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

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Epilogue as a Prologue

- **Observation of Quark Gluon Plasma is one of the most spectacular confirmations of Quantum Chromo-Dynamics- the theory of strong interactions.**

- **It has led to the creation of the conditions of the Early Universe a few micro-seconds after The Big Bang.**

- **It required the largest international effort ever mounted with several thousand engineers and scientists working in unison to build several accelerators and detectors costing billions of dollars and inventing computing techniques like grid computing to deal with the enormous bulk of the data generated.**

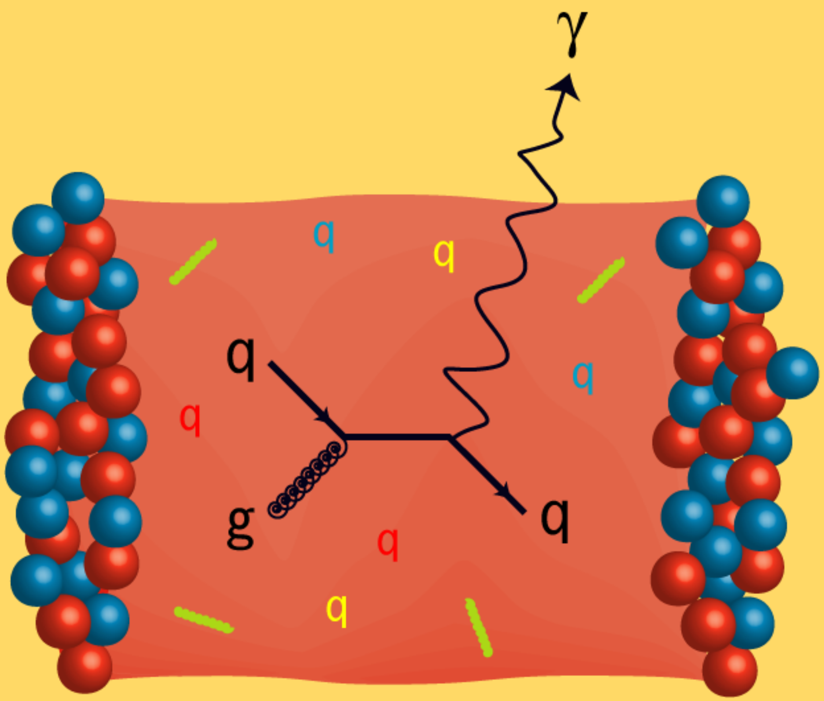
- **It has also led to several questions which need to be answered.**

- **Thirty seven years ago:**

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

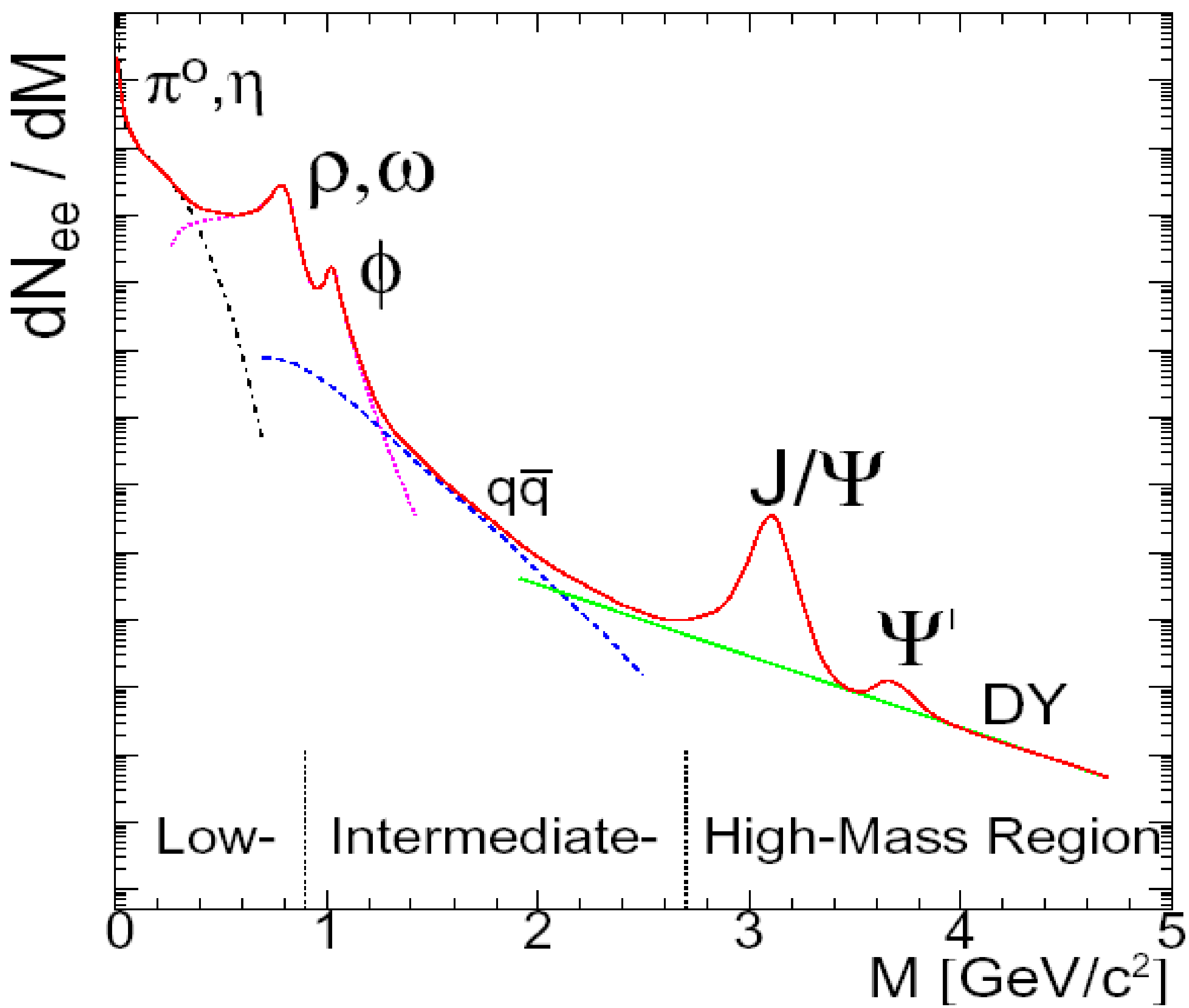
  Direct photons; real or virtual are penetrating probes for the bulk matter produced in hadronic collisions, as

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



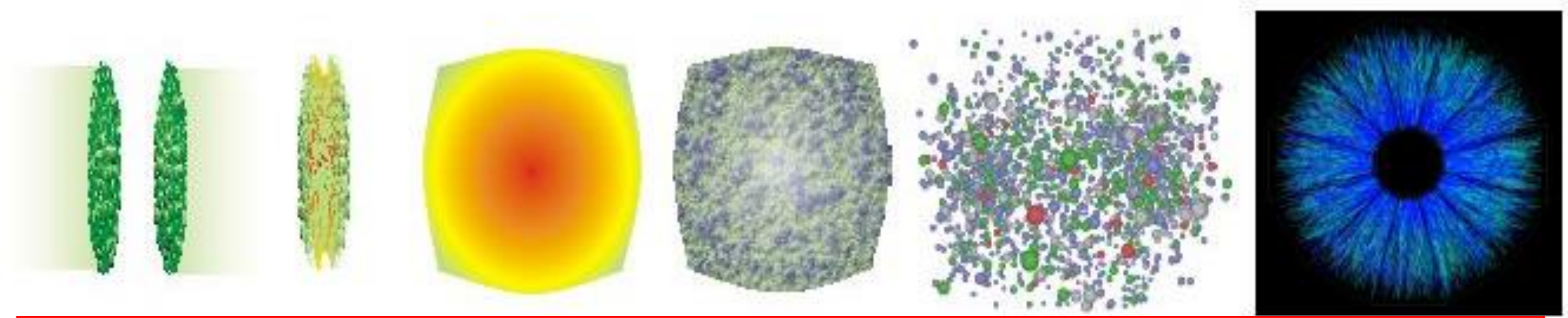
- Since then relentless efforts by researchers from across the world have established these as *reliable probes of hot and dense matter*.

Low, Intermediate, & High Mass Dileptons

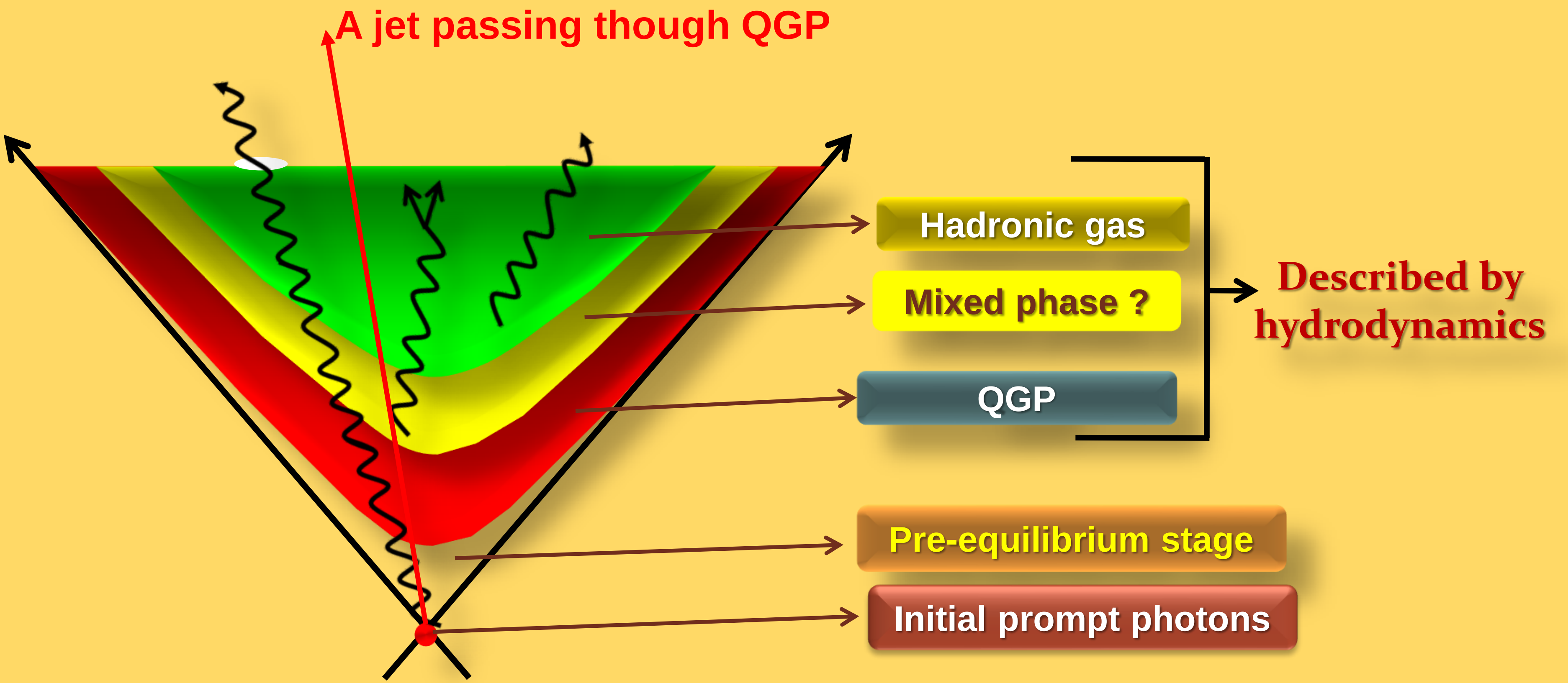


- **Low-mass:**
  Medium modified spectral density
- **Intermediate mass:**
  Radiation from QGP
- **High mass:**
  J/ψ etc., suppression
- **All masses:**
  Correlated Charm/ Bottom Decay.

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

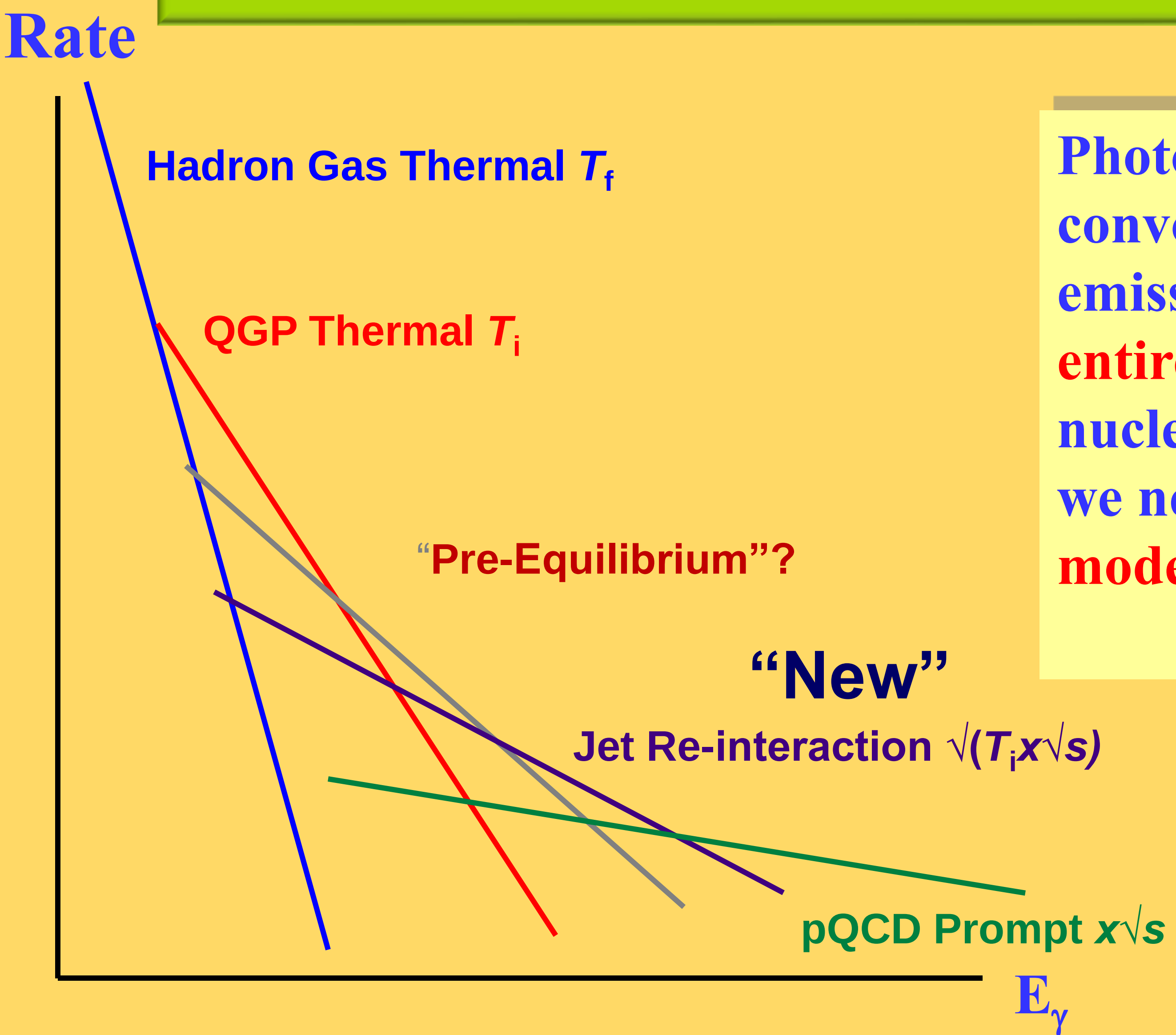


Single photons are penetrating probes. They are emitted at all stages and survive unscathed ($\alpha_e \ll \alpha_s$). They are "historians" of the heavy ion collision!



Different processes: different characteristic spectra!

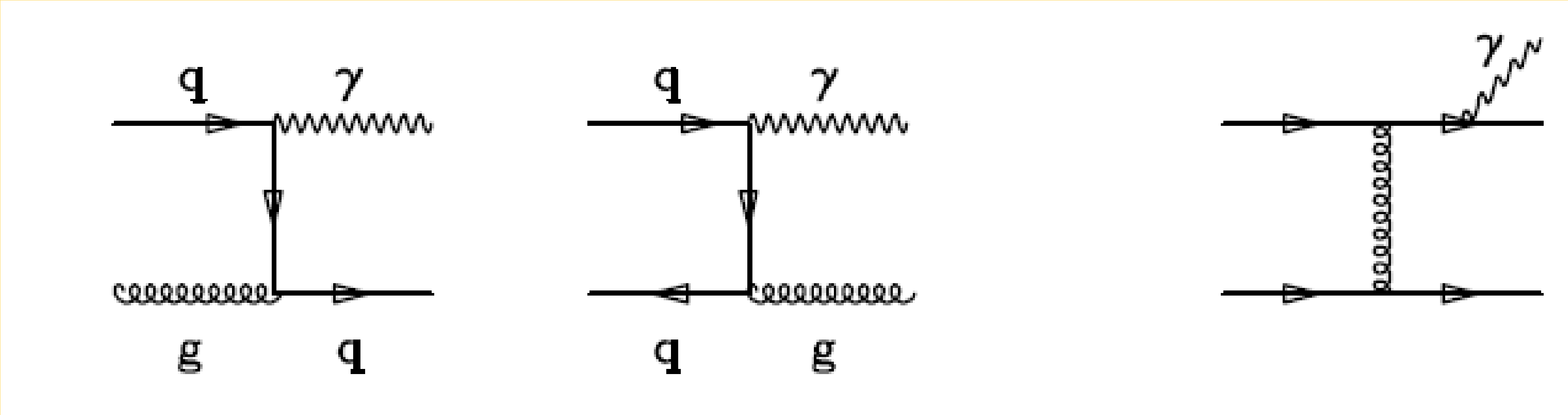
Direct Photons
Different Sources - Different Slopes



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

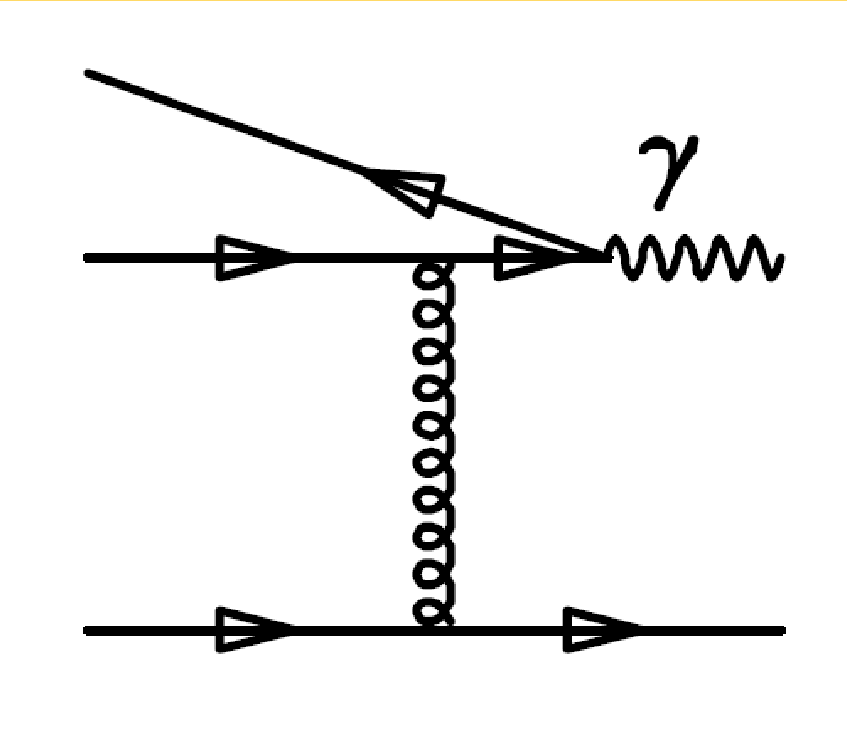
Fragmentation

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!]

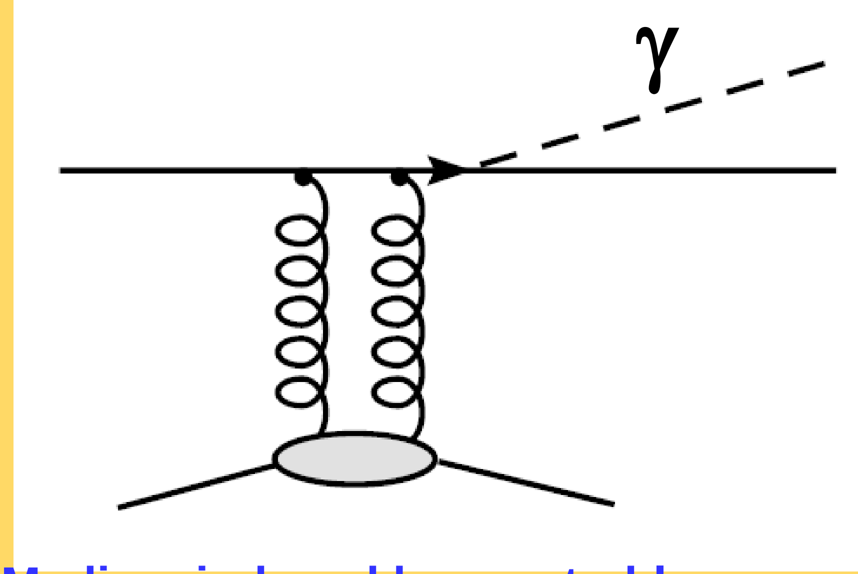
The quarks will lose energy *before fragmenting* if there is QGP; suppressing the fragmentation contribution.

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

In the QGP we also have:



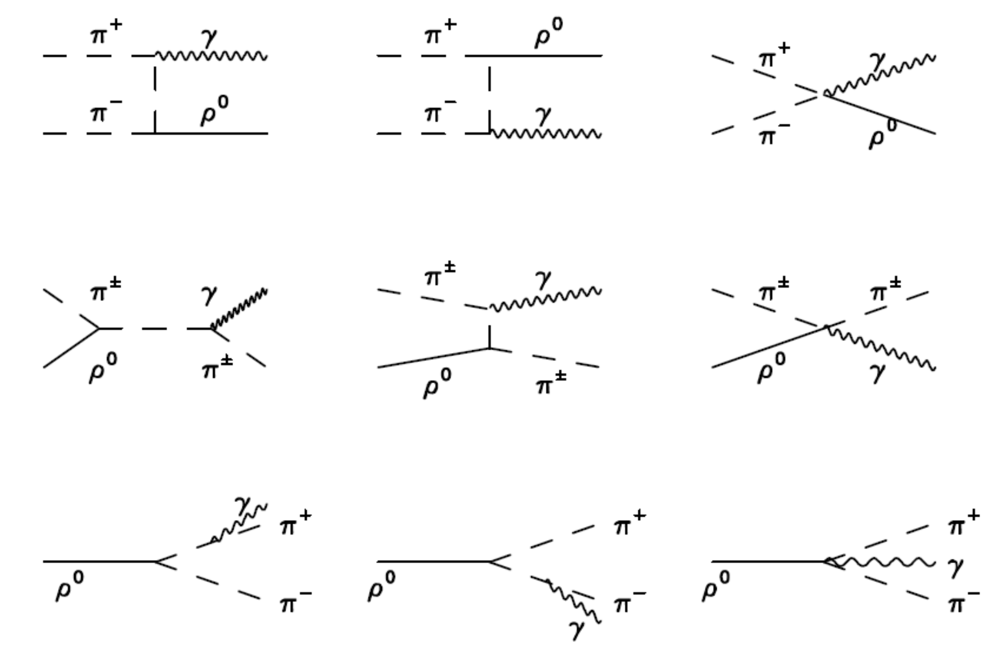
Annihilation with scatterring; *First calculated by Aurenche et al, PRD 58 (1998) 085003.*



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.

