The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR 1773 - 7

SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
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Heavy ion collisions at LHC
Part II

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Heavy ion collisions at the LHC

Part 2

François Arleo

CERN

Summary of the previous lecture

- Lattice QCD predicts a transition from hadronic matter to quark-gluon plasma at $T_c \simeq 200$ MeV
- Deconfinement occurs most probably through a crossover transition
- Heavy ion collisions at high energy allow for quark-gluon plasma formation
- Need for experimental signatures
  - Flow, strangeness, thermal photons, quarkonium production, jet quenching . . .

Outline

- Heavy-quarkonium production
  - Absorption, Debye screening, and recombination
- Thermal photon production
  - Leading-order rate and phenomenology
- Jet quenching
  - Quenching of single spectra
  - Towards photon-tagged measurements

Heavy-quarkonium production

Debye screening

QCD static potential screened at finite T

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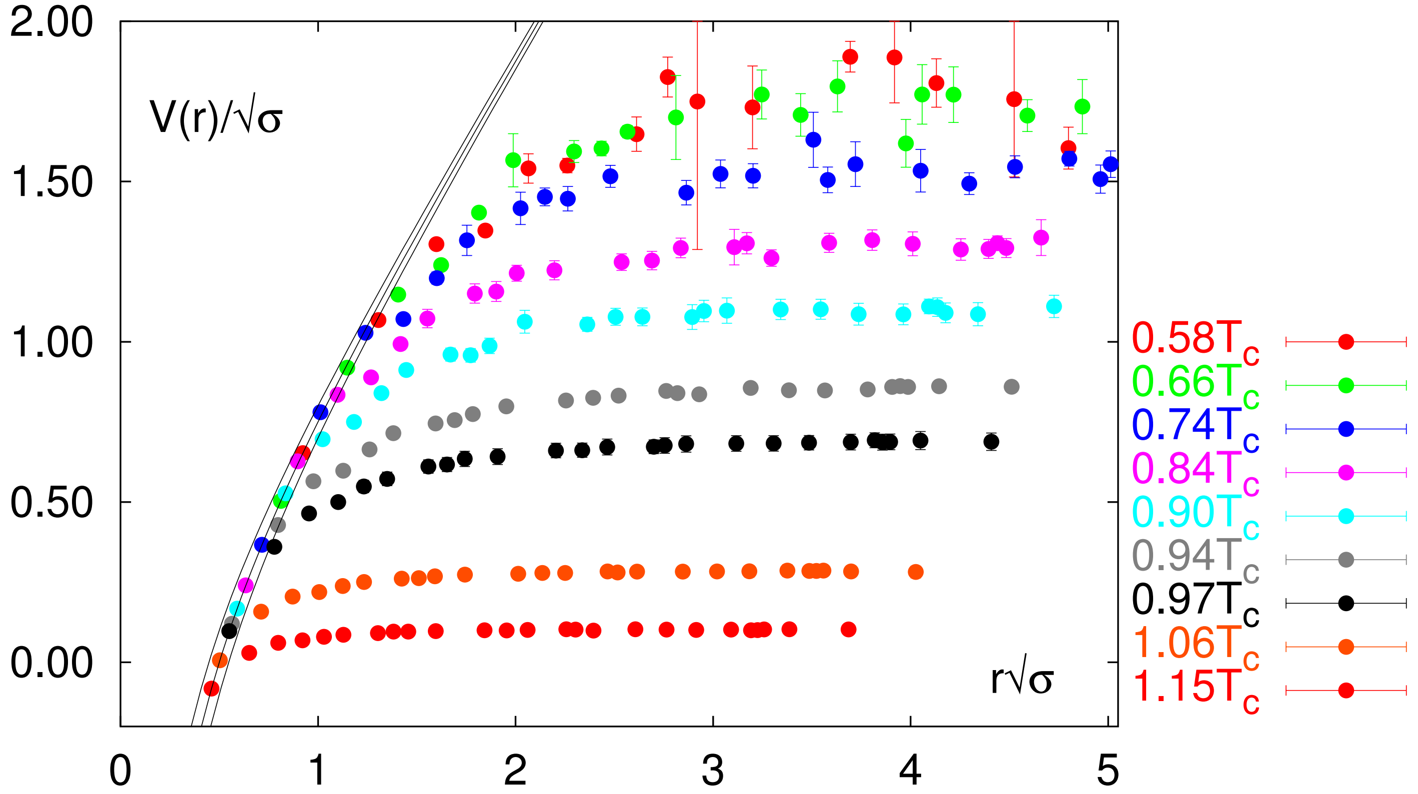

[Karsch et al. 2001]

Debye screening

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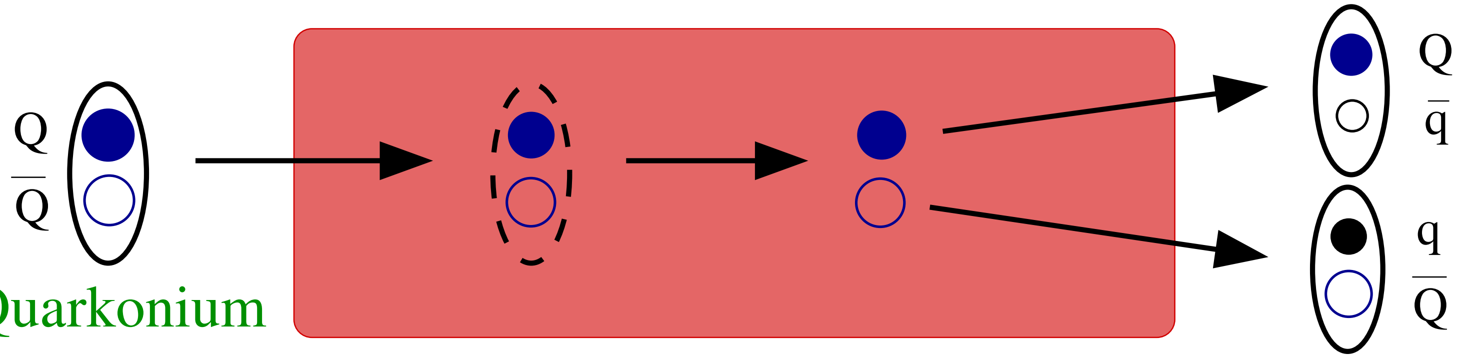


Heavy-quark bound states (J/ψ, Υ)

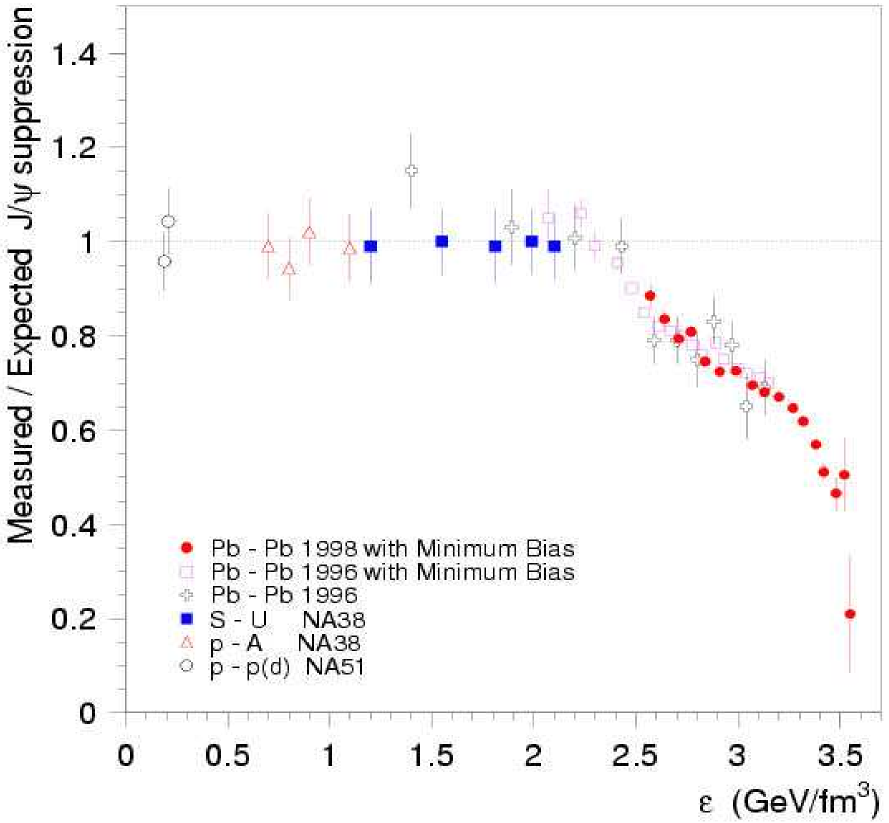
dissolved in quark-gluon plasma

[Matsui, Satz 1986]

Data

Experimentally

Impressive data from CERN NA50 experiment at SPS



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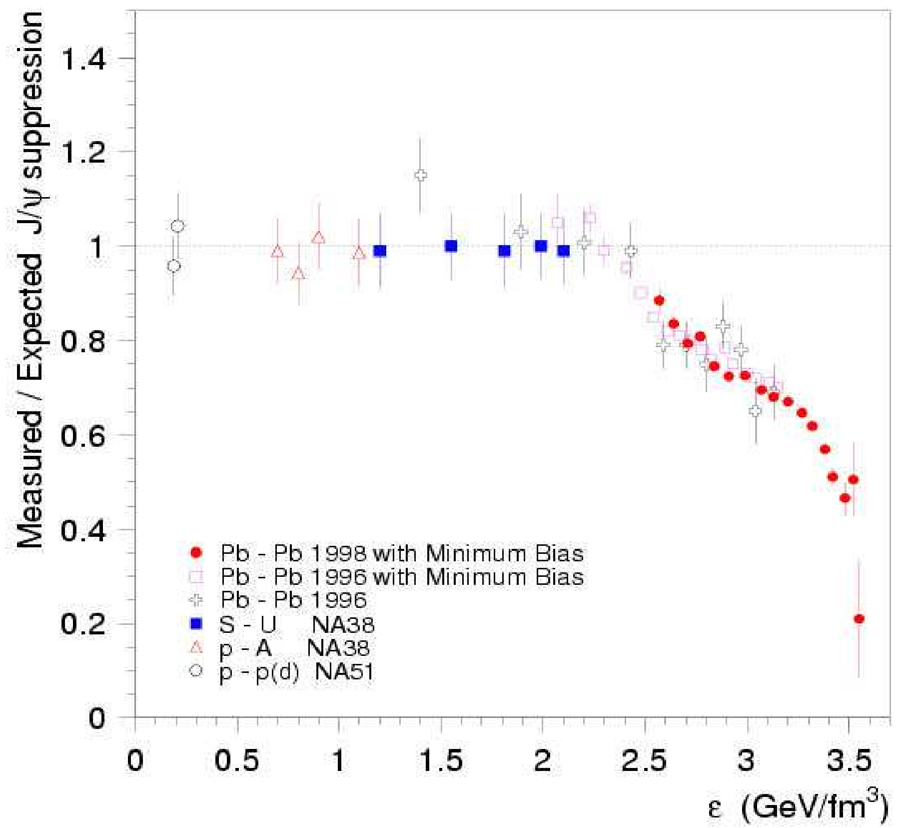

Strong suppression at large energy density

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Caveat

Suppression already occurs in proton-nucleus collisions !

