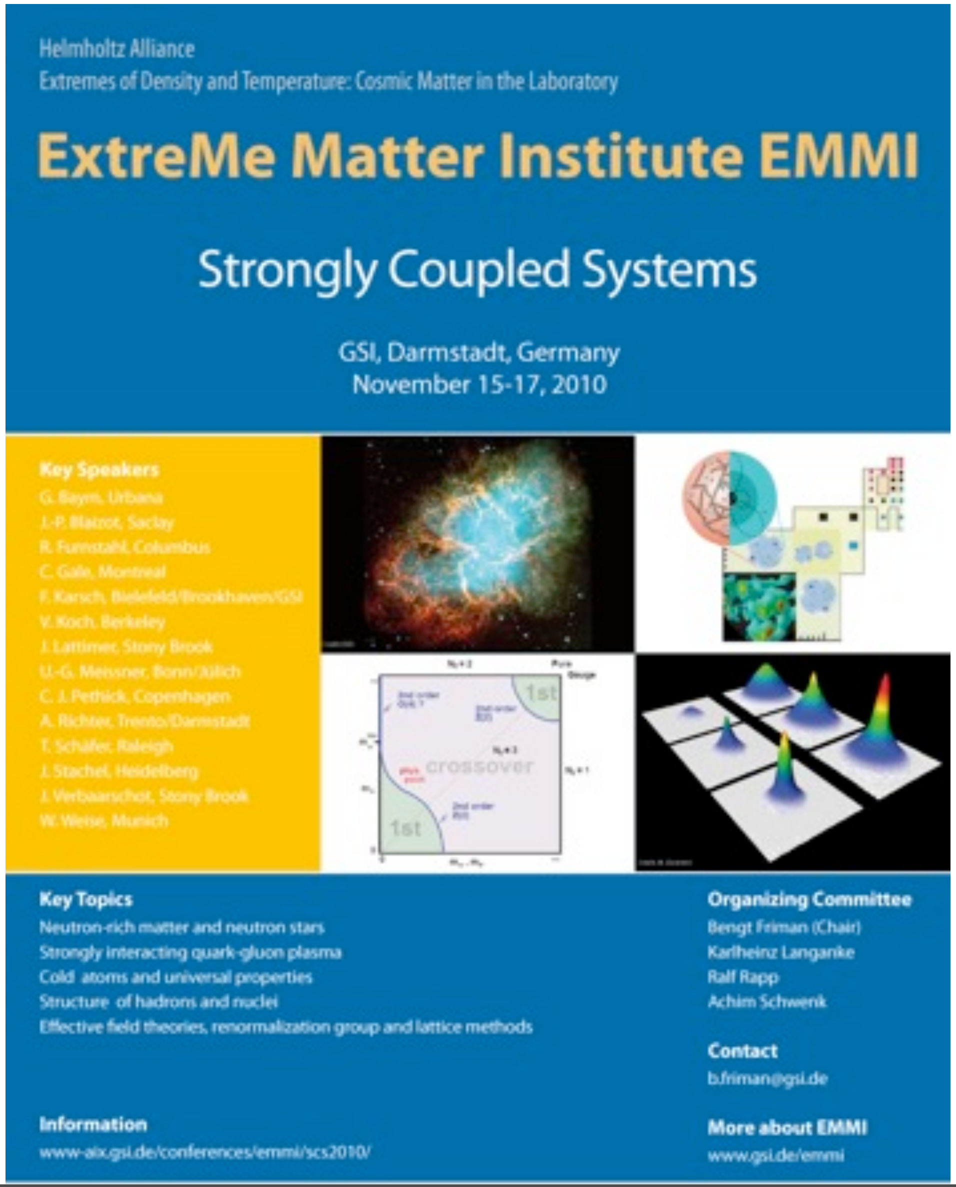
High p_T Photons in Heavy Ion Collisions

Charles Gale

McGill University



OUTLINE

- Sources & EM emissivity
- Rates: Photons
- Soft sector:
  - Real photons @ SPS
  - Soft photons @ RHIC
- RHIC hard(er) sector:
  - Jet quenching, Tomography?
  - Real photons & jets
- Conclusions

Info Carried by the Radiation

$$dR = -\frac{g^{\mu\nu}}{2\omega}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)$$
$$\times\langle j\,|\,J_\mu\,|\,i\rangle\langle i\,|\,J_\nu\,|\,j\rangle$$

Thermal ensemble average of the current-current correlator

Emission rates:

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\,\mathrm{Im}\Pi_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(photons)}$$

$$E_+E_-\frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6}\frac{1}{k^4}L^{\mu\nu}\,\mathrm{Im}\,\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(dileptons)}$$

McLerran, Toimela (85), Weldon (90), Gale, Kapusta (91)

Tomography: The "patient" here is hot and dense strongly interacting matter. Trying to get info about the QCD phase diagram

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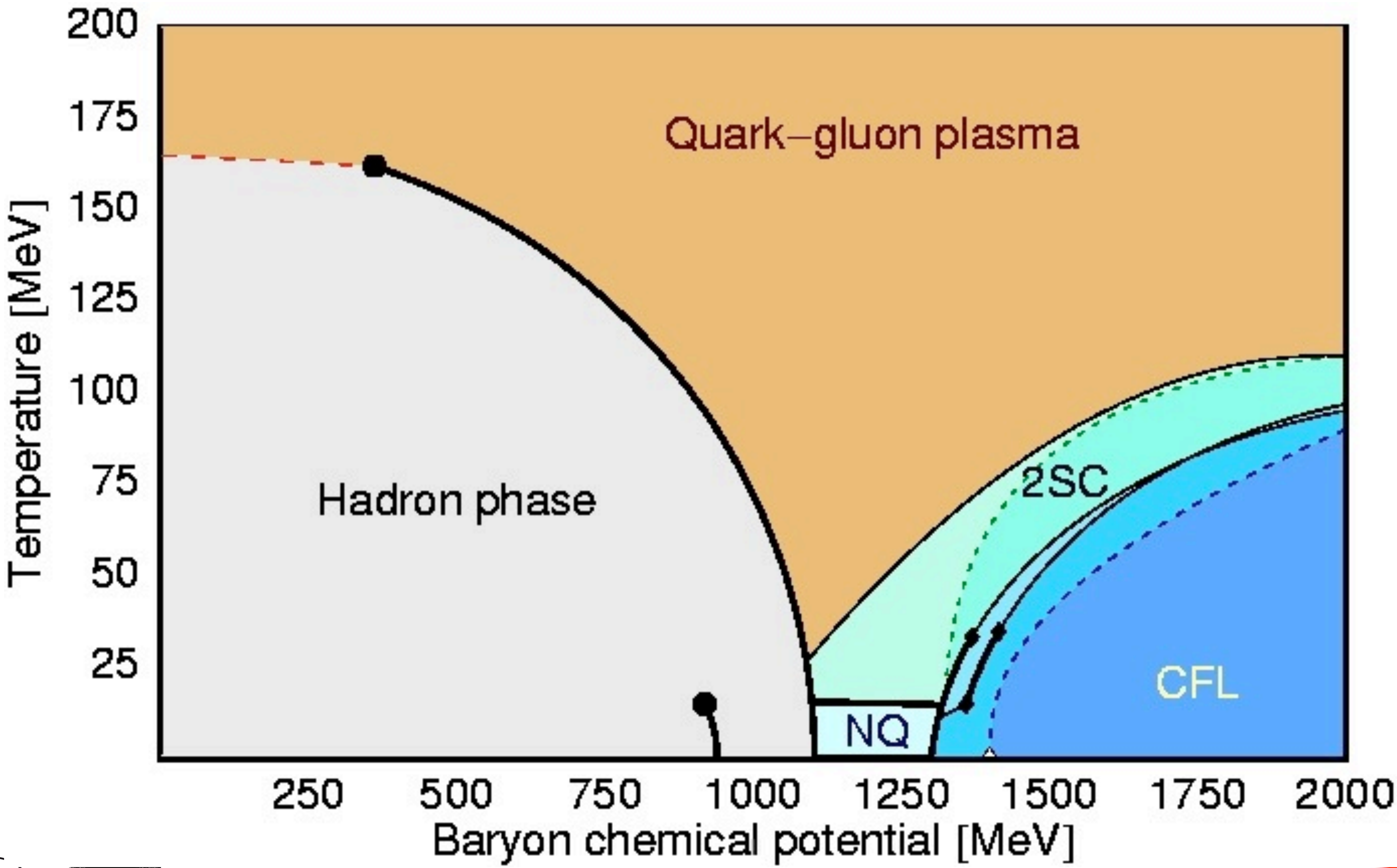

S. B. Ruster et al., PRD 72, 034004 (2005)

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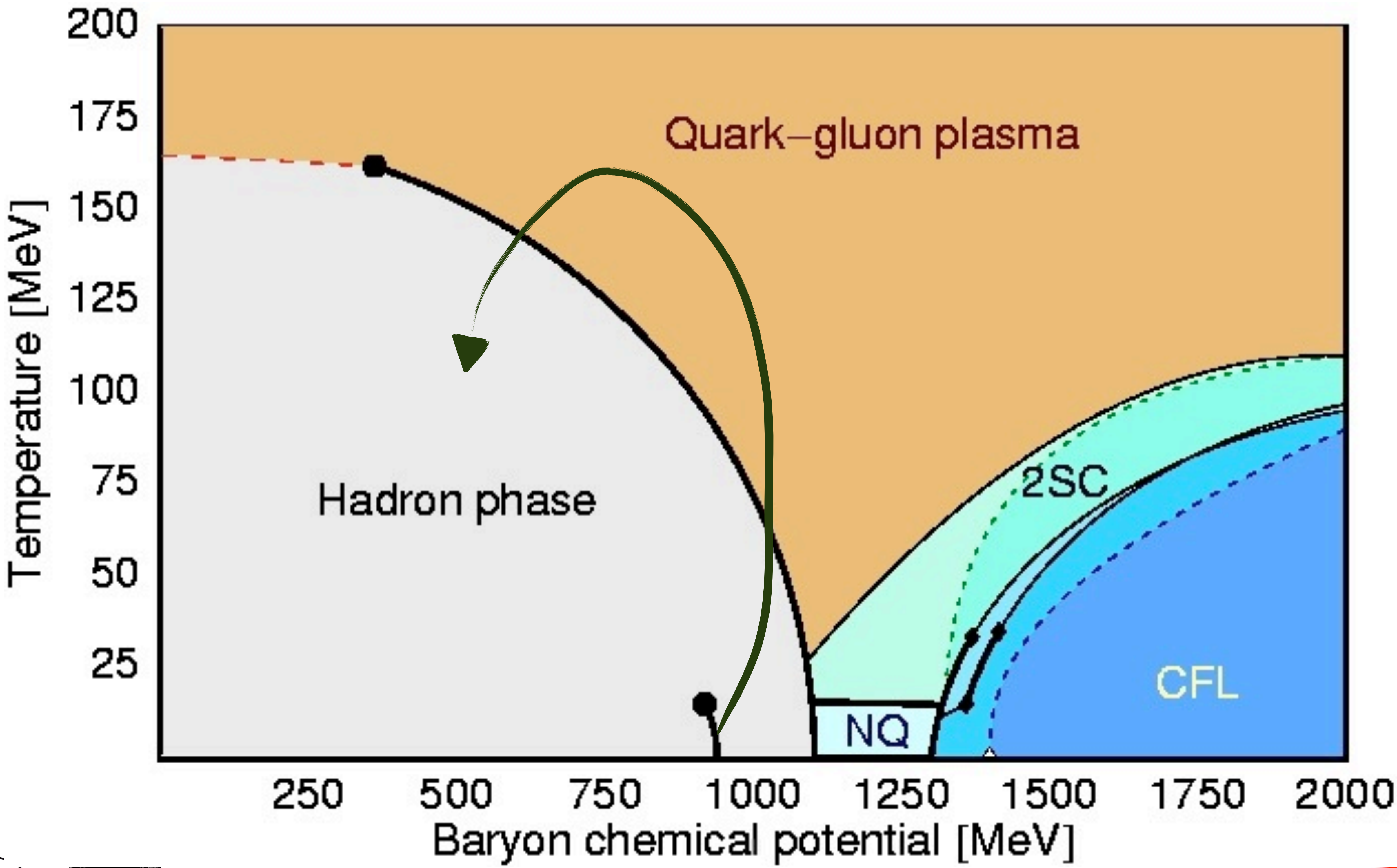


S. B. Ruster et al., PRD 72, 034004 (2005)

Caution: not all dynamical models are the same...

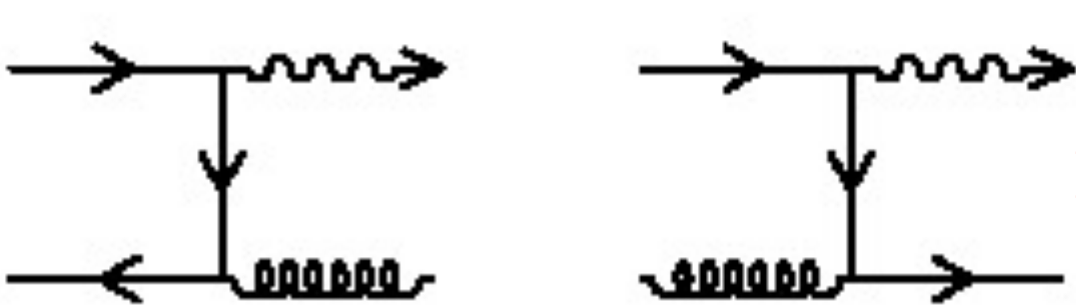
- Microscopic transport models (*e. g.* UrQMD, HSD)
- Hydrodynamic models ($\eta = 0, \eta \neq 0$)
- Thermal fireball models

- Those differ in details (symmetry assumptions, chemical potentials, freezeout conditions, cross sections...)
- Need to be constrained by hadronic observables!

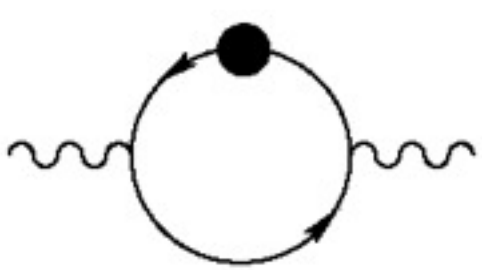
Electromagnetic radiation from QCD

- First approaches

McLerran, Toimela (1986); Kajantie, Kapusta, McLerran, Mekjian (1986)
Baier, Pire, Schiff (1988); Altherr, Ruuskanen (1992)

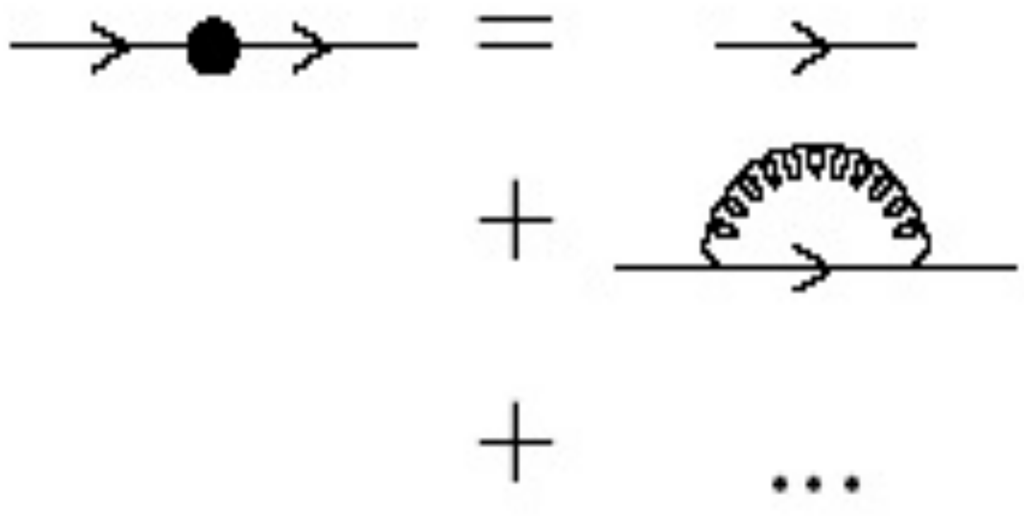


Rates diverge: $\sim \alpha\alpha_s \ln(\omega T / q^2 = 0)$

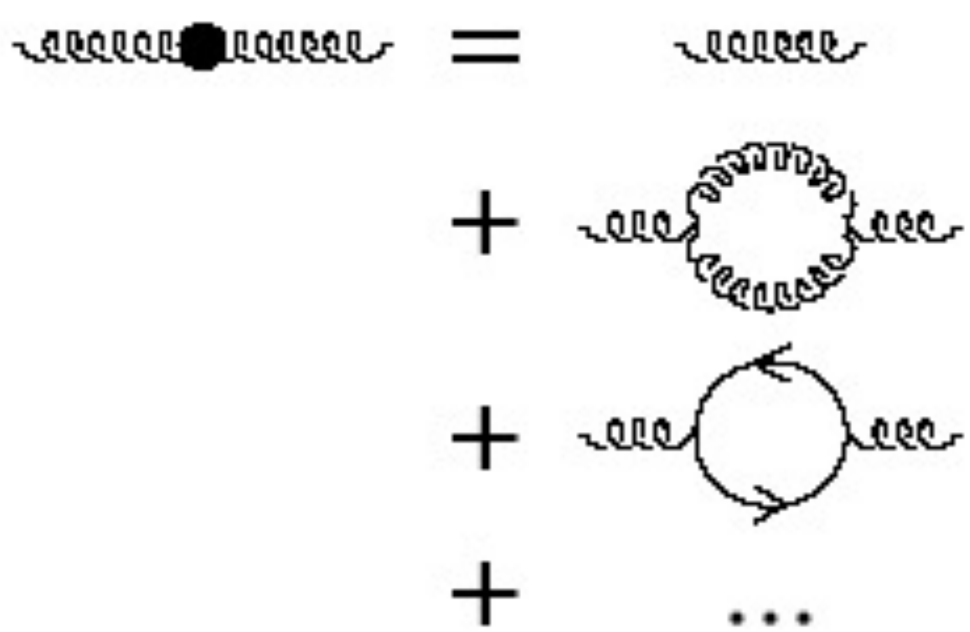


HTL resummation

- HTL program: resummation regulates the divergence. Quasi-particles acquire a mass:



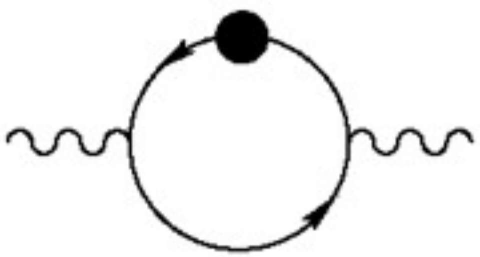
$$m_q^2 = \frac{4\pi}{3}\alpha_s T^2$$



$$m_g^2 = \frac{4\pi}{3}\alpha_s (1 + \frac{N_f}{6}) T^2$$

HTL program: Klimov (1981), Weldon (1982)

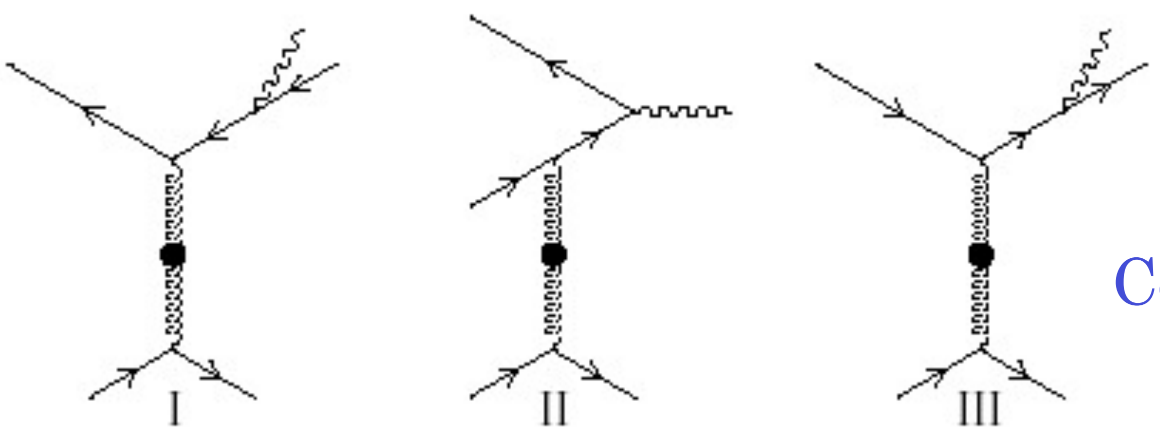
Braaten & Pisarski (1990); Frenkel & Taylor (1990)



$$\mathrm{Im}\,\Pi^{\mu}_{R\mu} \sim \ln\left(\frac{\varpi T}{\left(m_{th}\left(\sim gT\right)\right)^2}\right)$$

Kapusta, Lichard, Seibert (1991)
Baier, Nakkagawa, Niegawa, Redlich (1992)

Going to two loops: Aurenche, Kobes, Gelis, Petitgirard (1996)
Aurenche, Gelis, Kobes, Zaraket (1998)



Co-linear singularities: $\alpha_s^2\left(\frac{T^2}{m_{th}^2}\right) \sim \alpha_s$

2001: Results complete at $O(\alpha_s)$

Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

Chiral, Massive Yang-Mills:

O. Kaymakcalan, S. Rajeev, J. Schechter, PRD 30, 594 (1984)

$$L = \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, D_\mu U D^\mu U^\dagger + \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, \mathrm{M}\left(\mathrm{U} + \mathrm{U}^\dagger\right)$$

$$- \frac{1}{2} \mathrm{Tr}\left(F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu}\right) + m_0^2 \mathrm{Tr}\left(A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu}\right)$$

$$+ \text{ non-minimal terms}$$

Parameters and form factors are constrained by hadronic phenomenology:

- Masses & strong decay widths
- Electromagnetic decay widths
- Other hadronic observables:
  - *e.g.* $a_1 \to \pi\rho \quad D/S$

Vector Meson Spectral Densities: A Sample Calculation

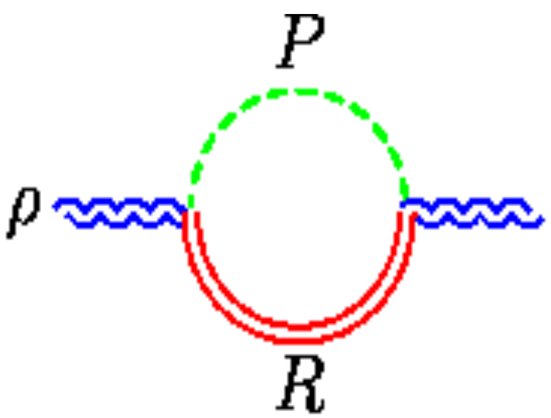
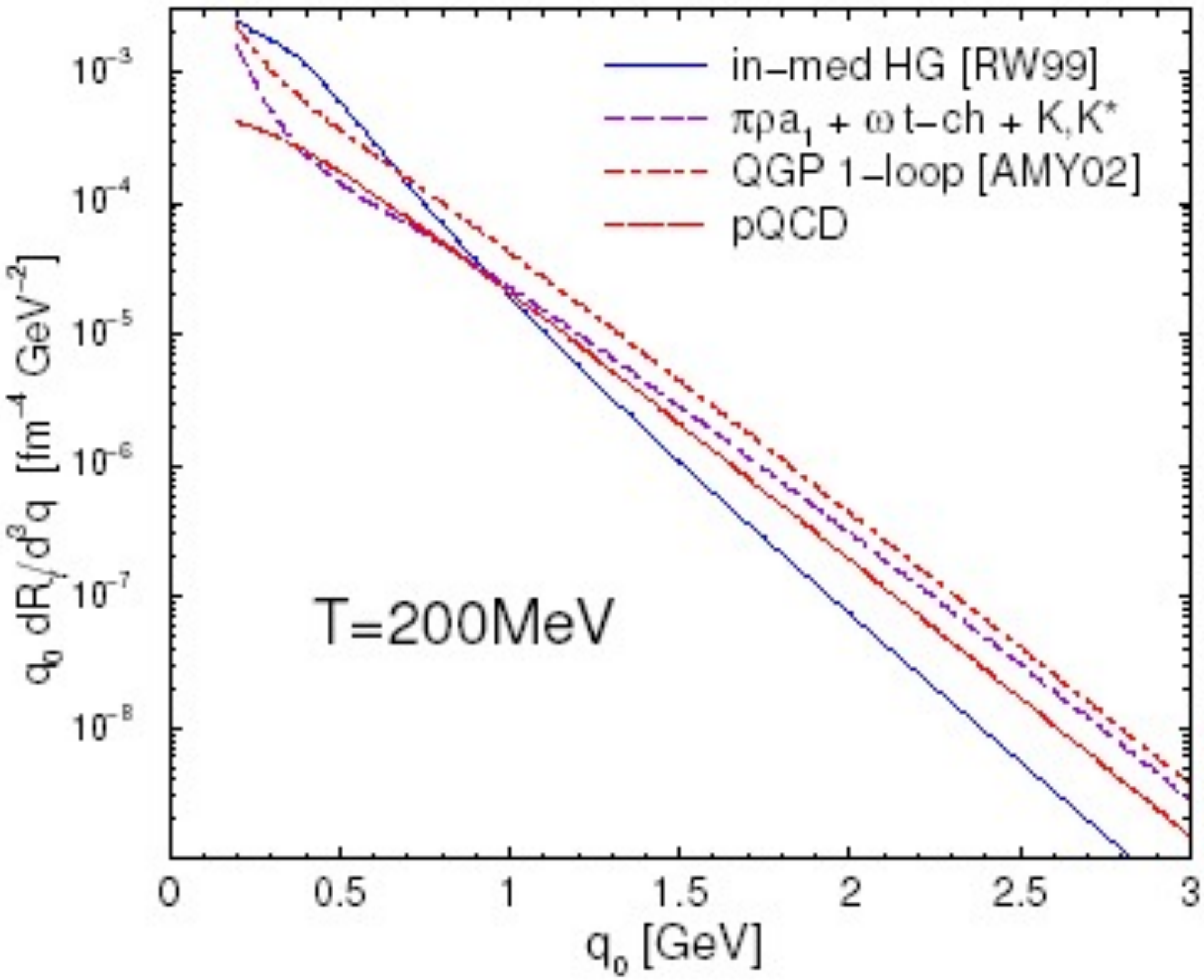


TABLE I. Mesonic resonances R with masses $m_R \leqslant 1300$ MeV and substantial branching ratios into final states involving direct ρ's (hadronic) or ρ-like photons (radiative).

