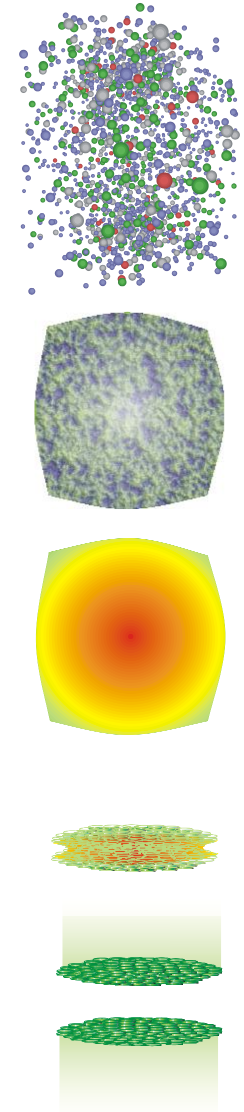


Thermal photons

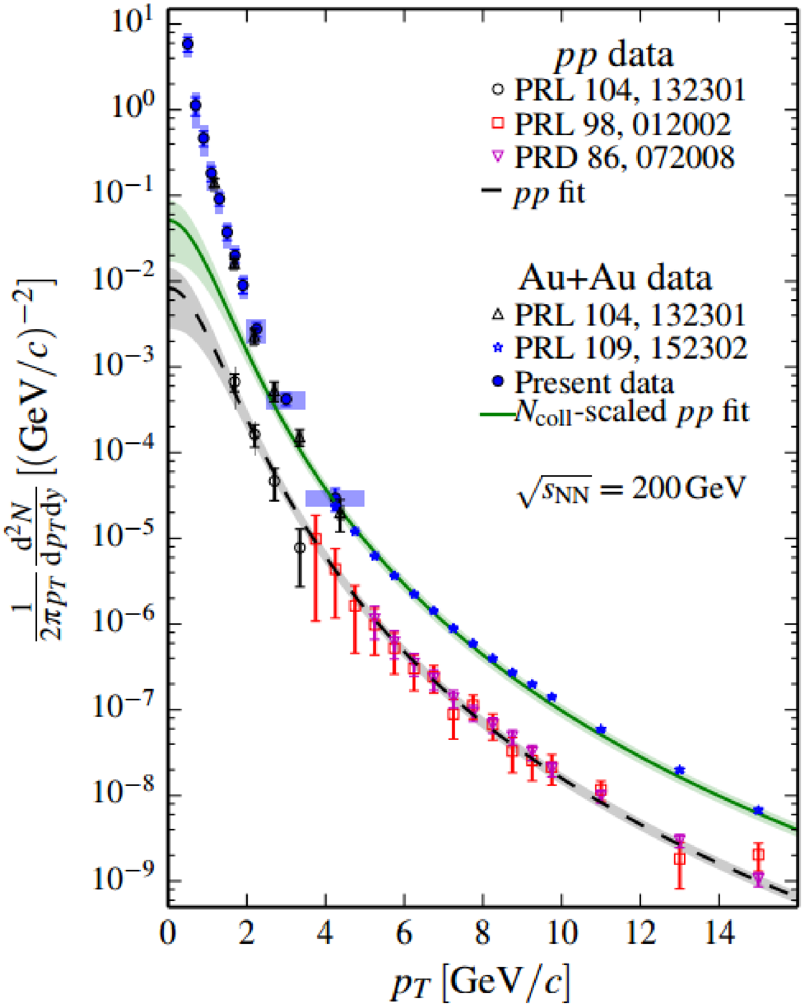
Thermal photons

Pre-equilibrium photons?

Prompt photons

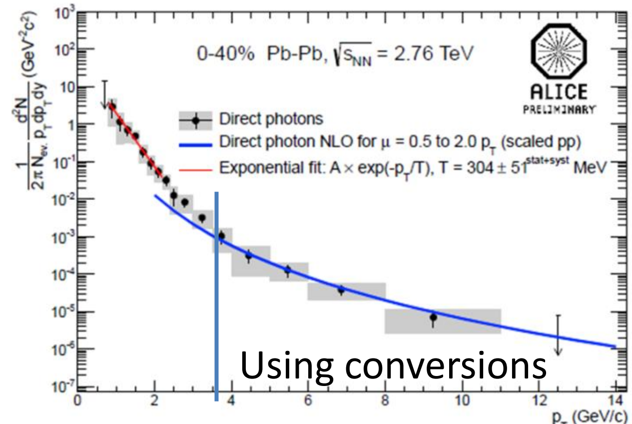


Direct photon p_T spectrum

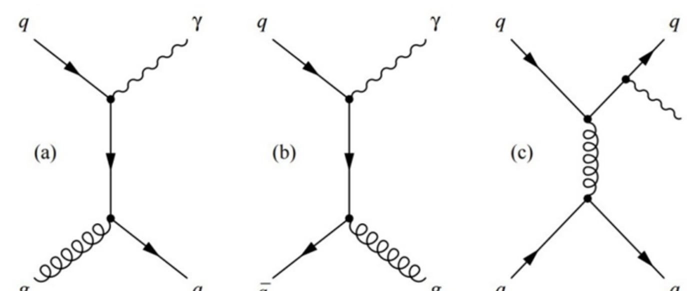


PRC 91, 064904 (2015)

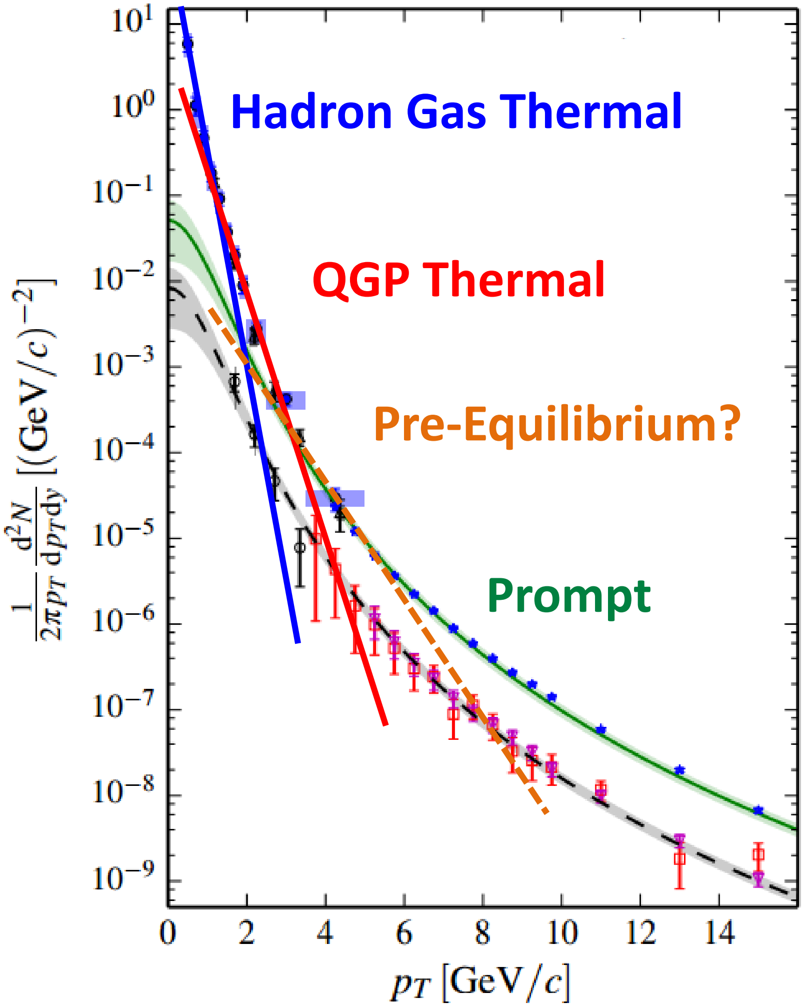
Large excess yield in A+A at low p_T



Prompt photons at high p_T
- → scaled p+p yields
- → pQCD calculations

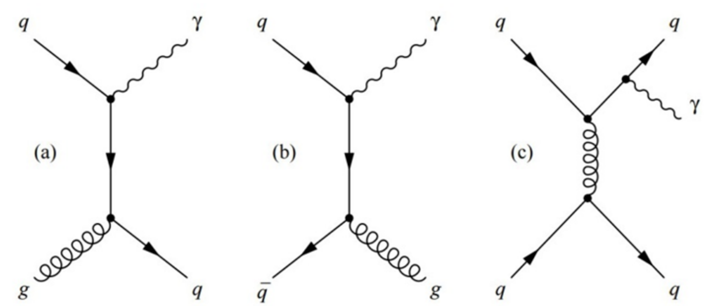


Direct photon p_T spectrum



Large excess yield in Au+Au at low p_T
→ Rates not well-constrained

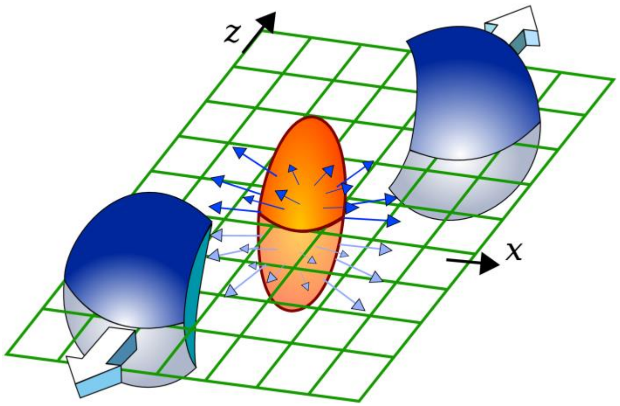
Prompt photons at high p_T
→ scaled p+p yields
→ pQCD calculations

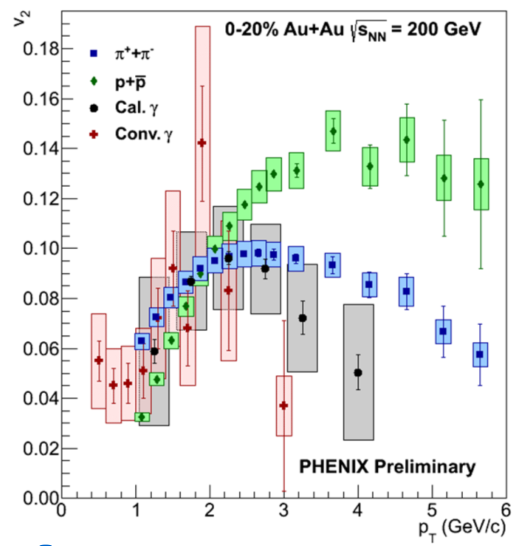


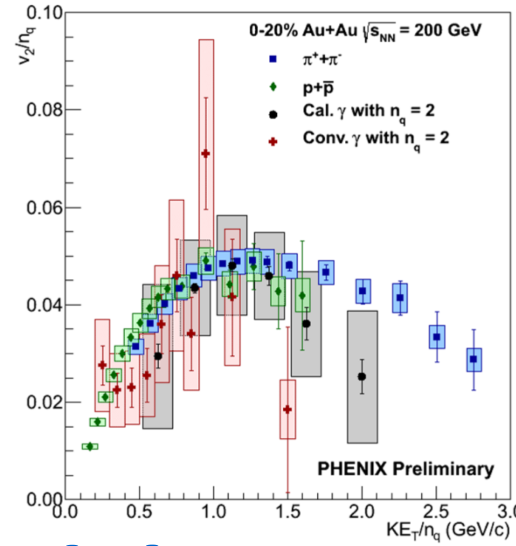
PRC 91, 064904 (2015)

Elliptic flow and n_q-scaling

$$\frac{dN}{d(\phi-\Psi)} = N\left[1 + 2v_2\cos\left(2(\phi-\Psi)\right)\right]$$

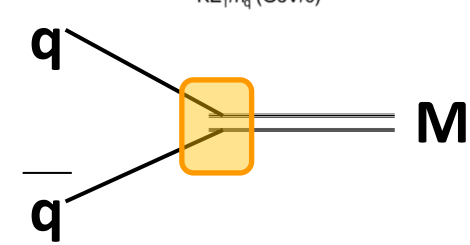






PRC 85 064914 (2012)

Coalescence model

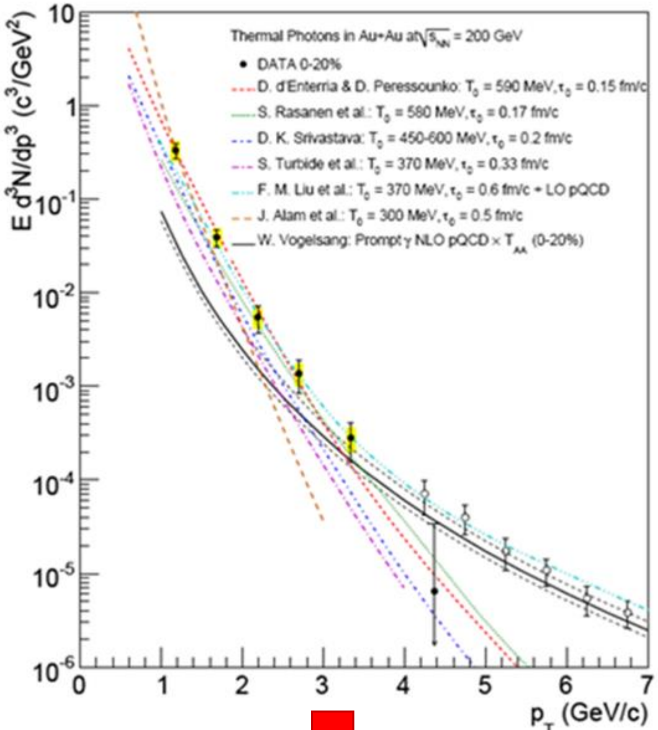


Quarks: $\frac{dN}{d\phi} \approx 1 + 2v_{2,q}(p_{T,q})\cos(2\phi)$

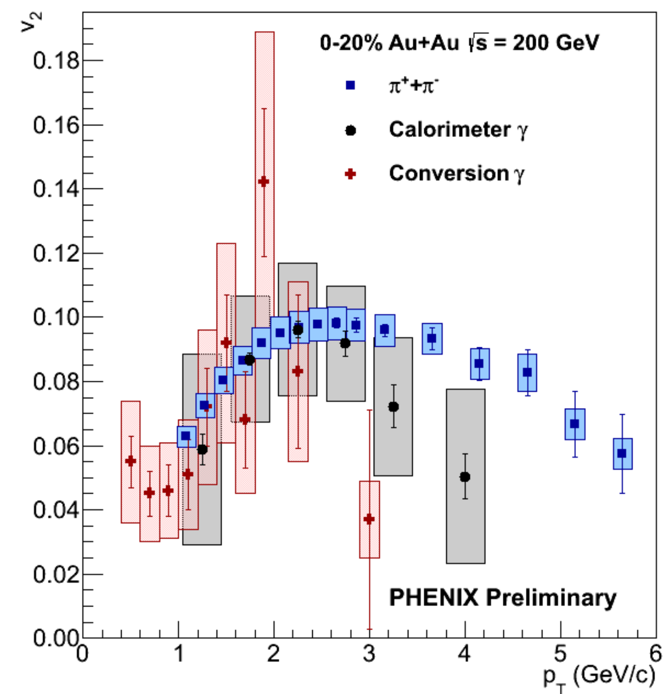
Mesons: $p_{T,M} \rightarrow 2p_{T,q}$ and $v_{2,M}(p_{T,M}) \rightarrow 2v_{2,q}(p_{T,M}/2)$

Baryons: $p_{T,B} \rightarrow 3p_{T,q}$ and $v_{2,B}(p_{T,B}) \rightarrow 3v_{2,q}(p_{T,B}/3)$

Direct photon puzzle



Thermal emission?
→ most produced early



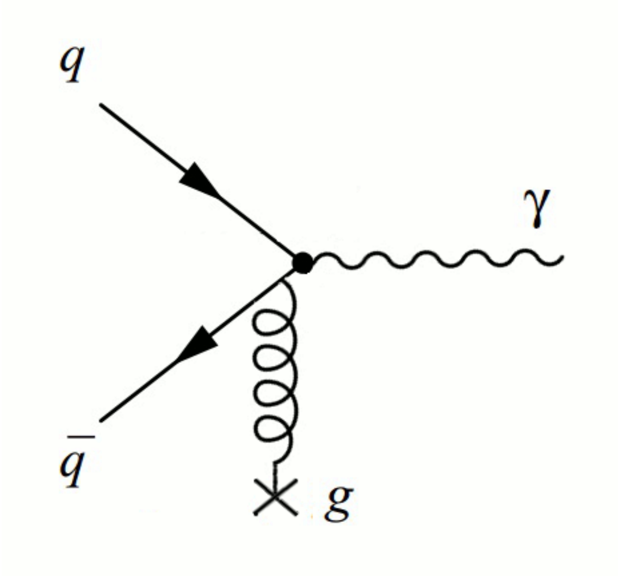
Looks like late emission
Direct photon v_2 ~ pion v_2

PRC 81 034911 (2010)

PRC 85 064914 (2012)

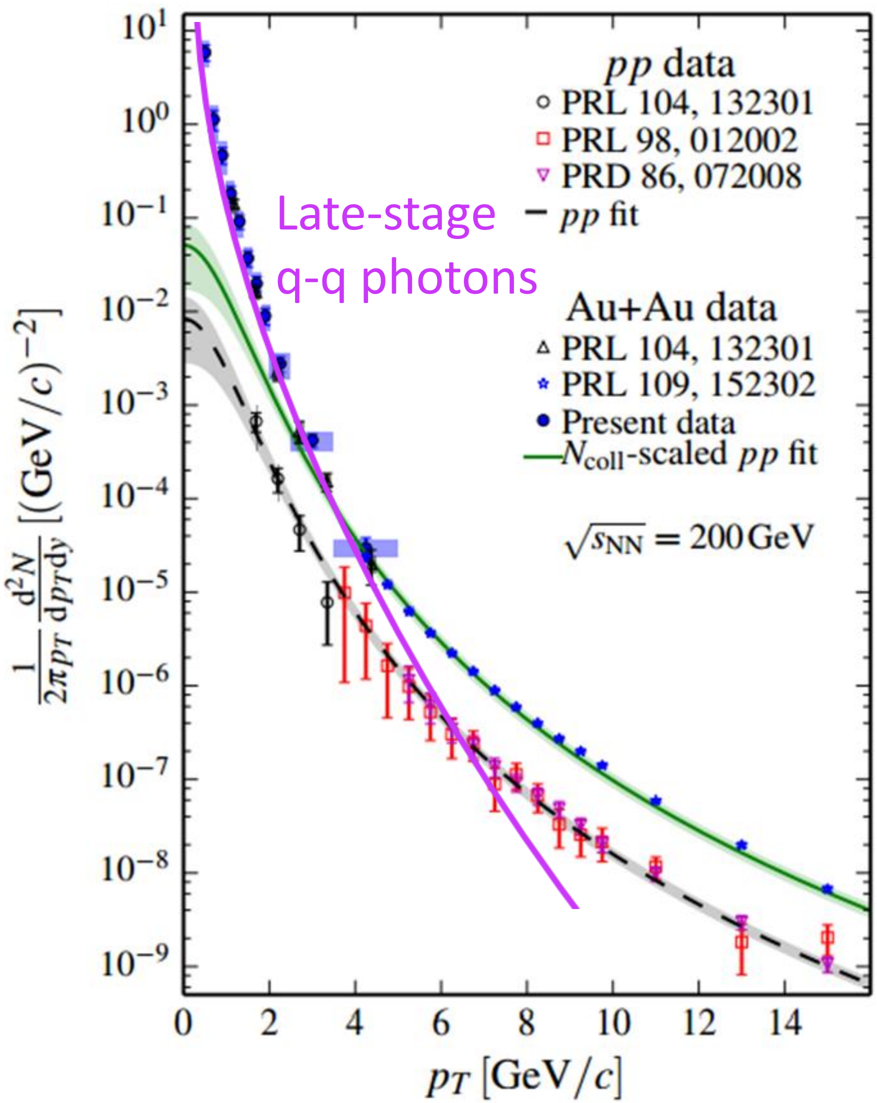
Photon production from q-$\bar{q}$ at hadronization

Could similar soft gluon interactions lead to an increase in $q - \bar{q}$ photon production as the system becomes color neutral?



This mechanism could produce MANY MANY photons

Two component model



PRC 91, 064904 (2015)

Prompt photons at high p_T

Late-stage $q - \bar{q}$ photons dominate at low p_T

→ Should see n_q-scaling of v_2 with $n_q = 2$

→ Can this source describe the shape of the excess p_T yield?

→ Can this source reproduce the v_2 at low p_T?

