Rencontres QGP-France-13

Etretat, 9-12 septembre 2013

Quarkonium experimental review

Philippe Rosnet
Laboratoire de Physique Corpusculaire
Université Blaise Pascal – CNRS/IN2P3

Menu

- ❑ Physics motivations
- ❑ Experimental considerations
- ❑ pp collisions
- ❑ Golden age at RHIC

—

- ❑ Leaden era at LHC
- ❑ And then …

Uderzo et Goscinny, *Astérix*

Historical appetizer

Samuel Ting group (BNL)
J.-J. Aubert et al., PRL 33 (1974) 1404

Burton Richter group (SLAC)
J.-E. Augustin et al., PRL 33 (1974) 1406

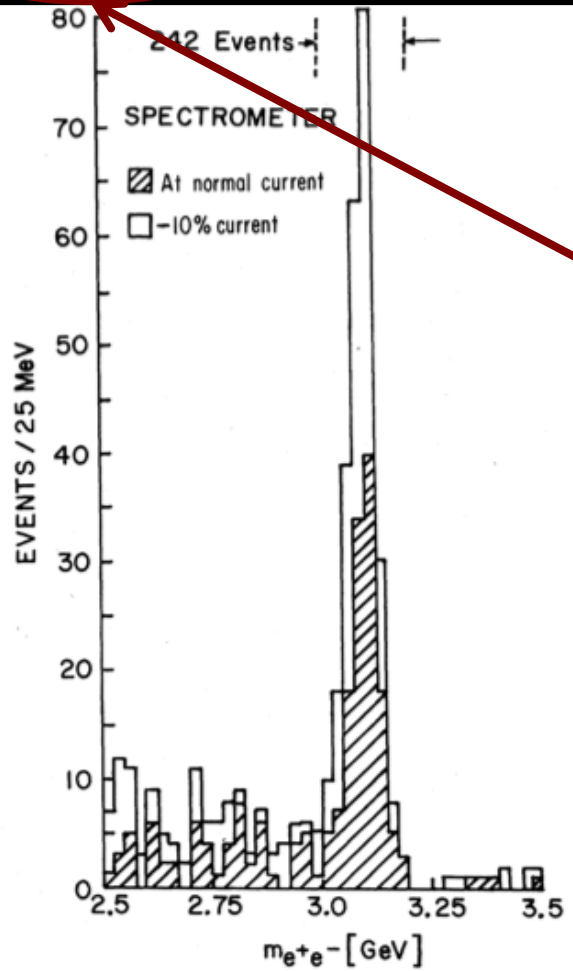
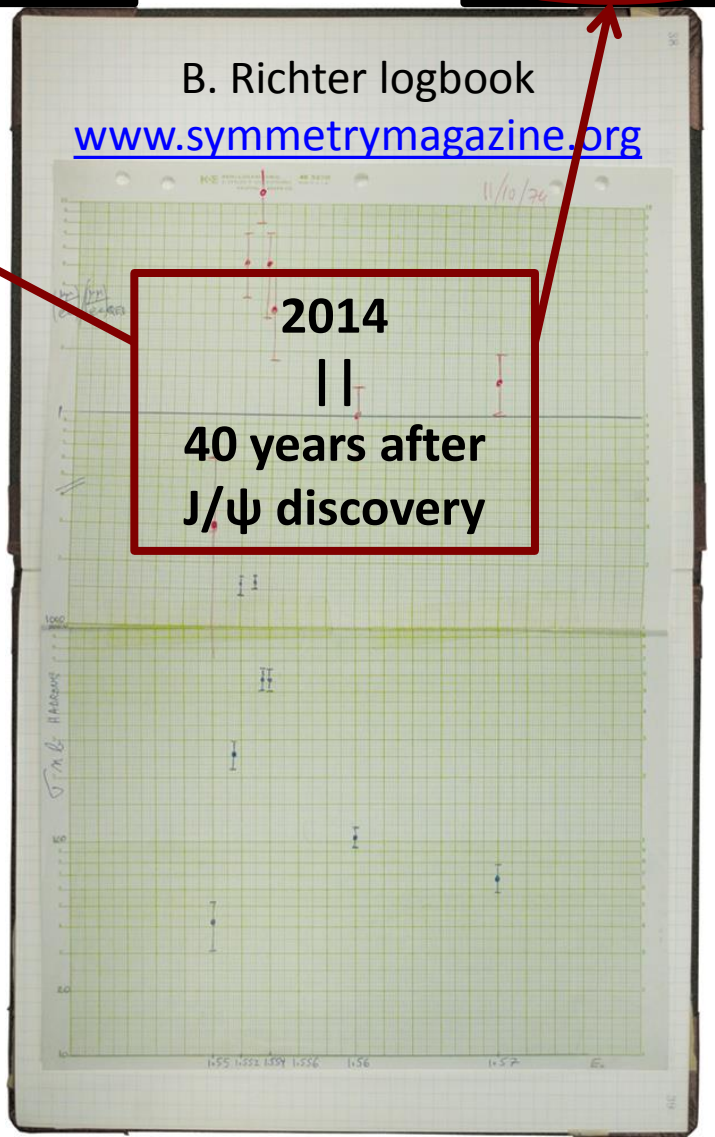


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.



B. Richter logbook
www.symmetrymagazine.org

2014
||
40 years after
J/ψ discovery

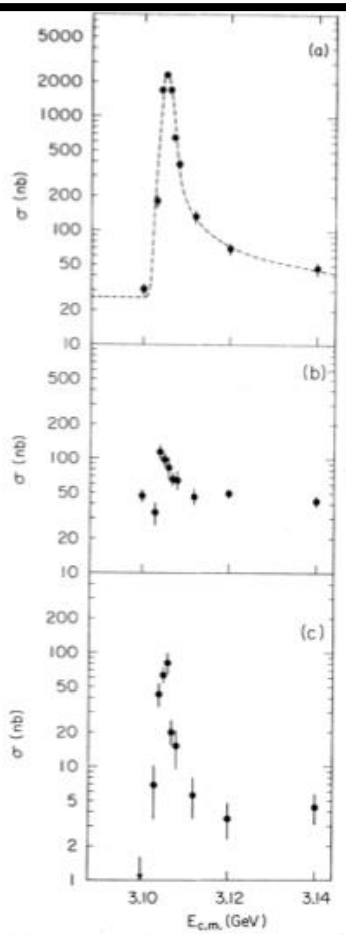
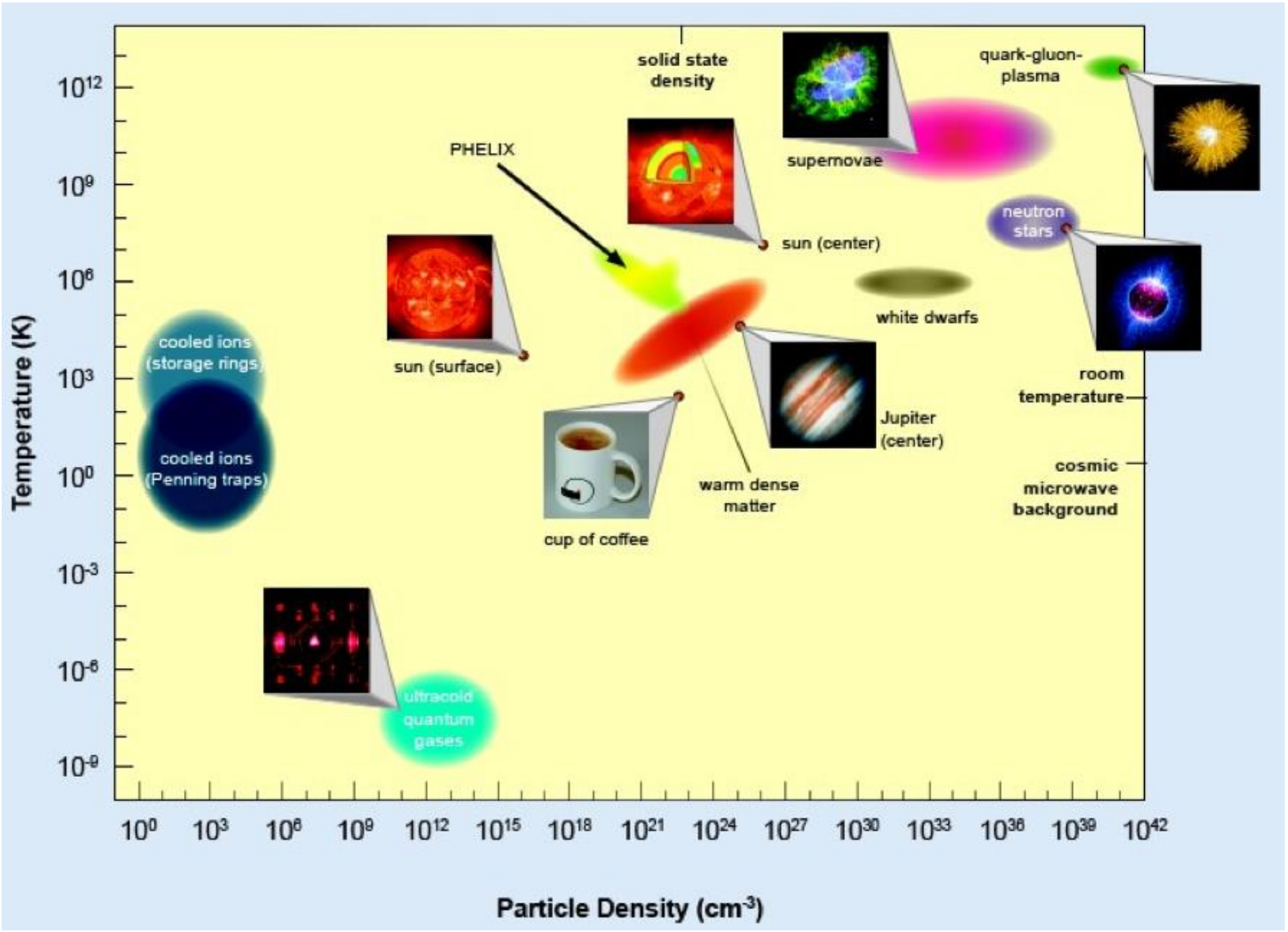


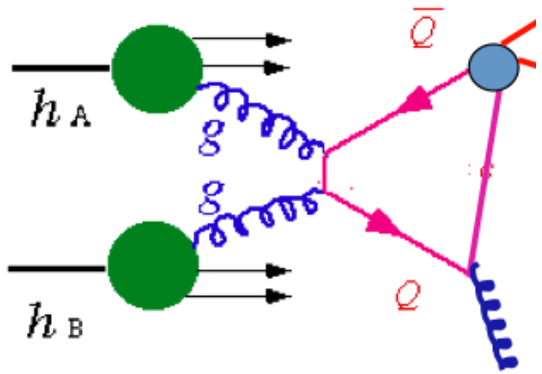
FIG. 1. Cross section versus energy for (a) multihadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

Physics motivations

Peter Braun-Munzinger, ICNFP 2013

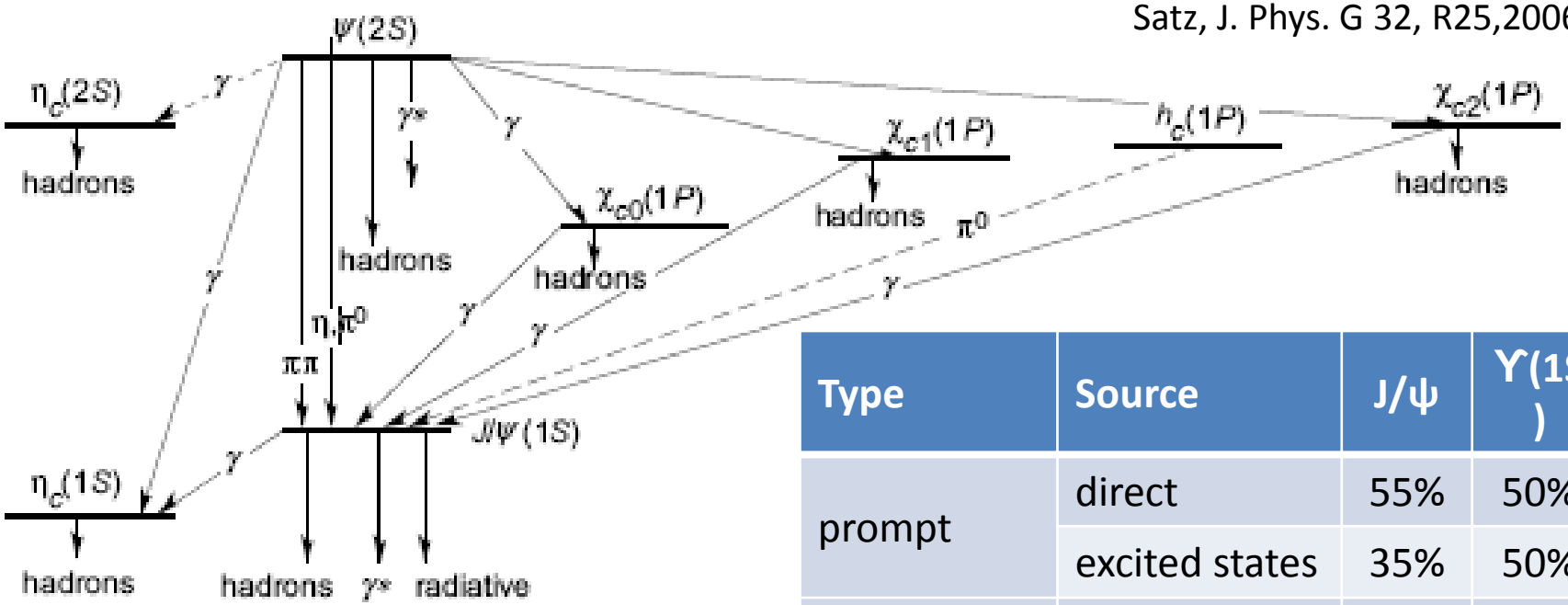


Quarkonia: from production to decay



state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Satz, J. Phys. G 32, R25,2006

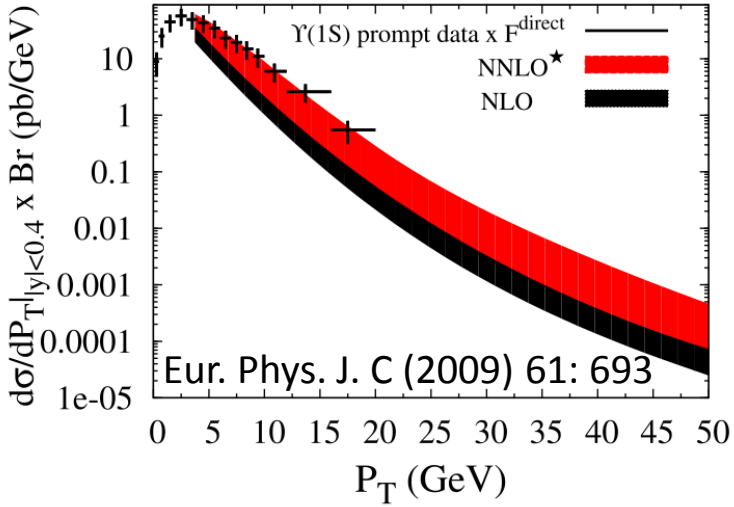


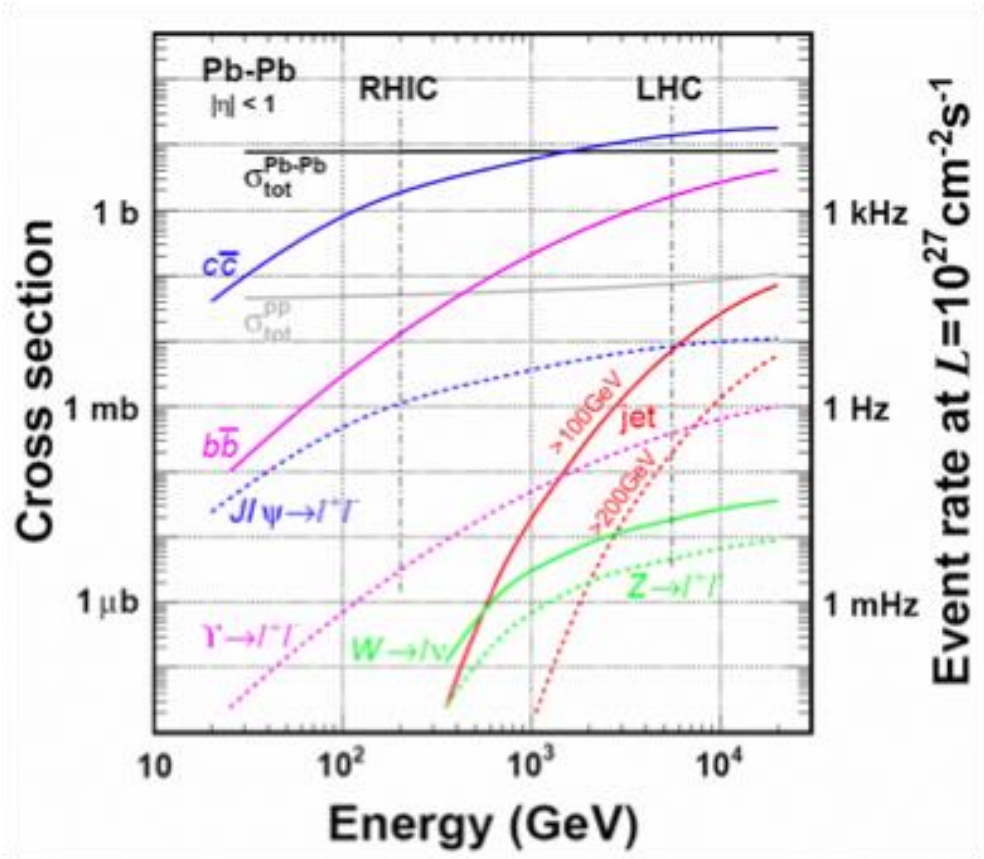
Type	Source	J/ψ	Υ(1S)
prompt	direct	55%	50%
	excited states	35%	50%
non-prompt	b-hadron	10%	-

