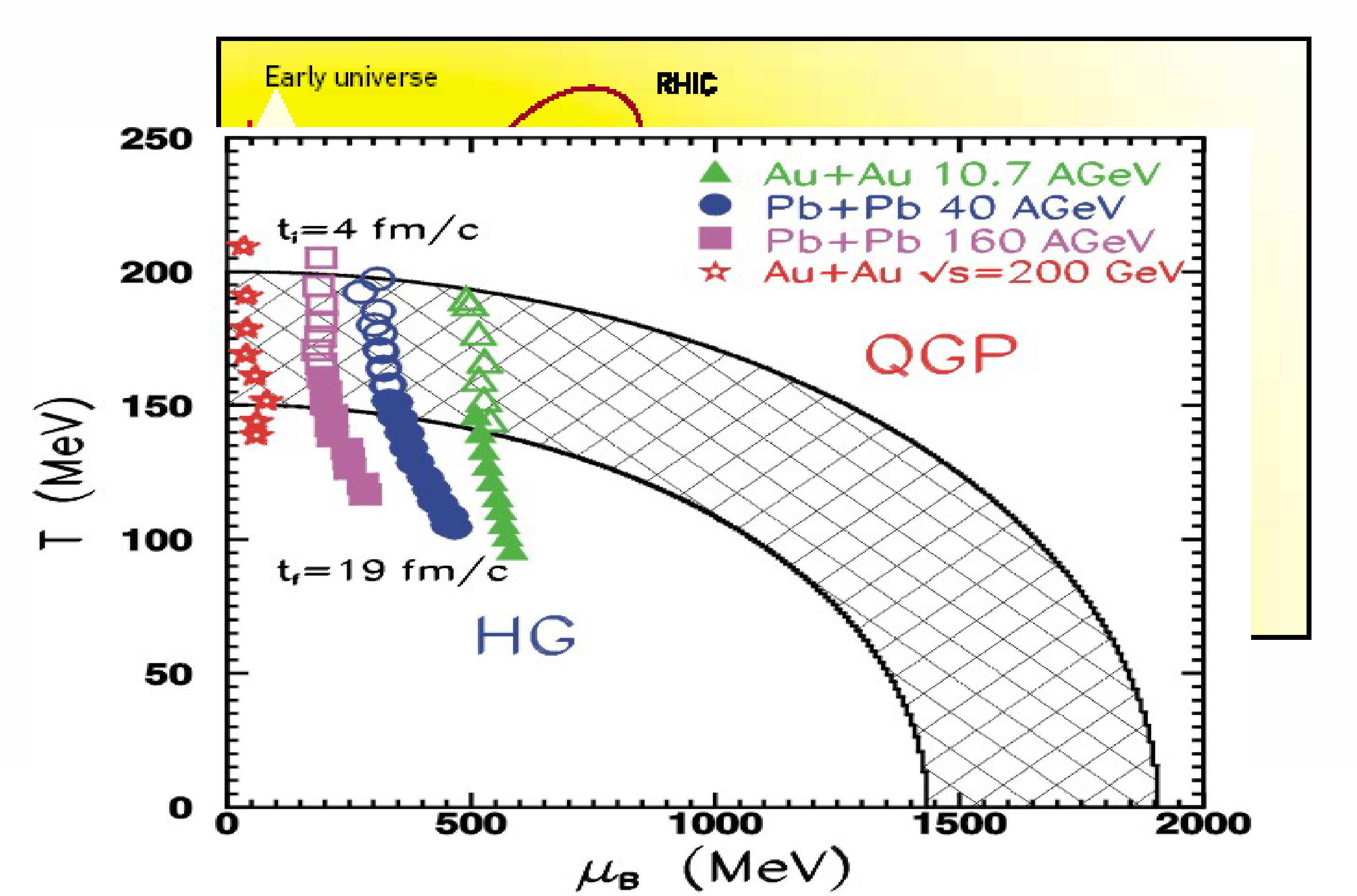
In-medium effects on electromagnetic probes

Hard Probes 2004

International Conference on
Hard and Electromagnetic Probes
of High Energy Nuclear Collisions

Charles Gale
McGill

In-medium: what medium?

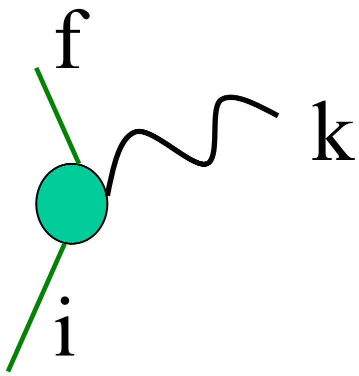


DOE/NSF NSAC
Long Range Plan

UrQMD

Phase-space trajectory goes through qualitatively different media

The information carried by EM radiation



$$R_{fi} = \frac{|S_{fi}|^2}{\tau V}$$

$$S_{fi} = < f \,|\int d^4x\, \hat{J}_\mu(x) A^\mu(x)\,|\, i > \text{[photons]}$$

$$S_{fi} = < f \,|\iint d^4x d^4y\, \hat{J}_\mu(x) D^{\mu\nu}(x-y) J^e_\nu(y)\,|\, i > \text{[dileptons]}$$

[photons]

$$R_{fi} = -\frac{g^{\mu\nu}}{2\varpi V}(2\pi)^4 \left\{\delta(P_i + k - P_f) + \delta(P_i - k + P_f)\right\}$$

$$\times < f \,|\, \hat{J}_\mu \,|\, i >< i \,|\, \hat{J}_\nu \,|\, f >$$

absorption (→ $\delta(P_i + k - P_f)$)

emission (→ $\delta(P_i - k + P_f)$)

Info carried out, II

Thermal rates: avg over initial states & sum over final

$$\varpi_i = \frac{e^{-\beta K_i}}{\sum_j e^{-\beta K_j}}$$

$$dR = -\frac{g^{\mu\nu}}{2\varpi}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)$$
$$\times < j\,|\,\hat{J}_\mu\,|\,i >< i\,|\,\hat{J}_\nu\,|\,f >$$

Thermal ensemble average of the current-current correlation function

Info, III

Isolate the correlation Function:

$$f^{\pm}_{\mu\nu}(k) = \pm\frac{1}{Z}\sum_{i,f} e^{-\beta K_i}(2\pi)^4\delta(p_i - p_f \pm k)$$
$$\times < f\,|\,\hat{J}_\mu\,|\,i >< i\,|\,\hat{J}_\nu\,|\,f >$$

Spectral representation

$$f^{-}_{\mu\nu}(k) = -\frac{2}{(e^{\beta\omega}-1)}\,\mathrm{Im}\,\Pi^{R}{}_{\mu\nu}(k)$$

A direct connection to the in-medium photon self-energy

Info, IV

Emission rates:

$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3} \operatorname{Im}\Pi_{\mu\nu}(k) \frac{1}{e^{\beta\omega}-1}$$ [photons]

$$E_+E_- \frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{k^4} L^{\mu\nu} \operatorname{Im}\Pi_{\mu\nu}(k) \frac{1}{e^{\beta\omega}-1}$$ [dileptons]

$$L^{\mu\nu} = p_+^\mu p_-^\nu + p_-^\mu p_+^\nu - g^{\mu\nu}(p_+ \cdot p_- + m_l^2)$$

Info, V

A model for the hadronic electromagnetic current: VMD

$$J_\mu = -\frac{e}{g_\rho} m_\rho^2 \rho_\mu - \frac{e}{g_\omega} m_\omega^2 \omega_\mu - \frac{e}{g_\phi} m_\phi^2 \phi_\mu$$

The current-field identity

(J. J. Sakurai)

$$\mathrm{Im} < J_\mu J_\nu >_T \overset{VMD}{\Longrightarrow} \mathrm{Im} < \rho_\mu \rho_\nu >_T \Rightarrow \mathrm{Im}\, D_{\mu\nu}^T \Rightarrow$$ Spectral density

$\therefore$ The photon/dilepton signal can tell us about the in-medium spectral densities of vector mesons

Vector Meson Spectral Densities: A Sample Calculation I

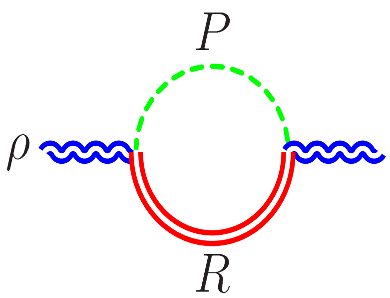


TABLE I. Mesonic resonances R with masses $m_R \leqslant 1300$ MeV and substantial branching ratios into final states involving direct ρ's (hadronic) or ρ-like photons (radiative).

R	$I^G J^P$	$\Gamma_{\rm tot}$ [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)

The interaction is constrained by basic hadronic phenomenology

Chiral $U(3)_L$ x $U(3)_R$ Massive Yang-Mills:

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

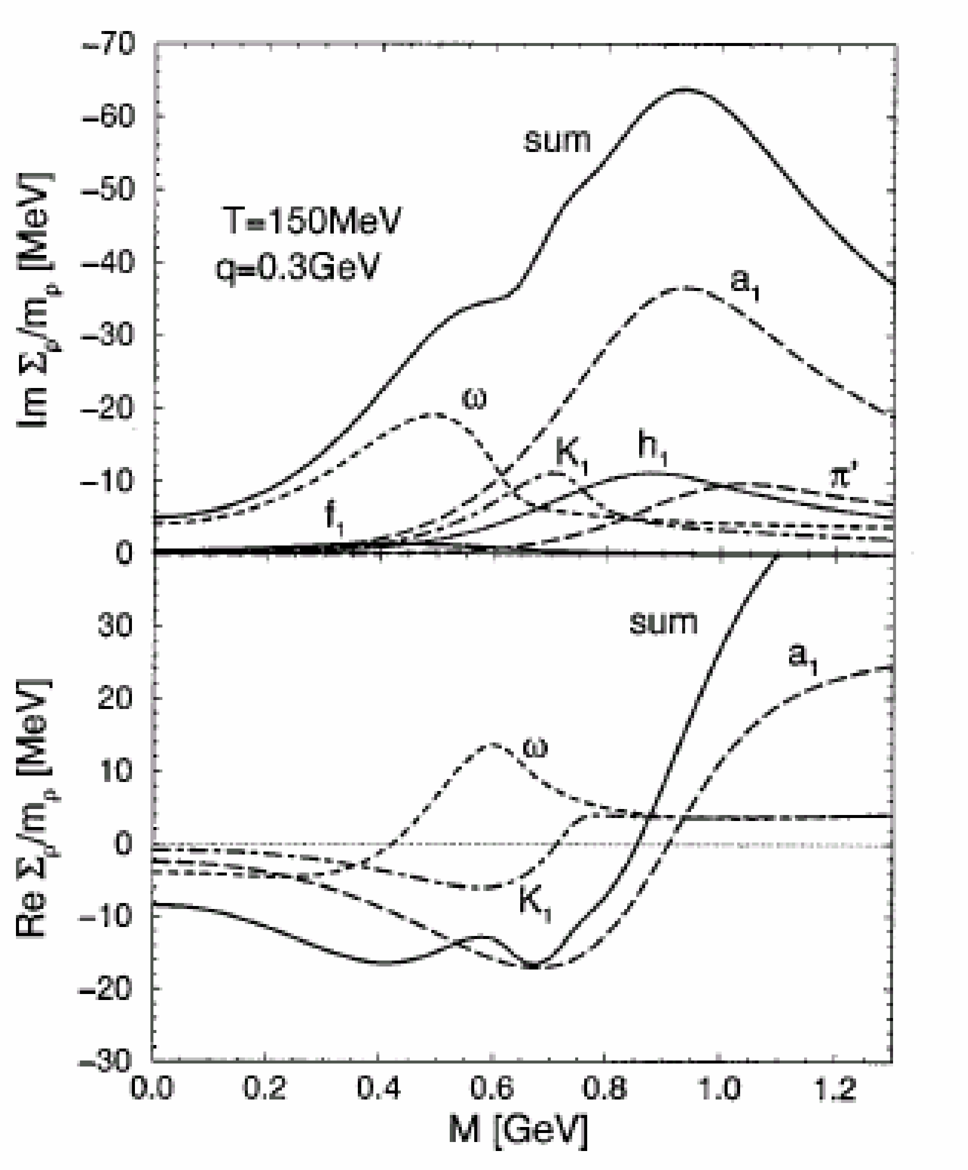
$$-\frac{1}{2}\mathrm{Tr}\left(F^L_{\mu\nu}F^{L\mu\nu} + F^R_{\mu\nu}F^{R\mu\nu}\right) + m_0^2 \mathrm{Tr}\left(A^L_\mu A^{L\mu} + A^R_\mu A^{R\mu}\right)$$

+ non-minimal terms

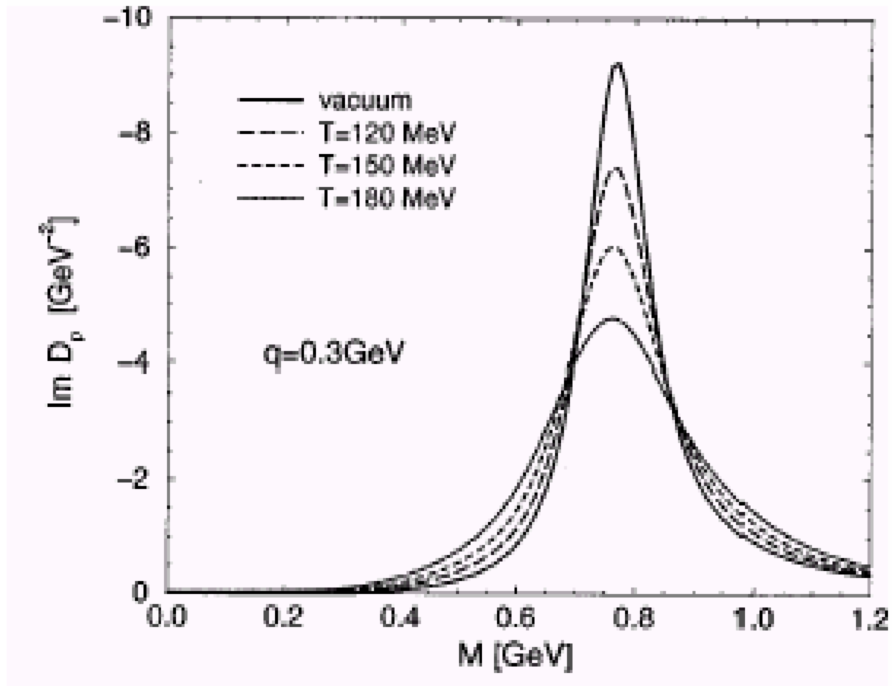
Parameters and form factors are constrained by hadronic phenomenology:

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

Vector Meson Spectral Densities



The spectral density is flattened and broadened



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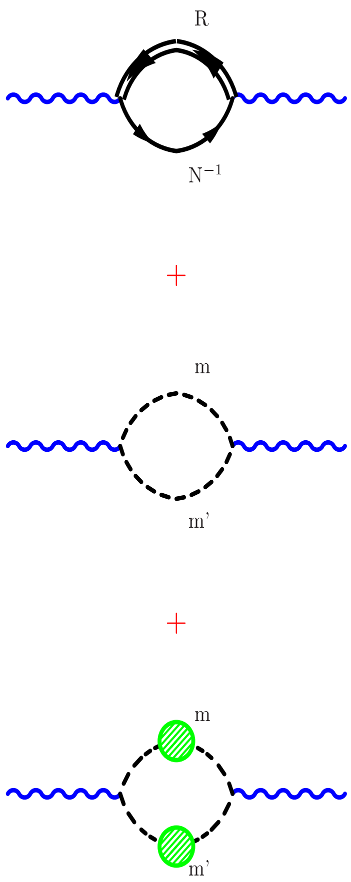
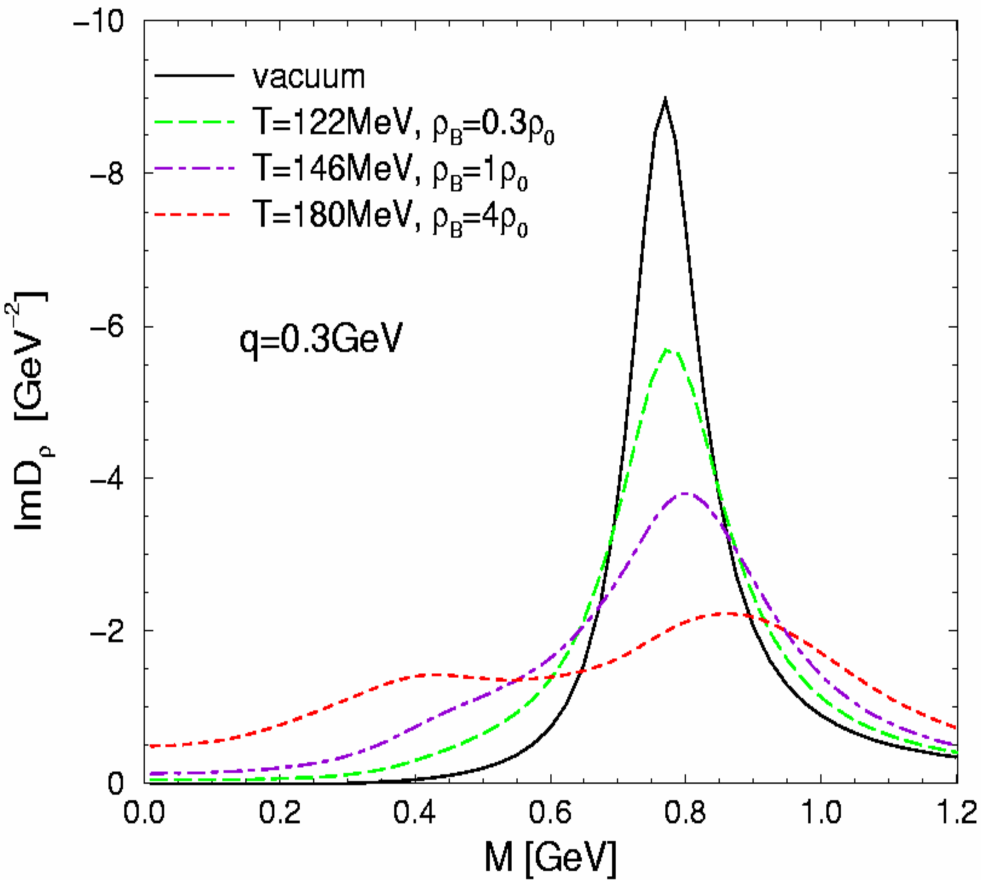
Vector Meson Spectral Densities, IV
(adding baryons)