Data-driven Monte Carlo

1^{st} quark: 1.) Randomly pick r^2,φ,η from flat distributions

2.) Randomly pick m_T → 3.) Calculate v_2 from p_T → 4.) Randomly pick φ

Blast Wave Distrib. (r,φ,η)

From PRD 89 026013 (2005):

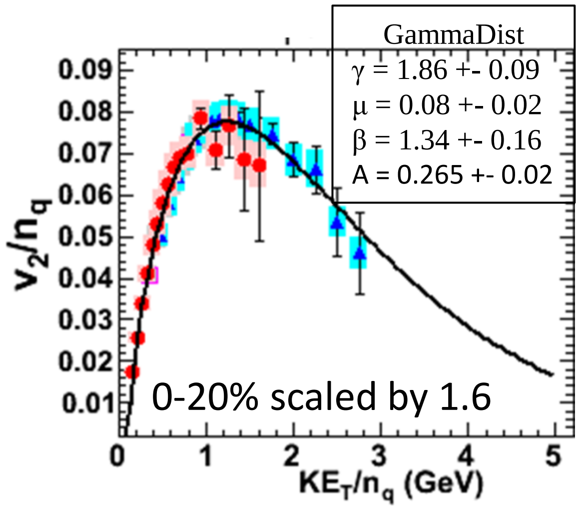
m_q = 300 MeV

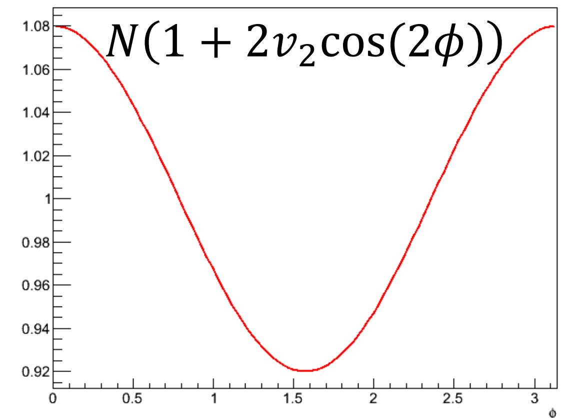
T = 106 MeV

R = 8.5 fm

β_S = 0.75 }

α = 1 } <β> = 0.5





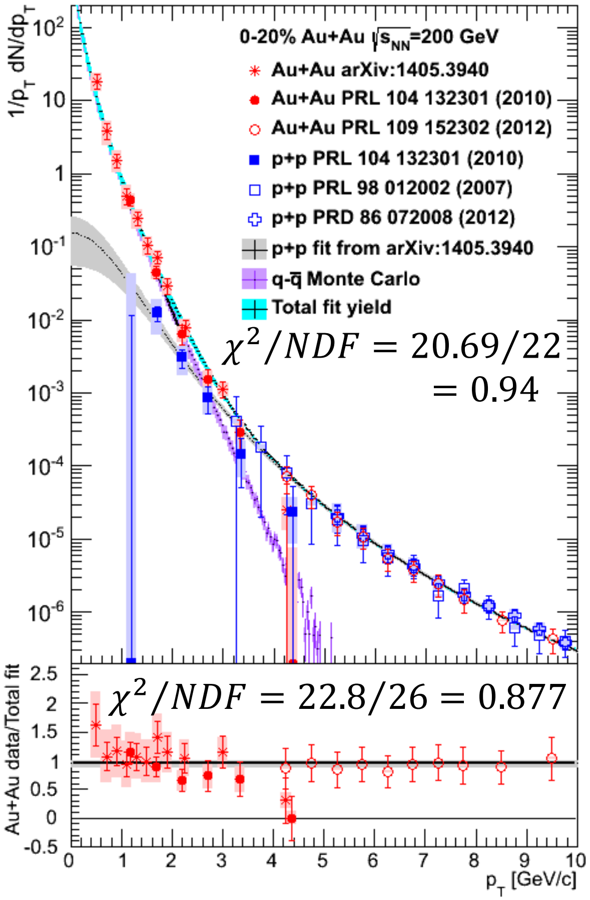
2^{nd}, 3rd quarks: 5.) Assume at the same Blast Wave Distrib. as 1^{st} quark

6.) Repeat steps 2-4 for 2^{nd}, 3^{rd} quark

Make pairs: 7.) Apply co-moving requirements (PRC 68 034904 (2003))

8.) Bring on mass shell, conserve KE

Direct photon p_T spectrum and v_2



Fit to the measured yields:

$$\frac{1}{p_T}\frac{dN}{dp_T} = N\left(\frac{1}{p_T}\frac{dN}{dp_T}\right)_{MC} + T_{AA}\left(\frac{1}{p_T}\frac{dN}{dp_T}\right)_{pp}$$

Free parameter

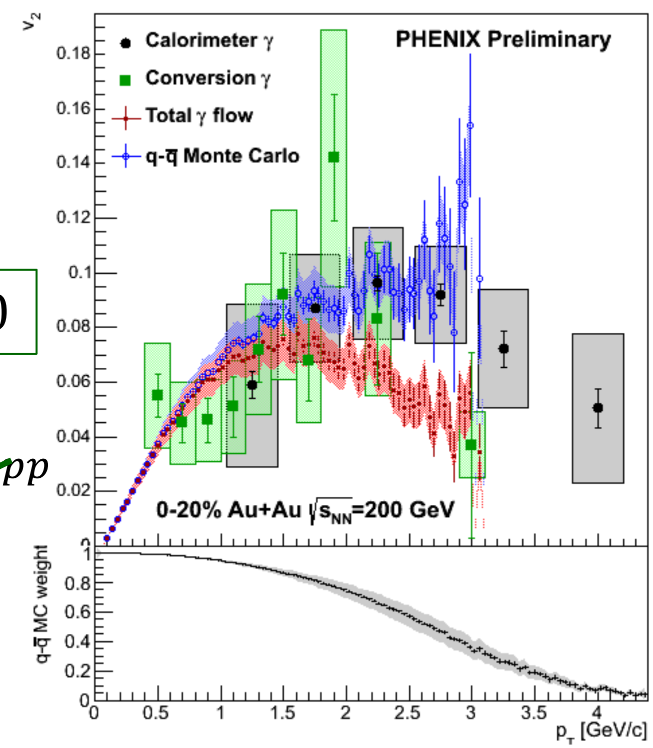
From p+p data, p+p fit at low p_T

Describes the p_T shape of the excess.

$q - \bar{q}$ MC weight

${v_2}^{pp} = 0$

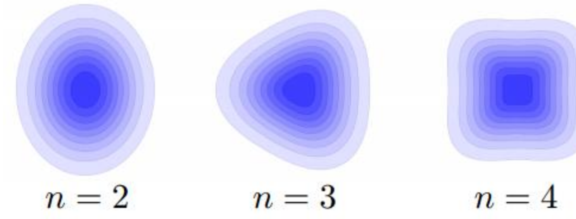
$$v_2 = \frac{Yield_{MC}}{Yield_{Total}}{v_2}^{MC} + \frac{Yield_{pp}}{Yield_{Total}}{v_2}^{pp}$$



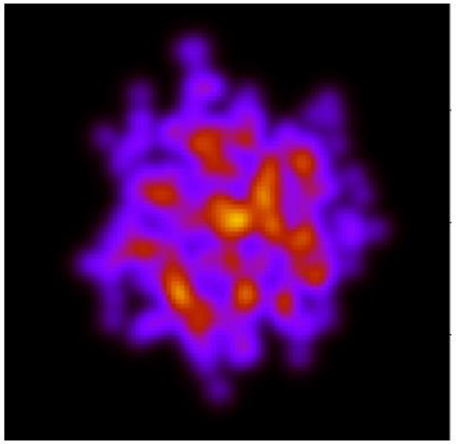
Reproduces the size of the large v_2.

→ systematically low at $p_T > 2$ GeV/c

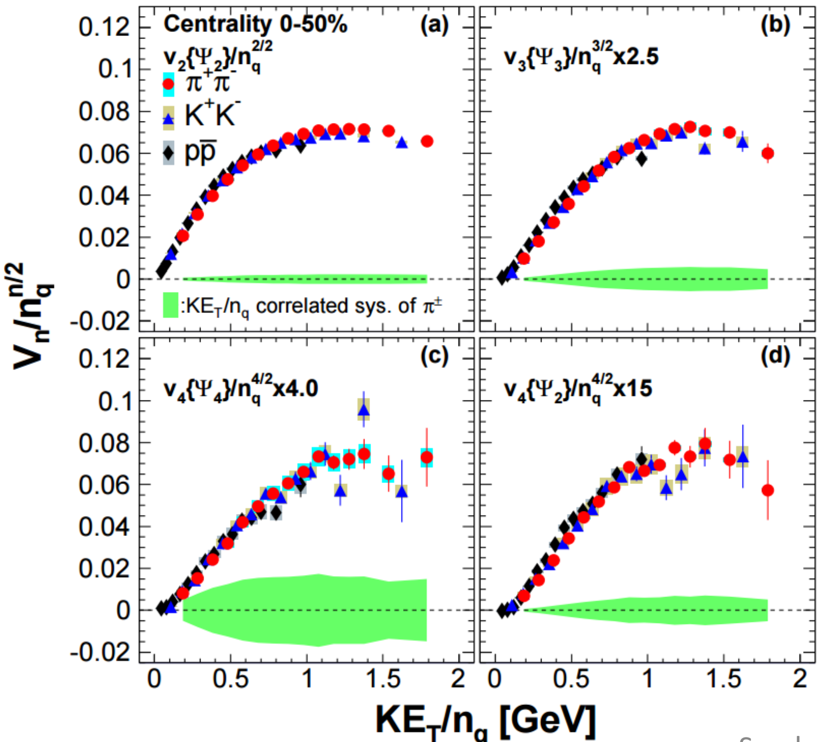
Higher orders of v_n



Sensitive to fluctuations in the initial energy distributions in the nuclei



Schenke, Jeon and Gale
PRL 106 042301 (2011)



arXiv:1412.1038

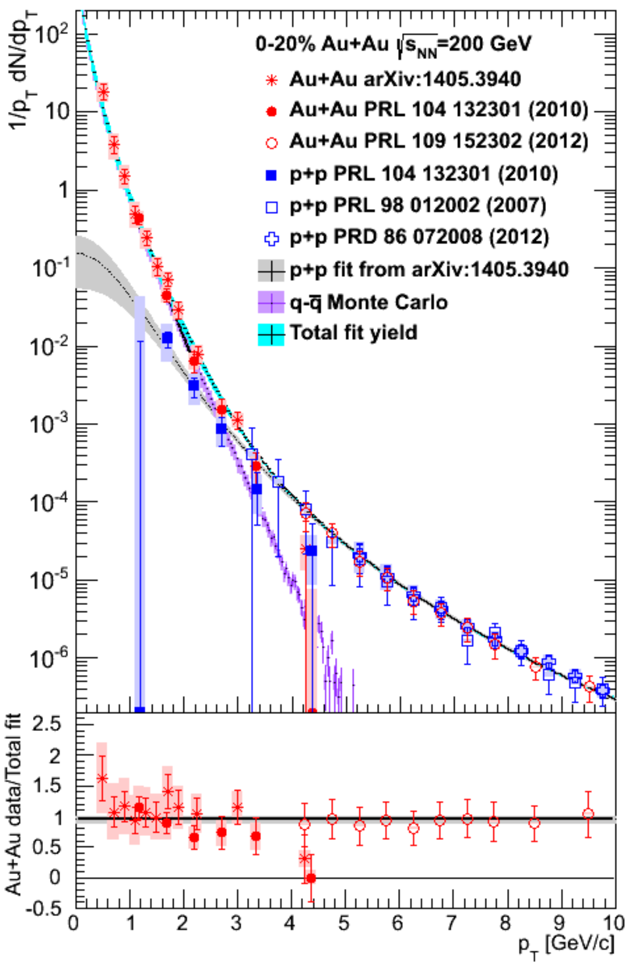
Modified n_q-scaling

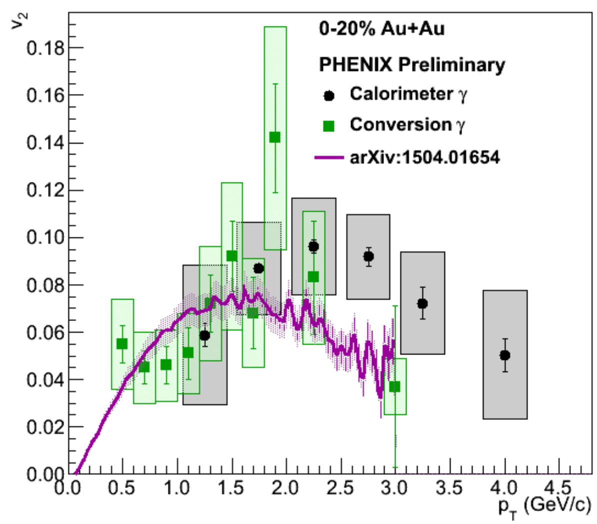
$$v_n/n_q^{n/2}$$

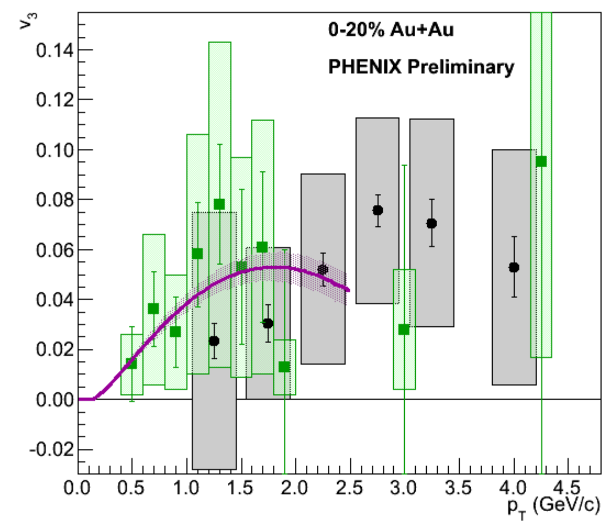
This scaling should extend to direct photons with $n_{q\gamma} = 2$

Results in 0-20% $\sqrt{s_{NN}}$ = 200 GeV Au+Au

$$\chi^2/NDF = 20.69/22 = 0.94$$



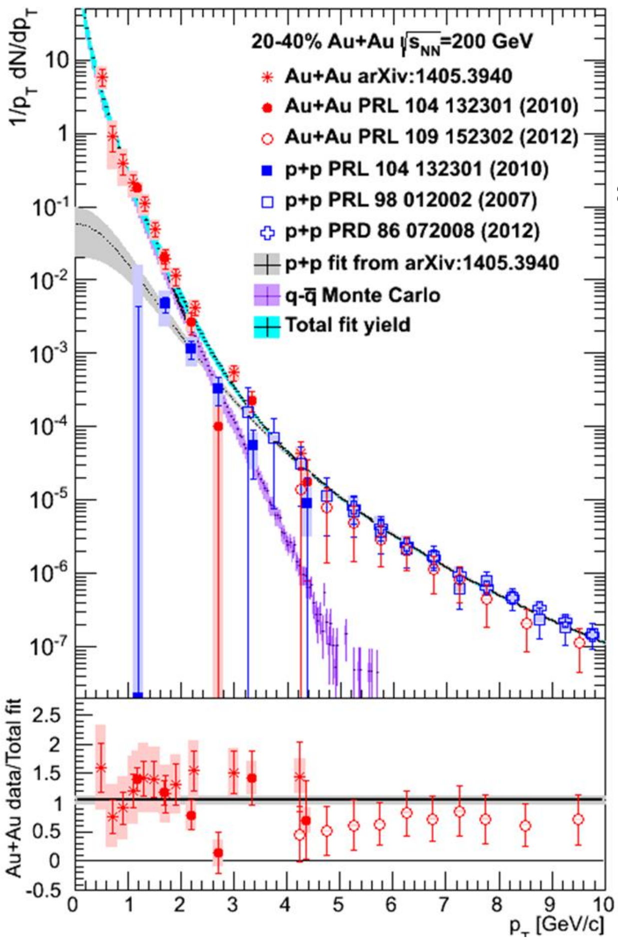


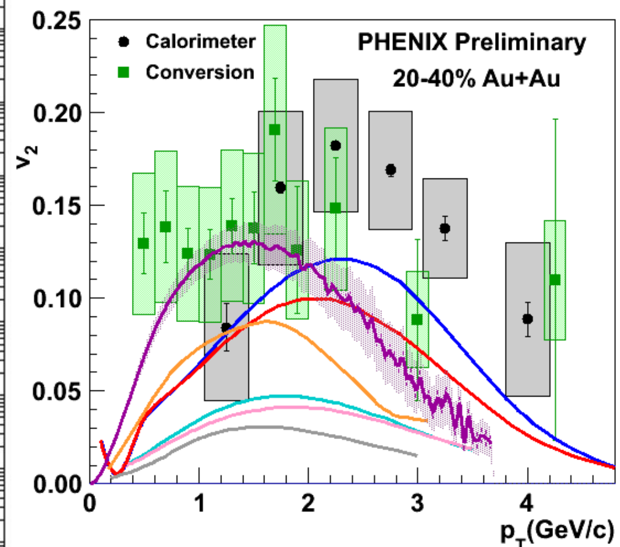


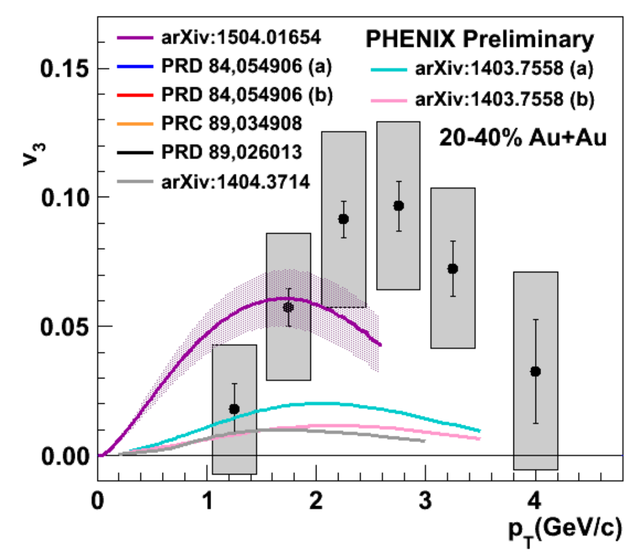
$$\chi^2/NDF = 22.8/26 = 0.877$$

Results in 20-40% $\sqrt{s_{NN}}$ = 200 GeV Au+Au compared with other models

$$\chi^2/NDF = 35.12/22 = 1.60$$

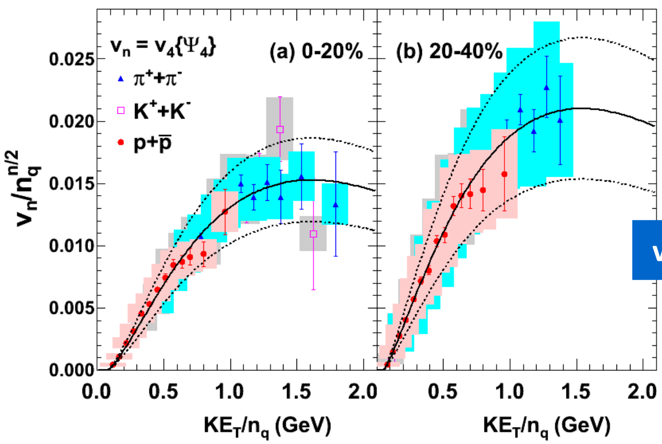




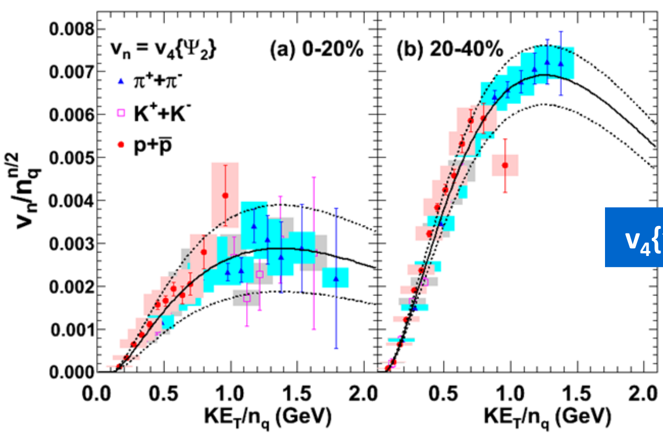


$$\chi^2/NDF = 32.5/26 = 1.25$$

$v_4\{\psi_4\}$ and $v_4\{\psi_2\}$ Predictions

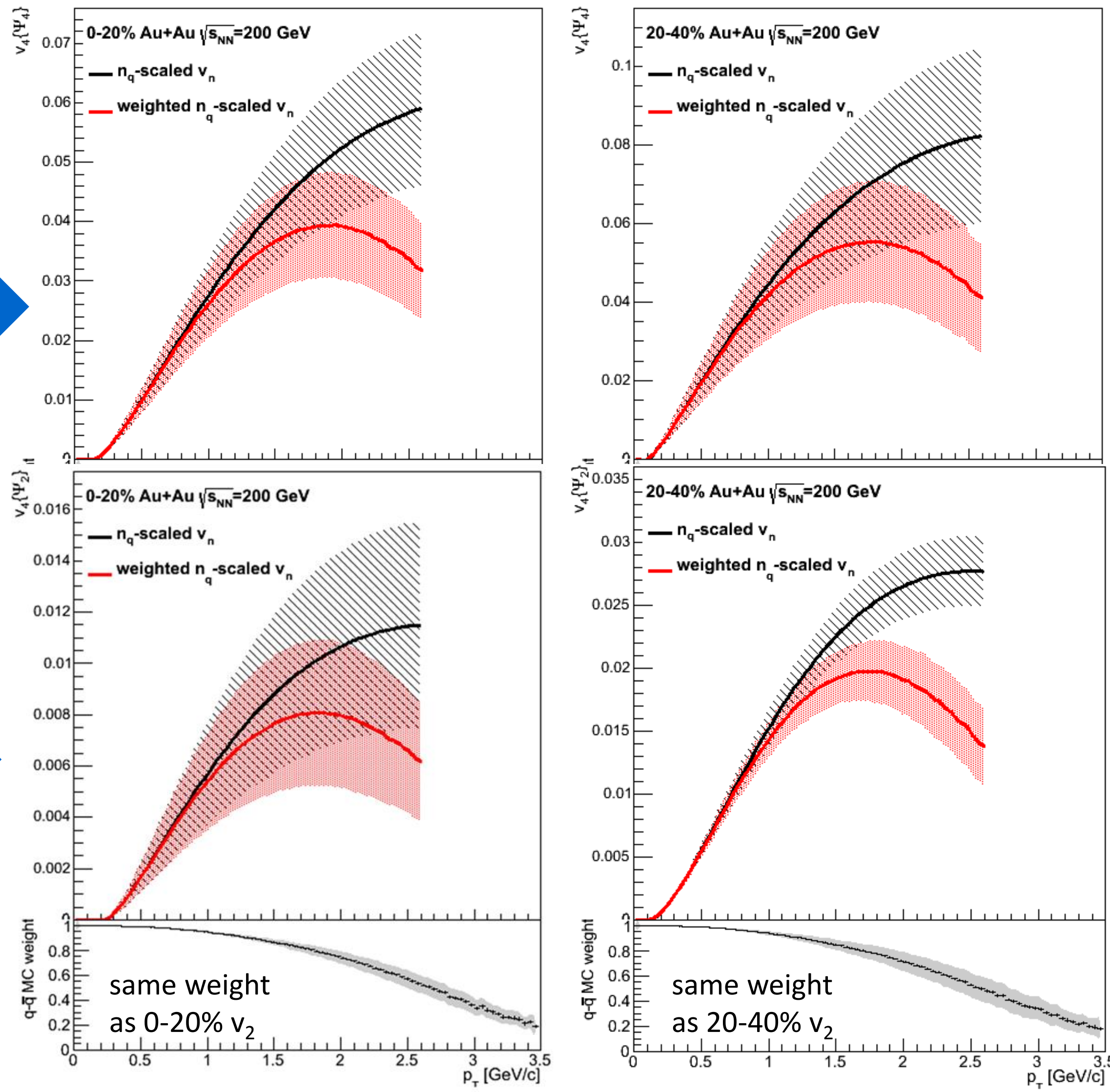


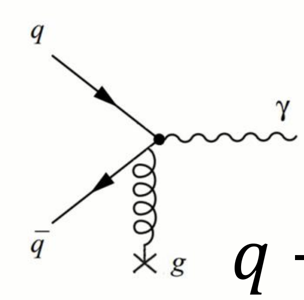
$v_4\{\psi_4\}$



$v_4\{\psi_2\}$

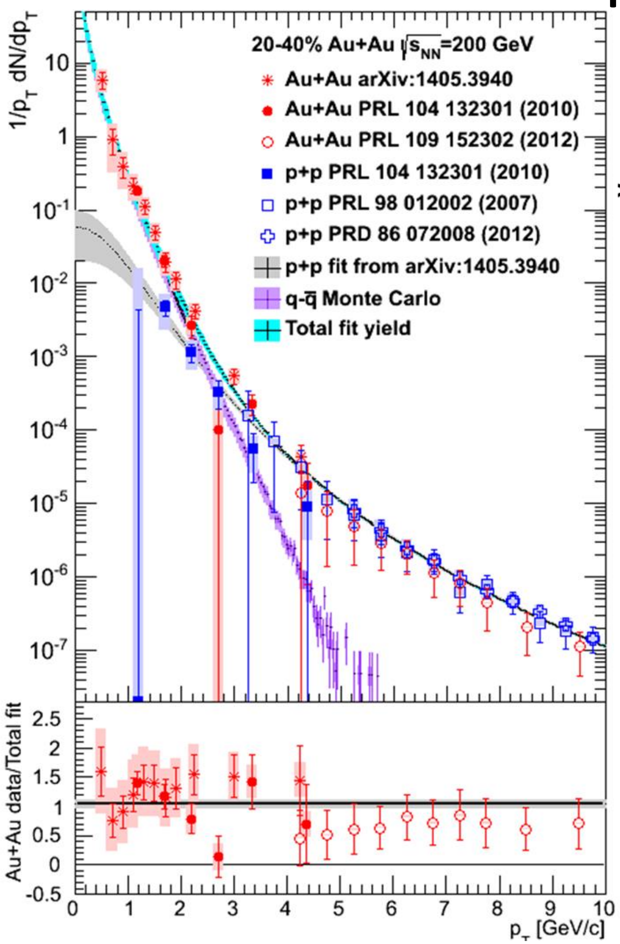
Fit with same functional form as v_2/n_q