Proton-proton collisions: QCD vacuum

- To test QCD-based model for quarkonium production

- Used as reference for the quantification of in-medium effects





- Large increase of heavy-flavour cross section from RHIC to LHC energy

- LHC = quarkonium factory

Heavy-ion collisions: hot and dense medium

✧ Quarkonia are produced by hard processes, via gluon fusion at LHC

➔ sensitive to medium effects: Quark-Gluon Plasma (QGP)

✧ Quarkonium sequential suppression via color screening [Matsui & Satz, PLB178 (1986) 178]

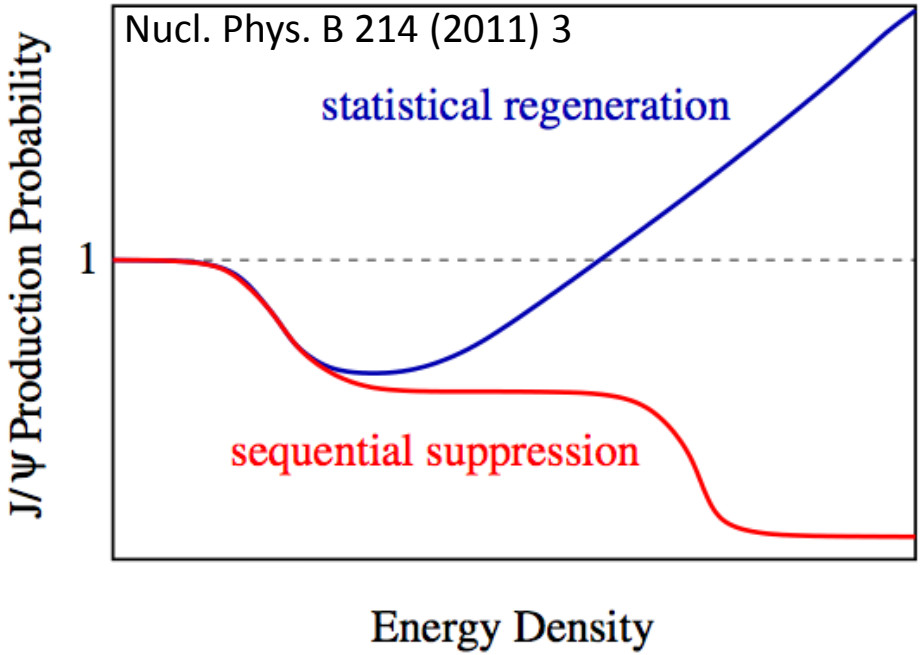
➔ QGP-thermometer

Satz, J. Phys. G 32, R25,2006

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

✧ Quarkonium statistical regeneration if large heavy quark multiplicity

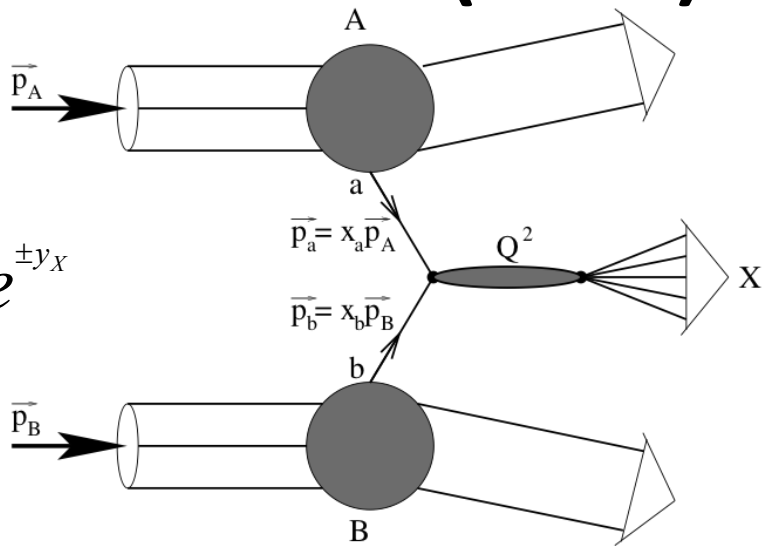
[Braun-Munzinger & Stachel, PLB490 (2000) 196 ; Thews, Schroedter & Rafelski, PRC65 (2001) 054905]

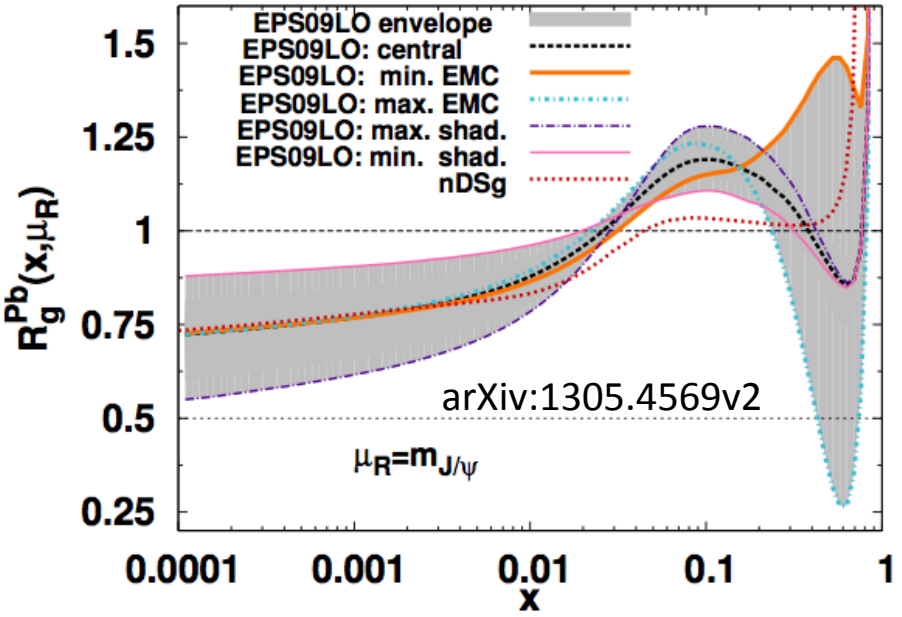


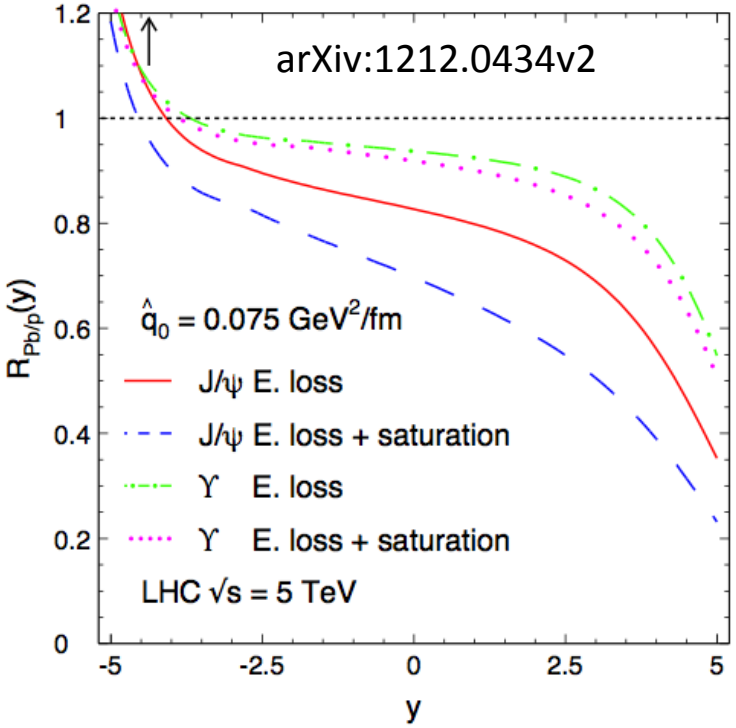
Proton-nucleus: cold nuclear matter (CNM)

- Shadowing, anti-shadowing
- Saturation (CGC)
- Energy loss
- Nuclear dissociation
- …

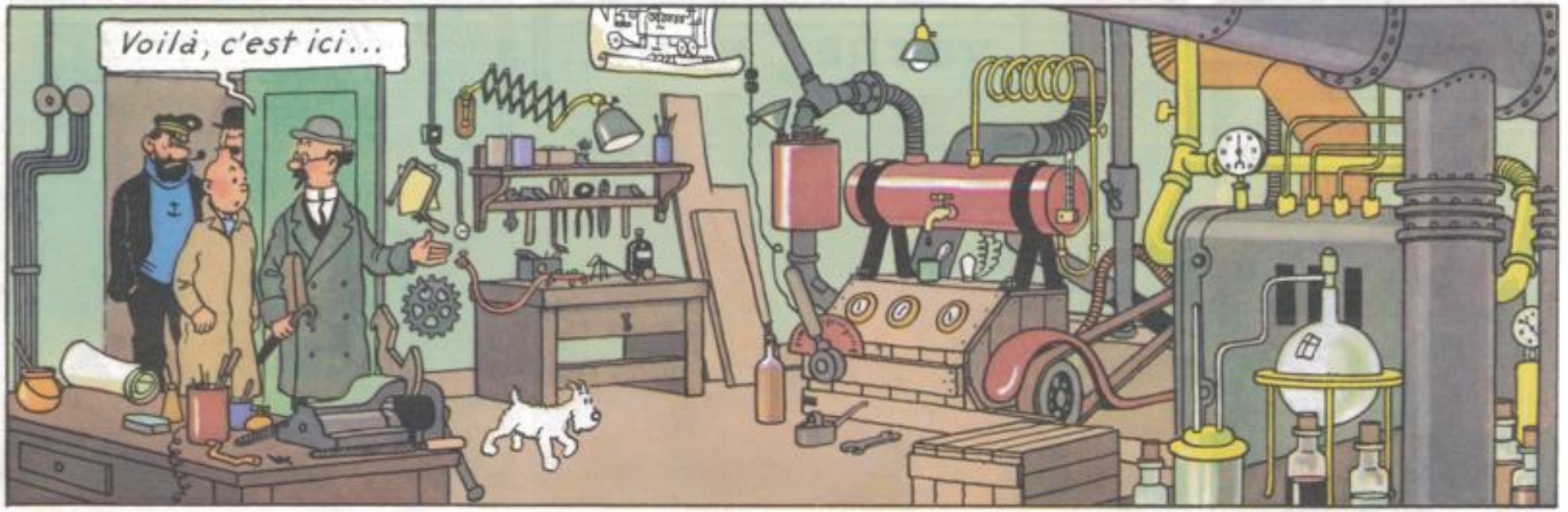
$$x_{a,b} = \frac{\sqrt{Q^2}}{\sqrt{s}} e^{\pm y_X}$$





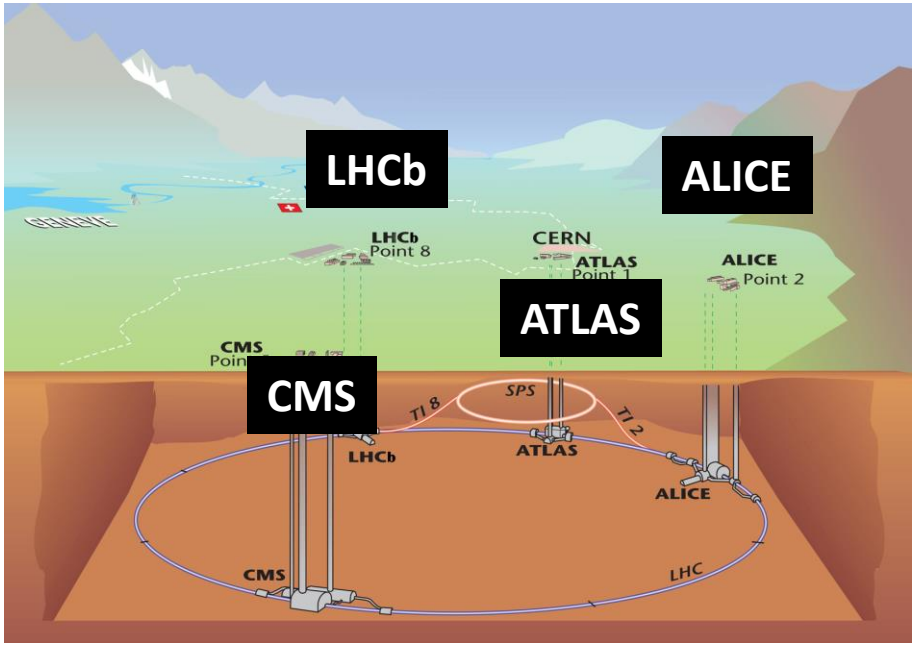


Experimental considerations



Hergé, *Les aventures de Tintin*, *Le trésor de Rackham le rouge*

Experimental context



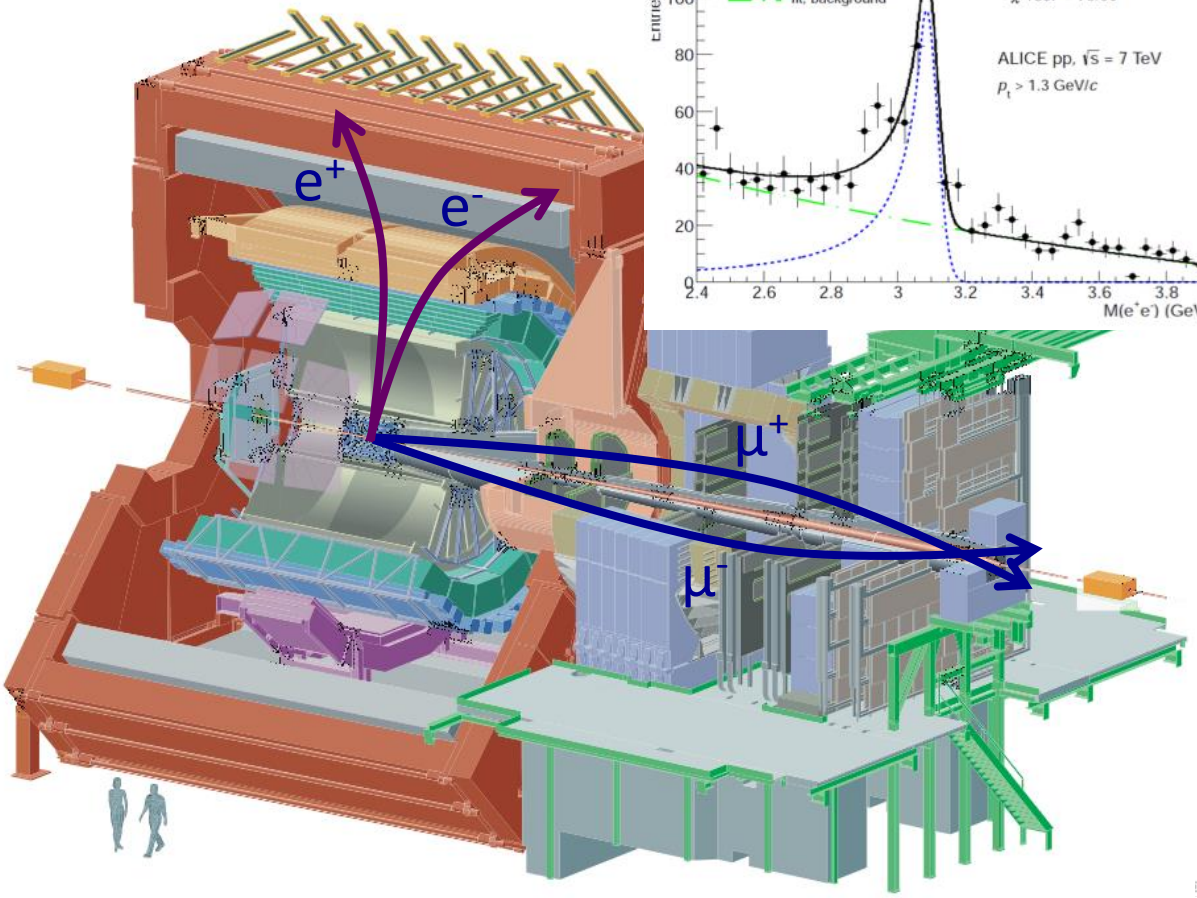
Relativistic Heavy Ion Collider (BNL)

