Exploring Quark Gluon Plasma using Photons, Jets, & Heavy Quarks

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Quantum Chromo Dynamics

- **$V(r) \sim \alpha_s(Q)/r + \sigma r$**
- **Small r (large Q): $\alpha_s(Q^2) \rightarrow 0$,**

  quarks behave as free particles:

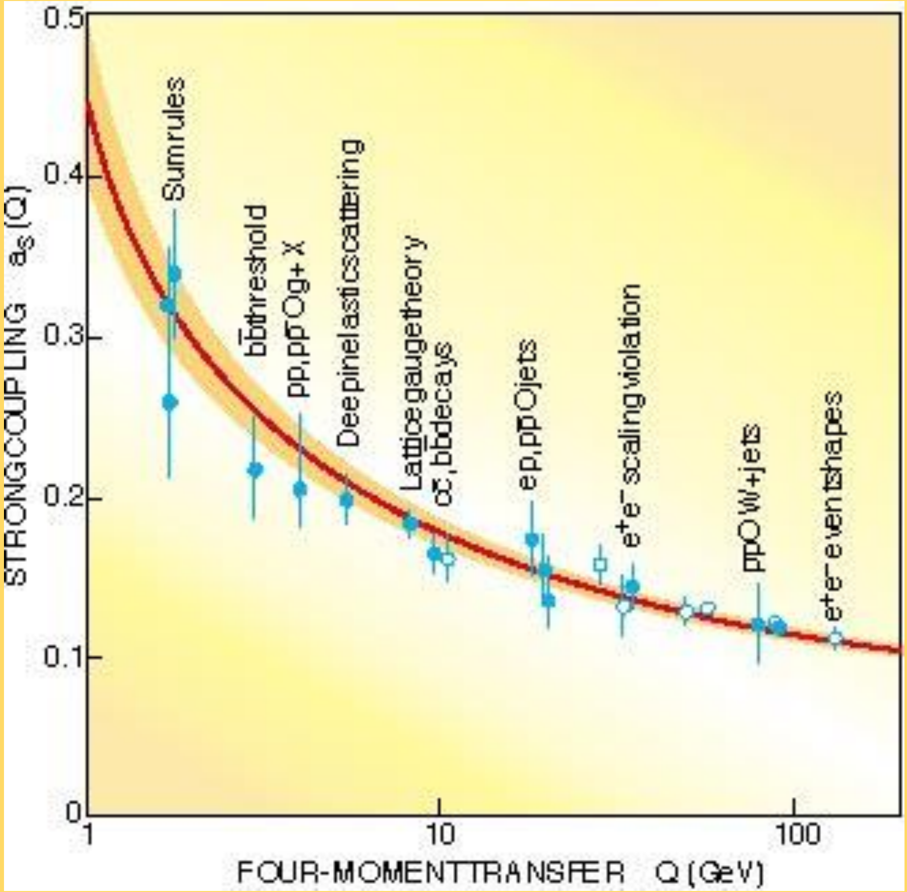
  Asymptotic Freedom.
- **Large r (small Q):**

  the second term goes to infinity;

  Infrared Slavery,

  No Free Quarks or Gluons.
- **Different from any other interaction**

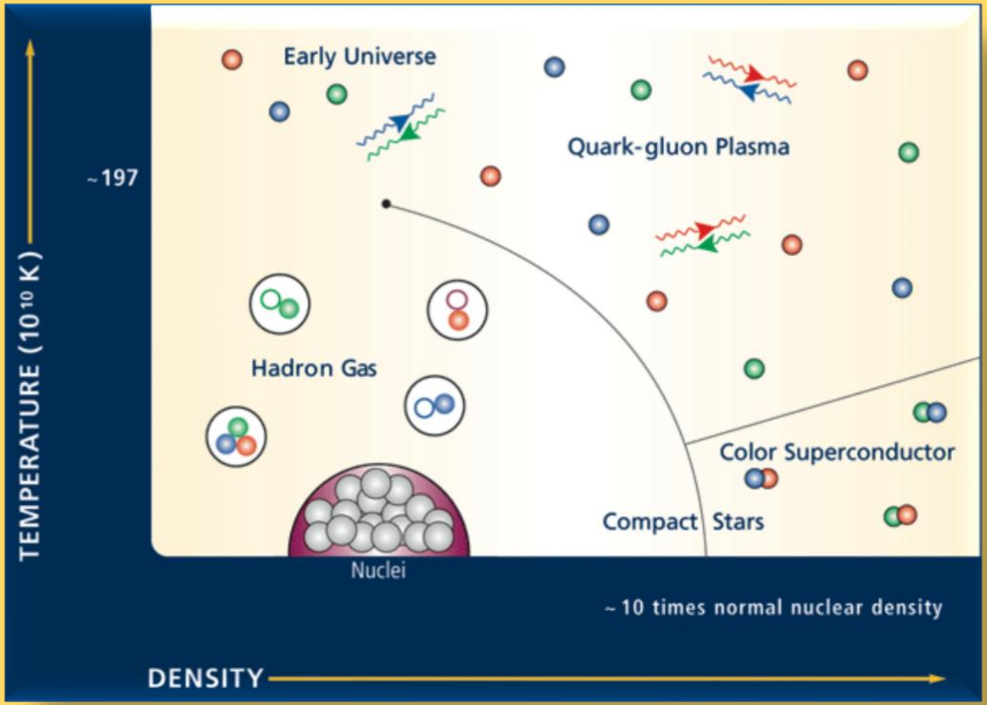
  we have come across.



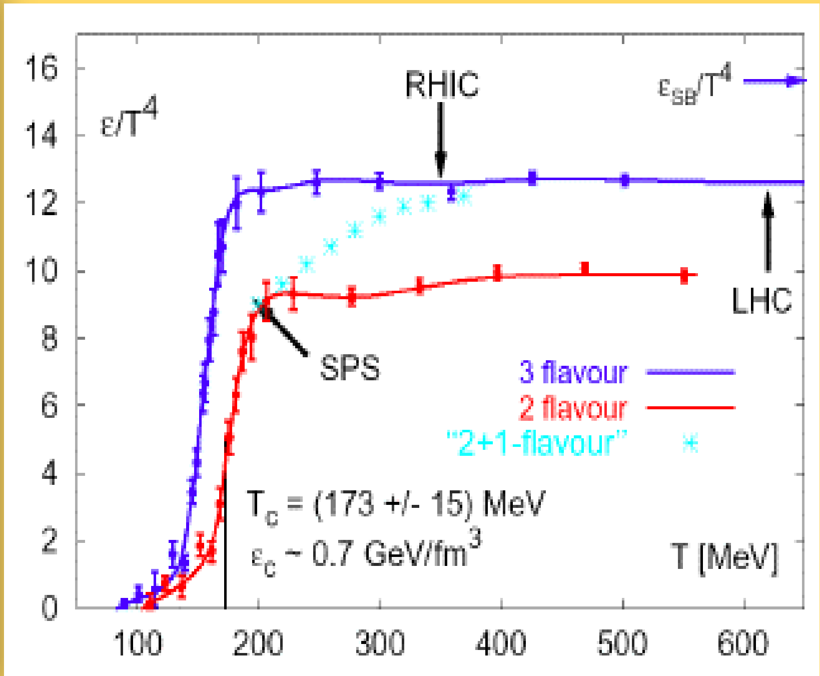
$$\alpha_s(Q^2) \approx \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2_{QCD})}$$

Achieved via quarks in 3 colours and 8 type of gluons
all of which carry colour charge.

Quark Gluon Plasma



F. Karsch, Prog. Theor. Phys. Suppl. 153, 106 (2004)



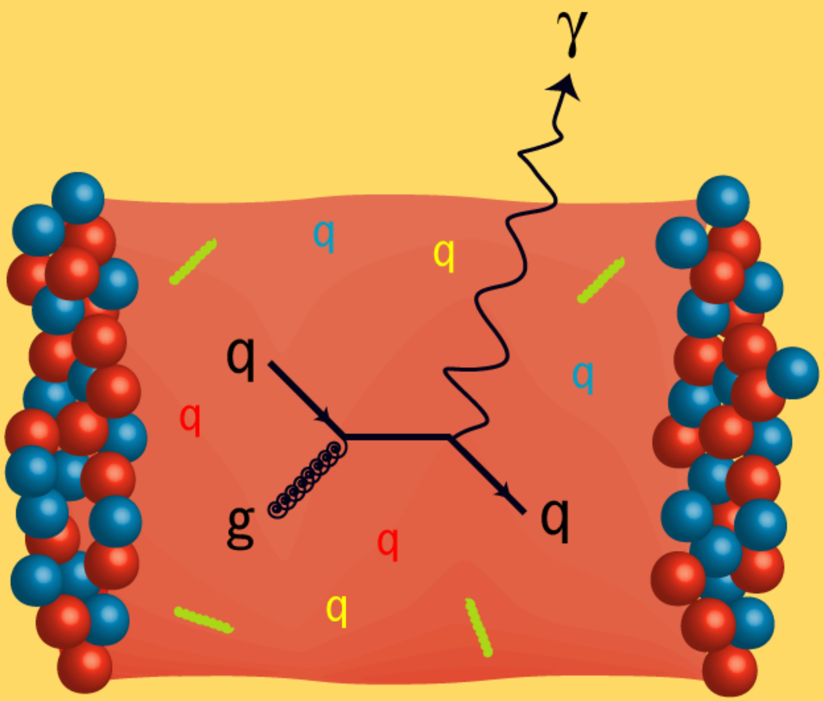
- Lattice QCD predicts transition to deconfined Quark Gluon Plasma phase at ~175MeV.
- Goal of Relativistic Heavy Ion Collisions – to produce and characterize QGP.

Thirty seven years ago:

E. L. Feinberg, Nuv. Cim. A 34 (1976) 391, pointed out that:

Direct photons; real or virtual are penetrating probes for the bulk matter produced in hadronic collisions, as

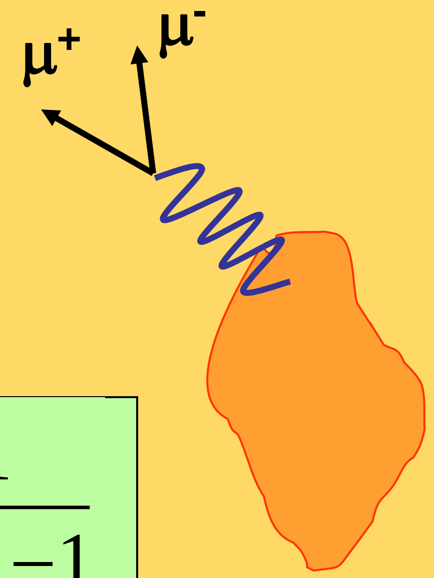
- They do not interact strongly.
- They have a large mean free path.



Since then relentless efforts by researchers from across the world have established these as *reliable probes of hot and dense matter*.

The Information Content of EM Probes

Emission rates:



Photons:

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

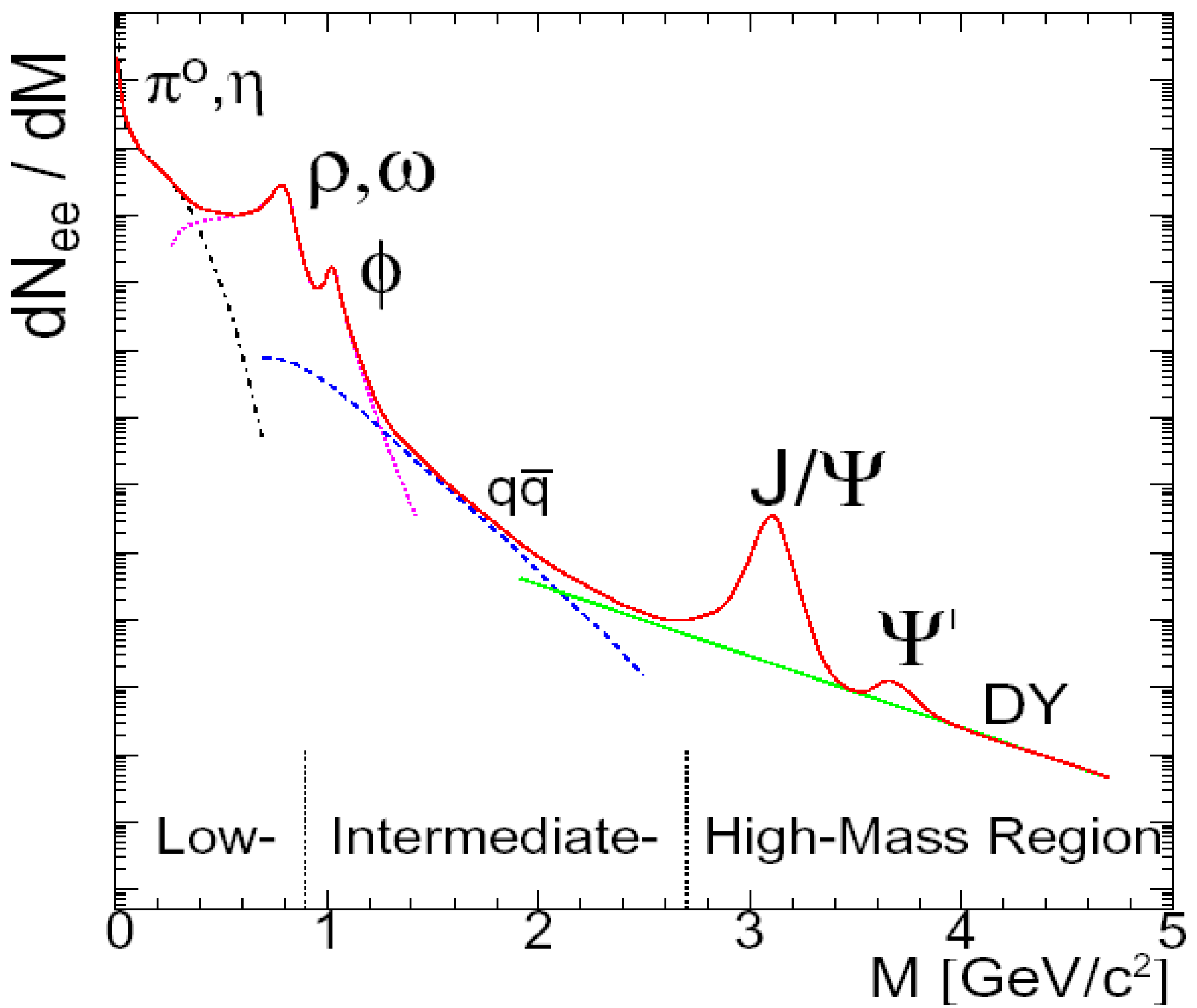
Dileptons:

$$\frac{d^6R}{d^3p_+ d^3p_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{k^4} L_{\mu\nu} \mathrm{Im}\,\Pi^{\mu\nu} \frac{1}{e^{\beta w}-1}$$

In- medium photon self energy: Directly related to the in-medium vector spectral densities!

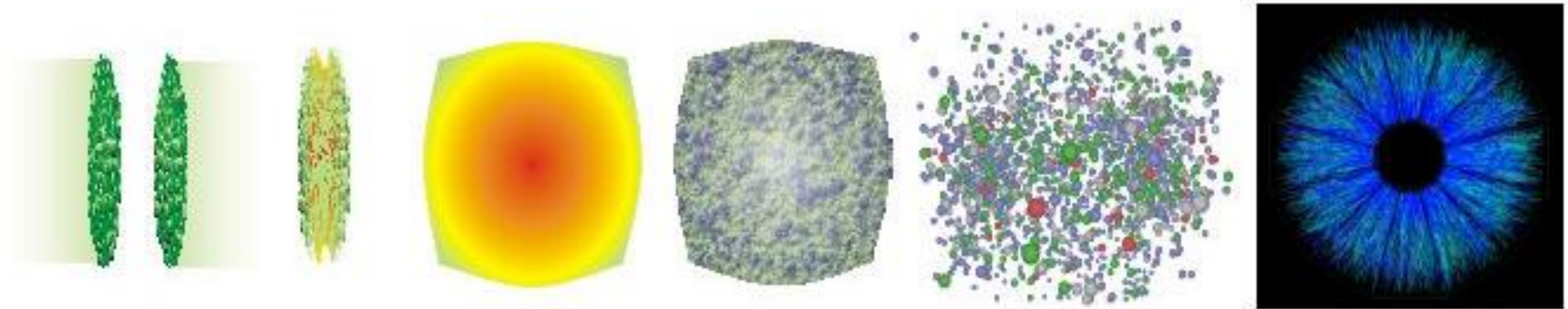
- **McLerran & Toimela, PRD 31 (1985) 545;**
- **Weldon, PRD 42 (1990) 2384;**
- **Gale & Kapusta, NPB 357 (1991) 65.**

Low, Intermediate, & High Mass Dileptons

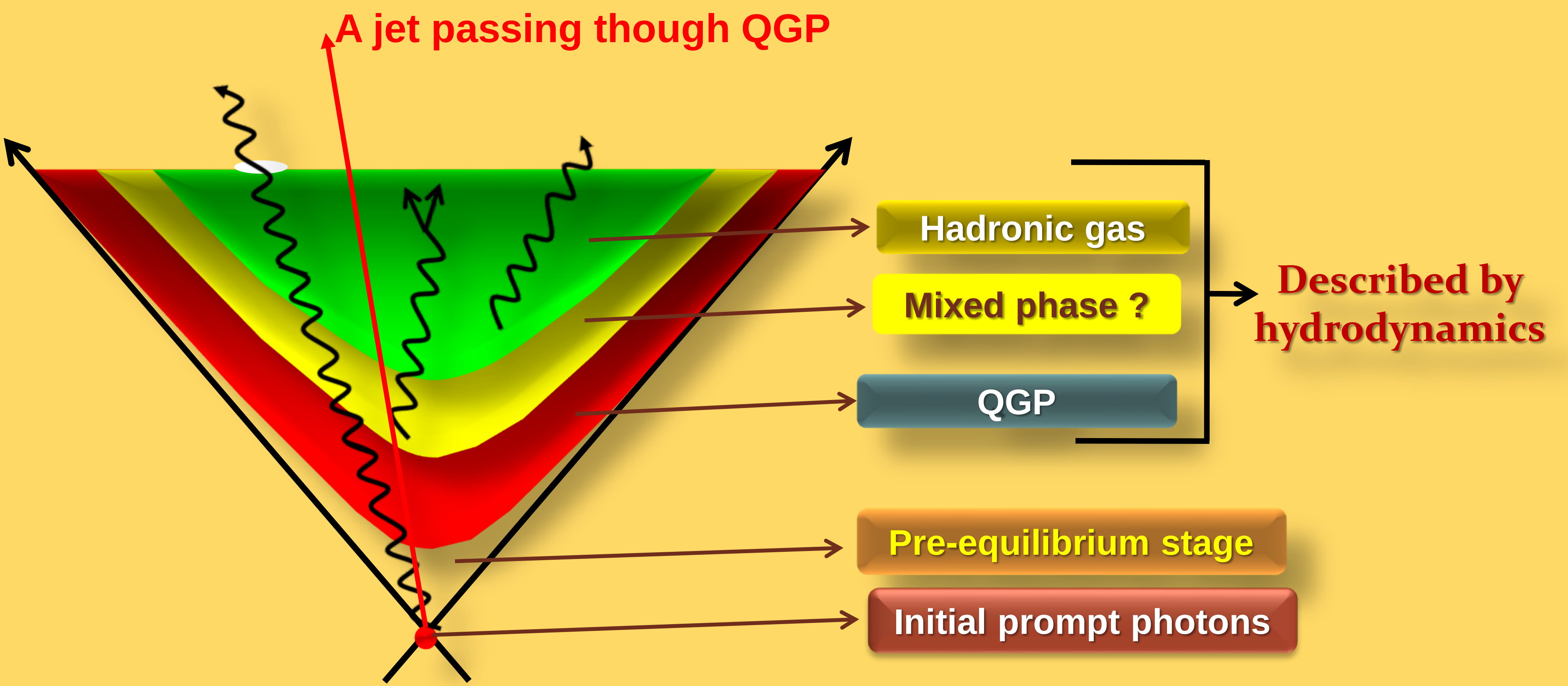


- **Low-mass:**
  Medium modified spectral density
- **Intermediate mass:**
  Radiation from QGP
- **High mass:**
  J/ψ etc., suppression
- **All masses:**
  Correlated Charm/ Bottom Decay.

The same model should explain both: Single Photons and Dileptons.

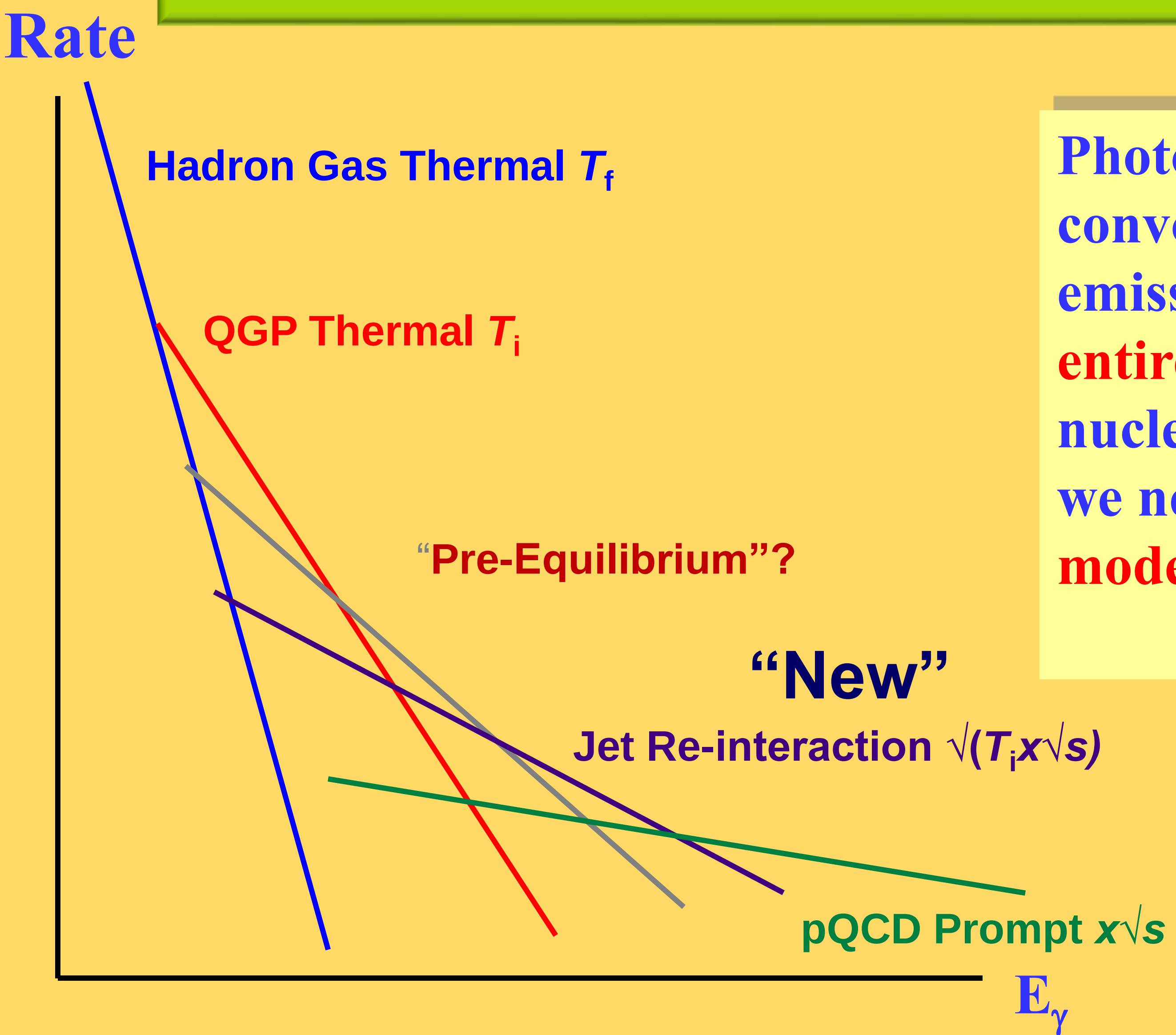


Single photons are penetrating probes. They are emitted at all stages and survive unscathed ($\alpha_e << \alpha_s$). They are "historians" of the heavy ion collision!



Different processes: different characteristic spectra!

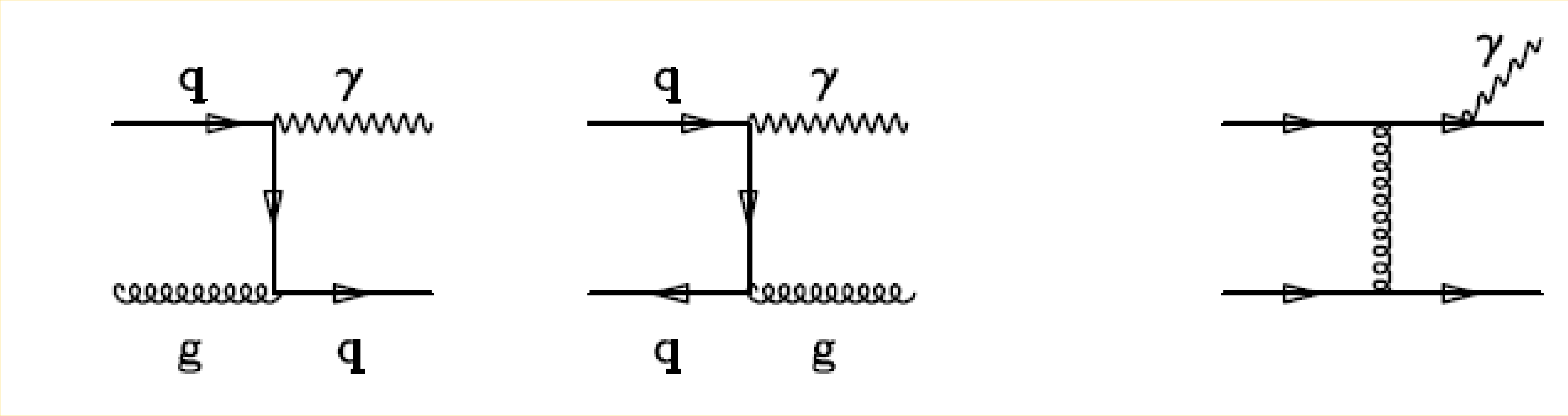
Direct Photons
Different Sources - Different Slopes



Photons are result of convolutions of the emissions from the entire history of the nuclear collision, so we need rates & a model for evolution.

- **Hydrodynamics.**
- **Cascades.**
- **Fire-balls.**
- **Cascade+Hydro.**

Partonic Processes for Production of Prompt Photons in Hadronic Collisions



Compton

Annihilation

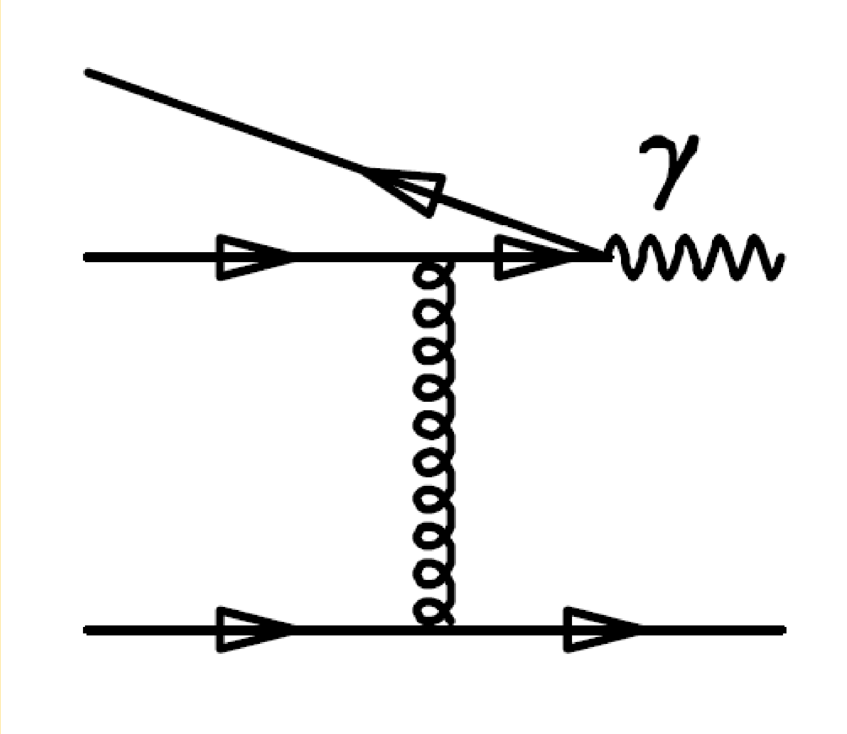
Fragmentation

Calculate using NLO pQCD [with shadowing & scaling with T_{AA}(b) for AA, partons remain confined to individual nucleons; do not forget the iso-spin!]

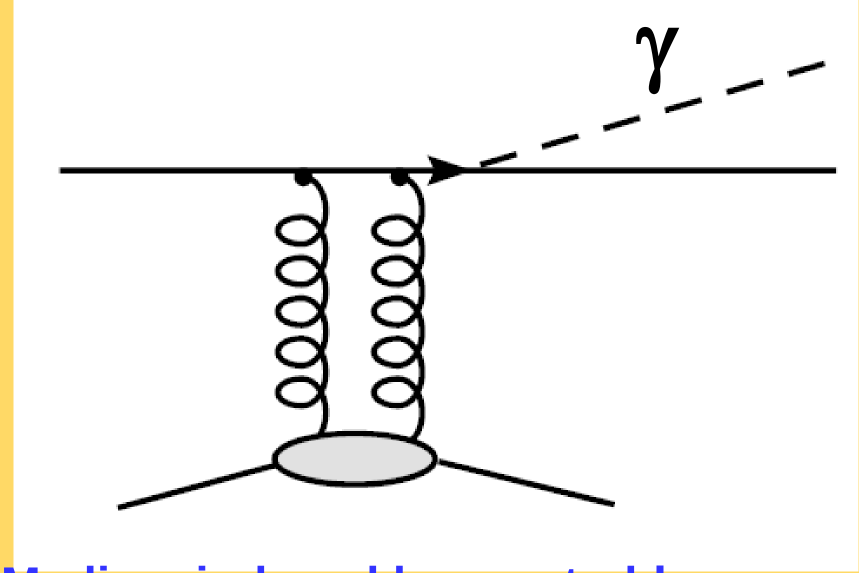
The quarks will lose energy *before fragmenting* if there is QGP; suppressing the fragmentation contribution.

See e.g., Jeon, Jalilian-Marian, Sarcevic, NPA 715 (2003) 795, "QM-2002".

In the QGP we also have:



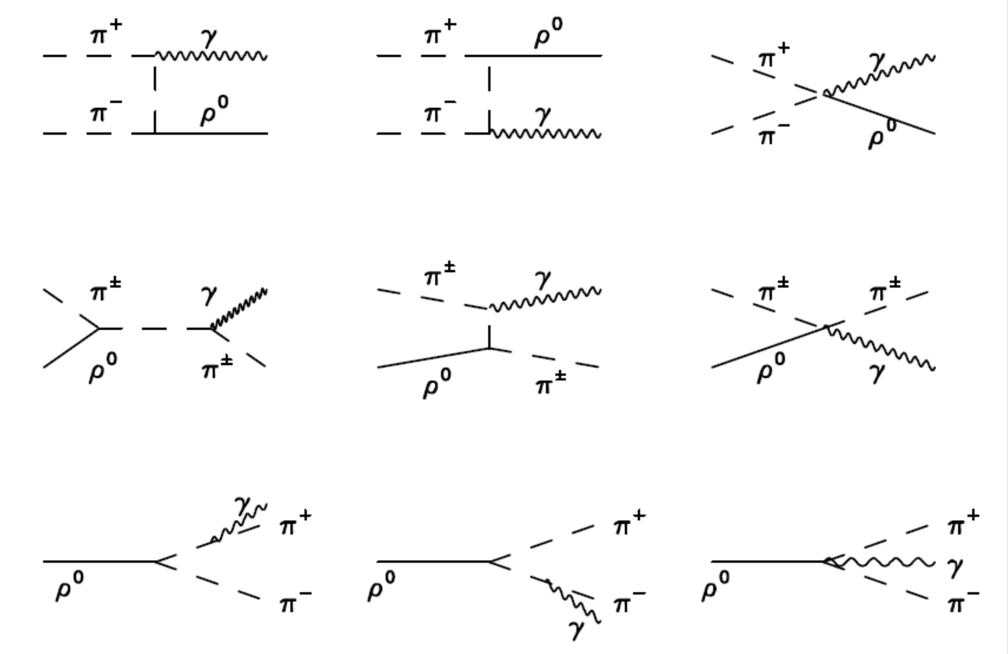
Annihilation with scatterring; *First calculated by Aurenche et al, PRD 58 (1998) 085003.*



Medium induced bremsstrahlung;
First calculated by *Zakharov*,
JETP Lett. 80 (2004) 1;
Turbide et al, PRC 72 (2005) 014905.
Zhang, Kang, & Wang, hep-ph/0609159.

