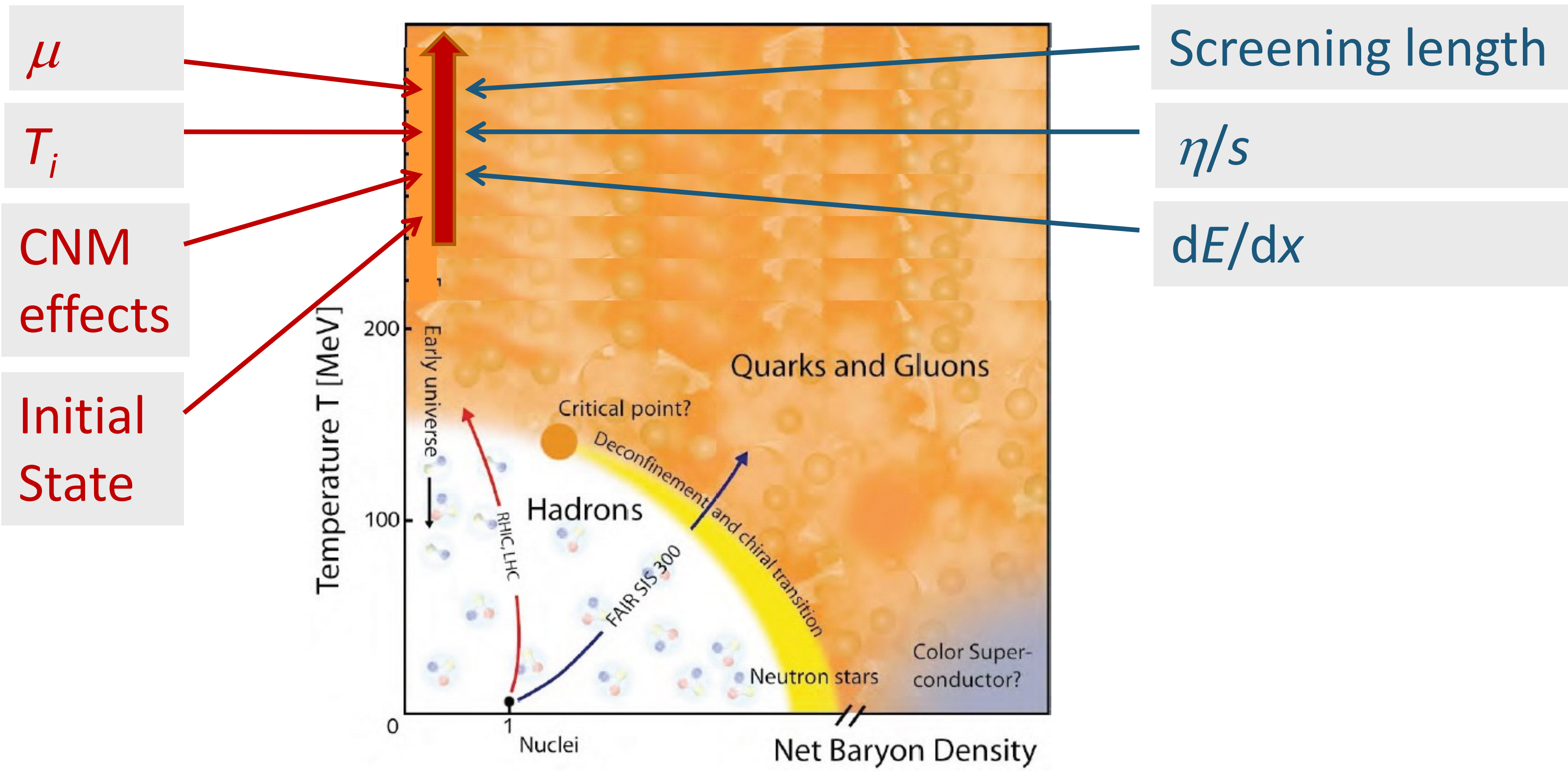
PHENIX HIGHLIGHTS

Stefan Bathe, QM2011

Measuring the Properties of the QGP

Conditions ⟹ Properties



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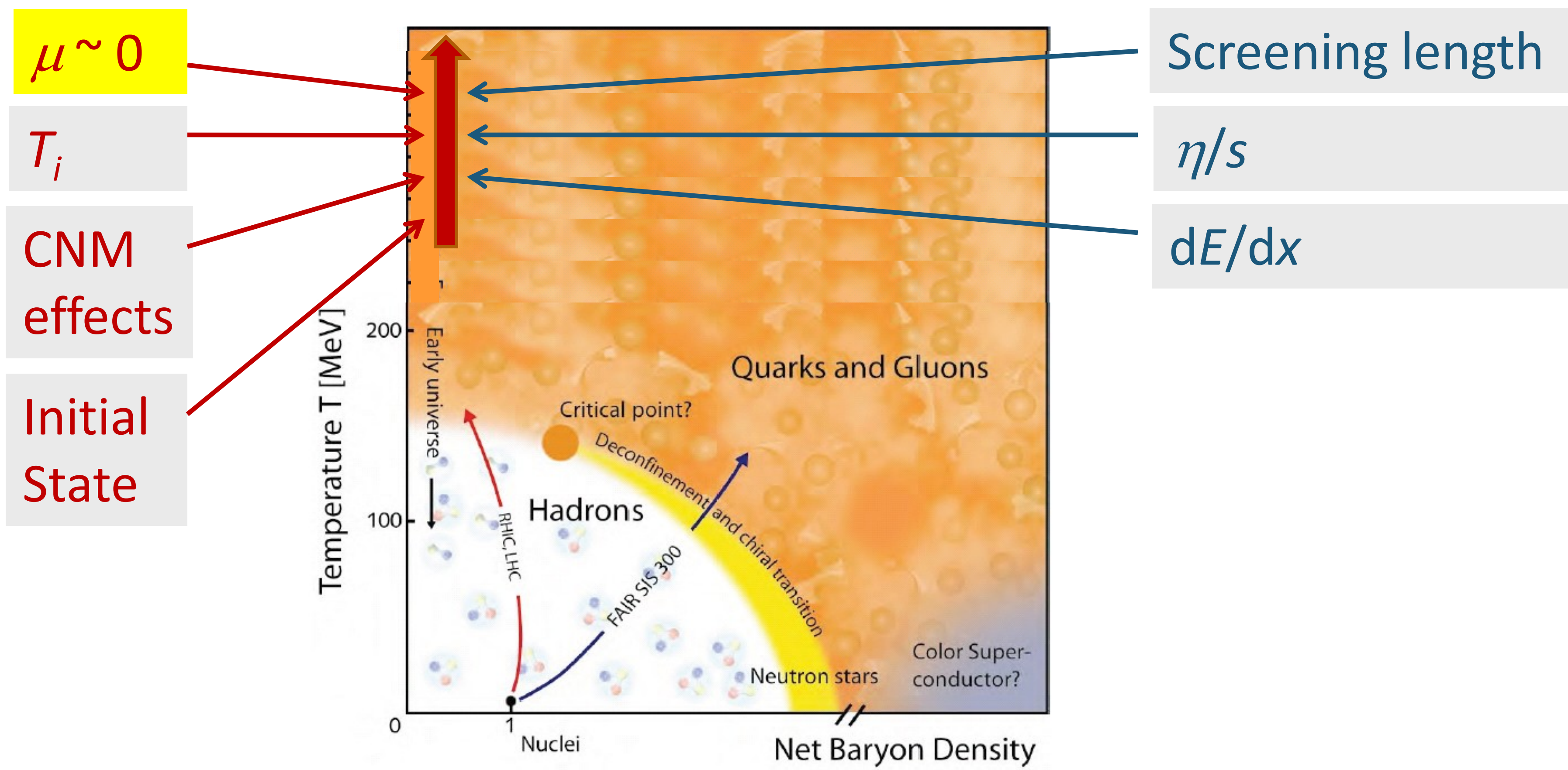
What I will show you today

- v_2 of thermal direct photons
  - Constrains T_i and τ_0
- CNM effects in *d*+Au
  - Density dependence of shadowing from J/ψ
  - Reconstructed jets
  - Low-*x* suppression from forward di-hadron correlations
- v_3
  - Disentangle initial state from η/s
  - Implications for 2-particle correlations
- E loss
  - Path-length dependence
- Results from energy scan

Measuring the Properties of the QGP

Conditions ⟹ Properties



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Measuring the Properties of the QGP

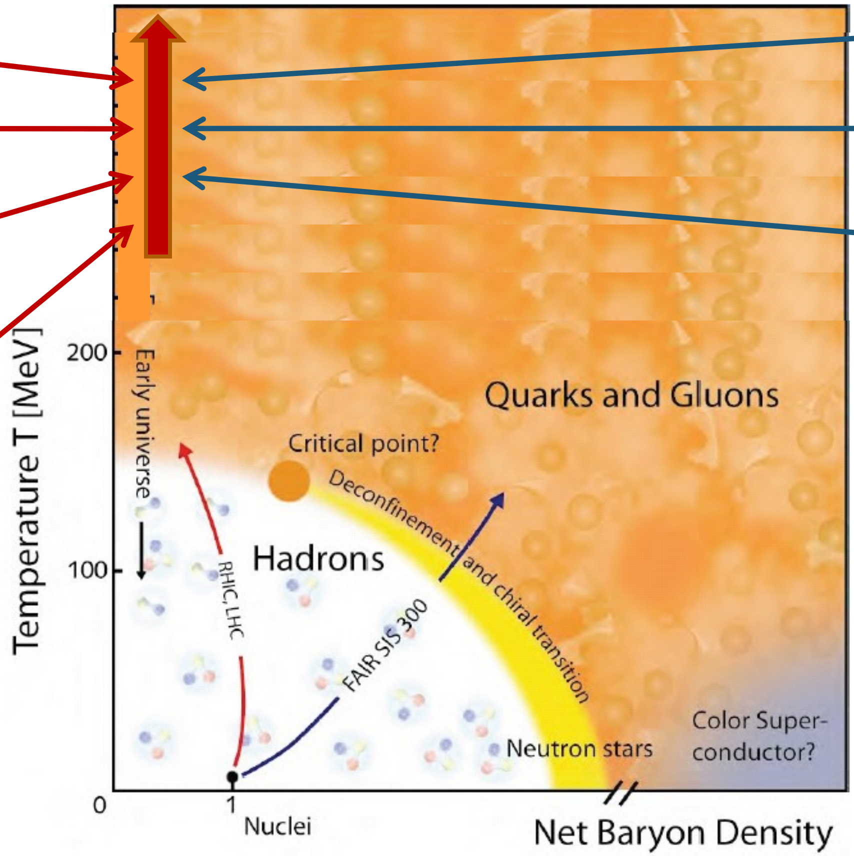
Conditions ⟹ Properties

$\mu \sim 0$

T_i

CNM effects

Initial State



Screening length

η/s

dE/dx

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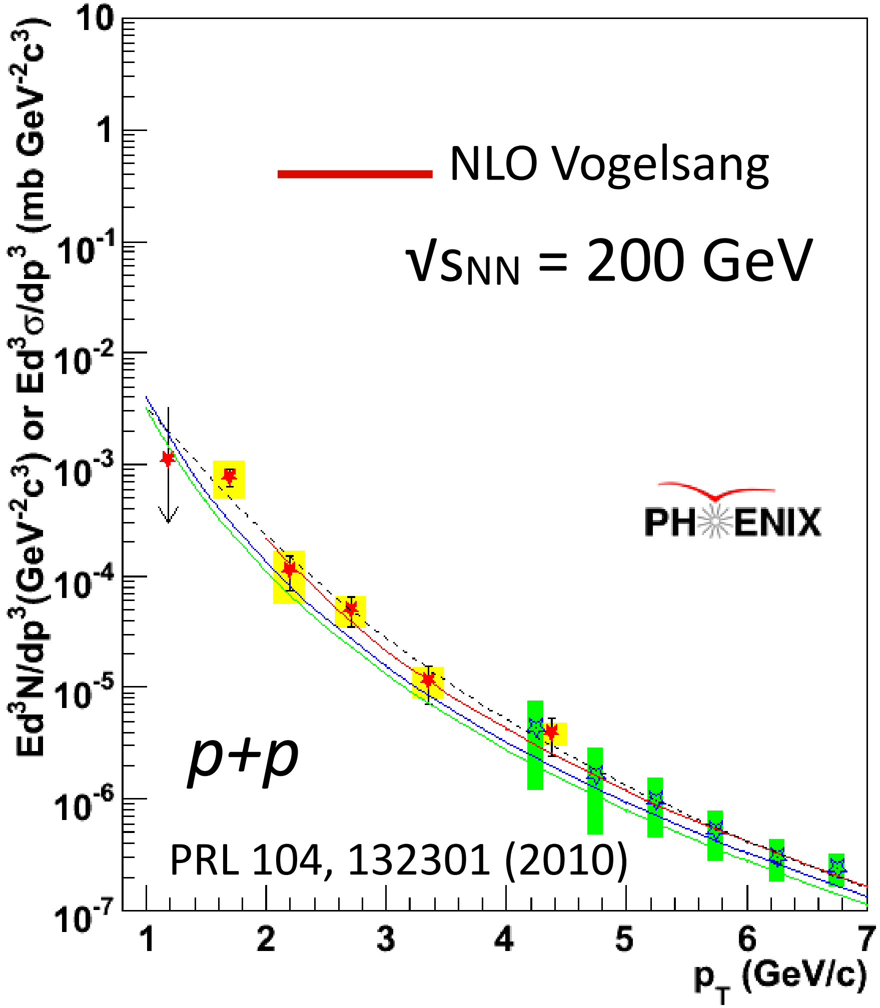
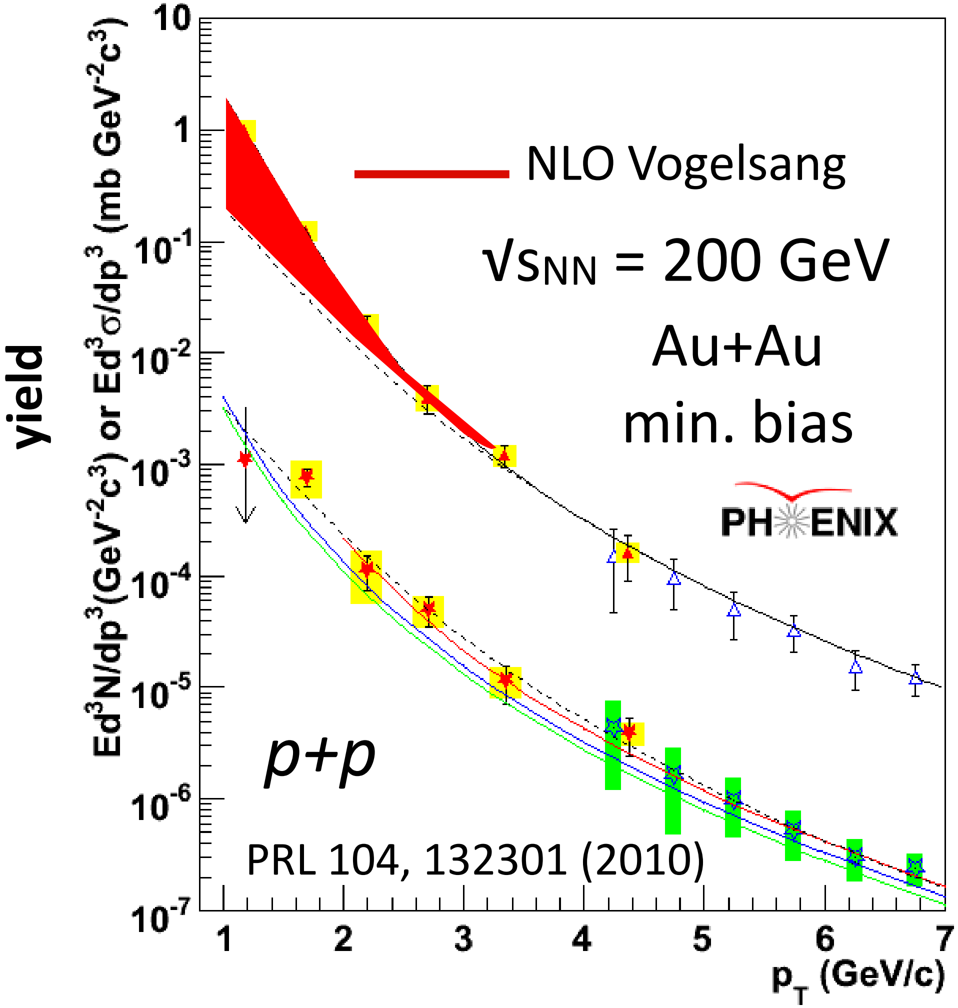
Direct Photon Excess in Au+Au

yield

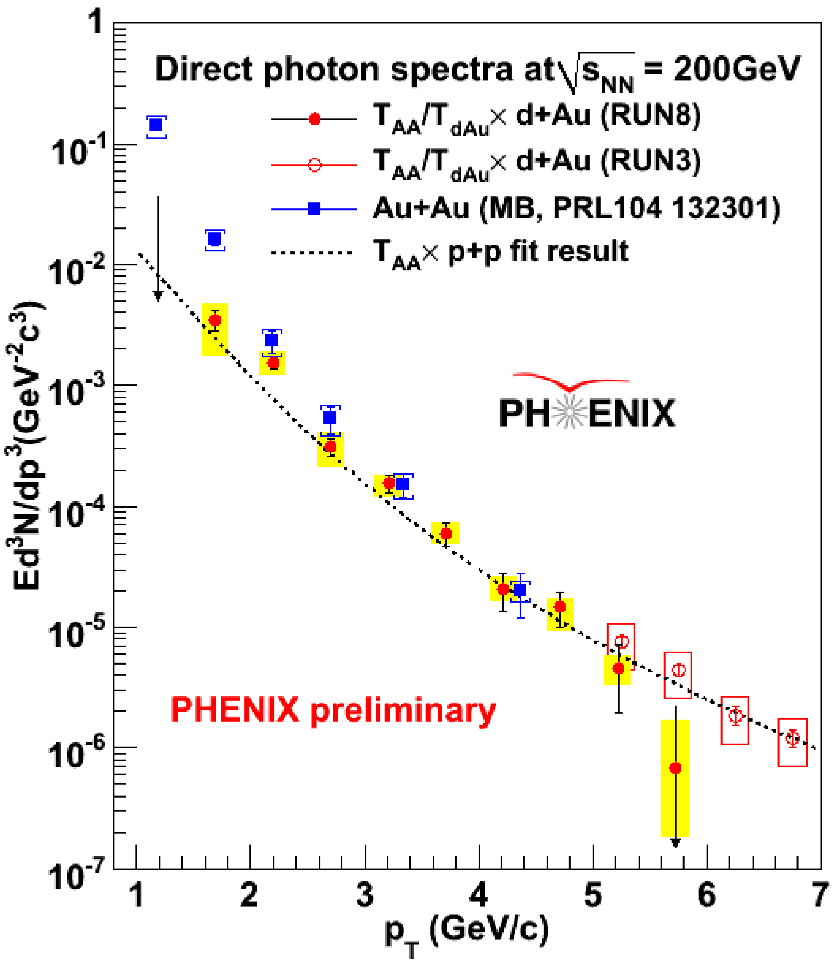


Direct Photon Excess in Au+Au



- Direct photon excess above *p+p* spectrum
- Exponential (consistent with thermal)
- Inverse slope = 220 ± 20 MeV
- T_i from hydro
  - 300 . . . 600 MeV
  - Depending on thermalization time

