Electromagnetic signature of jets

Quark Matter 2004

Oakland – January 11-17

Charles Gale
McGill

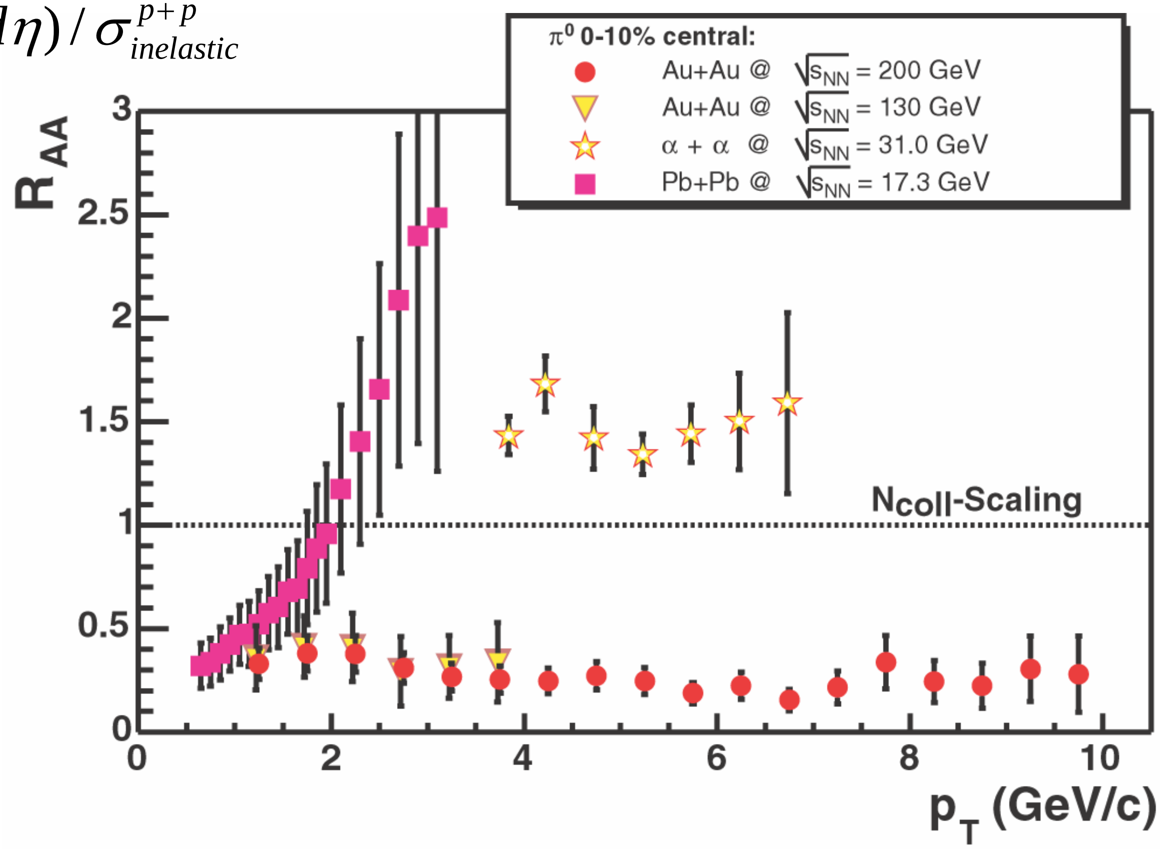
Outline

- Conditions for jet-quenching should lead to jet-plasma interaction as source of EM radiation.
- Real photon production: jet-photon conversion by the plasma.
- Lepton pairs: large invariant mass pairs produced by jet-plasma interaction.
- Simple estimates of source-strengths.
- Dilepton jet-tagging: a case study.

RHIC:Spectacular "jet-quenching"!

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

- This is a totally new phenomenon: all previous nucleus-nucleus measurements see enhancement, not suppression.
- Qualitatively new physics



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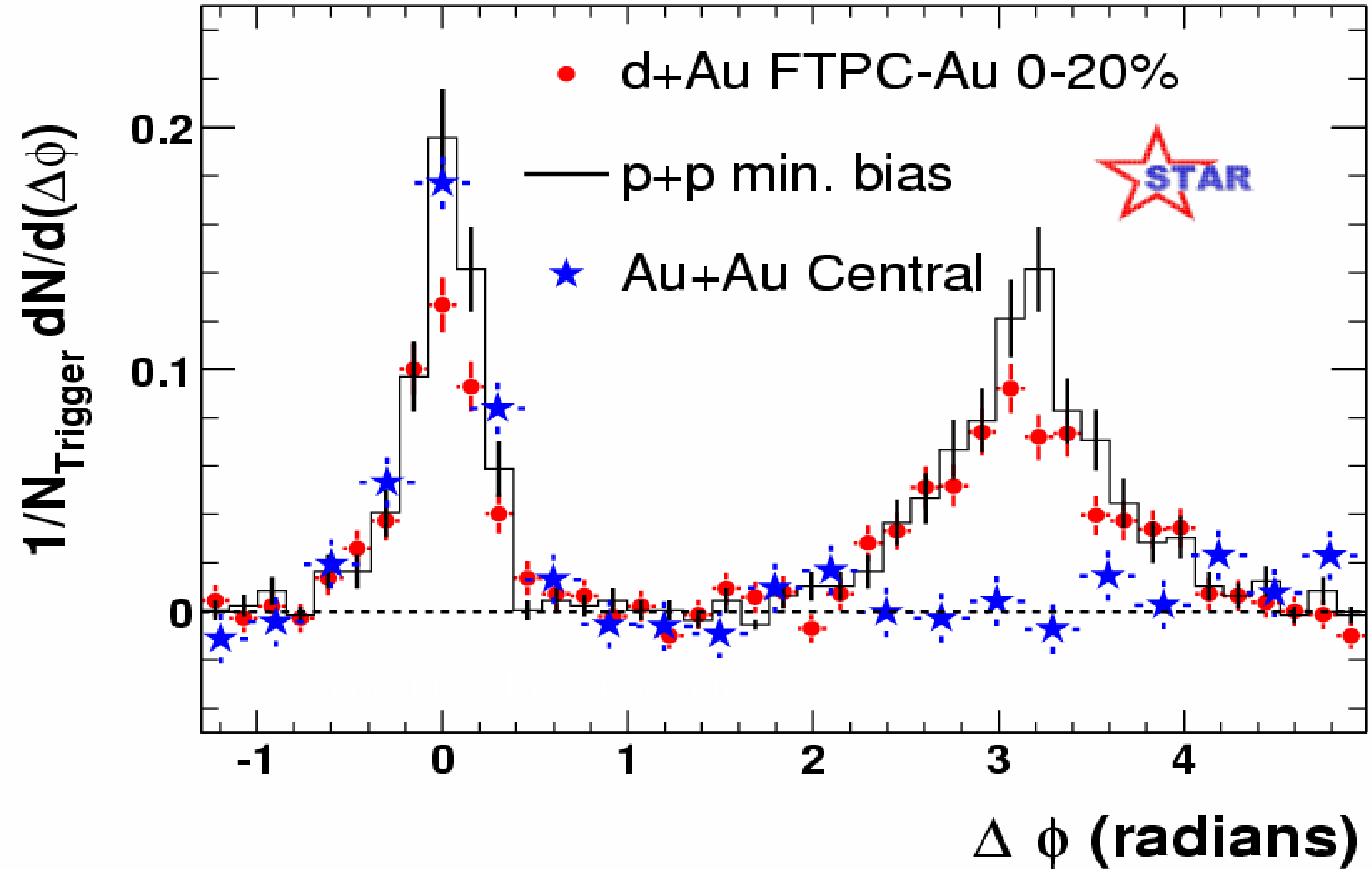
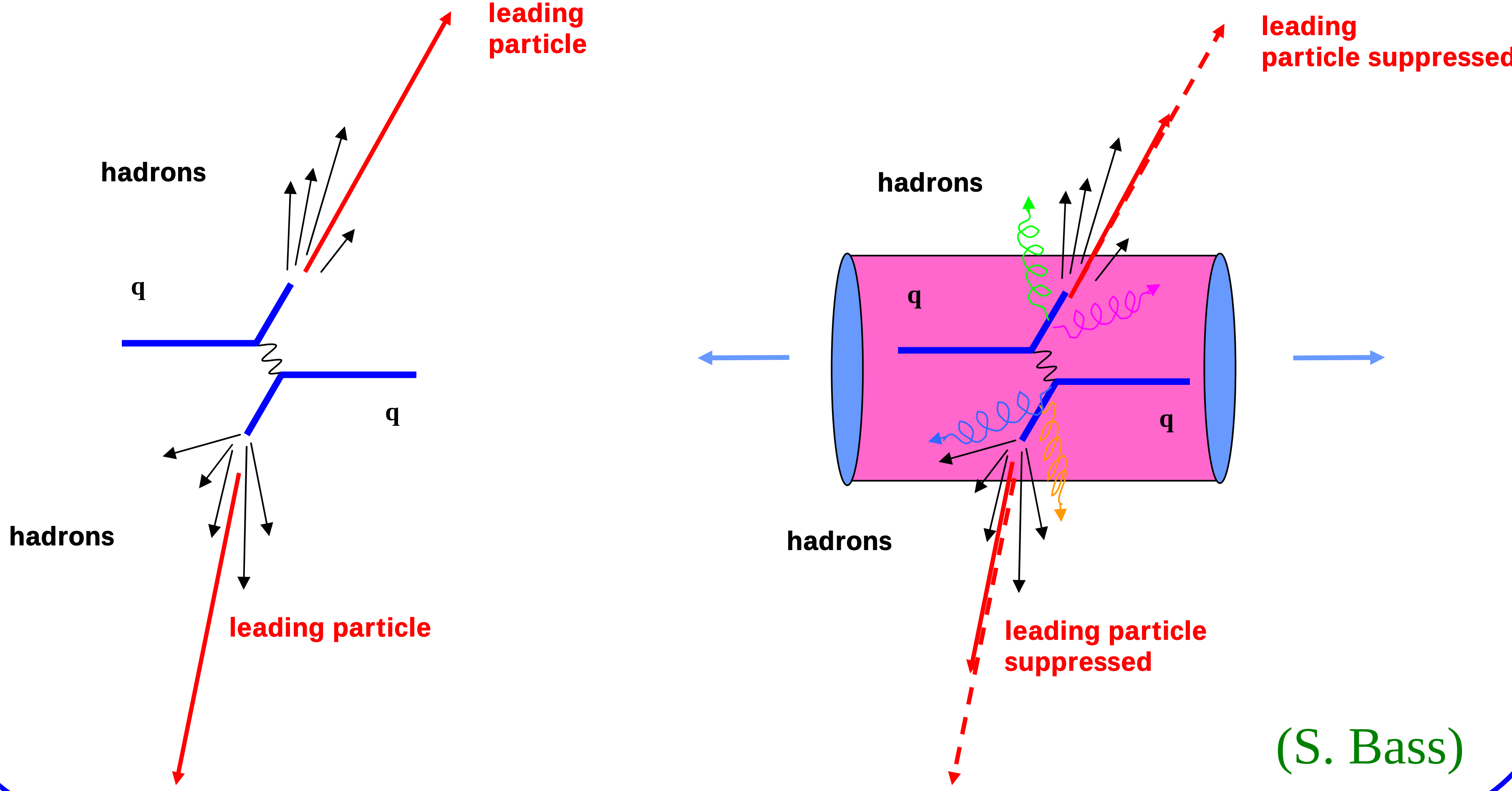