R. Rapp & Wambach, 1999



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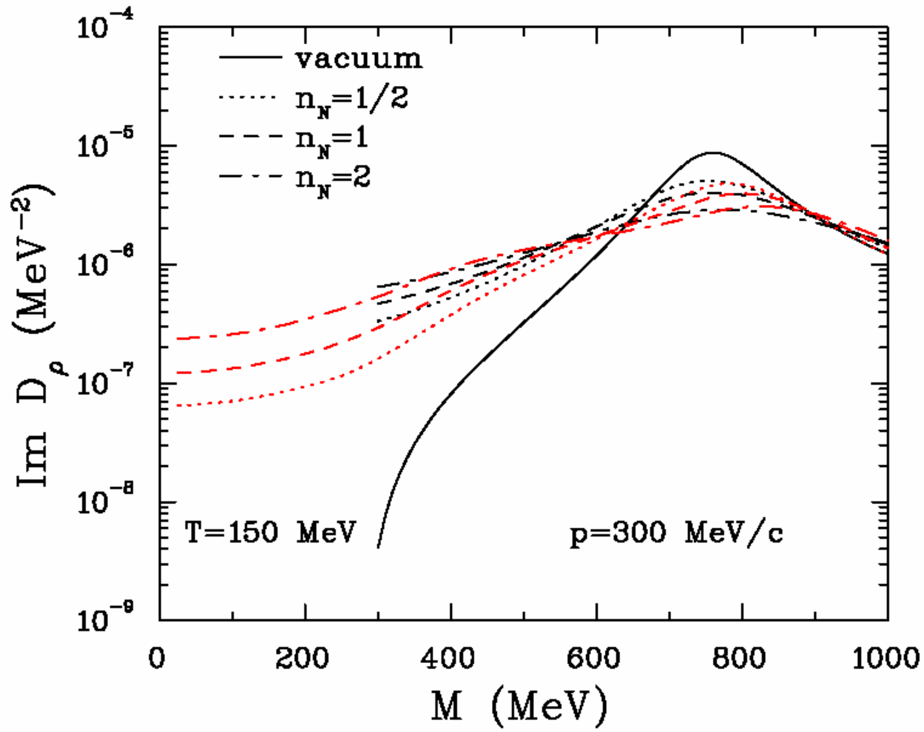
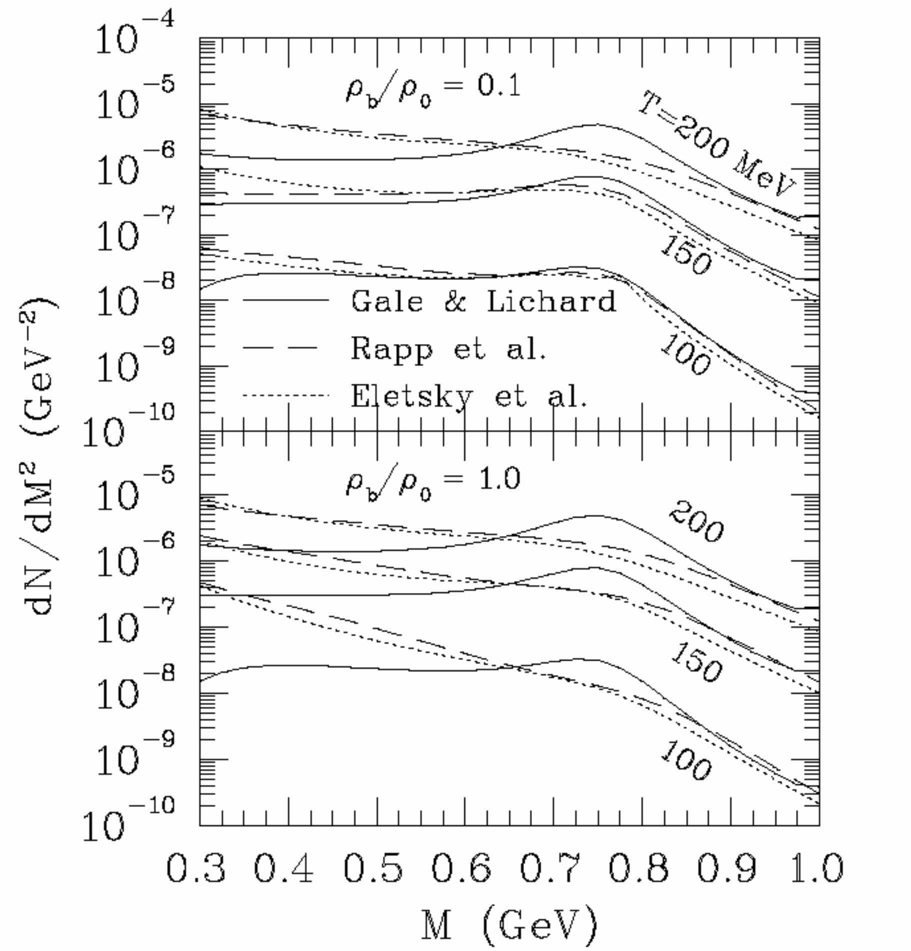
Resonance	Mass (GeV)	Width (GeV)	Branching ratio (ρN or $\rho\pi$)
$N(1700)$	1.737	0.249	0.13
$N(1720)$	1.717	0.383	0.87
$N(1900)$	1.879	0.498	0.44
$N(2000)$	1.903	0.494	0.60
$N(2080)$	1.804	0.447	0.26
$N(2090)$	1.928	0.414	0.49
$N(2100)$	1.885	0.113	0.27
$N(2190)$	2.127	0.547	0.29
$\Delta(1700)$	1.762	0.599	0.08
$\Delta(1900)$	1.920	0.263	0.38
$\Delta(1905)$	1.881	0.327	0.86
$\Delta(1940)$	2.057	0.460	0.35
$\Delta(2000)$	1.752	0.251	0.22
$\phi(1020)$	1.020	0.0045	0.13
$h_1(1170)$	1.170	0.36	1
$a_1(1260)$	1.230	0.40	0.68
$\pi(1300)$	1.300	0.40	0.32
$a_2(1320)$	1.318	0.107	0.70
$\omega(1420)$	1.419	0.174	1

- Should hold near the mass-shell
- Adler decoupling enforced

Two approaches:



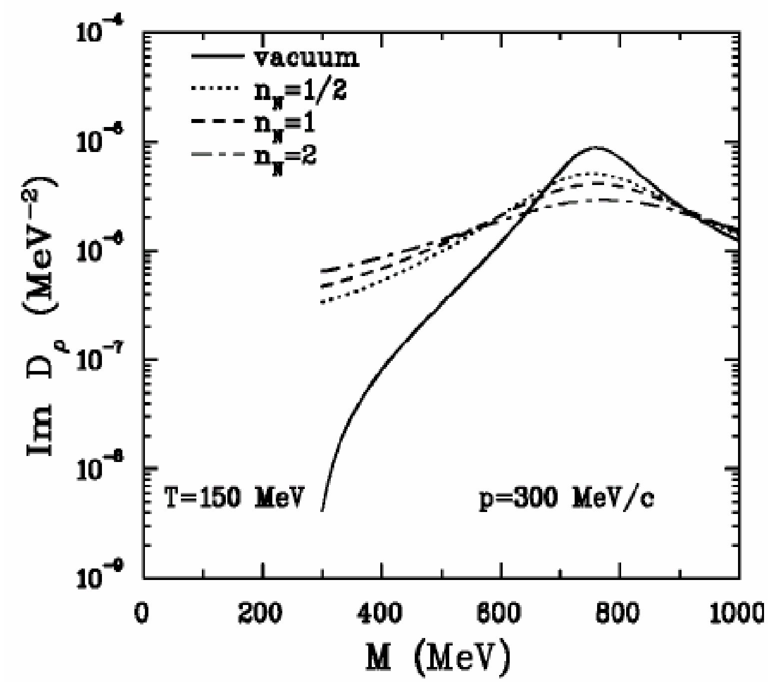


Rapp & Wambach (red line)

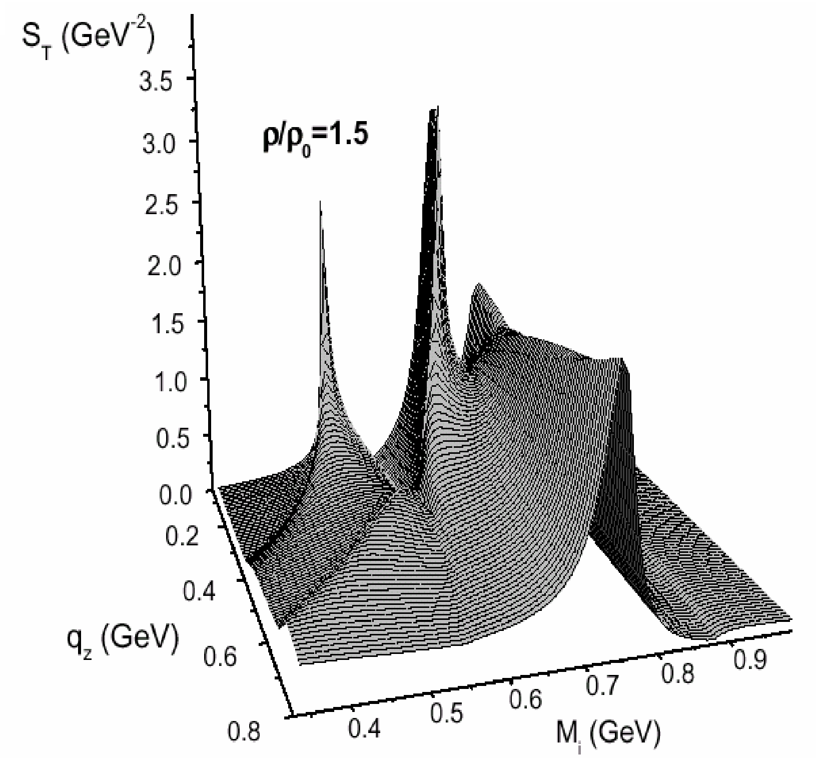
Eletsky, Ioffe, Kapusta (black line)

- Rates are also constrained by nuclear photoabsorption data
- Mass shifts & broadening are related by dispersion relations