- pp @ 200 GeV
- Au-Au @ 39 – 62 – 200 GeV
- d-Au @ 200 GeV
- Cu-Cu @ 200 GeV
- Cu-Au @ 200 GeV
- …

Large Hadron Collider (CERN)

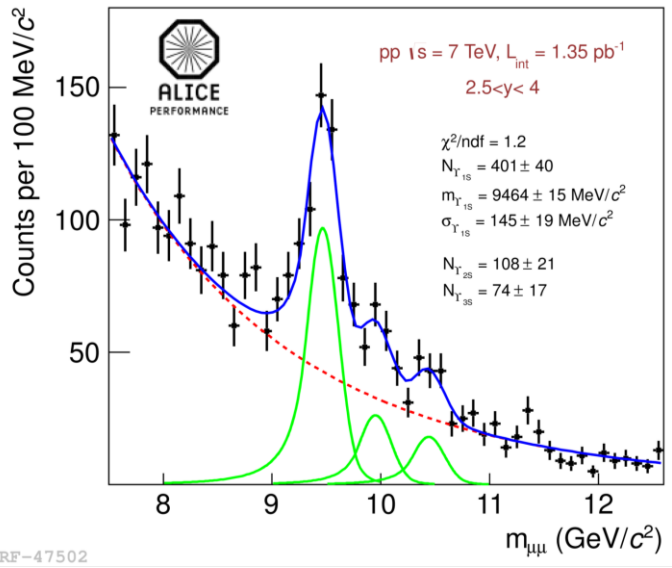
- pp @ 2.76 – 7 – 8 TeV
- Pb-Pb @ 2.76 TeV
- p-Pb & Pb-p @ 5.02 TeV

Experimental method



Decay channels

- $(J/\psi, \Upsilon, \ldots) \rightarrow \mu^+\mu^-$
- $(J/\psi, \Upsilon, \ldots) \rightarrow e^+e^-$



Experiment	PHENIX	STAR	ALICE	CMS
Rapidity range (p_T threshold)	$\lvert y_{ee}\rvert < 0.35$ $1.2 < \lvert y_{\mu\mu}\rvert < 2.3$	$\lvert y_{ee}\rvert < 1$ ($p_T^{J/\psi} > 3$ GeV)	$\lvert y_{ee}\rvert < 0.9$ $2.5 < y_{\mu\mu} < 4$	$\lvert y_{\mu\mu}\rvert < 2.4$ ($p_T^{J/\psi} > 3$-6.5 GeV)

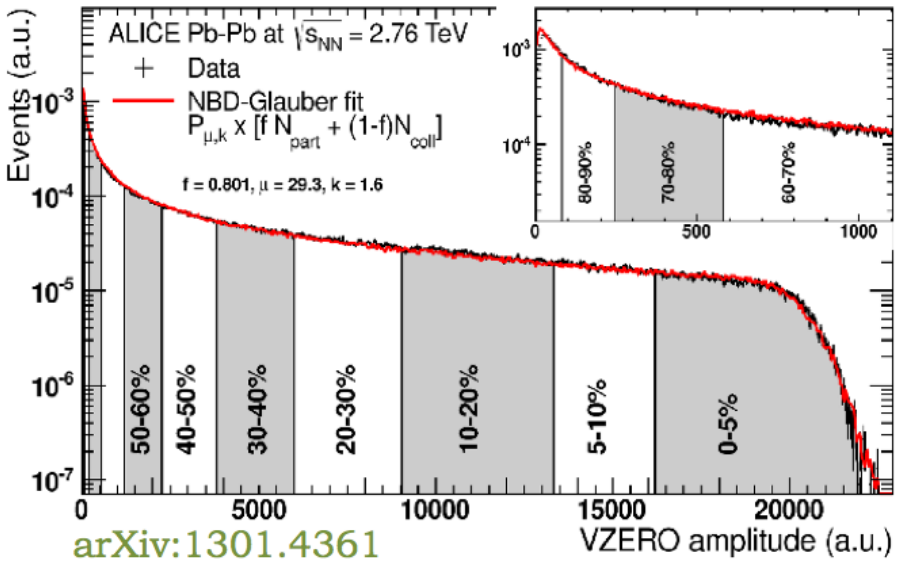
Nuclear modification factor

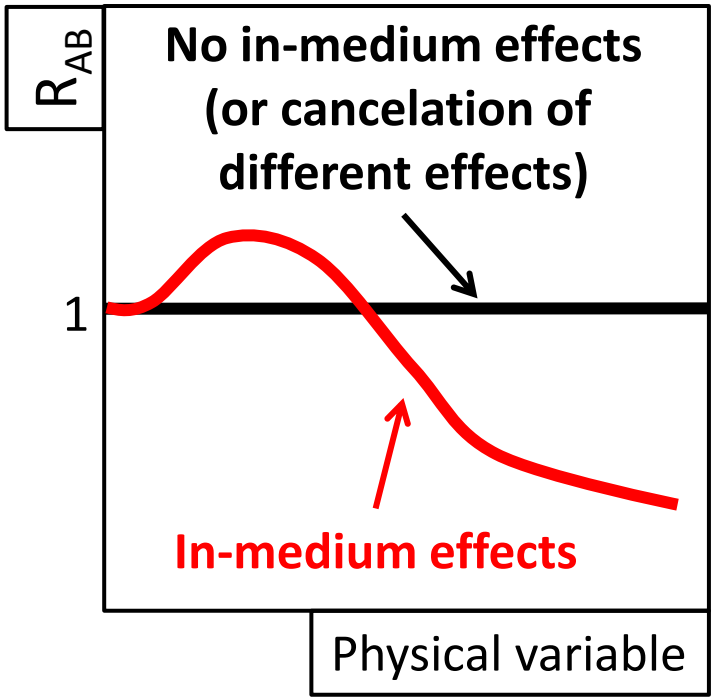
In-medium effects (QGP or CNM) quantified by the nuclear modification factor:

$$R_{AB}(N_{part}, y, p_T) = \frac{Y_{AB}(N_{part}, y, p_T)}{N_{coll}(N_{part})_{AB}\ Y_{pp}(y, p_T)}$$

- Y_{pp} and Y_{AB} the yield of quarkonium respectively in pp and A-B

- N_{coll} and N_{part} respectively the average number of binary collisions and participating nucleons in A-B estimated with a Glauber model



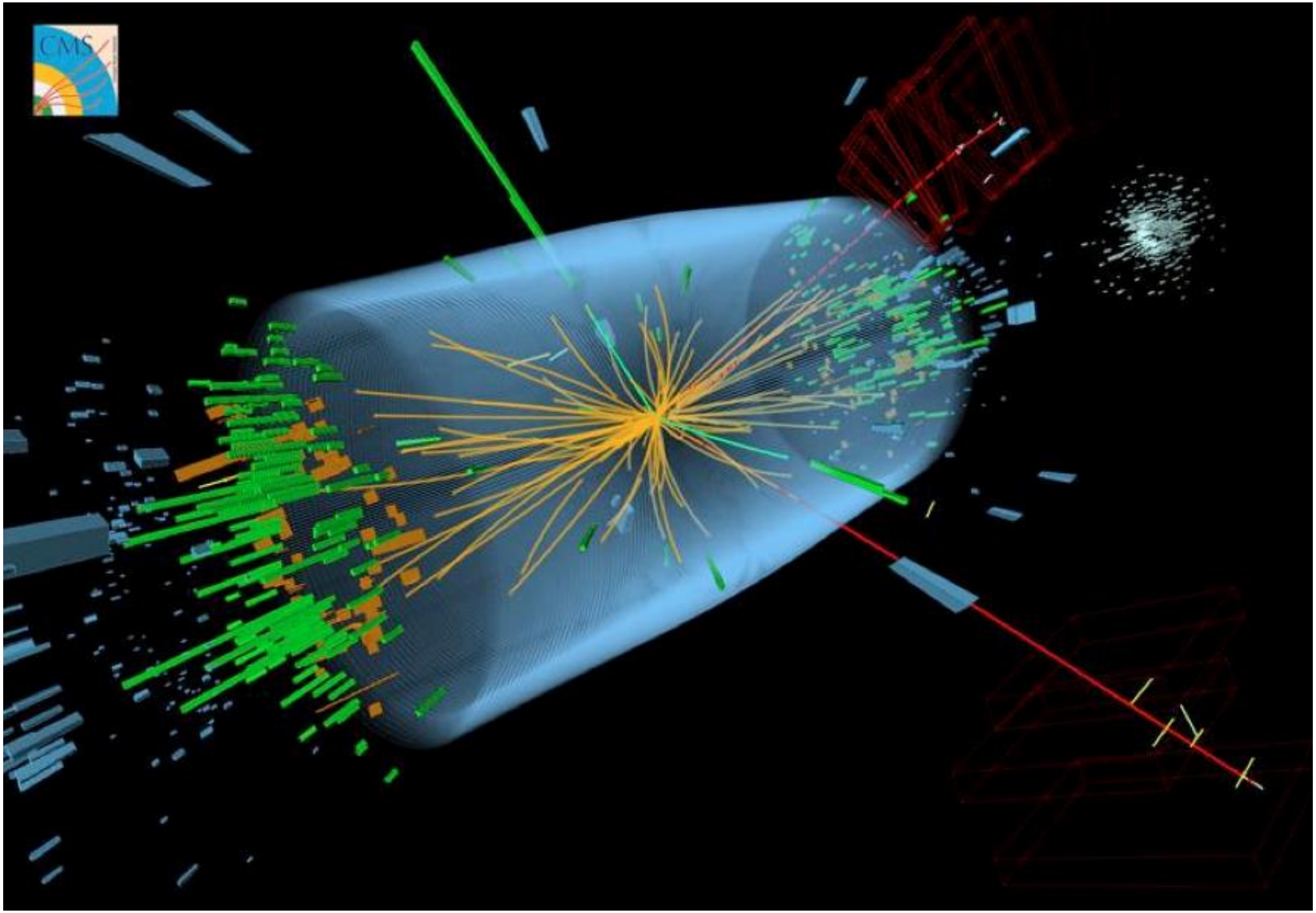


Potential data plots

N_{plots} ≈ 4 experiments (PHENIX, STAR, ALICE CMS)
× 3 beam systems (pp, pA, AA)
× N beam energy
× 4 quarkonia (J/ψ, ψ(2S), ϒ(1S), ϒ(2S))
× 2 observables (R_AA, v2)
× 3 variables (y, p_T, N_part)
× N' models
> 288

I apologize for the personal "bias" choice

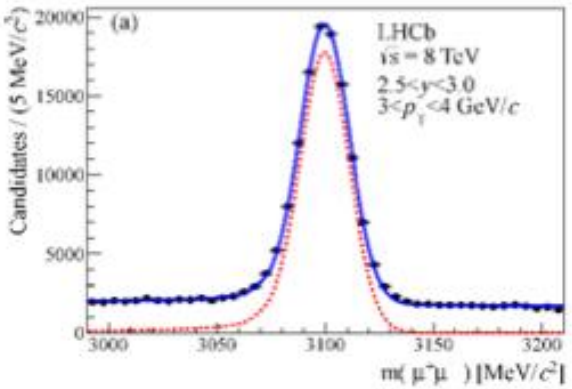
pp collisions

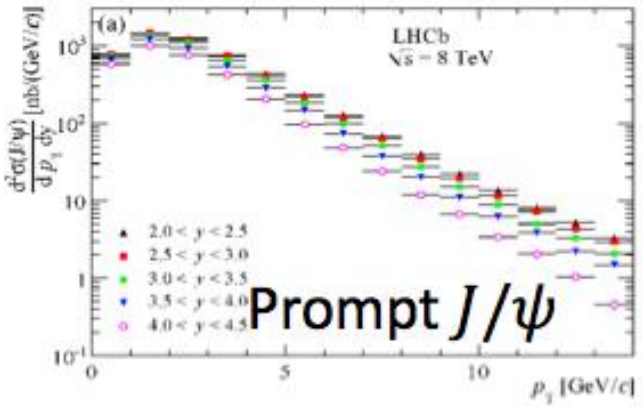


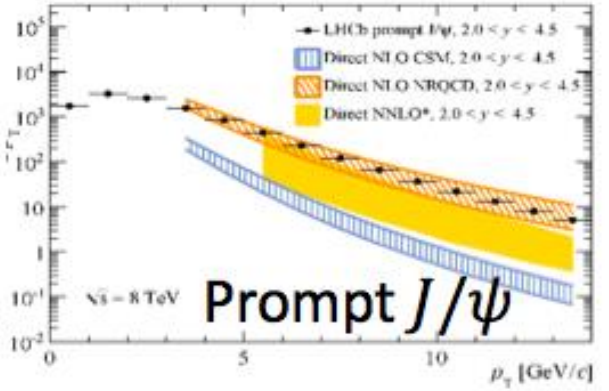
J/ψ at forward rapidity

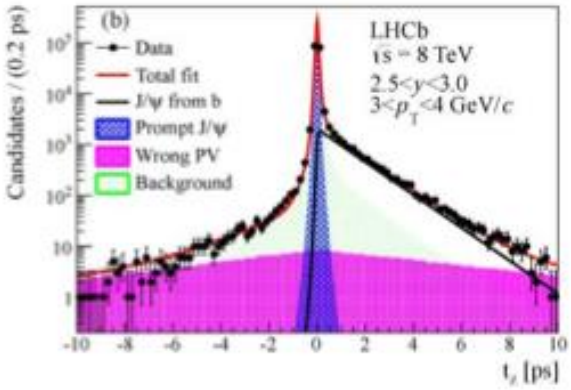
[Z. Yang (LHCb), EPS HEP 2013]

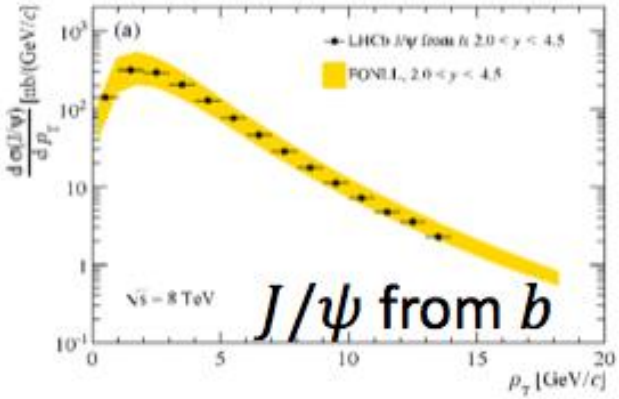
- pp 8 TeV data: 2.6 M signal events in $2 < y < 4.5$ and $p_T < 14$ GeV
- mass resolution: $\sigma_{J/\psi} = 14$ MeV

