Higher order flow and prospects of thermal photon measurements (PHENIX)

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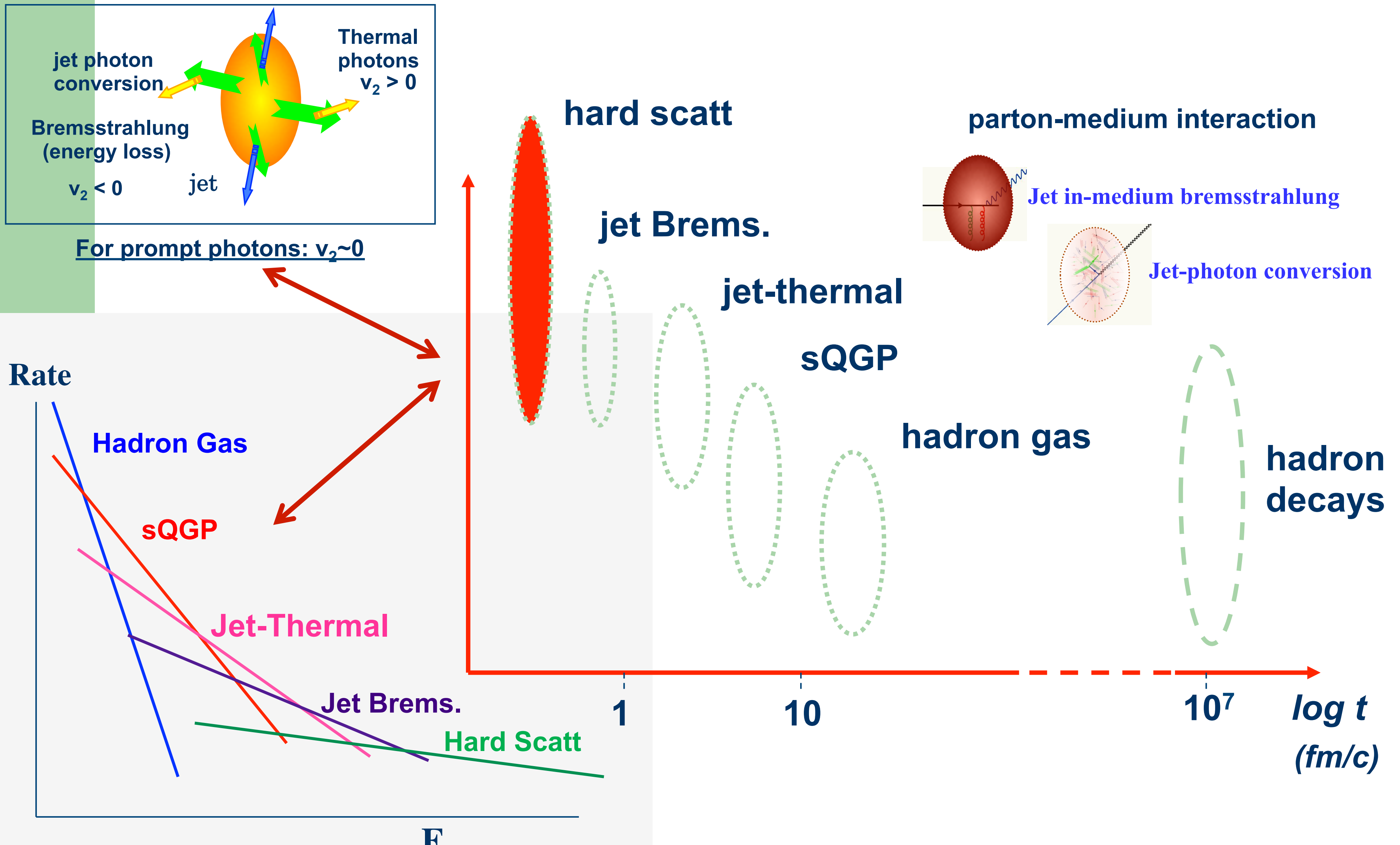
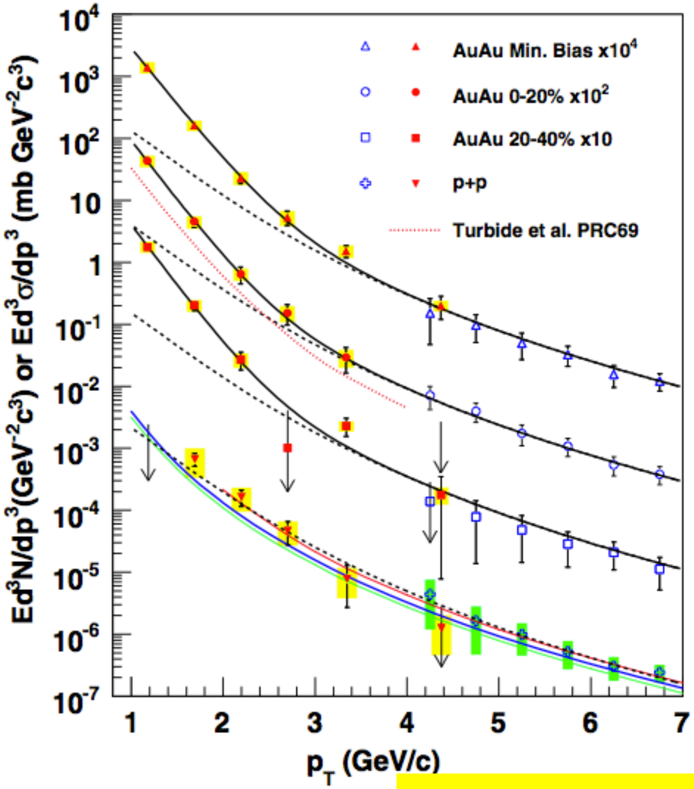
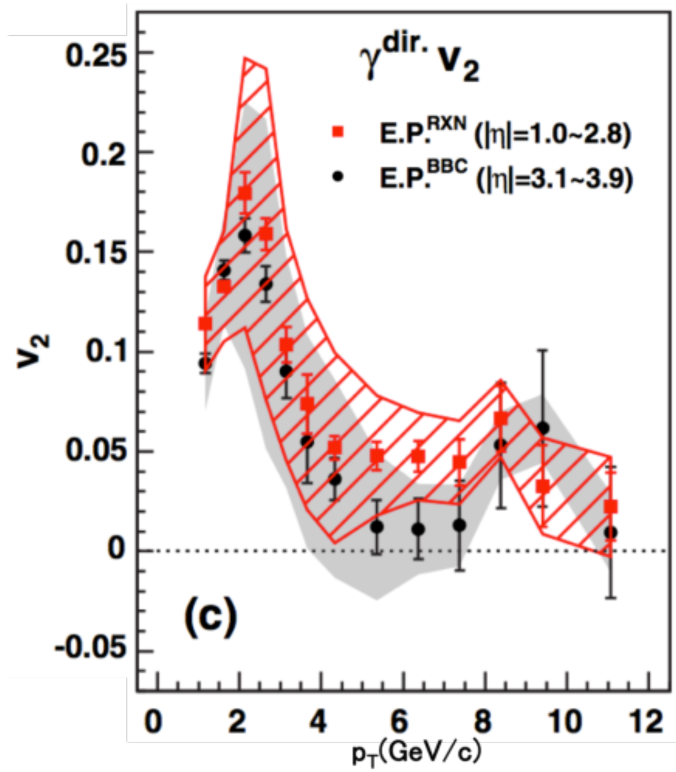
Direct photon production in a nutshell



Puzzle on direct photons at low p_T

- **Large yield** **Phys. Rev. Lett. 104**, 132301
  - Emission from the early stage where temperature is high
- **Large elliptic flow (v_2)** **Phys. Rev. Lett. 109**, 122302
  - Emission from the late stage where the collectivity is enough built up





Need to look for additional photon source?
→ higher order flow measurement would help

A new measurement:

Higher order flow

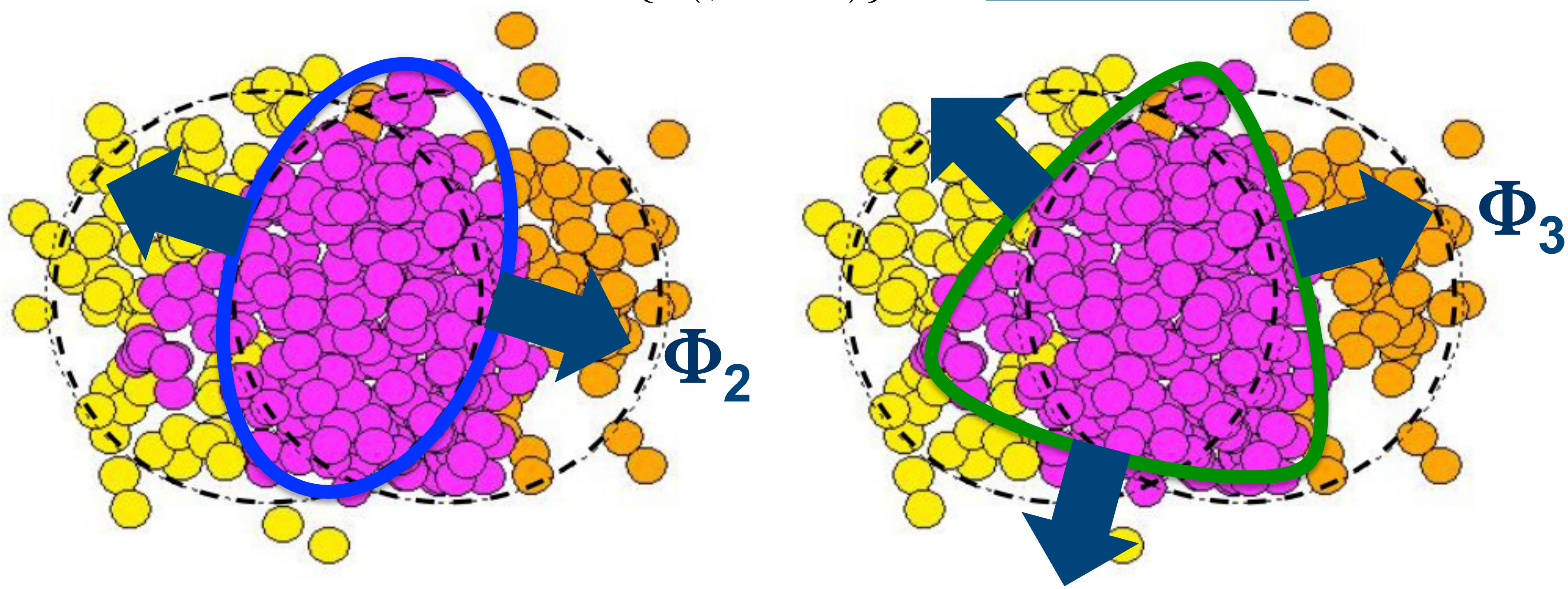
Higher order modulation of particle source