Vector Meson Spectral Densities, VI

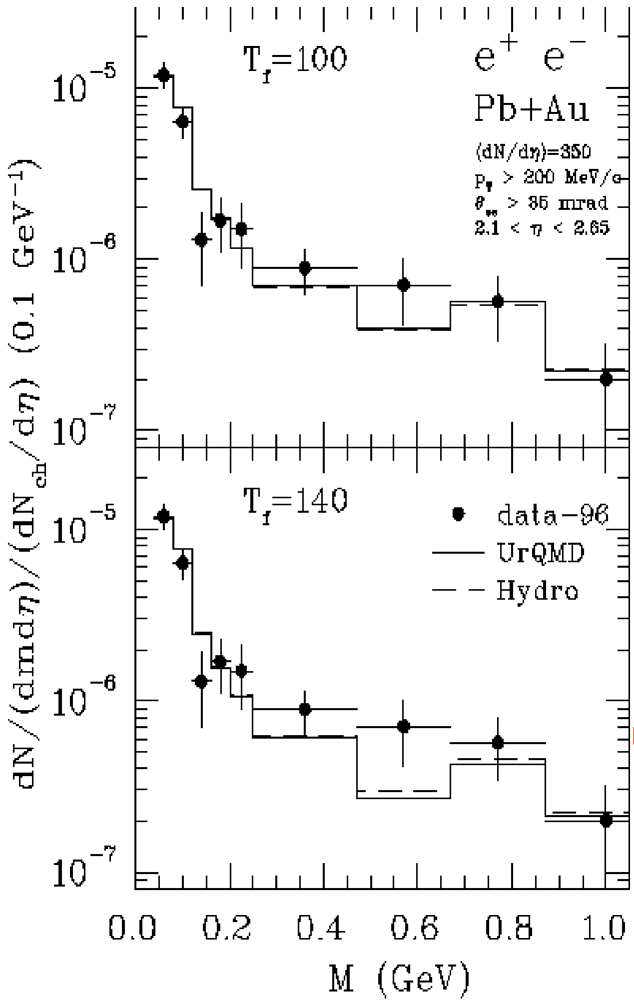


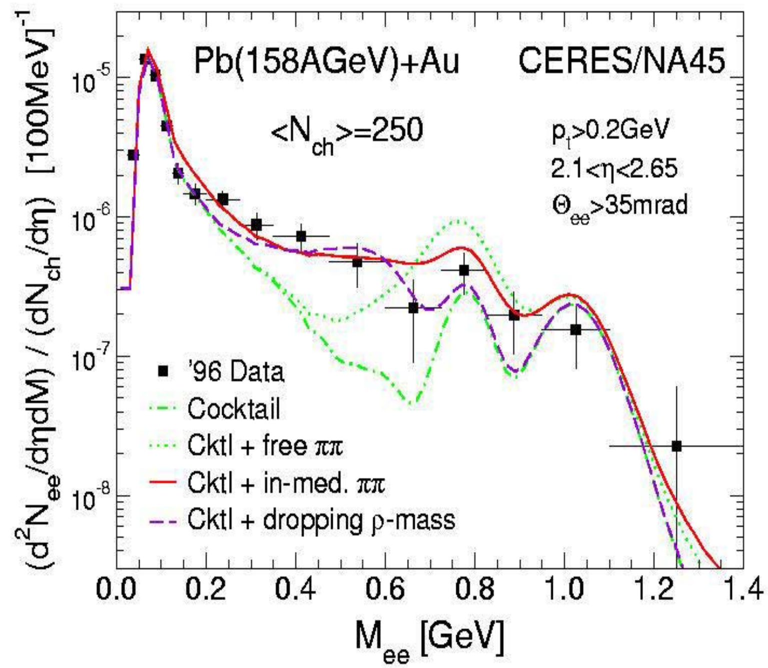
V. Eletsky, et al., PRC 2001



Teodorescu, Dutt-Mazumder, Gale, PRC 2002

Fold in With a Dynamical Evolution Model

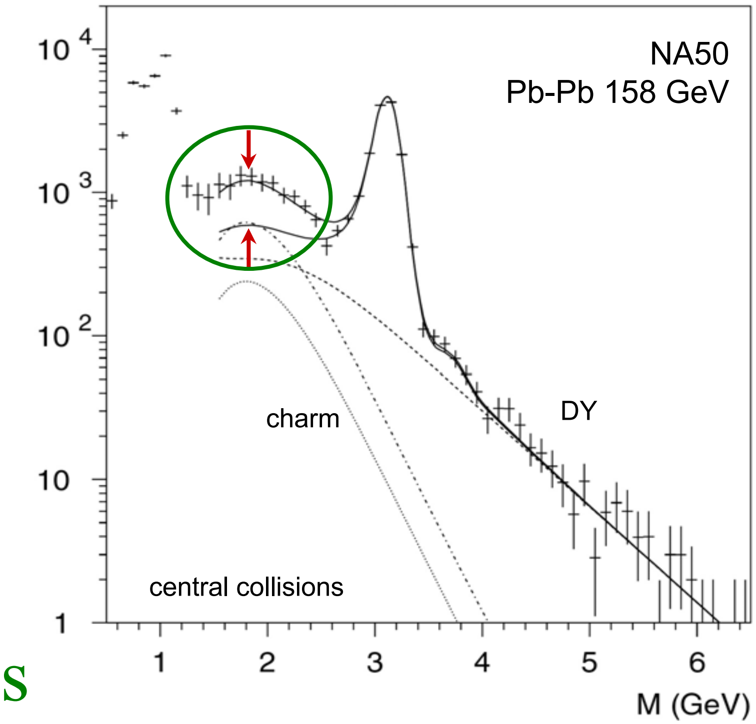




Huovinen *et al*., 2002

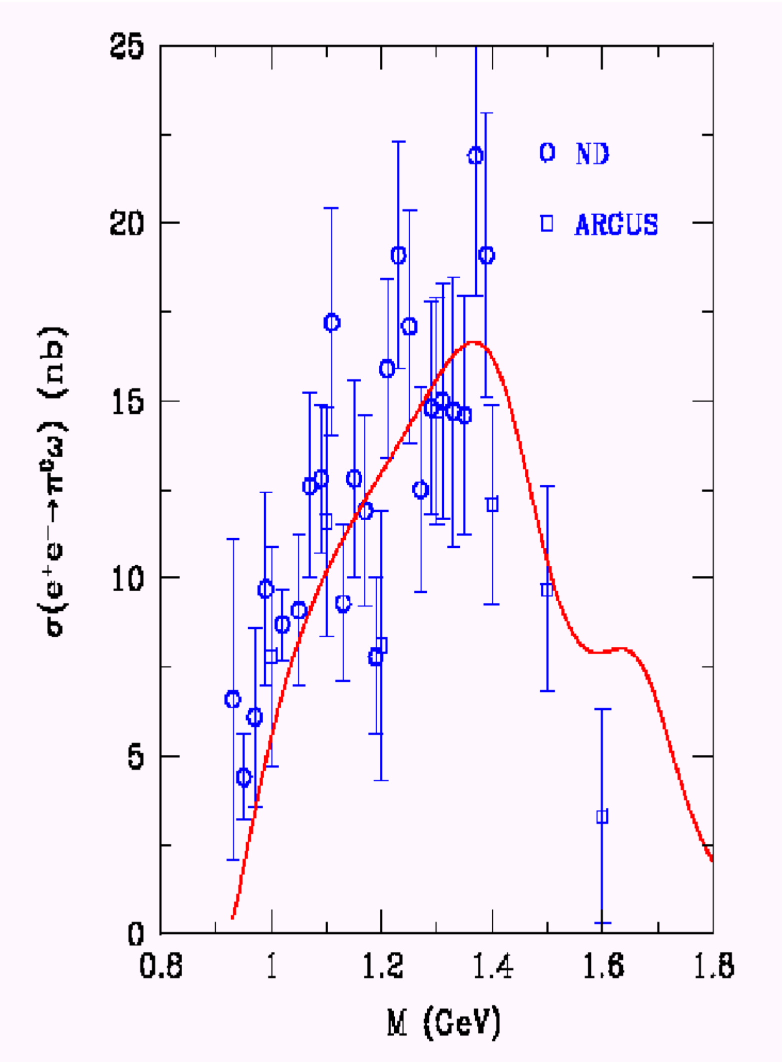
What's new? Photons…

The intermediate mass sector

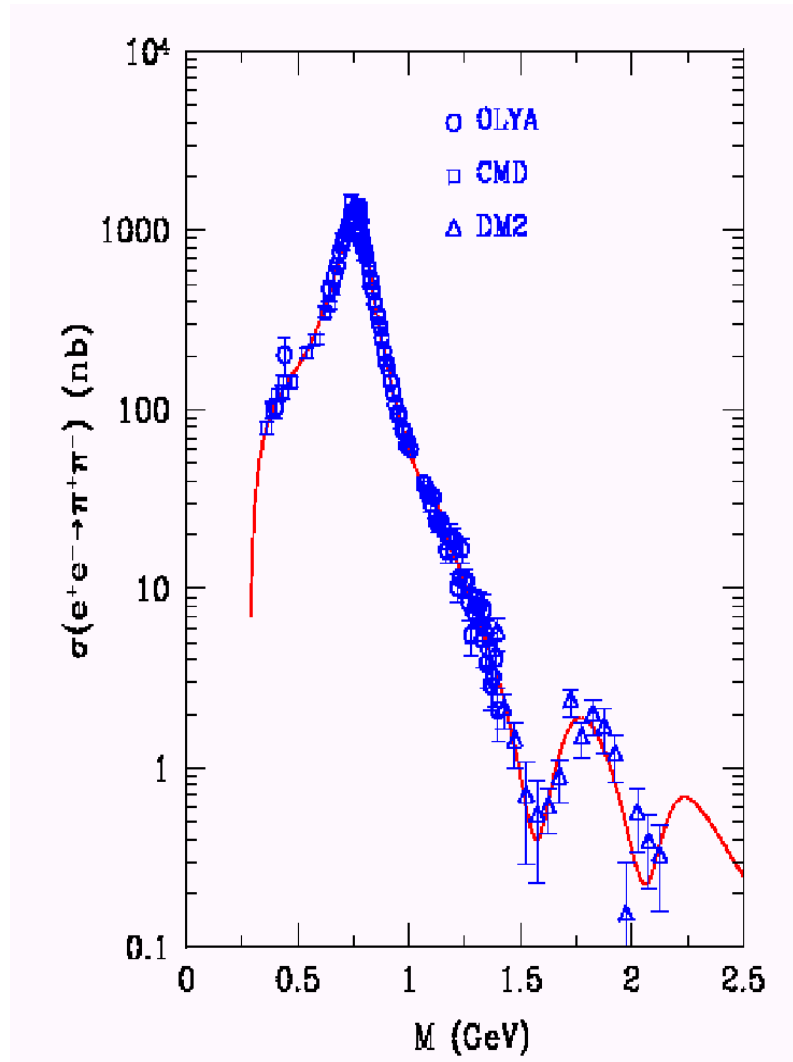


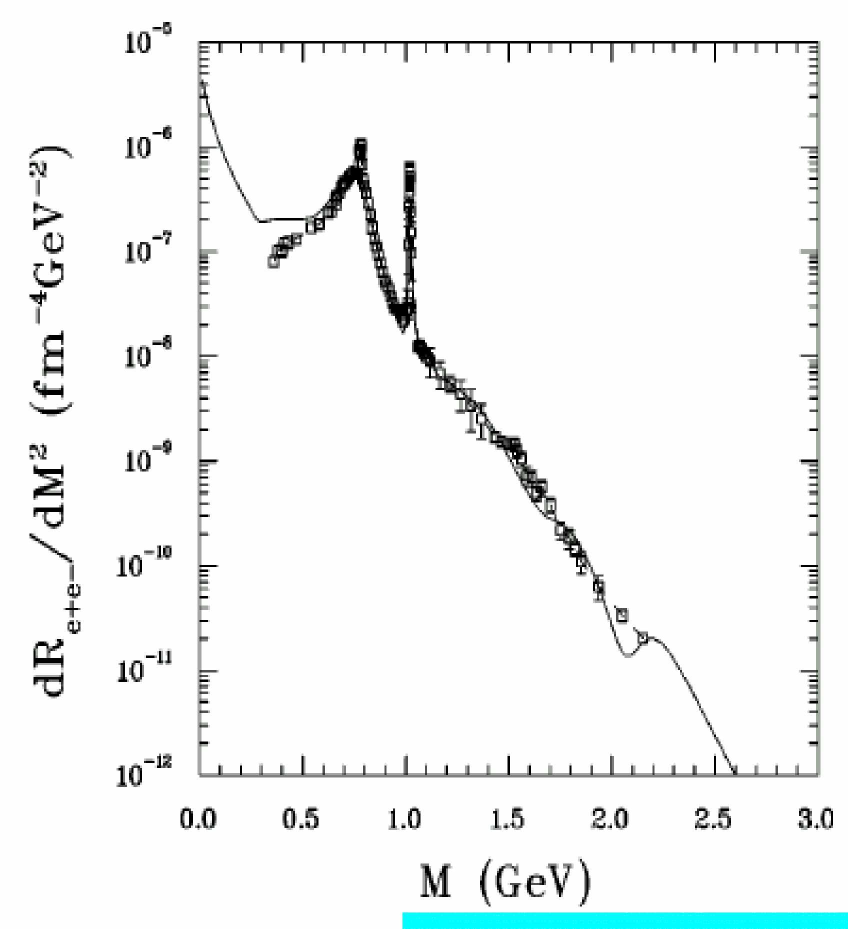
- Direct connection to Hard Probes
- Off-shell effects are potentially important for effective hadronic interactions Gao & Gale, PRC **57**, 254 (1998)
- A lot of data already exists!

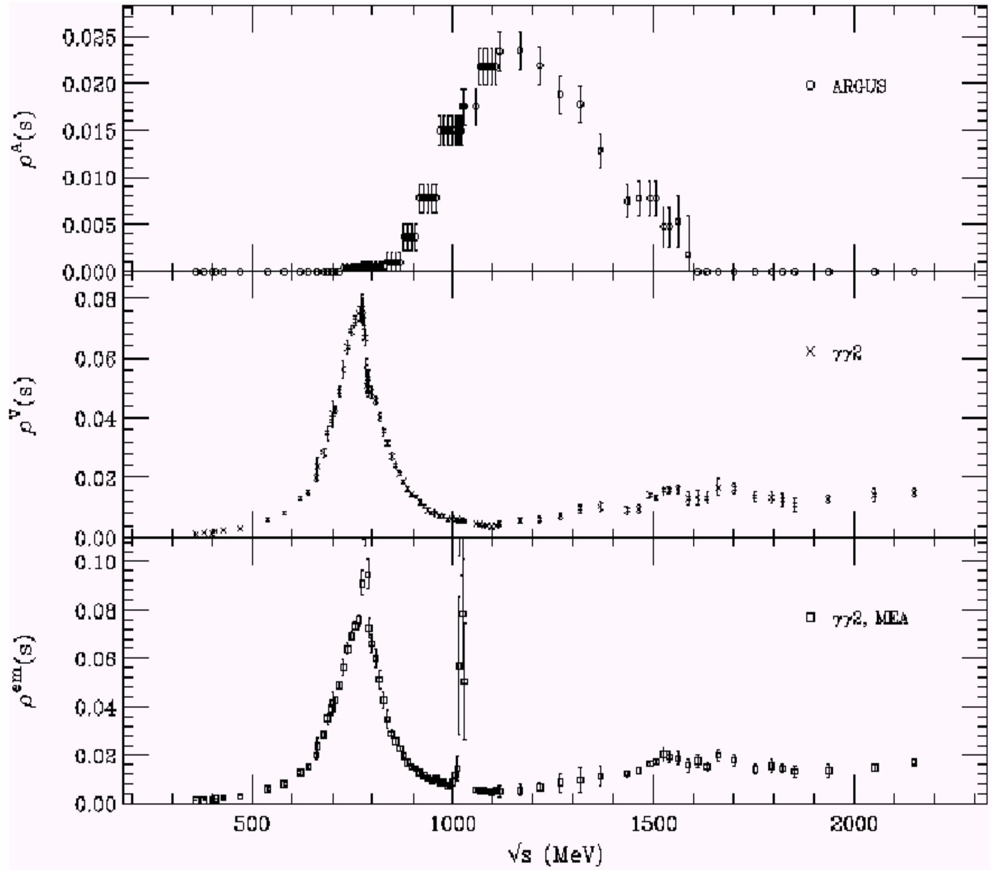
e+ e- Data: A Wealth of Information



OLYA
CMD
DM-1(2)
ARGUS
M3N
γγ2





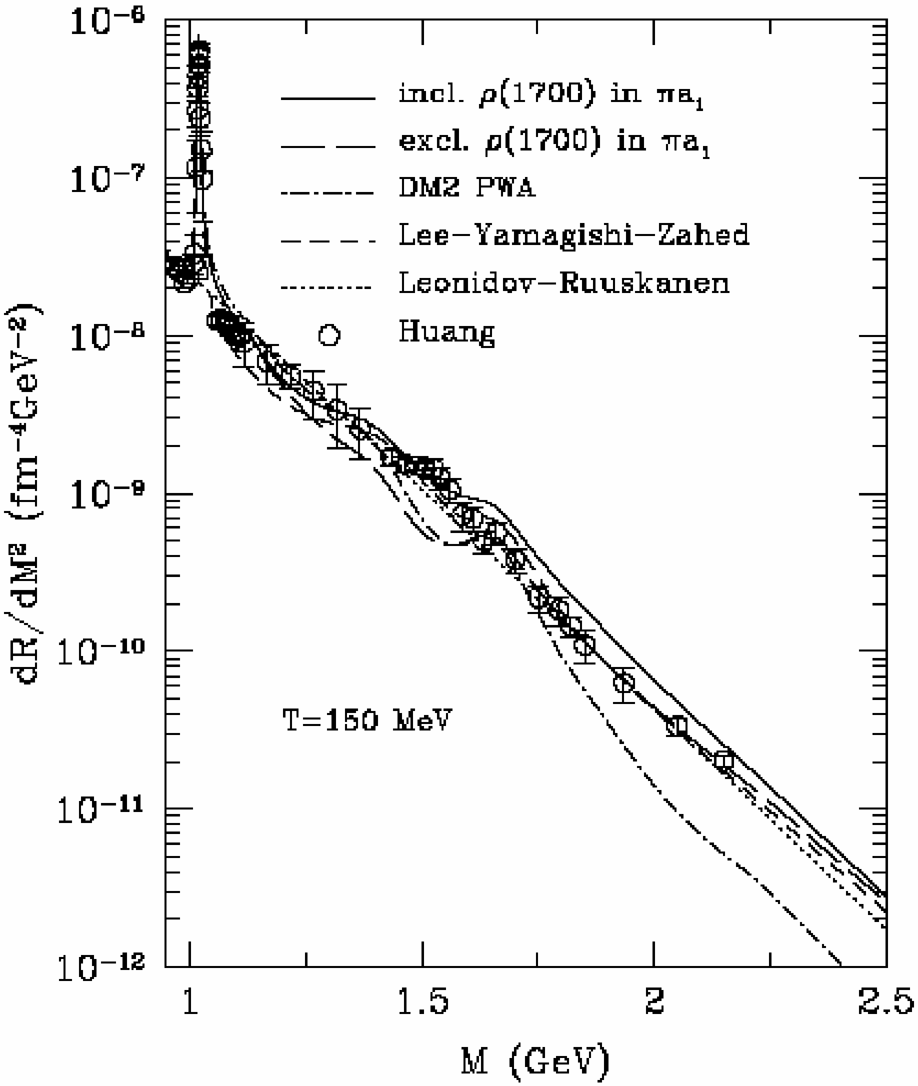


$$\frac{dR}{dM^2} = \frac{4\alpha^2}{2\pi} M T K_1(M/T)\left[\rho^{em}(M) - \left(\varepsilon - \frac{\varepsilon^2}{2}\right)\left(\rho^V(M) - \rho^A(M)\right)\right]$$

I. Kvasnikova, C. Gale, and D. K. Srivastava, PRC **65**, 064903 (2002)

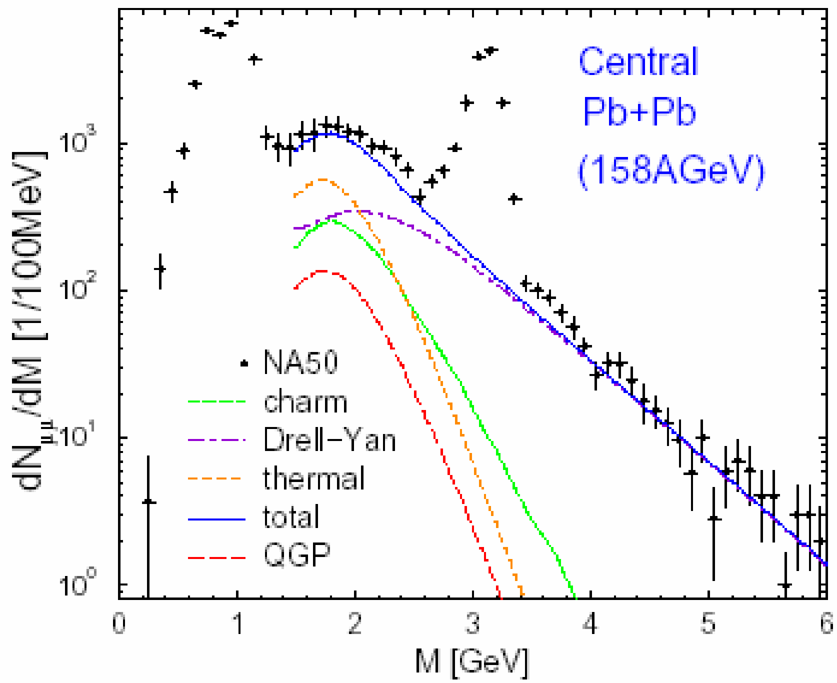
Z. Huang, PL **B361**, 131 (1995)