Complete leading order results: Arnold, Moore, Yaffe, JHEP 0112 (2001) 009. NLO is at most 20% and similar in shape (see JHEP 1305 (2013) 010).

Examples of Hadronic Processes Involving π & ρ for Production of Photons



First calculated by Kapusta, Lichard, & Seibert, PRD 44 (1991) 2774.

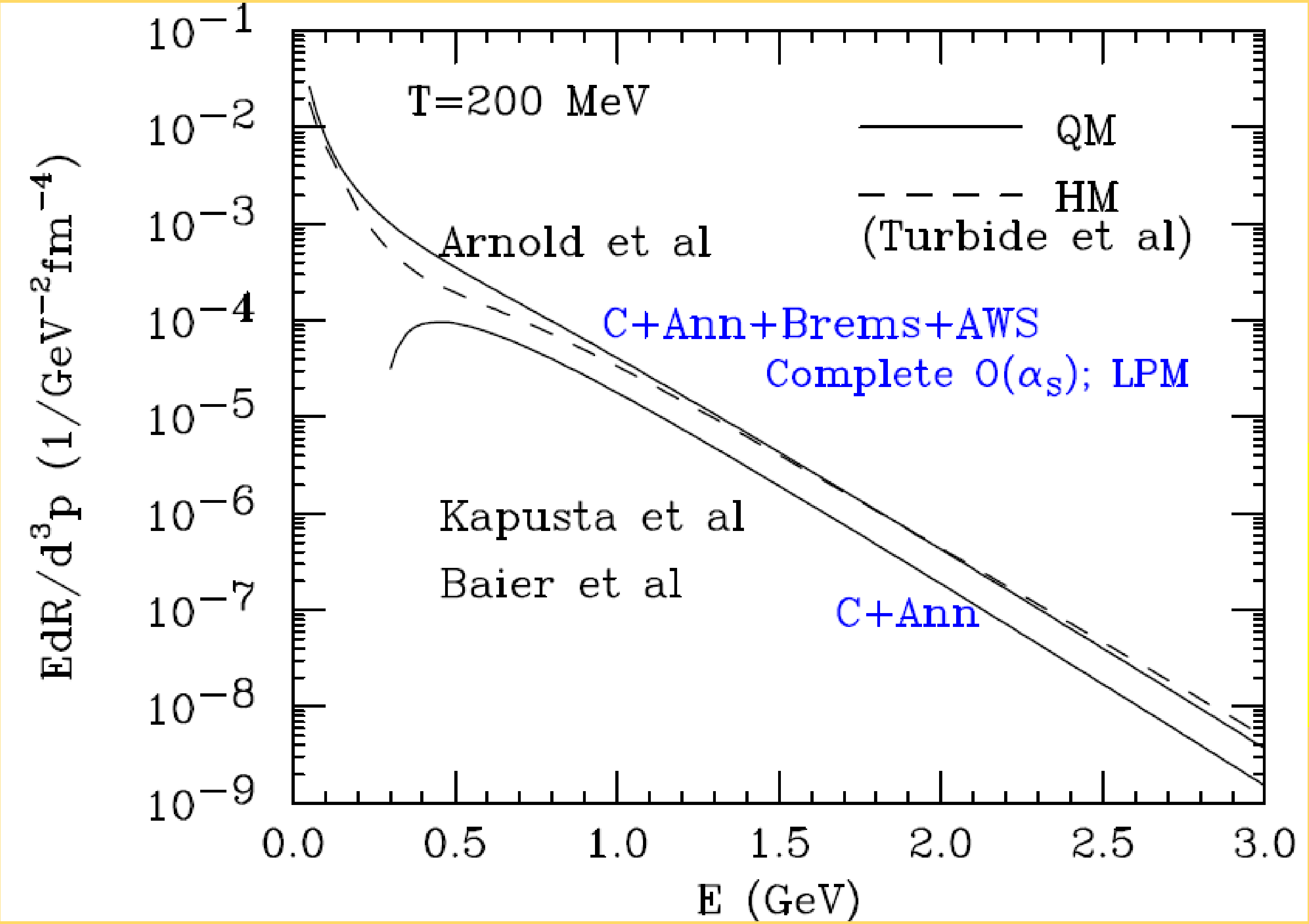
- Include $\pi\rho \rightarrow a_1 \rightarrow \pi\gamma$
  Xiong et al, PRD 46 (1992) 3798;
  Song, PRC 47 (1993) 2861.

- Include baryonic processes.
  Alam et al, PRC 68 (2003) 031901.

- Medium modifications; (Series of valuable papers, T and μ_b)
  Alam et al, Ann. Phys. 286 (2001) 159.

- Include strange sector, massive Yang- Mills theory, form-factors, baryons, t-channel exchange of ω mesons etc.
  Turbide, Rapp, Gale, PRC 69 (2004) 014903.

Complete Leading Order Rates from QGP & Exhaustive Reactions in Hadronic Matter



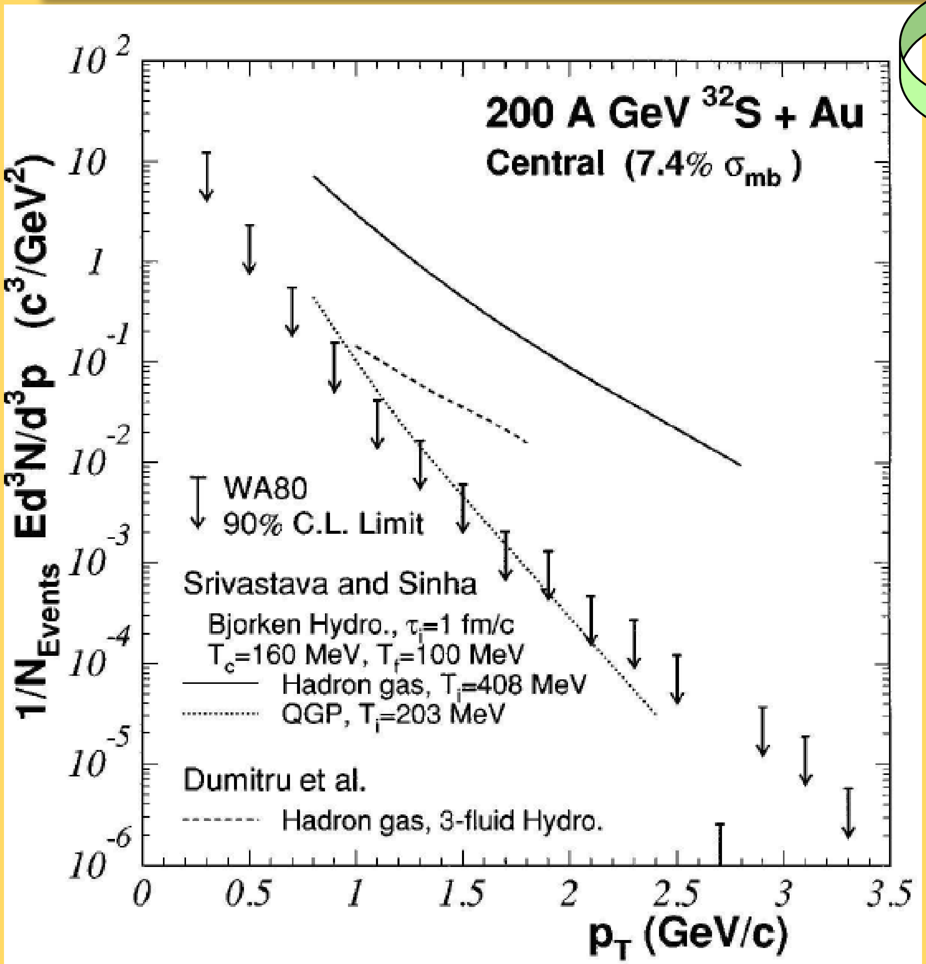
Rates are similar !!

We need QGP at higher T_0 for golden photons to clearly outshine others.

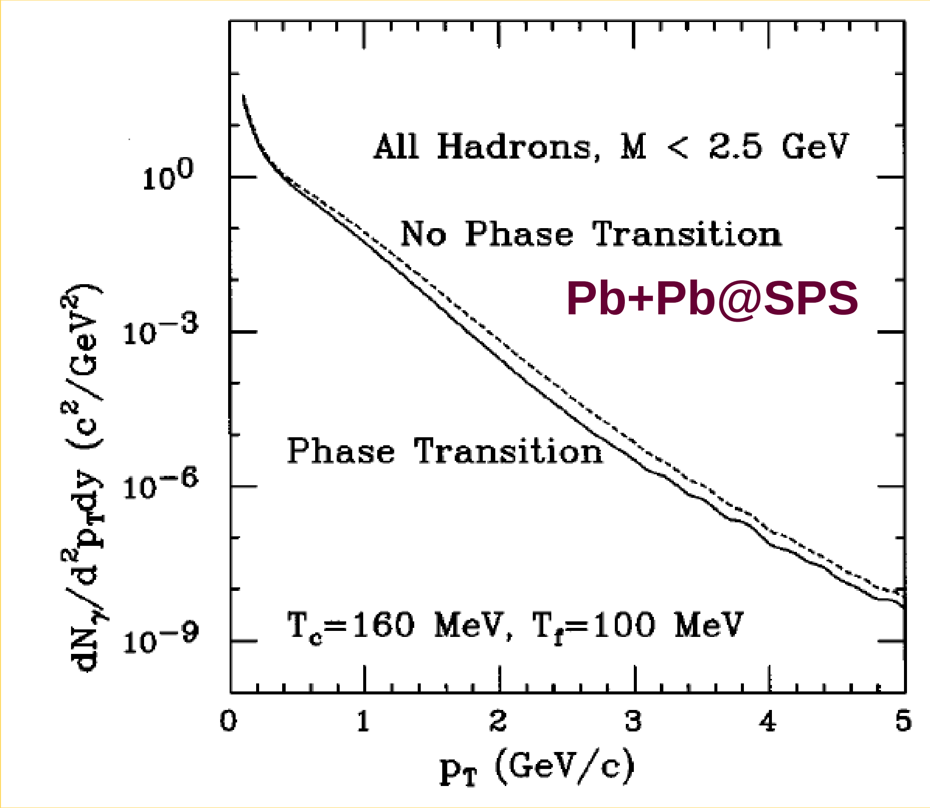
Arnold, Moore, & Yaffe, JHEP 0112 (2001) 009.

Turbide, Rapp, & Gale, PRC 69 (2004) 014903.

Upper Limit of Single Photons, WA80



Ruled out hadronic gas with limited hadrons: π, ρ, ω, & η.

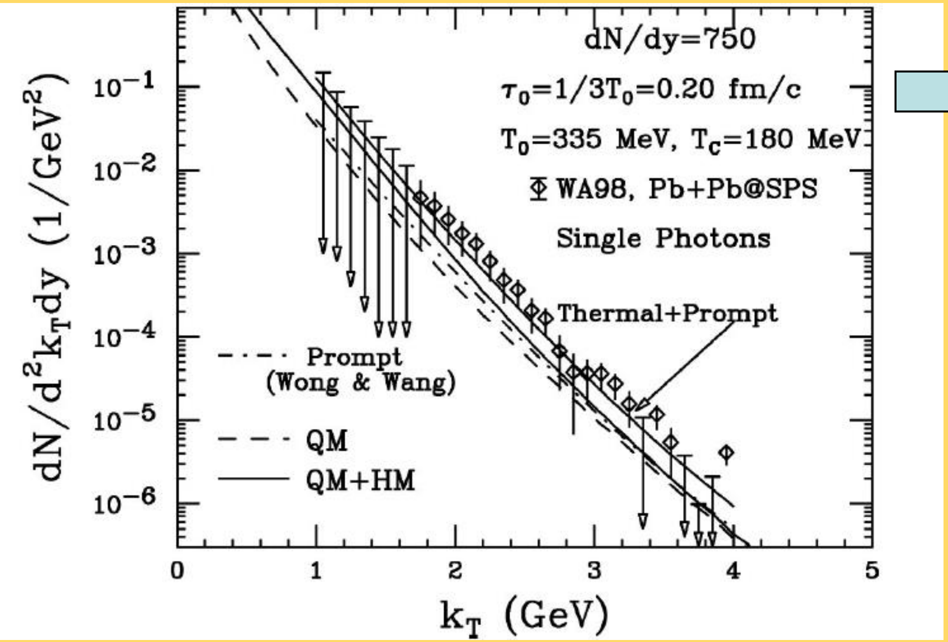


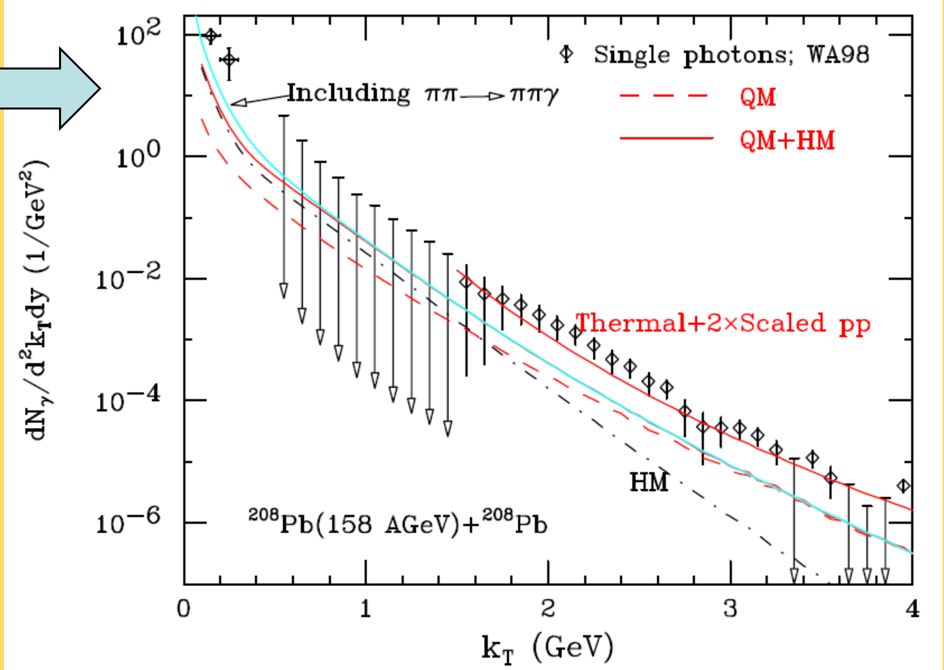
S. and Sinha, PRL 73 (1994) 2421;
Dumitru et al., PRC 51 (1995) 2166.

Sollfrank et al., Lee & Brown, Arbex et al., .

Cleymans, Redlich, & S.,
PRC 55 (1997) 1431.
However, n_{had} >> 2-3 /fm^3 ! For No Phase Transition.

WA98: 2-loop → Complete O(α_s) for QGP & $\pi\rho a_1$→ Exhaustive Hadronic Reactions for hadrons





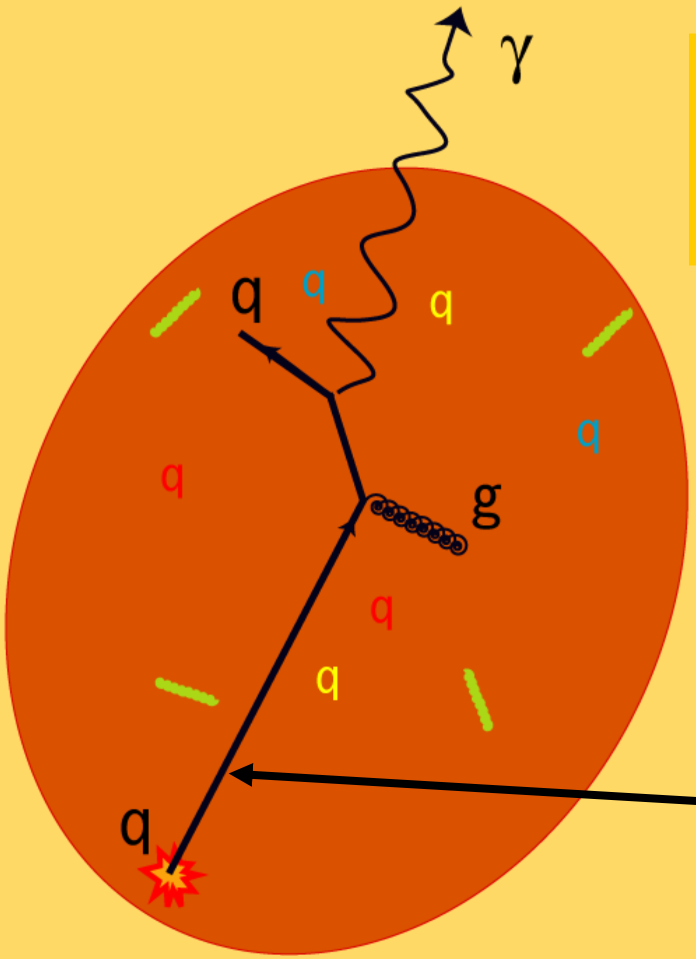
S. & Sinha, PRC 64 (2001)034902 (R).

S., PRC 71 (2005) 034905.

Hydrodynamics, QGP + rich EOS for hadrons

& accounting for the prompt photons

Interaction of hard-scattered parton with dense matter



Jet Photon Conversion

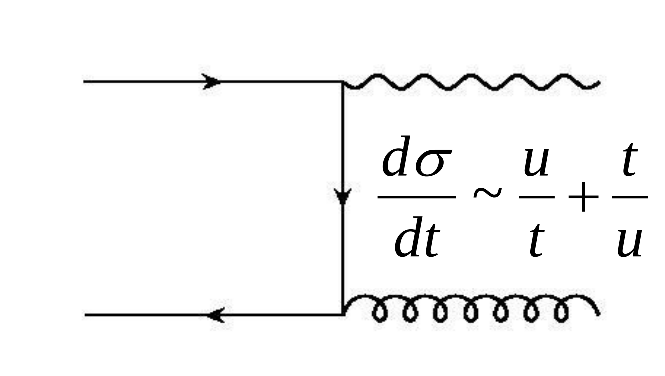
“External Probe!!”

Hard scattered parton

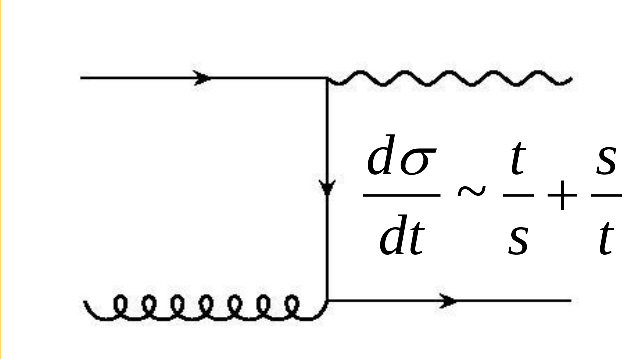
Fries, Mueller, & S. , PRL 90 (2003) 132301.

Jet-Initiated EM Radiations from QGP

- Annihilation and Compton processes peak in forward and backward directions:



$$\vec{p}_\gamma \approx \vec{p}_q$$
$$\vec{p}_\gamma \approx \vec{p}_{\bar{q}}$$



- one parton from hard scattering, one parton from the thermal medium; cutoff $p_{\gamma,min}$ > 1 GeV/c.

➢ photon carries momentum of the hard parton

➢ Jet-Photon Conversion

➢ This puts photon production and jet-quenching on the same page!!

Jet-Photon Conversion: Rates

- Annihilation and Compton rates:

quark (-jet) distribution

$$E_\gamma \frac{dN^{(A)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(p_\gamma)$$

$$\times \int d^3p \, f_{\bar{q}}(p)[1+f_g(p)]\sigma^{(A)}(s) \frac{\sqrt{s(s-4m^2)}}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

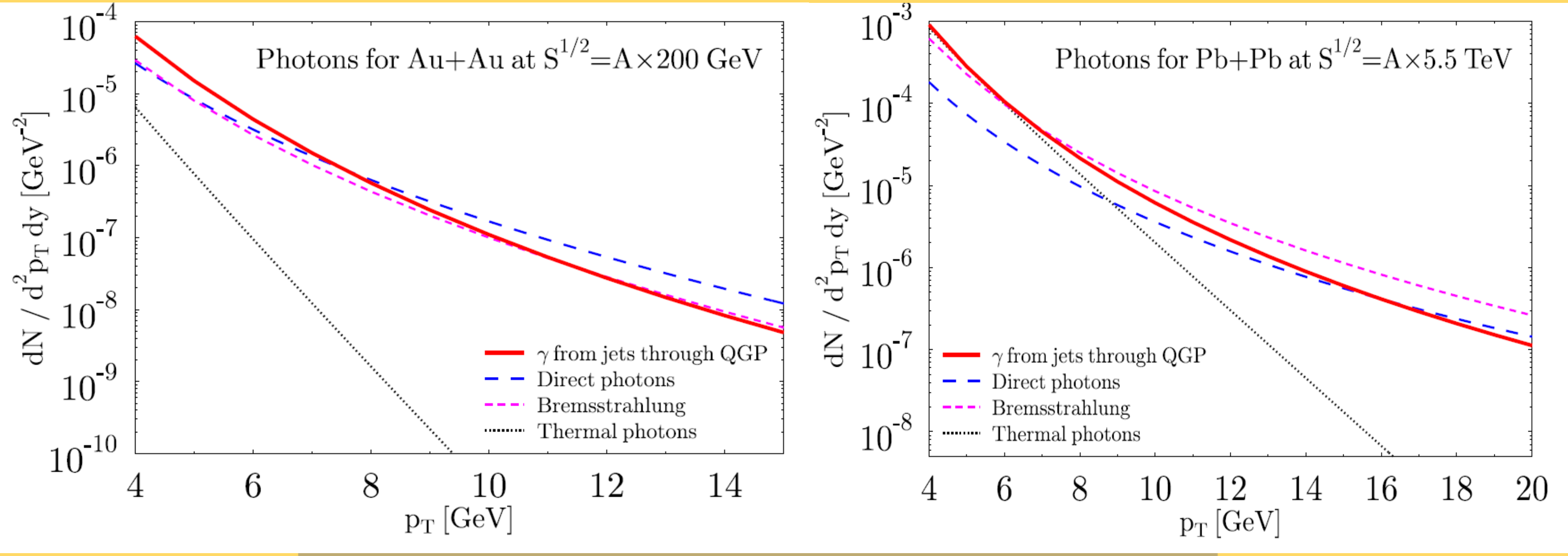
$$E_\gamma \frac{dN^{(C)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(p_\gamma)$$

$$\times \int d^3p \, f_g(p)[1-f_q(p)]\sigma^{(C)}(s) \frac{s-m^2}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

- thermal medium:

$$E_\gamma \frac{dN_\gamma}{d^3p_\gamma} = \frac{\alpha\alpha_s}{8\pi^2} \int d^4x \frac{2}{3}\left[f_q(p_\gamma) + f_{\bar{q}}(p_\gamma)\right] T^2 \left(\ln \frac{4E_\gamma T}{m^2} + C \right)$$

Photons from Passage of Jets through QGP

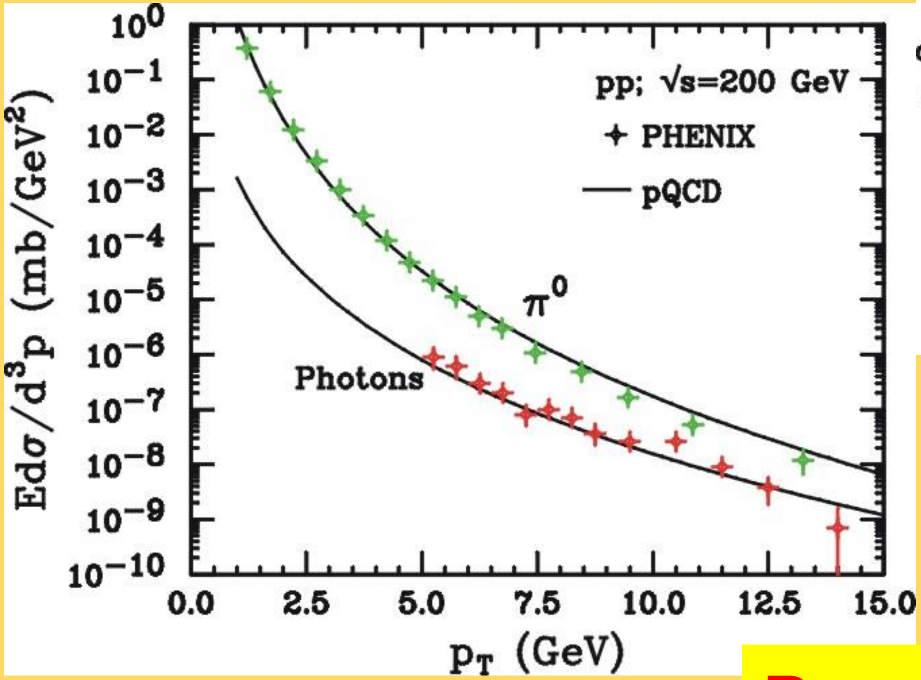


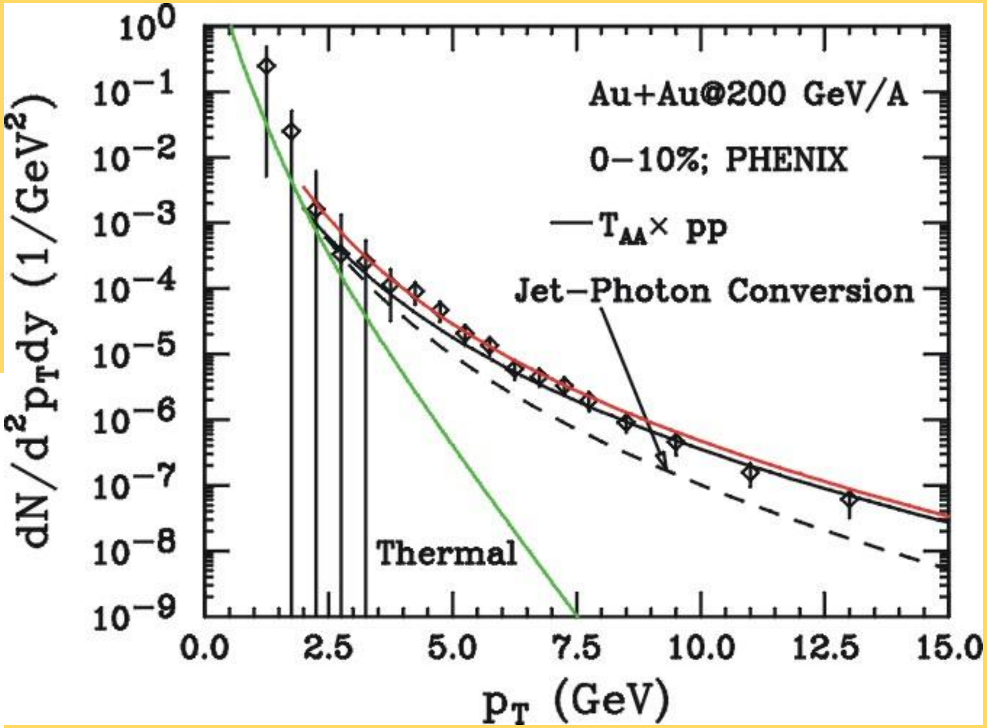
Fries, Mueller, & S., PRL 90 (2003) 132301.

This "bremsstrahlung" contribution will be suppressed due to E-loss and there will be an additional jet-induced bremsstrahlung, which is also similarly suppressed, leaving the jet-conversion photons as the largest source for p_T = 4-10 GeV.

FMS Results: Comparison to Data

calibrate pQCD calculation of direct and Bremsstrahlung photons via p+p data:



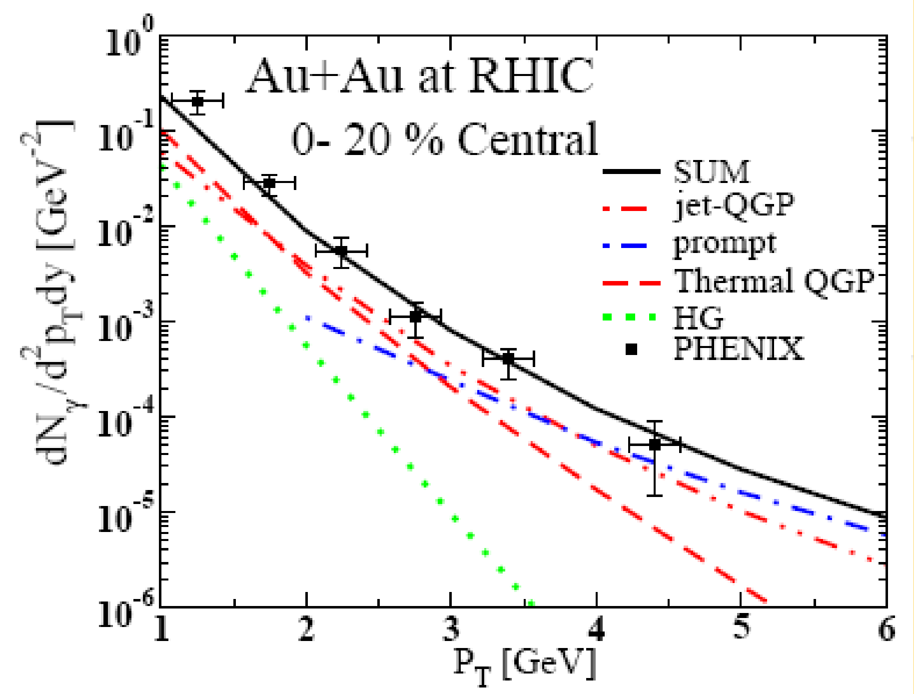


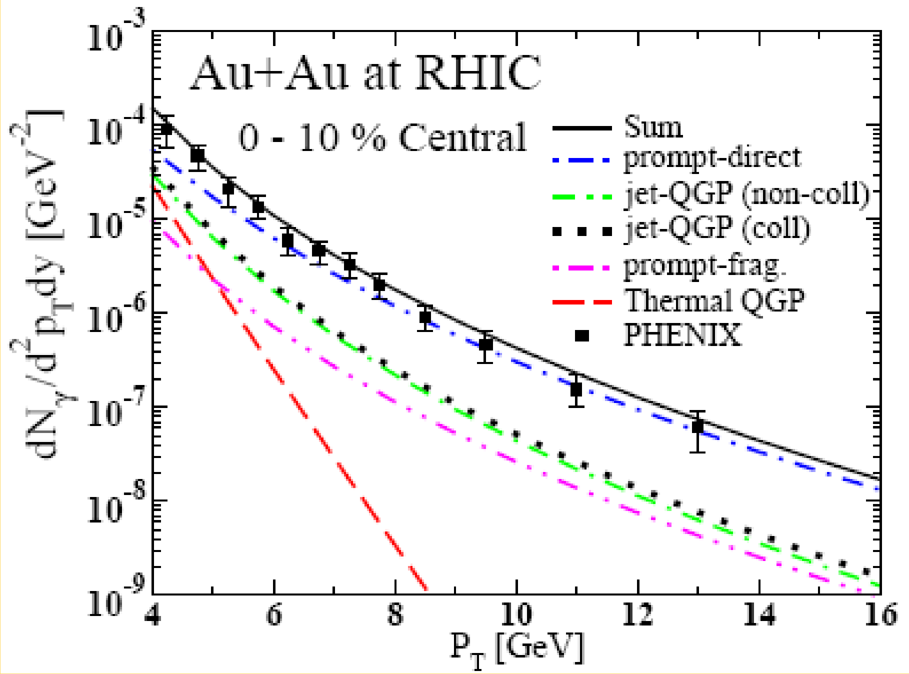
- for p_t<6 GeV, FMS photons give significant contribution to photon spectrum: 50% @ 4GeV.

Proper Isospins & Shadowing !!!