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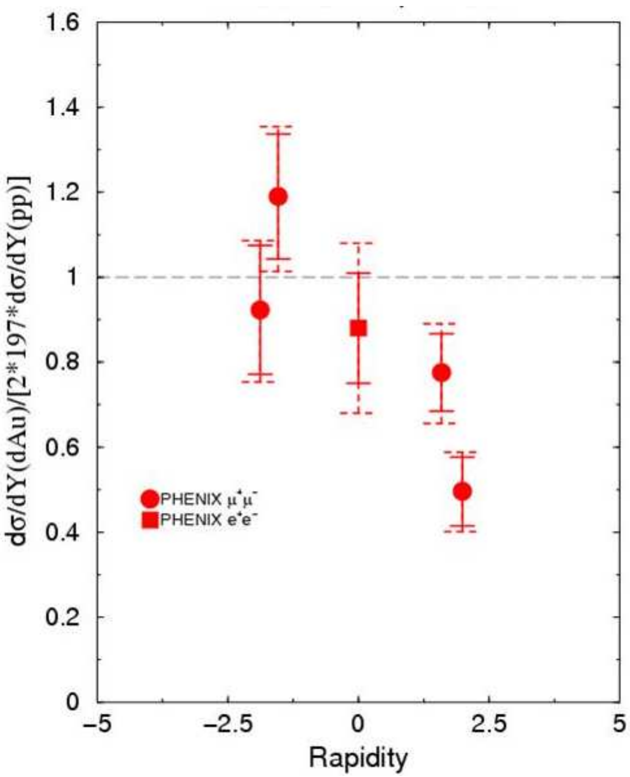

[PHENIX]

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Caveat

Suppression already occurs in proton-nucleus collisions !

Need to understand all nuclear effects that could affect J/ψ production:

- Nuclear absorption
- Inelastic interaction with light hadrons ("comovers")
- Debye screening
- Recombination

Nuclear absorption

J/ψ dissociation by the nucleons from the nucleus

$$J/\psi + N \rightarrow c\,(D) + \bar{c}\,(\bar{\Lambda})$$

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Simple model for J/ψ suppression

$$S = \exp(-\rho\,\sigma_{J/\psi N}\,L)$$

with

- ρ: nuclear density
- L: length covered by the J/ψ in the nucleus
- $\sigma_{J/\psi N}$: J/ψ-N inelastic cross section

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How much is $\sigma_{J/\psi N}$?

$\sigma_{J/\psi N}$ from theory

- Many theoretical approaches

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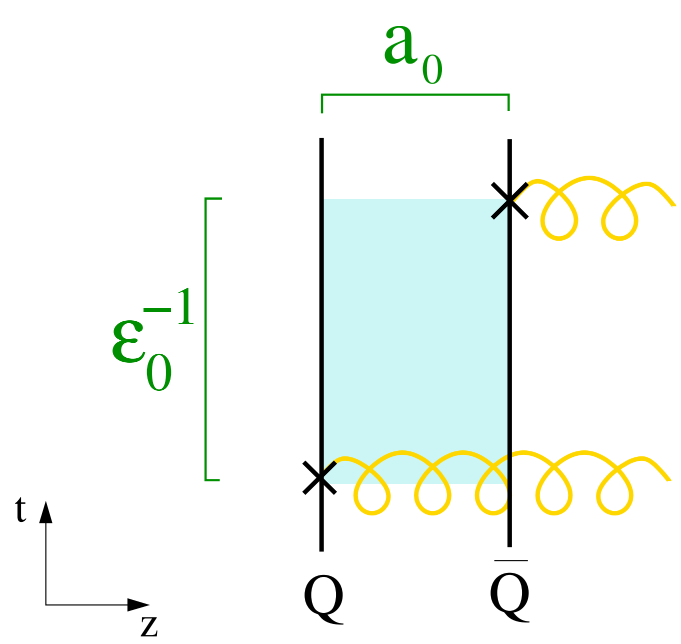
  - Short-distance QCD [Bhanot, Peskin 1979]



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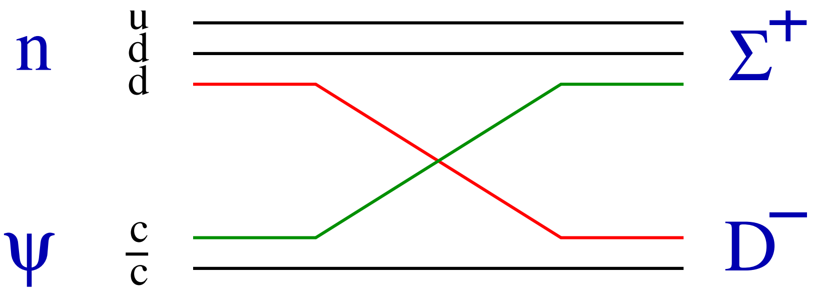

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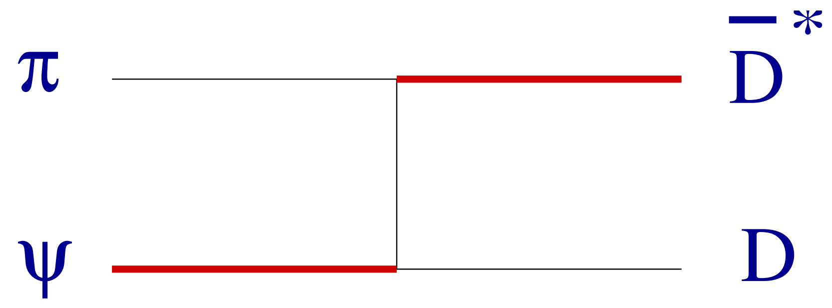

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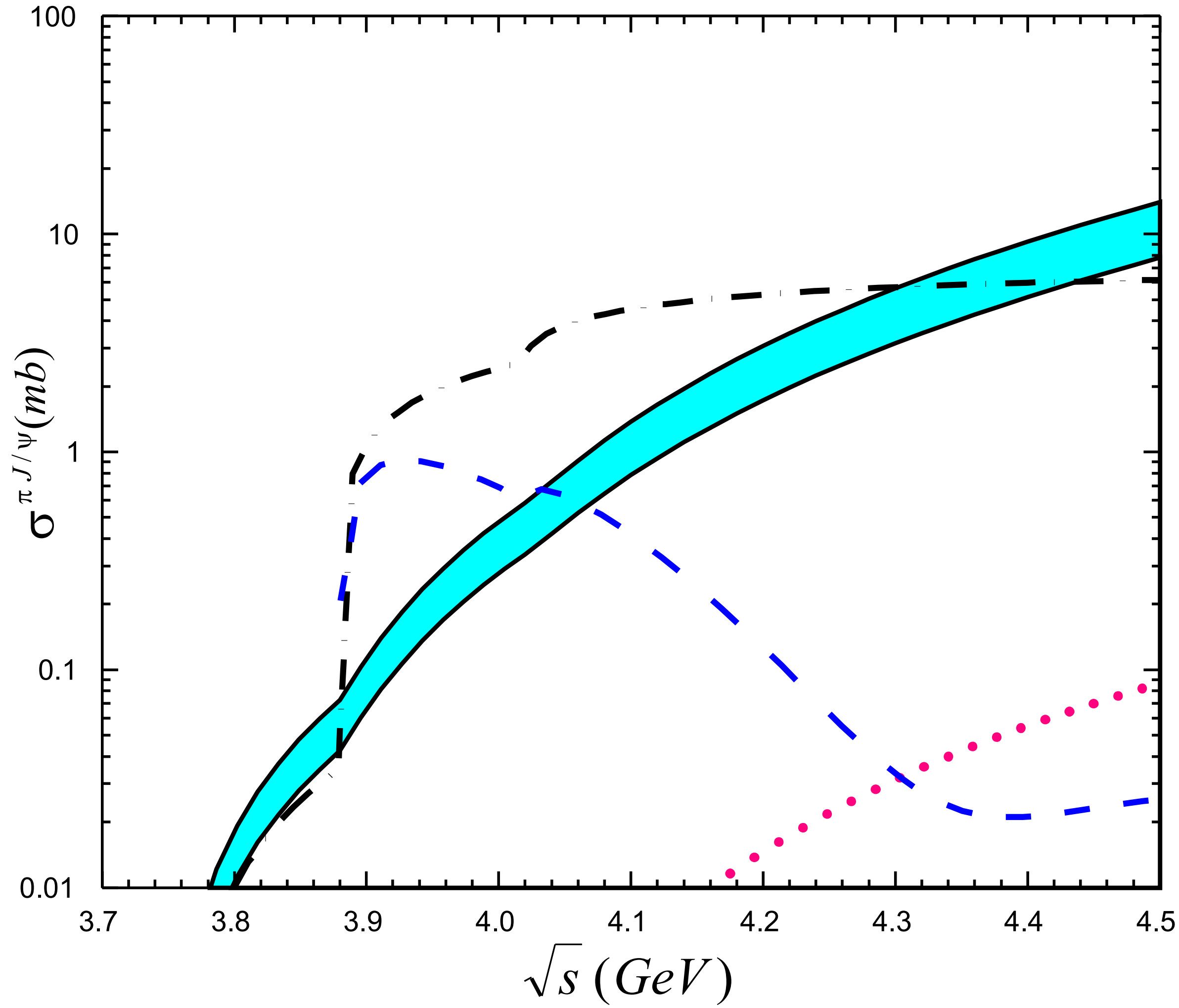
... but strongly depends on the energy

$\sigma_{J/\psi N}$ from theory



[Rapp, Grandchamp 2003]

$\sigma_{J/\psi N}$ from phenomenology

[FA, Tram to appear]

Exp.	$\sigma_{J/\psi N}$ (mb)	χ^2/ndf	$\sigma^{\text{sh}}_{J/\psi N}$ (mb)	χ^2/ndf
NA3	2.6 ± 0.3	0.3	2.8 ± 0.4	0.3
NA50	4.4 ± 0.3	1.4	4.3 ± 0.3	1.5
E672	12.7 ± 5.8	0.4	11.8 ± 5.6	0.4
E866	3.1 ± 0.3	1.1	2.7 ± 0.3	0.7
HERA-B	1.9 ± 0.6	0.1	1.9 ± 0.6	0.05
PHENIX	1.9 ± 0.9	1.9	1.8 ± 0.9	1.6
NMC	≤ 0.9	0.7	≤ 0.8	0.8
Global fit	3.3 ± 0.2	1.2	3.2 ± 0.2	1.1

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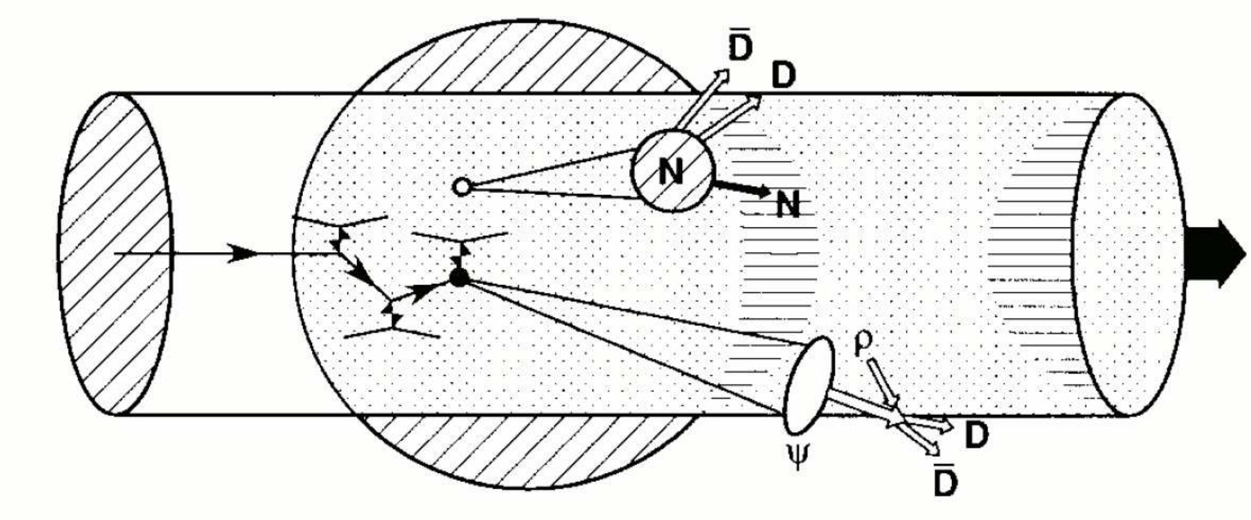
Qualitative agreement between data and theory

