UNIVERSITY OF JYVÄSKYLÄ

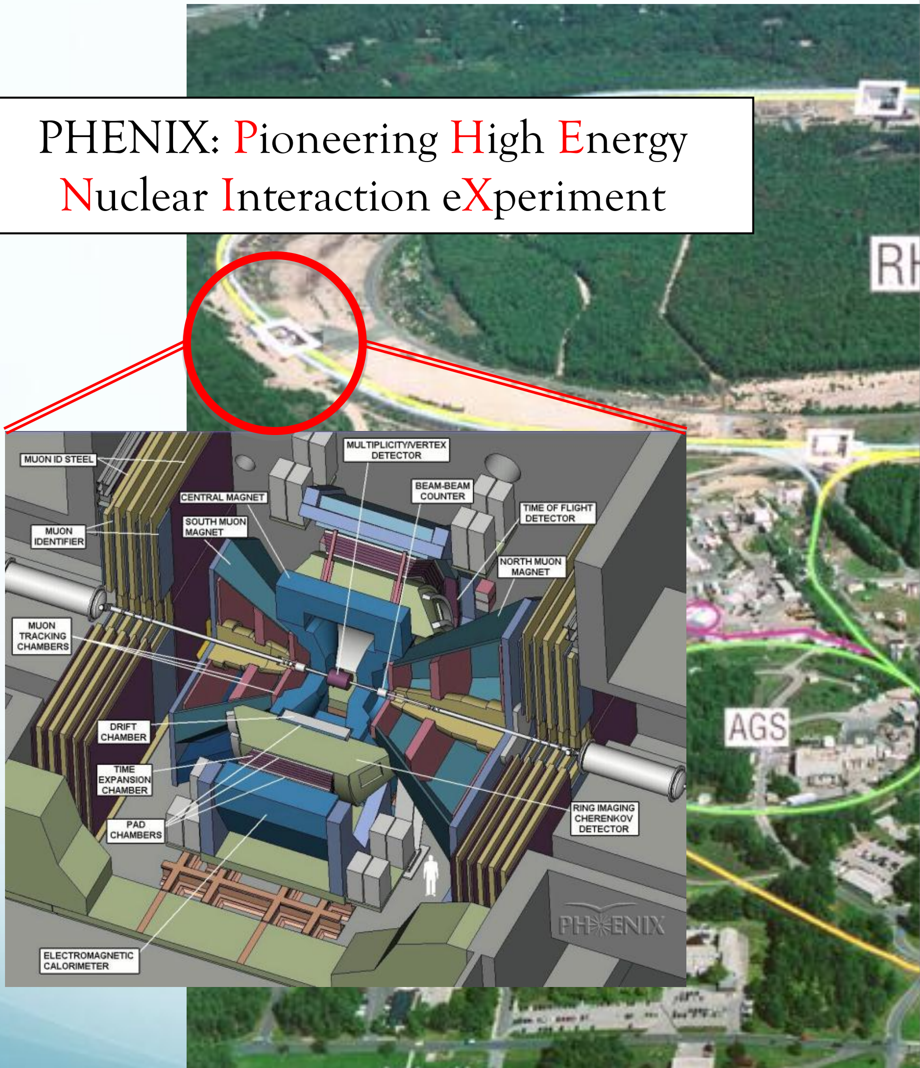
HELSINKI INSTITUTE OF PHYSICS

Recent results from PHENIX on the evolution of hot QCD matter

Norbert Novitzky for PHENIX collaboration
University of Jyväskylä, Finland
Helsinki Institute of Physics, Finland

PHENIX @ RHIC

PHENIX: Pioneering High Energy Nuclear Interaction eXperiment



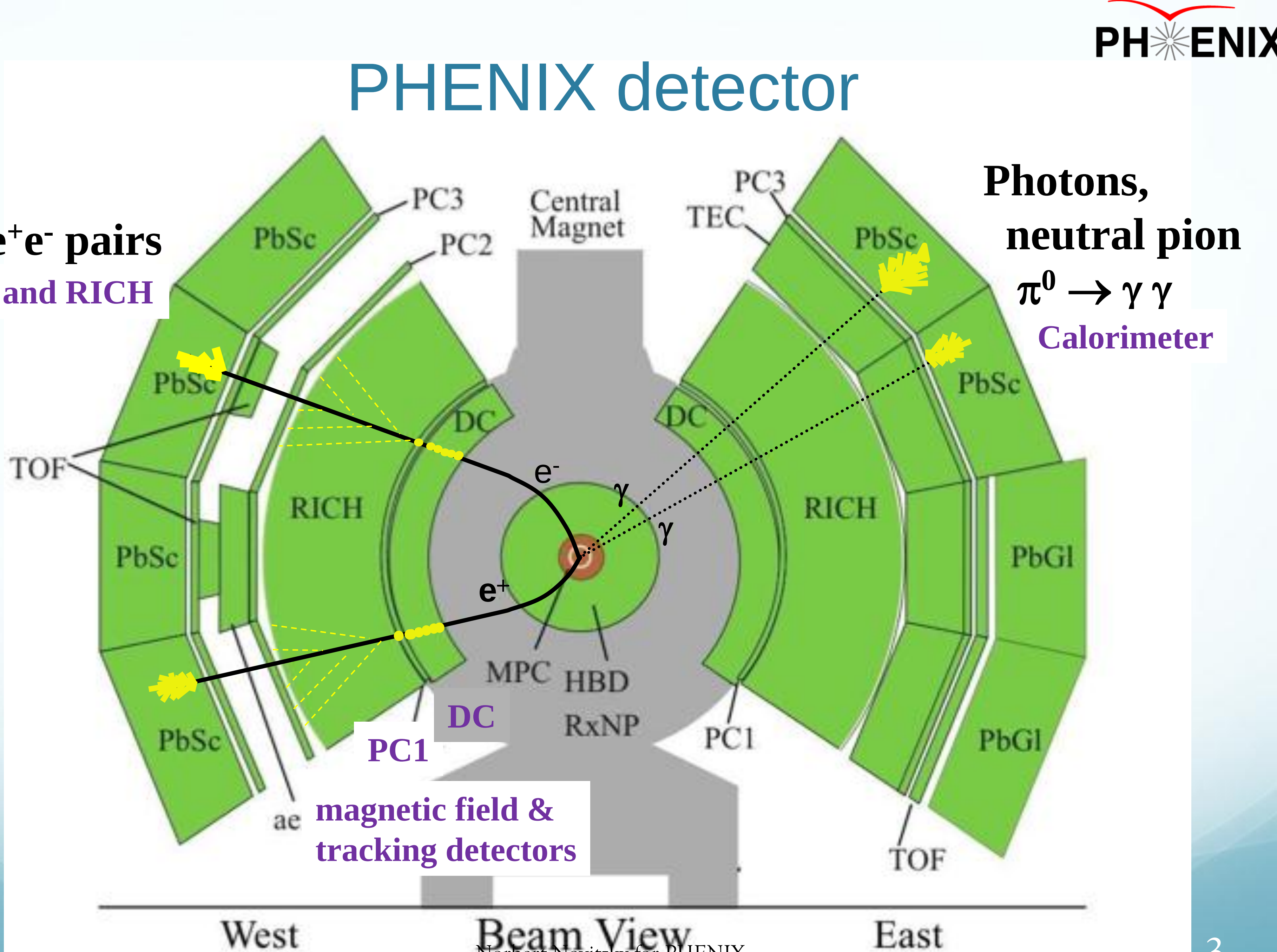
The Relativistic Heavy Ion Collider (RHIC):

- The beam species: p – Cu – Au – U
- Heavy ion collisions 7.7-200 GeV
- Asymmetric collisions
- Polarization of proton beams

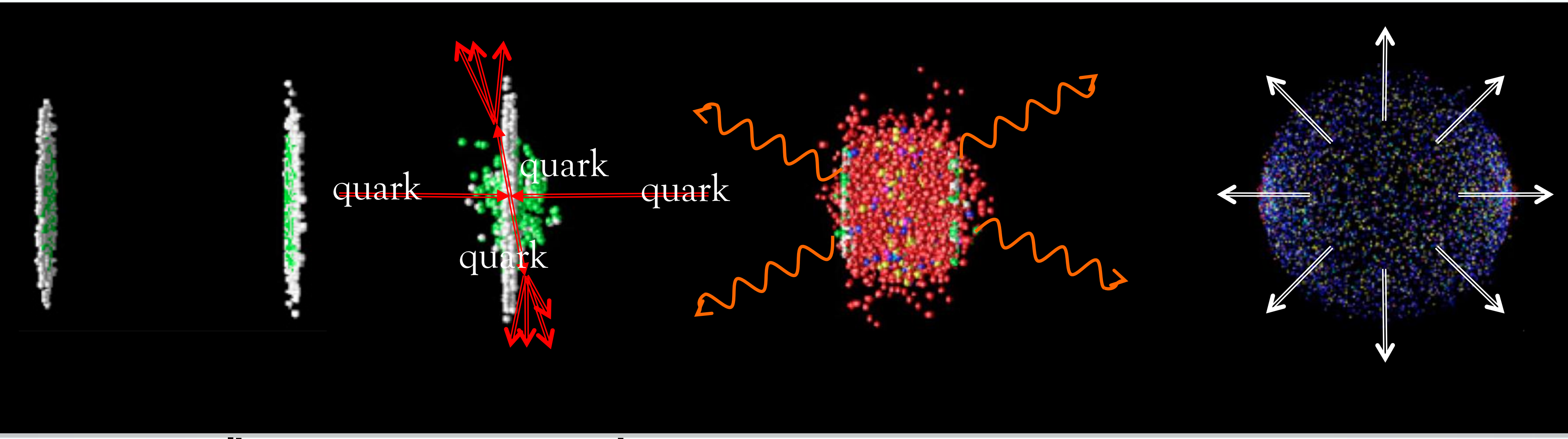
Measured:

- p+p @ 62.4 - 510 GeV (polarized)
- Au+Au @ 7.7 - 200 GeV
- Cu+Cu @ 22.4 - 200 GeV
- d+Au @ 200 GeV
- U+U @ 193 GeV
- Cu+Au @ 200 GeV