Fries, Mueller, & S., PRC 72 (2005) 041902(R).

AMY and One-Stop Treatment of Jet-Quenching and Jet-Initiated Photons

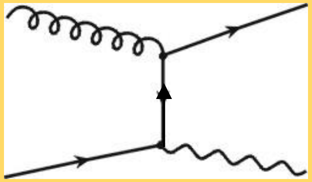


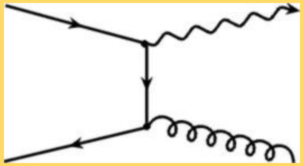


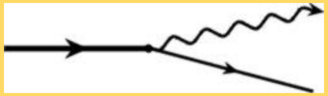
Turbide, Gale, Frodermann, & Heinz, hep-ph/0712.732

This supersedes Turbide, Gale, Jeon, & Moore, PRC 72 (2005) 014906; which used AMY but all the processes were calculated using hard spheres and ignoring transverse expansion.

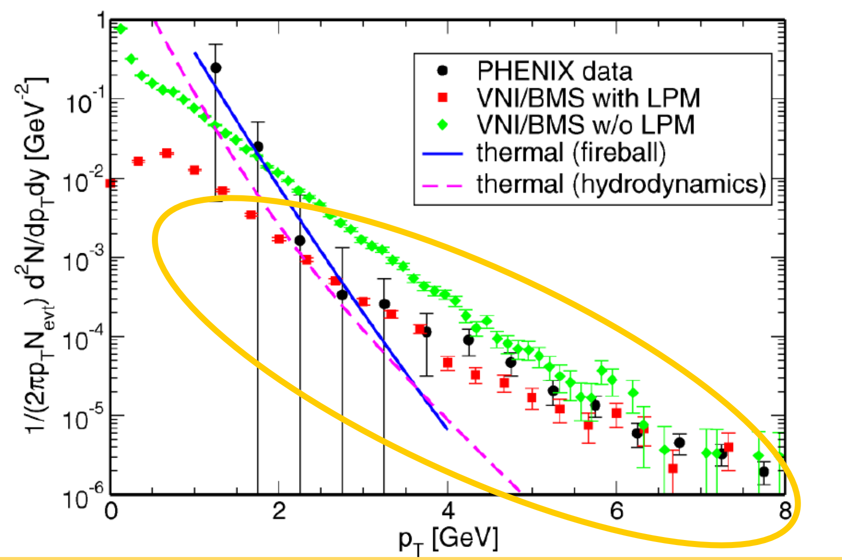
Parton Cascade Model

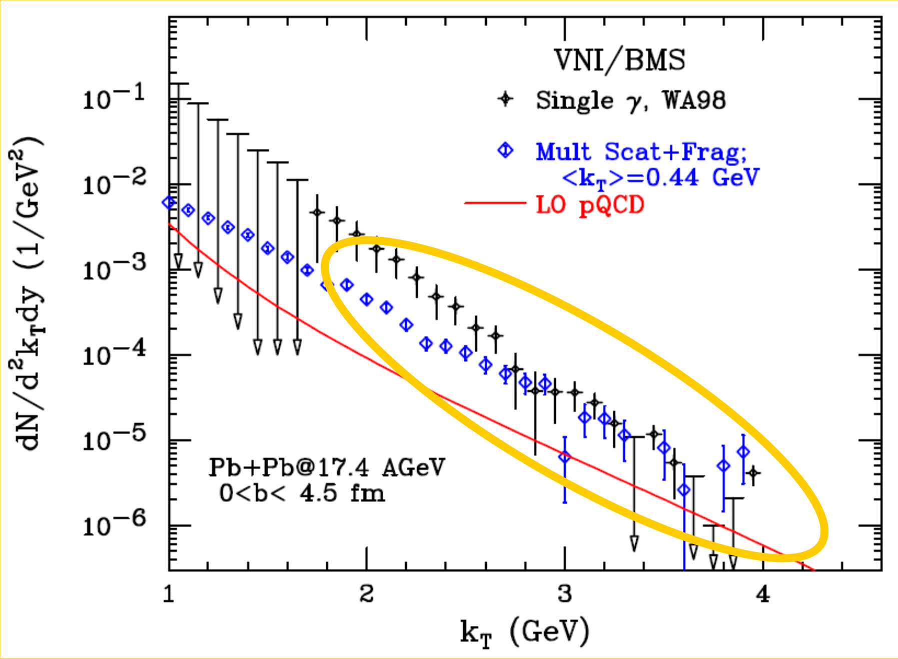






Embedded in the partonic cascades



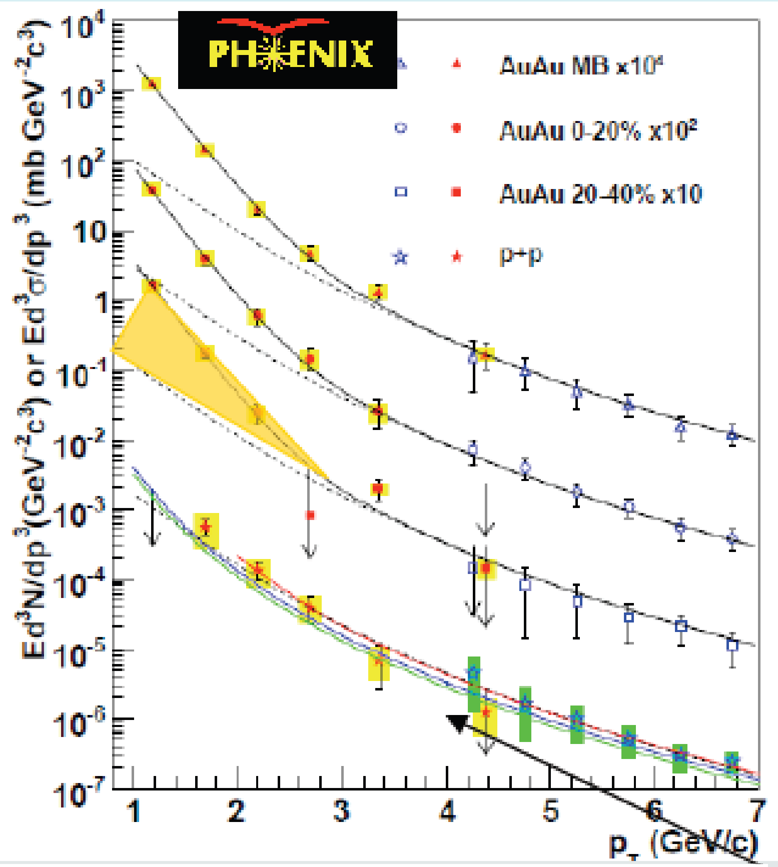


Renk, Bass, & S., PLB 632 (2006) 632.

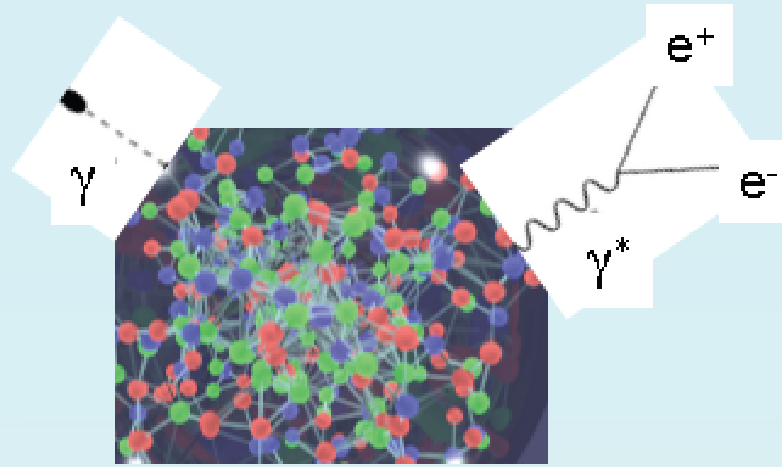
Bass, Mueller, & S., PRC 66 (2002) 061902 (R).

LPM plays a significant role.

Initial temperature? Thermal radiation



Phys.Rev.Lett.104:132301,2010

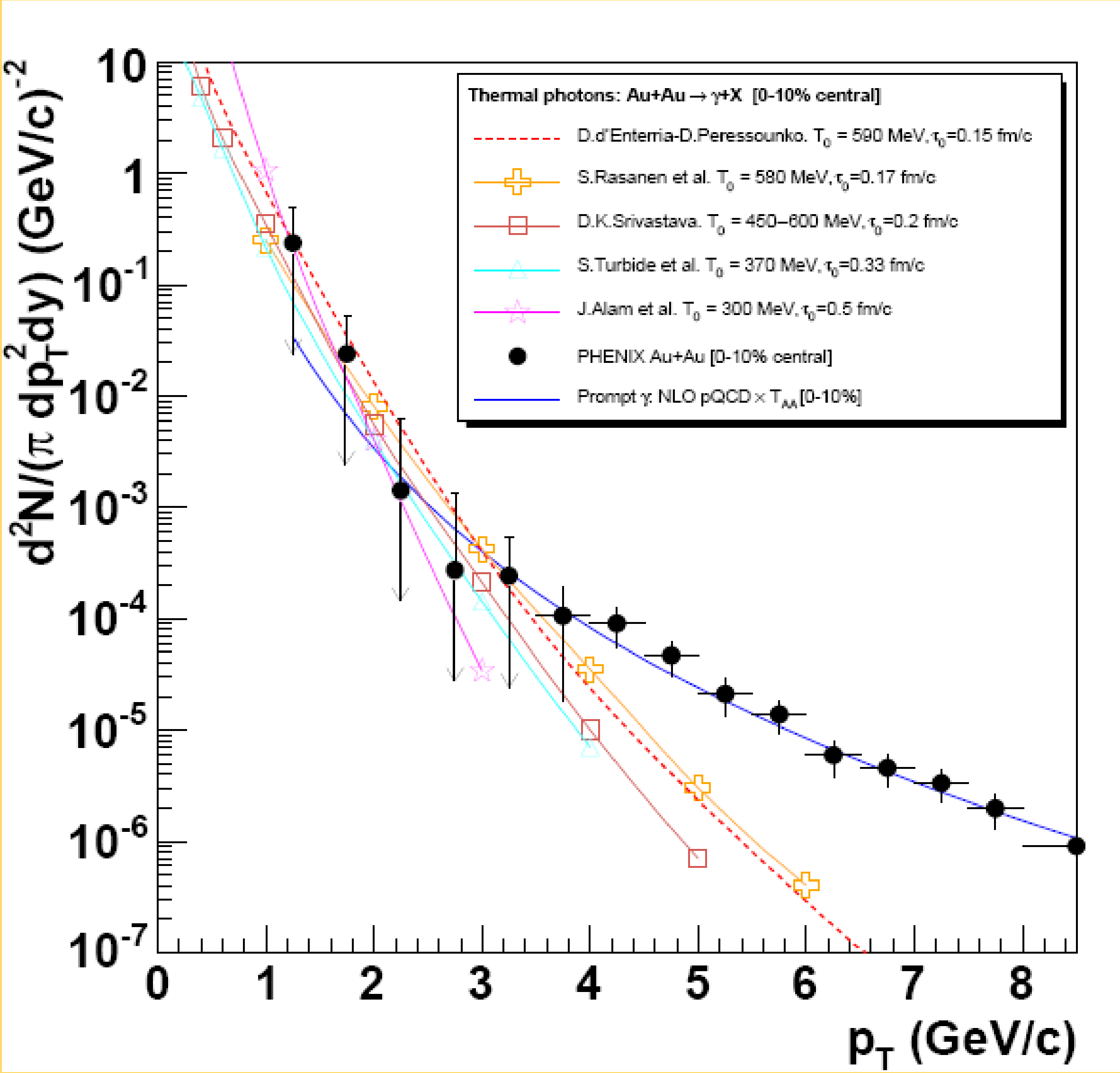


Low mass, high p_T e^+e^- → nearly real photons

Large enhancement above p+p in the thermal region

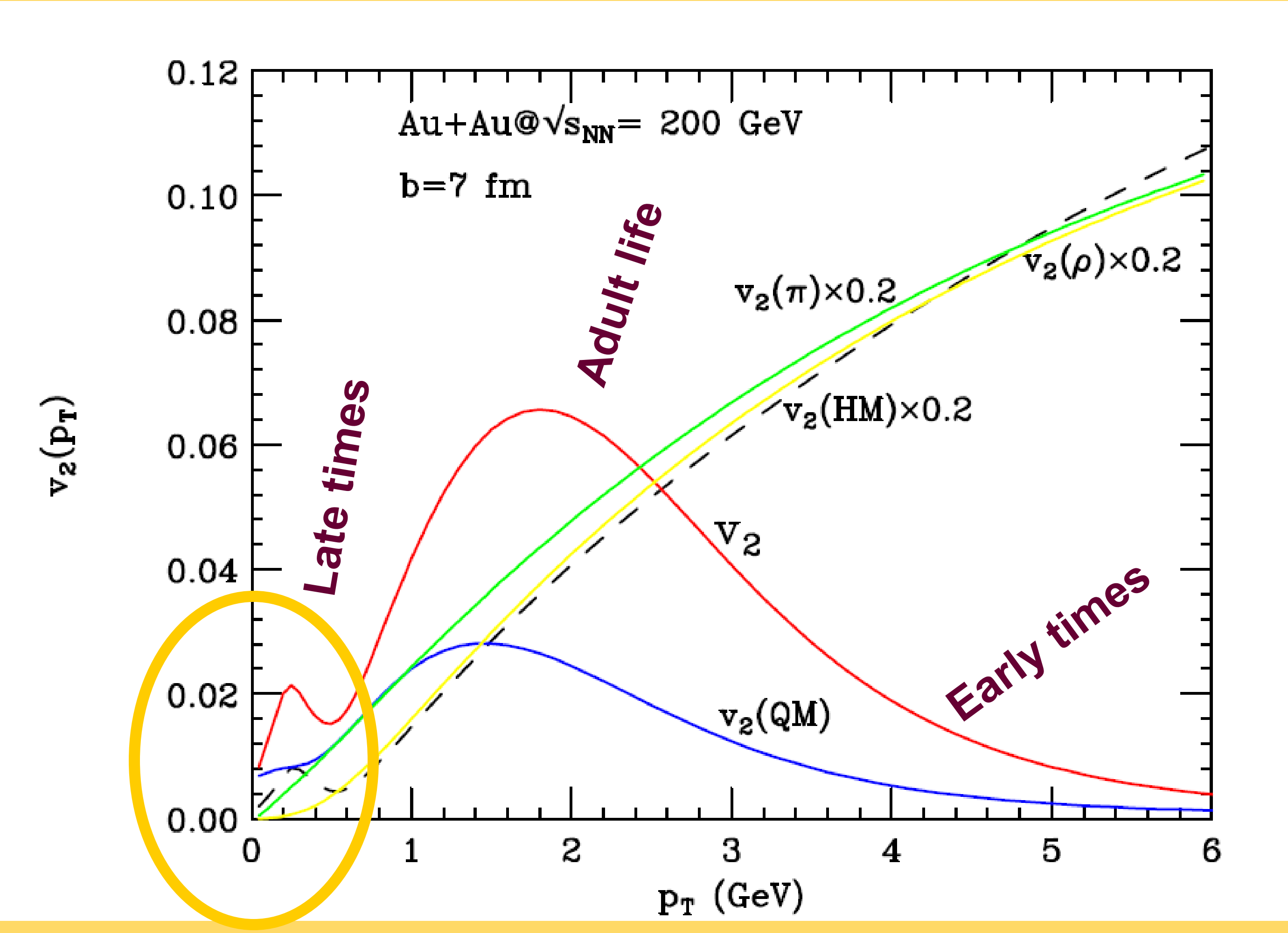
pQCD γ spectrum: q+g→q+γ (Compton scattering @ NLO) agrees with p+p data

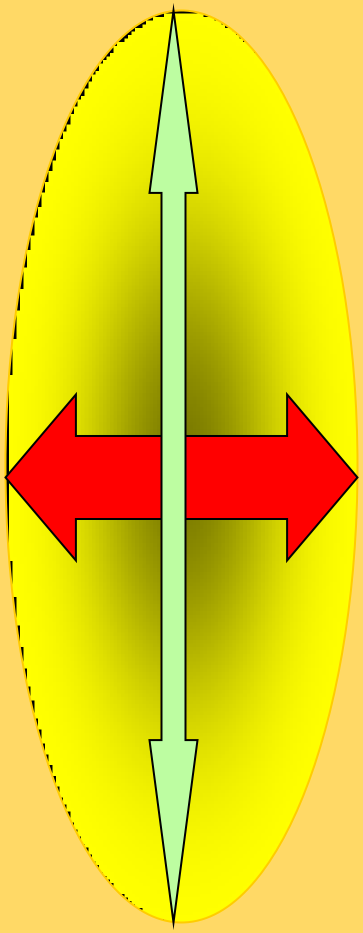
Thermal photons from Au+Au@RHIC



d’Enterria & Peressounko, EPJC 46 (2006) 451.

Elliptic Flow of Thermal Photons:
Measure Evolution of Flow !

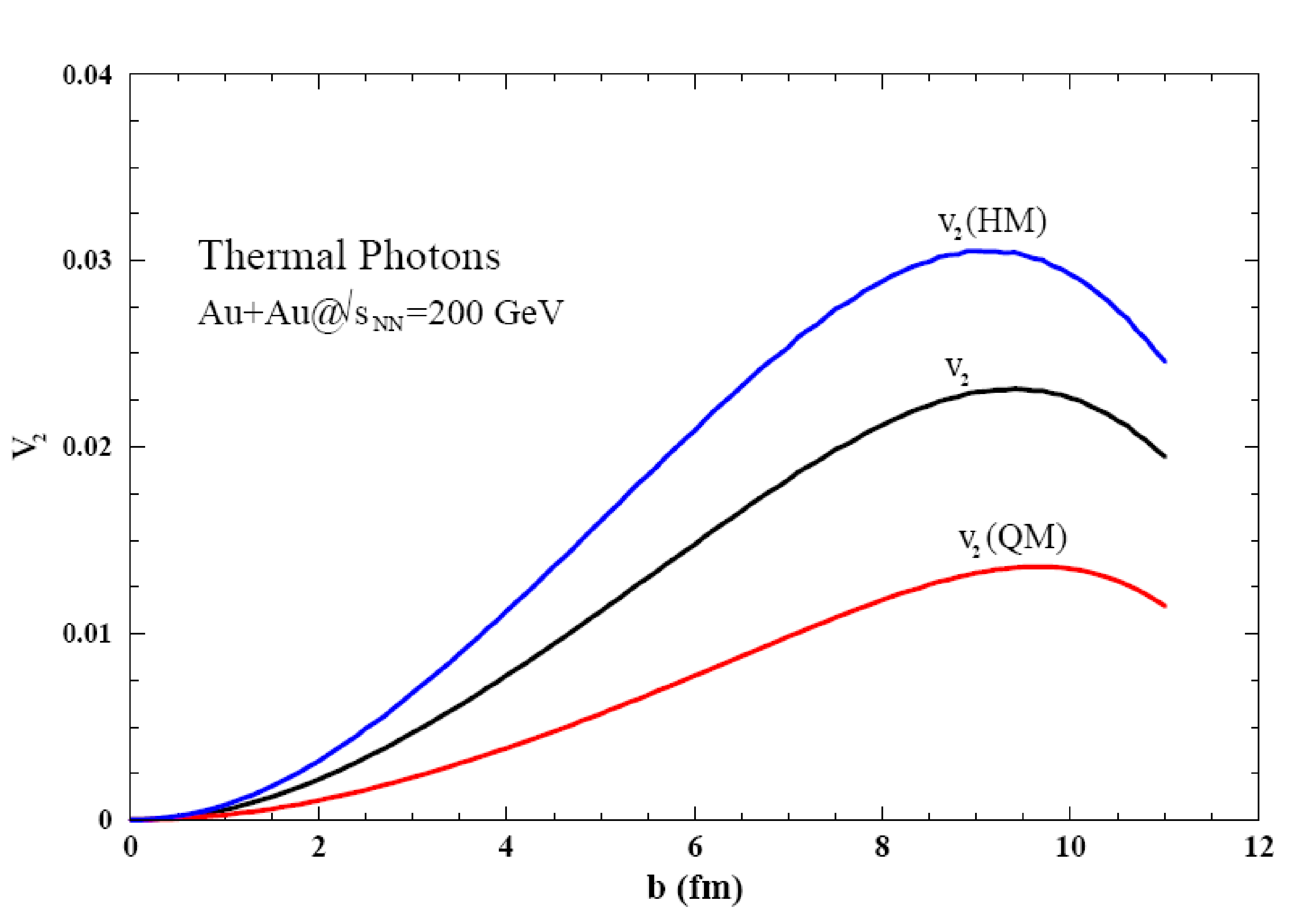




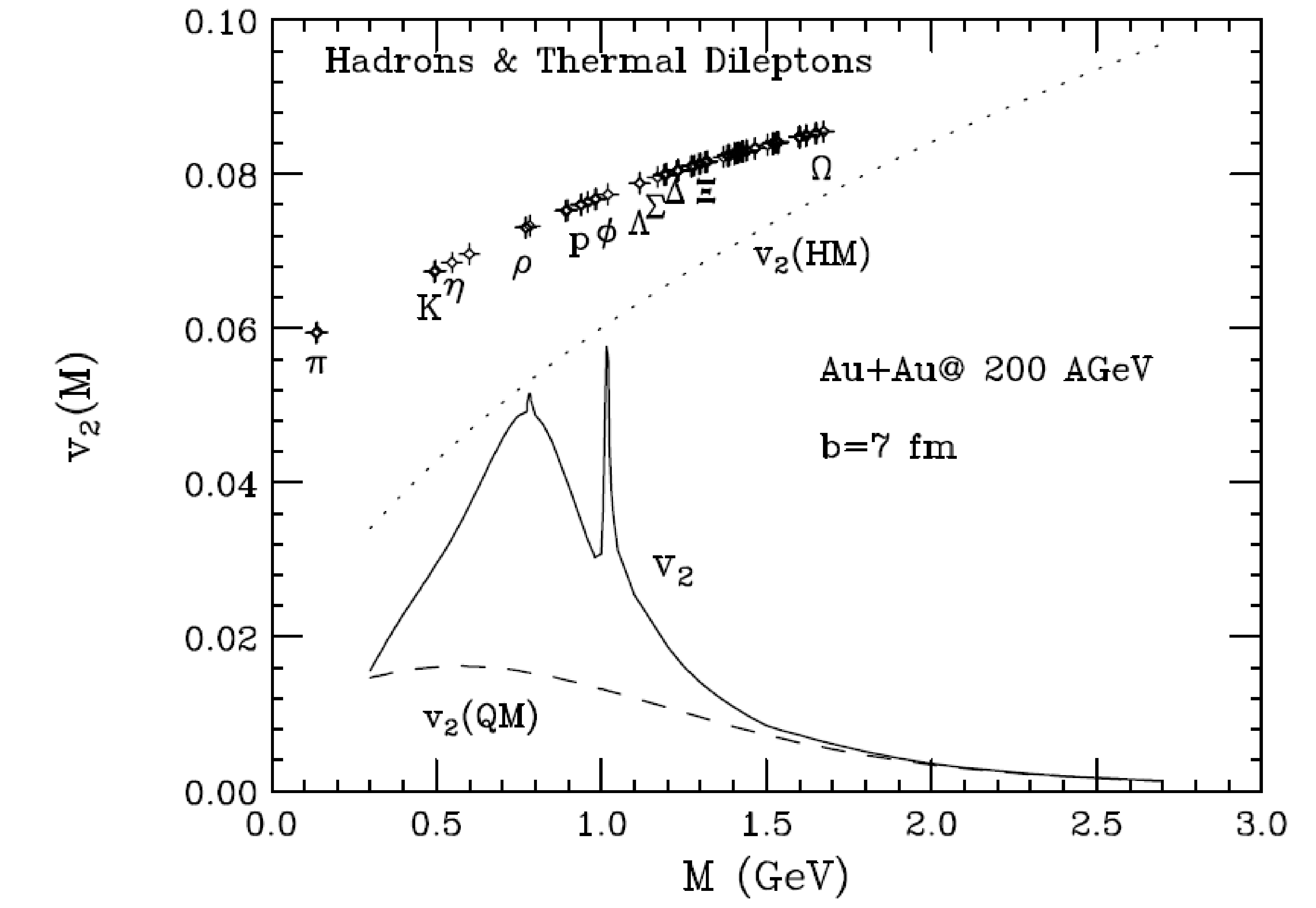
Chatterjee, Frodermann, Heinz, and S., PRL 96 (2006) 202302.

FIRST

Impact Parameter Dependence of v_2



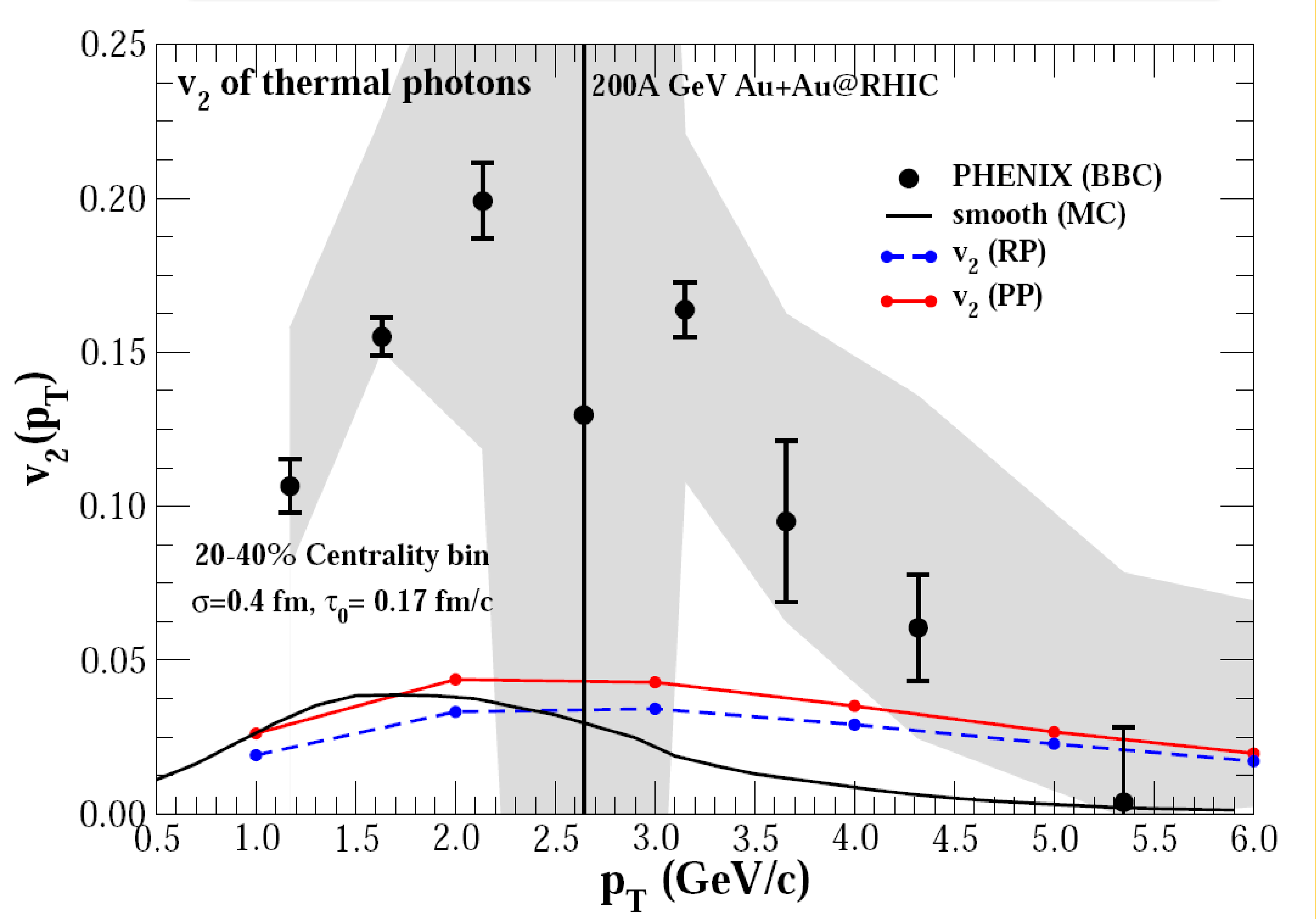
Elliptic Flow of Thermal Dileptons: *Measure Evolution of Flow !*



Chatterjee, Heinz, Gale, & S., PRC 75, 054909 (2007).

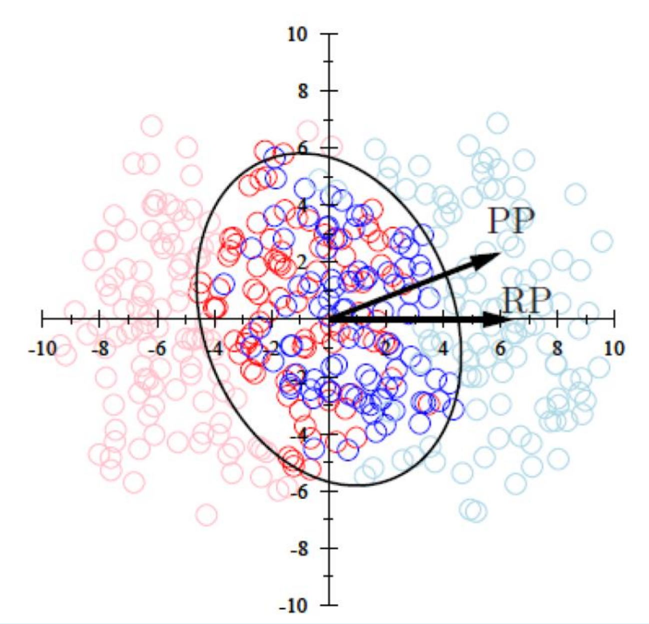
FIRST

Elliptic flow of thermal photons



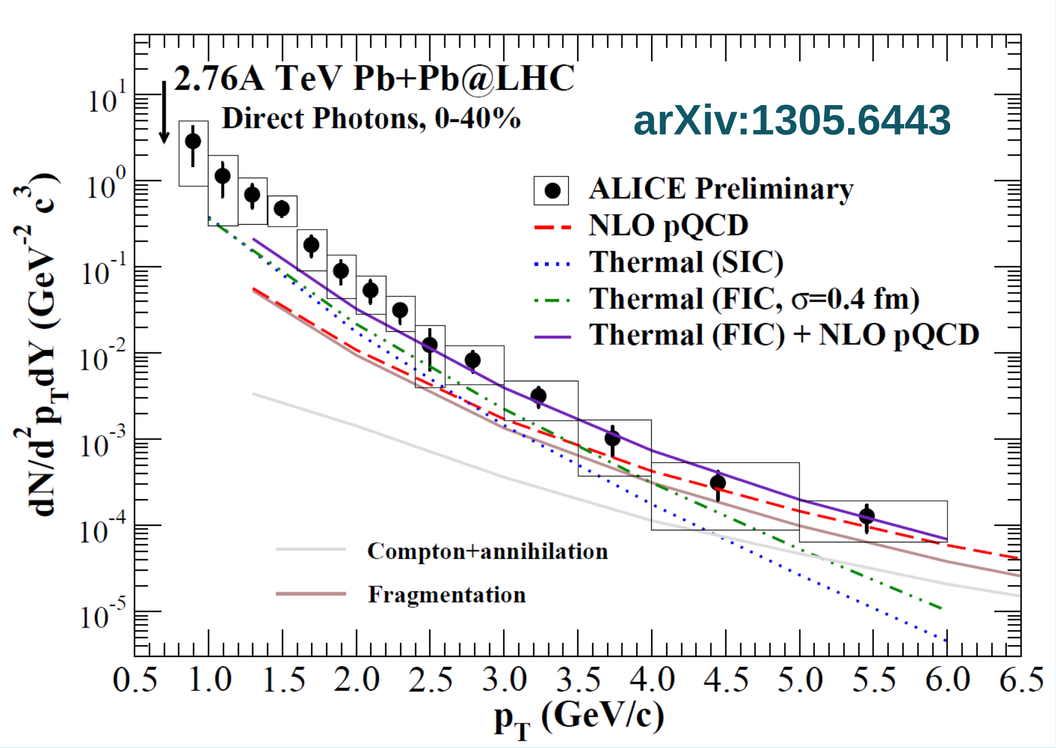
Chatterjee et al.