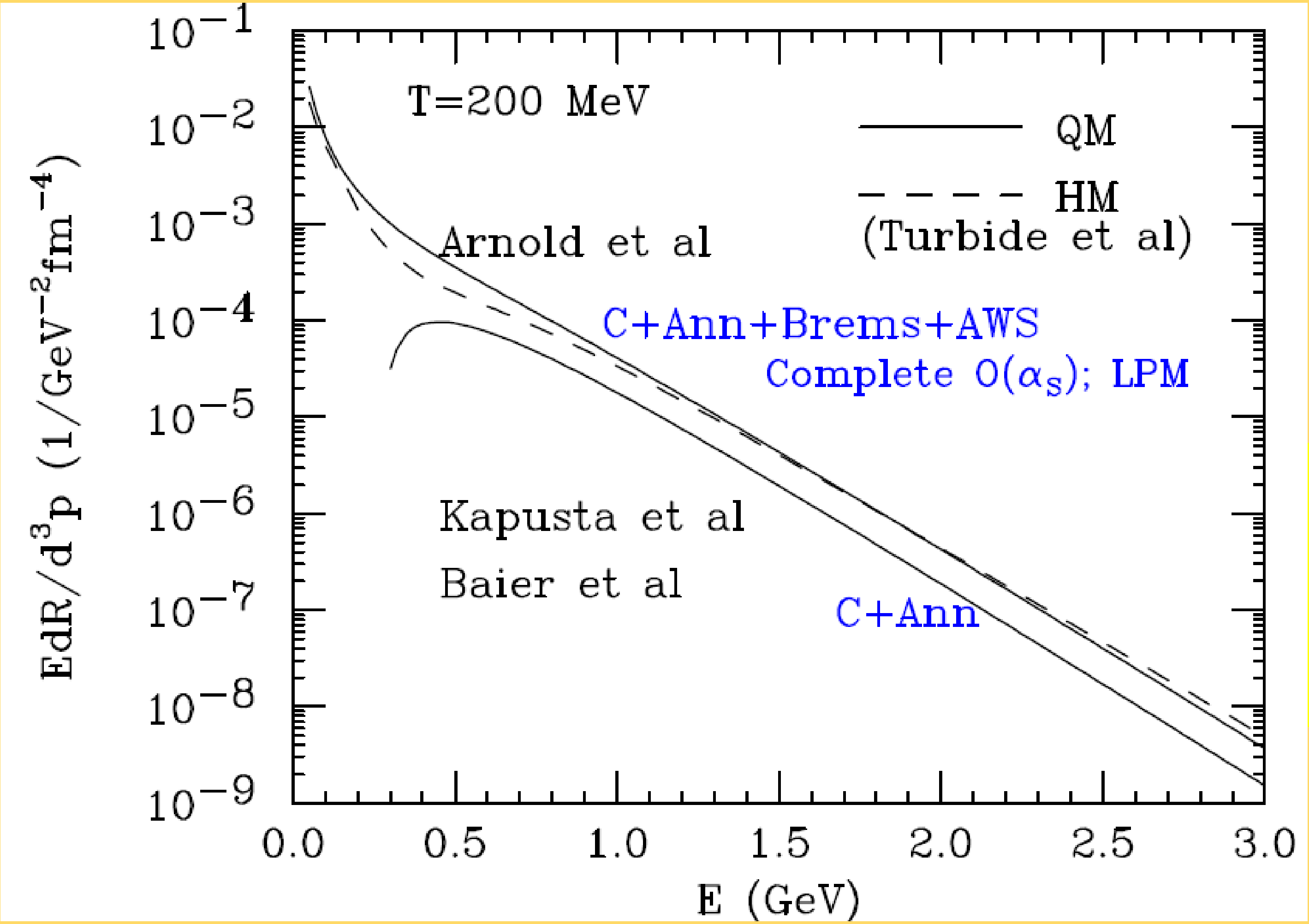
- Include $\pi\rho \rightarrow a_1 \rightarrow \pi\gamma$
  Xiong et al, PRD 46 (1992) 3798;
  Song, PRC 47 (1993) 2861.

- 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



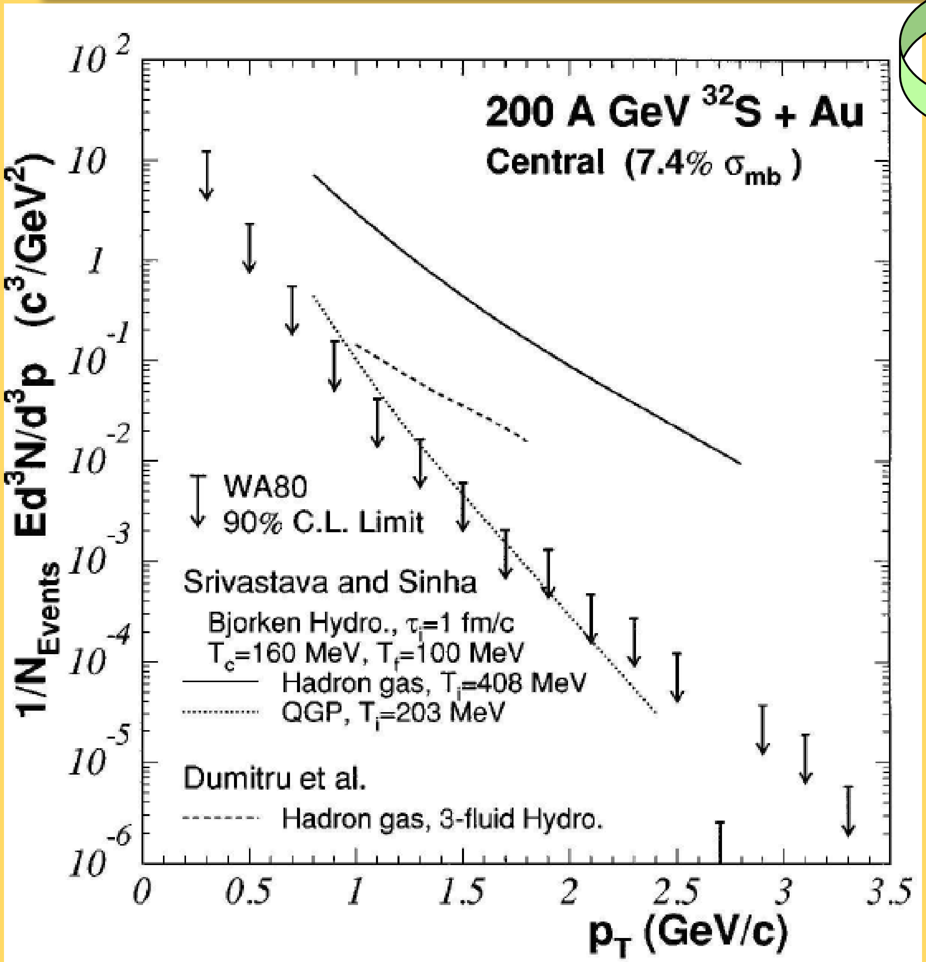
Rates are similar !!

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

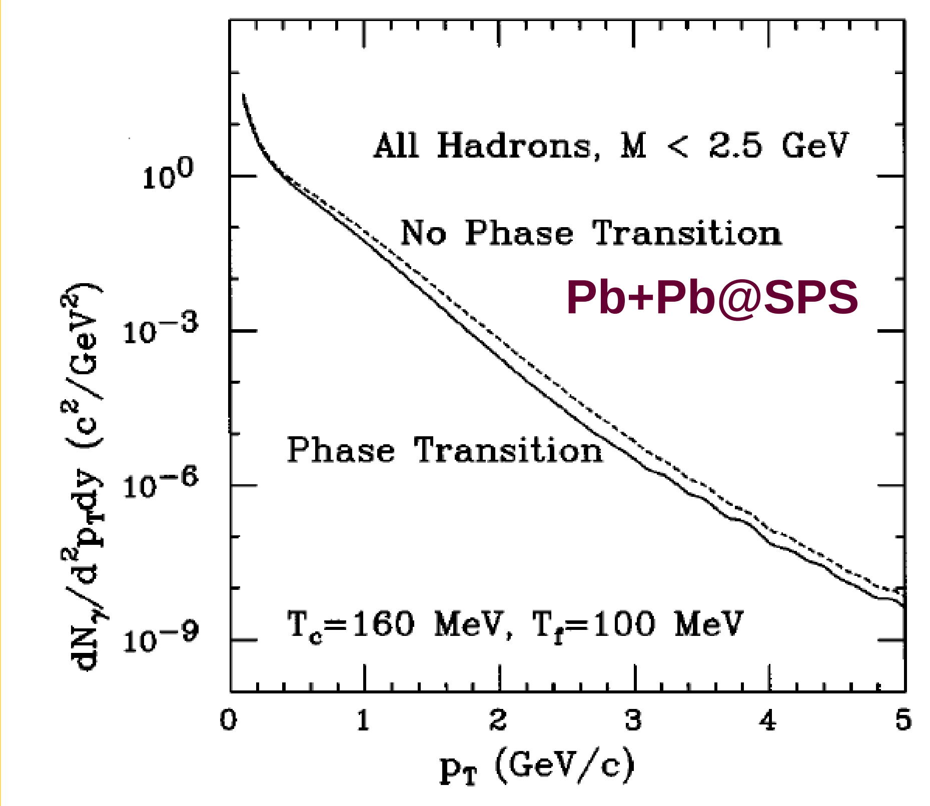
Arnold, Moore, & Yaffe, JHEP 0112 (2001) 009.

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

Upper Limit of Single Photons, WA80



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

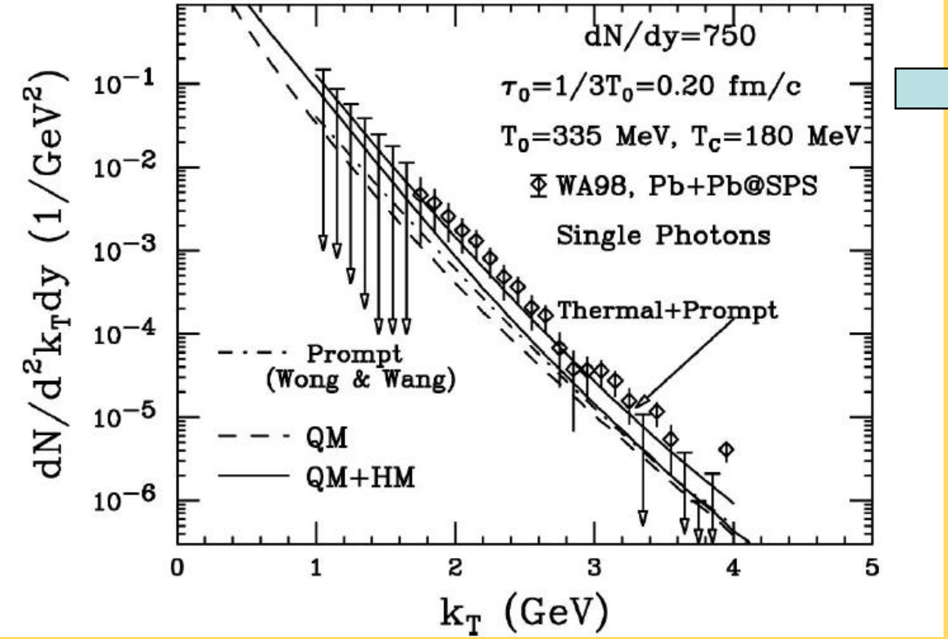


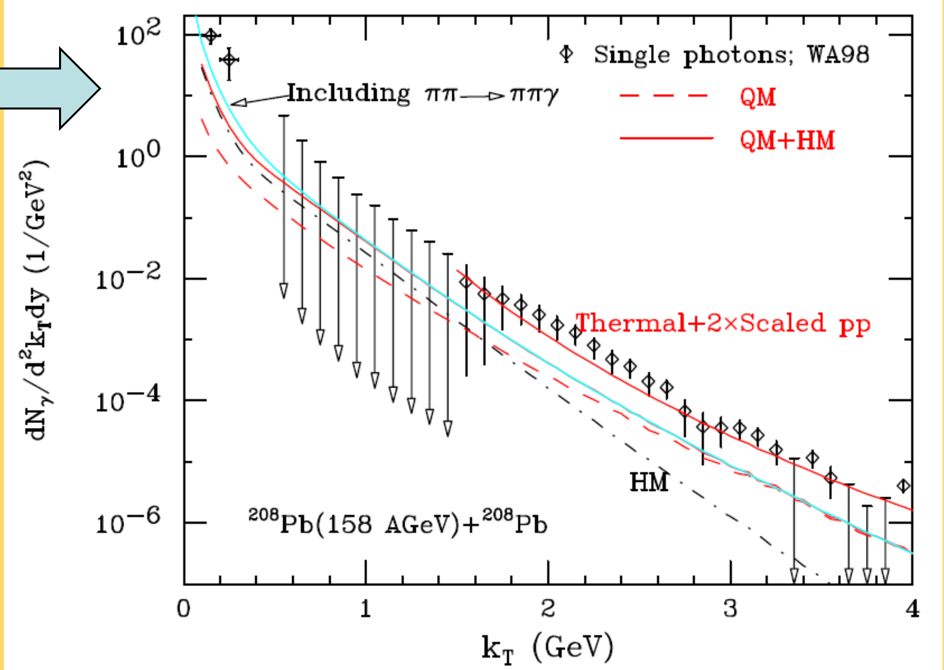
S. and Sinha, PRL 73 (1994) 2421;
Dumitru et al., PRC 51 (1995) 2166.

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





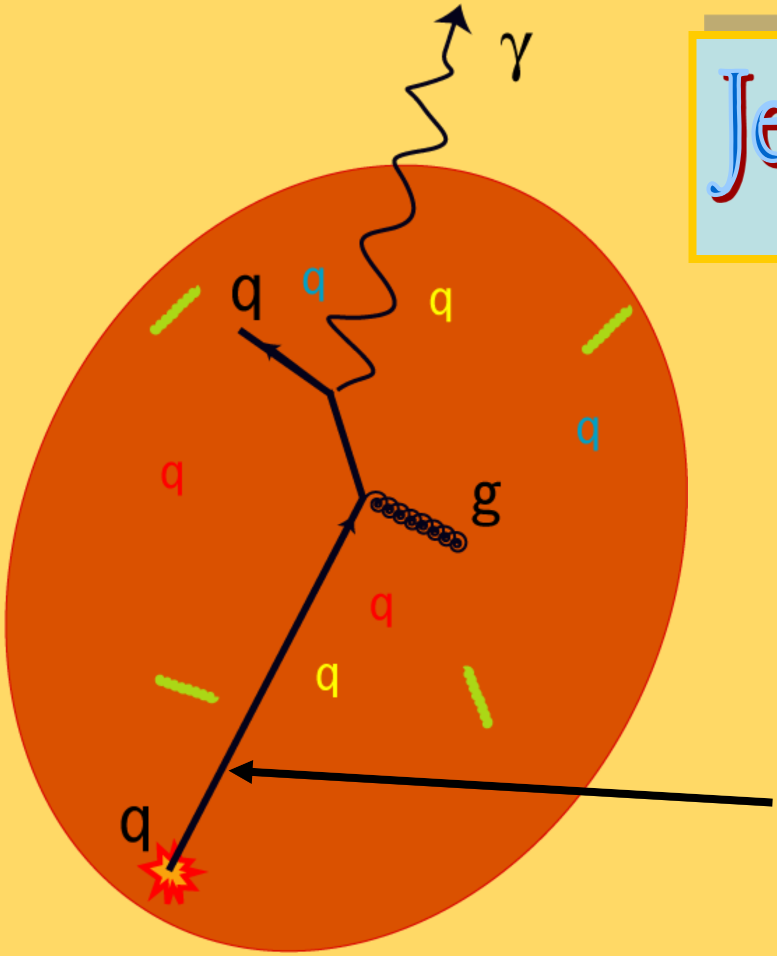
S. & Sinha, PRC 64 (2001)034902 (R).

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

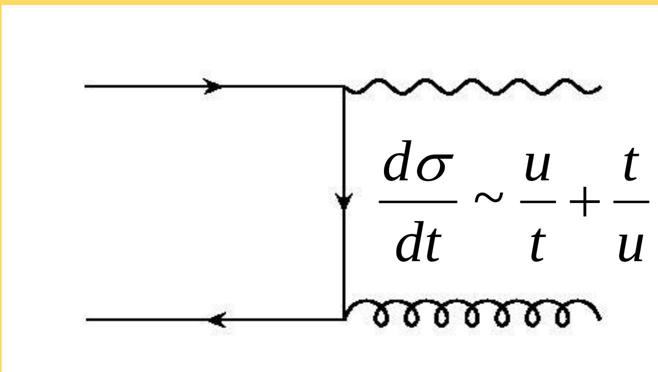
"External Probe!!"

Hard scattered parton

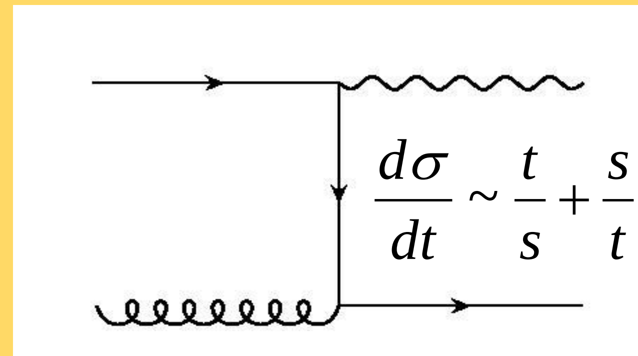
Fries, Mueller, & S. , PRL 90 (2003) 132301.

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

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

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

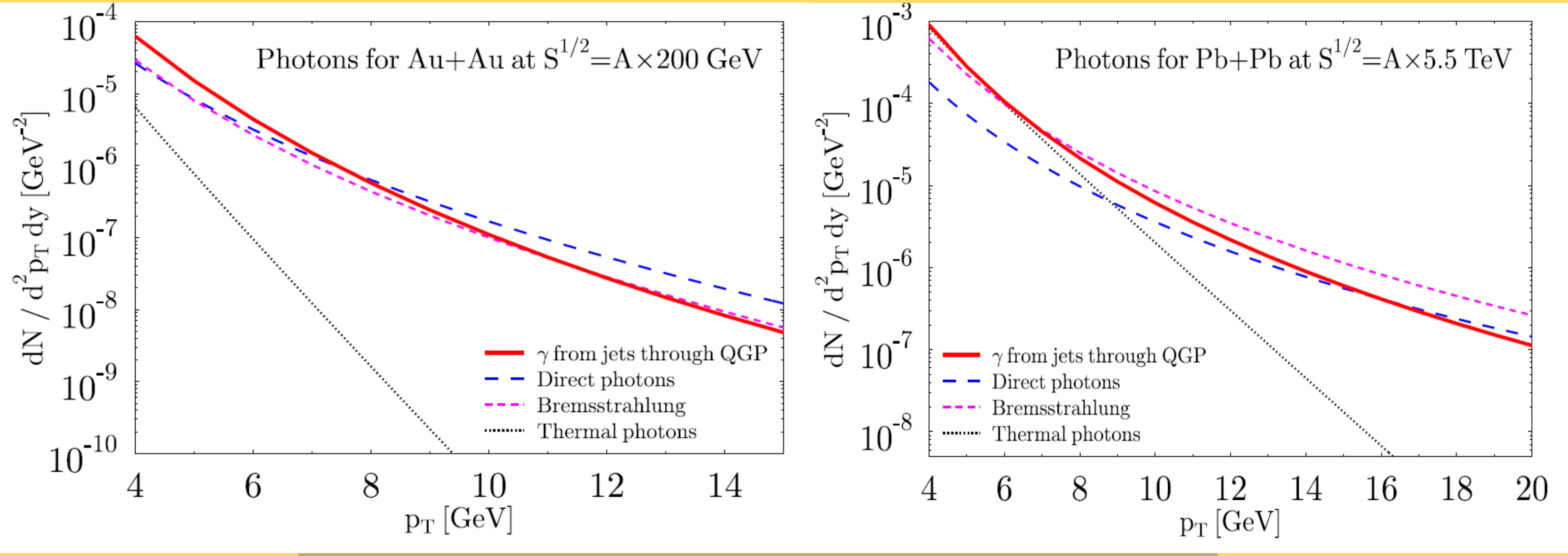
$$E_\gamma \frac{dN^{(C)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(p_\gamma)$$

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

- 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

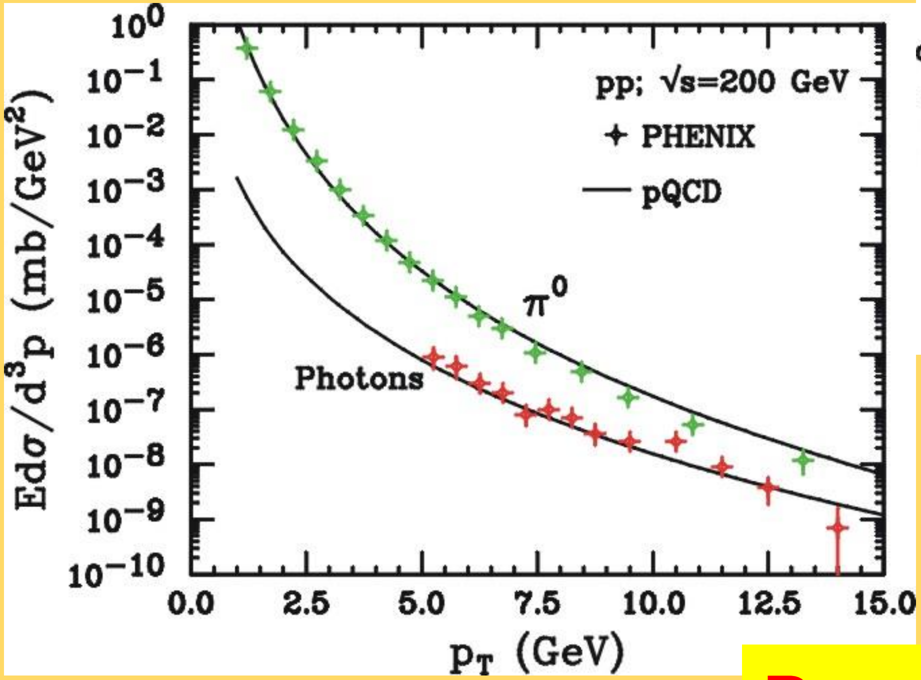


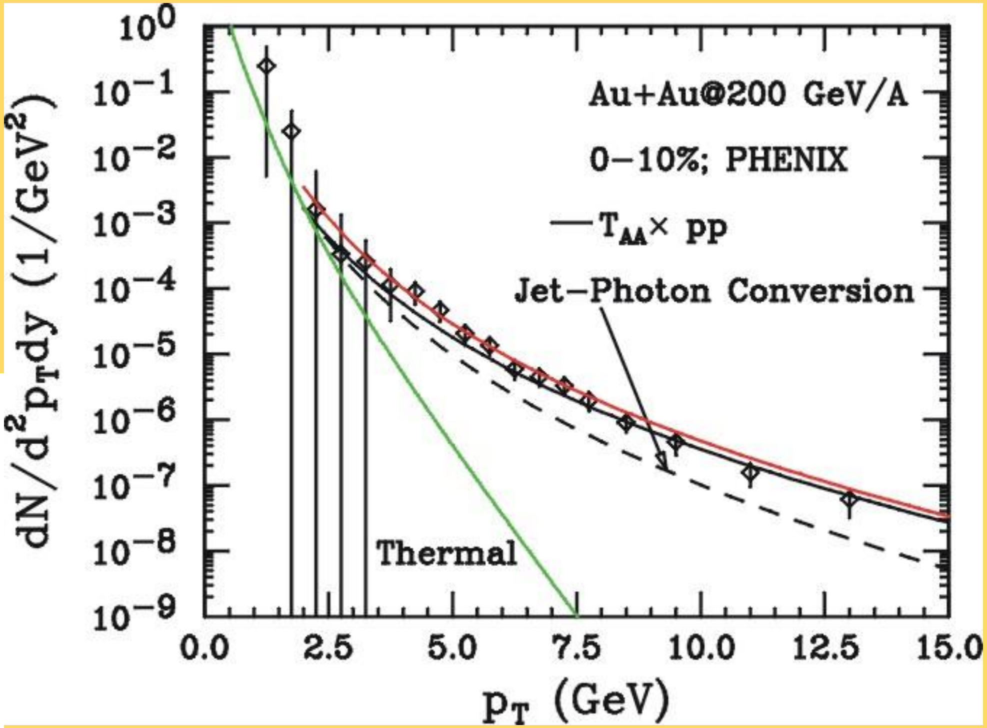
Fries, Mueller, & S., PRL 90 (2003) 132301.

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:



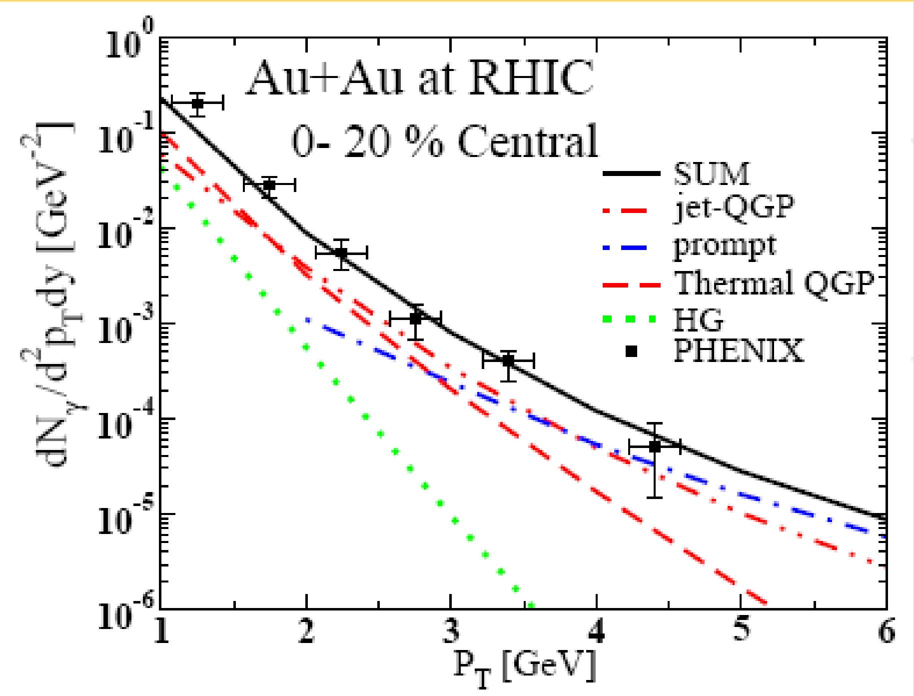


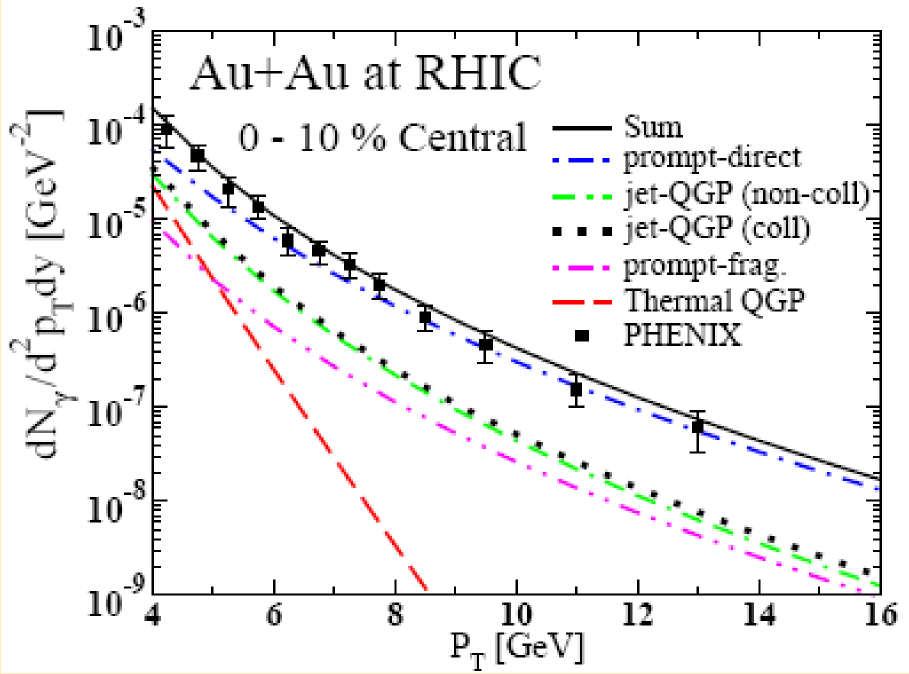
- for p_t<6 GeV, FMS photons give significant contribution to photon spectrum: 50% @ 4GeV.