PHENIX detector

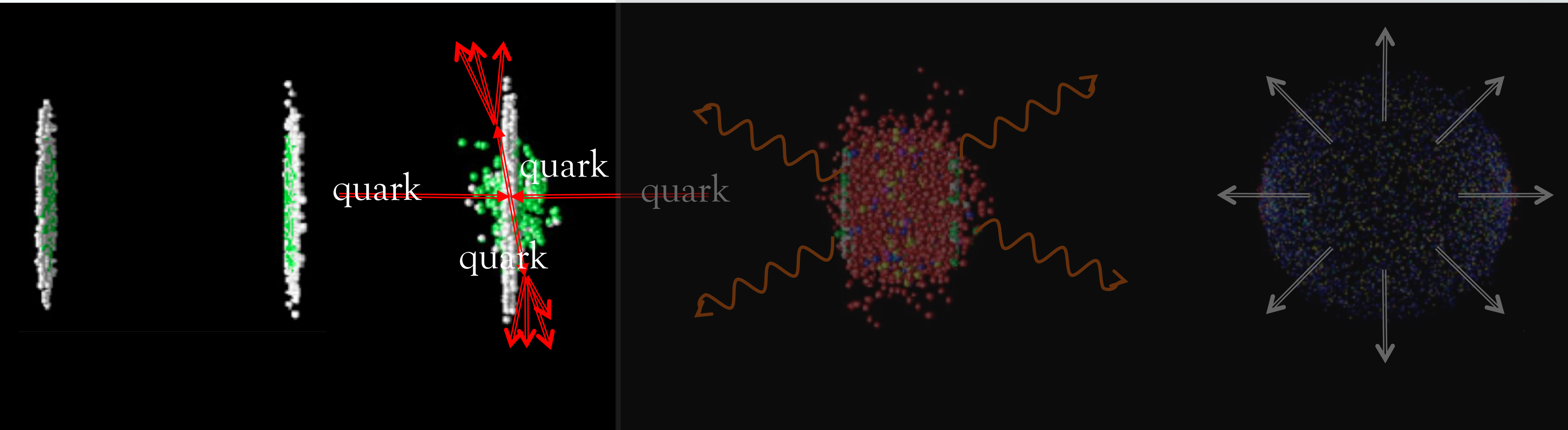


Little Big Bang



Time:	fraction of fm/c:	order of one fm/c	several fm/c
Process:	Hard scattering	Thermalization	Expansion
QGP probe	Jet quenching	High temperatures	Collective motion
	Opacity	**Luminosity**	**Fluidity**

Little Big Bang



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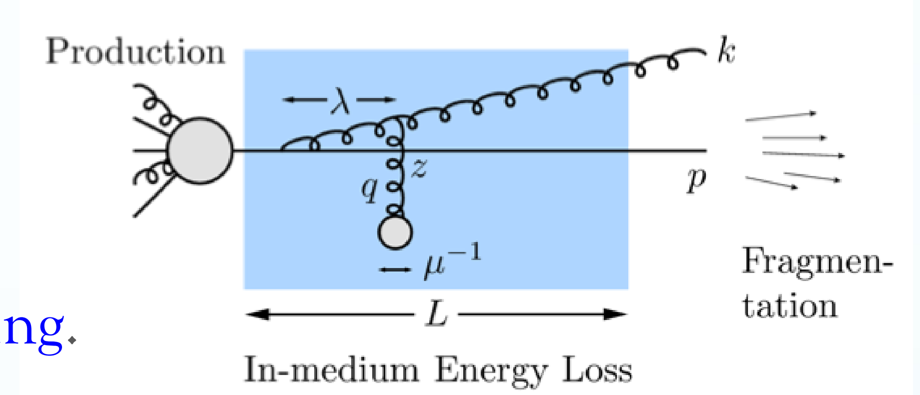
Parton Energy Loss

Hard parton propagating through

excited QGP:



Medium-induced gluon bremsstrahlung.

Essentially four categories:

- Opacity expansion (GLV) : *Gyulassy, Levai,. Vitev, PLB538, 2002*
- Multiple soft scattering (BDMPS-Z-ASW) :*Wiedemann, NPB588, 2000*
- Higher-twist (HT): *Guo, Wang, PRL. 85, 3591, 2000*
- Thermal field theory (AMY): *Arnold, Moore, Yaffe, JHEP 11, 001(2000)*

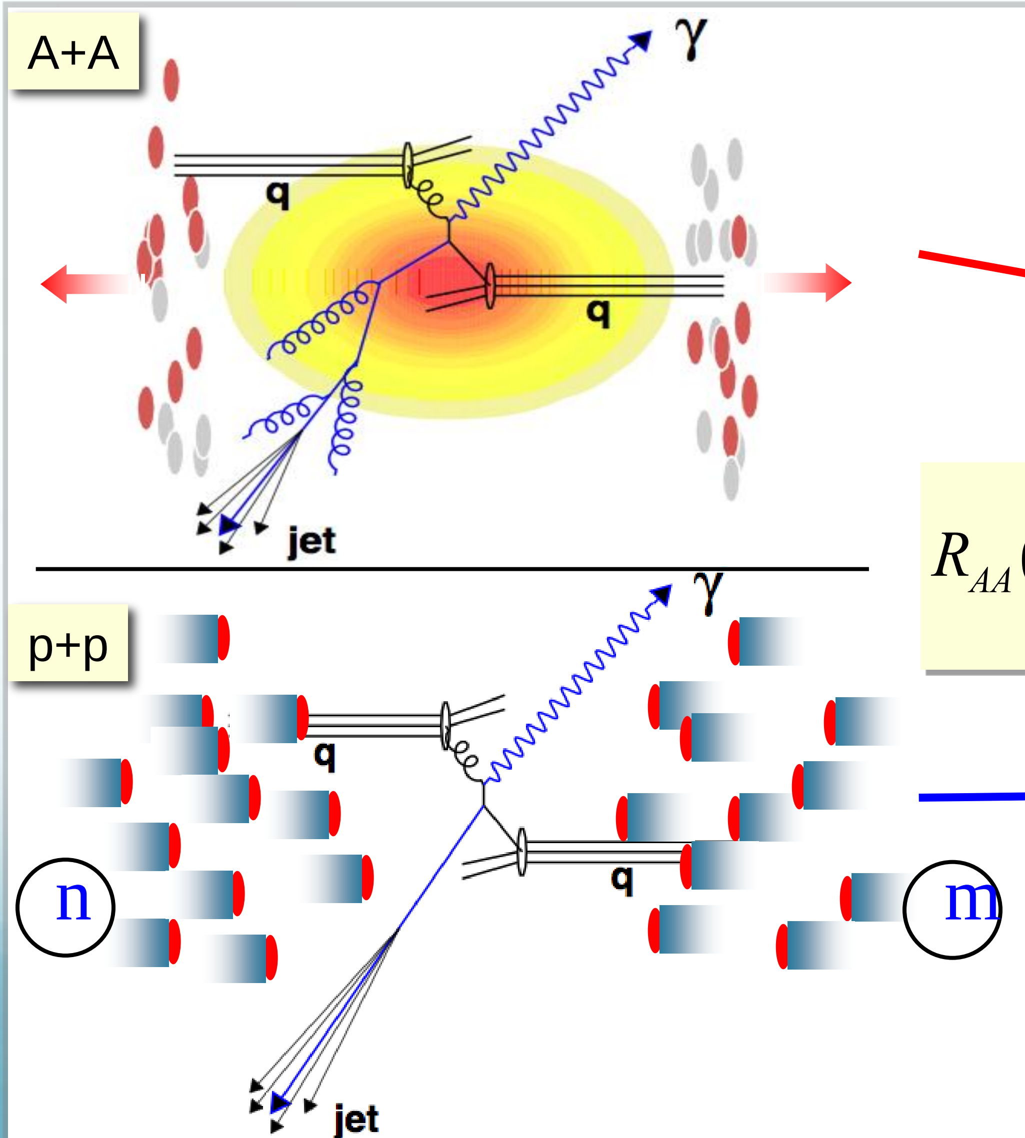
All models:

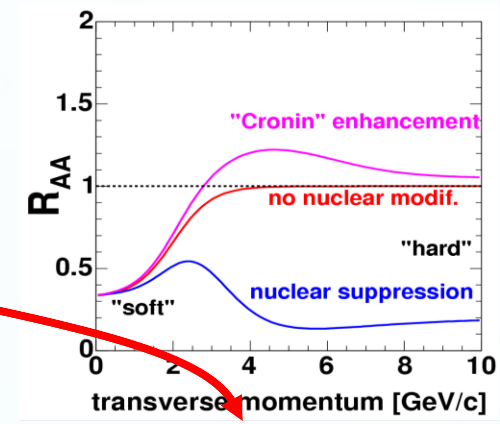
Models successfully describe the rate and p_T dependence of the jet quenching.

Large systematic uncertainties e.g. [*Phys.Rev.*, **2010**, *C81*, 024909]

Testing against multiple observables is essential to test physics of the models

Nuclear modification factor

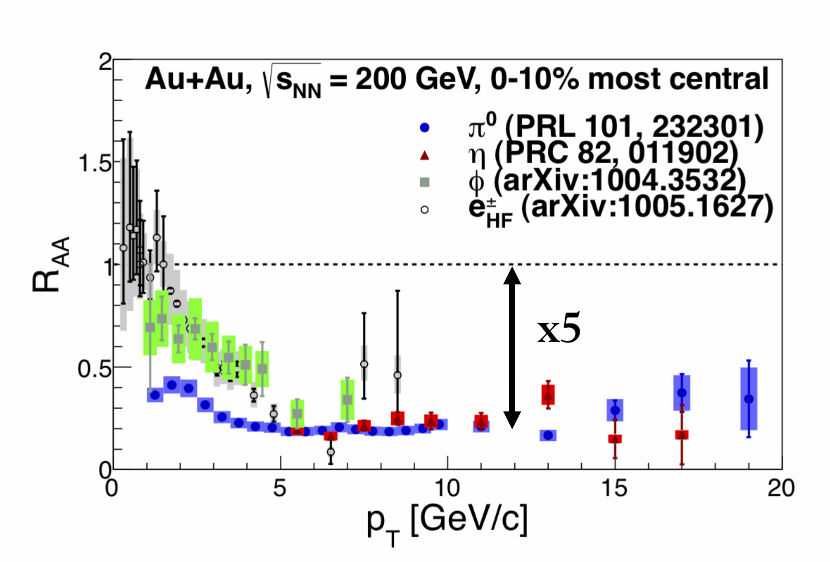


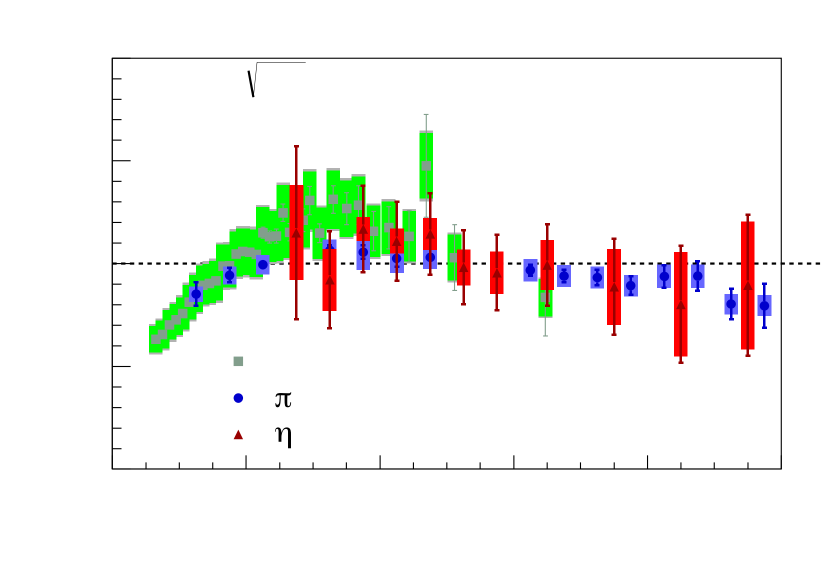


$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{pp}/dp_T d\eta}$$

$\propto \langle N_{binary} \rangle$ varies with impact parameter ***b***

Motivation – Low Energy Scan





Large suppression of particles was observed (up to factor of 5) in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