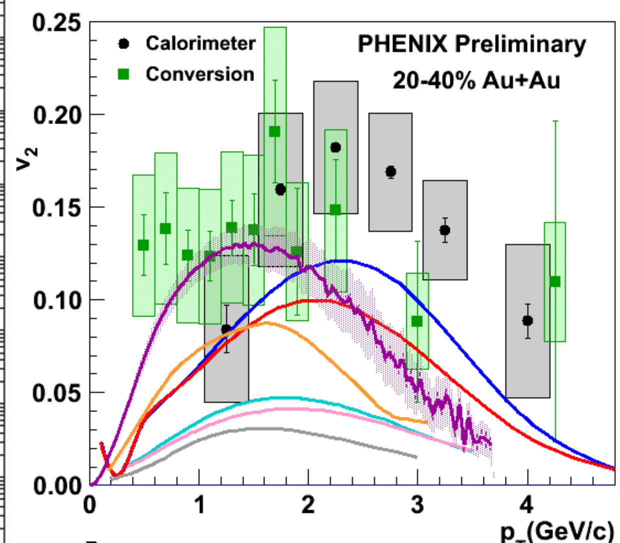


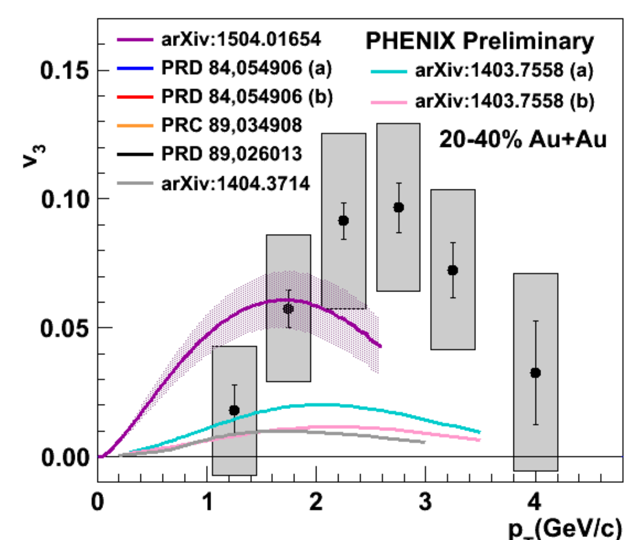


Conclusions

$q-\bar{q}$ photon production at confinement describes the direct photon p_T shape and large v_2 values







→ Data consistent with n_q-scaling of v_2, where $n_{q\gamma} = 2$

→ Modified n_q-scaling predicted for v_n

in 0-20%: $v_4\{\psi_4\} \sim 0.04$, $v_4\{\psi_2\} \sim 0.008$

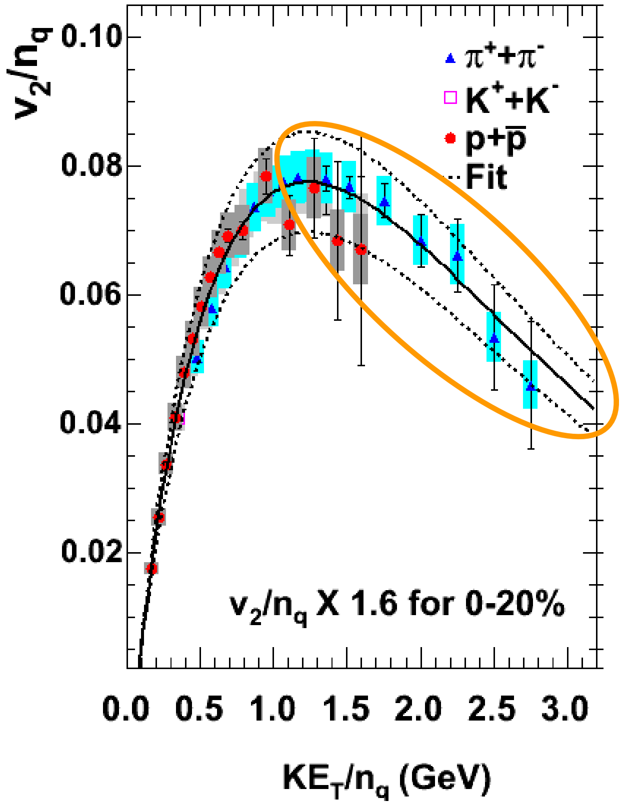
in 20-40%: $v_4\{\psi_4\} \sim 0.06$, $v_4\{\psi_2\} \sim 0.02$

For more information see arXiv:1504.01654 – In press at PRC

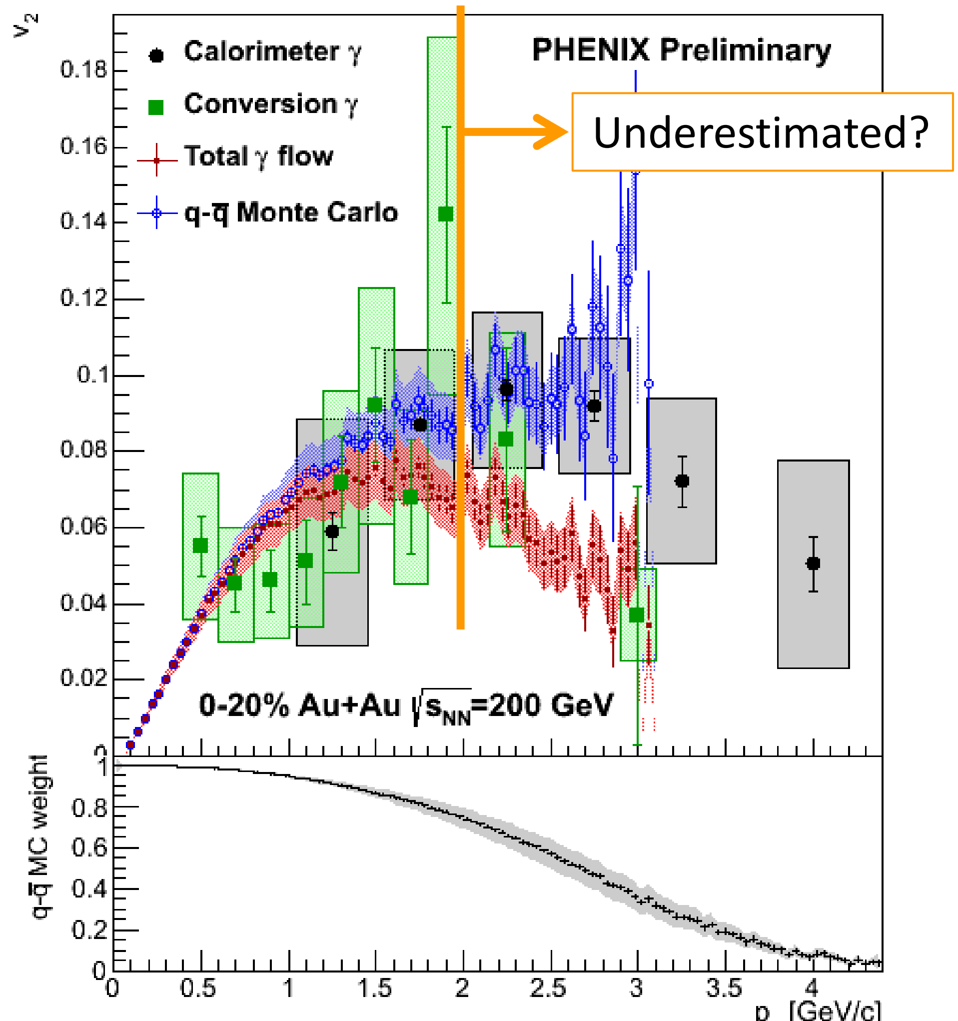
Backup

Future improvements

Use v_2/n_q from π, K, p as a proxy for the quark v_2

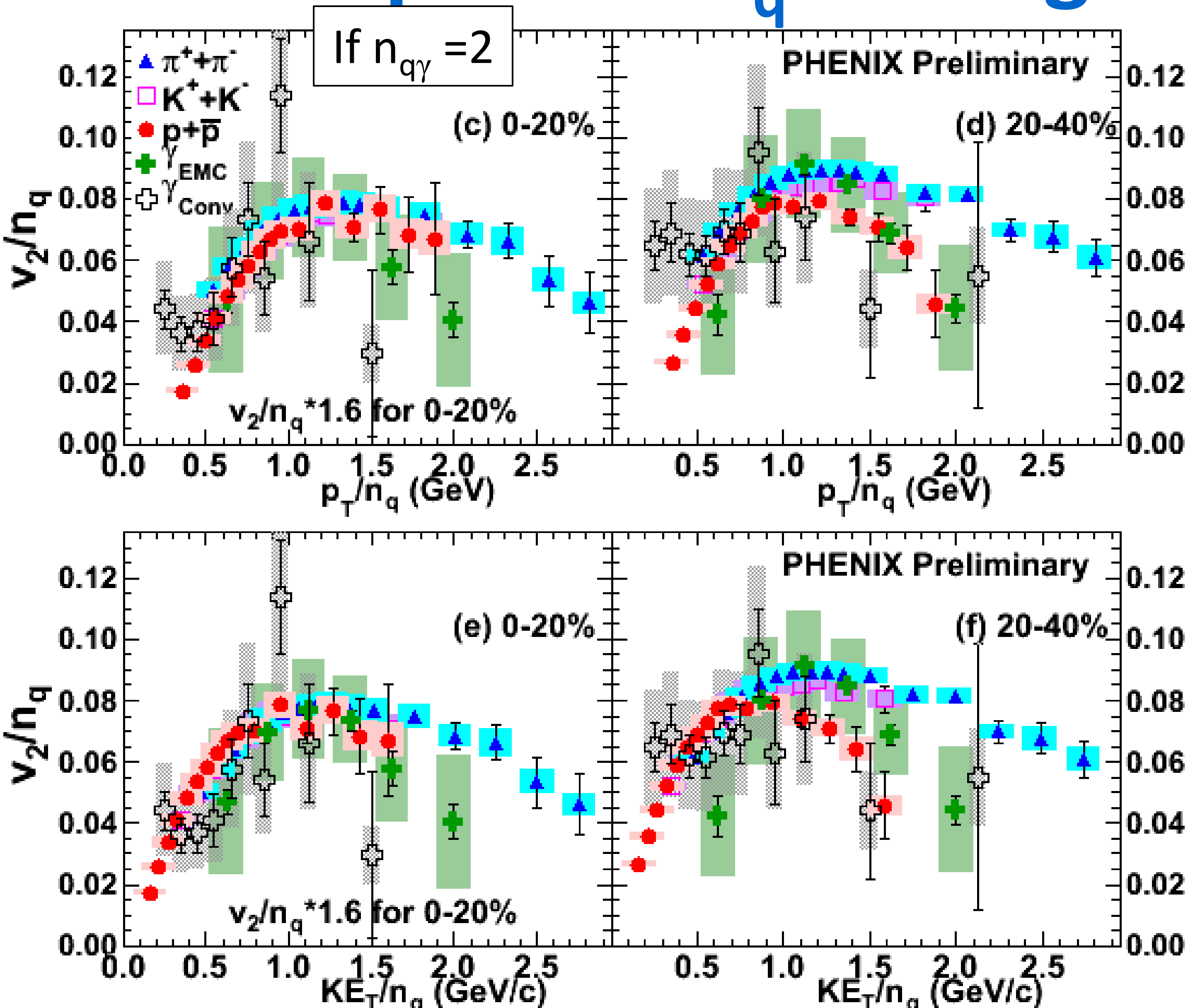


At high KE_T/n_q, hard components in π pull down this 'quark' v_2



Need better source for quark v_2
→ Hydro?

Direct photon n_q-scaling



Find optimal $n_{q\gamma}$ using χ^2

$$\chi^2 = \sum_{Cent.} \sum_{\pi,K,p} \sum_{KE_T/n_q} \frac{(v_{2\gamma}/n_{q\gamma} - v_{2h}/n_q)^2}{(\sigma_\gamma/n_{q\gamma})^2 + (\sigma_h/n_q)^2}$$

Published data in two KE_T/n_q ranges

The only free parameter

Data-Data Calculation

- v_{2h}/n_q from π, K, p identified hadron data
- $\Delta KE_T/n_q < 0.1$
- NDF changes with $n_{q\gamma}$, χ^2 discontinuous

Data-Fit Calculation

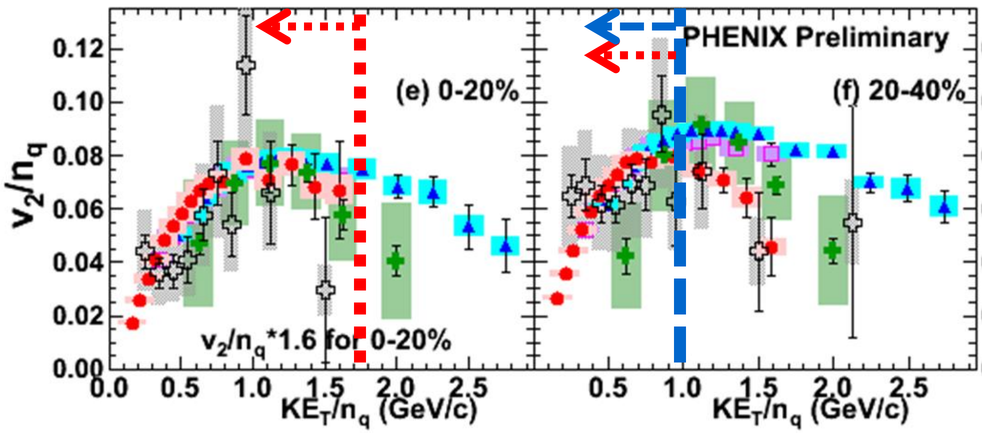
- v_{2h}/n_q from fit to π, K, p identified hadron data
  - Use probability density function of Gamma distribution, $G(x) = A\frac{((x-\mu)/\beta)^{\gamma-1}e^{-1(x-\mu)/\beta}}{\beta\Gamma(\gamma)}$
- TMinuit simultaneous fit to 0-20% and 20-40%

χ^2 Results

	$\sigma_\gamma = \sigma_{stat} \oplus \sigma_{sys}$		$\sigma_\gamma = \sigma_{stat}$	
HEADING	$n_{q\gamma} \pm (stat)$	$n_{q\gamma} = 2$	$n_{q\gamma} \pm (stat) \pm (sys)$	$n_{q\gamma} = 2$
Data, Range 1	$1.79^{+0.08}_{-0.27}$	2σ	$1.79^{+0.002+0.67}_{-0.01-0.72}$	1σ
Data, Range 2	1.79 ± 0.27	1σ	$1.79^{+0.002+1.09}_{-0.01-0.72}$	1σ
Fit, Range 1	1.59 ± 0.22	2σ	$1.79 \pm 0.02^{+0.85}_{-0.68}$	1σ
Fit, Range 2	1.83 ± 0.44	1σ	$1.88 \pm 0.07^{+1.18}_{-0.71}$	1σ