R	$I^G J^P$	Γ_{tot} [MeV]	ρh decay	$\Gamma^0_{\rho h}$ [MeV]	$\Gamma^0_{\gamma h}$ [MeV]
$\omega(782)$	0^-1^-	8.43	$\rho\pi$	~ 5	0.72
$h_1(1170)$	0^-1^+	~ 360	$\rho\pi$	seen	?
$a_1(1260)$	1^-1^+	~ 400	$\rho\pi$	dominant	0.64
$K_1(1270)$	$\frac{1}{2}1^+$	~ 90	ρK	~ 60	?
$f_1(1285)$	0^+1^+	25	$\rho\rho$	$\leqslant 8$	1.65
$\pi'(1300)$	1^-0^-	~ 400	$\rho\pi$	seen	?

Ralf Rapp and Charles Gale, Phys. Rev. C **60**, 024003 (1999)

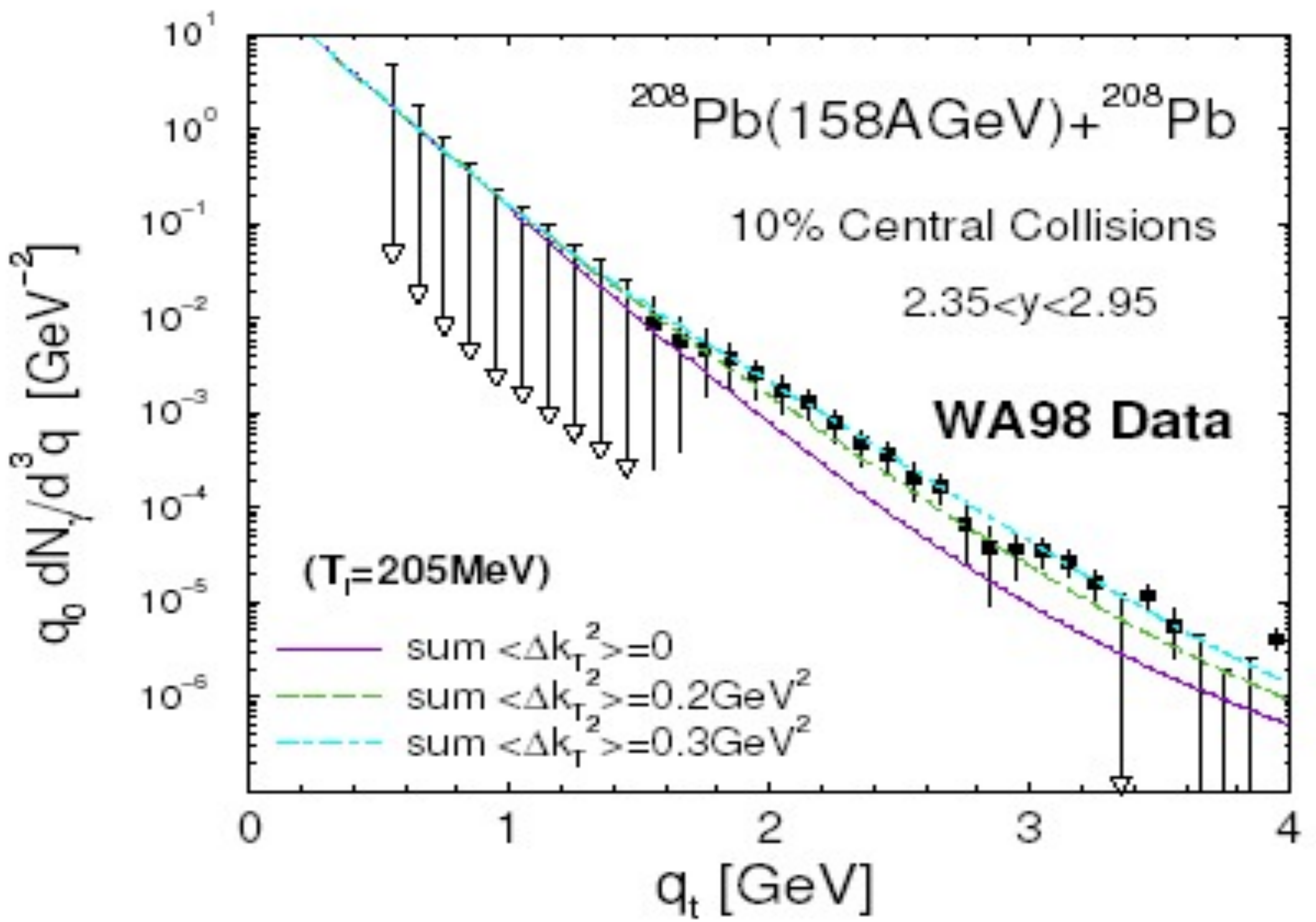
How big (small) is this? Relative contributions:



Turbide, Rapp & Gale
PRC (2004)

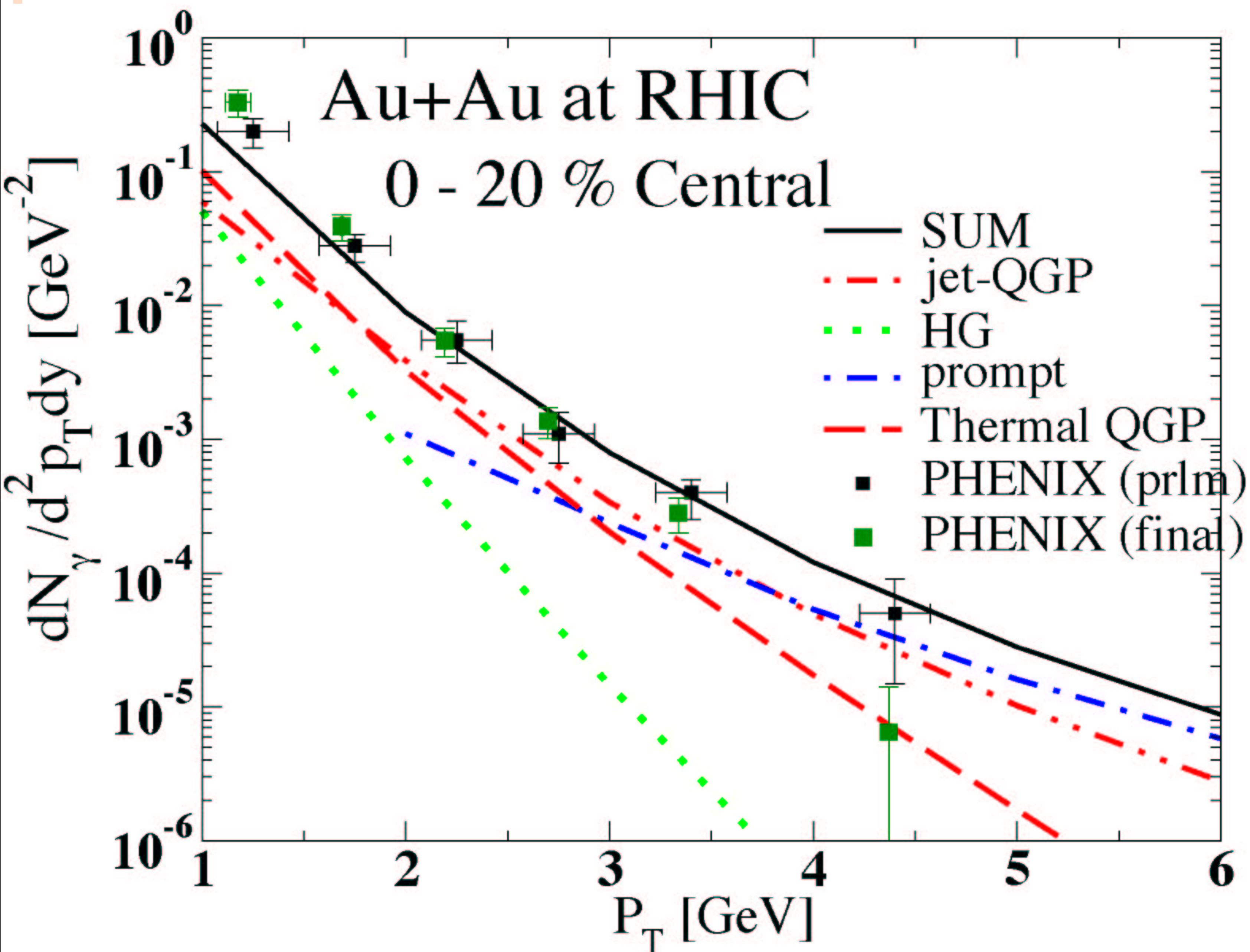
Phenomenological Exploration…

Results: The soft photon Sector (SPS)



Turbide, Rapp & Gale PRC 2004

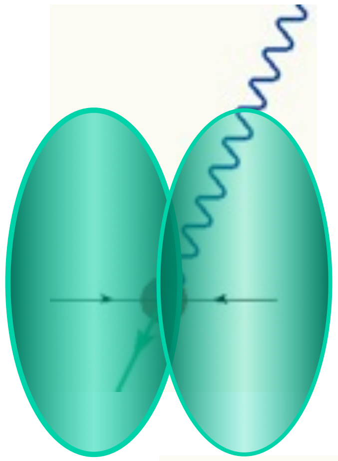
The soft sector II (RHIC)



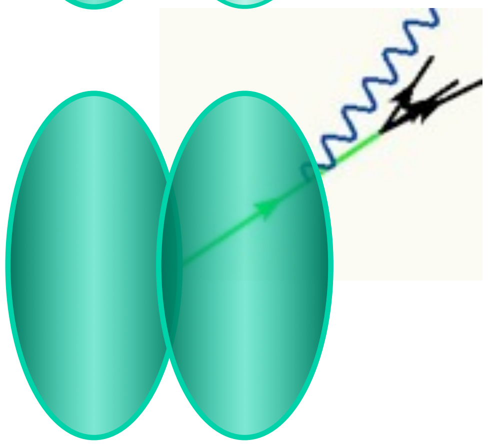
- At low p_T, spectrum dominated by thermal components (HG, QGP)
- At high p_T, spectrum dominated by pQCD
- Window for QPG contributions at mid-p_T
- Higher stats runs soon to be analyzed

G. Qin et al., PRC (2009)

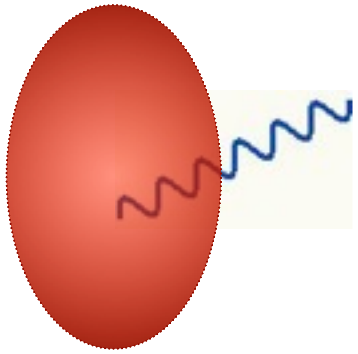
Sources of photons:



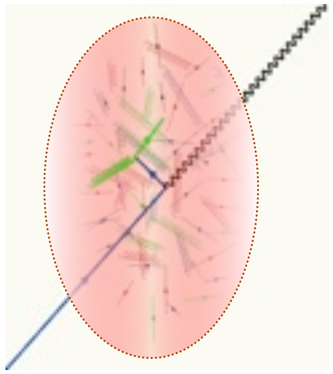
Hard direct photons. pQCD with shadowing
Non-thermal



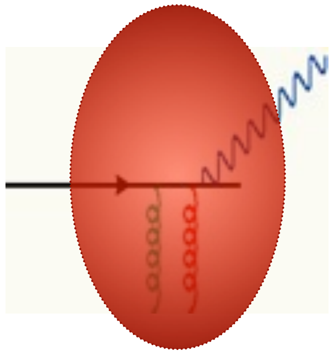
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal

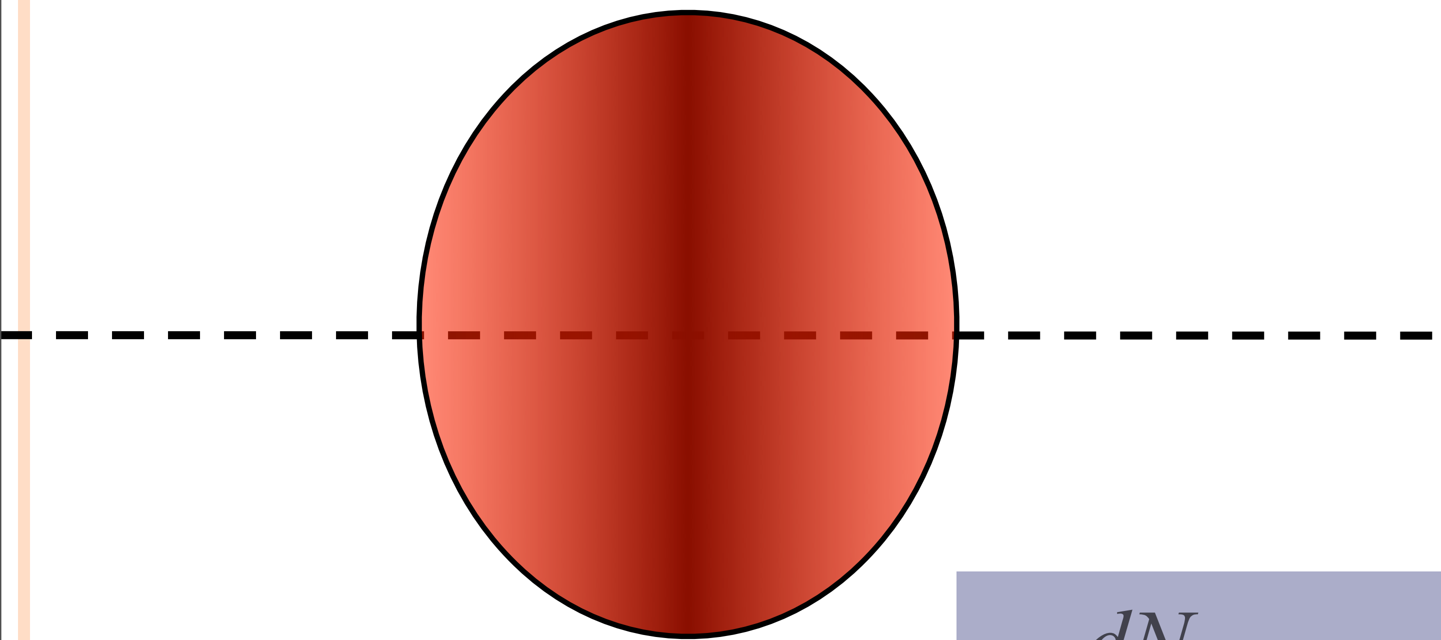


Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

BEYOND ONE-BODY DATA: FLOW AND CORRELATIONS

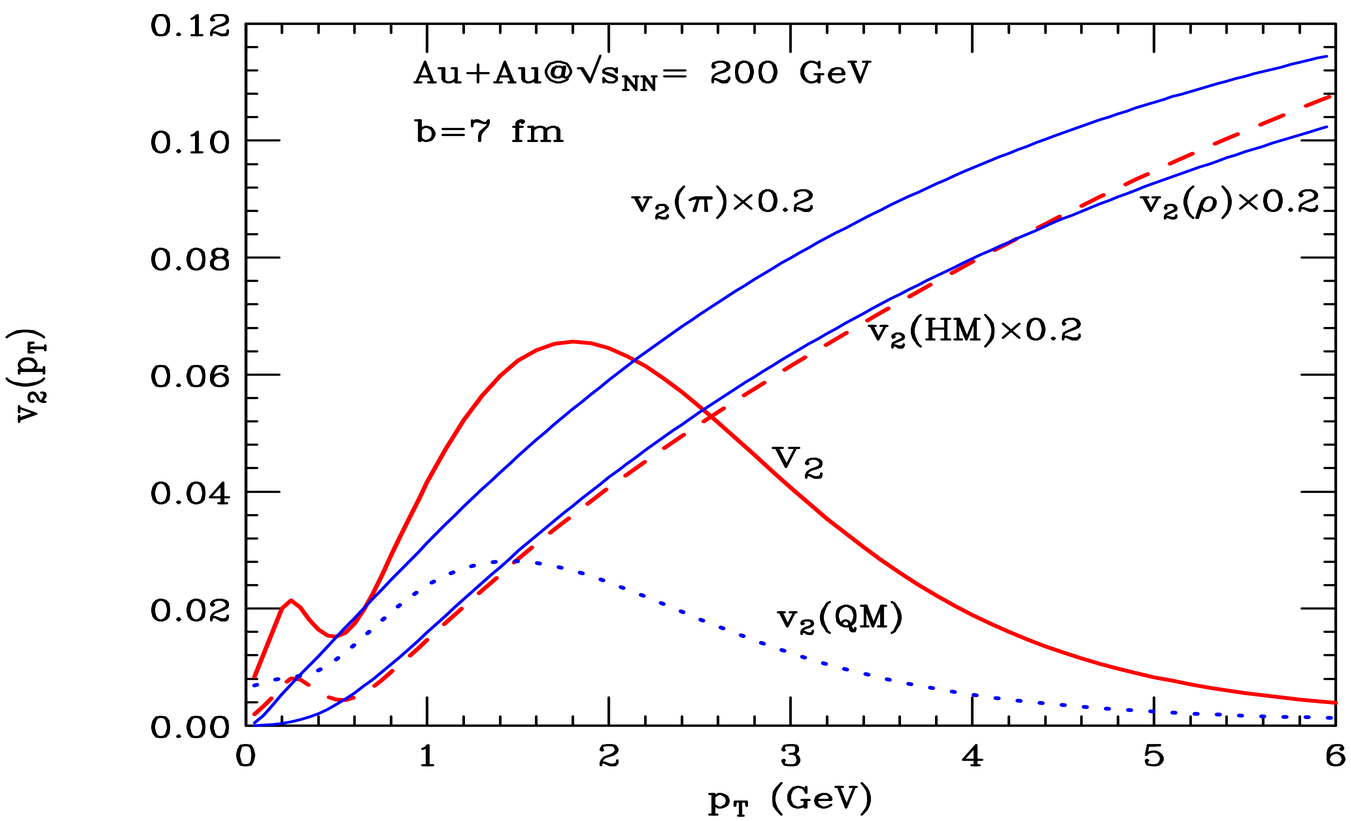


$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi\, p_T dp_T}\left[1 + \sum_n 2v_n \cos(n\phi)\right]$$

- Soft photons will go with the flow
- Lepton pairs are virtual photons: Same trend

Idea & high p_T: Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.*, PRL (2006)
All p_T: Turbide *et al.*, PRC (2008)

ELLIPTIC FLOW OF THERMAL PHOTONS: PREDICTIONS

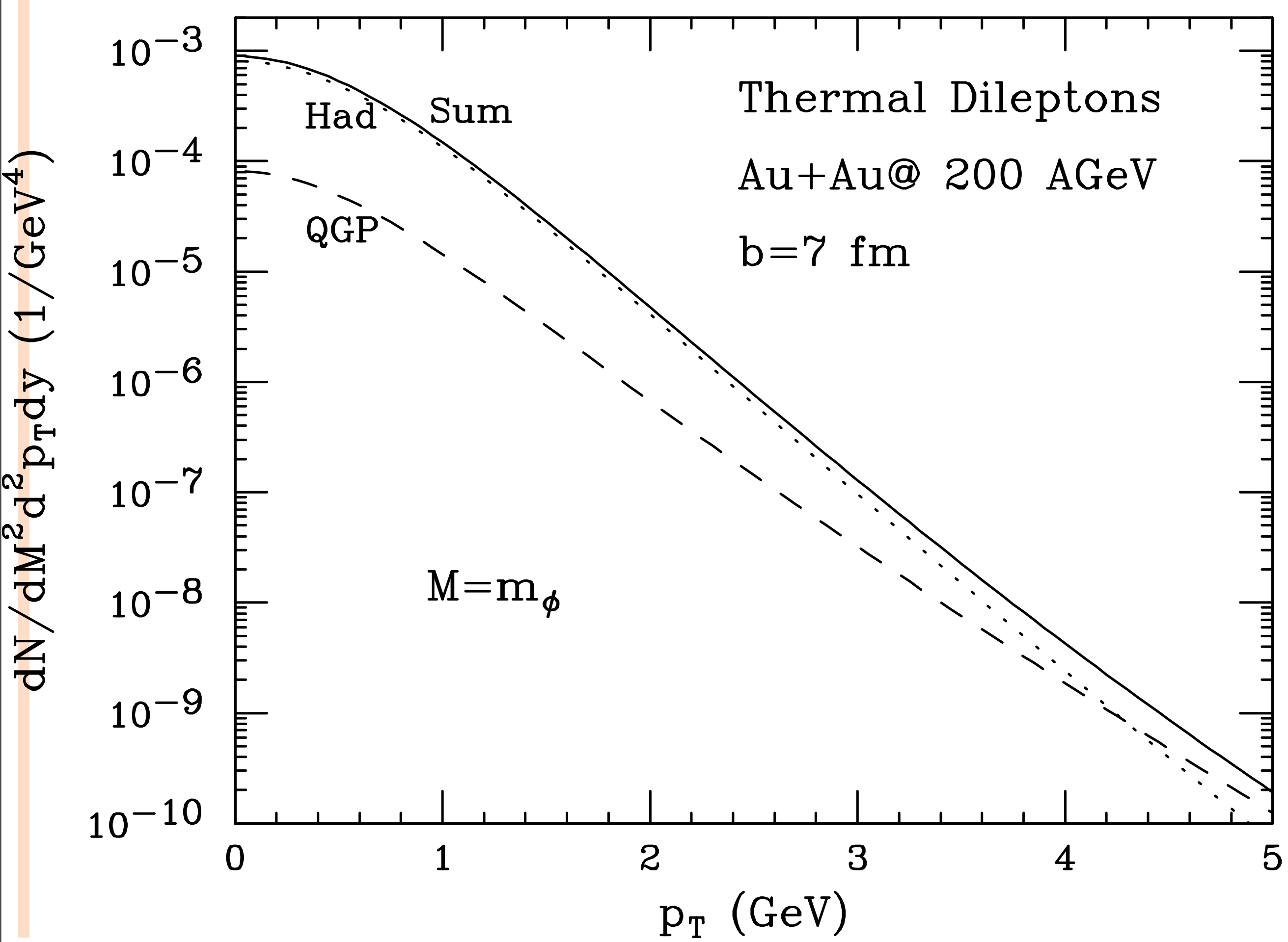


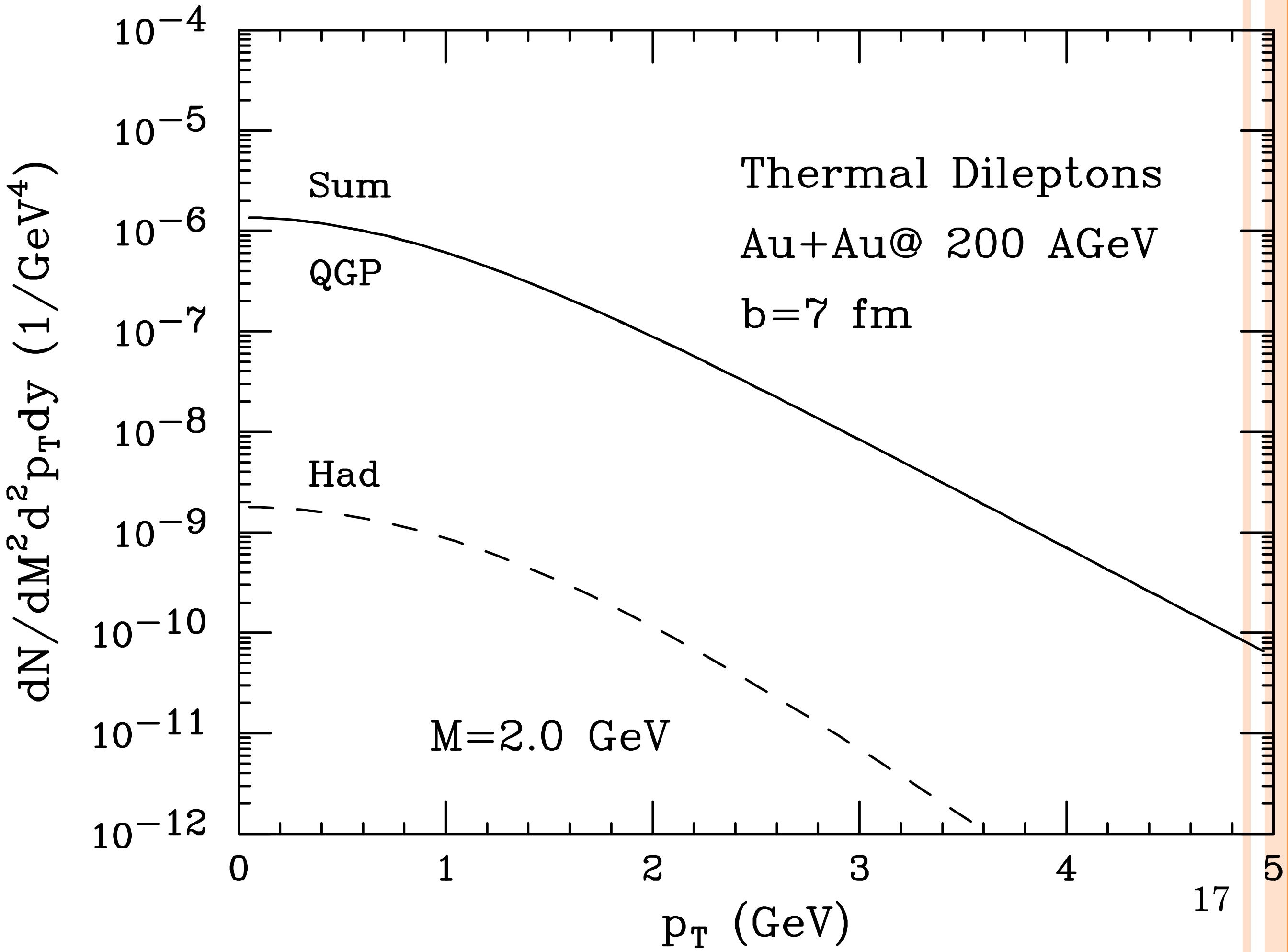
- Photons from the hadronic phase track the pions at low p_T and the rho's at higher p_T
- At high p_T, photons from QGP have small v_2: early times
- Hadronic photons dominate the spectrum at low (< 0.5 GeV) p_T
- Hydro evolution: ideal AZHYDRO

Heinz, Chatterjee, Frodermann, Gale, Srivastava, NPA (2007)