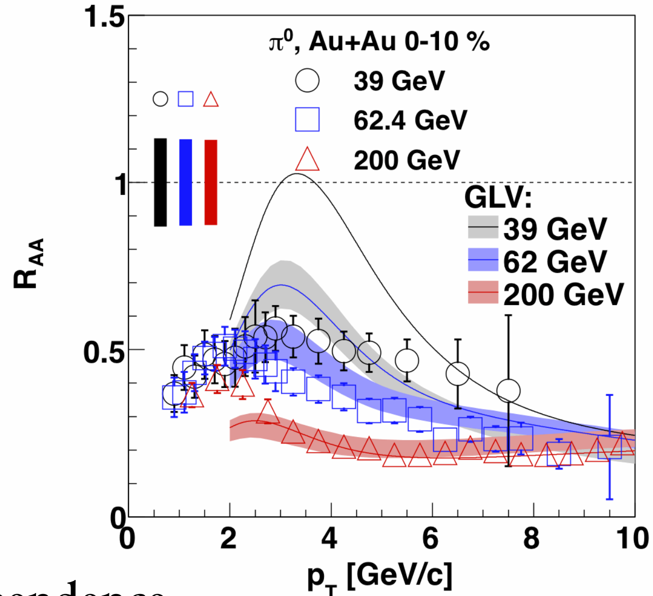
No suppression of particles was observed in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

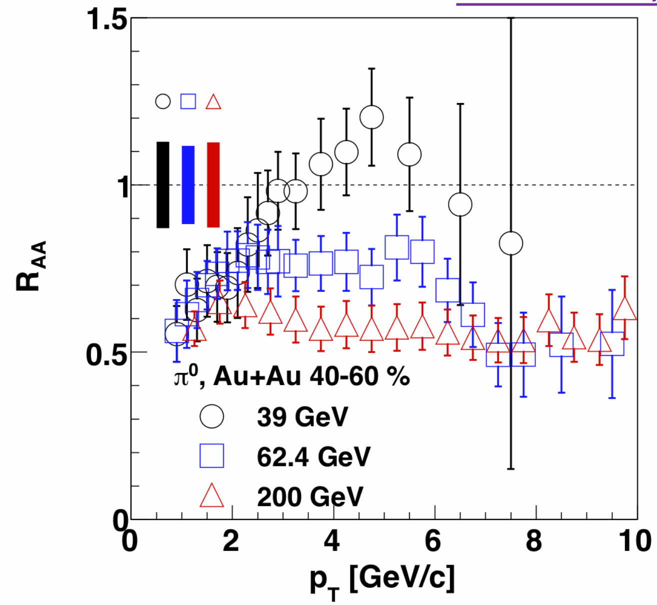
Convincing evidence for the **final state partonic** interaction - emergence of **sQGP**

Where the suppression starts to dominate?
How the suppression depends on p_T, system size, $\sqrt{s_{NN}}$?

R_{AA} in energy scan

arXiv:1204.1526v1





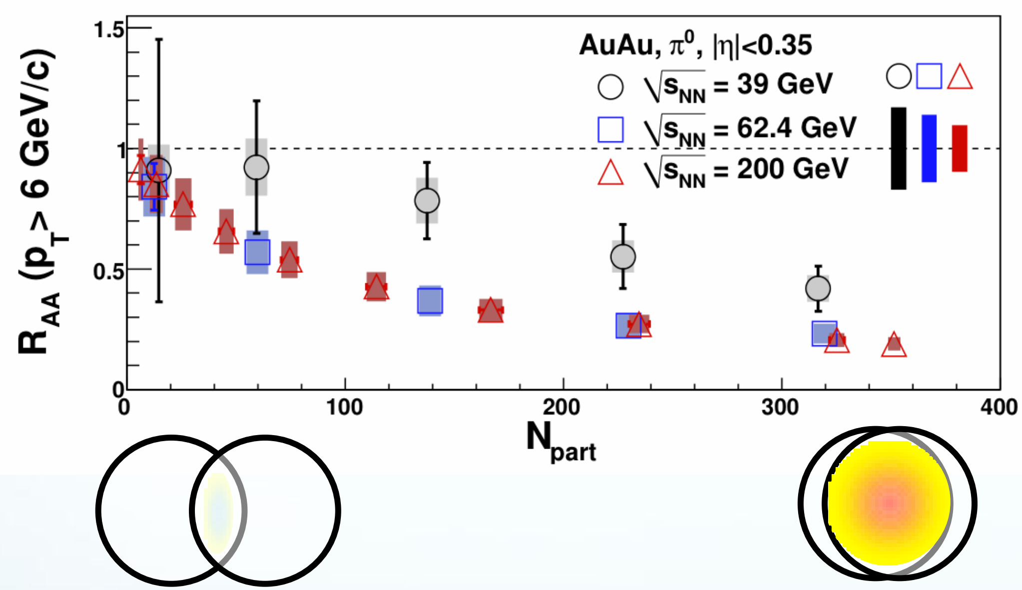
p_T dependence:
- 39 GeV shows strong suppression in the most central collision.
- The 62.4 and 200 GeV R_{AA} data points are comparable

Centrality dependence:
- In mid-peripheral collision, 39 GeV no suppression, 62.4-200 GeV suppressed

Theory:
- GLV model calculations are showing similar trend, but not fitting the data well. (two calculation with gluon mean free path +30%)

R_{AA} in averaged over p_T

arXiv:1204.1526v1



R_{AA} in different $\sqrt{s_{NN}}$:

•62.4-200 GeV are strongly suppressed

•39.0 GeV data shows suppression for higher centrality only (N_{part}>100)

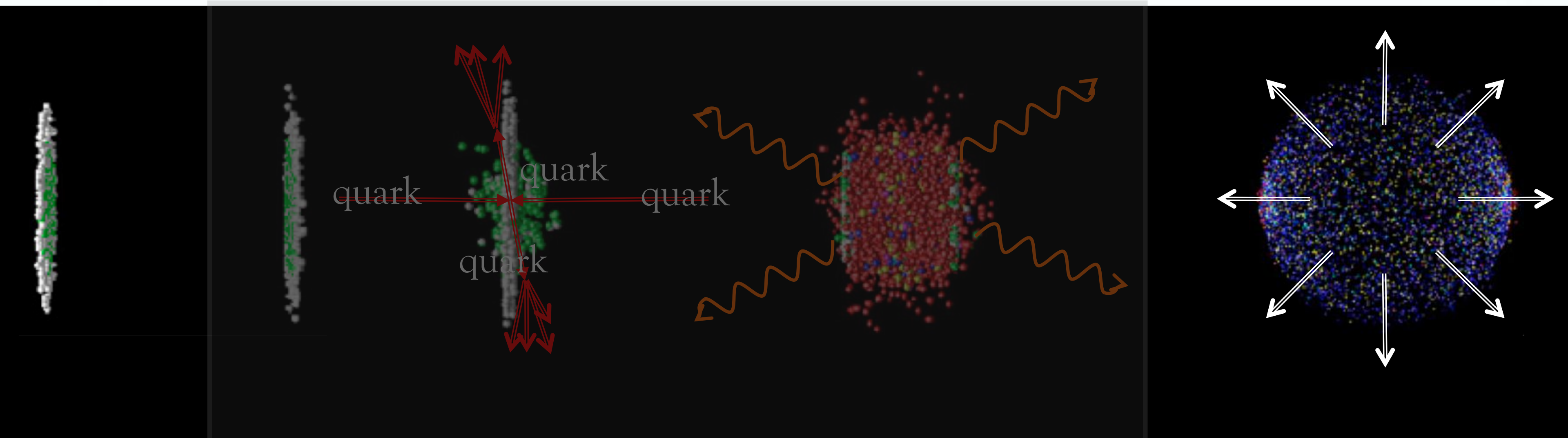
•For p_T > 6 GeV/c the 62.4 and 200 GeV data points are comparable

The suppression is most significant in most central collisions and it disappears earlier in lower $\sqrt{s_{NN}}$

Opacity – Summary

- Reaching high enough collision energy we create an opaque medium for partons
- R_{AA} measured in Au+Au and d+Au collisions shows the suppression is final state effect
- The opacity evolves as function of centrality, $\sqrt{s_{NN}}$, p_T
- An opaque medium is created in 39 GeV collision, but the opaqueness disappears in lower centralities