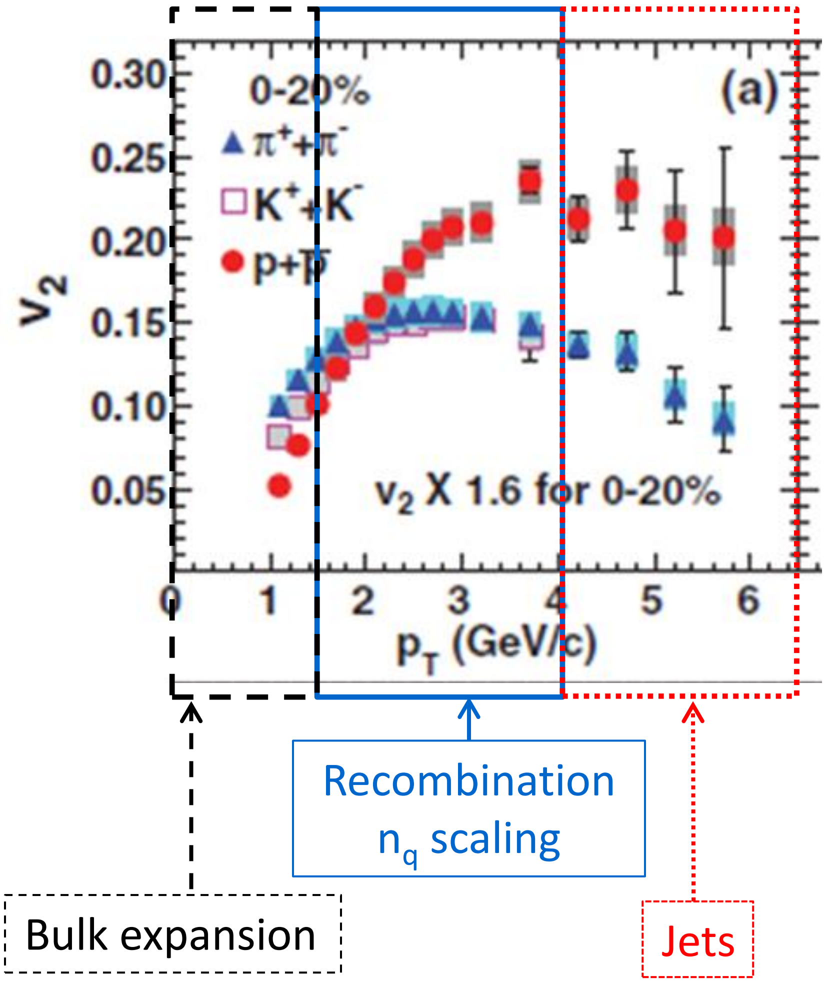
Optimal value of $n_{q\gamma} = 1.8$

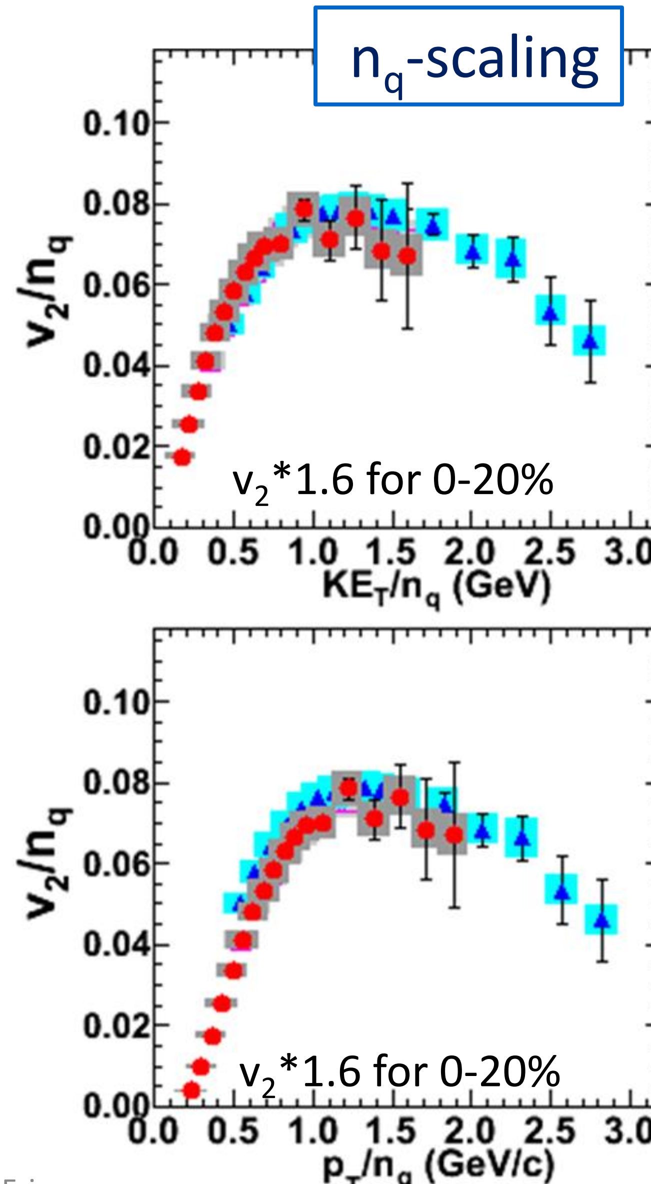
→ Need reduced systematic errors



Data is consistent with the $n_{q\gamma} = 2$ hypothesis

Hadronic flow

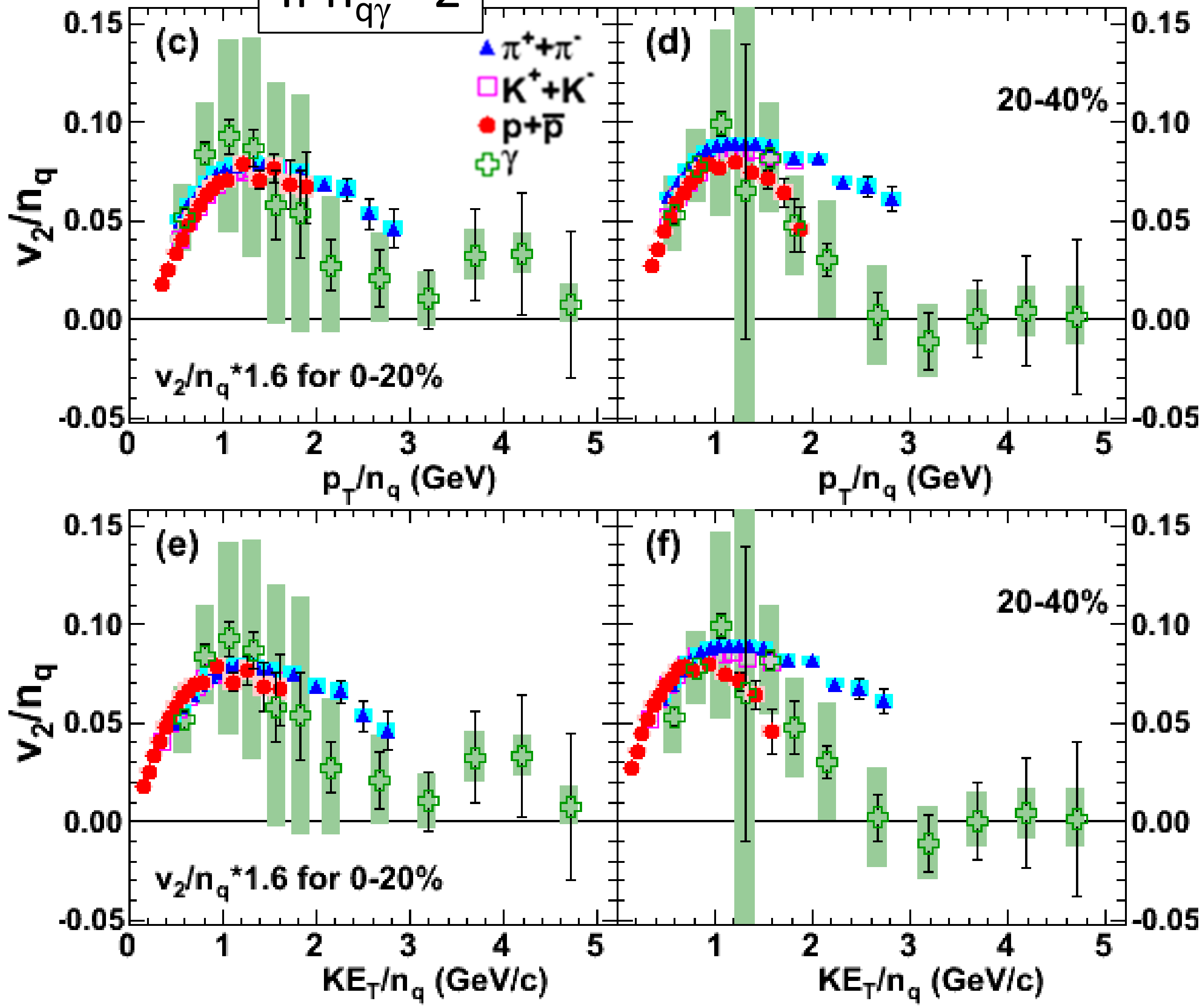




PRC 85 064914 (2012)

Direct photon n_q-scaling

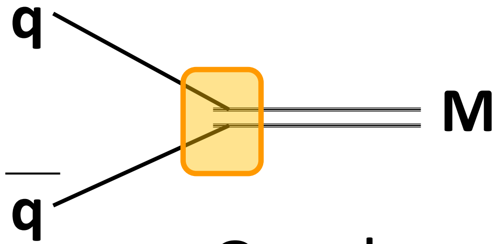
If $n_{q\gamma}$ =2



PRL 109 122302 (2012)

PRC 85 064914 (2012)

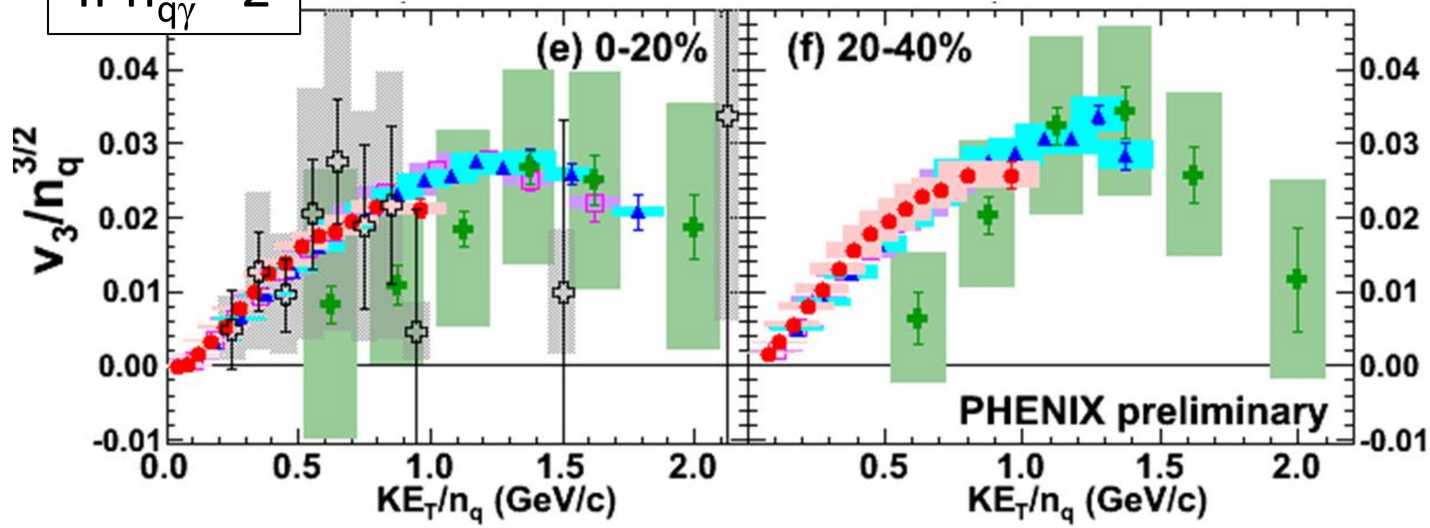
Coalescence Model

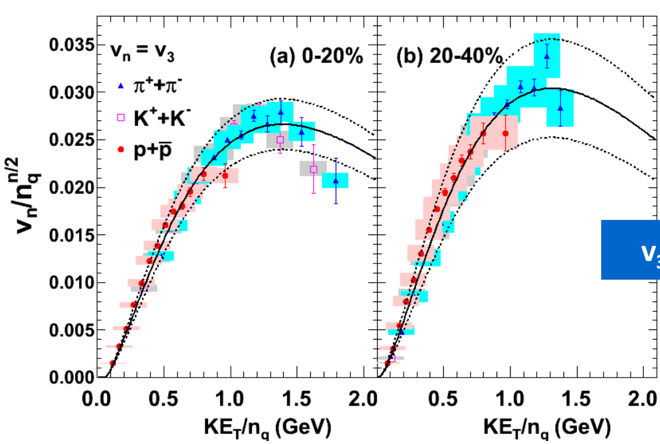


- Quarks: $dN/d\varphi \sim 1 + 2v_{2,q}(p_T)\cos(2\varphi)$
- Mesons: $v_2(p_T) = 2v_{2,q}(p_T/2)$
- Baryons: $v_2(p_T) = 3v_{2,q}(p_T/3)$
- Assumes co-moving quarks of same momentum
  - $p_{T,M} \rightarrow 2p_{T,q}$ $p_{T,B} \rightarrow 3p_{T,q}$
  - Momentum conservation maintained by mean-field interaction
- Quarks close in phase space

Direct photon v_3

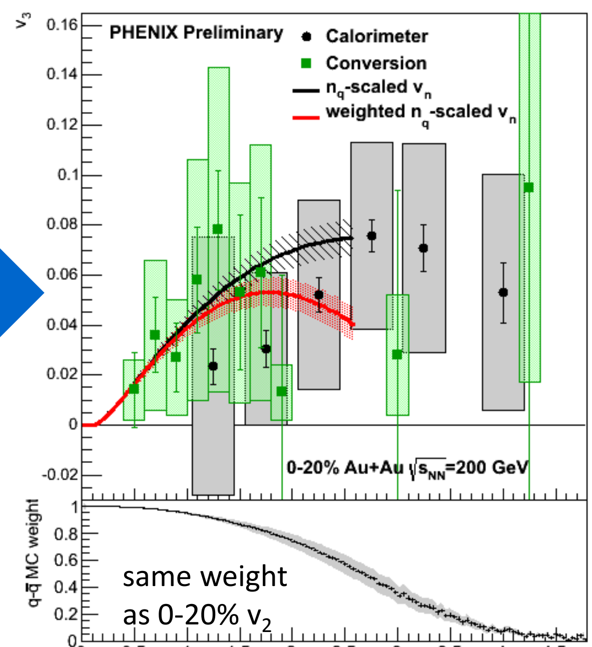
If $n_{q\gamma}$ =2



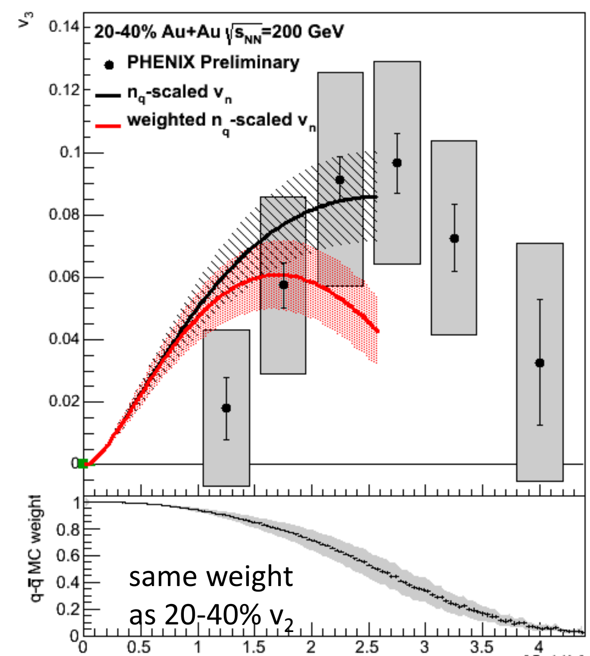


Fit with same functional form as v_2/n_q

v_3



same weight as 0-20% v_2

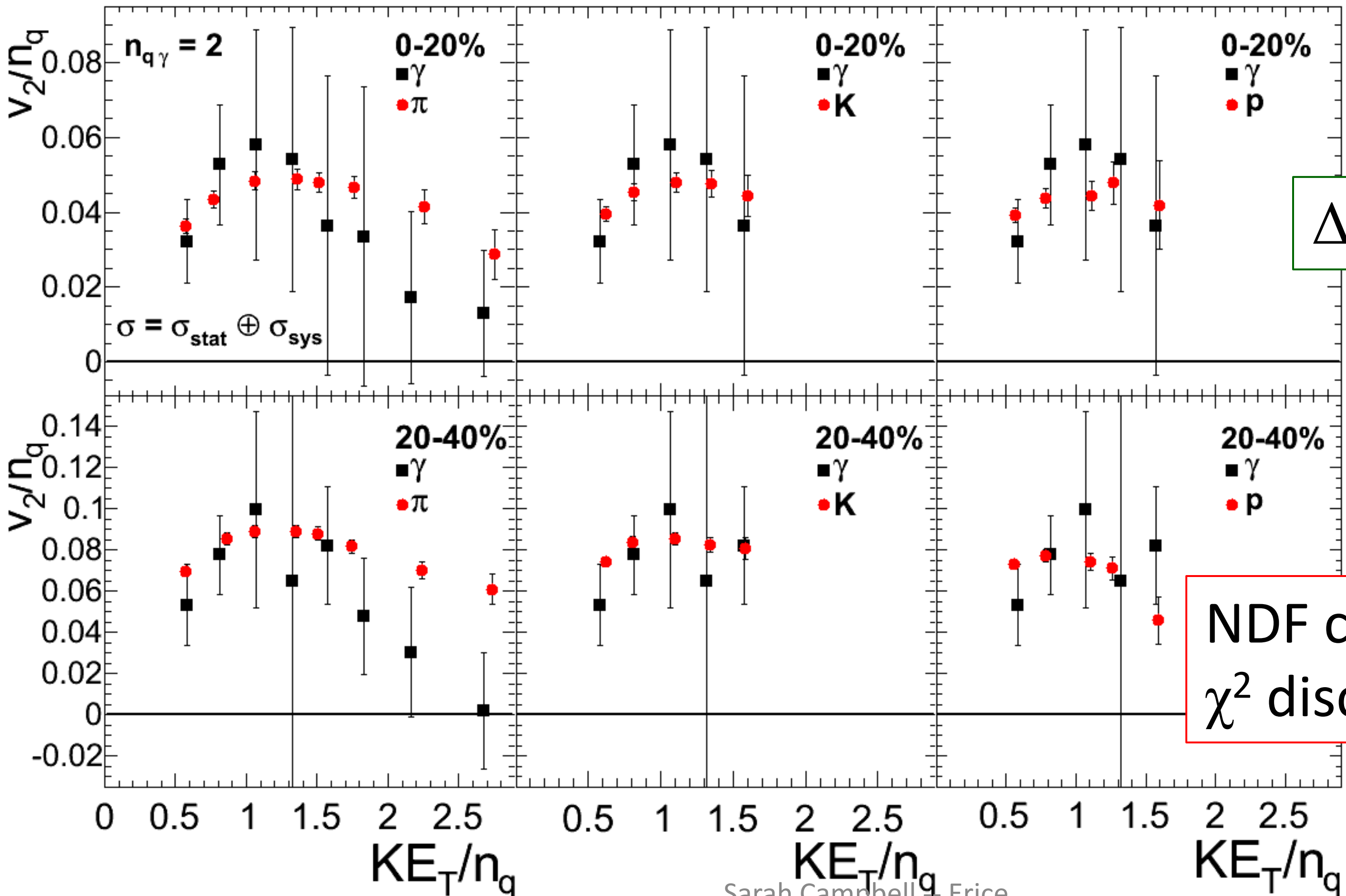


same weight as 20-40% v_2

Data-Data χ^2 Calculation

$$\chi^2 = \sum_{Cent.} \sum_{\pi,K,p} \sum_{KE_T/n_q} \frac{(v_{2\gamma}/n_{q\gamma} - v_{2h}/n_q)^2}{(\sigma_\gamma/n_{q\gamma})^2 + (\sigma_h/n_q)^2}$$

$\chi^2/NDF = 16.28/35$
$= 0.47$



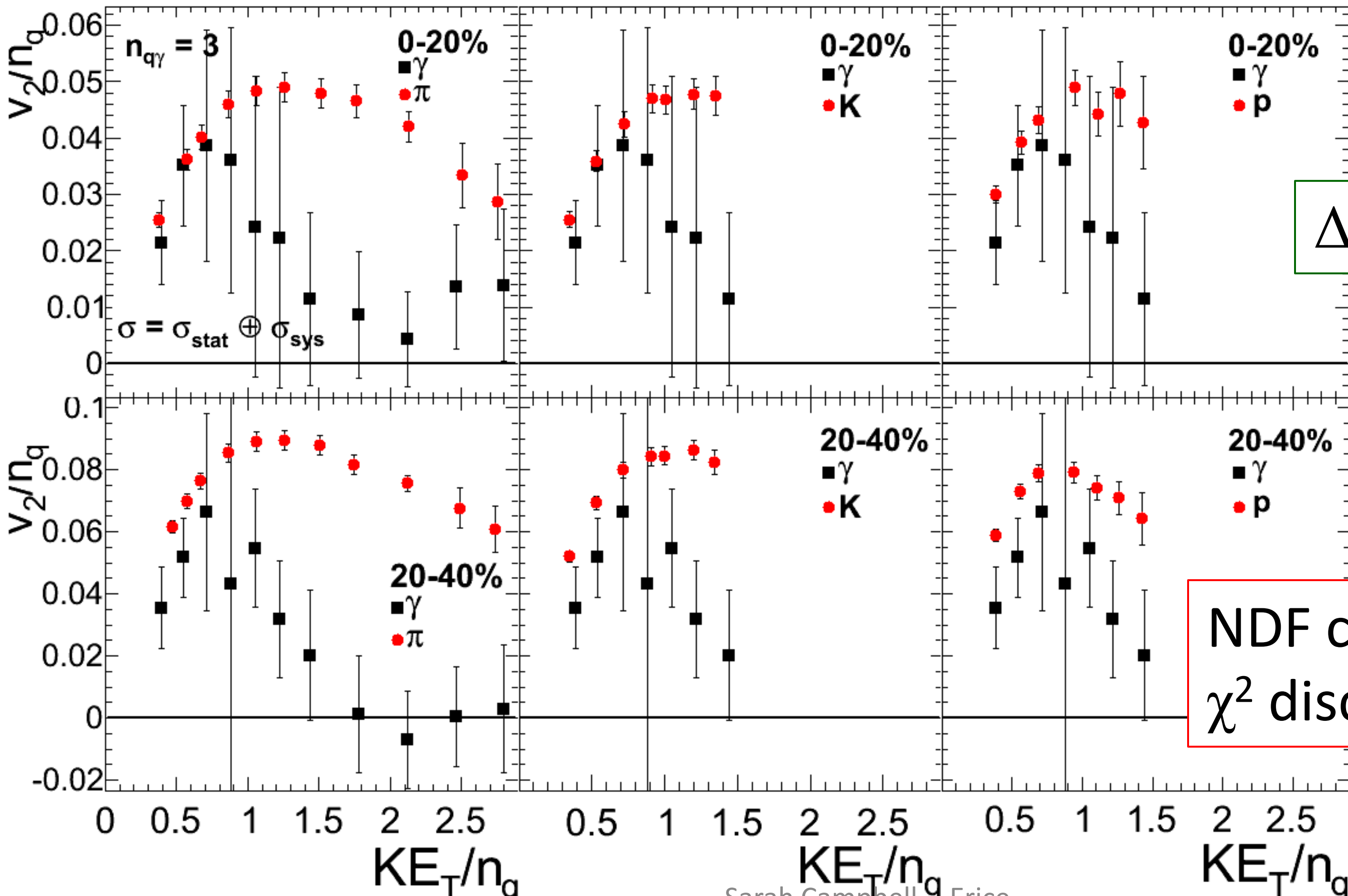
$\Delta KE_T/n_q < 0.1$

NDF changes with $n_{q\gamma}$
χ^2 discontinuous

Data-Data χ^2 Calculation

$$\chi^2 = \sum_{Cent.} \sum_{\pi,K,p} \sum_{KE_T/n_q} \frac{(v_{2\gamma}/n_{q\gamma} - v_{2h}/n_q)^2}{(\sigma_\gamma/n_{q\gamma})^2 + (\sigma_h/n_q)^2}$$

χ^2/NDF = 186.3/50
= 3.89



$\Delta KE_T/n_q < 0.1$

NDF changes with $n_{q\gamma}$
χ^2 discontinuous

Compare n_q-scaled v_2 for γ and hadrons

- $\chi^2 = \sum_{c,h,pT/nq} (v_{2,\gamma}/n_{q,\gamma} - v_{2,h}/nq_{,h})^2/(\sigma_\gamma{}^2 + \sigma_h{}^2)$
  - Sum over centrality, hadron for each γ data point in p_T/n_q
  - $\sigma^2 = \sigma_{sys}{}^2 + \sigma_{stat}{}^2$
- Match $v_{2,\gamma}$ and $v_{2,h}$ points so $p_{T,\gamma}/n_{q,\gamma} \sim p_{T,h}/n_{q,h}$
  - Need to be within 0.1 to be a match
- NDF = # points – 1 parameter → $n_{q,\gamma}$
  - As changes $n_{q,\gamma}$, NDF changes
- Find $n_{q,\gamma}$ at minimum χ^2/NDF
  - $n_{q,\gamma}$ error range from χ^2/NDF + 1
- Alternate comparison: use KE_T/n_q to match

Find optimal $n_{q\gamma}$ using χ^2

$$\chi^2 = \sum_{Cent.} \sum_{\pi,K,p} \sum_{KE_T/n_q} \frac{(v_{2\gamma}/n_{q\gamma} - v_{2h}/n_q)^2}{(\sigma_\gamma/n_{q\gamma})^2 + (\sigma_h/n_q)^2}$$