Event-by-event fluctuating initial density distribution

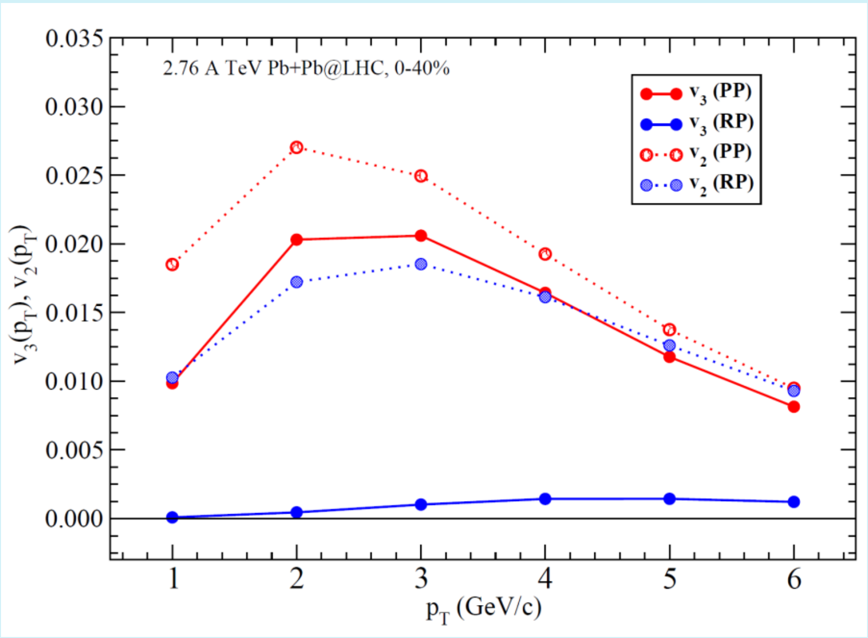


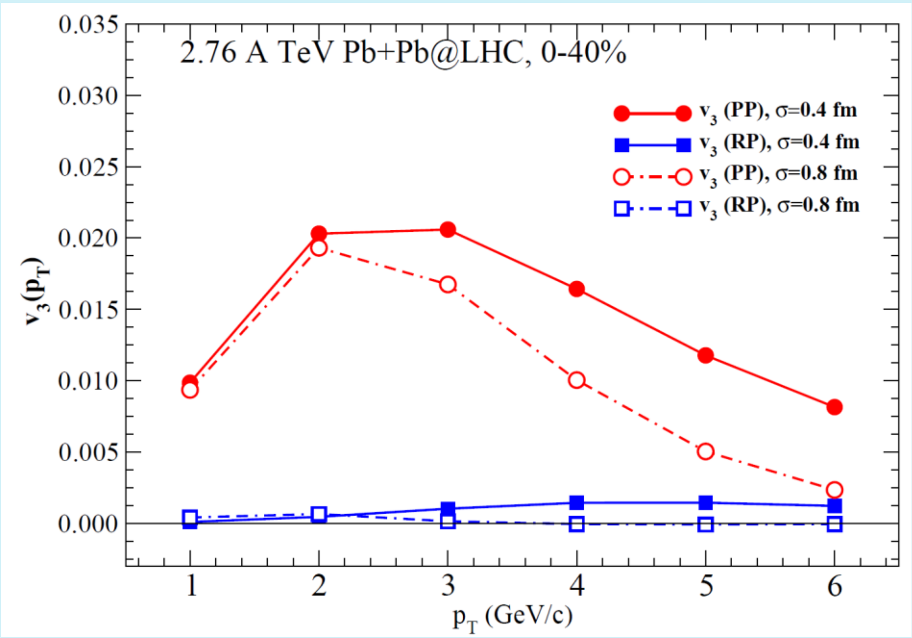
The '**hotspots**' in the fluctuating events produce more high p_T photons compared to a smooth initial state averaged profile.

Fluctuation size parameter σ=0.4 fm



Triangular flow of thermal photons





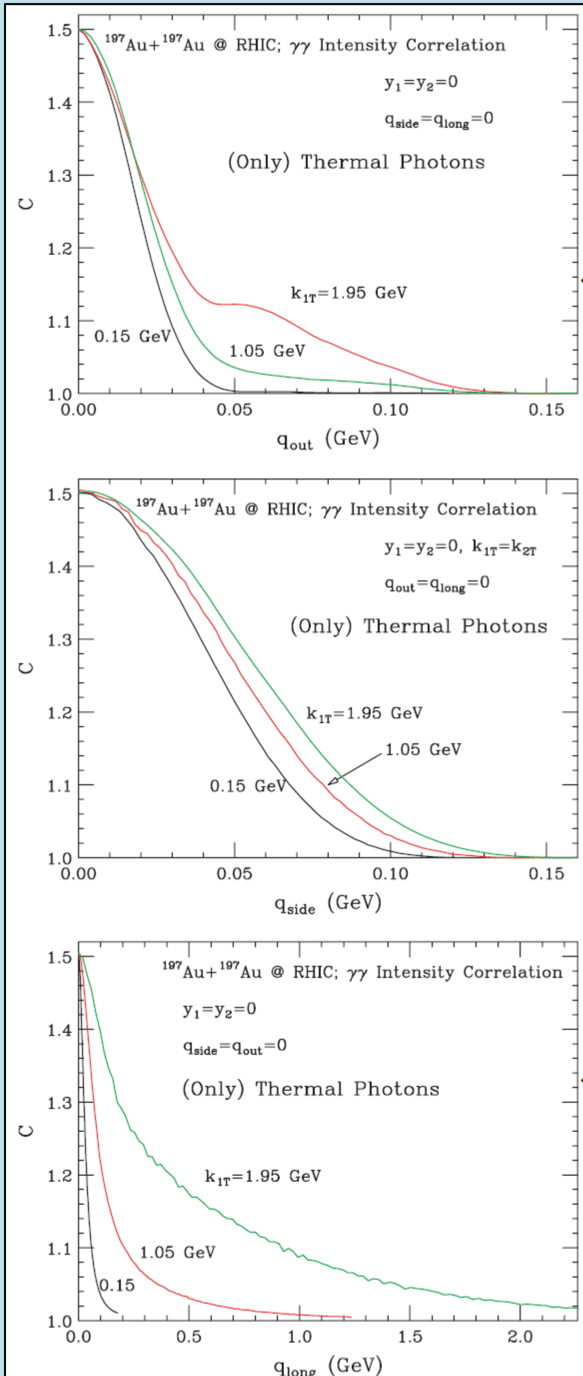
v_3 (p_T) for 2.76A TeV Pb+Pb@ LHC

σ dependence of v_3

Chatterjee, Holopainen, DKS [in preparation]

Intensity Interferometry of Thermal Photons

200A GeV Au+Au@RHIC
$\gamma\gamma$ intensity correlation



$C(q_{out}, q_{side}=q_{long}=0)$

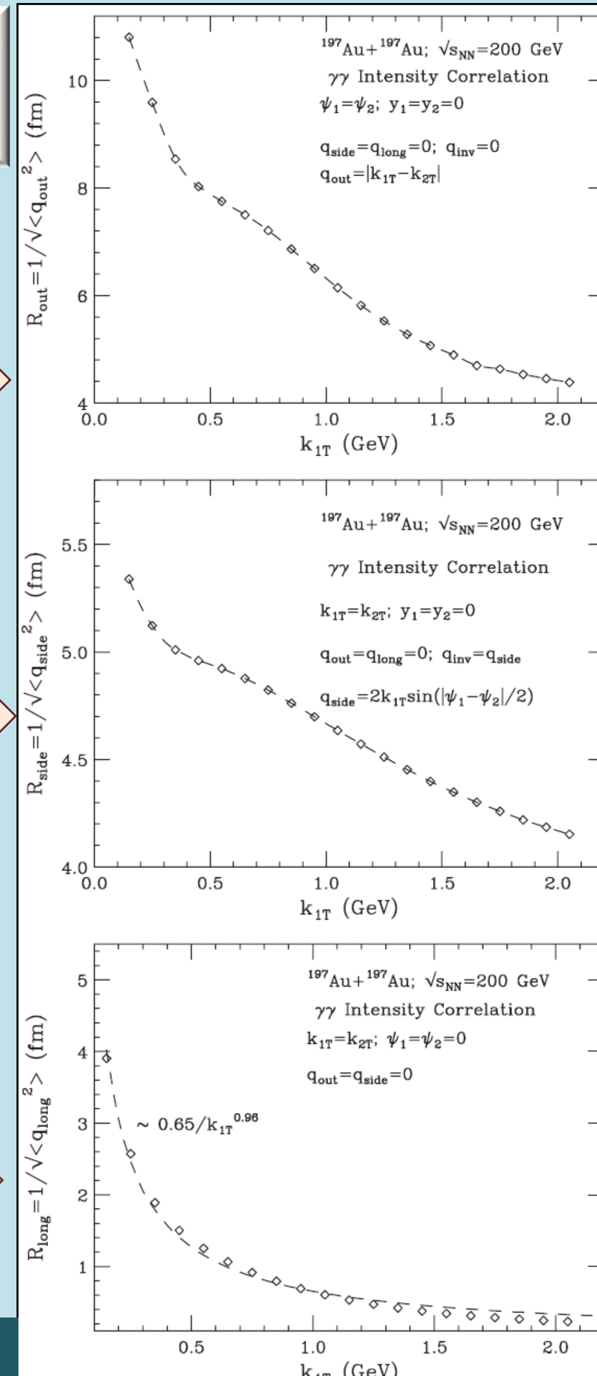
$R_{out}(K_{1T})$
$q_{side}=q_{long}=0$

$C(q_{side}, q_{out}=q_{long}=0)$

$R_{side}(K_{1T})$
$q_{out}=q_{long}=0$

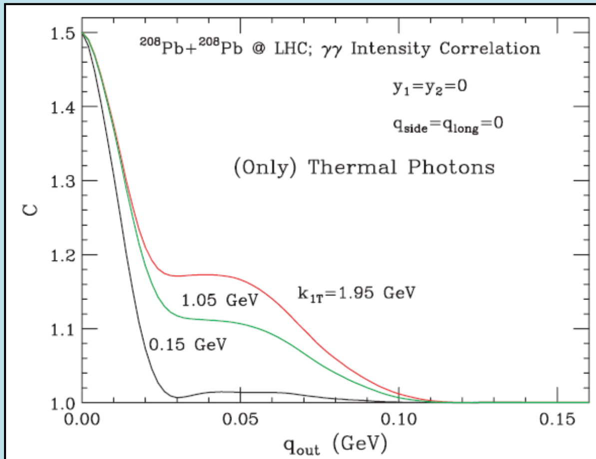
$C(q_{long}, q_{out}=q_{side}=0)$

$R_{long}(K_{1T})$
$q_{out}=q_{side}=0$



DKS, PRC 71 (2005) 034905.

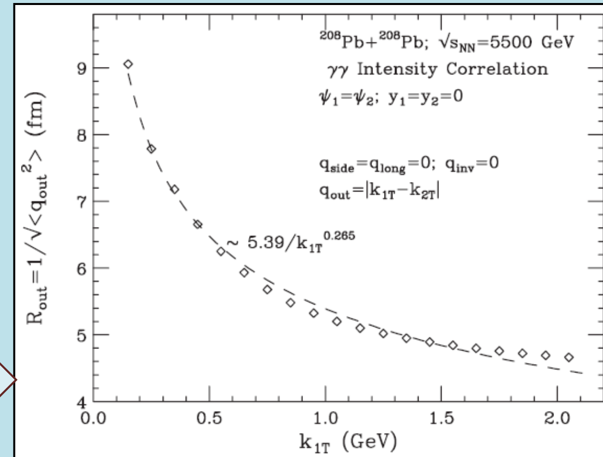
5.5A TeV Pb+Pb@LHC
$\gamma\gamma$ intensity correlation

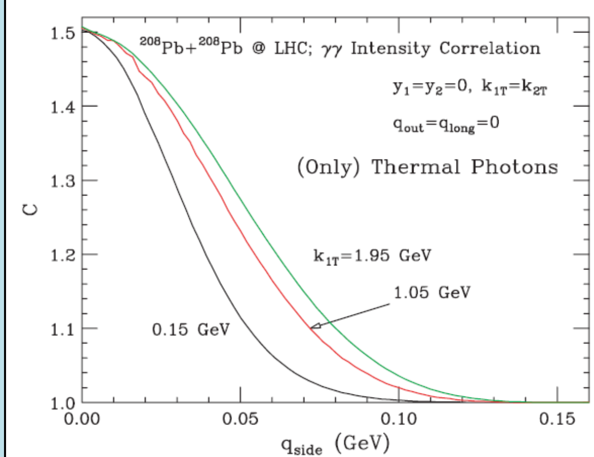


$C(q_{out}, q_{side}=q_{long}=0)$

$R_{out}(K_{1T})$

$q_{side}=q_{long}=0$

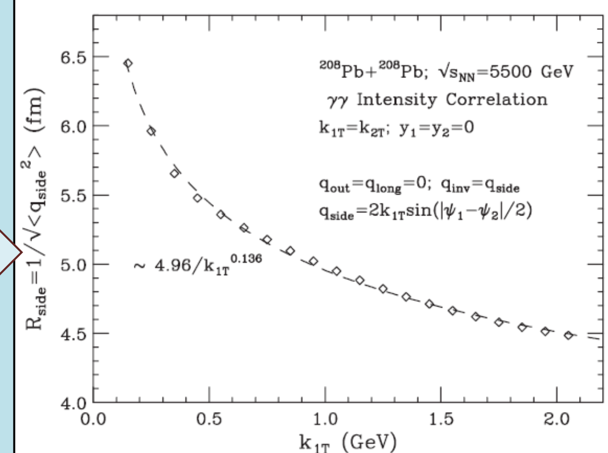


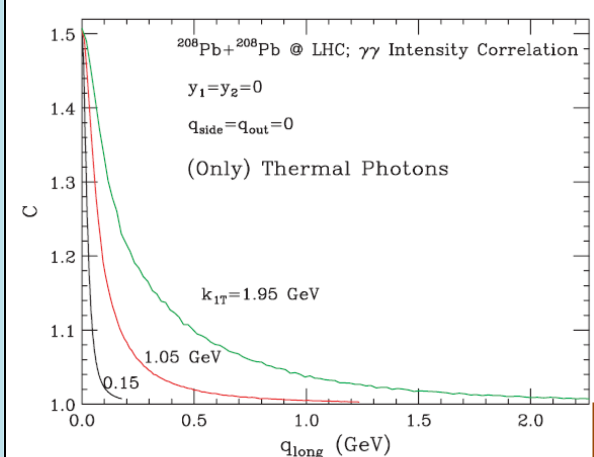


$C(q_{side}, q_{out}=q_{long}=0)$

$R_{side}(K_{1T})$

$q_{out}=q_{long}=0$

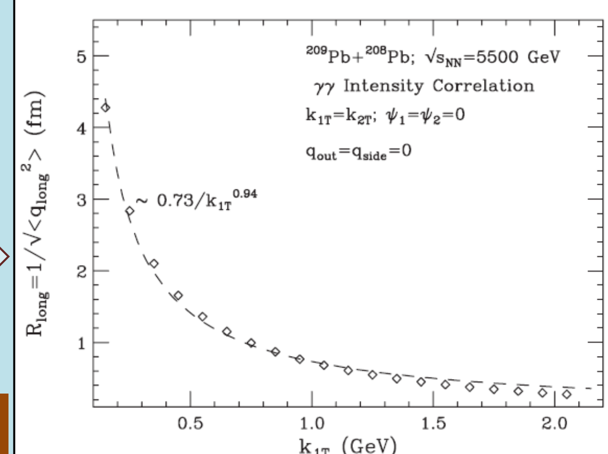




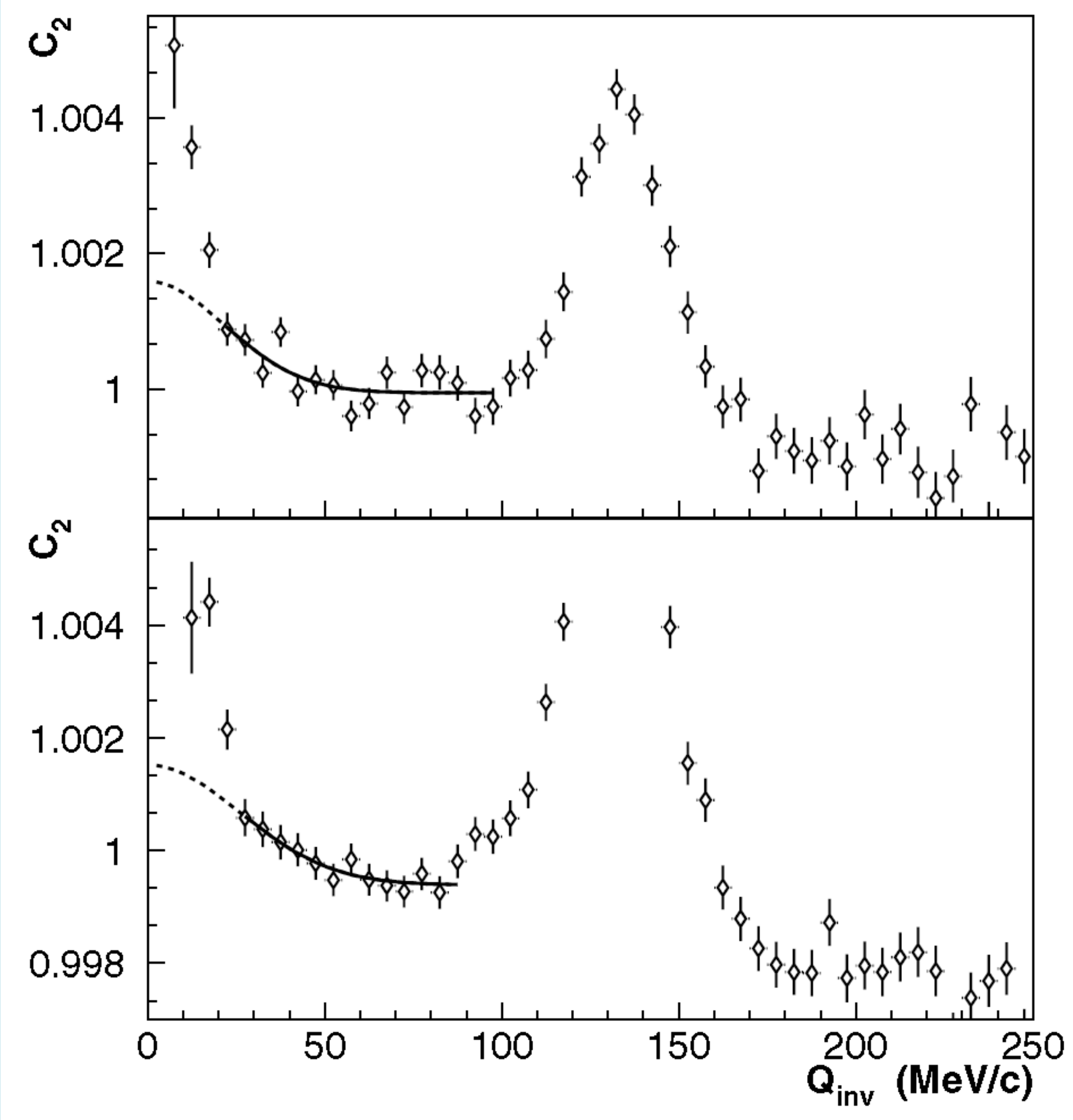
$C(q_{long}, q_{out}=q_{side}=0)$

$R_{long}(K_{1T})$

$q_{out}=q_{side}=0$



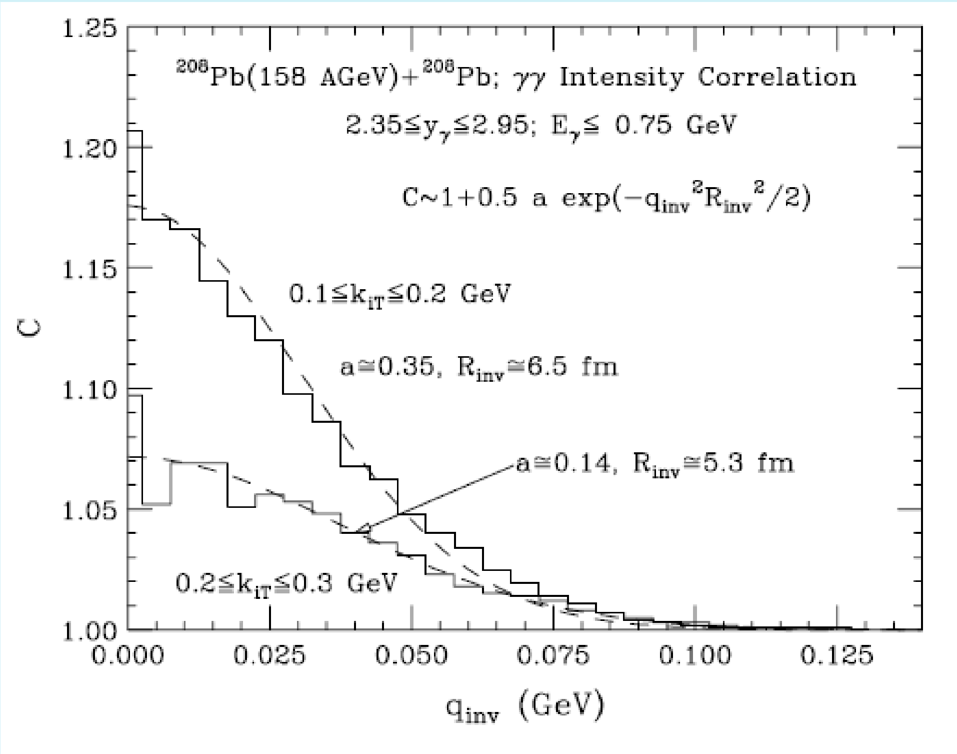
DKS, PRC 71 (2005) 034905.



The two-photon correlation function for *average photon* momenta 100 < K_T < *200 MeV/c (top) and 200* < K_T < 300 MeV/c *(bottom). The solid line shows* the fit result in the fit region used (excluding the π^0 peak at $Q_{inv} \approx m_{\pi 0}$ *) and the dotted line shows the extrapolation into* the low Q_{inv} *region where backgrounds are large.*

M. M. Aggarwal *et al.*, [WA98 collaboration] PRL 93, 022301 (2004)

Intensity Interferometry of Thermal Photons @SPS



A one-dimensional analysis of the correlation function *C* is performed in terms of the invariant momentum difference as follows:

$$C(q_{inv}) = 1 + \frac{1}{2}\lambda \exp\left[-q_{inv}^{2} R_{inv}^{2}/2\right]$$

$$q_{inv} = \sqrt{-(k_1^{\mu} - k_2^{\mu})^2} = \sqrt{-q_0^{2} + q^{2}}$$

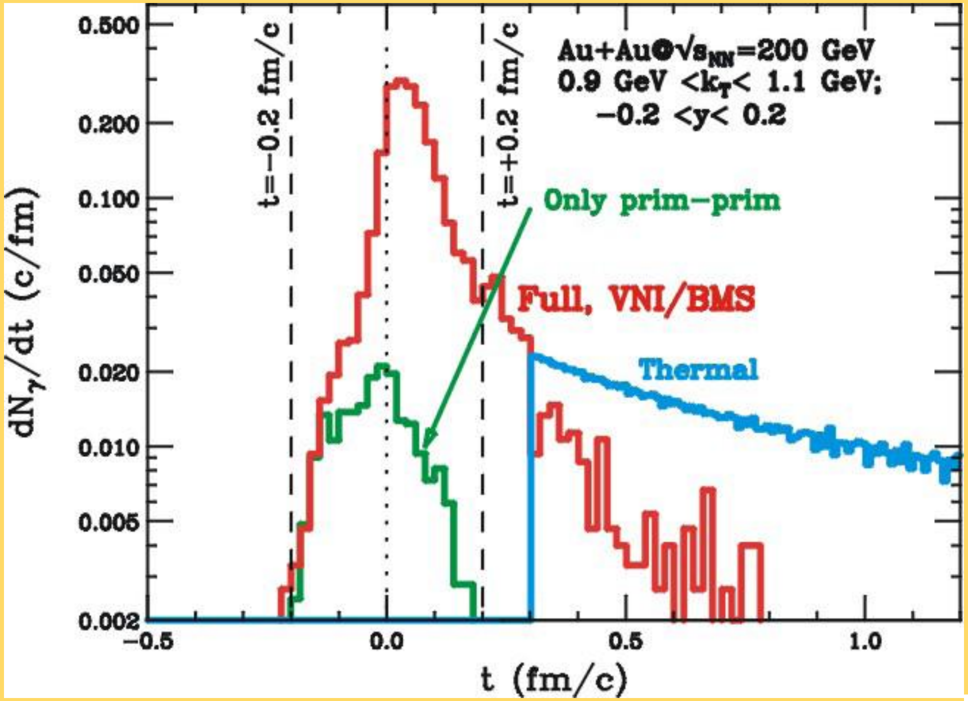
$$= \sqrt{2k_{1T}k_{2T}\left[\cosh(y_1 - y_2) - \cos(\psi_1 - \psi_2)\right]}$$

where, $q^2 = q_{out}^{2} + q_{side}^{2} + q_{long}^{2}$

WA98 measures R_{inv} as 8.34 ± 1.7 fm and 8.63 ± 2.0 fm, respectively

DKS, PRC 71 (2005) 034905.

For y_1=y_2=0 and ψ_1=ψ_2=0, q_{side}=q_{long}=q_{inv}=0, but q_{out}=k_{1T}-k_{2T} .ne.0



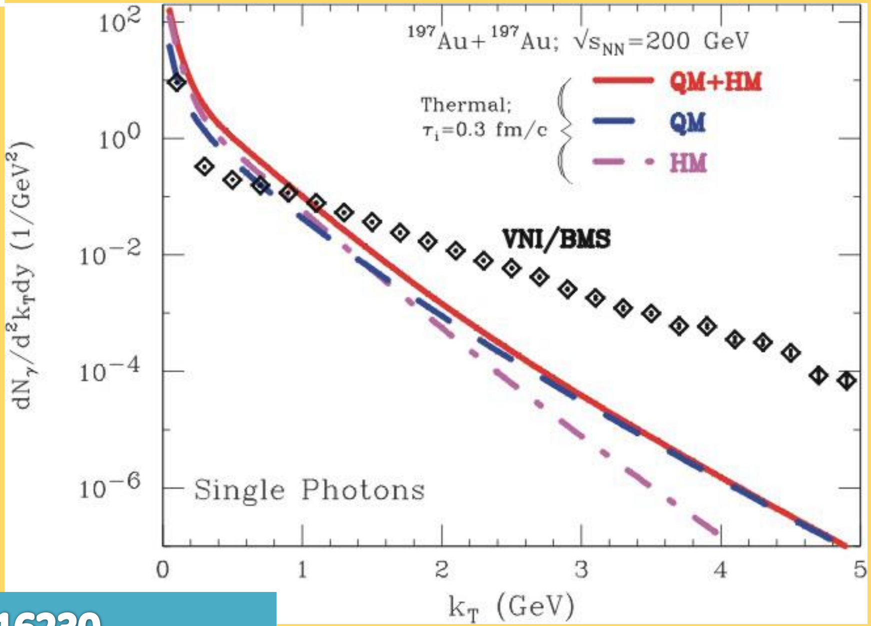
pre-equilibrium contributions are easier identified at large p_T.

window of opportunity above p_T = 2 GeV.

at 1 GeV, need to take thermal contributions into account.

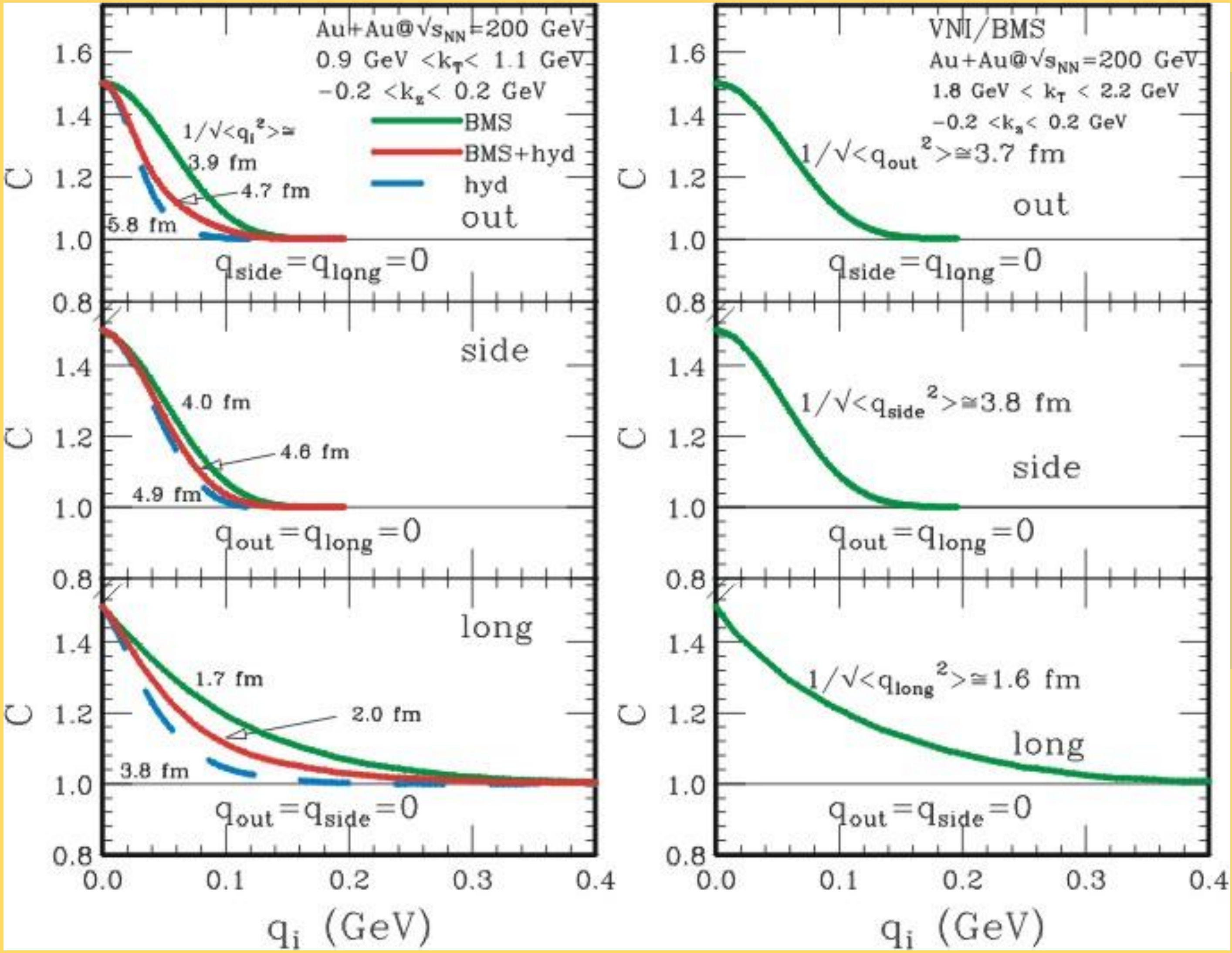
- short emission time in the PCM, 90% of photons before 0.3 fm/c

- hydrodynamic calculation with τ_0=0.3 fm/c allows for a smooth continuation of emission rate