A related measurement (to R_{AA}): Azimuthal correlation

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

Jet-quenching



(S. Bass)

Any help from electromagnetic radiation?

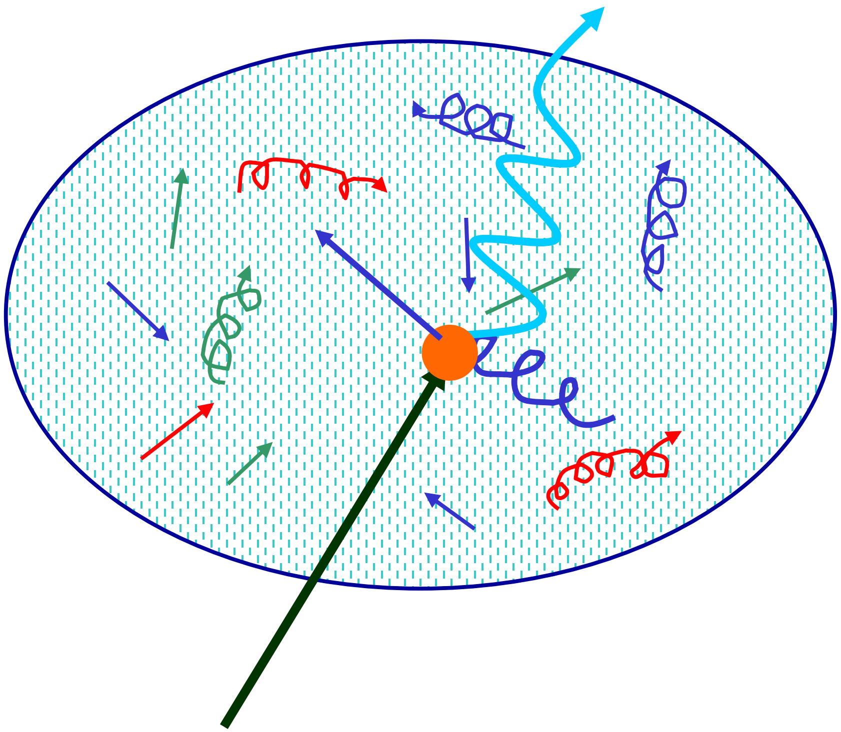
- Photons and dileptons are penetrating probes

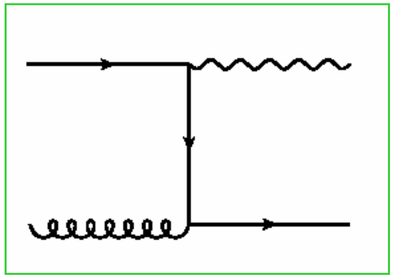
$$\alpha_s \approx 0.2$$

$$\alpha_{em} \approx 0.007$$

- New physics: collective, many-body effects
  - Quark-gluon plasma: “traditional” thermal radiation
  - In-medium modifications
    - Modified spectral densities
    - Chiral symmetry restoration
    - Mixing effects
    - Pion dispersion relation

Jet-Plasma interaction



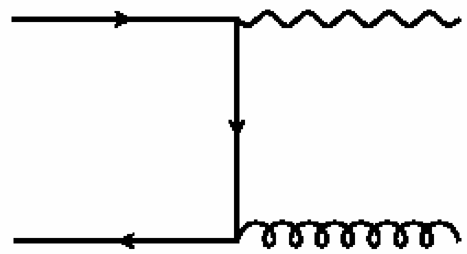


$qg \to q\gamma$

The plasma mediates a jet-photon conversion

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 $p_\gamma \approx p_{\bar{q}}$

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

The process can be visualized at q ($\bar{\text{q}}$) $\longrightarrow \gamma$

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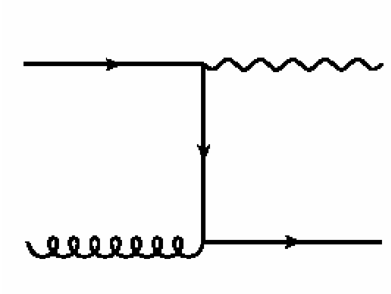
Photons from QCD Compton



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

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

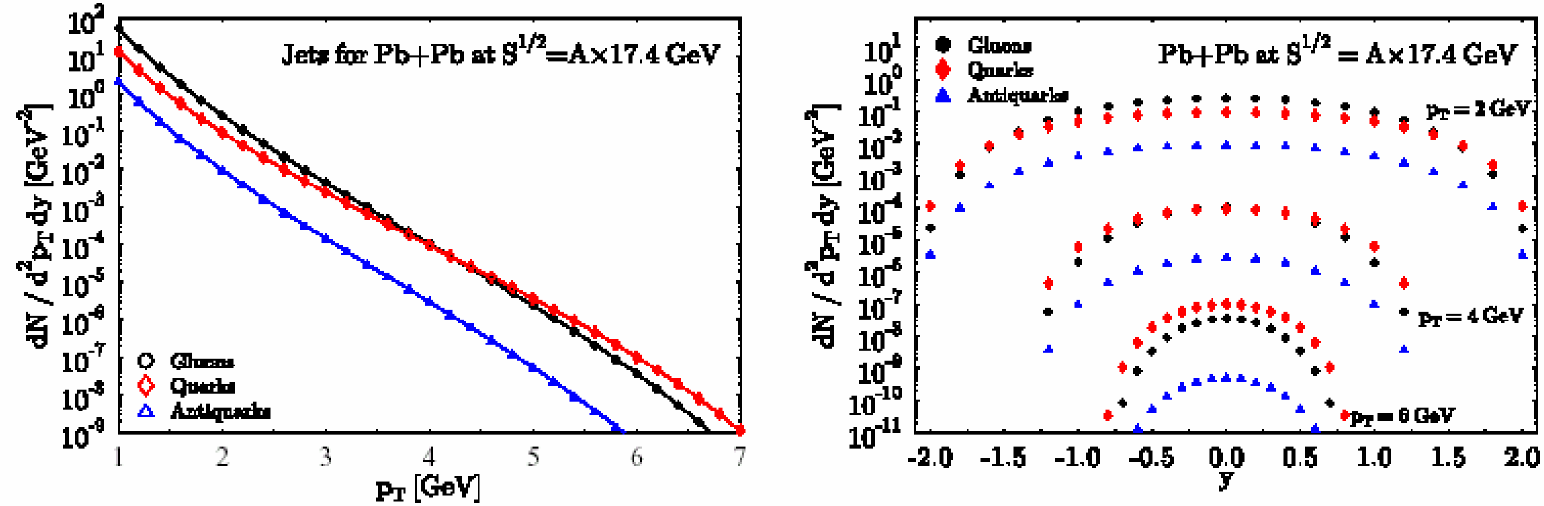
Photon yield from the jet-plasma interaction:

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

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

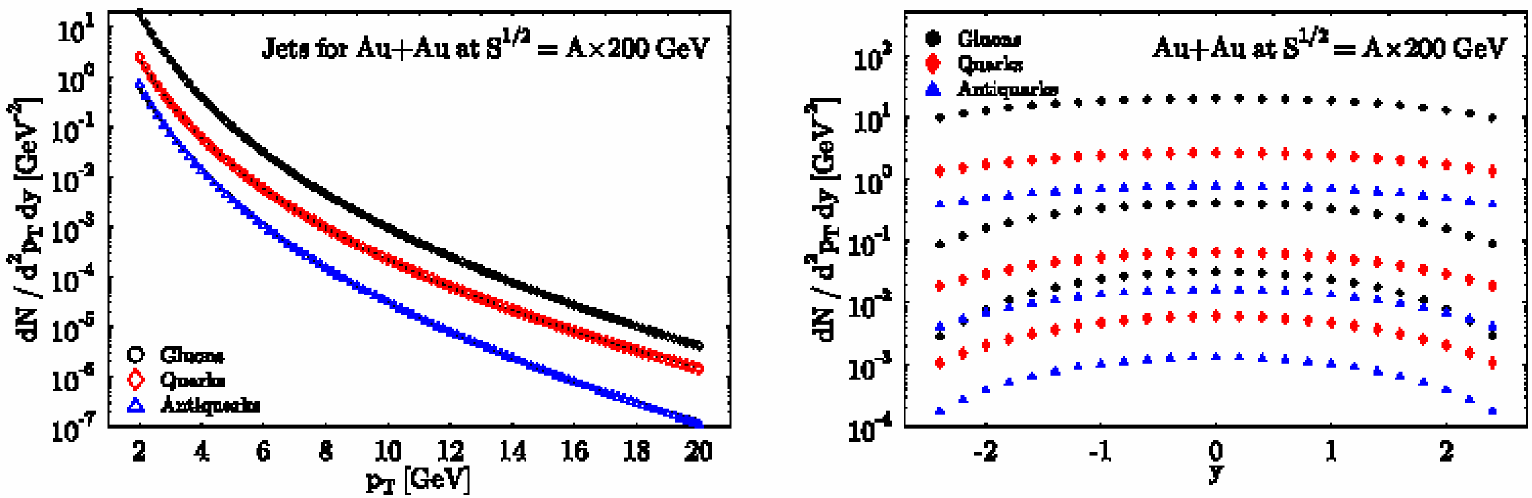
Jet characteristics are calculable

- SPS



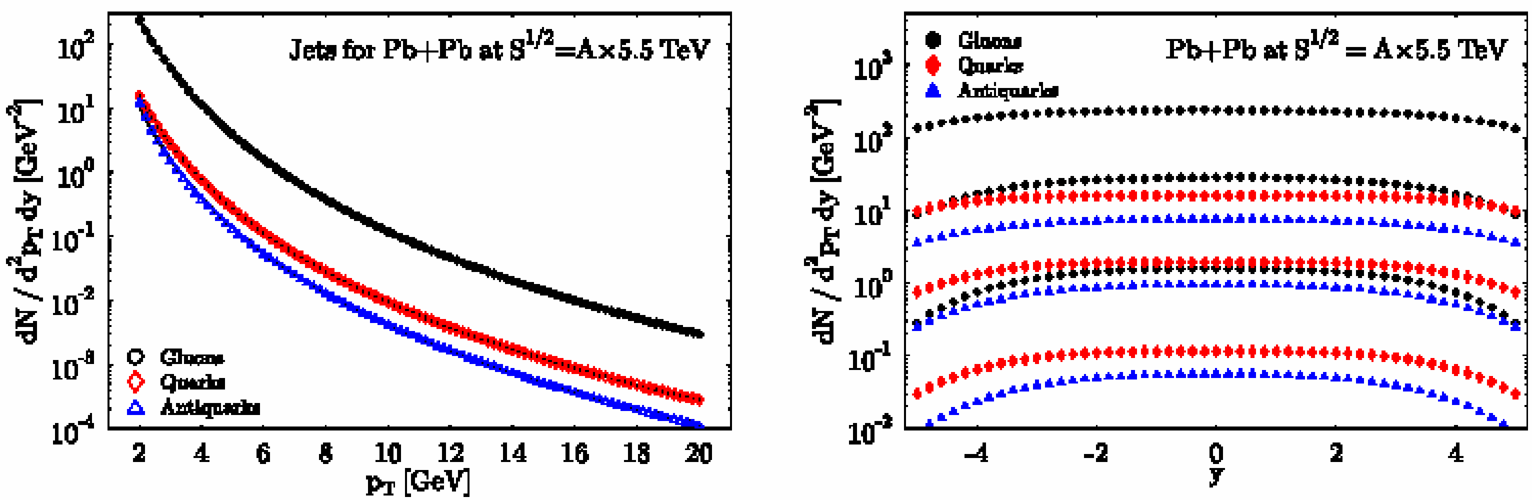
Jet characteristics are calculable

- SPS
- RHIC



Jet characteristics are calculable

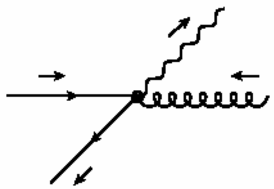
- SPS
- RHIC
- LHC



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

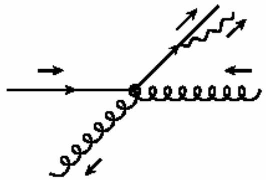
Photon sources

- Hard direct photons



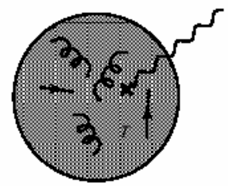
pQCD calculation including shadowing

- EM bremsstrahlung

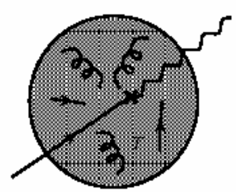


pQCD calculation including shadowing

- Thermal photons from hot medium

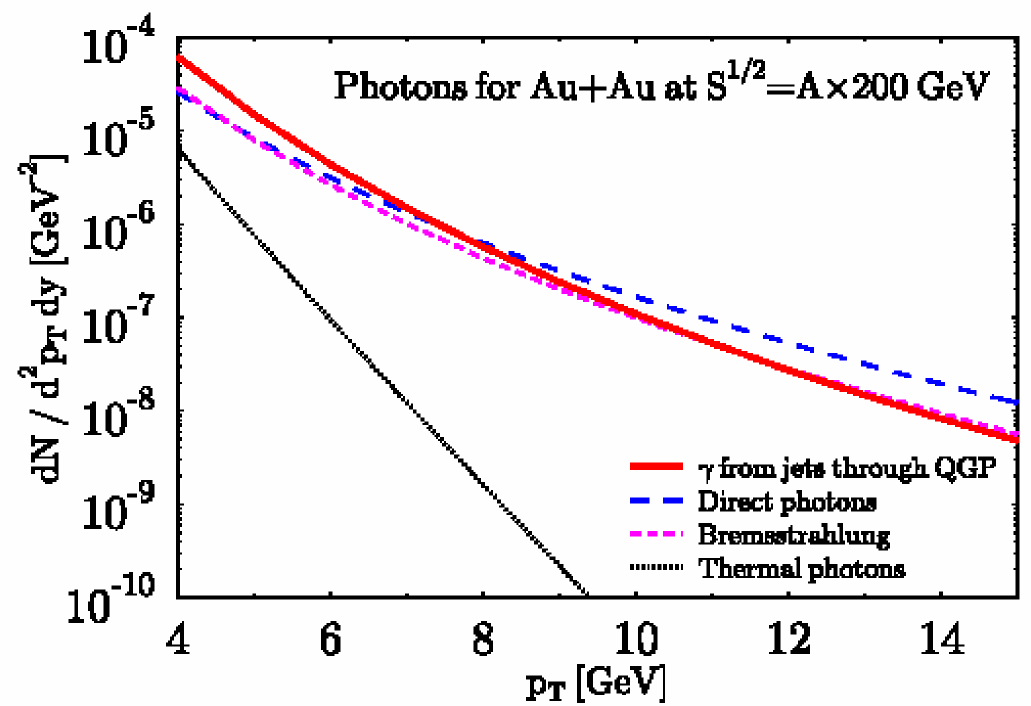


- Jet-photon conversion



Results (photons)