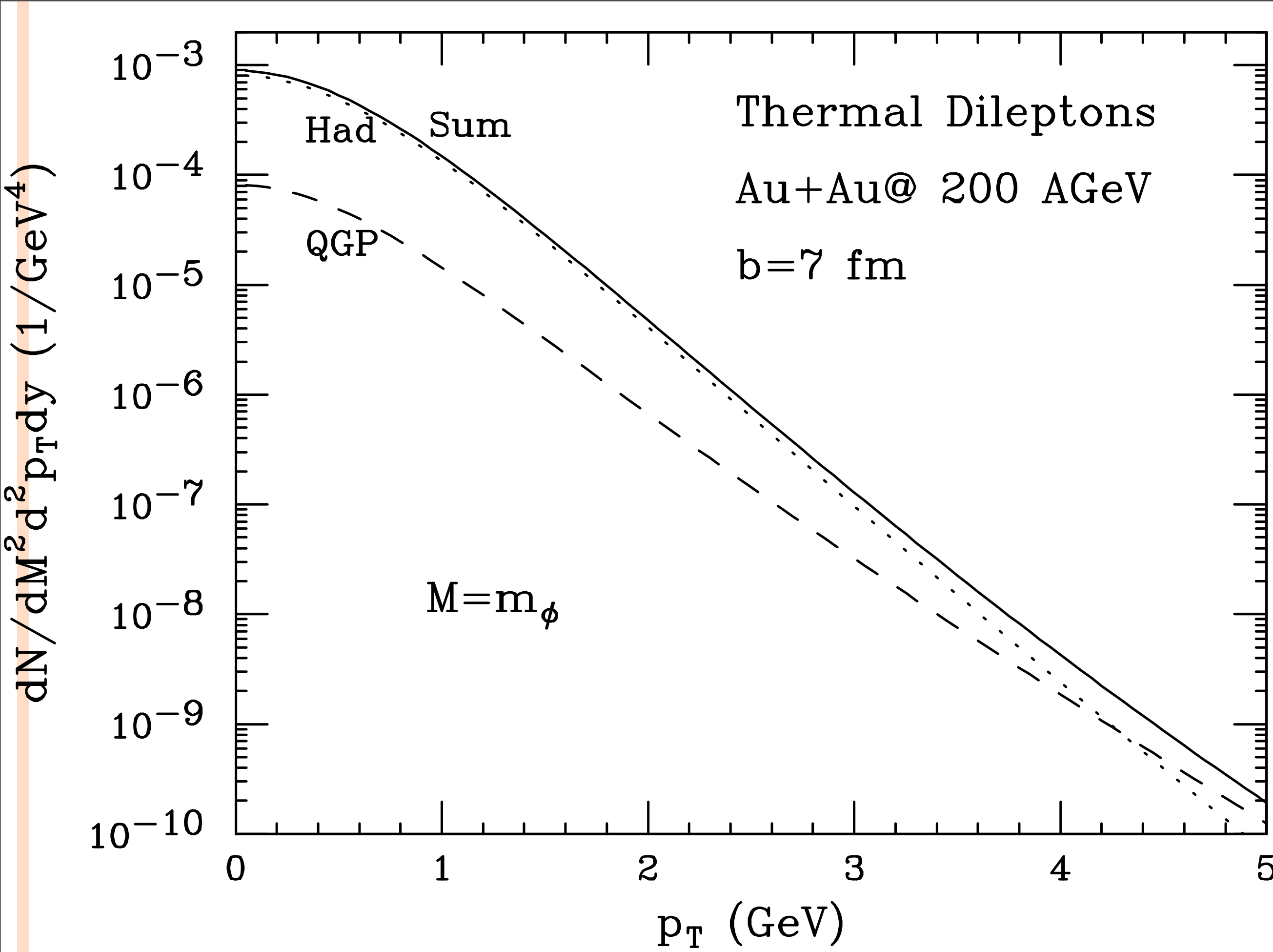
Elliptic flow of thermal dileptons

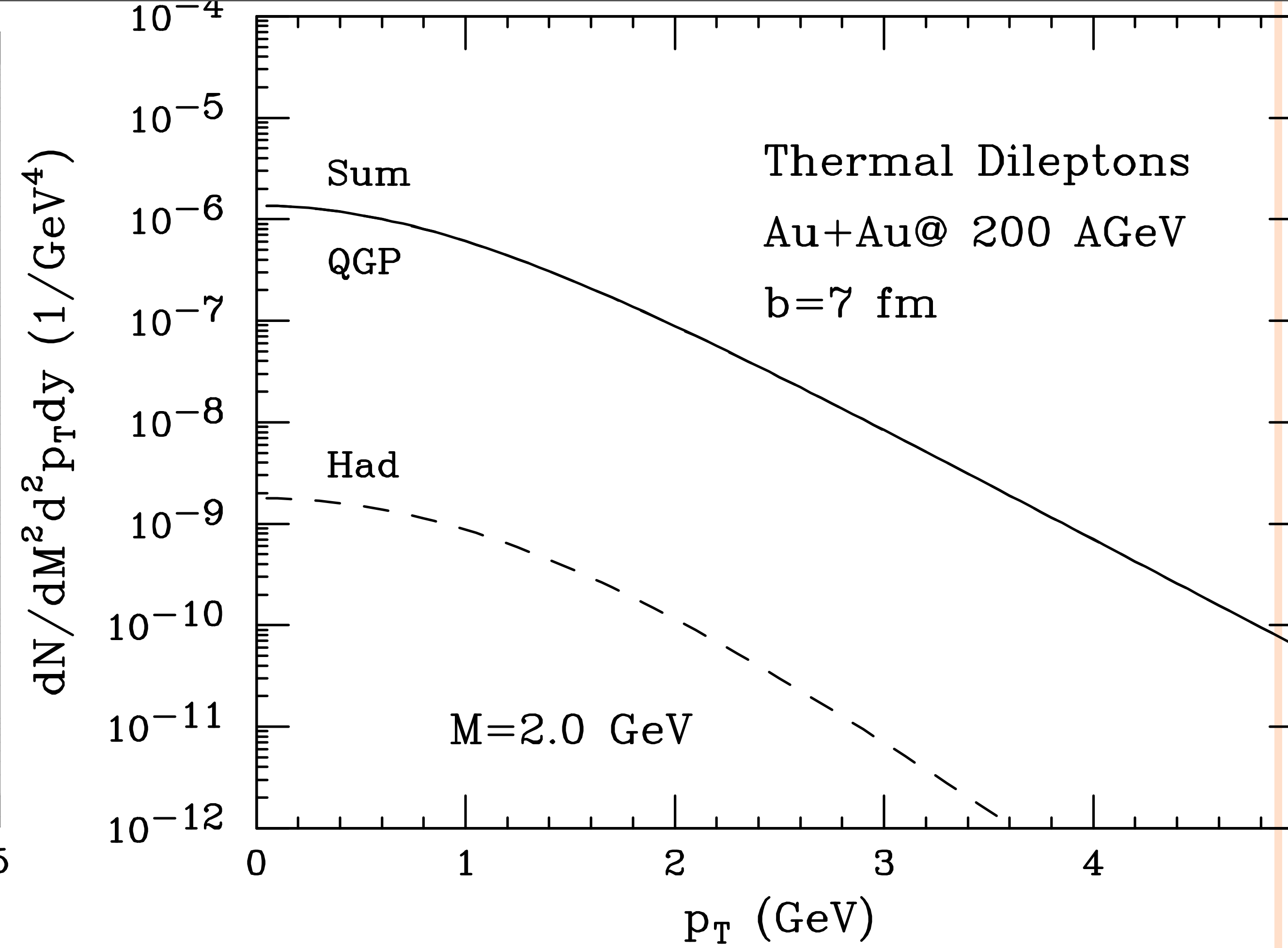
$$v_2(M, p_T, b) = \frac{\int d\phi \cos(2\phi) \frac{dN_{\ell\ell}}{dM^2 dy\, p_T dp_T d\phi}}{\int d\phi \frac{dN_{\ell\ell}}{dM^2 dy\, p_T dp_T d\phi}}$$



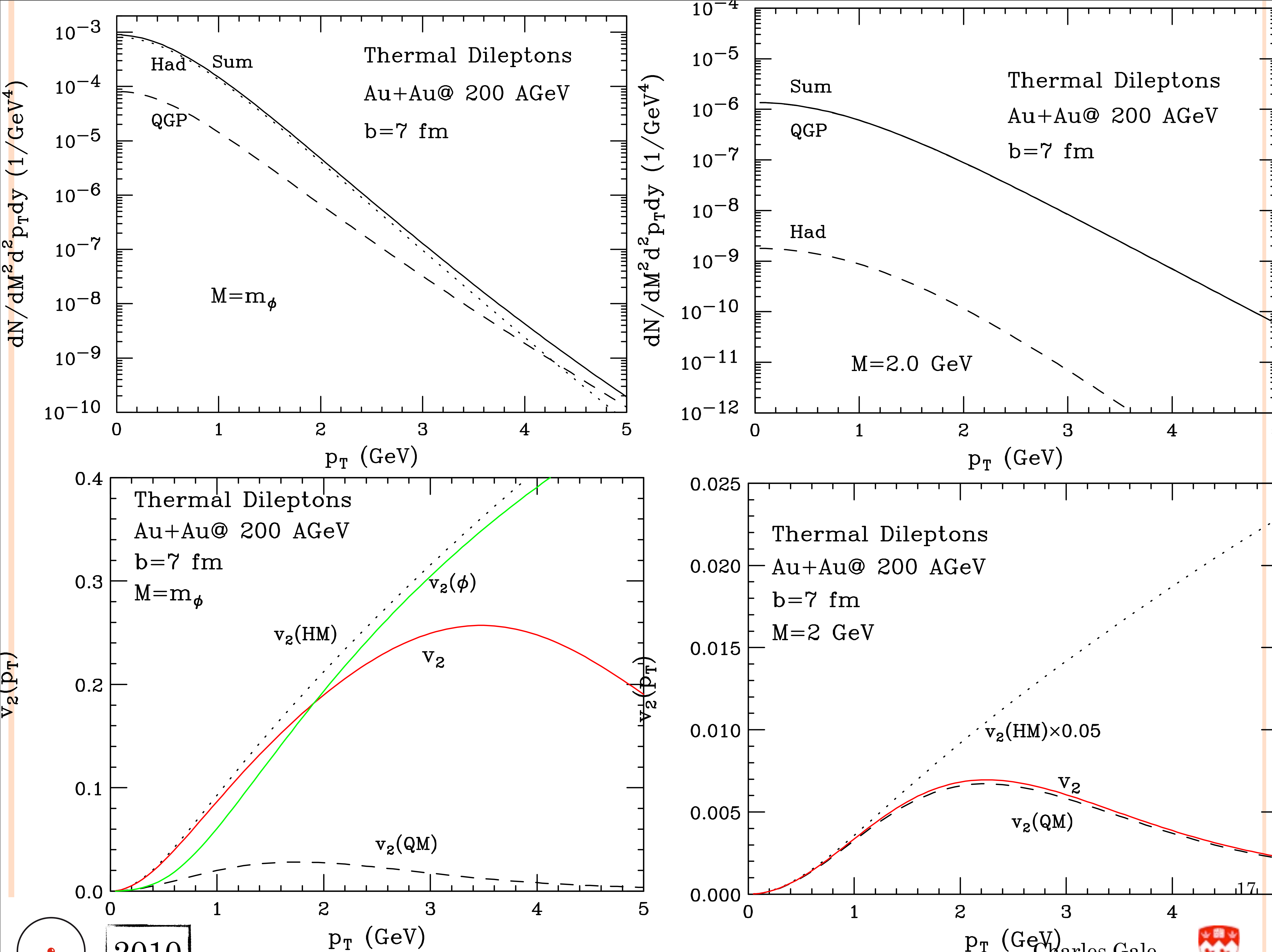


Chatterjee, Srivastava, Heinz, Gale PRC (2007)





Chatterjee, Srivastava, Heinz, Gale PRC (2007)



2010

Chatterjee, Srivastava, Heinz, Gale PRC (2007)

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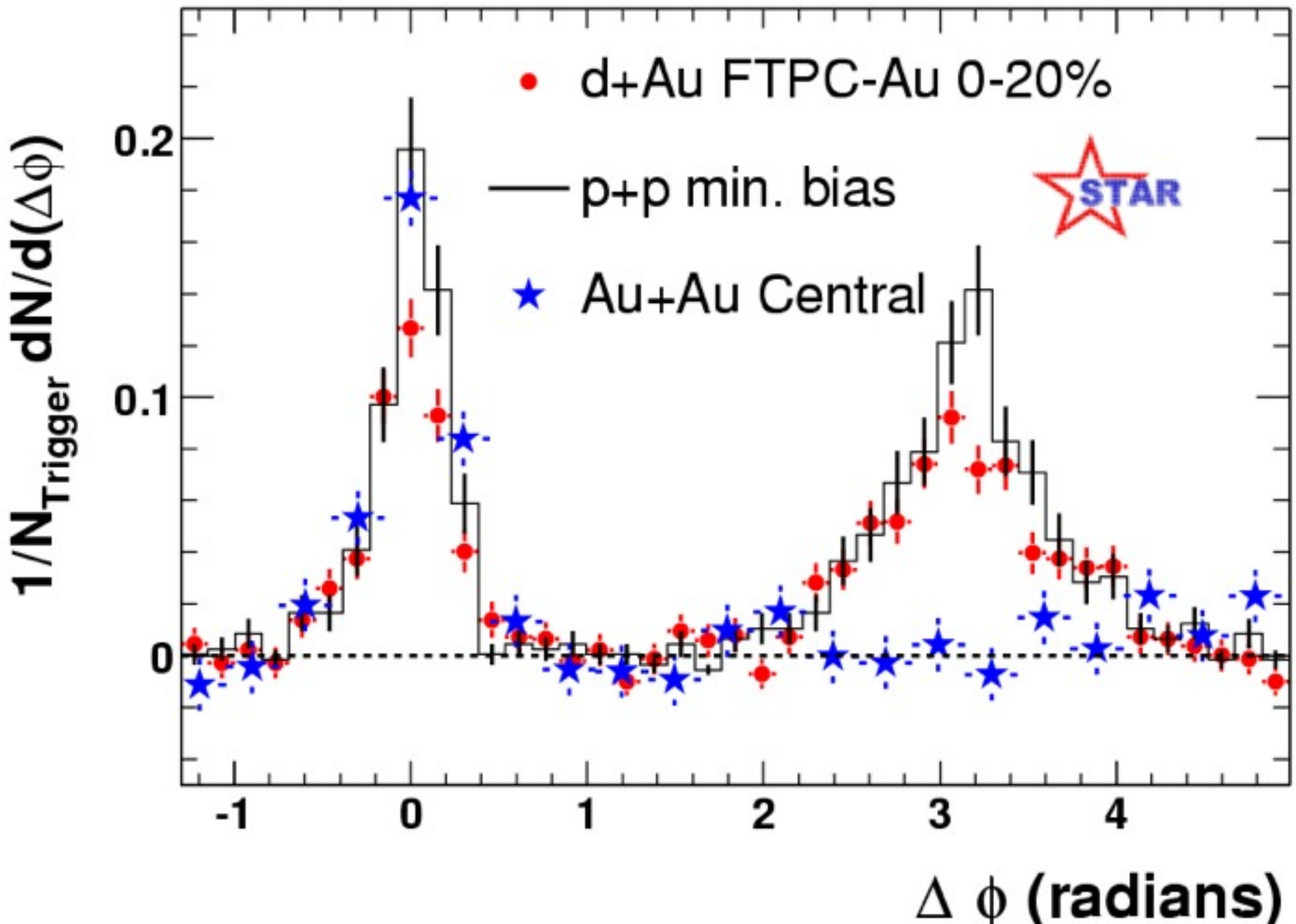
The hard sector @ RHIC: jet quenching

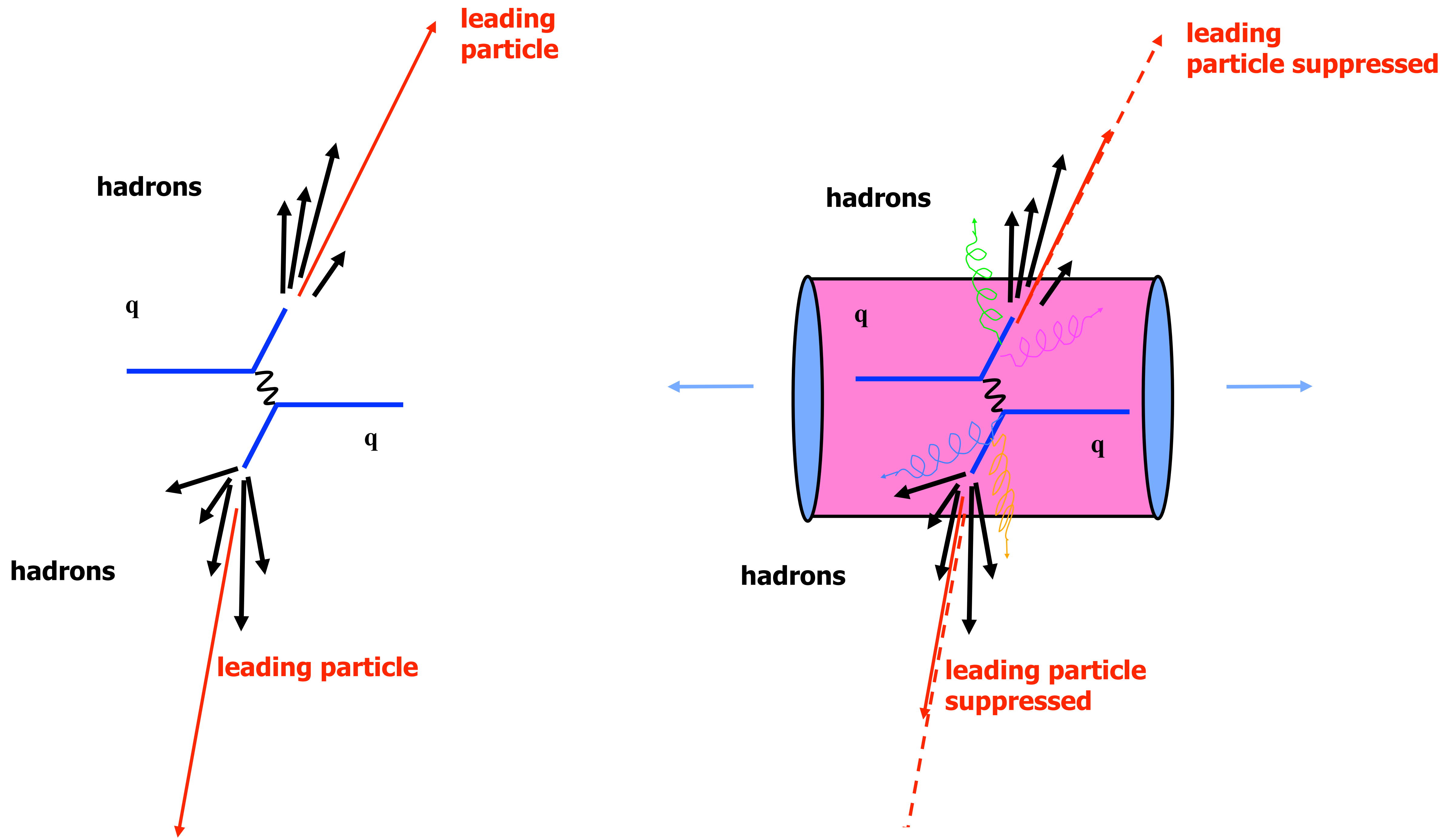


Azimuthal correlation:

– Shows the absence of “away-side” jet.

JET-QUENCHING = A DOOR OPEN TO TOMOGRAPHY

Jet-quenching = A door open to tomography



Dominant source of energy loss: medium-induced gluon Bremsstrahlung. However, see later…

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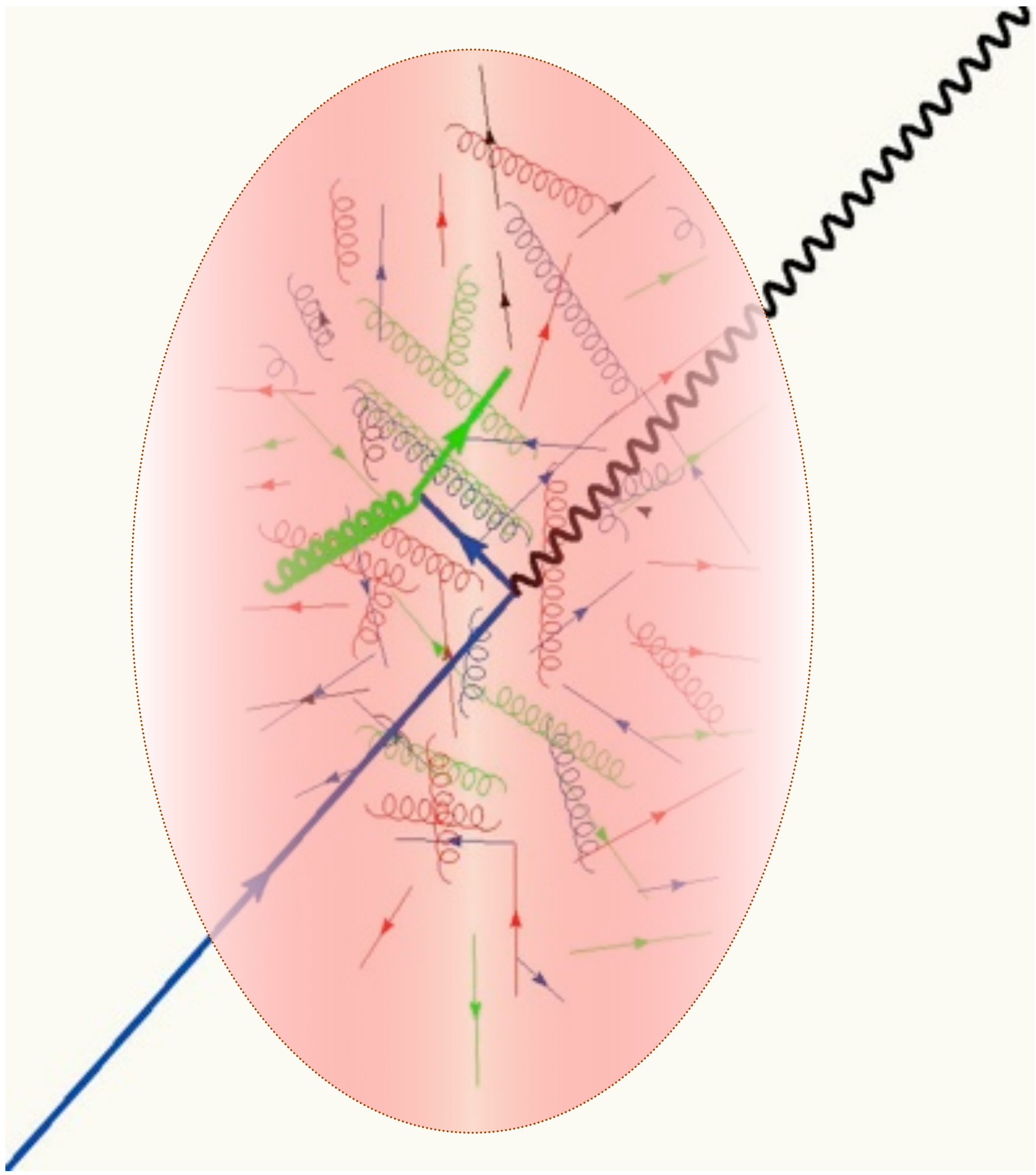
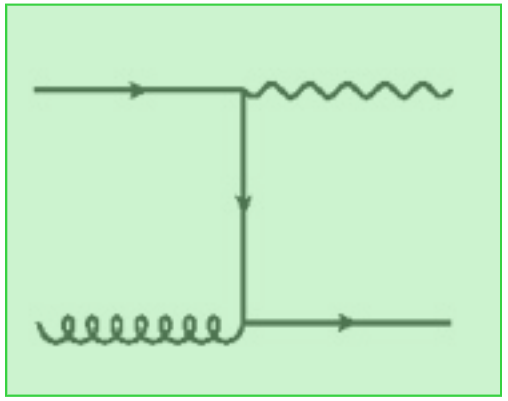
QUENCHING = JET-PLASMA INTERACTION. DOES THIS HAVE AN EM SIGNATURE?

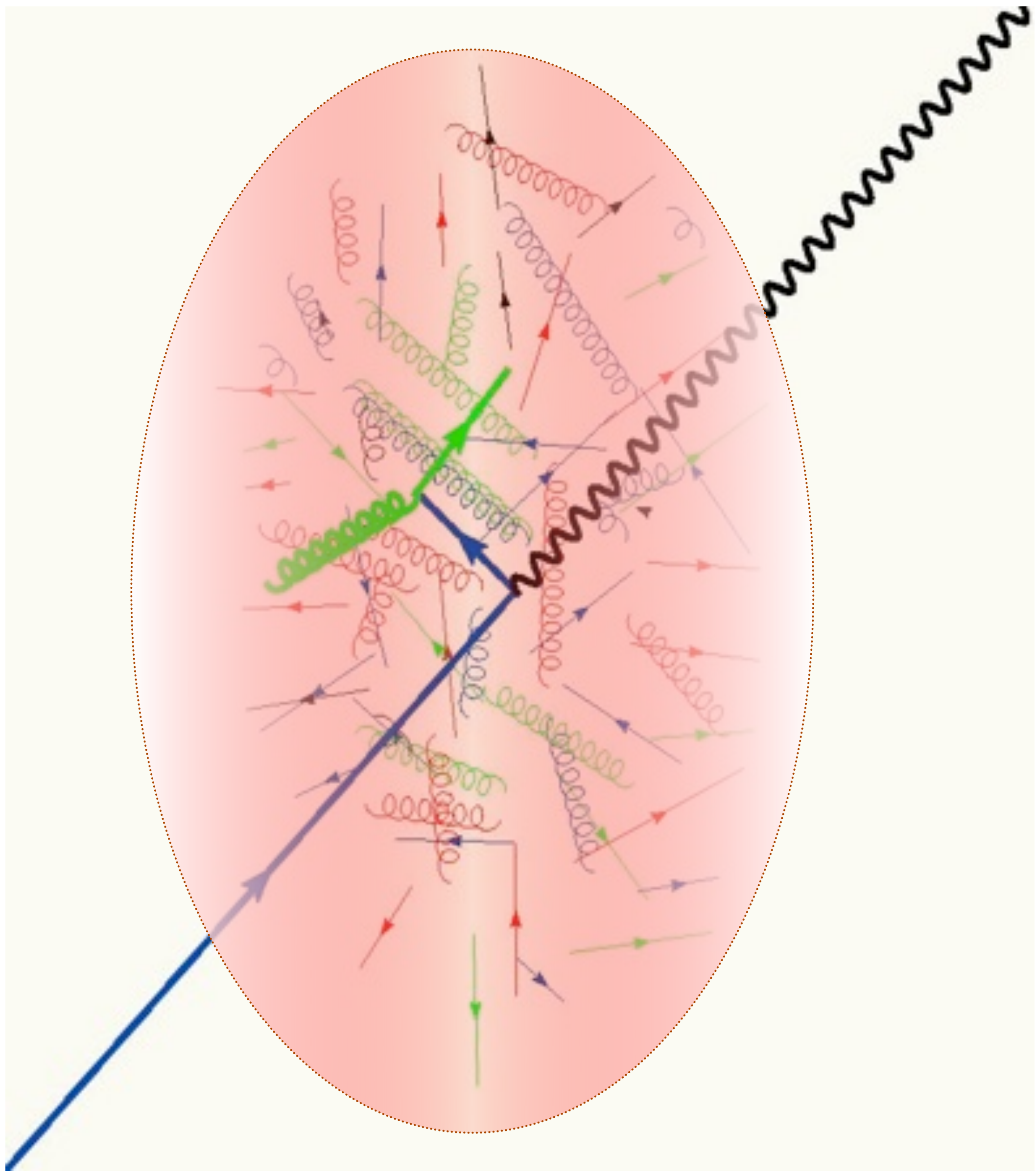


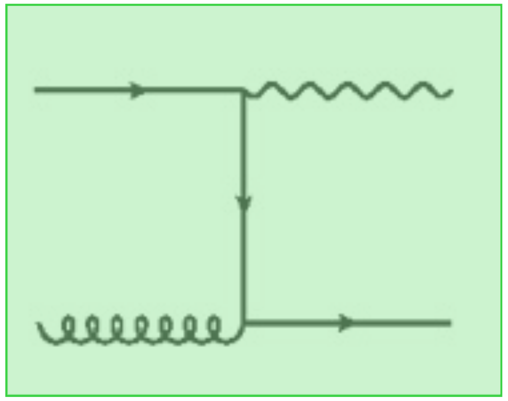


$$qg \to q\gamma$$

The plasma mediates a jet-photon conversion

Quenching = Jet-Plasma interaction. Does this have an EM signature?