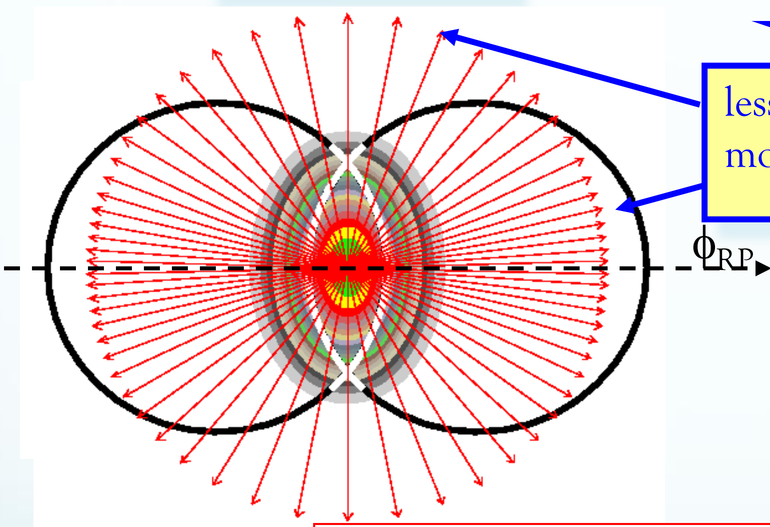
Little Big Bang

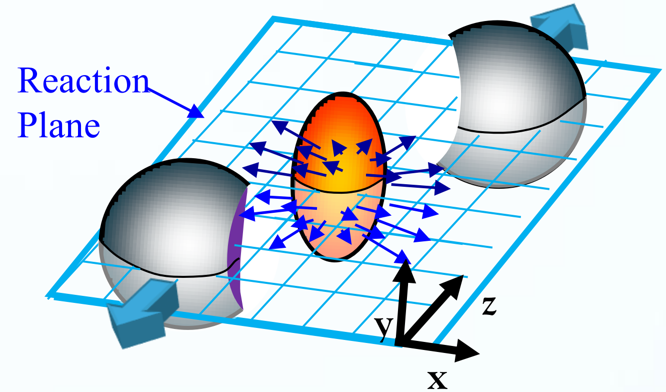


Time:	fraction of fm/c:	order of one fm/c	several fm/c
Process:	Hard scattering	Thermalization	Expansion
QGP probe	Jet quenching	High temperatures	Collective motion
	Opacity	**Luminosity**	**Fluidity**

Nuclear Geometry and Hydrodynamic flow

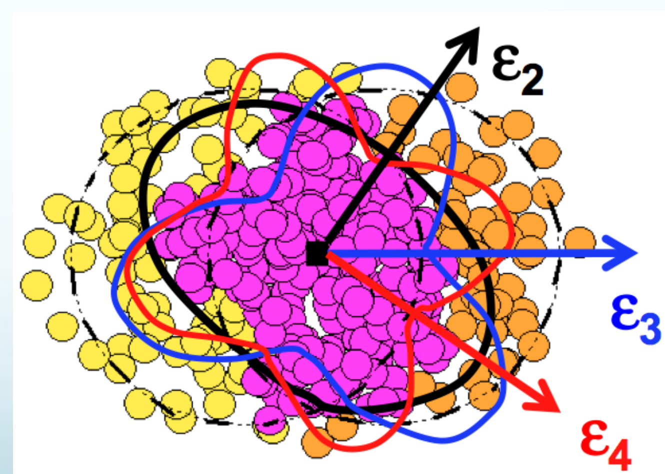
thermalization → larger pressure gradient in plane → less yield out more in plane



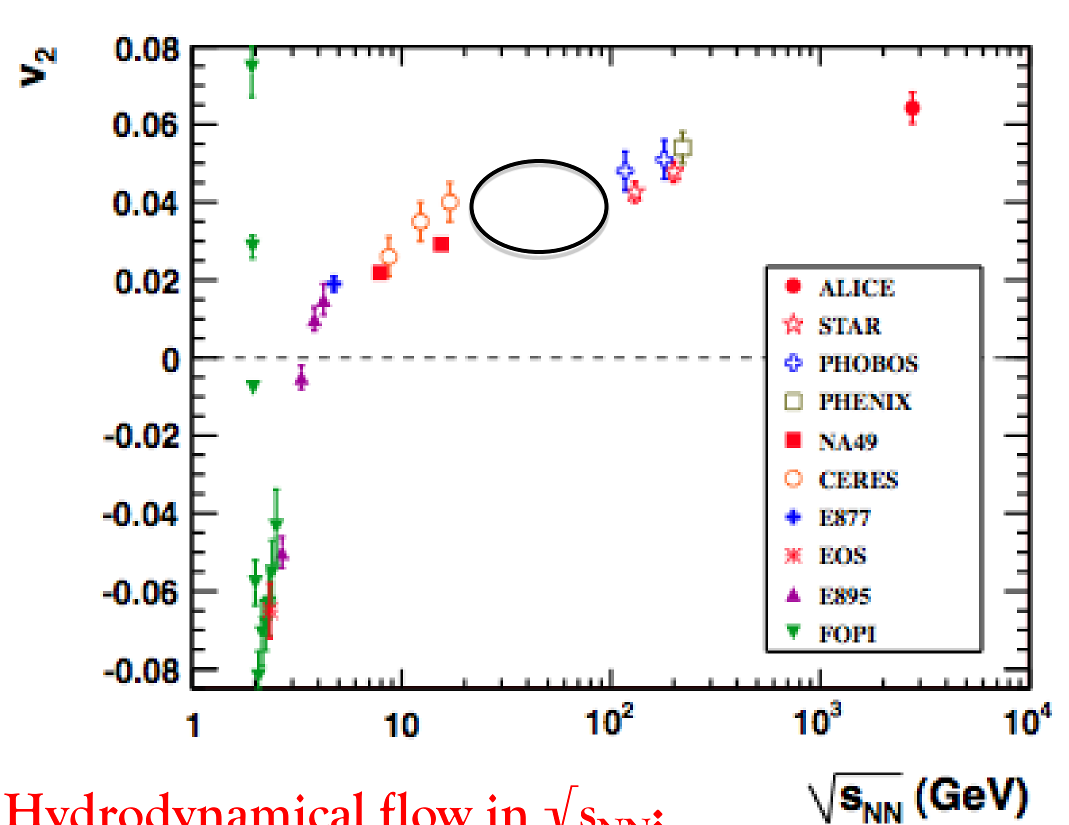


$$\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_n \cos n(\phi - \Phi_n)$$

Initial geometry has multiple shape components due to fluctuations.



Motivation – Low Energy Scan



The hydrodynamical flow of particles were measured in large range of collision energy.

- From few GeV up to few TeV

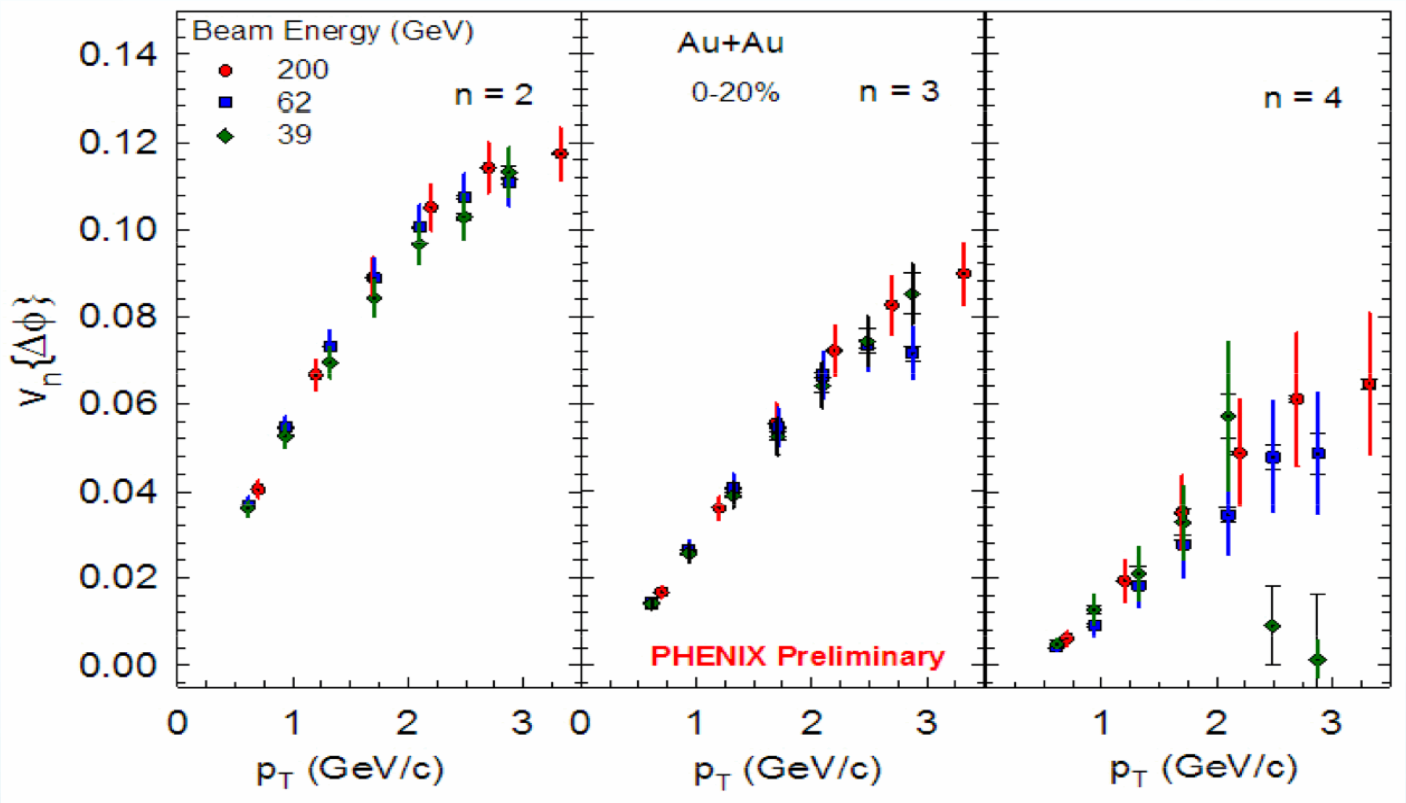
Hydrodynamical flow in $\sqrt{s_{NN}}$:

•Results follows the global trend for averaged v_2

•Flow seems to saturate $\sqrt{s_{NN}}$ > 100-200 GeV - indicates ideal "hydro".

