Physics of ultrarelativistic heavy-ion collisions

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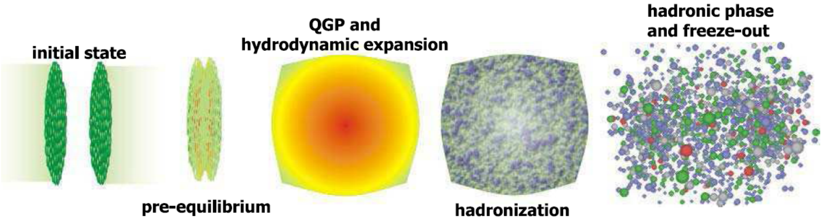
Taller de Altas Energías 2015, Benasque, Sep 20 - Oct 02, 2015
2nd Lecture: September 29, 2015

Part I

Reminder

Evolution stages of a nucleus-nucleus collision



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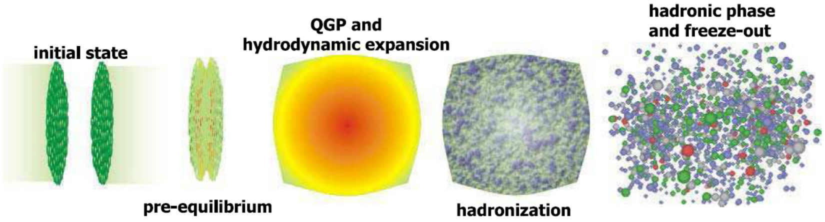

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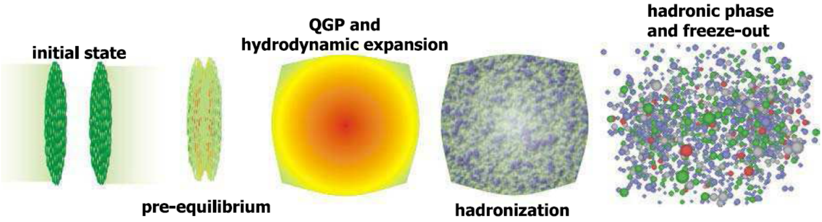

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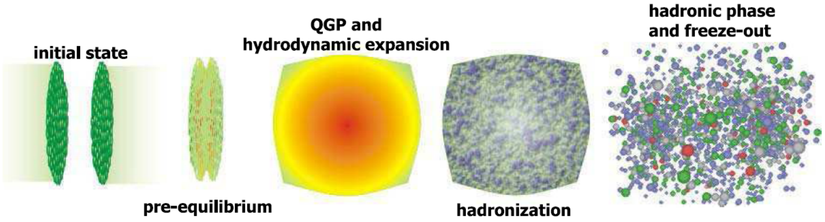

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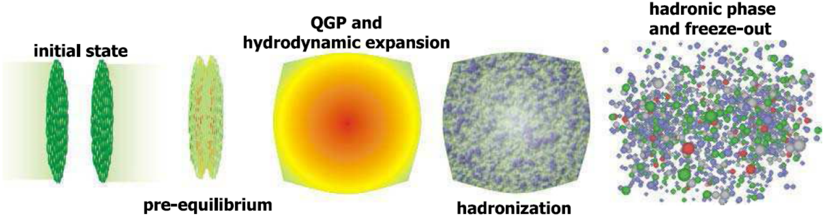

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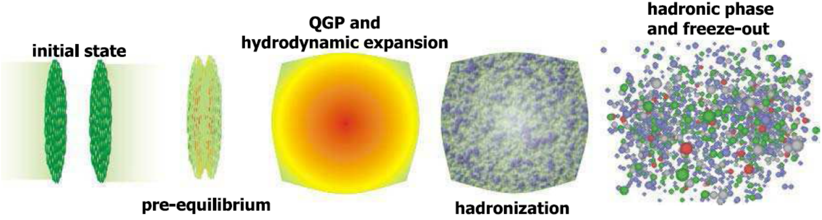

