# Advanced Topics in Particle Physics: LHC Physics

# Part III: Heavy-Ion Physics

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# 6 Quarkonia

# Quarkonia

- Quarkonia are heavy quark antiquark bound states, i.e. ccbar and bbar
- Since masses of charm and beauty quarks are high as compared to QCD scale parameter $\Lambda_{QCD}$ ~ 200 MeV non-relativistic Schrödinger equation can be used to find bound states

$$(-\frac{\nabla^2}{2(m_Q/2)} + V(r))\Psi(\vec{r}) = E\Psi(\vec{r})$$

with quark-quark potential of the form

$$V(r) = kr - \frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9}\frac{\vec{s}_1 \cdot \vec{s}_2}{m_Q^2}\delta(\vec{r}) + \ldots$$

confinement

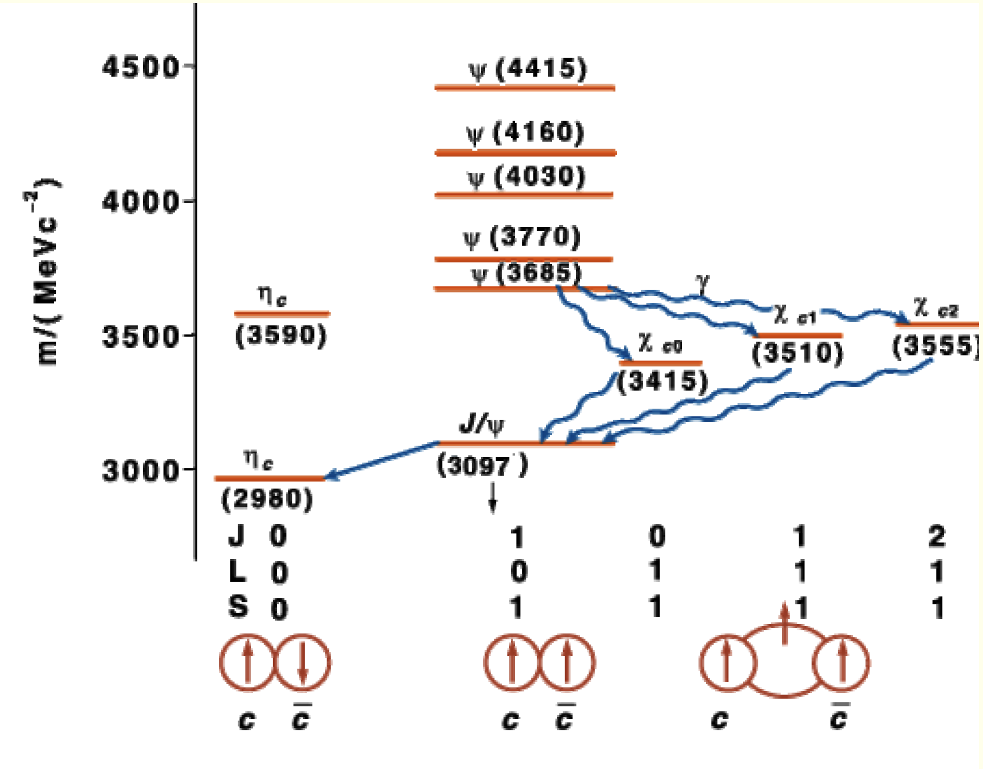
color Coulomb int.

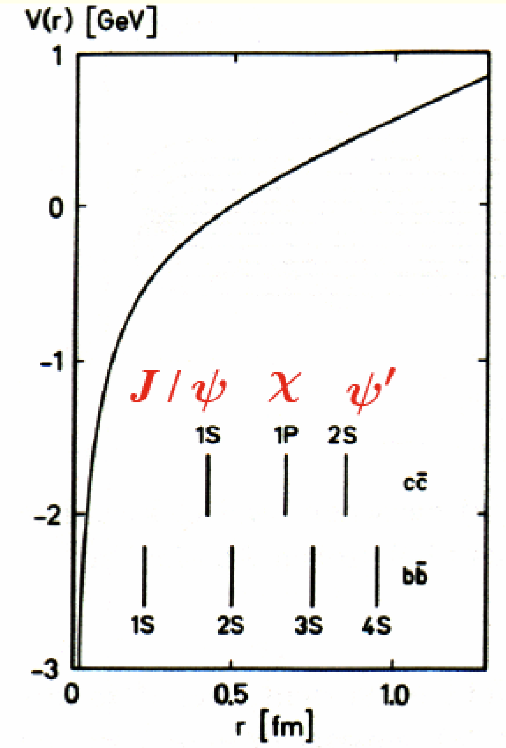
spin-spin int.

tensor, spin-orbit, higher order rel. corr.

- With $k$ ~ 0.9 GeV/fm, $\alpha_s(m_Q)$ ~ 0.35 and 0.20 for $m_c$ = 1.5 GeV and $m_b$ = 4.6 GeV obtain spectrum of quarkonia

# Charmonium States

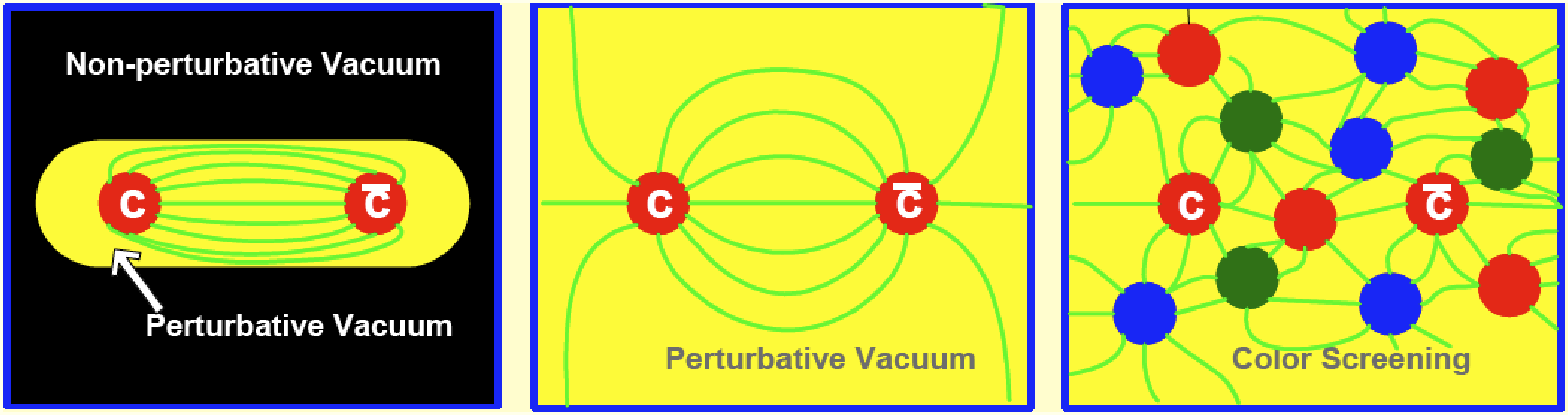



| | J/Ψ | χ | Ψ' |
|---|---|---|---|
| *m* (GeV) | 3,1 | ~ 3,5 | ~ 3,68 |
| *r* (fm) | ~ 0,45 | ~ 0,70 | ~ 0,88 |