- Fluctuation of participant position in the collision area produces higher order azimuthal anisotropy
- Magnitude is sensitive to initial condition, viscosity (η/s), and etc.

$$\frac{dN}{d(\phi-\Psi_n)} = N_0[1+2\sum_{n=1}^{\infty} v_n cos\{n(\phi-\Phi_n)\}]$$

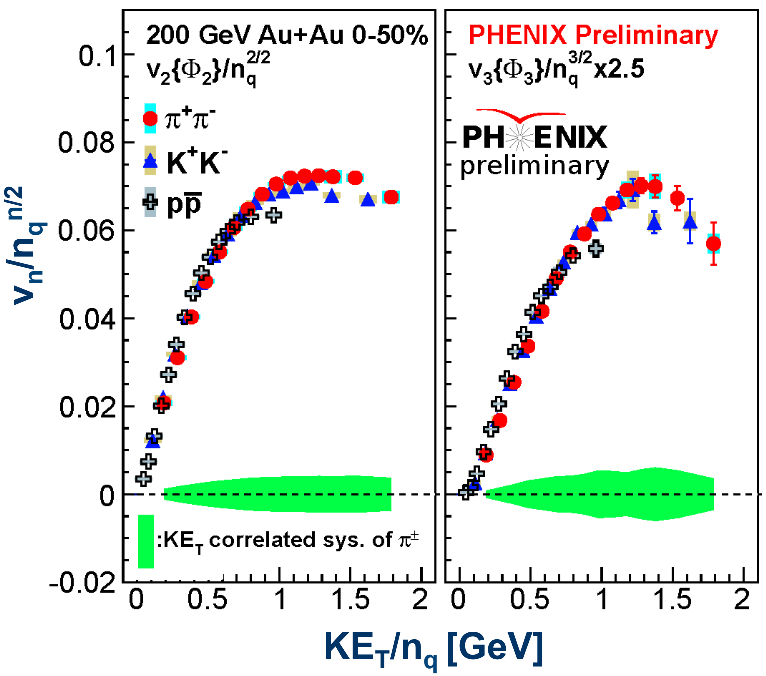
$$\nu_n = < cos\{n(\phi-\Phi_n)\} >$$

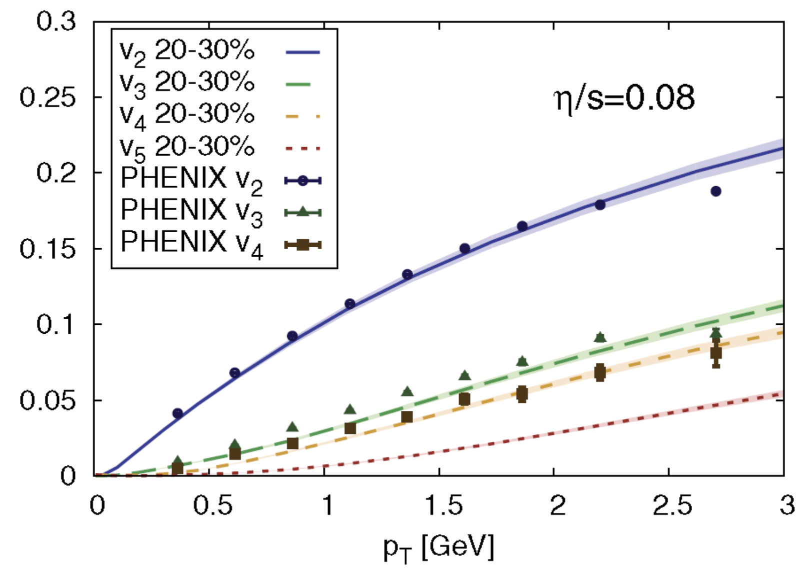
Φ_n : Event Plane



Observation of hadron v_3

- Charged hadron v_3 measurement has been performed at RHIC
  - PHENIX, PRL 107, 252301 (2011), STAR, Phys. Rev. C 88, 014904 (2013)
- KE_T scaling of identified hadron v_3 is also observed
  - PHENIX preliminary, paper in preparation
- Viscous hydrodynamics ($\eta/s=0.08$) well described PHENIX data





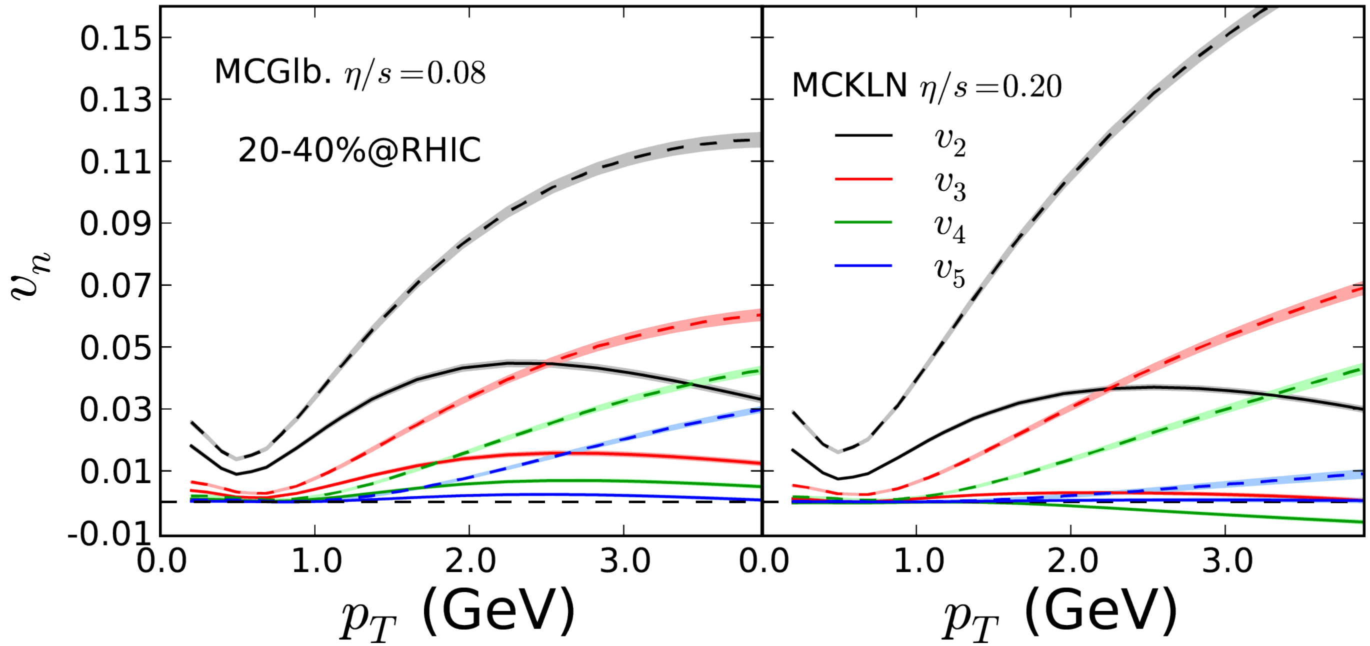
B. Schenke, S. Jeon and C. Gale, PRC 85, 024901 (2012)

Expectation in direct photon v_2 and v_3

Photon sources	v_2	v_3
Hadron-gas interaction	Positive and sizable (following hadrons)	Positive and sizable (following hadrons)
QGP	Positive and very small	Positive and very small
Primordial (jets)	~zero	~zero
Jet-induced	Either positive or negative	?
Magnetic field effect	Positive, always above zero even at p_T=0	Zero