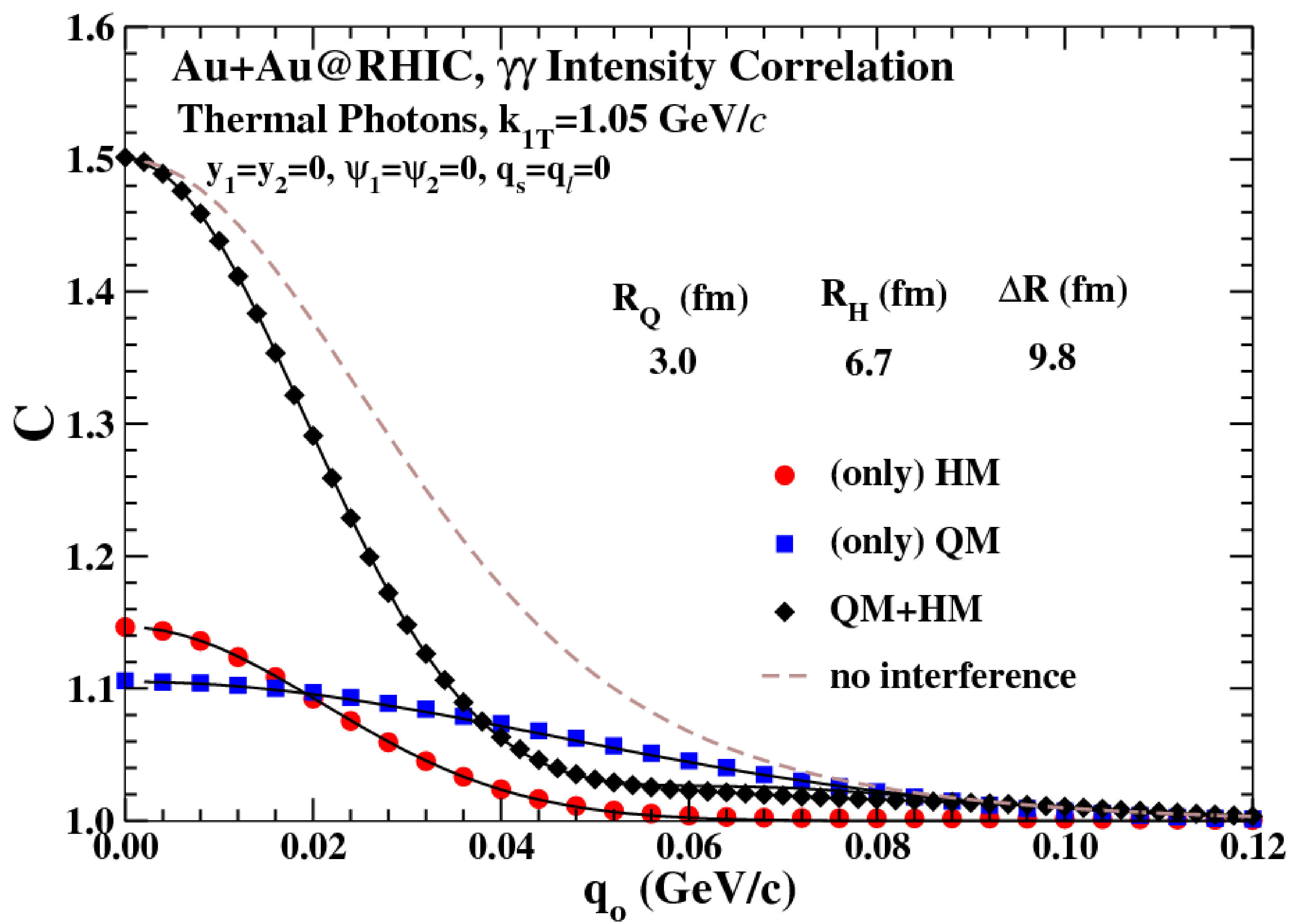
Bass, Mueller, & DKS, PRL 93 (2004) 16230

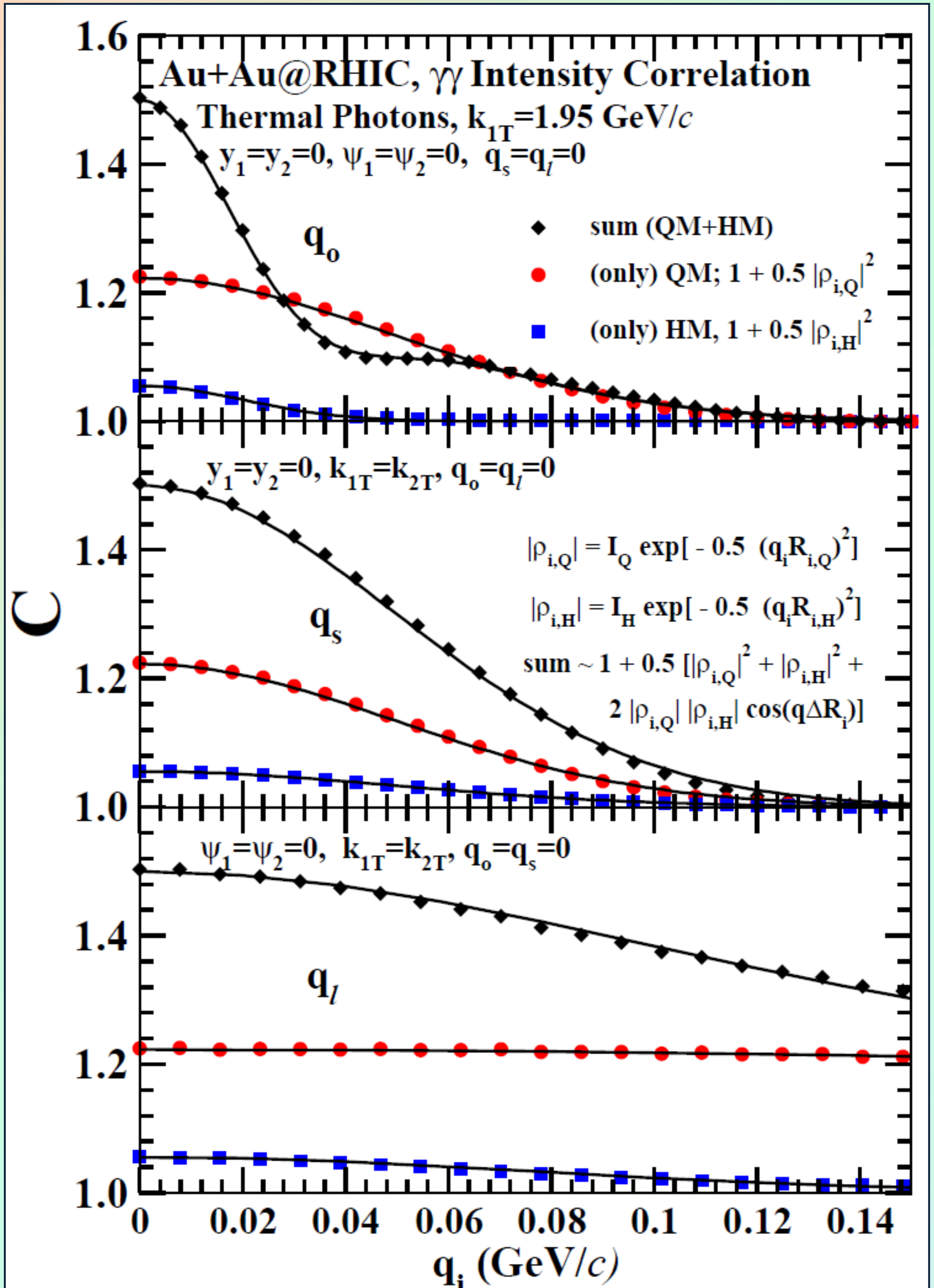
Photons: HBT Interferometry



- p_t=2 GeV: pre-thermal photons dominate, small radii
- p_t=1 GeV: superposition of pre- & thermal photons: increase in radii

Outward correlation function of thermal photons for 200A GeV Au+Au collision at RHIC





DKS and R. Chatterjee; arXiv: 0907.1360

The outward, sideward, and longitudinal correlation functions for thermal photons produced in central collision of gold nuclei at RHIC taking τ_0 = 0.2 fm/c. Symbols denote the results of the calculation, while the curves denote the fits.

Correlation function in the two phases can be approximated as

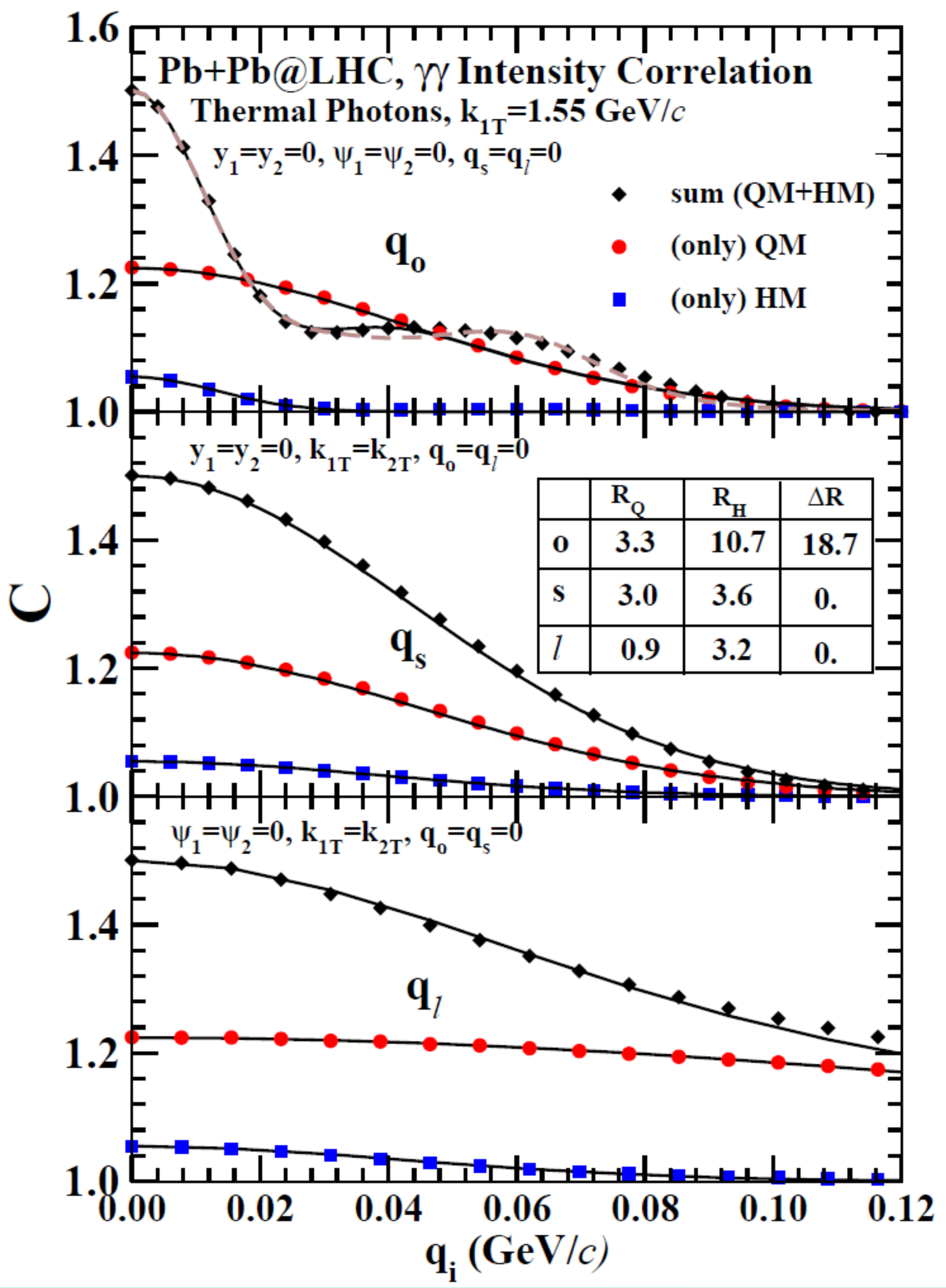
$$C(q_{i,\alpha}) = 1 + 0.5\,|\rho_{i,\alpha}|^2$$

where,

$$\rho_{i,\alpha} = I_i \exp[-0.5\,q_i^2 R_{i,\alpha}^2]$$

i=out, side, and long

α= quark matter (Q) or hadronic matter (H)

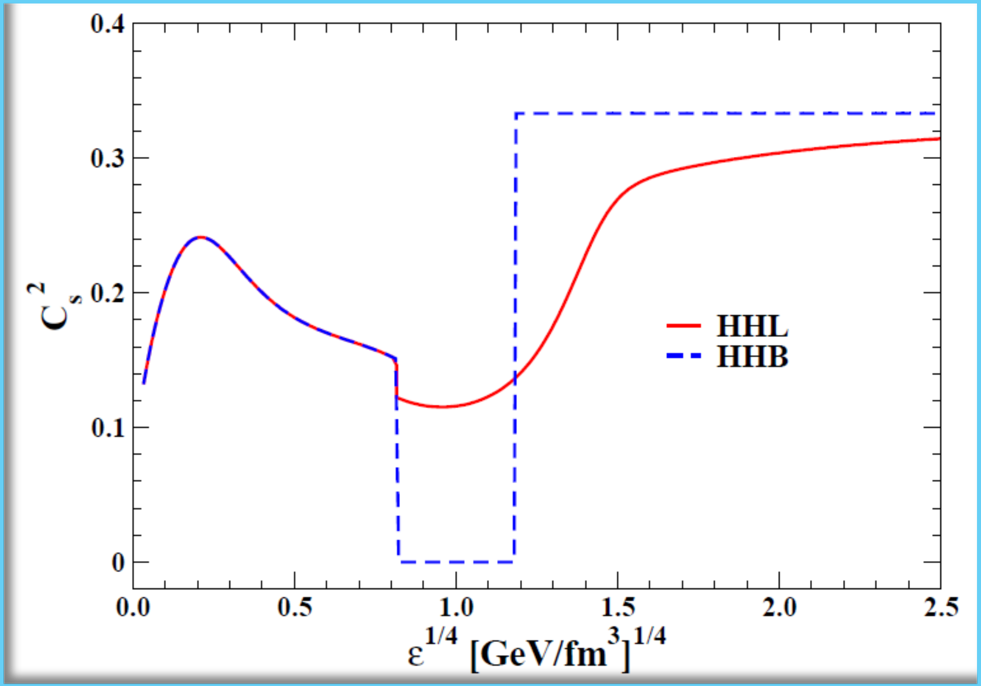


The outward, sideward, and longitudinal correlation functions for thermal photons produced in central collision of lead nuclei at LHC taking τ_0 = 0.2 fm/c. Symbols denote the results of the calculation, while the curves denote the fits.

	R_Q	R_H	ΔR
o	3.3	10.7	18.7
s	3.0	3.6	0.
l	0.9	3.2	0.

DKS and R. Chatterjee
arXiv: 0907.1360

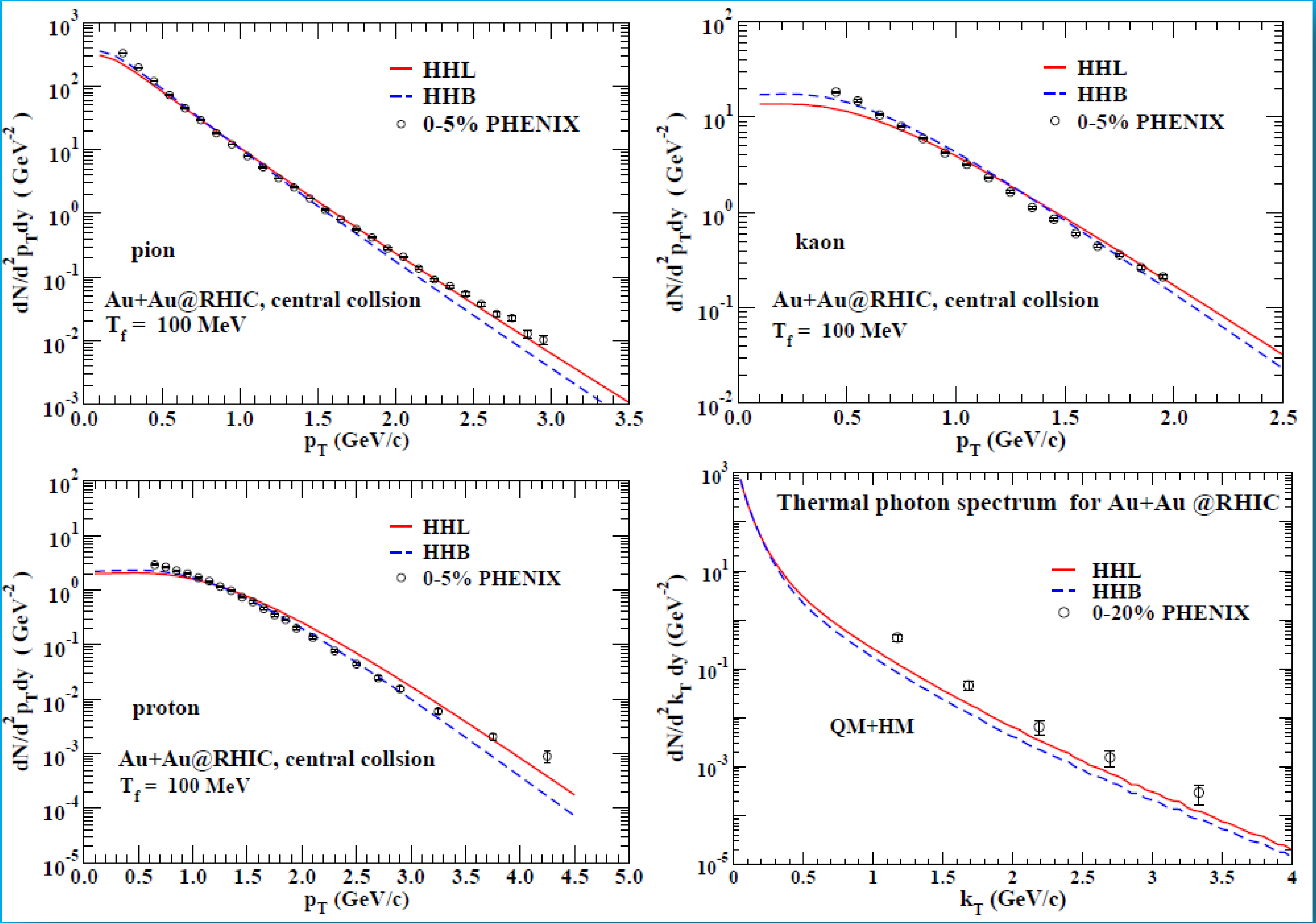
How Sensitive Are We to Equation of State?



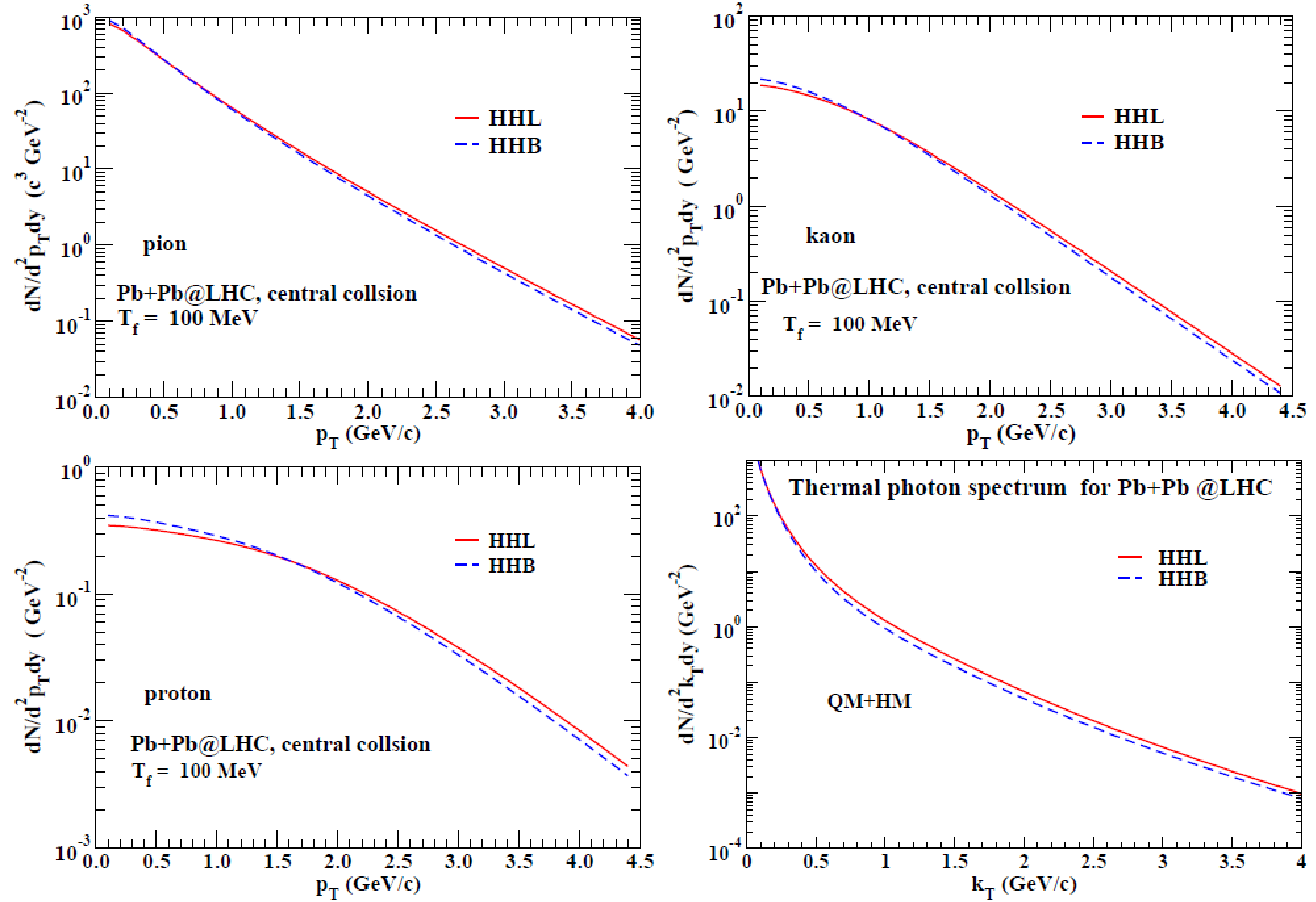
(i) Volume corrected hadron and Hagedorn resonance gas matched with a Bag Model ((HHB).

(v) Volume corrected hadron and Hagedorn resonance gas matched with Lattice calculations (HHL).

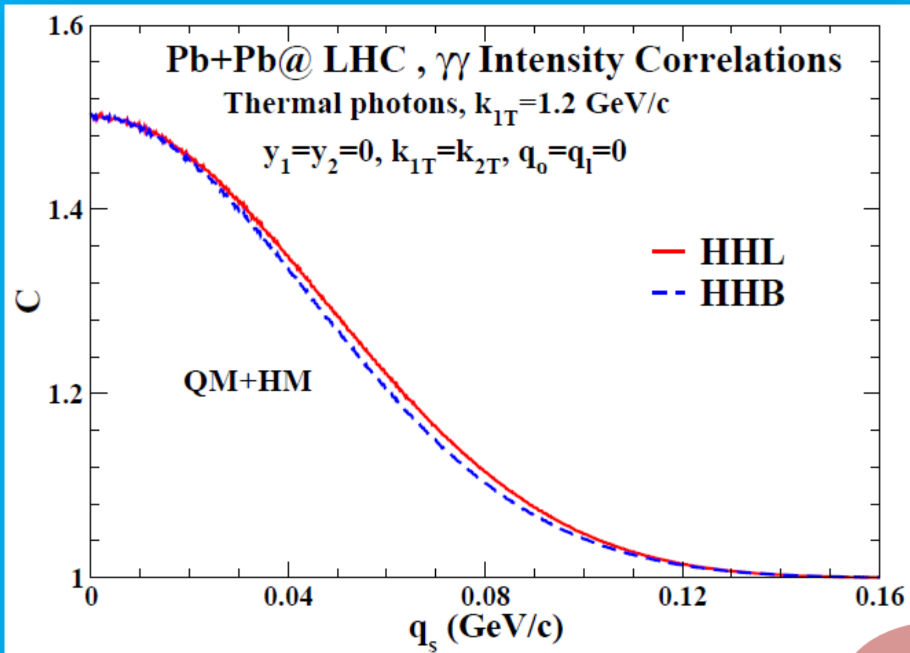
Speed of sound



Pion, kaon, proton and thermal photon p_T spectra at RHIC for the equations of state, HHB and HHL. All the calculations are for impact parameter b=0 fm.

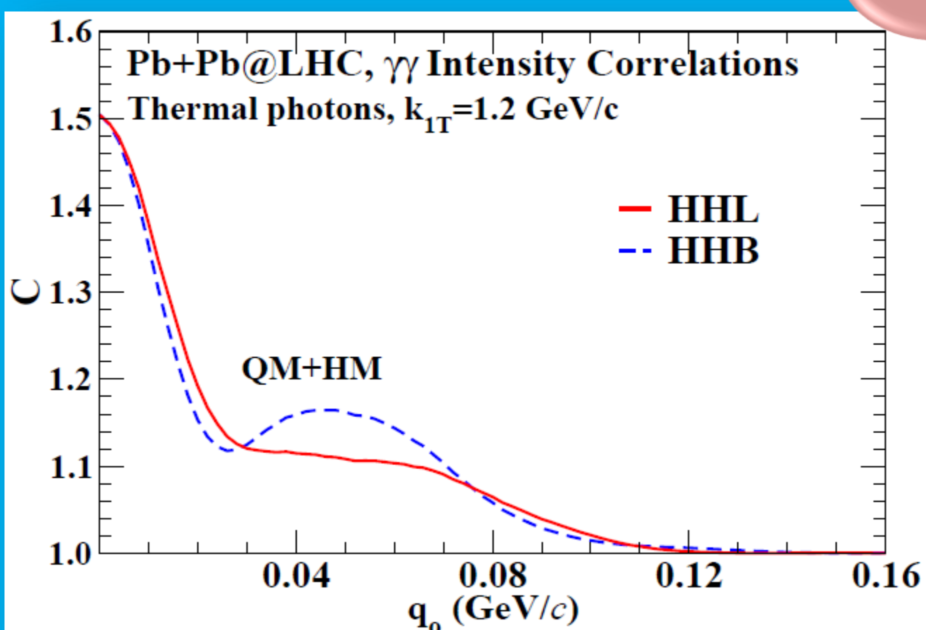


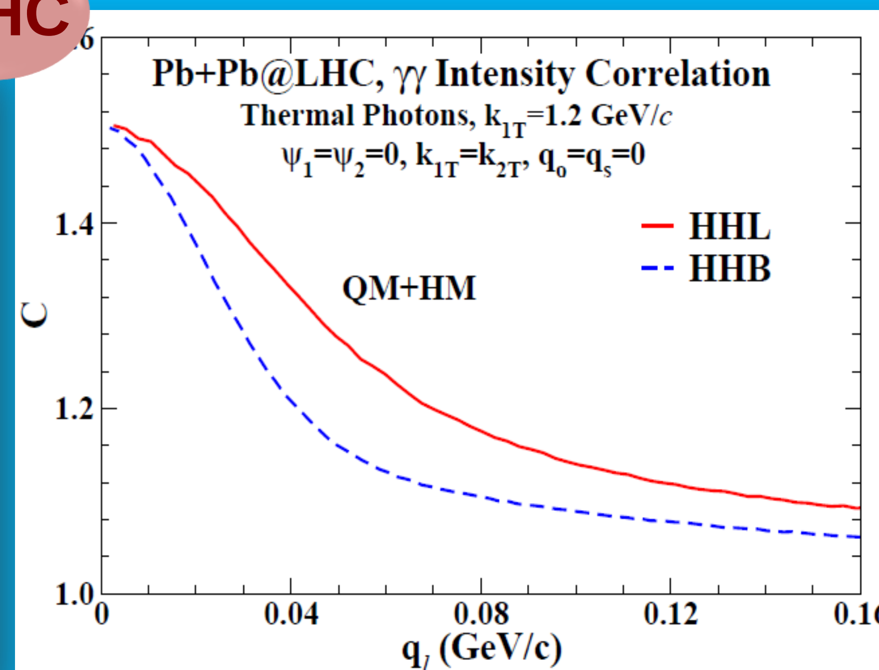
Pion, kaon, proton and thermal photon p_T spectra at LHC for the equations of state, HHB and HHL. All the calculations are for impact parameter b=0 fm.



- **Determine Equation of State of strongly interacting matter.**
- **Discover interference of photons from quark matter and hadrons, predicted by DKS and R. Chatterjee.**

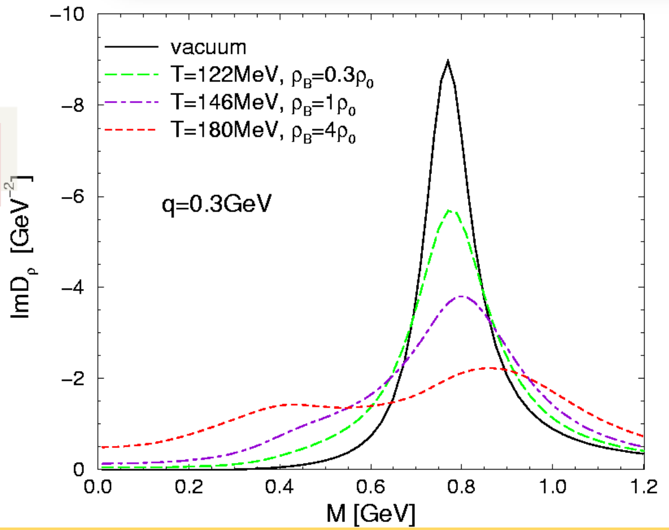
LHC

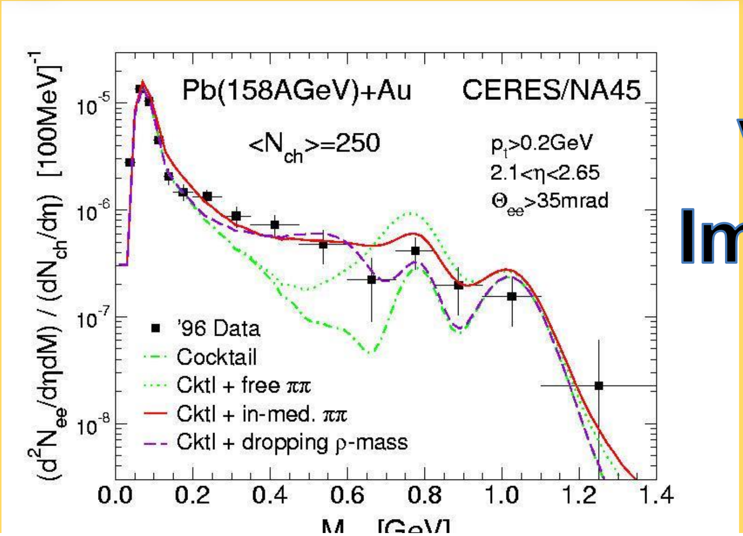




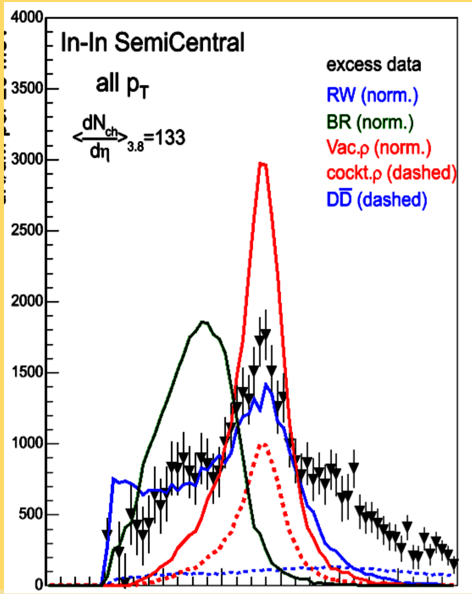
Dropping m_ρ vs. increasing Γ_ρ

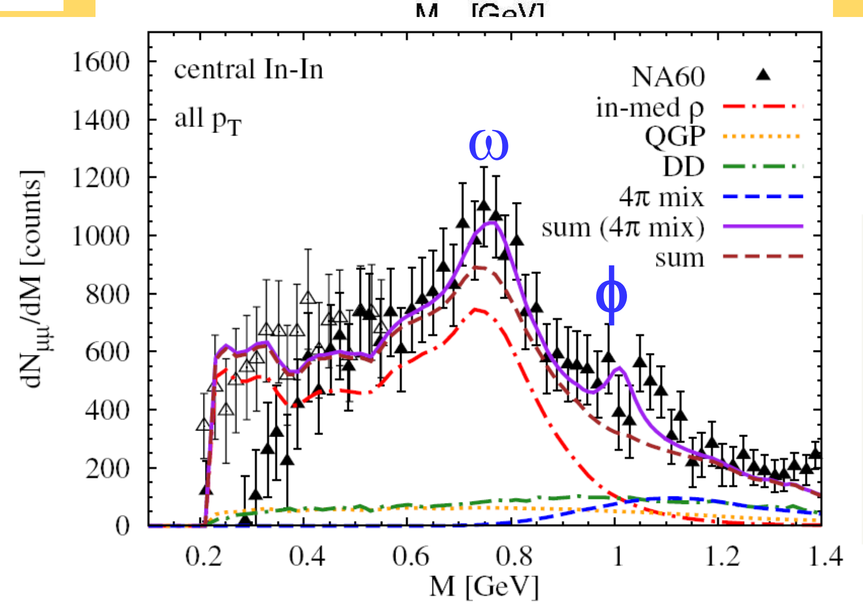
RW





Vastly Improved Data



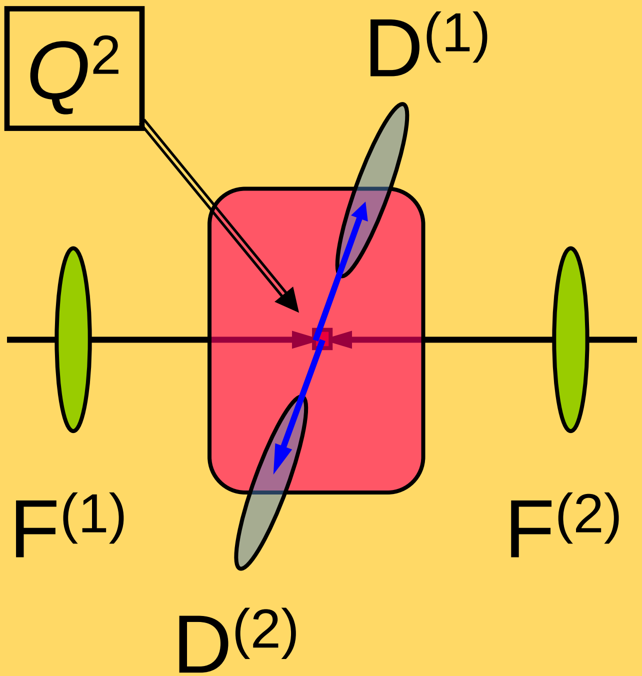


van Hees and Rapp, PRL 97 (2006) 102301.