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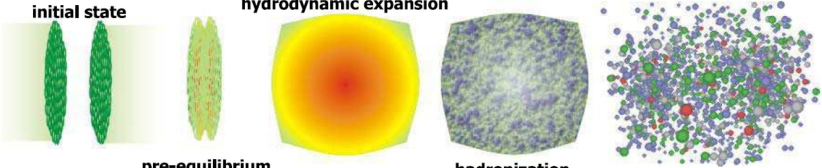

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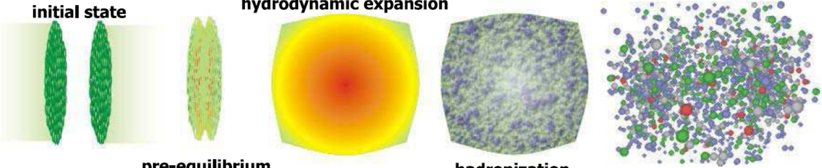

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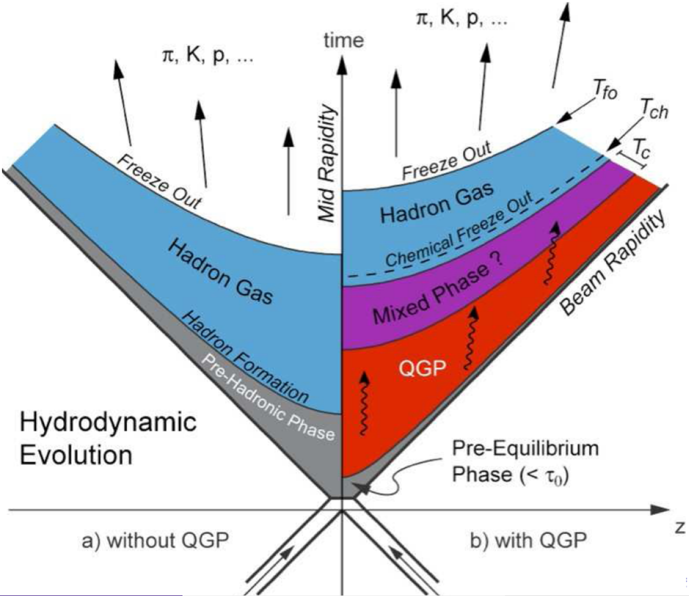
Measurement at stage 5 & 6 to learn about stage 3

Evolution stages: with or without QGP



It is always good to recall some obvious things

- Duration: about 10 fm/c (*i.e.* $3\,10^{-23} s$)
- Impossible to throw a probe, simultaneously, in the plasma
- 3-body collisions extremely rare between particles
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I would classify them in 3 categories:

1. enhancement/creation/emission — what's the initial rate ?
2. suppression/dissociation — what's the initial rate ?
3. quenching/shift in spectra — what's the initial spectrum ?

Part II

How to probe the QGP from the inside

Probes to study the QCD phase diagram

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- Color screening: **quarkonium** melting
- Chemical equilibrium, ...: **strangeness enhancement**
- Compression effect: **azimuthal asymmetry**
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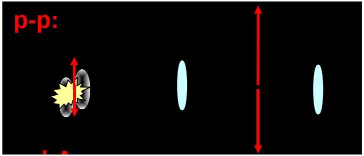
- Creation of a dense matter: **jet** quenching, **heavy-quark** energy loss, ...

Need for proton-proton & proton-nucleus studies



p-p = “QCD vacuum” (reference)

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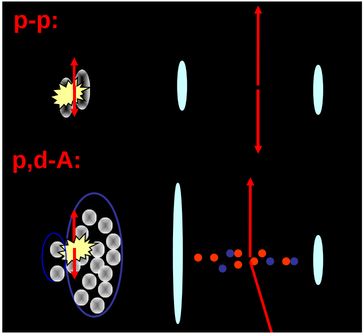

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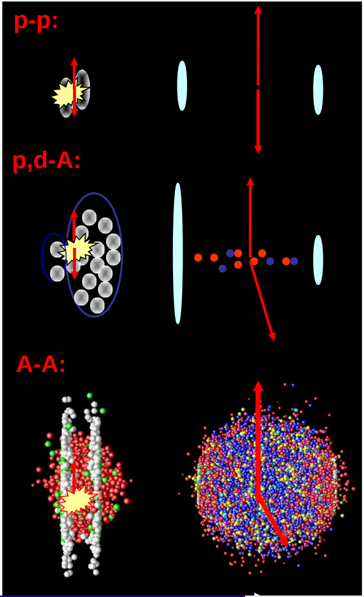