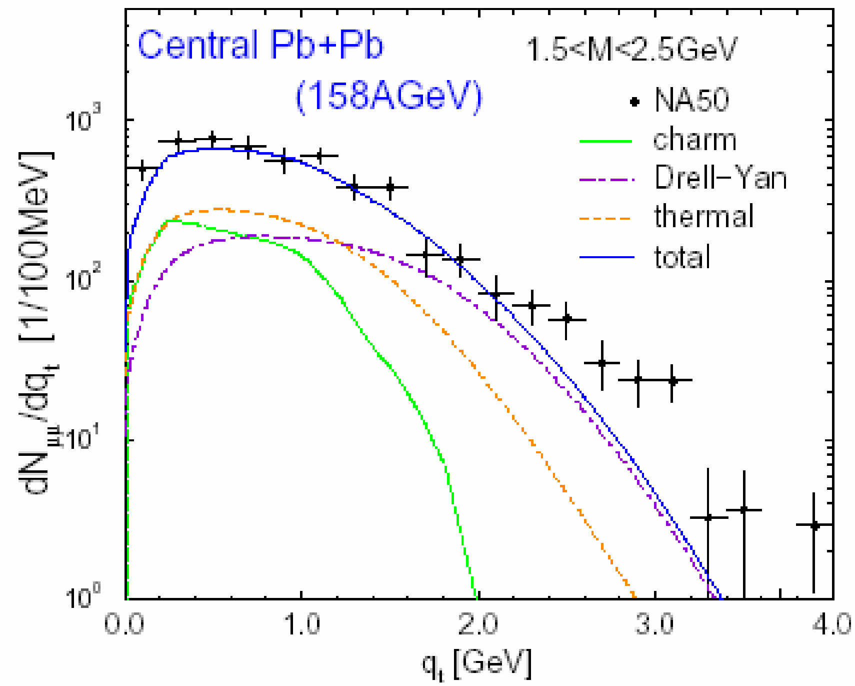
A larger comparison

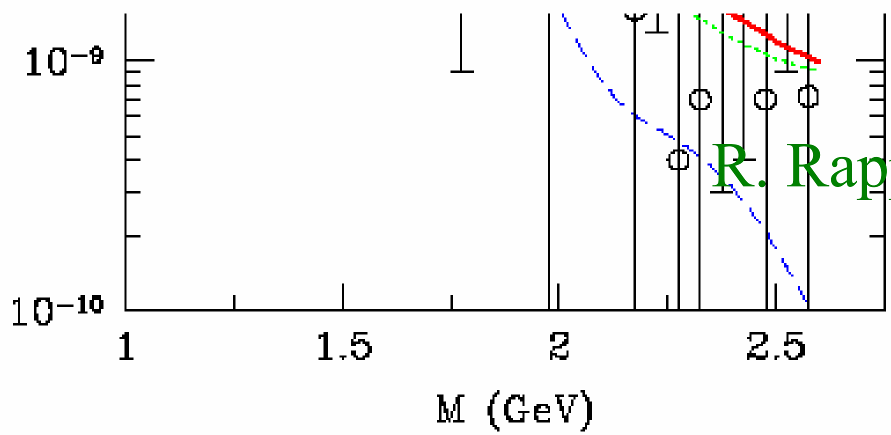


Agreement across approaches

Intermediate mass data







R. Rapp & E. Shuryak, PLB (2000)

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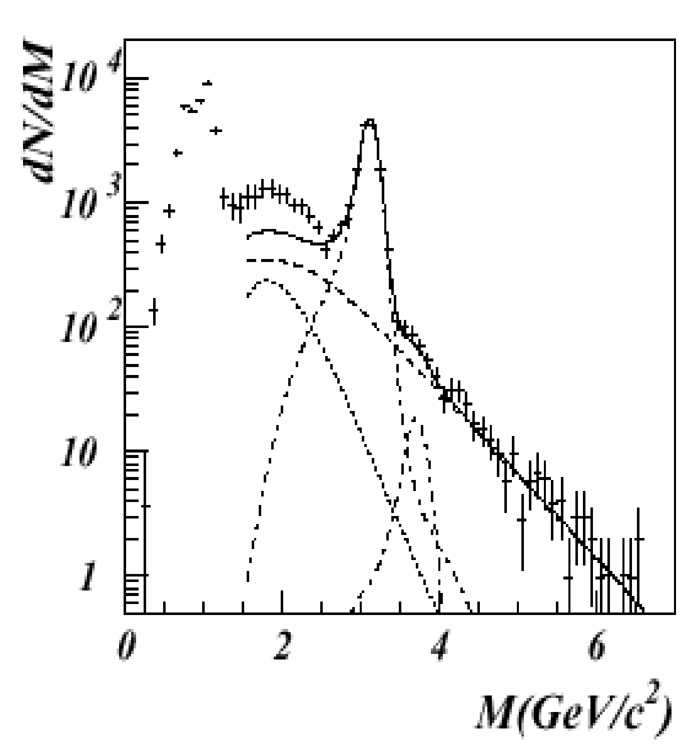
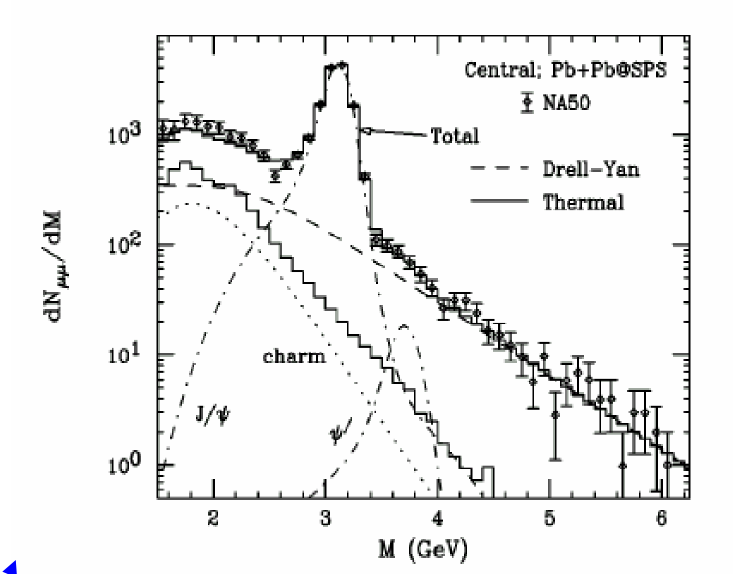
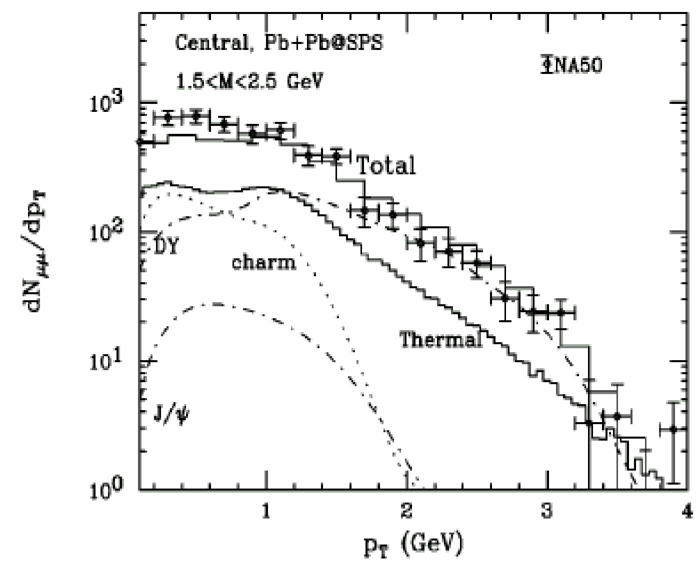
NA50 Data (cont'nd)



I. Kvasnikova, C. Gale, and
D. K. Srivastava, PRC 2002





- In agreement with multiplicity dependence
- Includes detector acceptance & efficiency
  (O. Drapier, NA50)

Intermediate masses: partial summary

- Agreement across models: thermal dileptons are seen
- Case for charm enhancement: weak
- QGP: at most 15-20%
- DY? (J. Qiu)
- NA60

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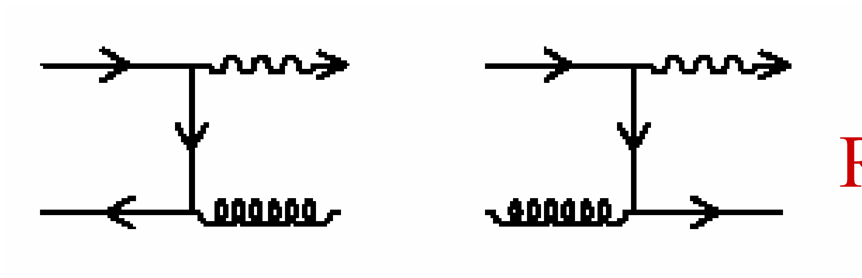
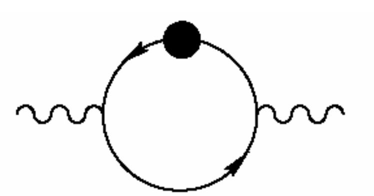
Electromagnetic radiation from the partonic sector

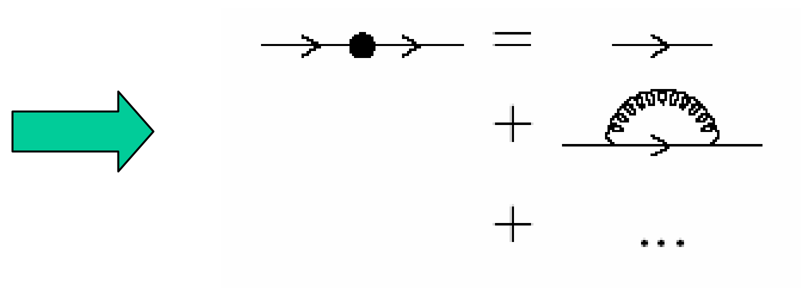
"Basic" approaches

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



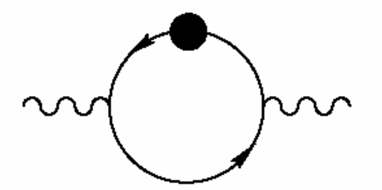
Rates diverge: $\sim \alpha\alpha_s \ln(\omega T / q^2 = 0)$





HTL resummation

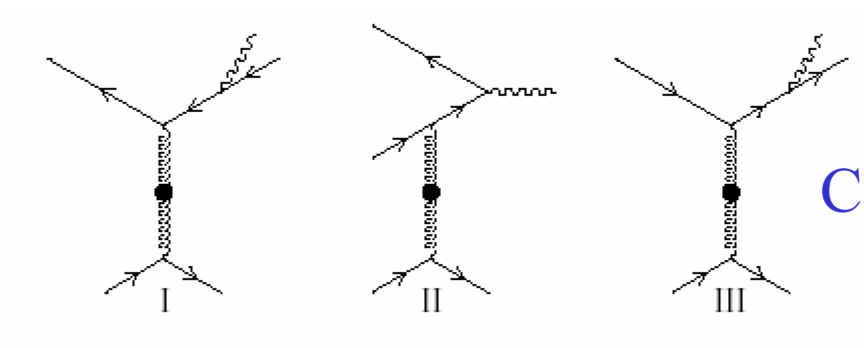
- HTL program: Klimov (1981), Weldon (1982)
  Braaten & Pisarski (1990); Frenkel & Taylor (1990)



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

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

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



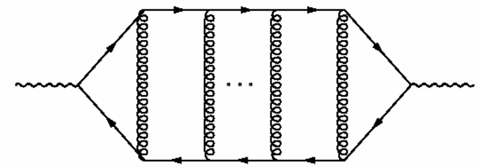
Co-linear singularities:

$$\alpha_s\left(\frac{T^2}{m_{th}^2}\right) \sim \alpha_s$$

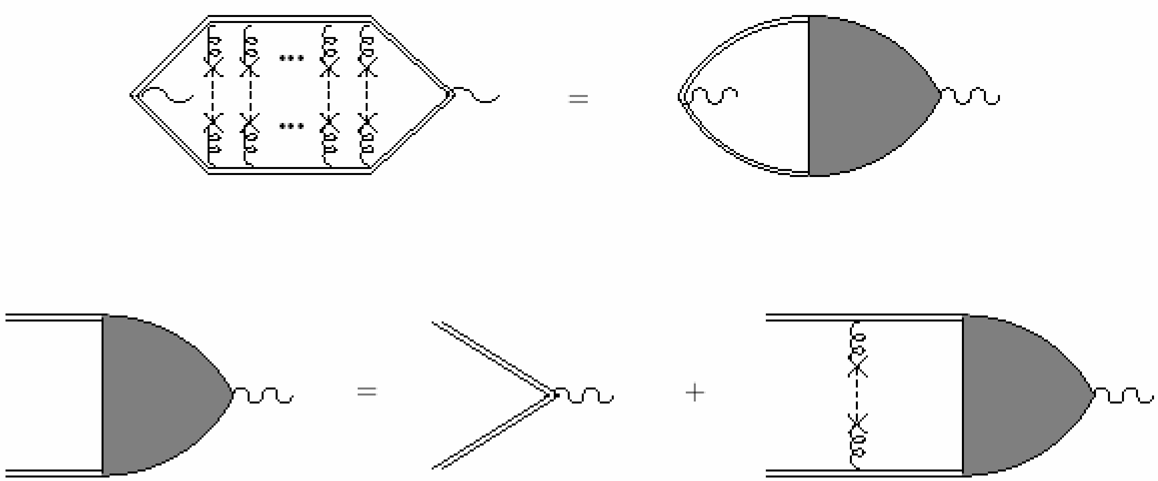
Singularities can be re-summed

Arnold, Moore, and Yaffe

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

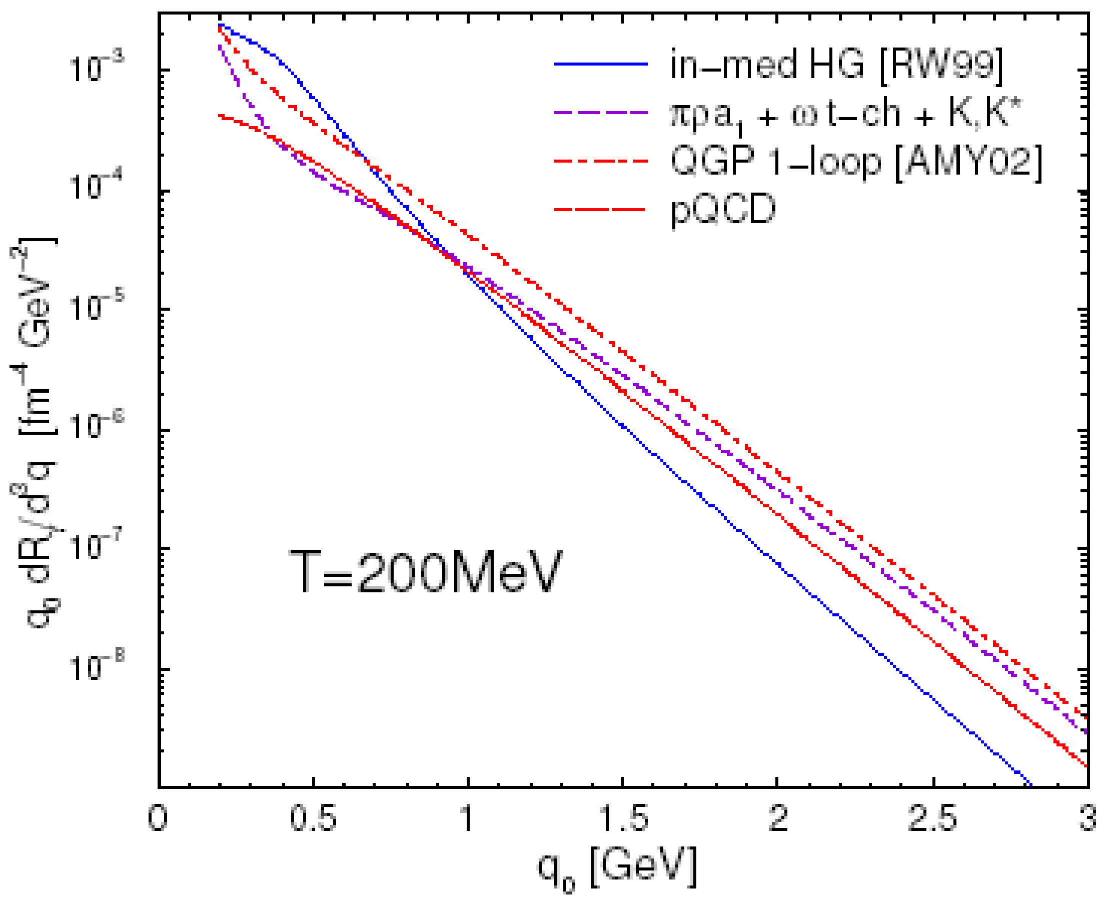


- Incorporates LPM
- Complete leading order in α_s
- Inclusive treatment of collinear enhancement, photon and gluon emission



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

How big (small) is this?