The only free parameter

Data-Data Calculation

- v_{2h}/n_q from π, K, p identified hadron data

Data-Fit Calculation

- v_{2h}/n_q from fit to π, K, p identified hadron data

Find optimal $n_{q\gamma}$ using χ^2

$$\chi^2 = \sum_{Cent.} \sum_{\pi,K,p} \sum_{KE_T/n_q} \frac{(v_{2\gamma}/n_{q\gamma} - v_{2h}/n_q)^2}{(\sigma_\gamma/n_{q\gamma})^2 + (\sigma_h/n_q)^2}$$

The only free parameter

Data-Data Calculation

- v_{2h}/n_q from π, K, p identified hadron data

Data-Fit Calculation

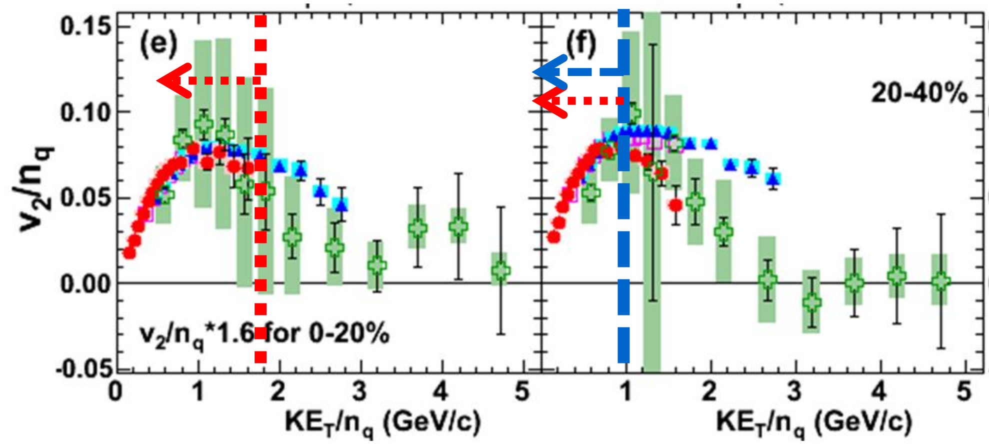
- v_{2h}/n_q from fit to π, K, p identified hadron data

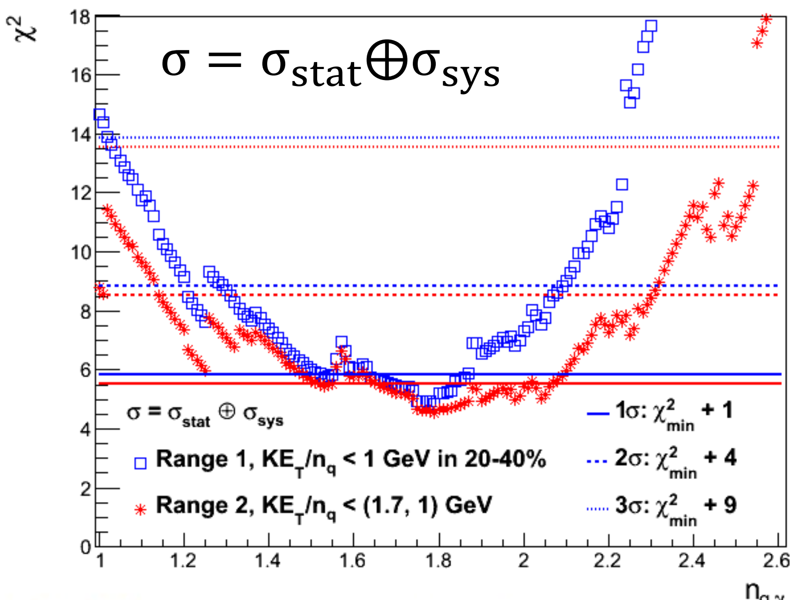
- $\Delta KE_T/n_q < 0.1$
- NDF changes with $n_{q\gamma}$, χ^2 discontinuous

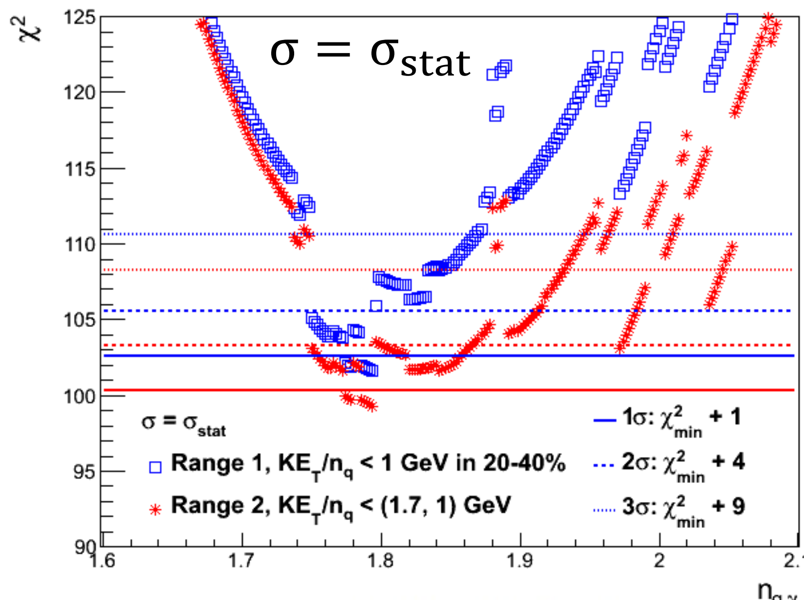
Data-Data Results

$$\chi^2 = \sum_{Cent.} \sum_{\pi,K,p} \sum_{KE_T/n_q} \frac{(v_{2\gamma}/n_{q\gamma} - v_{2h}/n_q)^2}{(\sigma_\gamma/n_{q\gamma})^2 + (\sigma_h/n_q)^2}$$

Range 1: KE_T/n_q < 1 GeV in 20-40%
Range 2: KE_T/n_q < 1.7 GeV in 0-20%
KE_T/n_q < 1 GeV in 20-40%







HEADING	$n_{q\gamma} \pm (stat)$	$n_{q\gamma} \pm (stat) \pm (sys)$
Data, Range 1	$1.79^{+0.08}_{-0.27}$	$1.79^{+0.002+0.67}_{-0.01-0.72}$
Data, Range 2	1.79 ± 0.27	$1.79^{+0.002+1.09}_{-0.01-0.72}$

Data-Fit Calculation

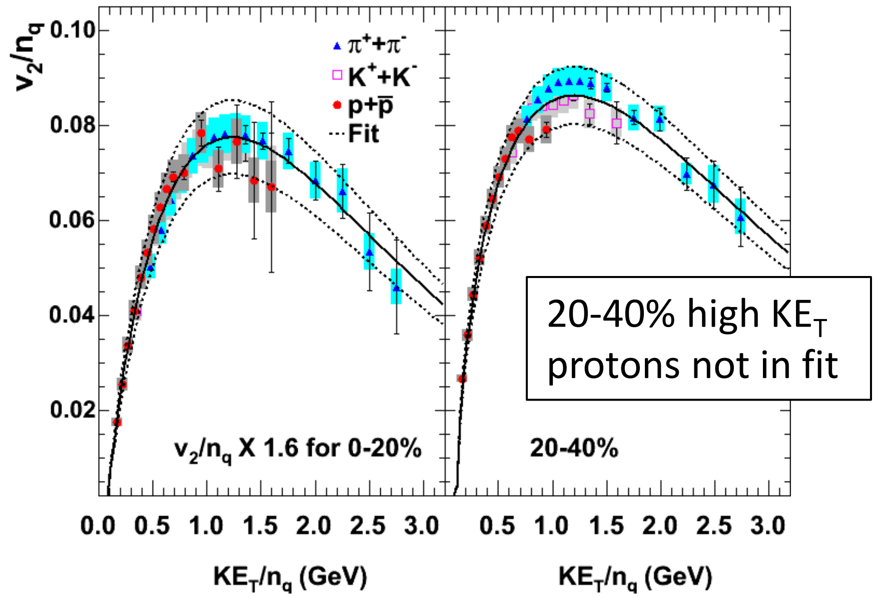
Simultaneous fit to 0-20% and 20-40% with TMinuit

$$\chi^2 = \sum_{Cent.} \sum_{\pi,K,p} \sum_{KE_T/n_q} \frac{(v_{2\gamma}/n_{q\gamma} - v_{2h}/n_q)^2}{(\sigma_\gamma/n_{q\gamma})^2 + (\sigma_h/n_q)^2}$$

Fit to π, K, p v_2/n_q

Use probability density function of Gamma distribution,

$$G(x) = A\,\frac{((x-\mu)/\beta)^{\gamma-1} e^{-1(x-\mu)/\beta}}{\beta\Gamma(\gamma)}$$



	$\sigma_\gamma = \sigma_{stat} \oplus \sigma_{sys}$	$\sigma_\gamma = \sigma_{stat}$
HEADING	$n_{q\gamma} \pm (stat)$	$n_{q\gamma} \pm (stat) \pm (sys)$
Fit, Range 1	1.59 ± 0.22	$1.79 \pm 0.02^{+0.85}_{-0.68}$
Fit, Range 2	1.83 ± 0.44	$1.88 \pm 0.07^{+1.18}_{-0.71}$

χ^2 Results

	Uncorrelated sys errors		Fully-correlated sys errors	
	$\sigma_\gamma = \sigma_{stat} \oplus \sigma_{sys}$		$\sigma_\gamma = \sigma_{stat}$	
HEADING	$n_{q\gamma} \pm (stat)$	χ^2/NDF	$n_{q\gamma} \pm (stat) \pm (sys)$	χ^2/NDF
Data, Range 1	$1.79^{+0.08}_{-0.27}$	$4.85/20 = 0.24$	$1.79^{+0.002+0.67}_{-0.01-0.72}$	$101.6/20 = 5.1$
Data, Range 2	1.79 ± 0.27	$4.53/17 = 0.27$	$1.79^{+0.002+1.09}_{-0.01-0.72}$	$99.5/17 = 5.9$
Fit, Range 1	1.59 ± 0.22	$3.51/13 = 0.26$	$1.79 \pm 0.02^{+0.85}_{-0.68}$	$44.67/14 = 3.19$
Fit, Range 2	1.83 ± 0.44	$1.55/5 = 0.31$	$1.88 \pm 0.07^{+1.18}_{-0.71}$	$34.14/6 = 5.68$

χ^2/NDF < 1
→ over-estimating uncorrelated errors

χ^2/NDF > 1
→ under-estimating uncorrelated errors

Need systematic errors separated in correlated and uncorrelated types to interpret χ^2/NDF values.

χ^2 Results

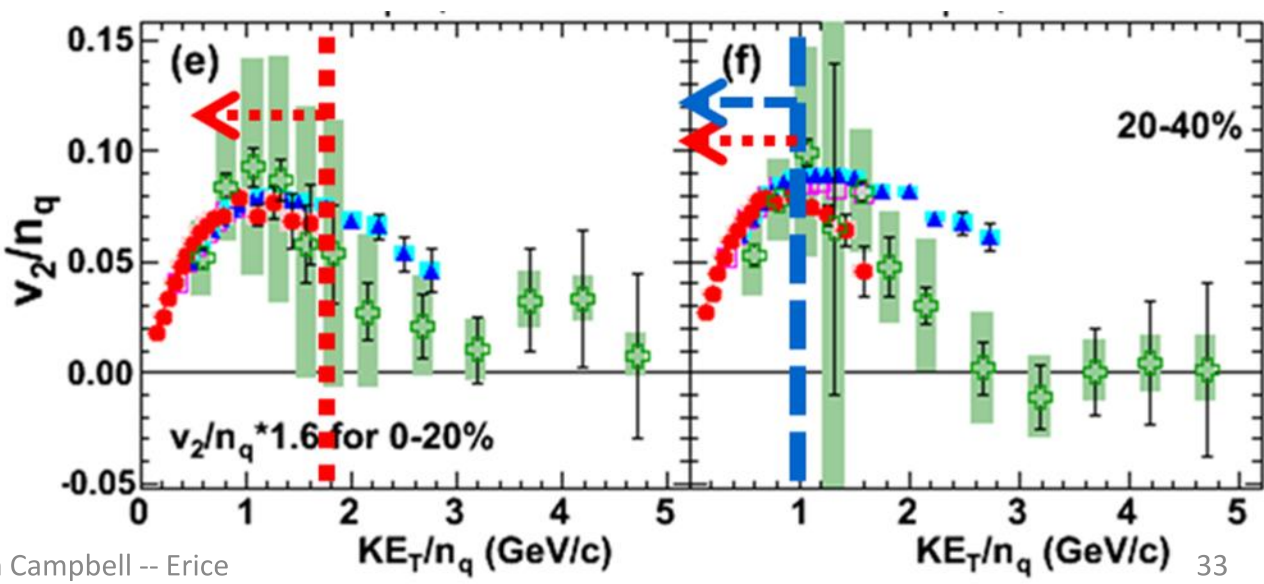
	$\sigma_\gamma = \sigma_{stat} \oplus \sigma_{sys}$		$\sigma_\gamma = \sigma_{stat}$	
HEADING	$n_{q\gamma} \pm (stat)$	$n_{q\gamma} = 2$	$n_{q\gamma} \pm (stat) \pm (sys)$	$n_{q\gamma} = 2$
Data, Range 1	$1.79^{+0.08}_{-0.27}$	2σ	$1.79^{+0.002+0.67}_{-0.01-0.72}$	1σ
Data, Range 2	1.79 ± 0.27	1σ	$1.79^{+0.002+1.09}_{-0.01-0.72}$	1σ
Fit, Range 1	1.59 ± 0.22	2σ	$1.79 \pm 0.02^{+0.85}_{-0.68}$	1σ
Fit, Range 2	1.83 ± 0.44	1σ	$1.88 \pm 0.07^{+1.18}_{-0.71}$	1σ

Range 1:

- KE_T/n_q < 1 GeV in 20-40%

Range 2:

- KE_T/n_q < 1.7 GeV in 0-20%
- KE_T/n_q < 1 GeV in 20-40%



Blast Wave m_T Distrib

From Physical Review C 48, 2462 (1993):

$$\frac{d^3N}{dm_T dy d\phi} \propto m_T^2 r cosh(y) e^{\frac{p_T sinh(\rho) cos(\phi) - m_T cosh(\rho) cosh(y)}{T}}$$

where T is the temperature,

$$m_T = \sqrt{p_T^2 + m_q^2}$$

$$\rho = atanh\left(\beta_S \left(r/R\right)^{\alpha}\right)$$

From PRD 89 026013 (2005):

m_q = 300 MeV

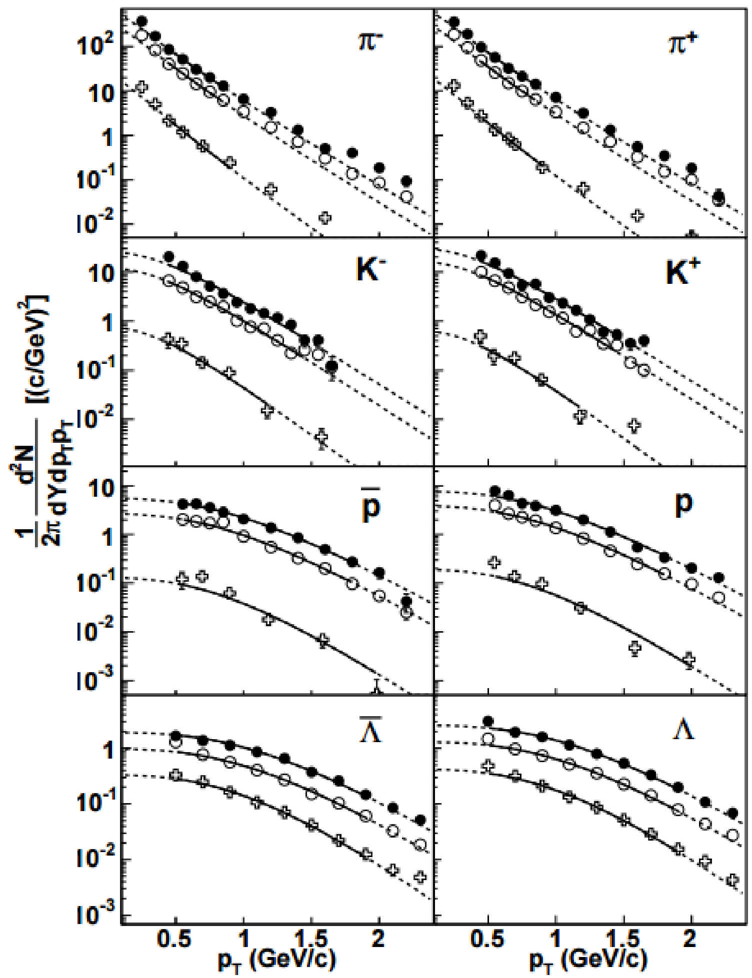
T = 106 MeV

R = 8.5 fm

β_S = 0.75

α = 1

} $\langle\beta\rangle$ = 0.5



Comoving requirements

From probability functions in PRC 68 034904 (2003):

Mesons

$$f_M(x_1,x_2;p_1,p_2)=\frac{9\pi}{2(\Delta_x\Delta_p)^3}\Theta(\Delta_x^2-(x_1-x_2)^2)\Theta(\Delta_p^2-\frac{1}{4}(p_1-p_2)^2+\frac{1}{4}(m_1-m_2)^2), \quad (3)$$

where Δ_x and Δ_p are the covariant spatial and momentum coalescence radii, and they are related by the uncertainty

$$|x_1 - x_2| < \Delta x$$
$$|p_1 - p_2| < 2\Delta p$$

$$\Delta x_M = \Delta x_B = 0.85 \text{ fm}$$
$$\Delta p_M = \Delta p_B = 0.2 \text{ GeV/c}$$
$$m_1 = m_2 = m_3$$

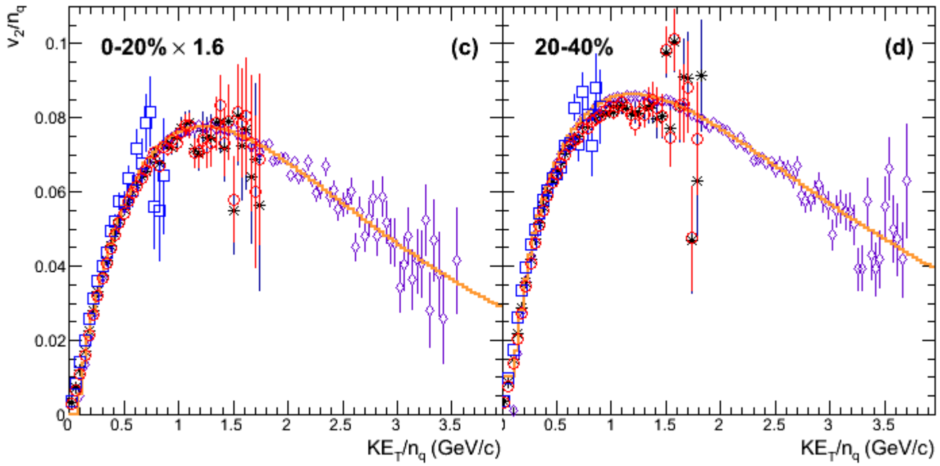
Baryons

$$\begin{aligned} f_B(x_1,x_2,x_3;p_1,p_2,p_3) &= \frac{9\pi}{2\Delta_x^3\Delta_p^3}\Theta\left(\Delta_x^2-\frac{1}{2}(x_1-x_2)^2\right) \\ &\times\Theta\left(\Delta_p^2-\frac{1}{2}(p_1-p_2)^2\right)\frac{9\pi}{2\Delta_x^3\Delta_p^3} \\ &\times\Theta\left(\Delta_x^2-\frac{1}{6}(x_1+x_2-2x_3)^2\right) \\ &\times\Theta\left(\Delta_p^2-\frac{1}{6}[(p_1+p_2-2p_3)^2\right. \end{aligned}$$

$$|x_1 - x_2| < \Delta x\sqrt{2}$$
$$|x_1 + x_2 - 2x_3| < \Delta x\sqrt{6}$$
$$|p_1 - p_2| < \Delta p\sqrt{2}$$
$$|p_1 + p_2 - 2p_3| < \Delta p\sqrt{6}$$