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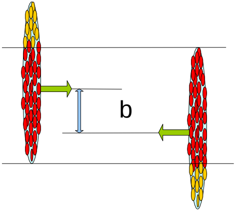
A-A = "hot & dense QCD matter"



Plasma volume
dialed varying
impact parameter b
("centrality")

Observables: nuclear modification factors

- $R_{AB} = \frac{dN_{AB}}{\langle N_{coll} \rangle dN_{pp}} \stackrel{\int b}{\rightarrow} \frac{\sigma_{AB}}{AB\sigma_{pp}}$
- For that, we need to know/measure σ_{pp} – dN_{pp}

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[we could divide by the yield from another centrality bin or even do $R_{\rm PC}(y)$]

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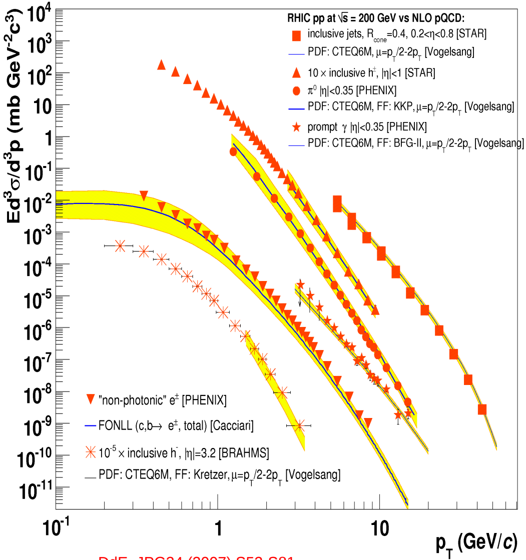
- For a soft/frequent probe, the yield rather scales like N_{part}

  [production on the surface rather than over the whole nuleus]



DdE, JPG34 (2007) S53-S81

p-p ⇒ X ,$\sqrt{s}$ = 200 GeV

- Jets, high-p_T hadrons, prompt-γ, heavy-Q ...

  High-quality measurements

  within p_T~2-45 GeV/c

- NLO [1], NLL [2] pQCD + recent PDFs, FFs in good agreement with all data.

[1] W. Vogelsang *et al.*

[2] M. Cacciari *et al.*

Slide borrowed from D. d'Enterria

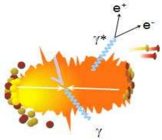
Part III

Thermal photons

Thermal photon to measure the QGP temperature

- Three sources: (i) Hadron decay γ → Background

  (ii) Prompt γ
  (ii) Thermal γ } → Direct photon signal



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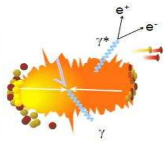
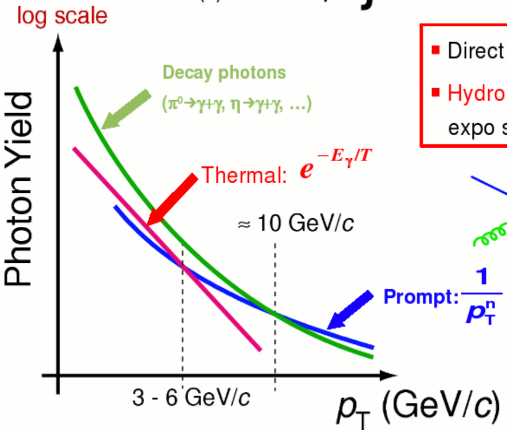
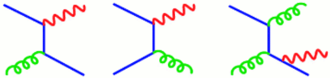




- Direct measure of the medium T
- Hydro model needed to relate expo slope to temperature.