Proper Isospins & Shadowing !!!

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

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

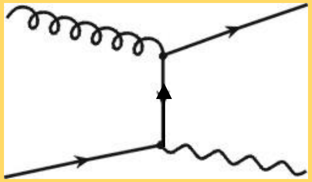
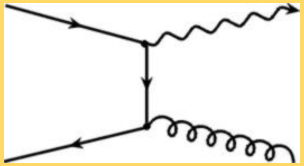
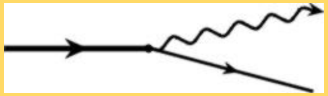




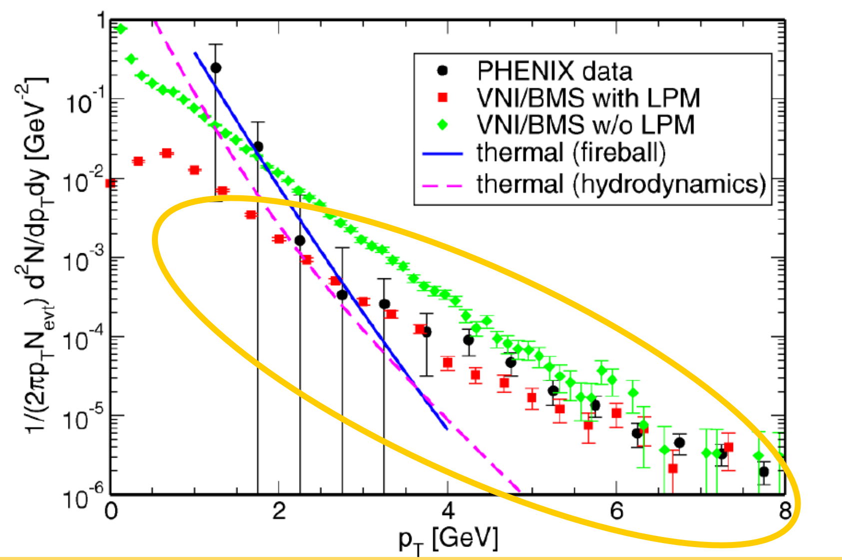
Turbide, Gale, Frodermann, & Heinz, hep-ph/0712.732

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.

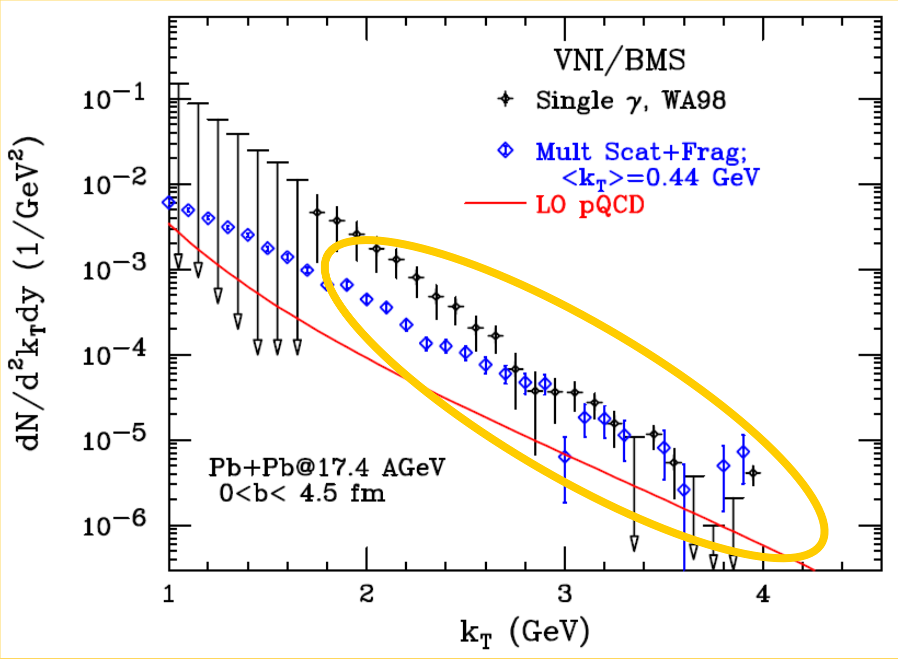
Parton Cascade Model


Embedded in the partonic cascades



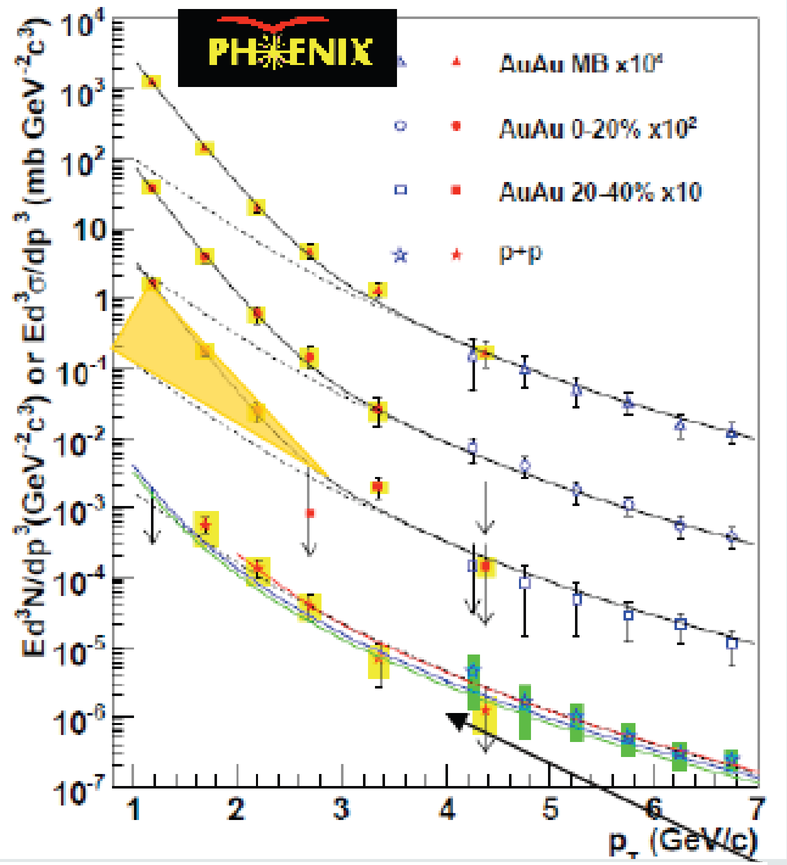
Renk, Bass, & S., PLB 632 (2006) 632.



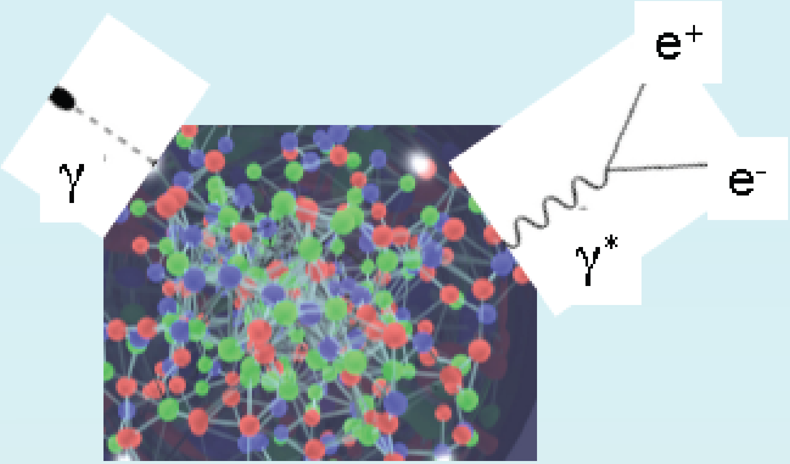
LPM plays a significant role.

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

Initial temperature? Thermal radiation



Phys.Rev.Lett.104:132301,2010

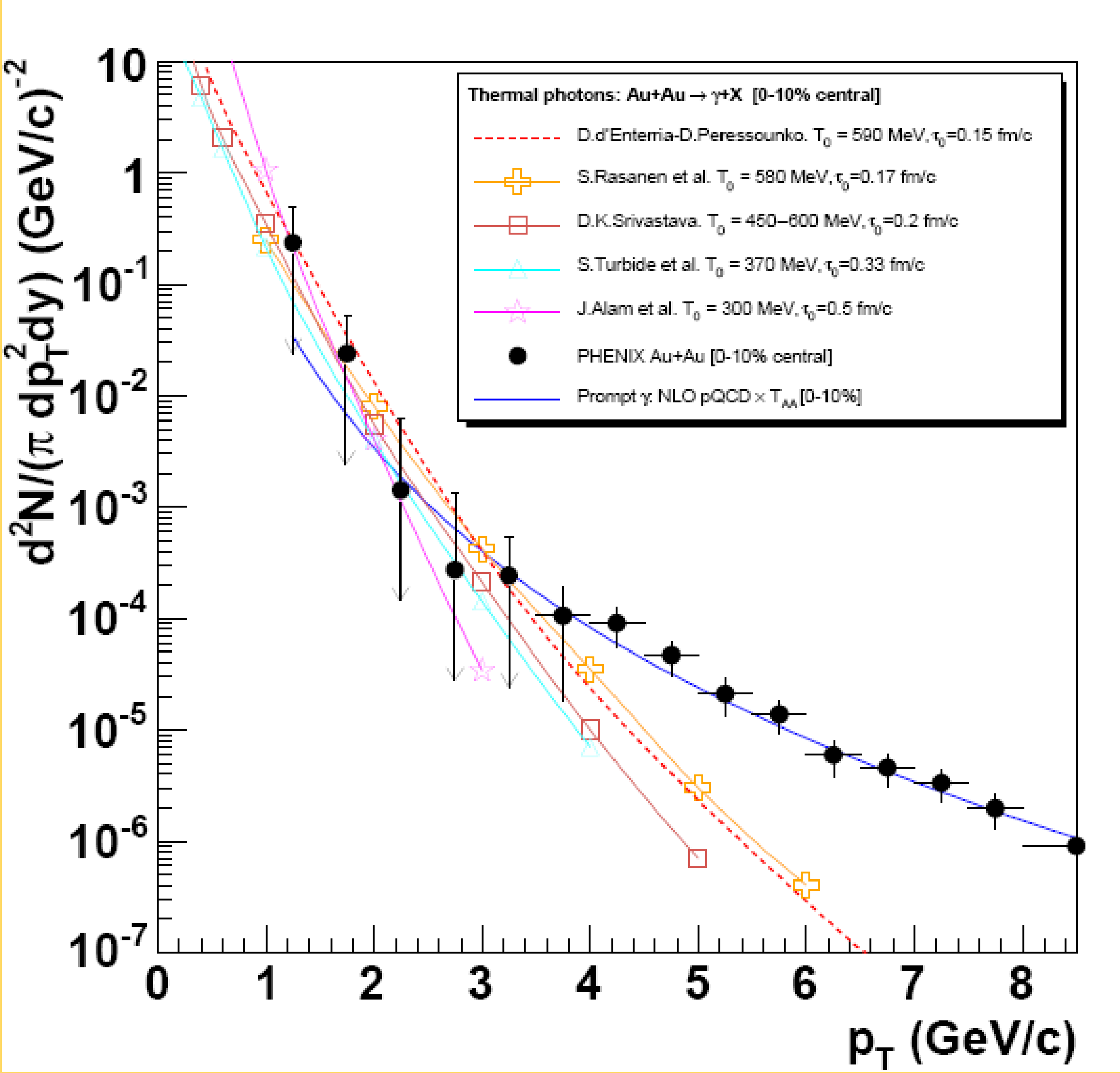


Low mass, high p_T e^+e^- → nearly real photons

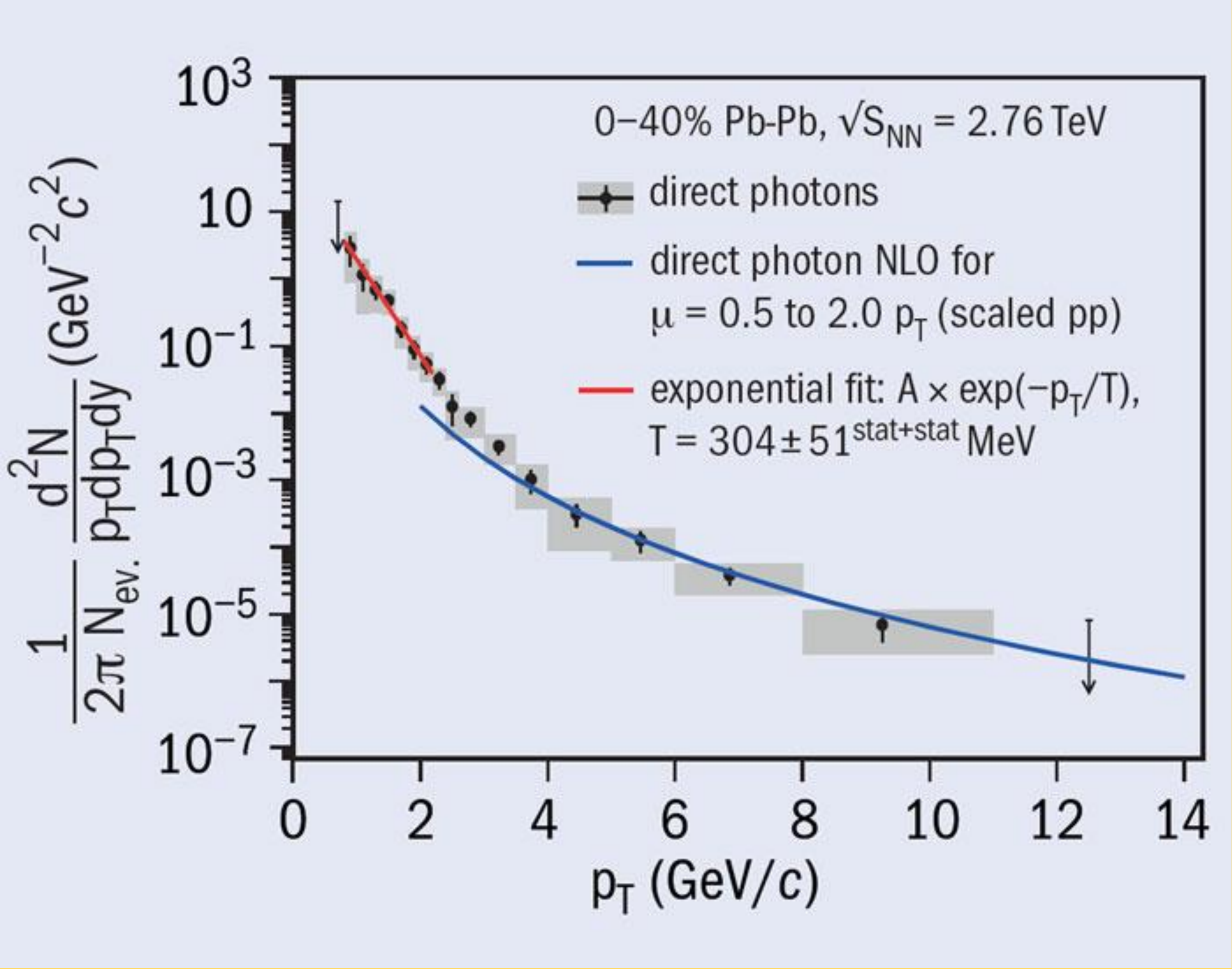
Large enhancement above p+p in the thermal region

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.



Highest temperature in the Universe since The Big Bang!

Anisotropic Flow

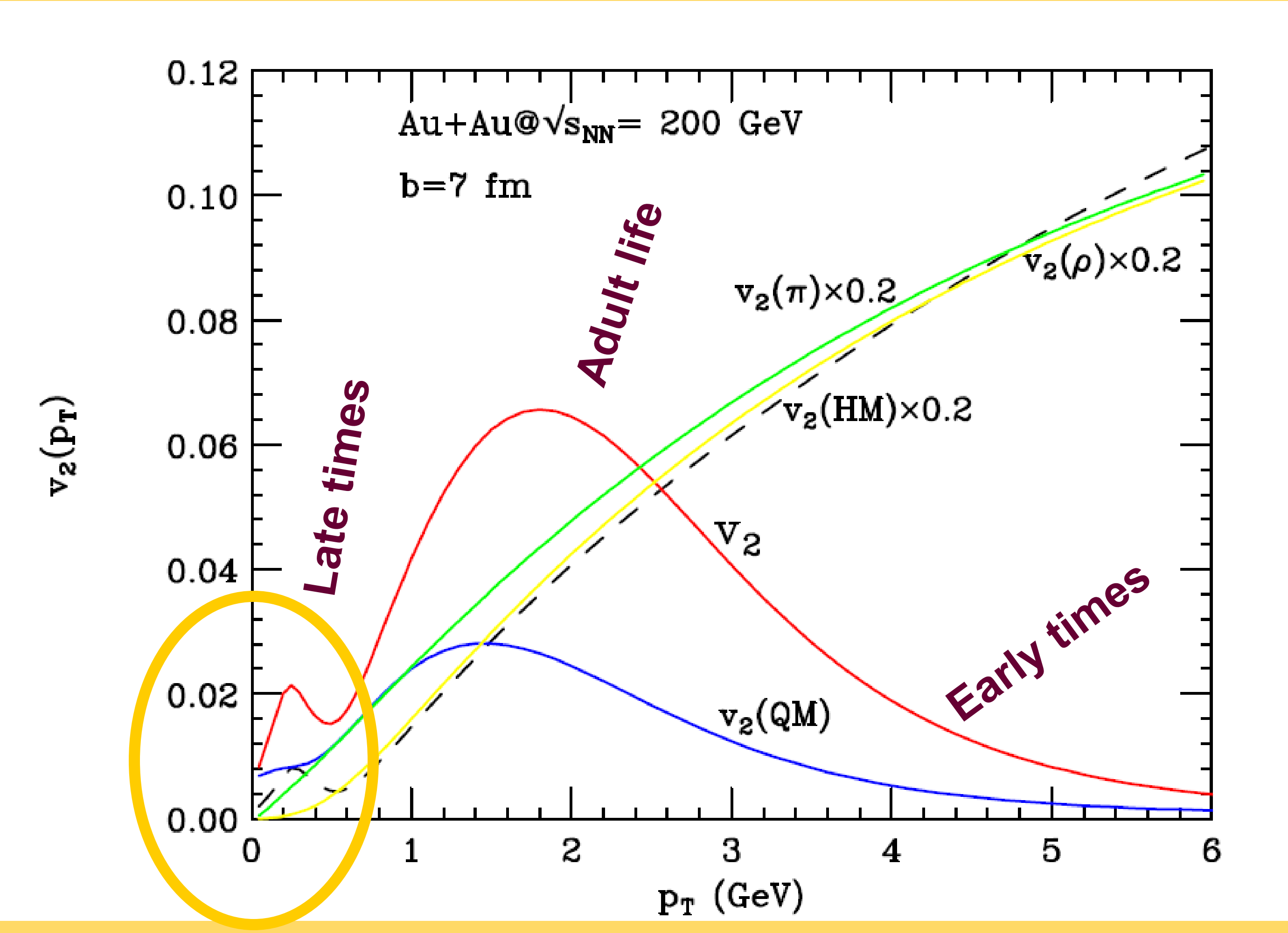
- Characterized by the azimuthal Fourier coefficient of the spectrum:

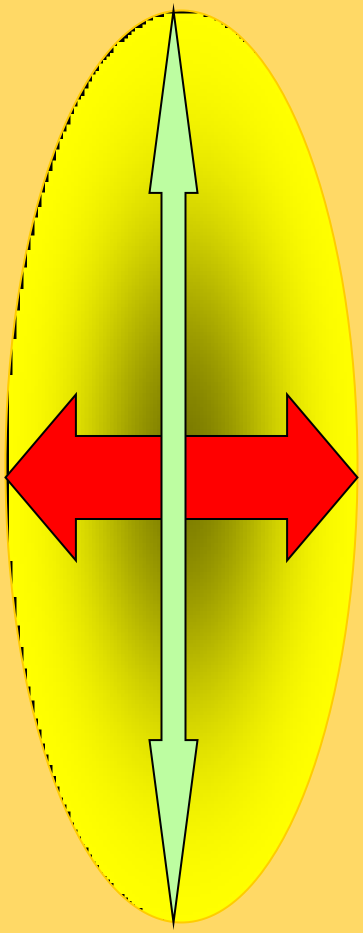
$$\frac{dN(b)}{d\varphi p_T dp_T dy} = \frac{dN(b)}{2\pi p_T dp_T dy}\left[1 + 2v_2(p_T, b)\cos(2\varphi) + \ldots\right]$$

where

$$v_2(p_T, b) = \frac{\int d\varphi \cos(2\varphi) E \dfrac{dN(b)}{d\varphi p_T dp_T dy}}{\int d\varphi E \dfrac{dN(b)}{d\varphi p_T dp_T dy}}$$

Elliptic Flow of Thermal Photons:
Measure Evolution of Flow !