- RHIC



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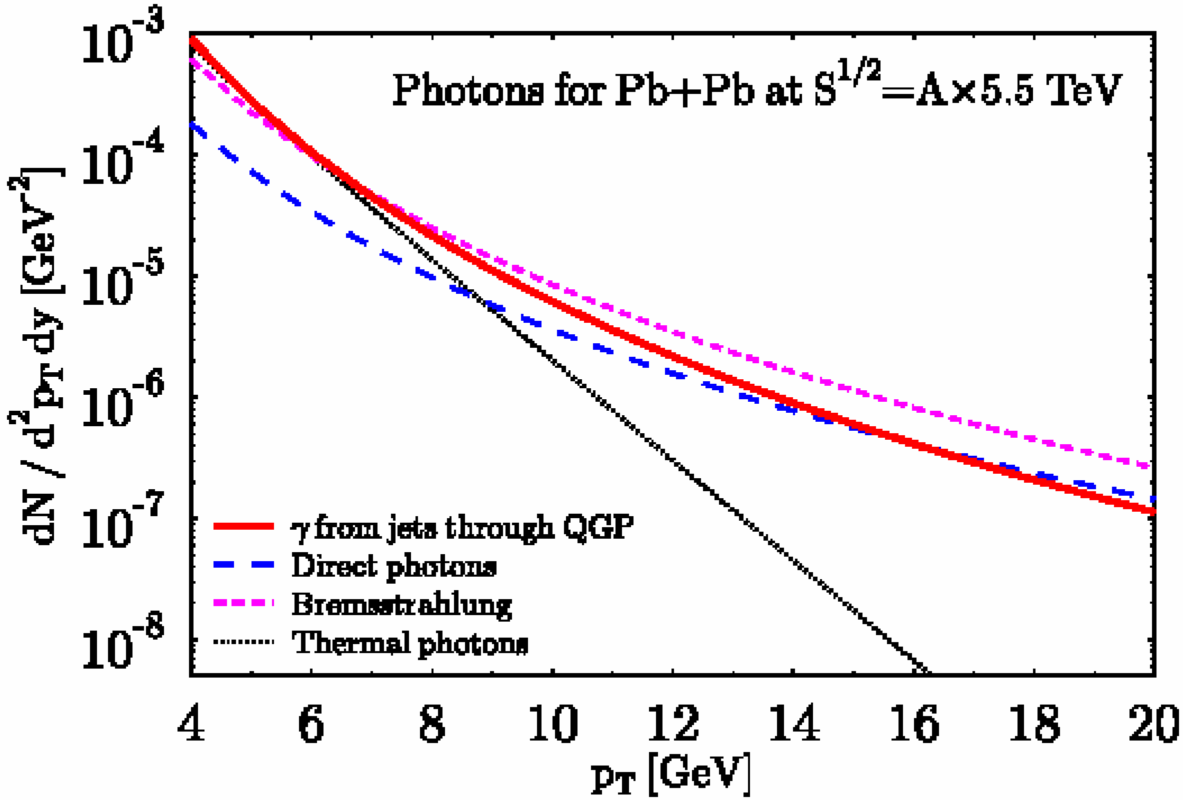
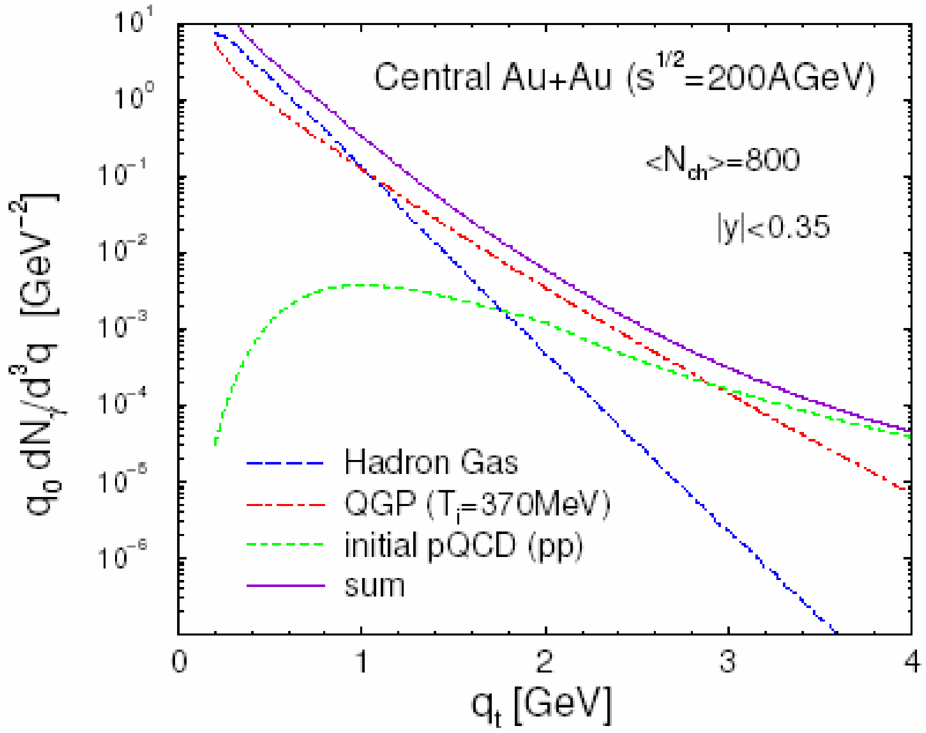
Results (photons)

- LHC



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

How does this compare with “traditional” predictions?

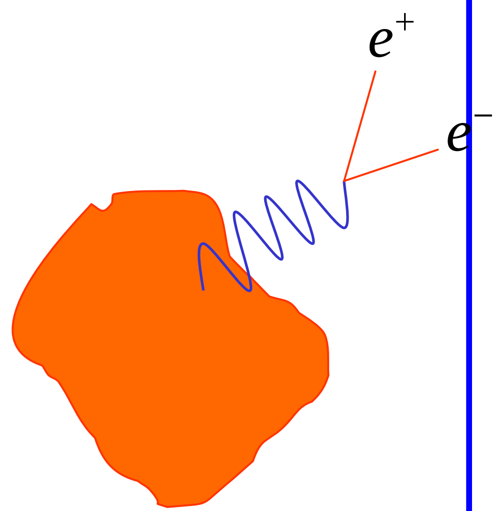


- No contradiction: complementary (also true for dileptons)
- Still a small window for thermal plasma radiation
- Initial pQCD component will be measured in pp reactions *at the same energies!*
- Similar conclusions for the LHC

Turbide, Gale & Rapp, PRC (2004)