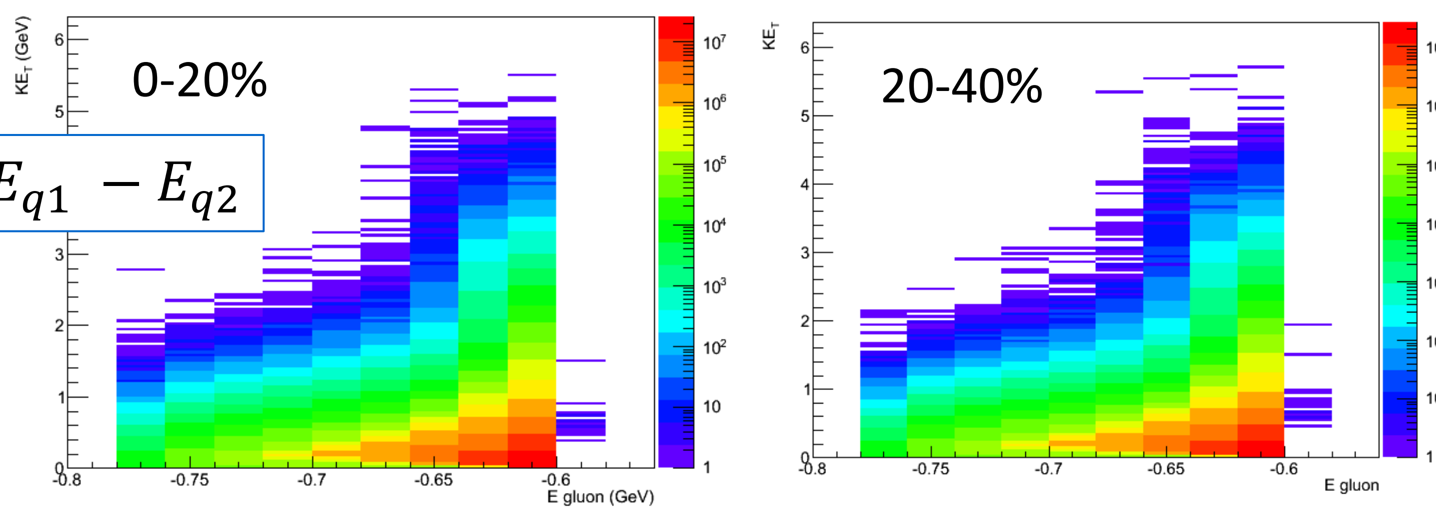
Kinetic energy conservation

Kinetic energy conservation best reproduced the n_q-scaling seen in the data



Gluon's energy component

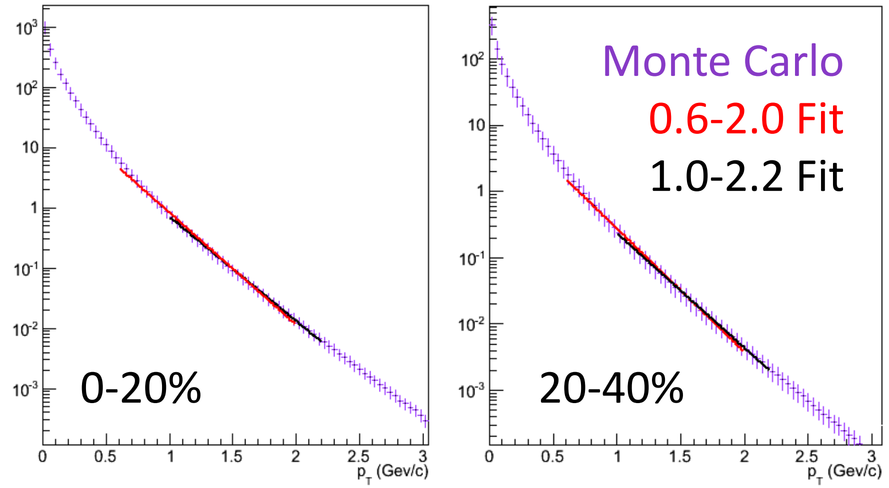
$$E_{gluon} = E_{\gamma} - E_{q1} - E_{q2}$$



Gluons remove ~600 MeV of energy

p_T shape: Inverse slopes

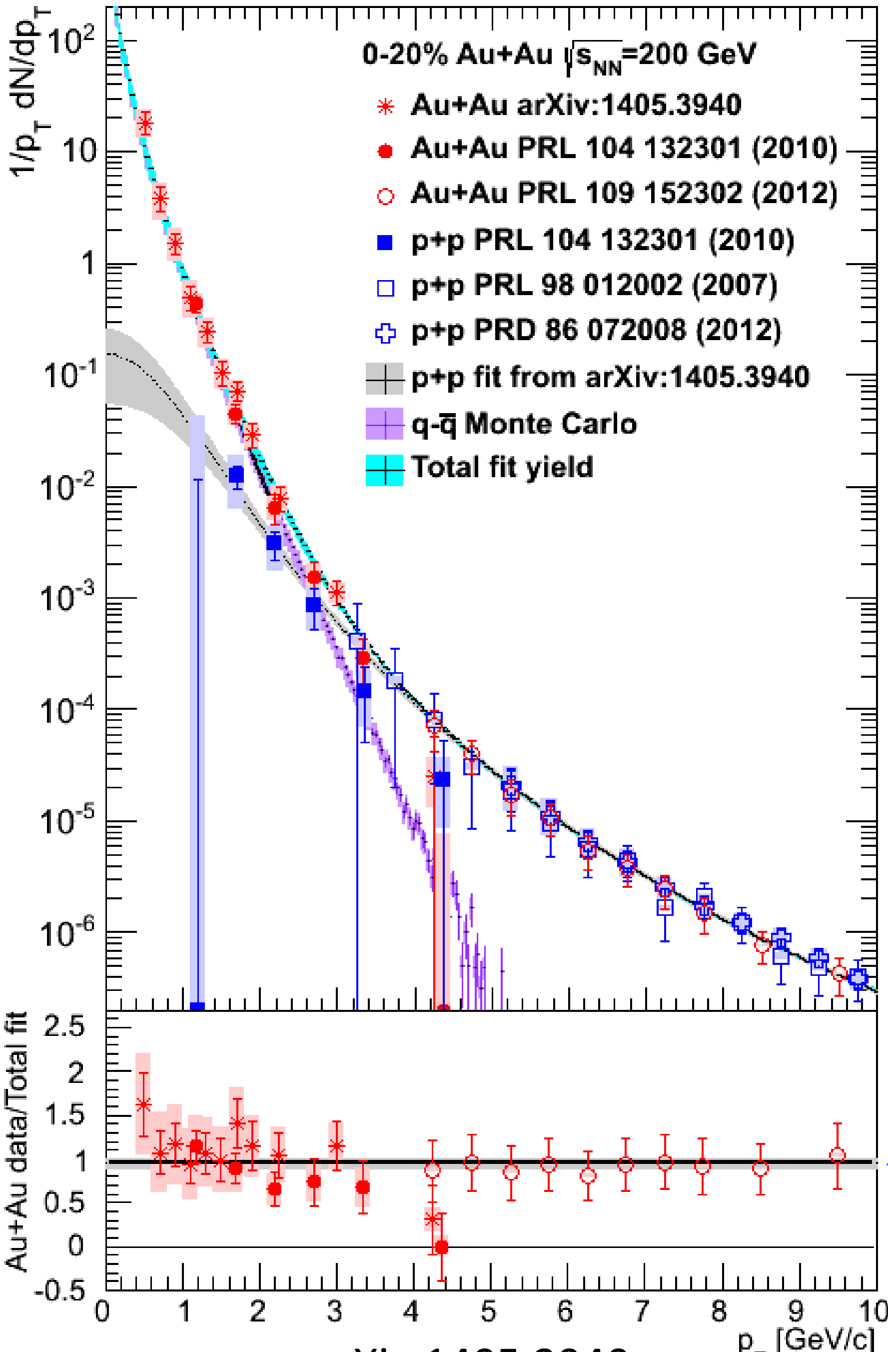
Fit p_T shape with exponential, $Ae^{-p_T/T}$



Centrality	p_T range	Monte Carlo	Au+Au data [2, 3]
0-20%	$0.6 < p_T < 2.0$ GeV/c	233 ± 6	$239 \pm 29 \pm 7$
0-20%	$1.0 < p_T < 2.2$ GeV/c	251 ± 8	$221 \pm 19 \pm 19$
20-40%	$0.6 < p_T < 2.0$ GeV/c	233 ± 8	$260 \pm 33 \pm 8$
20-40%	$1.0 < p_T < 2.2$ GeV/c	251 ± 10	$217 \pm 18 \pm 16$

Can this source describe the shape of the excess p_T yield?

→ Inverse slopes are consistent with values from data



arXiv:1405.3940

0-20% p_T spectrum

Fit to the measured yields:

$$\frac{1}{p_T}\frac{dN}{dp_T} = N\left(\frac{1}{p_T}\frac{dN}{dp_T}\right)_{MC} + T_{AA}\left(\frac{1}{p_T}\frac{dN}{dp_T}\right)_{pp}$$

The only free parameter

From p+p data, p+p fit at low p_T

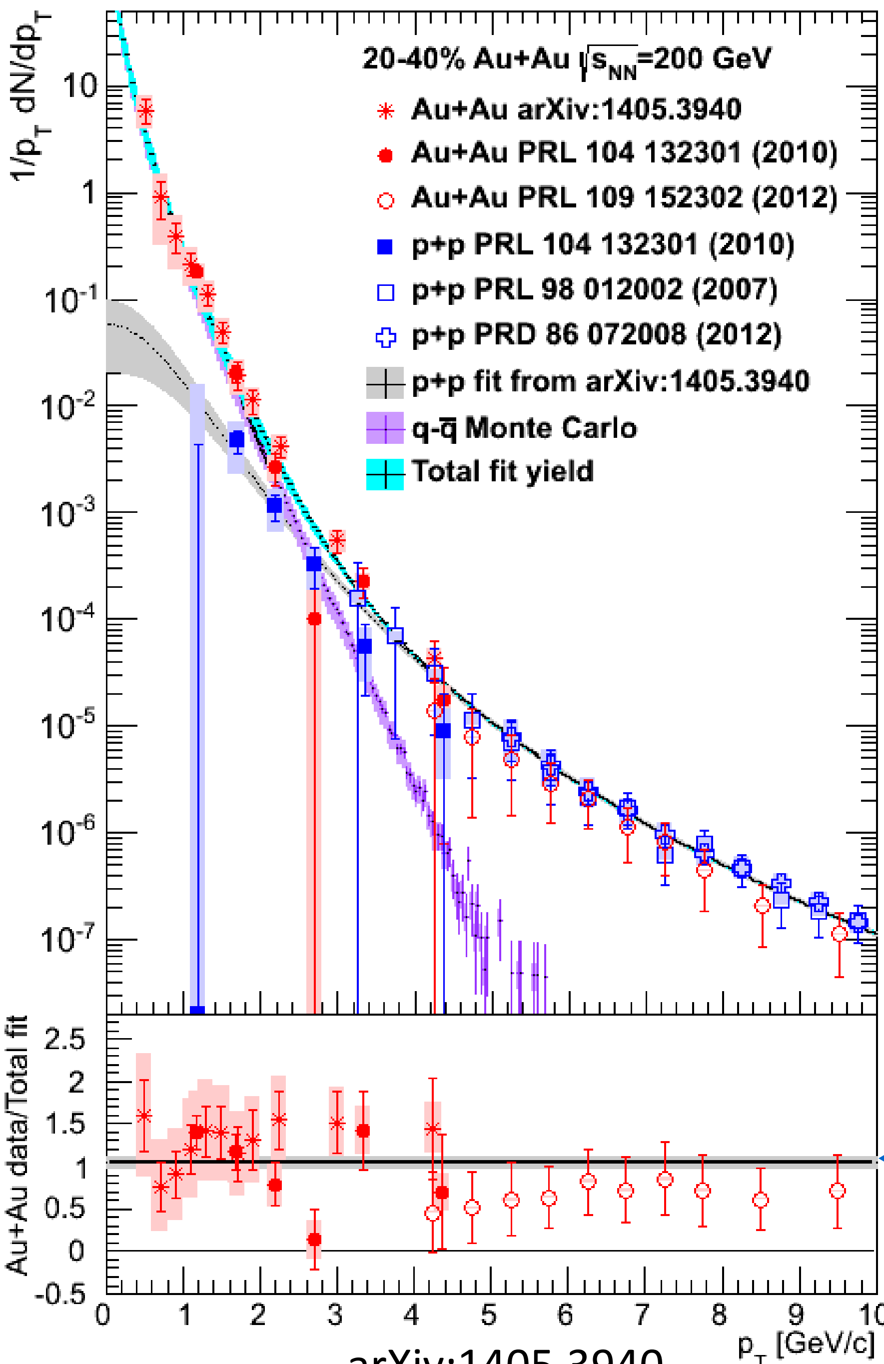
$$\chi^2/NDF = 20.69/22 = 0.94$$

Can this source describe the shape of the excess p_T yield?

→ Yes

Flat!

$$\frac{Au+Au\ data}{Total\ fit} = 0.951 \pm 0.051$$



arXiv:1405.3940

20-40% p_T spectrum

Fit to the measured yields:

$$\frac{1}{p_T}\frac{dN}{dp_T} = N\left(\frac{1}{p_T}\frac{dN}{dp_T}\right)_{MC} + T_{AA}\left(\frac{1}{p_T}\frac{dN}{dp_T}\right)_{pp}$$

$$\chi^2/NDF = 35.12/22 = 1.60$$

Can this source describe the shape of the excess p_T yield?

→ Yes

Flat!

$$\frac{Au+Au\ data}{Total\ fit} = 1.038\ \pm 0.046$$

$$\chi^2/NDF = 32.5/26 = 1.25$$

0-20% v_2

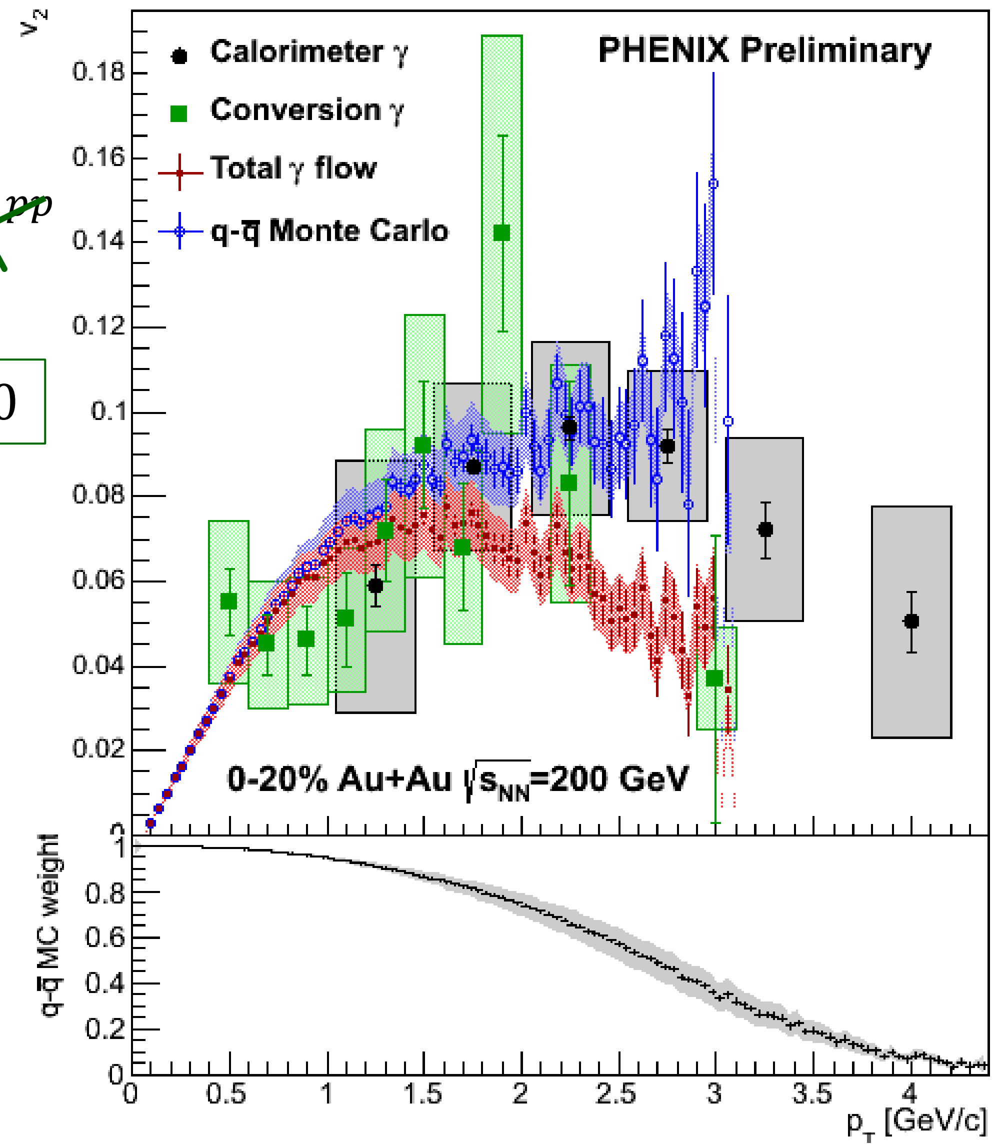
$$v_2 = \frac{Yield_{MC}}{Yield_{Total}} v_2{}^{MC} + \frac{Yield_{pp}}{Yield_{Total}} v_2{}^{pp}$$

q-q MC weight

$v_2{}^{pp} = 0$

Can this source reproduce the v_2 at low p_T?

→ Yes, systematically low at p_T > 2 GeV/c



arXiv:1504.01654

20-40% v_2

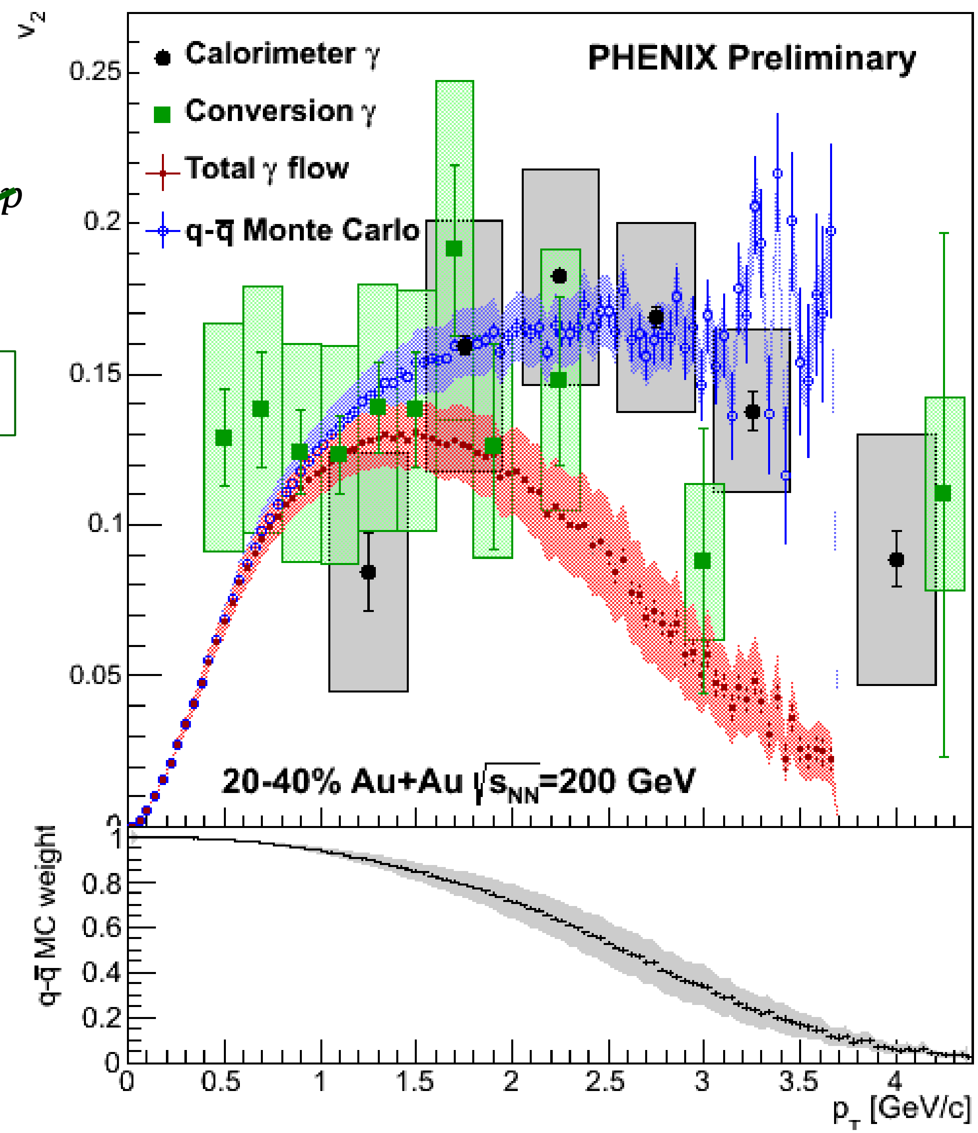
$$v_2 = \frac{Yield_{MC}}{Yield_{Total}} v_2^{MC} + \frac{Yield_{pp}}{Yield_{Total}} v_2^{pp}$$

q-q MC weight

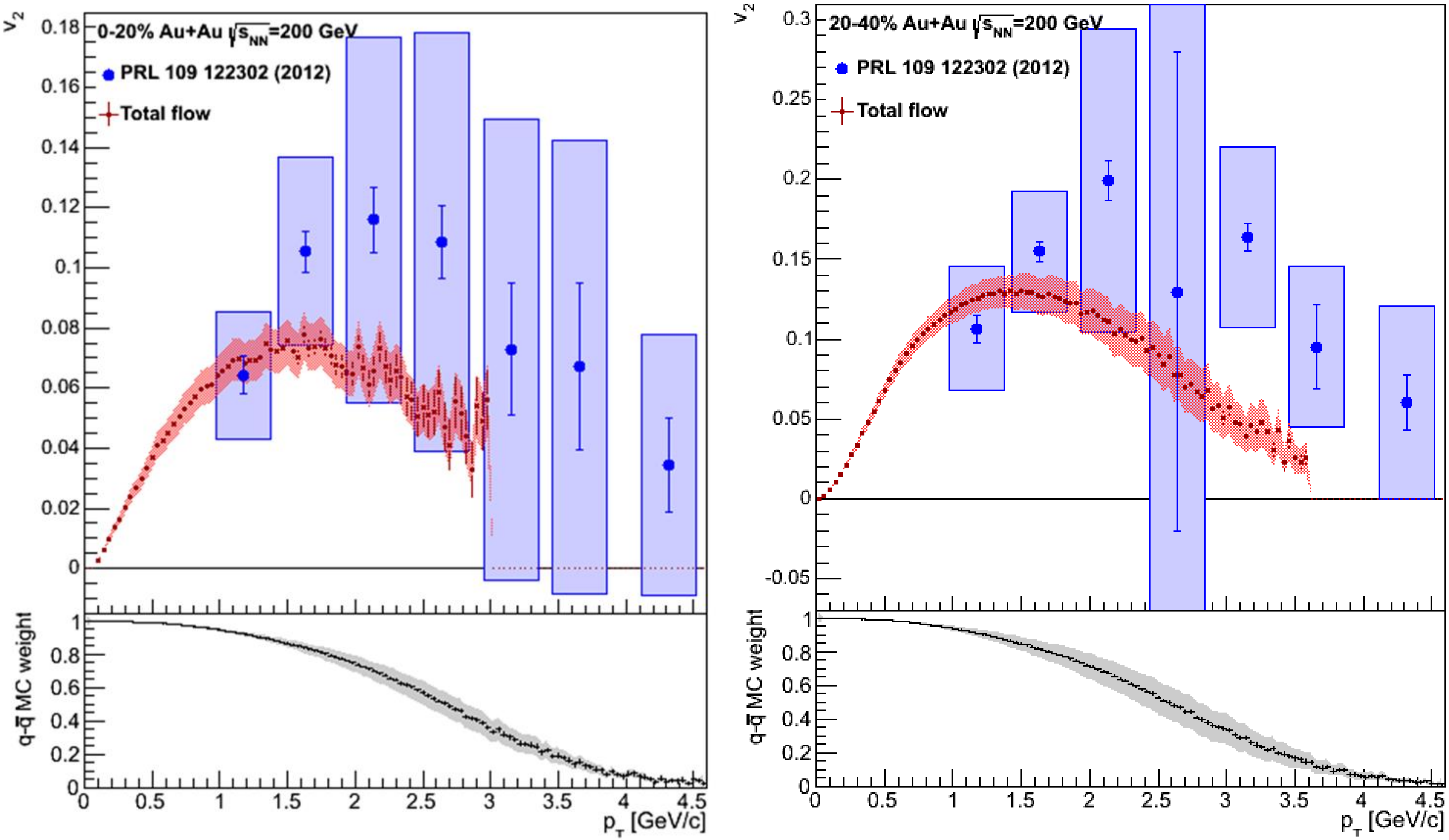
$v_2^{pp} = 0$

Can this source reproduce the v_2 at low p_T?