$$m_{\mathrm{Charm-Quark}} \approx 1.3 - 1.5\,\mathrm{GeV}$$

# Debye Screening and Effective Heavy-Quark Potential in the QGP (I)



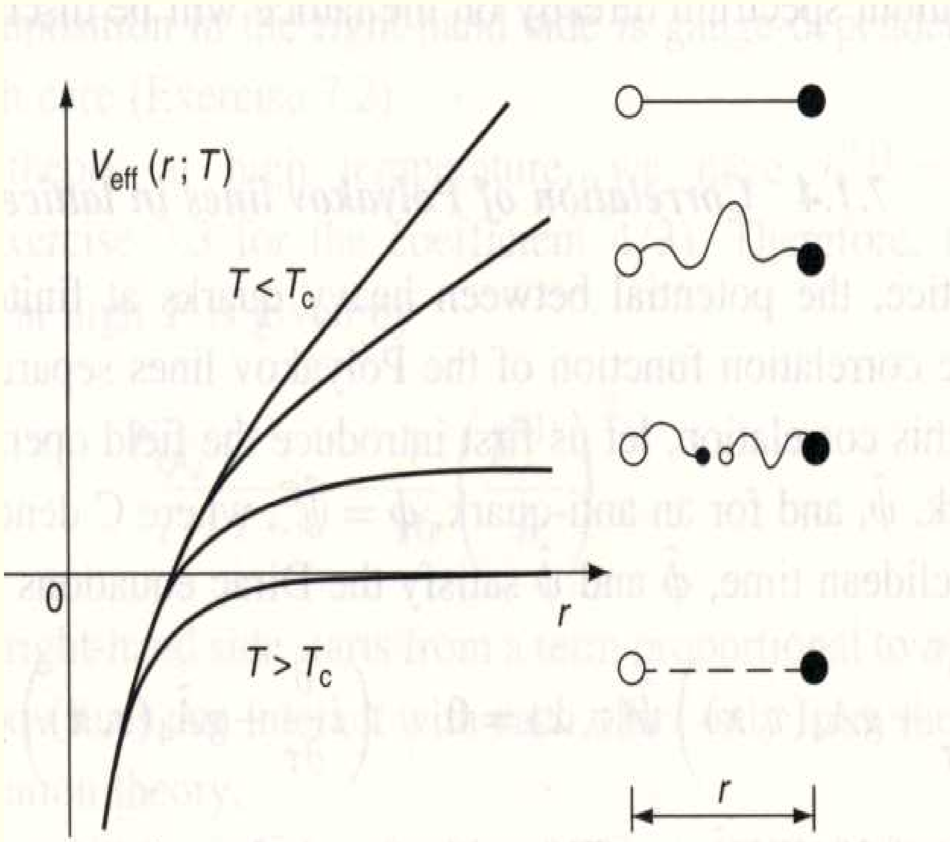

Effect of medium with finite temp. (i.e. QGP) on heavy-quark potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr \;\rightarrow\; V_{\text{eff}}(r,T) = -\frac{4}{3}\frac{\alpha_s}{r} e^{-r/r_D(T)} + \overbrace{k\, r_D(T)\left(1 - e^{-r/r_D(T)}\right)}^{\rightarrow kr \text{ for } T\rightarrow 0}$$

where $r_{\mathrm{D}}(T) \sim \frac{1}{g(T)\cdot T}, \quad \alpha_s = \frac{g^2}{4\pi} \qquad g(T) \approx \frac{24\pi^2}{(33-2n_{\mathrm{f}})\ln(T/\Lambda)}$

In the QGP the heavy-quark interaction is strongly screened for distances above the Debye screening length $r_D$

# Debye Screening and Effective Heavy-Quark Potential in the QGP (II)




$$V_{\text{eff}}(r, T) \rightarrow -\frac{4}{3}\frac{\alpha_s}{r}e^{-r/r_D}$$

"Yukawa potential"

Unlike Coulomb potential, Yukawa potential does not always have bound states

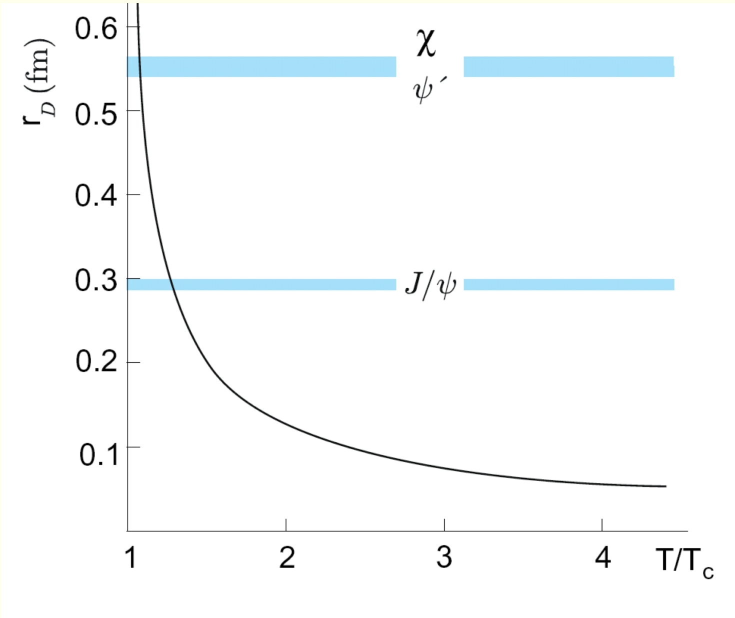
→ Dissociation of quarkonia if $r_D$ is sufficiently small, i.e., no bound states for hadrons with "Bohr" radius $r > r_D$

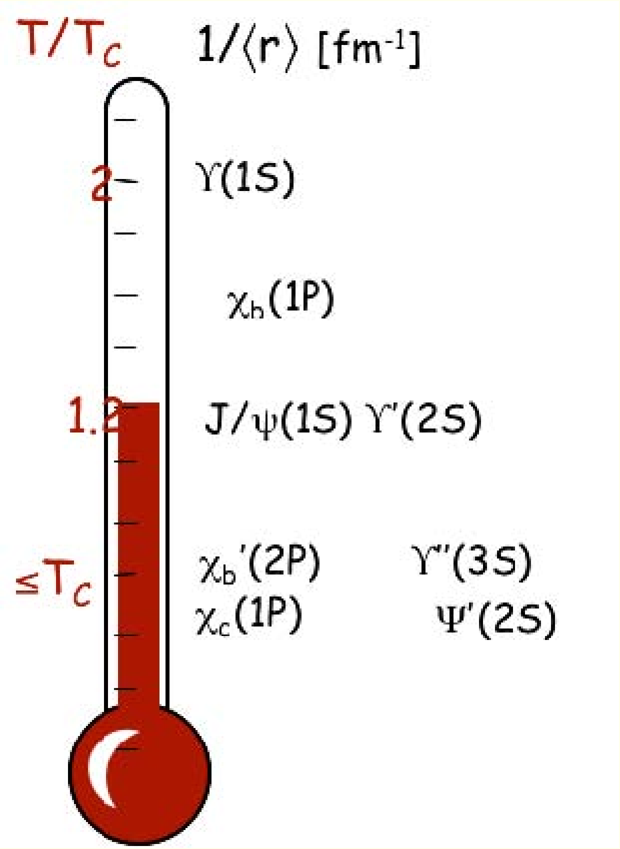
# J/Ψ Suppression as a QGP Signal

- Charmonium will dissociate/cannot form in a QGP
- J/ψ suppression was proposed in 1986 by Matsui and Satz as a QGP signature (Phys. Lett. B 178 (1986) 416)

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents cc binding in the deconfined interior of the interaction region …/… It is concluded that J/Ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation

# Different Dissociation Temperatures for Different ccbar and bbar States: A "QGP Thermometer"




| | $J/\psi$ | $\psi$' | $\chi_c$ | $\Upsilon$ | $\Upsilon$' |
|---|---|---|---|---|---|
| state | 1s | 2s | 1p | 1s | 2s |
| mass(GeV) | 3.1 | 3.7 | 3.5 | 9.4 | 10.0 |
| r (fm) | 0.45 | 0.88 | 0.70 | 0.23 | 0.51 |
| $T_D/T_c$ | 1.17 | 1.0 | 1.0 | 2.62 | 1.12 |
| $\epsilon_D$ (GeV/fm$^3$) | 1.92 | 1.12 | 1.12 | 43.3 | 1.65 |