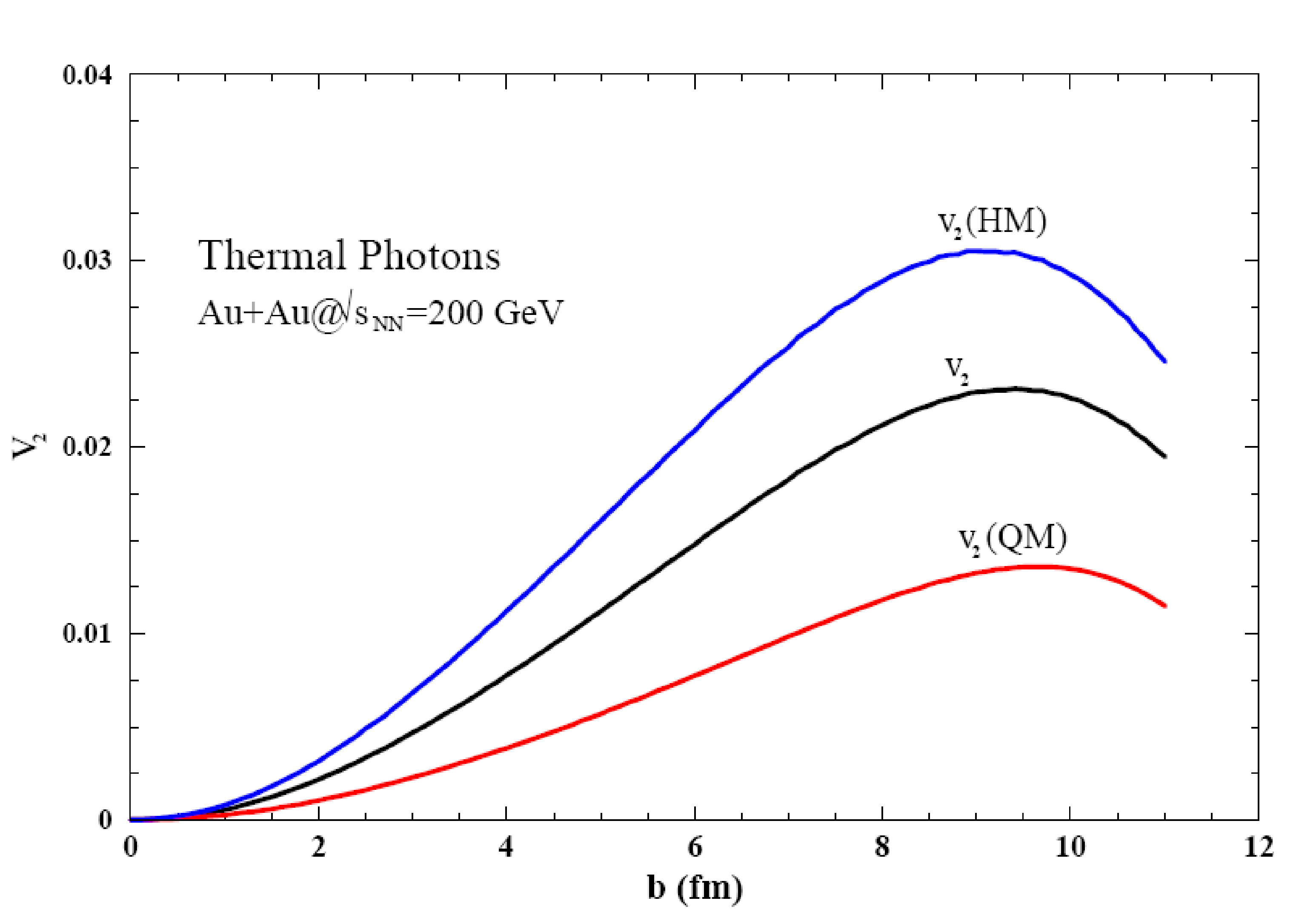




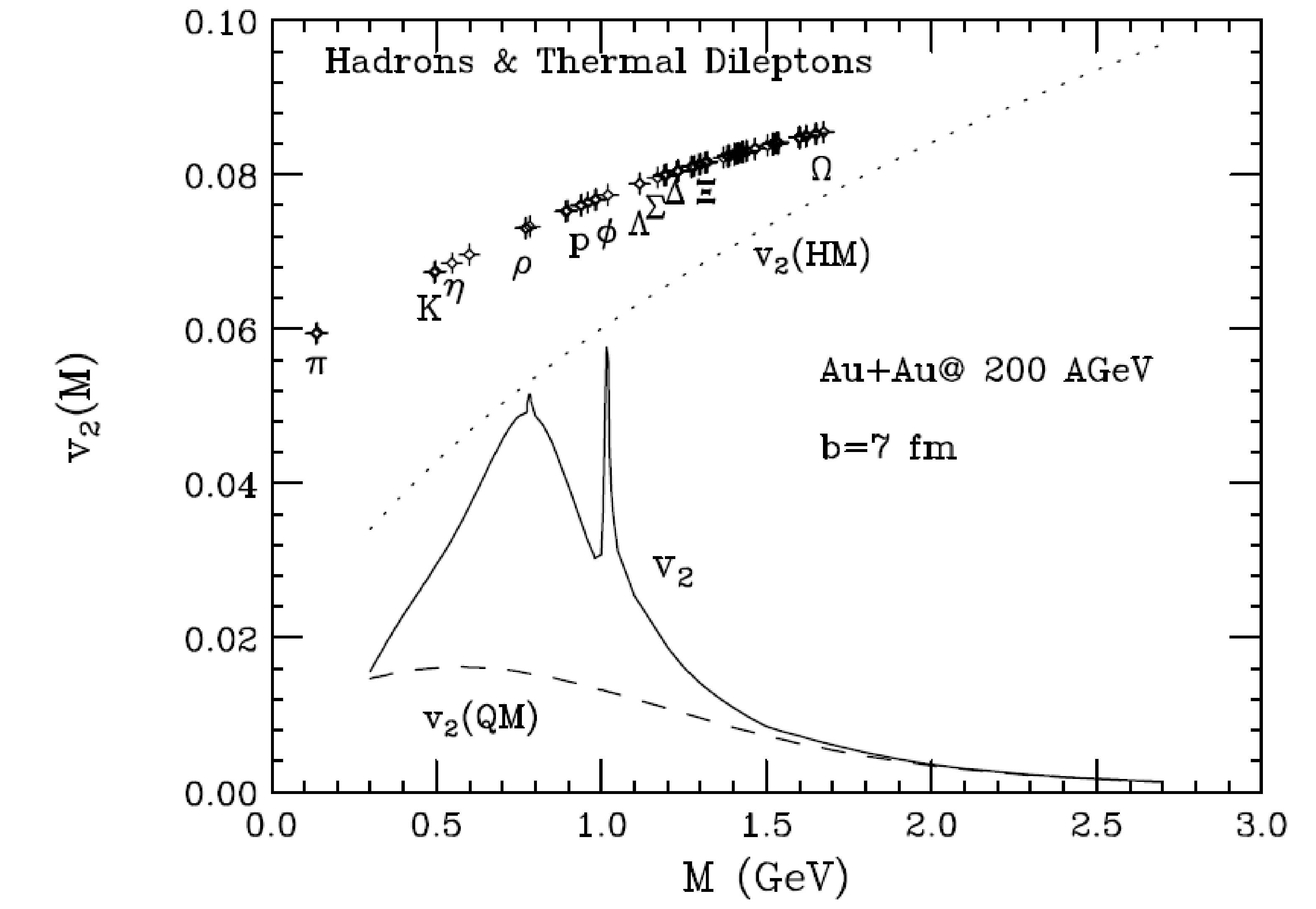
FIRST

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

Impact Parameter Dependence of v_2



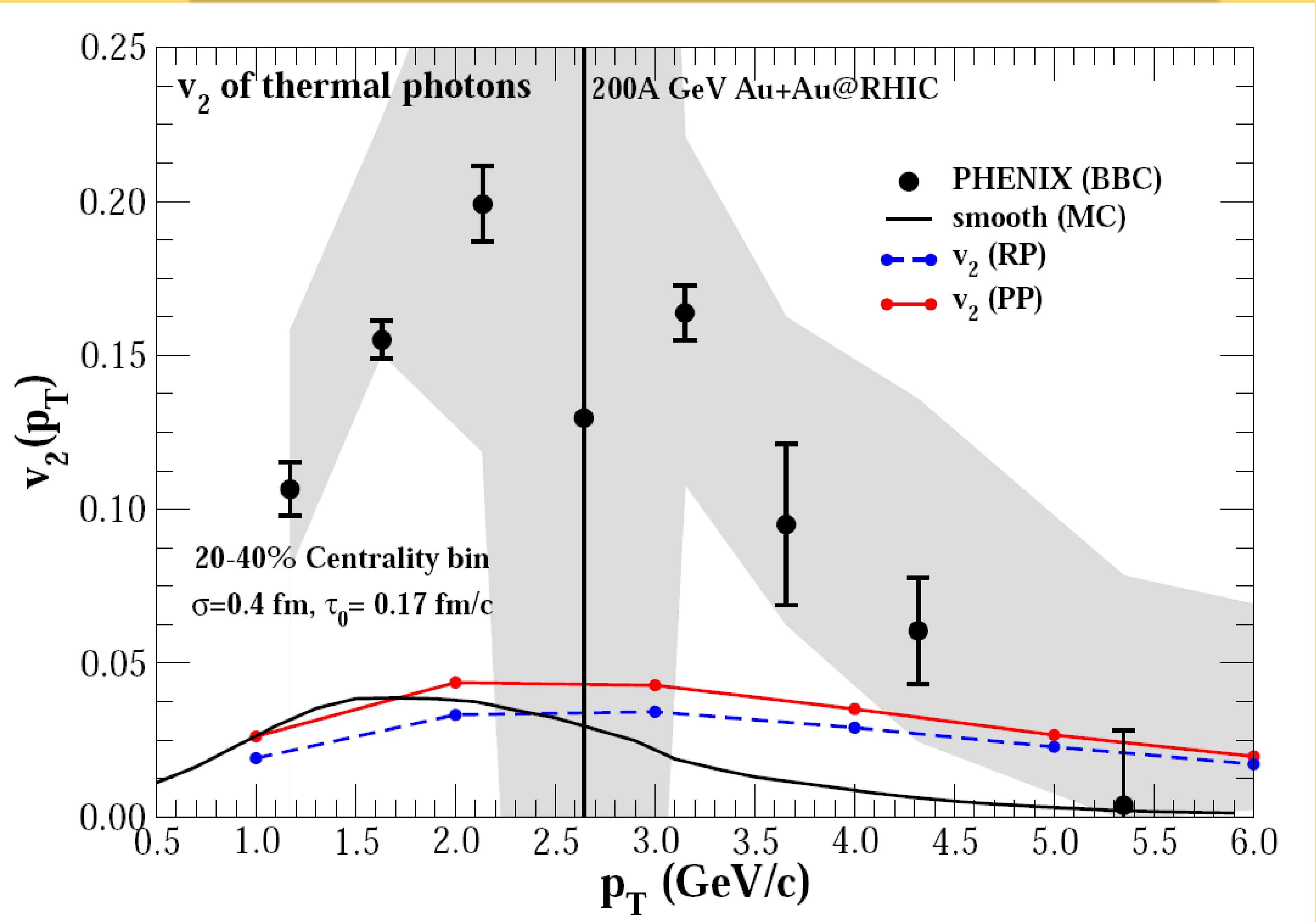
Elliptic Flow of Thermal Dileptons: *Measure Evolution of Flow !*



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

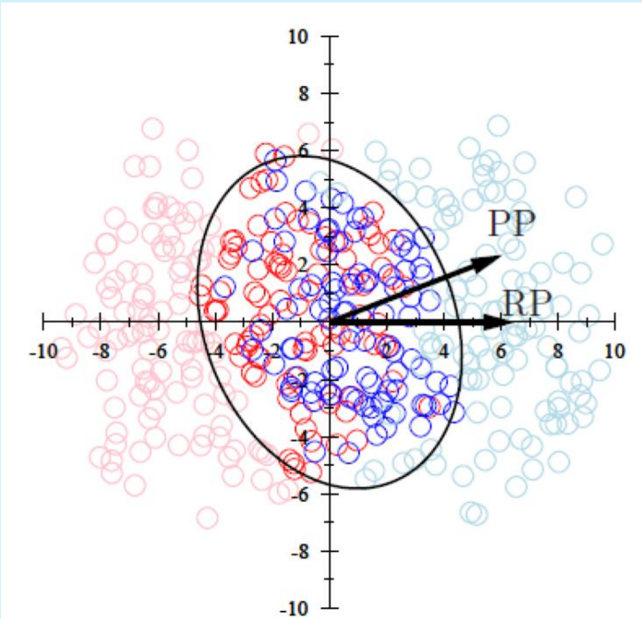
FIRST

Elliptic flow of thermal photons

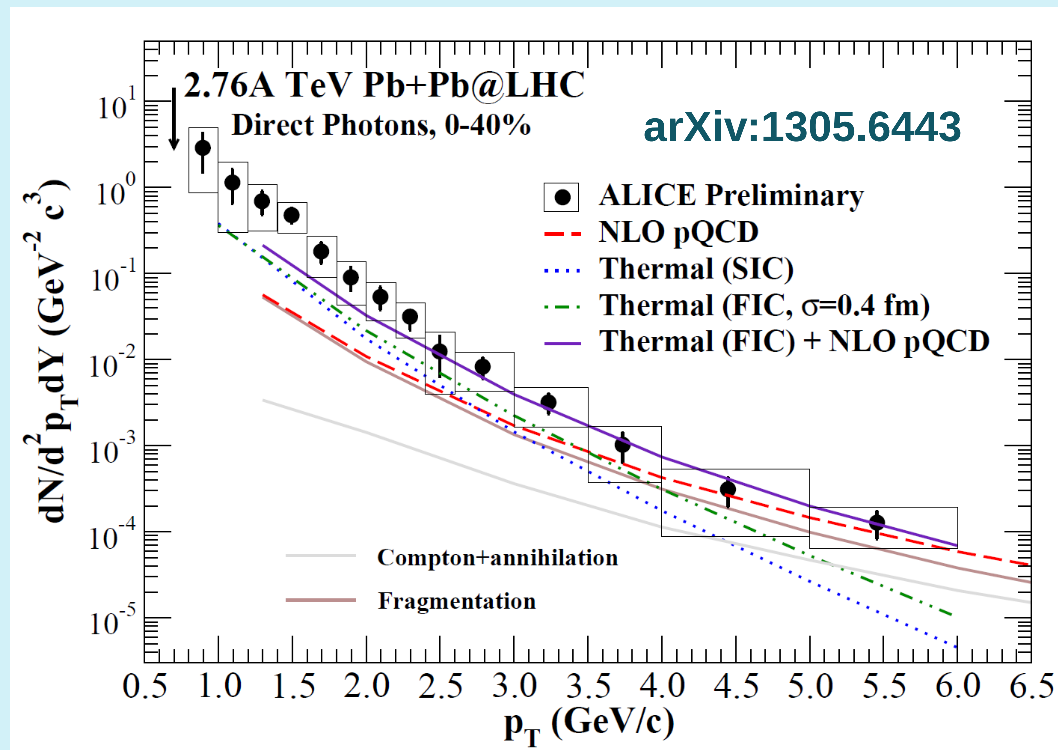


Chatterjee et al.

Event-by-event fluctuating initial density distribution

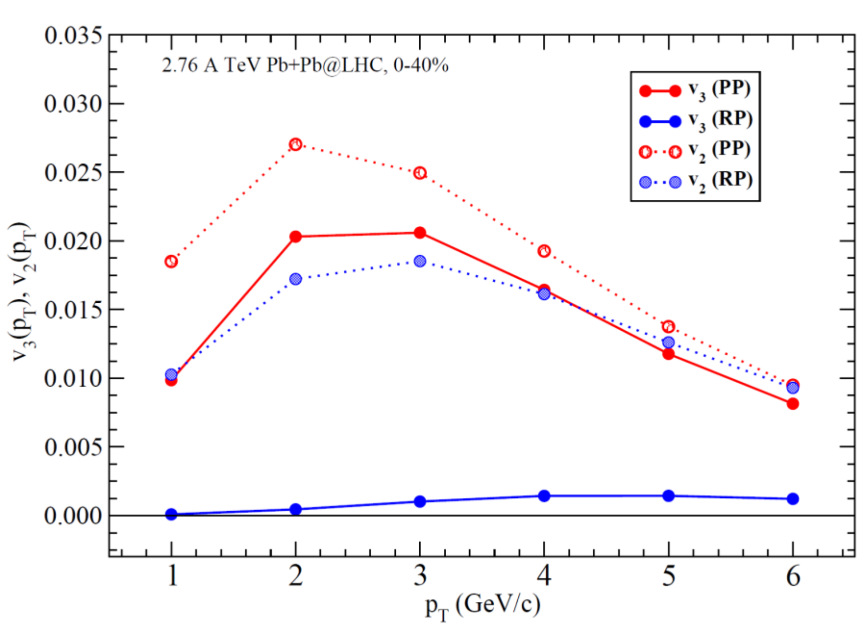


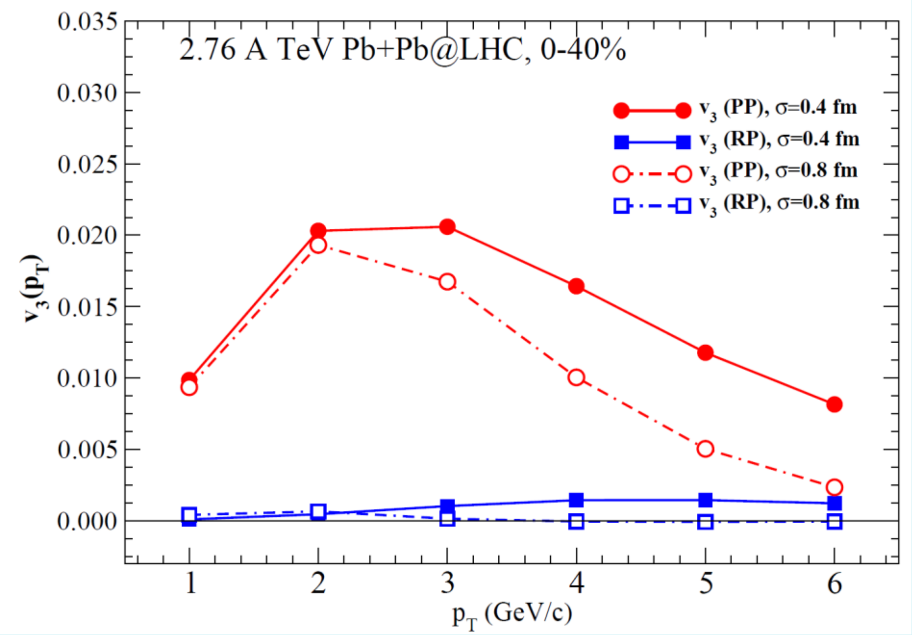
The 'hotspots' in the fluctuating events produce more high p_T photons compared to a smooth initial state averaged profile.



Fluctuation size parameter σ=0.4 fm

Triangular flow of thermal photons



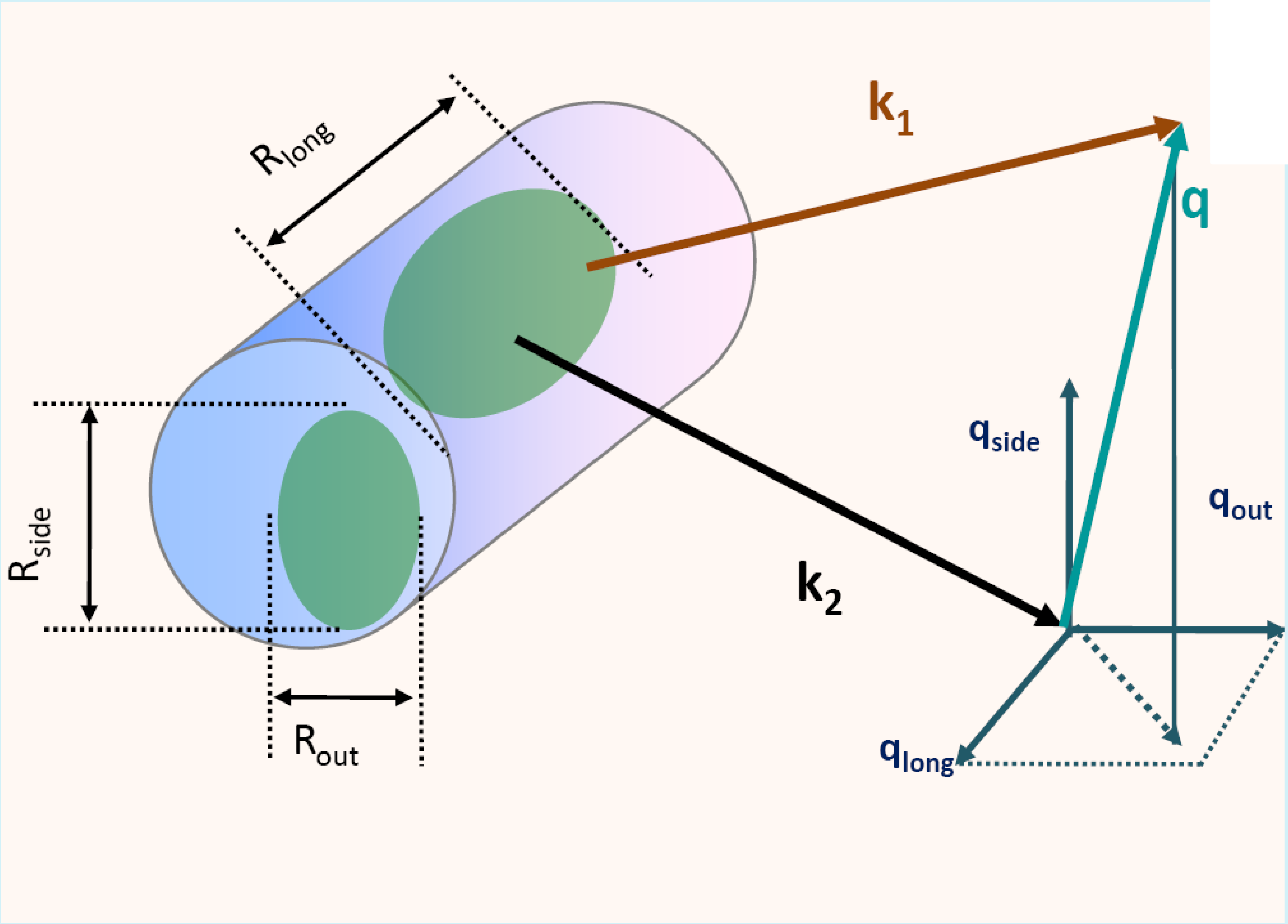


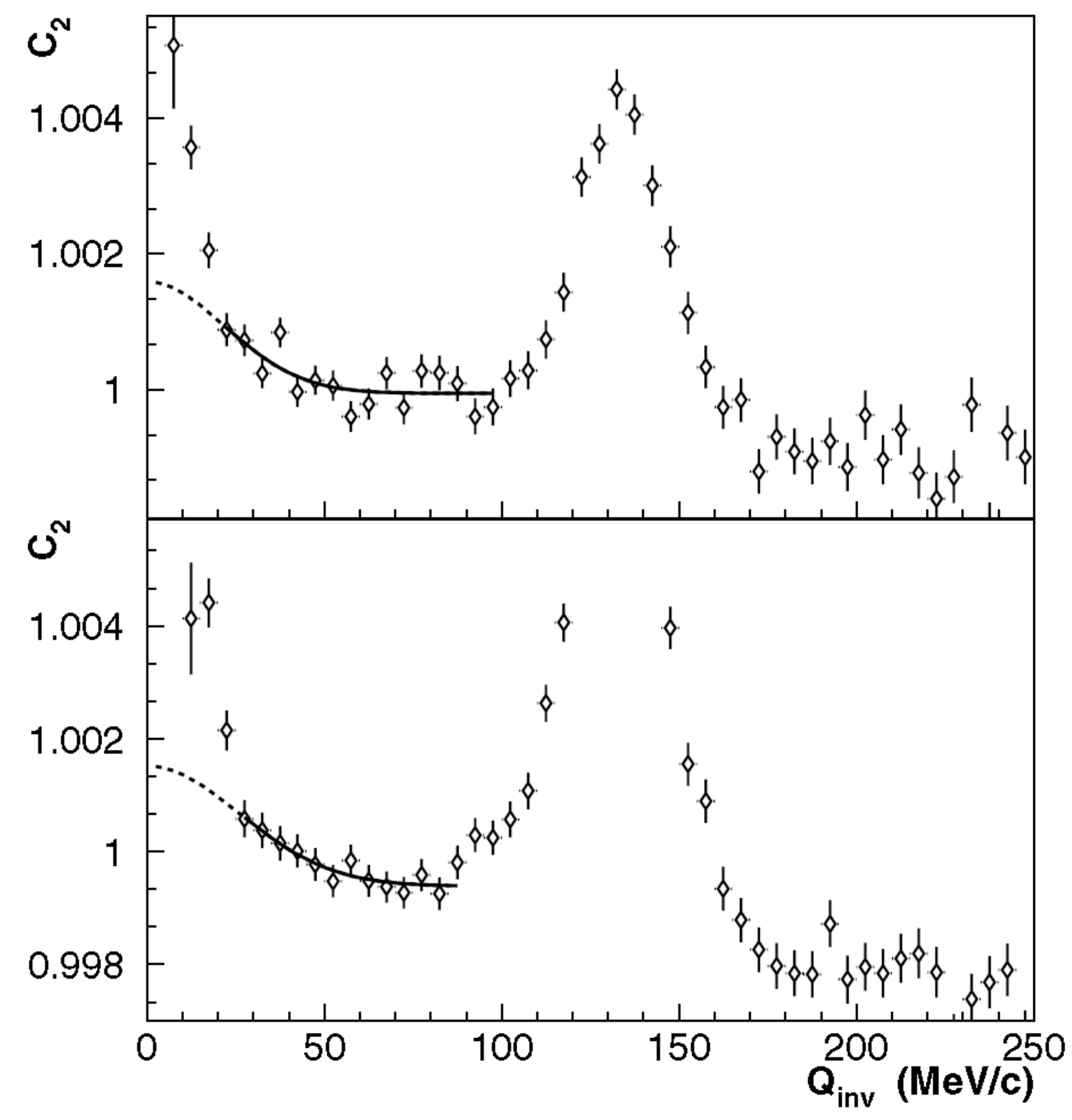
v_3 (p_T) for 2.76A TeV Pb+Pb@ LHC

σ dependence of v_3

Chatterjee, Holopainen, DKS [in preparation]