Critical *d*+Au Check

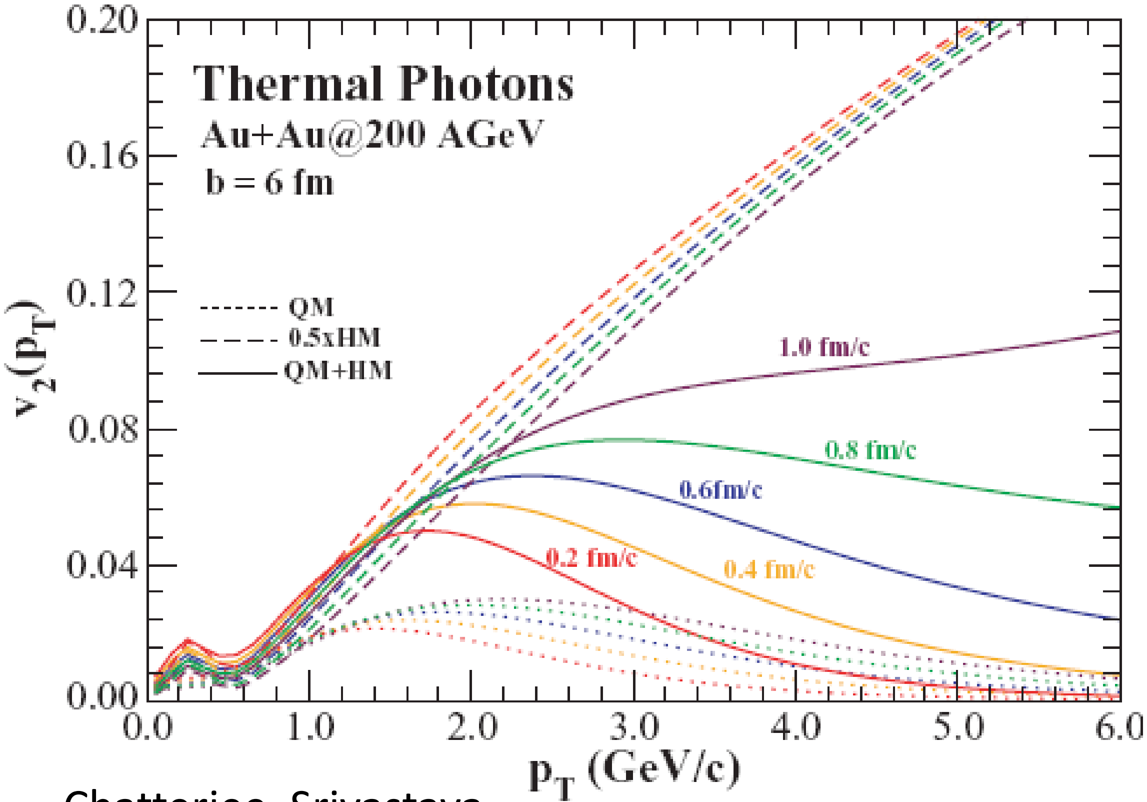


- New:
  - no exponential excess in *d*+Au

Poster: Y. Yamaguchi

Direct photon v_2 further constrains T_i

Hydro after τ_0



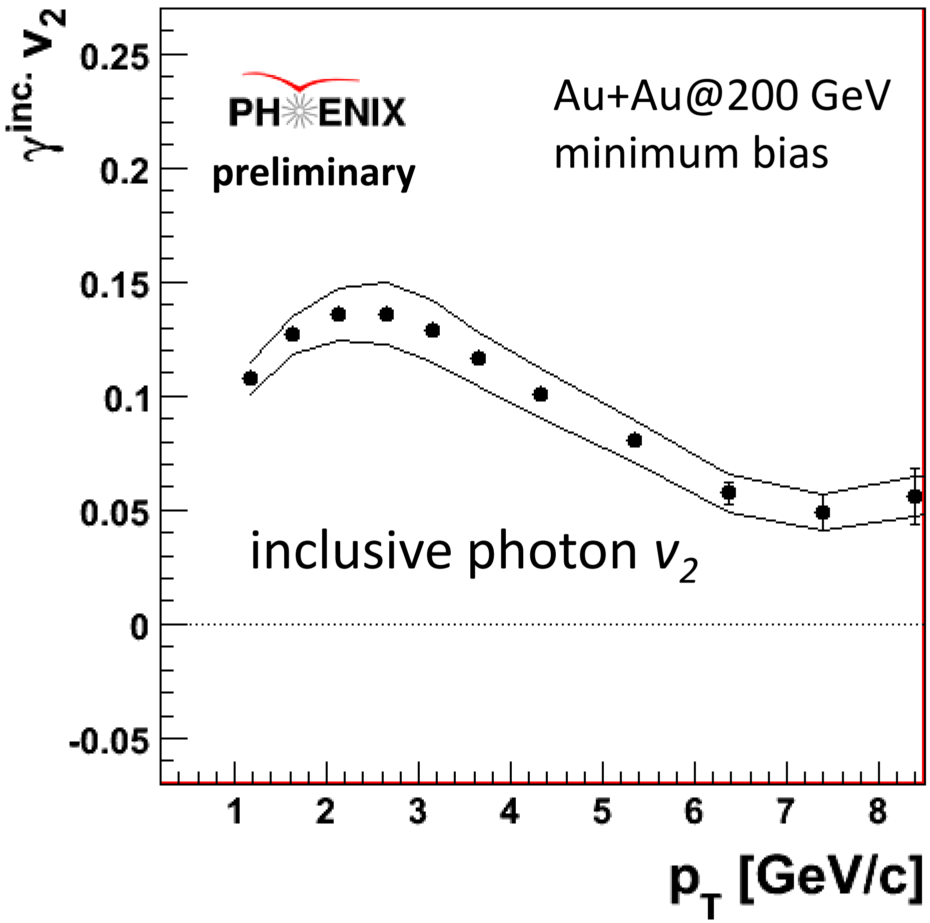
Chatterjee, Srivastava
PRC79, 021901 (2009)

- expected v_2:
  - prompt photons: 0 (time zero)
  - thermal photons

early → small (flow not built up)

late → large (like hadrons)

Direct Photon v_2



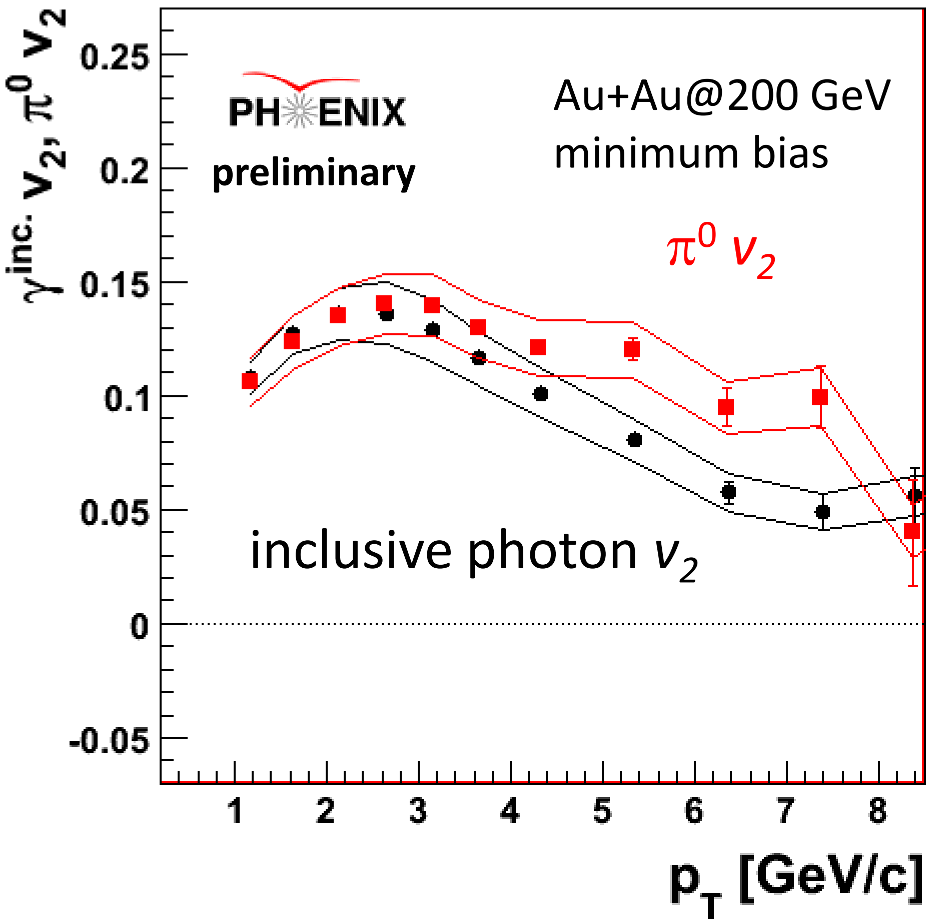
Statistical subtraction

inclusive photon v_2
- decay photon v_2

= direct photon v_2

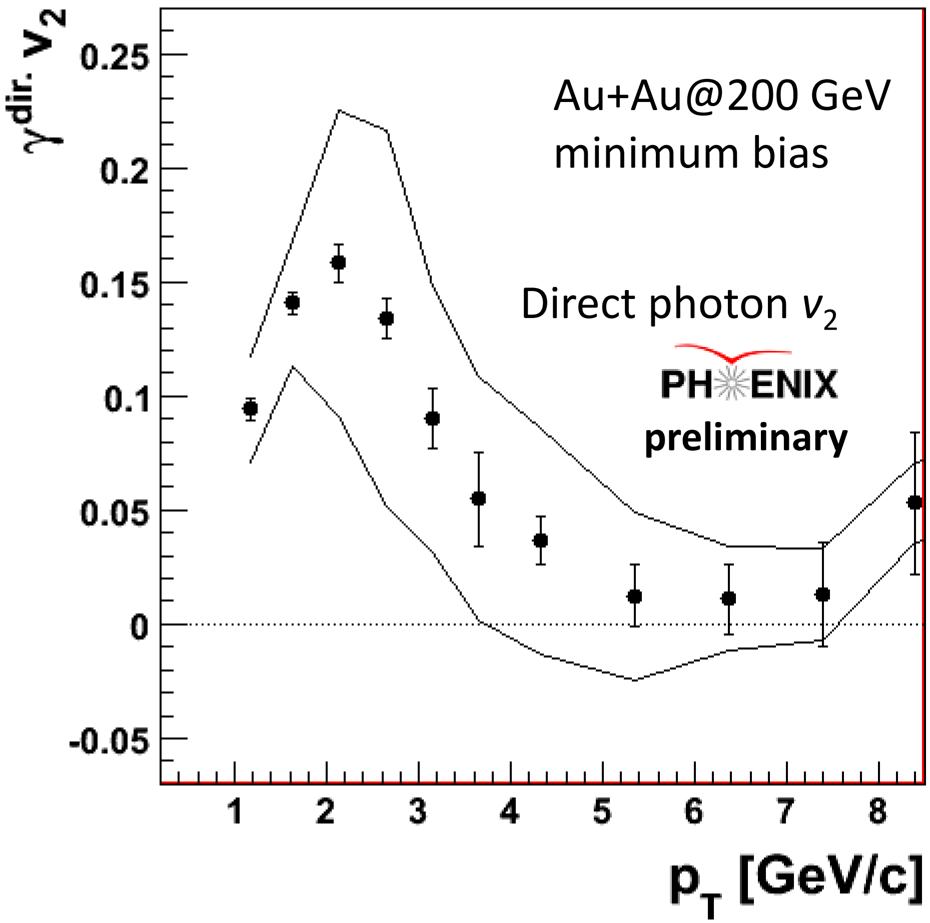
$$v_2^{dir.} = \frac{R_\gamma v_2^{inc.} - v_2^{BG}}{R_\gamma - 1}$$

Direct Photon v_2



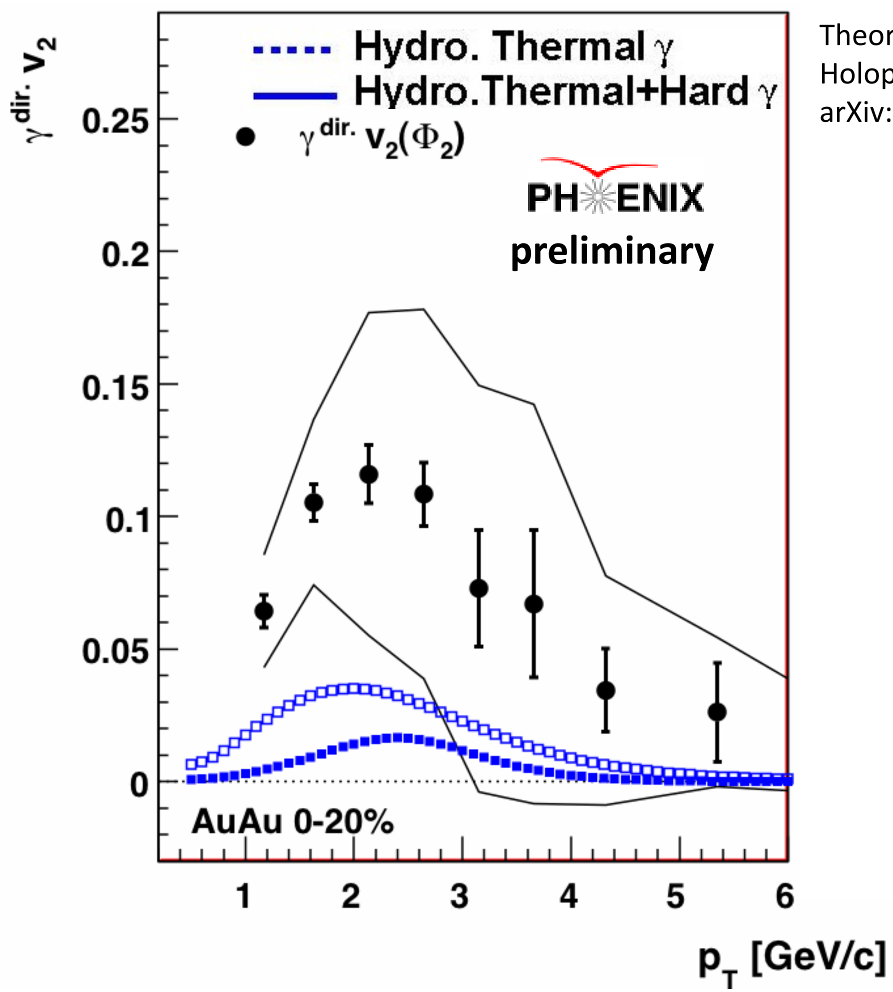
- π^0 v_2 similar to inclusive photon v_2
- Two possibilities
  - A: there are no direct photons
  - B: direct photon v_2 similar to inclusive photon v_2
- Key: precise measurement of direct photon excess

Direct Photon v_2



- direct photon v_2 large (~15 %) at p_T =2.5 GeV
- $v_2 \rightarrow 0$ where prompt photons dominate

Theory Comparison: Direct Photon v_2



Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

- Models under-predict direct photon v_2
- Measurement further constrains T_i and τ_i
- Challenge to theorists

Plenary: S. Esumi (flow), Tue
Parallel: E. Kistenev (direct photons) Thu

Measuring the Properties of the QGP

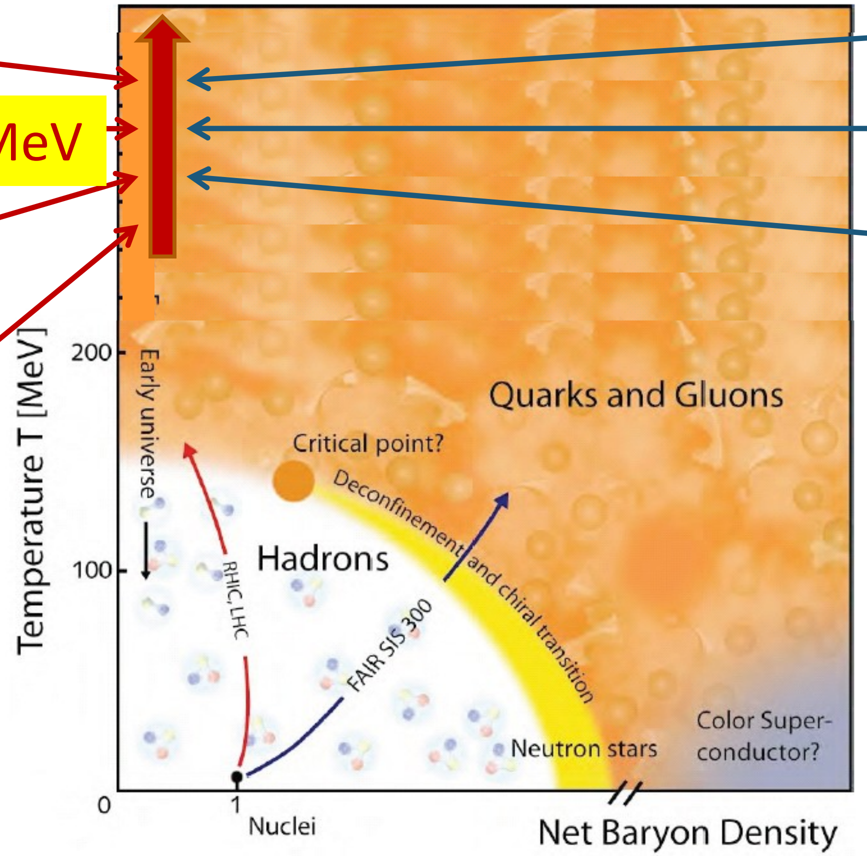
Conditions ⟹ Properties

$\mu \sim 0$

T_i =300-600 MeV

CNM effects

Initial State



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Screening length

η/s

dE/dx

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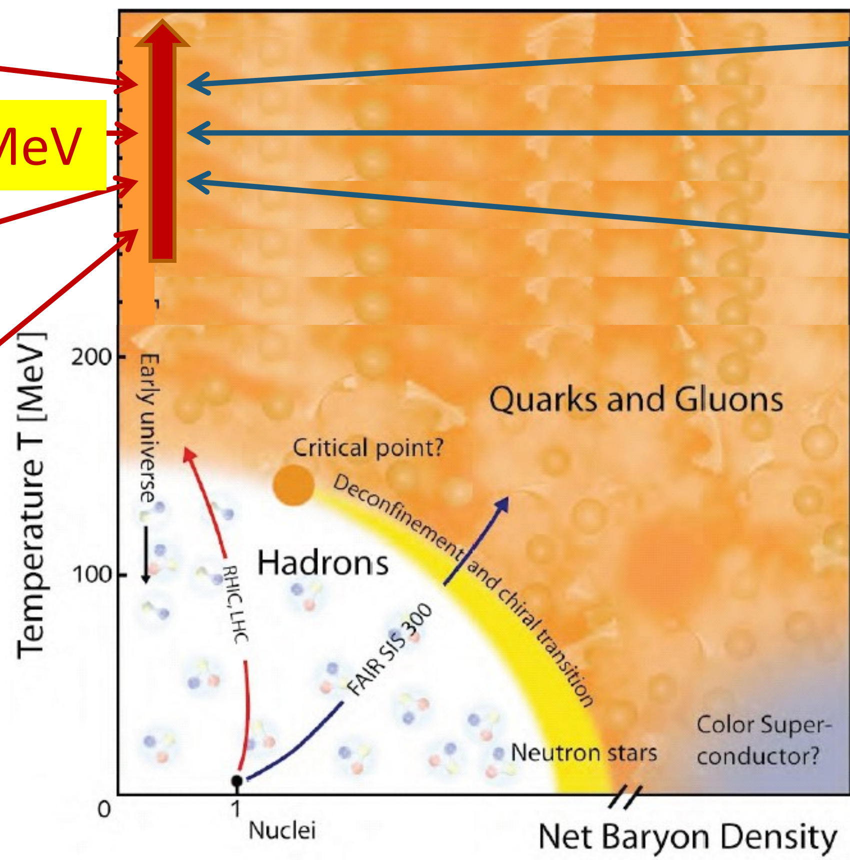

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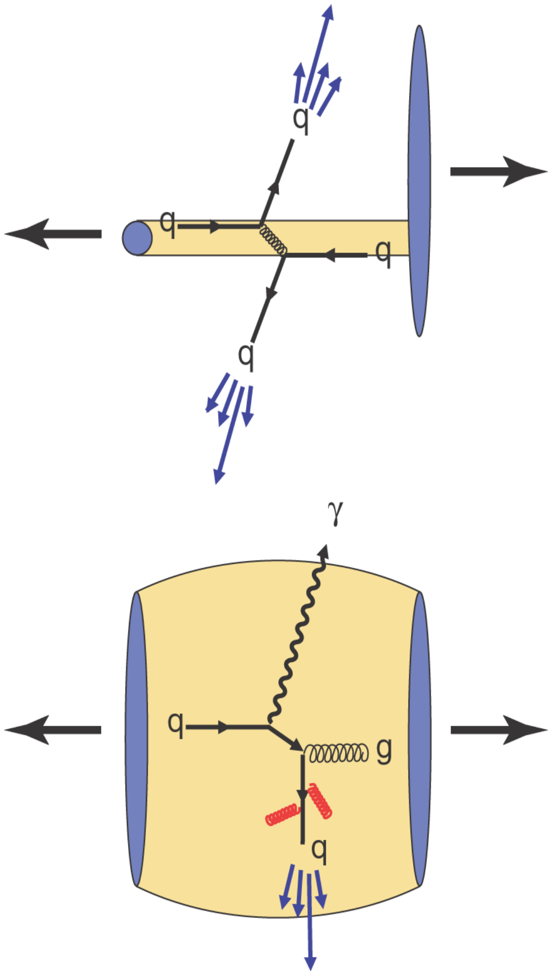
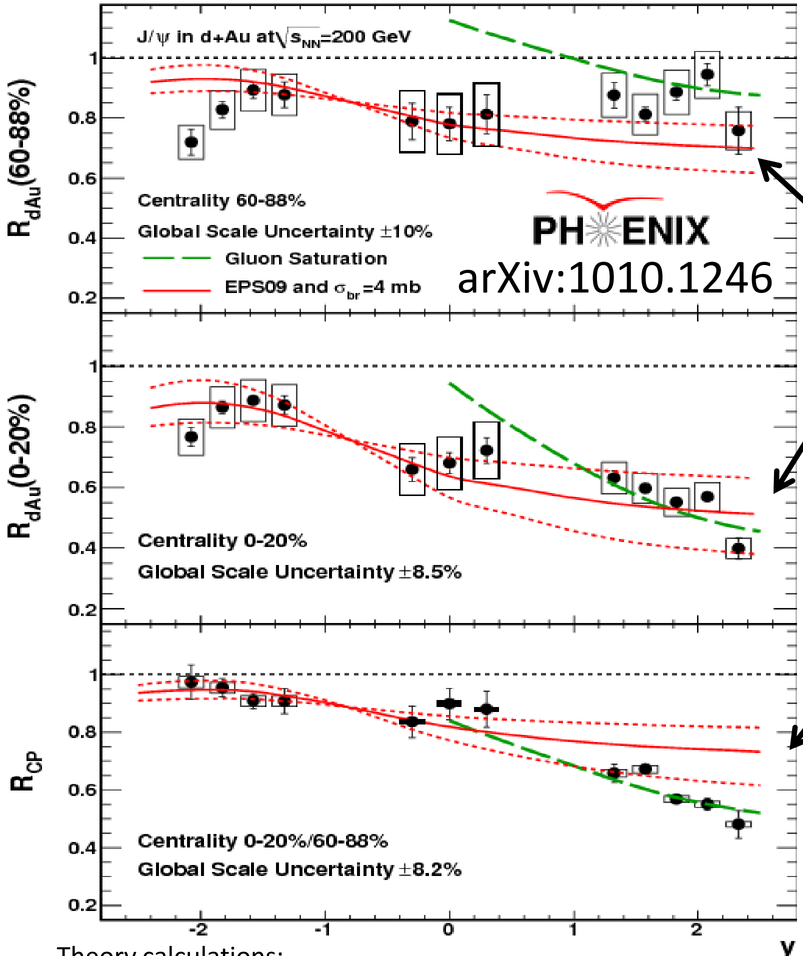
Cold Nuclear Matter Effects