→ Yes, systematically low at p_T > 2 GeV/c

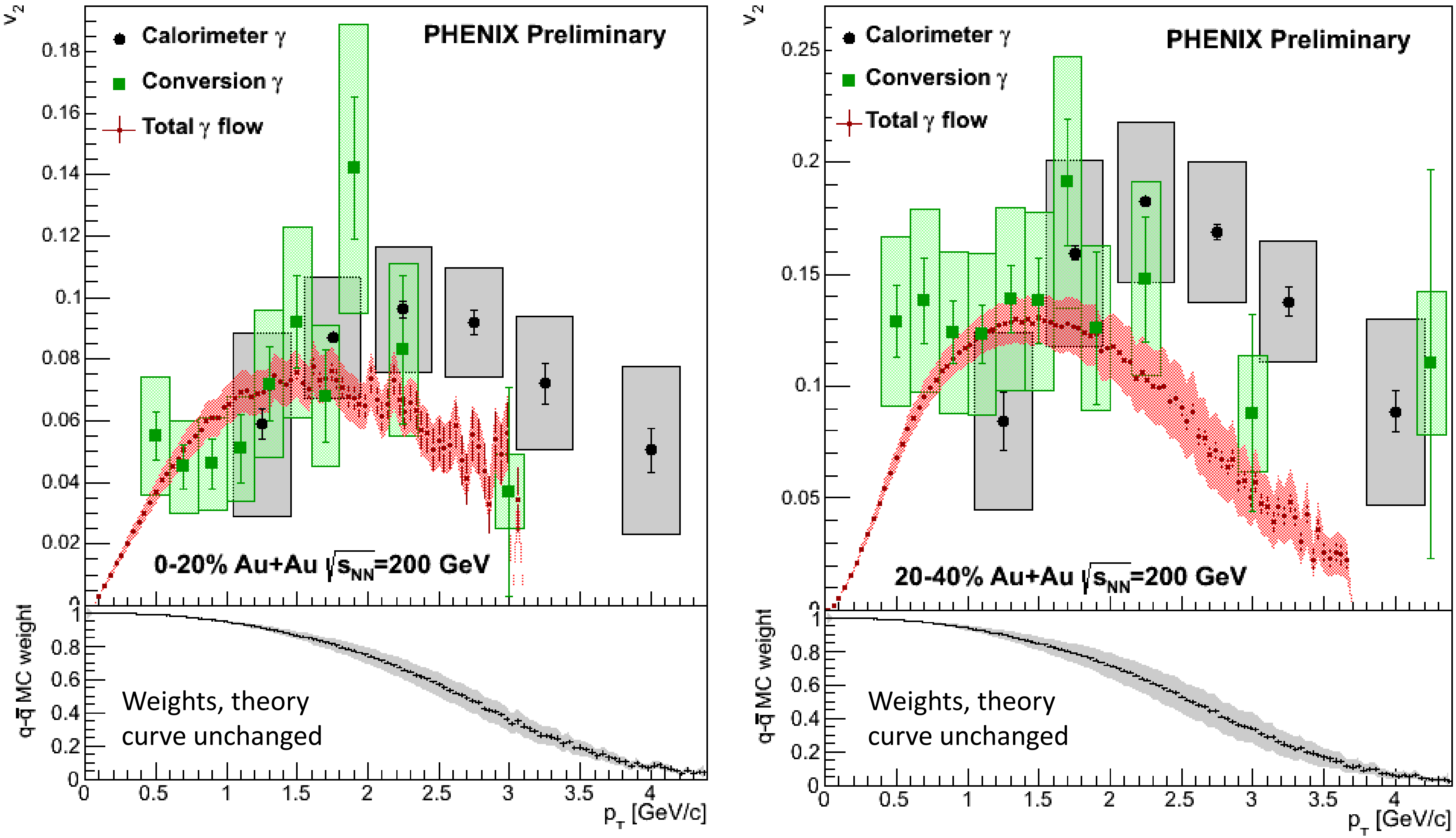


At low p_T



Can this source reproduce the v_2 at low p_T? → Yes

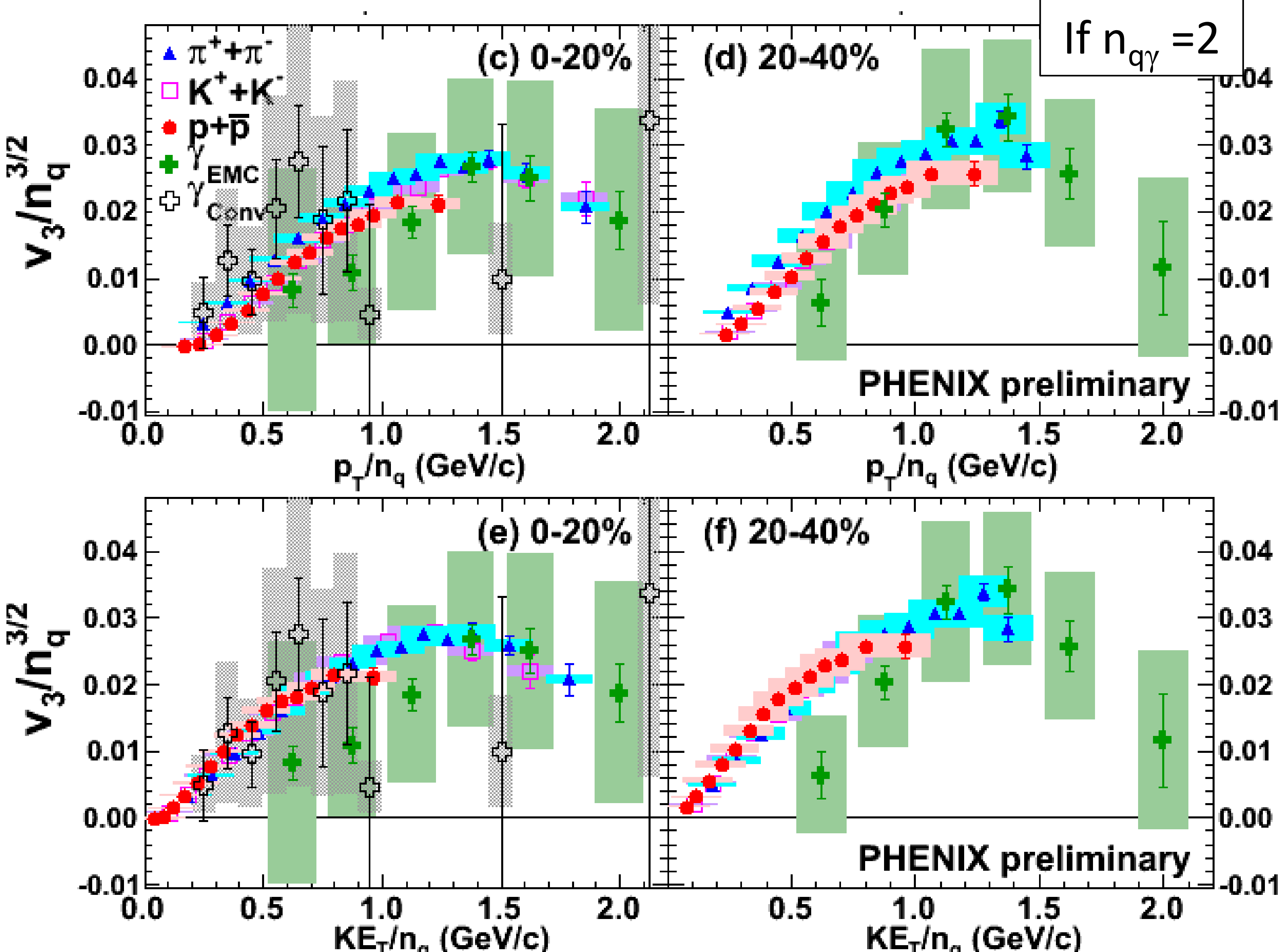
With preliminary results



Can this source reproduce the v_2 at low p_T? → Yes

Direct photon v_3 modified n_q-scaling

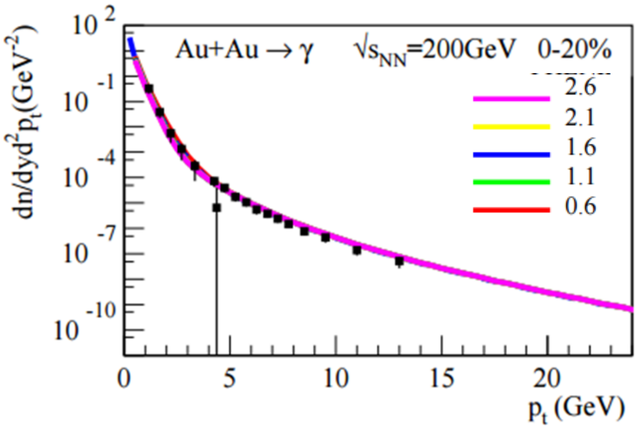
If $n_{q\gamma}$ =2

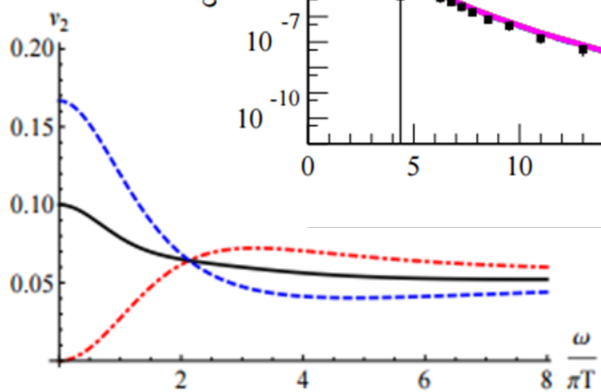


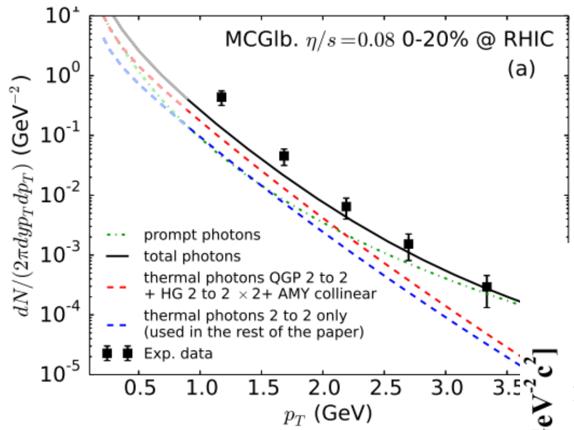
arXiv:1412.1038

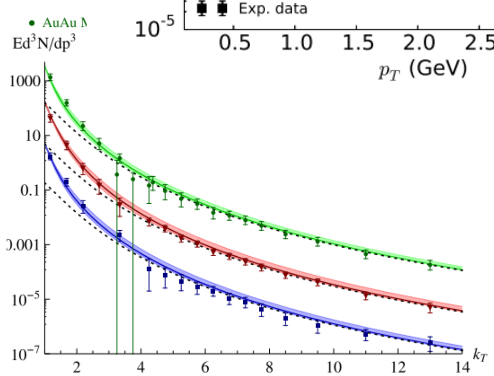
A Few Theories

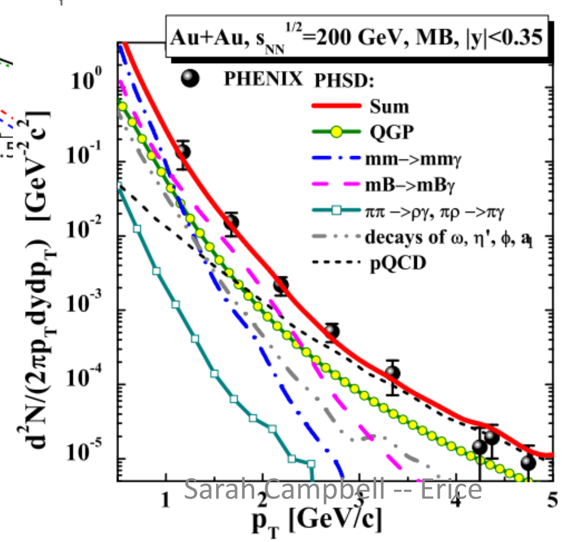
- Delayed QGP formation
- Magnetic fields
- Initial state Glasma effects
- Hydrodynamic models
- In HG: baryon-baryon, meson-baryon interactions

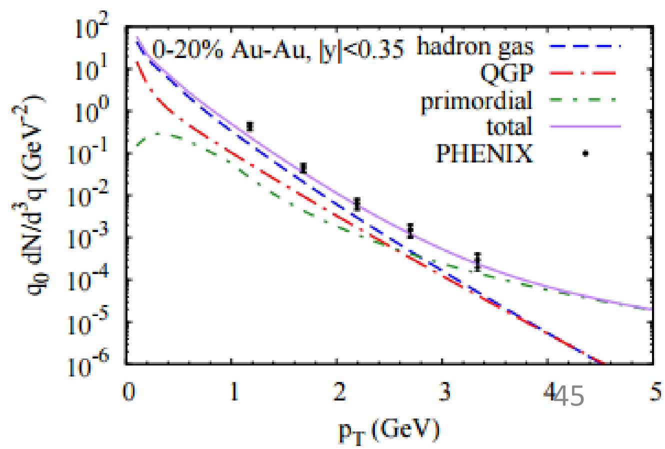




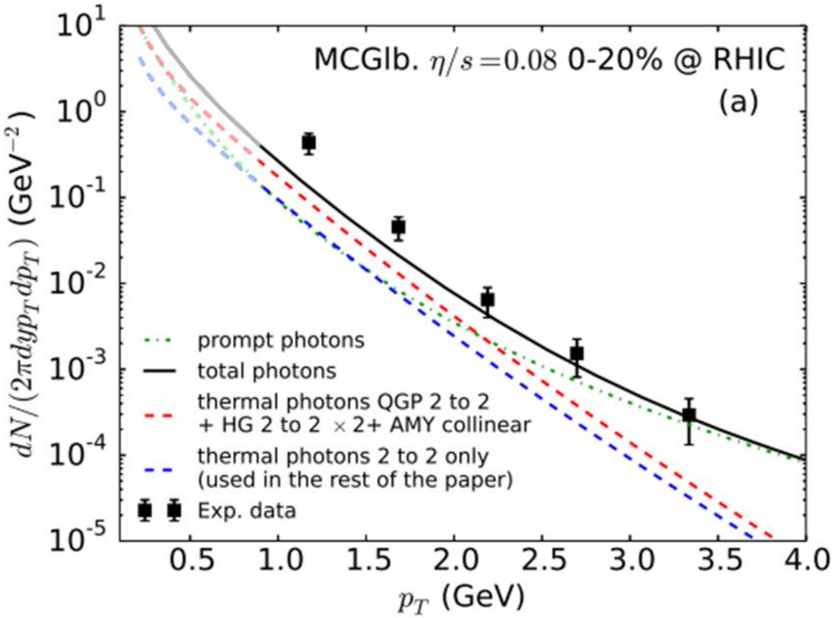


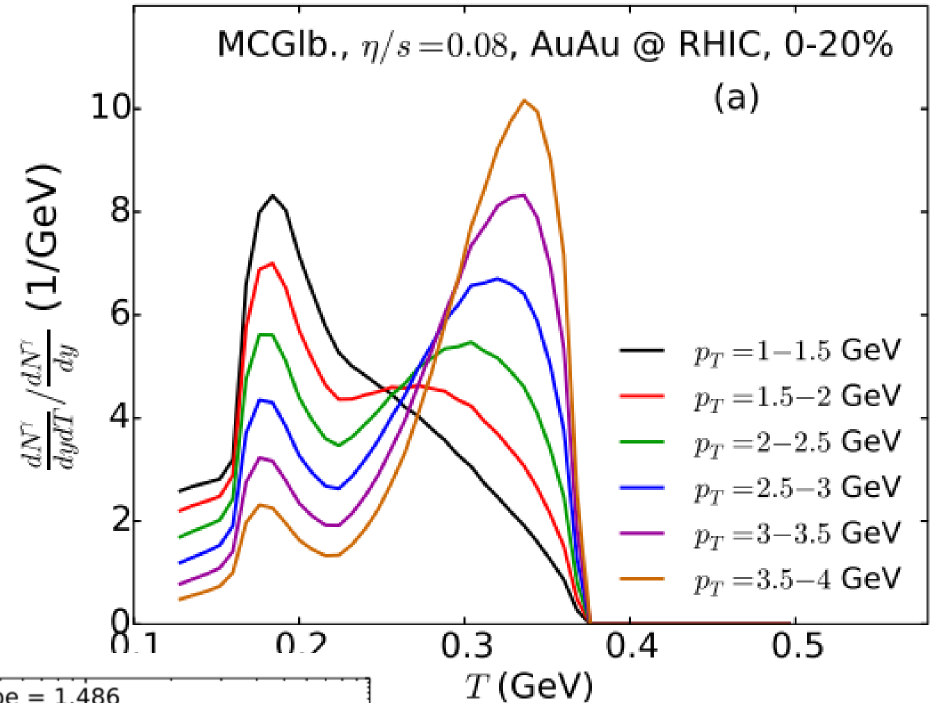


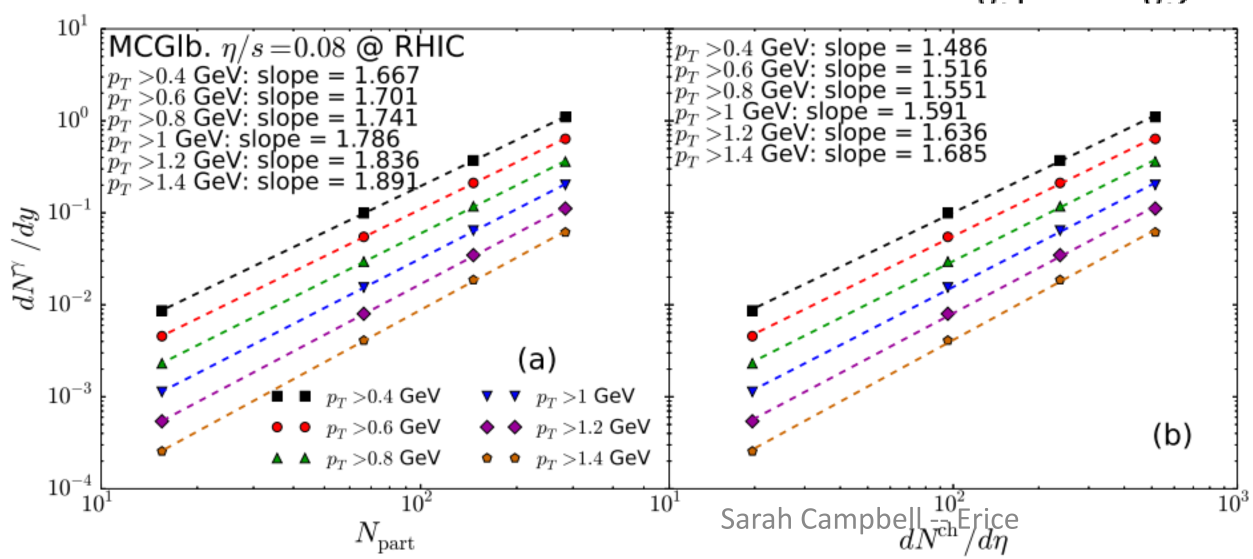




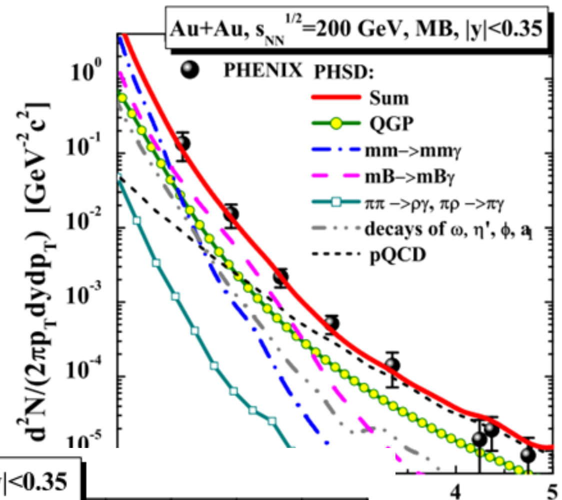
Chun: Hydro

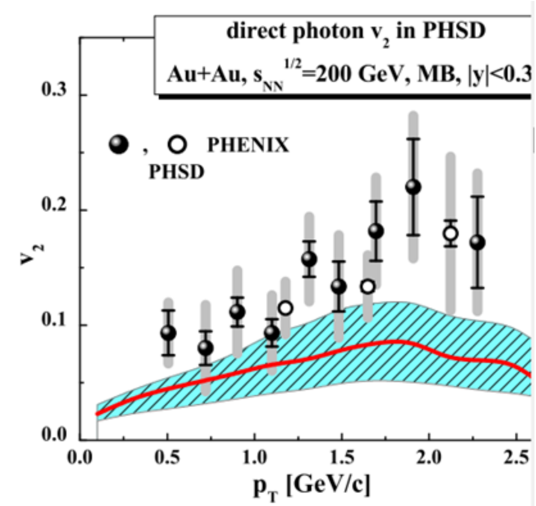

MCGlb. $\eta/s = 0.08$ 0-20% @ RHIC
(a)
$dN/(2\pi dy p_T dp_T)$ (GeV^{-2})
p_T (GeV)
prompt photons
total photons
thermal photons QGP 2 to 2 + HG 2 to 2 × 2+ AMY collinear
thermal photons 2 to 2 only (used in the rest of the paper)
Exp. data