Only brodening of ρ (RW) observerd, no mass shift (BR)

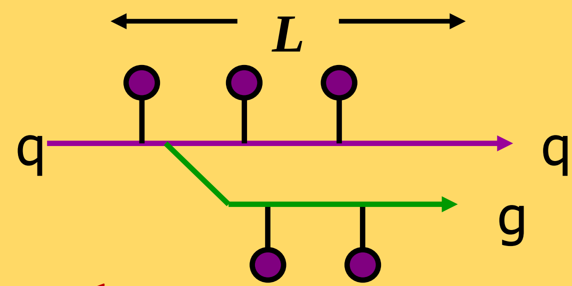
Passage of Jets Through QGP

PQCD framework: Jets



Medium modified fragmentation functions:

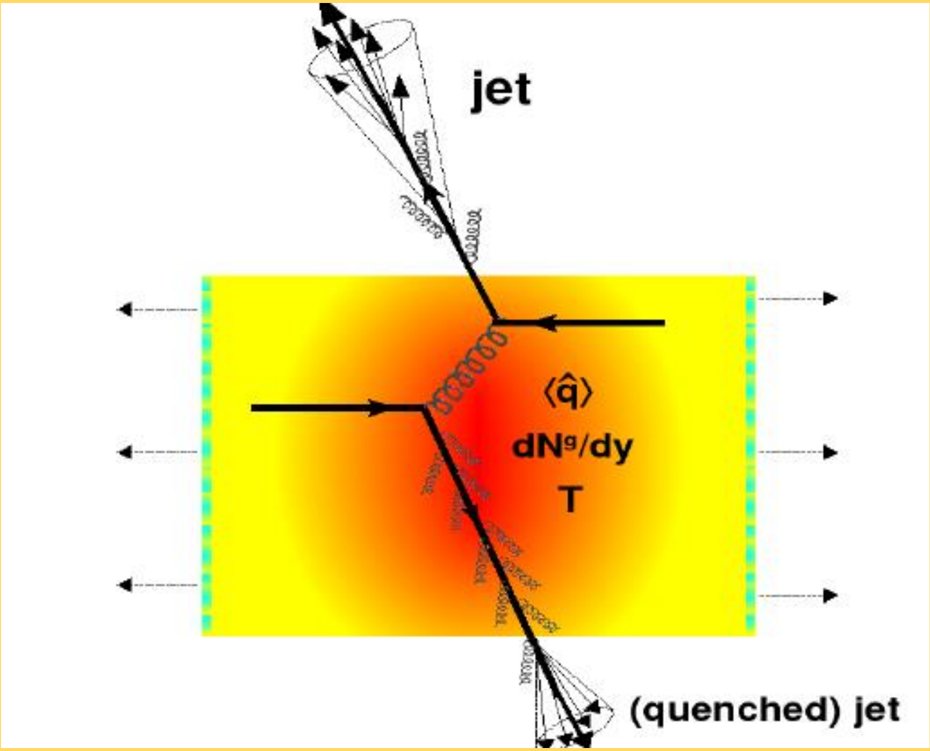
$$\tilde{D}_{p\to h}(z) = D_{p\to h}\left(\frac{z}{1-\Delta E/E}\right)$$



Measured medium property: $\hat{q} \sim \int dx \left\langle F^{+i}(x) F_{+i}(0) \right\rangle$

Factorization:

$$\sum_X \frac{d\sigma_{AA'\to hh'+X}}{dQ^2} = \sum_{p,p'} F^{(1)}_{A\to p} F^{(2)}_{A'\to p'} \otimes \sum_{\tilde{p}\tilde{p}'} \frac{d\sigma_{pp'\to\tilde{p}\tilde{p}'}}{dQ^2} \otimes \tilde{D}^{(1)}_{\tilde{p}\to h} \tilde{D}^{(2)}_{\tilde{p}'\to h'}$$



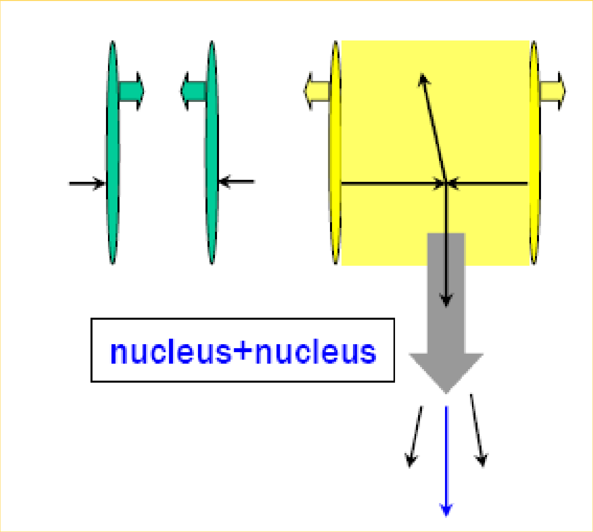
- Jet quenching is considered as one of the most promising signatures of formation of QGP

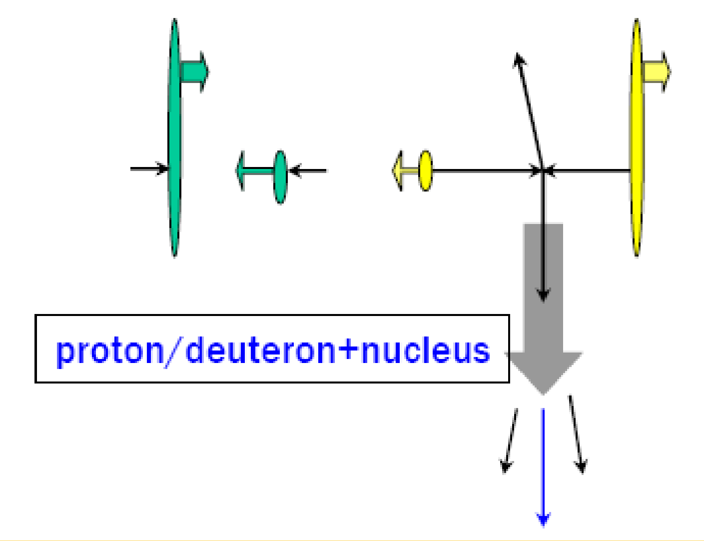
- It is defined as the suppression of high momentum particle spectra, arising due to energy loss of partons prior to fragmentation.

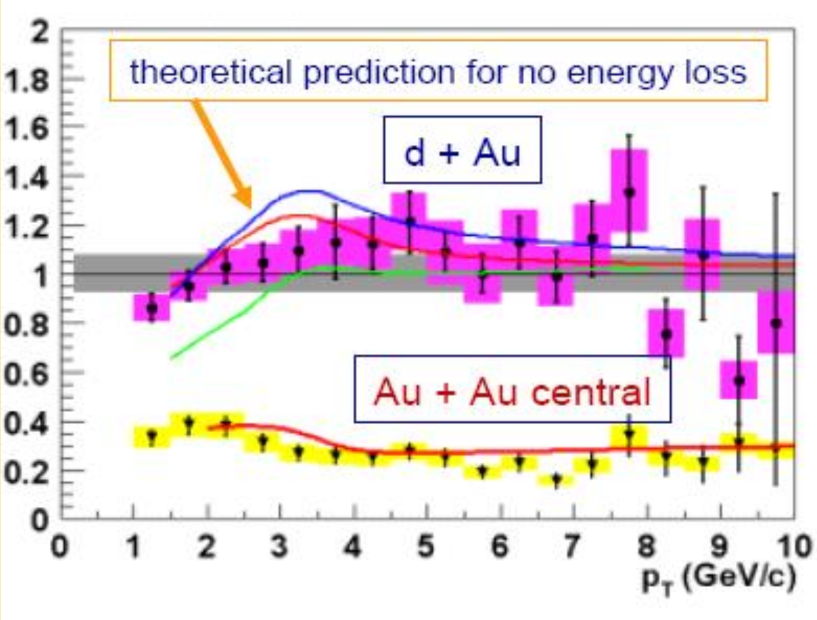
It is quantatively measured through the nuclear modification factor R_{AA}, which is defined as:

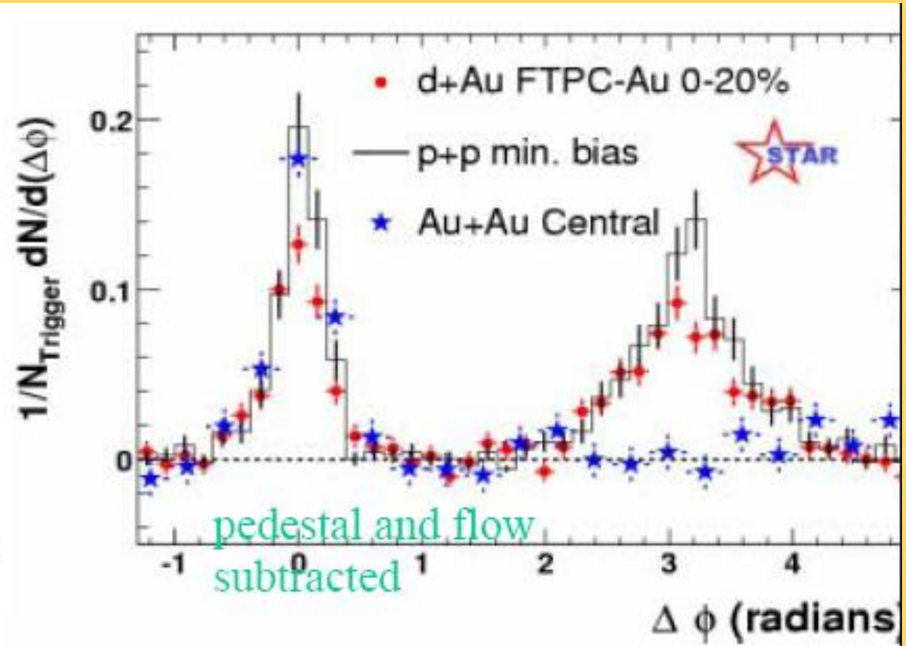
$$R_{AA}(p_T, b) = \frac{d^2 N_{AA}(b) / dp_T dy}{T_{AA}(b)\, d^2\sigma_{NN} / dp_T dy}$$

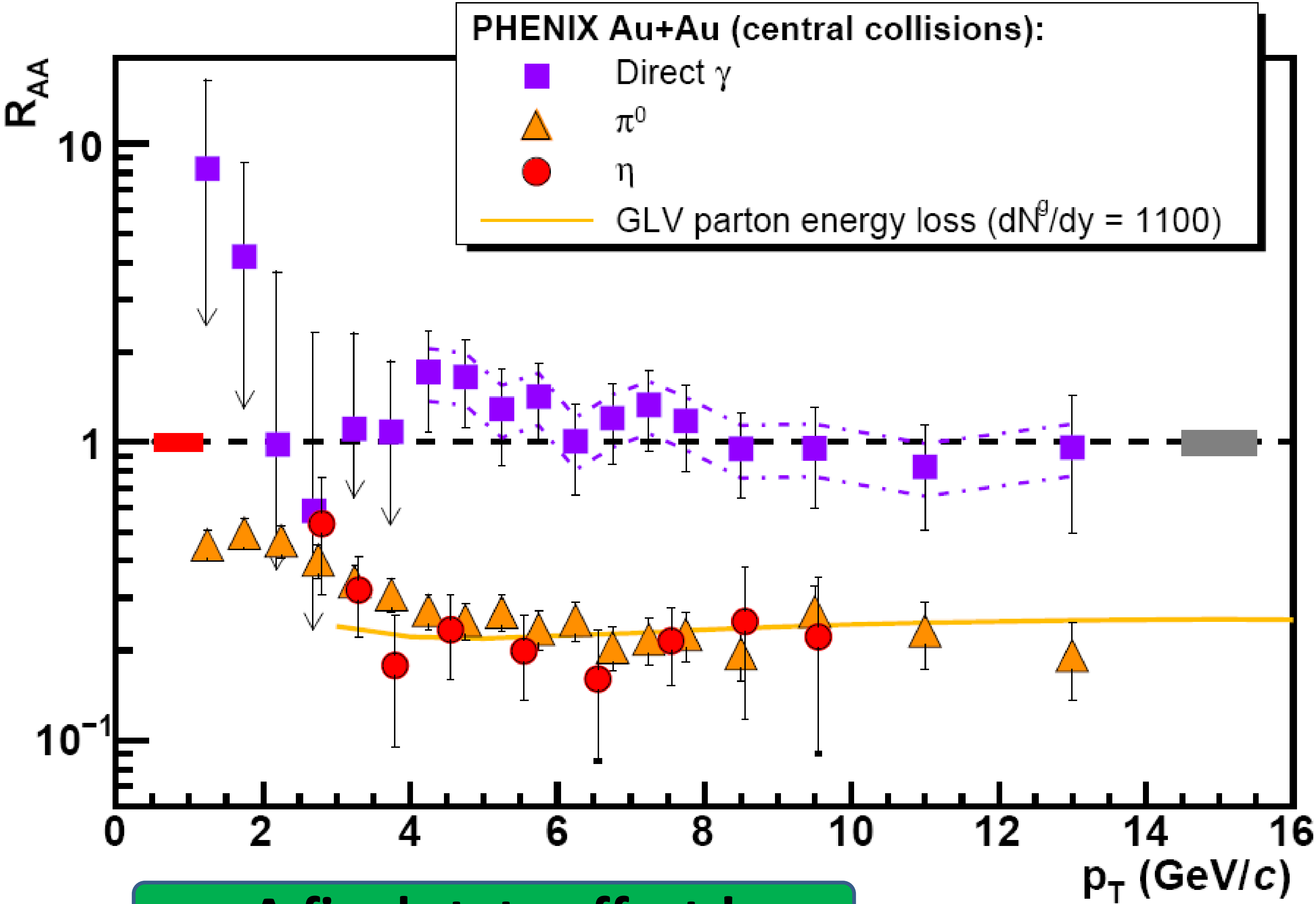
Confirmation of High Density Matter











A final state effect !

Photon tagged jets

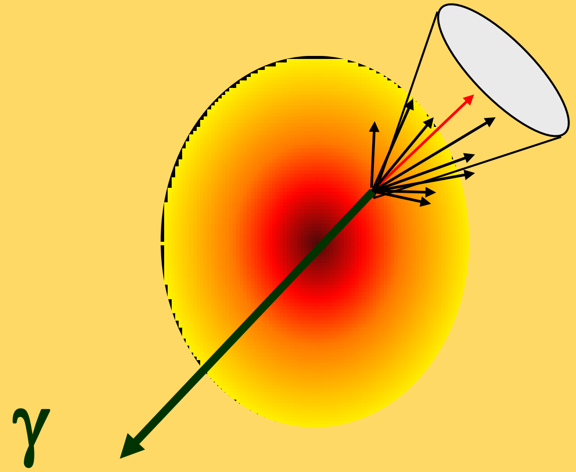
γ-jet correlation

– $E_\gamma = E_{jet}$

– Opposite direction

- **Direct photons are not affected by the medium**
- **Parton in-medium-modification through the fragmentation function**

$D(z),\ z = p^{hadron}/E_\gamma$



Wang, Huang, & Sarcevic, PRL 77 (1996) 231.
See also, Renk, PRC 74 (2006) 034906, for differentiation of mechanisms of E-loss, and several results at this meeting.

- Golden Channels :

$g + q \rightarrow \gamma + q$ (Compton)

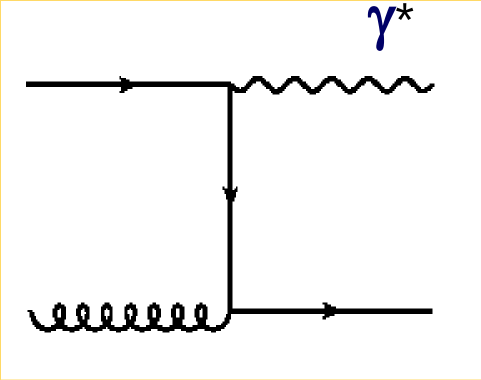
$q + \overline{q} \rightarrow \gamma + g$ (Annihilation)

- $p_T > 10$ GeV/c

Dilepton vs. photon tagged jets

Photon tagged jets:

- Difficult measurement:
- At low p_T, $\pi^0 \rightarrow \gamma\gamma$ large background.
- At higher p_T, background problem better but opening angle becomes smaller.



Compton

Dilepton tagged jets:

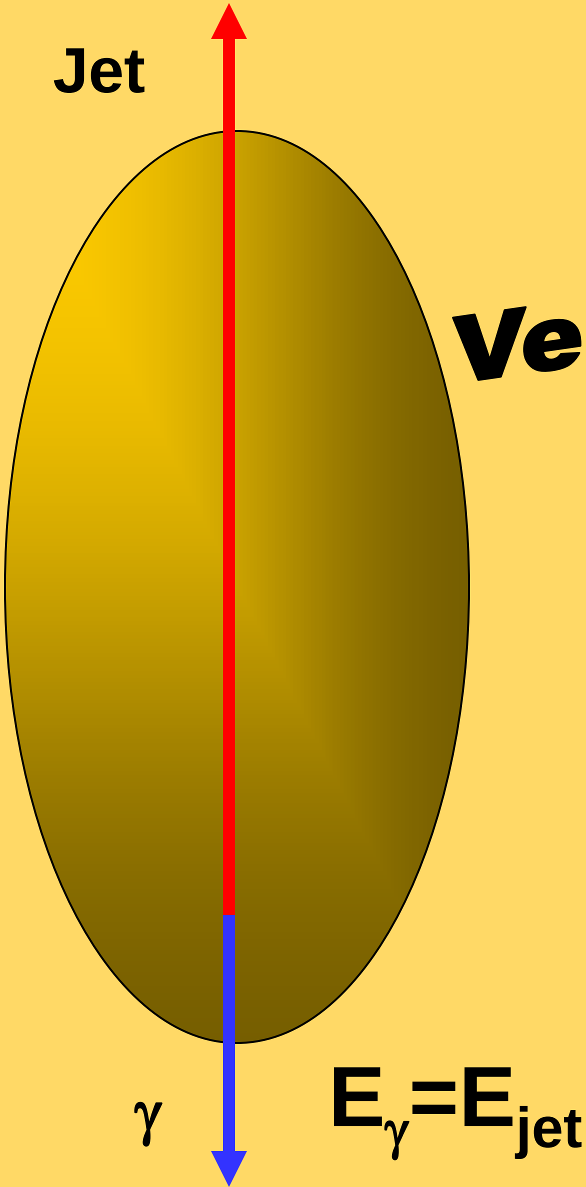
- Lower yield but lower back-ground.
- Charm and beauty decay could be identified.
- M and p_T: two handles!
- Gold plated standard via Z^0 tagging at LHC.

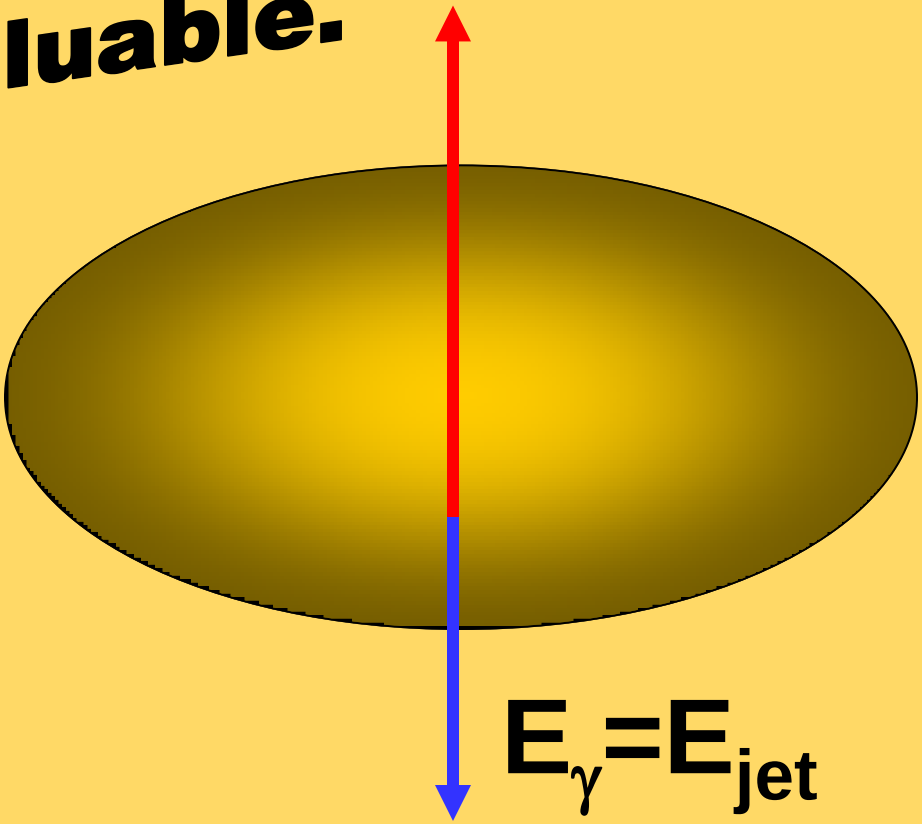
S., Gale, & Awes, PRC 67 (2003) 054904;
Lokhtin et al, PLB 599 (2004) 260.

Azimuthal tagging of jets with photons/dileptons

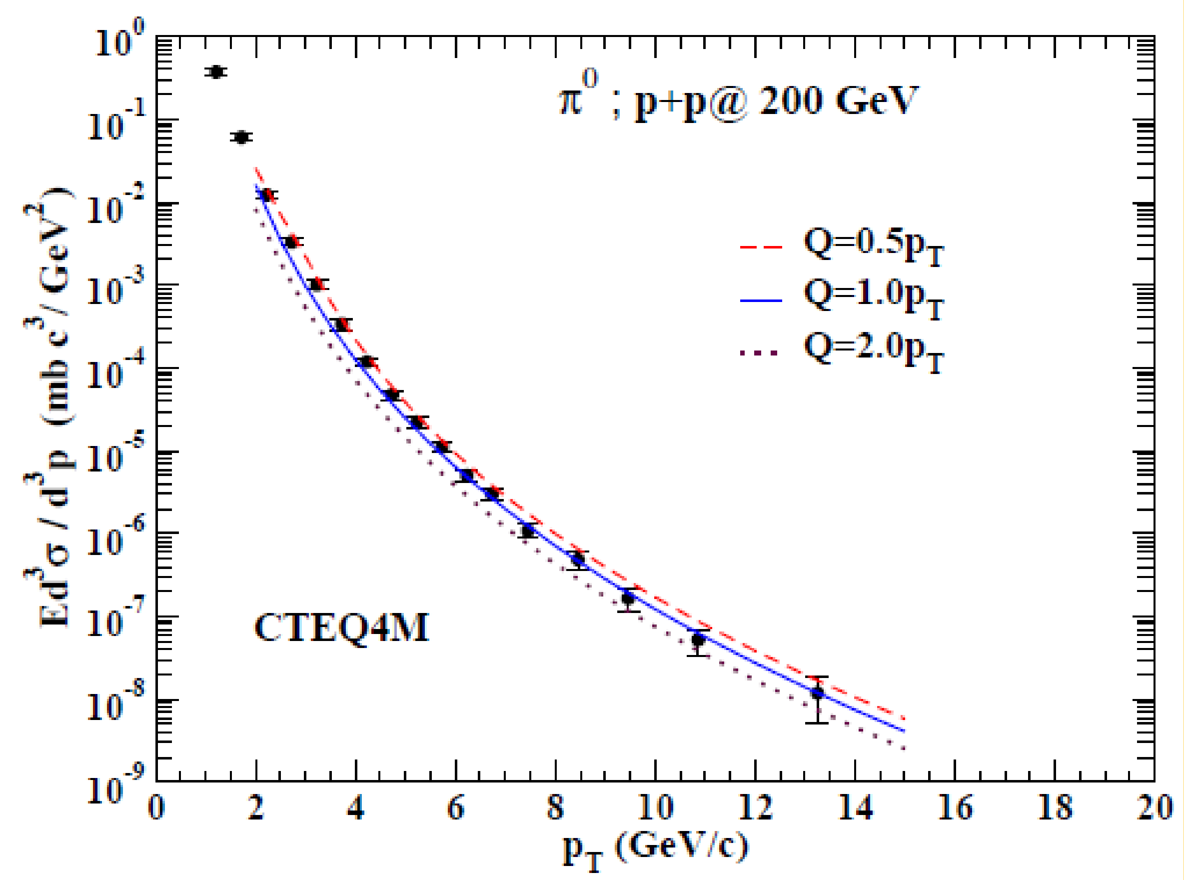
Jets of a given enegy traversing different path-lengths!

Very Valuable.





❖Neutral pion production for p-p collisions at RHIC



S. De and DKS, arXiv:1107.5659

$$Q = Q_R = Q_F = cp_T$$

- Next-to- leading order $O(\alpha_s{}^3)$ calculations are used.
- CTEQ4M parton distribution function.
- BKK fragmentation function.

While calculating particle production in AA collisions, we include:

- Nuclear shadowing. → (EKS98 parameterization)
- Energy loss of partons in the medium.
- Average path length traversed by the parton.
  - The average path length L(φ,b) traversed by a parton for non-central collisions of impact parameter b.

$$L(\varphi,b) = \frac{\iint l(x,y,\varphi,b)T_{AB}(x,y;b)dxdy}{\iint T_{AB}(x,y;b)dxdy}$$

We follow a simple phenomenological model based on the formalism of Baier et.al. and first used by S. Jeon et al at RHIC energies, to estimate parton energy loss.

- The formation time of the radiated gluon: $t_{form} = \frac{\omega}{k_T^2}$

ε - energy loss per collision, λ_a- mean free path:

$t_{form} \le \lambda_a$ → BH limit $\varepsilon \approx \alpha_s \frac{N_c}{\pi} E$

$\lambda_a < t_{form} < L$ → LPM limit $\varepsilon \approx \alpha_s \frac{N_c}{\pi} \sqrt{E_{LPM} E}$

$t_{form} \ge L$ → Coherence limit $\varepsilon \approx \alpha_s \frac{N_c}{\pi} \langle k_T^2 \rangle L$

where $E_{LPM} = \lambda_a \langle k_T^2 \rangle$

- The probability for a parton to scatter n times before it leaves the medium

$$P_a(n,L) = \frac{(L/\lambda_a)^n}{n!} e^{-L/\lambda_a}$$

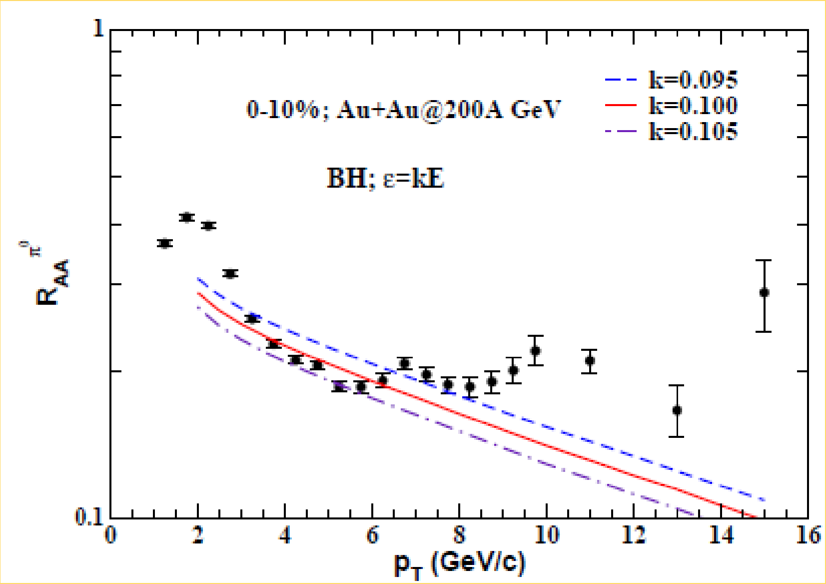
- The effect of energy loss of partons and multiple scatterings are implemented through the modification of $D_{c/h}(z,Q^2)$ following the model of Wang-Huang-Sarcevic.