- Important for interpretation of HI data
  - Measure Cold Nuclear Matter (CNM) effects in d+Au collisions
- RHIC versatile
  - Can collide any nuclear species on any other

J/ψ in *d*+Au: Shadowing non-linear

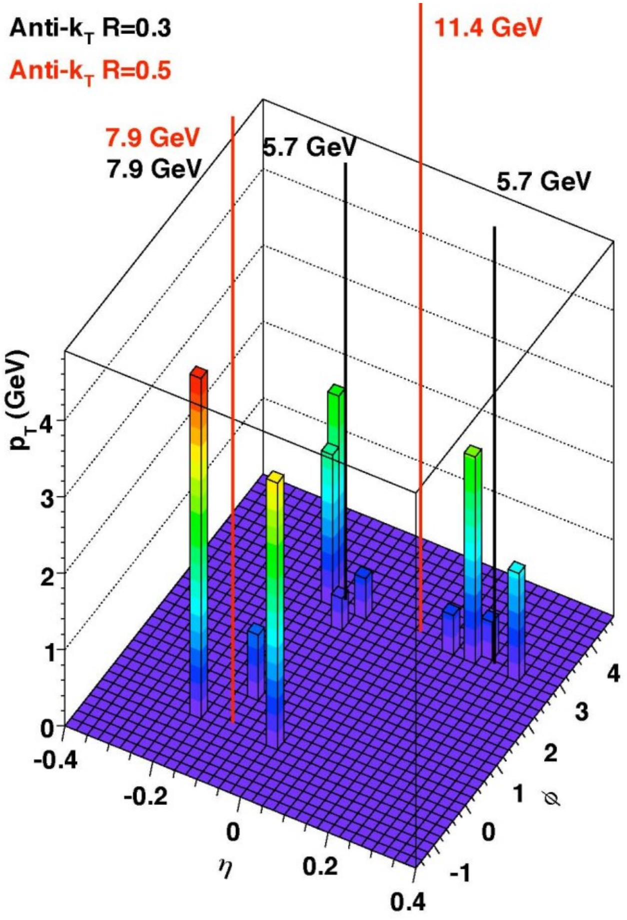


Theory calculations:
Eskola, Paukkunen, Salgado, JHEP04, 065
Vogt, PRC71, 054902
Kharzeev , Tuchin, NPA770, 40
Kharzeev ,Tuchin, NPA735, 248

- EPS09 shadowing with linear dependence on nuclear thickness matches for central collisions
- Overpredicts suppression for peripheral collisions
- R_{CP} shows this clearly
- Thickness (impact parameter) dependence of shadowing is non-linear!

Plenary: C. Luiz da Silva (heavy flavor), Fri
Parallel: A. Sen (quarkonia) Tue

Reconstructed Jets in *d*+Au



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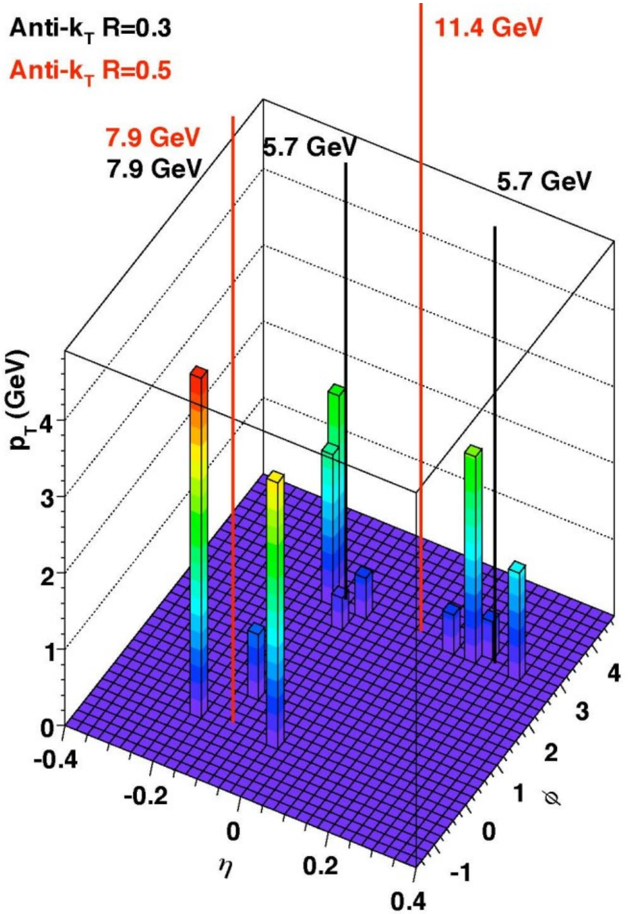
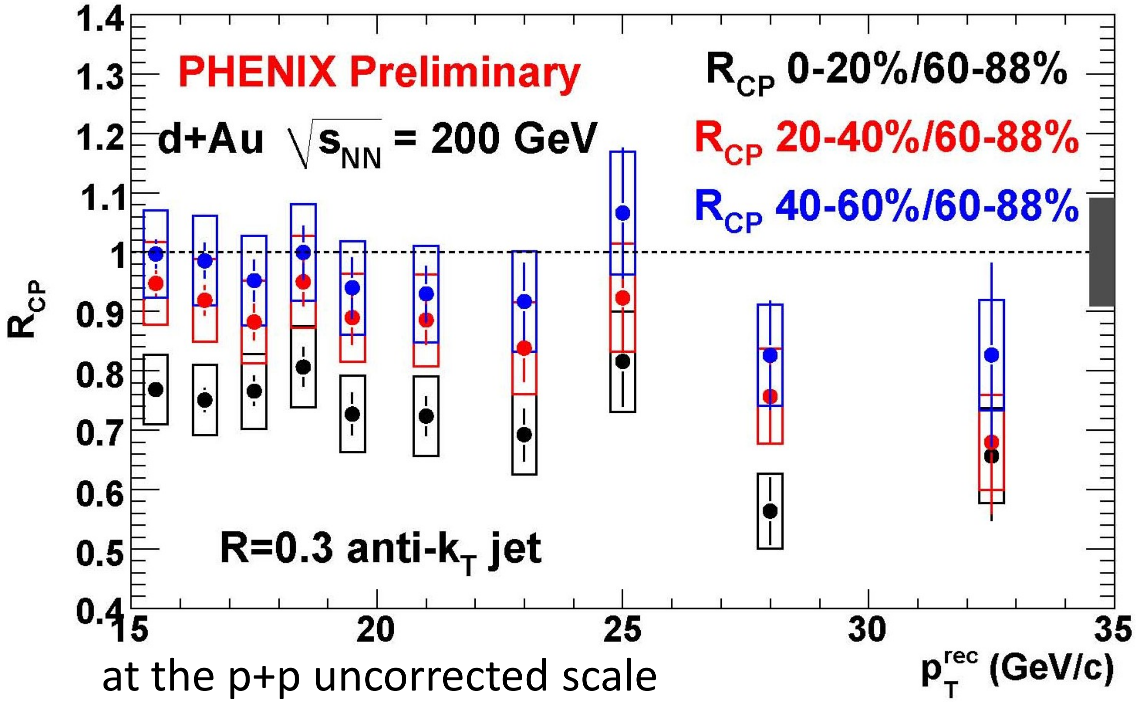


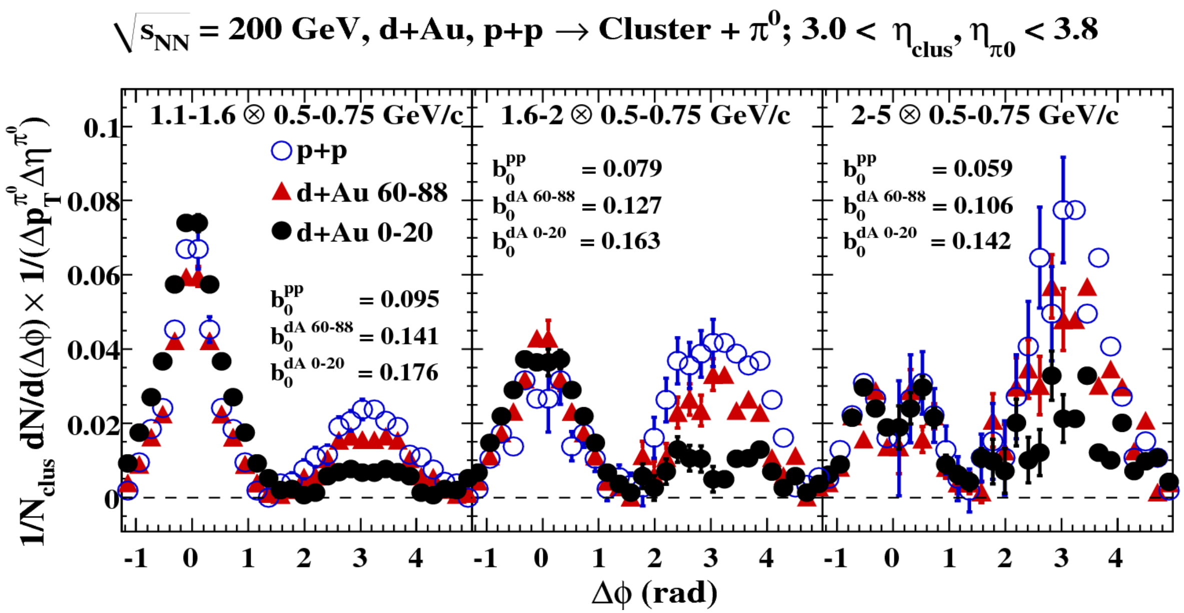


at the p+p uncorrected scale

Jet R_{cp} in central *d*+Au modified
- caution: this is not R_{dA}!
- consistent with π^0 R_{cp}
- anti-shadowing?

Parallel: N. Grau (gamma-hadron, jets) Tue
Poster: D. Perepelitsa (jets in dAu)

Forward di-hadron correlations



Color Glass Condensate?

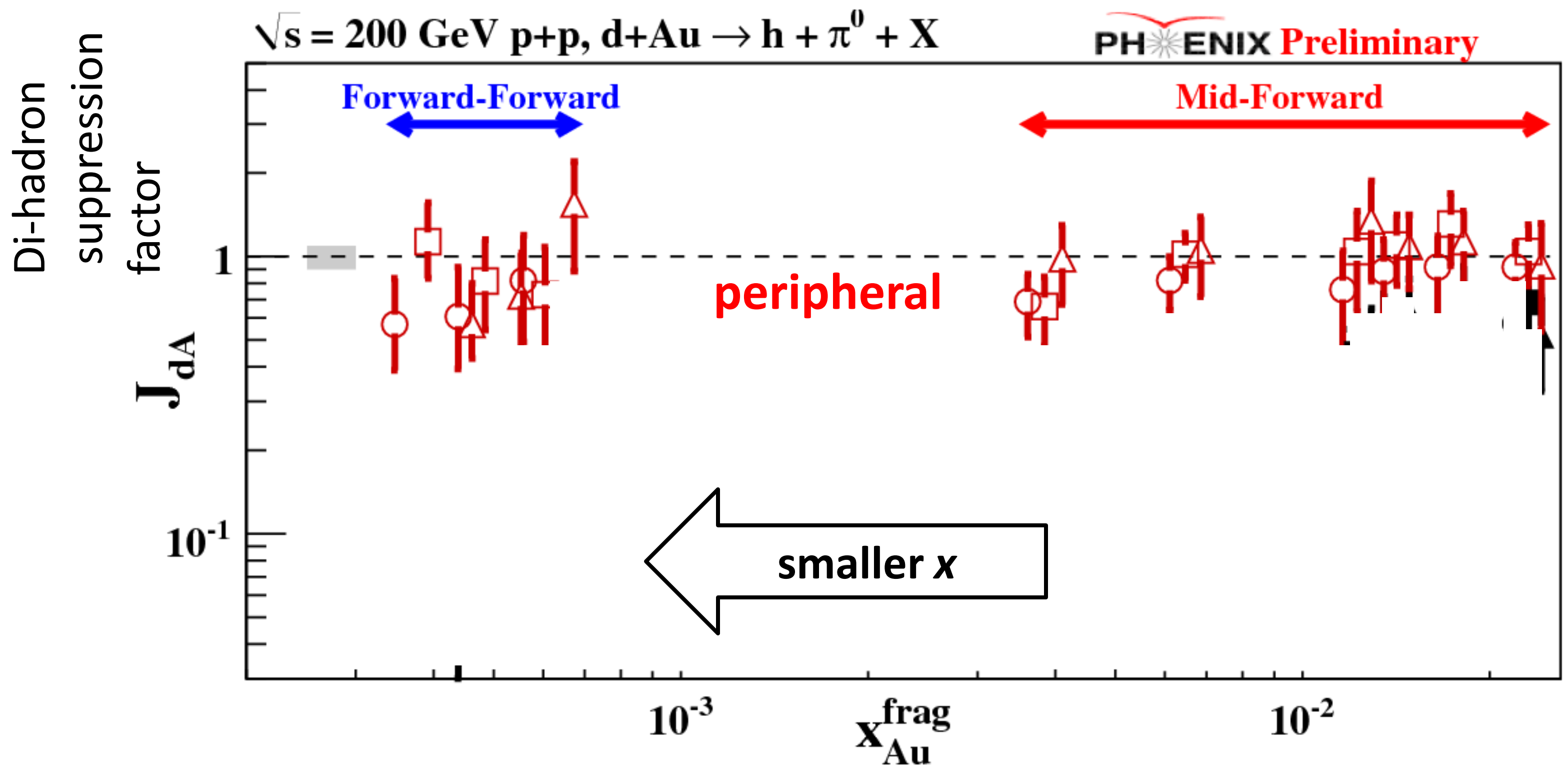
new forward
EM calorimeter
|η| = 3.0-3.8

Pocket formula:

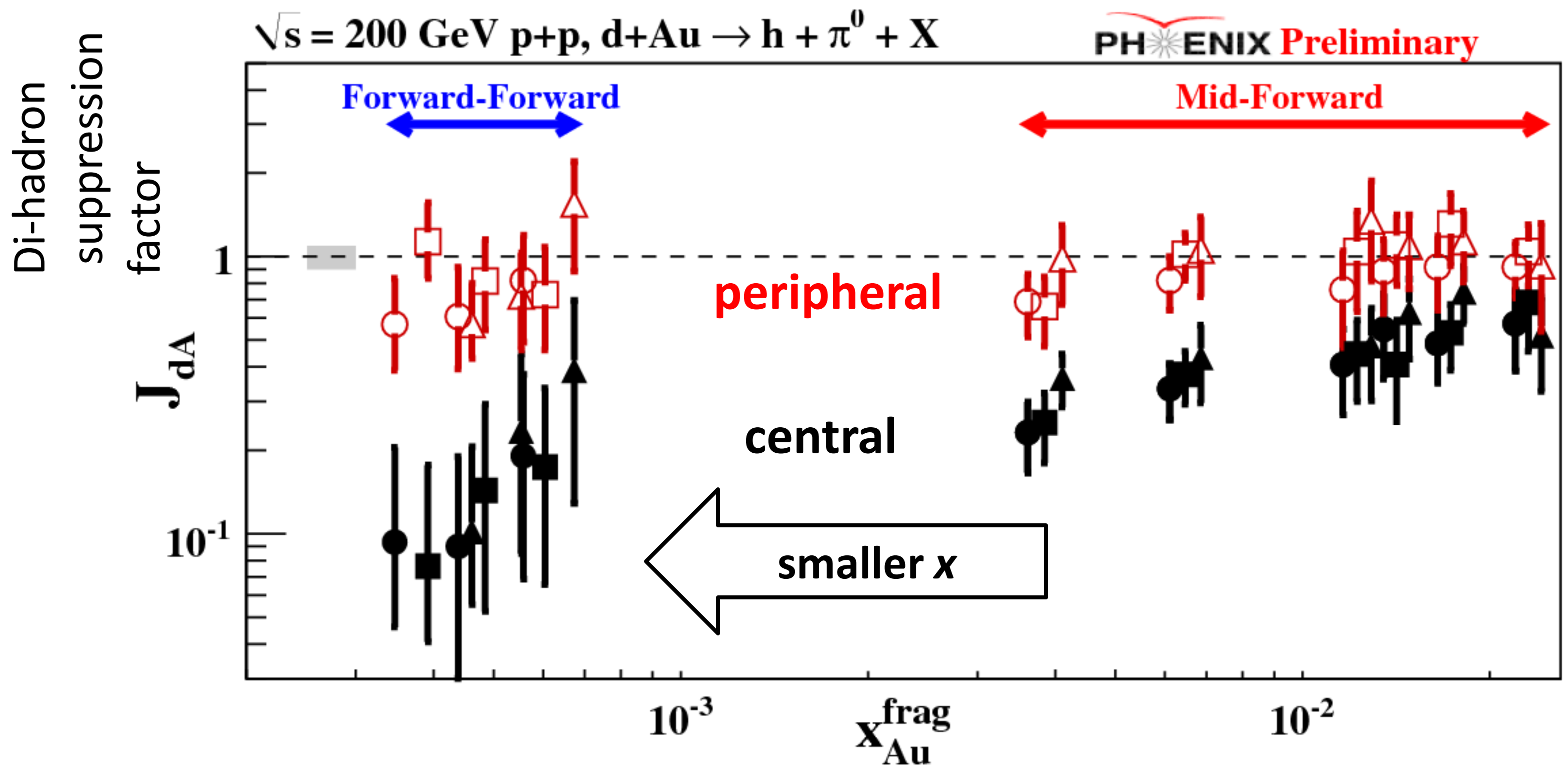
$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

Initial state low-x gluon suppression



Initial state low-x gluon suppression



Parallel: M. Chiu (small x dAu correl) Thu
Poster: Z. Citron (small x dAu correlations)

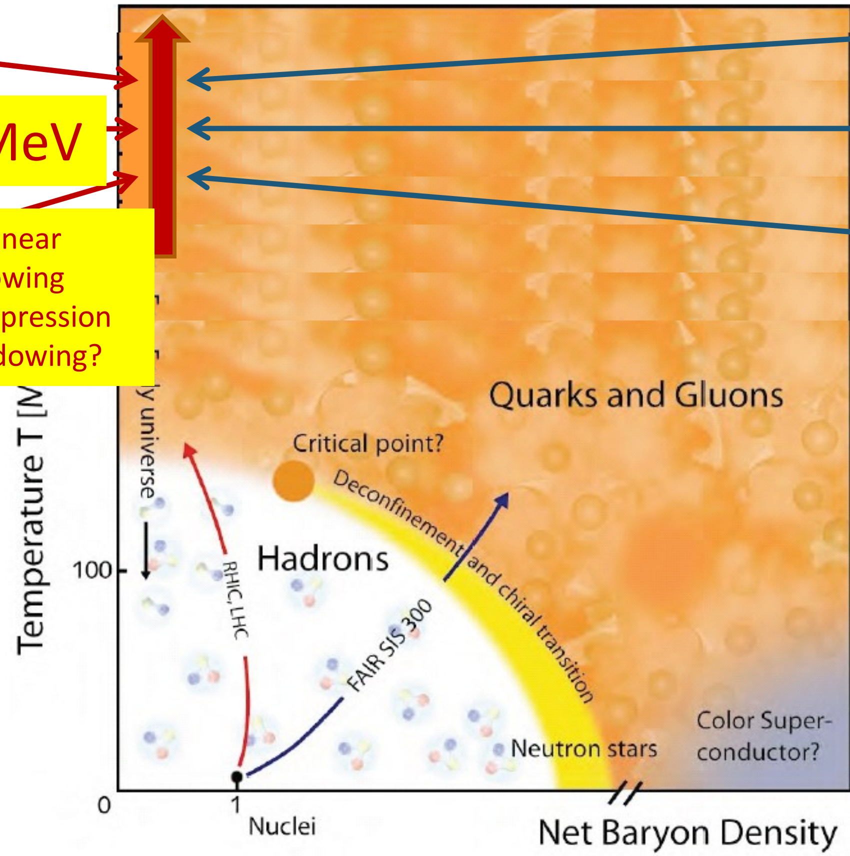
- Di-hadrons suppressed at low *x*
- Important for interpretation of HI results

Measuring the Properties of the QGP

Conditions ⟹ Properties

Conditions:

- $\mu \sim 0$
- T_i =300-600 MeV
- CNM effects: non-linear shadowing, low-x suppression, anti-shadowing?
- Initial State



Properties:

- Screening length
- η/s
- dE/dx

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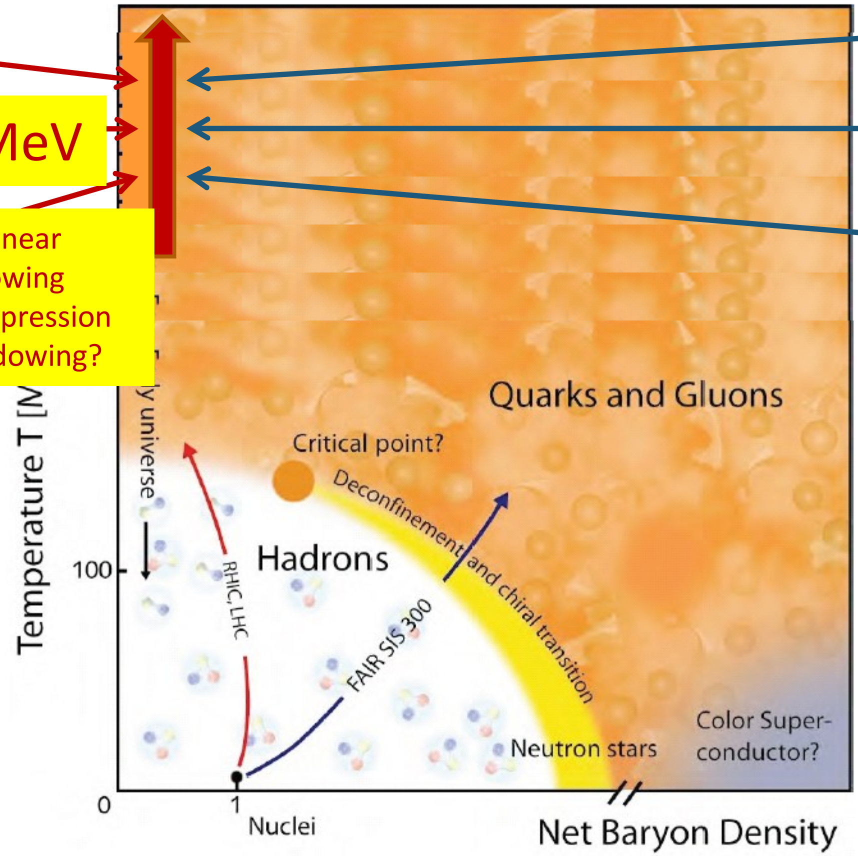
Initial State



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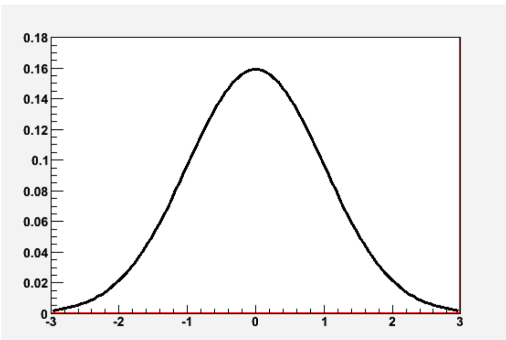
Screening length

η/s

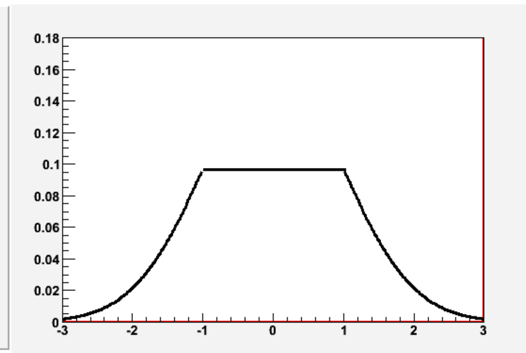
dE/dx

Initial State determines flow strength

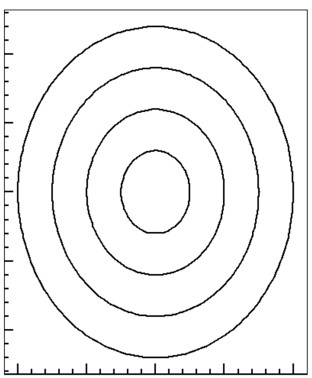
Glauber

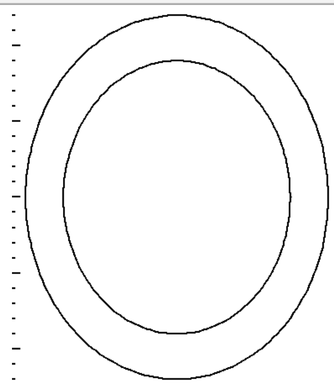


CGC



Radial gluon distribution





2-D density profile

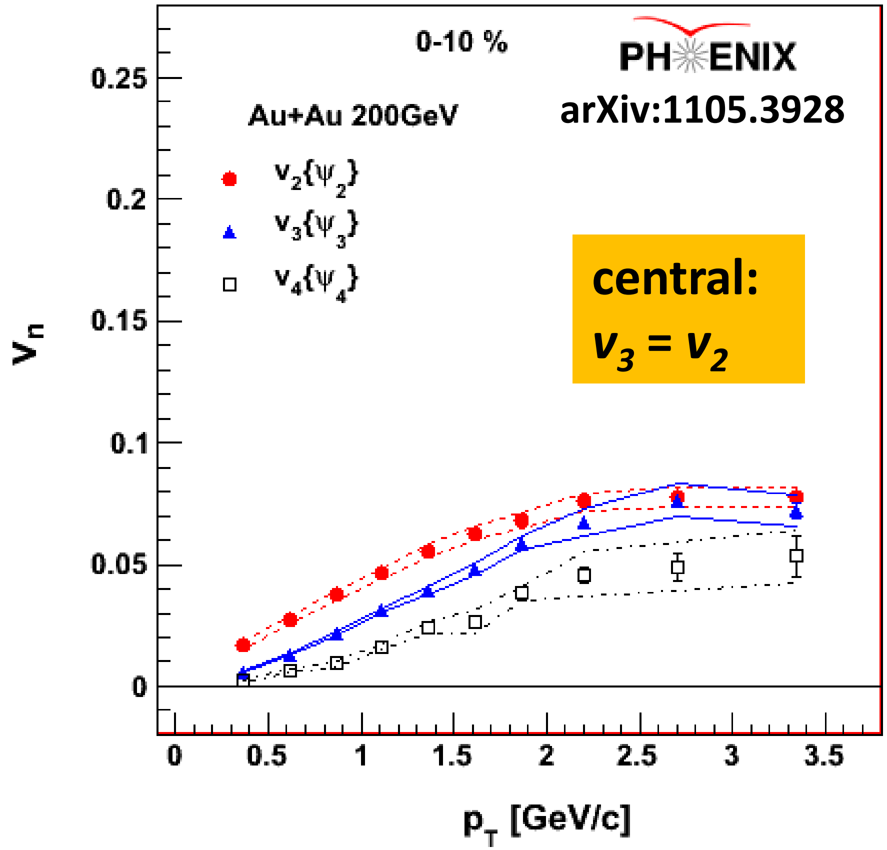
Smaller eccentricity

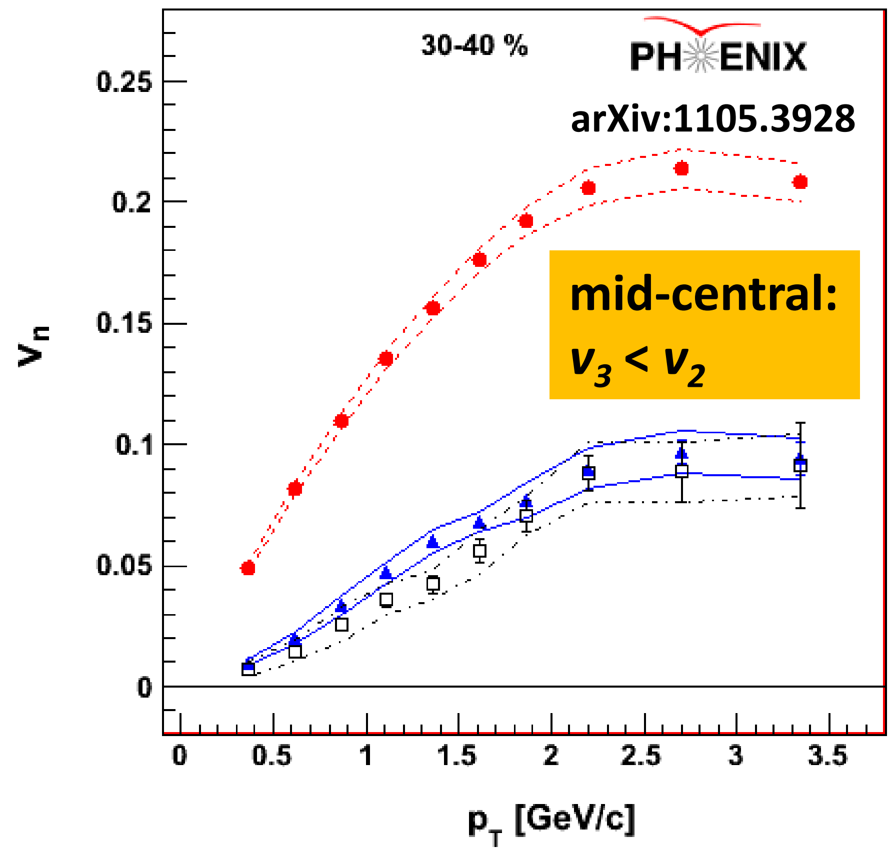
larger eccentricity

Initial state determines v_2 strength (largest uncertainty)

Disentangle initial conditions from flow strength

v_3 has fluctuations origin

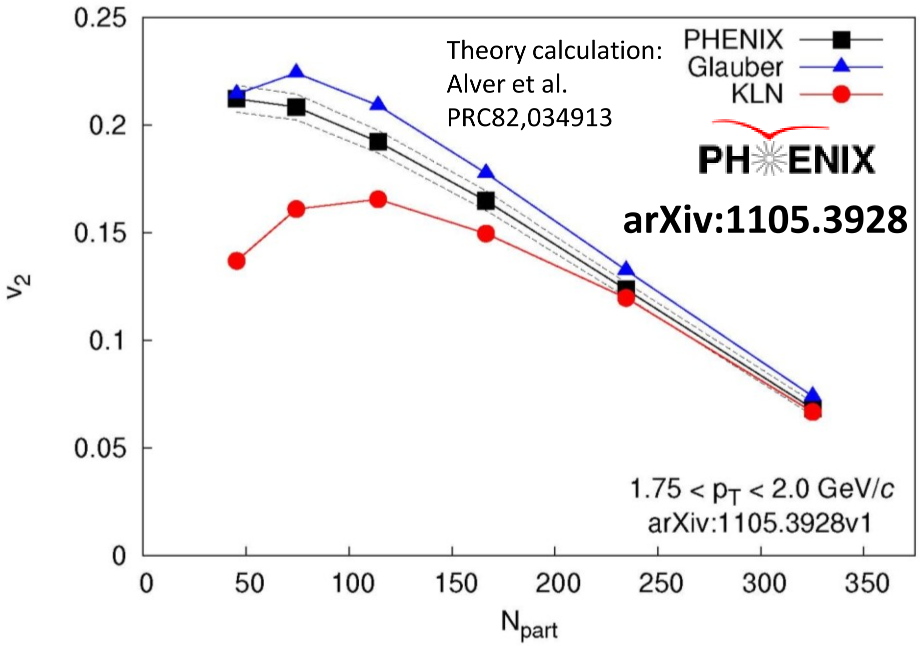




weak centrality dependence of v_3 => fluctuations origin

v_3 disentangles initial state and η/s

v_2 described by Glauber and CGC



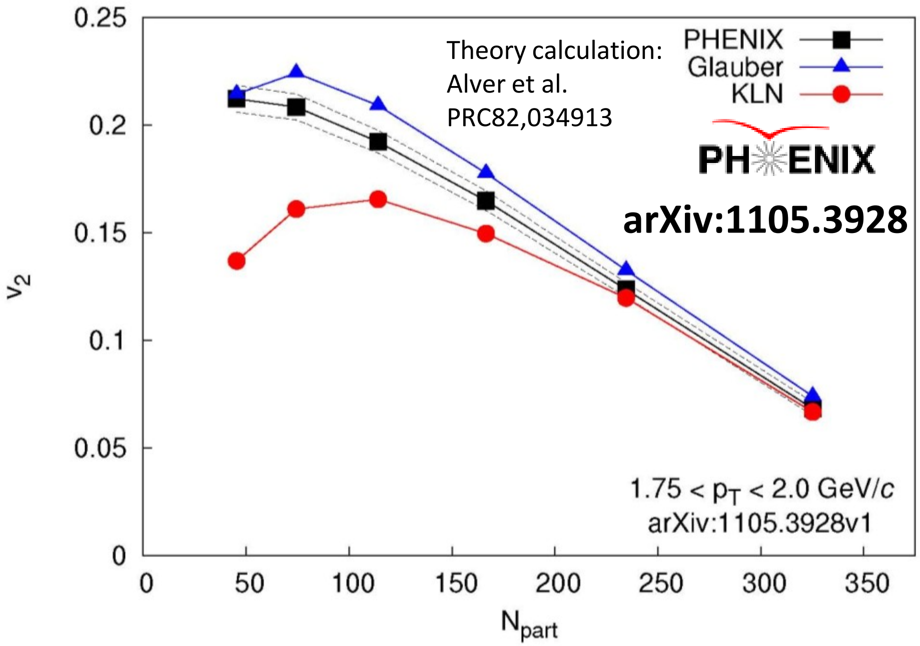
- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

← Two models →

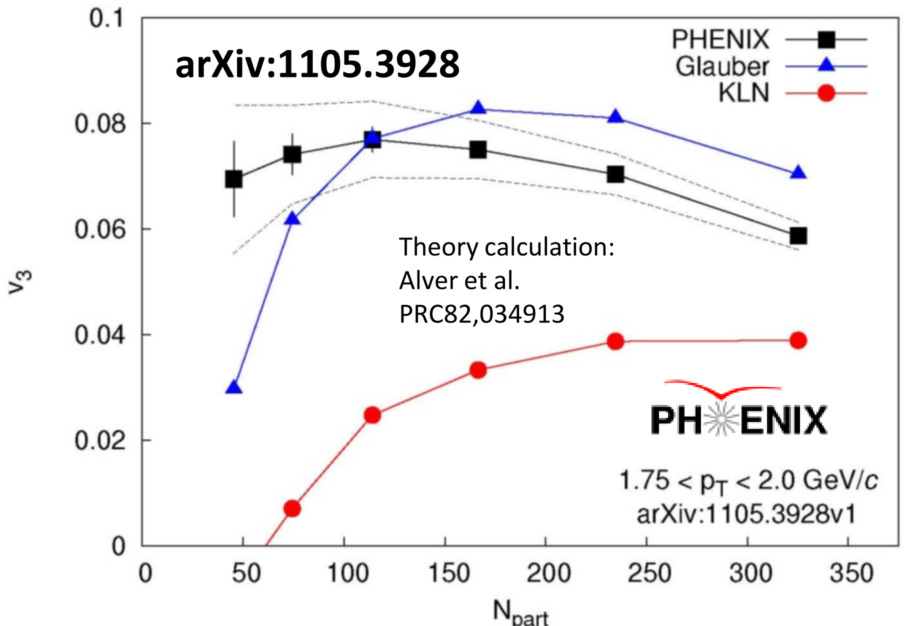
- KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

v_3 disentangles initial state and η/s

v_2 described by Glauber and CGC



v_3 described only by Glauber



Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

← Two models →

- MC-KLN
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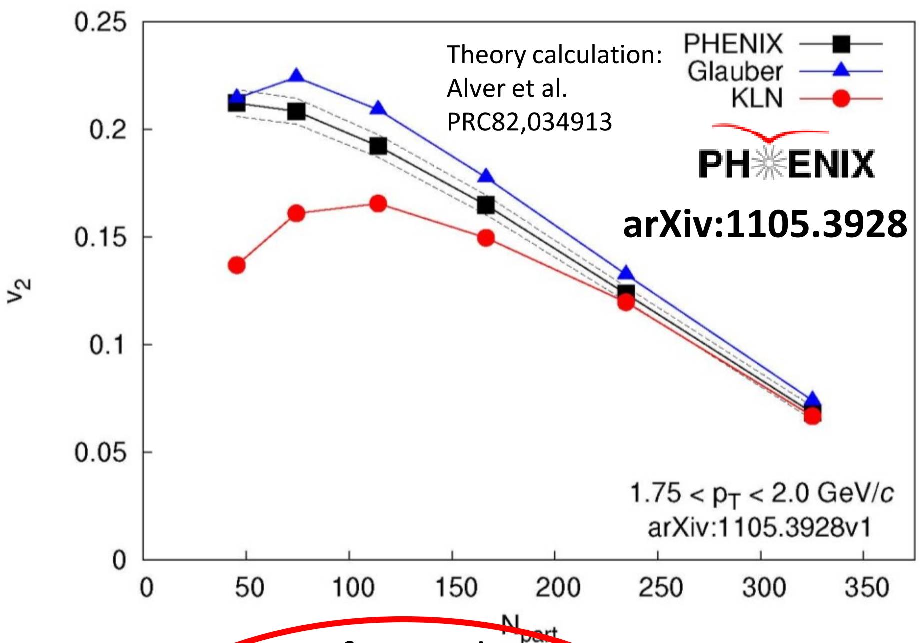

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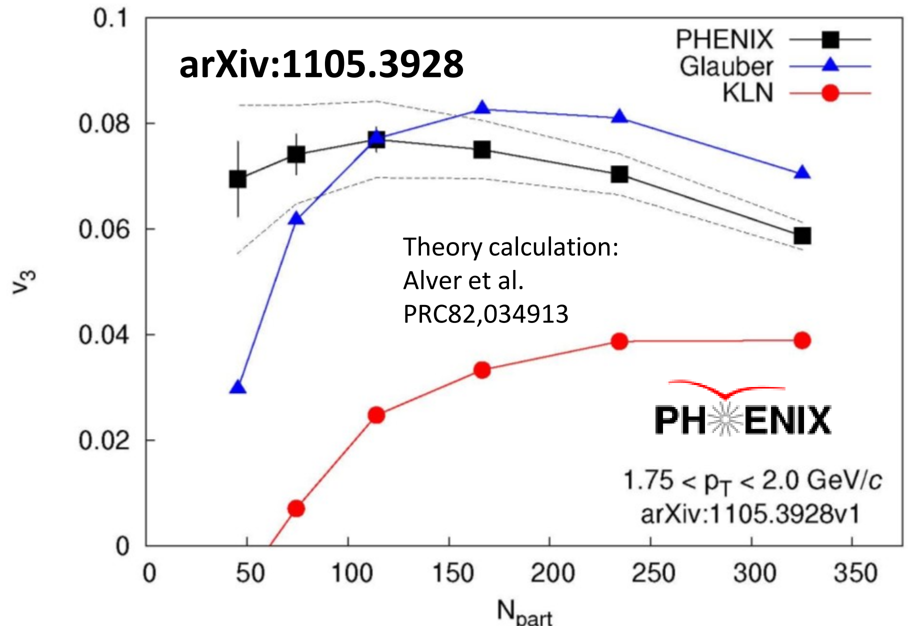


Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

favored

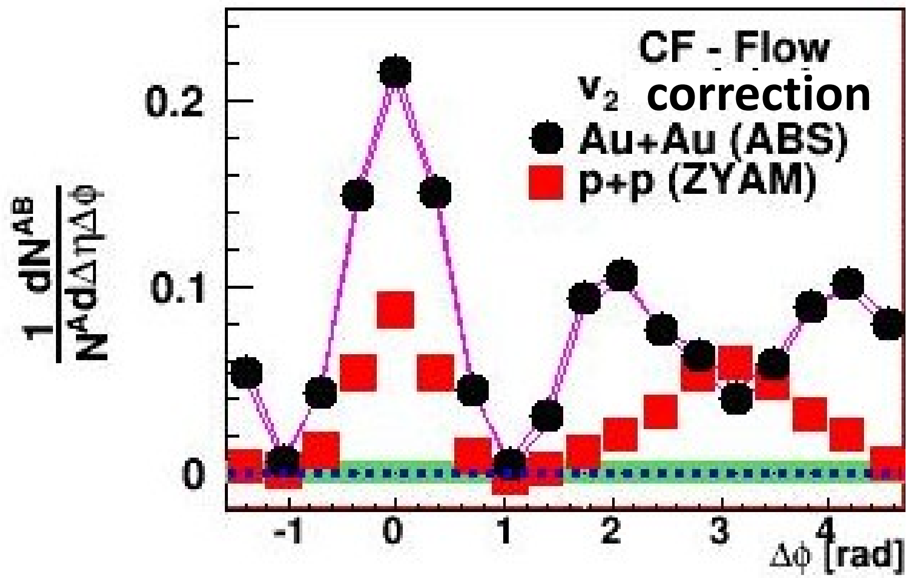
- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