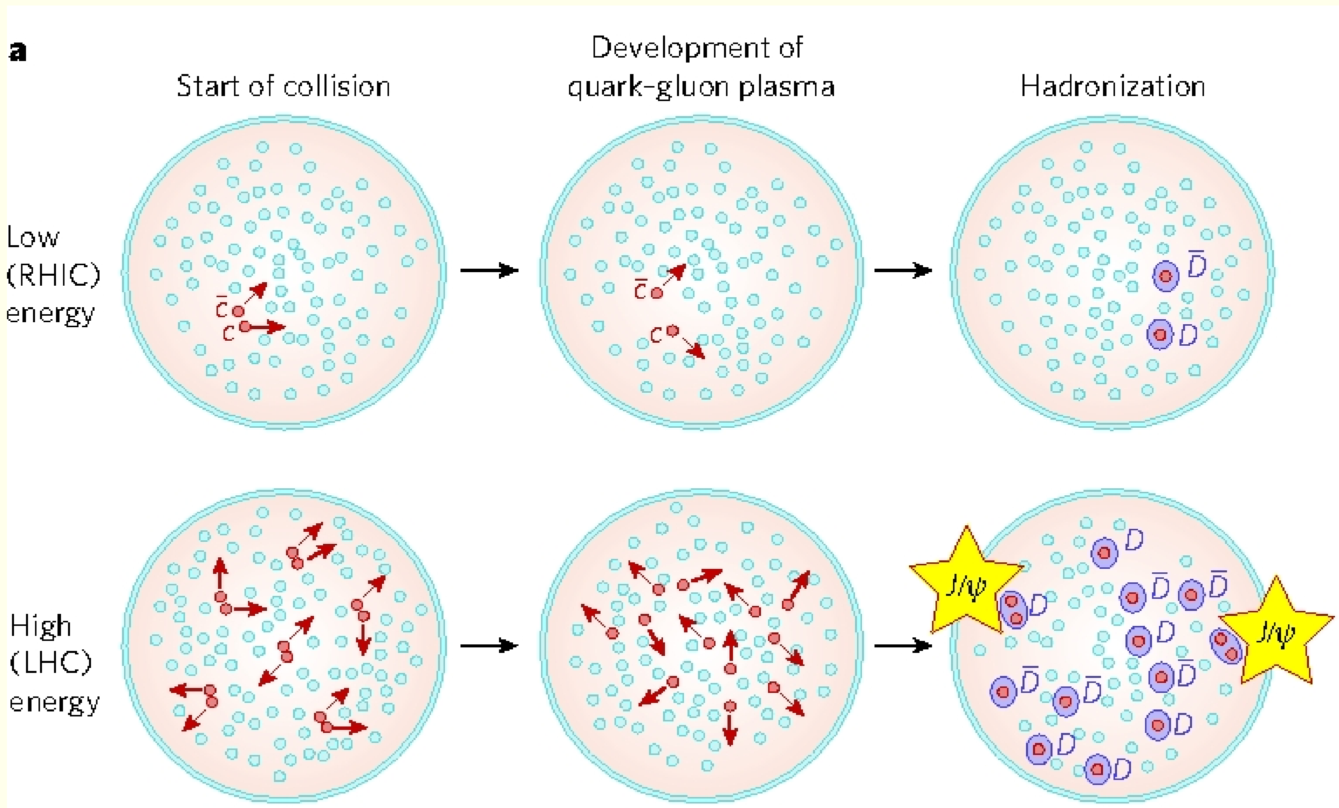
Exact values very model dependent, but basic feature: J/Ψ, Ψ', $\chi_c$, ϒ' not bound at or little above $T_c$, ϒ survives much longer

# Hadronization of Charm Quarks

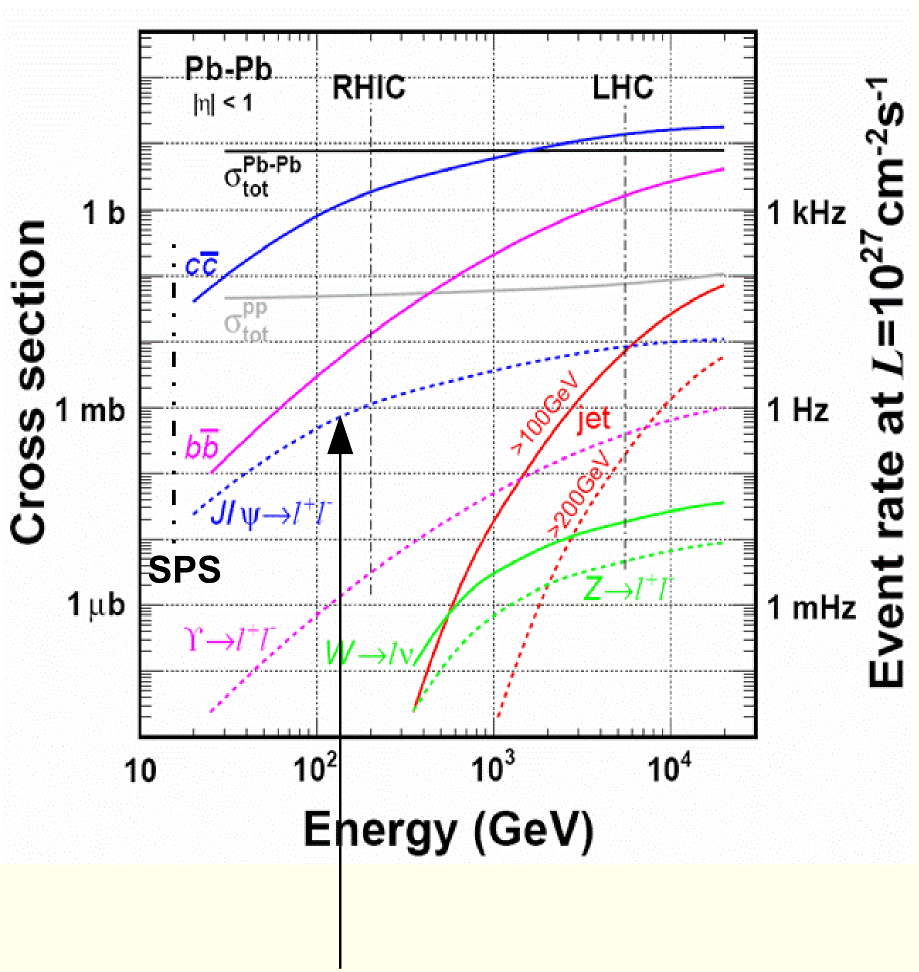
All charm quarks have to appear in charmed hadrons at hadronization of the QGP. J/ψ's can form again from deconfined quarks in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \propto N_{cc}^{2}$

(P. Braun-Munzinger and J. Stachel,Phys. Lett. B490 (2000) 196)

Expect J/ψ suppression at low beam energies (SPS, RHIC) and J/ψ enhancement at high energies (LHC)



# Production of Charm and Beauty




Number of heavy-quark pairs per central PbPb or AuAu collision from these cross sections:

N($q\bar{q}$) per central AA (b=0)

| | SPS | RHIC | LHC |
|---|---|---|---|
| charm | 0.2 | 10 | 130 |
| bottom | --- | 0.05 | 5 |

J/Ψ is only a small fraction of order of 1% of these 6% detected via $l^+l^-$ decay

# Measurement of Quarkonia

$\mathrm{BR}(\mathrm{J}/\psi \to \mathrm{hadrons}) \approx 0.88$

$\mathrm{BR}(\mathrm{J}/\psi \to \mathrm{e}^+\mathrm{e}^-) \approx 0.06$

$\mathrm{BR}(\mathrm{J}/\psi \to \mu^+\mu^-) \approx 0.06$

$\mathrm{BR}(\psi' \to \mathrm{hadrons}) \approx 0.98$

of these $\mathrm{BR}(\psi' \to \mathrm{J}/\psi) \approx 0.60$

$\mathrm{BR}(\psi' \to \mu^+\mu^-) \approx 0.008$

$\mathrm{BR}(\Upsilon \to \mathrm{hadrons}) \approx 0.90$

$\mathrm{BR}(\Upsilon \to \mathrm{e}^+\mathrm{e}^-) \approx 0.025$

$\mathrm{BR}(\Upsilon \to \mu^+\mu^-) \approx 0.025$

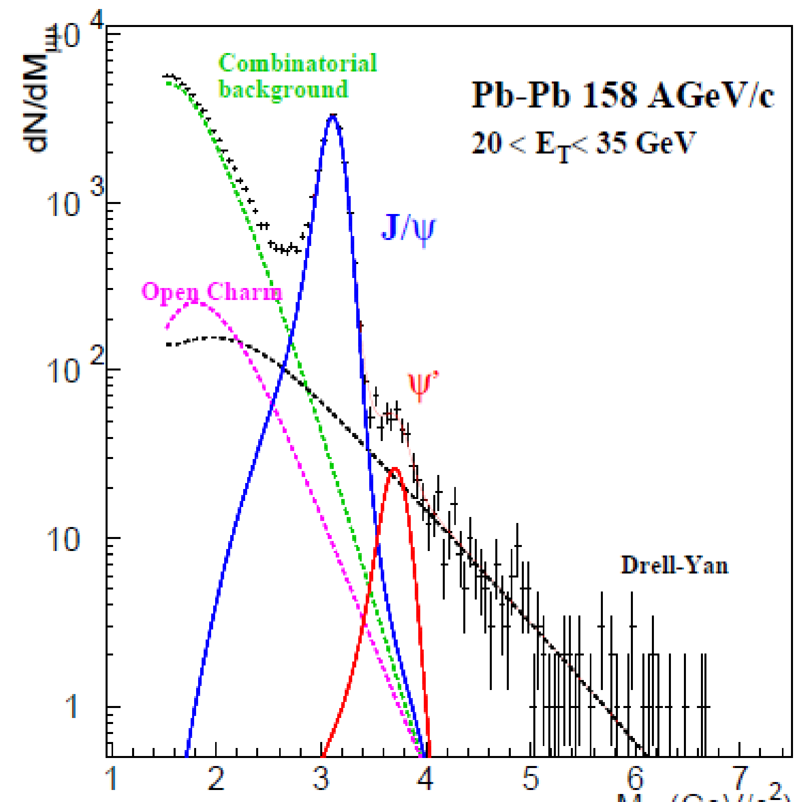
J/Ψ, Ψ' and Y via e+e- or μ+μ-

$\chi_c$ very difficult, usually done via

$\chi_c \to \mathrm{J}/\psi + \gamma$

Of measured J/Ψ typically:

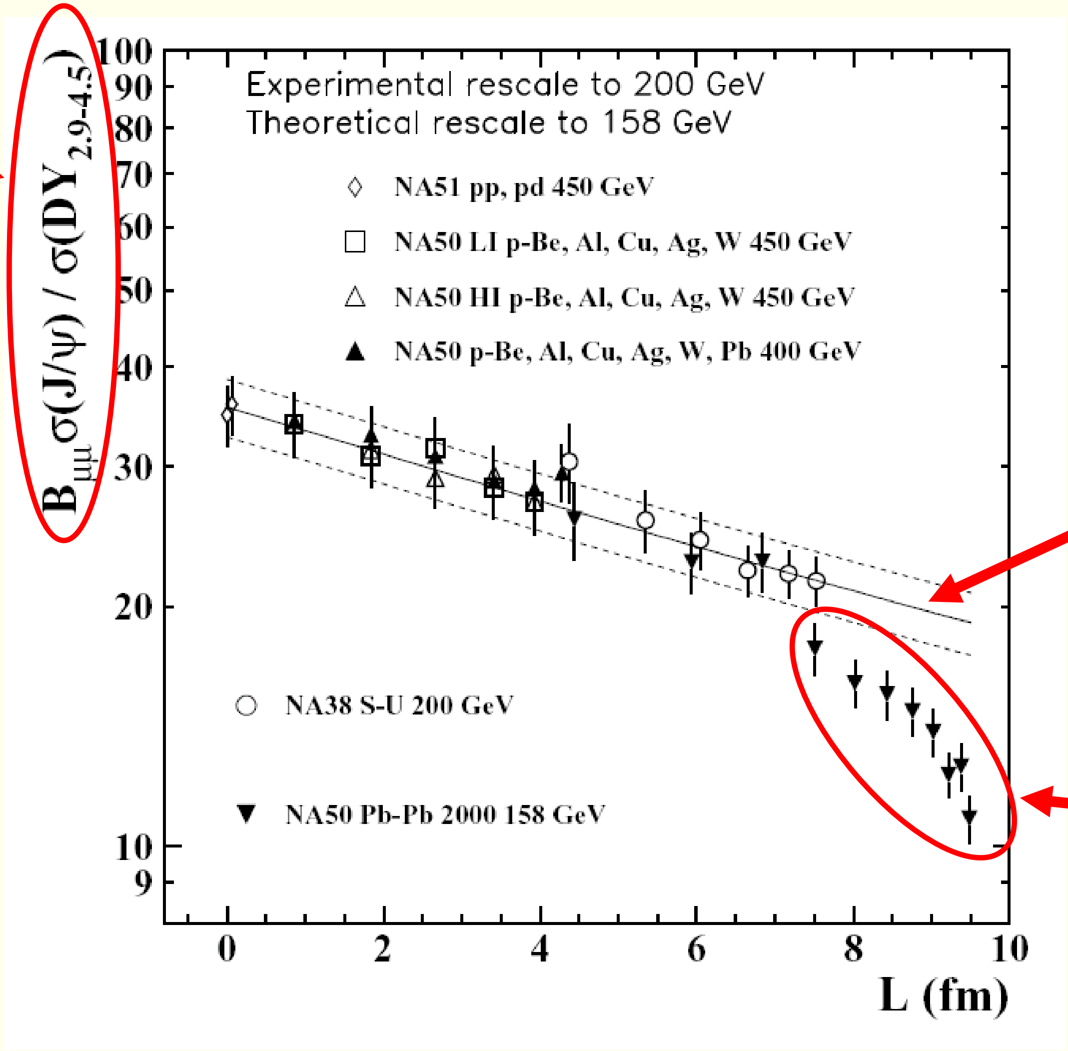
- $\approx 60\%$ directly produced
- $\approx 10\%$ from $\psi' \to J/\psi$
- $\approx 30\%$ from $\chi_c \to J/\psi$




NA50 at CERN SPS

# J/Ψ production in PbPb collisions at SPS energy

Normalization to Drell-Yan process

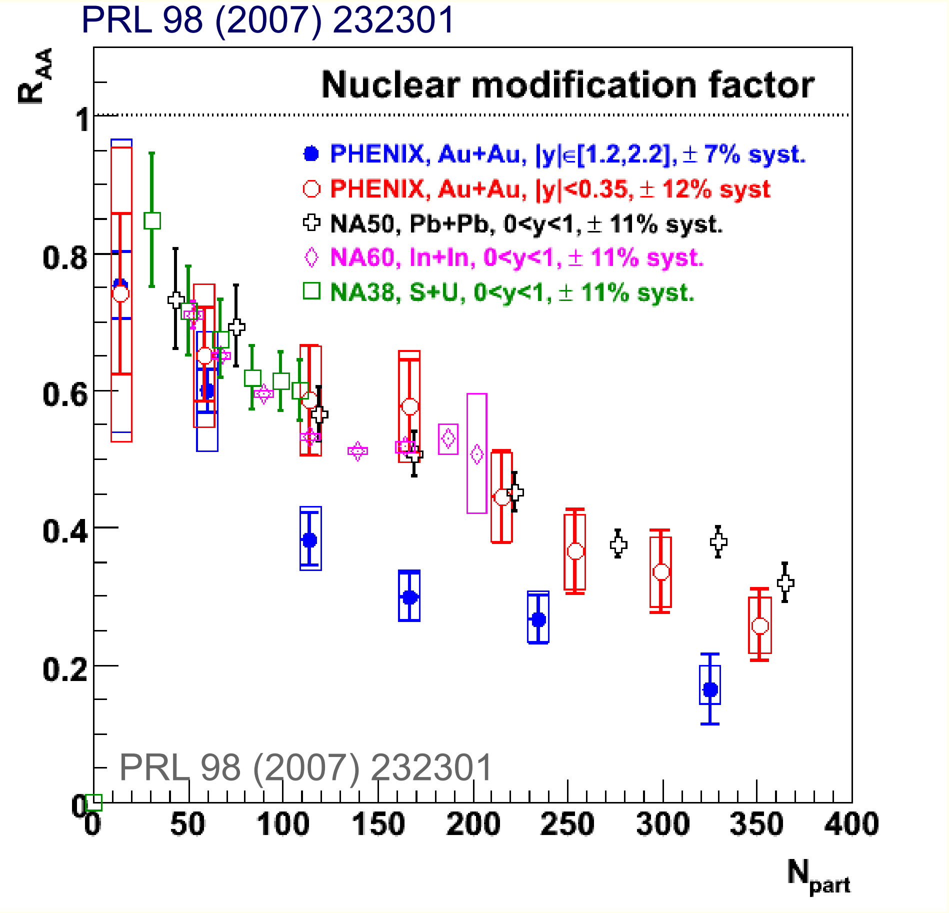



Normal J/Ψ suppression in nuclear matter

Anomalous J/Ψ suppression due to QGP?