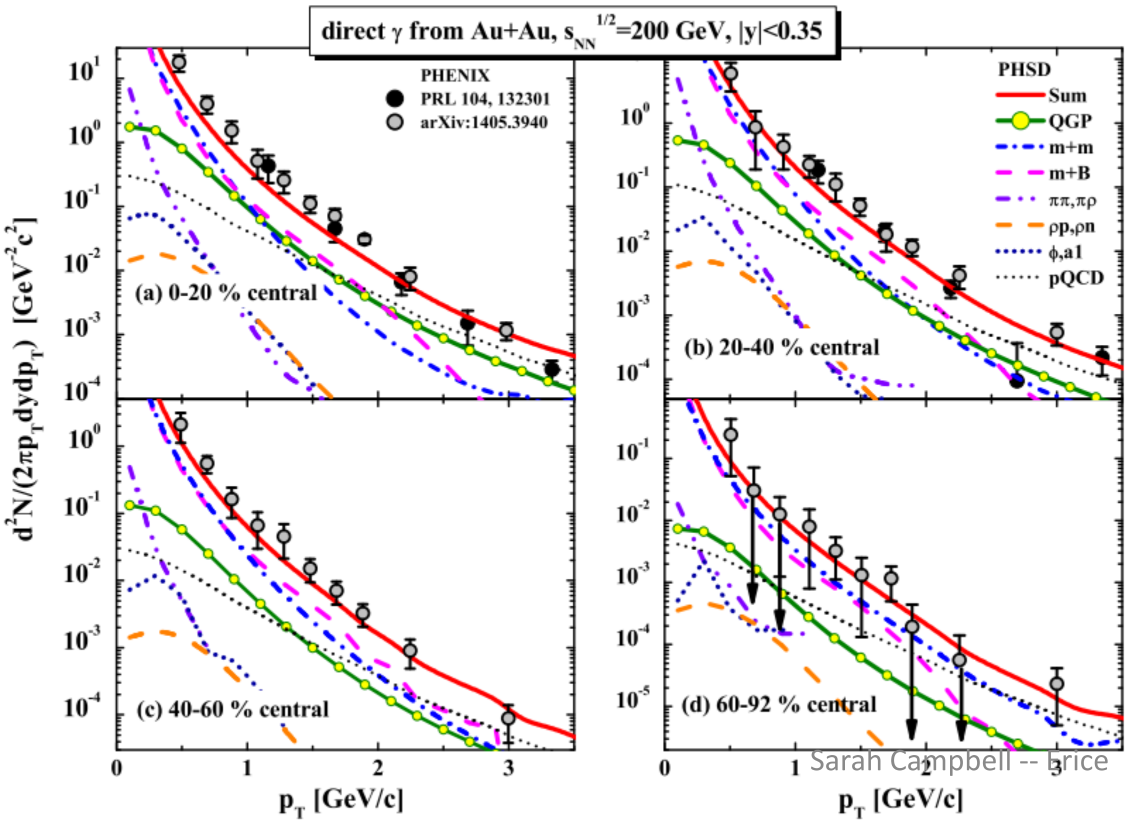

MCGlb., $\eta/s = 0.08$, AuAu @ RHIC, 0-20%
(a)
$\frac{dN^\gamma}{dydT} / \frac{dN^\gamma}{dy}$ (1/GeV)
T (GeV)
$p_T = 1-1.5$ GeV
$p_T = 1.5-2$ GeV
$p_T = 2-2.5$ GeV
$p_T = 2.5-3$ GeV
$p_T = 3-3.5$ GeV
$p_T = 3.5-4$ GeV


MCGlb. $\eta/s = 0.08$ @ RHIC
$p_T > 0.4$ GeV: slope = 1.667
$p_T > 0.6$ GeV: slope = 1.701
$p_T > 0.8$ GeV: slope = 1.741
$p_T > 1$ GeV: slope = 1.786
$p_T > 1.2$ GeV: slope = 1.836
$p_T > 1.4$ GeV: slope = 1.891
(a)
$p_T > 0.4$ GeV
$p_T > 0.6$ GeV
$p_T > 0.8$ GeV
$p_T > 1$ GeV
$p_T > 1.2$ GeV
$p_T > 1.4$ GeV
dN^γ/dy
N_{part}
$p_T > 0.4$ GeV: slope = 1.486
$p_T > 0.6$ GeV: slope = 1.516
$p_T > 0.8$ GeV: slope = 1.551
$p_T > 1$ GeV: slope = 1.591
$p_T > 1.2$ GeV: slope = 1.636
$p_T > 1.4$ GeV: slope = 1.685
(b)
$dN^{ch}/d\eta$

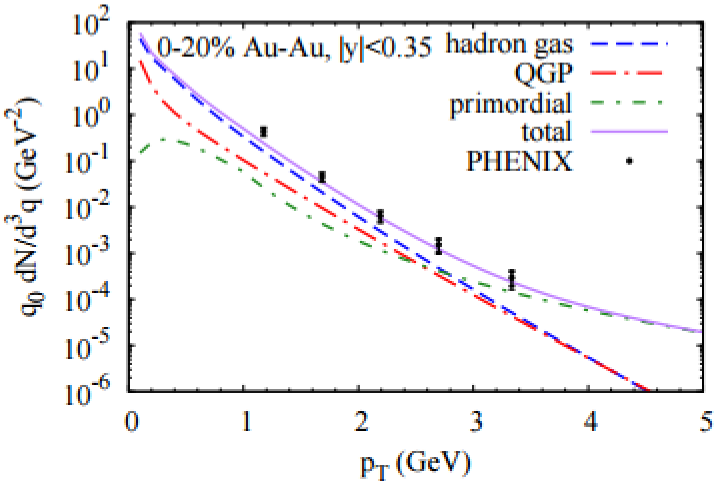
PHSD

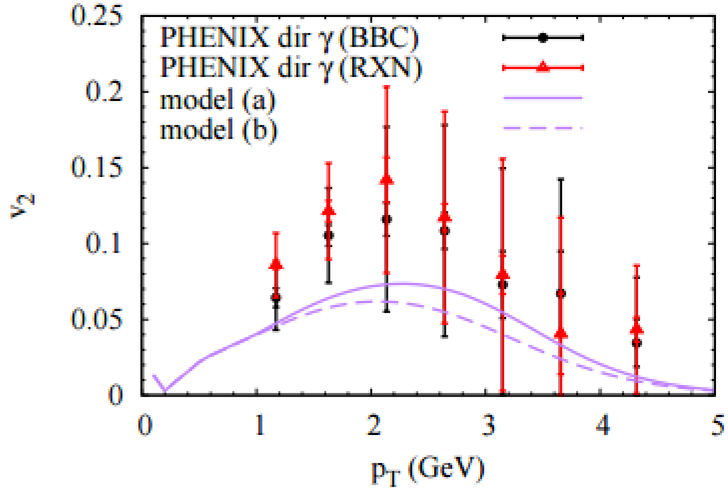

Au+Au, $s_{NN}^{1/2}$=200 GeV, MB, |y|<0.35
PHENIX PHSD:
Sum
QGP
mm->mmγ
mB->mBγ
ππ ->ργ, πρ ->πγ
decays of ω, η', φ, a1
pQCD
$d^2N/(2\pi p_T dydp_T)$ [$GeV^{-2}c^2$]
4
5

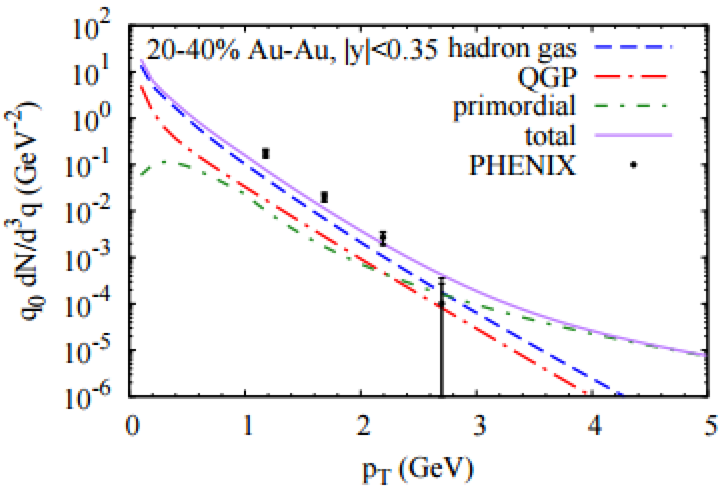

direct photon v_2 in PHSD
Au+Au, $s_{NN}^{1/2}$=200 GeV, MB, |y|<0.3
PHENIX
PHSD
v_2
p_T [GeV/c]

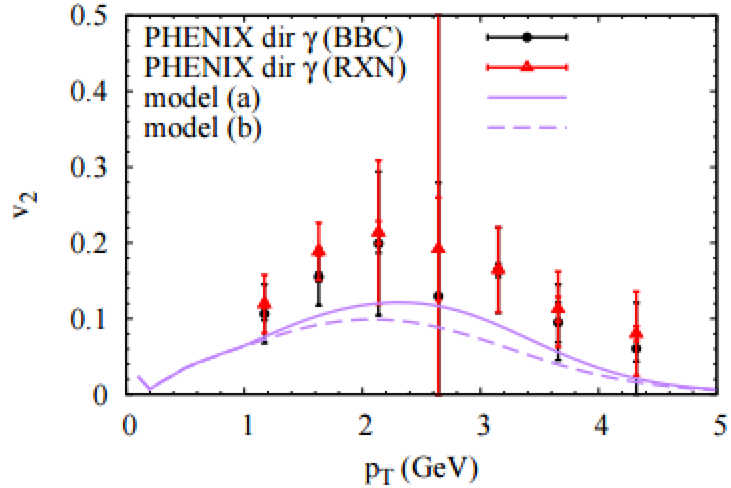

direct γ from Au+Au, $s_{NN}^{1/2}$=200 GeV, |y|<0.35
PHENIX
PRL 104, 132301
arXiv:1405.3940
PHSD
Sum
QGP
m+m
m+B
ππ,πρ
ρp,ρn
φ,a1
pQCD
(a) 0-20 % central
(b) 20-40 % central
(c) 40-60 % central
(d) 60-92 % central
$d^2N/(2\pi p_T dydp_T)$ [$GeV^{-2}c^2$]
p_T [GeV/c]
p_T [GeV/c]

fireball

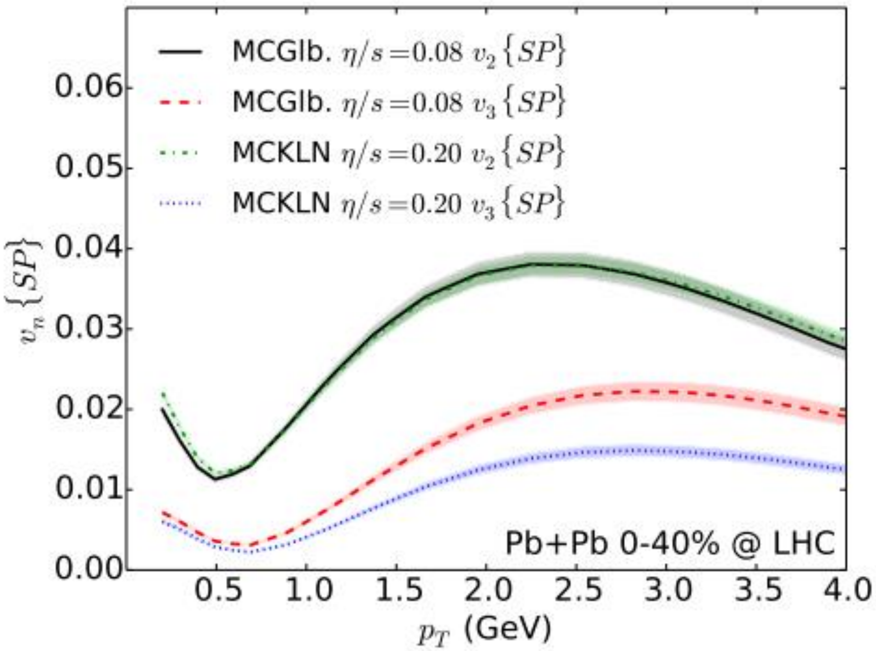

0-20% Au-Au, |y|<0.35
hadron gas
QGP
primordial
total
PHENIX
$q_0\, dN/d^3q\ (GeV^{-2})$
p_T (GeV)


PHENIX dir γ (BBC)
PHENIX dir γ (RXN)
model (a)
model (b)
v_2
p_T (GeV)

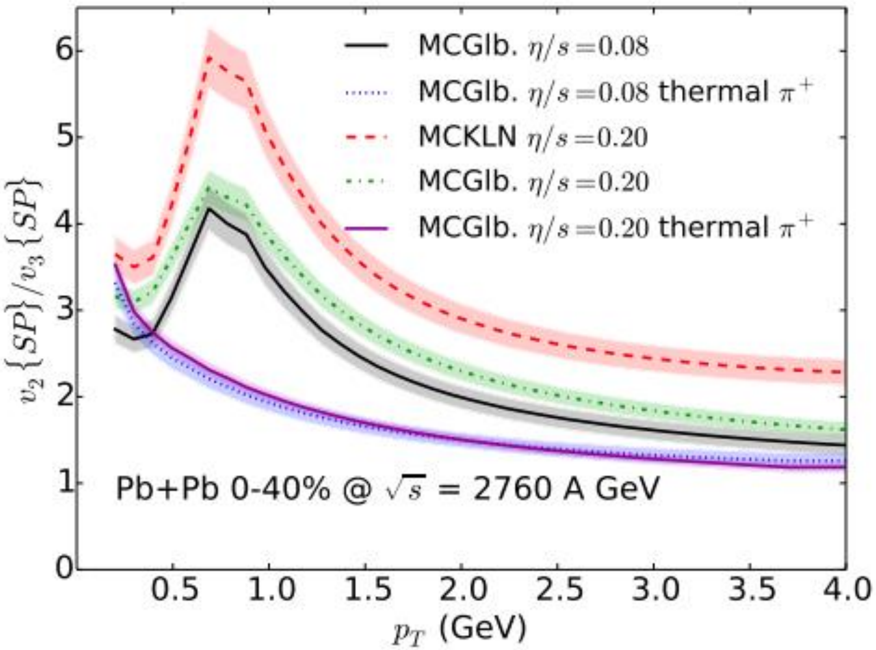

20-40% Au-Au, |y|<0.35
hadron gas
QGP
primordial
total
PHENIX
$q_0\, dN/d^3q\ (GeV^{-2})$
p_T (GeV)


PHENIX dir γ (BBC)
PHENIX dir γ (RXN)
model (a)
model (b)
v_2
p_T (GeV)

v2/v3

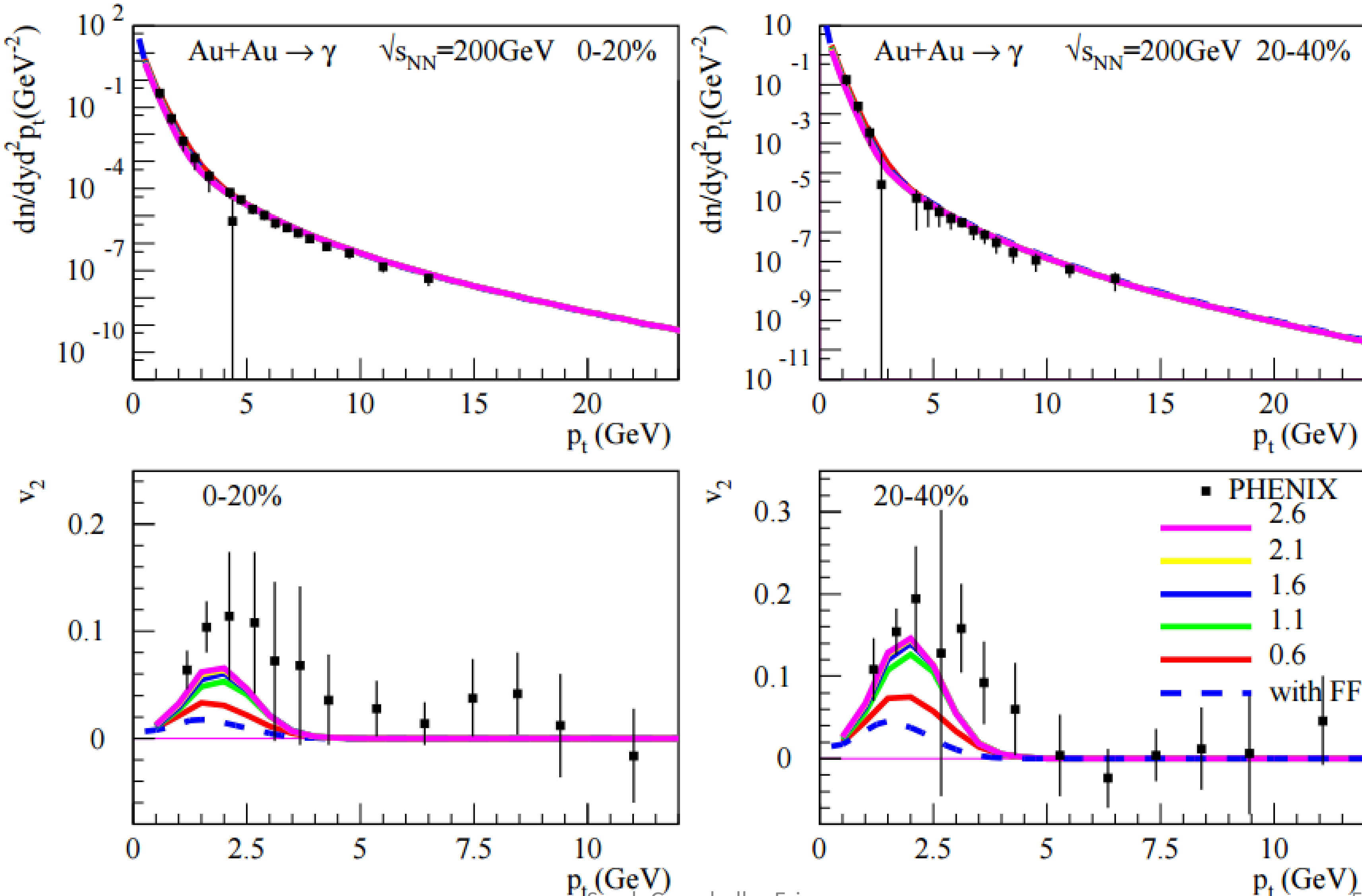


MCGlb. $\eta/s = 0.08$ $v_2\{SP\}$
MCGlb. $\eta/s = 0.08$ $v_3\{SP\}$
MCKLN $\eta/s = 0.20$ $v_2\{SP\}$
MCKLN $\eta/s = 0.20$ $v_3\{SP\}$
$v_n\{SP\}$
Pb+Pb 0-40% @ LHC
p_T (GeV)



MCGlb. $\eta/s = 0.08$
MCGlb. $\eta/s = 0.08$ thermal π^+
MCKLN $\eta/s = 0.20$
MCGlb. $\eta/s = 0.20$
MCGlb. $\eta/s = 0.20$ thermal π^+
$v_2\{SP\}/v_3\{SP\}$
Pb+Pb 0-40% @ $\sqrt{s}$ = 2760 A GeV
p_T (GeV)

FM Liu SX Liu



Au+Au → γ √sNN=200GeV 0-20%
Au+Au → γ √sNN=200GeV 20-40%
dn/dyd²pt(GeV⁻²)
pt (GeV)
v2
0-20%
20-40%
PHENIX
2.6
2.1
1.6
1.1
0.6
with FF

Magnetic field contribution?

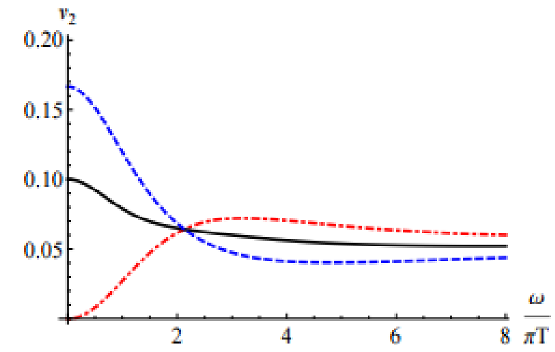


FIG. 2: The red(dot-dashed) and blue(dashed) curves correspond to the v_2 of the photons with in-plane and out-plane polarizations, respectively. The black(solid) curve correspond to the one from the averaged emission rate of two types of polarizations. Here we consider the contribution from massless quarks at $B_z = 1(\pi T)^2$.

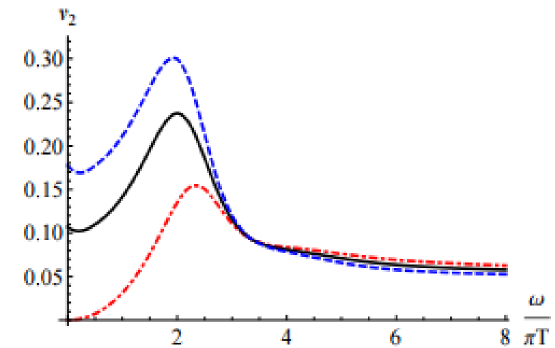


FIG. 3: The colors correspond to the same cases as in Fig.2. Here we consider the contributions from solely the massive quarks with $m = 1.143$ at $B_z = 1(\pi T)^2$.

Also seen at LHC in ALICE