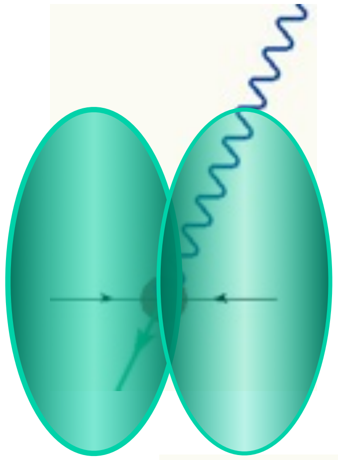


$qg \to q\gamma$

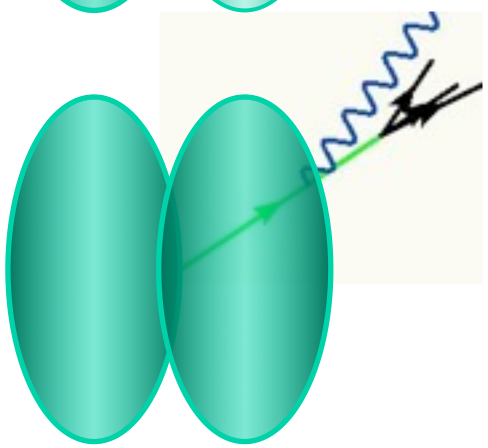
The plasma mediates a jet-photon conversion

Fries, Mueller & Srivastava, PRL **90**, 132301 (2003)

Sources of photons:



Hard direct photons. pQCD with shadowing
Non-thermal



Fragmentation photons. pQCD with shadowing
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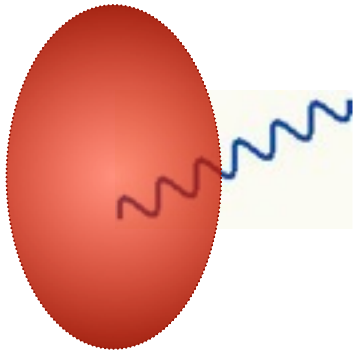
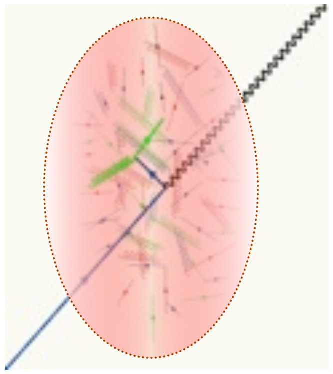
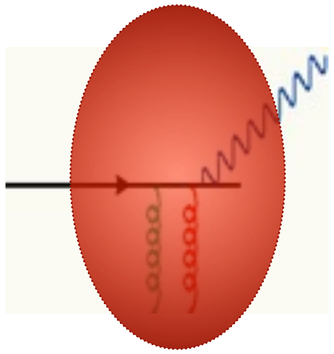


Thermal photons
Thermal



Jet-plasma photons
Thermal



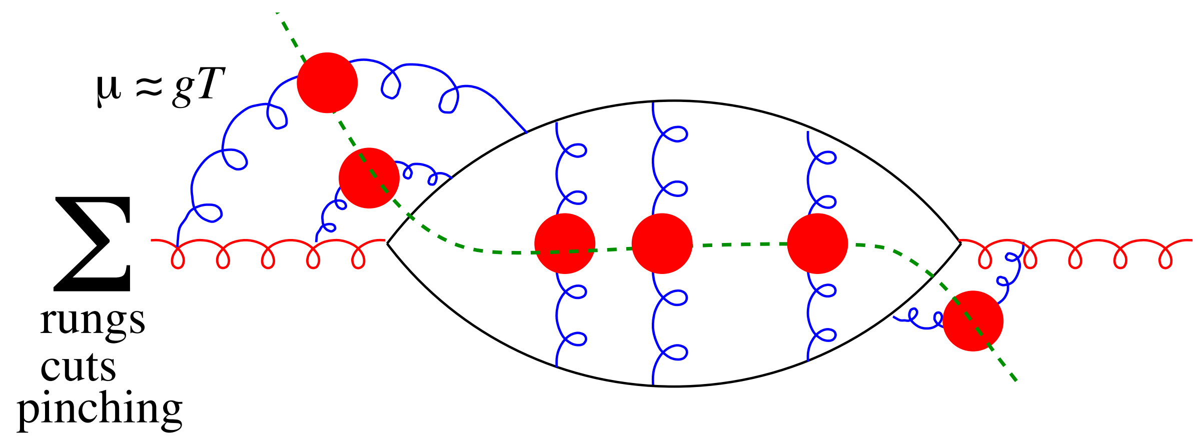
Jet in-medium bremsstrahlung
Thermal

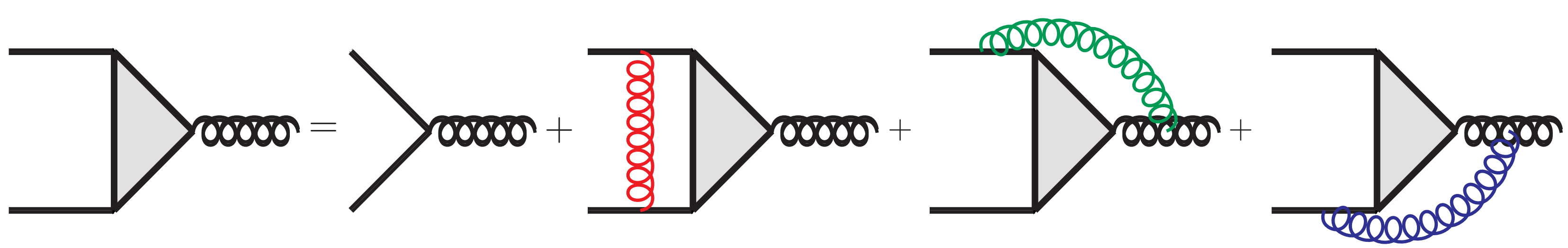
A THEORETICAL CONNECTION BETWEEN JET ENERGY LOSS AND THE ELECTROMAGNETIC EMISSIVITY

Use the approach of Arnold, Moore, and Yaffe:

JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)

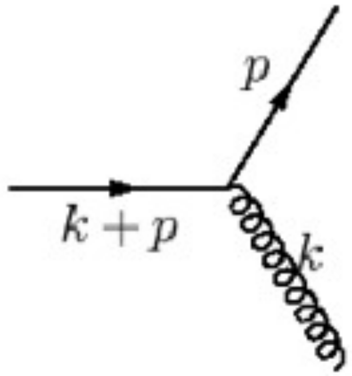
- Incorporates LPM
- Complete leading order in α_S
- Inclusive treatment of collinear enhancement, photon and gluon emission





Can be expressed in terms of the solution to a linear integral equation

E loss/gain: some systematics



$$= \Gamma^{q}_{qg}(k+p,k)$$

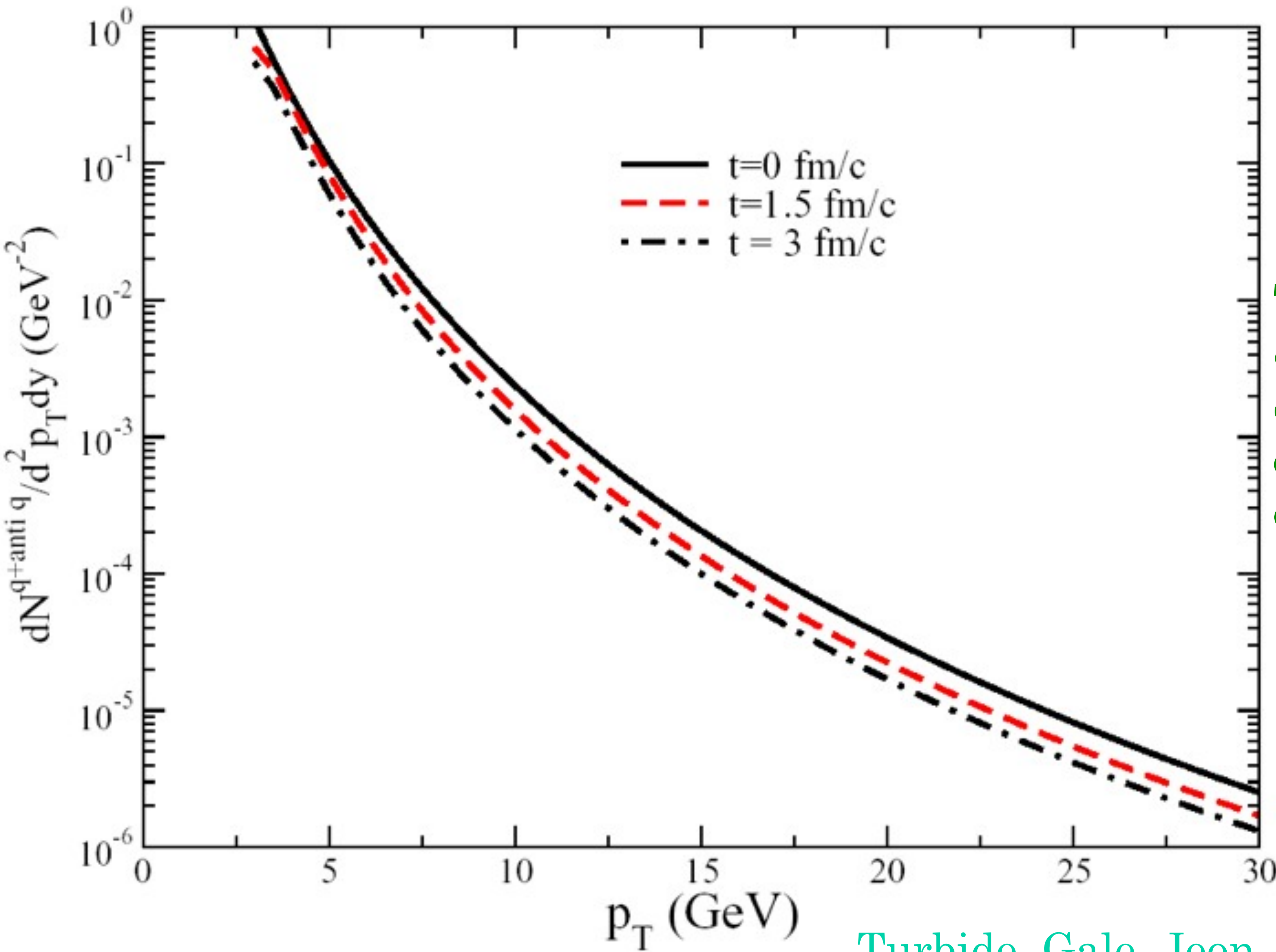
- Includes E gain
- Evolves the whole distribution function

$$\frac{dP_q(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^{q}_{qg}(p+k,k)}{dkdt} - P_q(p)\frac{d\Gamma^{q}_{qg}(p,k)}{dkdt} + 2P_g(p+k)\frac{d\Gamma^{g}_{q\bar{q}}(p+k,k)}{dkdt}$$

$$\frac{dP_g(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^{q}_{qg}(p+k,p)}{dkdt} + P_g(p+k)\frac{d\Gamma^{g}_{gg}(p+k,k)}{dkdt} - P_g(p)\left(\frac{d\Gamma^{g}_{q\bar{q}}(p,k)}{dkdt} + \frac{d\Gamma^{g}_{gg}}{dkdt}\Theta(2k-p)\right)$$

Coupled master equations

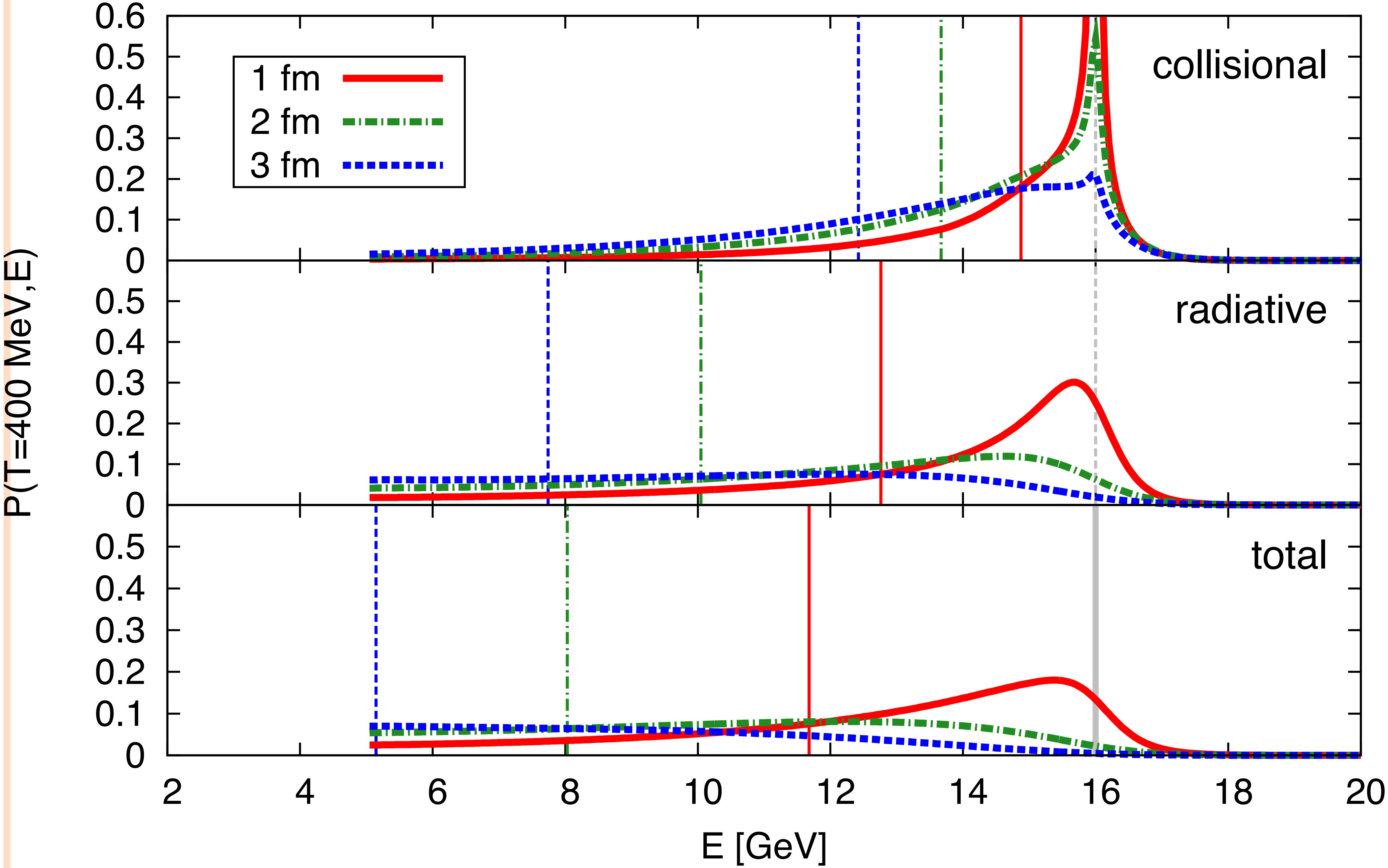
Time-evolution of a parton distribution



The entire distribution is evolved by the collision Kernel(s) of the FP equation

Turbide, Gale, Jeon, and Moore, PRC (2004)

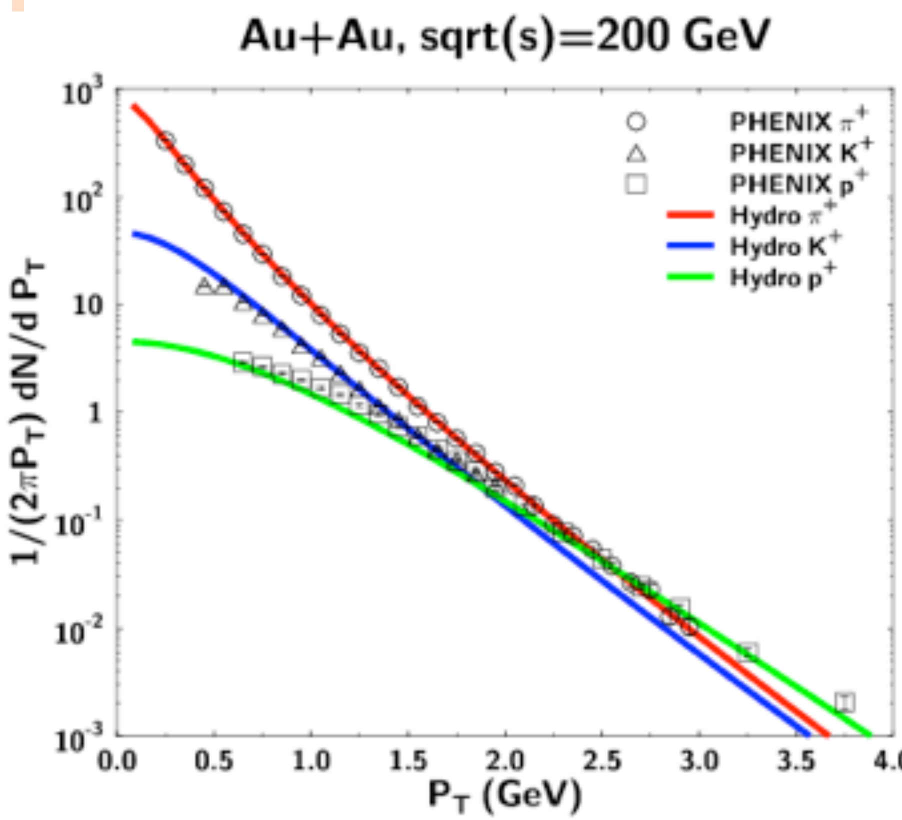
Radiative vs. Collisional Eloss

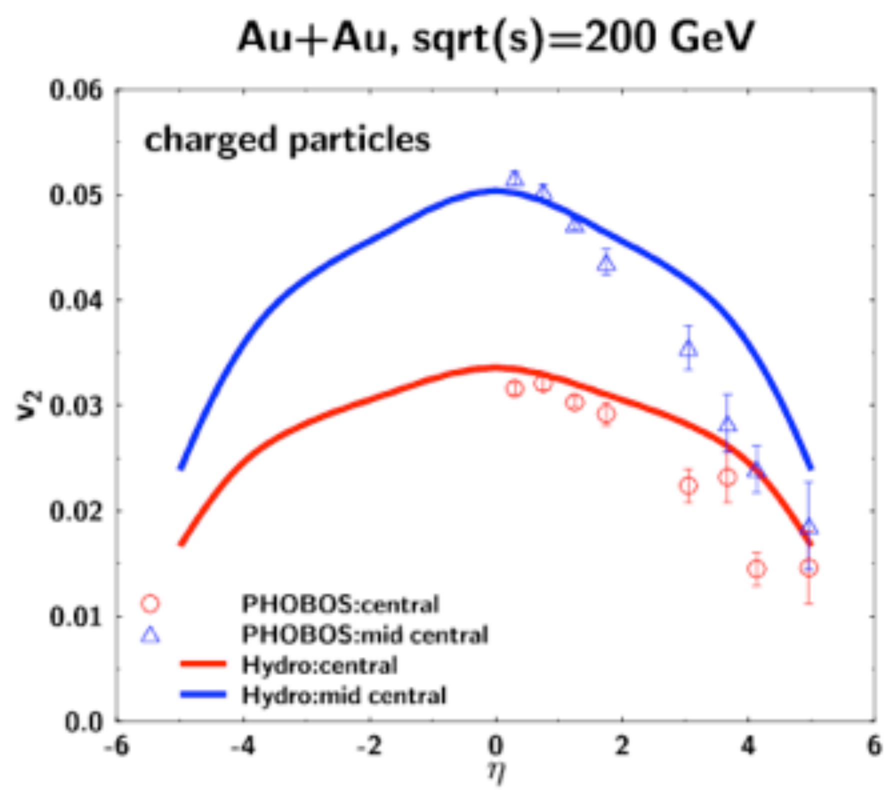


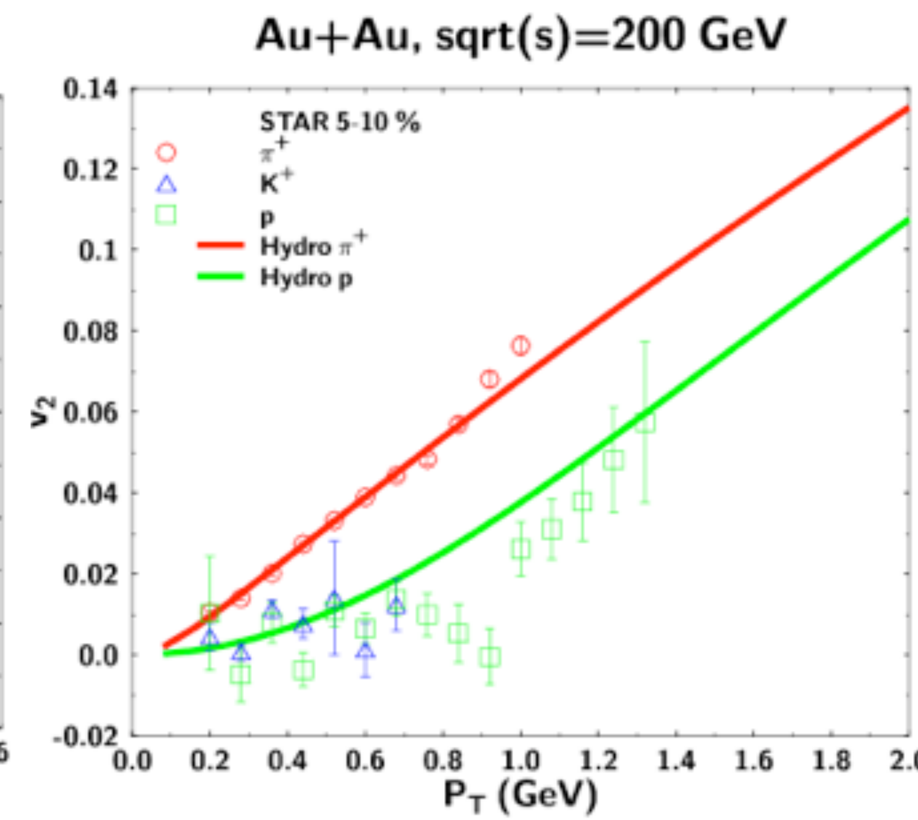
G. Qin, J. Ruppert, C. Gale, S. Jeon, G. D. Moore, M. G. Mustafa, PRL (2008)

Schenke, Gale, and Qin, PRC (2009)