Two models

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

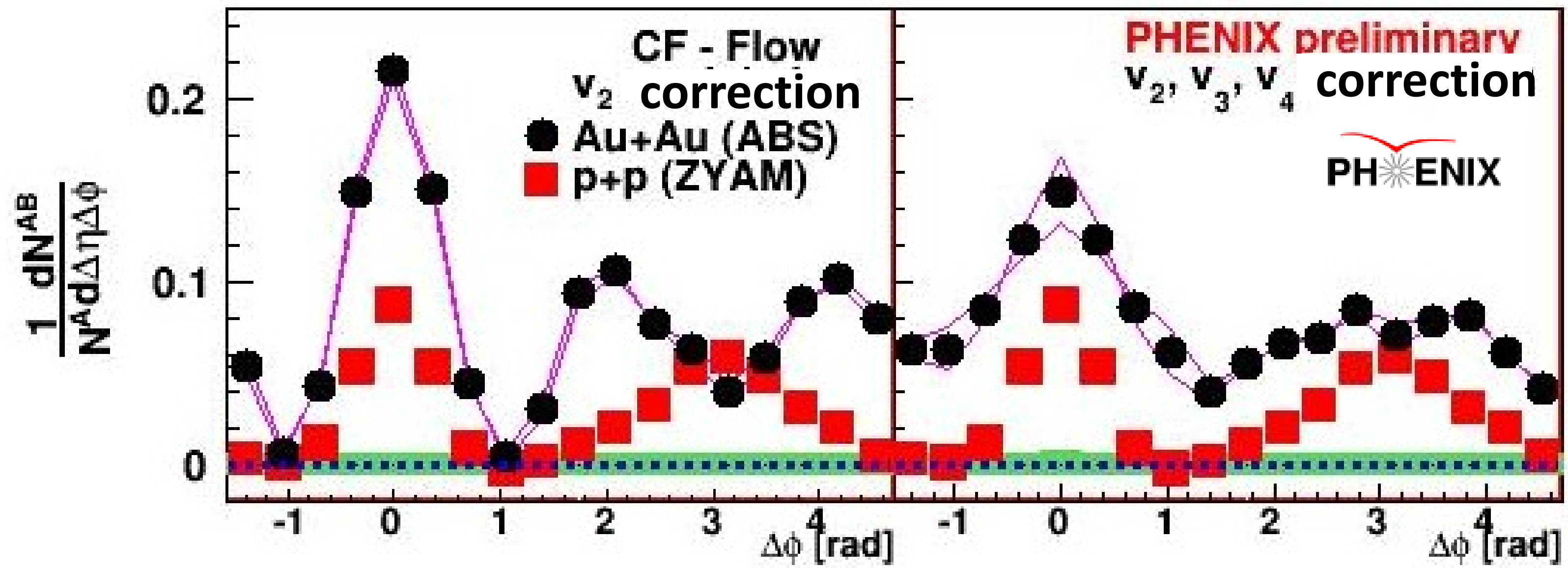
Plenary: S. Esumi, Tue
Parallel: R. Lacey (v3, jet shape) Mon

v_3 explains double-hump



- v_2 correction only
  - double-hump

v_3 explains double-hump



- v_2 correction only
  - double-hump
- v_2, v_3, v_4 correction
  - double-hump disappeared
  - Peak still broadened

Plenary: S. Esumi, Tue
Parallel: R. Lacey (v3, jet shape) Mon

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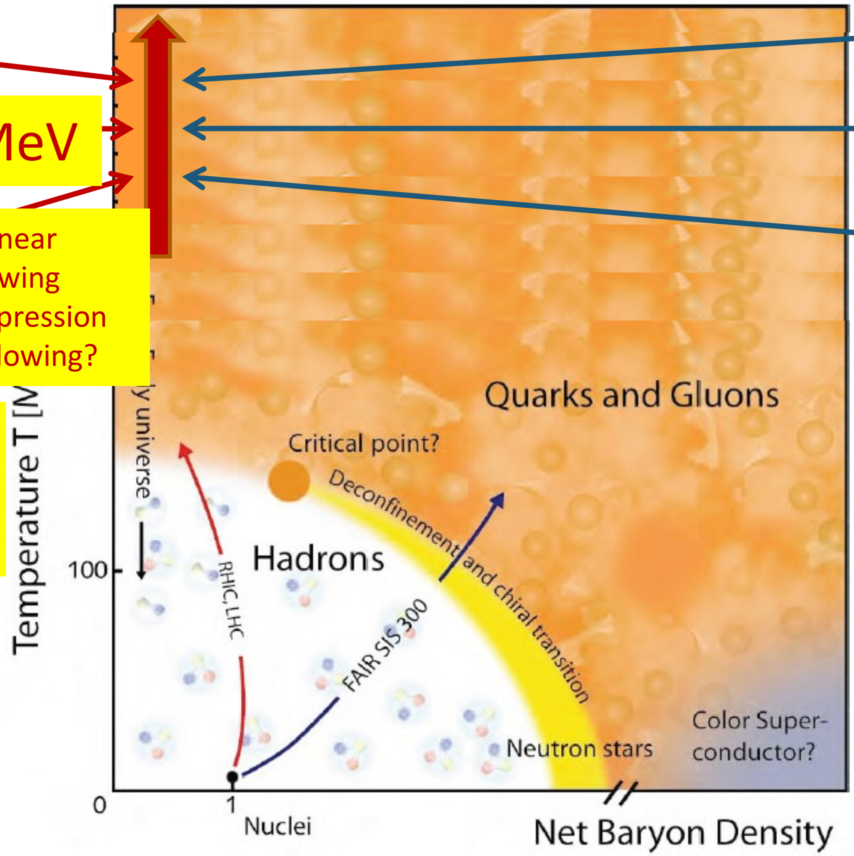
non-linear shadowing
low-x suppression
anti-shadowing?

Initial State $\overset{?}{\rightarrow}$ Glauber



Screening length

$\eta/s \overset{?}{\rightarrow} 1/4\pi$

dE/dx

?

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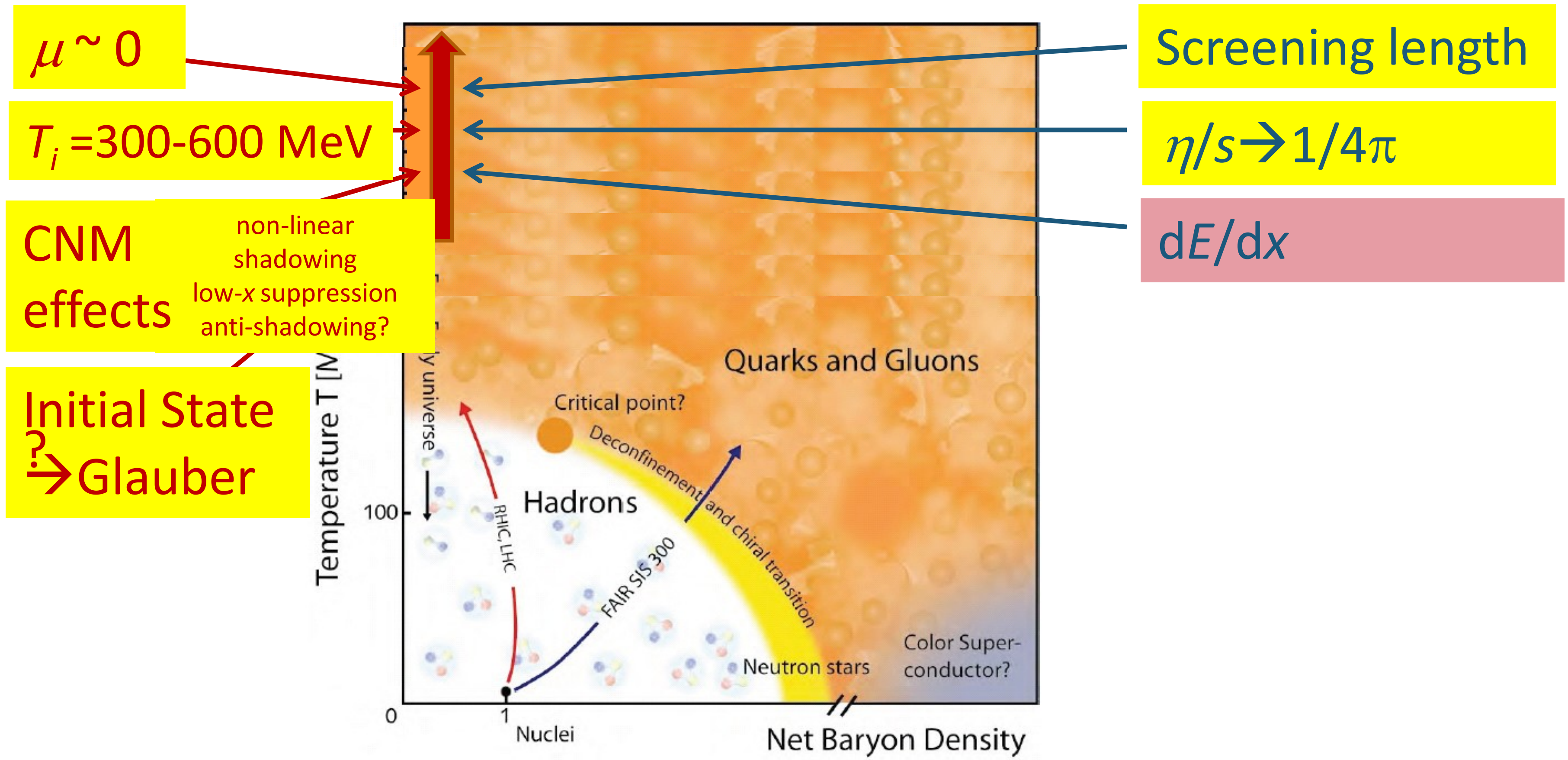

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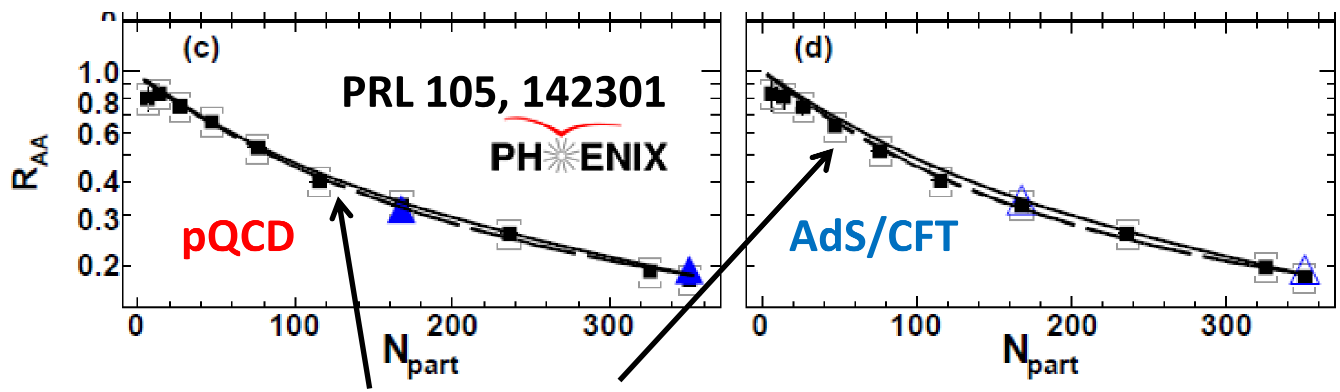
Path-length dependence of E loss

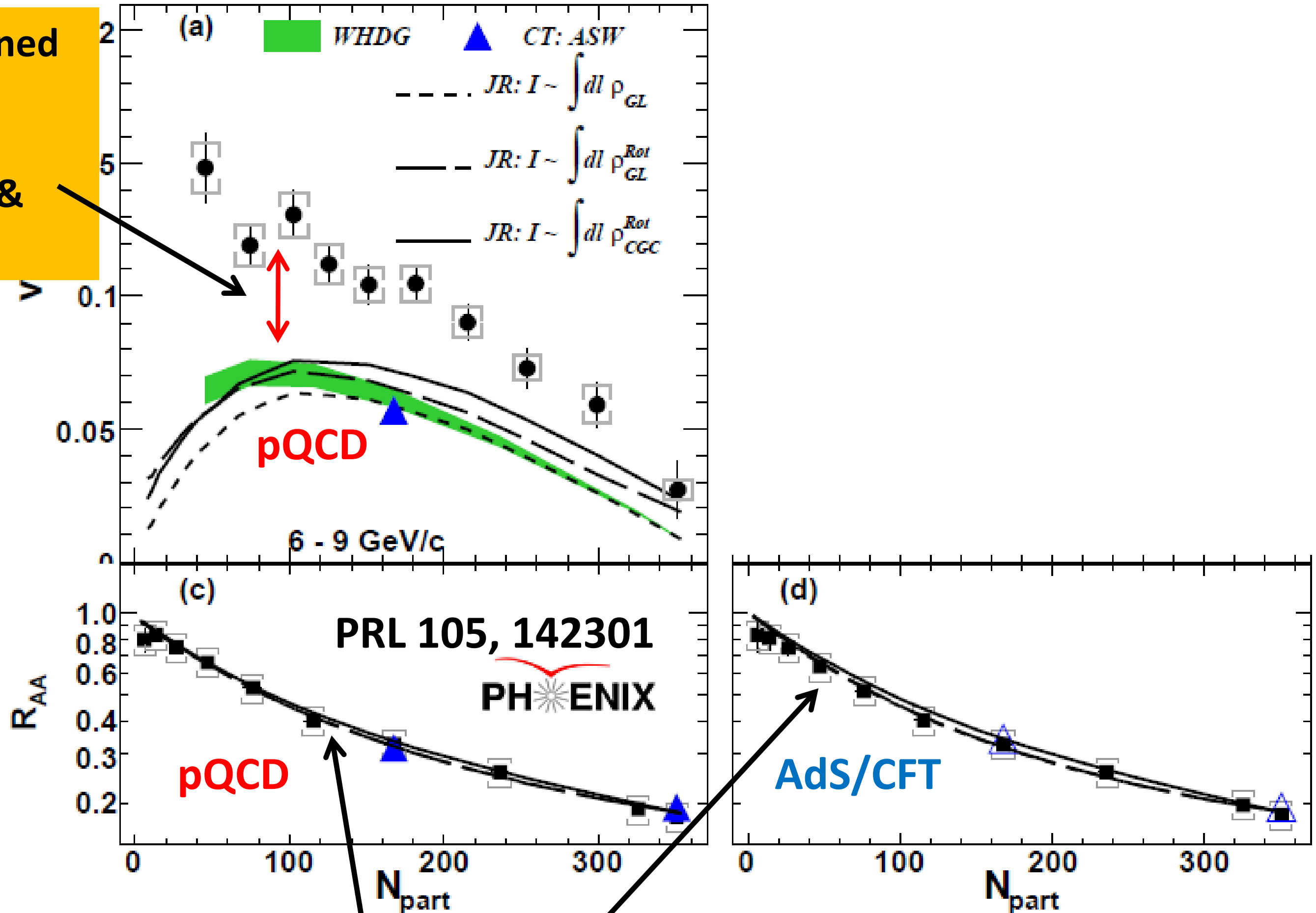


R_{AA} **explained by both models**

Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645

Path-length dependence of E loss

v_2 not explained by pQCD (even with fluctuations & saturation)



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***R_{AA}* explained by both models**

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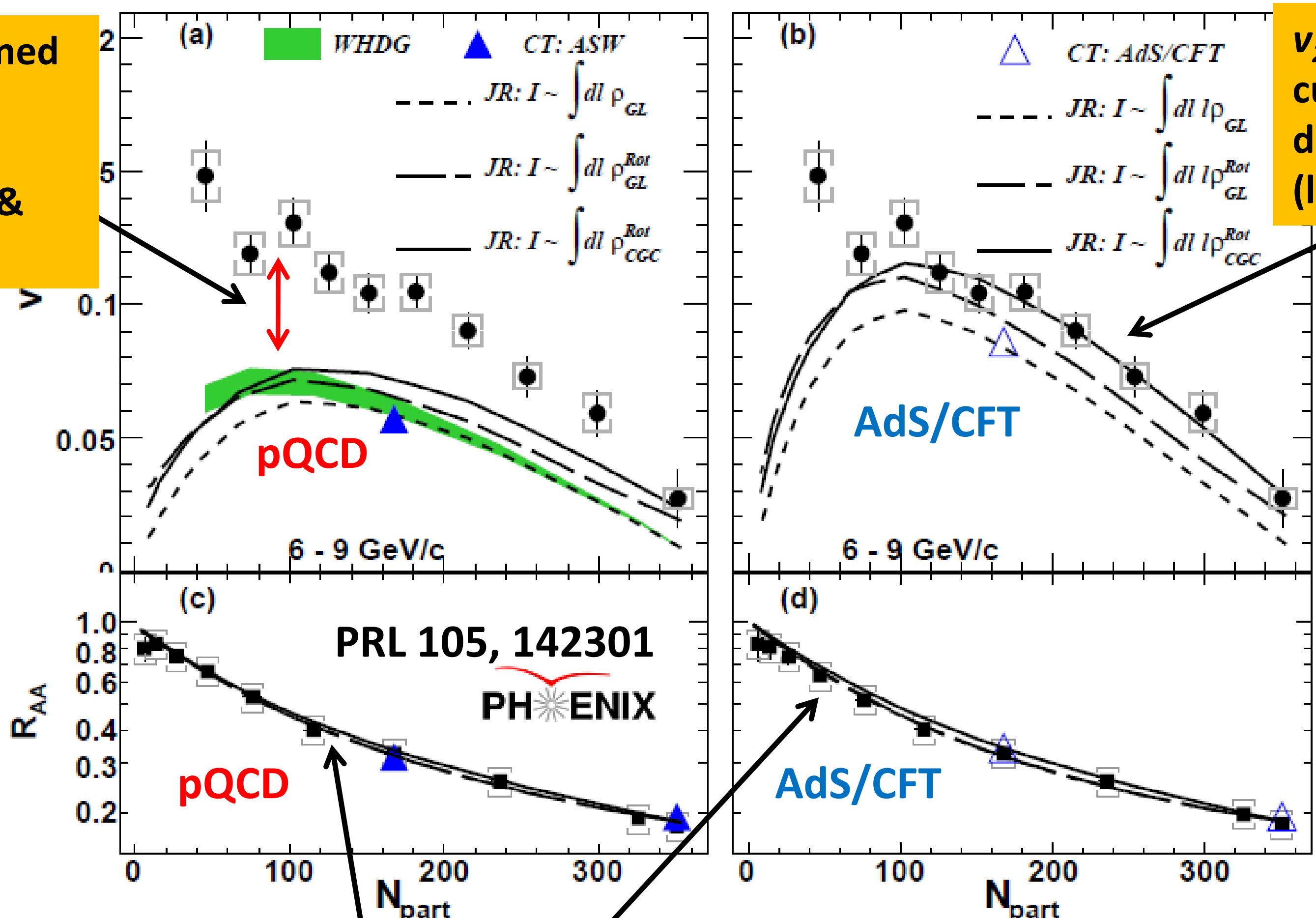
v_2 explained by cubic path length dependence (like AdS/CFT)



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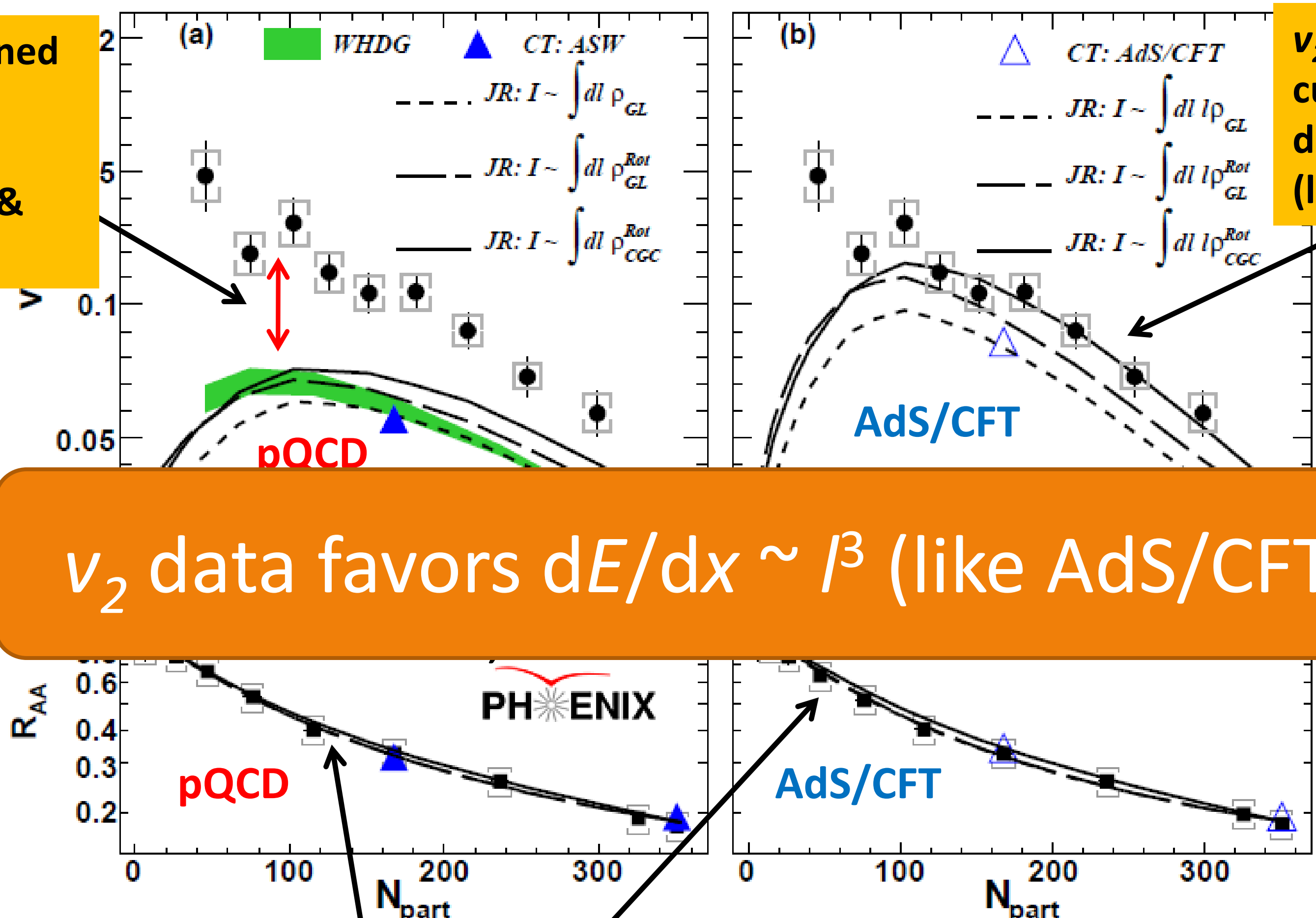

v_2 data favors $dE/dx \sim l^3$ (like AdS/CFT)