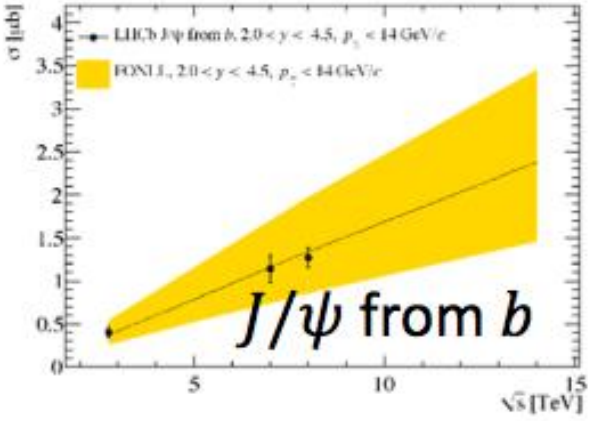










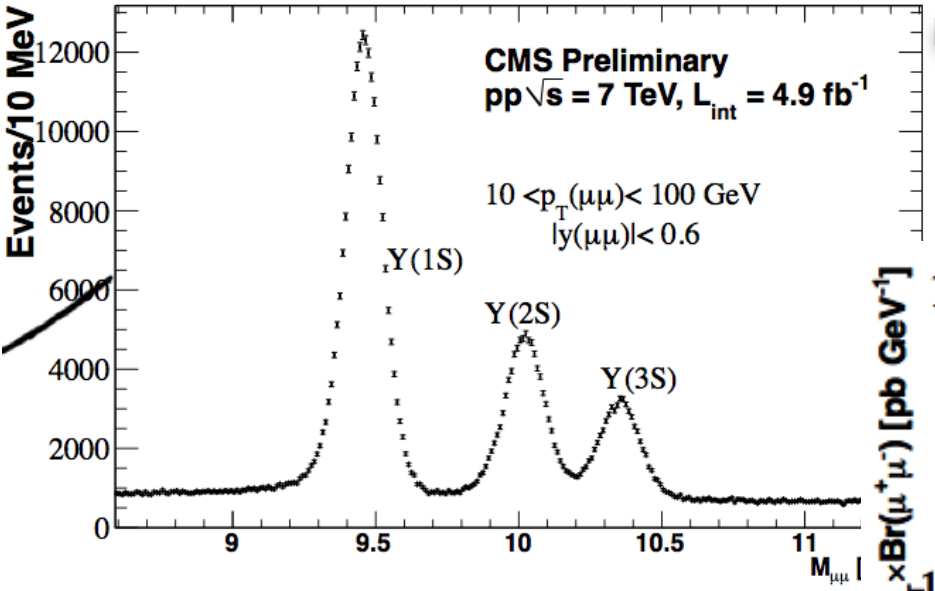


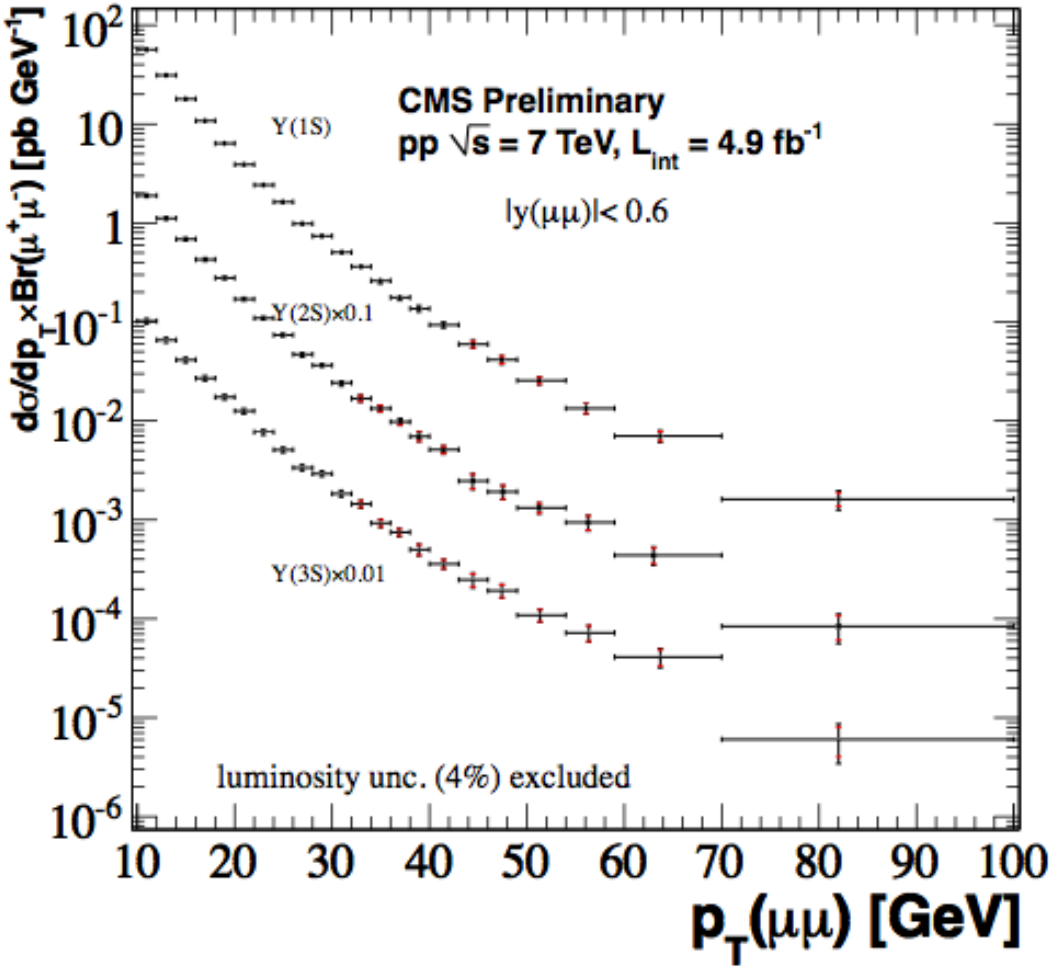
Good agreement between data and theory:

- prompt J/ψ with NLO NRQCD
- non-prompt J/ψ from b decay with FONLL

Upsilon high p_T spectra

[I. Krästmer (CMS), EPS HEP 2013]



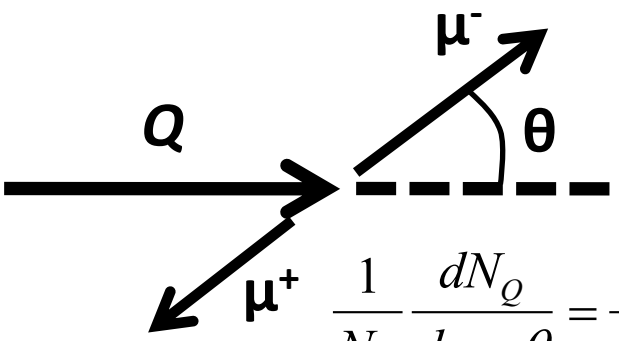


- Similar behaviour for all three states

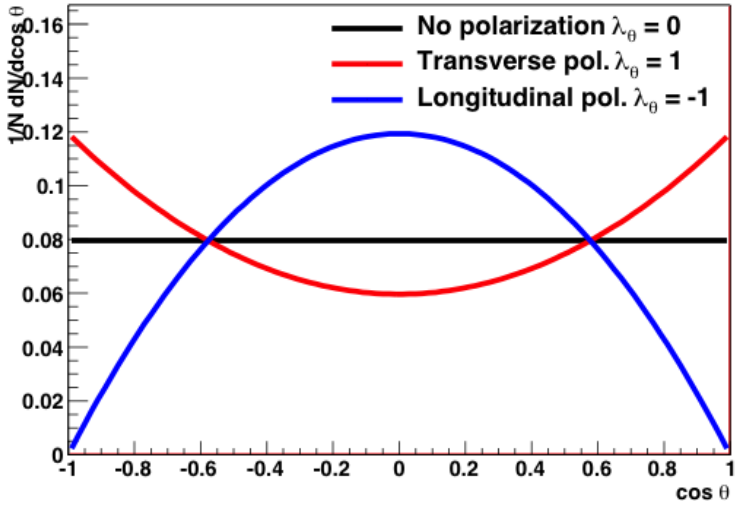
- Change of slope for p_T > 20 GeV suggesting a change in the nature of the production process

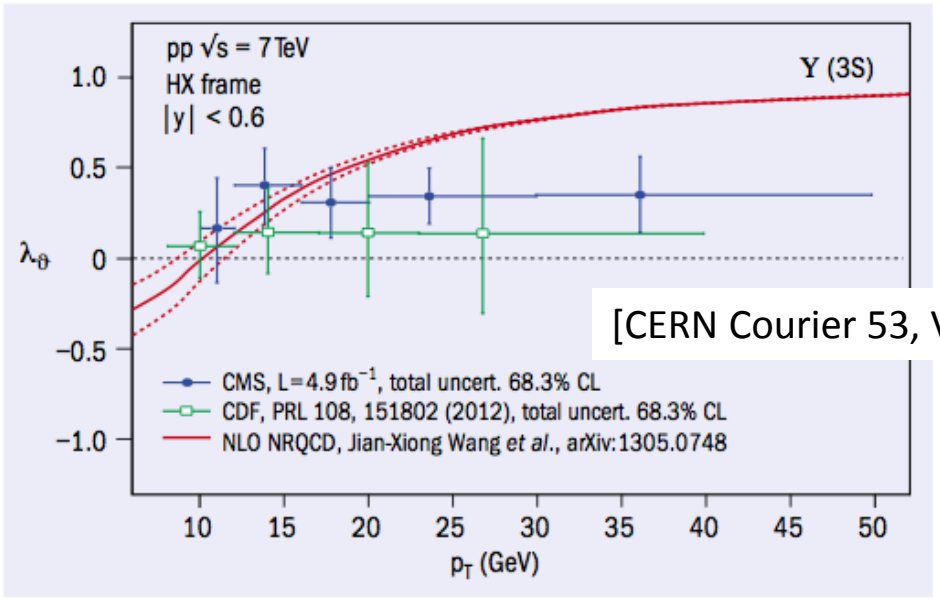
Quarkonium polarization

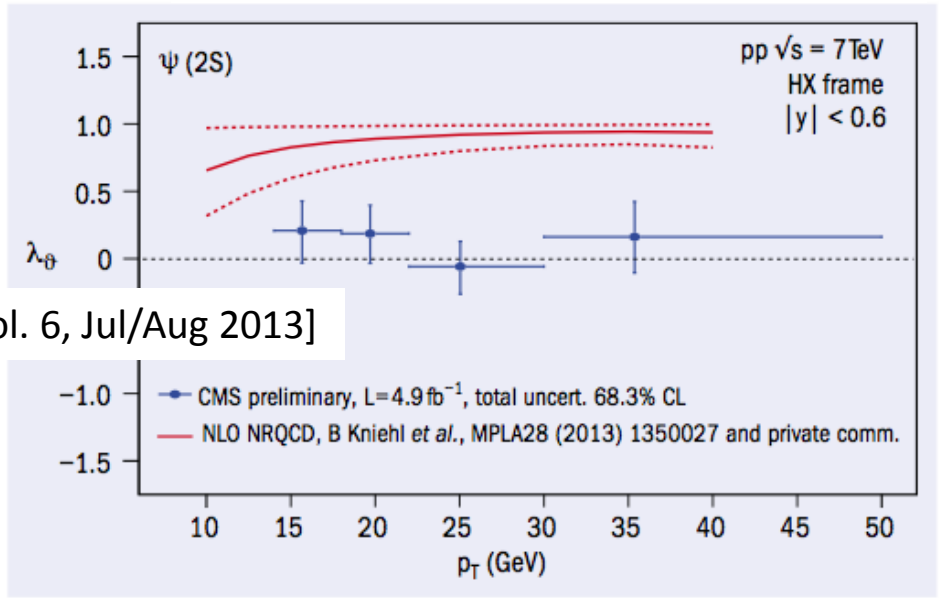
Decay in quarkonium Q (spin 1) rest-frame:



$$\frac{1}{N_Q}\frac{dN_Q}{d\cos\theta} = \frac{3}{4\pi(\lambda_\theta + 3)}\left[1 + \lambda_\theta \cos^2\theta\right]$$



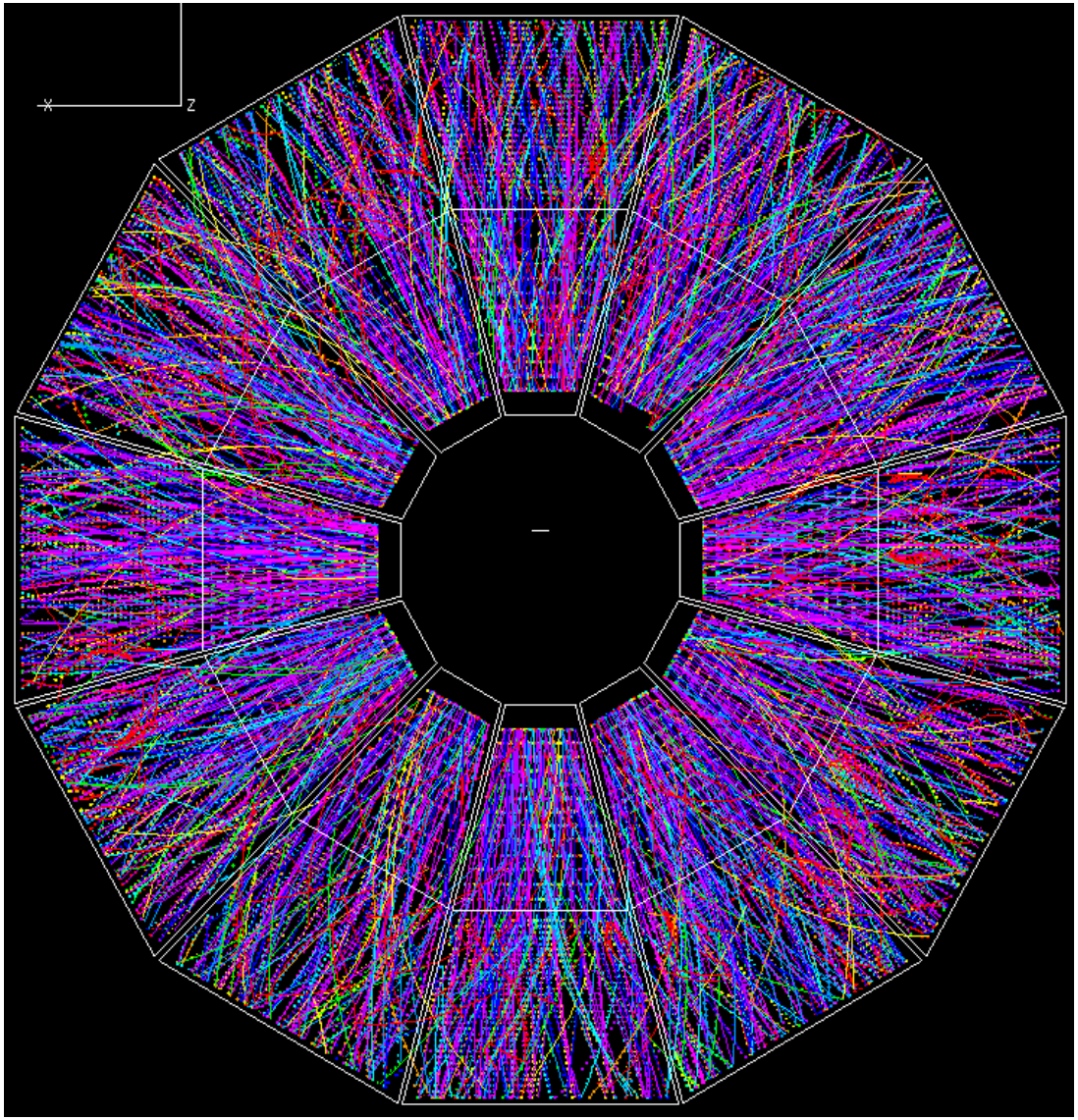




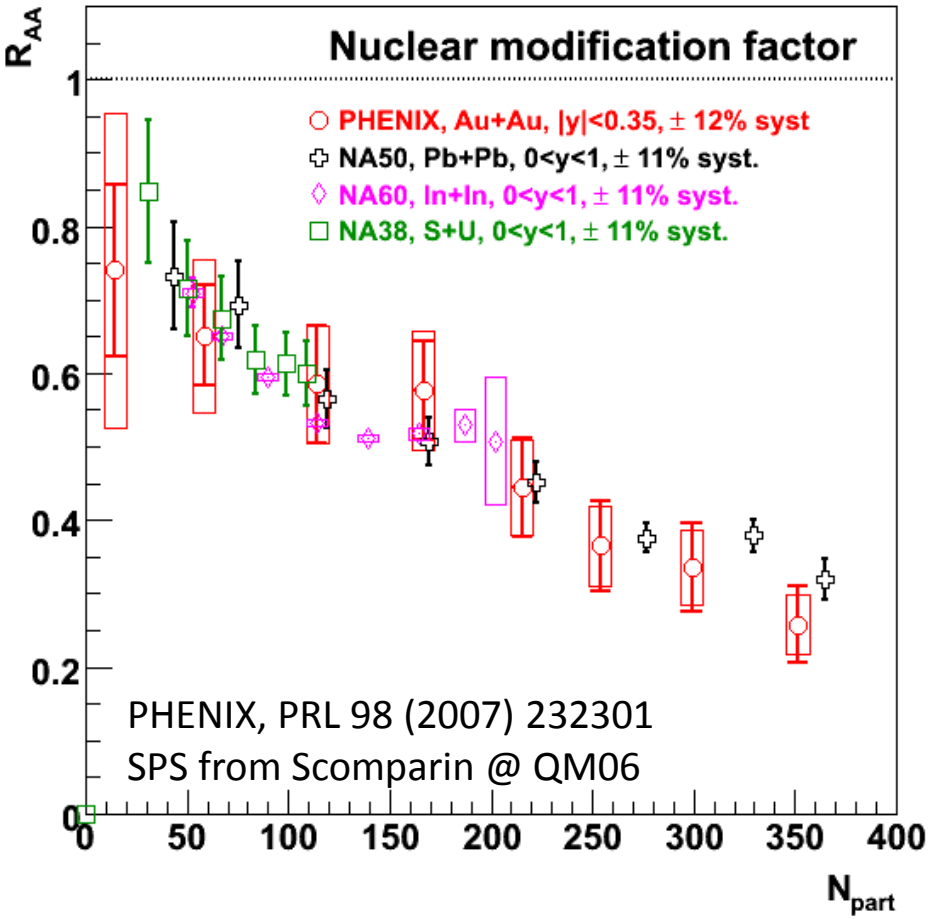
[CERN Courier 53, Vol. 6, Jul/Aug 2013]