In central PbPb collisions about 40% less J/Ψ than expected from pA systematics

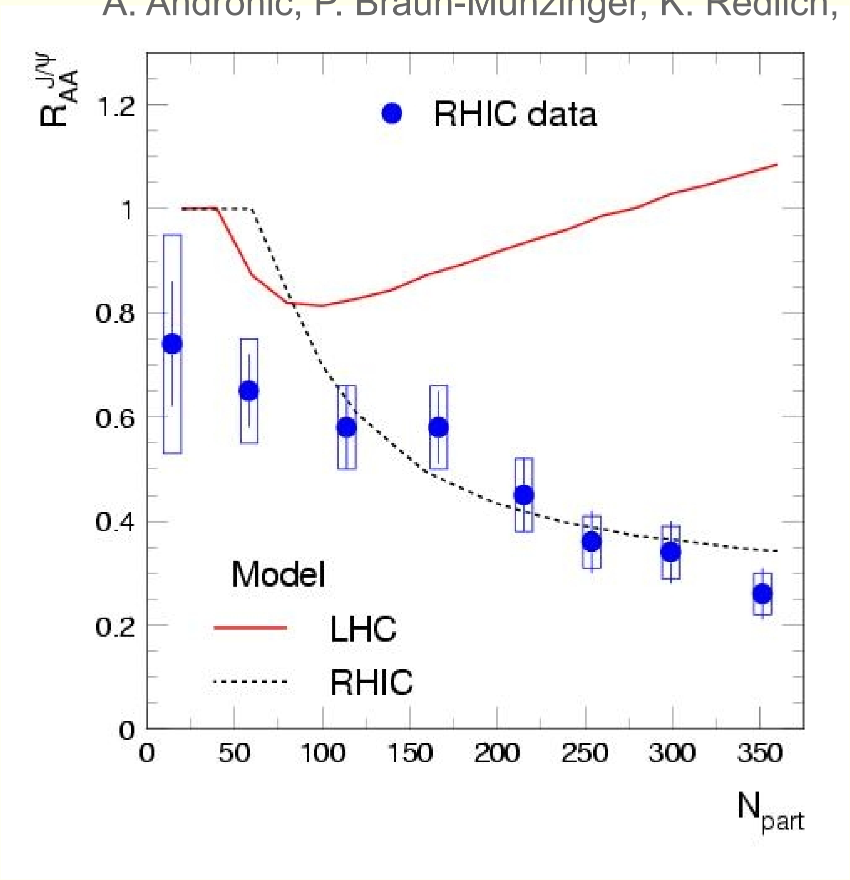
# J/Ψ Suppression at RHIC

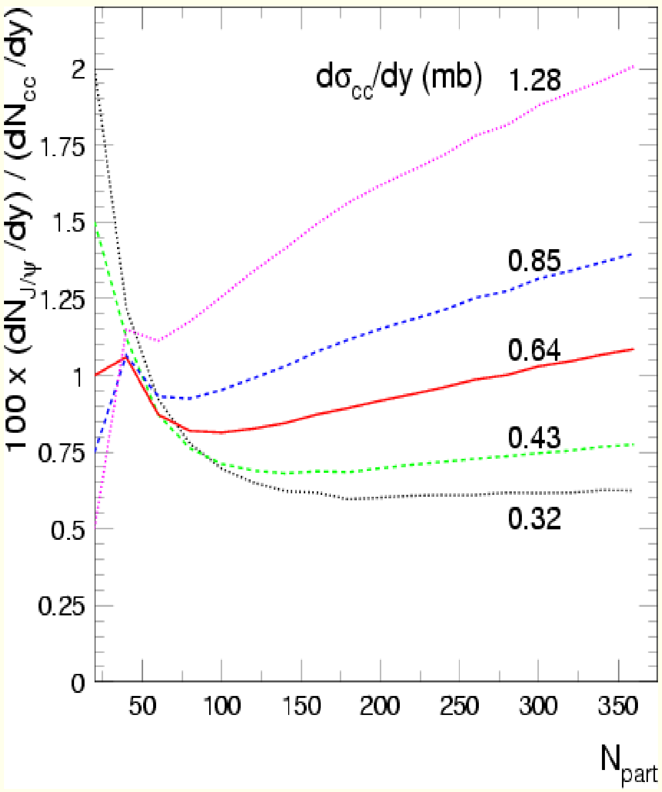



- At mid-rapidity suppression at RHIC very similar to SPS even though energy densities are larger
- Suppression at forward/backward rapidity stronger than at midrapidity!
- These general features are in agreement with J/Ψ formation from deconfined charm quarks ("recombination")

# Quarkonium Production at RHIC and LHC in the Statistical Hadronization Model

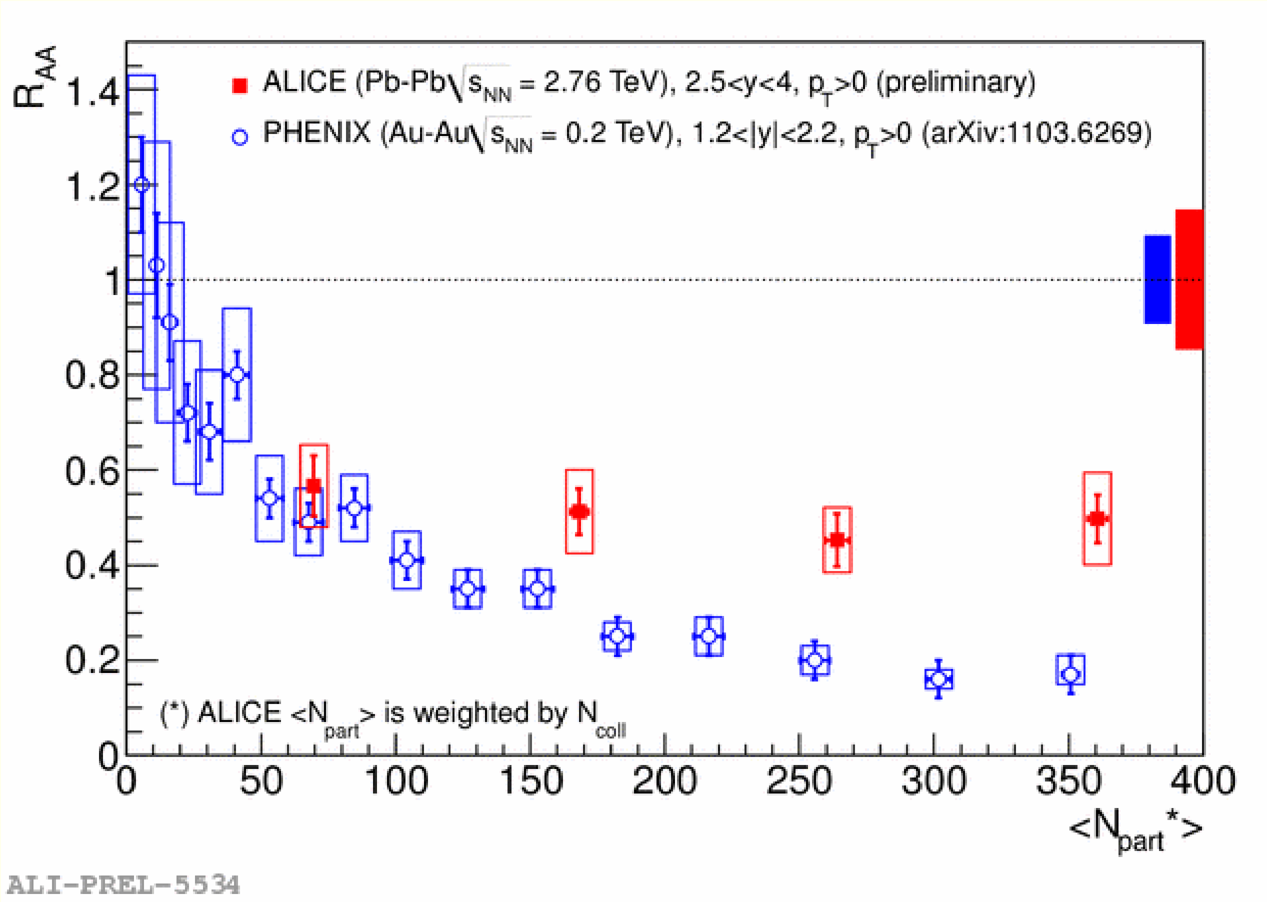
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259




Note: Stat. model does not make any prediction about ccbar production cross section, this is input; depending on ccbar cross section in nuclear collisions at LHC there can be J/Ψ enhancement