R_{AA} explained by both models

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Marquet, Renk, PLB685, 270
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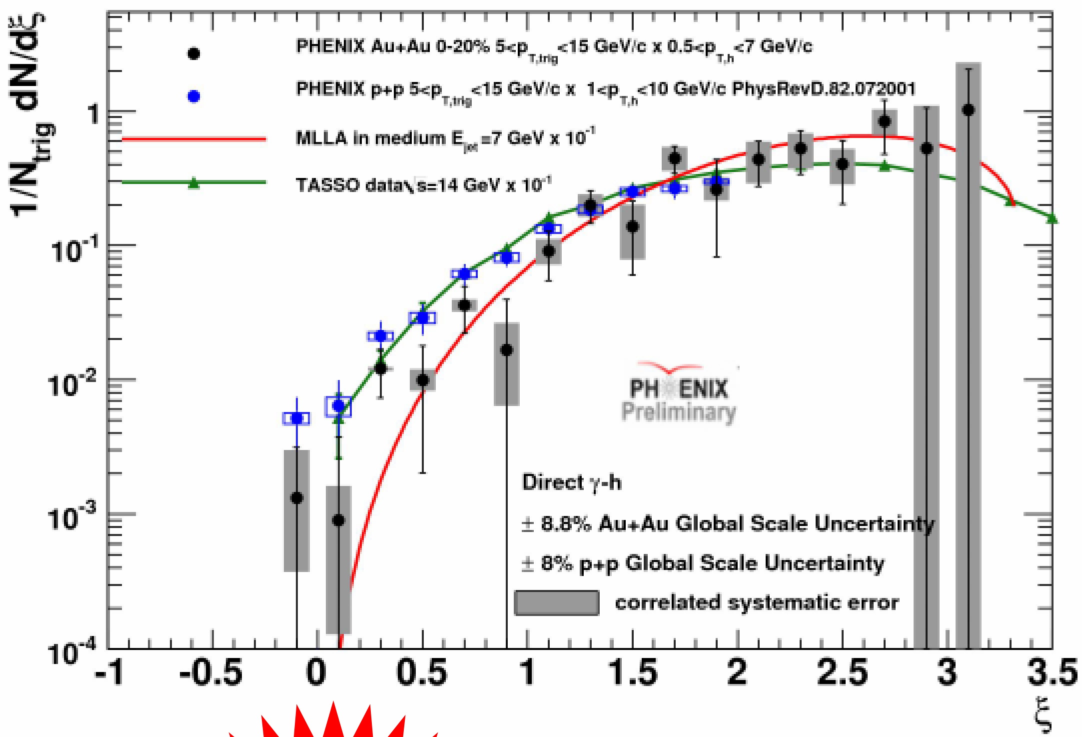
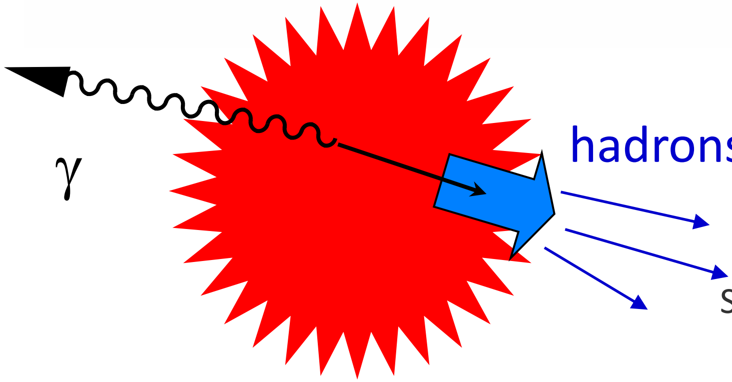
Plenary: M. Purschke (R_AA) Wen
Parallel: N. Grau (gamma-hadron, jets) Tue
Parallel: D. Sharma (light vector mesons) Mon
Poster: M. Tannenbaum (E loss RHIC vs. LHC)

γ-h: fragmentation function in Au+Au



Tasso:
Braunschweig et al. , Z. Phys. 320 C47, 187
MLA:
Borghini, Wiedemann, hep-ph/0506218

- *p+p* consistent with $e^{+}+e^{-}$
- Au+Au consistent with E loss model



$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

Parallel: N. Grau (gamma-hadron, jets) Tue
Poster: M. Tannenbaum (E loss RHIC vs. LHC)

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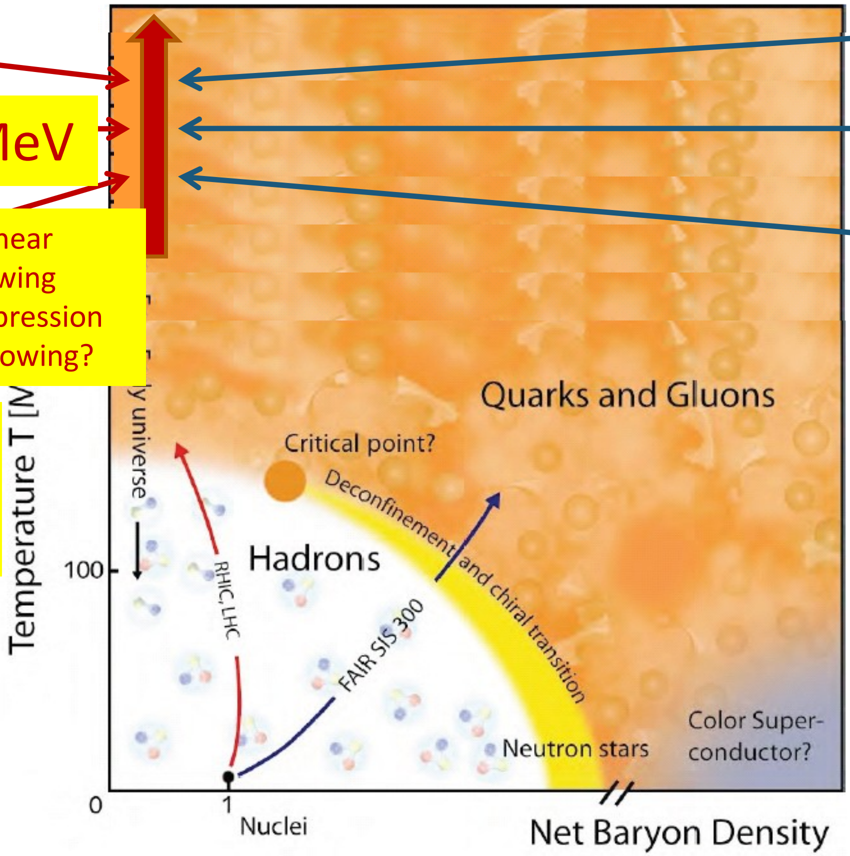
anti-shadowing?

Initial State $\overset{?}{\to}$ Glauber

Screening length

$\eta/s \overset{?}{\to} 1/4\pi$

$dE/dx \to l^3$



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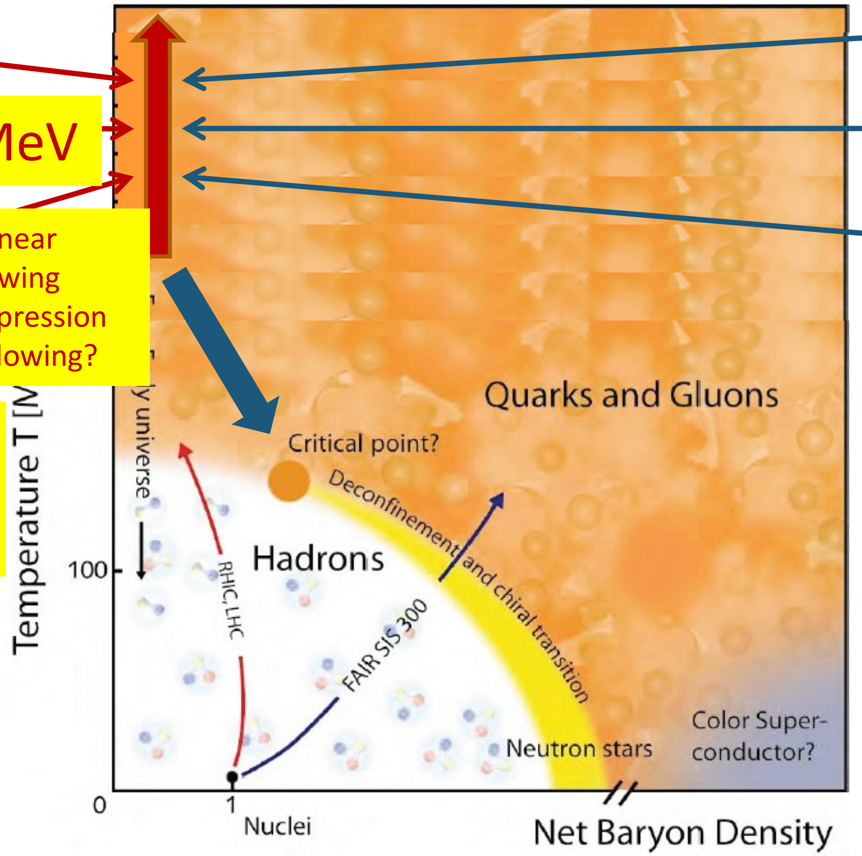


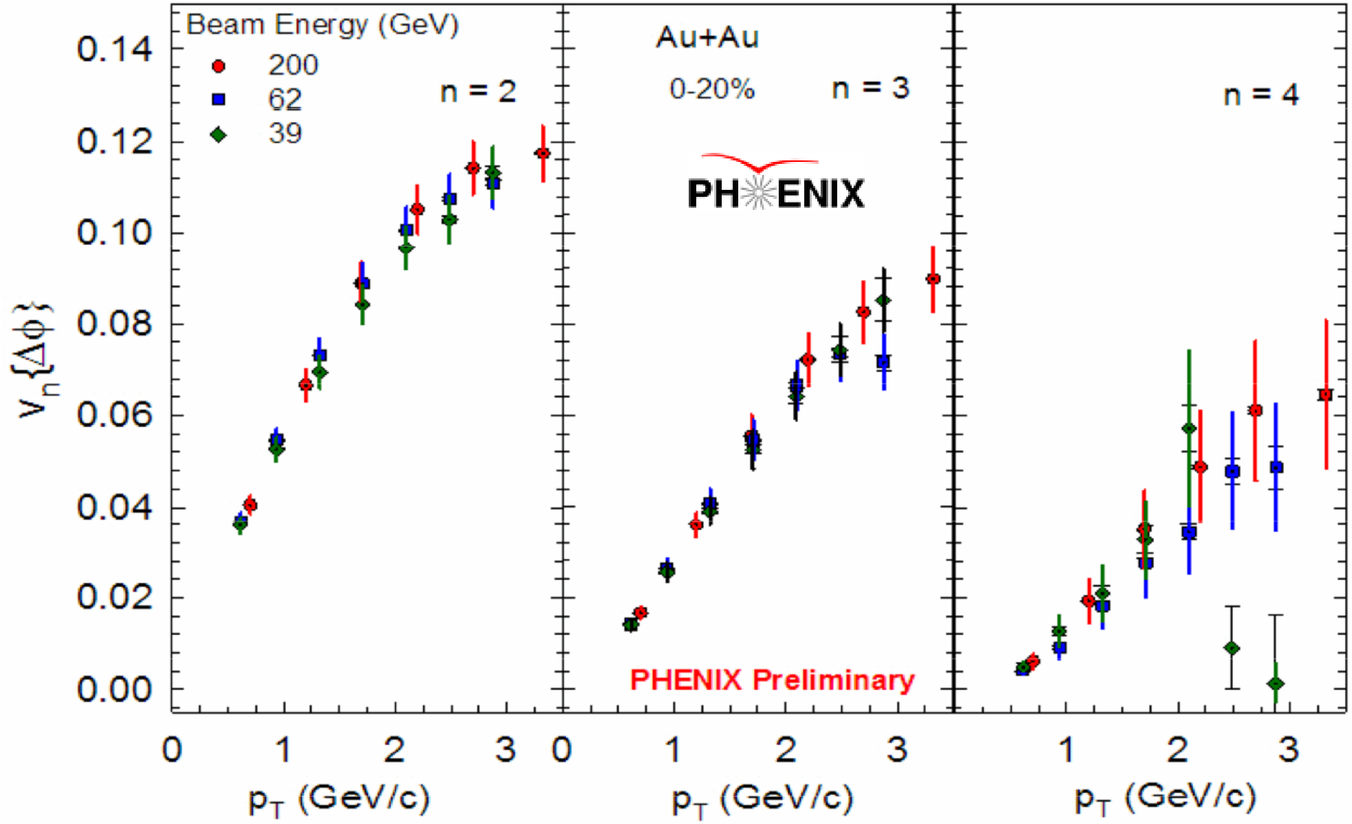
Screening length

$\eta/s \overset{?}{\rightarrow} 1/4\pi$

dE/dx → l^3

Stefan Bathe for PHENIX, QM2011

v_2, v_3, v_4 independence of $\sqrt{s_{NN}}$ (for 39, 62, 200 GeV)

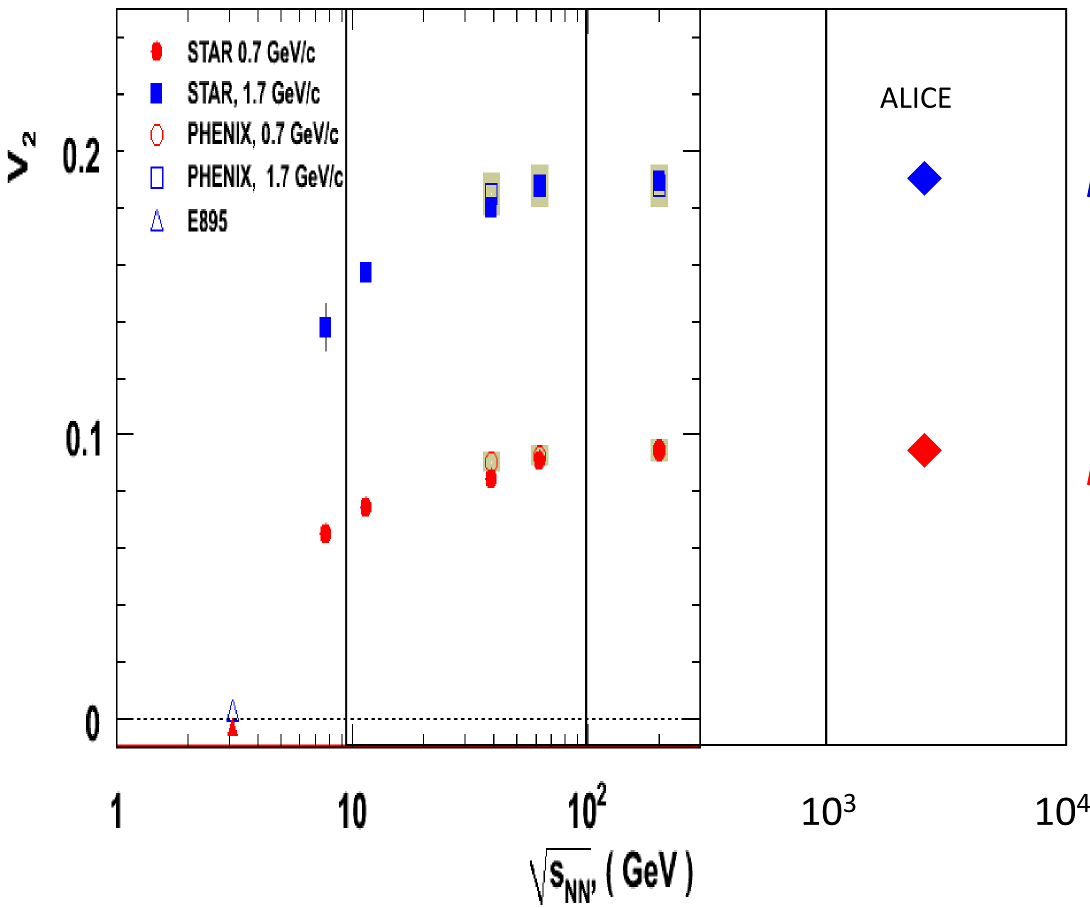


v_2, v_3, v_4 independence of $\sqrt{s_{NN}}$ for 39, 62.4, 200 GeV

Just like at 200 GeV, disentangle initial state and η/s

v_2 saturation with $\sqrt{s_{NN}}$

Preliminary, STAR, PHENIX and E895 data



p_T = 1.7 GeV

v_2 saturation $\lesssim$ 39 GeV

p_T = 0.7 GeV

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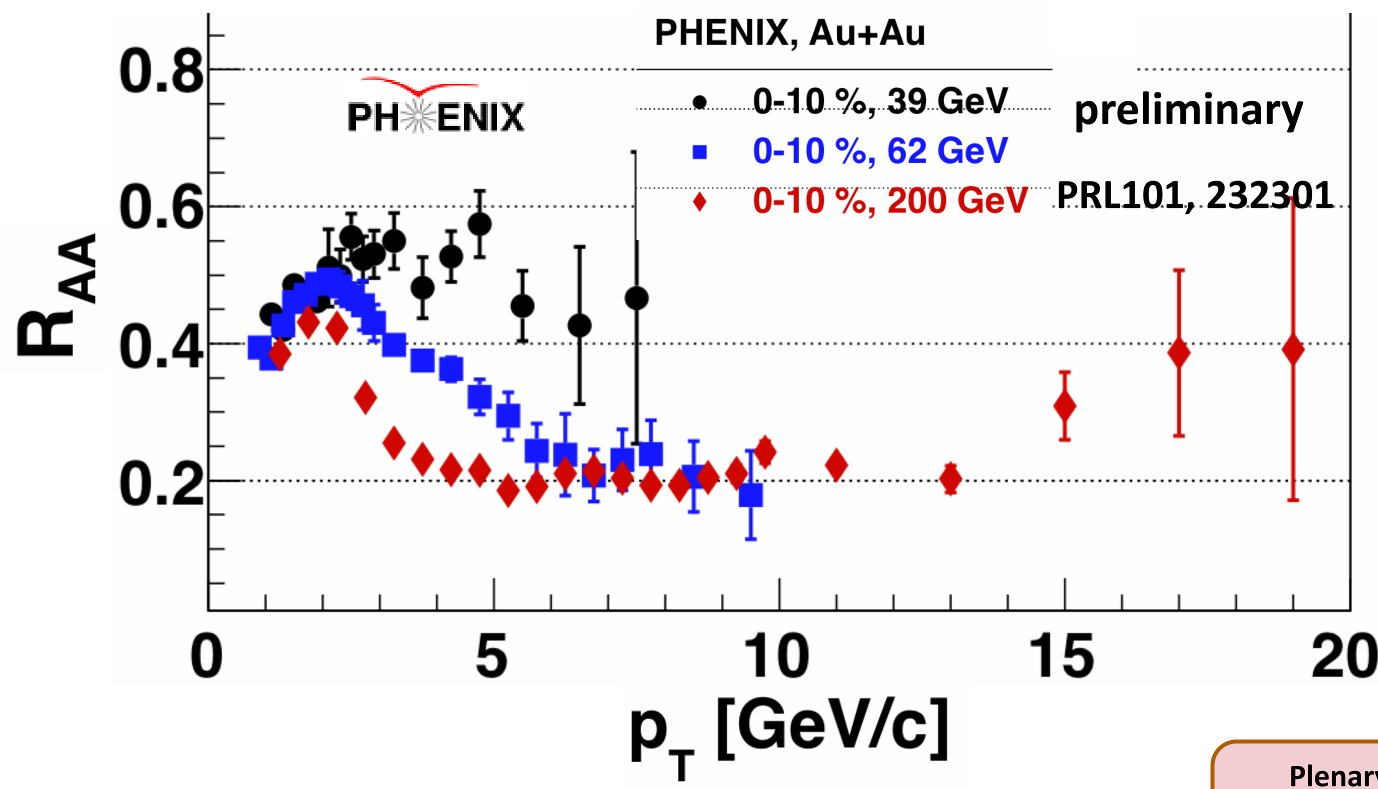
Plenary: S. Esumi, Tue
Parallel: R. Lacey (v3, jet shape) Mon
Parallel: X. Gong (energy scan: bulk) Fri
Poster: S. Mizuno (PID v3)