Comovers

Inelastic interaction with the partons / hadrons produced in the collision

[Gavin, Vogt 1990-1996]

[Armesto, Capella, Ferreiro, Kaidalov, Sousa 1995-]



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May occur in high multiplicity events

- nucleus-nucleus collisions
- proton-nucleus collisions at high energy

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Suppression due to comovers

$$S \simeq \exp\left[-\frac{\langle \sigma_{\rm co}\, v\rangle}{\pi\ R^2}\ln\left(\frac{\tau_f}{\tau_0}\right)\frac{dN}{dy}\right]$$

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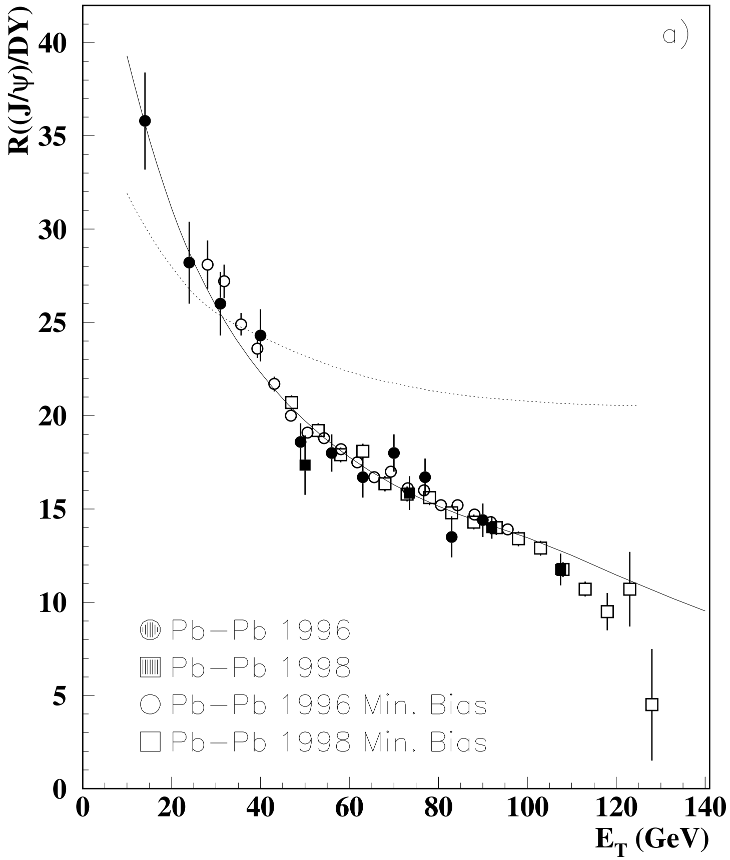
σ_{co}: charmonium-pion (or gluon) cross section at low energy

Comovers

At SPS energy

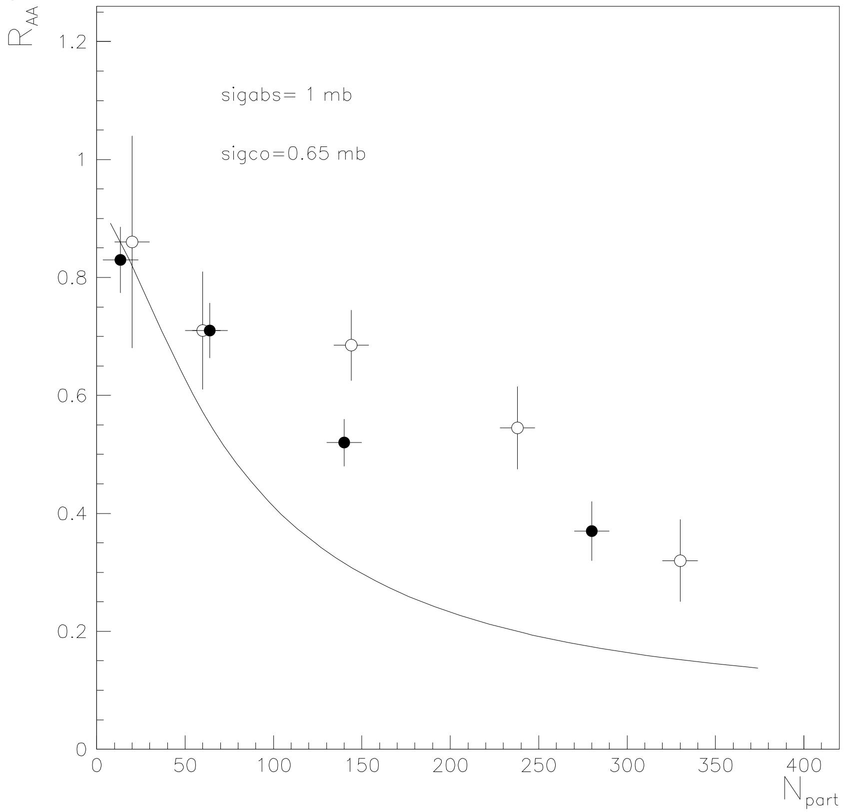


[Capella, Ferreiro, Kaidalov 2000]

- Good understanding of NA50 data with $\sigma_{co} \simeq 0.5$ mb

Comovers

At RHIC energy



[Capella, Ferreiro 2005]

- Too strong suppression as compared to PHENIX data

Debye screening

We have seen at the heavy quark-potential (as given by lattice QCD) is screened at finite temperature

$$V(r, m_{\rm D}) = -\frac{g^2\, N_c}{8\,\pi\, r}\ \exp\left(-m_{\rm D}\, r\right)$$

where $m_{\rm D} \sim g\, T$ is the Debye mass

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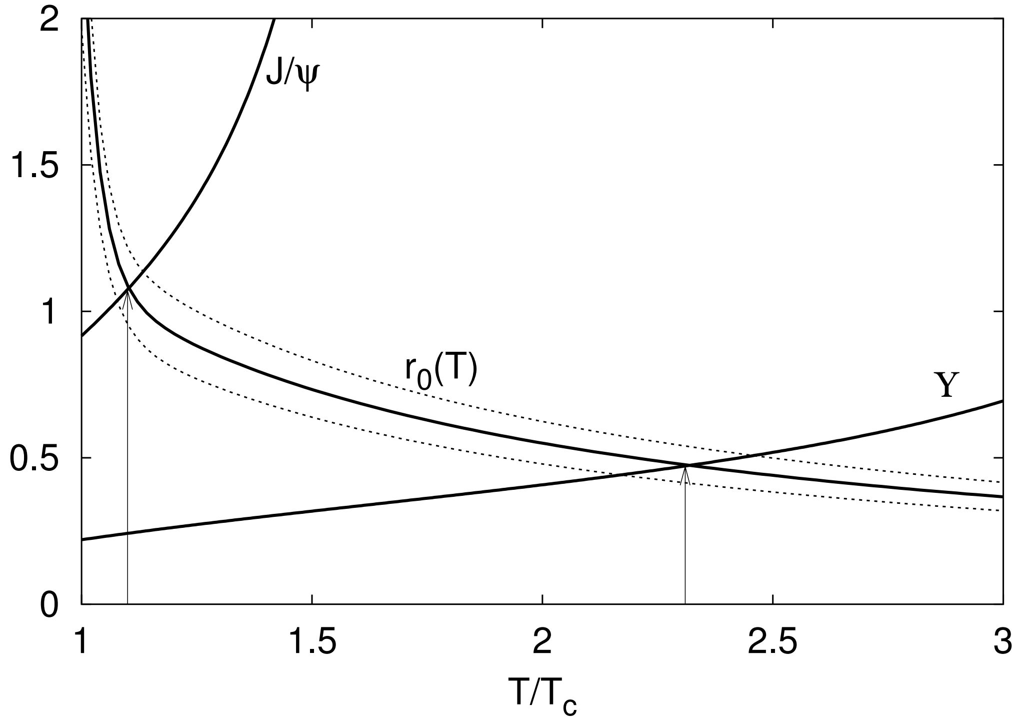
Properties of the heavy-quarkonium state (ϵ, $\langle r^2 \rangle$) are given solving the Schrödinger equation in this potential

$$\left[\frac{1}{m_Q}\nabla^2 + V(r)\right] \psi(r) = -\epsilon\, \psi(r)$$

Debye screening



[Digal, Petreczky, Satz 2001]

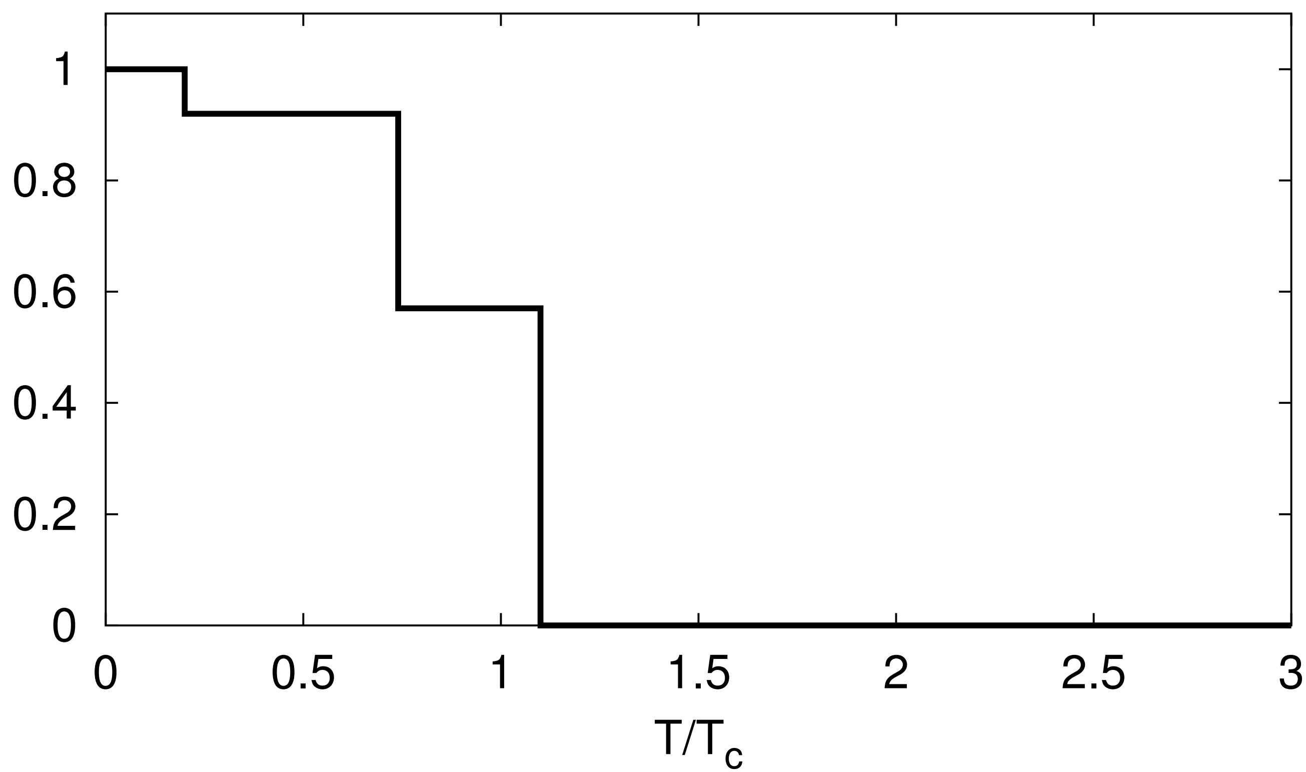
- Dissociation happens when $r_{J/\psi} \simeq r_0(T)$

Debye screening

$q\bar{q}$	T/T_c
J/Ψ	1.10
$\chi_c(1P)$	0.74
$\psi(2S)$	0.1-0.2
$\Upsilon(1S)$	2.31
$\chi_b(1P)$	1.13
$\Upsilon(2S)$	1.10
$\chi_b(2P)$	0.83
$\Upsilon(3S)$	0.75

- Allow for the extraction of the dissociation temperatures

Debye screening



[Digal, Petreczky, Satz 2001]

- Leads to sequential suppression due to the feed-down process

Statistical recombination

What happens when the number of charm quarks produced initially is large ?