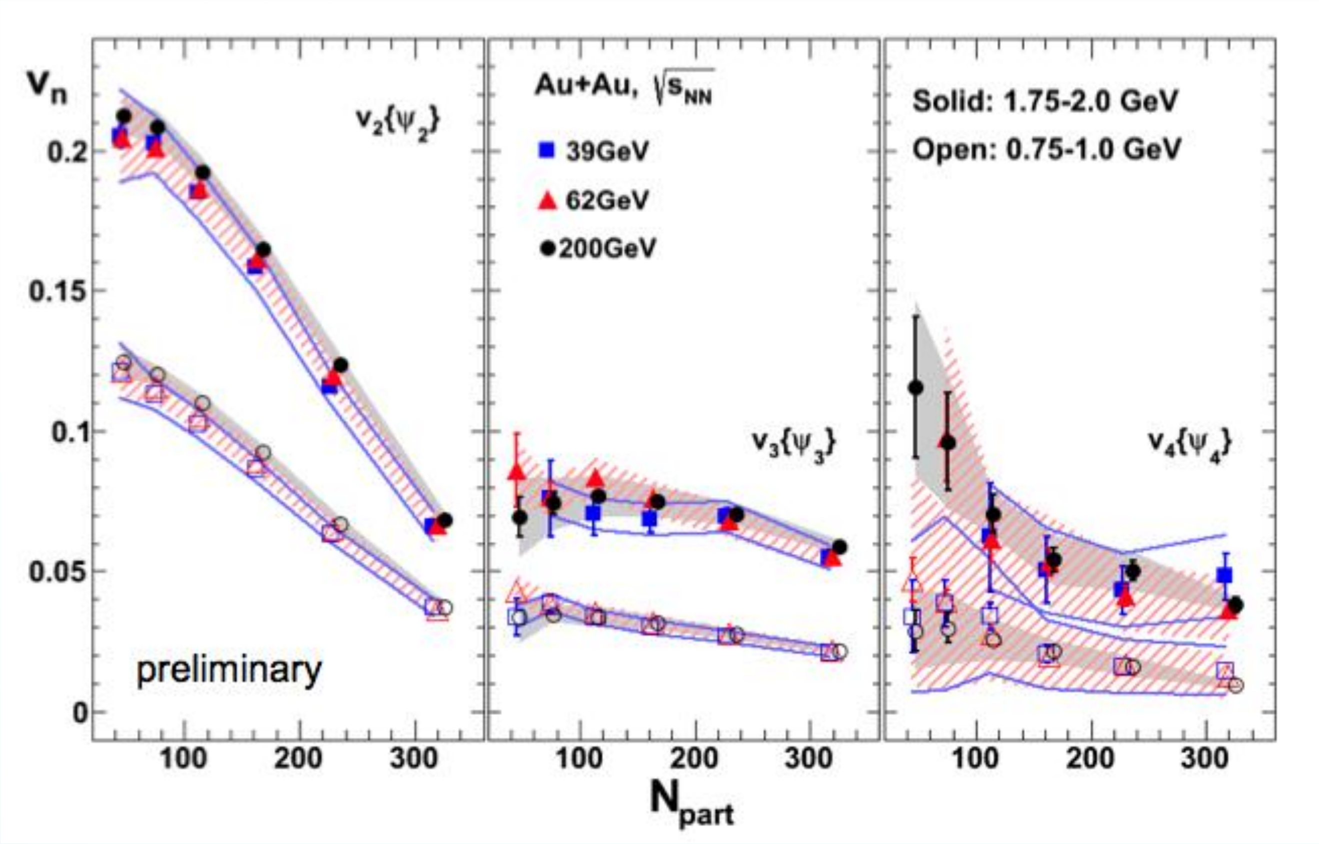
Evolution between SPS and RHIC energies - same trend ?

v_n as a function of p_T in Energy Scan



- Various beam energy: 39, 62, 200 GeV
- No significant beam energy dependence within uncertainties
- v_n follows expected behavior down to 39 GeV

v_n as a function of centrality

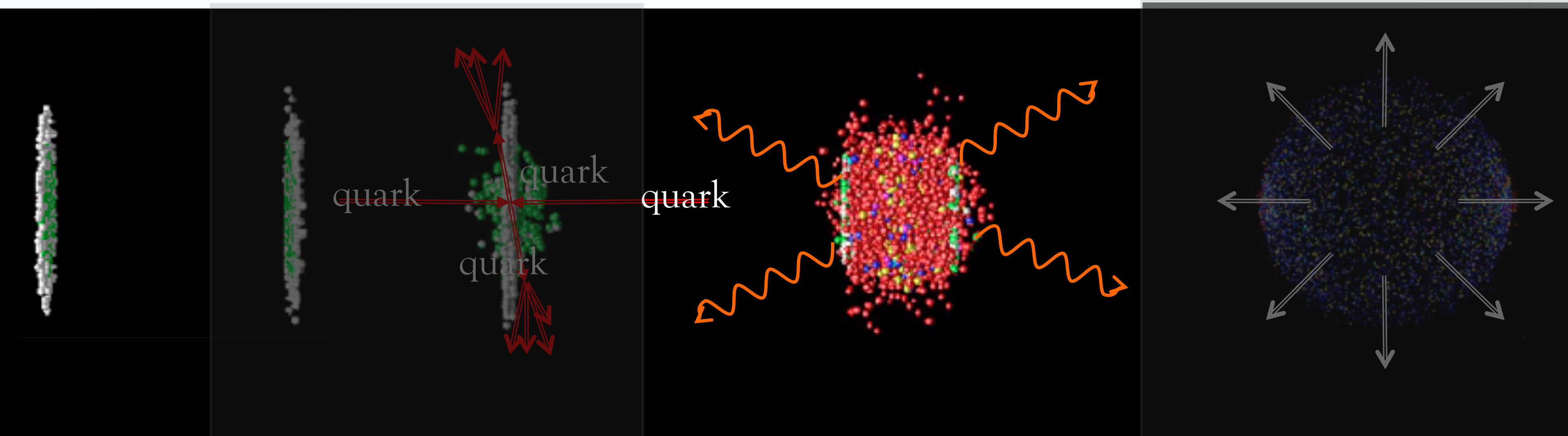


- Various beam energy: 39, 62, 200 GeV
- Increasing flow towards more peripheral collisions
- Averaged v_n follows also expected behavior

Fluidity – Summary

- The plasma created in heavy ion collisions has hydrodynamical behavior
- The flow is depending on initial geometry of the collision
- v_n shows the same behavior in collisions of Au+Au at $\sqrt{s_{NN}}$ = 39 – 200 GeV
- Flow follow the expected behavior in $\sqrt{s_{NN}}$

Little Big Bang



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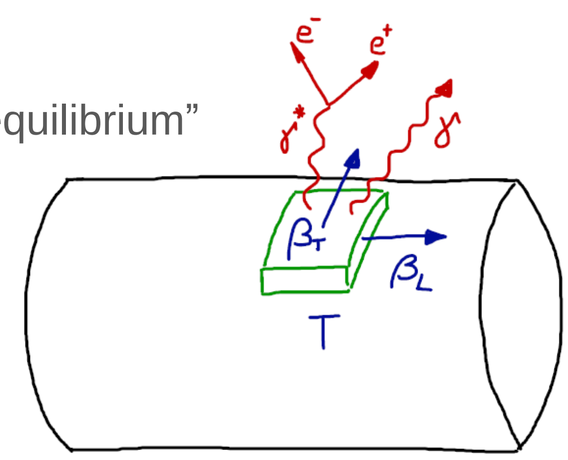
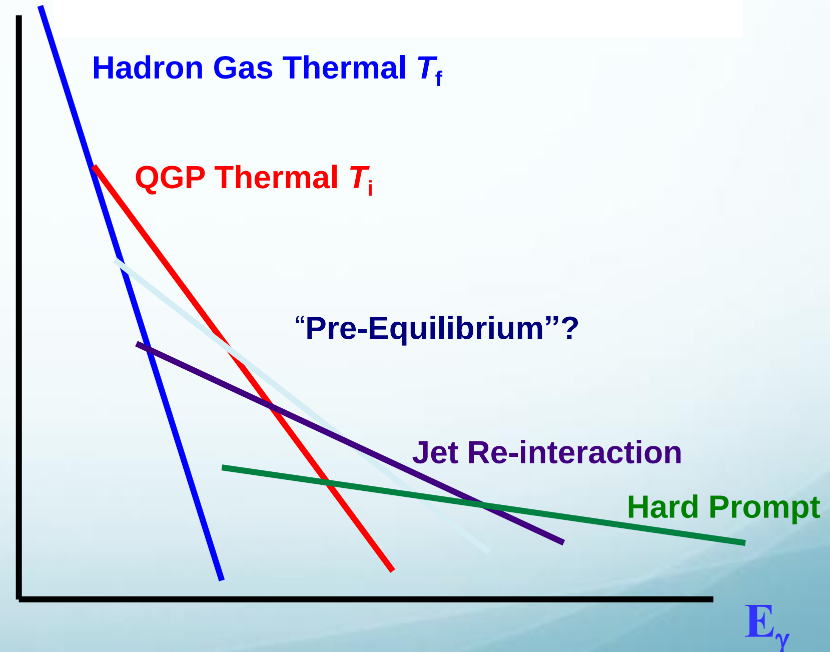
Schematic View of Thermal Photons

- Longitudinally and radially expanding fire ball in “local equilibrium”
  - Real and virtual photons
  - Integrated over space-time
  - Local equilibrium:

$$\mu\ e^{-W/T}$$



- Real and virtual photon momentum spectrum
  - Temperature information
    - sensitive to early times due to $e^{-\omega/T}$
  - Collective expansion, $\omega = p_\mu u^\mu$
    - Radial expansion results in blue and red shift
    - Longitudinal expansion results in red shift