Higher order flow of photons

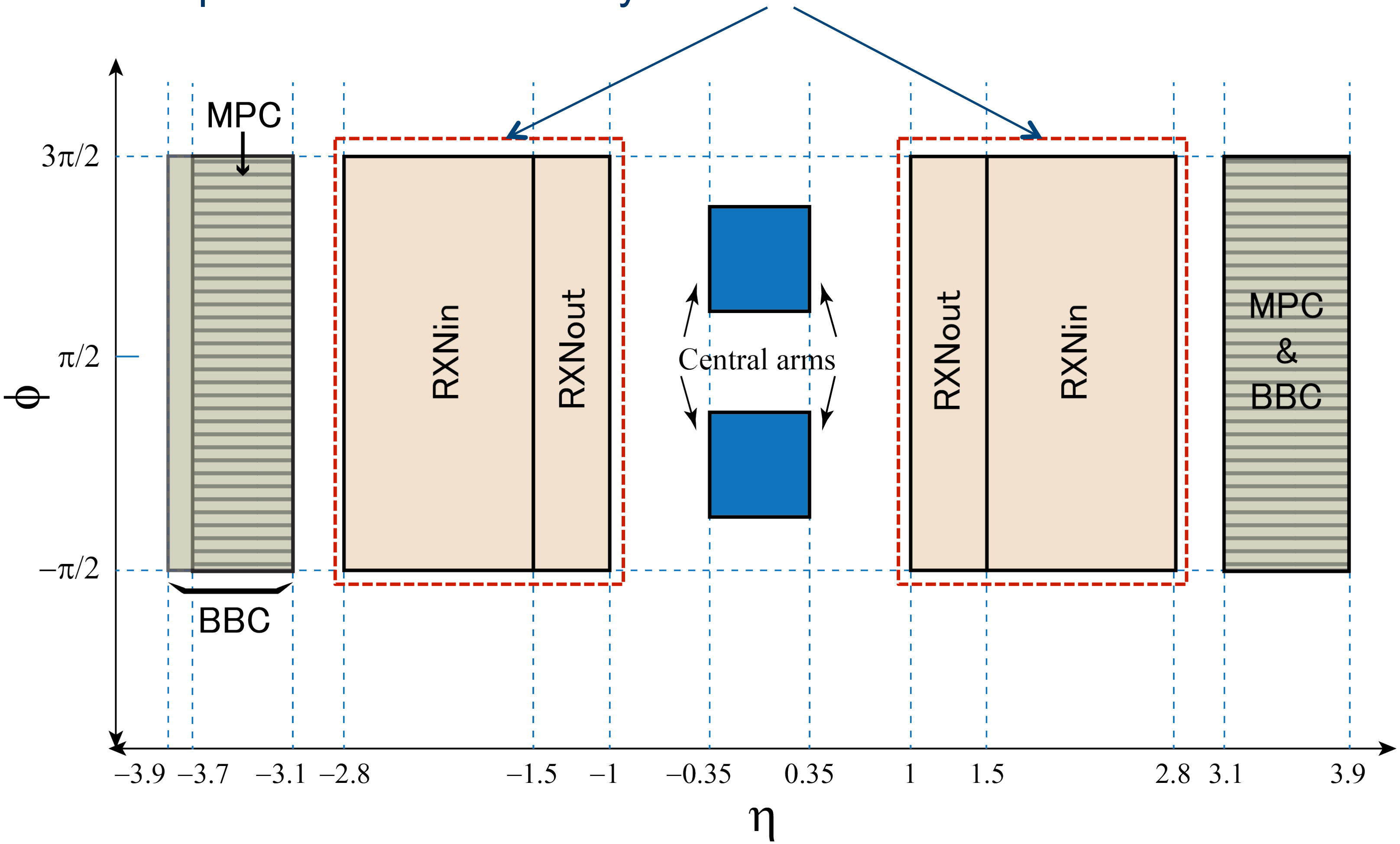
- Same hydrodynamics framework with two different initial conditions
  - v_2 values are much smaller than that of the PHENIX result
- v_3 ~= v_2/(2-3)



C. Shen and U. Heinz, J-F. Paquet, I. Kozlov, and C. Gale, arXiv:1308.2111

PHENIX detector configuration

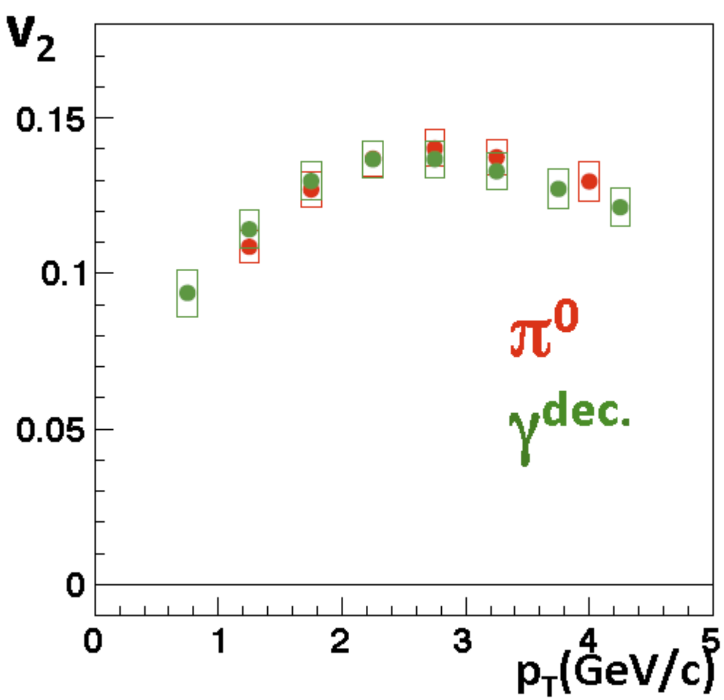
- Photons are measured with central arms
- Event plane is determined by RXNin+RXNout

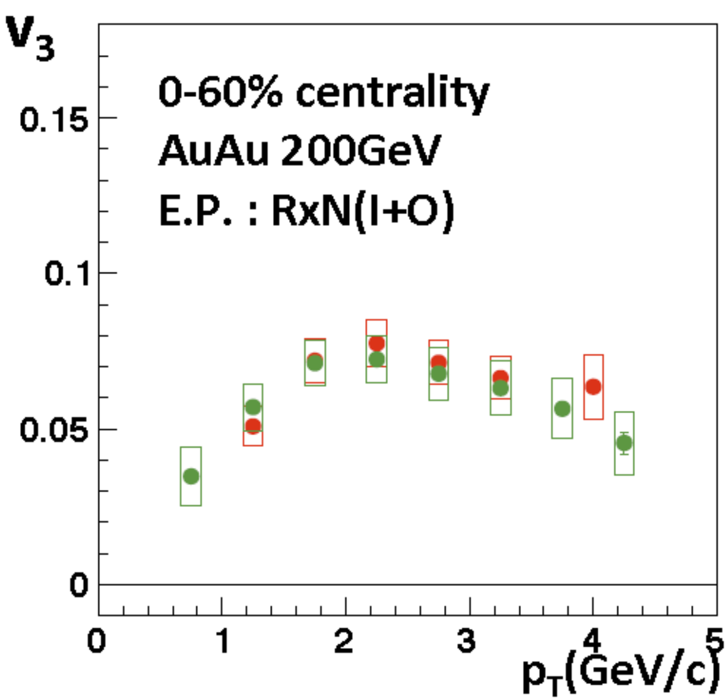


Recent measurement from PHENIX

- $|\eta_{rxn}-\eta_{meas}|$ =~2 (event plane determined by RXNIn+RXNOut)
- Measurement of π^0 v_n
- Decay photon v_n obtained from a MC calculation using π^0 v_n as input
  - v_n for other hadrons are obtained by KE_T-scaling + m_T scaling

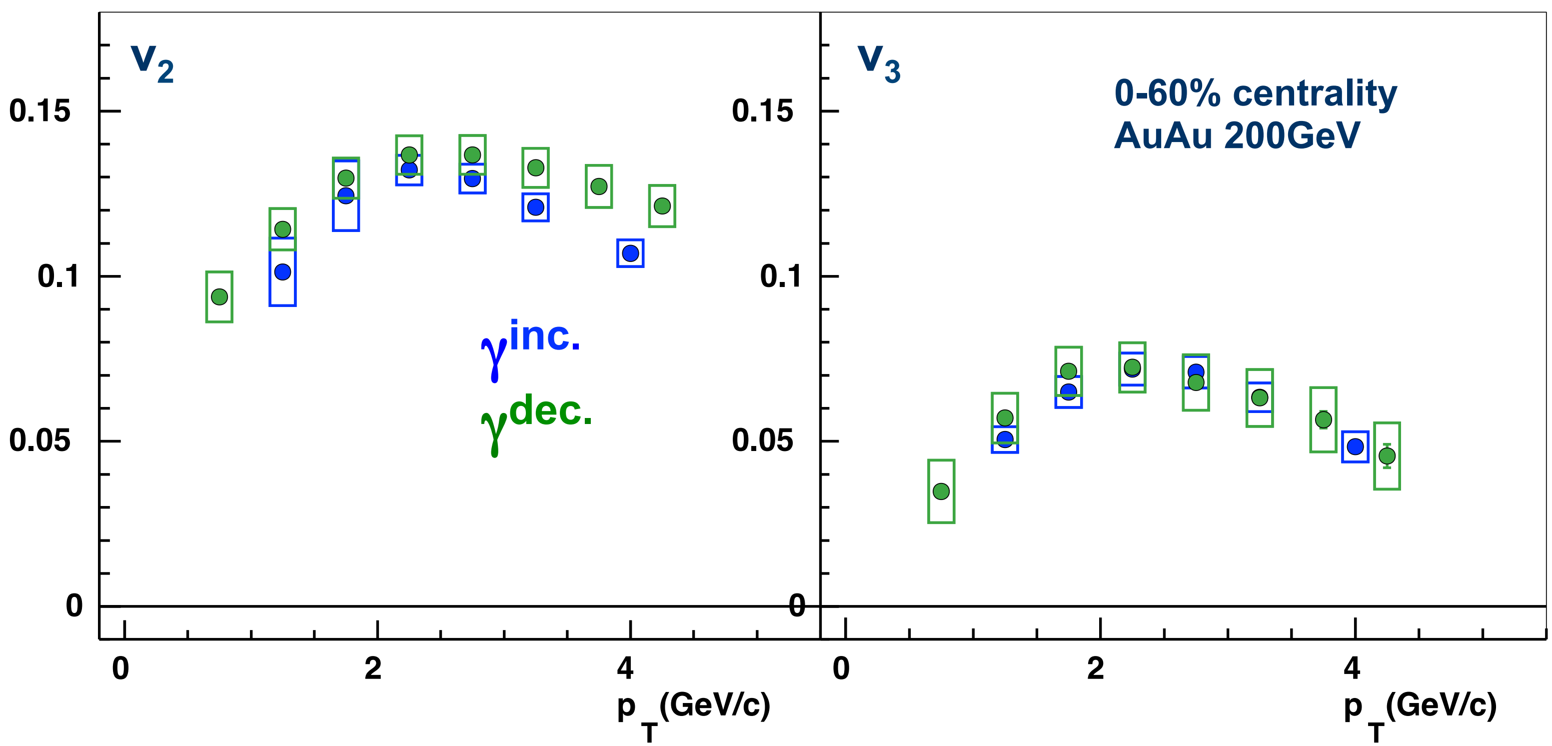
The table of each meson spectra ratio to π^0	
η/π^0	0.45±0.060
ω/π^0	0.83±0.120
ρ/π^0	1.00±0.300
η'/π^0	0.25±0.075