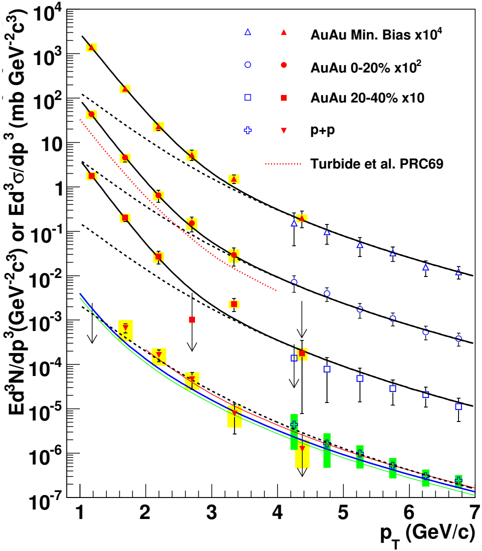


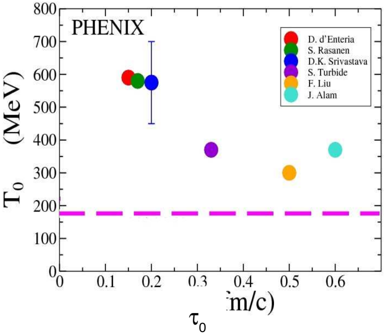
- Initial parton-parton colls.
- Measurable in p-p.
- Computable in pQCD.

Slide borrowed from D. d'Enterria

Thermal photon to measure the QGP temperature

- Hydrodynamical models vs. Au-Au γ,γ^* excess over p-p & pQCD:





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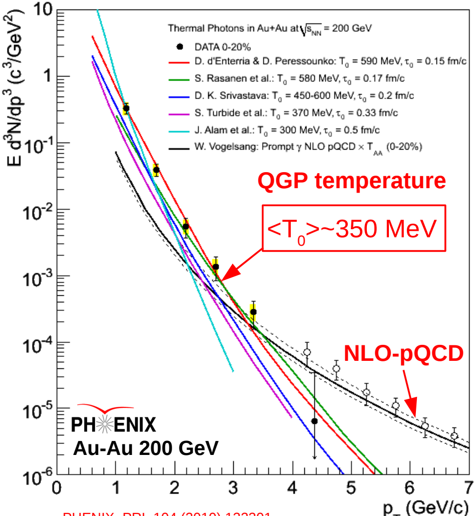
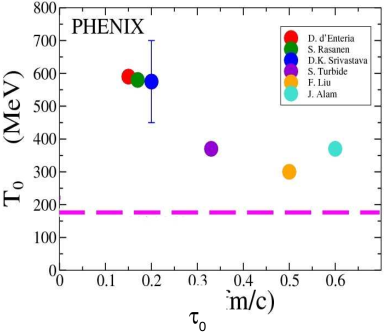


PHENIX, PRL 104 (2010) 132301



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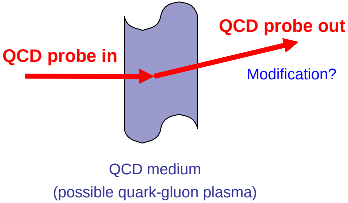
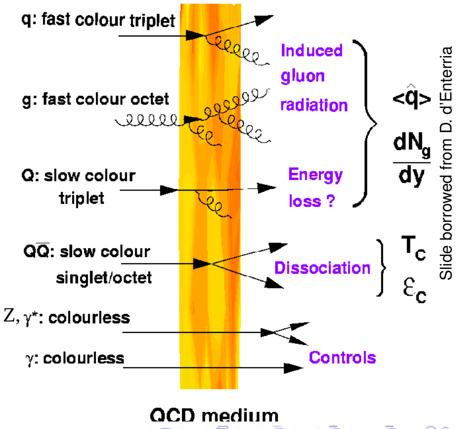
Part IV

Hard probes: Heavy-flavour, heavy-quarkonia and jets

Hard probes

- Hard-probes of QCD matter:
  - jets, γ, $Q\bar{Q}$ ... well controlled experimentally & theoretically (pQCD)
  - self-generated in collision at τ<1/Q~0.1 fm/c,
  - tomographic probes of hottest & densest phases of medium .