Intensity Interferometry of Thermal Photons

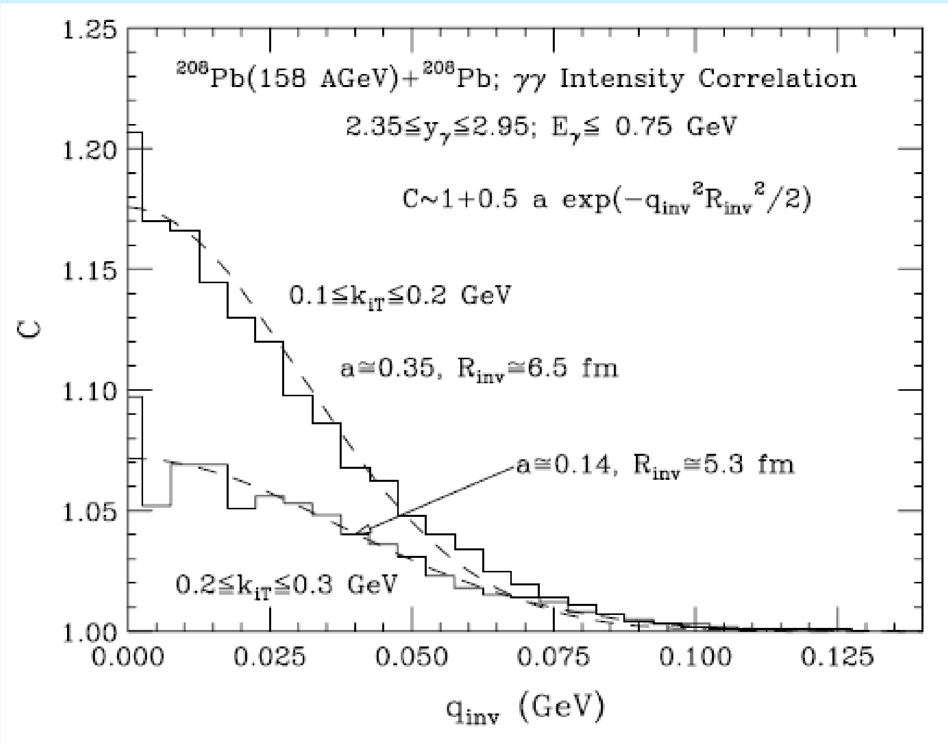




The two-photon correlation function for *average photon* momenta 100 < K_T *< 200 MeV/c (top) and 200 <* K_T < 300 MeV/c *(bottom). The solid line shows* the fit result in the fit region used (excluding the π^0 peak at *$Q_{inv} \approx m_{\pi 0}$) and the dotted line shows the extrapolation into* the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

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

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

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

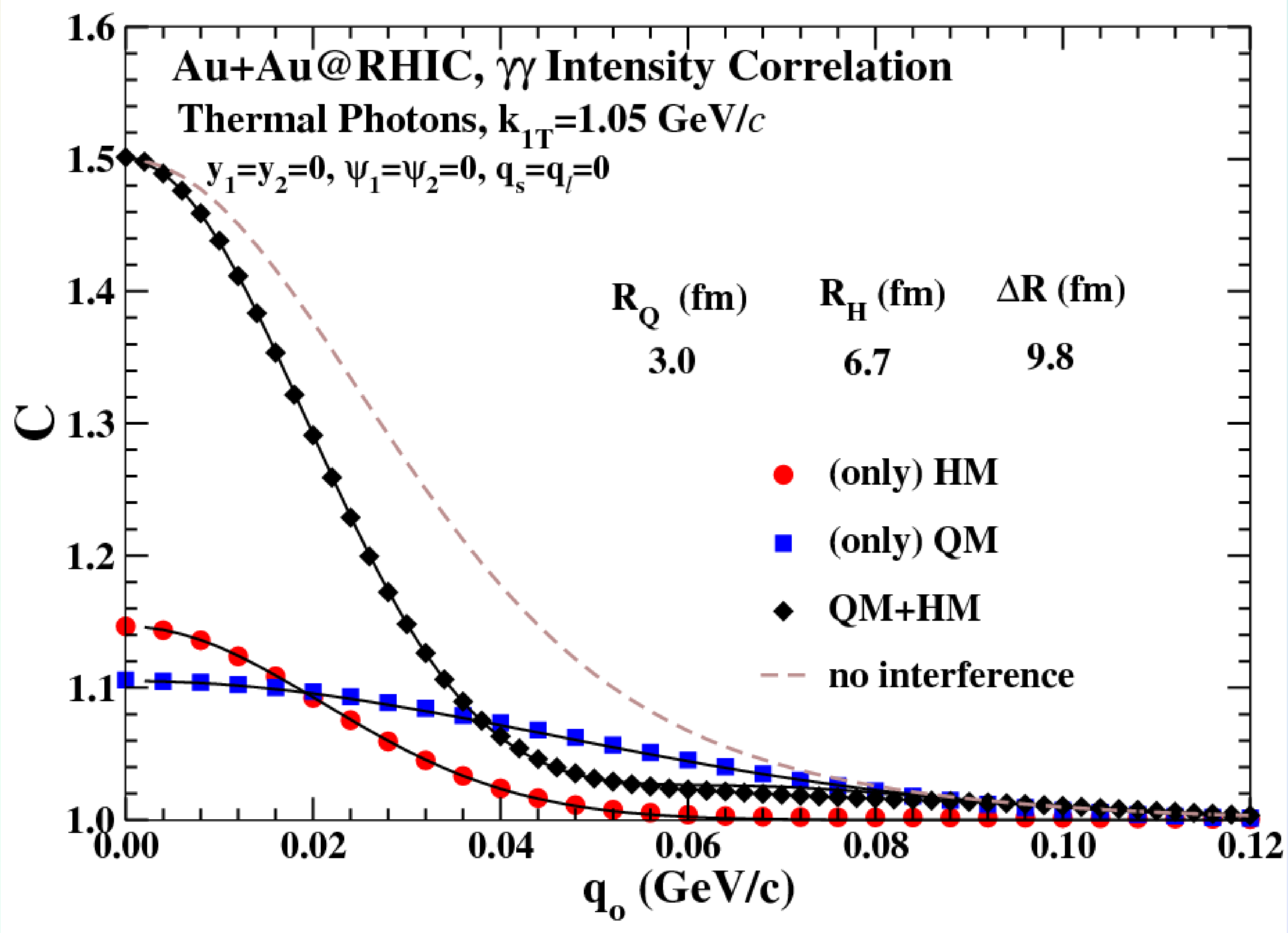
where, $q^2 = q_{out}^2 + q_{side}^2 + q_{long}^2$

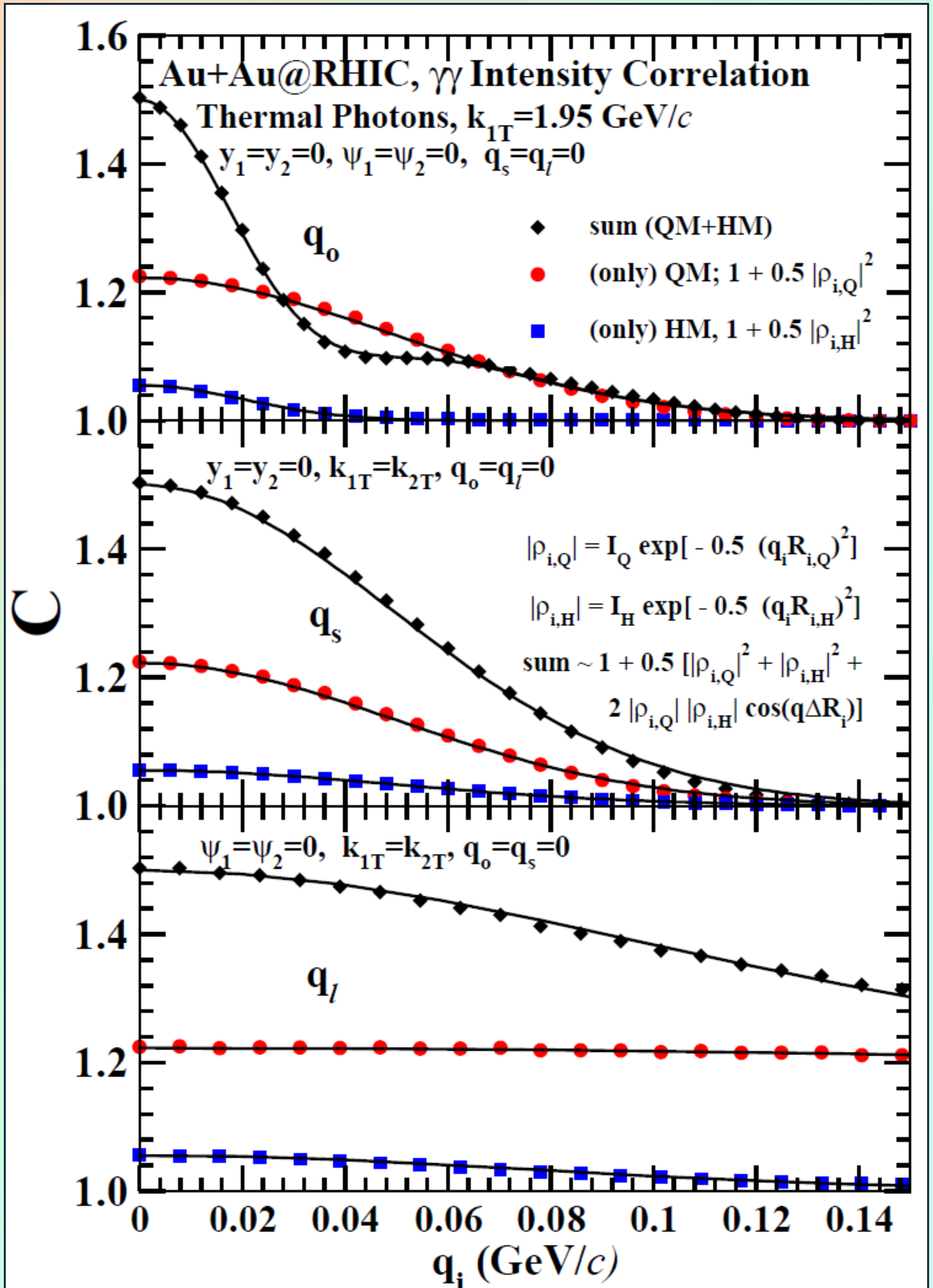
WA98 measures R_{inv} as 8.34 ± 1.7 fm and 8.63 ± 2.0 fm, respectively

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

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

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

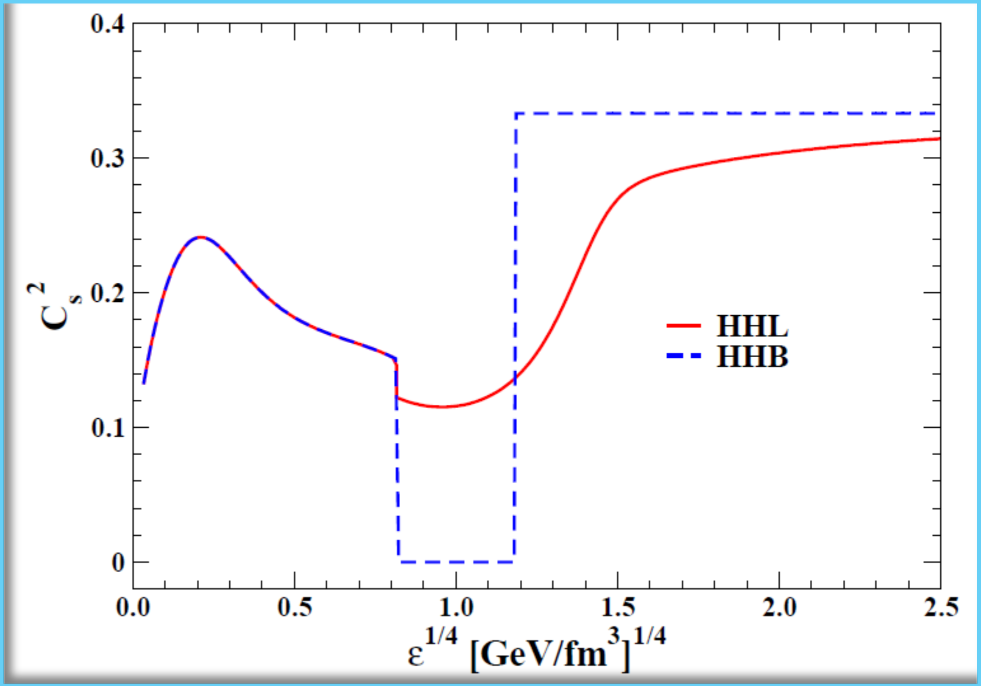
where,

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

i=out, side, and long

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

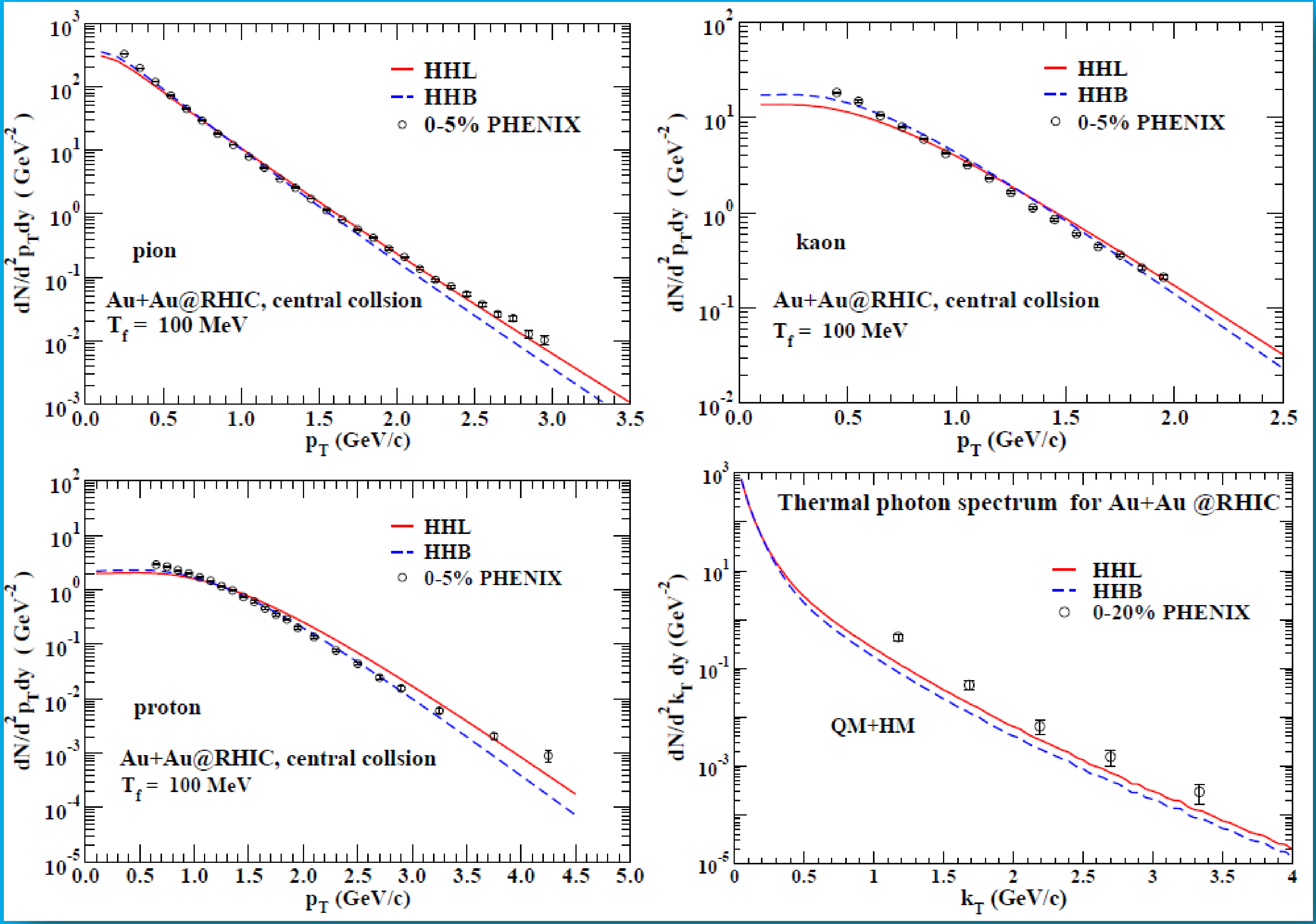
How Sensitive Are We to Equation of State?



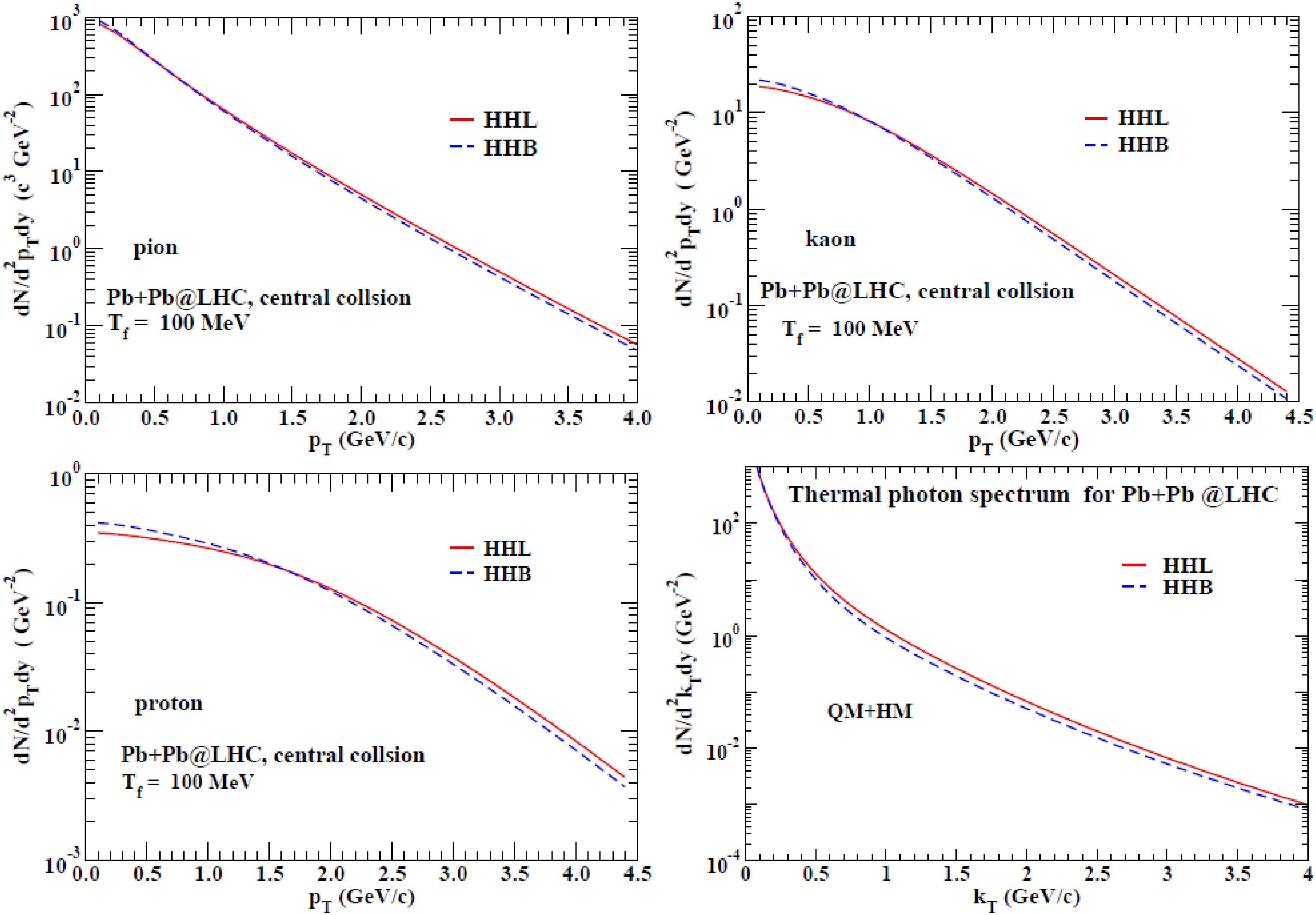
(i) Volume corrected hadron and Hagedorn resonance gas matched with a Bag Model ((HHB).

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

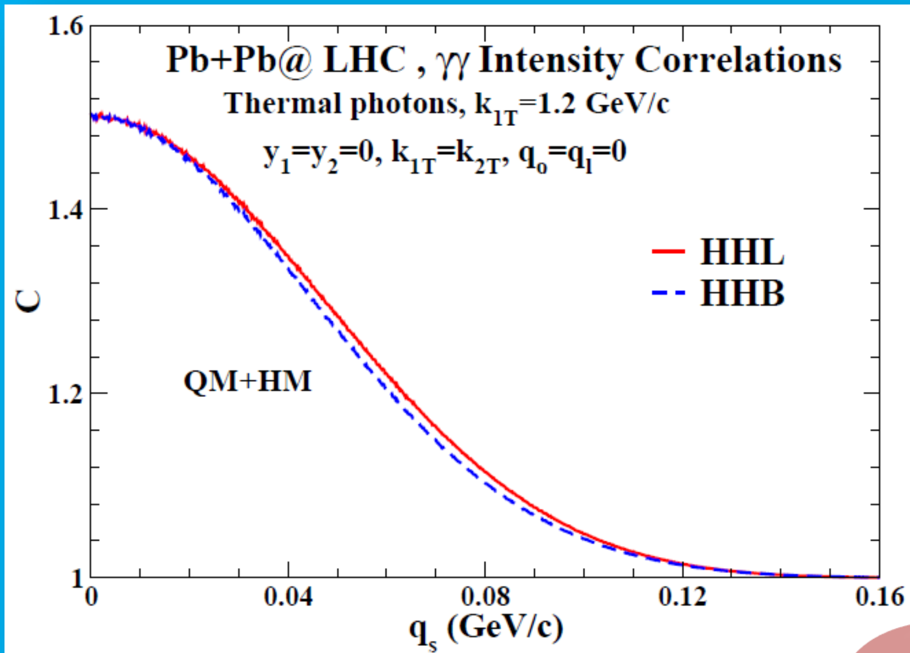
Speed of sound



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.

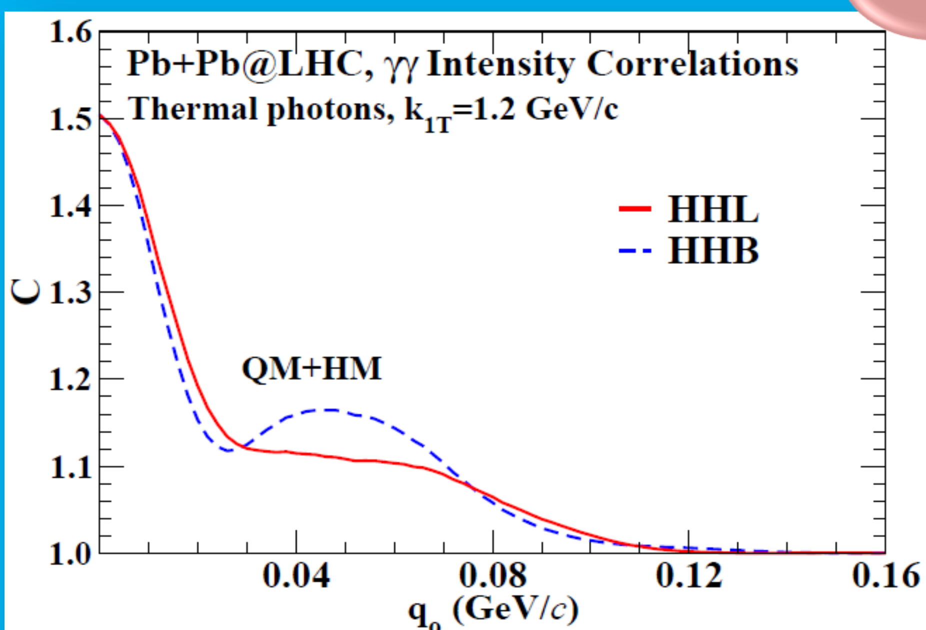


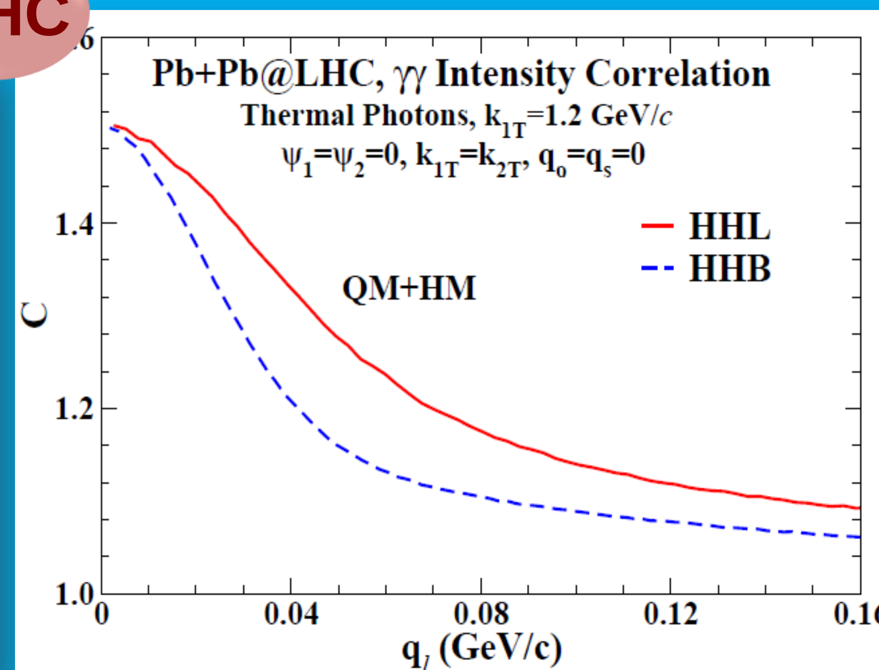
Pion, kaon, proton and thermal photon p_T spectra at LHC for the equations of state, HHB and HHL. All the calculations are for impact parameter b=0 fm.