# First ALICE Data on J/Ψ $R_{AA}$ in Pb+Pb at the LHC

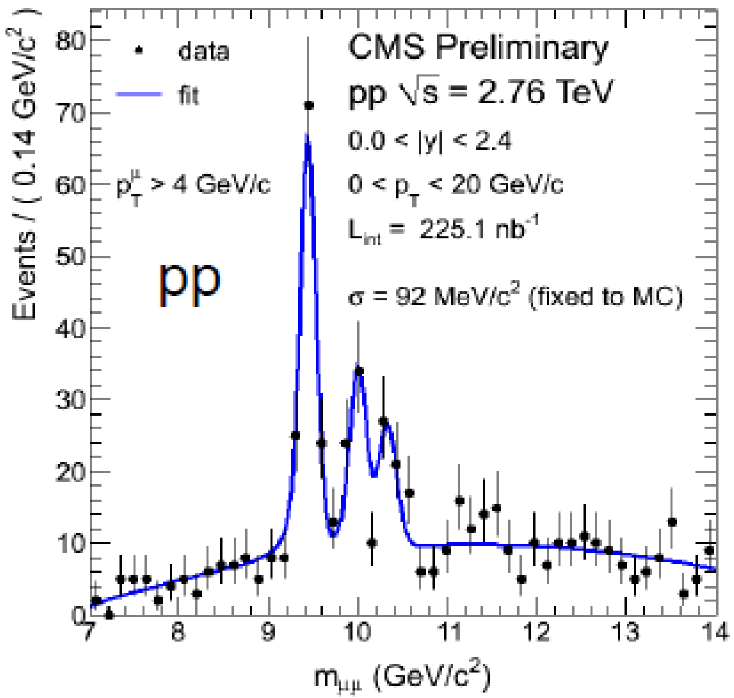


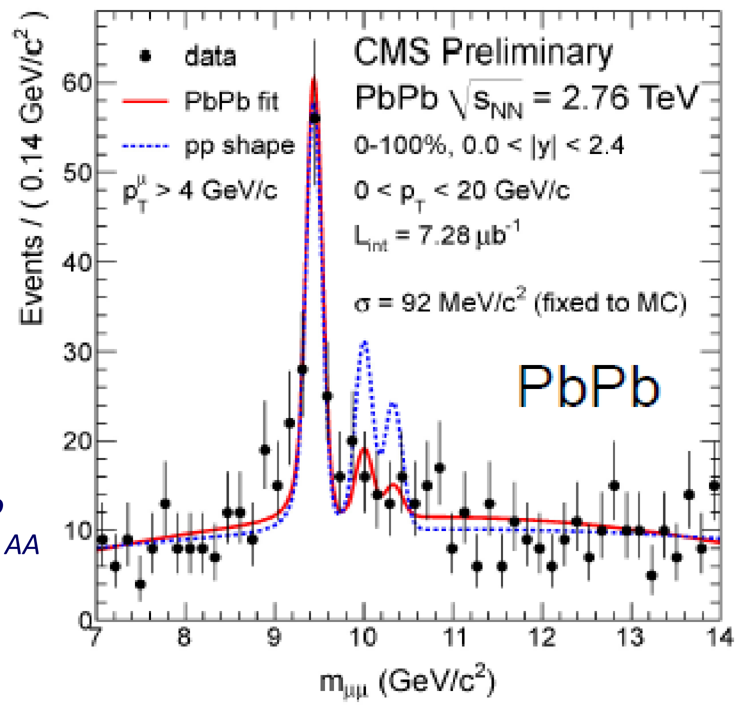

Contribution from B feed-down small: ~ 10% from p-p measurement (LHCb, arXiv:1103.0423)

J/Ψ $R_{AA}$ in central collisions is larger at LHC in 2.5<y<4 than at RHIC in 1.2<|y|<2.2. And shadowing at LHC estimated to be large.
Conclusion: the $R_{AA}$ for J/Ψ is large! Could point to charm quark recombination.

# First information on Upsilon States in Pb+Pb at LHC

Final data: Phys.Rev.Lett. 107 (2011) 052302




$R_{AA}$

$$\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\Big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

Consistent with expectation that more loosely bound 2S and 3S states are more strongly suppressed

# 7 Thermal Photons

# Motivation for Measuring Direct Photons in Heavy-Ion Collisions

## High $p_T$ (> 6 GeV/$c$):

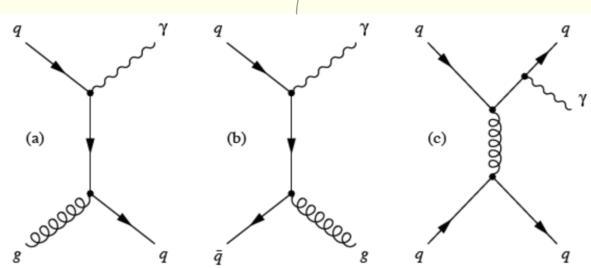
- High-$p_T$ direct photons produced in initial hard parton-parton scatterings
- Photons leave the subsequently produced medium (quark-gluon plasma !?) unaltered
- Test hard scattering predictions
- Measure rate of hard processes

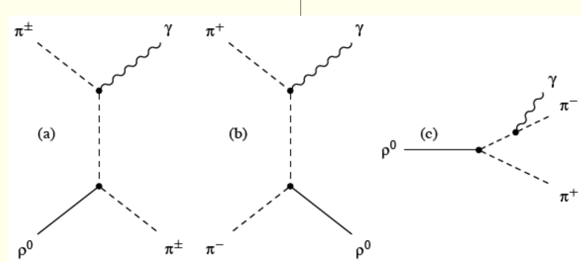
## Low / Intermediate $p_T$:

- Low $p_T$ thermal direct photons expected to reflect the initial temperature of the thermalized fireball
- Temperatures above $T_c$ indicate quark-gluon plasma phase
- Search for evidence for jet-plasma interactions?

# Known and Expected Photon Sources

- **Photons in A+A**
  - **Direct Photons**
    - **hard**
      - **direct**
      - **bremsstrahlung fragmentation**
    - **Preequilibrium photons**
    - **thermal**
      - **QGP**
      - **Hadron gas**
    - **Jet-medium interaction**
      - **jet-γ-conv.**
      - **medium induced γ bremsstr.**
  - **Decay Photons**