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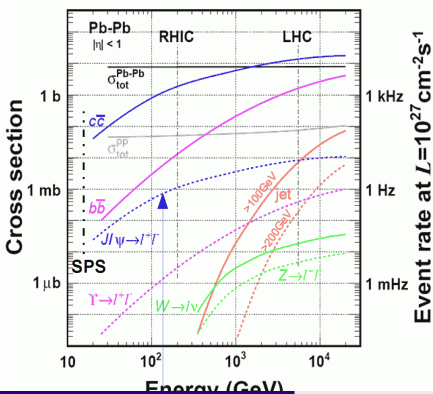
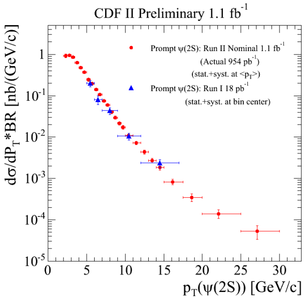
- Interaction with nuclear/QGP matter might be tractable with pQCD
- Abundance (mainly at low P_T) :



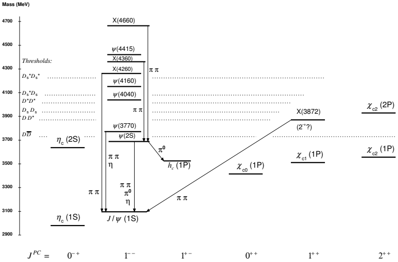
N($q\bar{q}$) per central AA (b=0)

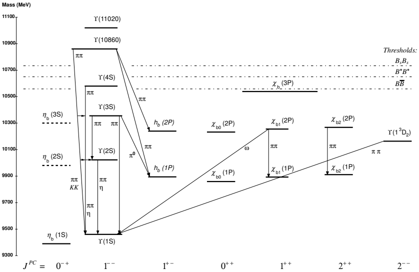
	SPS	RHIC	LHC
charm	0.2	10	130
bottom	---	0.05	5



Quarkonia ($Q\bar{Q}$) in the QGP

- Two families:





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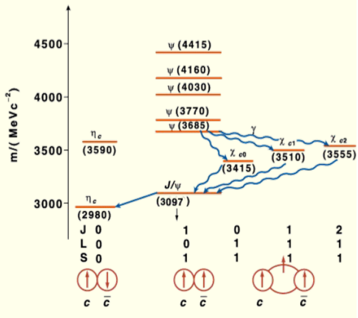

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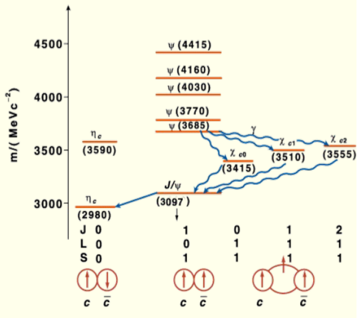
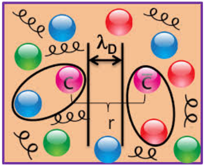


- Expected to melt in the QGP by Debye screeening



Matsui, Satz 1986

Quarkonia: the QGP thermometer

- Different melting/dissociation (T_d) temperatures: depend on the size

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

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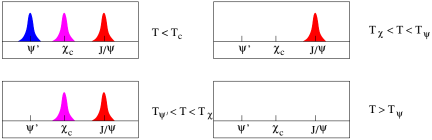

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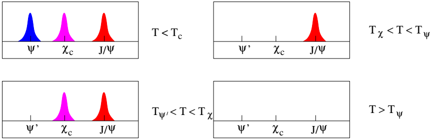
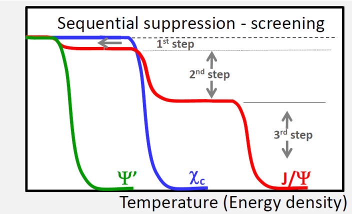
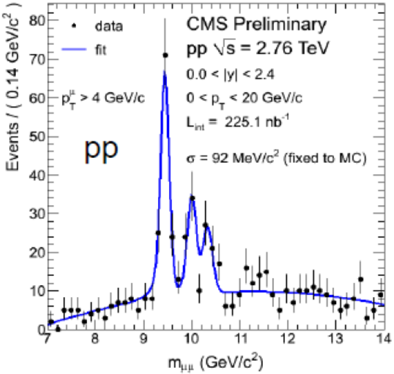
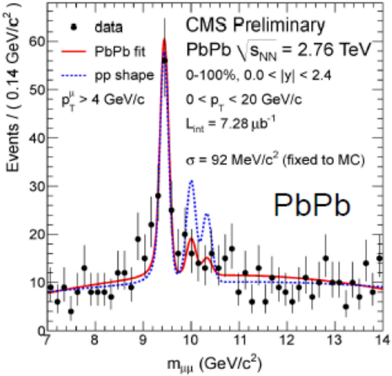