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

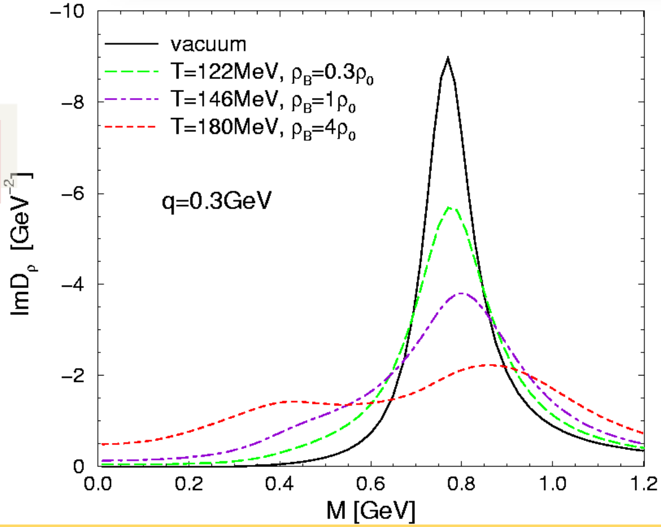
LHC

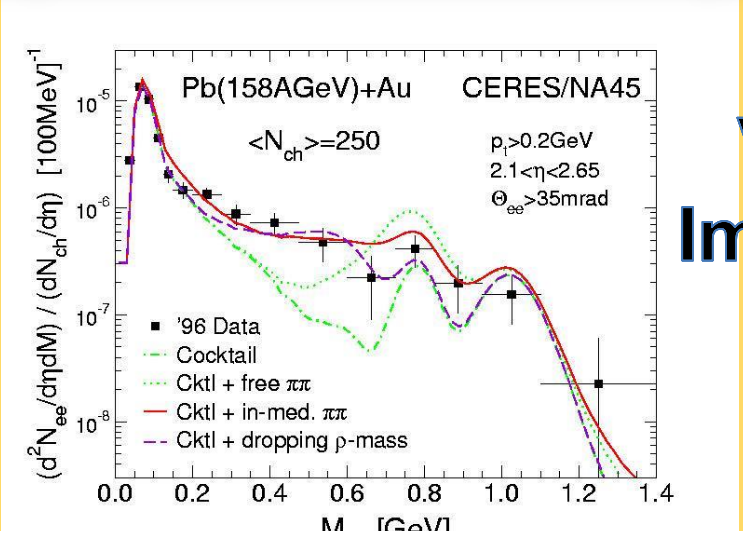




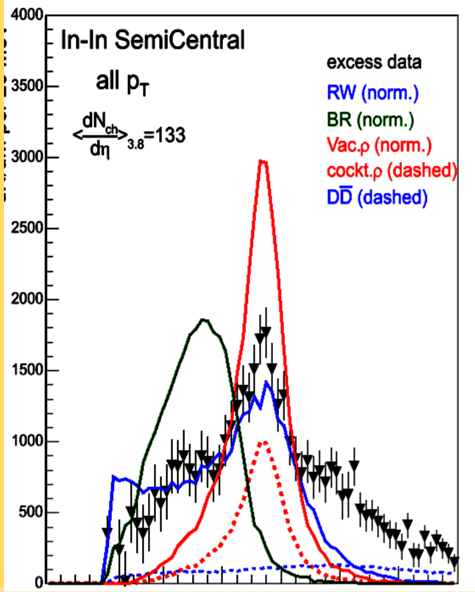
Dropping m_ρ vs. increasing Γ_ρ

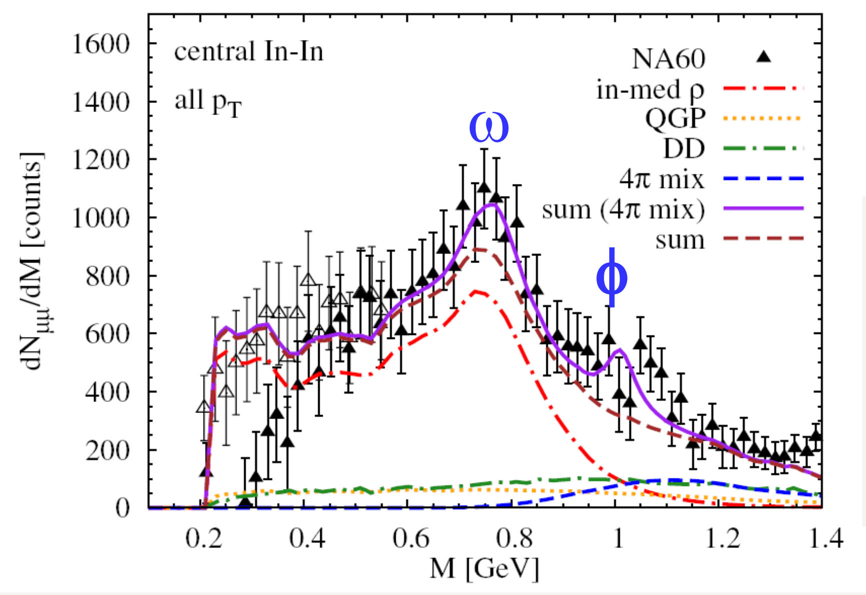
RW





Vastly Improved Data



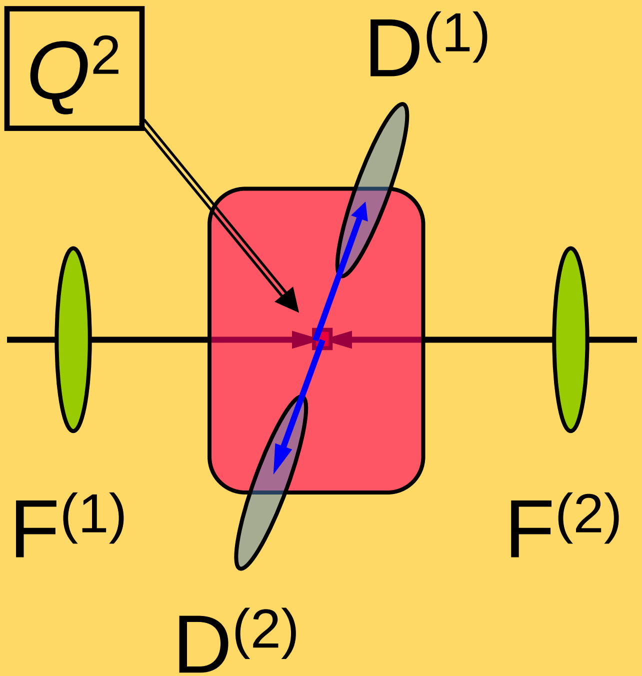


van Hees and Rapp, PRL 97 (2006) 102301.

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

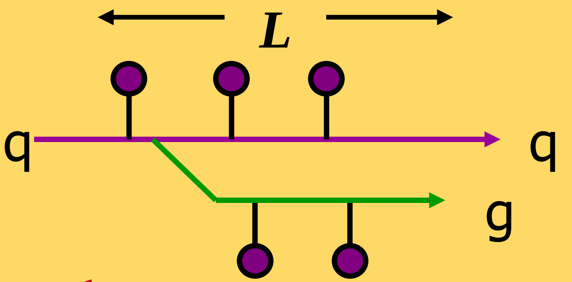
Passage of Jets Through QGP

PQCD framework: Jets



Medium modified fragmentation functions:

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

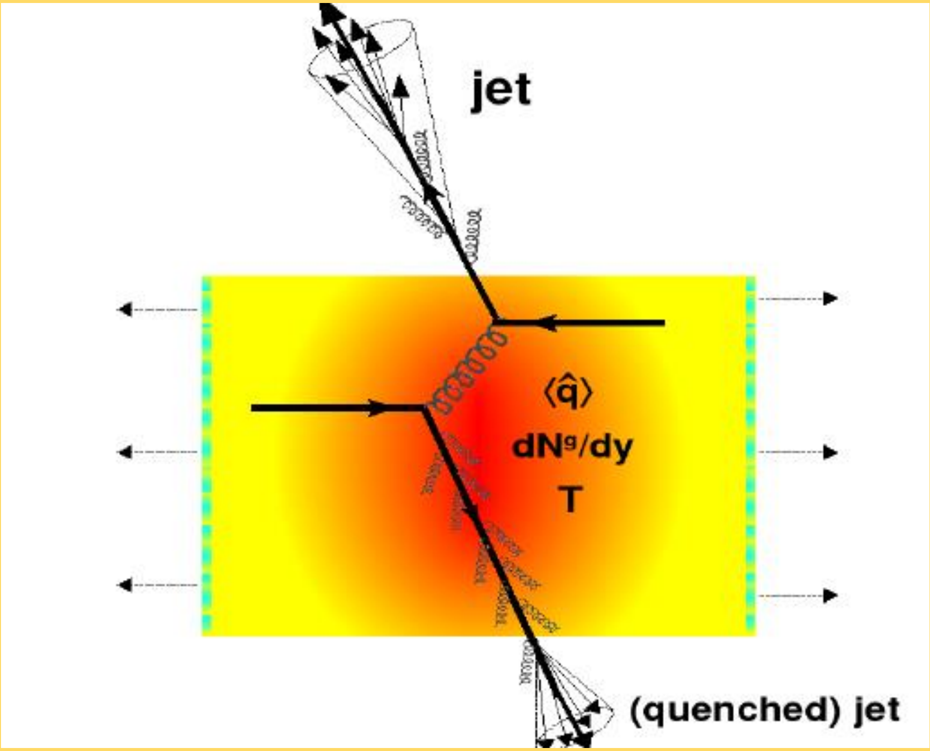


Measured medium property:

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

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.

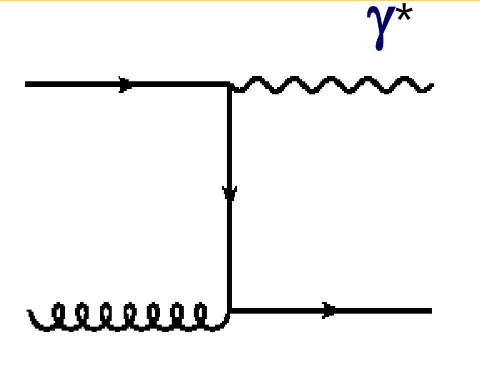
It is quantatively measured through the nuclear modification factor R_{AA}, which is defined as:

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

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.



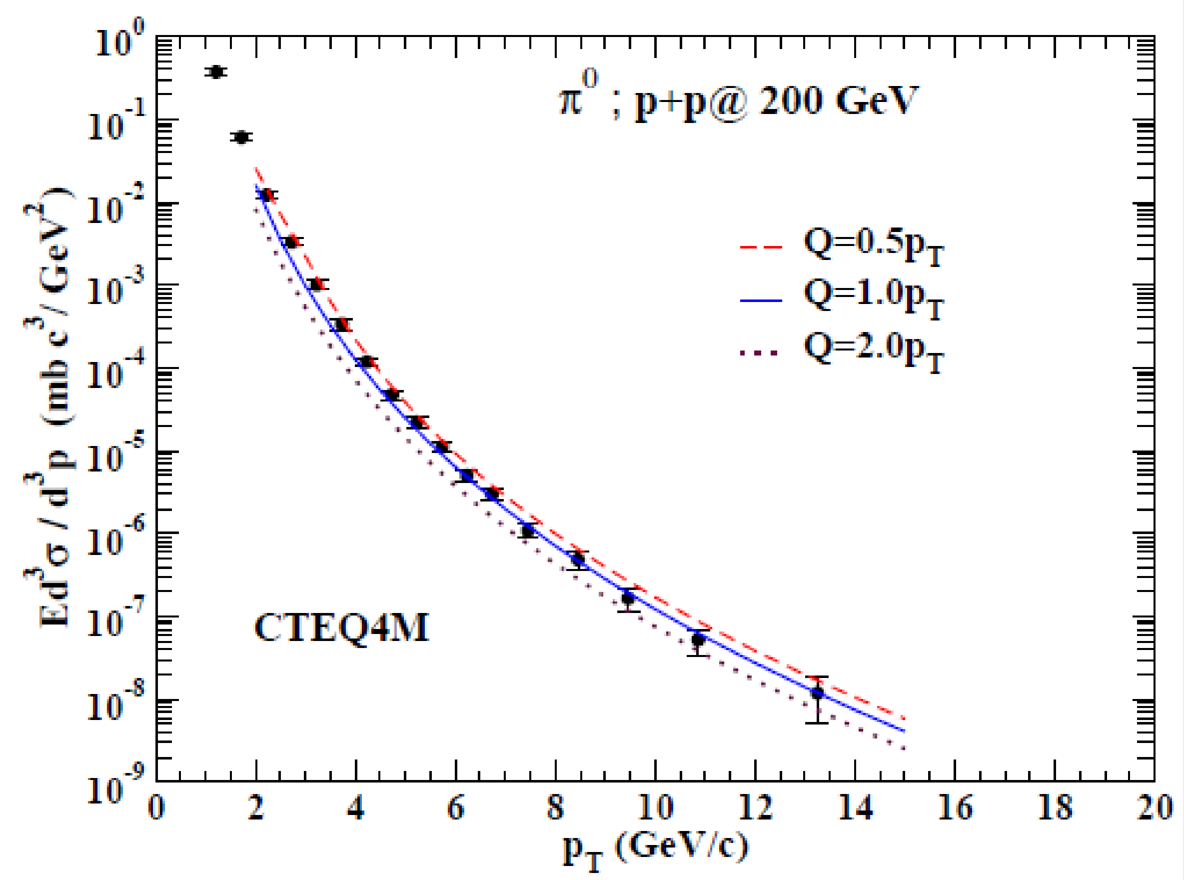
Compton

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.

❖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

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

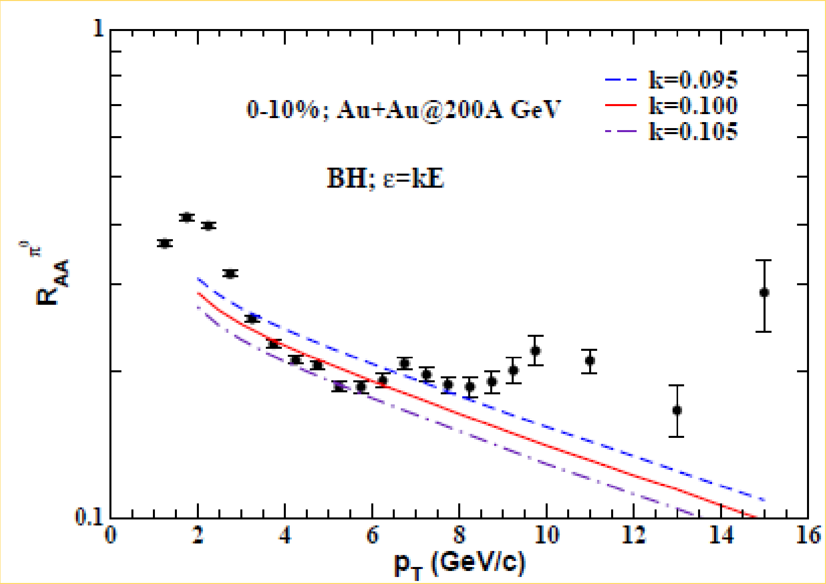
- The effect of energy loss of partons and multiple scatterings are implemented through the modification of $D_{c/h}(z,Q^2)$ following the model of Wang-Huang-Sarcevic.

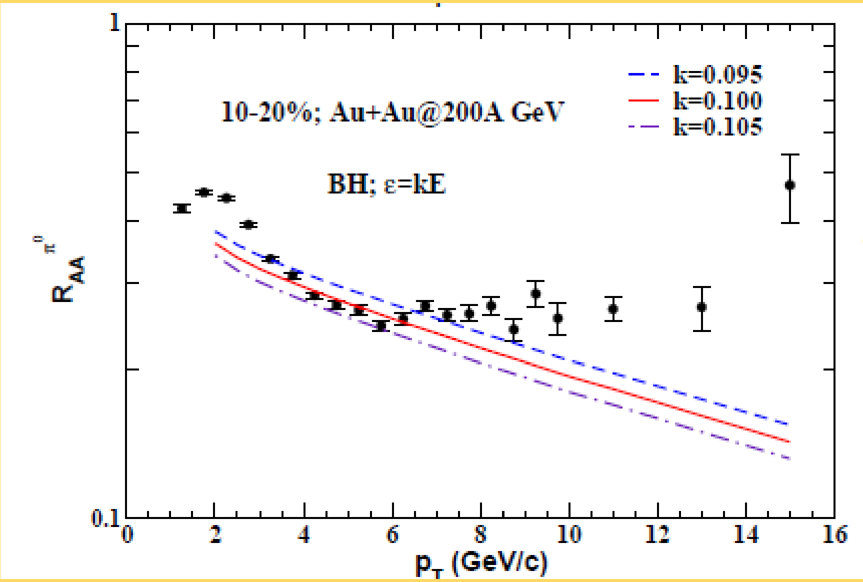
$$zD_{c/h}(z,L,Q^2) = \frac{1}{C_N^a} \sum_{n=0}^{N} P_a(n,L) \times \left[z_n^a D_{c/h}^0(z_n^a,Q^2) + \sum_{m=1}^{n} z_m^a D_{g/h}^0(z_m^a,Q^2) \right]$$

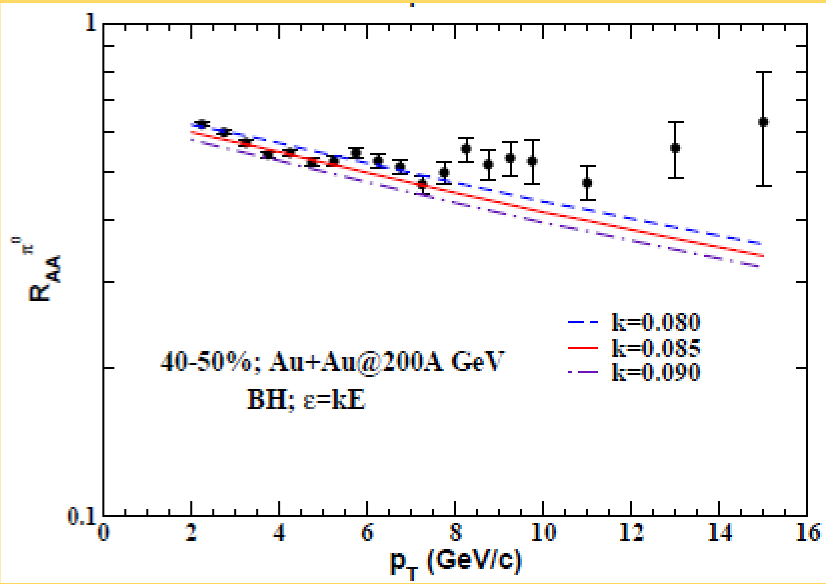
where, $C_N^a = \sum_{n=0}^{N} P_a(n,L)$, $z\,E_T^a = z_n^a\,(E_T^a - \sum_{i=0}^{n} \varepsilon_a^i)$ and $z_m^a \varepsilon_a^m = zE_T^a$

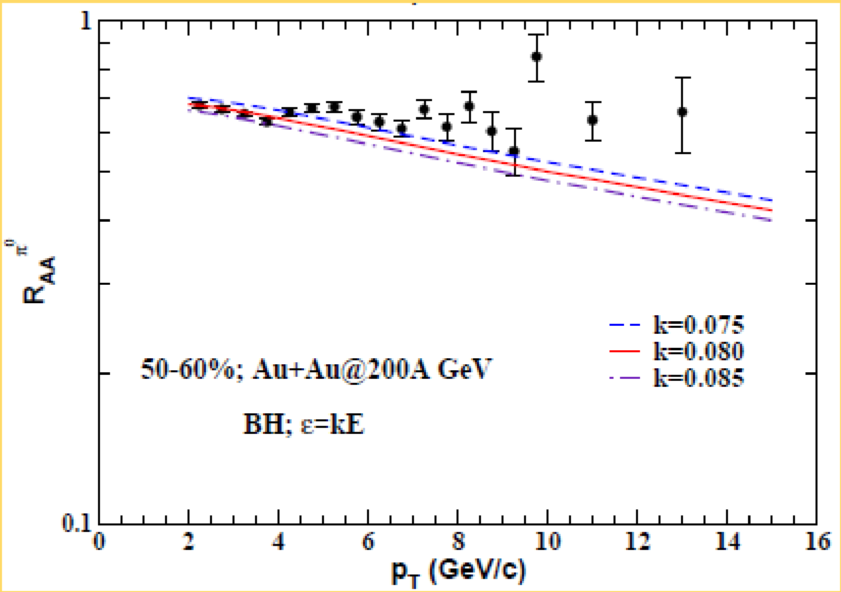
R_{AA} of neutral pions for Au-Au collisions at RHIC