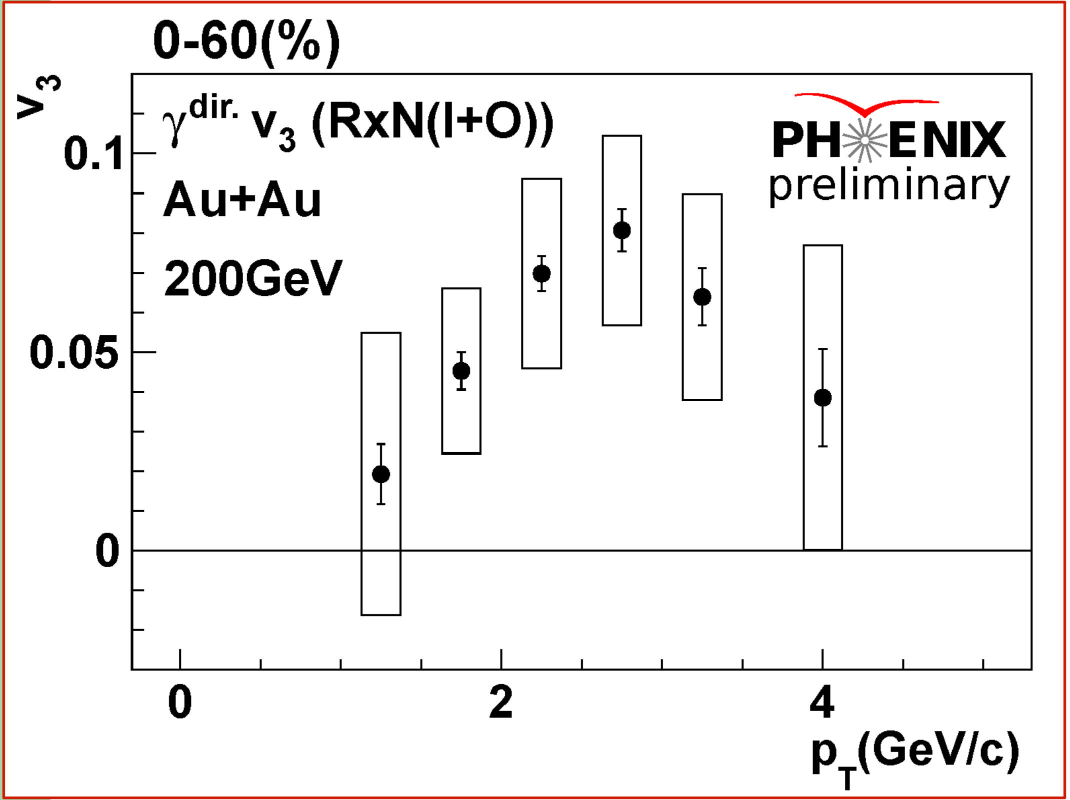
Inclusive and decay photon v_n

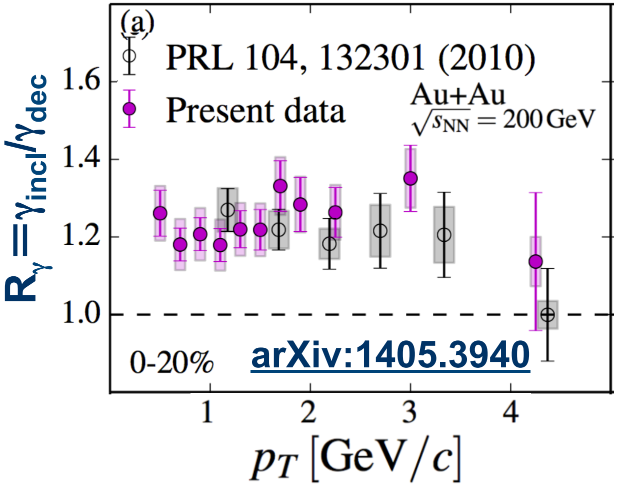
- $|\eta_{rxn}-\eta_{meas}|$ =~2 (event plane determined by RXNIn+RXNOut)
- Measurement of inclusive photon v_n
  - Compared with decay photon v_n calculation
- Difference of v_n between inclusive and decay photons is small



Direct photon v_3 in Au+Au collisions

- Non-zero positive v_3 has been observed
- v_3~ v_2/2 (cf. v_2=~0.15 @ 2GeV/c)



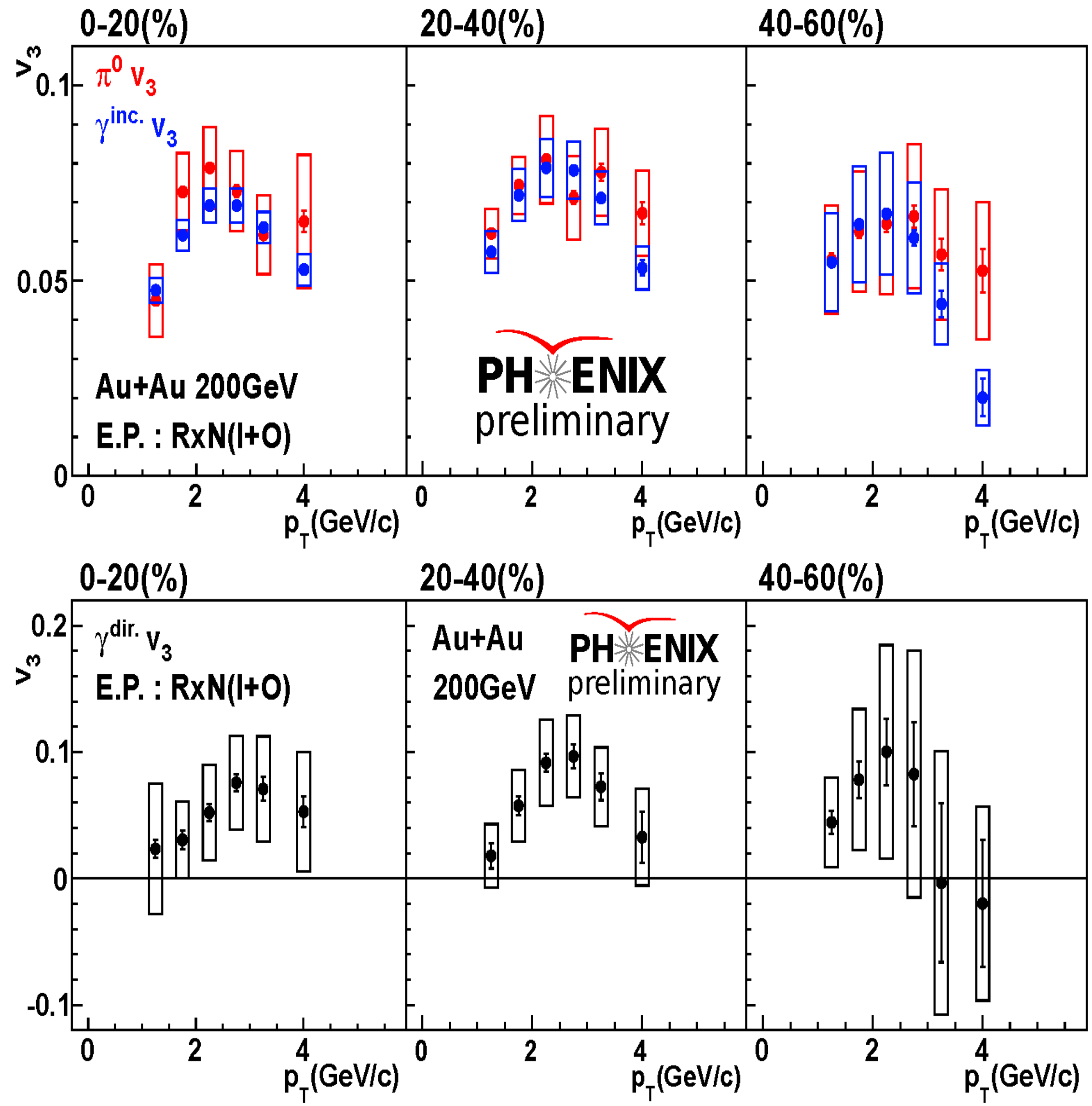


$$\nu_n^{dir.} = \frac{R_\gamma \nu_n^{inc.} - \nu_n^{dec.}}{R_\gamma - 1}$$

Syst. error source	Value
π^0 counting	15-30%
Photon ID	~3-5%
Event plane	~22%
Rγ - 1	~40%
Total	**~30-50%**