3D Hydro: the dynamical background

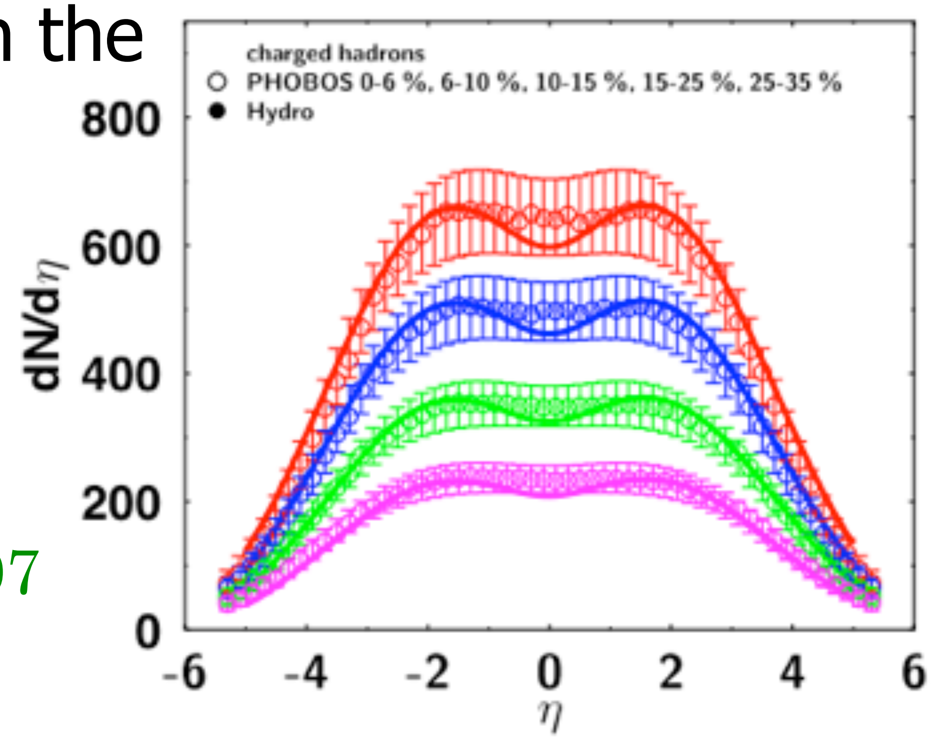


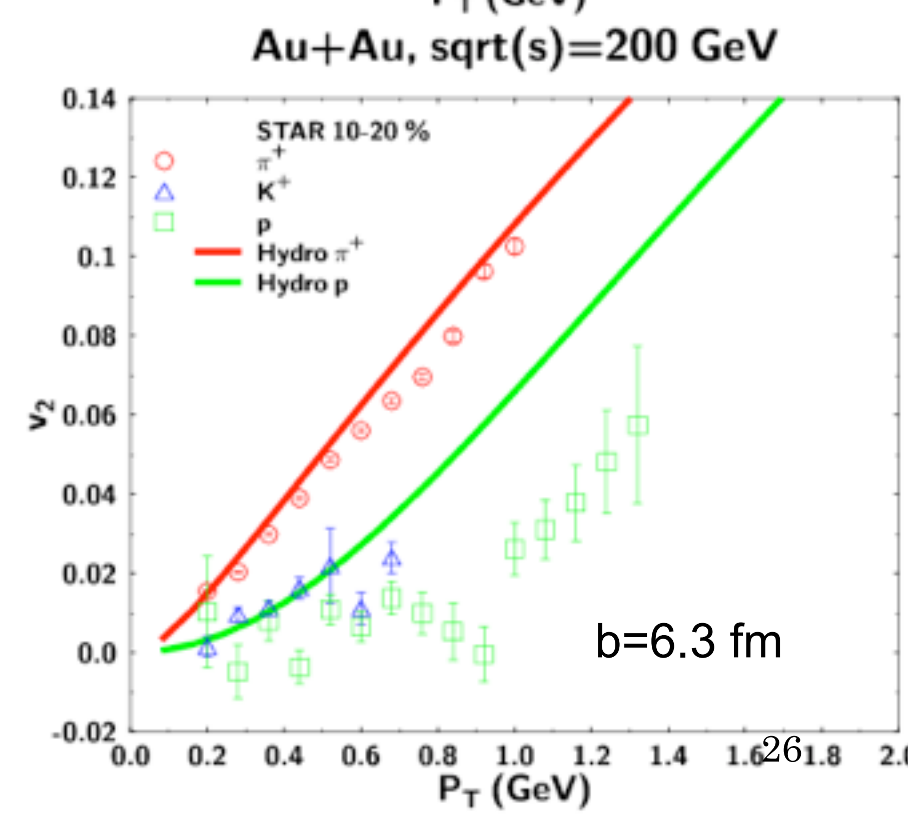




- Aims to address data in the soft sector with one consistent approach

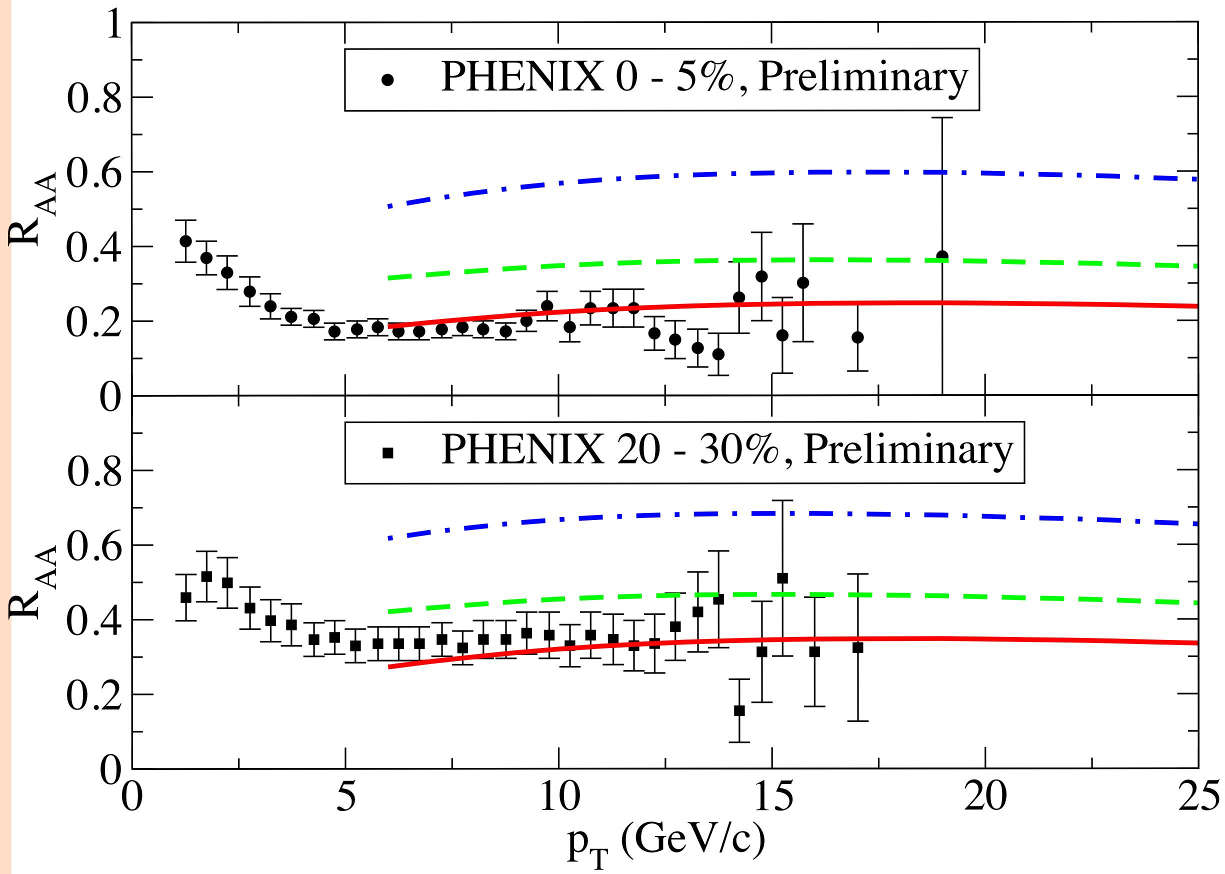
Nonaka & Bass PRC 2007





Baseline: Hadronic data & pp photon data

$$R_{AA}(p_T) = \frac{(Yield\ per\ collision)}{< N_{coll} > (Yield\ per\ pp\ collision)} = \frac{d^2 N^{A+A} / dp_T d\eta}{< N_{coll} > (d^2\sigma^{pp} / d\eta) / \sigma^{p+p}_{inelastic}}$$

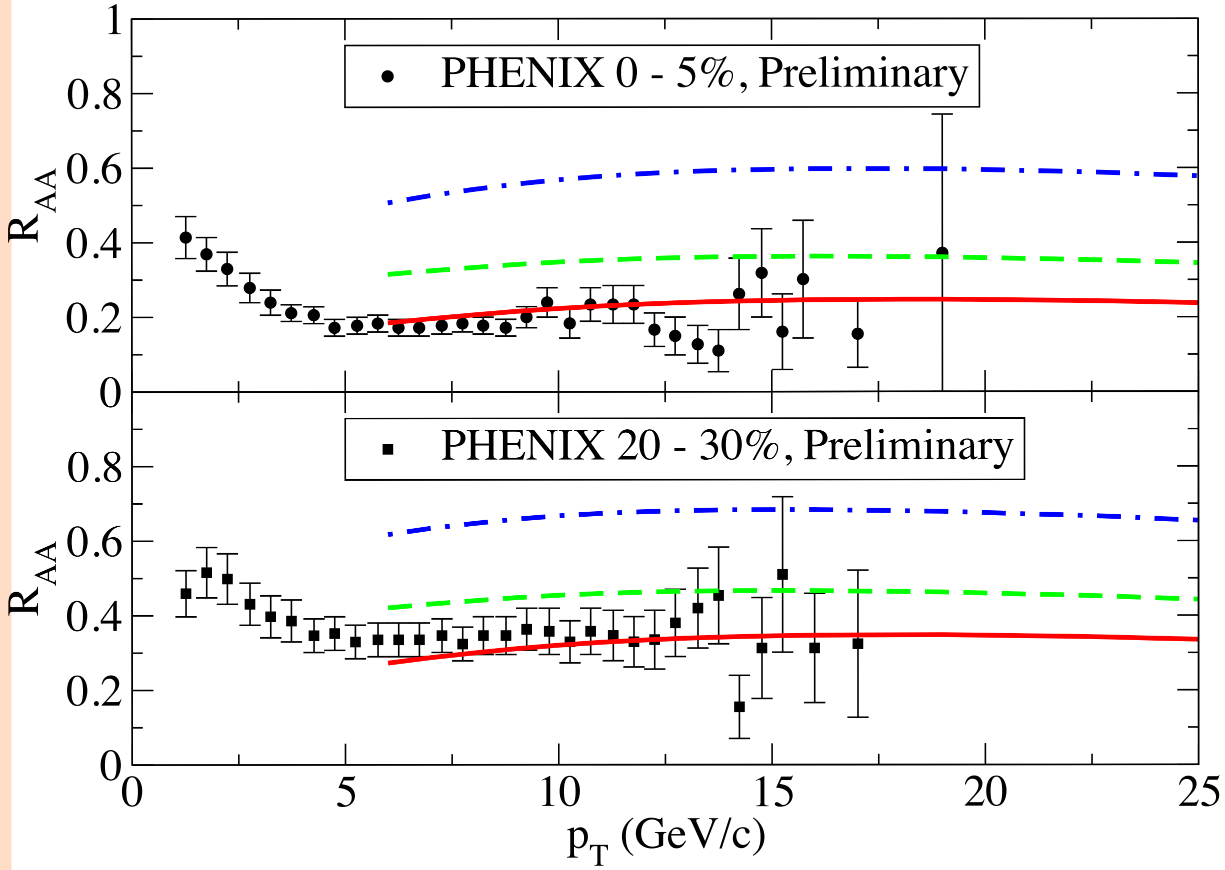


$\alpha_s = 0.27$

Qin et al.,PRC (2009)

Baseline: Hadronic data & pp photon data

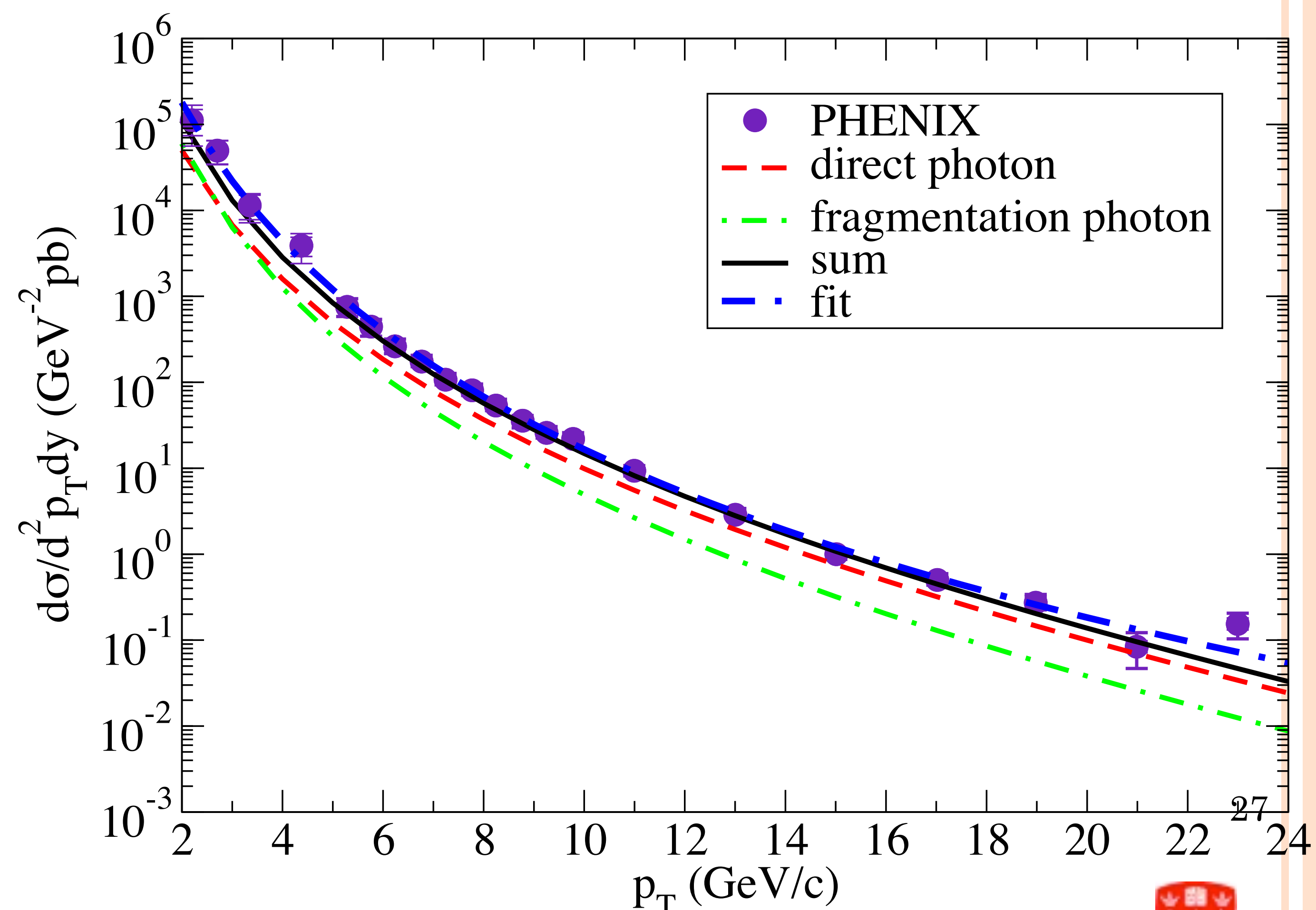
$$R_{AA}(p_T) = \frac{(Yield\ per\ collision)}{< N_{coll} > (Yield\ per\ pp\ collision)} = \frac{d^2 N^{A+A} / dp_T d\eta}{< N_{coll} > (d^2\sigma^{pp} / d\eta) / \sigma^{p+p}_{inelastic}}$$



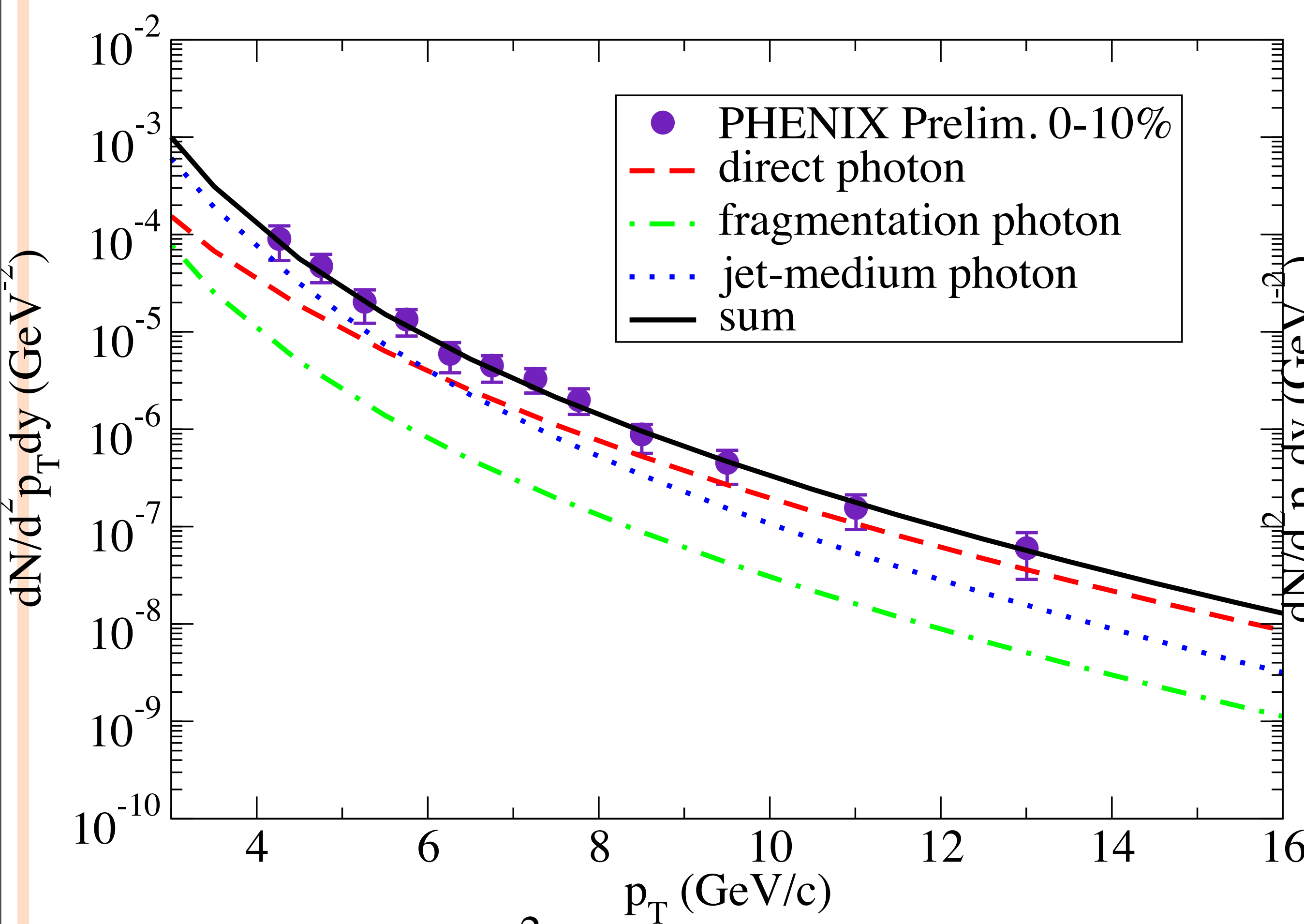
Qin et al.,PRC (2009)

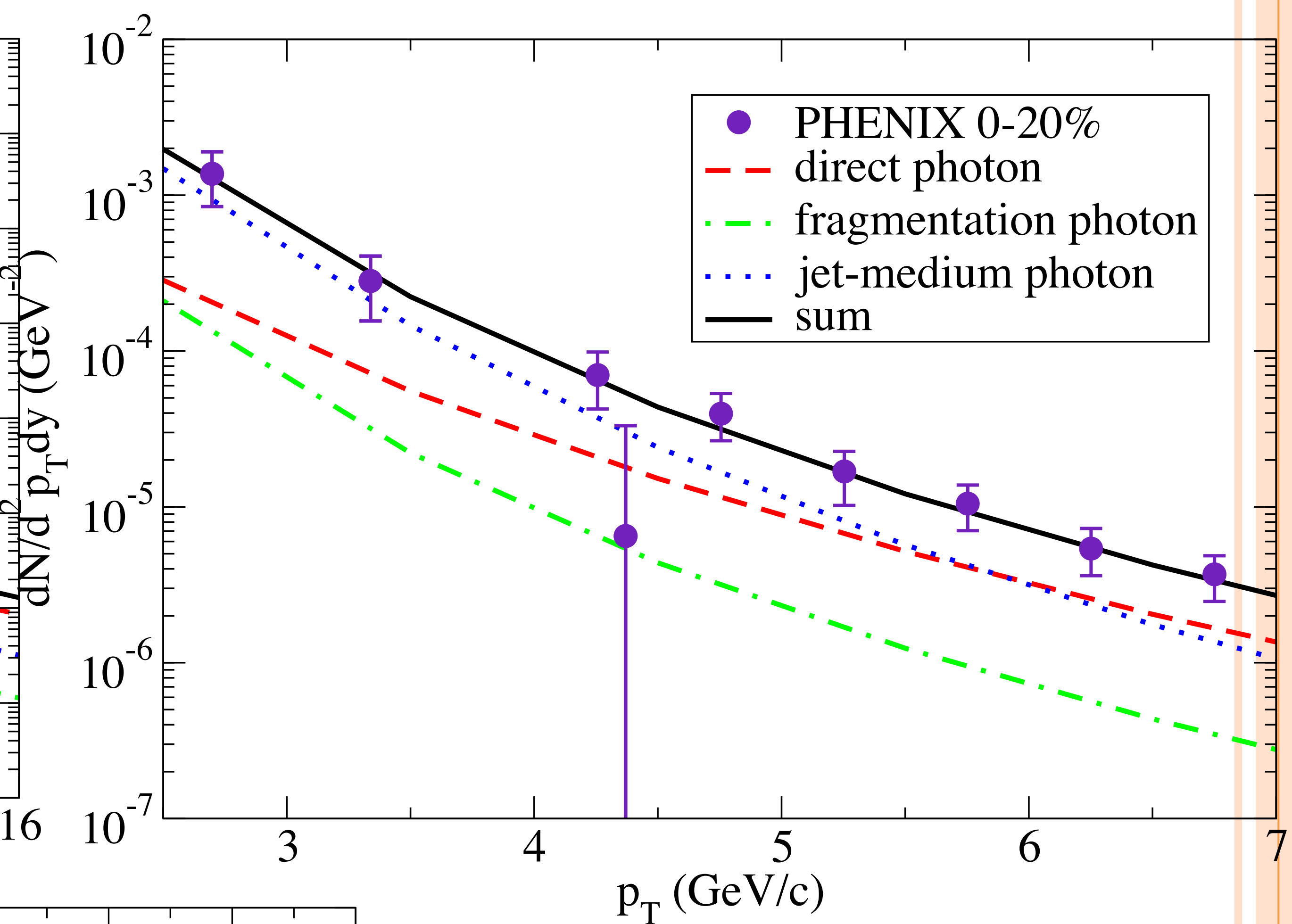
$$\alpha_s = 0.27$$

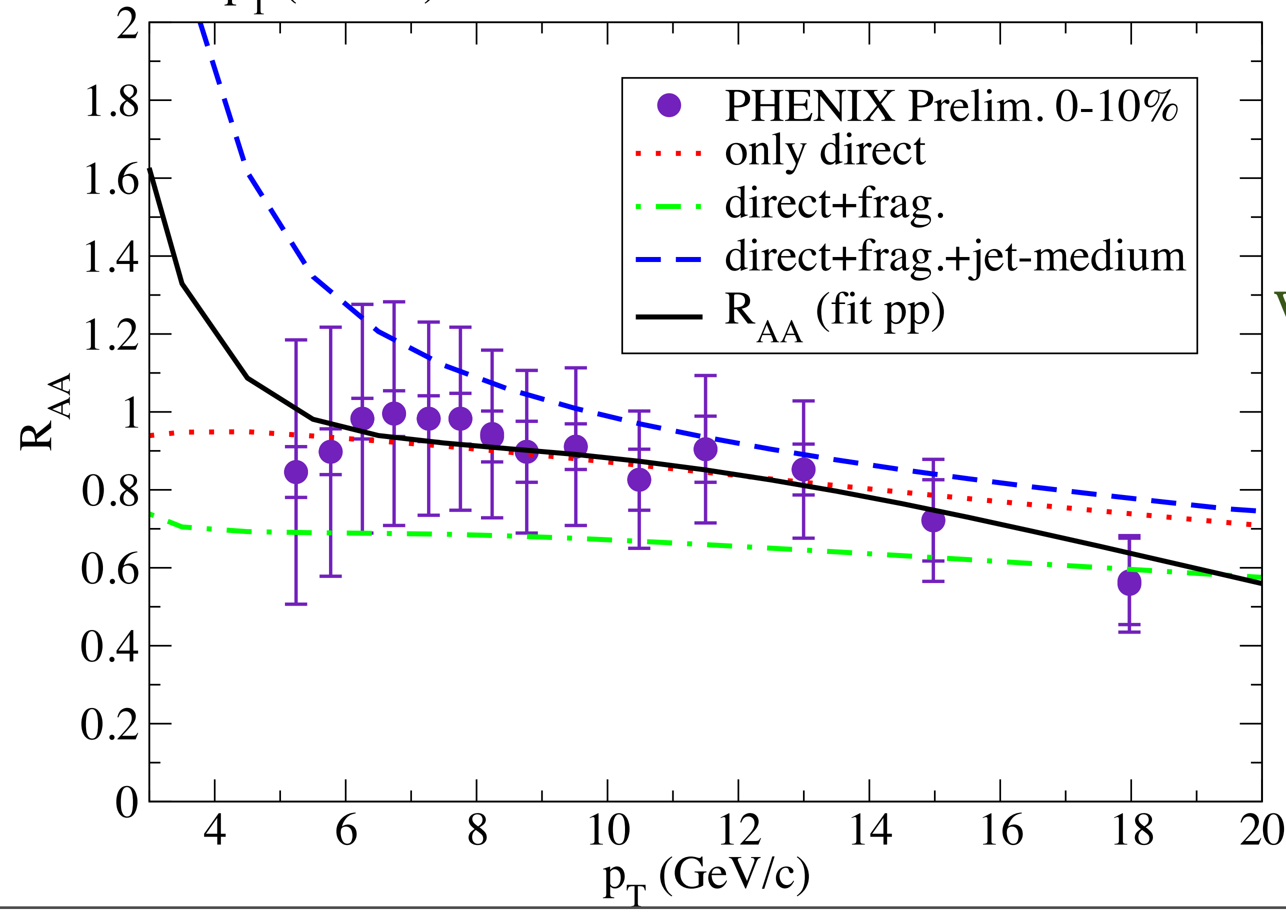
Photons: NLO QCD



AA PHOTON SPECTRA



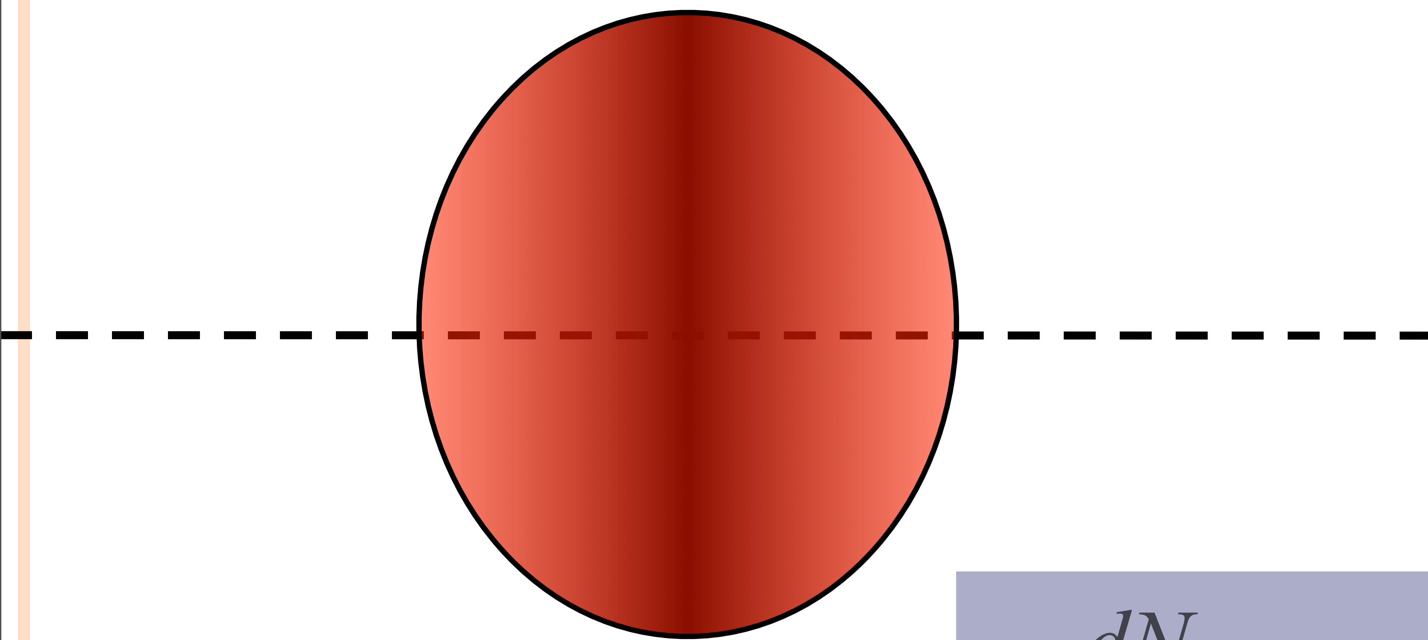




- Photon data consistent with hadrons (same hydro)
- pp NLO sensitivity
- R_{AA}: potential to discriminate