BH regime



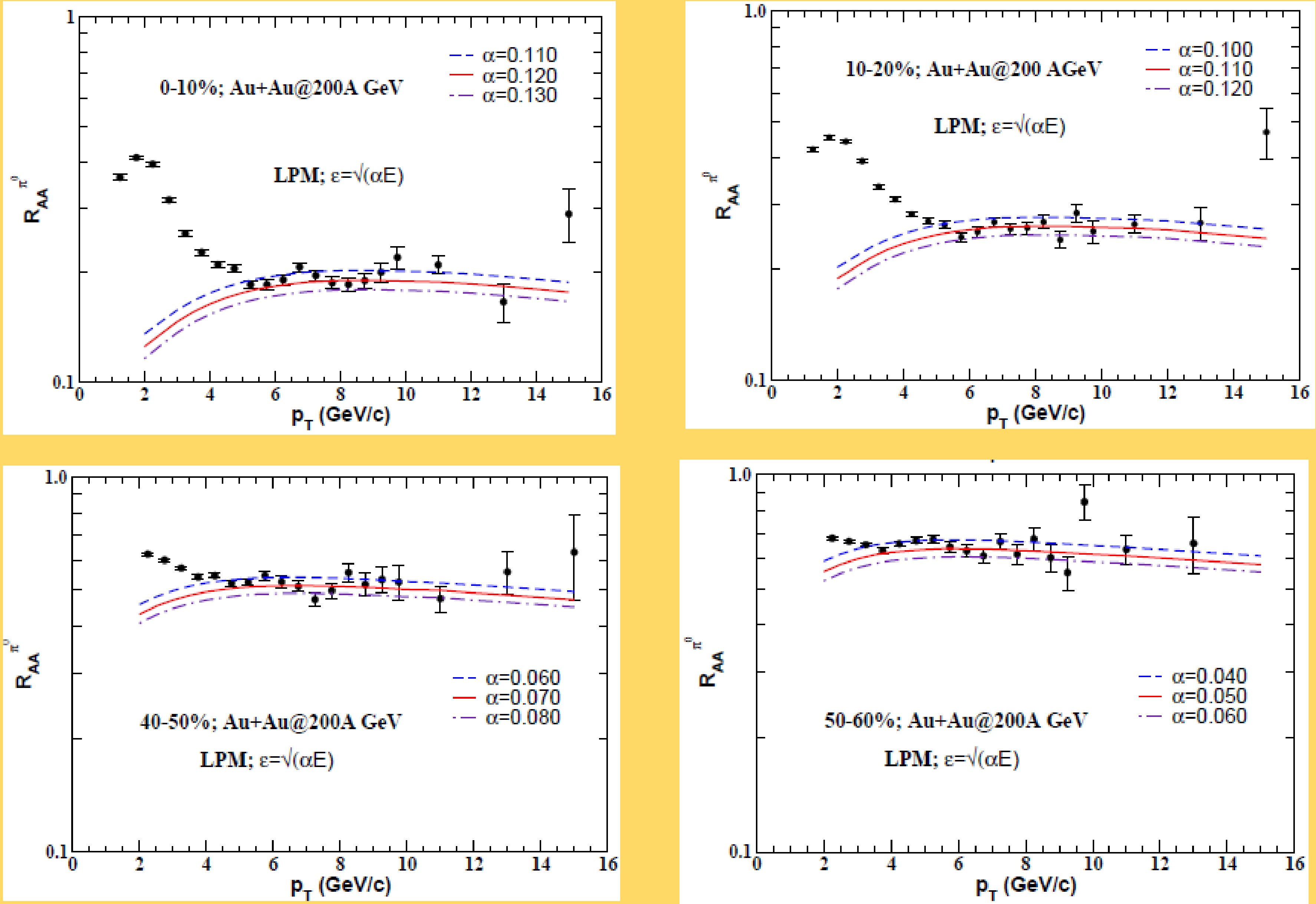




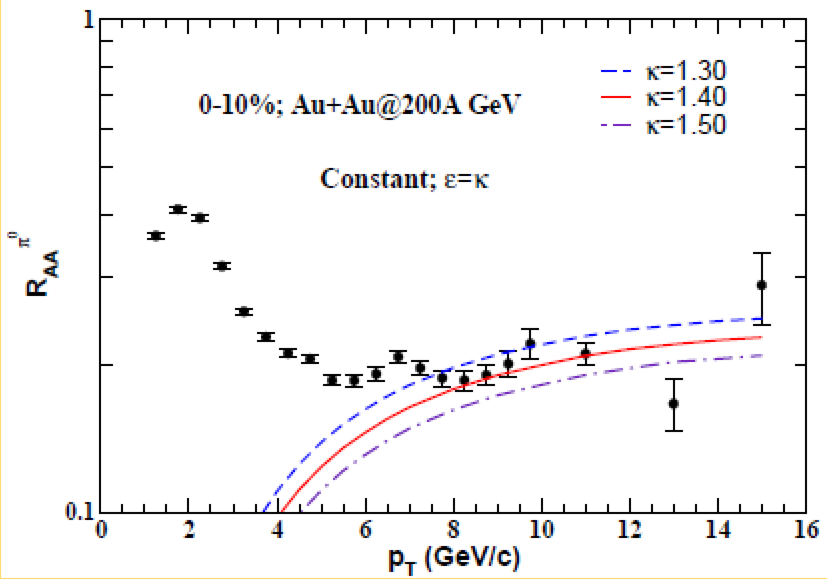


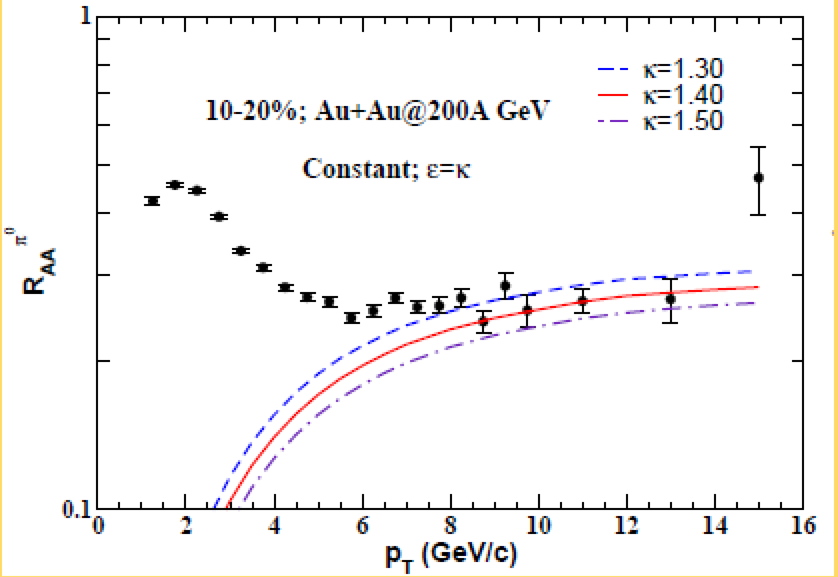
LPM regime

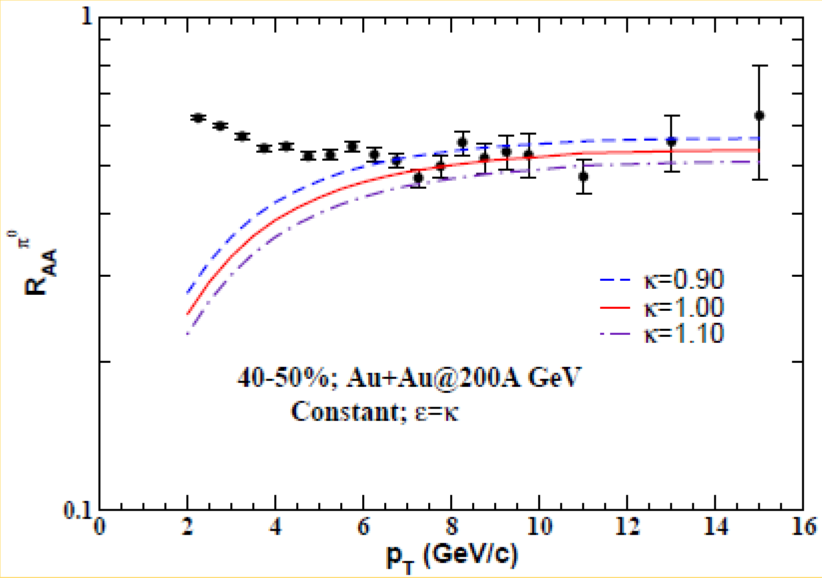
S. De and D. K. S. , arXiv:1107.5659

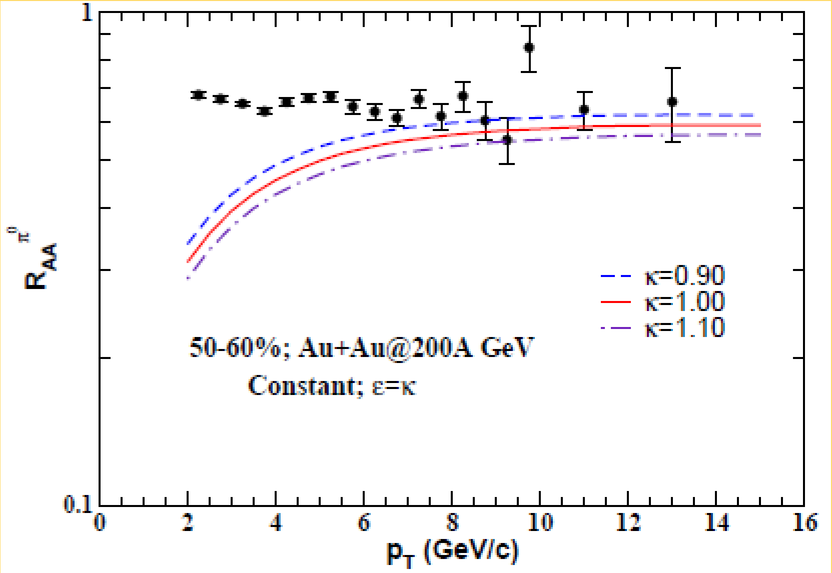


Complete Coherence Regime

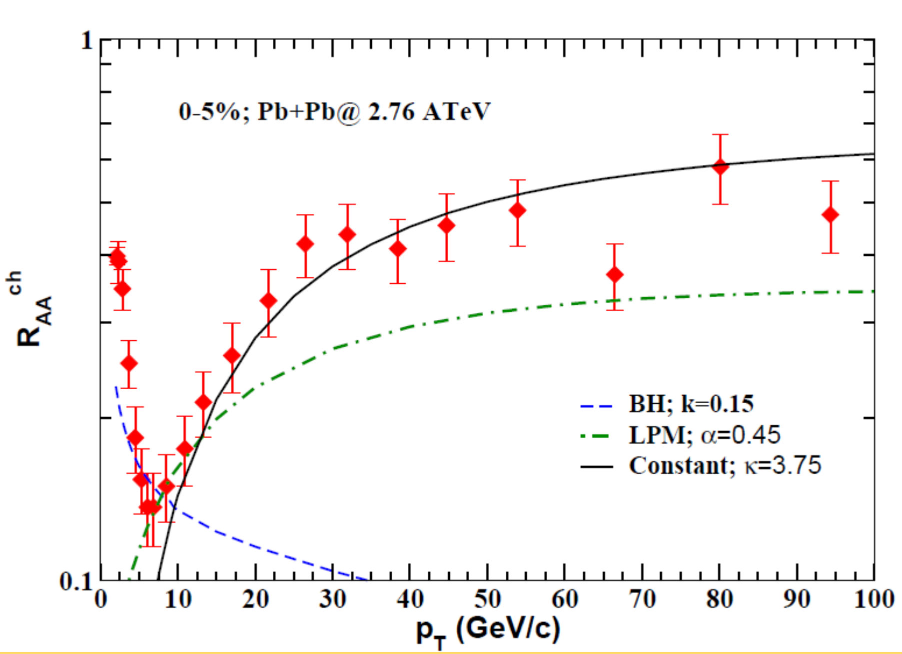


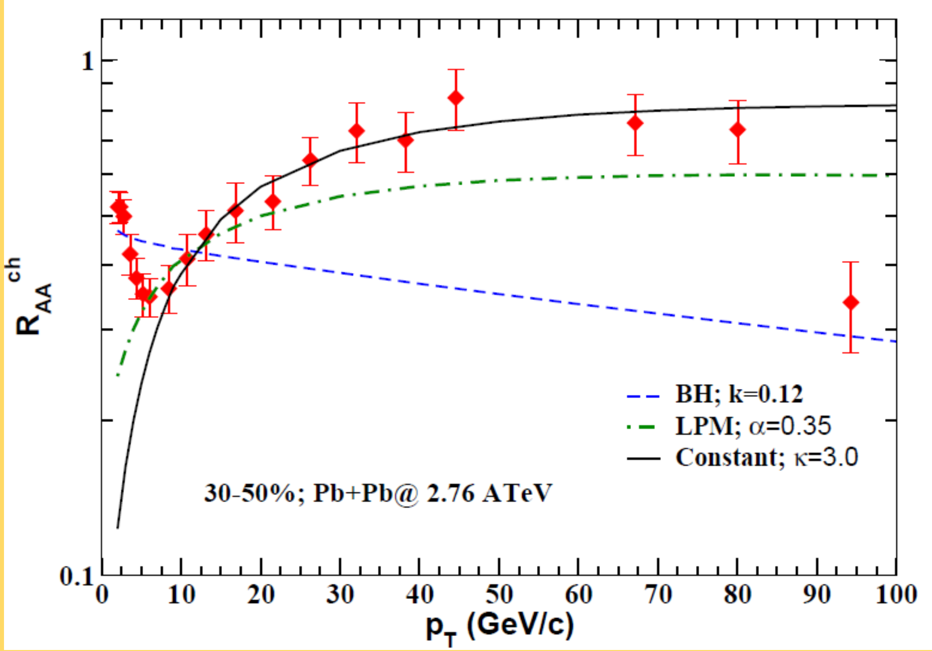






R_{AA} of charged hadrons for Pb+Pb @ 2.76 ATeV : CMS preliminary



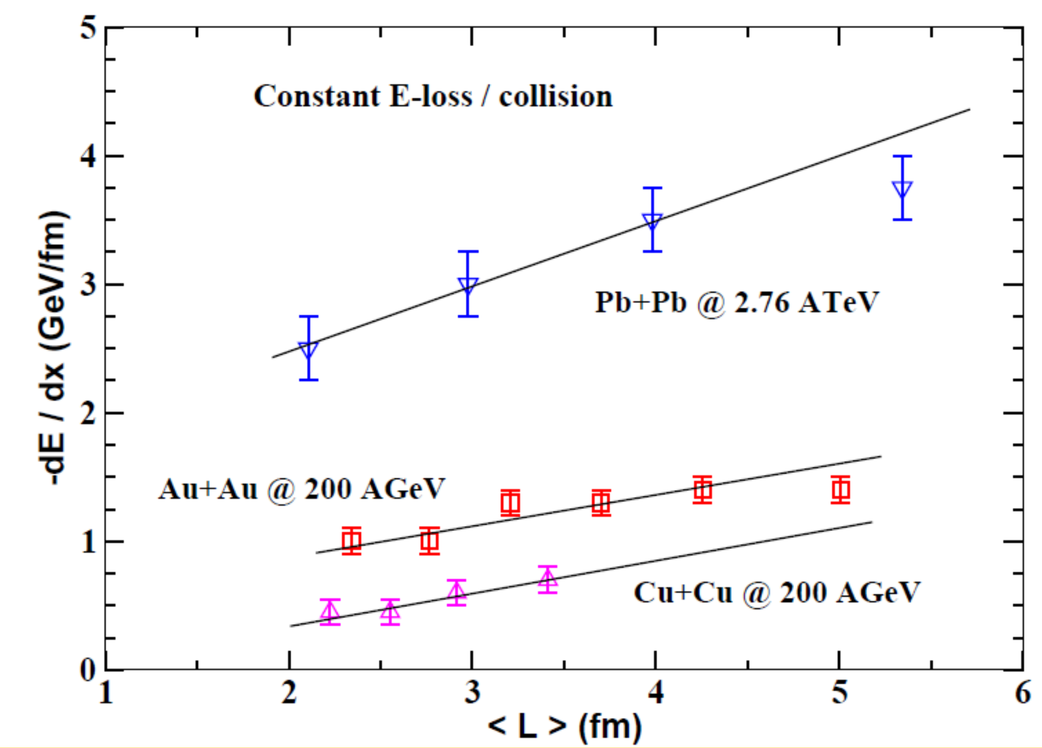


Centrality dependence of dE /dx at RHIC & LHC

Taking the case of parton energy loss in the complete coherence regime, - dE/dx = ε / λ

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, $\Delta E \propto L^2$

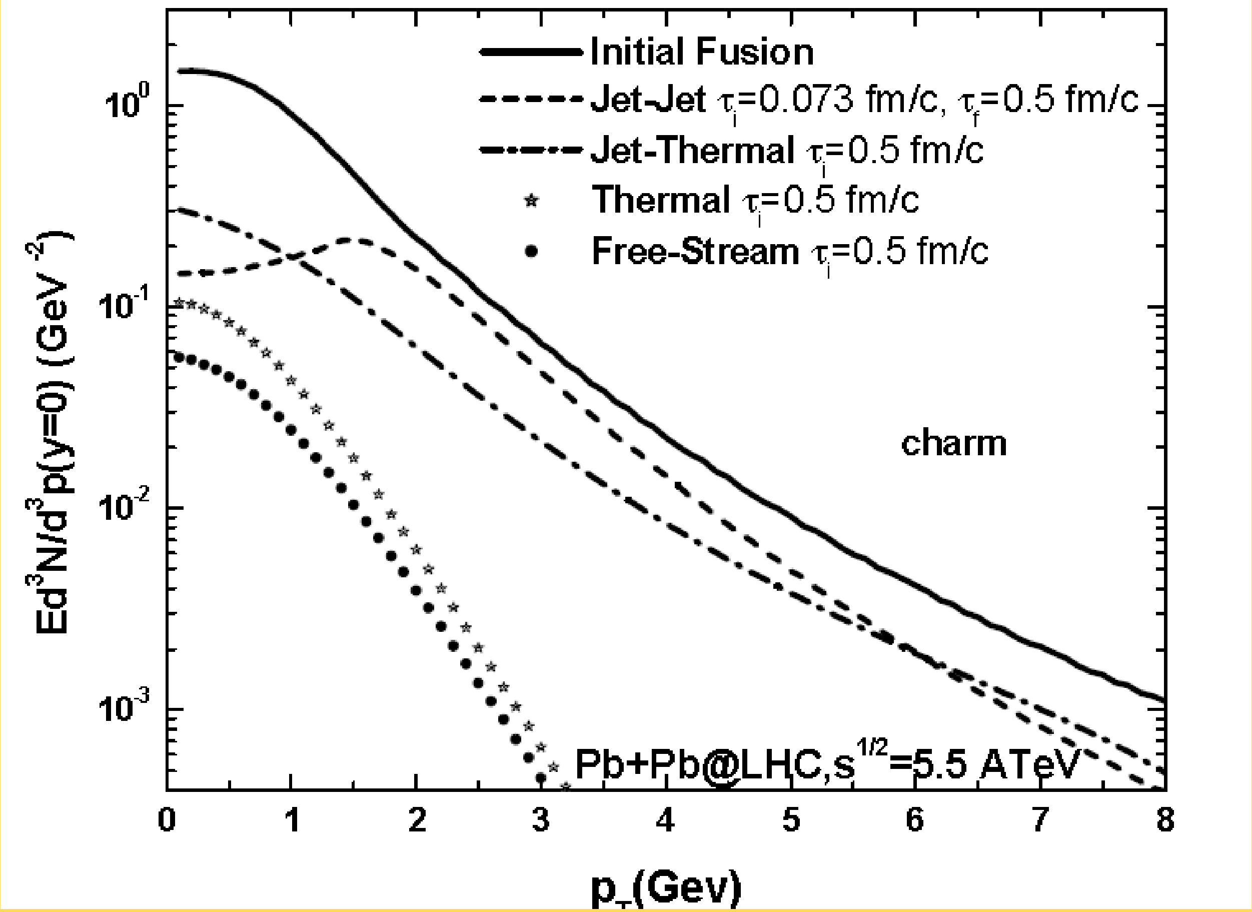
Heavy Quark Propagation

Initial Fusion

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

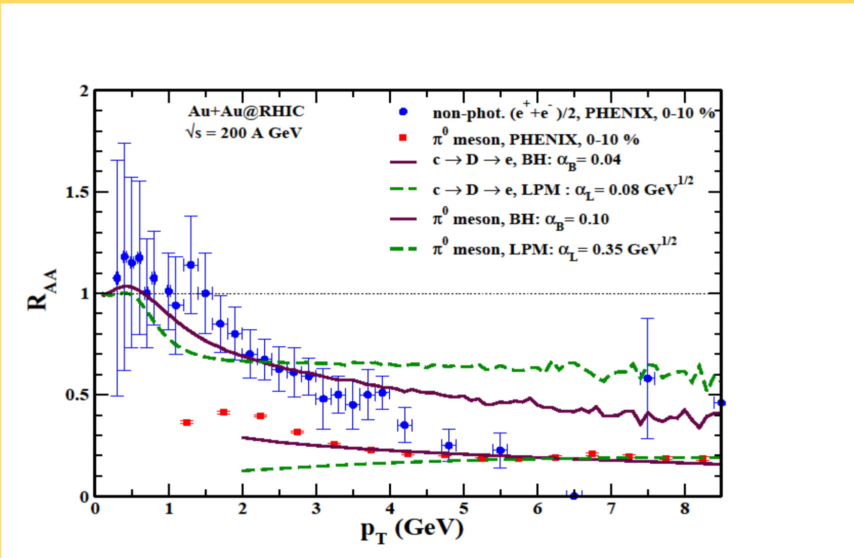
Heavy Quark Production

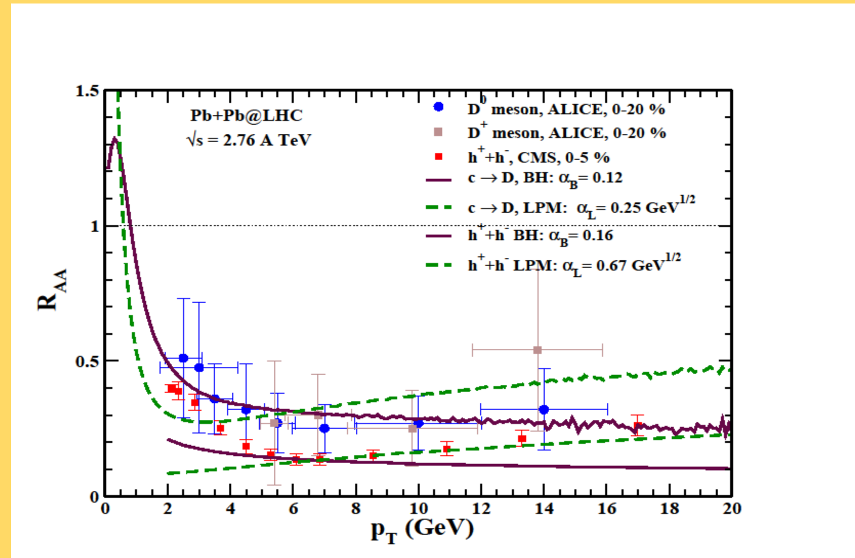
M. Younus & DKS, J. Phys. G 37, 115006 (2010)



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: $\alpha_B^{\mathrm{Light}} \approx 2.5 \, \alpha_B^{\mathrm{Heavy}}$ LHC: $\alpha_B^{\mathrm{Light}} \approx 1.3 \, \alpha_B^{\mathrm{Heavy}}$

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.


THANK YOU

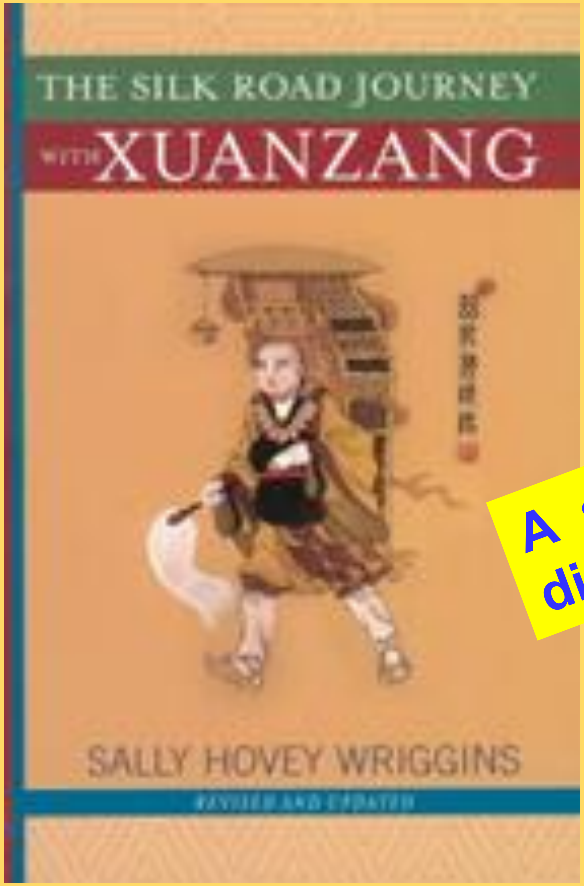
Back up slides

If I had more time:

- <u>**Intensity Interferometry of direct photons**</u>

- **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



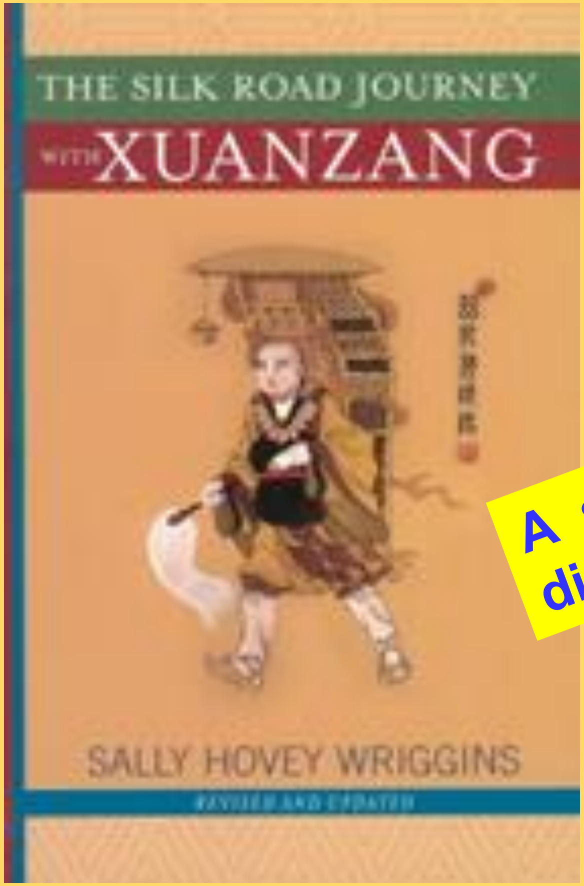
A slight digression.