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The c quarks may recombine statistically in the quark-gluon plasma to produce J/ψ states

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Comparing

initial production: $\sigma_{J/\psi} \propto n_c$

recombination: $\sigma_{J/\psi} \propto n_c^2$

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Comparing

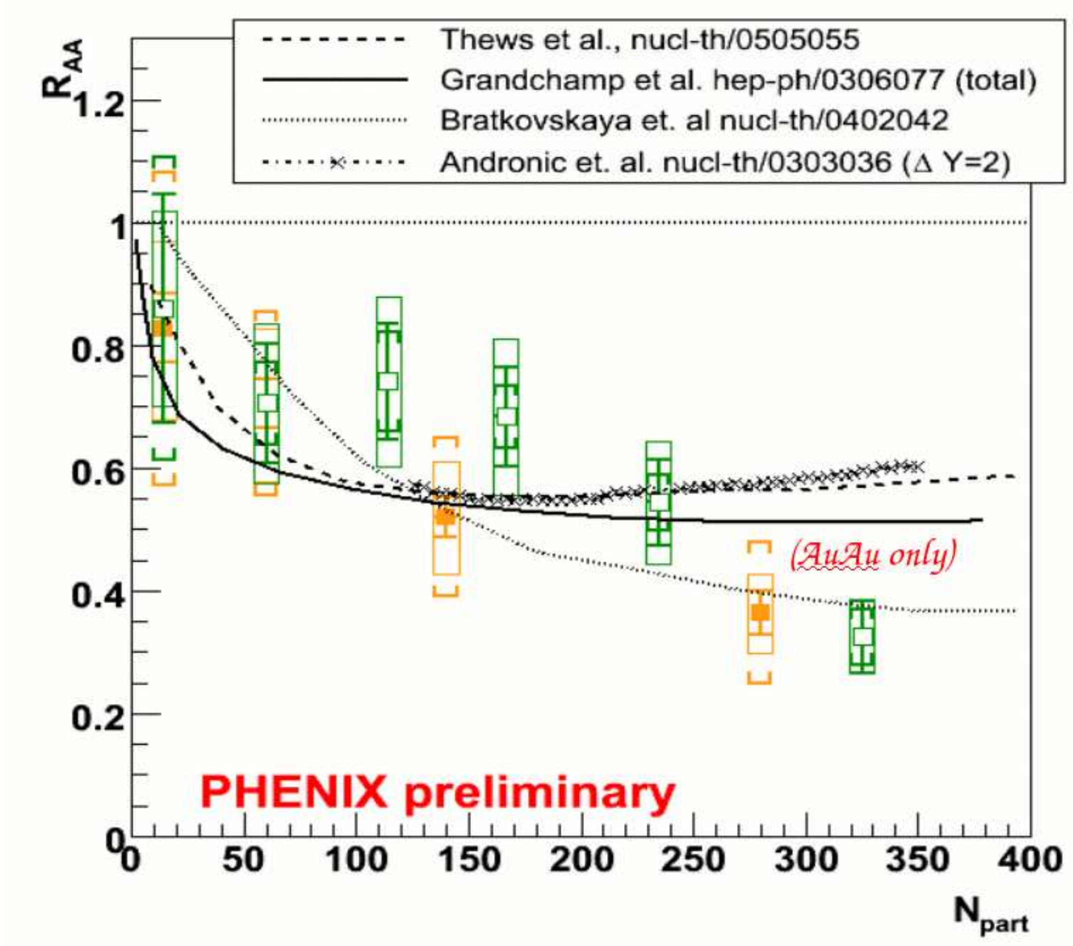
initial production: $\sigma_{J/\psi} \propto n_c$

recombination: $\sigma_{J/\psi} \propto n_c^2$

The latter takes over when $n_c \gg 1$

Enhancement of J/ψ production at high energy !

Statistical recombination

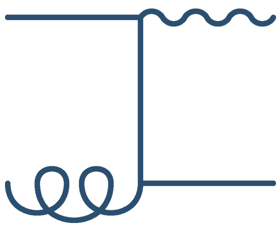


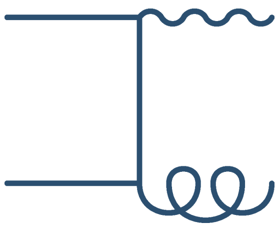
- In good agreement with PHENIX preliminary data

Thermal photons

First steps

Scattering of thermal quark and gluons in the plasma yield photons with momenta of the order of the medium temperature





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Enhancement of thermal photon production

at small $p_\perp = \mathcal{O}(T)$

Perturbative calculation

- Photon/dilepton rate calculated within thermal field theory
  [McLerran, Toimela; Kajantie, Kapusta, McLerran, Mekjian 1986]
  [Baier, Pire, Schiff 1988; Altherr, Ruuskanen 1992]

Log singularity $\alpha\ \alpha_s\ \ln\left(\omega\, T/Q^2\right)$ appears for real photons !

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- Resummation of Hard Thermal Loops
  [Kapusta, Lichard, Seibert 1991]
  [Baier, Nakkagawa, Niegawa, Redlich 1992]

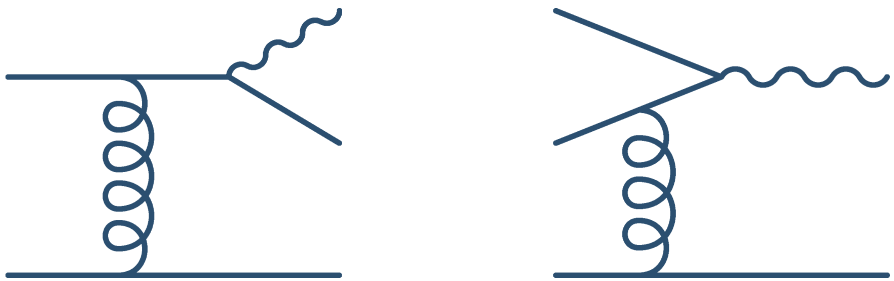
$$\ln\left(\frac{\omega\ T}{Q^2}\right) \to \ln\left(\frac{\omega\ T}{m_{\rm th}^2}\right)$$

where the thermal mass $m_{\rm th} \sim \sqrt{\alpha_s}\ T$ acts as an IR cutoff

Going to two loops

- "Higher-order" diagrams

  [Aurenche, Gelis, Kobes, Petitgirard 1996-1997]
  [Aurenche, Gelis, Kobes, Zaraket 1998]



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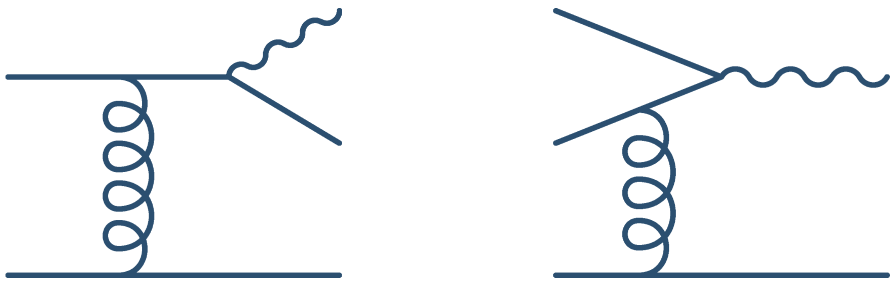

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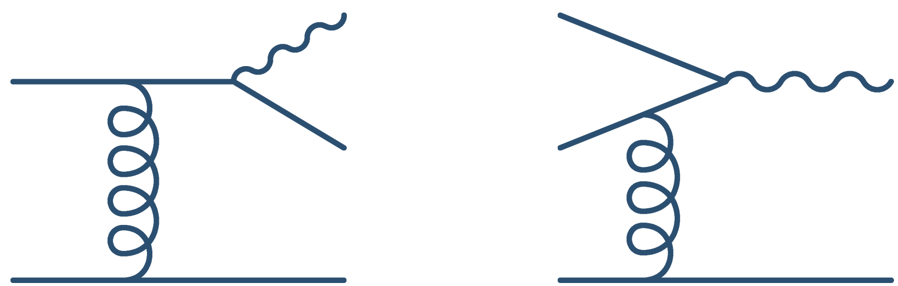

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Q. Are there many more like these ?

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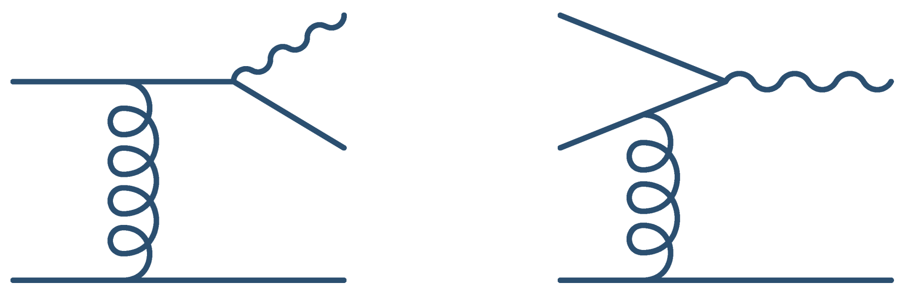

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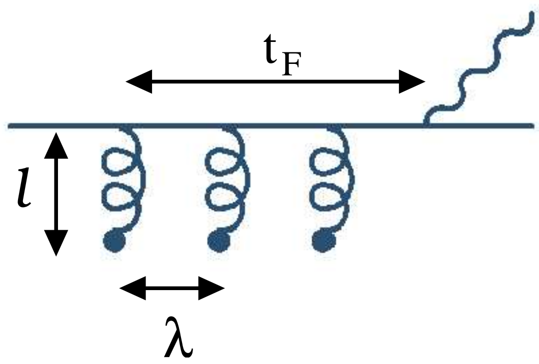
A. YES !