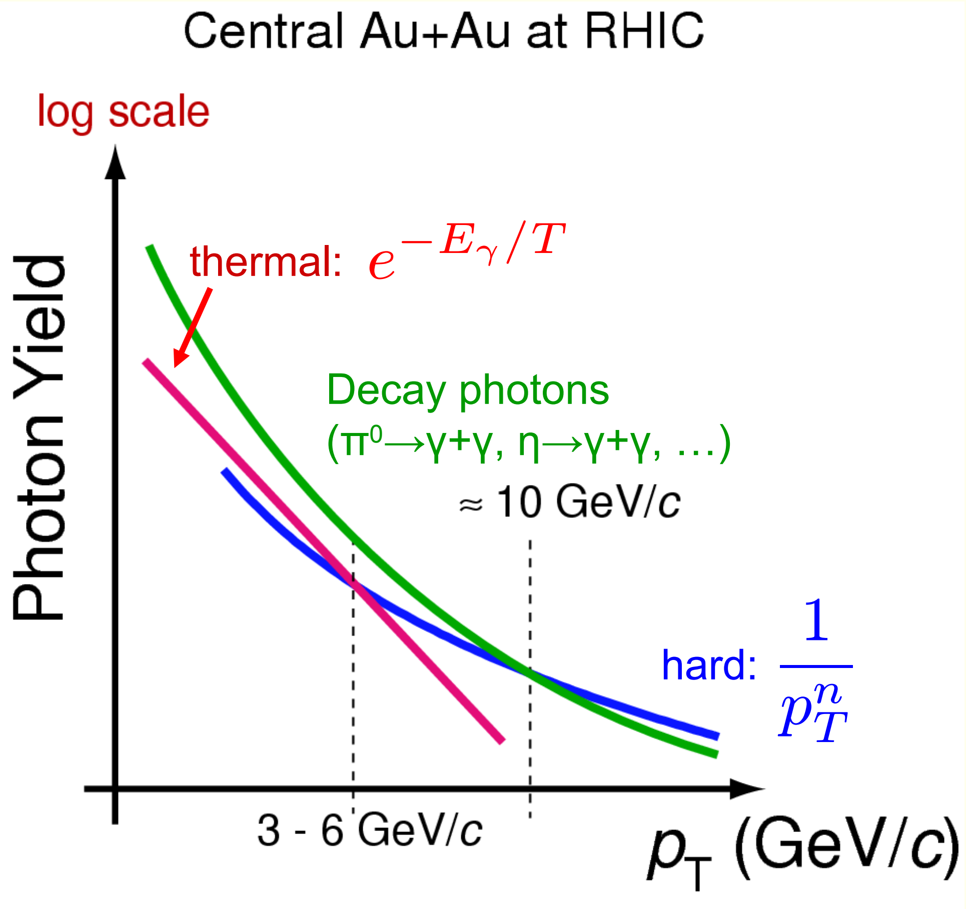




$$\text{e.g.}: g + q_{\text{QGP}} \rightarrow q + \gamma$$

gluon jet

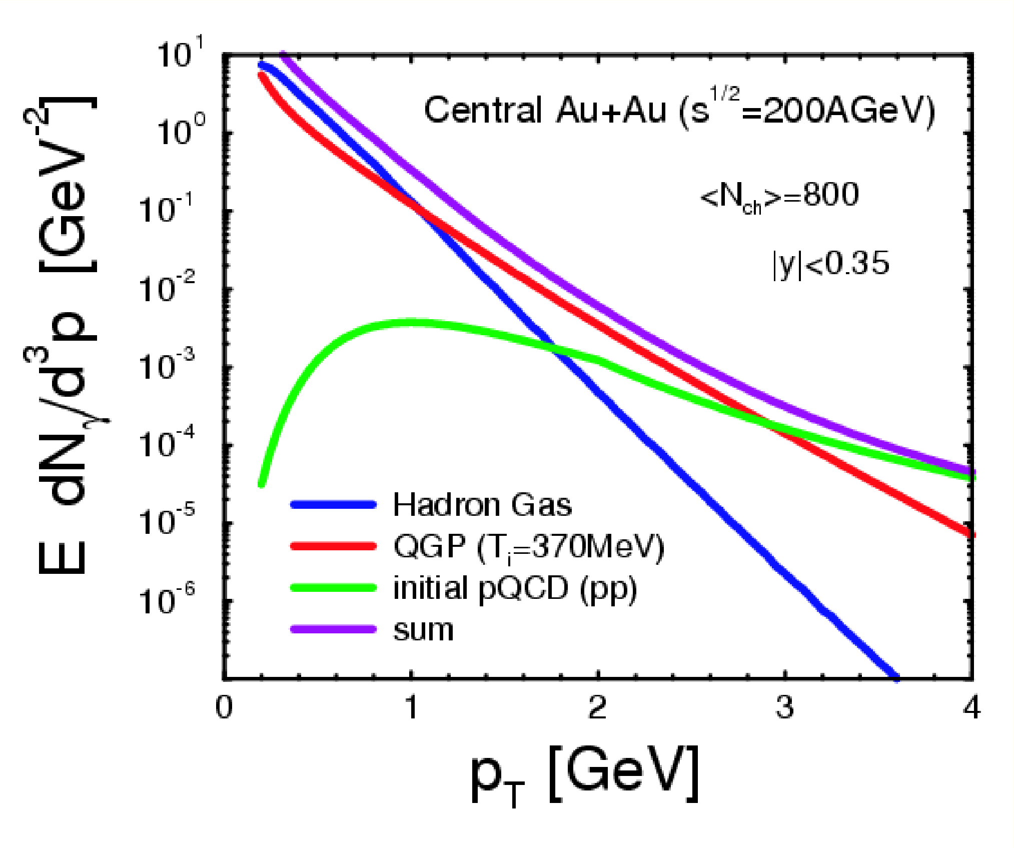
$$\sigma_{jet(q)\rightarrow\gamma(p)} \propto \delta(q-p)$$

# Schematic Photon Spectrum in A+A




- Thermal photons expected to be significant contribution below $p_T$ ~ 3 GeV/*c*
- Hard photons dominant direct photon source for $p_T$ > ~ 6 GeV/*c*
- Jet-photon conversion might be significant contribution below $p_T$ ~ 6 GeV/*c*

# Calculation: Sources of Direct Photons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV




Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

Window for thermal photons from QGP in this calculation: $p_T$ = 1 - 3 GeV/*c*

# Direct Photons in A+A Collisions: Measurements

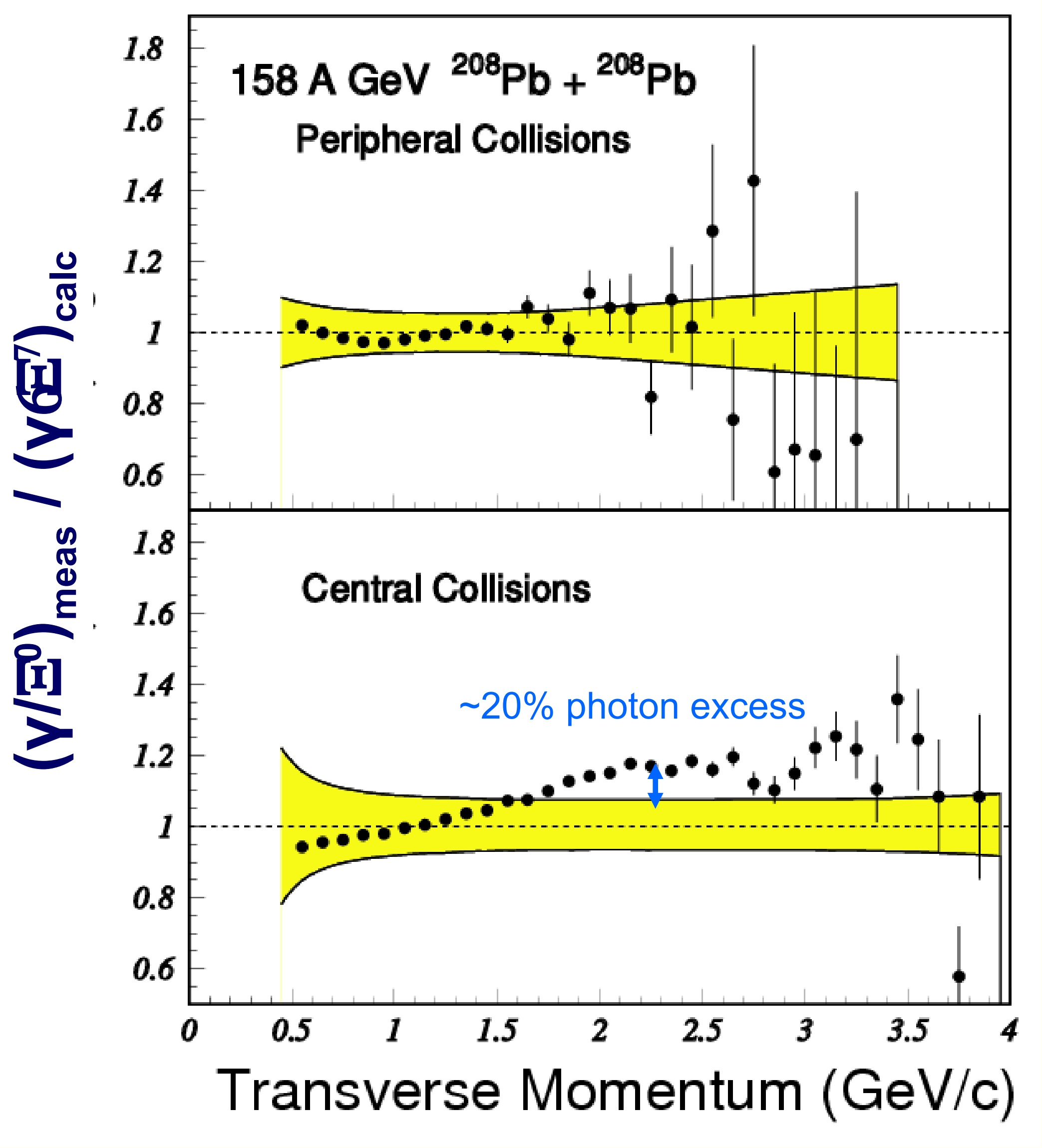
- So far (January 2012) only two measurements
  - Central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 17.3 GeV (WA98)
  - Central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)

- After an photon excess has been established experimentally, one needs to figure out whether there is a contribution from thermal direct photons. This needs theoretical guidance.

- Methods:
  - Measure photons with electromagnetic calorimeter (WA98, PHENIX)
  - Measure virtual photons ($\gamma^* \rightarrow e^+e^-$),

    and assume $$\frac{\gamma_{\text{direct}}}{\gamma_{\text{inclusive}}} = \left.\frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}}\right|_{m_{ee}<30\,\text{MeV}}$$ (PHENIX)

# Direct Photon Measurement by WA98



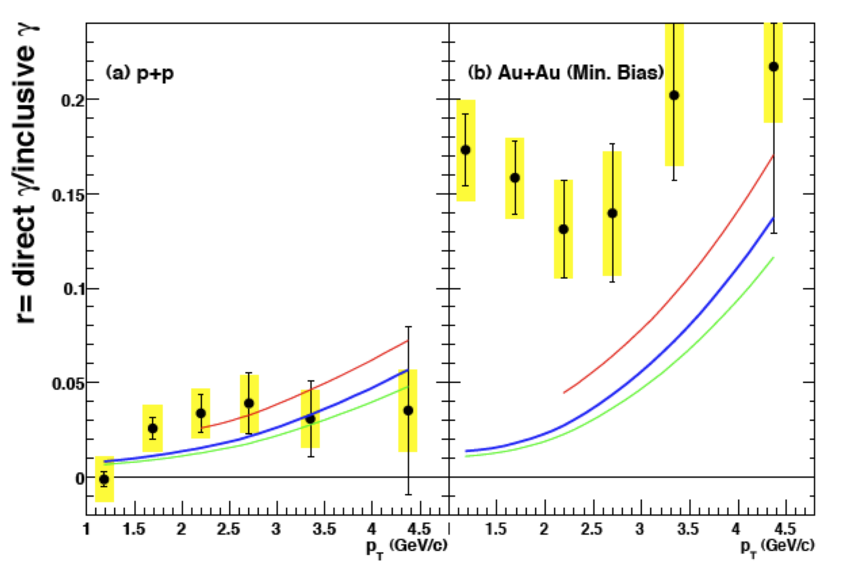

- No signal in peripheral collisions
- 20% photon excess in central Pb+Pb collisions
- Interpretation od the excess: Consistent with QGP scenario but also with a hadronic scenario + initial state effects