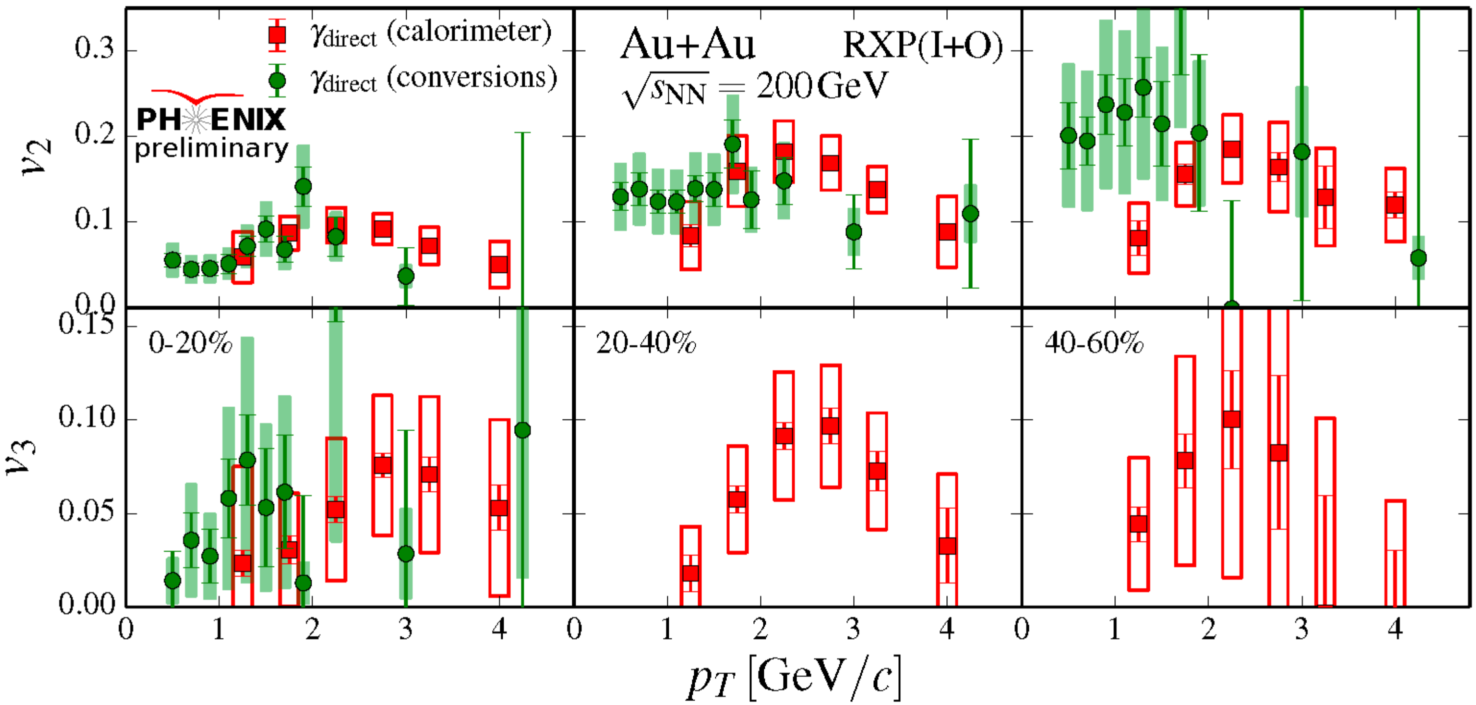
Centrality dependence of v_3

- Top: Centrality dependence of v_3 of π^0 and inclusive photons
- Bottom: Centrality dependence of v_3 of direct photons
- $|\eta_{rxn}-\eta_{meas}|$ =~2
- Weak centrality dependence if seen in direct photon v_3
  - Unlike v_2, eccentricity should be small
  - Mostly coming from fluctuation of the initial state?



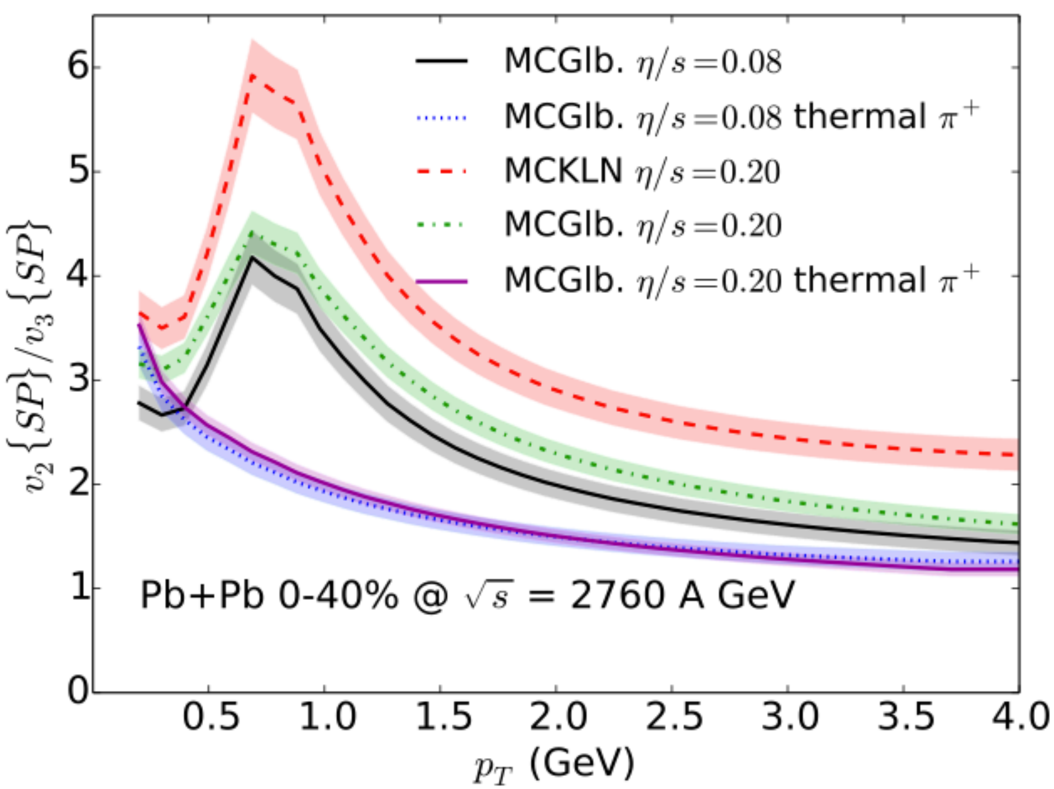
Comparing v_2 and v_3 of direct photons

- Weaker centrality dependence in v_3
  - Similar trend for charged hadrons (PRL 107, 252301 (2011)) and π^0.
- General trend to note: $v_3 \sim v_2/2$



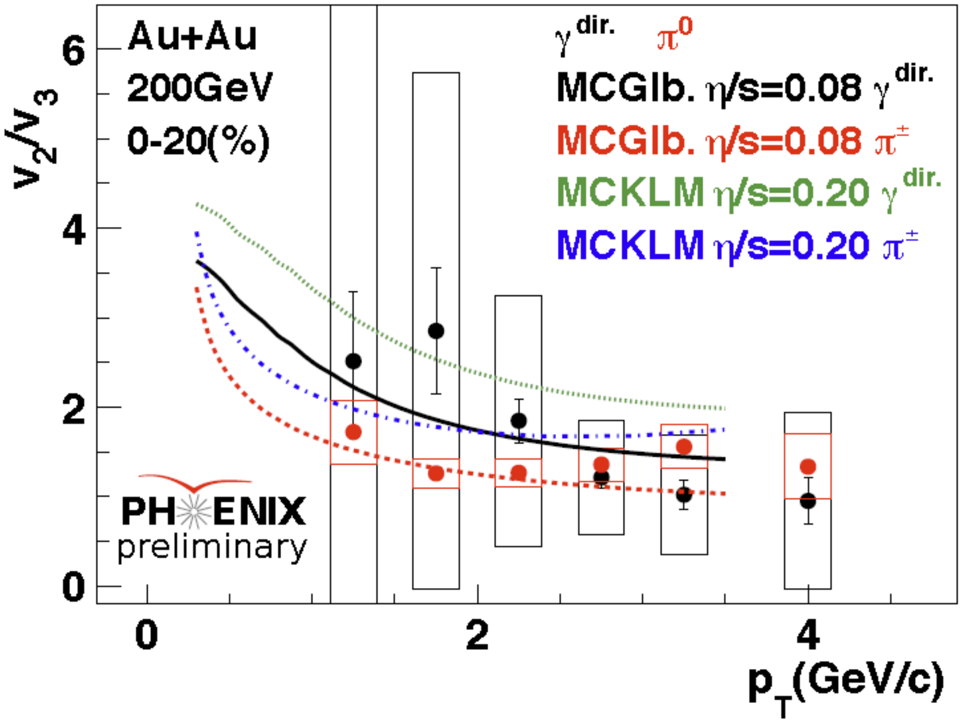
Ratio of v_2 to v_3

- A quantity sensitive to initial condition and viscosity
  - Glauber or KLN initial condition, and difference η/s
- Calculation for the LHC energy is shown below
  - arXiv:1403.7558



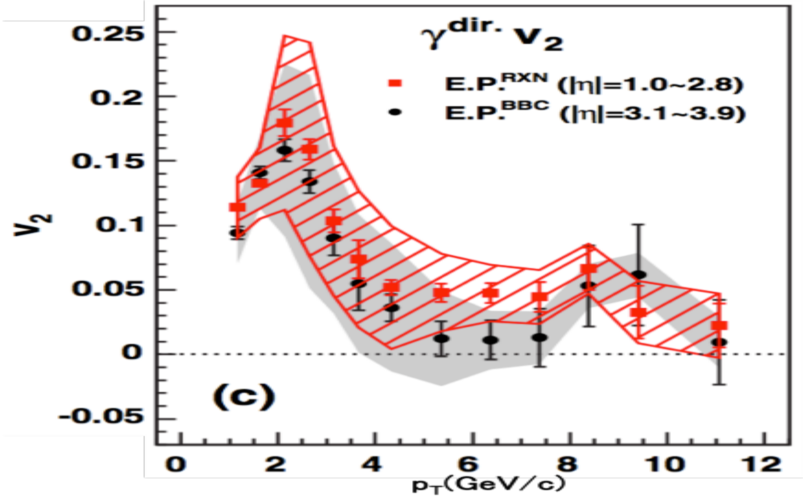
Measurement of ratio of v_2 to v_3

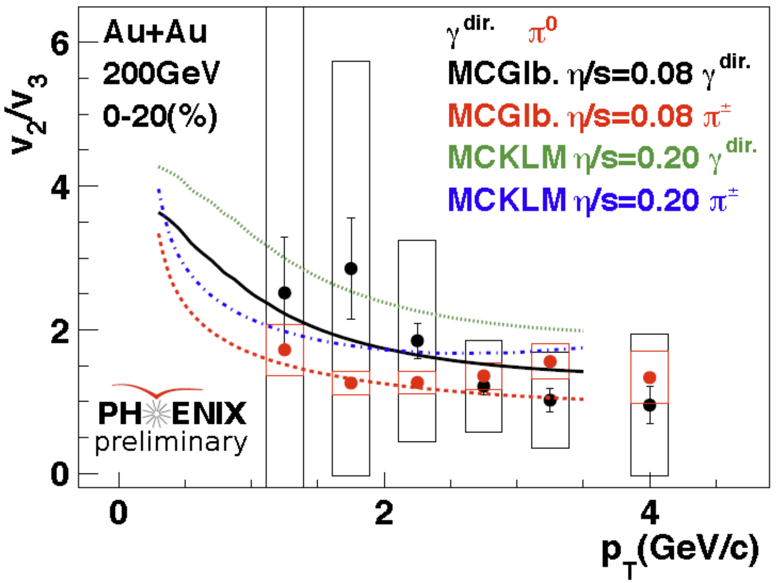
- Overall trends both for $\pi^{+/-}$ and direct photons are well described by the calculation
  - Based on arXiv:1403.7558, private communication for RHIC energy
- Systematic error estimate is currently very conservative
  - Working on better understanding of systematic errors



Things to do..