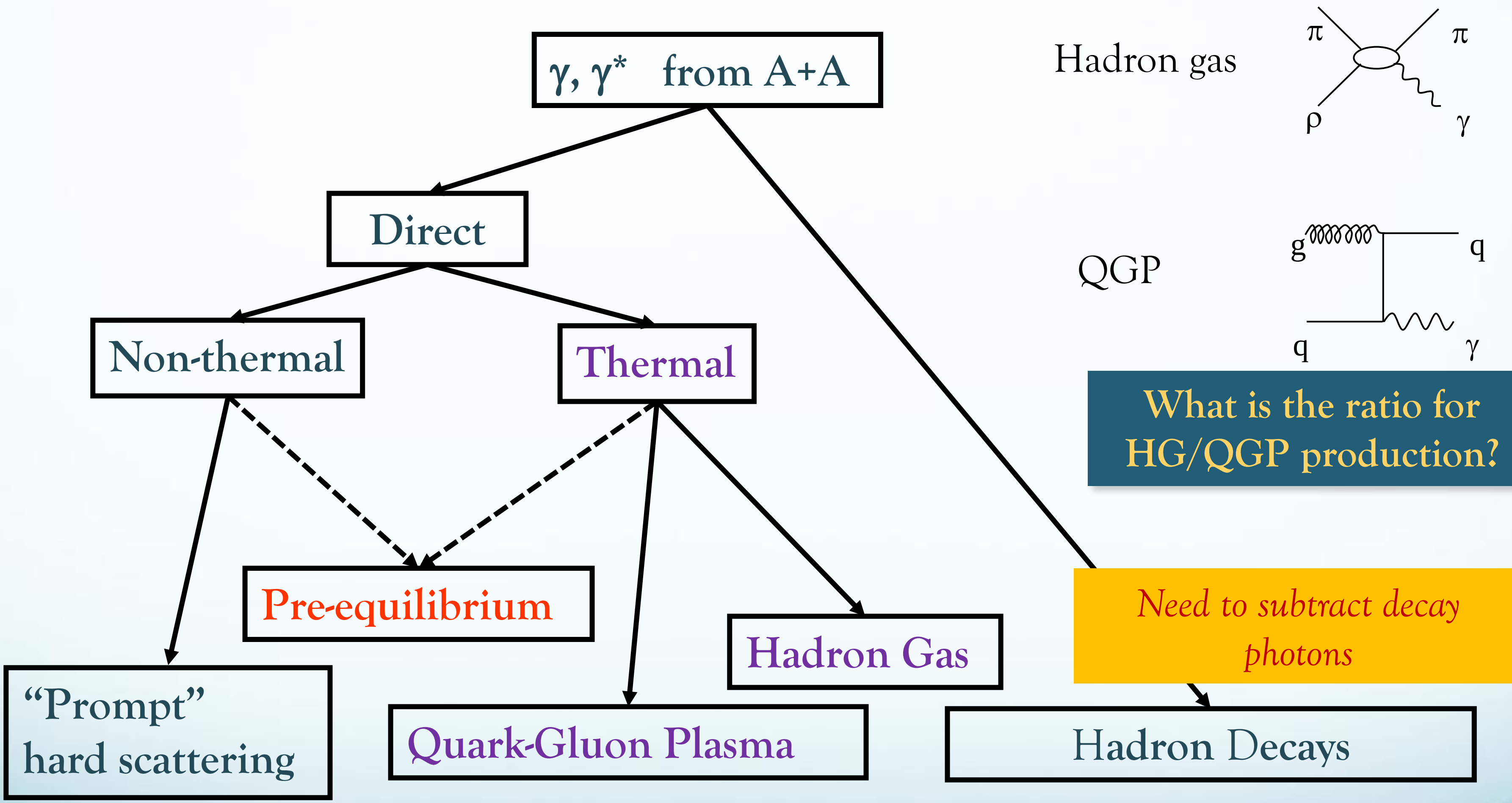


Photons

Production of photons:

Hadron gas

QGP

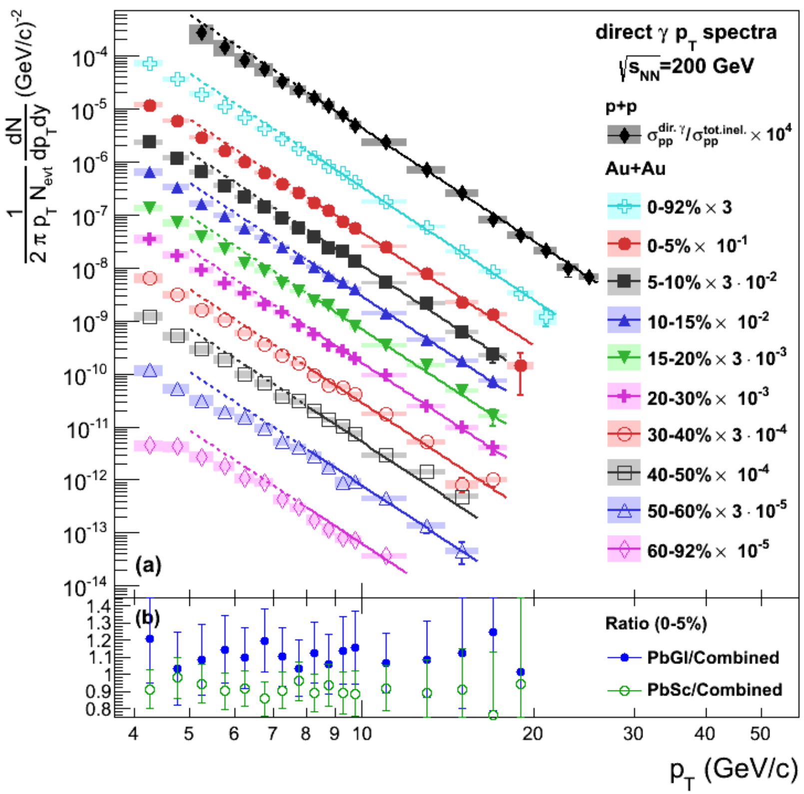


What is the ratio for HG/QGP production?

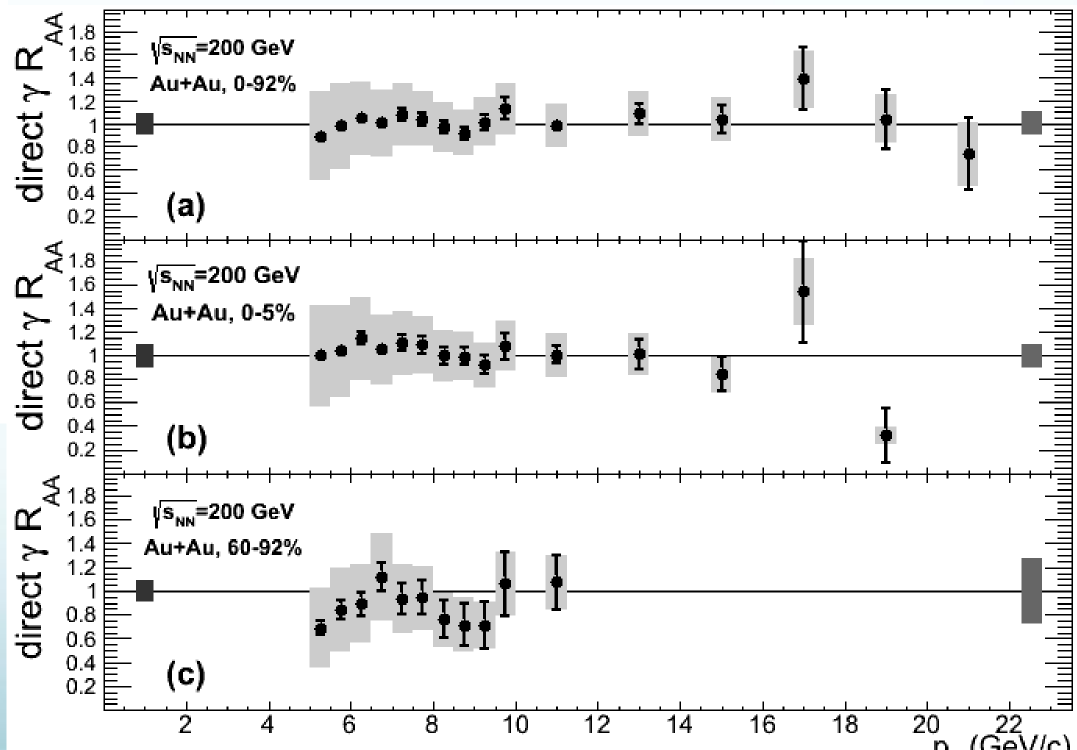
Sensitive to space-time evolution

Prompt Photon in Au+Au

PHENIX arXiv:1205.5533



- **PHENIX photon data**
  - **High p_T (4 to 25 GeV) from calorimeter**
- **Nuclear Modification Factor**
  - **Consistent with binary scaling of p+p**
  - **No evidence for cold nuclear matter or hot medium effects out to 20 GeV/c**

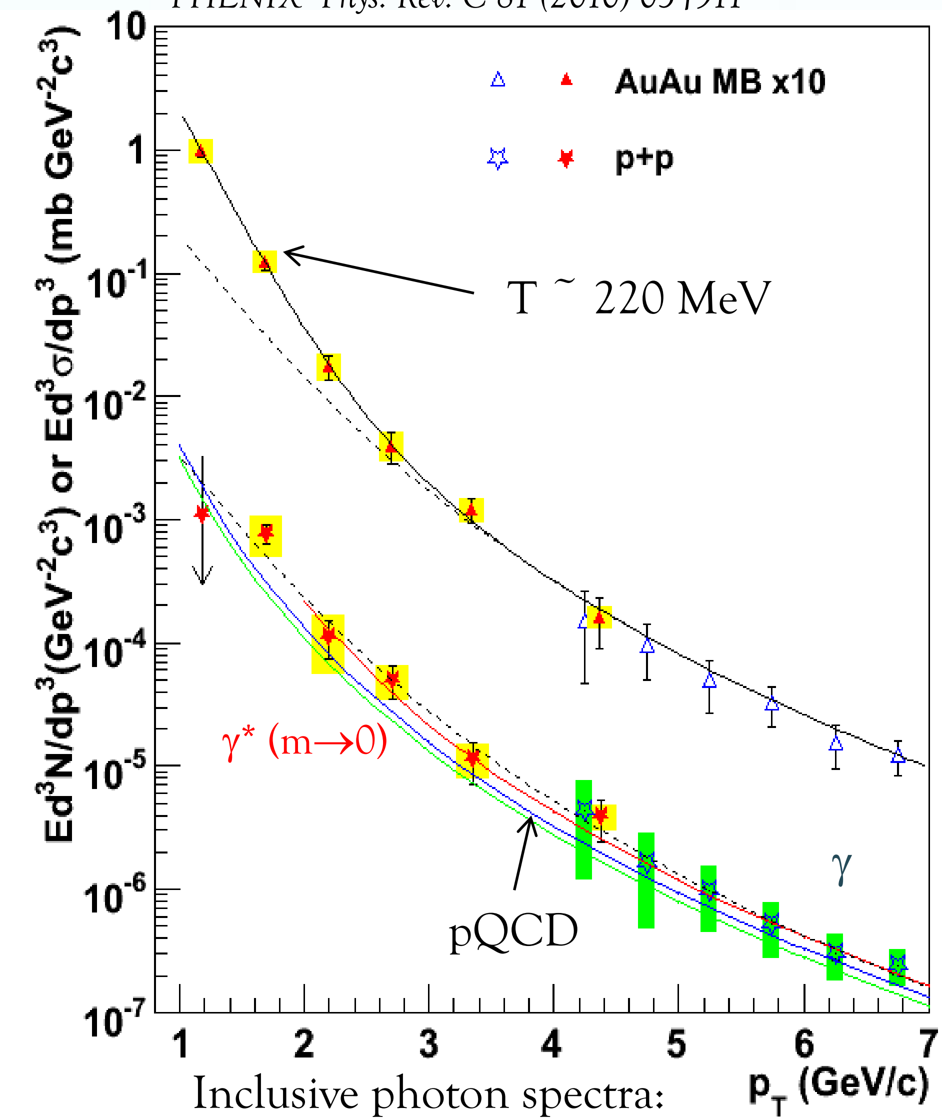


PHENIX arXiv:1205.5533

Hard scattering × N_{coll}
describes prompt γ from Au+Au
for p_T above 5 GeV/c

Thermal Photon in Au+Au

PHENIX *Phys. Rev. C* 81 (2010) 034911



Inclusive photon spectra:

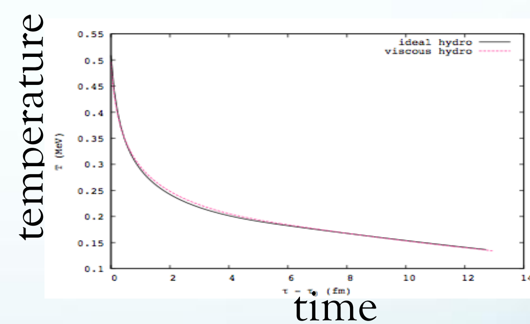
Exponential – thermal

Powerlaw – prompt

$\gamma^* (m \rightarrow 0) = \gamma ;\ m << p_T$

- Direct photons from real photons:
  - Measure inclusive photons and subtract decay photons
- Direct photons from virtual photons:
  - Measure e^+e^- pairs at $m_\pi < m << p_T$

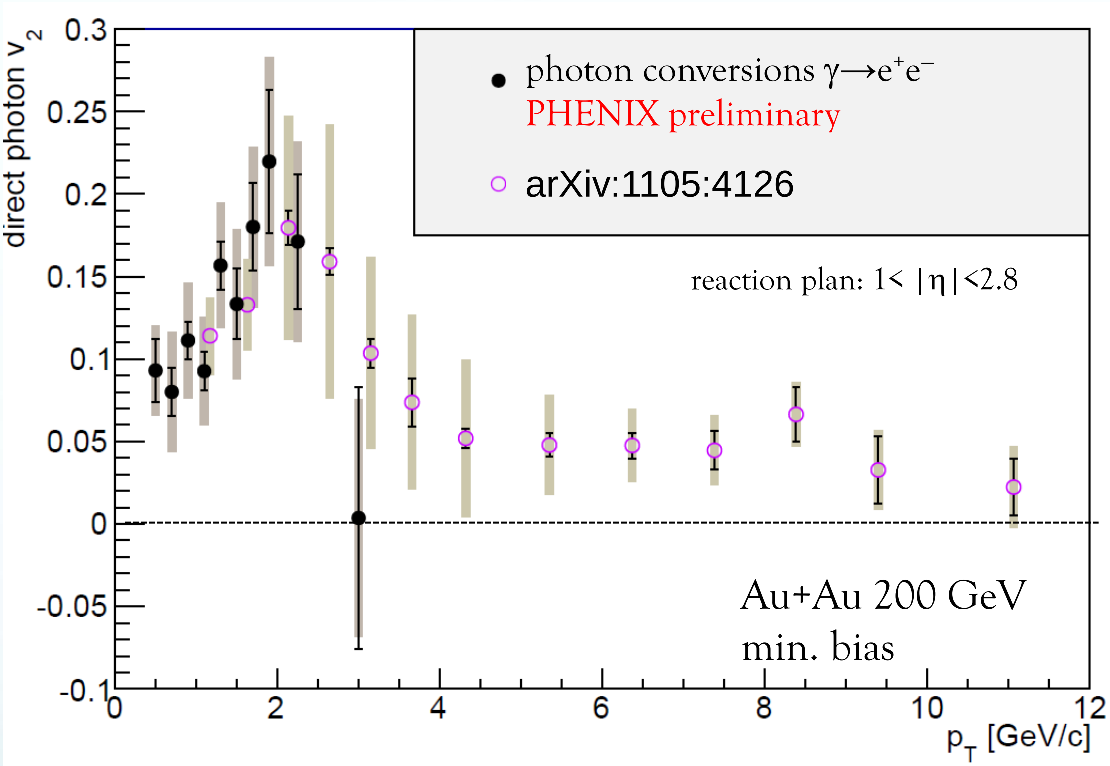
Hydro calculation:



First thermal photon measurement:
T_{ini} > 220 MeV > T_C

Need to consider radial flow! Compare to models!

Thermal photon v_2



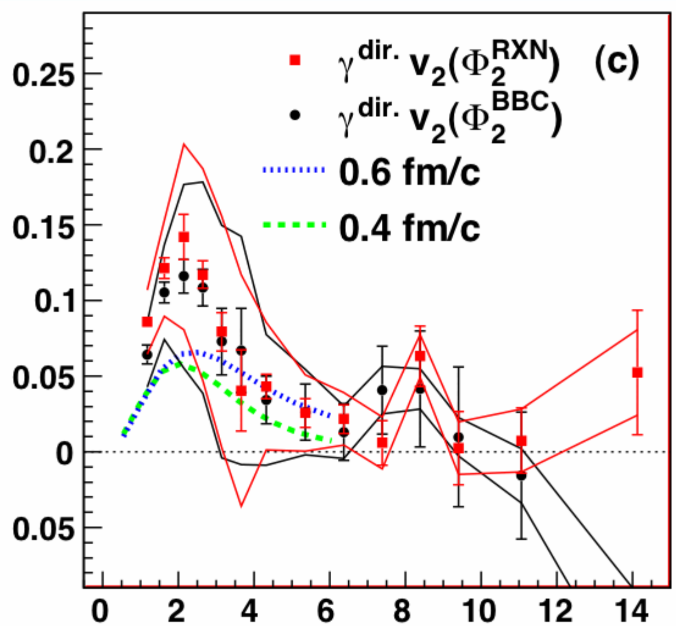
- Independent analysis based on photon conversions $\gamma \rightarrow e^+e^-$
- Background free inclusive photon sample
- R_γ from same data
- Completely independent systematic uncertainties
- p_T reach extended down to 0.5 GeV/c
- Two independent and consistent results!

Large elliptic flow of thermal photons
Maximum v_2 ~ 0.2 at 2 GeV/c

Thermal photon Puzzle

Models fail to describe simultaneously photon yield, T and v2!

R. Chatterjee and D. K. Srivastava
PRC 79, 021901(R) (2009)
PRL96, 202302 (2006)

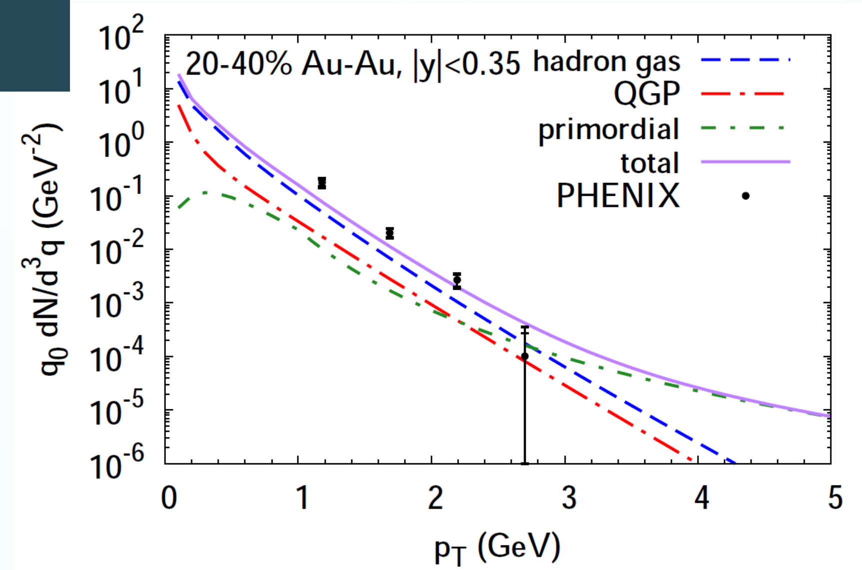


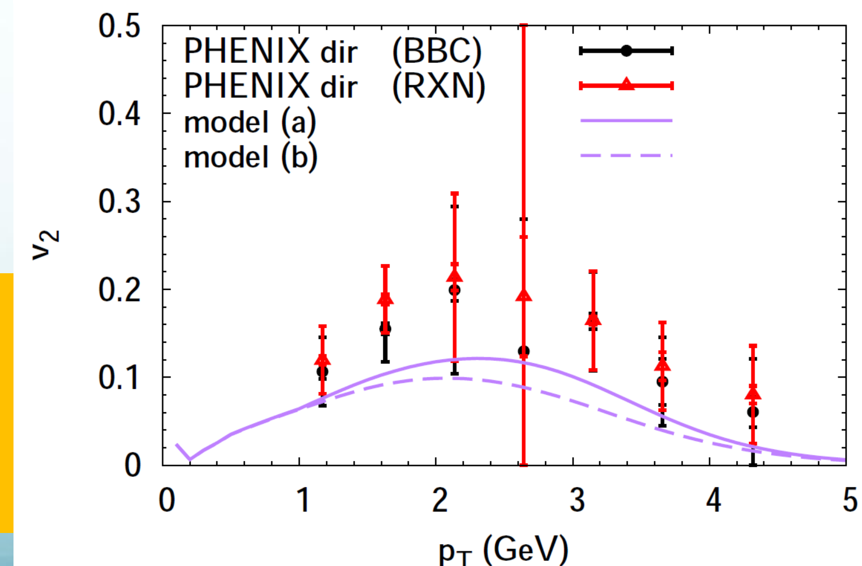
Large flow requires late emission!

Apparent contradiction with yield, which points towards early emission!

T_{ini} ~ 325MeV

Hees/Gale/Rapp
Phys.Rev.C84:054906,2011.