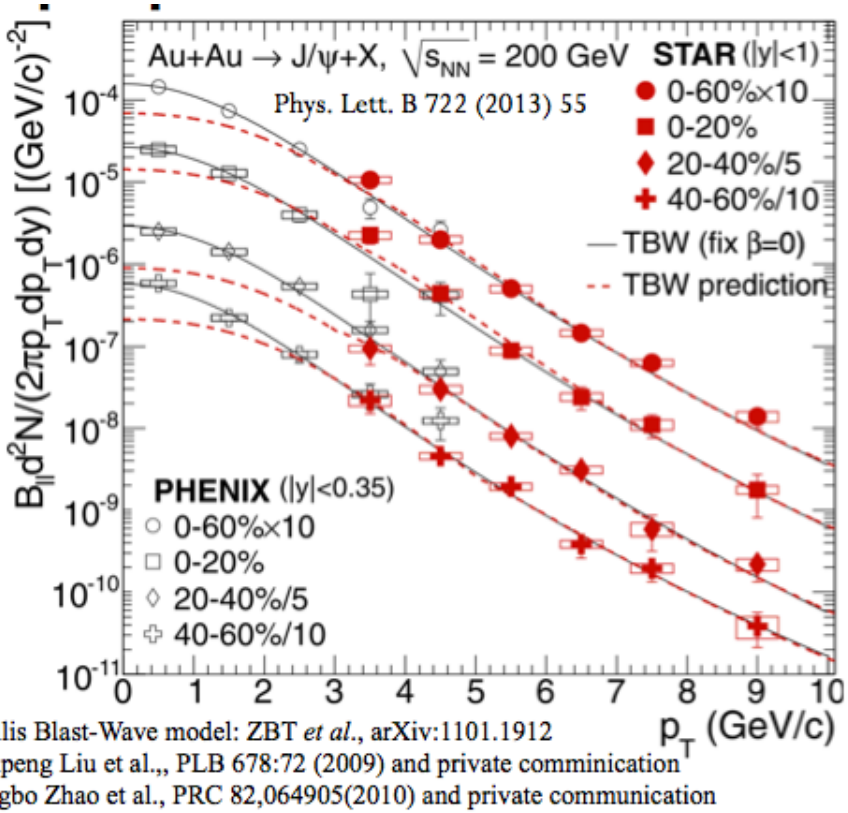
- Advantages of ψ(2S) and ϒ(3S): essentially direct production
- No agreement at high p_T between prediction and measurements

Golden age at RHIC



J/ψ in Au-Au@200 GeV





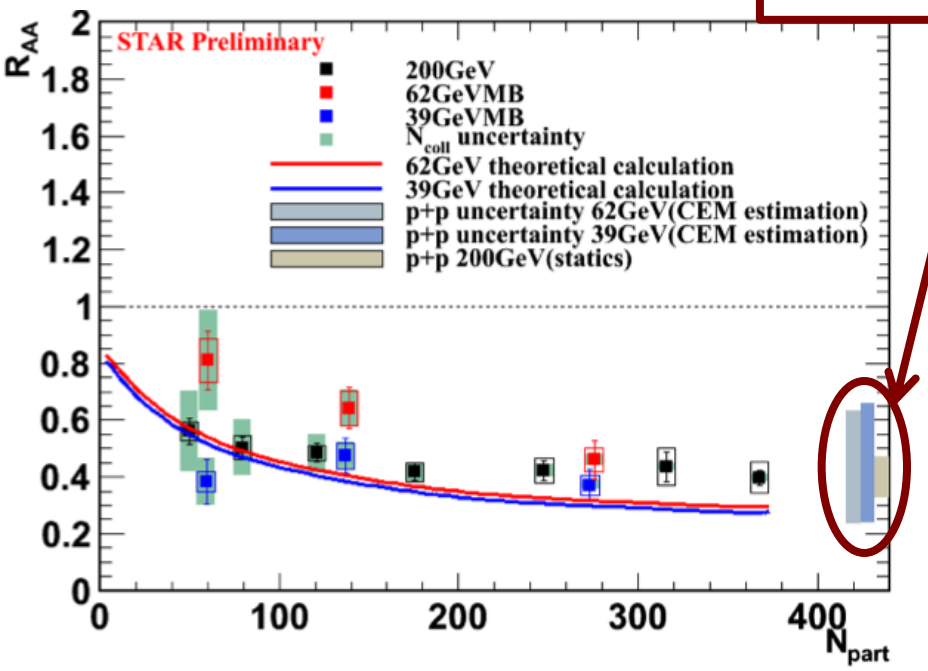
At mid rapidity, same suppression at RHIC and at SPS, while density must be higher

J/ψ p_T spectra are softer than light hadron's, indicating a small radial flow or a significant contribution from charm quark recombination

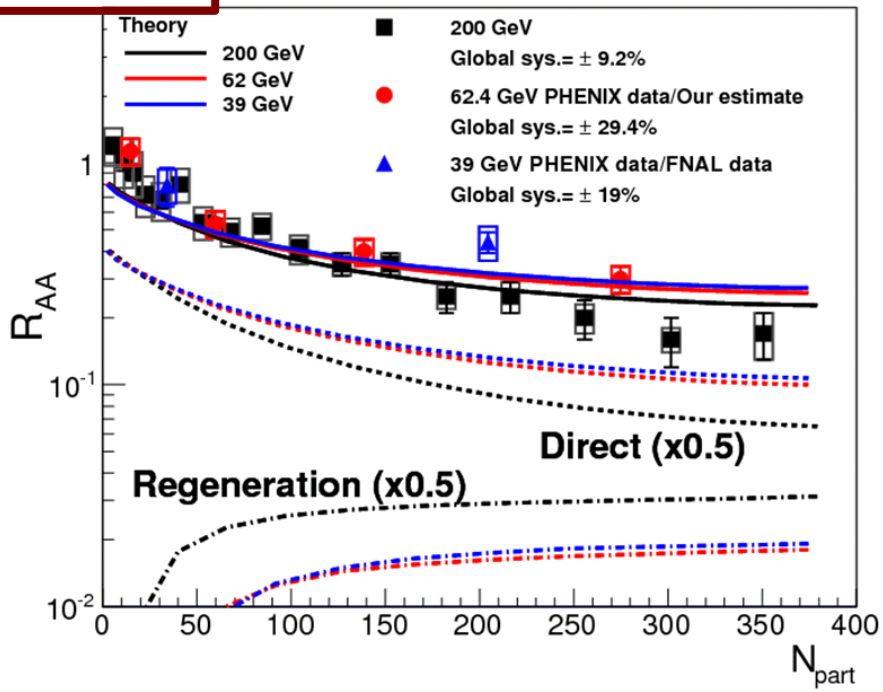
J/ψ Au-Au energy scan

Necessity to measure pp reference at A-A energy

Mid rapidity (STAR)
[D. Kikola, SQM 2013]



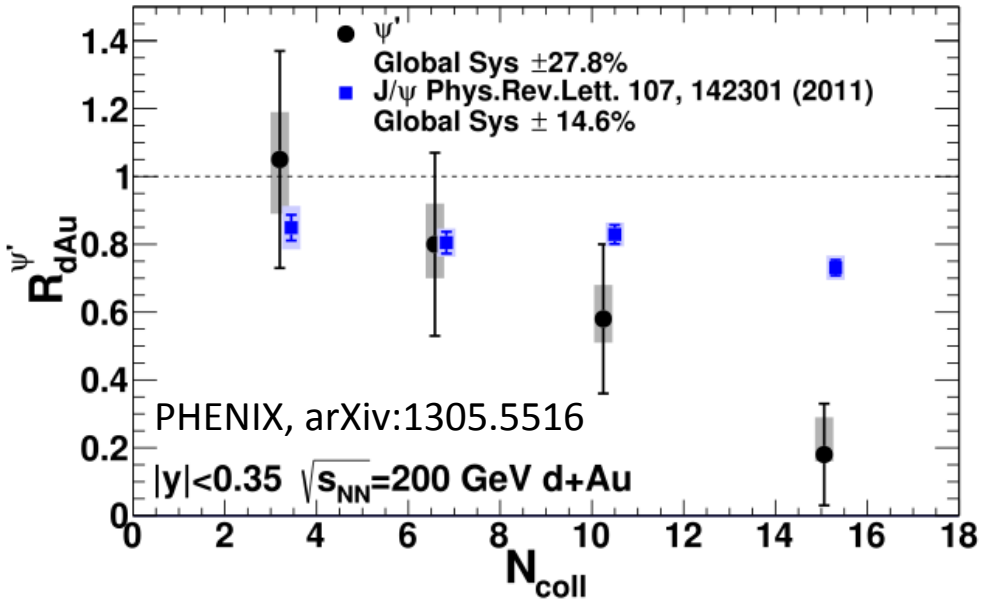
Forward rapidity (PHENIX)
[D. Jouan, SQM 2013]



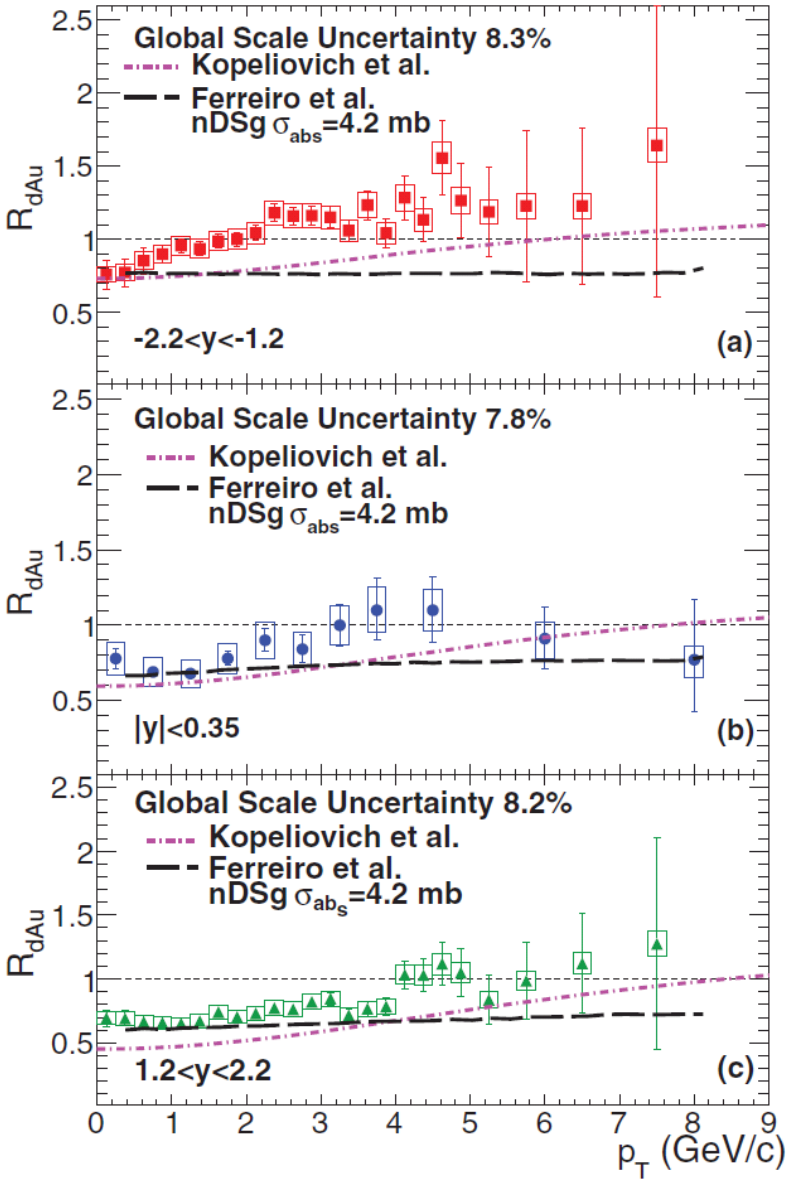
- Significant suppression at 39 and 62 GeV, similar as at 200 GeV
- Model with two main components (direct suppression and regeneration) consistent with data [Zhao & Rapp PRC 82 064905 2010]

J/ψ in d-Au@200 GeV

- R_{dAu} decrease from backward ($x \approx 8\times10^{-2}$) to forward ($x \approx 3\times10^{-3}$) rapidity
- R_{dAu} increase with p_T
- p_T distribution for different rapidity not simultaneously reproduced by models
- Ψ' more suppressed than J/ψ in d-Au ?



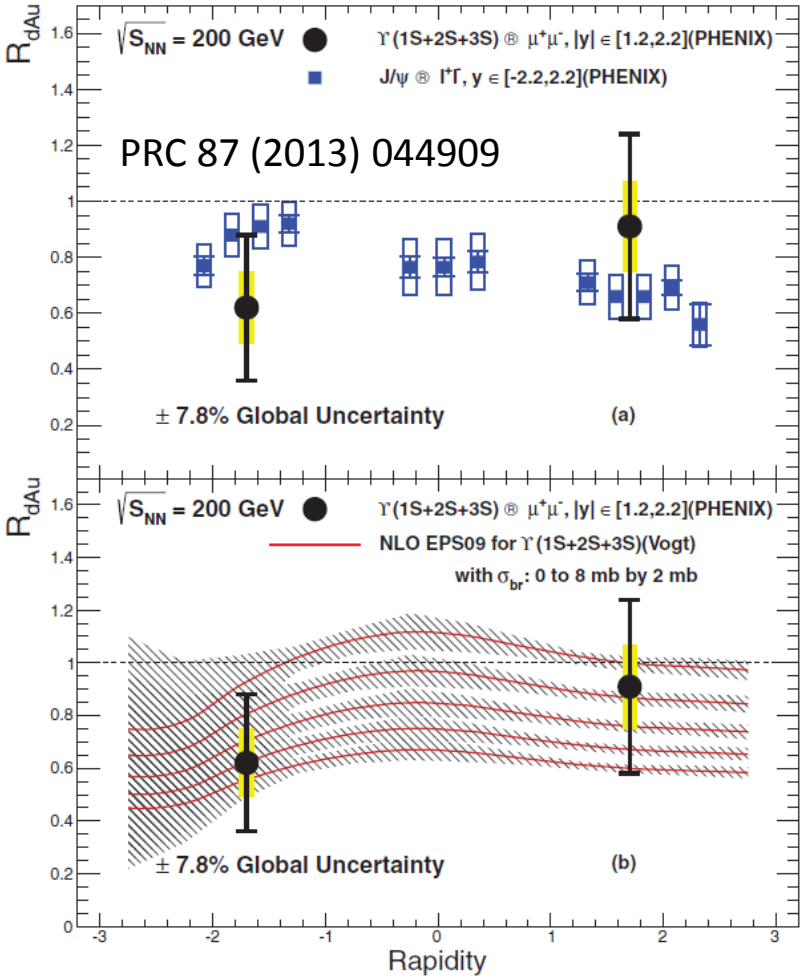
PRC 87 (2013) 034904



Upsilon

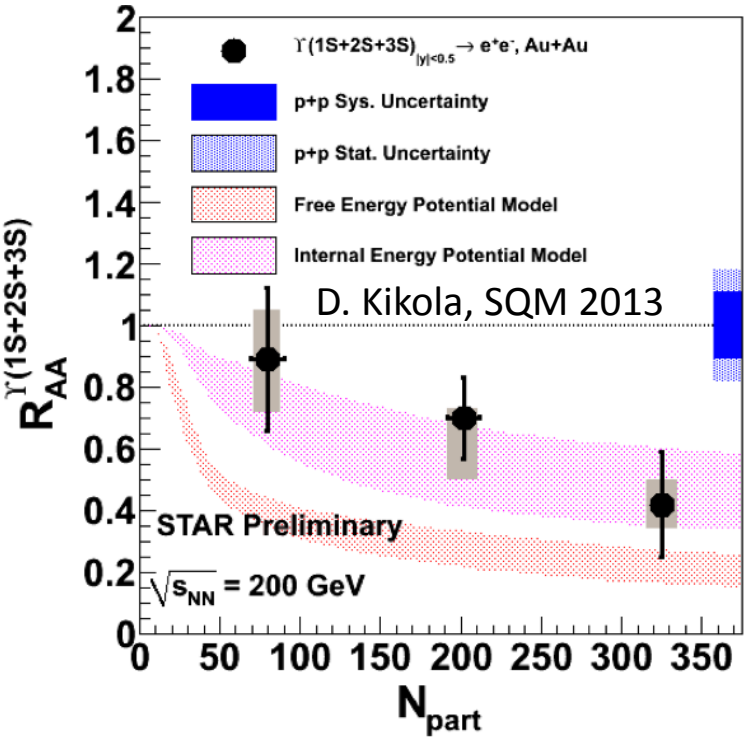
d-Au collisions (PHENIX):