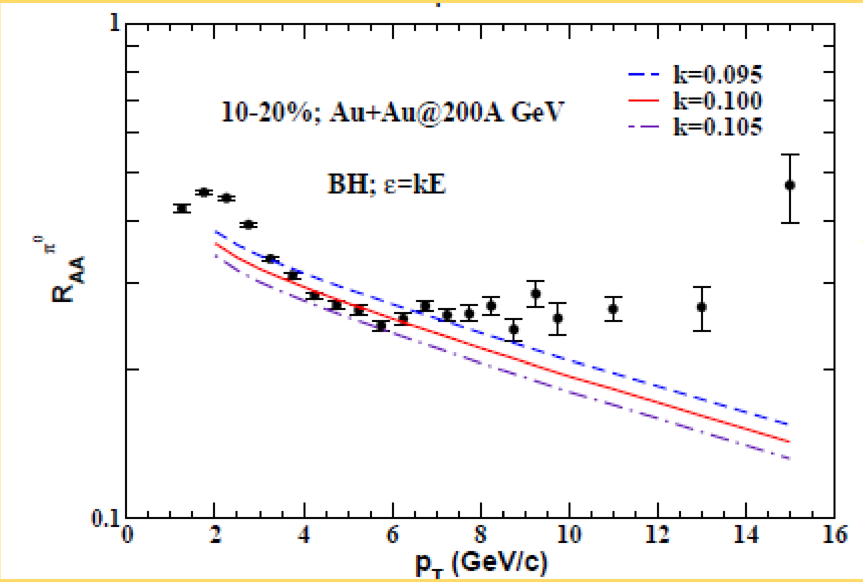
$$zD_{c/h}(z,L,Q^2) = \frac{1}{C_N^a} \sum_{n=0}^{N} P_a(n,L) \times \left[z_n^a D_{c/h}^0(z_n^a, Q^2) + \sum_{m=1}^{n} z_m^a D_{g/h}^0(z_m^a, Q^2) \right]$$

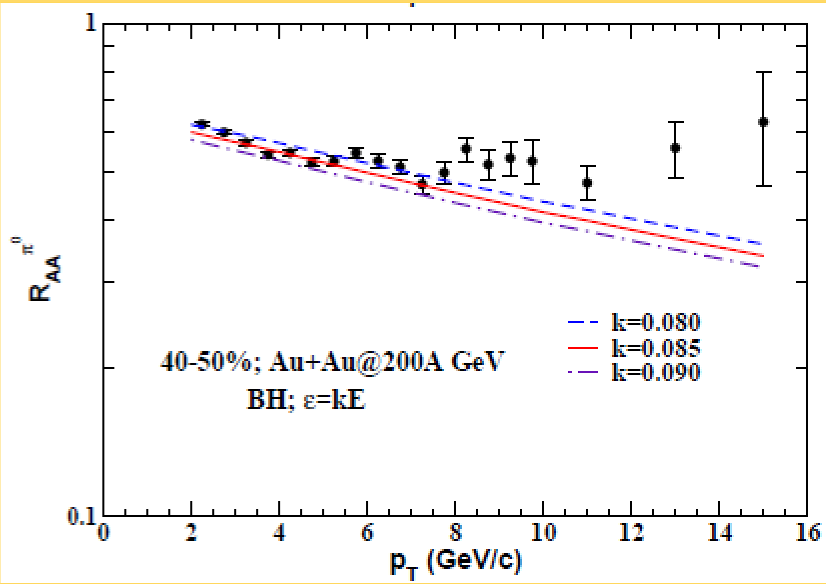
where, $C_N^a = \sum_{n=0}^{N} P_a(n,L)$, $z E_T^a = z_n^a (E_T^a - \sum_{i=0}^{n} \varepsilon_a^i)$ and $z_m^a \varepsilon_a^m = zE_T^a$

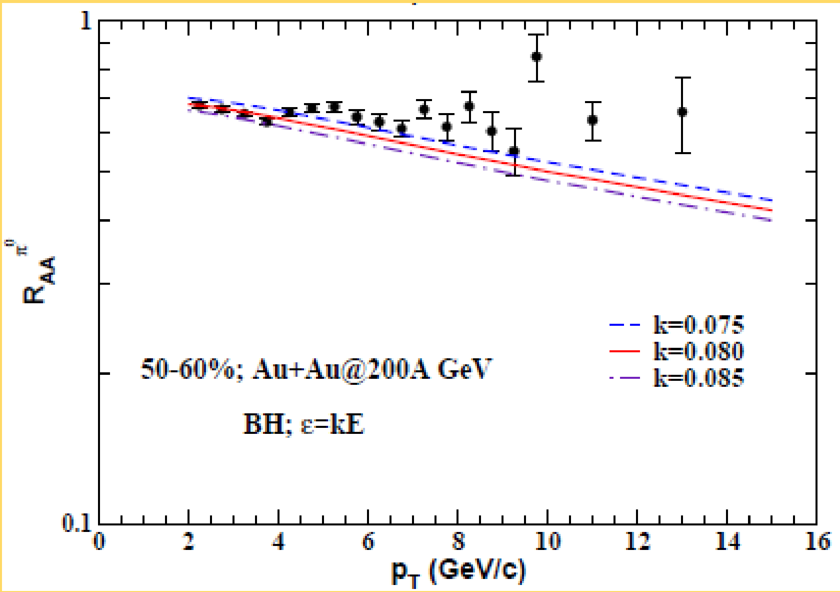
R_{AA} of neutral pions for Au-Au collisions at RHIC

BH regime



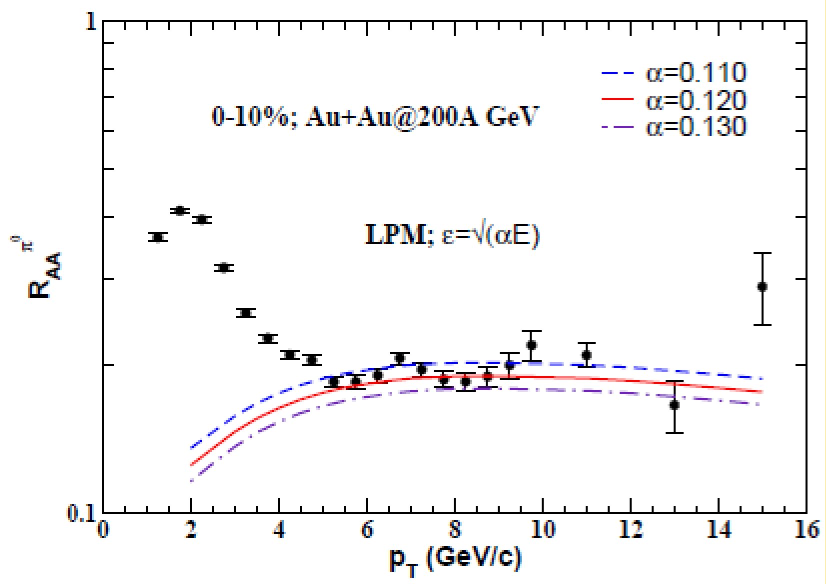


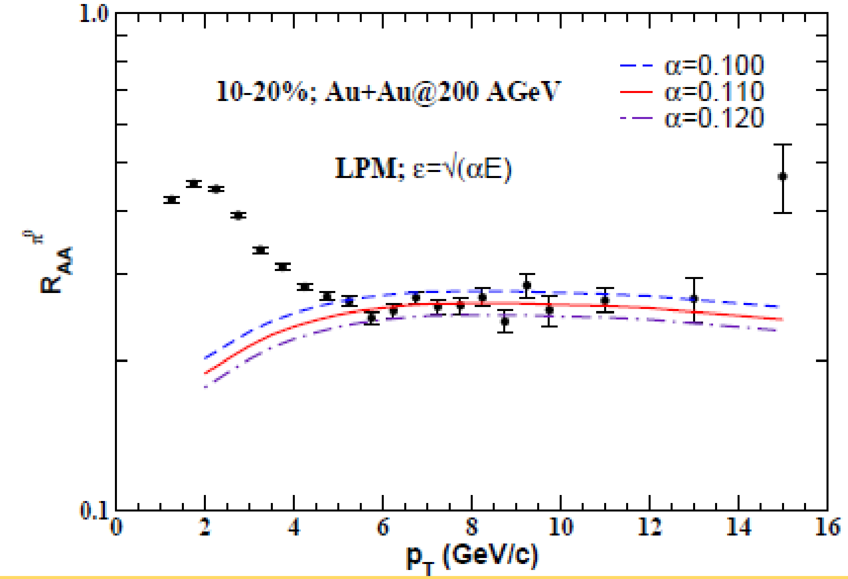


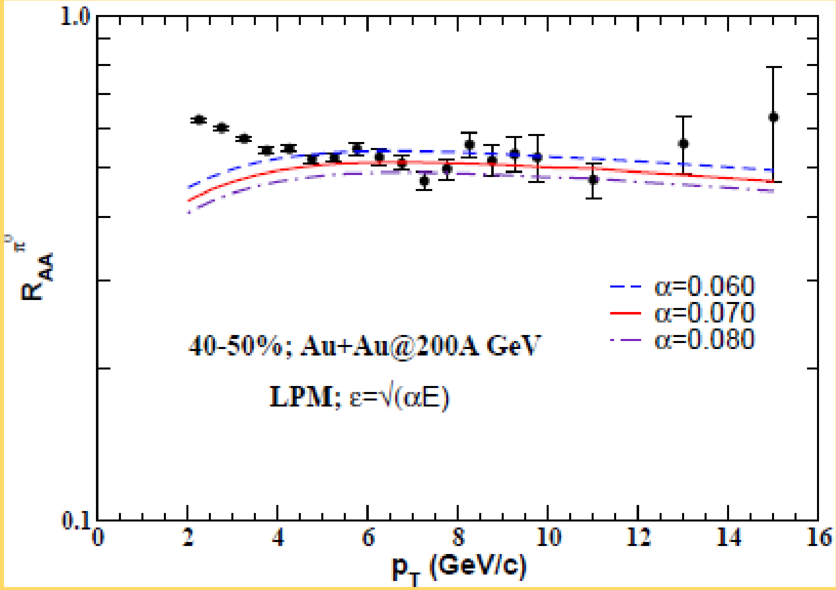


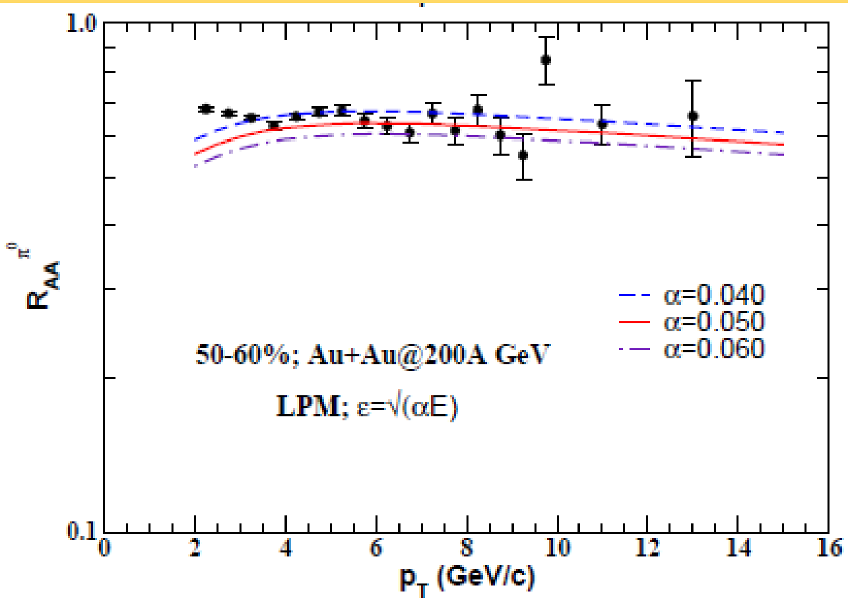
LPM regime

S. De and D. K. S. , arXiv:1107.5659

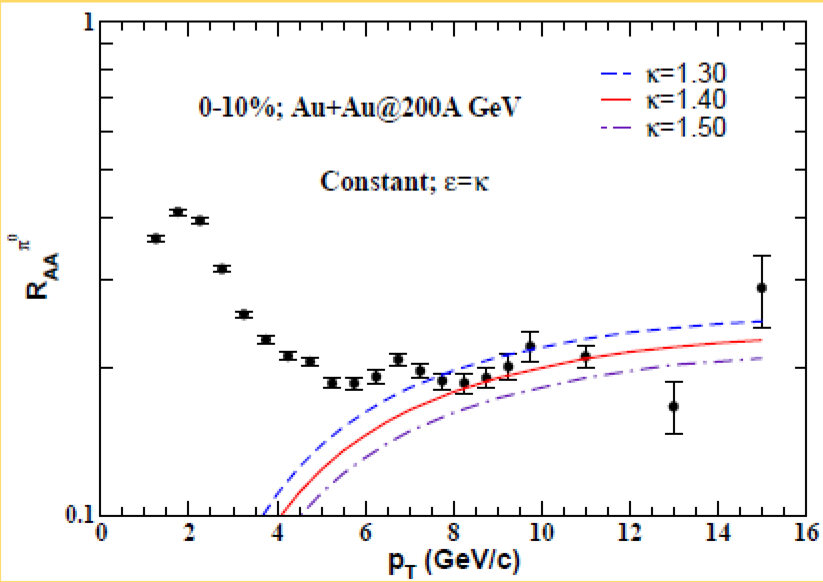


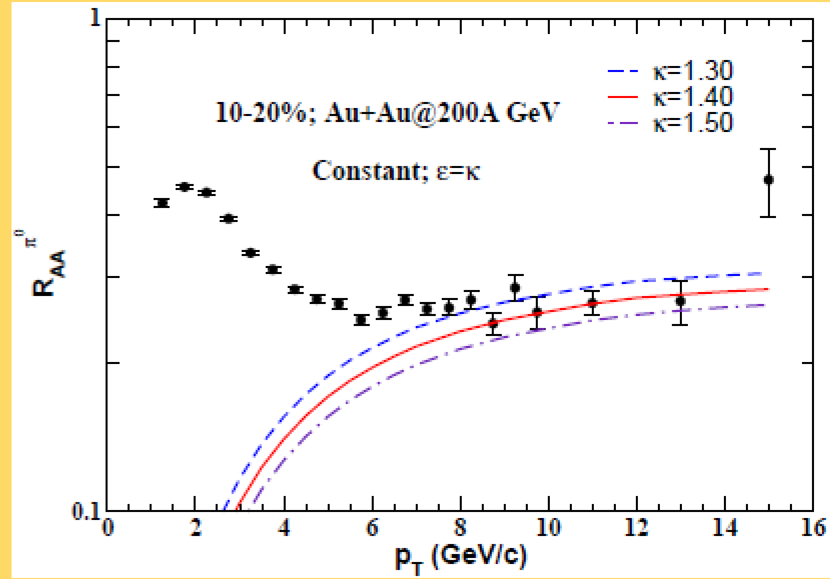


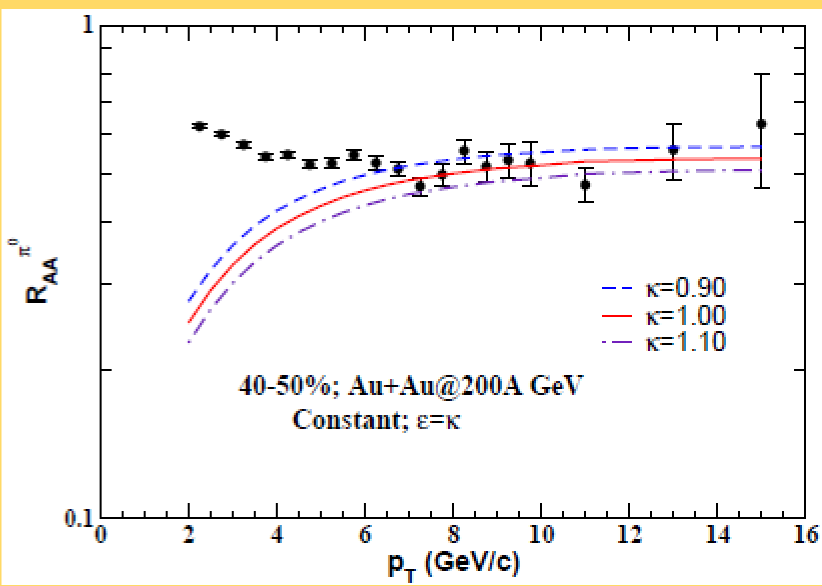


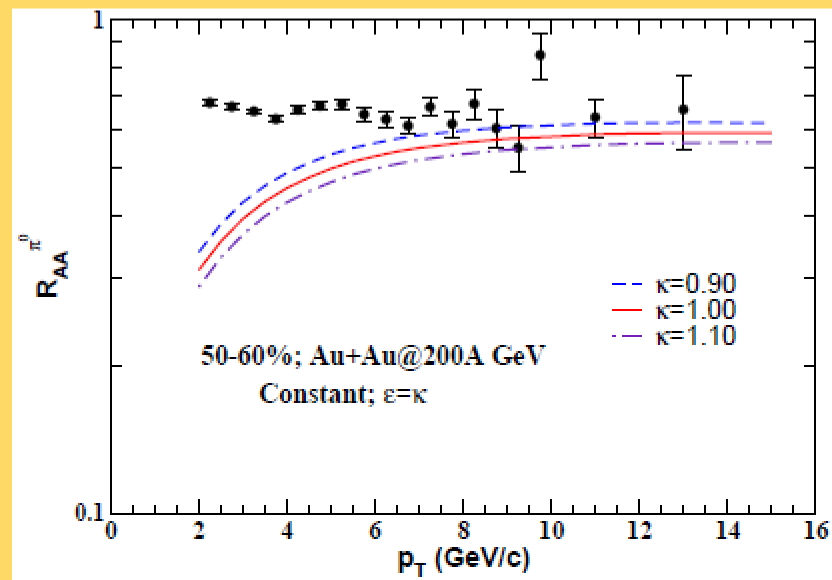


Complete Coherence Regime

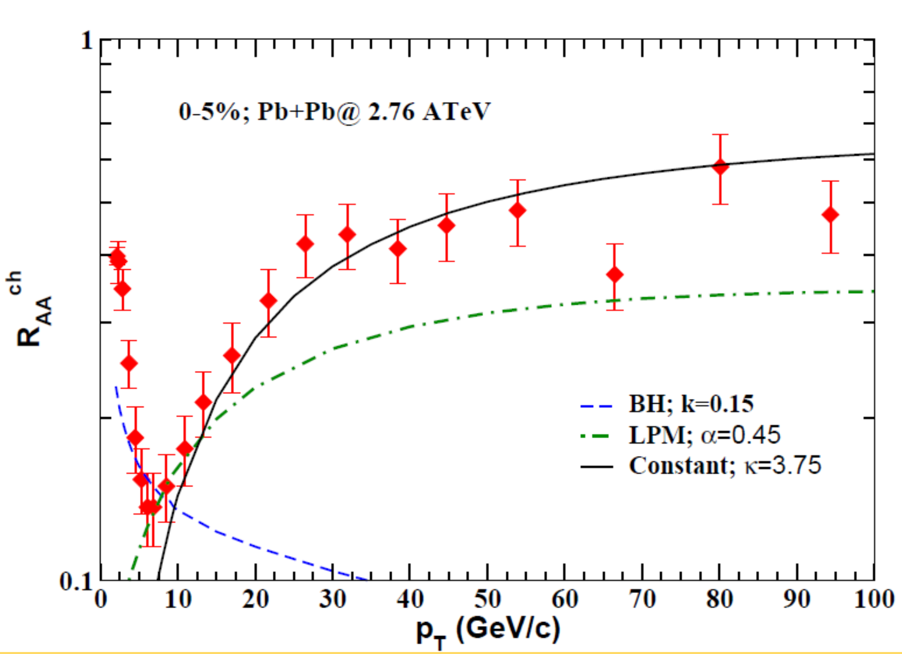


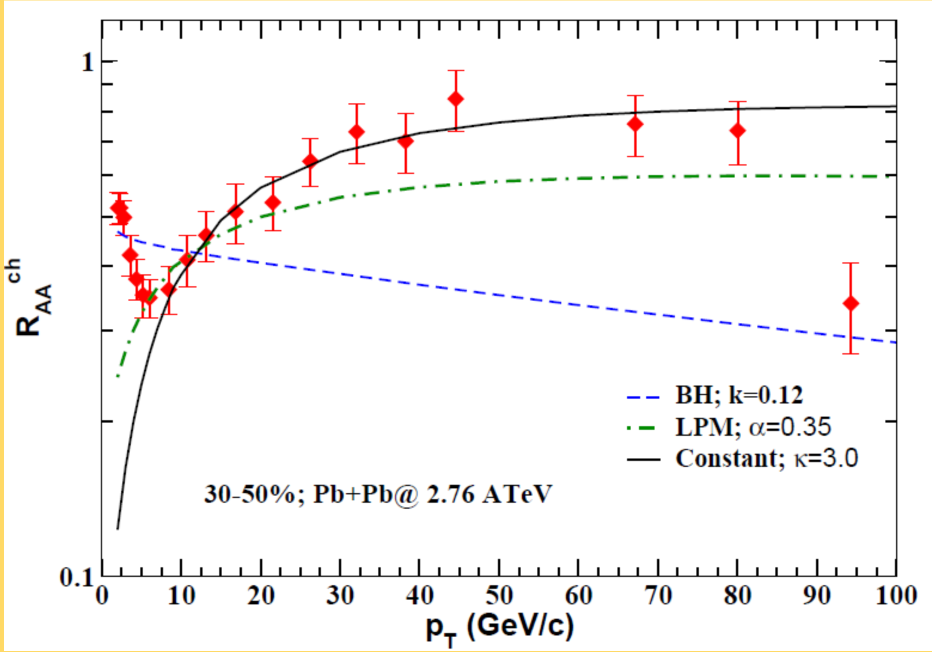






R_{AA} of charged hadrons for Pb+Pb @ 2.76 ATeV : CMS preliminary



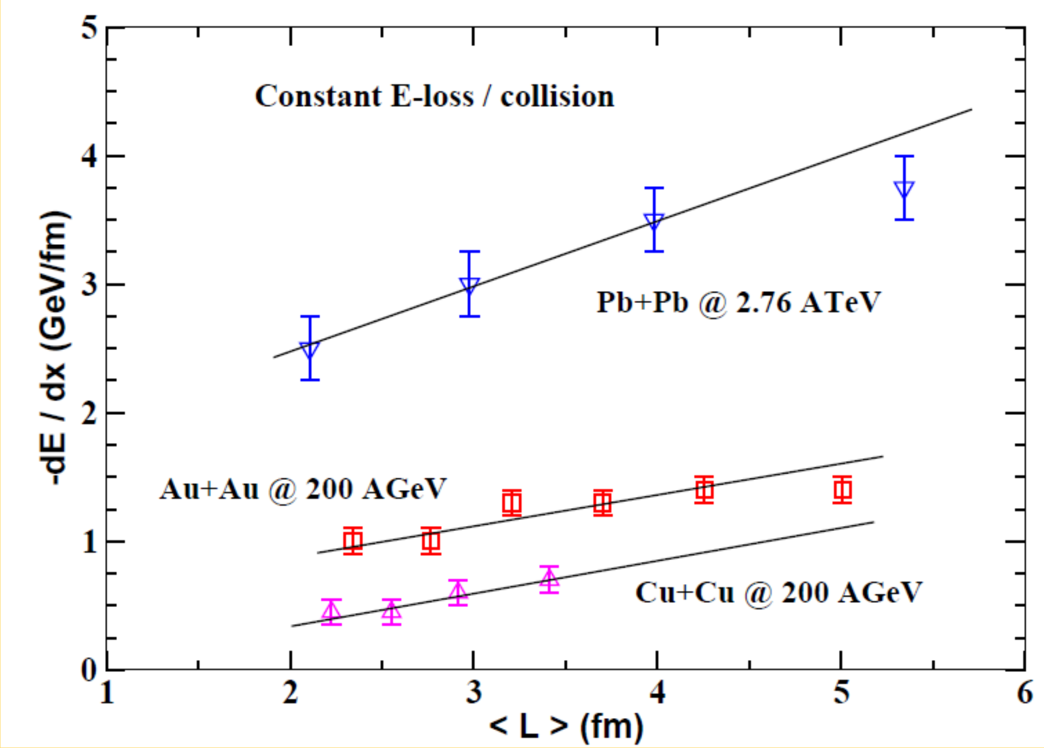


Centrality dependence of dE /dx at RHIC & LHC

Taking the case of parton energy loss in the complete coherence regime, $-dE/dx = \varepsilon / \lambda$

The concerned partons having $p_T \geq 8\ GeV/c$ at RHIC and

$p_T \geq 10\ GeV/c$ at LHC



Pb+Pb @ 2.76 ATeV
0-5%, ALICE coll.

<L>~ 6.90 fm
-dE/dx =2.4 GeV/fm

We see that the energy lost by the partons, $\Delta E \propto L^2$

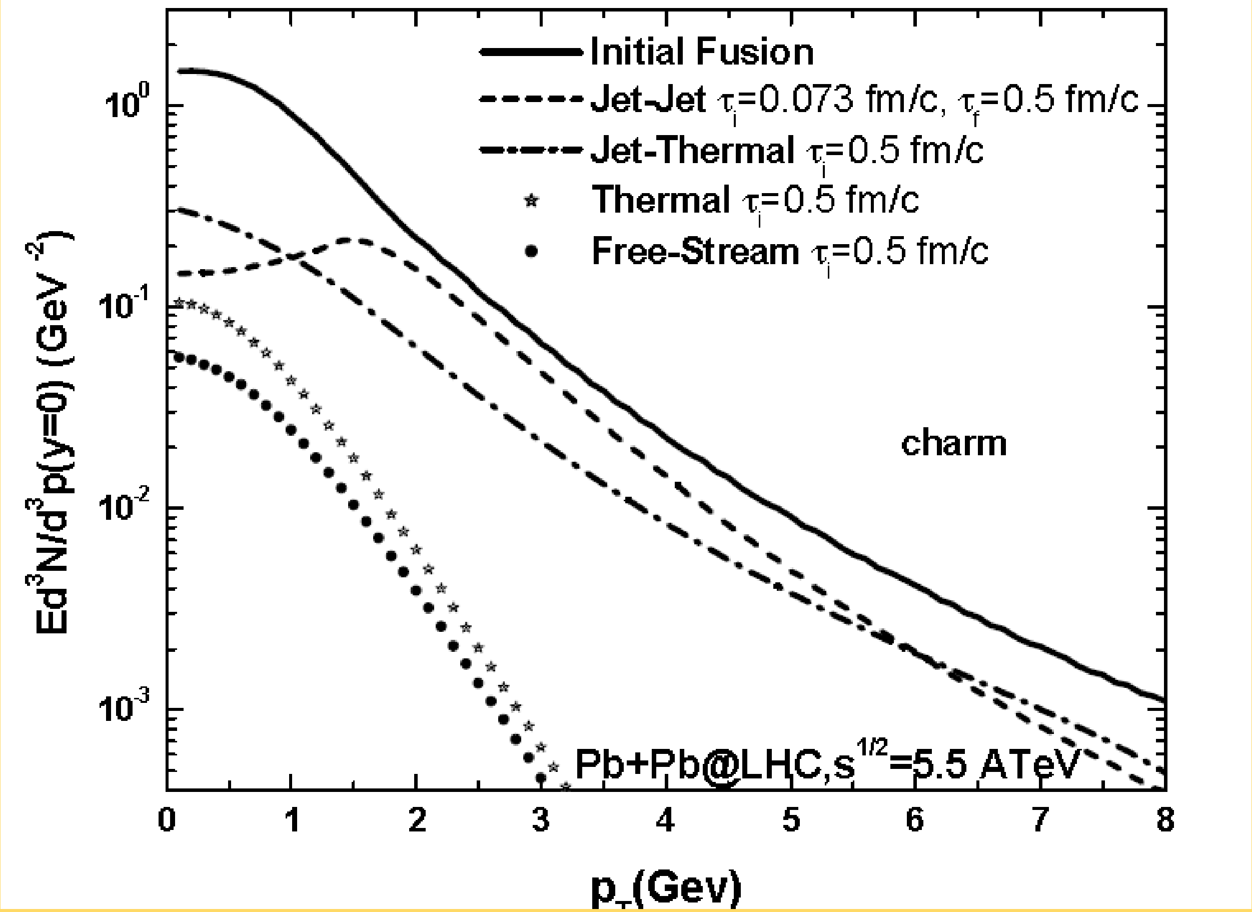
Heavy Quark Propagation

Initial Fusion

- Jet-jet interaction
- Thermal production
- Passage of jets through Quark Gluon Plasma.
- NLO effects.
- Back to back correlations
- dE/dx

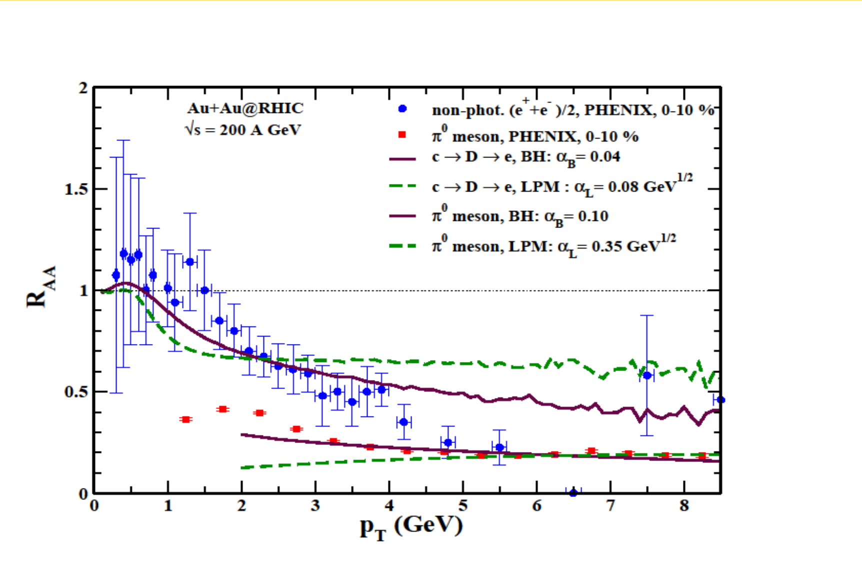
Heavy Quark Production

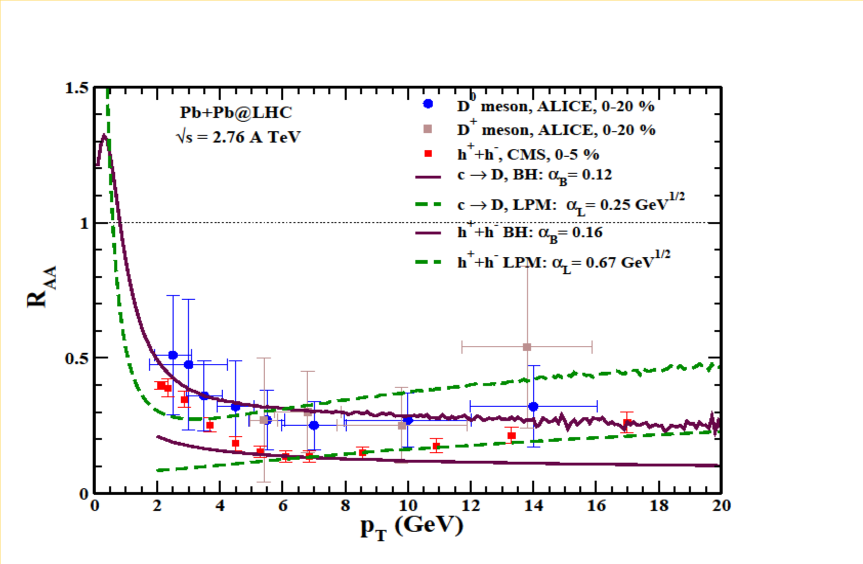
M. Younus & DKS, J. Phys. G 37, 115006 (2010)



Taking pp collisions as the base-line may not be appropriate as mechanisms other than initial fusion may contribute. There is also a growing evidence for multiple scatterings of partons in pp collisions.

Energy and flavour dependence of parton energy loss





Refs: JPG 39, 095003 (2012); 015001 (2012); arXiv: 1112.2492

- Bethe- Heitler Limit of Incoherent Radiation: $\Delta p = \alpha_B \, p$
- LPM Limit of Coherent Radiation: $\Delta p = \alpha_L \sqrt{p}$

RHIC: $\alpha_B^{Light} \approx 2.5 \, \alpha_B^{Heavy}$

LHC: $\alpha_B^{Light} \approx 1.3 \, \alpha_B^{Heavy}$

Conclusions

- The discovery of quark gluon plasma has provided confirmation of one of the most spectacular predictions of QCD- the theory of strong interactions.
- Single photons, dileptons, jets, and heavy quarks provide interesting details of initial stage of the plasma and its dynamics.
- The initial state in these collisions is hot ~300-500 MeV and dense, 20-100 GeV/fm^3, similar to the matter in early universe.

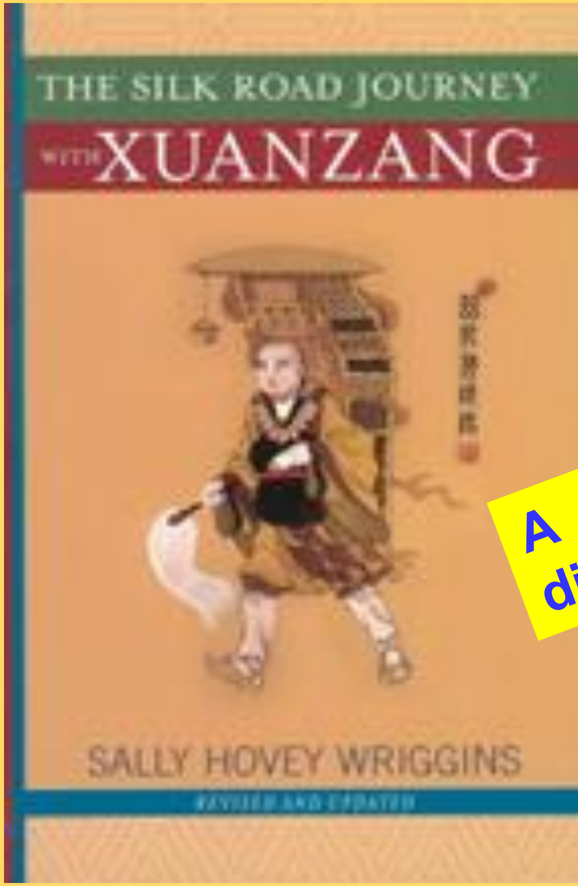
Back up slides

If I had more time:

- **Intensity Interferometry of direct photons**

- **D. K. Srivastava,** PLB 307(1993)1.
- **D. K. Srivastava and J. I. Kapusta**, PRC 48 (1993) 1335.
- **D. K. Srivastava**, PRD 49 (1994) 4523.
- **S. A. Bass, B. Muller, D. K. Srivastava**, PRL 16 (2004) 162301;
- **D. K. Srivastava,** PRC 71 (2005) 034905.
- **D. K. Srivastava & R. Chatterjee**, PRC 80(2009) 054914.
- **S. De, R. Chatterjee, D. K. Srivastava**, J. Phys. G37 (2010) 115004.