Landau-Pomeranchuk-Migdal effect

- Ladder diagrams with $t_F \gtrsim \lambda \gg \ell$ need to be resumed



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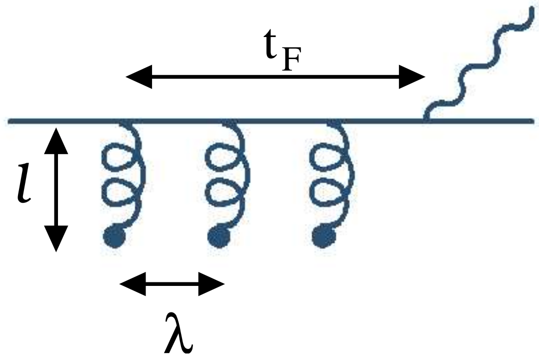

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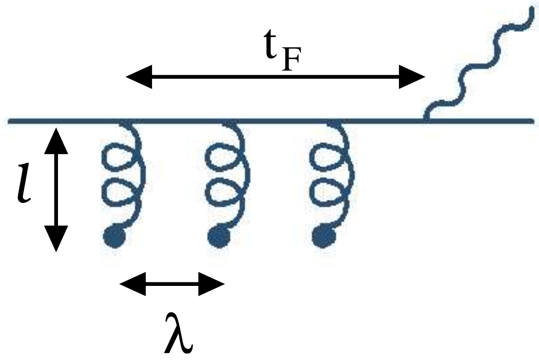
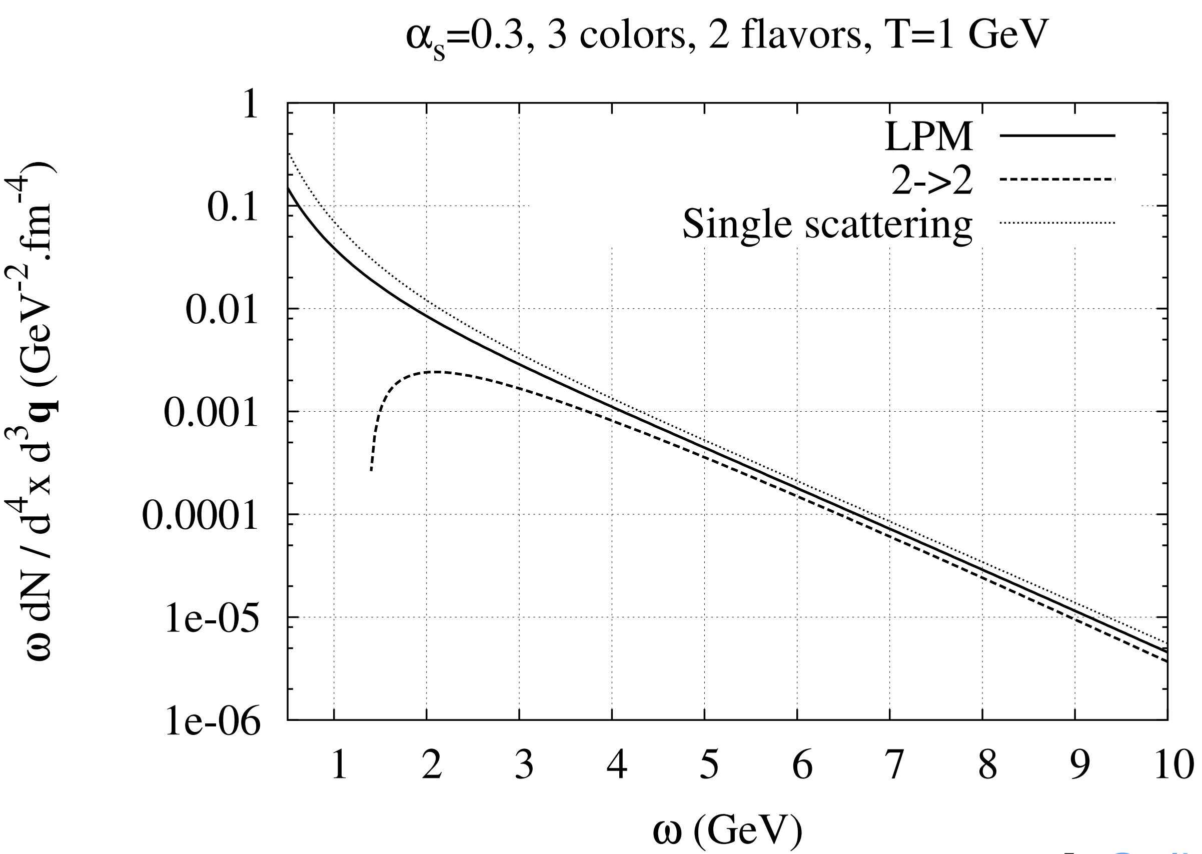


- No sensitivity on long-range interactions $\ell \gg \lambda$ with complicated topologies
- Resummation procedure together with numerical computation of the genuine leading-order thermal rate

[Arnold, Moore, Yaffe 2001-2002]

Landau-Pomeranchuk-Migdal effect



[Gelis 2002]

- Strong LPM suppression as compared to the single - scattering case
- Convergence at high $\omega \gg T$

Landau-Pomeranchuk-Migdal effect

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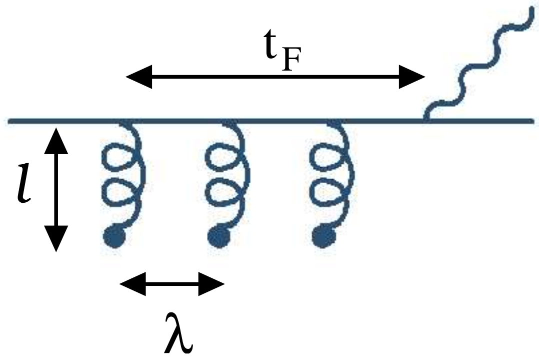

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Leading $\mathcal{O}\left(\alpha_s\right)$ thermal photon rate
in QGP under control

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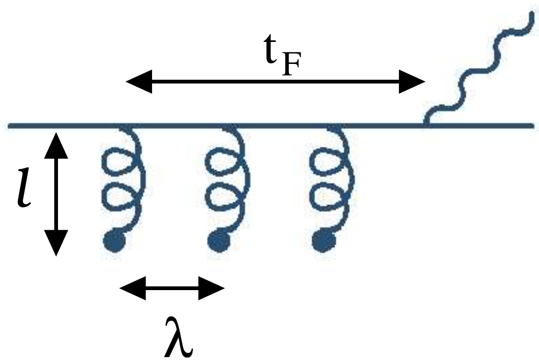

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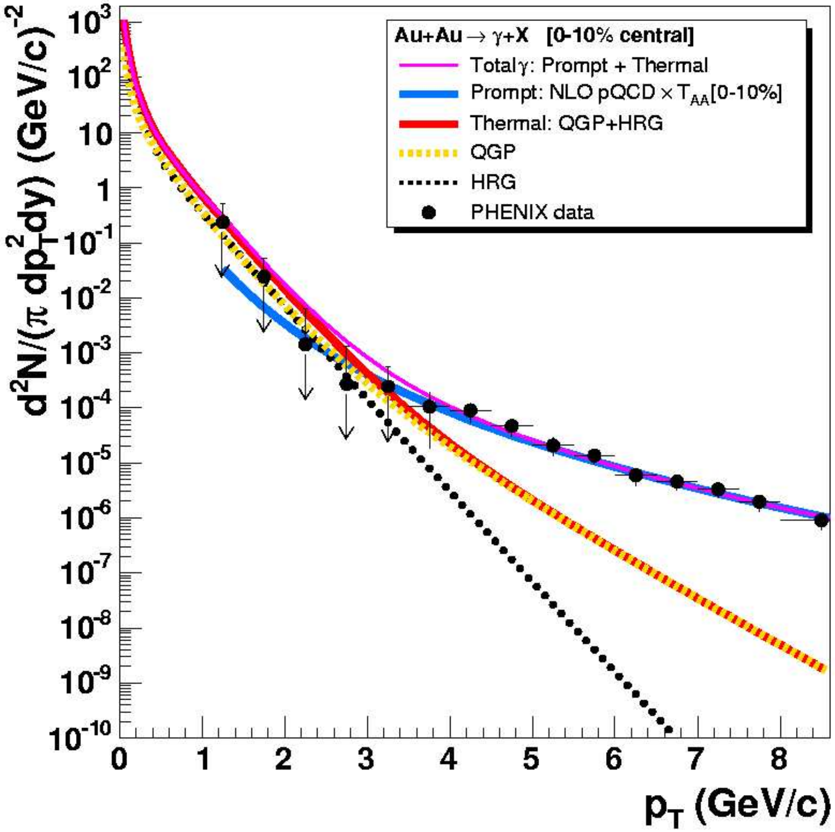
[Arnold, Moore, Yaffe 2001-2002]

Problem

Large uncertainty from hydrodynamics

Predictions

At RHIC

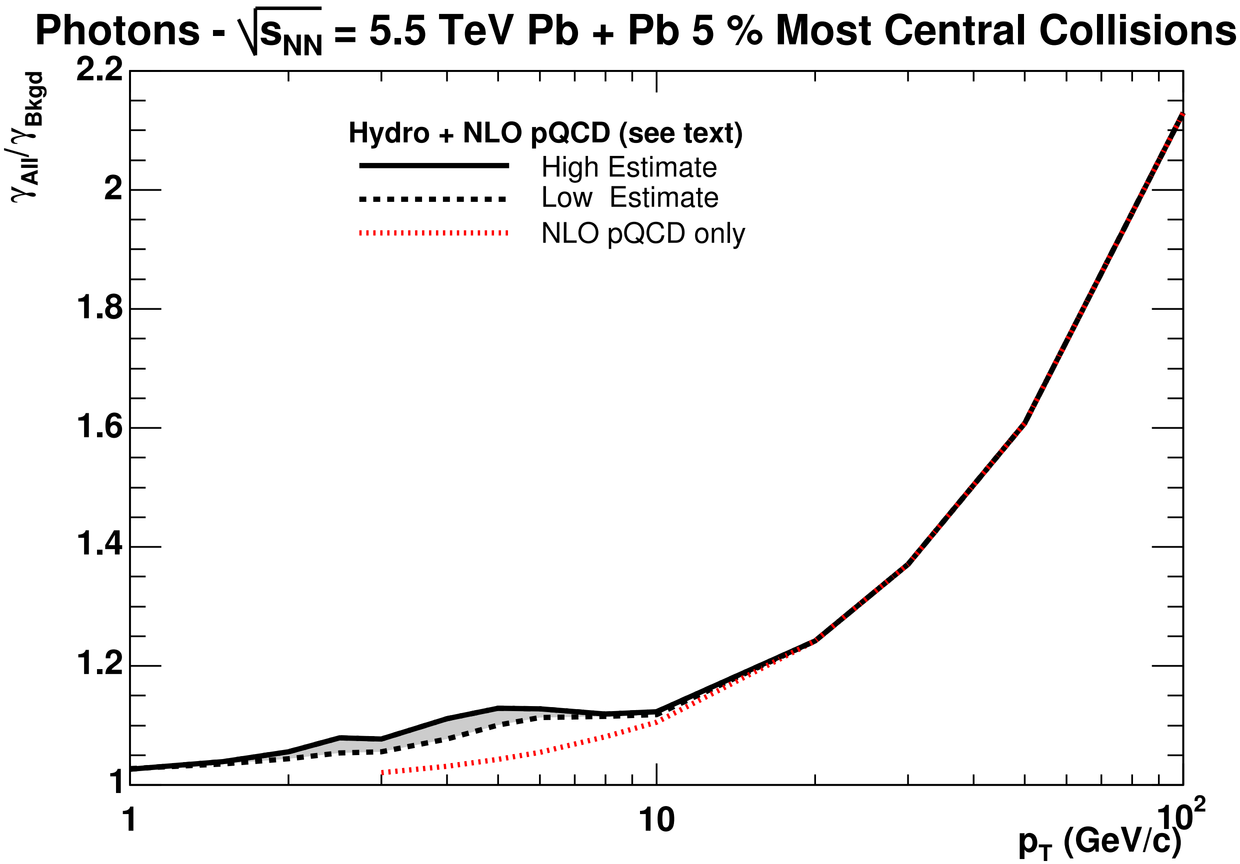


[d'Enterria, Peressounko 2005]

- Possible thermal photon signals in PHENIX data (?)