Qin et al., PRC (2009)

Beyond one-body data: Flow and correlations

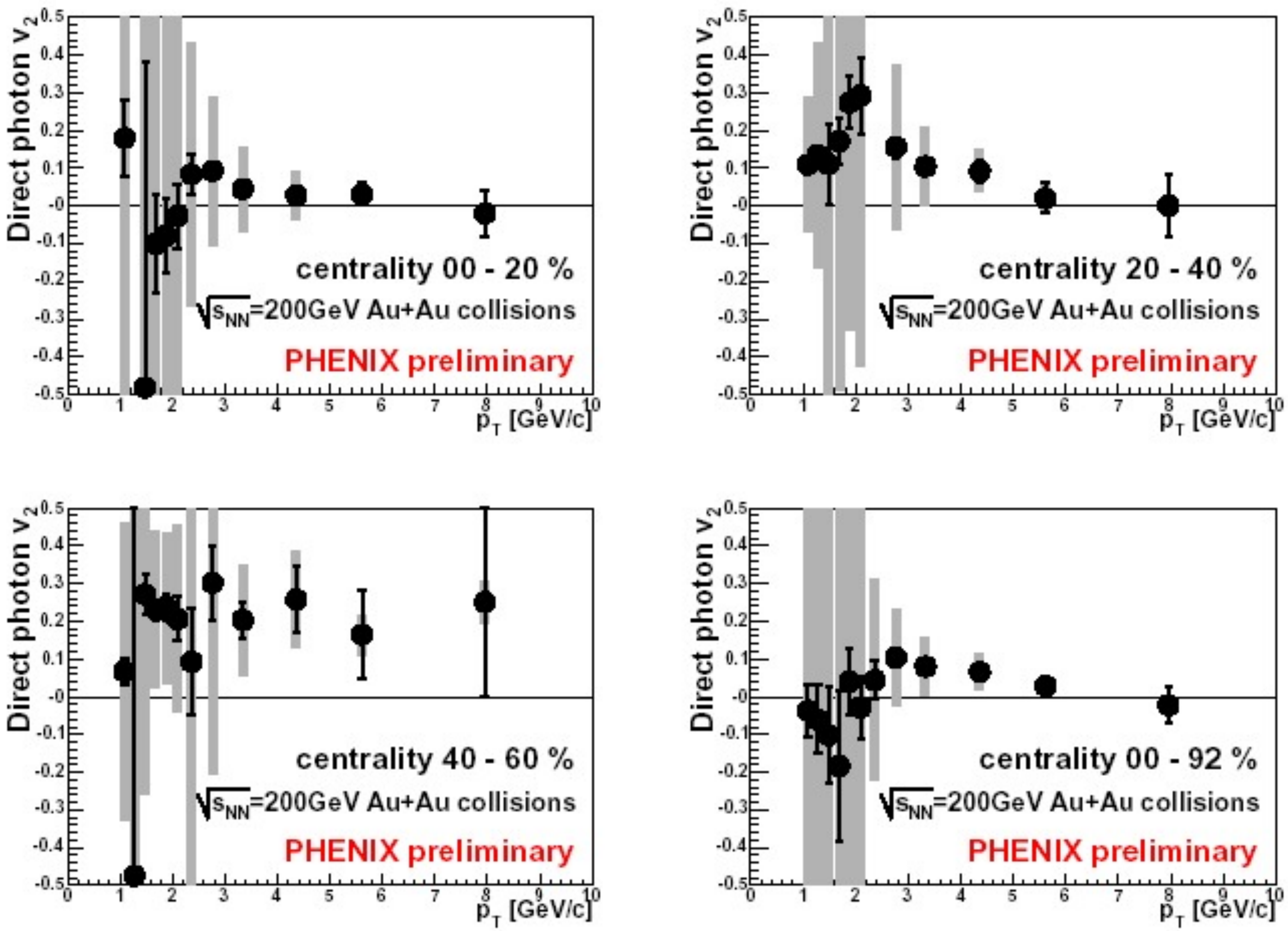


$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi\, p_T dp_T}\left[1 + \sum_n 2v_n \cos(n\phi)\right]$$

- Soft photons will go with the flow
- Jet-plasma photons will come out of the hadron-blind region. "Optical" v2 < 0

Idea & high p_T: Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.*, PRL (2006)
All p_T: Turbide *et al.*, PRC (2008)

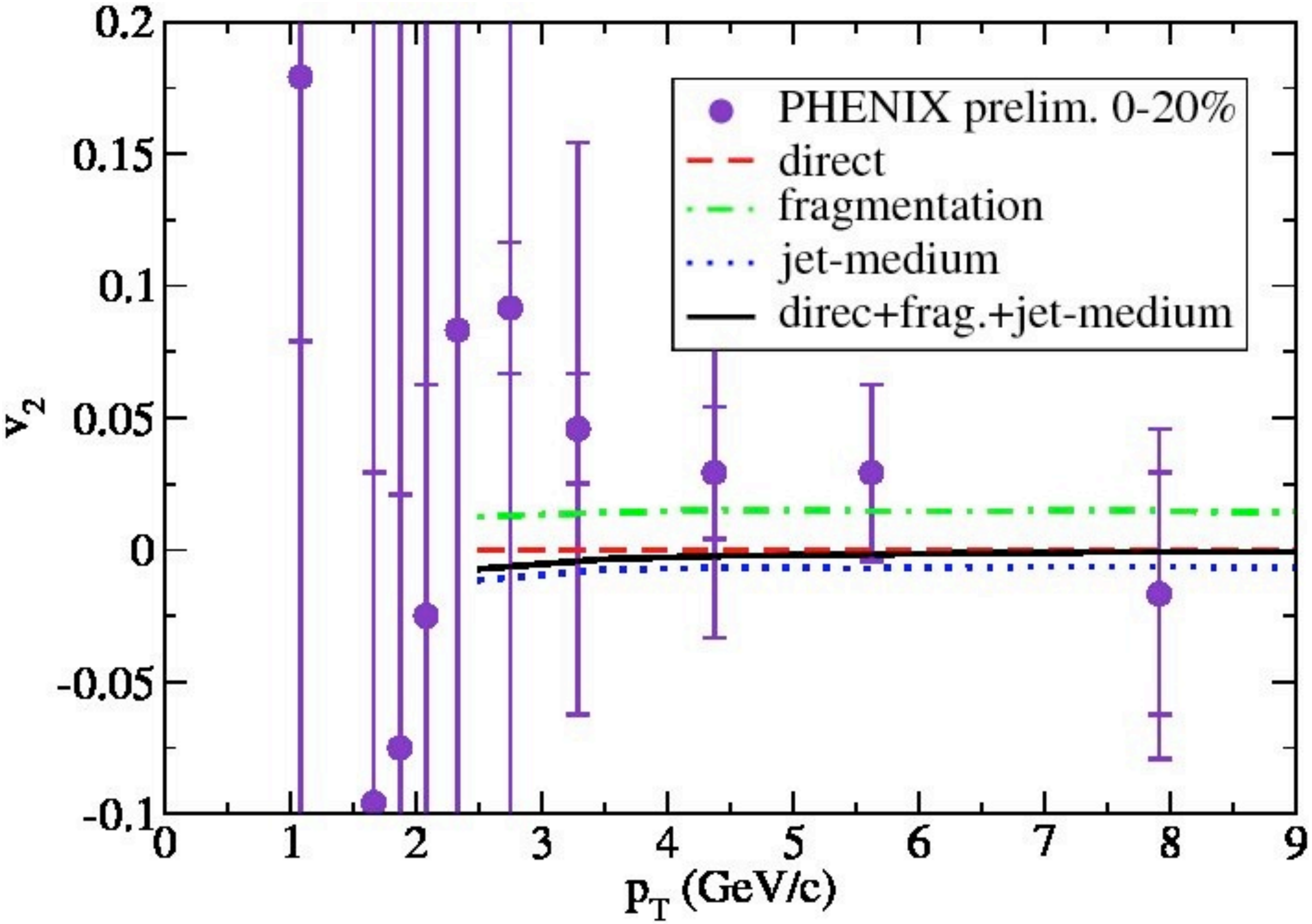
Data: Results from PHENIX



T. Sakaguchi
RHIC/AGS 07

v2: small! Consistent with zero (within errors)

Data: Results from PHENIX



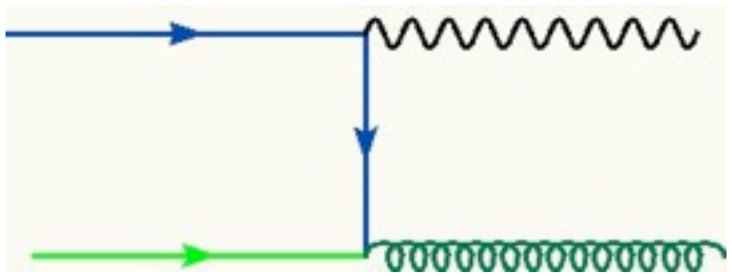
T. Sakaguchi
RHIC/AGS 07

Qin et al., PRC (2009)

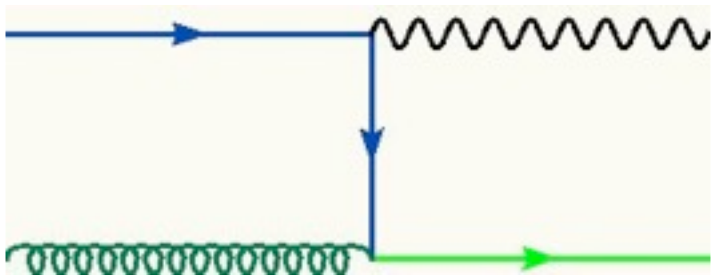
v2: small! Consistent with zero (within errors)

Beyond one-body data: Photon-tagged jets and photon-hadron correlations

At LO the photon is strongly correlated with the away-side jet



LO



X.-N. Wang, Huang, Sarcevic., Phys. Rev. Lett. 77, 231 - 234 (1996)

Proposed advantage:

At LO:

How does it look
in a full calculation?

✓Calibrated probe of the QGP.

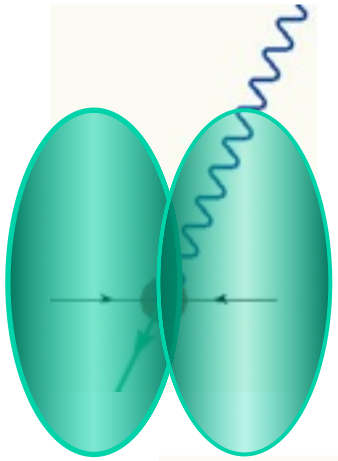
✓In γ-jet azimuthal correlations

$E_\gamma = E_{parent\ \ parton}$

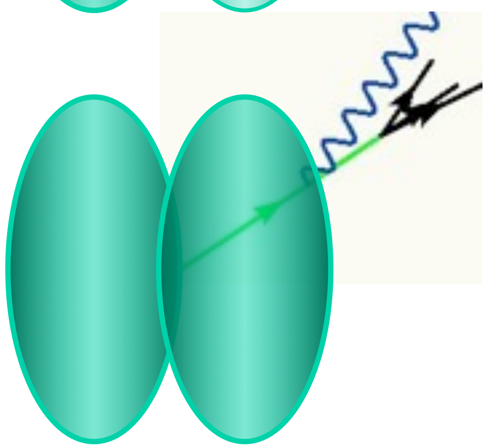
✓In h-jet azimuthal correlations

$E_{leading\ particle} \neq E_{parent\ \ parton}$

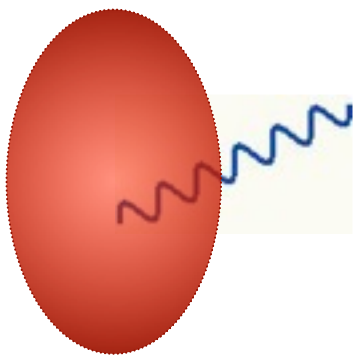
But, recall sources of photons:



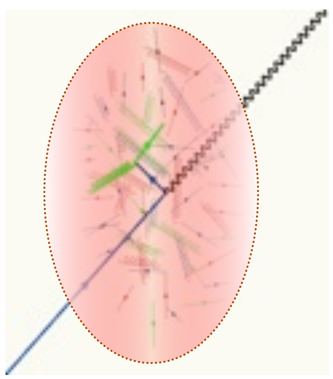
Hard direct photons. pQCD with shadowing
Non-thermal



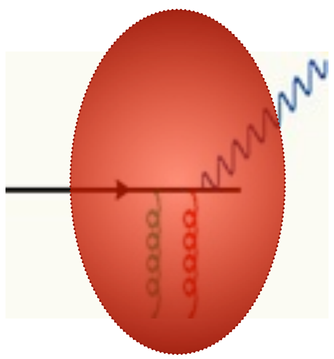
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal



Jet-plasma photons
Thermal



Jet in-medium bremmstrahlung
Thermal

Some definitions...

$$P(E_h \mid E_\gamma, \phi) = \frac{P(E_h, E_\gamma, \phi)}{P(E_\gamma, \phi)}$$

The hadron spectrum, given a trigger photon (yield-per-trigger)

$$P(E_h, E_\gamma, \phi) = dN(E_h, E_\gamma, \phi) / dE_h dE_\gamma d\phi$$

Joint probability for producing a back-to-back pair

$$P(E_j \mid E_\gamma, \phi) = \frac{P(E_j, E_\gamma, \phi)}{P(E_\gamma, \phi)}$$

Initial distribution of away-side jet before evolution in the medium

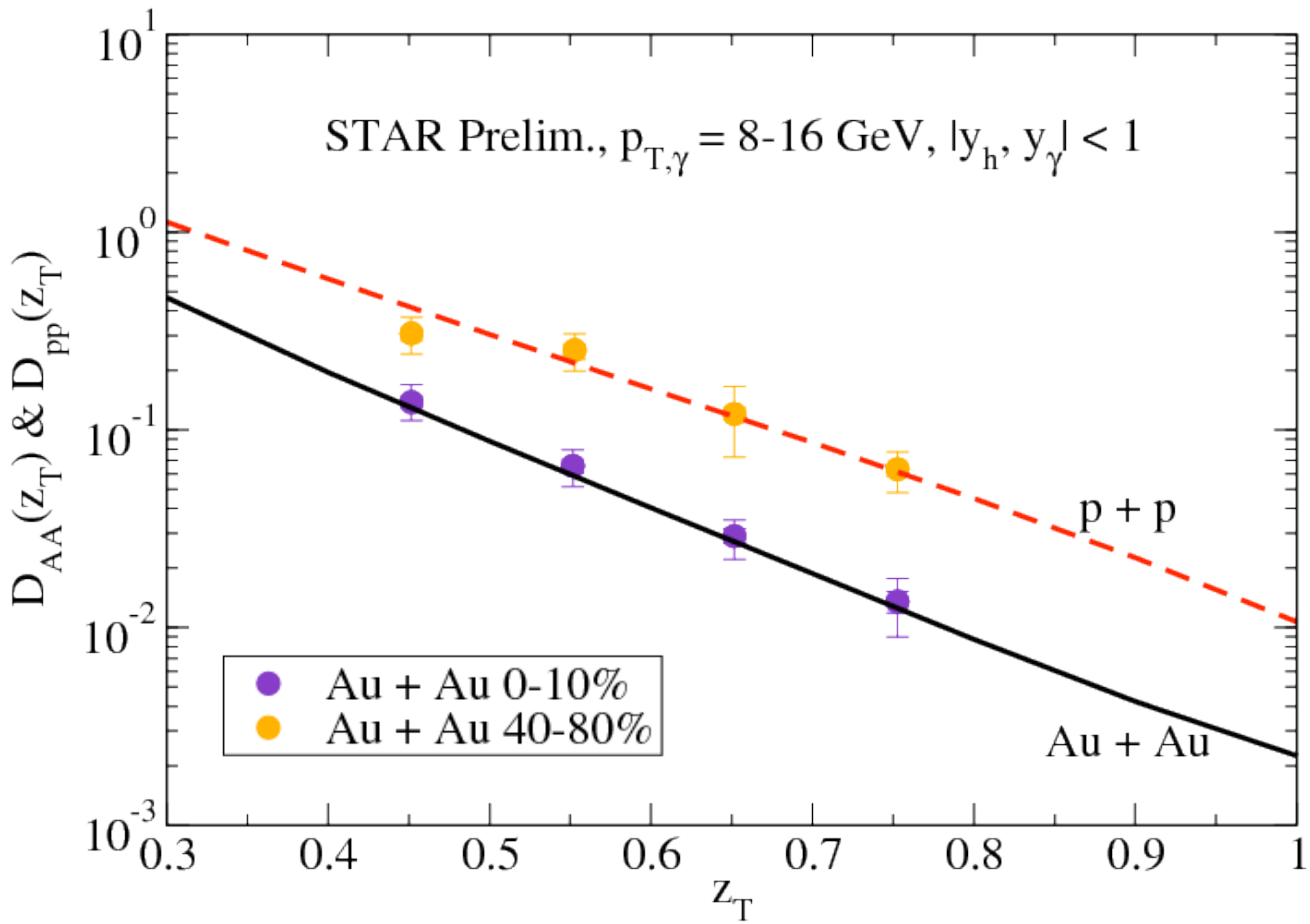
$$I_{AA} = \frac{P_{AA}(E_h \mid E_\gamma, \phi)}{P_{pp}(E_h \mid E_\gamma)}$$

Yield per trigger in AA collisions/yield per trigger in pp collision

$$= \frac{D^\gamma_{AA}(z)}{D^\gamma_{pp}(z)} \quad (z = \frac{p_T}{E^\gamma_T})$$

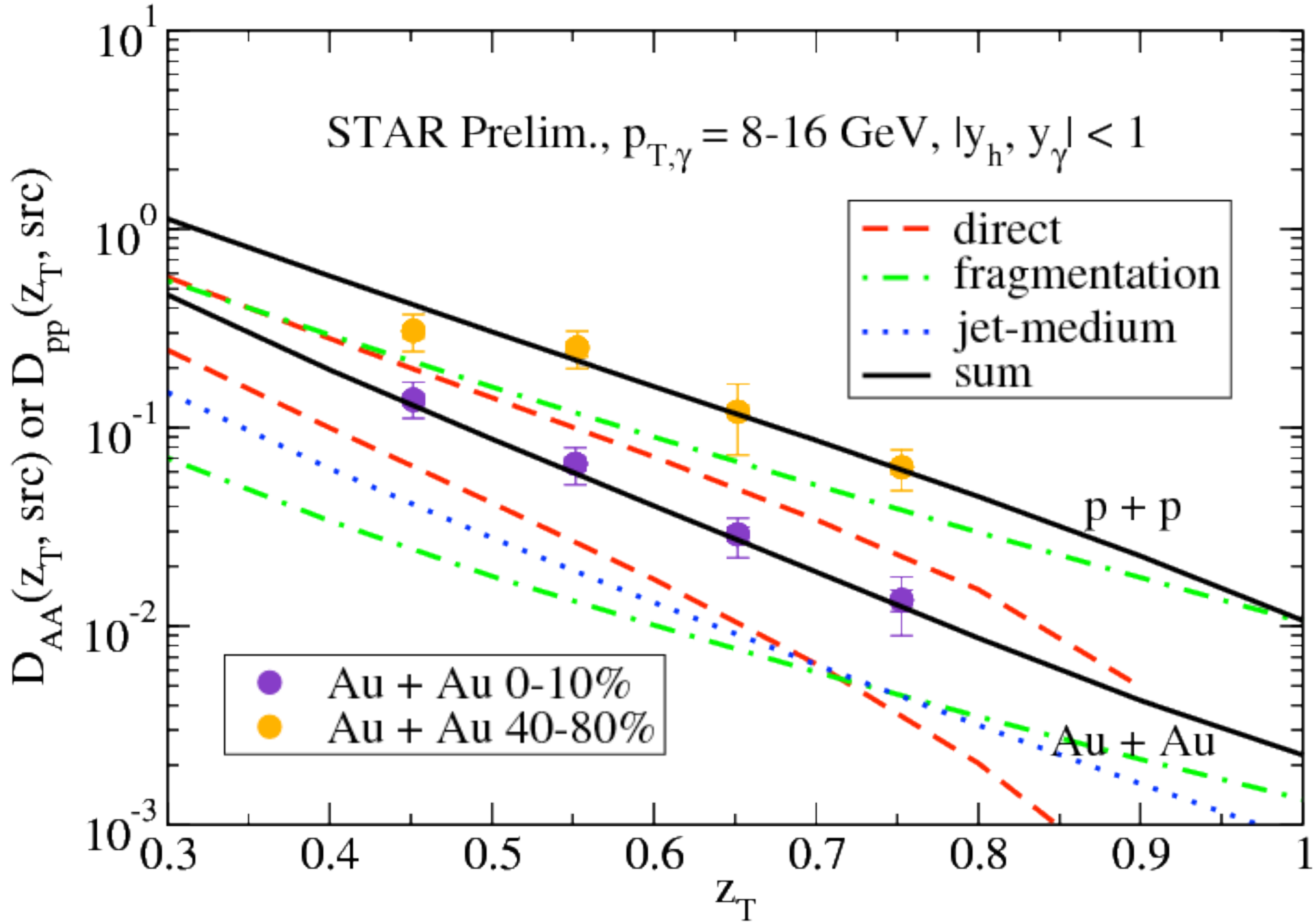
Inclusive fragmentation function in AA/ (...) in pp

Results: AA



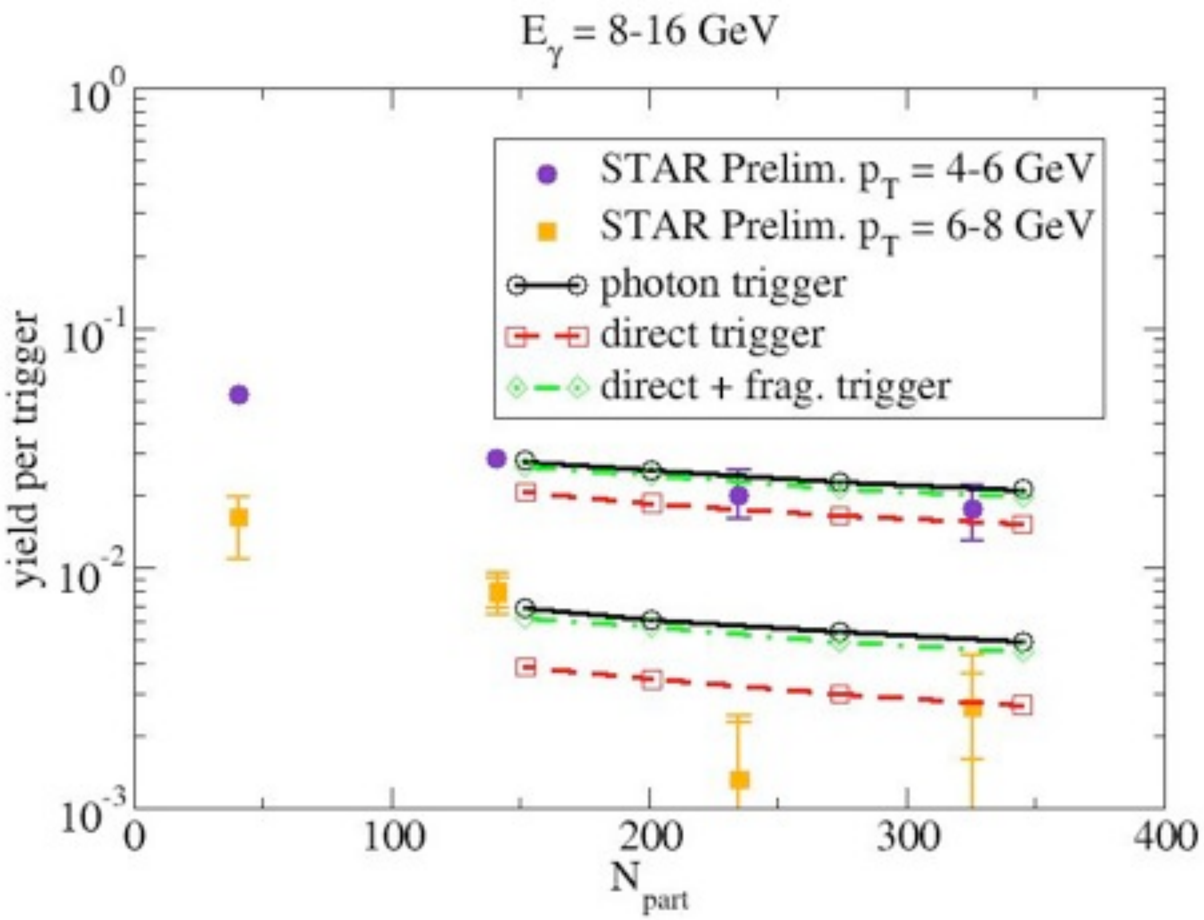
G. Qin *et al.*, PRC (2009)

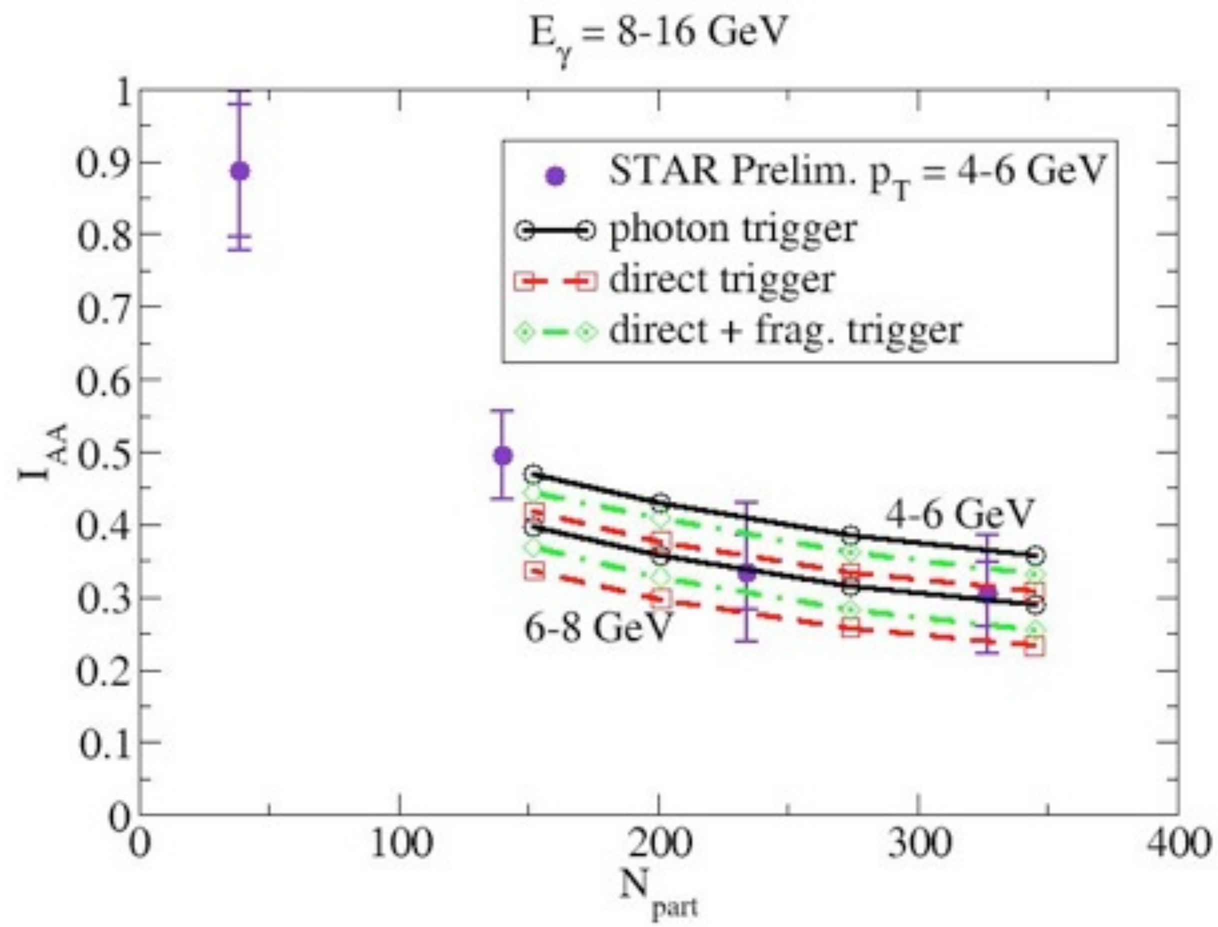
Results: AA



G. Qin *et al.*, PRC (2009)

What is the quantitative importance of the additional processes in correlation studies?