Quarkonia: LHC results





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

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

Part V

Some complications from “cold” nuclear matter effects

Expected nuclear effects on (involved in) quarkonium production in proton-nucleus collisions

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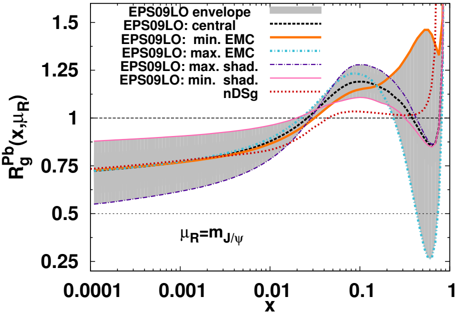
I will not speak about any QGP-like effect in *pA* collisions here

Typical gluon nuclear PDFs



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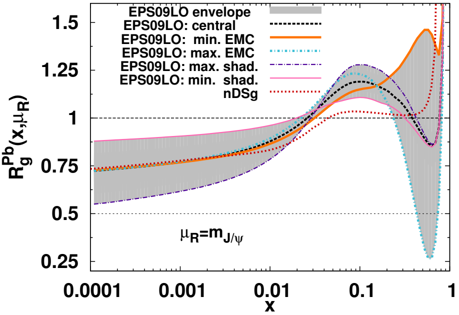

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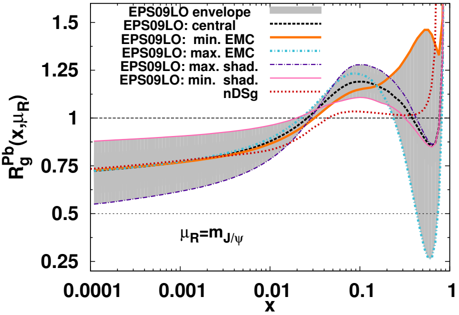

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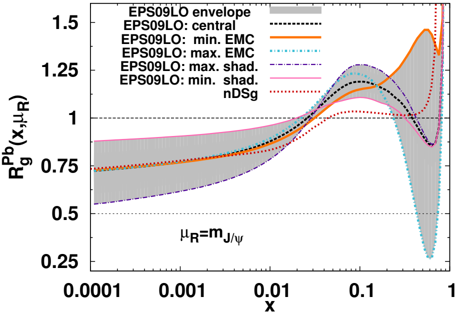

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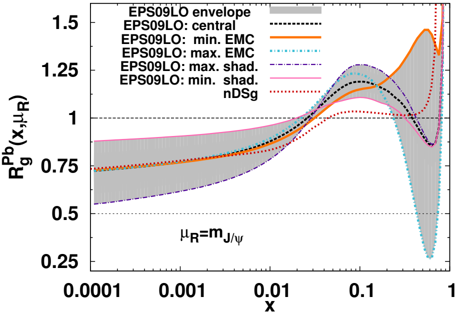

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- Naive high energy limit: $\sigma_{\text{break-up}} \simeq \pi/m_Q^2$? $\simeq 0.5$ mb for charmonia ?

Baseline: absorption and nPDFs in a collinear pQCD framework

See e.g. **E.G. Ferreiro, F. Fleuret, J.P.L., A. Rakotozafindrabe, PLB 680 (2009) 50**