Predictions

At LHC



[Niemi et al. 2003]

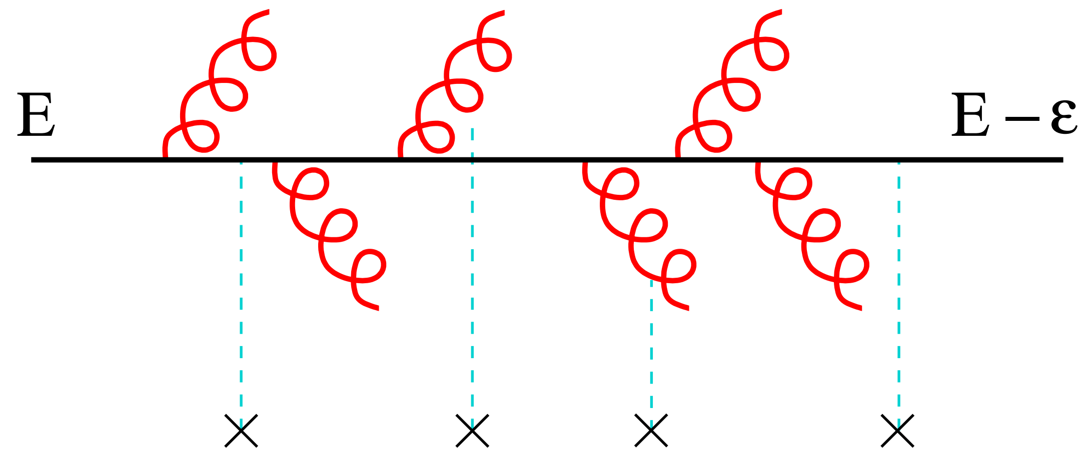
- Can be seen at LHC below $p_\perp \lesssim 10$ GeV

Jet quenching

Energy loss

Multiple soft collisions of the hard parton

- Gluon radiation $dI/d\omega$ proportional to the medium density



[Baier, Dokshitzer, Mueller, Peigné, Schiff 1996, 1997]
[Gyulassy, Wang 1994; Gyulassy, Lévai, Vitev 2000]
[Zakharov 1996 1997 1998 ; Wiedemann 2000 2001]

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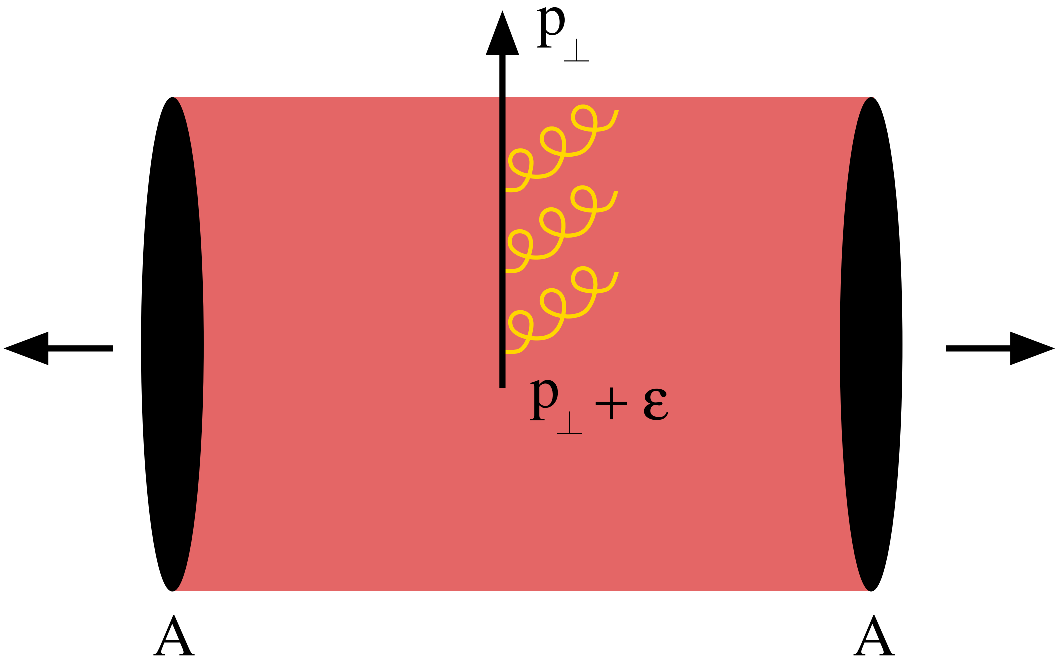
How to probe this mechanism ?

Energy loss



A clear experimental observable

Quenching of jets (or hadrons) in heavy ion collisions

[Bjorken 1982; Gyulassy & Wang 1992]

Quantifying the quenching

$$R_{AA}(p_\perp) = \frac{\mathrm{d}\mathcal{N}_{AA}(p_\perp)}{\mathrm{d}\mathbf{p}_\perp} \Big/ \frac{A^2\,\mathrm{d}\mathcal{N}_{pp}(p_\perp)}{\mathrm{d}\mathbf{p}_\perp}$$

$$\approx \int_0^{+\infty} d\epsilon\,\mathcal{P}(\epsilon) \times \frac{\mathrm{d}\sigma_{pp}(p_\perp+\epsilon)}{\mathrm{d}\mathbf{p}_\perp} \Big/ \frac{\mathrm{d}\sigma_{pp}(p_\perp)}{\mathrm{d}\mathbf{p}_\perp}$$

where $\mathrm{d}\sigma_{pp}(p_\perp)/\mathrm{d}\mathbf{p}_\perp$ is known in perturbative QCD

$$\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}\,\mathbf{p}_\perp} = \sum_{i,j,k=q,g} \int dx_1 dx_2 F_{i/p}(x_1, M) F_{j/p}(x_2, M)$$

$$\times \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 \frac{\mathrm{d}\widehat{\sigma}^k_{ij}}{\mathrm{d}\,\mathbf{p}_\perp\,\mathrm{d}y}\,\frac{dz}{z^2}\,D_{\pi/k}(z, M_F)$$

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- $\mathcal{P}(\epsilon)$ probability for a hard parton to lose an energy ϵ

Knowledge of $\mathcal{P}(\epsilon)$ essential

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Knowledge of $\mathcal{P}(\epsilon)$ essential

- Problem

How to relate $\mathcal{P}(\epsilon)$ to

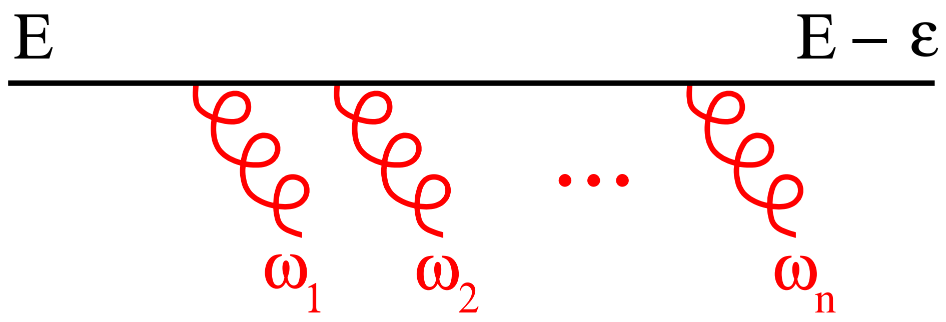
the gluon spectrum $dI/d\omega$?

[Baier, Dokshitzer, Mueller, Schiff 2001]

Quenching weight $\mathcal{P}(\epsilon)$

Independent gluon radiation ➛ Poisson approximation

[Baier, Dokshitzer, Mueller, Schiff 2001]



$$\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right)$$

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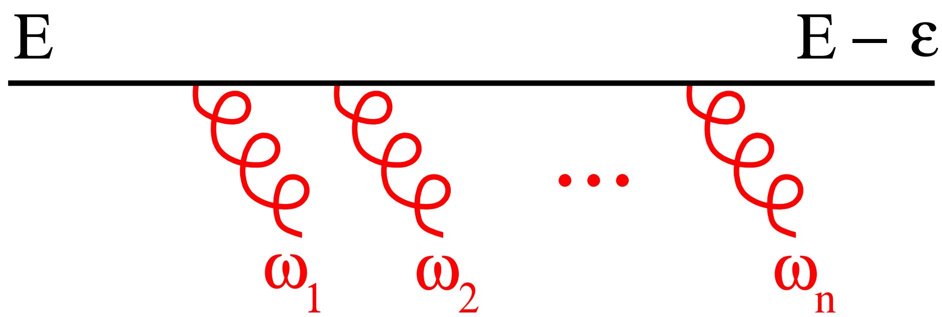

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- Unique ingredient: gluon spectrum $dI/d\omega$

Scale

Relevant scale for the induced gluon spectrum $dI/d\omega$

[Baier, Dokshitzer, Mueller, Schiff 2001]

$$\omega_c = \frac{1}{2}\,\hat{q}\,L^2$$

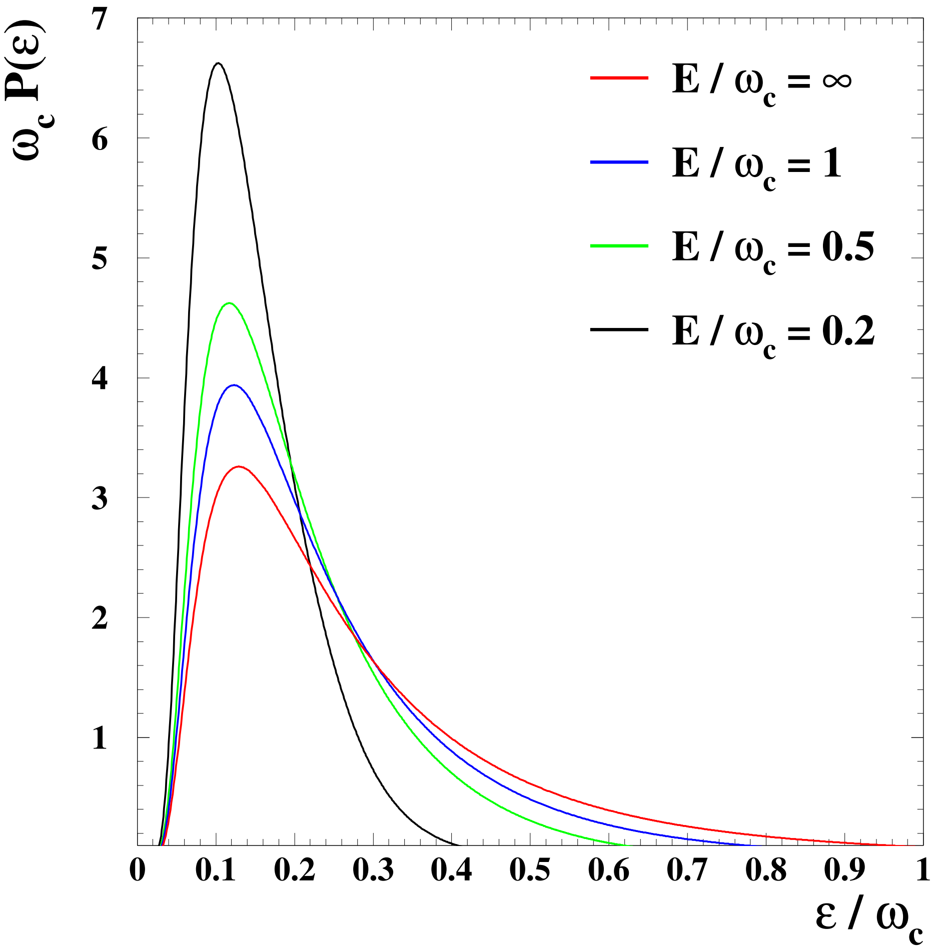
- $\hat{q}$: transport coefficient
  - scattering property of the medium
- L : length of matter covered by the hard parton
  - should be integrated over the whole production volume