- We are not happy with current uncertainties
- Statistical errors can be reduced by running more
  - Increasing acceptance also helps
  - Question is how much more?
  - Need input from theory side!
- Reducing systematic errors needs different method and/or more careful look at data
- **Lowering cms energy for systematic studies**
  - **e.g. measuring spectra, v_2 and/or v_3 at 62GeV**

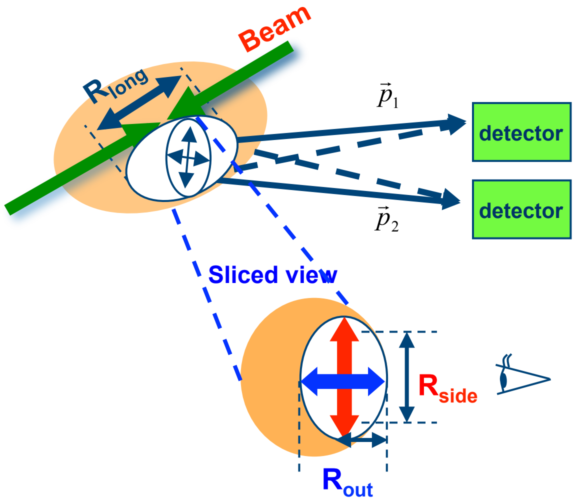




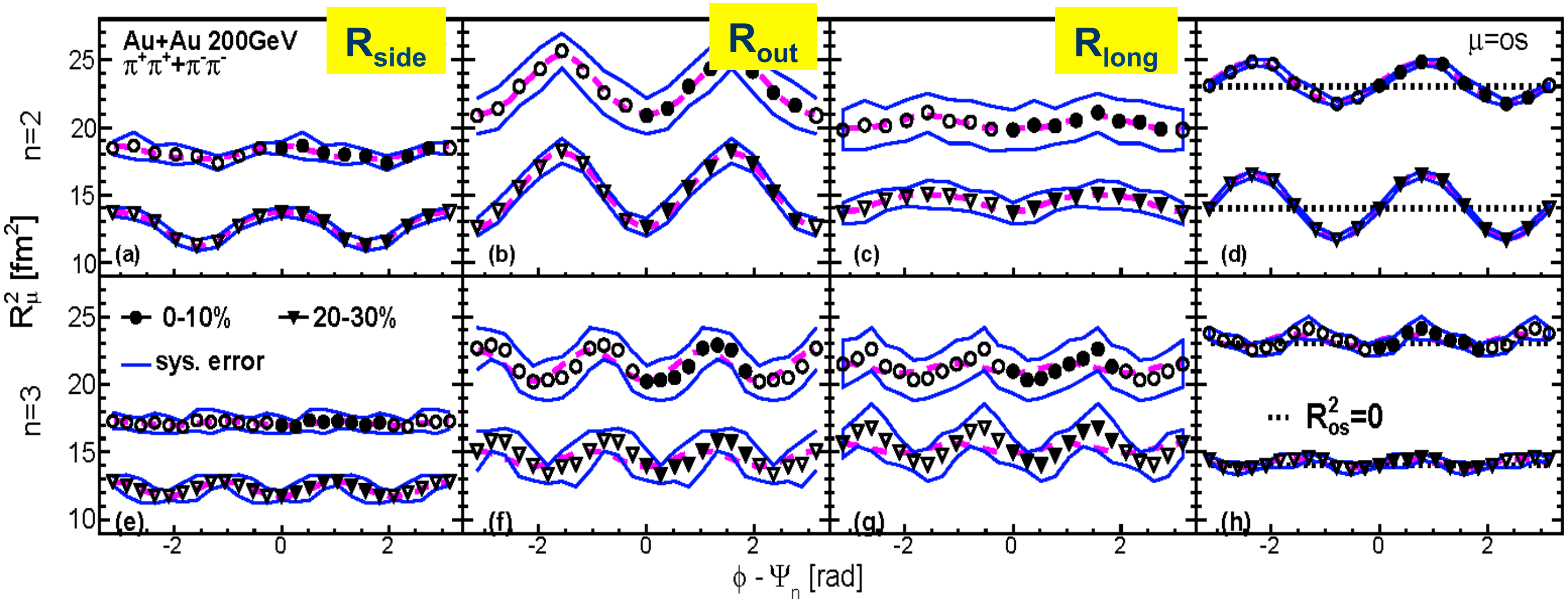
Future measurement

Dynamics of Au+Au collisions (from HBT)

- HBT radii as a function of Δφ (φ-Ψ_n) has been measured
- PHENIX and STAR observed 2nd order modulation of HBT radii in 200GeV Au+Au collisions
  - Both the source shape at freezeout and the emission duration of particles have elliptic pattern
- PHENIX observed the triangular pattern, too



PHENIX, PRL 112, 222301 (2014)

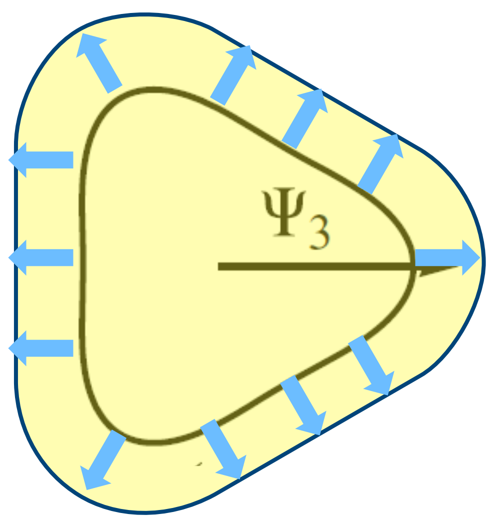


3rd order HBT radii has rich feature

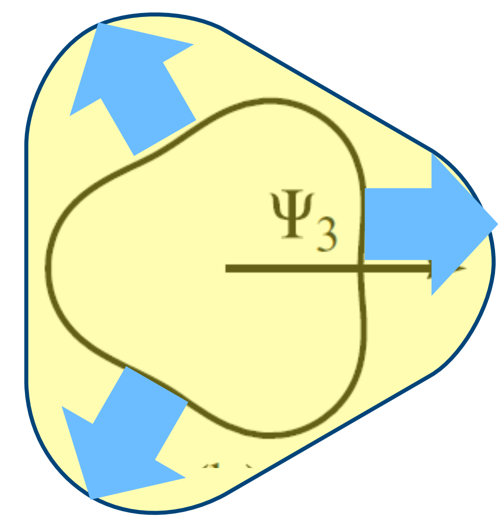
- Simple triangular geometry at freezeout does not yield 3rd order modulation in HBT radii (static source) unlike 2nd order
  - Plumbert, Shen and Heinz, PRC88, 044914 (2013)
  - Either triangular geometry coupled with azimuthally symmetric radial flow (geometry deform), or non-zero triangular flow in a spatially isotropic source (flow anisotropy), or both.

- Coupling of static source with dynamic motion of the system!
  - System dynamics can be observed through HBT

Geometry deform dominant



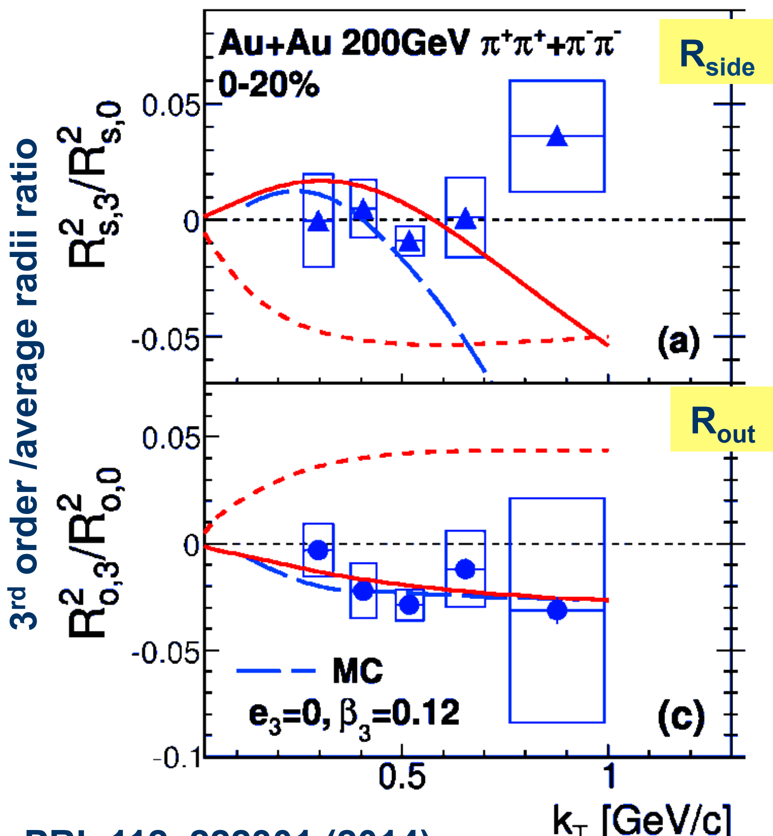
Flow anisotropy dominant



Geometry or flow dominant?

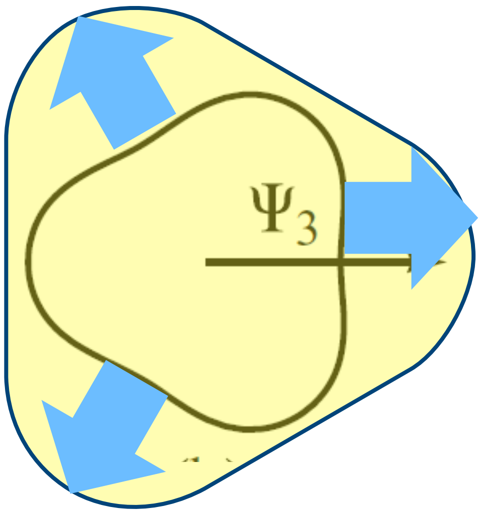
- Charged pion HBT results favor flow anisotropy dominant scenario

Solid - Flow dominant
Dotted - Geometry dominant



PRL 112, 222301 (2014)

Flow anisotropy dominant



PRC88, 044914 (2013)

Direct photon HBT?