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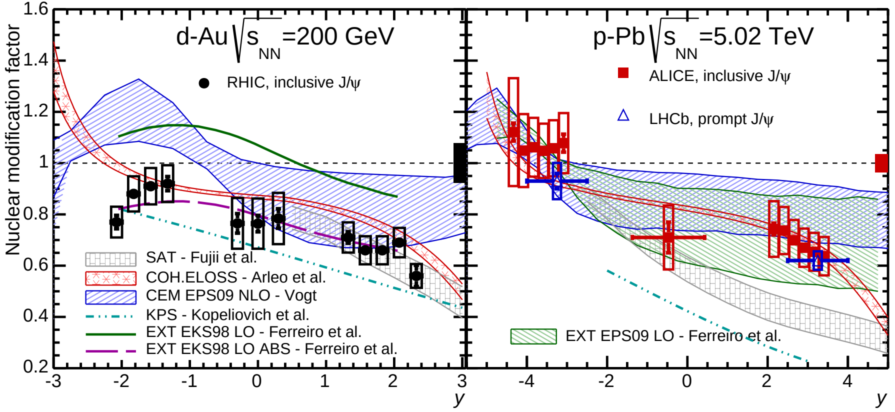
- the nuclear PDF (+ b dependence), $\mathcal{F}^A_g(x_1, \vec{r}_A, z_A, \mu_f)$, assumed to be factorisable in terms of the nucleon PDFs : **S.R. Klein, R. Vogt, PRL 91 (2003) 142301.**

$$\mathcal{F}^A_g(x_1, \vec{r}_A, z_A; \mu_f) = \rho_A(\vec{r}_A, z_A) \times g(x_1; \mu_f) \times (1 + [R^A_g(x, \mu_f) - 1] N_{\rho_A} \frac{\int dz\, \rho_A(\vec{r}_A, z)}{\int dz\, \rho_A(0, z)})$$

J/ψ suppression

Plot from the Sapore Gravis Network review: arXiv:1506.03981



J/ψ suppression: energy independent ?

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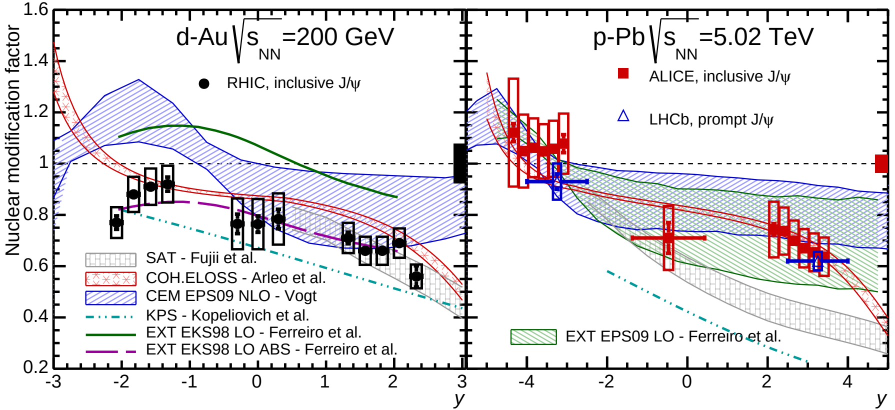


- Most models – except maybe the Eloss *without shadowing* predicted an increase of the suppression
- Now . . . –although they were done with care– the LHC results rely on a *pp* cross section interpolation

A puzzle with excited states ?

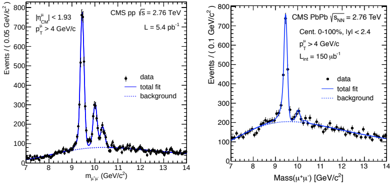
Selected for a Viewpoint in *Physics*
PRL **109,** 222301 (2012) PHYSICAL REVIEW LETTERS week ending 30 NOVEMBER 2012

Observation of Sequential Υ Suppression in PbPb Collisions

S. Chatrchyan *et al.**
(CMS Collaboration)

A puzzle with excited states ?

CMS PRL 109 222301 (2012), JHEP04(2014)103



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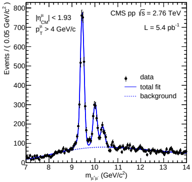

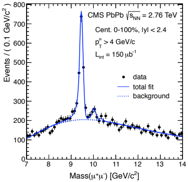

In addition to QGP formation, differences between quarkonium production yields in PbPb and pp collisions can also arise from cold-nuclear-matter effects [21]. However, such effects should have a small impact on the double ratios reported here. Initial-state nuclear effects are expected to affect similarly each of the three Υ states, thereby canceling out in the ratio. Final-state "nuclear absorption" becomes weaker with increasing energy [22] and is expected to be negligible at the LHC [23].