Turbide, Rapp & Gale (2004)

Phenomenological Exploration…

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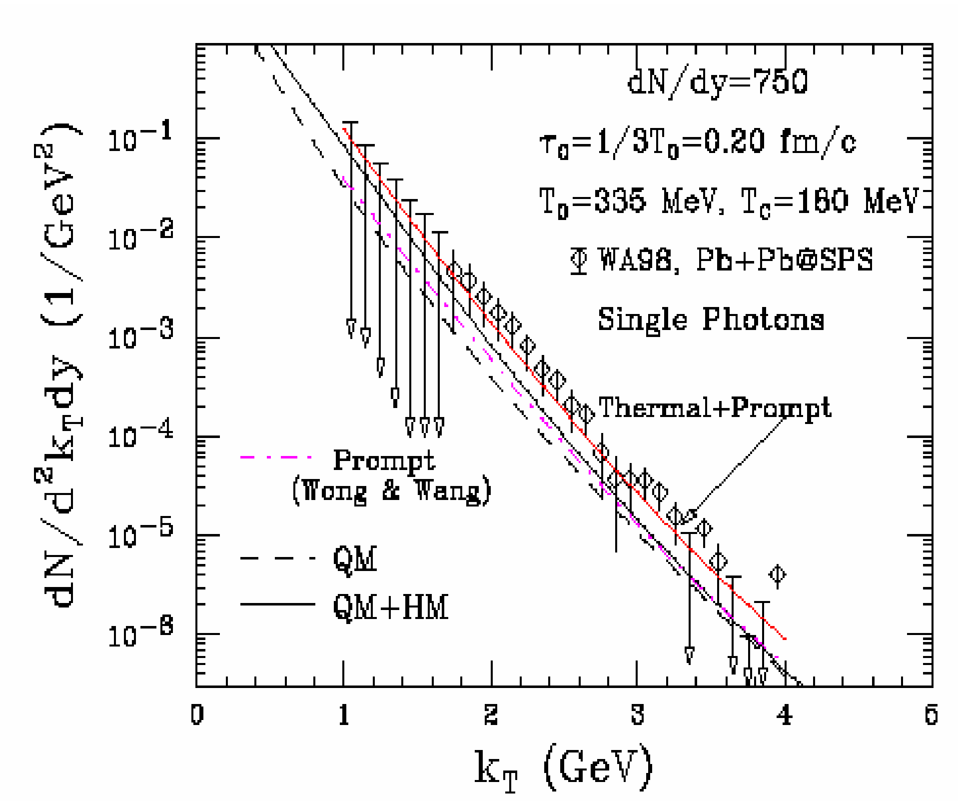
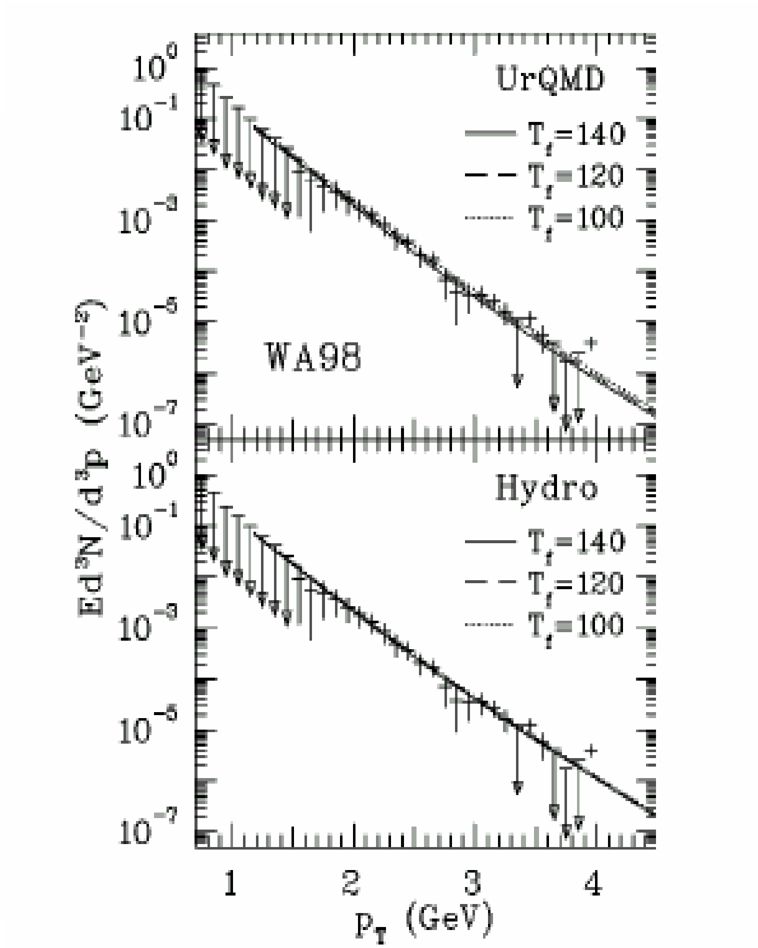
Photons?

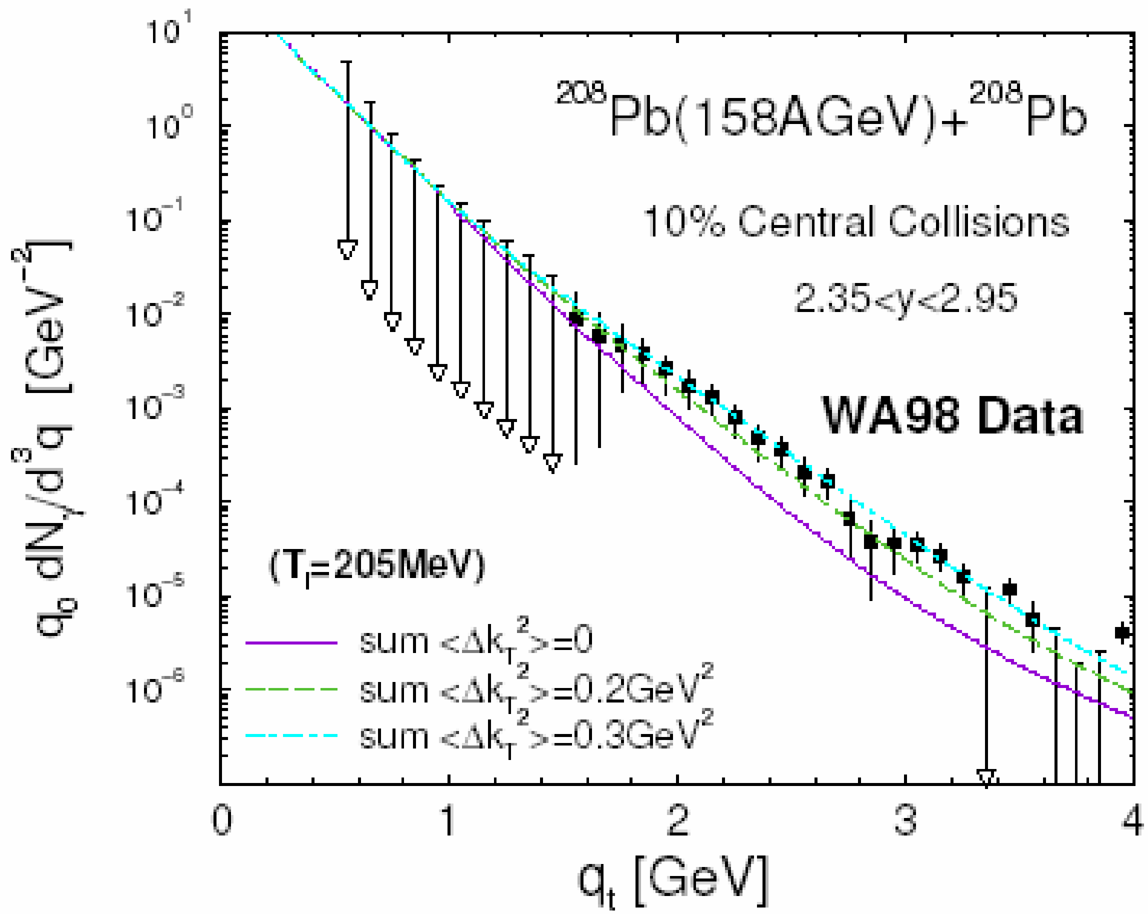


Sinha & Srivastava, 2001



Huovinen et al., 2002

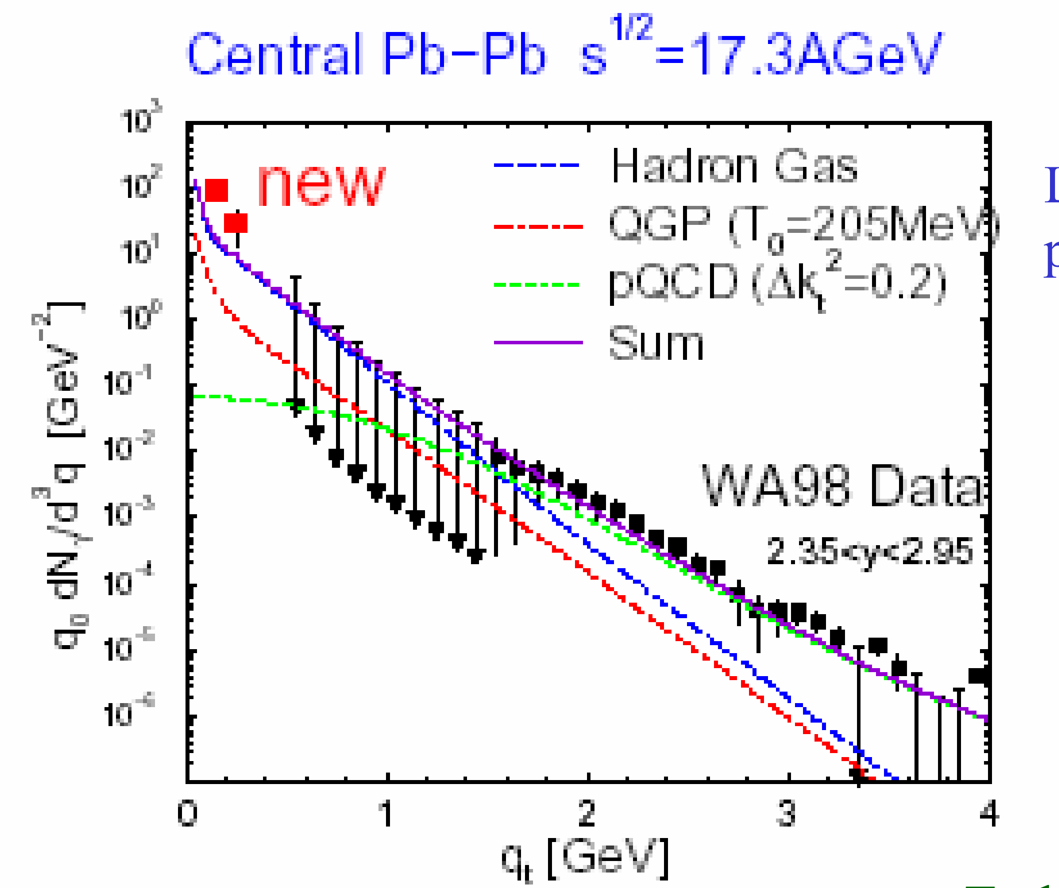
No baryons



Turbide, Rapp & Gale
PRC 2004

- Same spectral densities as low mass dileptons
- Same dynamical model; same boundary conditions
- Cronin contribution estimated from pA data (E629, NA3)
- QGP: small

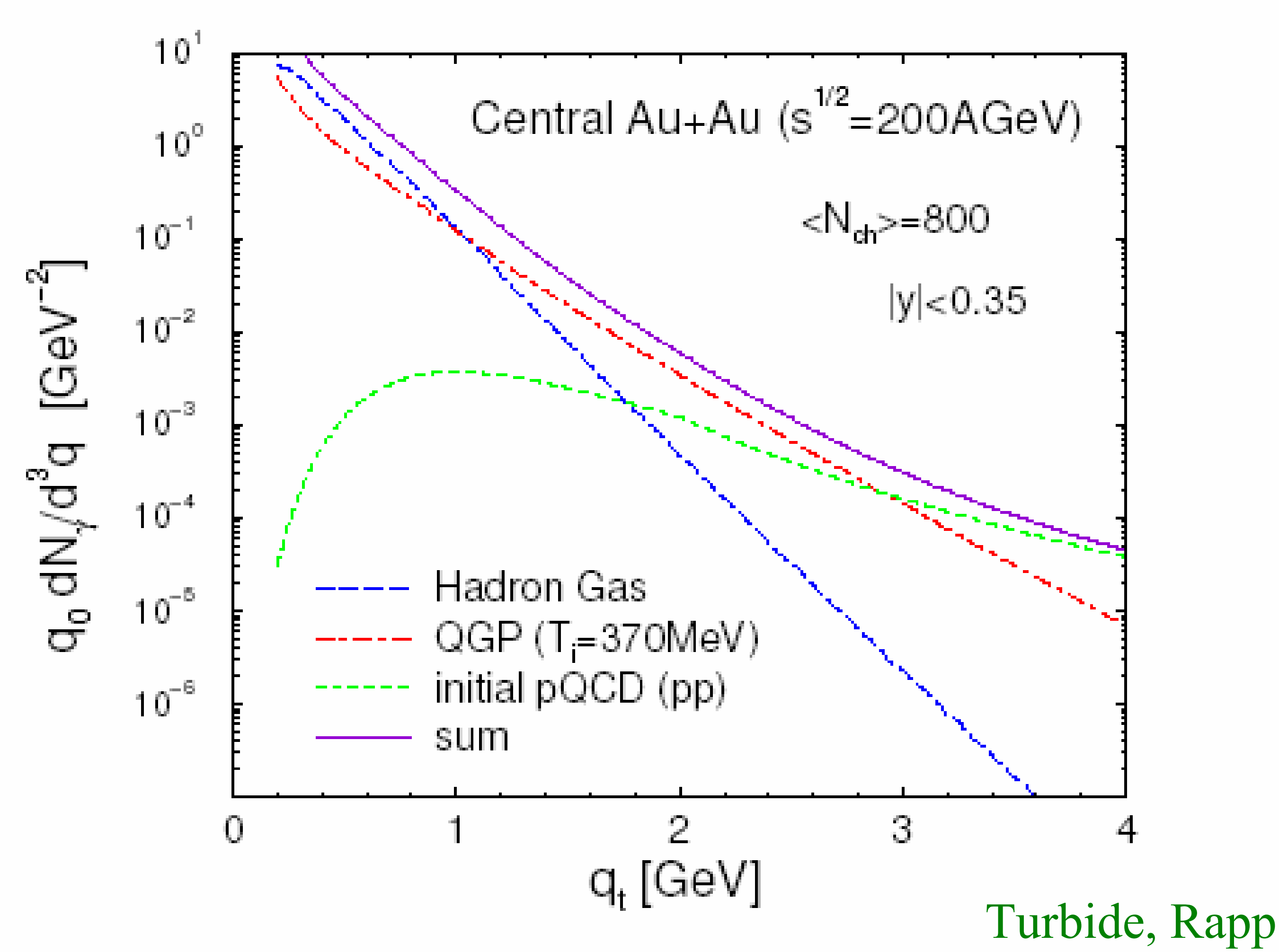
WA98: new analysis



Low p_T spectrum sensitive to the pion-pion cross section in the scalar-scalar channel: Chiral symmetry?