- Low statistics
- Suggests a backward suppression

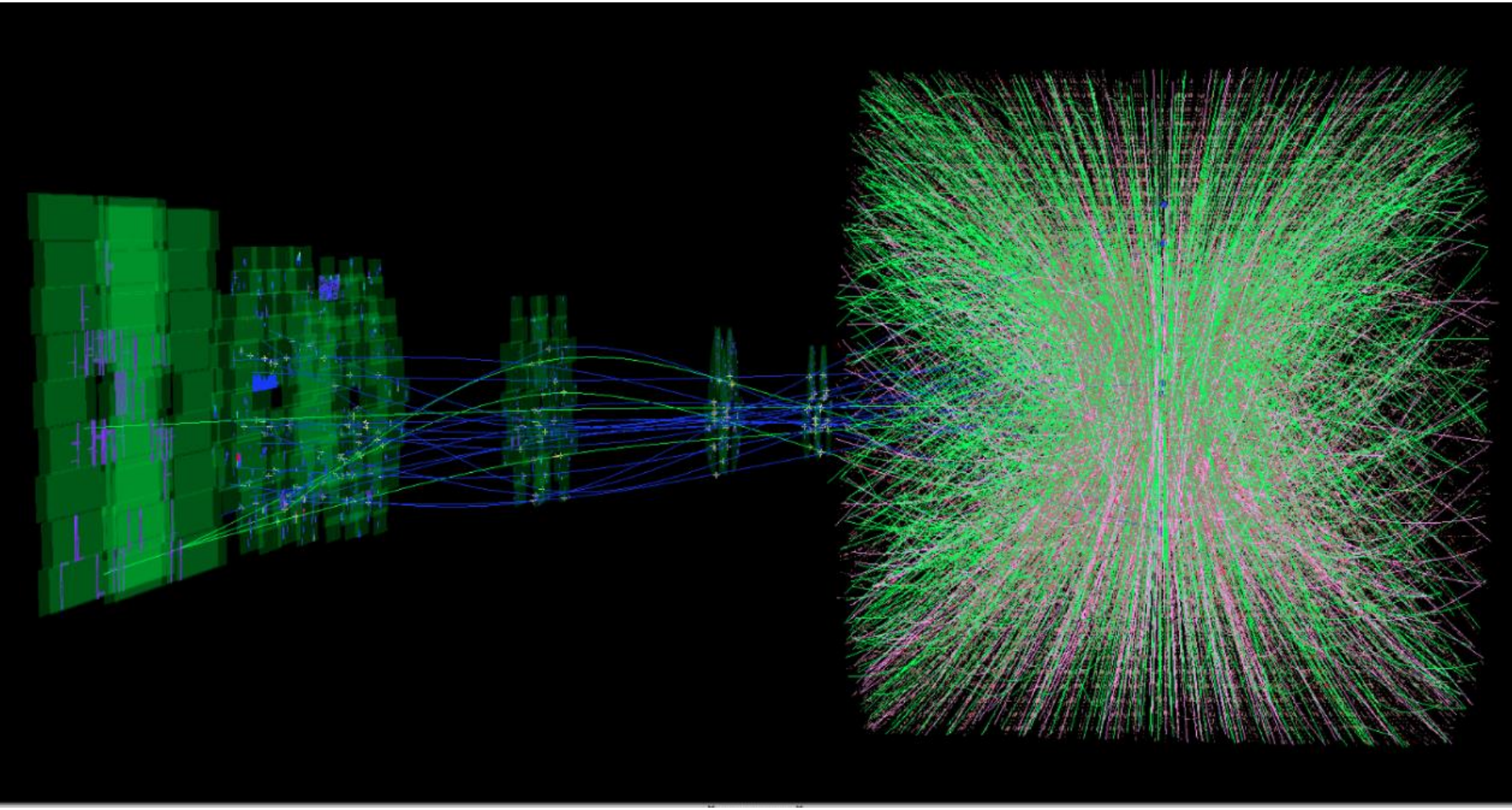


Au-Au collisions (STAR):

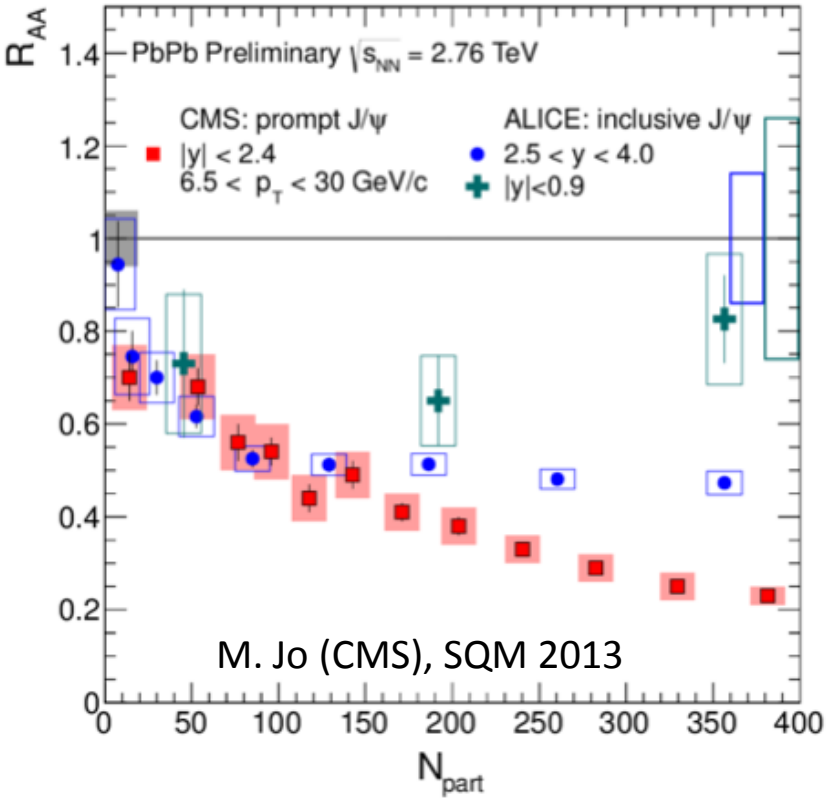
- New high statistic pp baseline
- Suppression stronger with centrality
- consistent with model assuming complete Υ(2S) and Υ(3S) suppression
[Strickland et al., PRL 107, 132301 (2011)]

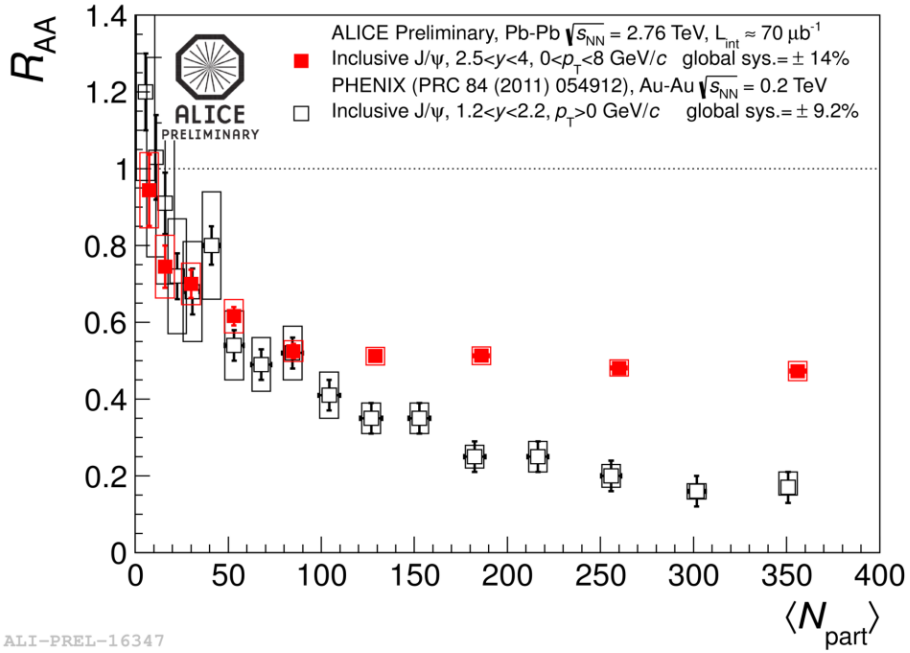


Leaden era at LHC



J/ψ in Pb-Pb (1)

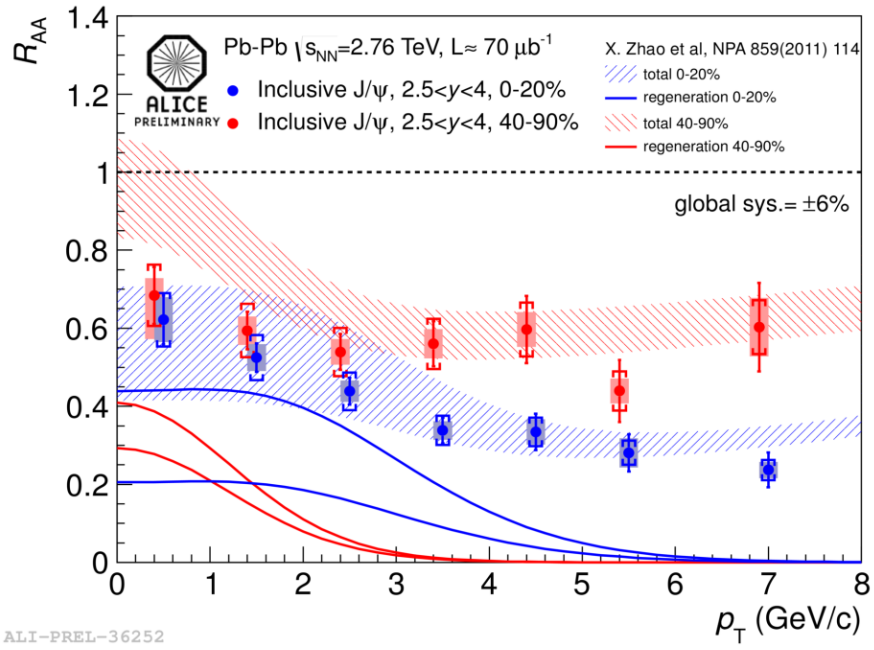


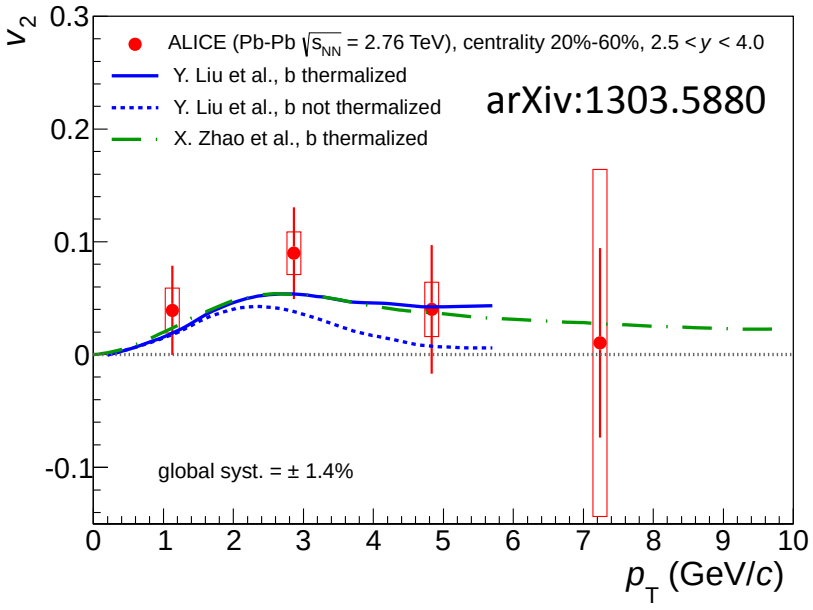


- Stronger suppression at forward rapidity
- Stronger suppression at high p_T (CMS)

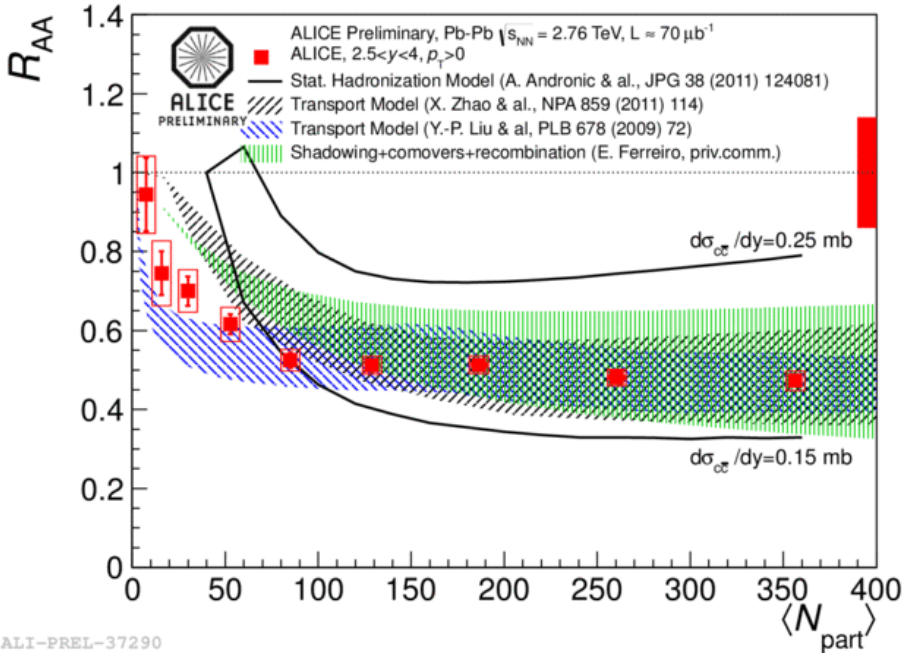
- Stronger centrality dependence at lower energy (RHIC) ➔ qualitatively in agreement with regeneration contribution

J/ψ in Pb-Pb (2)

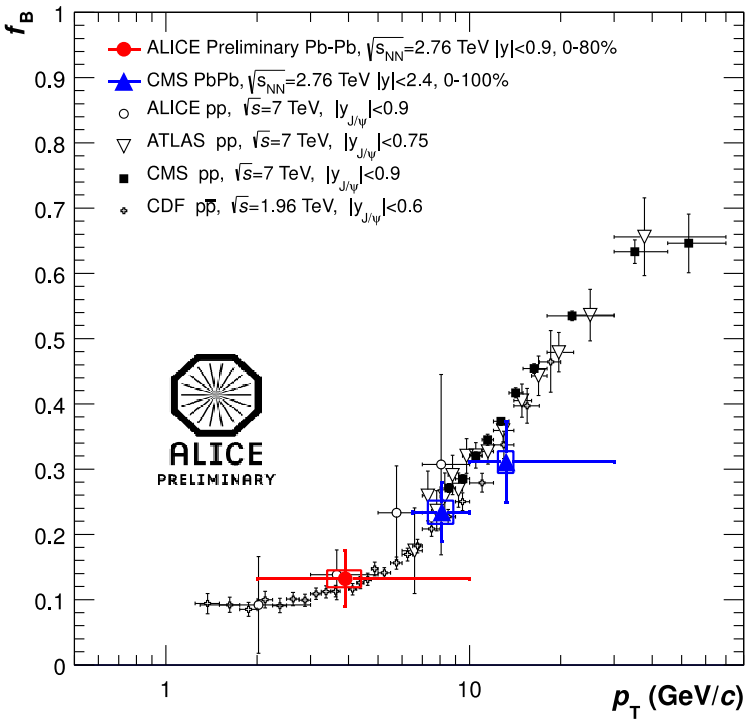


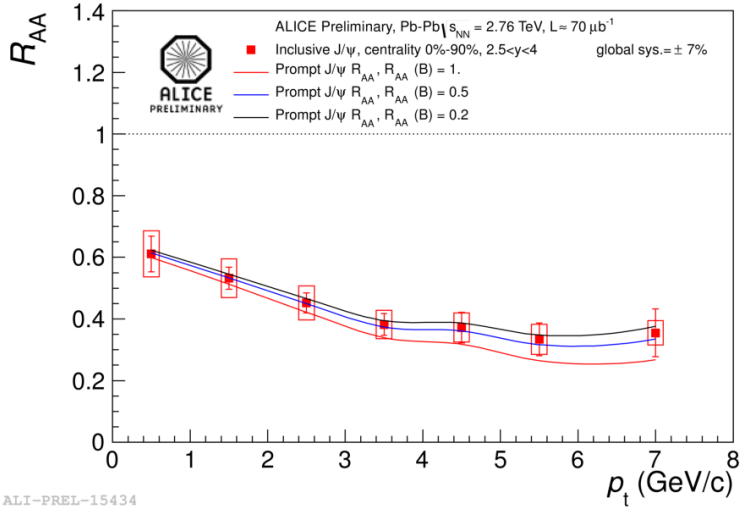


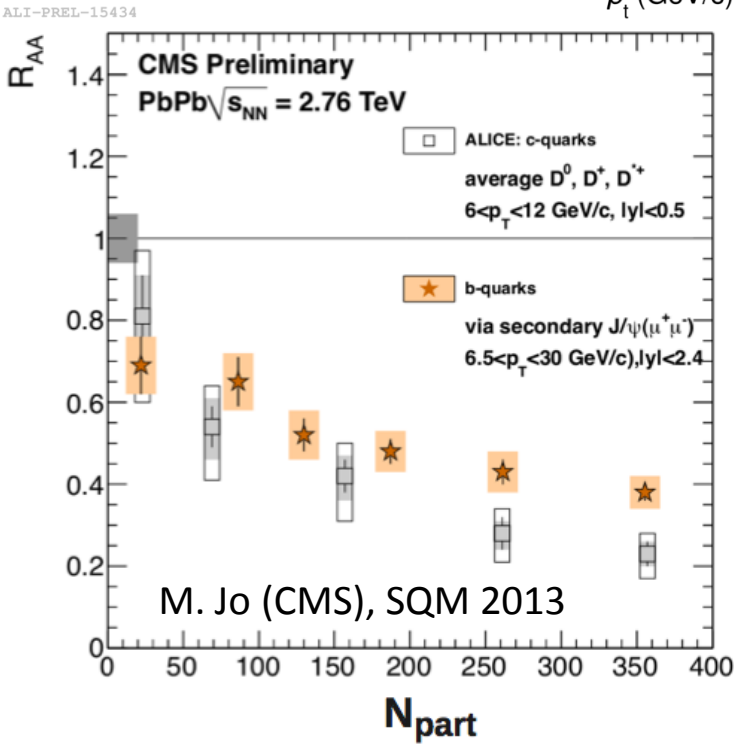
- Suppression stronger at high p_T, especially in most central collisions, in agreement with regeneration prediction
- Indication of non zero elliptic flow
- Regeneration looks necessary