$\sqrt{s_{NN}}$ dependence of energy loss

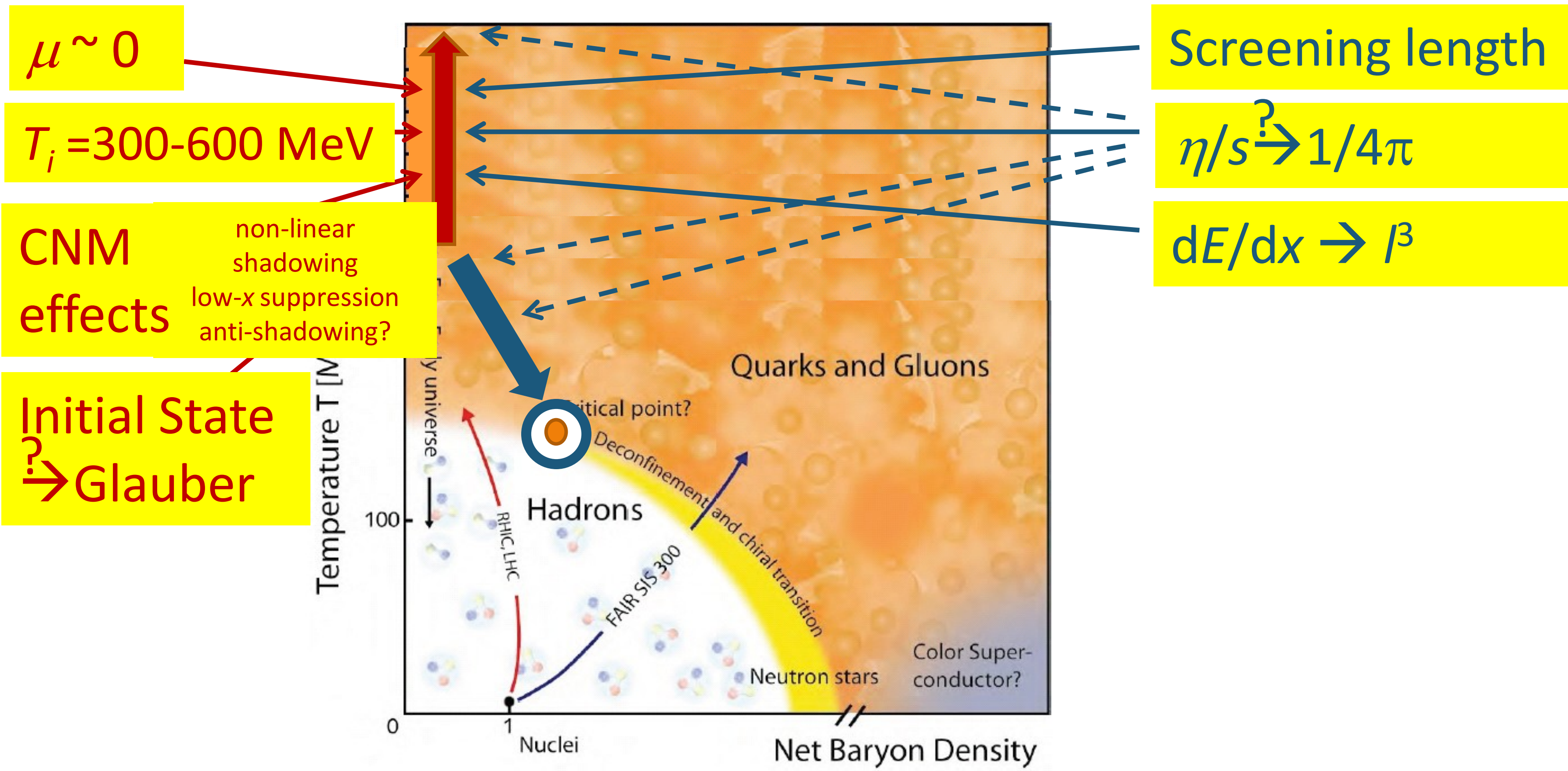


Plenary: M. Purschke (R_AA) Wen
Parallel: N. Novitsky (energy scan) Fri
Poster: O. Chvala (RAA in 39 and 62 GeV)

- R_{AA} suppressed also at 39 GeV
- R_{AA} at 62 GeV approaches 200 GeV level at high p_T

Measuring the Properties of the QGP

Conditions ⟹ Properties



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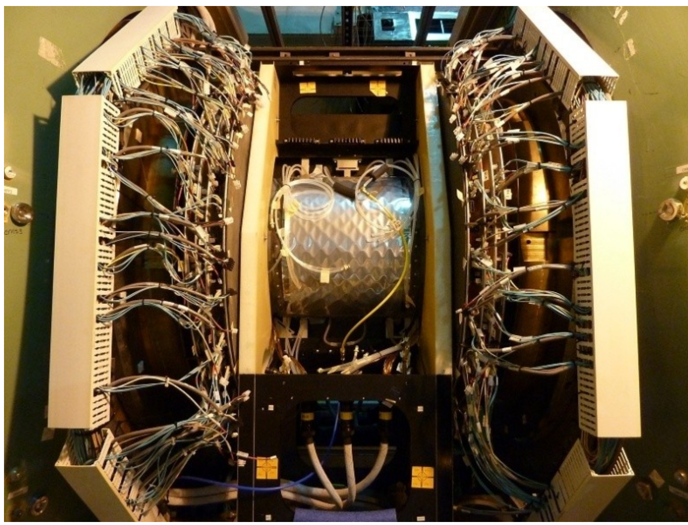
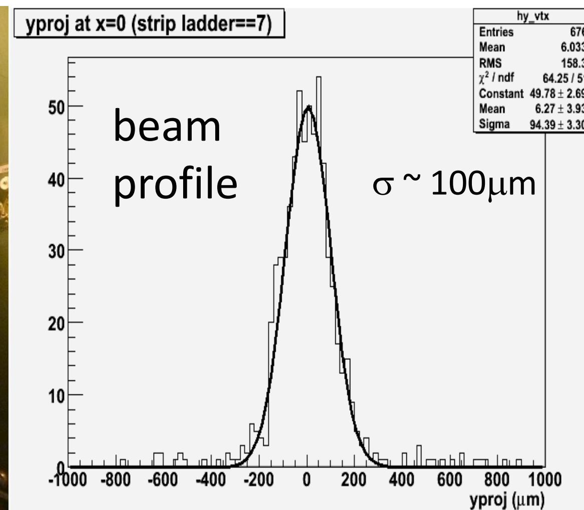
Near-Term Future: Silicon Vertex Detector

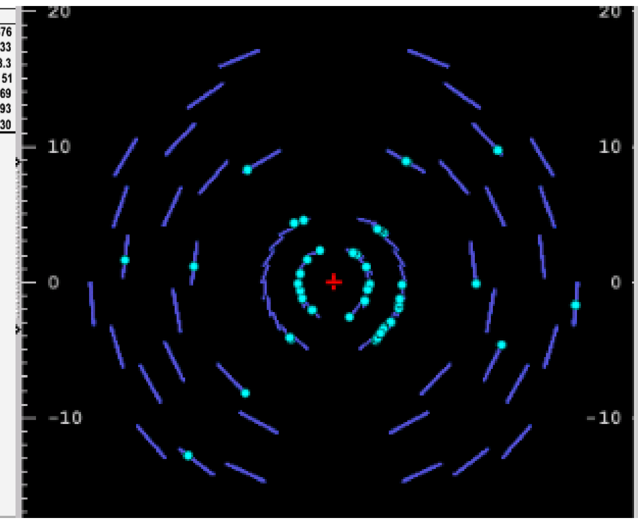
Status

- VTX successfully commissioned in 2011 *p+p* run
- VTX taking data in Au+Au now!

Data: p+p@500 GeV, 2011







Physics

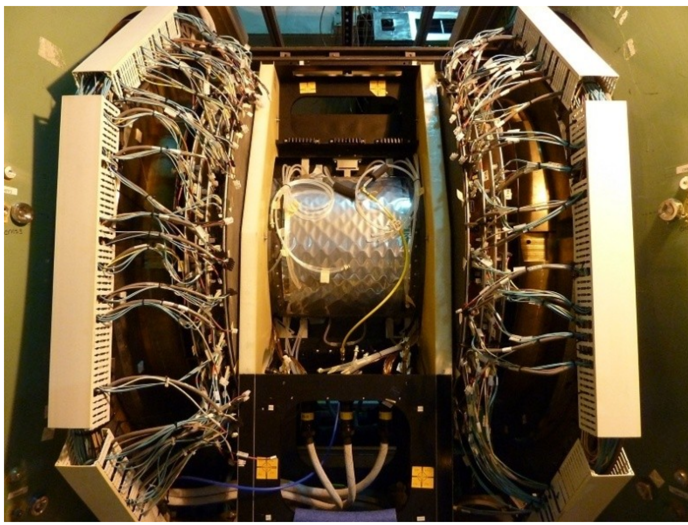
- R_{AA} of *c*, *b* separately
- v_2 of *c*, *b* separately
- Jet tomography (di-hadron, γ-*h*, *c*-*h*, *c*-$\bar{c}$)

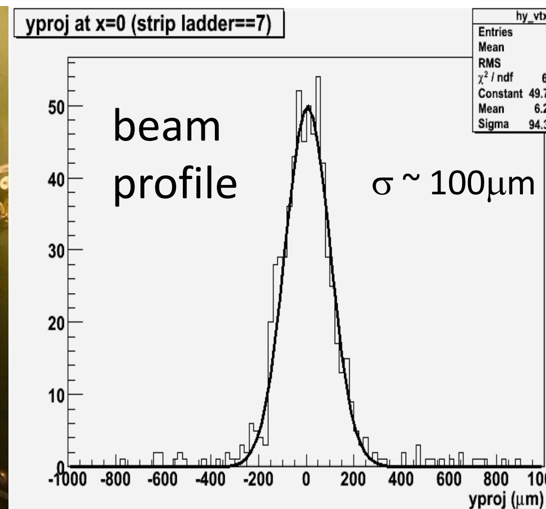
Near-Term Future: Silicon Vertex Detector

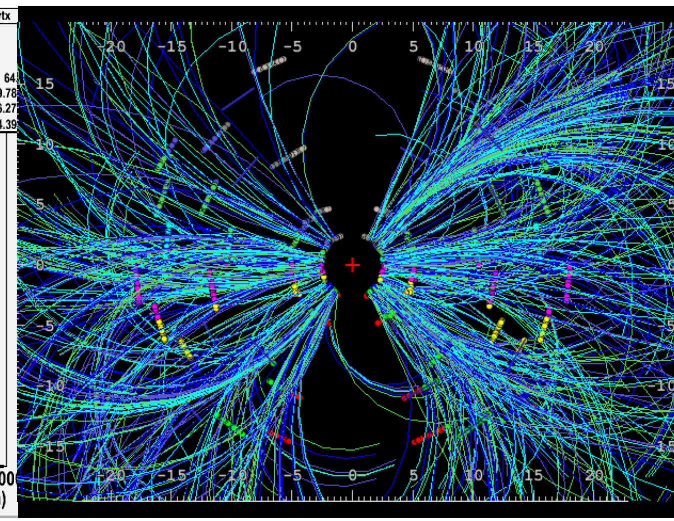
Status

- VTX successfully commissioned in 2011 *p+p* run
- VTX taking data in Au+Au now!

Data: Au+Au@200 GeV, 2011







Parallel: A. Sickles (Decadal Plan) Thu
Poster: M. Chiu (Fast TOF, 10 ps)
Poster: M. Kurosawa (VTX (pixel))
Poster: T.Hachiya (VTX (pixel))
Poster: R. Akimoto (VTX (pixel))

Physics

- R_{AA} of *c*, *b* separately
- v_2 of *c*, *b* separately
- Jet tomography (di-hadron, γ-*h*, *c*-*h*, *c*-$\bar{c}$)

What I could not cover in this talk

- T_i
  - Plenary: S. Esumi, Tue
  - Parallel: E. Kistenev (direct photons) Thu
  - Poster: Y. Yamaguchi (direct photons dAu)
- v_3, jet shape, η/s
  - Plenary: S. Esumi, Tue
  - Parallel: R. Lacey (v3, jet shape) Mon
  - Parallel: X. Gong (energy scan: bulk) Fri
  - Poster: S. Mizuno (PID v3)
- Chiral Symmetry
  - Parallel: M. Makek (Results from HBD) Thu
- Heavy Flavor
  - Plenary: C. Luiz da Silva, Fri
  - Parallel: A. Sen (quarkonia) Tue
  - Parallel: M. Durham (open heavy flavor) Fri
  - Poster: S. Whitaker (Upsilon RAA)
  - Poster: A. Takahara (J/psi photoproduction)
  - Poster: H. Thewman (high p_T single e in p+p)
- Energy Loss
  - Plenary: M. Purschke (R_AA) Wen
  - Parallel: N. Grau (gamma-hadron, jets) Tue
  - Parallel: N. Novitsky (energy scan) Fri
  - Parallel: D. Sharma (light vector mesons) Mon
  - Poster: M. Tannenbaum (E loss RHIC vs. LHC)
  - Poster: O. Chvala (RAA in 39 and 62 GeV)
  - Parallel: D. Sharma (light vector mesons) Mon
- Cold nuclear matter
  - Parallel: M. Chiu (small x dAu correl) Thu
  - Parallel: J. Kamin (dAu dileptons) Fri
  - Poster: Z. Citron (small x dAu correlations)
  - Poster: D. Perepelitsa (jets in dAu)
- Future
  - Parallel: A. Sickles (Decadal Plan) Thu
  - Poster: M. Chiu (Fast TOF, 10 ps)
  - Poster: M. Kurosawa (VTX (pixel))
  - Poster: T.Hachiya (VTX (pixel))
  - Poster: R. Akimoto (VTX (pixel))

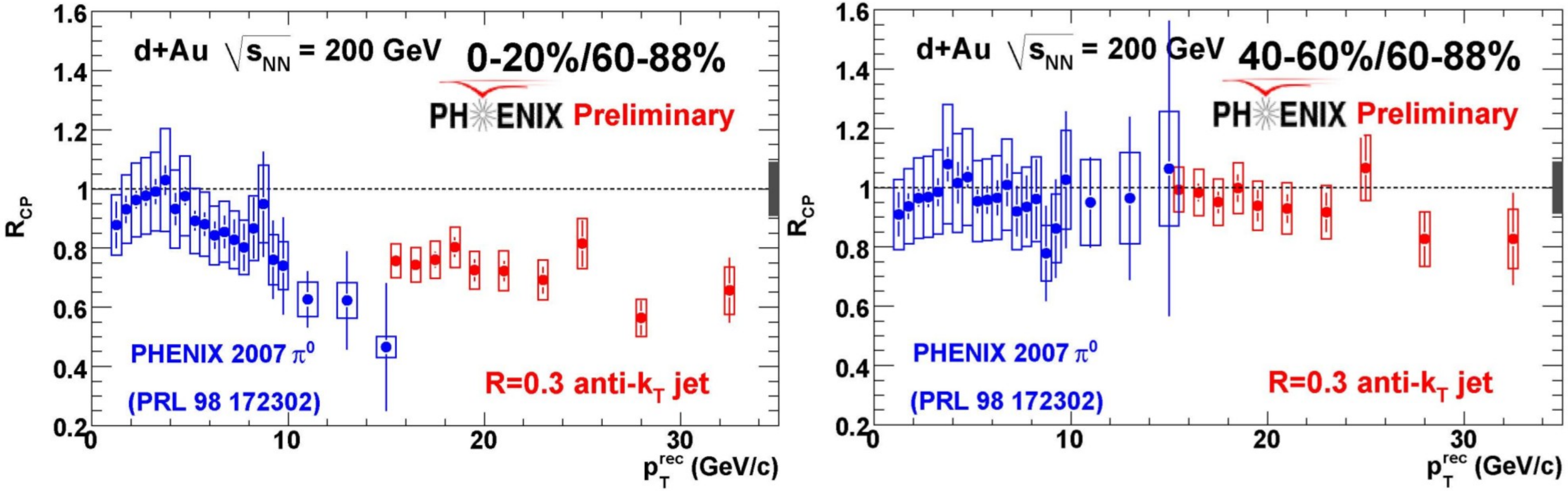
Conclusions

- v_2 of thermal direct photons **large**
  - Further constrains T_i and τ_0
- CNM effects in *d*+Au
  - **Non-linear** density dependence of shadowing from J/ψ
  - **Reconstructed jet** R_{cp} modified
  - **Low-*x* suppression** from forward di-hadron correlations
- v_3
  - **Disentangle initial state from η/s**
  - **Double-hump disappears** in 2-particle correlations
- **Energy loss**
  - **Cubic** path-length dependence
- Energy Scan
  - **v_2 saturation** 39 GeV
  - **R_{AA} suppressed** also at 39 GeV

Thank you!

Backup

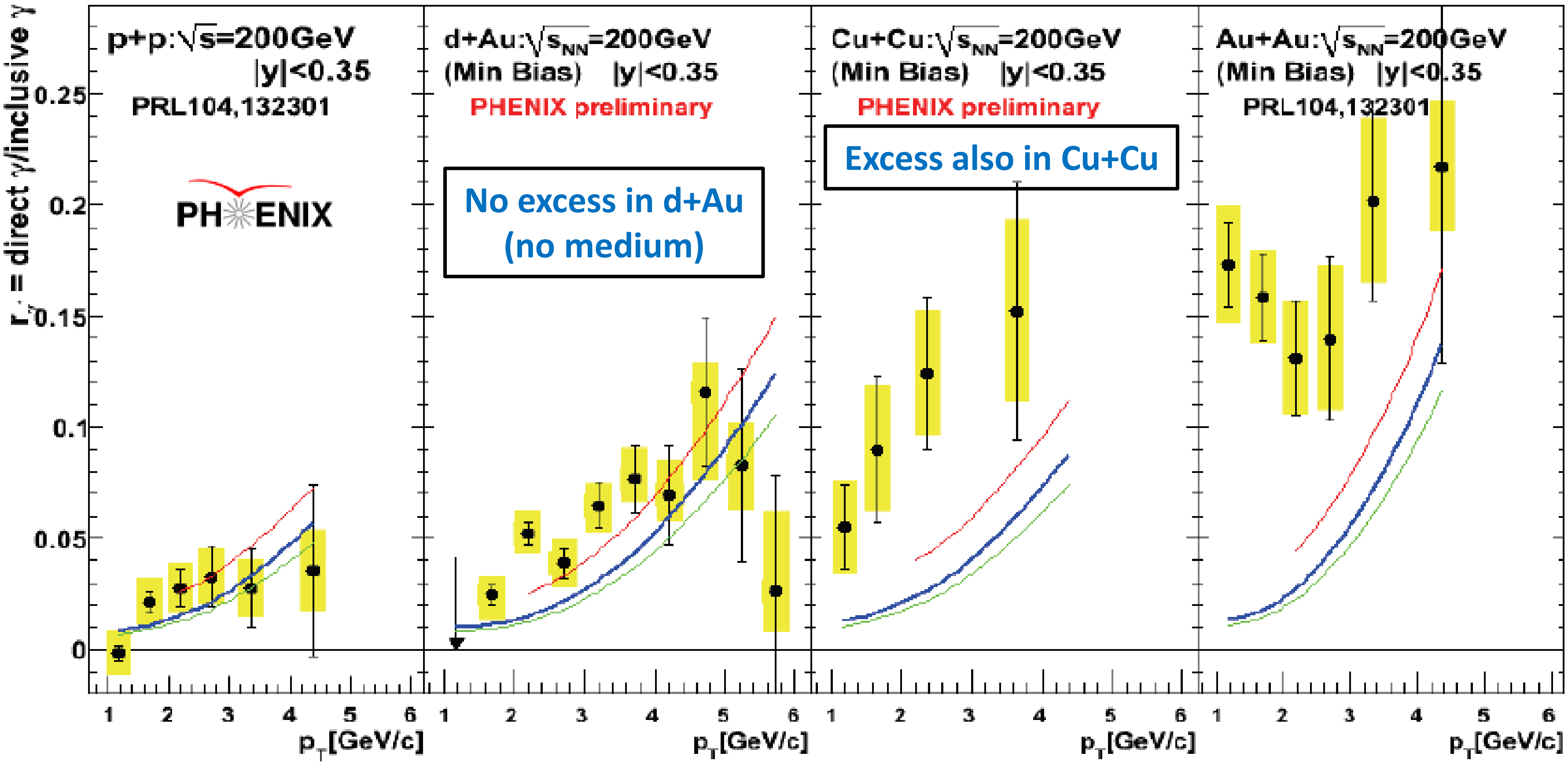
Jet-π^0 comparison *d*+Au



- π^0 R_{cp} calculated from published R_{dA}
- Consistent in overlapping p_T range