“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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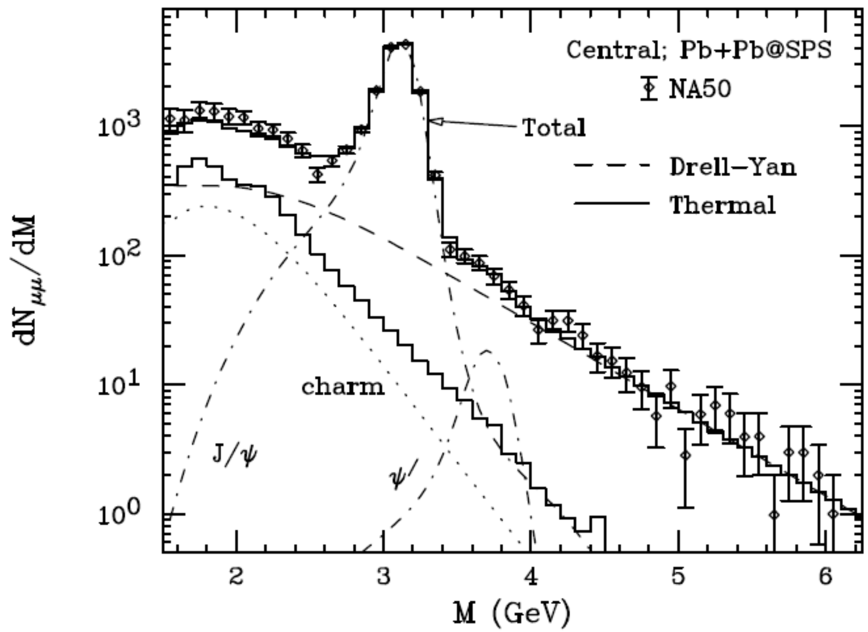
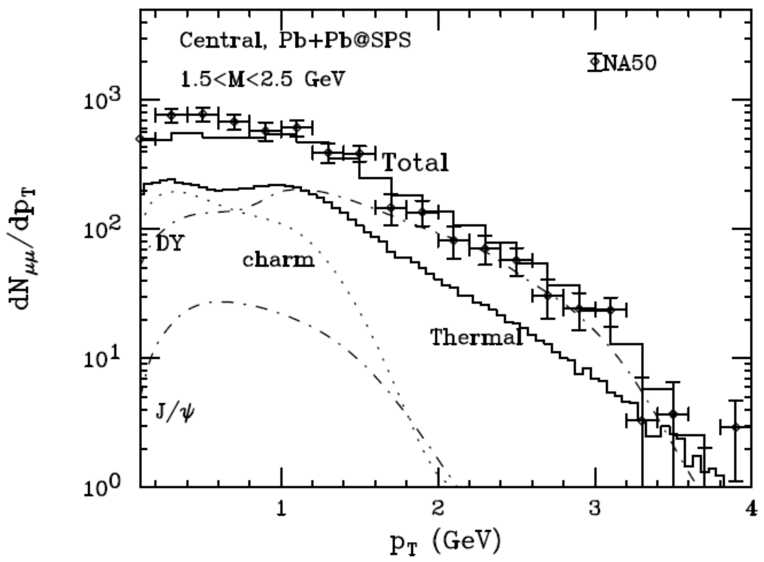
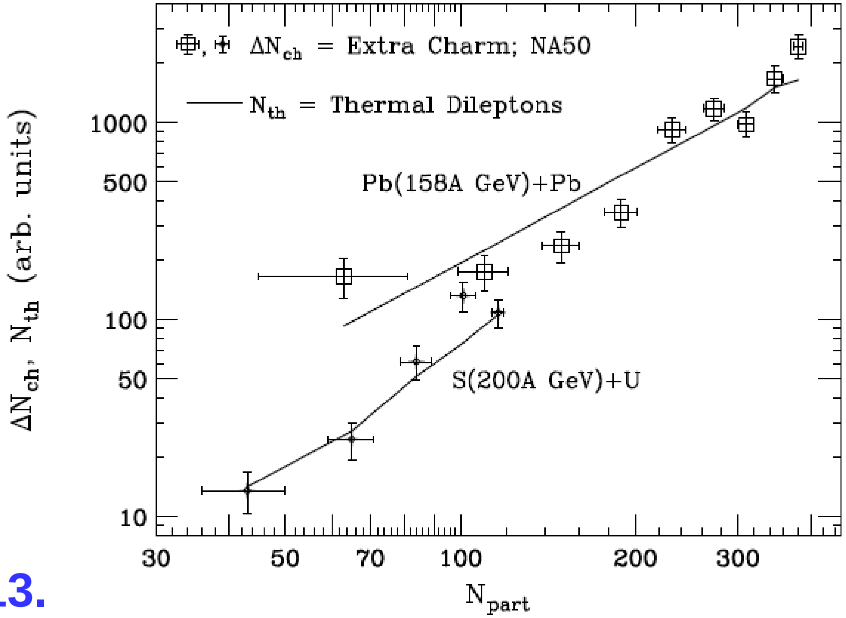
Intermediate Mass; NA50





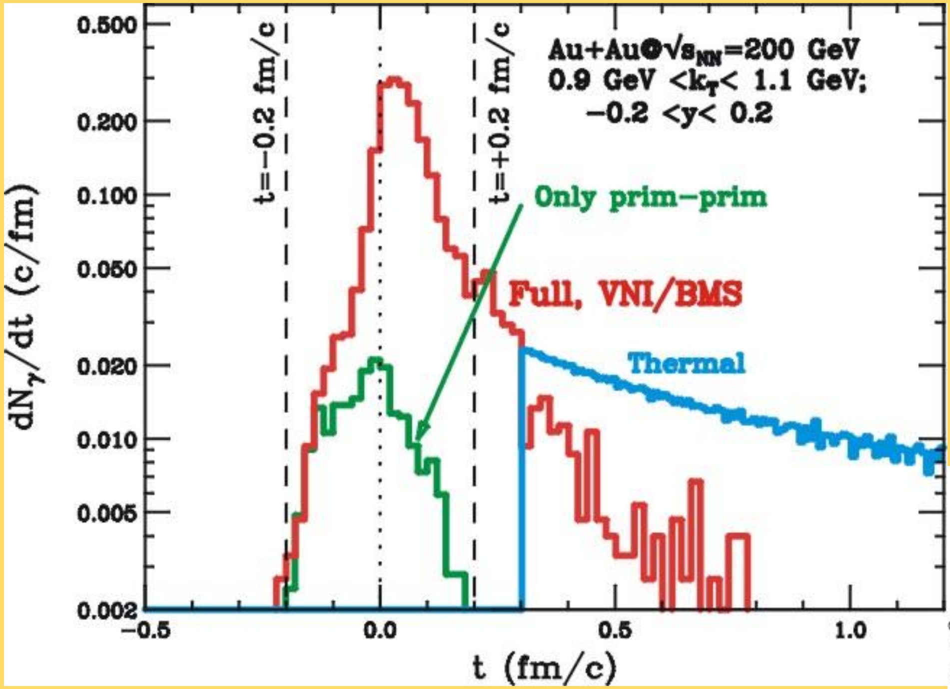


Kvasnikova, Gale, & Srivastava,
PRC 65 (2002) 064903.

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:

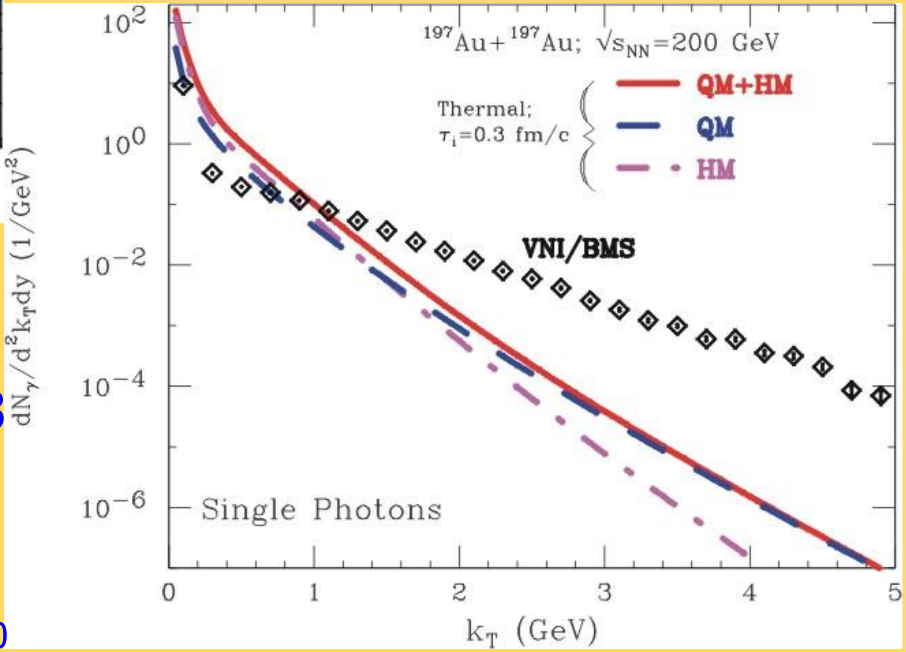
•window of opportunity above p_t=2 GeV

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

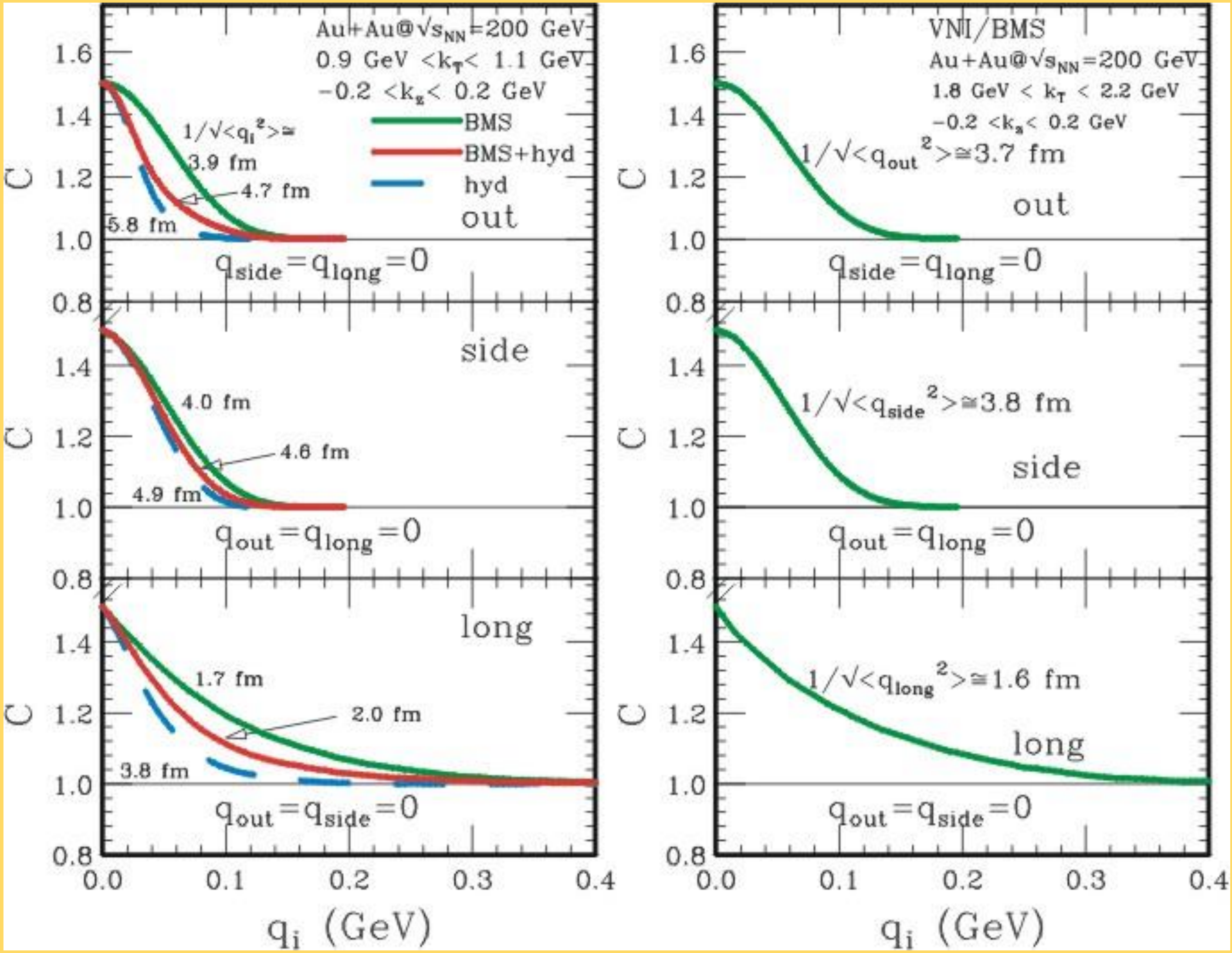
• short emission time in the PCM, 90% of photons before 0.3 fm/c

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

➢ caveat: medium not equilibrated at τ_0



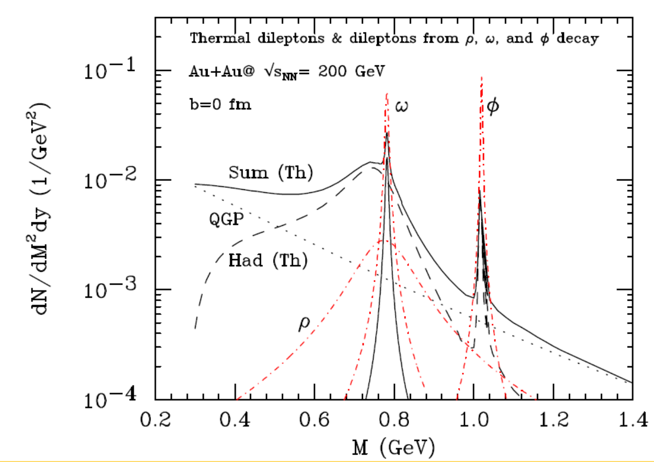
Photons: HBT Interferometry

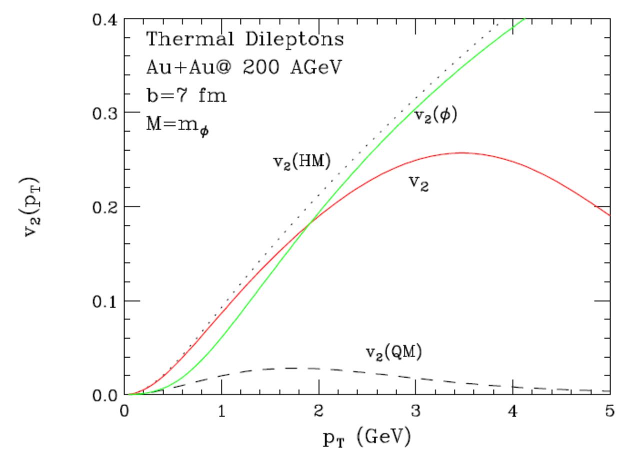


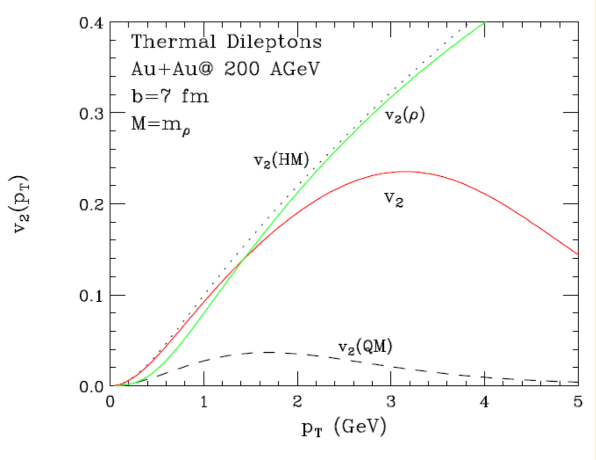
- p_t=2 GeV: pre-thermal photons dominate, small radii
- p_t=1 GeV: superposition of pre- & thermal photons: increase in radii

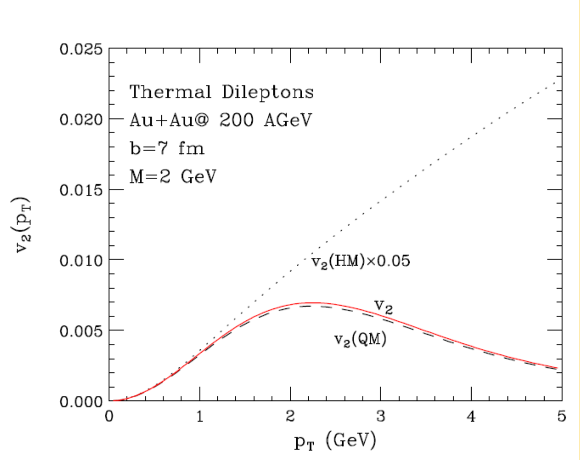
Bass, Mueller, & Srivastava, PRL 93 (2004) 16230; Srivastava, PRC 71 (2005) 034905.

Elliptic Flow of Thermal Dileptons

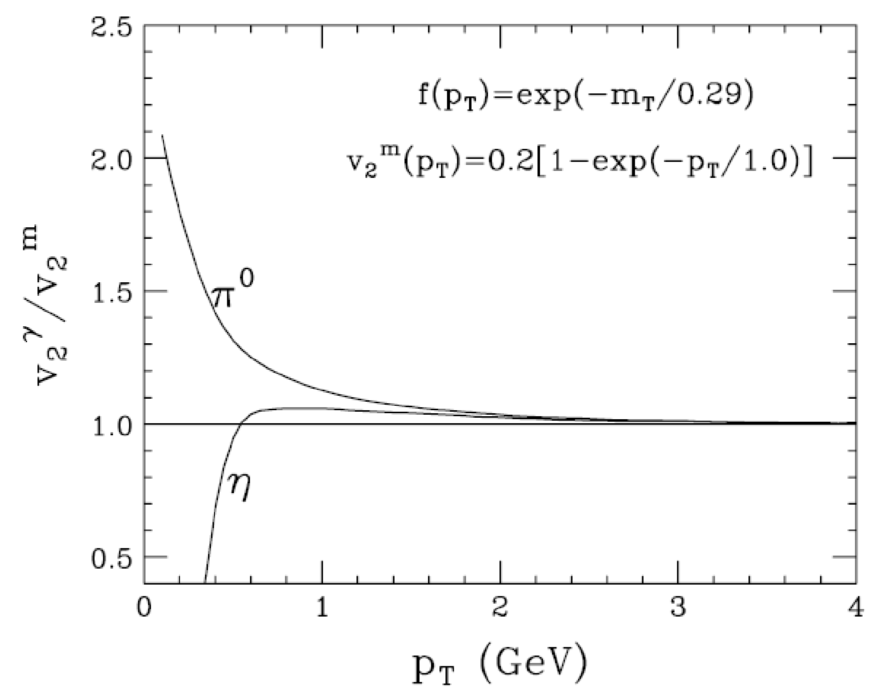


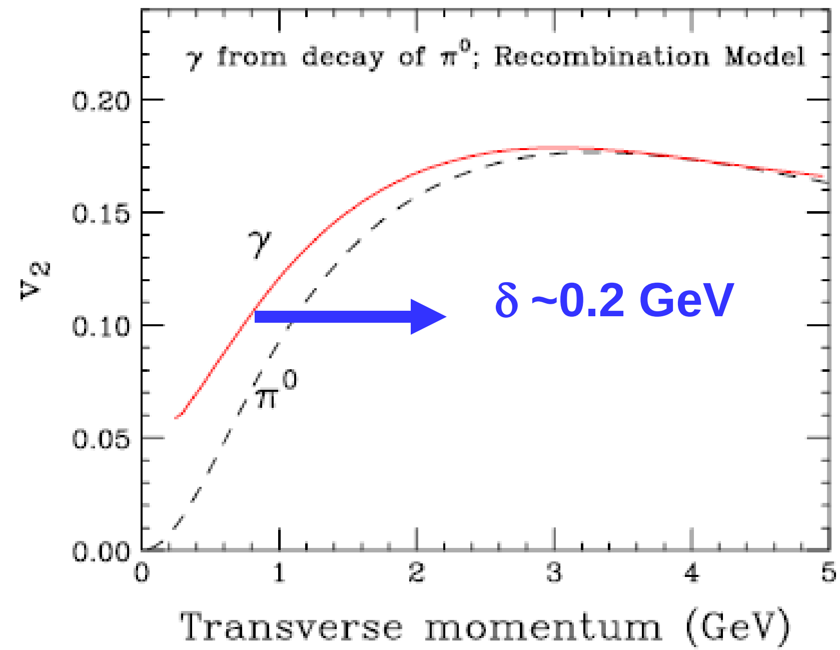






Elliptic Flow of Decay Photons





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

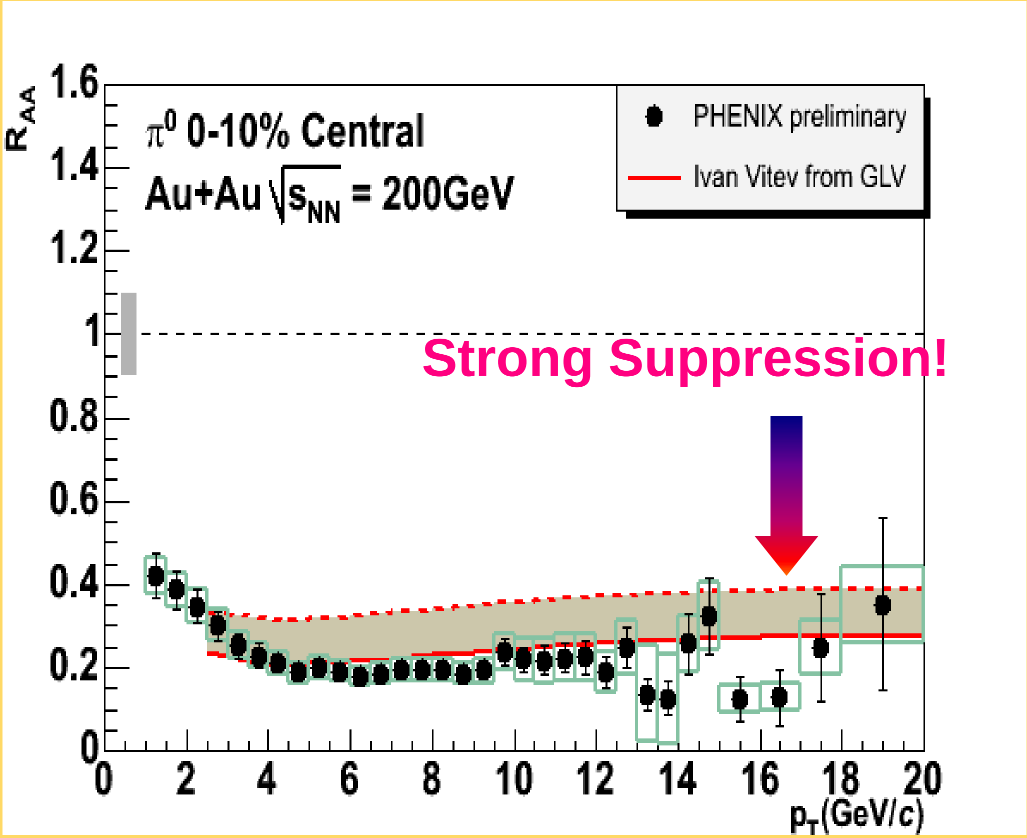
where

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

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

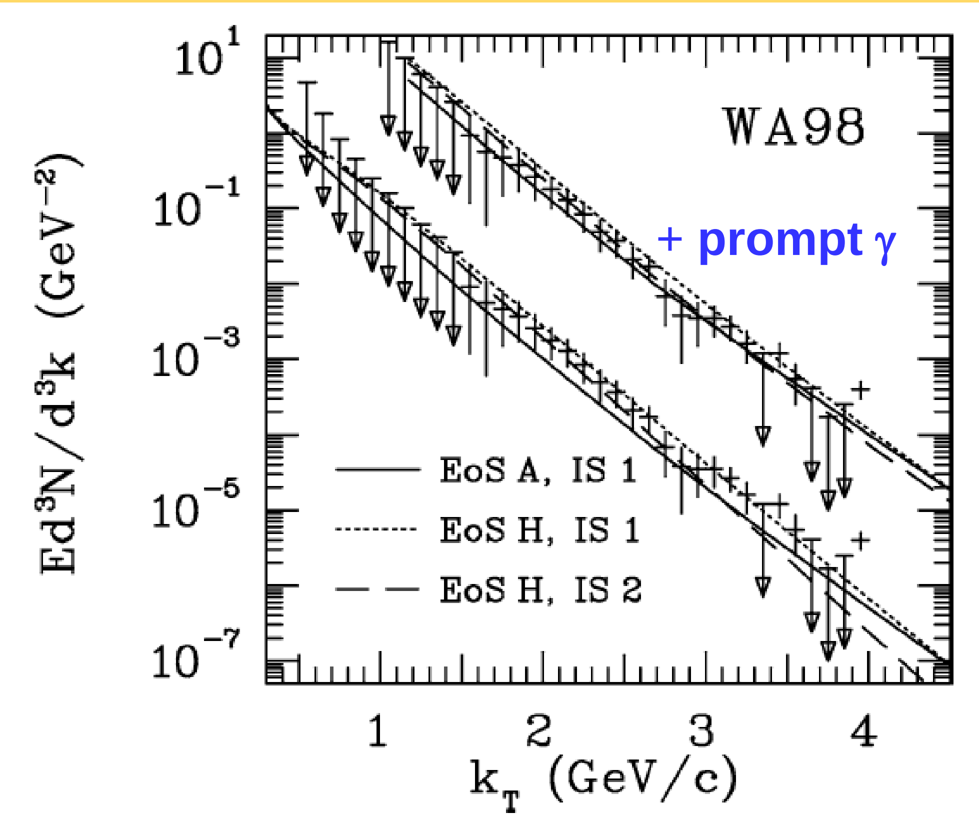


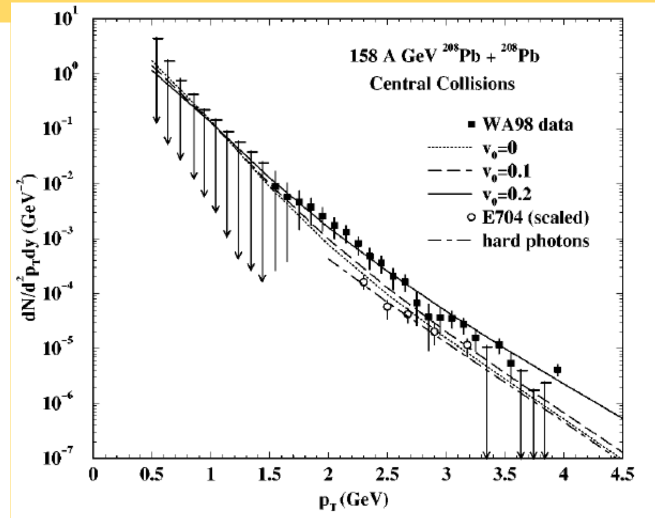
- Large suppression implies large energy loss. Model calculations indicate high gluon densities $dN_g/dy \sim 1100$

- Implies large energy density (as do also E_T measurements) $\varepsilon > 10$ GeV/fm^3 well above critical energy density $\varepsilon_{crit} \sim 1$ GeV/fm^3

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

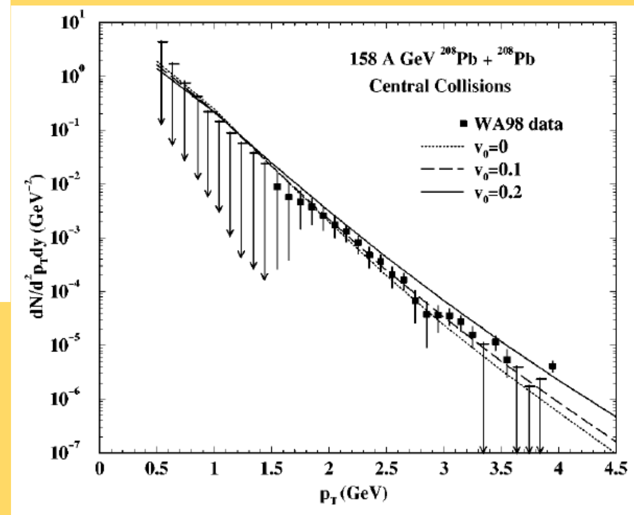
QGP or Hot Hadrons? Enter WA98





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/fm³ at T_i = 245-275 MeV)

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