Non-prompt J/ψ from b-hadron decays

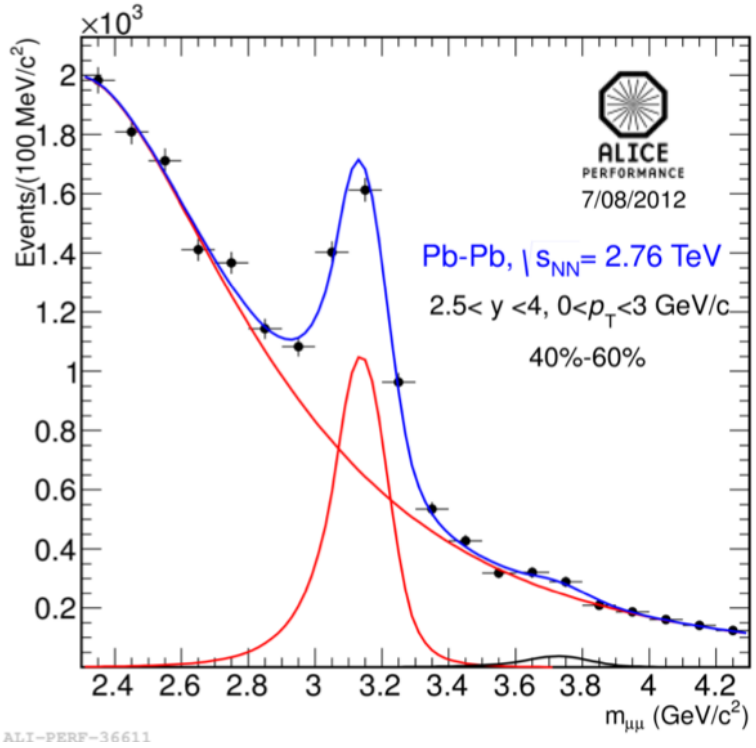






- Similar trend of f_B as a function of p_T in pp and Pb-Pb
- More confident that non-prompt J/ψ have negligible effects on inclusive R_{AA}
- First measurement of non-prompt J/ψ R_{AA}

Ψ(2S) compare to J/ψ



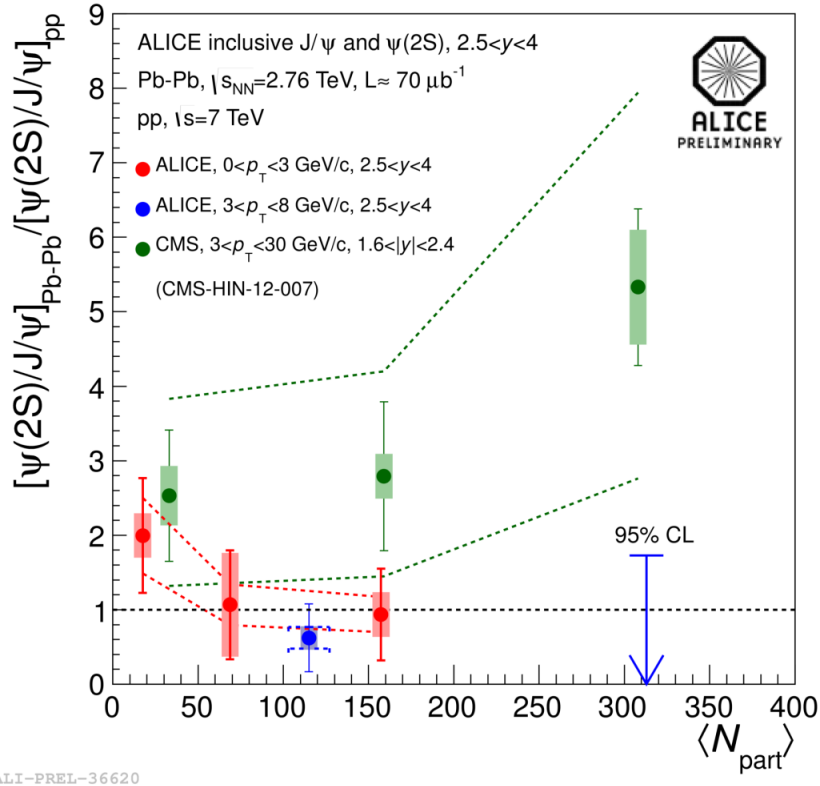
- Dashed line due to the error on pp reference
- Main systematic uncertainties from signal extraction and MC inputs for acceptance calculation

- No evidence of ψ(2S) enhancement in ALICE compare to CMS?
- Theoretical prediction:

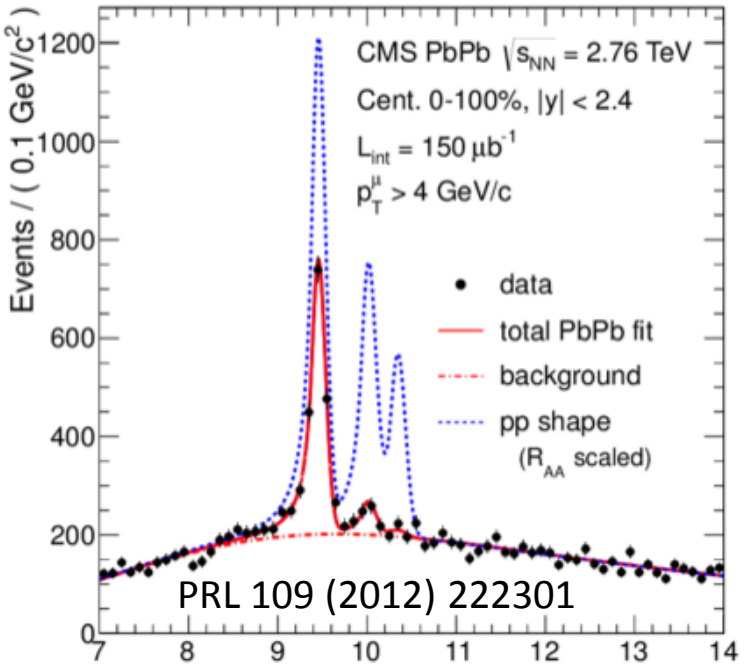
$$R = \frac{R_{AA}^{\psi(2S)}}{R_{AA}^{J/\psi}} < 1$$

in both

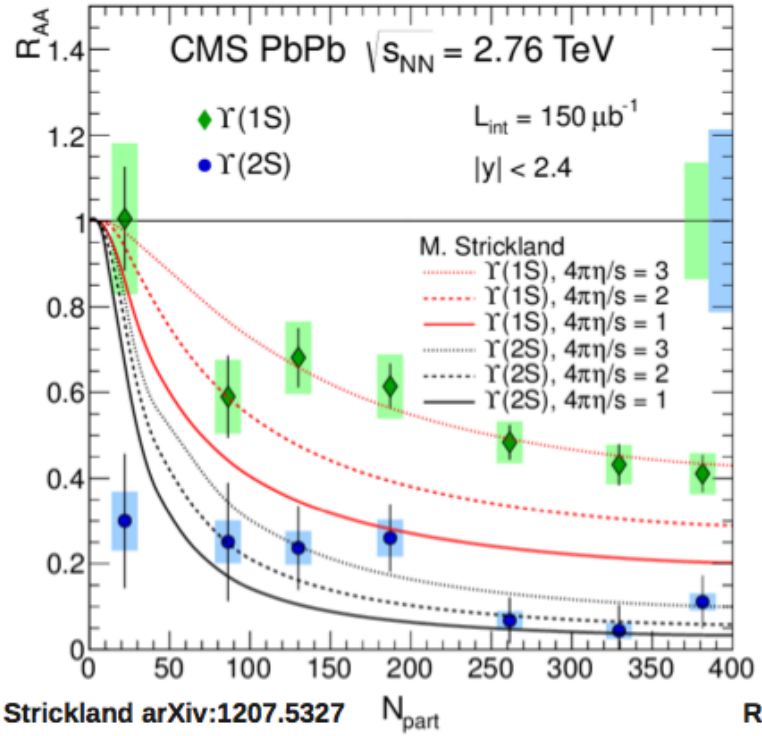
- transport model [NPA 859, 114]
- statistical recombinaison [PLB 490, 196]

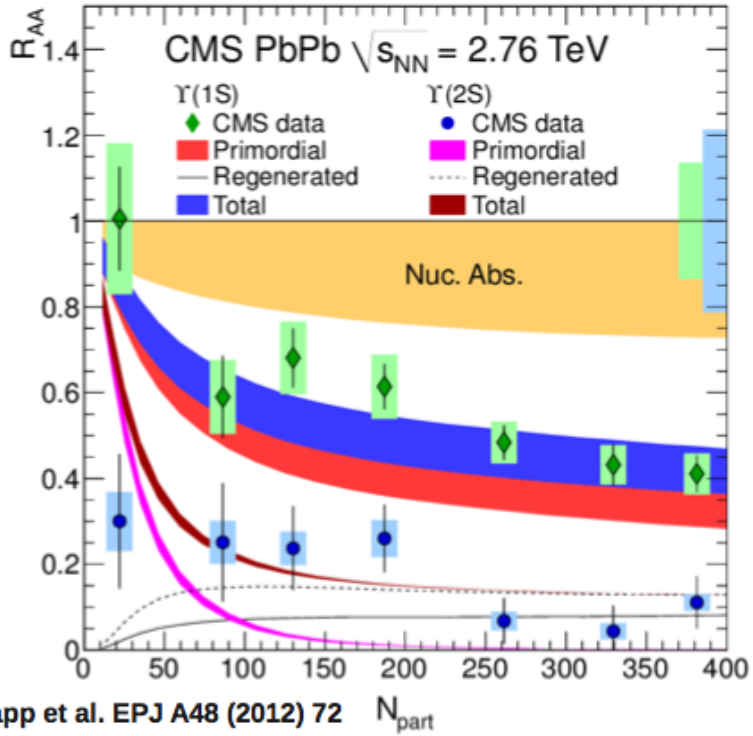


Υ(nS) in Pb-Pb

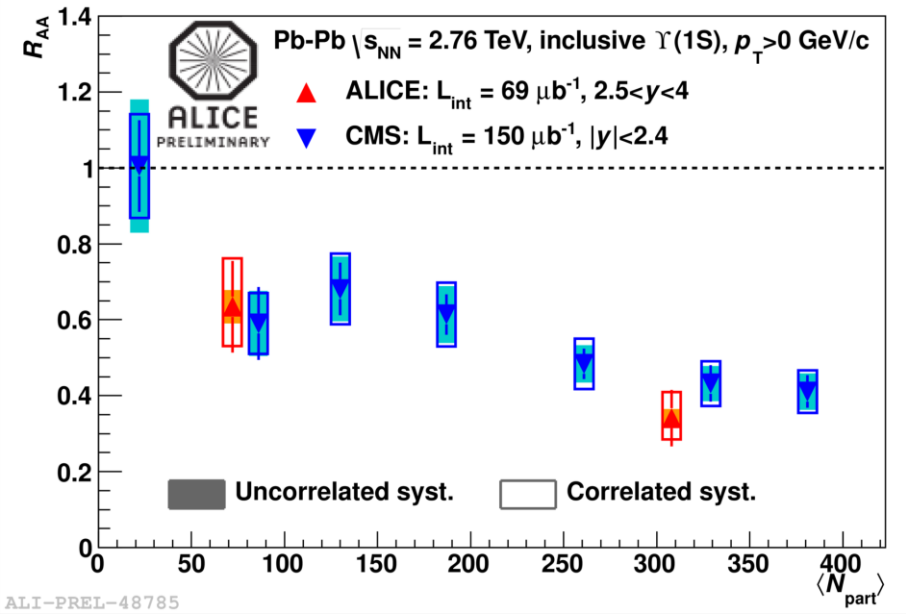


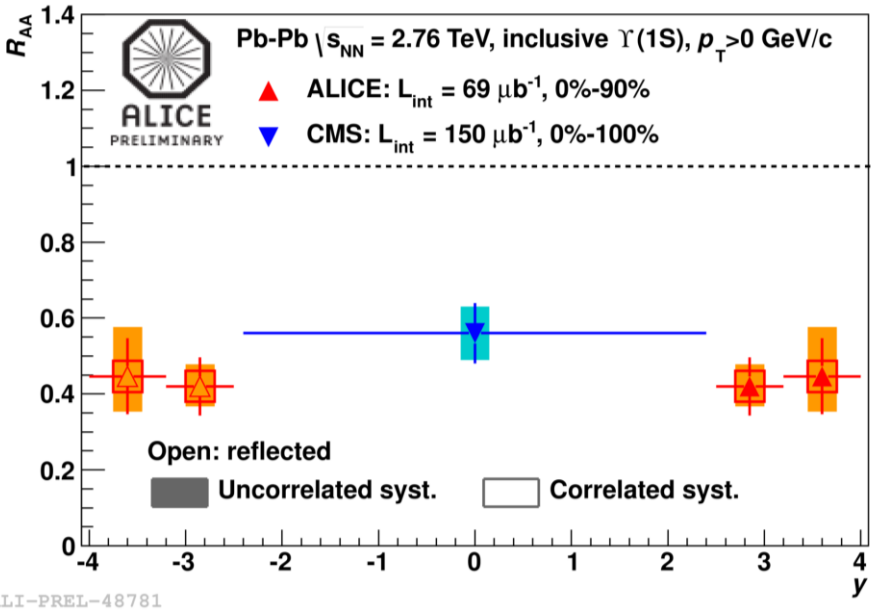
- Clear suppression of Υ(nS) observed by CMS
- Strickland: some tension to describe Υ(1S) and Υ(2S) simultaneously with the same η/s value
- Rapp et al.: regeneration and nuclear absorption could be significant also for bottomonia