Turbide, Rapp & Gale, in preparation

@ RHIC



Turbide, Rapp & Gale PRC (2004)

Exotica? (squeezing dileptons out of broken symmetries, part I)

- Medium-induced symmetry breaking:
  - Lorentz symmetry → scalar-vector mixing

$$\rho - a_0 \,,\, \sigma - \varpi$$

(–Isospin mixing
–G-parity violation)

$\sigma - \varpi$:

S. A. Chin (1977); A. Weldon (1992); Saito, Tsushima, Thomas, Williams (1998); Wolf, Friman, Soyeur (1998)

Mixing Enables a Hybrid Correlator

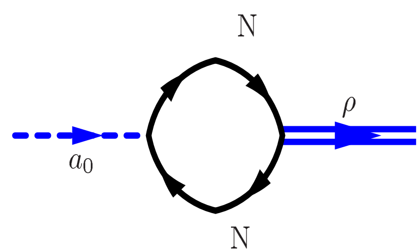
$$\Pi_\mu = \int d^4x\, e^{iq\cdot x} \langle g.s.| T\{ j_\mu^V(x) j^S(0)\} | g.s.\rangle$$

- Vanishes in vacuum
- Non-zero in matter

New channels:

$\pi + \eta \rightarrow a_0 \rightarrow \rho \rightarrow e^+e^-$

$(\pi + \pi \rightarrow \sigma \rightarrow \omega \rightarrow e^+e^-)$



$a_0(980)$

$I^G(J^{PC}): 1^-(0^{++})$

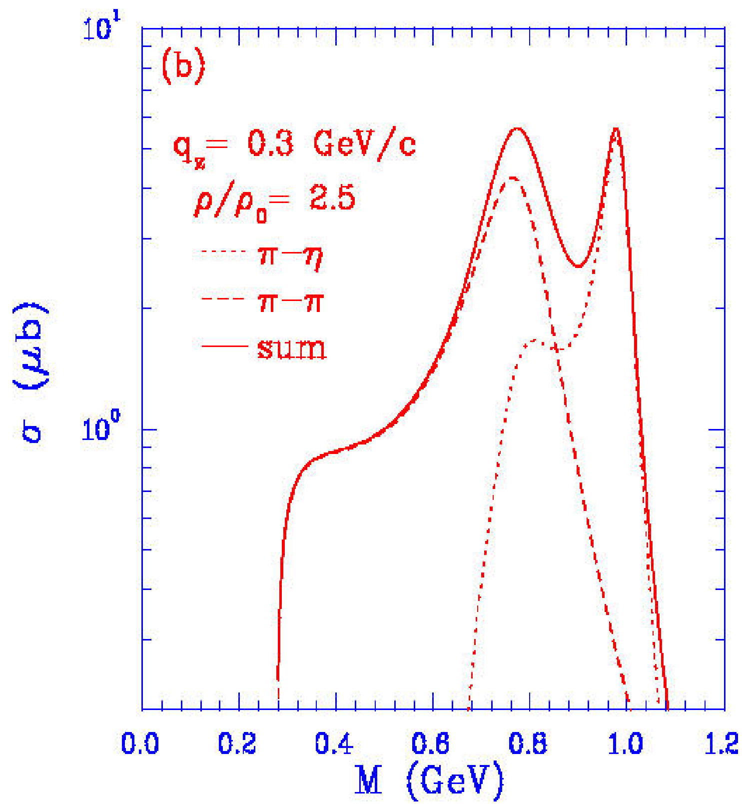
$\rho - a_0$ *Polarization*

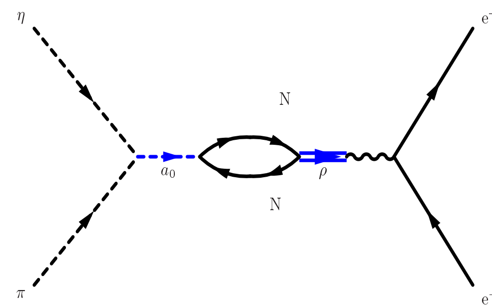
$$\Pi_\mu(q_0,\vec{q}) = \frac{g_\rho g_{a_0}}{\pi^3} 2q^2 (2m_n^* - \frac{\kappa q^2}{2m_n}) \int \frac{d^3k}{E^*(k)} \frac{k_\mu - \frac{q_\mu}{q^2}(k\cdot q)}{q^4 - 4(k\cdot q)^2}$$

- Axis: $q=(q_0,0,0,q_z)$ $\Pi_1 = \Pi_2 = 0$
- Current conservation: $q^\mu \Pi_\mu = 0$
- One indep. Component Π_0
- Static limit $\lim_{\vec{q}\to 0} \Pi_0 = 0$
- Recall: $\Pi_L(q_0,0) = \Pi_T(q_0,0)$

A New Resonant Structure

$$\pi\eta \rightarrow a_0 \rightarrow NN \rightarrow \rho \rightarrow e^+e^-$$

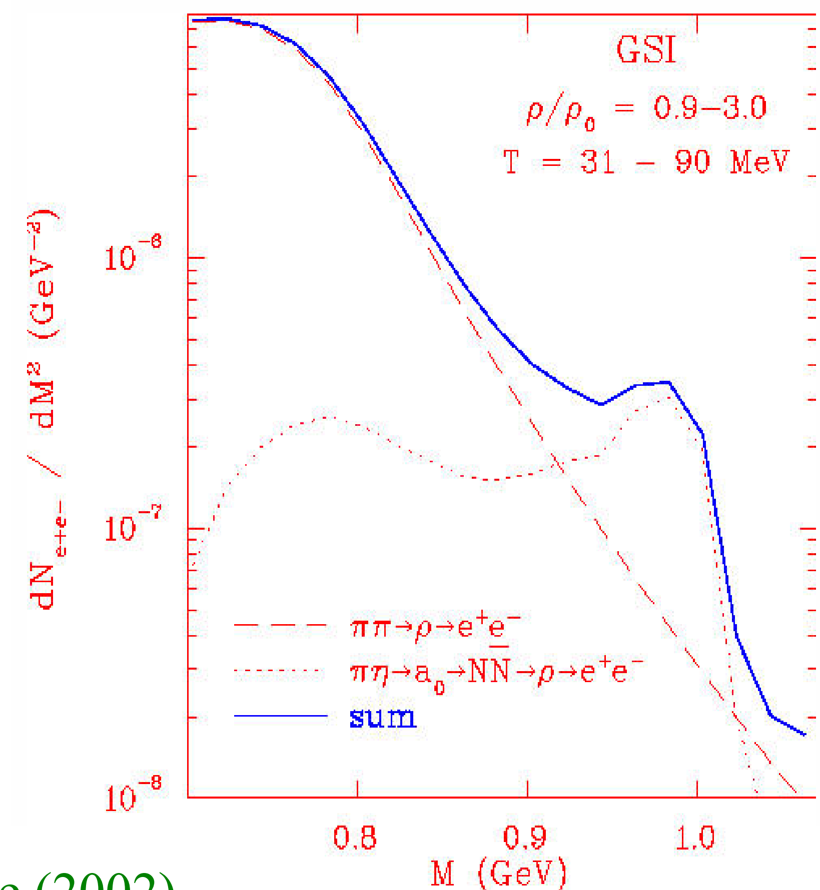




The coupling to the a_0 generates a peak that is completely absent in the vacuum dilepton spectrum: a genuine in-medium signature

Is This Observable?

At the GSI, HADES has the required resolution, and the energy is appropriate to maximize the effect



Teodorescu, Dutt-Mazumder, Gale (2002)

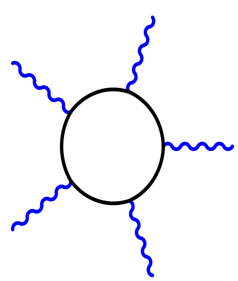
Squeezing dileptons out of broken symmetries, part II

- Furry's theorem at finite T:

$$\langle n | A_{\mu_1} A_{\mu_2} \ldots A_{\mu_{2n+1}} | n \rangle e^{-\beta E_n} =$$

$$-\langle -n | A_{\mu_1} A_{\mu_2} \ldots A_{\mu_{2n+1}} | -n \rangle e^{-\beta E_n}$$

Sum over all states contains: $\langle -n | A_{\mu_1} A_{\mu_2} \ldots A_{\mu_{2n+1}} | -n \rangle e^{-\beta E_n}$



$\equiv 0$

Furry

Squeezing dileptons out of broken symmetries, part II

- Furry's theorem at finite T and charge density:

$$\langle n | A_{\mu_1} A_{\mu_2} \ldots A_{\mu_{2n+1}} | n \rangle e^{-\beta(E_n - \mu Q_n)} = -\langle -n | A_{\mu_1} A_{\mu_2} \ldots A_{\mu_{2n+1}} | -n \rangle e^{-\beta(E_n - \mu Q_n)}$$

- The mirror term this time is

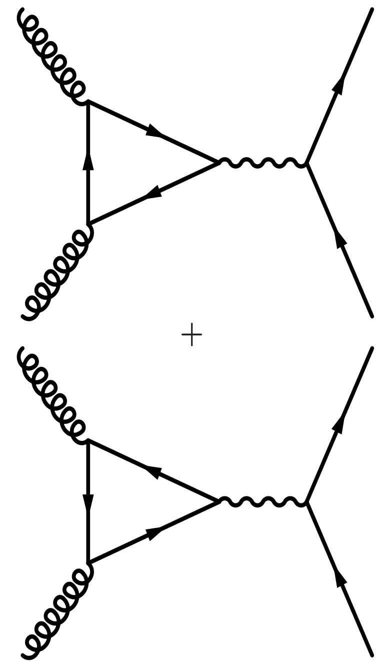
$$\langle -n | A_{\mu_1} A_{\mu_2} \ldots A_{\mu_{2n+1}} | -n \rangle e^{-\beta(E_n + \mu Q_n)}$$

So What?

- Then: $gg \to e^+e^-$

$$T^{\mu\rho\nu} = \frac{1}{\beta}\sum_{n=-\infty}^{\infty}\int_{-\infty}^{\infty} eg^2 \mathrm{Tr}[t^a t^b]\frac{d^3q}{(2\pi)^3}\mathrm{Tr}[\gamma^\mu\gamma^\beta\gamma^\rho\gamma^\delta\gamma^\nu\gamma^\alpha]$$

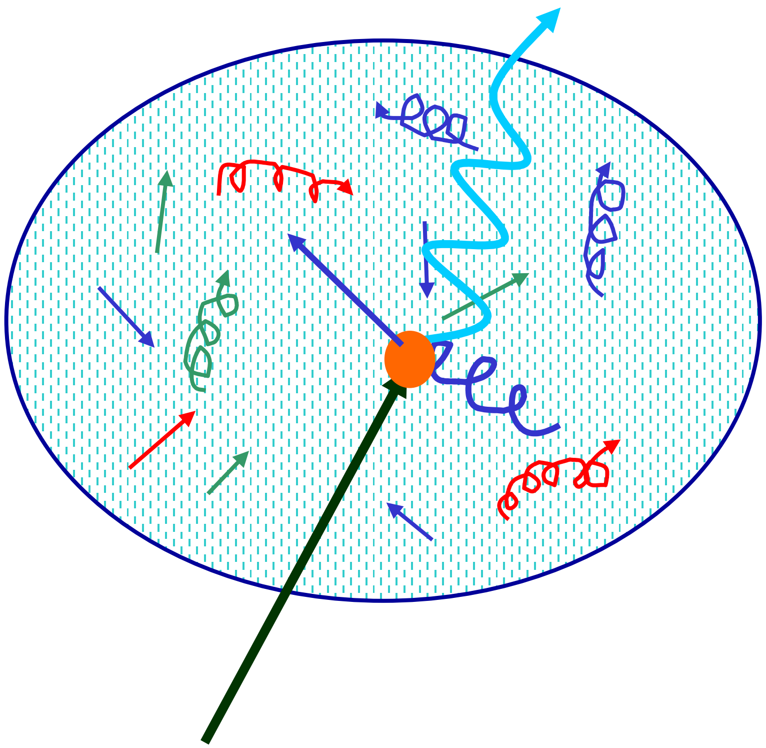
$$\times\frac{(q+p-k)_\alpha q_\beta (q+p)_\delta}{(q+p-k)^2 q^2 (q+p)^2}$$

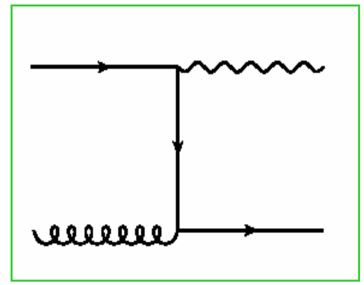


$\therefore$ Electromagnetic signature of early gluon densities!

Majumder, Bourque, Gale PRC (2004), and
In progress

Quenching = Jet-Plasma interaction





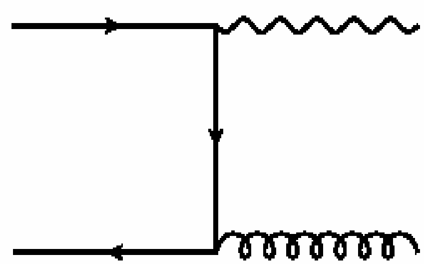
$$qg \to q\gamma$$

The plasma mediates
a jet-photon
conversion

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

Jet-plasma interactions: EM signatures

- Real photons from quark-antiquark annihilation



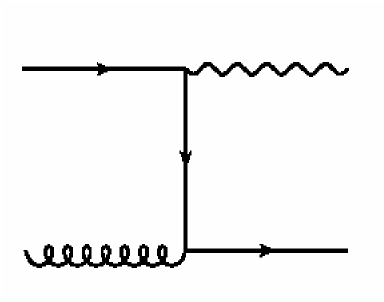
$$\frac{d\sigma}{dt} = \frac{8\pi\alpha\alpha_s e_q^2}{9s^2}\left(\frac{u}{t} + \frac{t}{u}\right)$$

- Small t and u dominate the phase space, leading to $p_\gamma \approx p_q$ and $p_\gamma \approx p_{\bar{q}}$

$$E_\gamma \frac{d\sigma}{d^3 p_\gamma} \approx \sigma(s)\frac{1}{2}\left[\delta^3(p_\gamma - p_q) + \delta^3(p_\gamma - p_{\bar{q}})\right]$$

The process can be visualized as q $(\bar{q}) \rightarrow \gamma$

Photons from QCD Compton



$$\frac{d\sigma}{dt} = -\frac{\pi\alpha\alpha_s e_q^2}{3s^2}\left(\frac{u}{s}+\frac{s}{u}\right)$$

$$E_\gamma \frac{d\sigma}{d^3p_\gamma} \approx \sigma(s)\delta^3(p_\gamma - p_q)$$

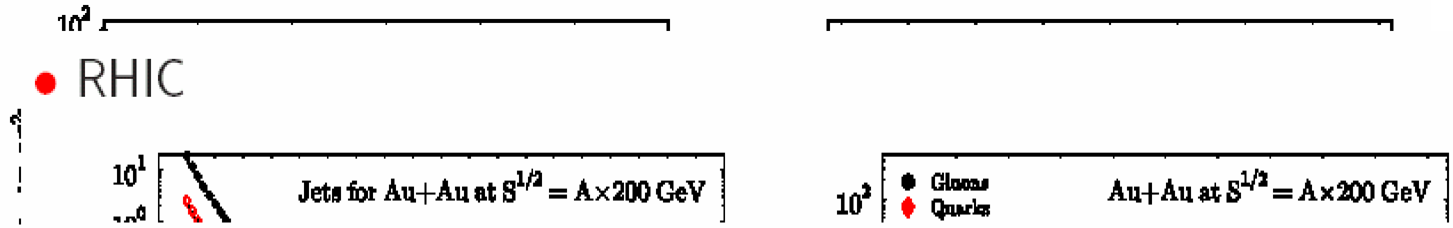
Photon yield from the jet-plasma interaction:

$$E_\gamma \frac{dN^{(A)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6}\sum_{q=1}^{N_f} f_q(p_\gamma) \times \int d^3p\, f_{\bar{q}}(p)[1+f_g(p)]\sigma^{(A)}(s)\frac{\sqrt{s(s-4m^2)}}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

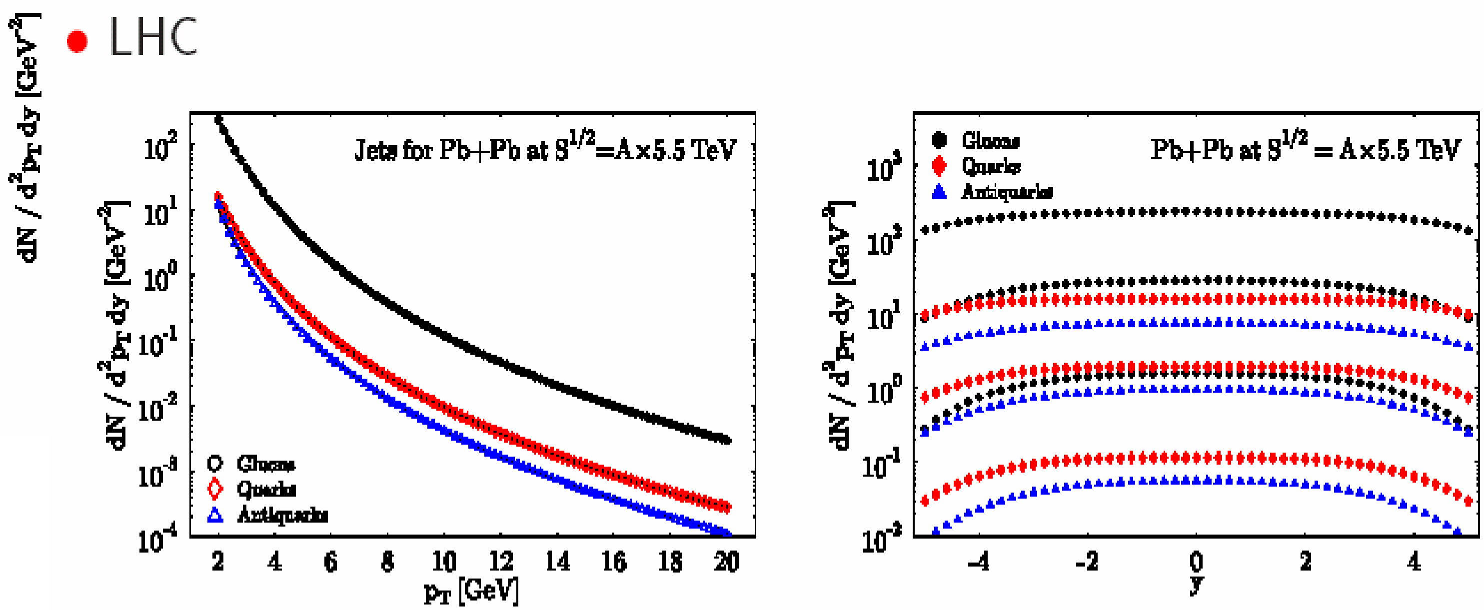
$$E_\gamma \frac{dN^{(C)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6}\sum_{q=1}^{N_f} f_q(p_\gamma) \times \int d^3p\, f_g(p)[1-f_q(p)]\sigma^{(C)}(s)\frac{s-m^2}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

Jet characteristics are calculable

- SPS
- RHIC



- LHC

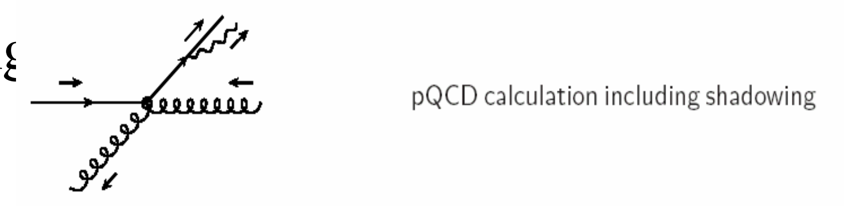


LO calculations with $K = 2.5$ including nuclear shadowing.