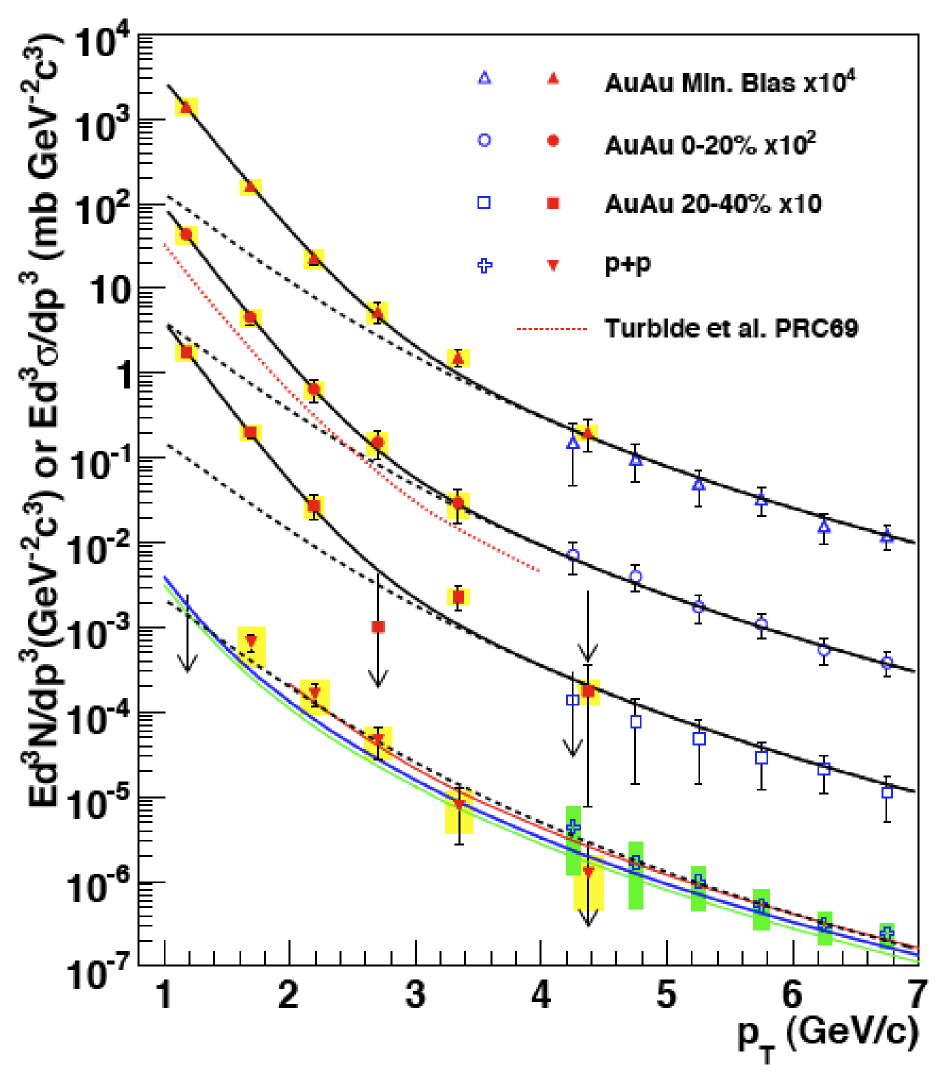
**158 AGeV Pb + Pb:**

$\sqrt{s_{NN}}$ | **17,3 GeV**

Phys.Rev.Lett.85:3595-3599,2000

# Internal Conversion Methods: Results




- Enhancement in Au+Au above p+p described by an exponential (as expected for a thermal source)

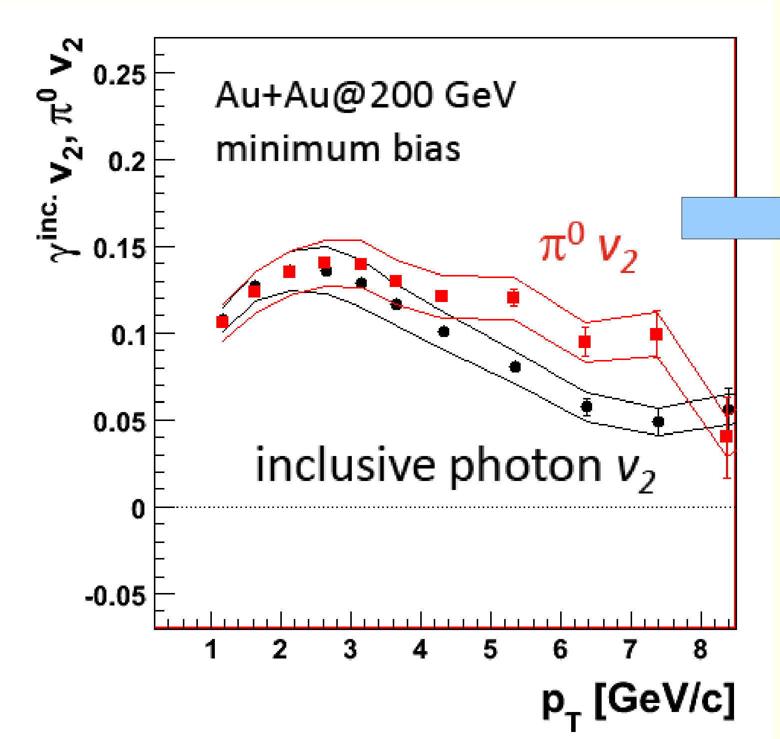
$$Y_{Au+Au} = N_{\rm coll} \cdot Y_{p+p} + A \cdot e^{-p_T/T}$$

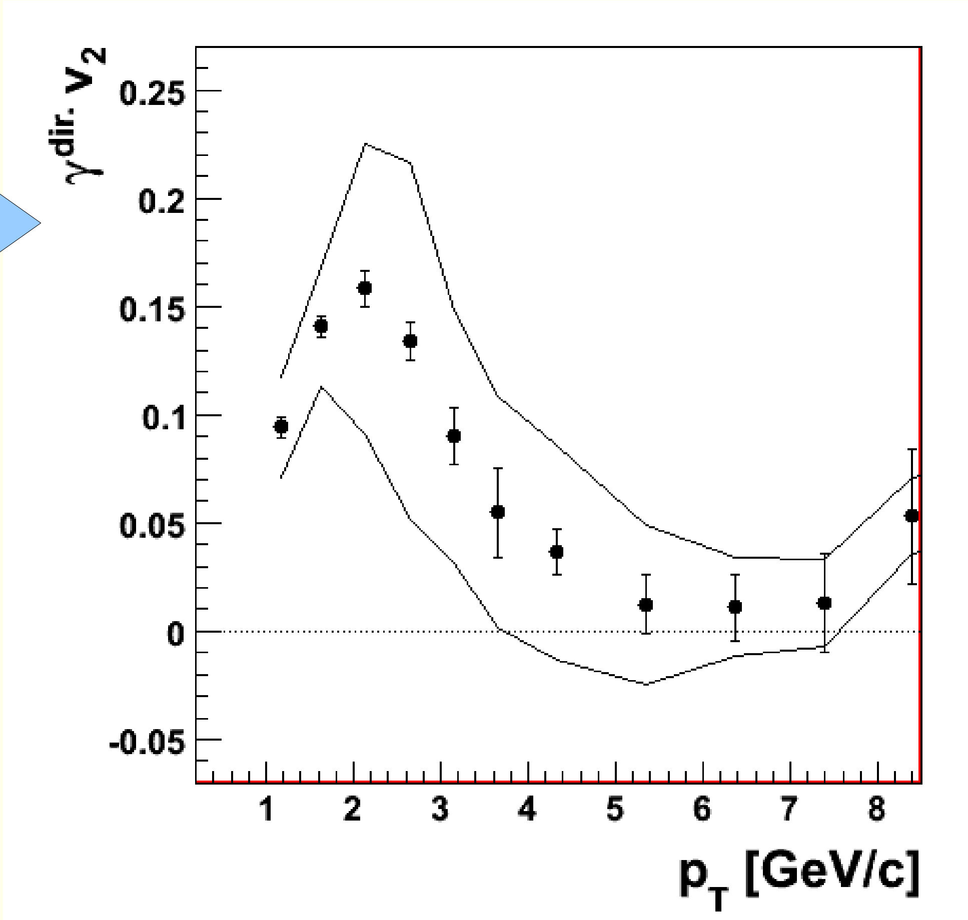
- Slope parameter (0-20%): $T$ = (221 ± 23 ± 18) MeV
- Initial temp. from hydro: $T_i$ = 300 … 600 MeV

Expected to be a lower limit for the initial temperature $T_i$!

# Direct Photon $v_2$ (PHENIX)

PHENIX, arXiv:1105.4126 (→ link)




$$v_2^{\mathrm{dir.}\,\gamma} = \frac{R_\gamma \cdot v_2^{\mathrm{incl.}} - v_2^{\mathrm{decay.}\,\gamma}}{R_\gamma - 1}$$

Large direct photon $v_2$ is a challenge to theory because most thermal photons are expected to be created early (when the temp. is largest and) when $v_2$ has not fully built up