Confirmation from *d*+Au and Cu+Cu

- Fraction of direct photons compared to pQCD



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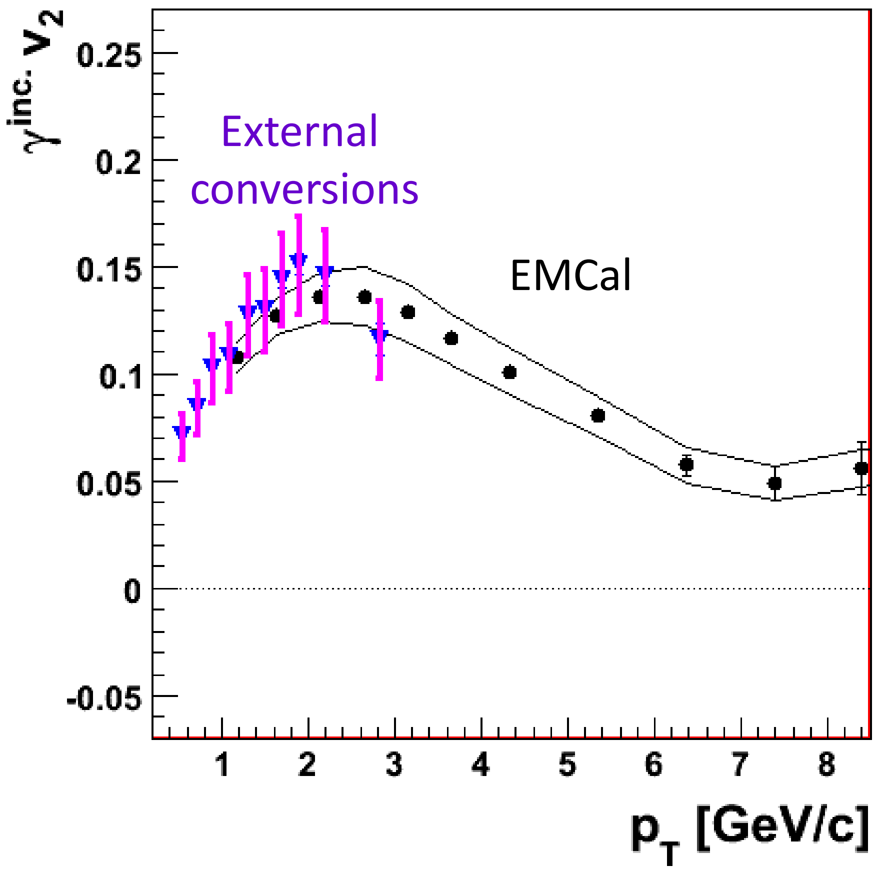
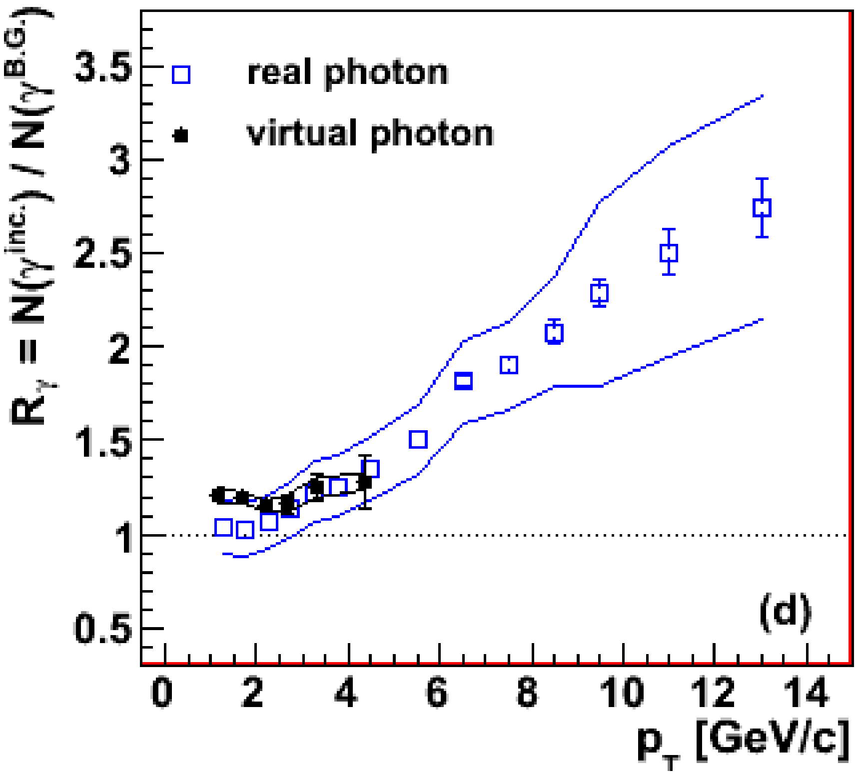
Inclusive Photon v_2



- Measured with EMCal
- Issue:
  - Hadronic contamination at low pT
    - Hadrons deposit only fraction of energy
    - depends on hadron species
    - Difficult to estimate
- Confirmed with external conversion
  - No hadronic contamination

Direct photon excess R_γ

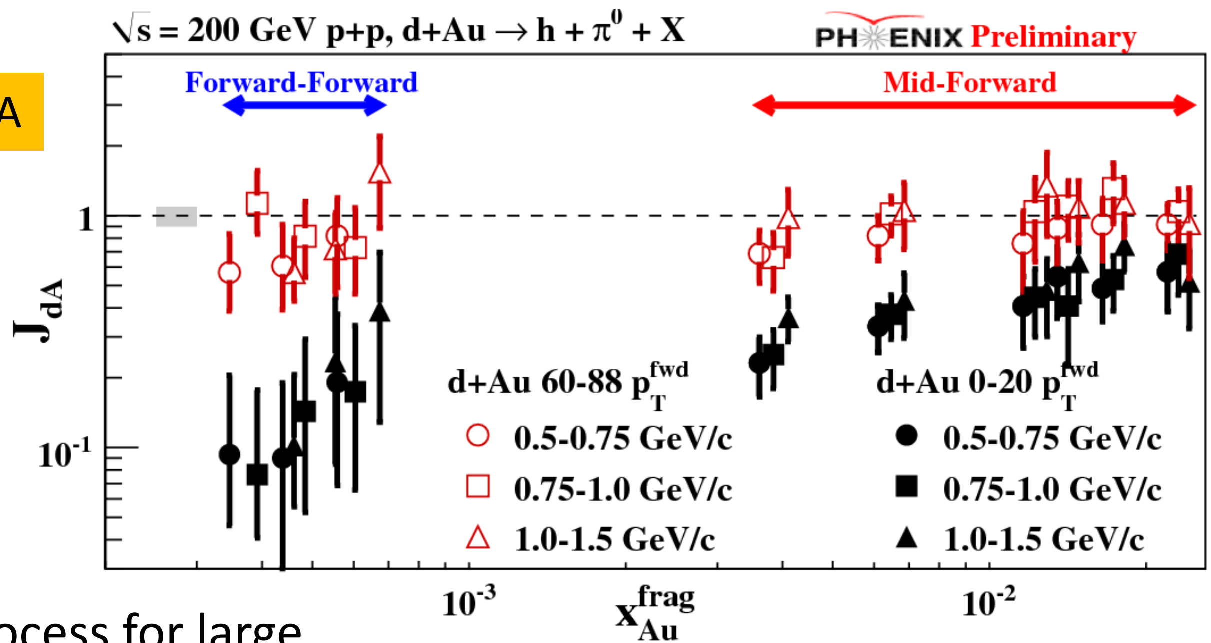


- Key to this analysis
  - Precise measurement of R_γ through internal conversion
- 20 % direct photon fraction
- => direct photon similar to inclusive photon v_2 (or π^0 v_2)

Correlations at Forward Rapidity

JdA=RdA*IdA

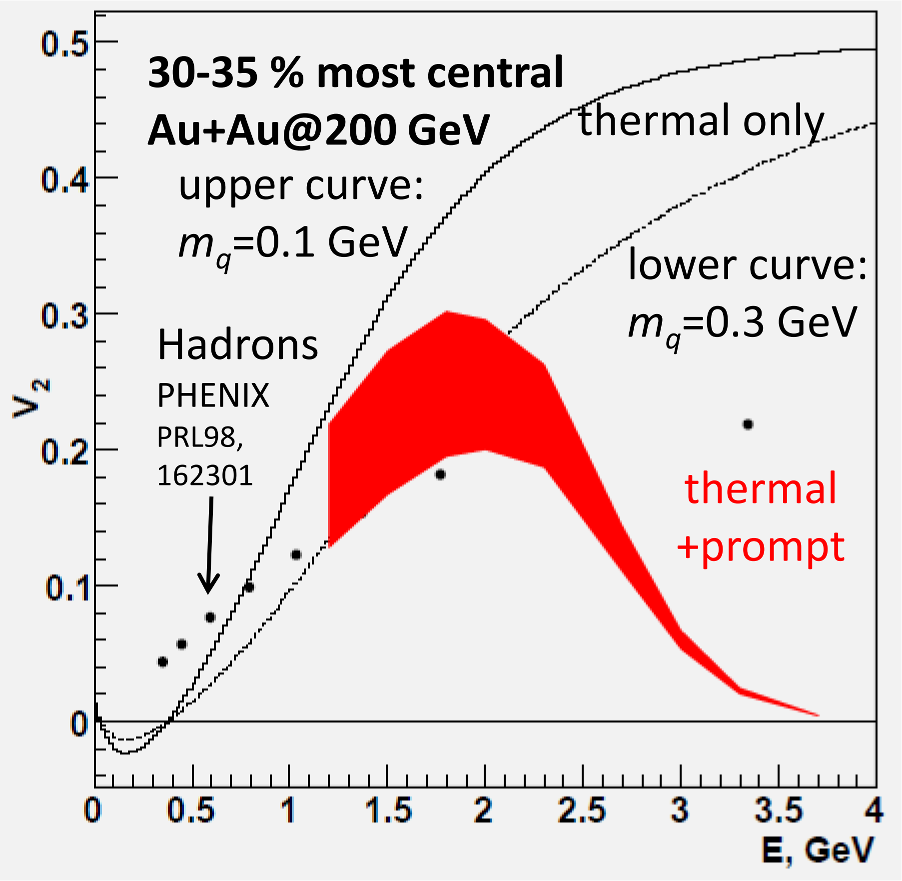
- J_{dA} suppressed in central d+Au
- Caveat:
  - Double parton interactions (DPI) enhanced in d+Au
    - may be dominant process for large forward rapidity (rather than 2->2 process)
    - M. Strikman and W. Vogelsang, arXiv:1009.6123
  - Then xfrag not sensitive to rapidity



Pocket formula:

$$x_{Au}^{frag} = \frac{<p_{T1}> e^{-<\eta_1>} + <p_{T2}> e^{-<\eta_2>}}{\sqrt{s}}$$

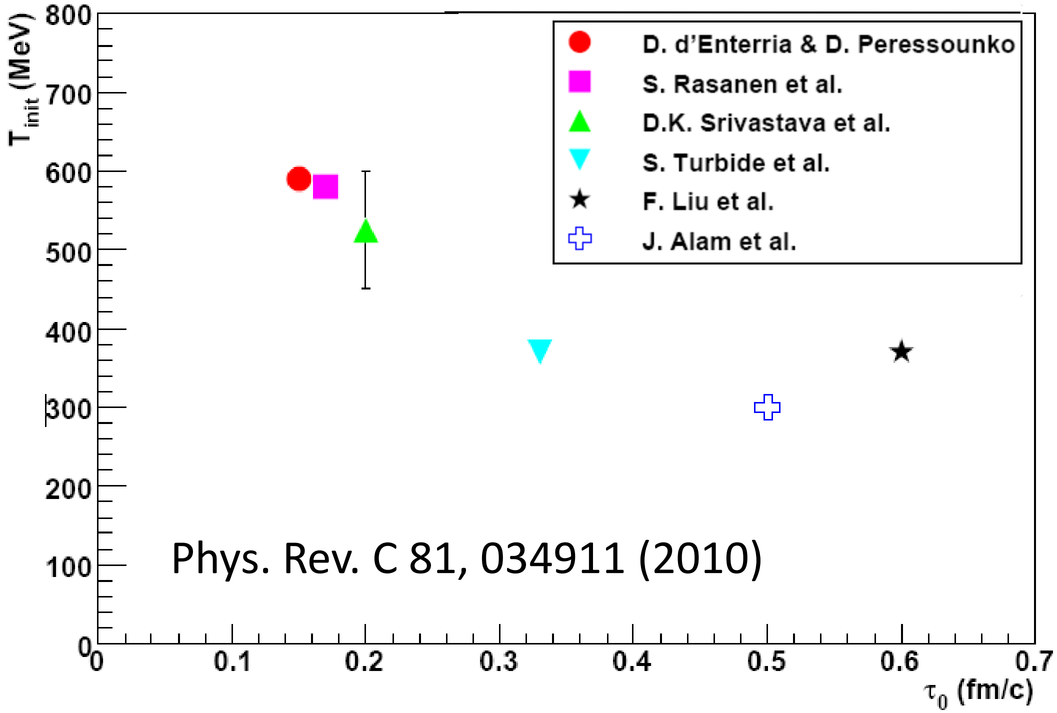
Direct photon flow calculation



V. Pantuev, arXiv:1105.NNNN

- expanding fireball in longitudinal and radial direction
- photons are produced from matter which flows
- Doppler

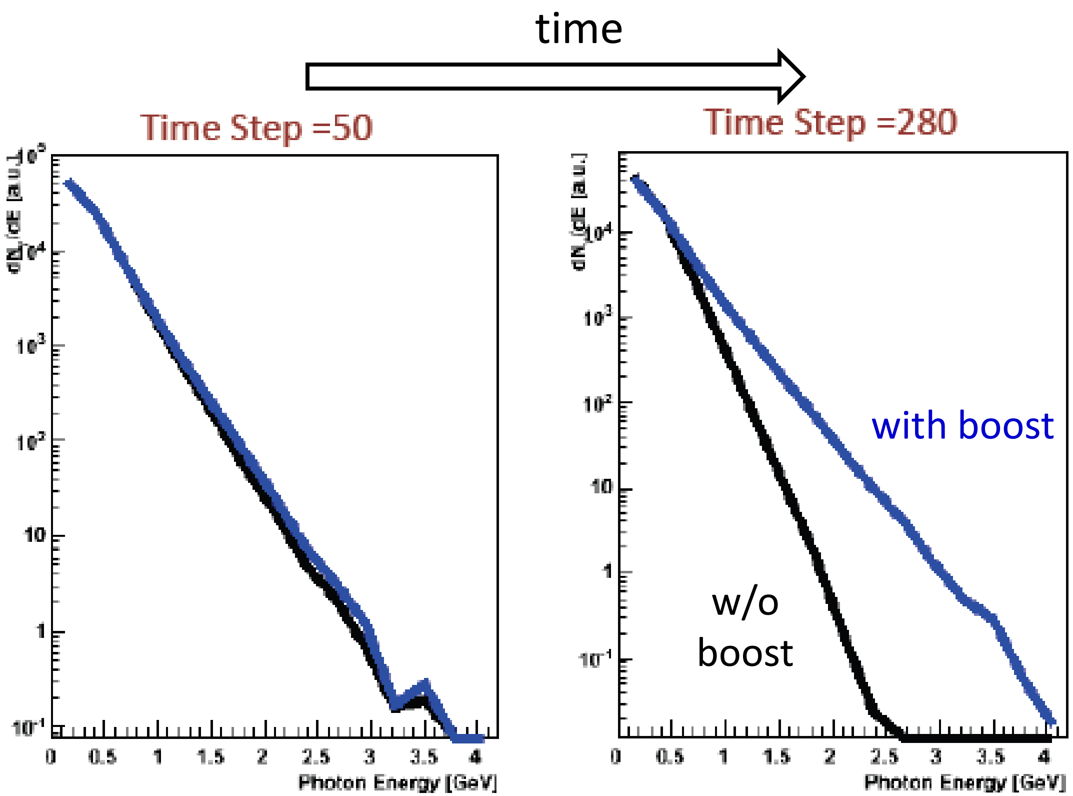
T_i from hydro



- T_i from hydro
  - 300 . . . 600 MeV
  - Depends on thermalization time, τ_0
  - anti-correlation: $T_i \Leftrightarrow \tau_0$

Theory calculations:
d'Enterria, Peressounko, EPJ46, 451
Huovinen, Ruuskanen, Rasanen, PLB535, 109
Srivastava, Sinha, PRC 64, 034902
Turbide, Rapp, Gale, PRC69, 014903
Liu et al., PRC79, 014905
Alam et al., PRC63, 021901(R)

What is the initial Temperature, T_i?



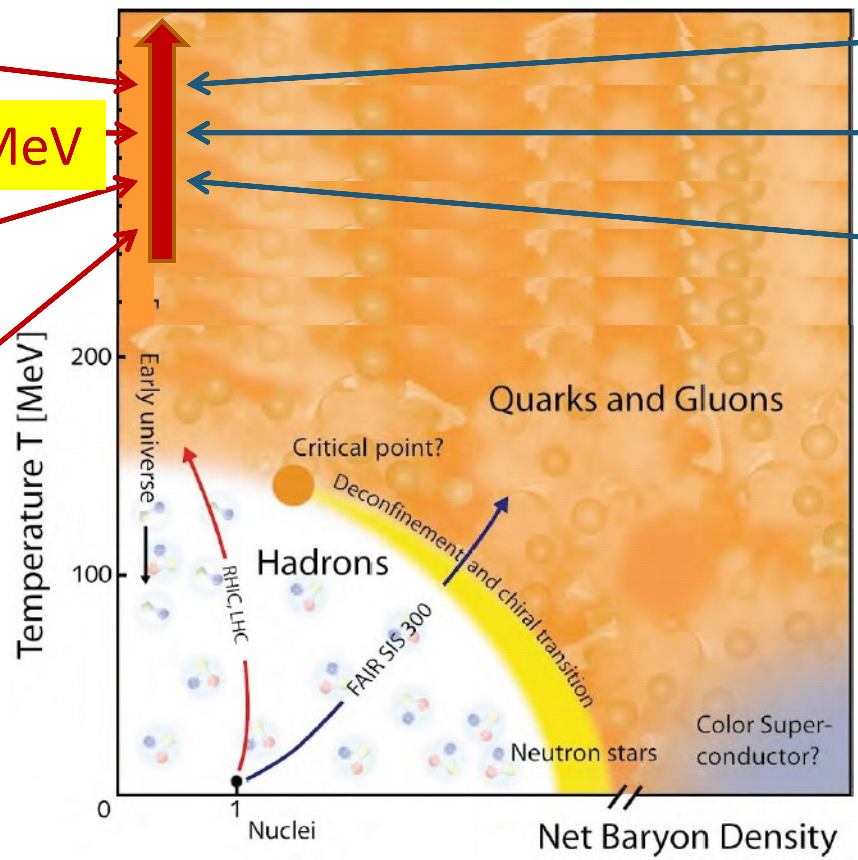
figures: K. Mendoza, U. Colorado

- integrate over space-time evolution
- Early photons
  - large temperature
    - large inverse slope
- Late photons
  - Low temperature, but large velocity boost
    - also large inverse slope
- => need model for quantitative answer

Measuring the Properties of the QGP

Conditions ⟹ Properties

- $\mu \sim 0$
- T_i =300-600 MeV
- CNM effects
- Initial State



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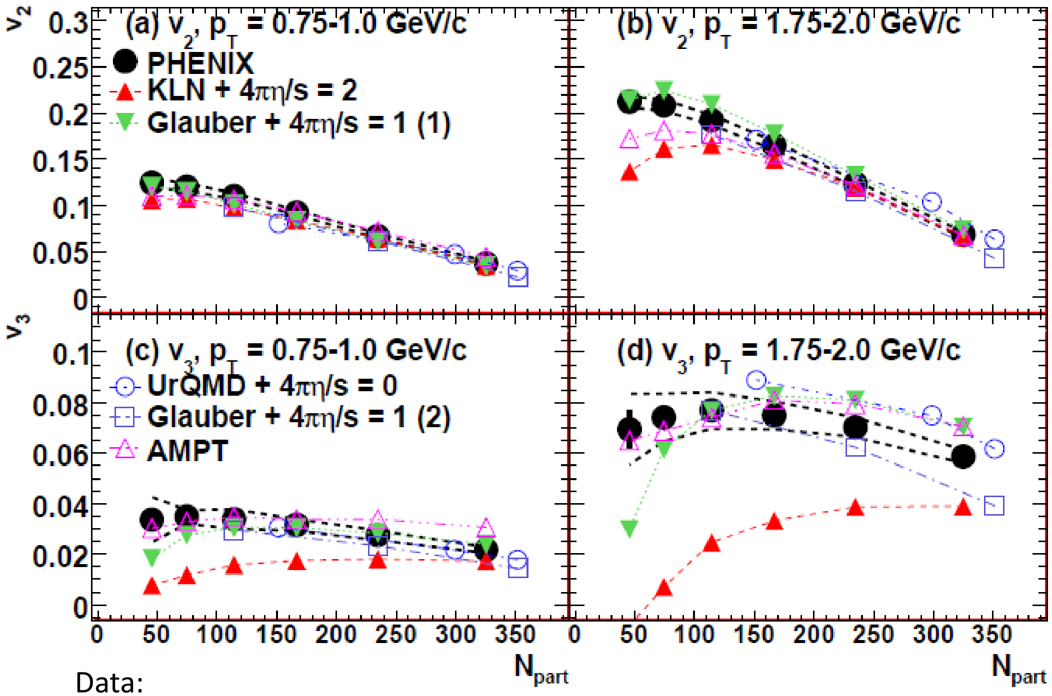
- Screening length
- η/s
- dE/dx

Factorizing initial state and viscosity



- v_2 described by both models
  - Glauber
    - Glauber initial state
    - $\eta/s = 1/4\pi$
  - KLN
    - CGS initial state
    - $\eta/s = 2/4\pi$
- v_3 described by only one model
  - Glauber
    - Glauber initial state
    - $\eta/s = 1/4\pi$

Data:
PHENIX, arXiv:
Models:

B. Alver et al., Phys. Rev. C82, 034913 (2010).
B. Schenke et al., Phys. Rev. Lett. 106, 042301 (2011).
H. Petersen et al., Phys. Rev. C82, 041901 (2010).
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998).
M. Bleicher et al., J. Phys. G25, 1859 (1999).
]G.-L. e. a. Ma (2010), 1011.5249.