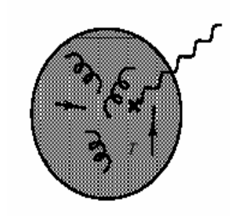
Photon sources

- Hard direct photons

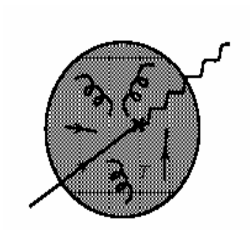
- EM bremsstrahlung



- Thermal photons from hot medium



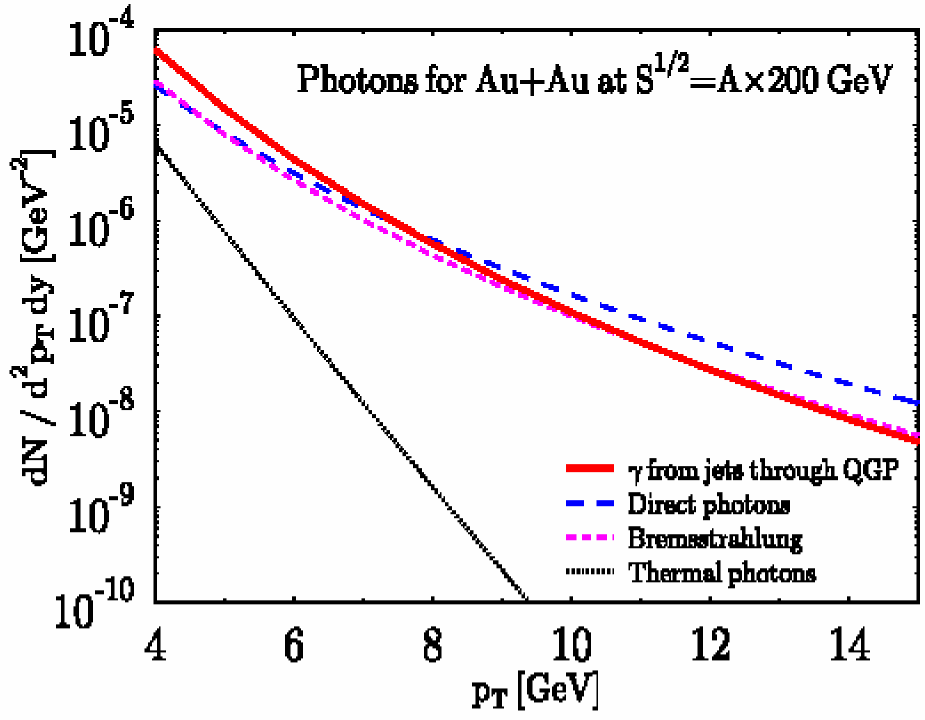
- Jet-photon conversion



Charles Gale
McGill

Results (photons)

- RHIC



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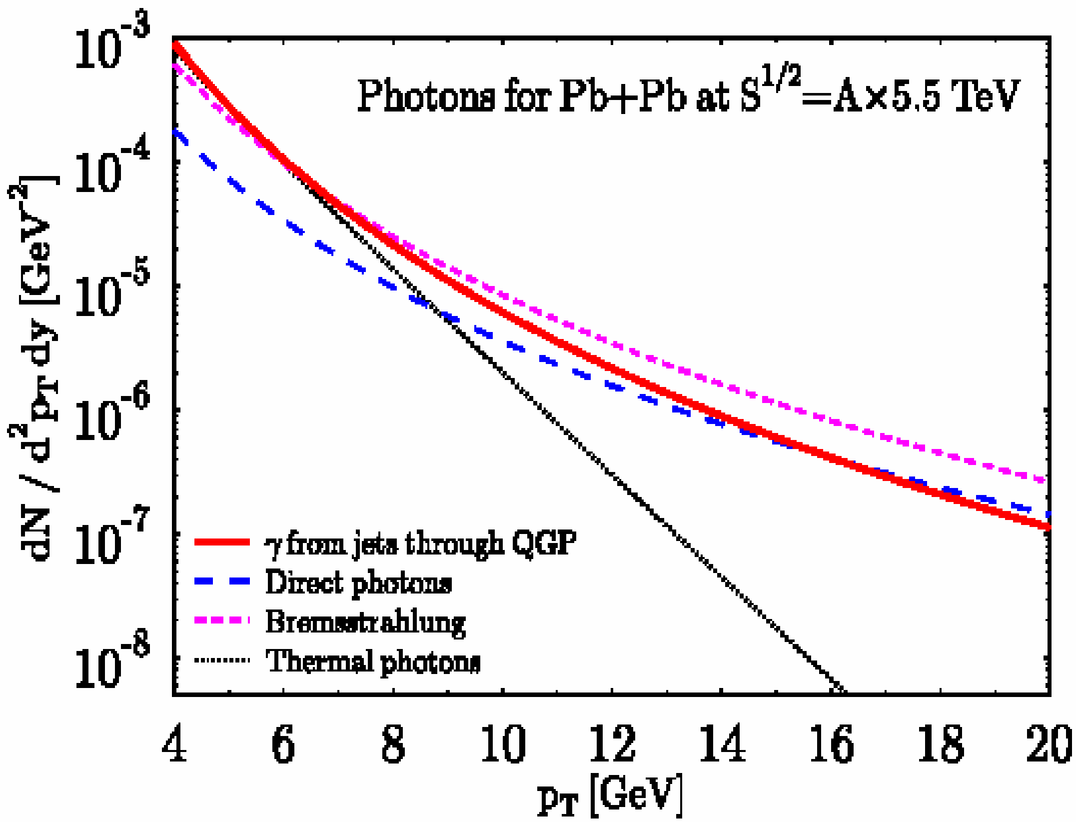
Results (photons)

- LHC

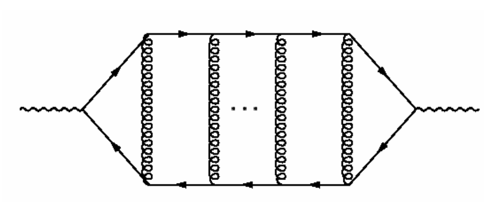


Fries, Mueller & Srivastava, PRL **90**, 132301 (2003)

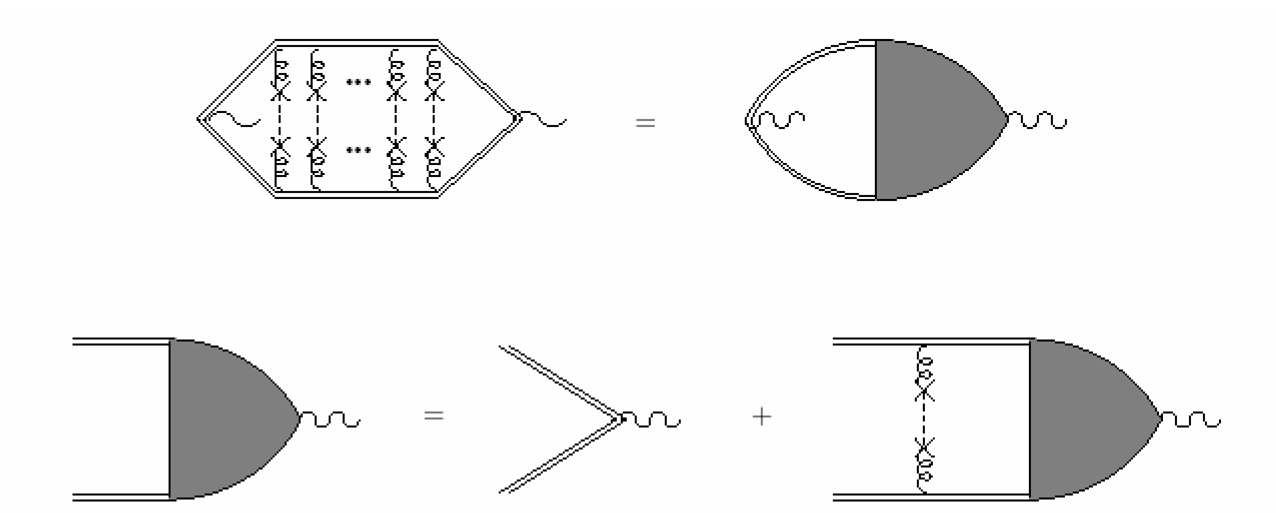
Energy loss in the jet-photon conversion? Jet bremsstrahlung?

Use the approach of Arnold, Moore, and Yaffe

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

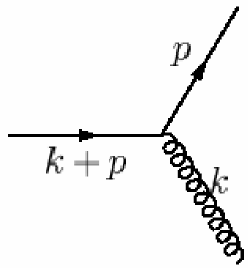


- Incorporates LPM
- Complete leading order in α_s
- Inclusive treatment of collinear enhancement, photon and gluon emission



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

E loss/gain: some systematics



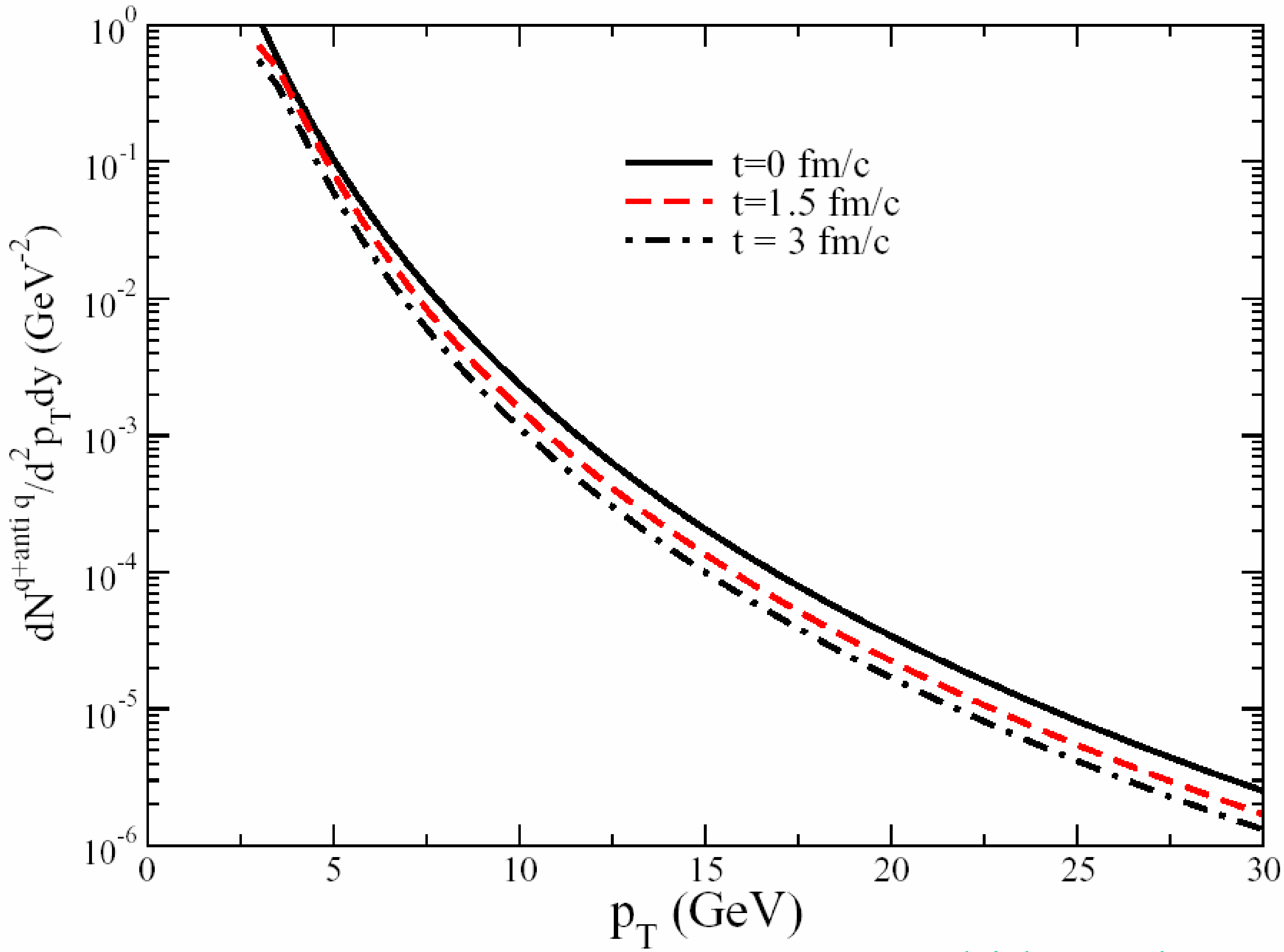
$$= \Gamma^q_{qg}(k+p,k)$$

- Includes E gain
- Evolves the whole distribution function

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

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

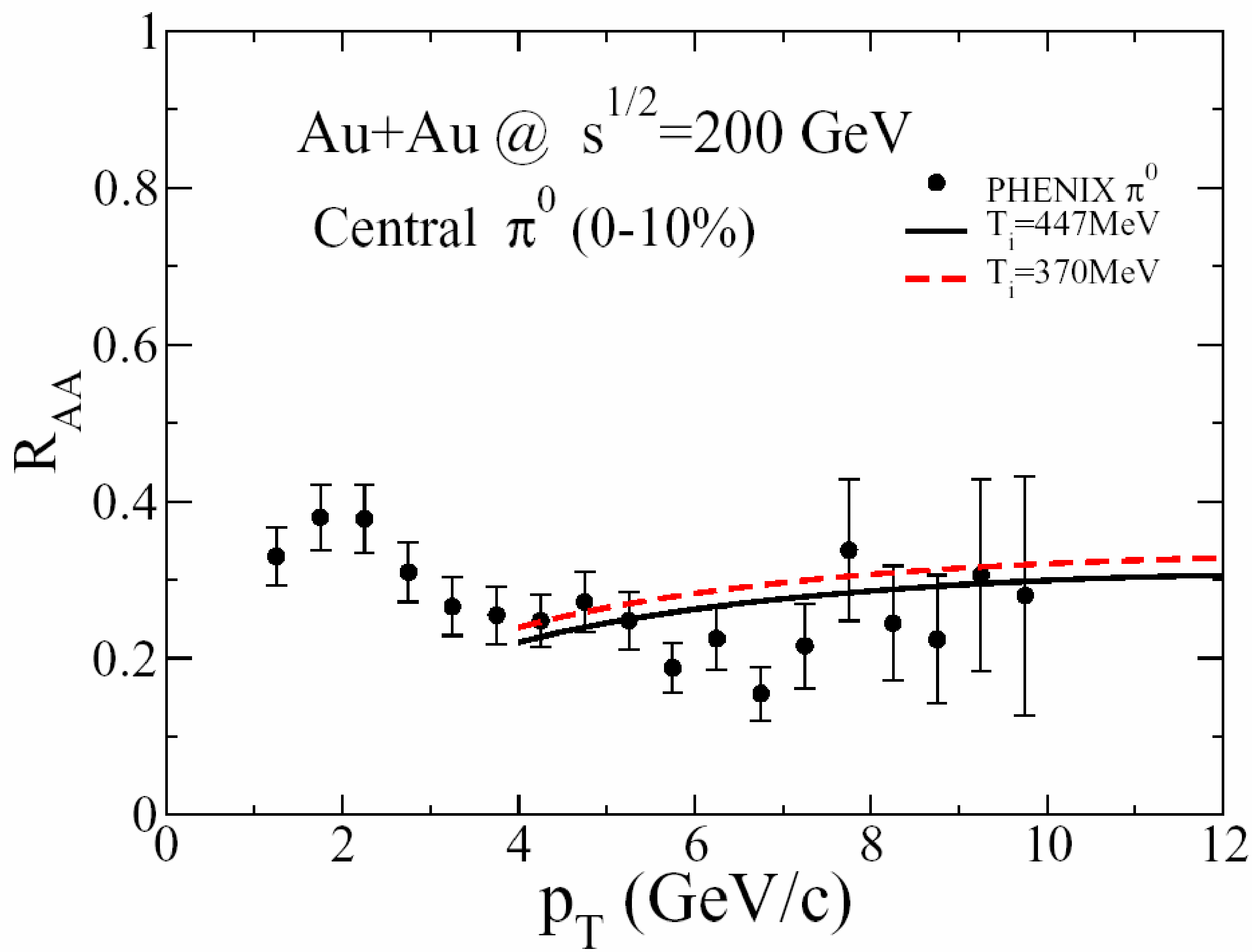
Time-evolution of quark distribution



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

Turbide, Gale, Jeon, and Moore (2004)