Dilepton Rates & In-medium Information

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



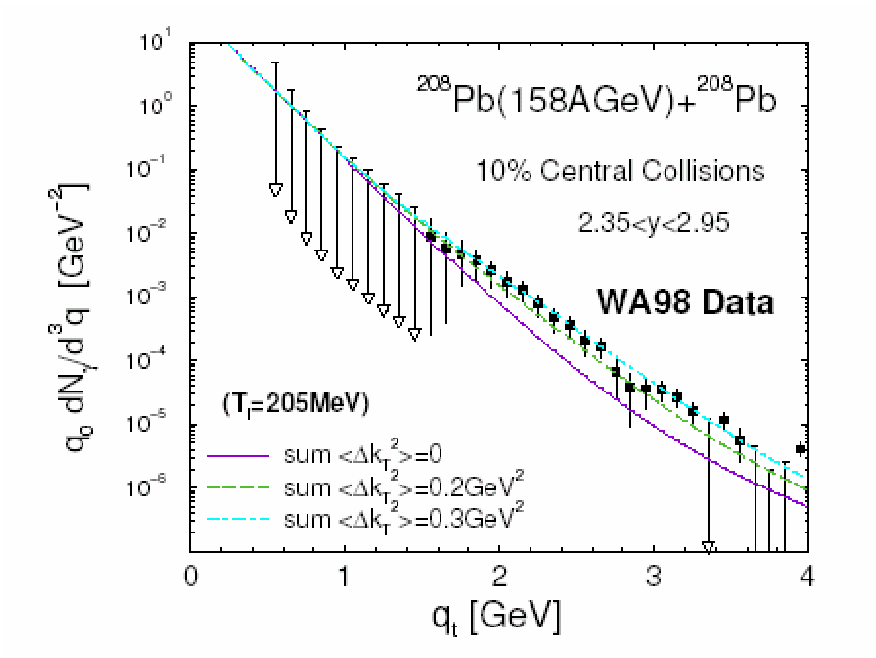
Lepton tensor

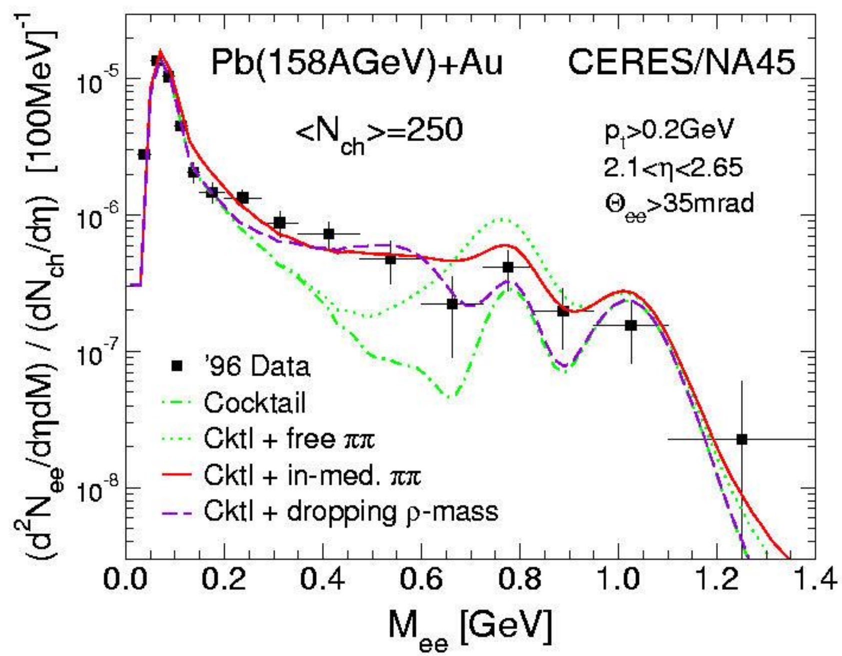
In-medium photon self-E

$$\mathrm{Im}\,\Pi_{\mu\nu} \sim \mathrm{Im} \int d^4 x \, e^{-iq\cdot x} << J_\mu(x) J_\nu(0) >>_T$$

Directly related to the in-medium vector spectral densities

Same spectral densities:Low mass dileptons and real photons

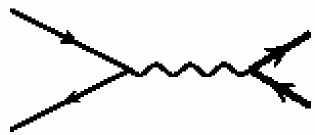




S. Turbide, R. Rapp, and C. Gale, PRC (2004)

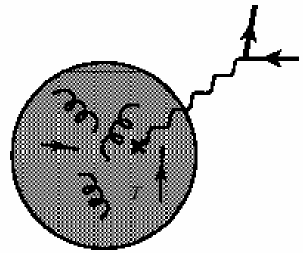
Dilepton sources

- Drell-Yan dileptons

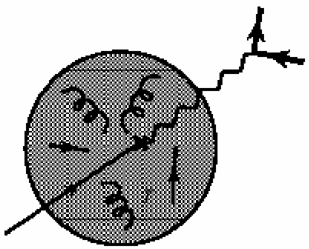


pQCD calculation including shadowing

- Thermal dileptons



- Jet-virtual photon conversion



Lepton pairs from jet-plasma interactions

$$f(p) = f_{th}(p) + f_{jet}(p)$$

$$f_{th}(p) = \exp(-E/T)$$

$$f_{jet}(p) = \frac{1}{g}\frac{(2\pi)^3}{\pi R_\perp^2 \tau p_T \cosh y}\frac{dN_{pQCD}}{d^2 p_T dy} \times \delta(\eta - y)\theta(\tau - \tau_i)\theta(\tau_{\max} - \tau)\theta(R_\perp - r)$$

Rates for $ab \to \ell^+\ell^-$ are calculable in relativistic kinetic theory

$$R = \int \frac{d^3 p_a}{(2\pi)^3} f_a(p_a) \int \frac{d^3 p_b}{(2\pi)^3} f_b(p_b)\sigma(M^2) v_{\mathrm{rel}}$$

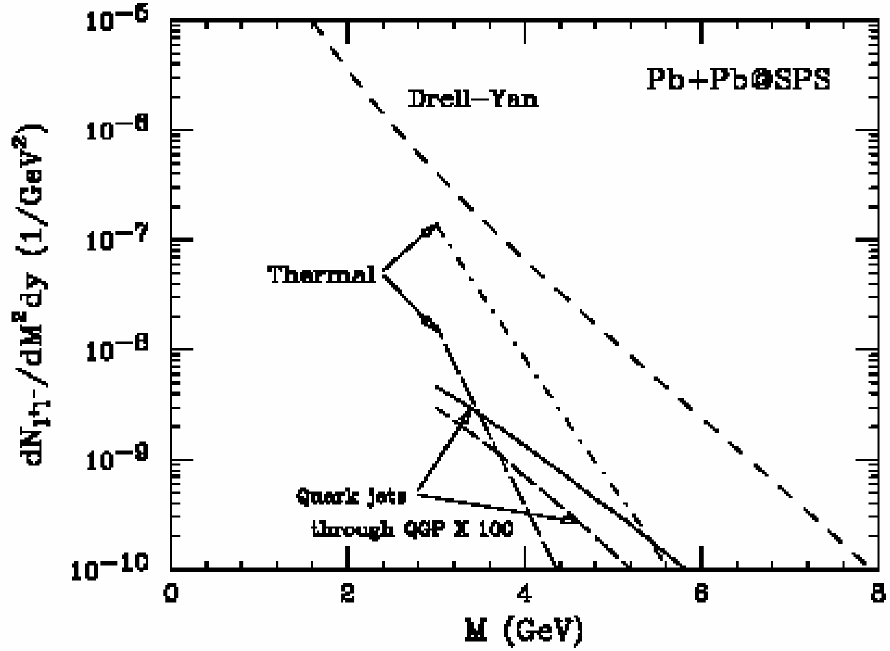
Dynamical ingredients

Bjorken model				
	τ_0(fm/c)	T_0 (GeV)	$\lambda_g^{(i)}$	$\lambda_q^{(i)}$
SPS	0.20	0.345	1.0	1.0
	0.50	0.254	1.0	1.0
RHIC	0.15	0.447	1.0	1.0
	0.50	0.297	1.0	1.0
LHC	0.073	0.897	1.0	1.0
Self-screened parton cascade				
RHIC	0.25	0.67	0.34	0.064
LHC	0.25	1.02	0.43	0.082

Different initial conditions are explored

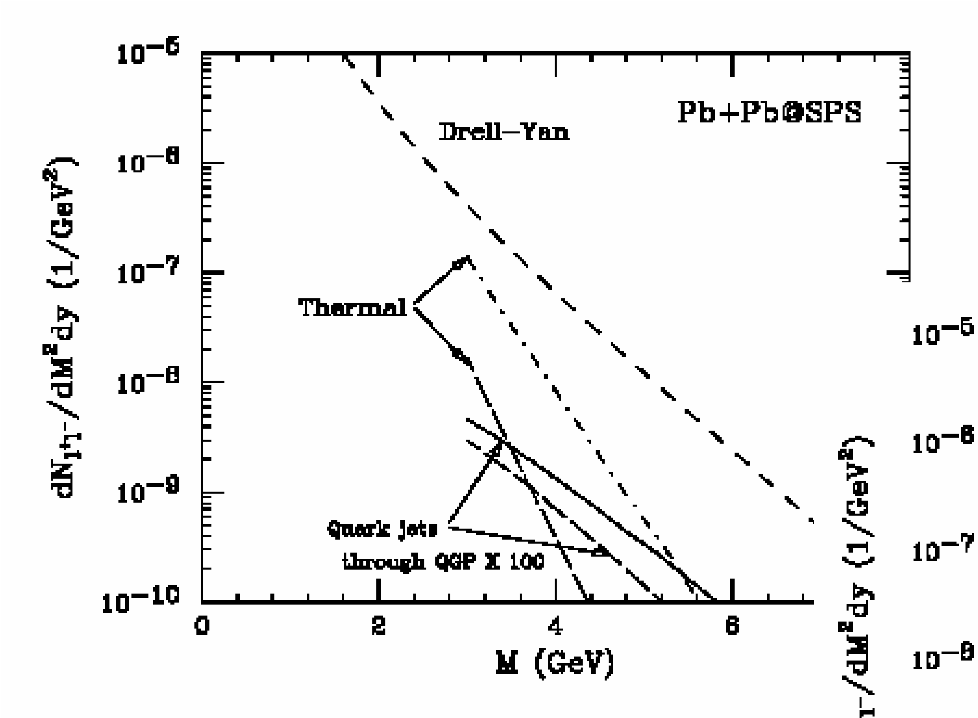
Results I (dileptons)