Calculating quenching weights

[Baier, Dokshitzer, Mueller, Schiff 2001]

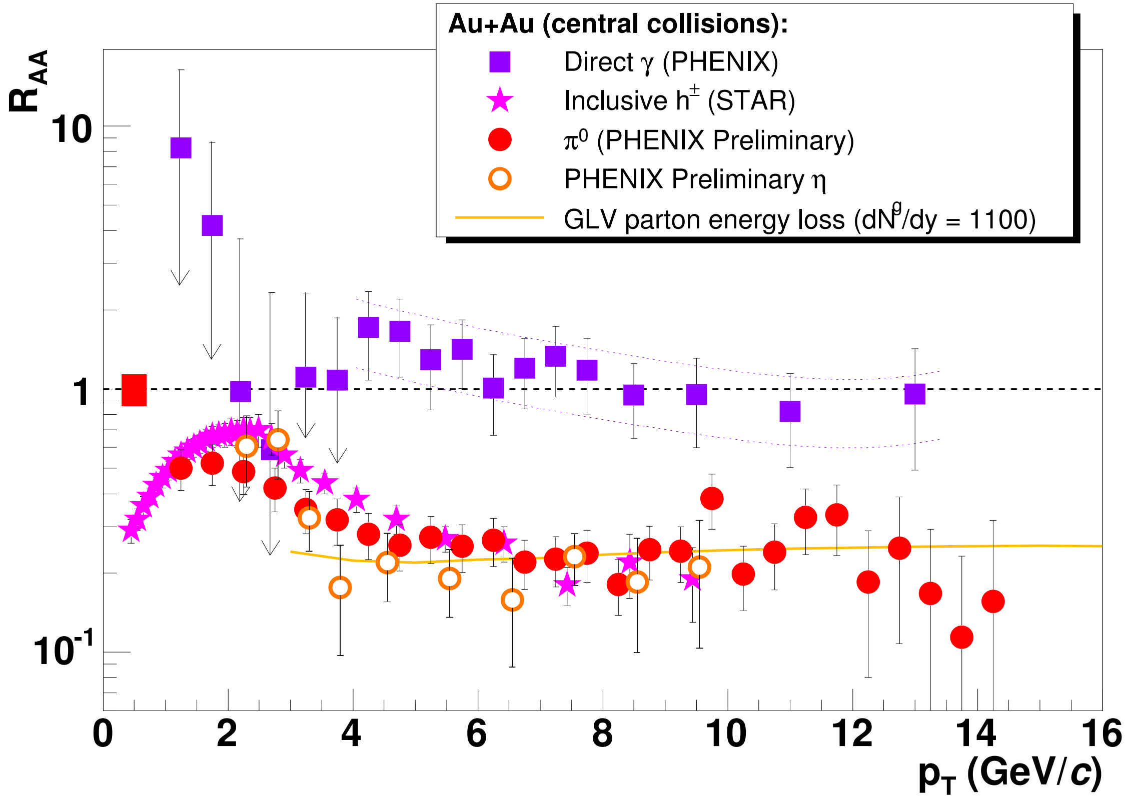
[Salgado Wiedemann 2002]

[FA 2002]



Data

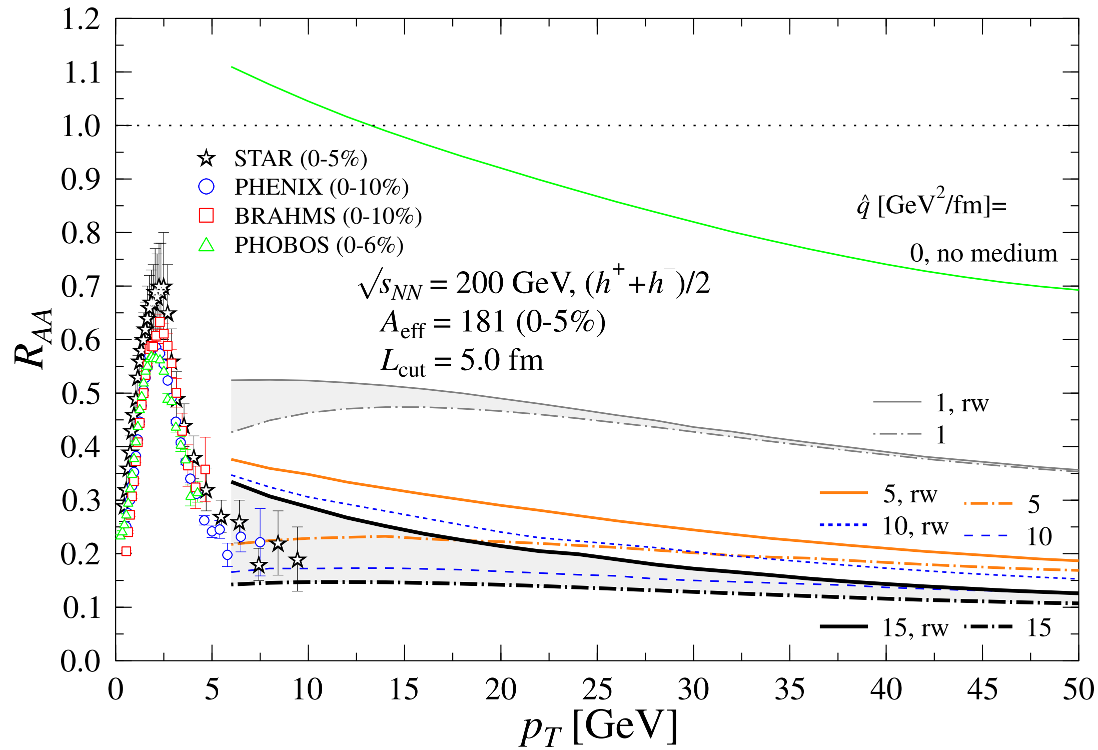
Experimentally



[PHENIX 2004]

- Strong suppression observed at RHIC for large $p_\perp$ pions
- Almost no suppression for prompt photons

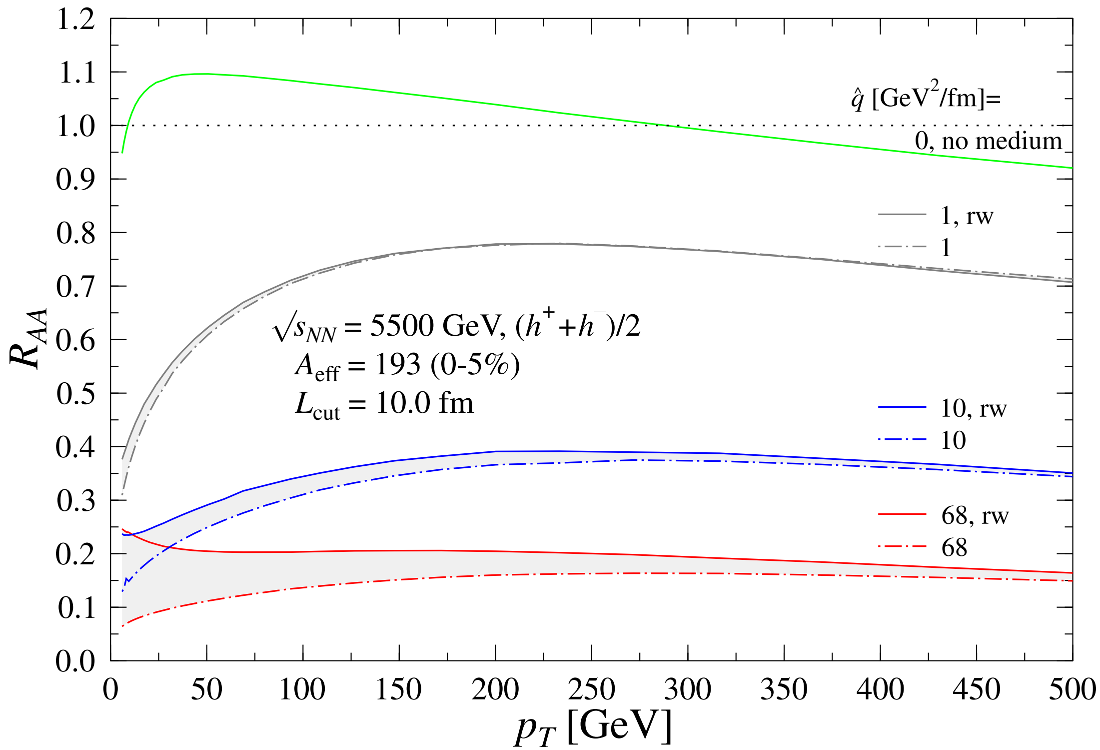
Theory at RHIC



[Eskola et al. 2004]

- Good agreement with theoretical expectations provided $\hat{q} \simeq 5$–15 GeV^2/fm
  - Evidence for very dense medium formation at RHIC !

Theory at RHIC



[Eskola et al. 2004]

- Factor of 5 suppression up to very large $p_\perp$

Limitations

Parton energy not fixed

Single inclusive spectra in pQCD to leading-order

$$\frac{\mathrm{d}\sigma^{\pi}}{\mathrm{d}\,\mathbf{p}_{\perp}\,\mathrm{d}y} = \sum_{i,j,k=q,g} \int dx_1 dx_2 F_{i/p}(x_1, M) F_{j/p}(x_2, M) \times \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 \frac{\mathrm{d}\widehat{\sigma}_{ij}k}{\mathrm{d}\,\mathbf{p}_{\perp}\,\mathrm{d}y} \frac{dz}{z^2} D_{\pi/k}(z, M_F)$$

do not allow one to determine

- parton energy $k_{\perp}$ thus the variable $z = p_{\perp_\pi}/k_{\perp}$
- medium-modified fragmentation functions