- Direct photon HBT and v_n will shed light to the time-dependent source geometry and flow evolution
  - By combining with hadron HBT and v_n
- Even higher flow, such as v_4,would give a measure of the fluctuation of the initial geometry (i.e., double order of v_2)
- Statistics starved measurement
  - As starved as heavy quarks or jets (which is good as a future plan!)

	Inclusive	2nd order modulation	3rd order modulation	4th order modulation
Hadron flow	○	○	○	○
Hadron HBT	○	○	○	
Direct photon flow	○	○	○	
Direct photon HBT				

Direct photon HBT measurement by now

- WA98 results (in Pb+Pb @ $\sqrt{s_{NN}}$=17.3GeV)
  - PRL 93, 022301 (2004)
  - Not a 3D HBT
- Yield at lowest p_T was obtained from correlation length

λ_{inv}

R_{inv}

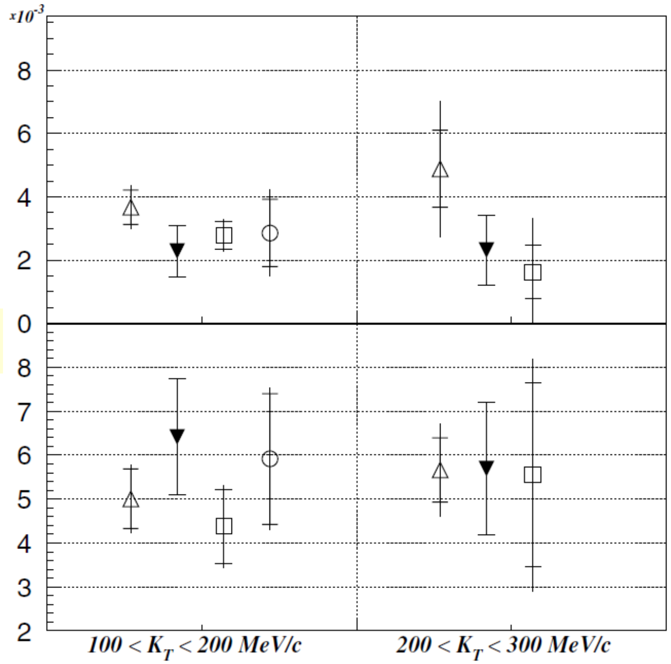
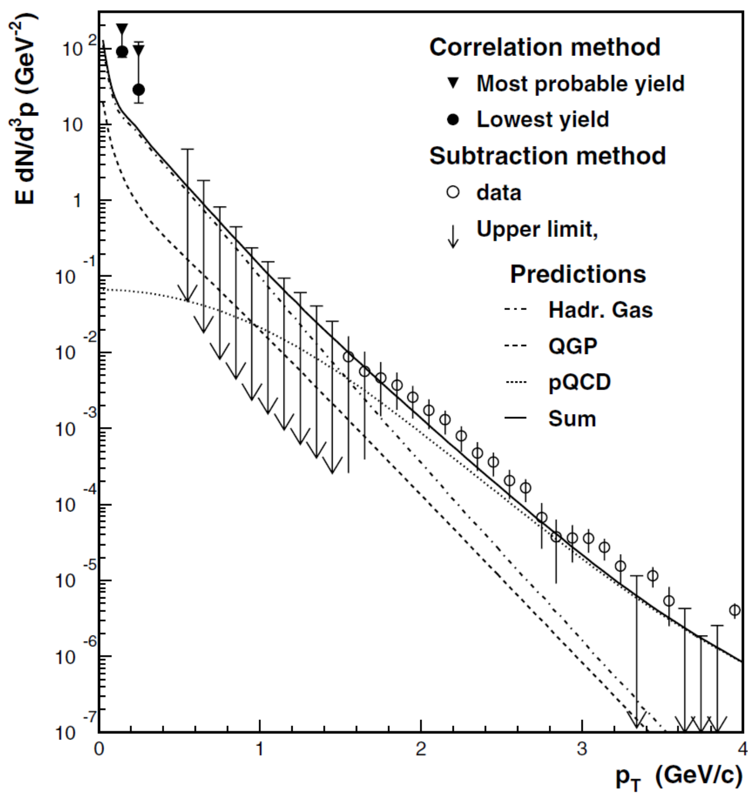


FIG. 3. Comparison of parameters of correlation functions with different particle identification criteria: △, all clusters; ▼, narrow electromagnetic; □, all neutral; ○, narrow neutral electromagnetic (no significant result for high K_T).

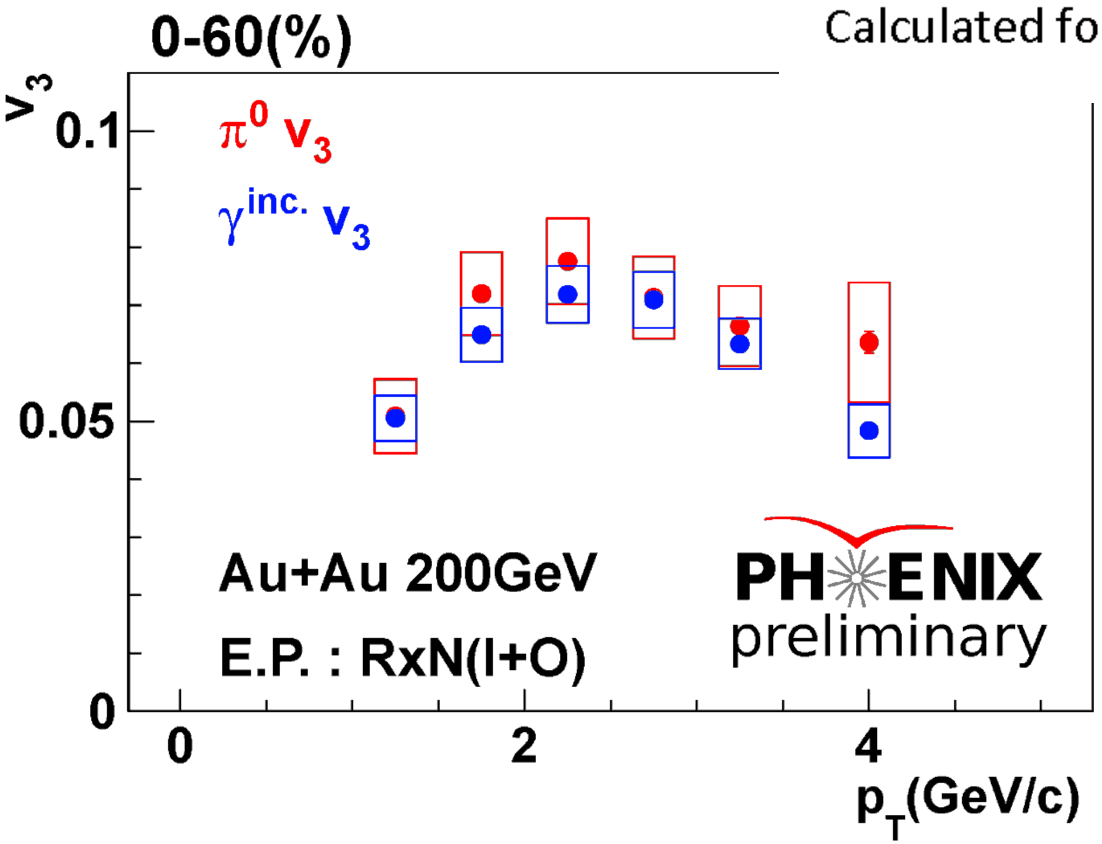


Summary

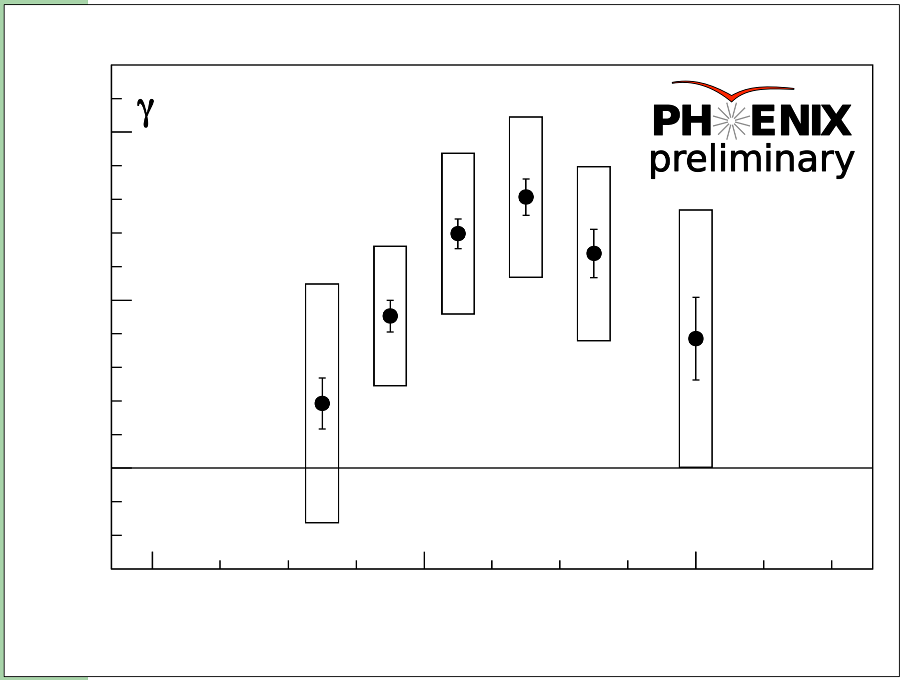
- Direct photon v_3 are measured as a function of centrality and p_T
  - Sizably positive
  - Magnitude is comparable to that of hadrons
  - $v_3 \sim v_2/2$
- v_3 has weaker centrality dependence
- v_2/v_3 ratio is measured
  - Well described by viscous hydrodymanics with $\eta/s=0.08$ and Glauber initial condition
  - Systematic errors are being improved
- Running at other cms energy may help (62GeV, etc.)
- Future measurement
  - Combining HBT and flow measurements of hadrons and direct photons may be able to disentangle the initial spatial anisotropy and time evolution
  - Statistics starved measurement, as starved as heavy quarks or jets