Photons – Summary

- Photon spectrum was measured at $\sqrt{s_{NN}}$ = 200 GeV
- Thermal photons were measured by PHENIX
- Thermal photon puzzle:
  - Two independent measurements were done to determine the v_2 of photons
  - Theory cannot explain yet the high yield and high flow of thermal photons

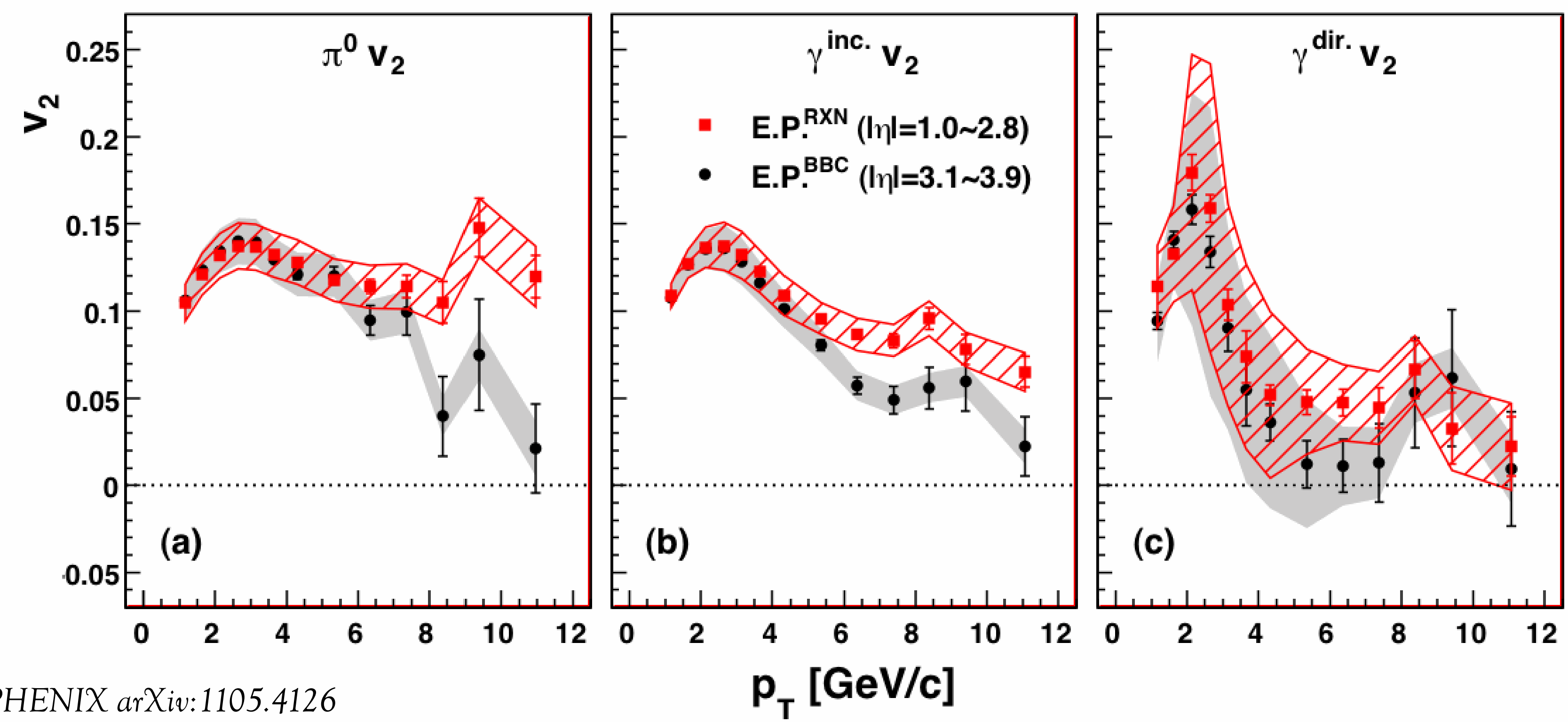
THANK YOU

Backup

Elliptic flow of Photons

- How to determine elliptic flow of thermal photons?
  - Establish R_γ, i.e. fraction of thermal photons in inclusive photon yield
  - Measure inclusive photon v_2^{incl}
  - Predict hadron decay photon v_2^{hadr} from pion $v_2^{\pi 0}$
  - Subtract hadron decay contribution

$$v_2^{dir} = \frac{R_\gamma v_2^{incl} - v_2^{hadr}}{R_\gamma - 1}$$

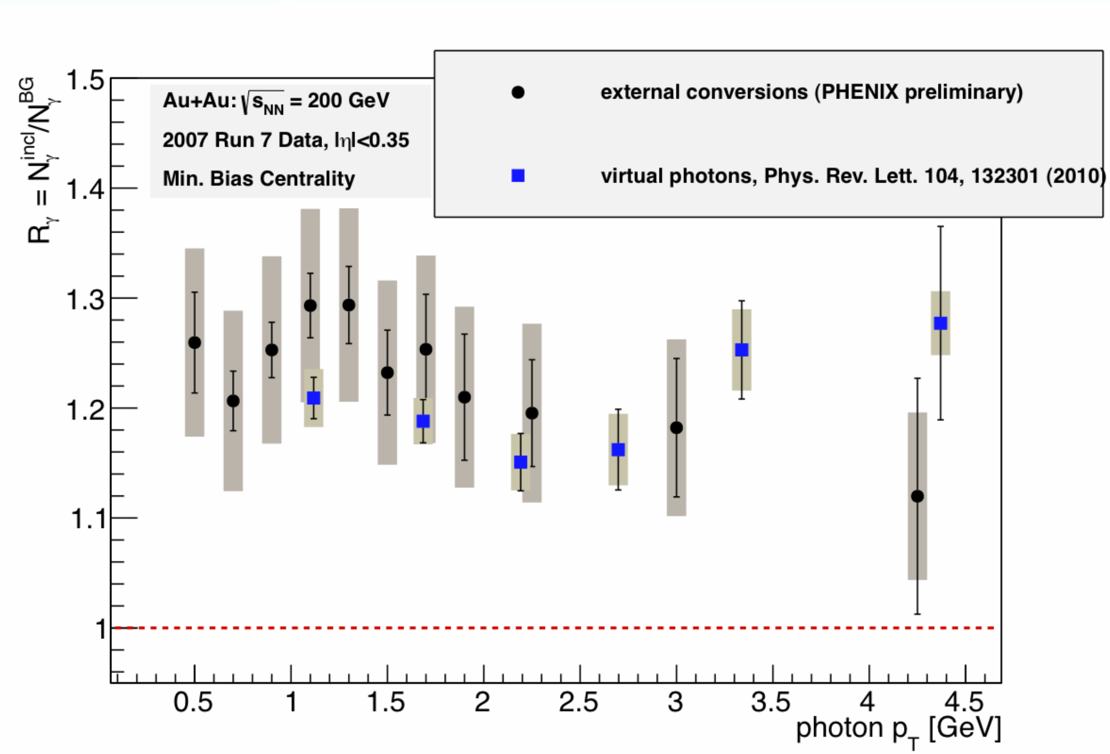


PHENIX *arXiv:1105.4126*

Large v_2 of low p_T thermal photon

Thermal Photons

- PHENIX has developed new method to detect direct photons:
  - Use photon conversions to e^+e^-
  - Tag contribution from π^0 decays
  - Independent systematic uncertainties



conditional tagging efficiency

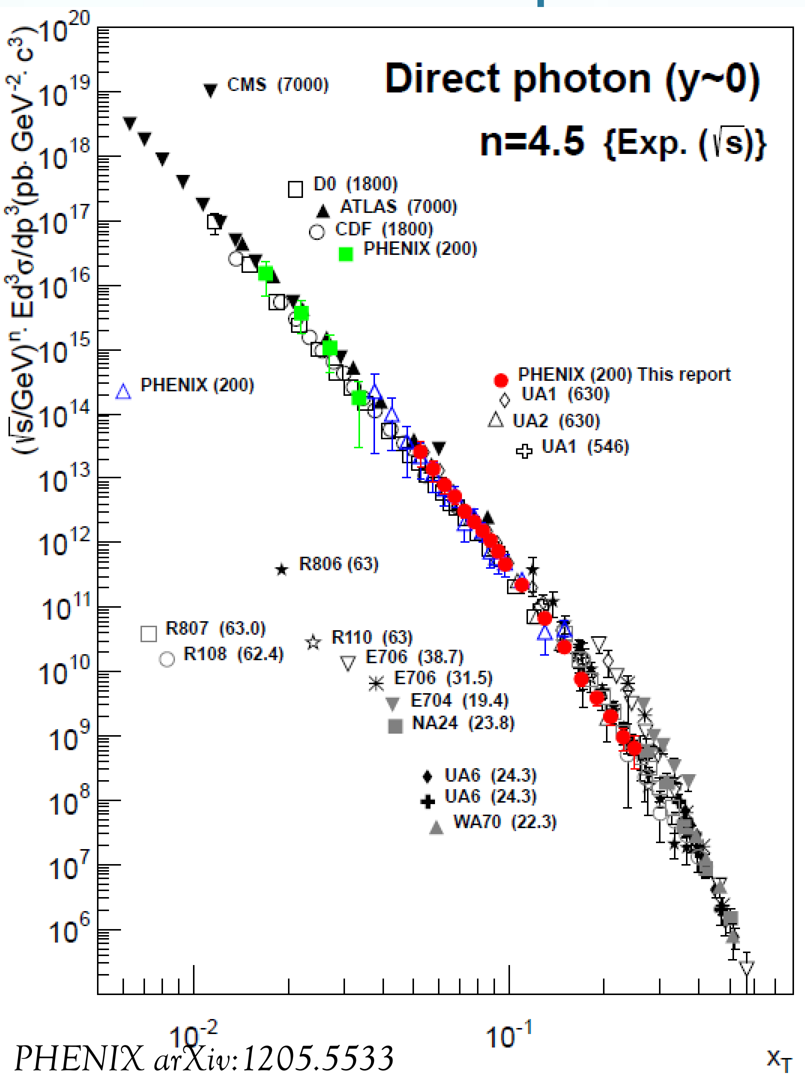
measured raw yields

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\varepsilon f \times \left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}}\right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}}\right)^{MC}}$$

simulated based On hadron data

Thermal photons observed in virtual and real photons consistent within systematic uncertainties

Prompt Photon in p+p and d+Au



PHENIX arXiv:1205.5533

Well established reference for prompt photons

- PHENIX photon data
  - High p_T (4 to 25 GeV) from calorimeter
  - Low p_T (<4 GeV) from virtual photons
- p+p data consistent with pQCD
  - x_T scaling of cross section $\left(\sqrt{s}\right)^{4.5}$
  - NLO calculation agree well with data
- d+Au data consistent with N_{coll} scaling
  - No evidence for cold nuclear matter effects