- SPS

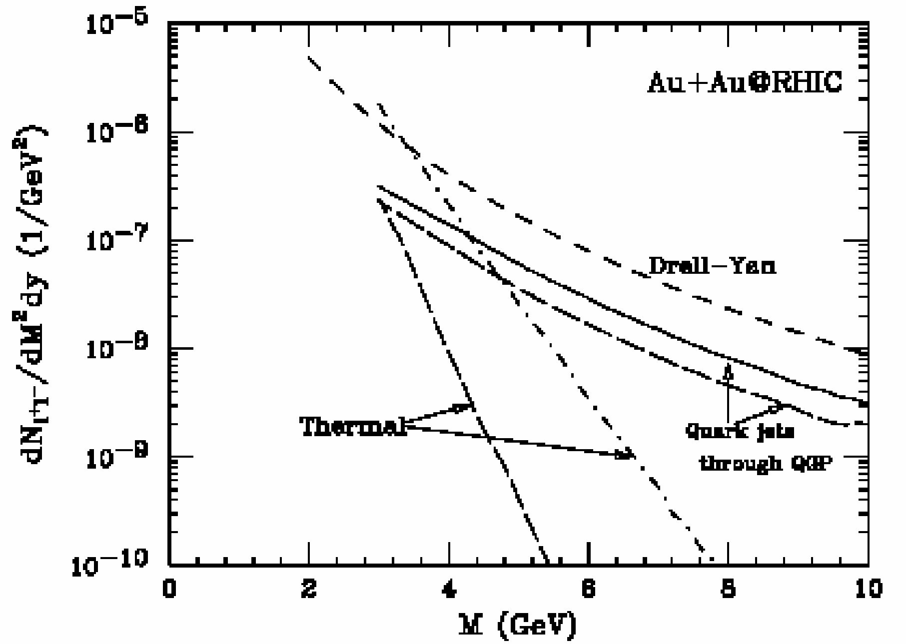


Results I (dileptons)

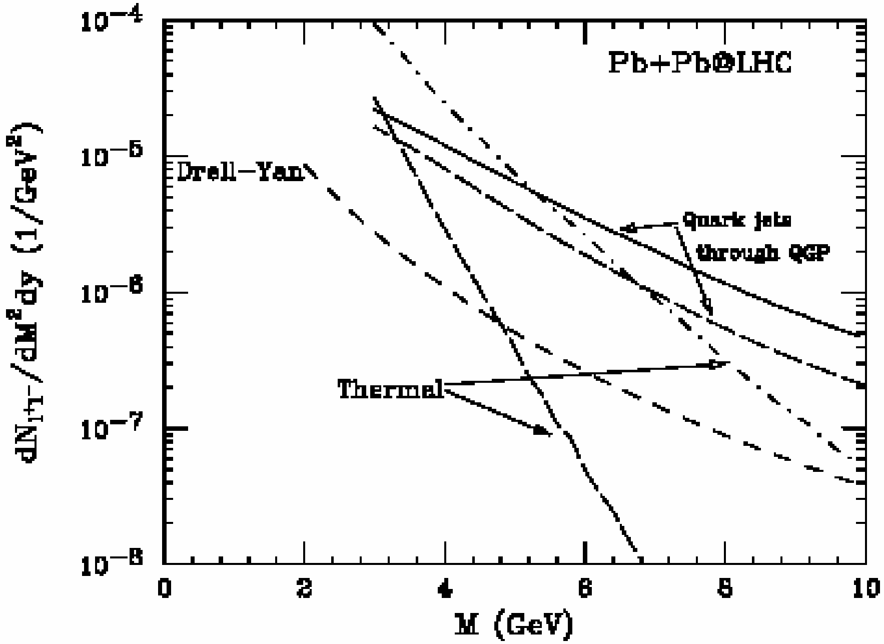
- SPS

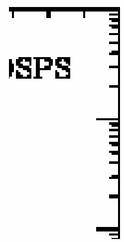


- RHIC

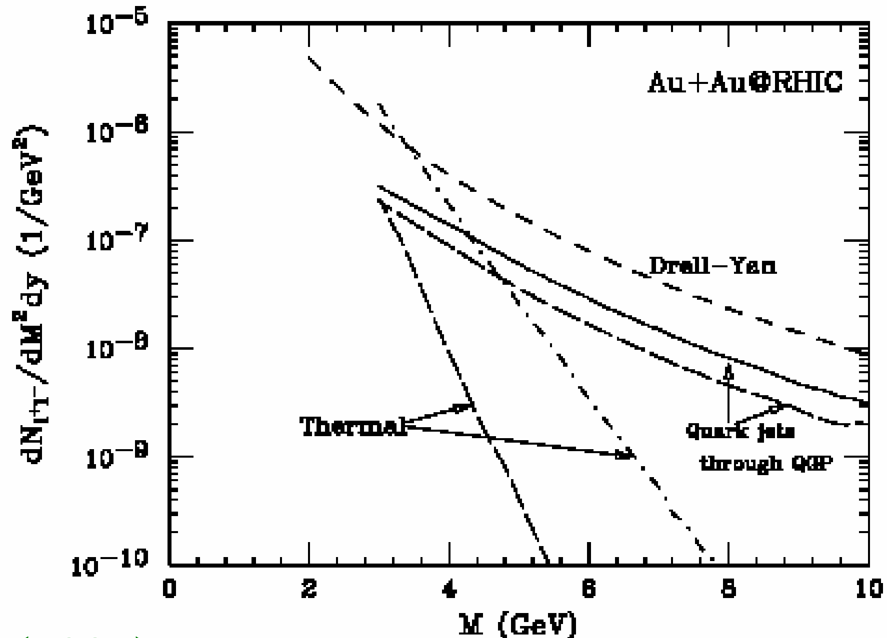


Results I (dileptons)





- RHIC

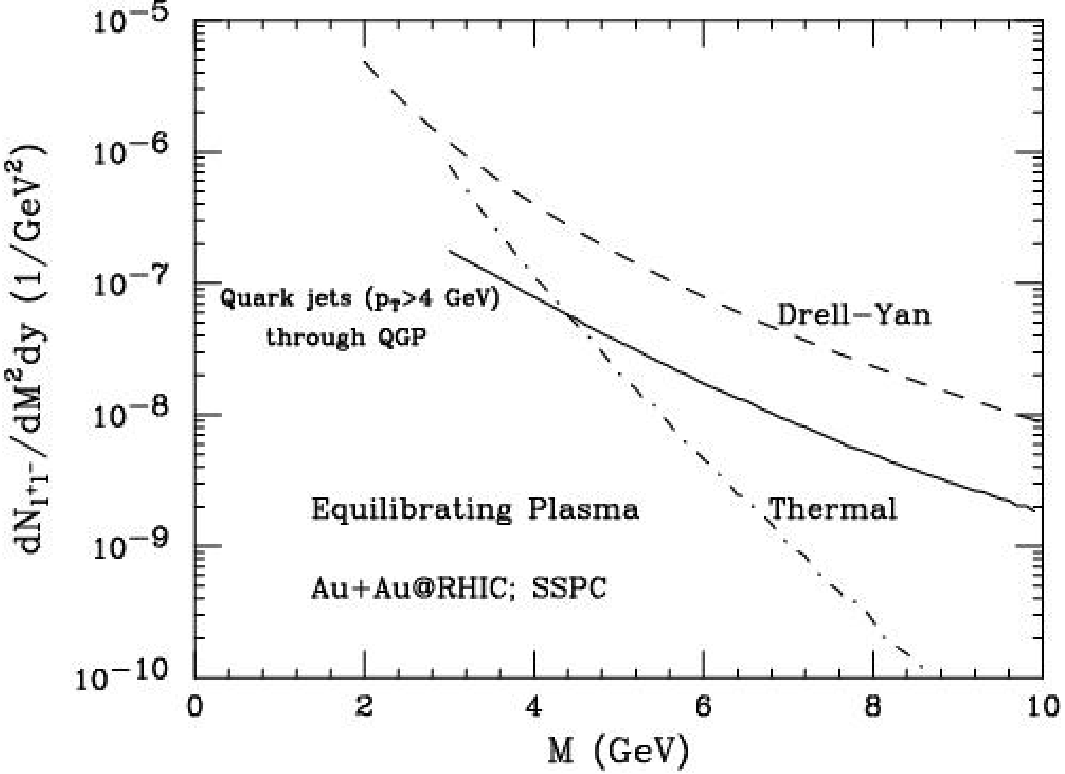


- LHC

Srivastava, Gale & Fries, PRC **67**, 034903 (2003)

Results II

Initial fugacities from the parton cascade:



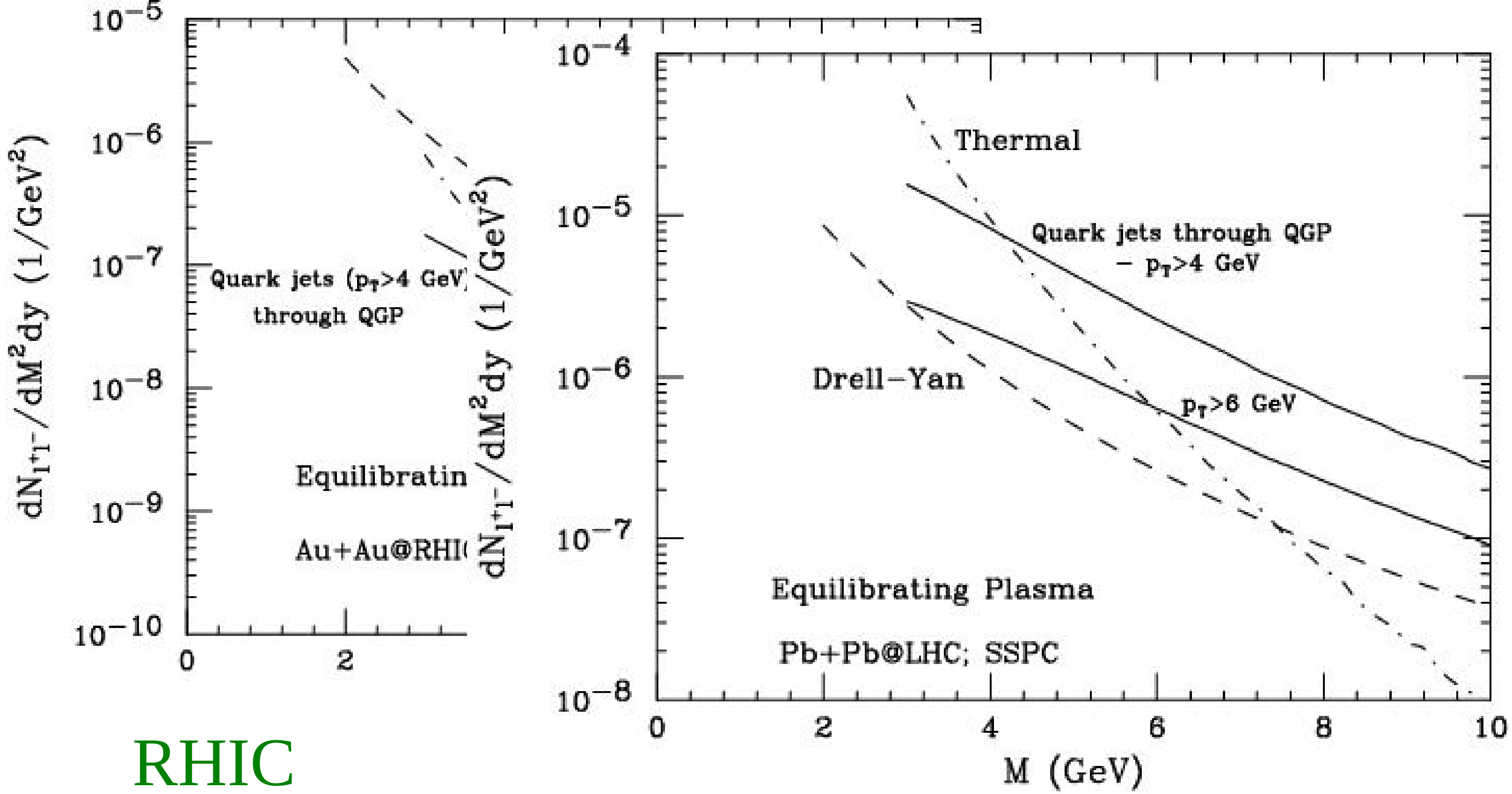
RHIC

After solving the relevant master equations

(Biro, van Doorn, Thoma, Mueller, Wang (PRC (1993))

Results II

Initial fugacities from the parton cascade:



RHIC

LHC

After solving the relevant master equations

(Biro, van Doorn, Thoma, Mueller, Wang (PRC (1993))

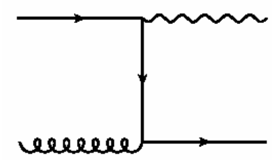
Jet-plasma interactions: measurable EM signatures!

- RHIC:
  - Jet-plasma interaction is the dominant source of photons up to $p_T \sim 6$ GeV.
  - Large-mass dilepton yield larger than thermal emission, competes with Drell-Yan, which will be measured.
- LHC:
  - Direct photon signal is still important
  - Large mass lepton pairs dominate over Drell-Yan emission.

EM probes as tools: can lepton pairs be used to learn about jets?

- Real photons have been proposed as a jet-tag:

X.-N. Wang, Z. Huang, and I. Sarcevic, PRL **77** (1996);
X.-N. Wang and Z. Huang, PRC **55** (1997)

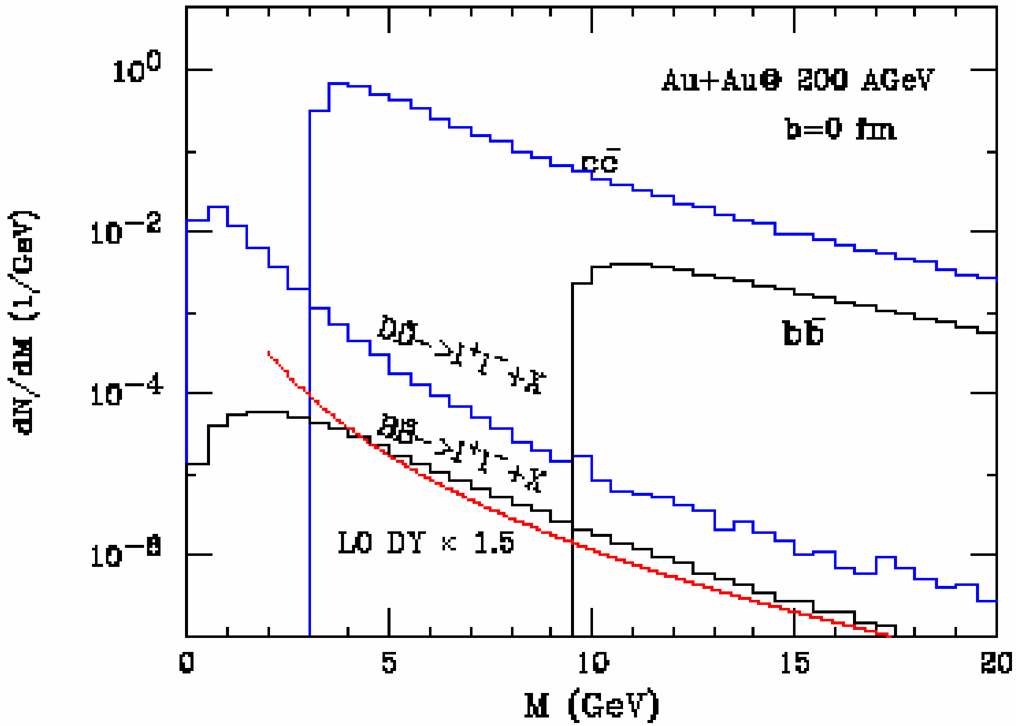


•Difficult measurement:

- At low p_T, $\pi_0 \rightarrow \gamma\gamma$ large background
- At higher p_T, background problem better