Limitations

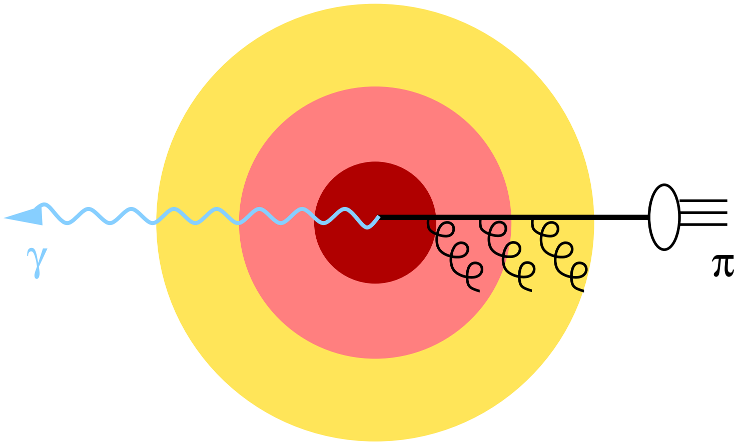
Parton energy not fixed

Need to go beyond single-inclusive production to better understand the medium-modified fragmentation processes

prompt photon — hard pion correlations

Correlations

- To leading-order in α_s



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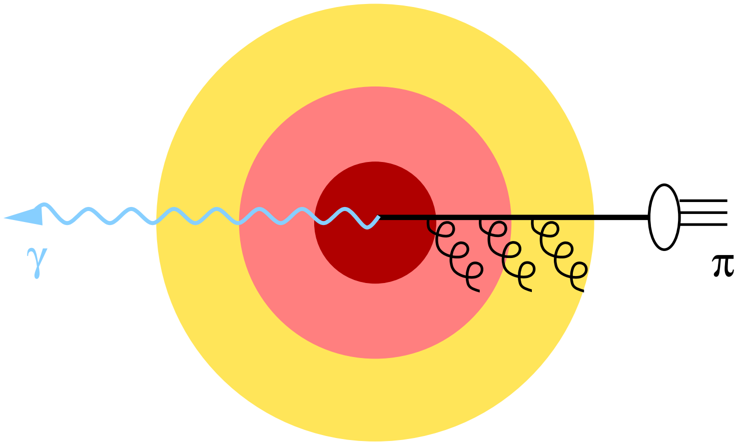


$$\mathbf{k}_\perp \simeq -\mathbf{p}_{\perp\gamma}$$

- Momentum imbalance

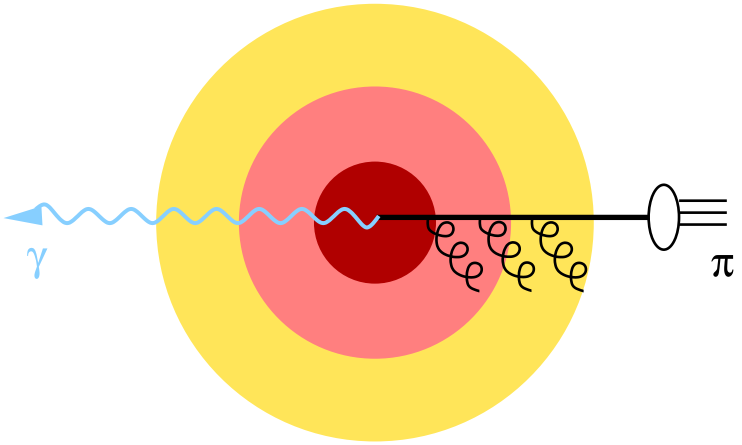
$$z_{\gamma\pi} \equiv -\frac{\mathbf{p}_{\perp\pi} \cdot \mathbf{p}_{\perp\gamma}}{|\mathbf{p}_{\perp\gamma}|^2} \simeq z$$

allows for the estimate of the fragmentation variable z

[FA, Aurenche, Belghobsi, Guillet 2004]
[FA 2006]

Correlations

- To leading-order in α_s



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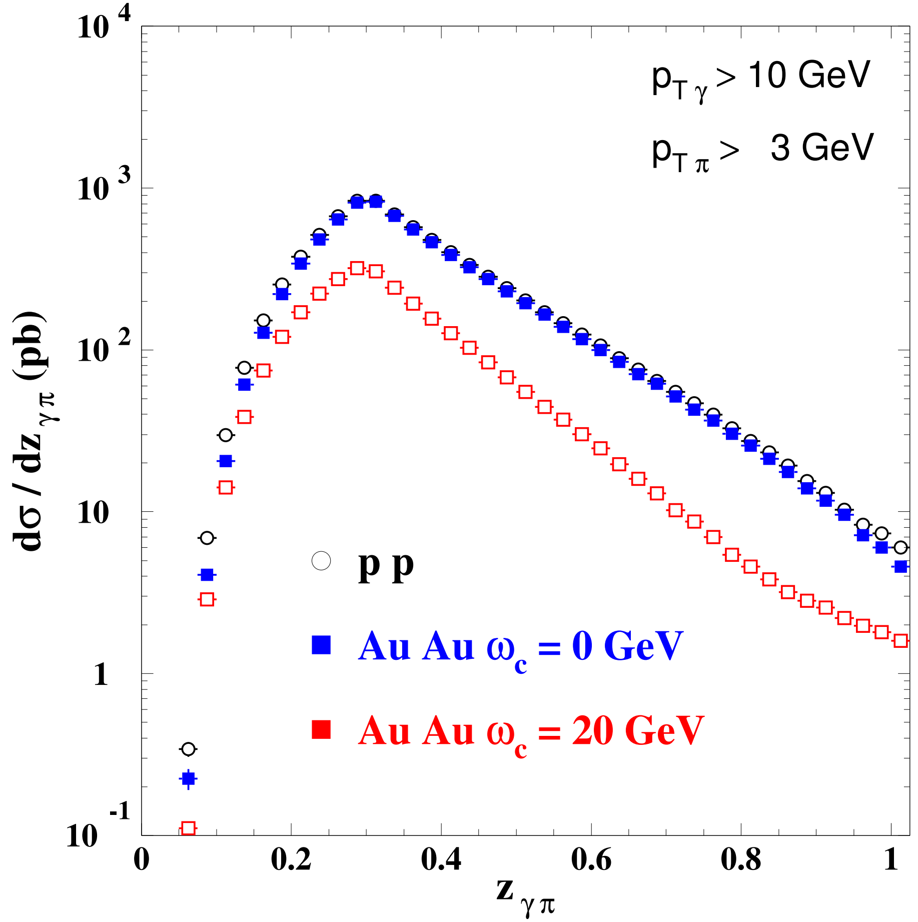
perturbative calculation of correlation distributions

in $p\,p$ et A A collisions at RHIC & LHC

[FA, Aurenche, Belghobsi, Guillet 2004]

[FA 2006]

Probing medium-modified fragmentation



- Pronounced effects at large z
- Reflects fragmentation functions

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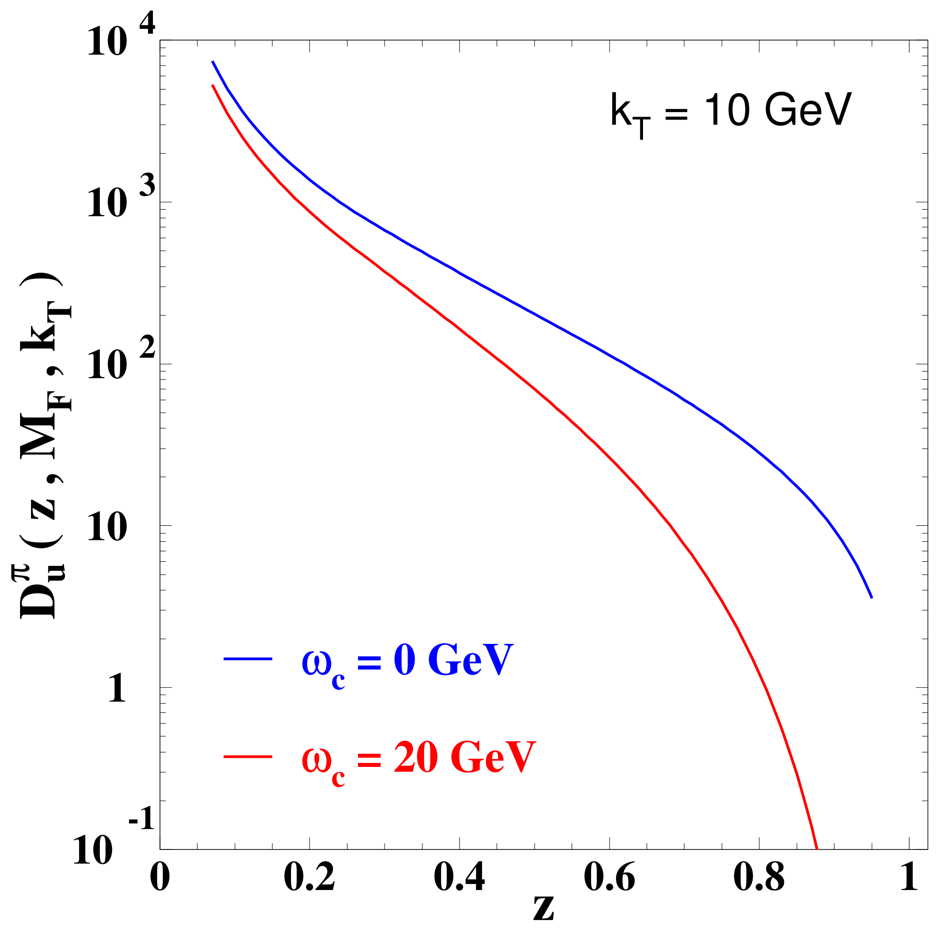

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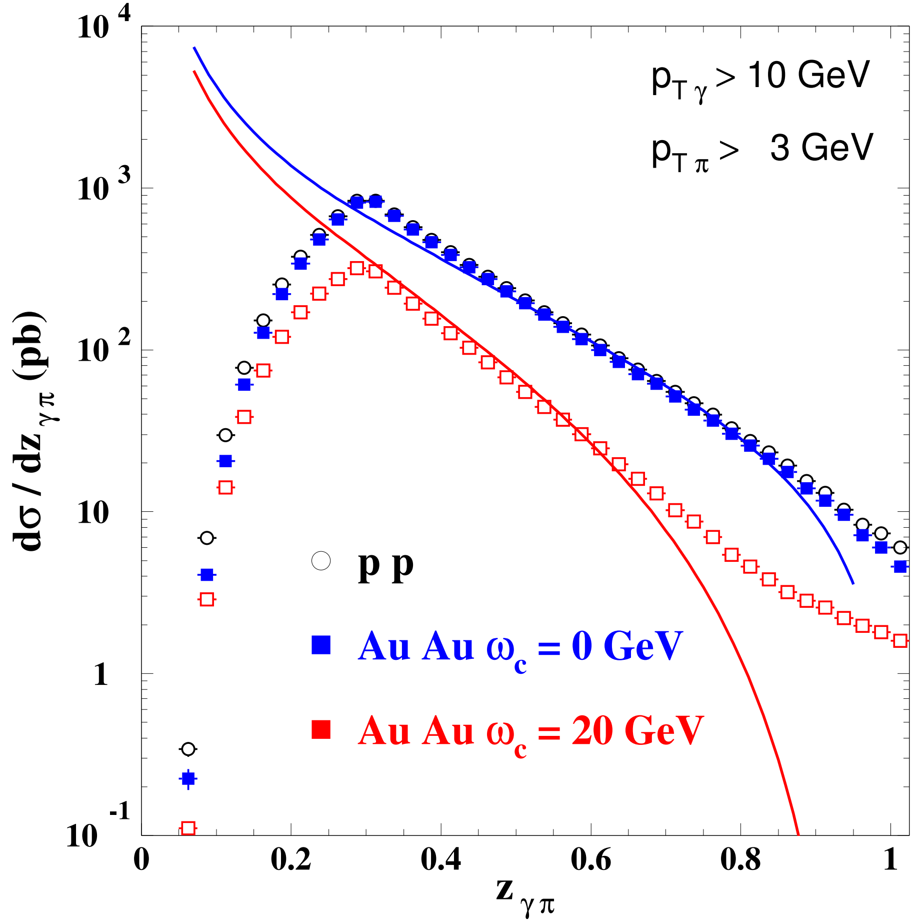

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  - Crucial need to understand all possible nuclear effects

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- Photon production
  - Possible hints for thermal production at RHIC (?)
- Jet quenching
  - Significant results obtained at RHIC
  - Need for more exclusive observables (jet shapes, photon tagged measurements) at the LHC

Heavy ions at the LHC

The medium produced at the LHC is expected to be

longer, denser, bigger than at RHIC !

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  - Debye screening or recombination: LHC will tell
- Jet quenching
  - Access to medium-induced gluon radiation through the study of jet structure