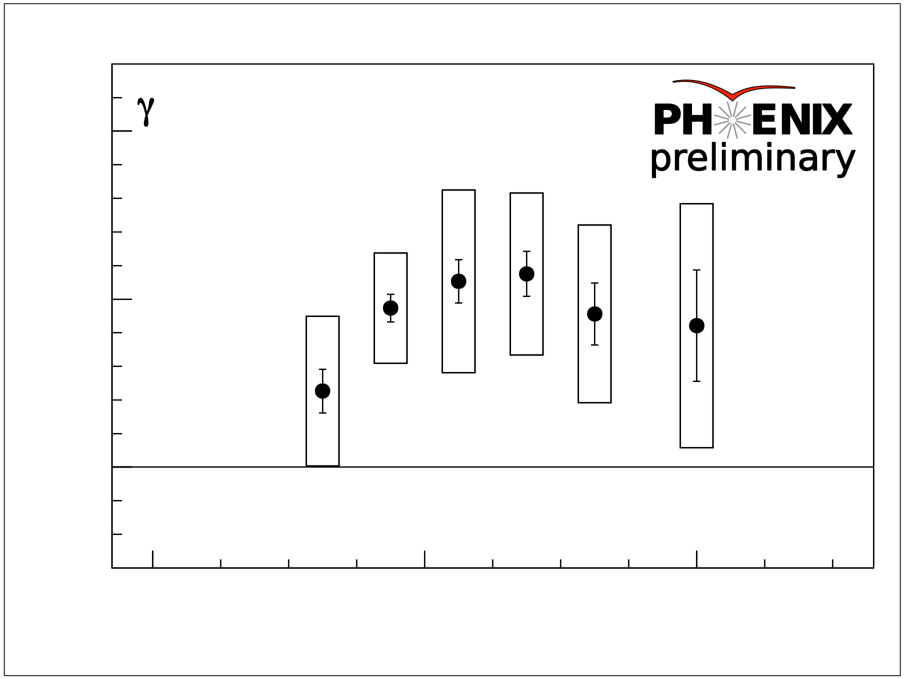
Backup

Theory curves: private communication by Ch. Shen, Ch. Gale, J.-F. Paquest, U. Heinz as in 1403.7558, Calculated for RHIC.



Comparison $\gamma^{dir.}$ v_3



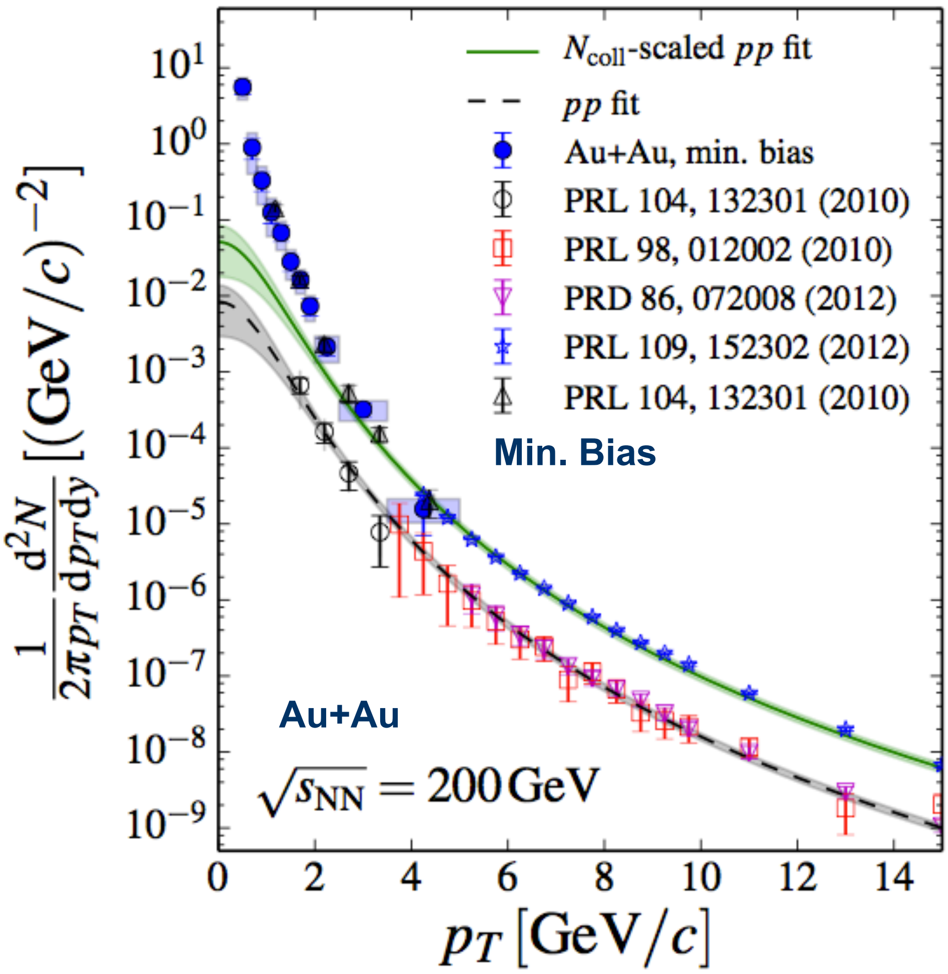


RxN(I+O) : 1.0 <|η|< 2.8
RxN(In)+MPC : 1.5 <|η|< 3.8

The magnitude of v_3 is comparable.

Comparable measurement is achieved

arXiv:1405.3940

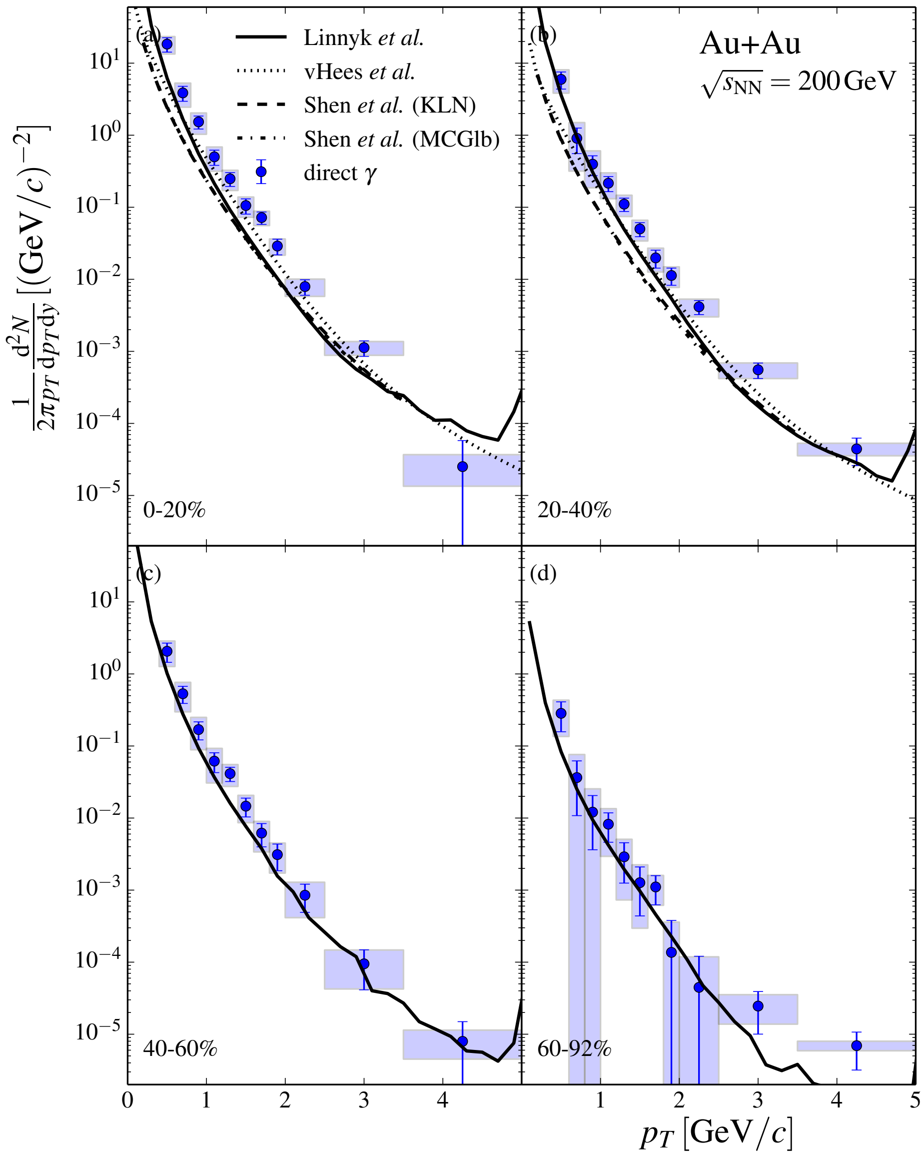


Ncoll-scaled pp fit
external conversion
pp virtual photon
pp in EMCal(Run2003 data)
pp in EMCal(Run2006 data)
AuAu in EMCal(Run2004 data)
AuAu from virtual photon(Run4 data)

Using external photon convers method achieved good agreem with previous results.

Yield : data vs theories

arXiv:1405.3940



Linnyk et al.: PHSD transport model; Linnyk, Cassing, Bratkovskaya, P.R.C 89, 034908(2014)

vHees et al.: Fireball model; van Hees Gale, Rapp; P.R.C 84, 054906(2011)

Shen et al.: Ohio hydro for two different initial conditions; Shen, Heinz, Paquet, Gale; P.R.C 84, 064903(2014)

The yield itself is still not perfec described.

How about measurement?

~A technology choice: MPC-EX~

- Muon Piston Calorimeter extension (MPC-EX) ($3.1<|\eta|<3.8$)
  - Shower max detector in front of existing MPC. Now sits at ~1m from IP
  - Measure direct photons/π^0 in forward rapidity region in p+p, p+A

- Study of how high in centrality in A+A we can go is on-going
  - In the future, placing in a very far position (from Interaction Point) would be an option