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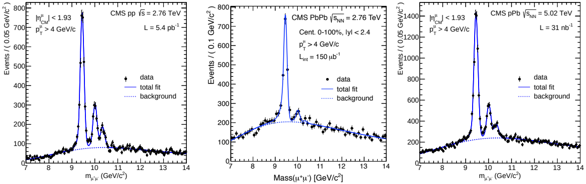

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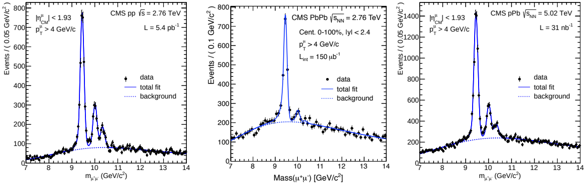

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If the effects responsible for the relative $nS/1S$ suppression in pPb collisions factorise, they could be responsible for half of the PbPb relative suppression !!!

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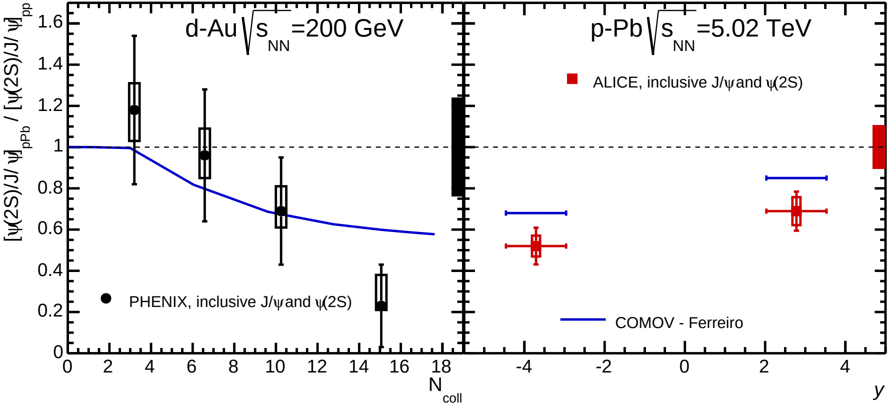
- $\sigma^{co-\psi}$ fixed from fits to low-energy *AA* data **N. Armesto, A. Capella, PLB 430 (1998) 23**

  [$\sigma^{co-J/\psi} = 0.65$ mb for the J/ψ and $\sigma^{co-\psi(2S)} = 6$ mb for the $\psi(2S)$]

CIM result vs. data

Theory: E.G. Ferreiro arXiv:1411.0549; Plot from the SGNR review: arXiv:1506.03981; PHENIX PRL 111, 202301 (2013); ALICE JHEP 02 (2014) 072



Given that all the other models discussed so far predict no difference and that the comover cross sections from *AA* data at SPS were re-used, this is encouraging. . .

Part VI

Competing “hot” nuclear effects vs. the melting ?

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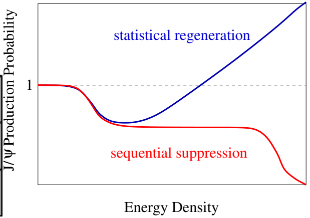
- Opposite effect at high energy ?: recombination/regeneration

N($q\bar{q}$) per central AA (b=0)	SPS	RHIC	LHC
charm	0.2	10	130
bottom	---	0.05	5



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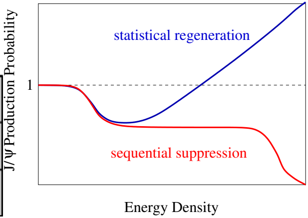

- Way out: p_T cut: reduce recombination; look at $b\bar{b}$: less recombination

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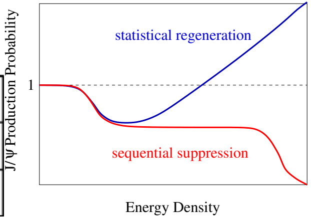

- Way out: p_T cut: reduce recombination; look at $b\bar{b}$: less recombination
- Competing suppression effect as well: comovers

(within a normal hadron phase)