Data cant (at this point!) make a statistically significant difference...

THE FUTURE: BEYOND ONE-BODY OBSERVABLES (CORRELATIONS, PHOTON-TRIGGERED JETS...)

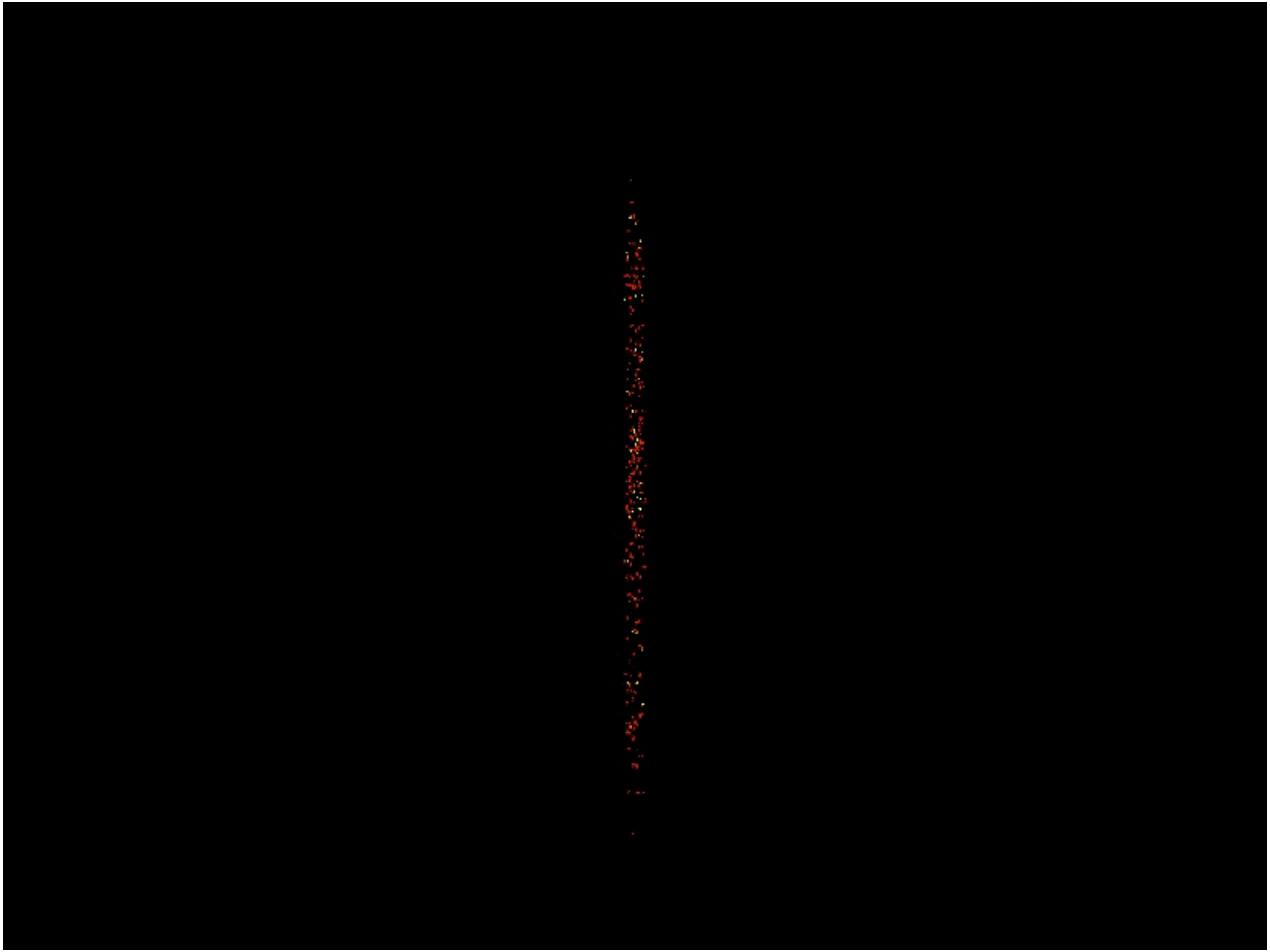
Schenke, Gale and Jeon, PRC (2009)

The future: beyond one-body observables (correlations, photon-triggered jets...)

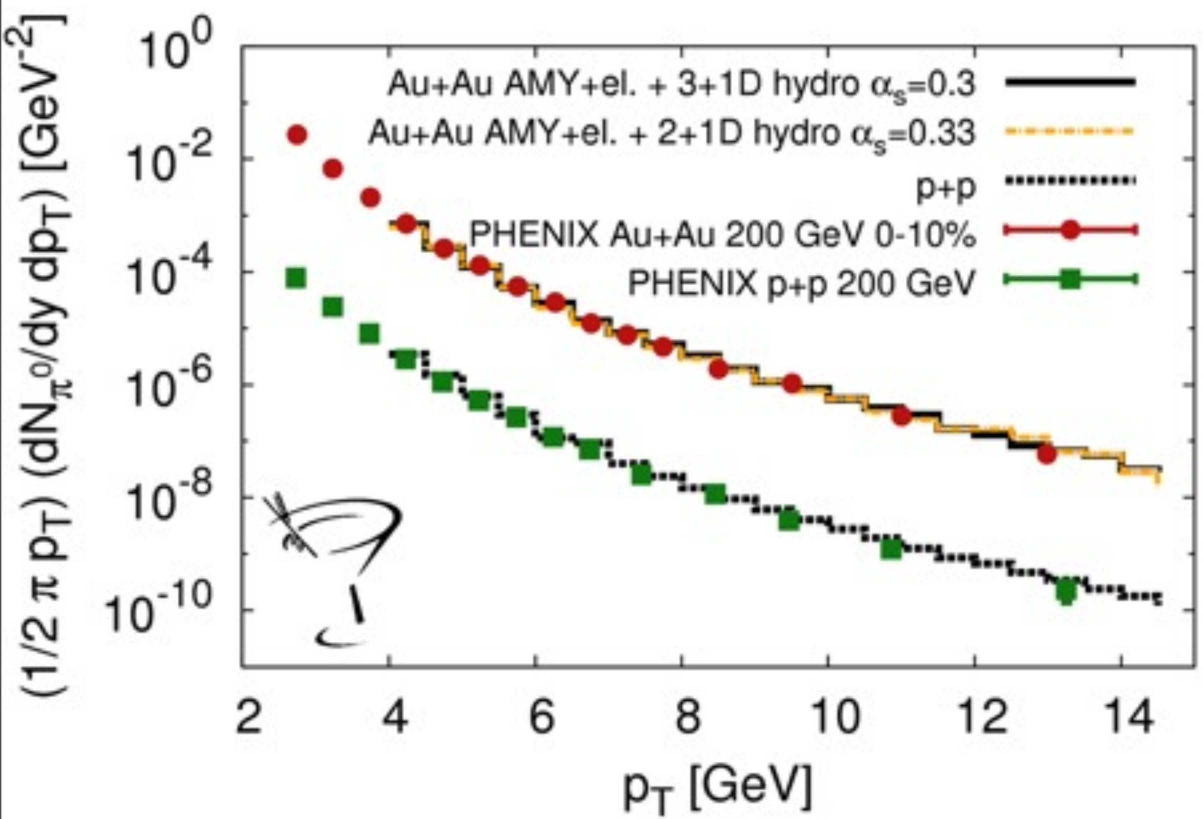
- Monte Carlo simulations of relativistic nuclear collisions; already different approaches on the scene
- MARTINI (Modular Algorithm for the Relativistic Treatment of heavy IoN Interactions)
  - Combines: PYTHIA, any hydro for thermal background, any jet energy loss procedure

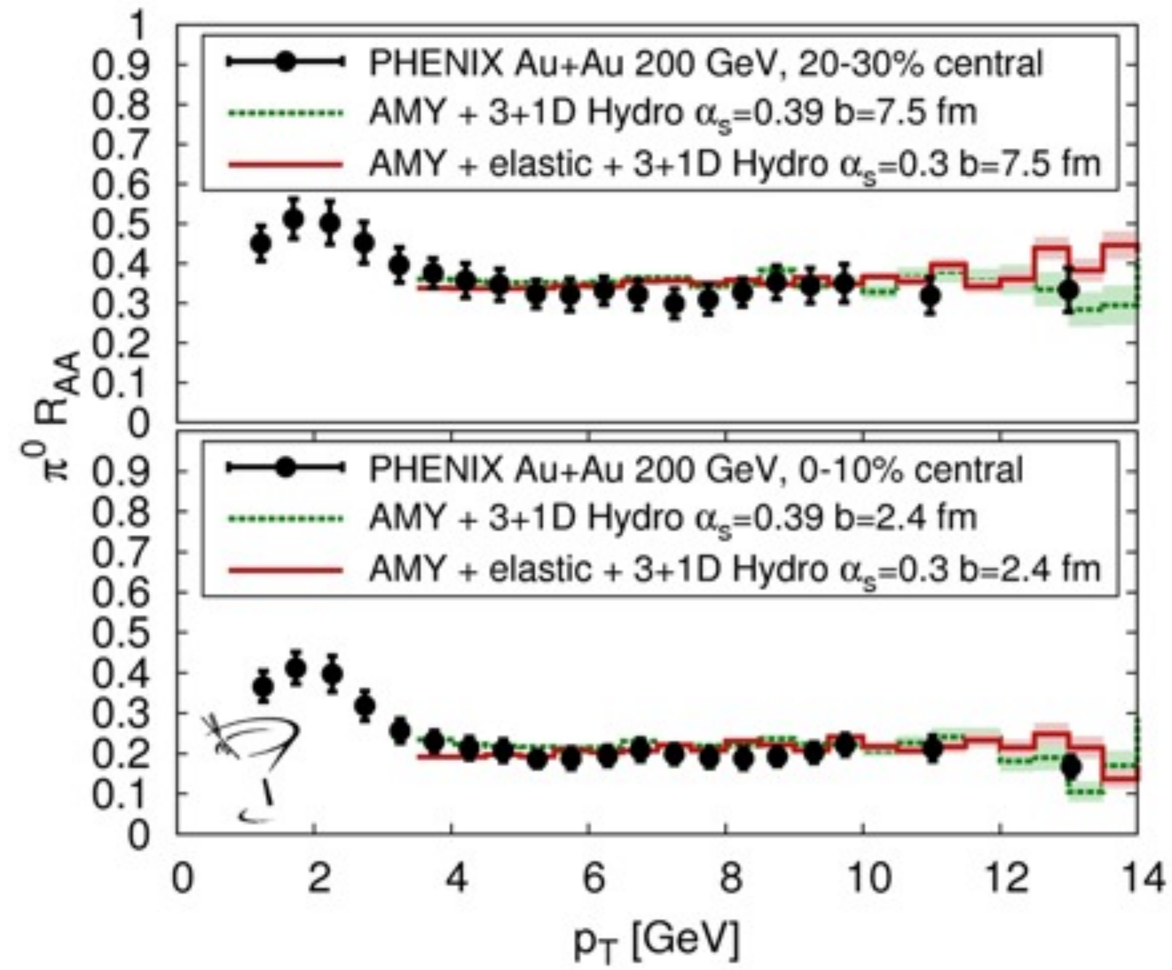
Schenke, Gale and Jeon, PRC (2009)

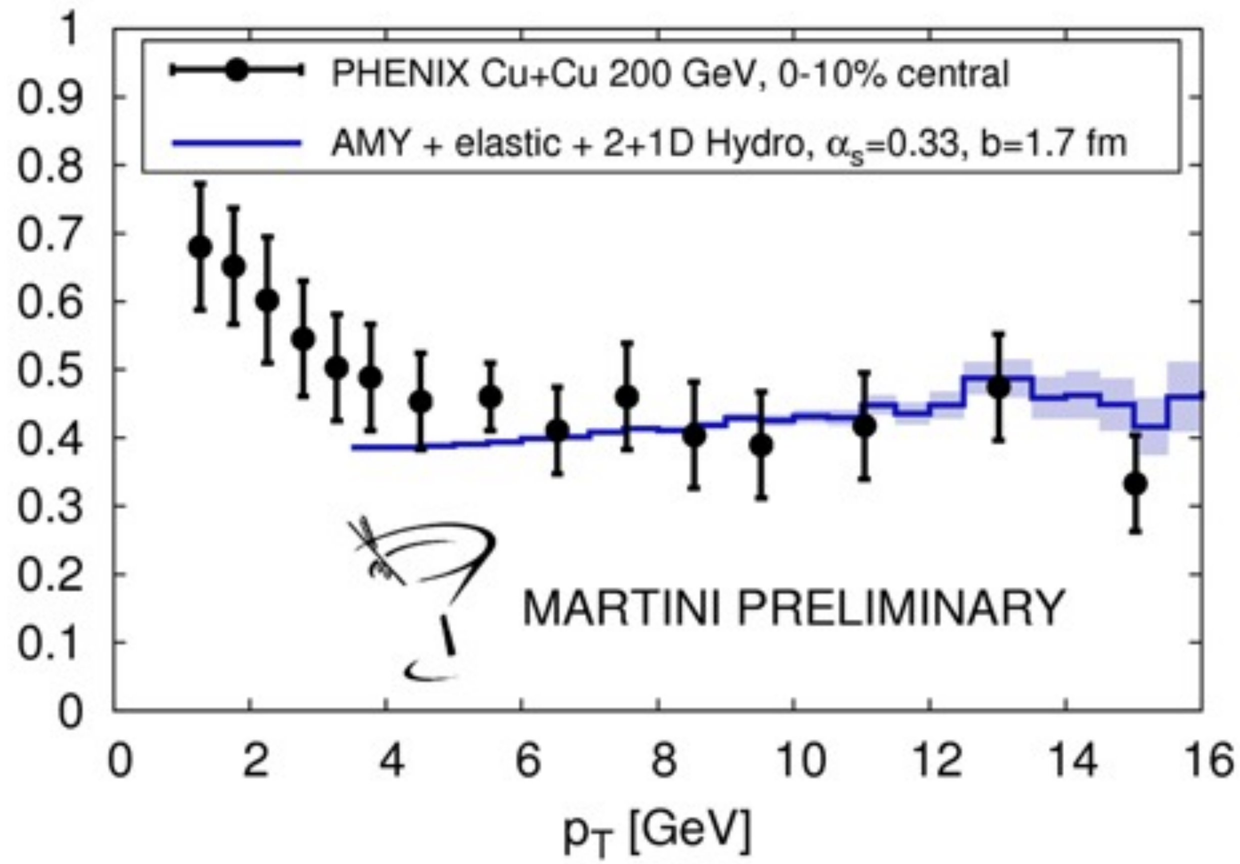
A MARTINI EVENT...