Most Reliable Historians of Ancient India



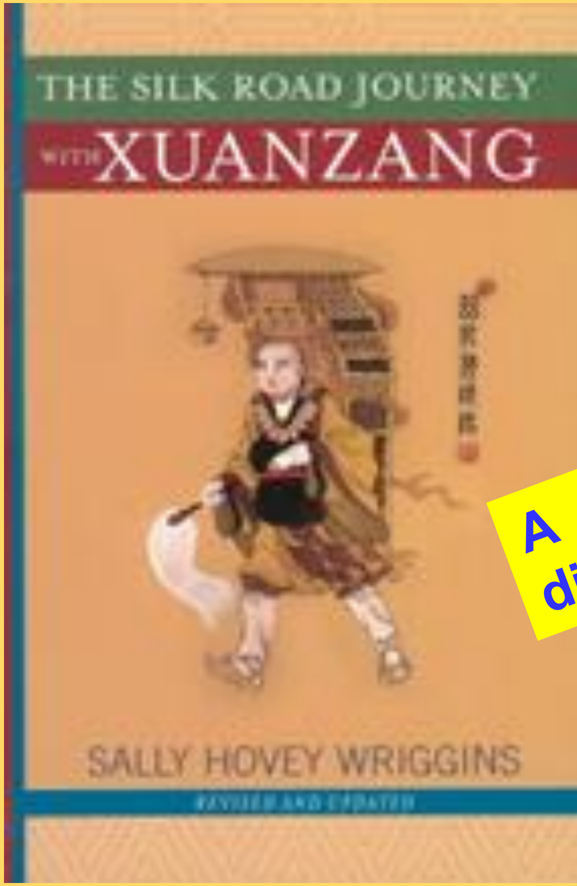
A slight digression.

"A Record of Budhist Kingdoms":
Fa Hien (337-422 AD):
visited India during 399-414 AD.

"Journey to the Western World":
Huen Tsang (Yuoan Chwang) 603-664 AD:
visited India during 630-645 AD.

They traversed India like photons and dileptons and left most valuable records!!

Most Reliable Historians of Ancient India



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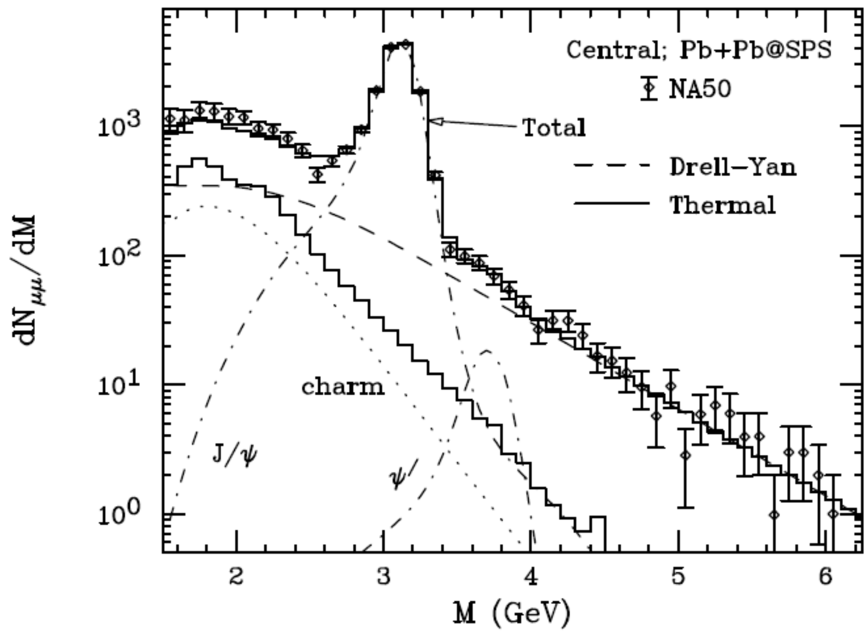
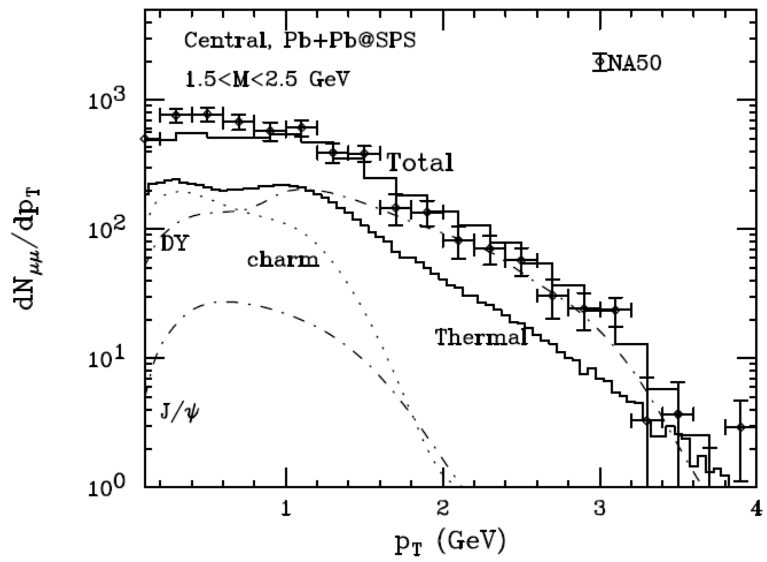
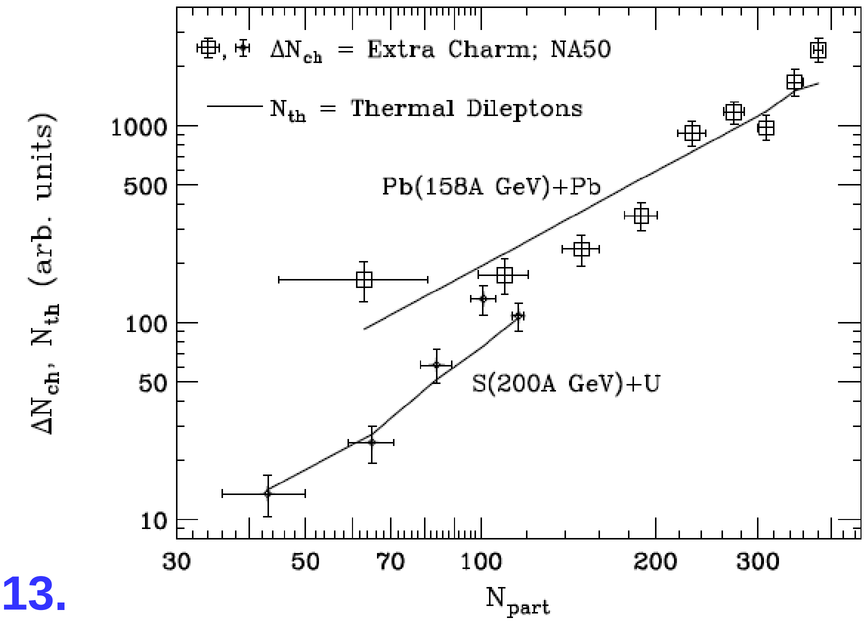
Intermediate Mass; NA50





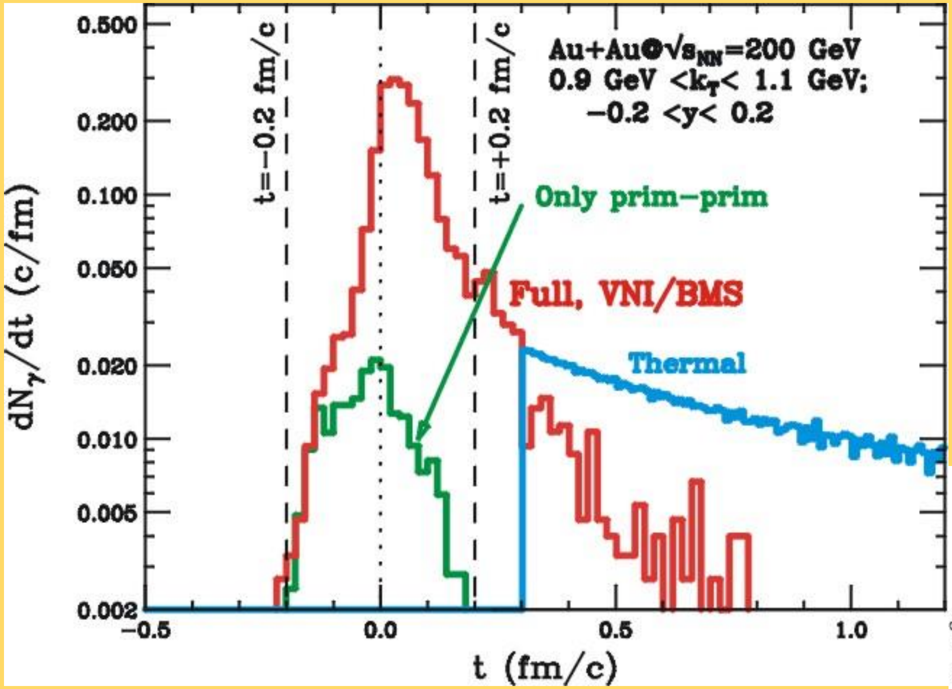


Kvasnikova, Gale, & Srivastava,
PRC 65 (2002) 064903.

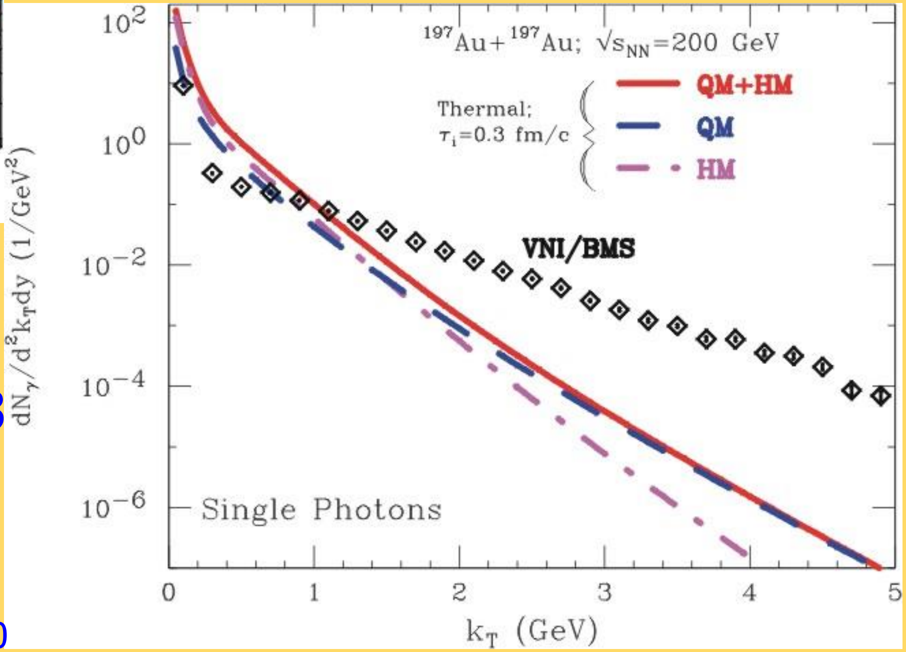
Acceptance and detector resolution accurately modeled.

See also Rapp & Shuryak, PLB 473 (2000) 13.

Photons: pre-equilibrium vs. thermal

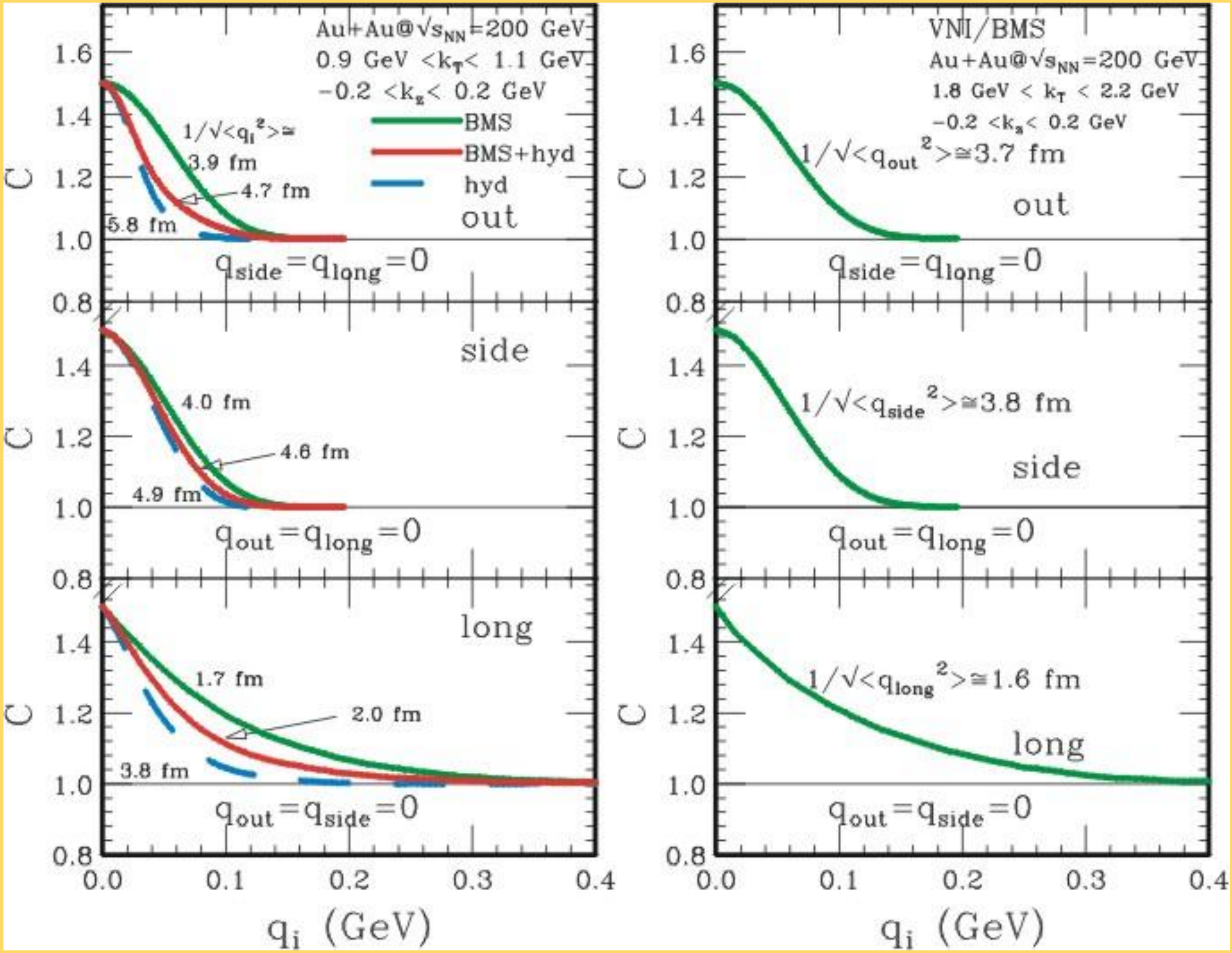


- ➢pre-equilibrium contributions are easier identified at large p_t:
- •window of opportunity above p_t=2 GeV
- •at 1 GeV, need to take thermal contributions into account



- • short emission time in the PCM, 90% of photons before 0.3 fm/c
- ➢ hydrodynamic calculation with τ_0=0.3 fm/c allows for a smooth continuation of emission rate
- ➢ caveat: medium not equilibrated at τ_0

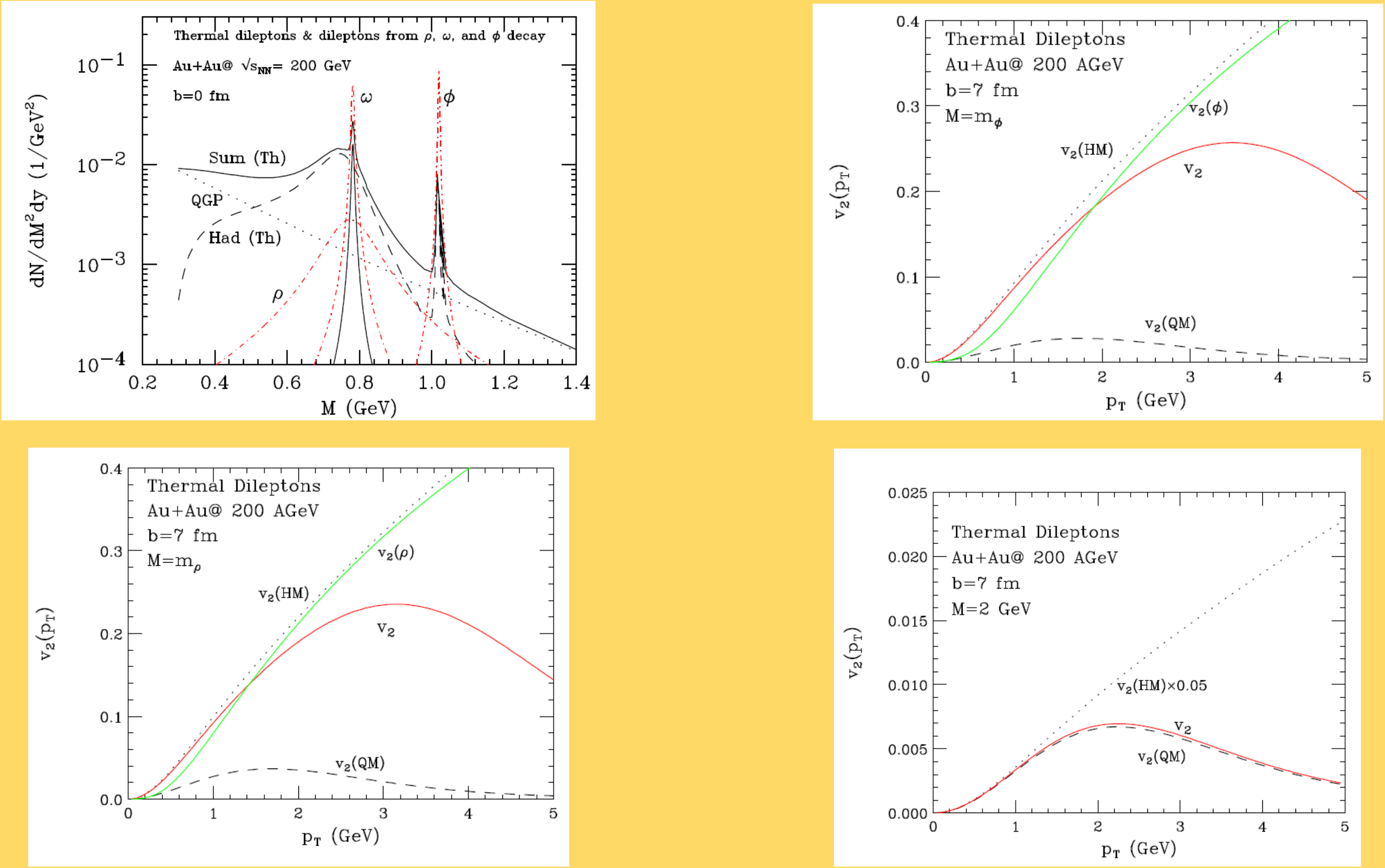
Photons: HBT Interferometry



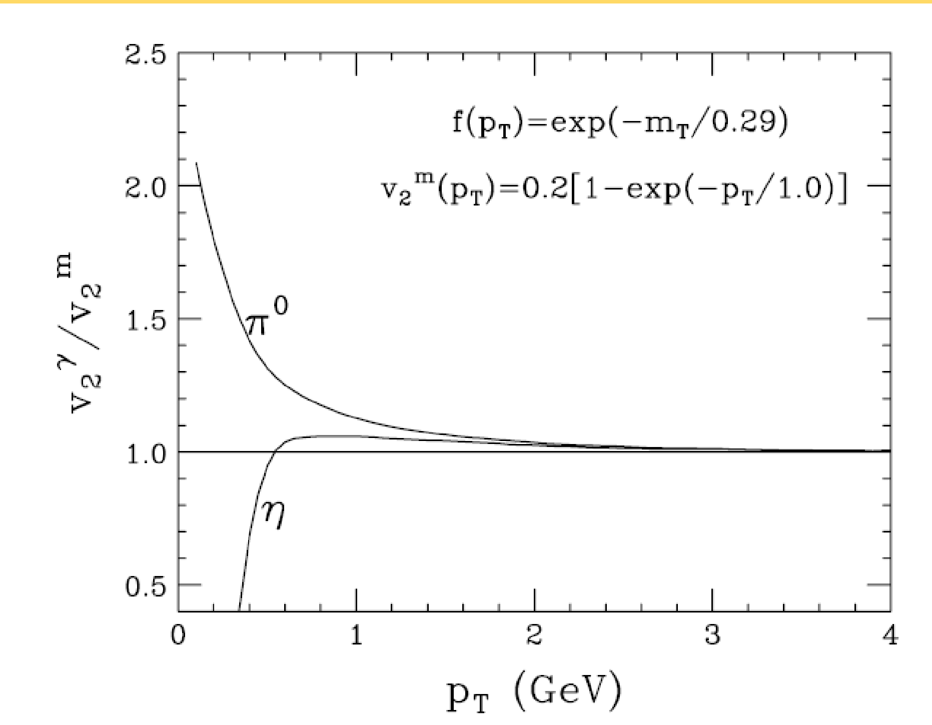
- p_t=2 GeV: pre-thermal photons dominate, small radii
- p_t=1 GeV: superposition of pre- & thermal photons: increase in radii

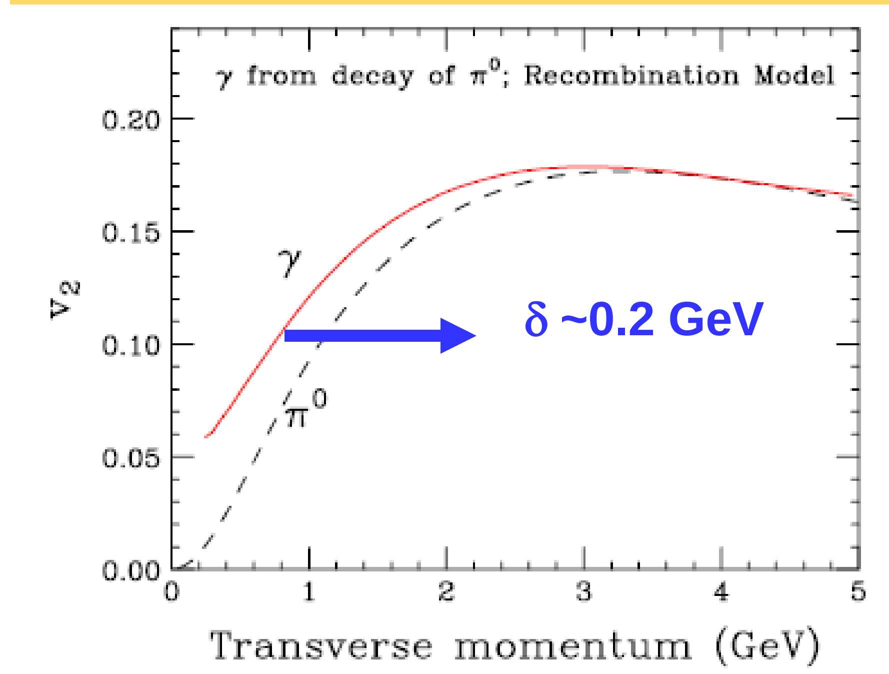
Bass, Mueller, & Srivastava, PRL 93 (2004) 16230; Srivastava, PRC 71 (2005) 034905.

Elliptic Flow of Thermal Dileptons



Elliptic Flow of Decay Photons





$$v_2(k_T) \approx v_2^{\pi^0}(p_T), \quad (7)$$

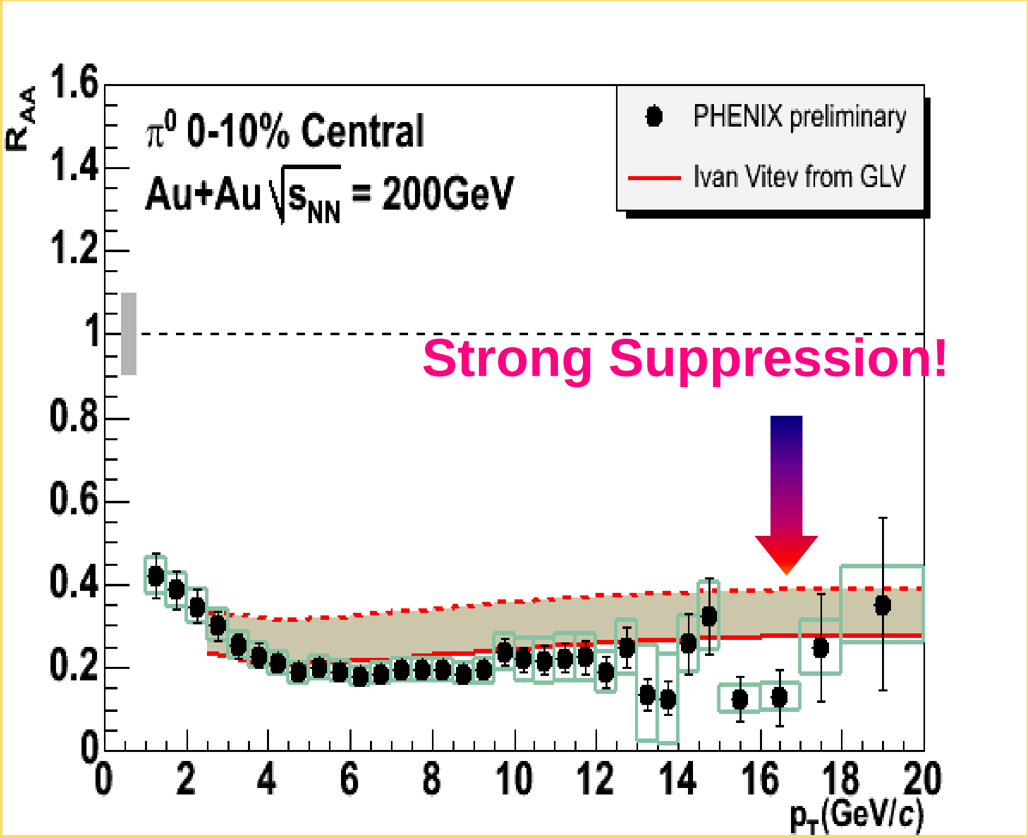
where

$$p_T \approx k_T + \delta \quad (8)$$

and $\delta \approx 0.1$–0.2 GeV, for $k_T > 0.2$ GeV, to an accuracy of better than 1%–3%.

Layek, Chatterjee, Srivastava, PRC 74 (2006) 044901.

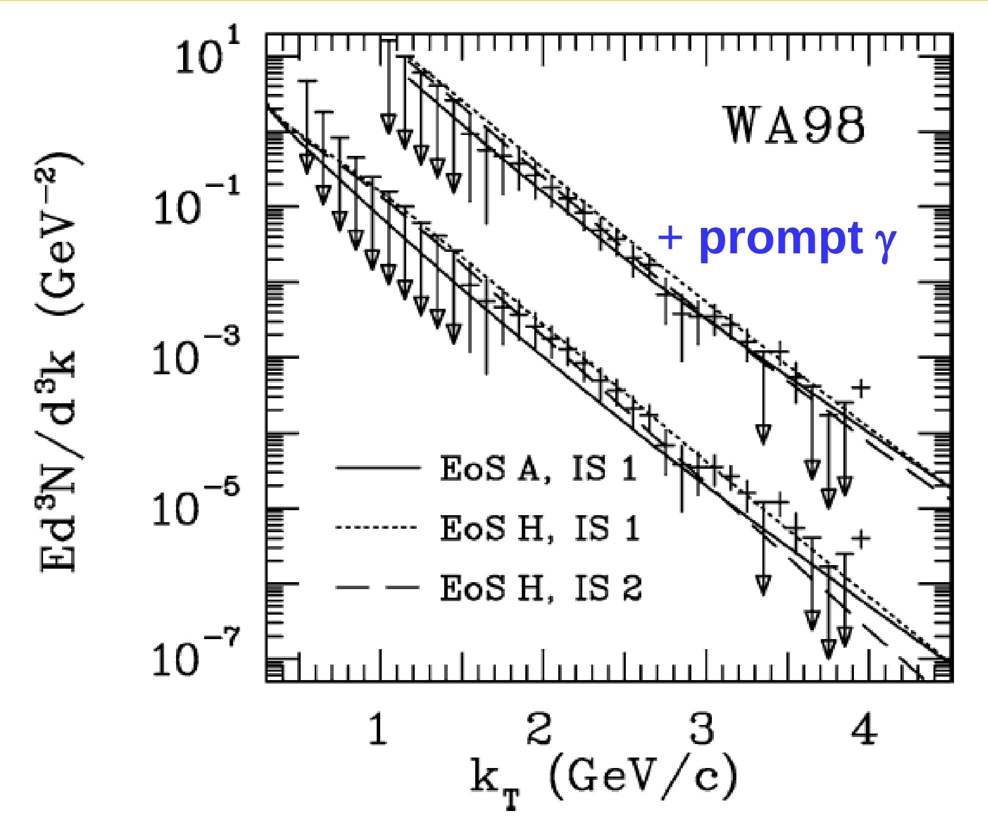
Theoretical Interpretation of High-p_T π^0 Suppression

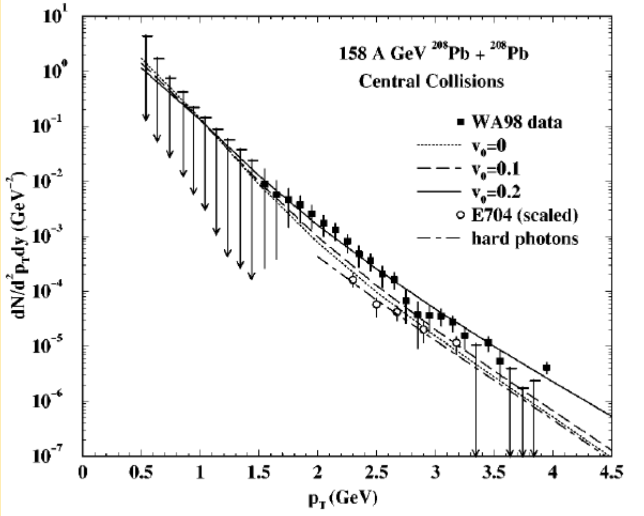


- **Large suppression implies large energy loss. Model calculations indicate high gluon densities $dN_g/dy \sim 1100$**
- **Implies large energy density (as do also E_T measurements) ε > 10 GeV/fm^3 well above critical energy density $\varepsilon_{crit} \sim 1$ GeV/fm^3**

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{\rm ch}^{AA}/d\eta dp_T}{\langle N_{\rm coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{\rm ch}^{pp}/d\eta dp_T}$$

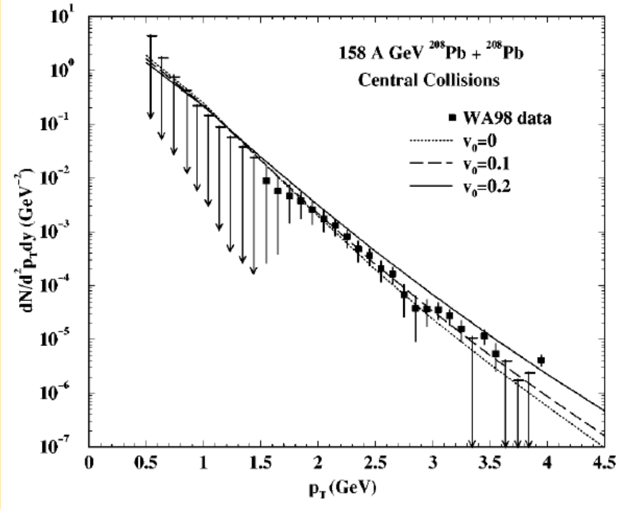
QGP or Hot Hadrons? Enter WA98





QGP

v_0.ne.0



Hadrons
($m_{had} \rightarrow 0$ at T_i=205 MeV for all hadrons)

Huovinen et al, PLB 535 (2002) 109.
QGP or hadrons ($n_{had} >> 1/fm^3$ at T_i = 245-275 MeV)

Alam et al, PRC 63 (2001) 021901 (R).