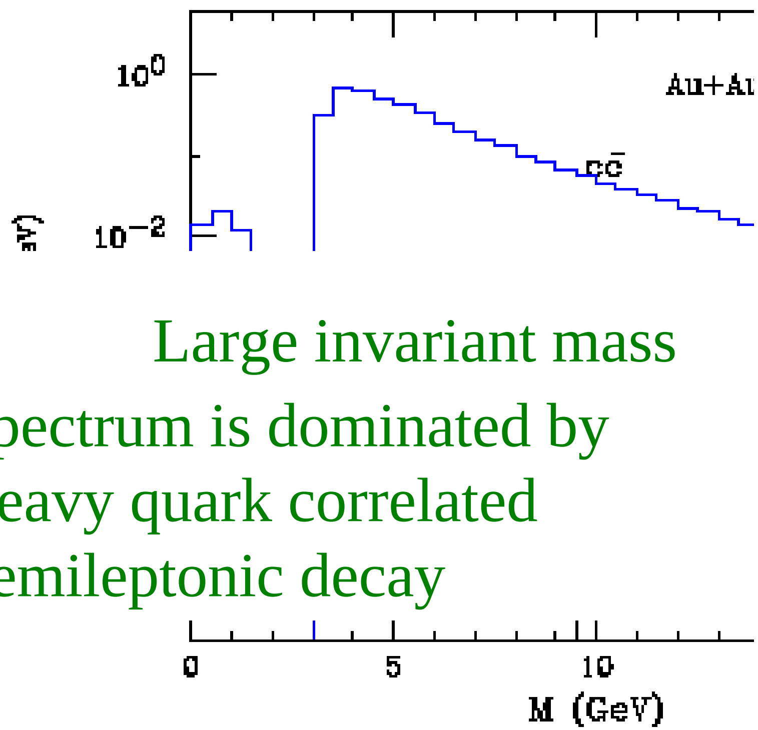
  but opening angle becomes smaller

Dilepton-tagged jets: inclusive mass spectrum



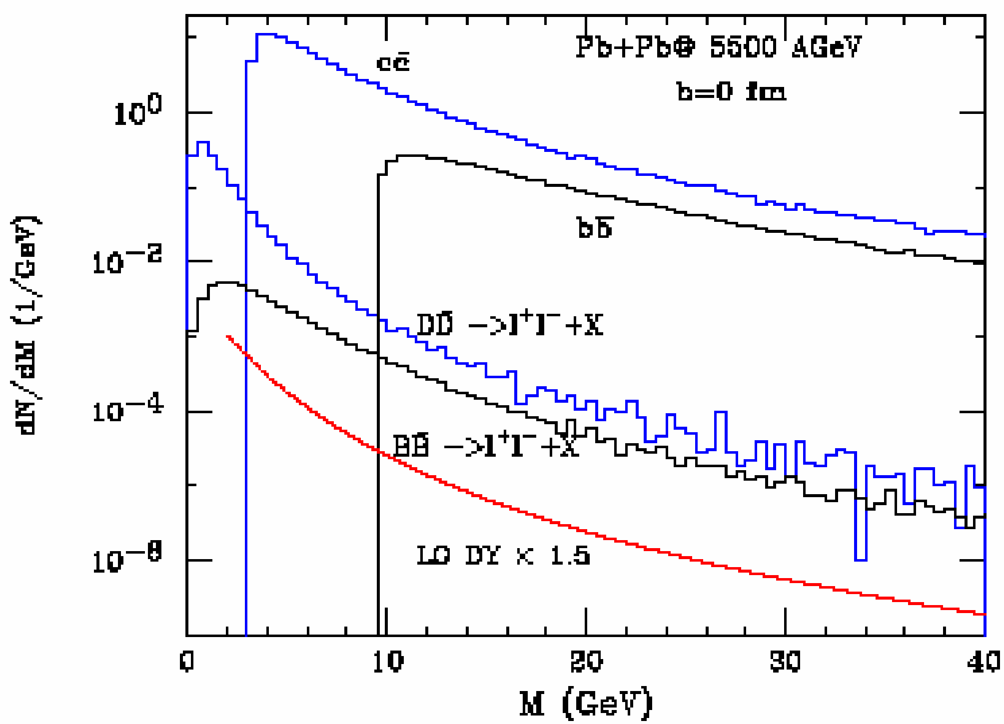
RHIC

Dilepton-tagged jets: inclusive mass spectrum



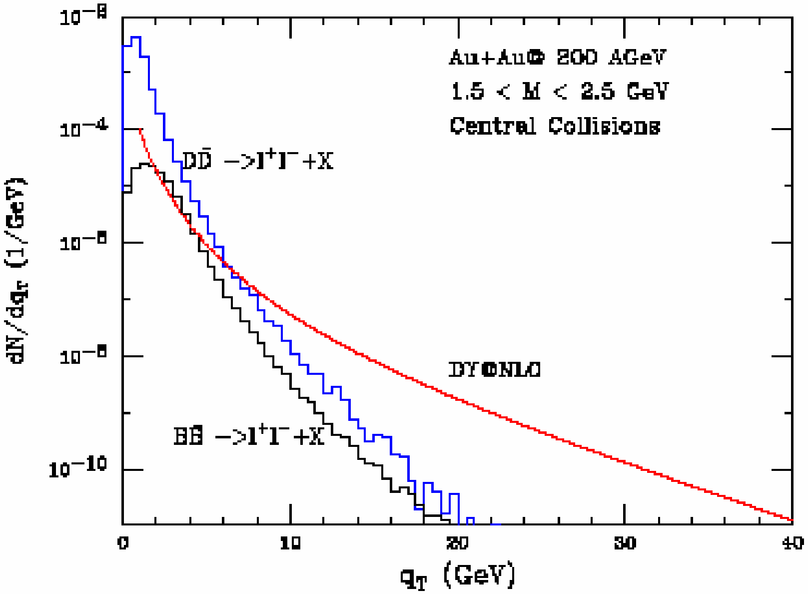
Large invariant mass spectrum is dominated by heavy quark correlated semileptonic decay

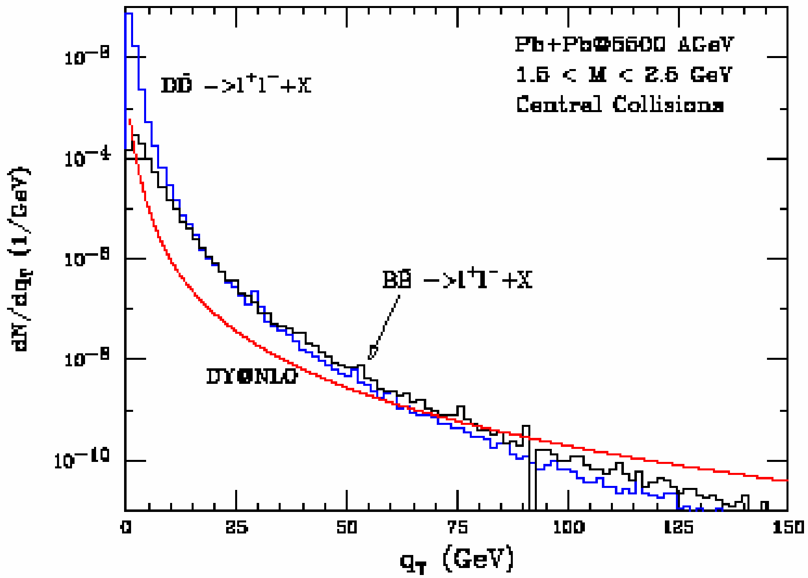
RHIC

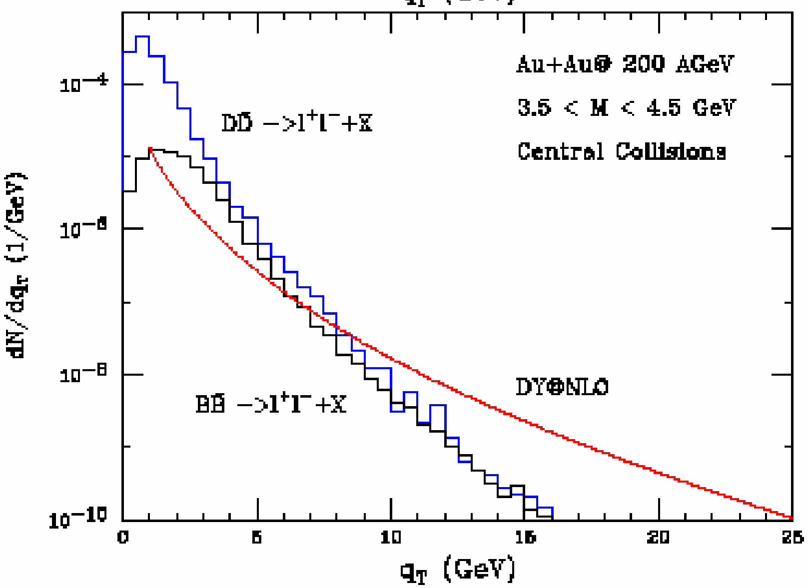


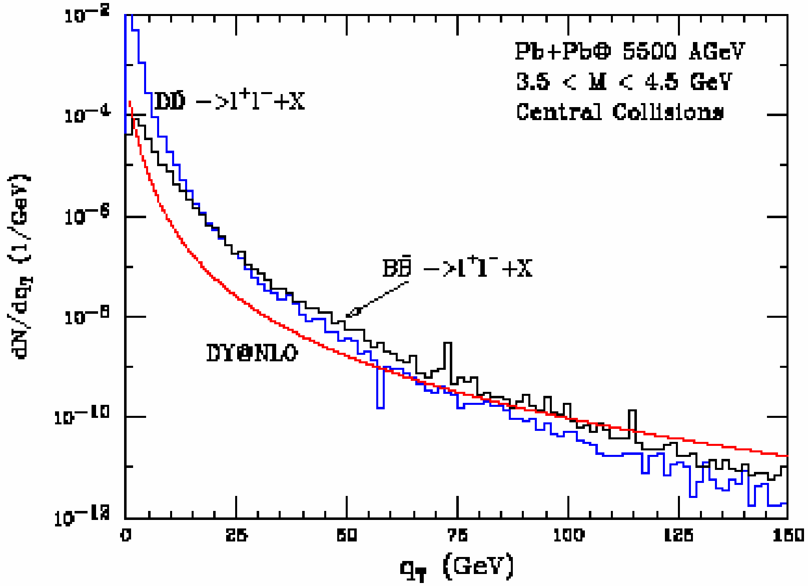
LHC

Is there a window?









Summary & Conclusion

- 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.

  To do:

  – Work out and incorporate the systematics of jet energy loss.
- Dilepton jet-tagging is feasible.

Collaborators:

- T. C. Awes, Oak Ridge National Laboratory
- Rainer Fries, University of Minnesota
- R. Rapp, Texas A&M
- Dinesh Srivastava, Variable Energy Cyclotron Centre
- Simon Turbide, McGill University