MARTINI AT WORK: HADRONS

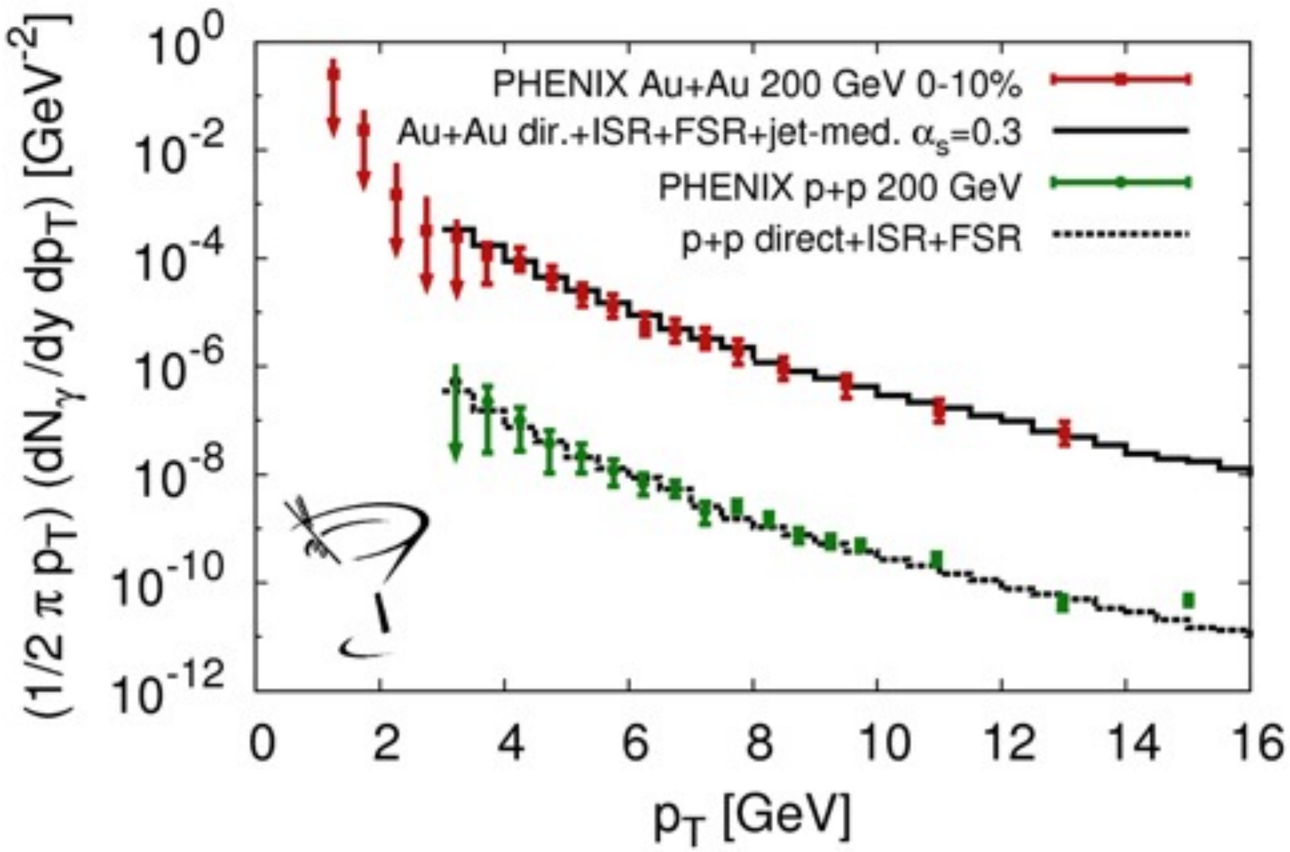


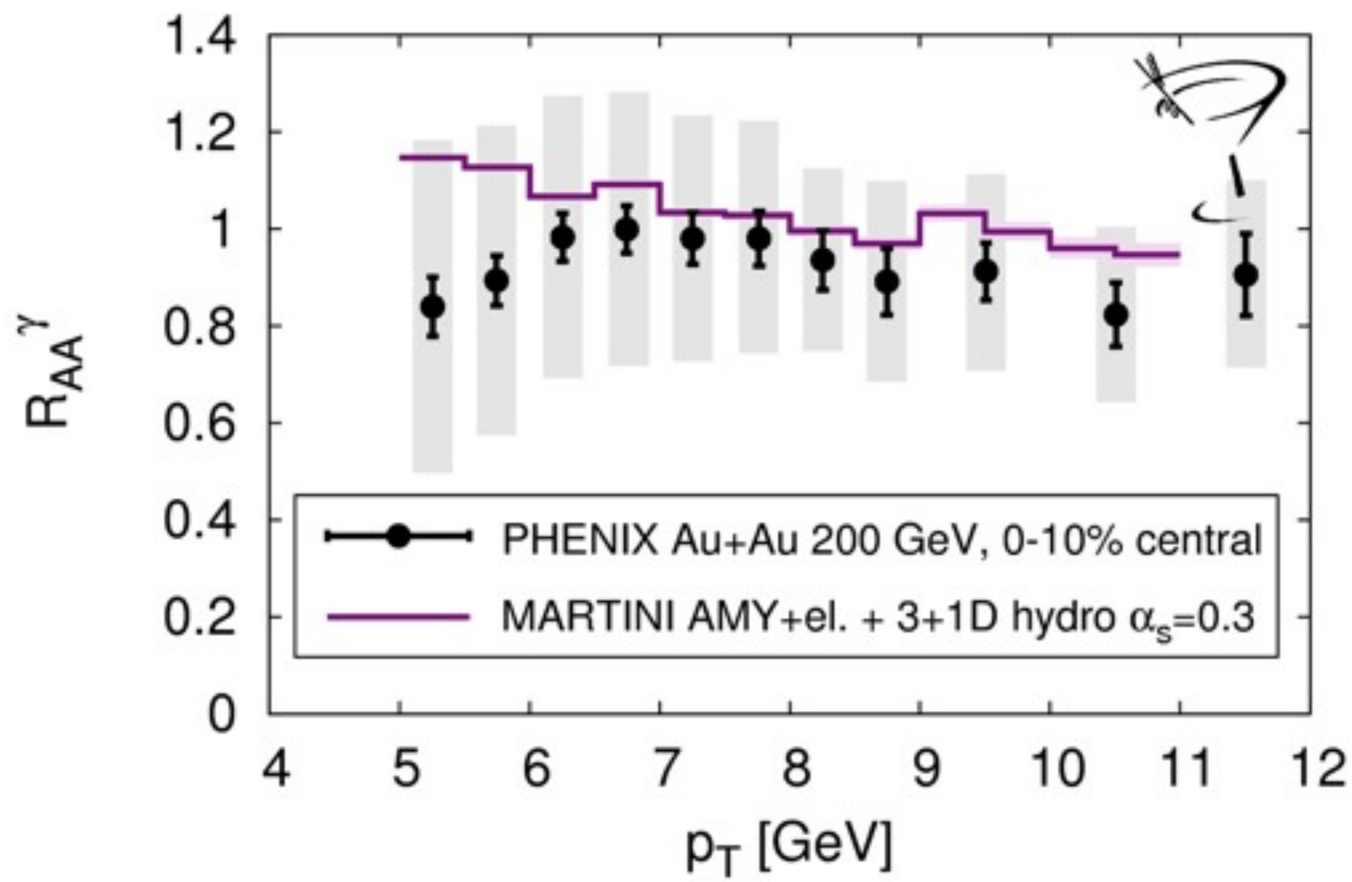


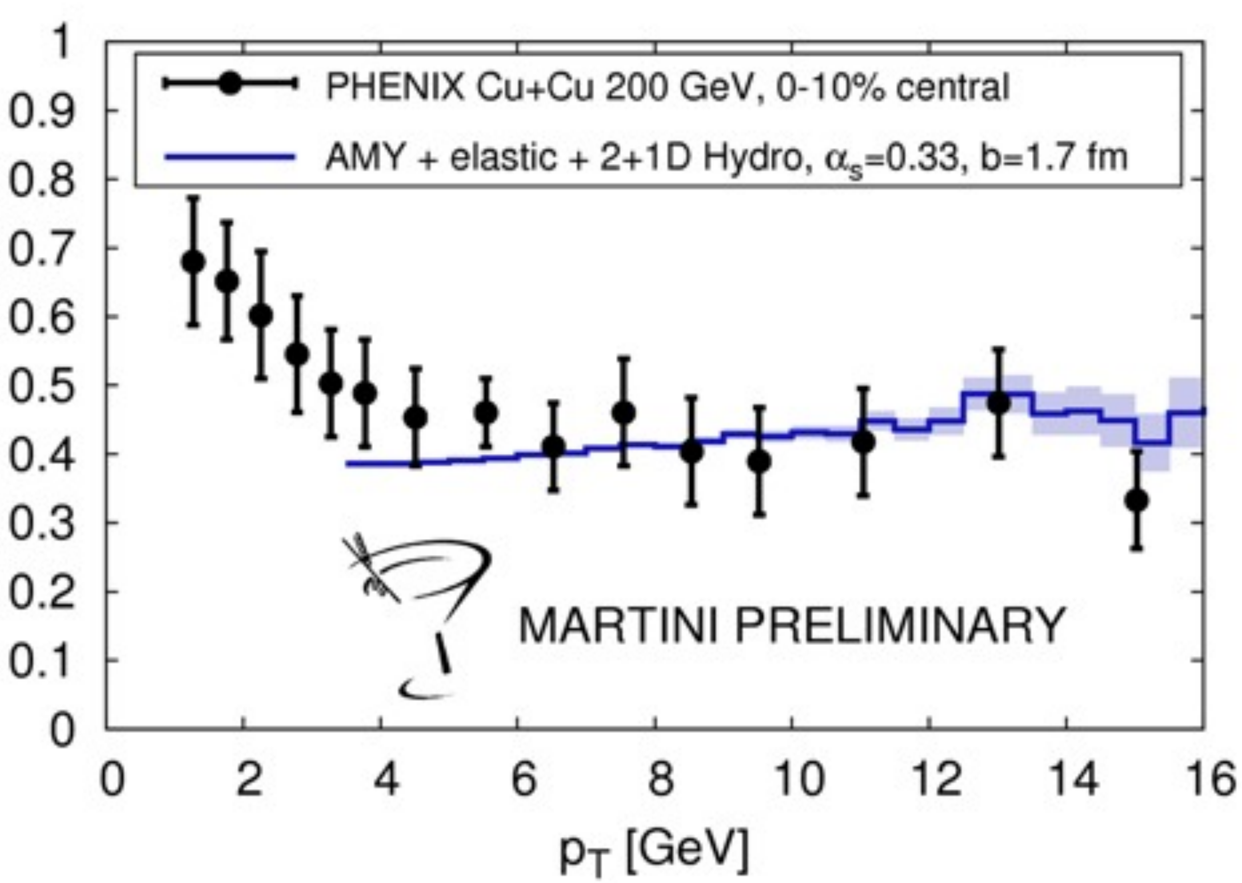


Charles Gale

MARTINI AT WORK: PHOTONS



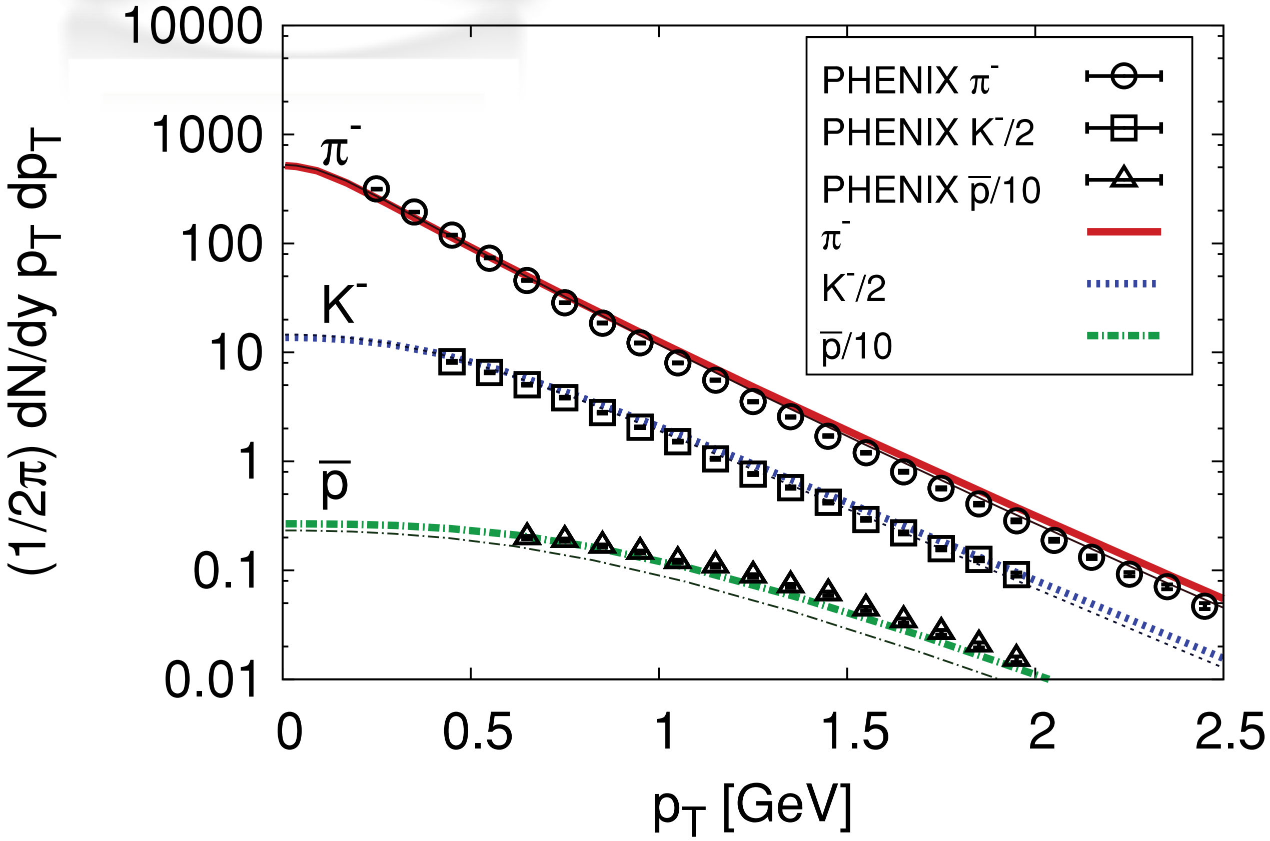


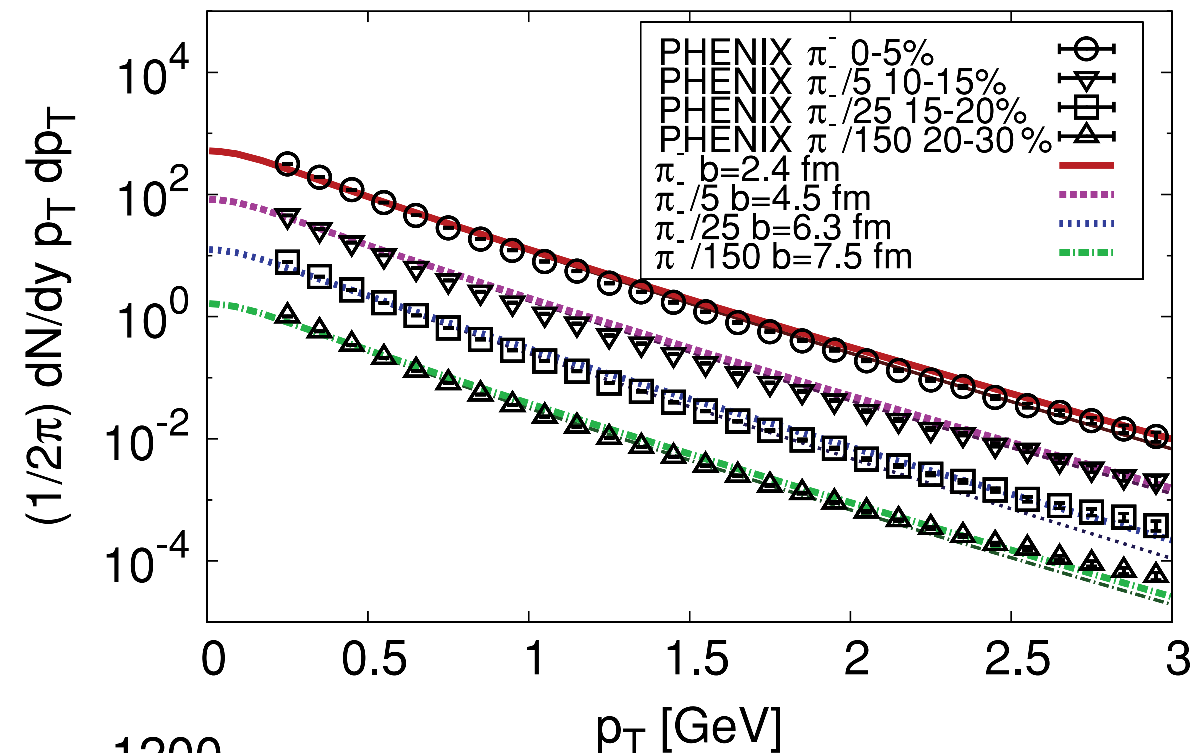


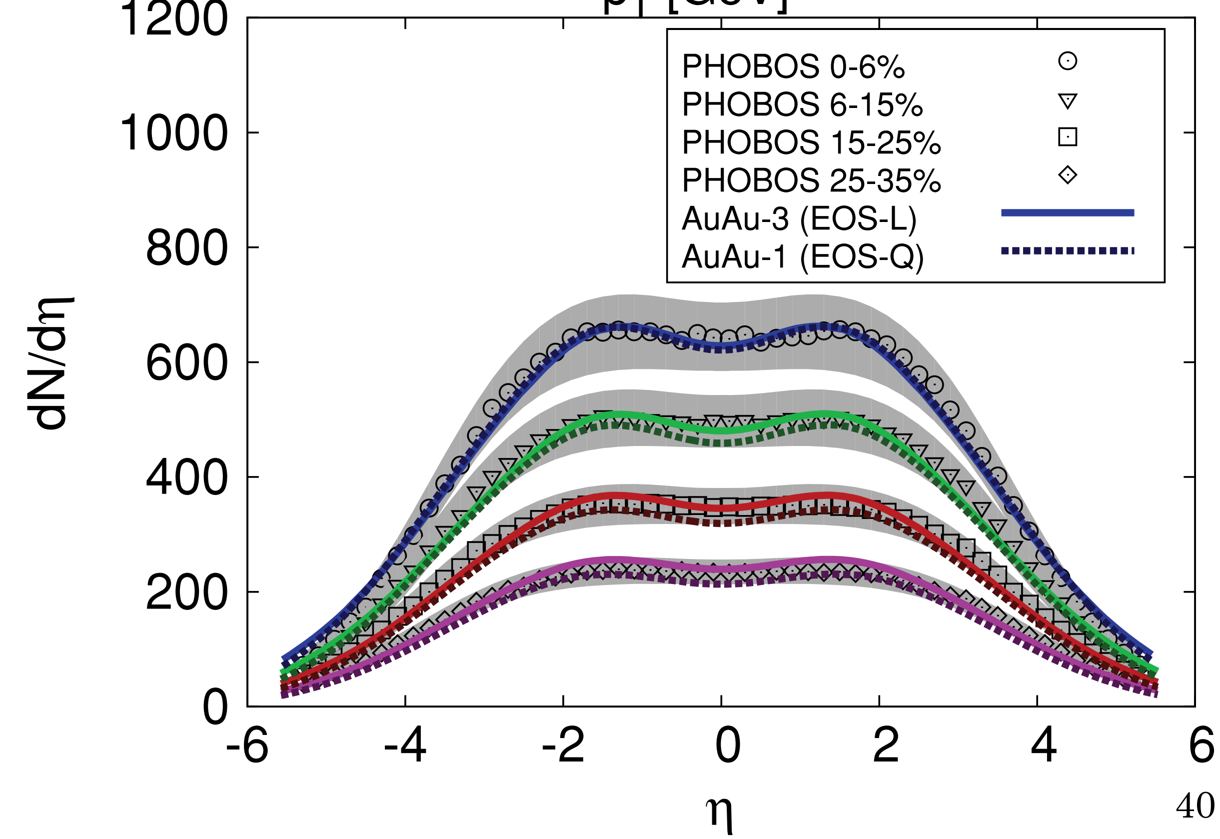
Charles Gale

MUSIC:

The future (part II)



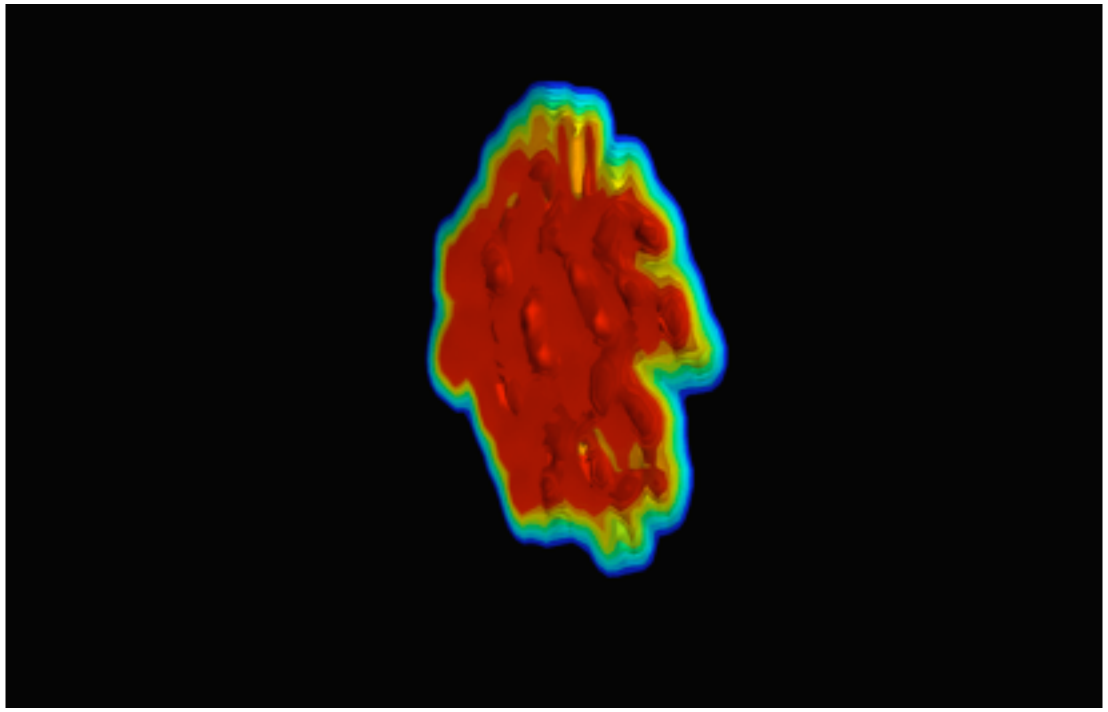




- 3D relativistic hydro
  - Schenke, Jeon, and Gale, Phys. Rev. **C** 82, 014903 (2010).
- Viscous: Schenke, Jeon, Gale, arXiv:1009.3244 [hep-ph]

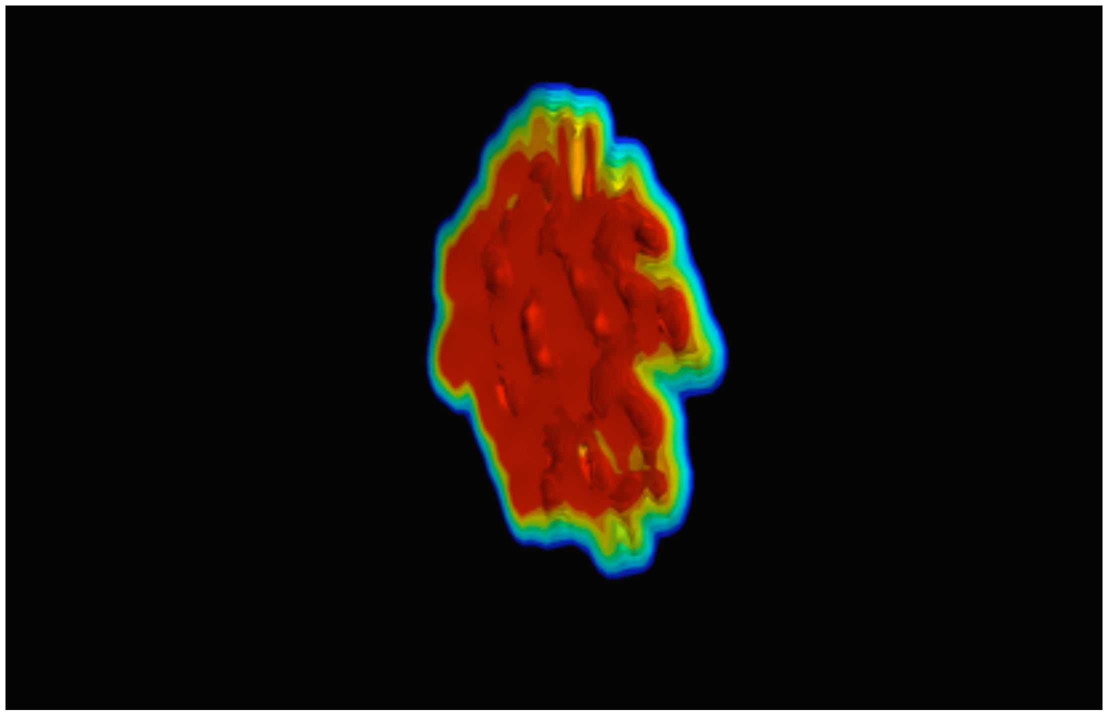
Viscosity? Initial state fluctuations?

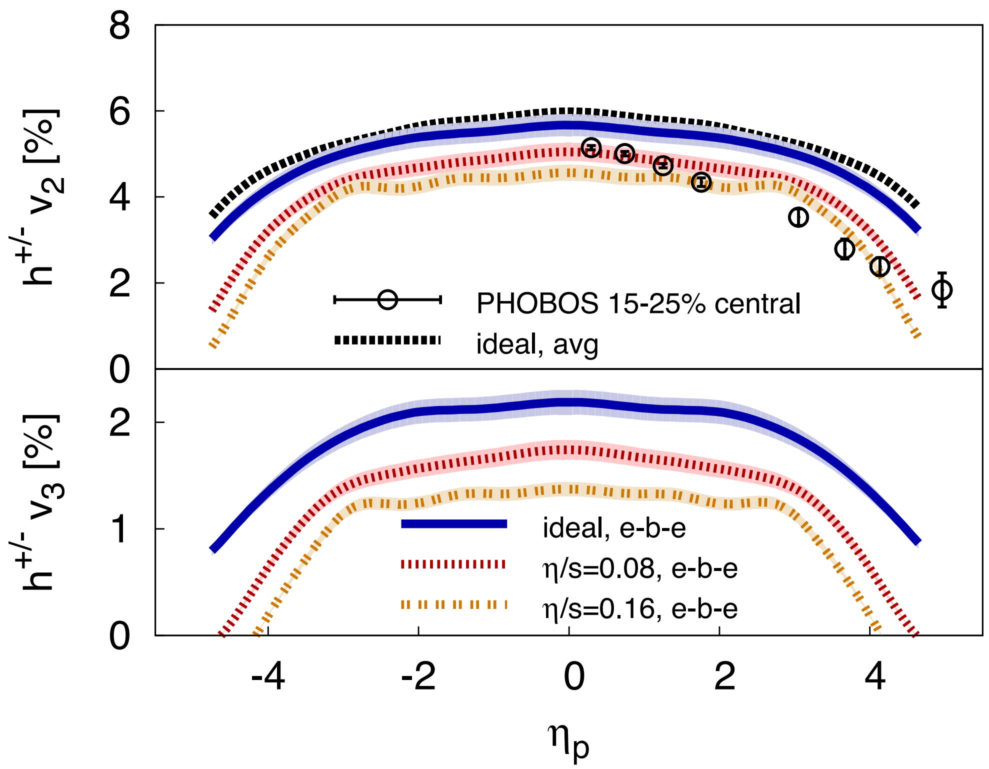
Lumpy
MUSIC

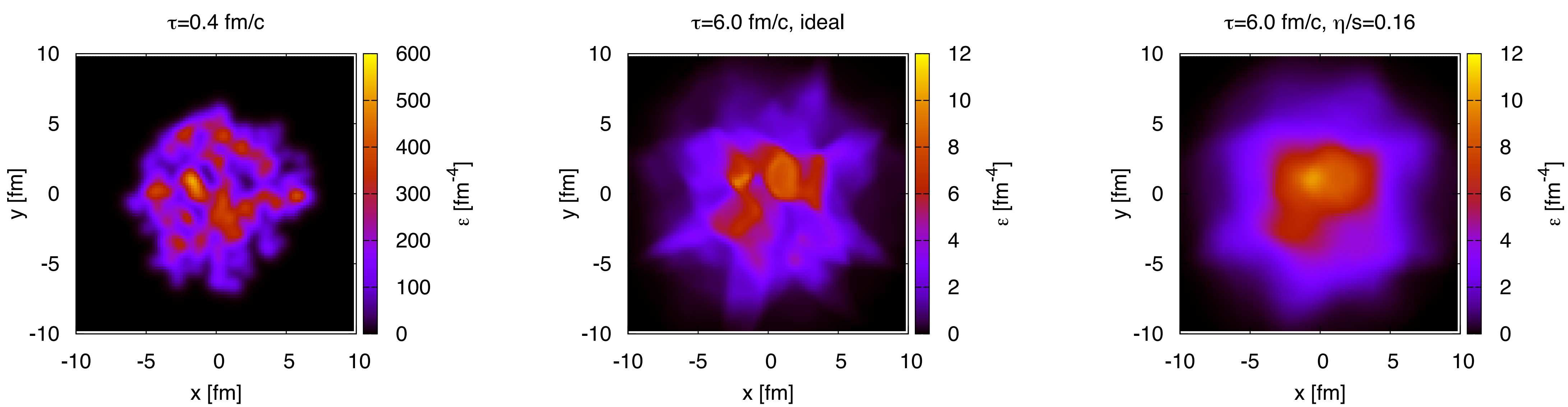


VISCOSITY? INITIAL STATE FLUCTUATIONS?

Lumpy MUSIC







Schenke, Jeon, Gale, arXiv:1009.3244 [hep-ph]

Conclusions

- Photons and hard probes (e.g. jets) can and should be treated together and consistently
- The RHIC data is compatible with a picture where jets loose energy (radiative + elastic), and where plasma channels participate in both energy loss and photon production
- Photon and hard probes help in the modelling of soft matter
- Viscosity? More coming up...
- Correlation measurements: The future
- LHC!!
- Jet-Jet correlations at NLO
- **JET**

Charles Gale

Conclusions

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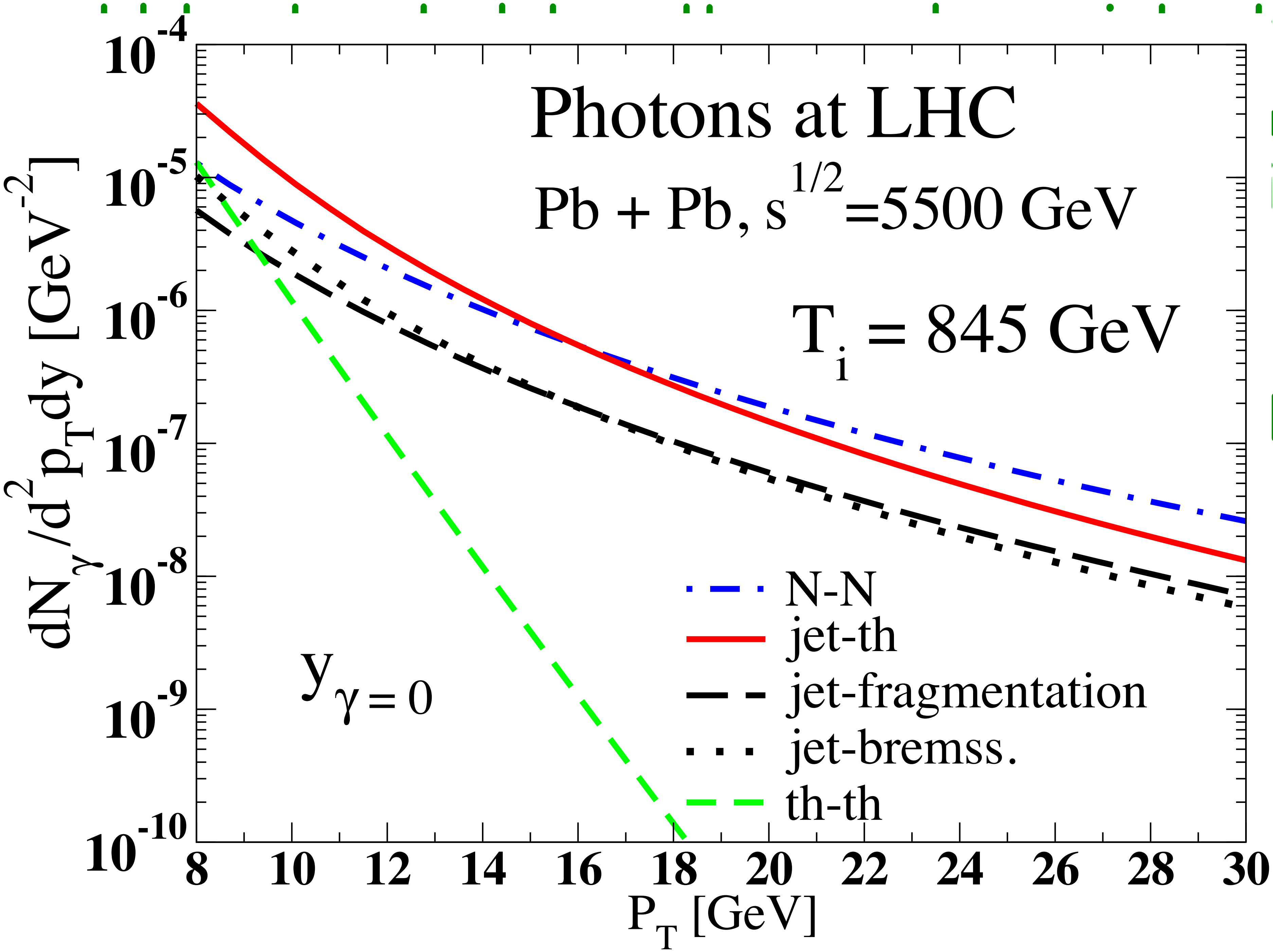

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Happy birthday Jochen!!