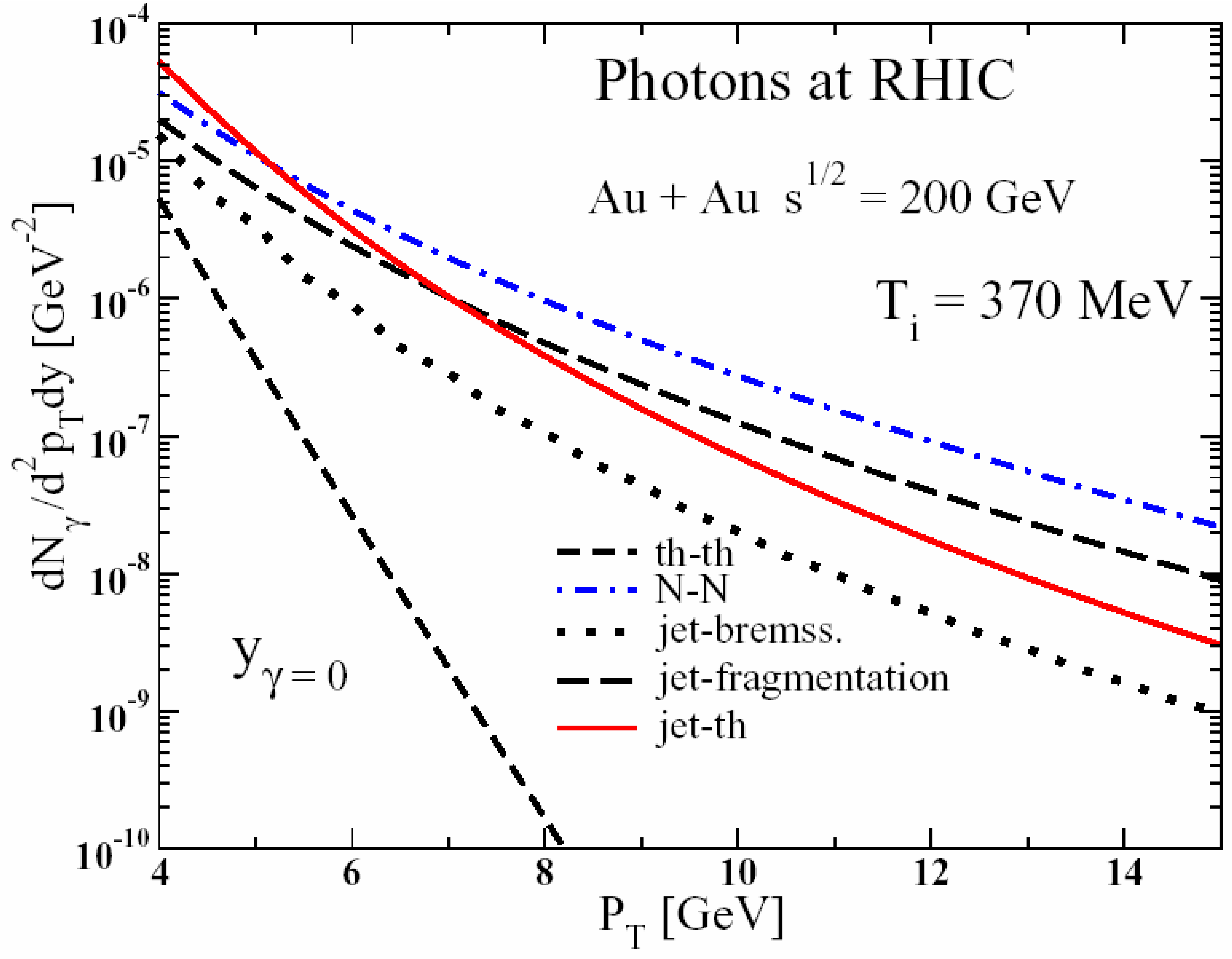
Energy loss: hadrons



Energy loss systematics not in conflict with experimental data

Turbide, Gale, Jeon, and Moore (2004)

RHIC jet-plasma photons



With E loss

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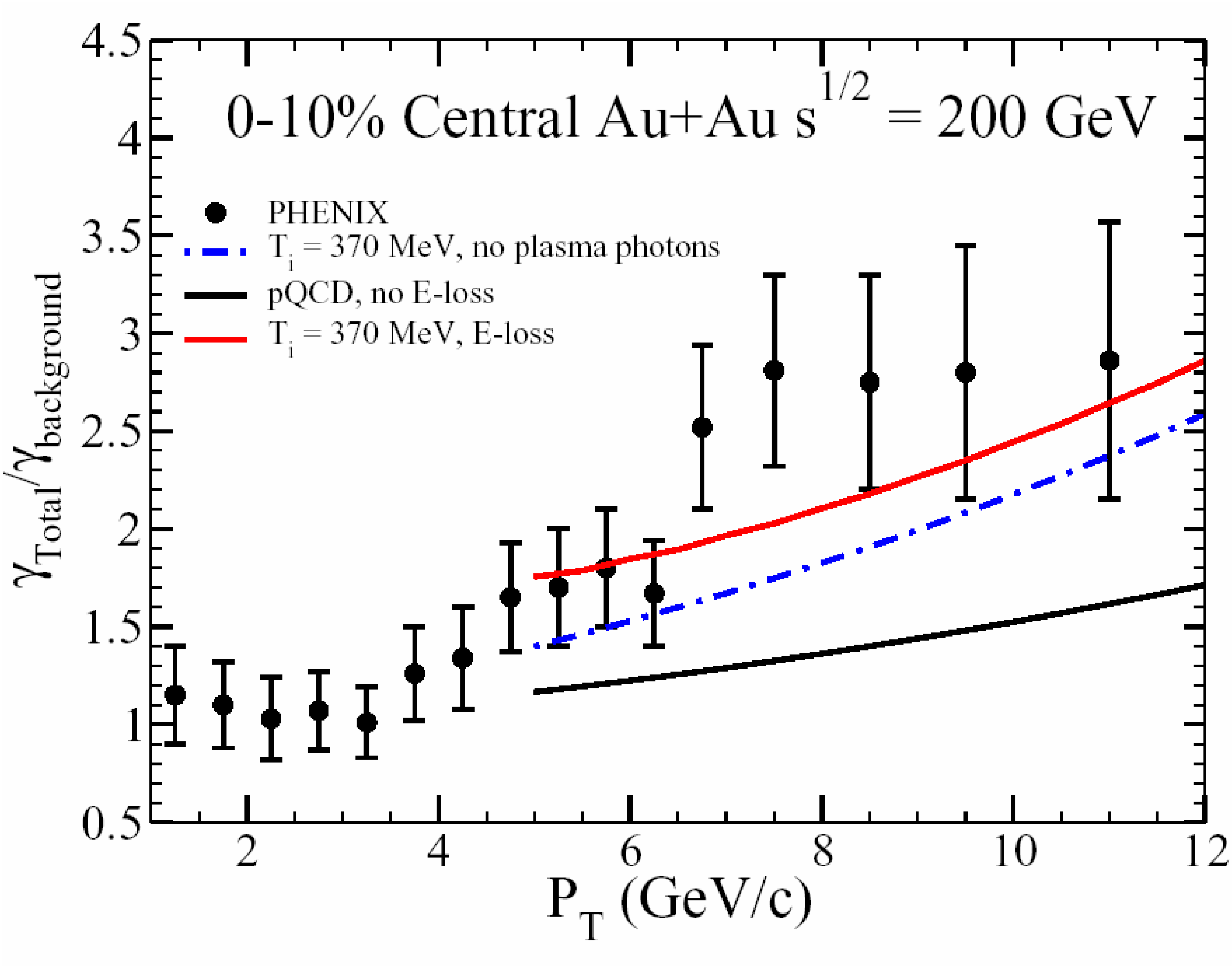
E loss: photons



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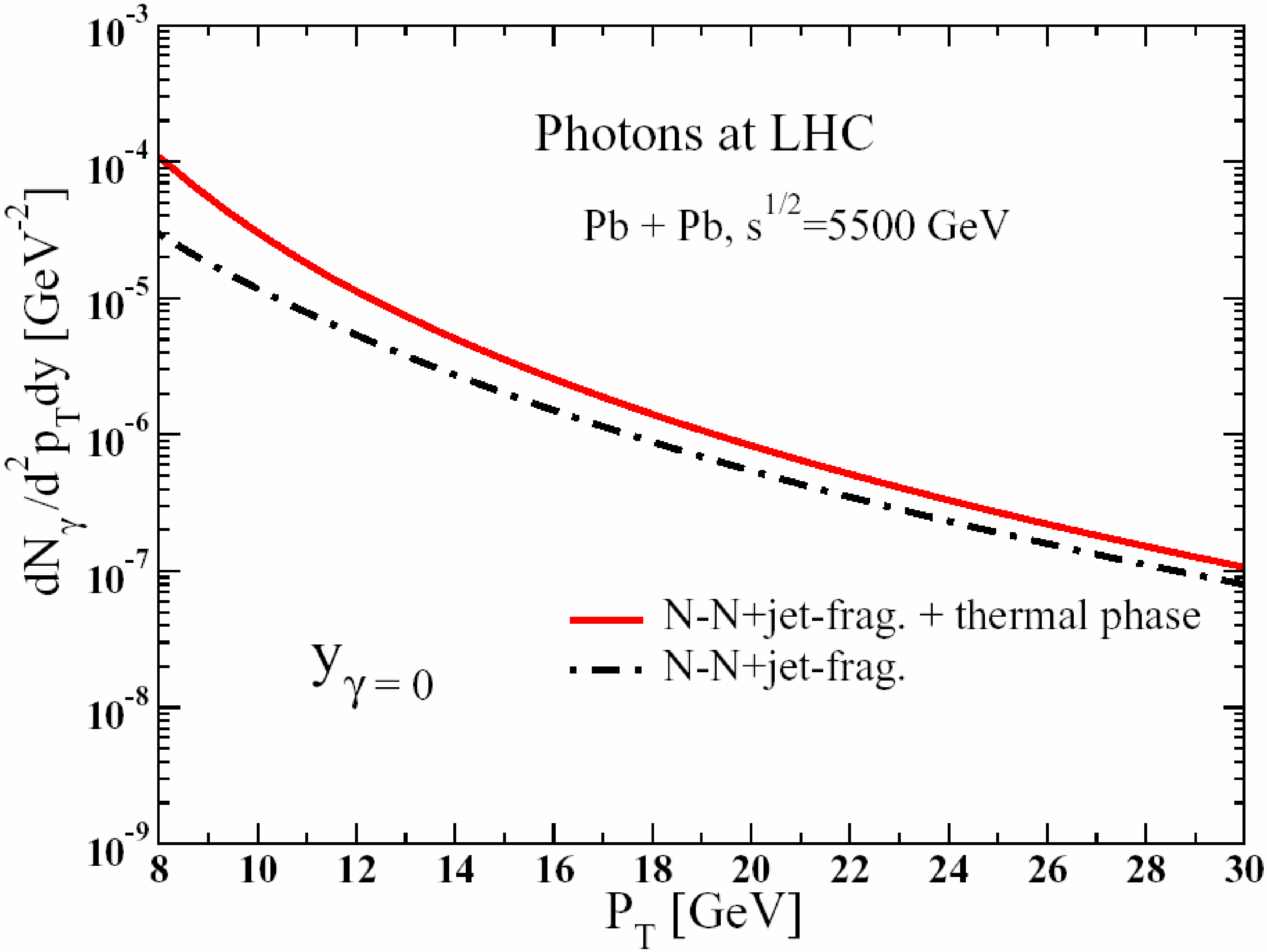

Photons at LHC
Pb + Pb, $s^{1/2}$=5500 GeV
N-N+jet-frag. + thermal phase
N-N+jet-frag.
$y_{\gamma=0}$
$dN_\gamma/d^2p_T dy$ [GeV^{-2}]
P_T [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
8
10
12
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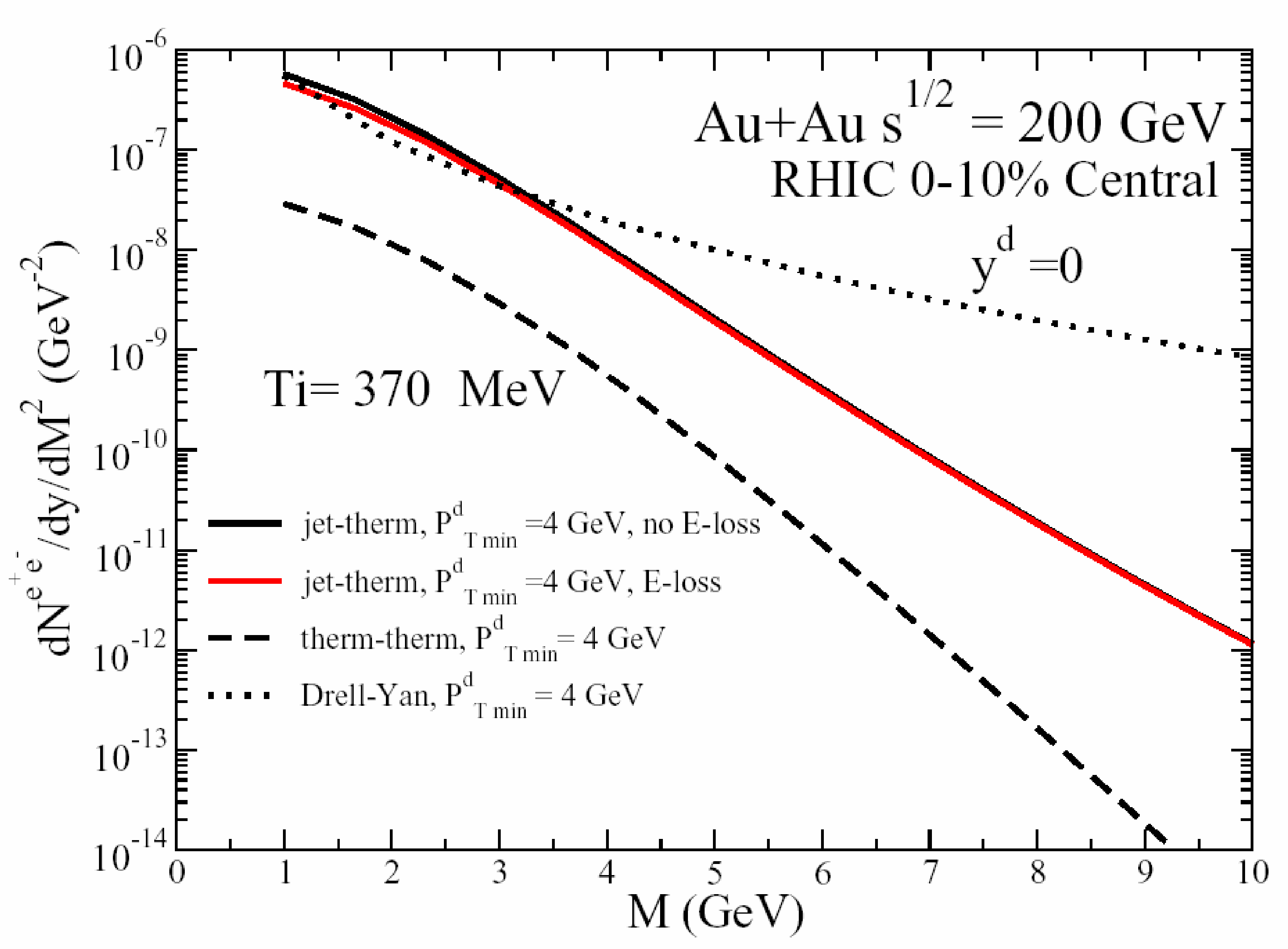

Fries, Srivastava, Gale (2004)

Jet-plasma interactions: measurable EM signatures!

- RHIC:
  - Jet-plasma interaction is the dominant source of photons up to $p_T \sim 6$ GeV.
  - Conclusions unchanged by energy-loss considerations
  - Dilepton signal competes with Drell-Yan (NLO)
- LHC:
  - Jet-plasma photon signal is still important
  - Large mass lepton pairs dominate over Drell-Yan emission.

Towards a consistent treatment of jets & EM radiation

Summary & Conclusion

- Low and intermediate mass dileptons: theory is in good shape: NA60
- Soft real photons: a (first) window to chiral symmetry?
- There are measurable electromagnetic signatures of jet-plasma interaction: those constitute complementary observables that would signal the existence of conditions suitable for jet-quenching to take place.
- EM radiation and hard probes: the start of a beautiful friendship…

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY


Castello di Trento ("Trint", watercolour, painted by A.Durer on his way back from Venice (1495)

International workshop on electromagnetic probes of relativistic nuclear collisions

June 2-12, 2005

P. Braun-Munzinger, C. Gale, R. Rapp (coordinator)