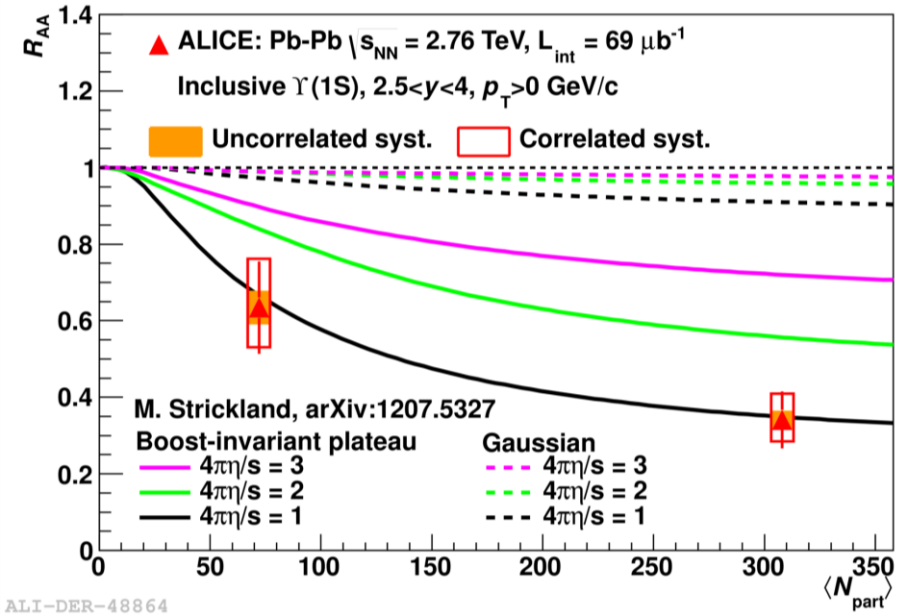




ϒ(1S) in Pb-Pb: from mid to forward rapidity

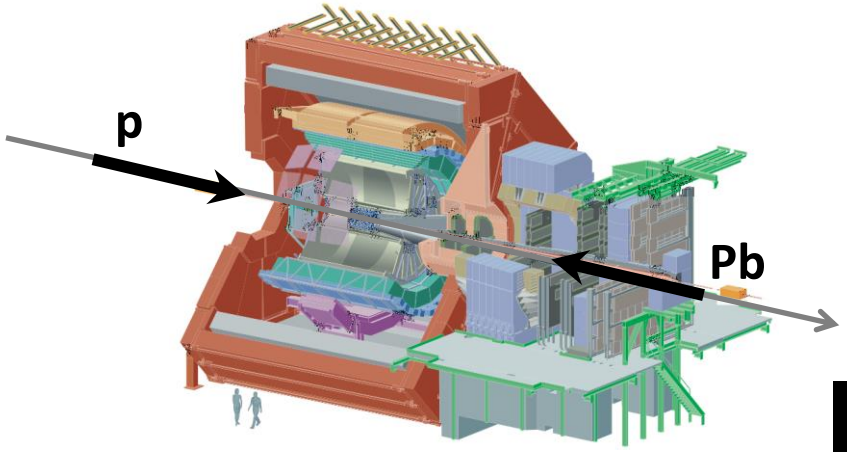


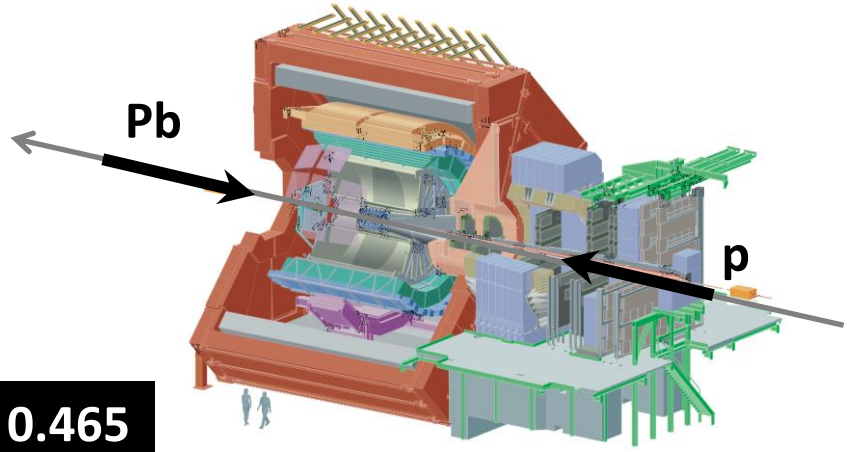




- No evidence of rapidity dependence of ϒ(1S)
- Strickland: some tension to describe ϒ(1S) of ALICE and CMS with the same η/s value

p-Pb collisions at 5.02 TeV





$y_{CM/Lab} = 0.465$

$2.5 < y_{Lab}^{p\text{-}Pb} < 4$

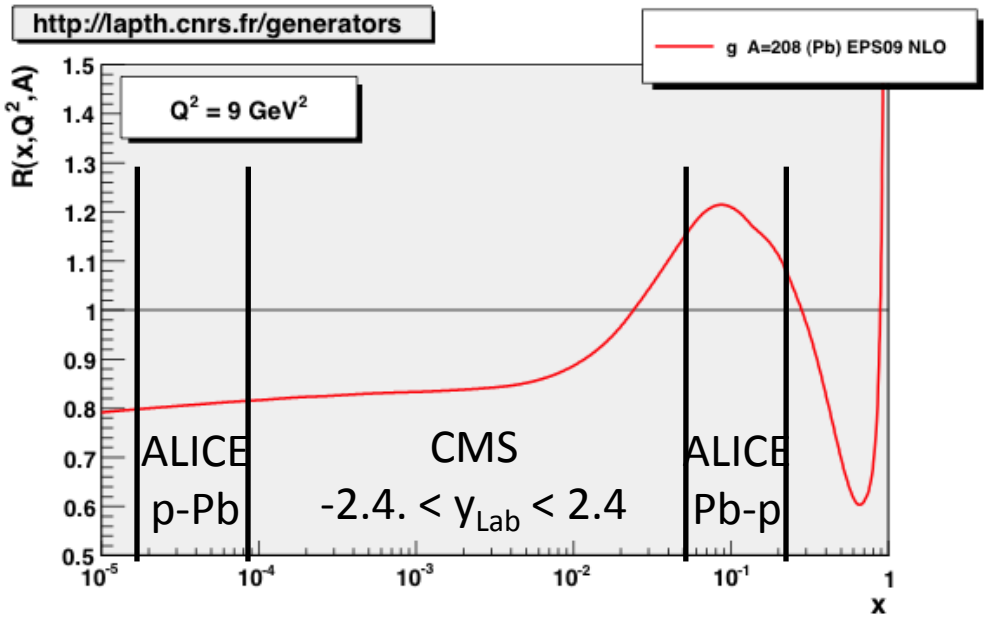
$2.04 < y_{CM}^{p\text{-}Pb} < 3.54$

$-4. < y_{Lab}^{Pb\text{-}p} < -2.5$

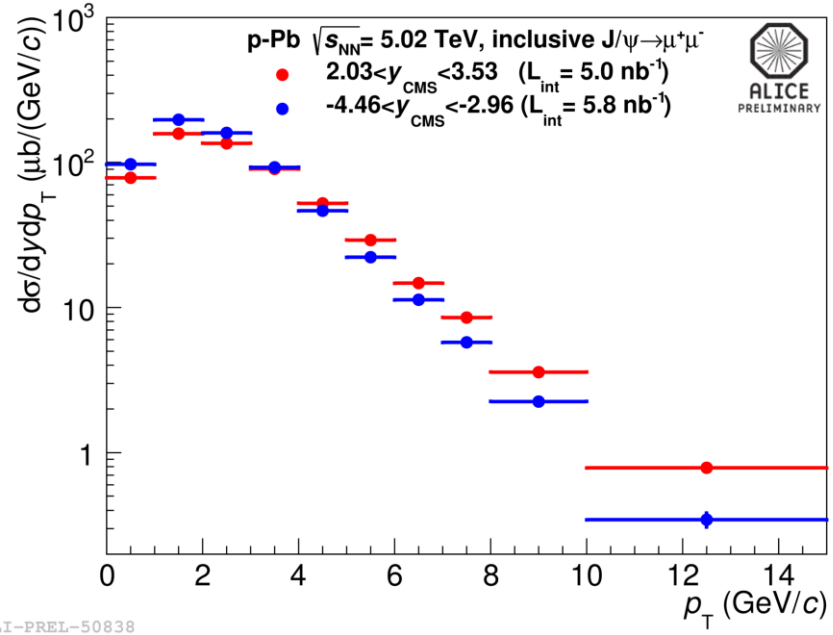
$-4.46 < y_{CM}^{Pb\text{-}p} < -2.96$

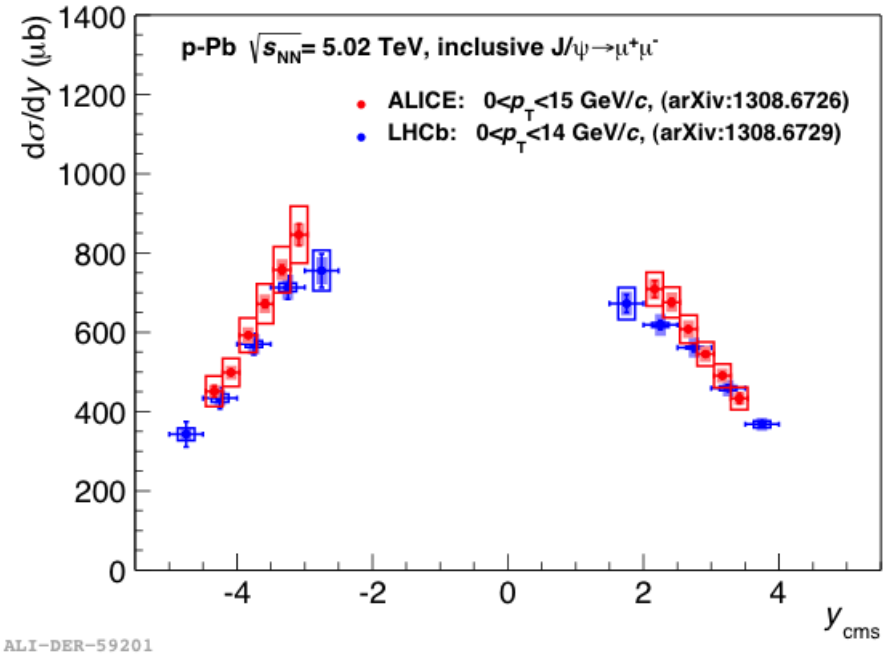
$$x_p = \frac{\sqrt{Q^2}}{\sqrt{s}} e^{y_{CM}}$$

$$x_{Pb} = \frac{\sqrt{Q^2}}{\sqrt{s}} e^{-y_{CM}}$$



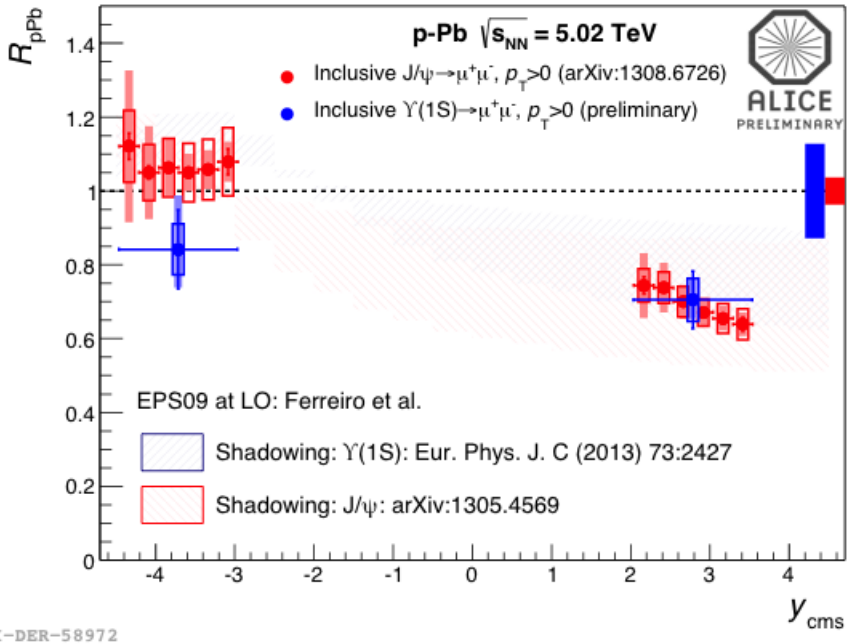
J/ψ in p-Pb

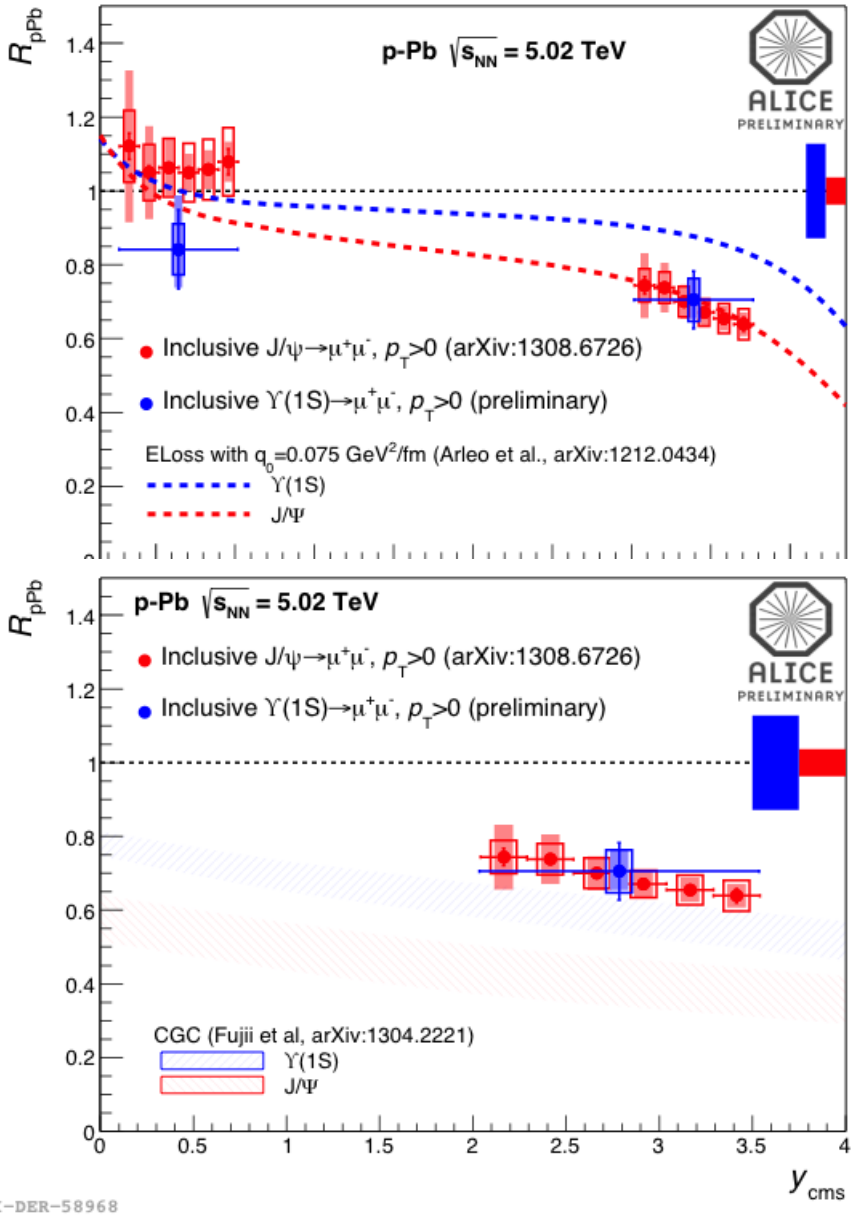




- Precise measurement: systematic errors of about 6-8% (signal extraction), statistical errors negligible
- Cross section higher in the backward (Pb-p) than in forward (p-Pb) rapidity region
- Small discrepancy between ALICE and LHCb for $|y_{CMS}| \approx 2$

J/ψ and ϒ(1S) in p-Pb (1)



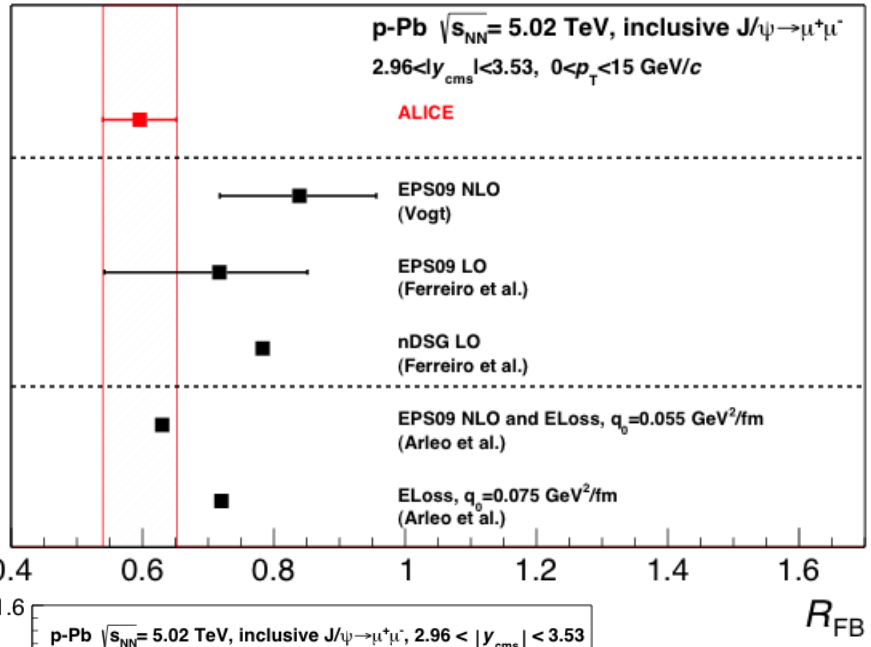


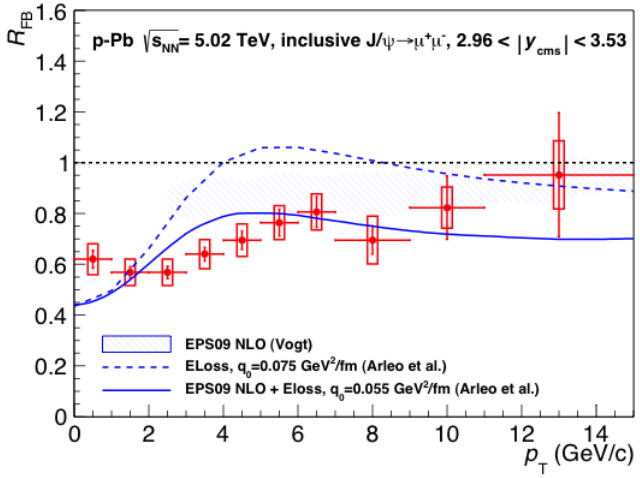
- J/ψ and ϒ(1S) R_{pPb} are similar at forward rapidity ➔ shadowing
- <u>Models without nuclear break-up</u>:
  - Good agreement with EPS09 at LO
  - Energy loss underestimate slightly ϒ(1S) suppression at forward rapidity
  - CGC overestimate J/ψ suppression at forward rapidity

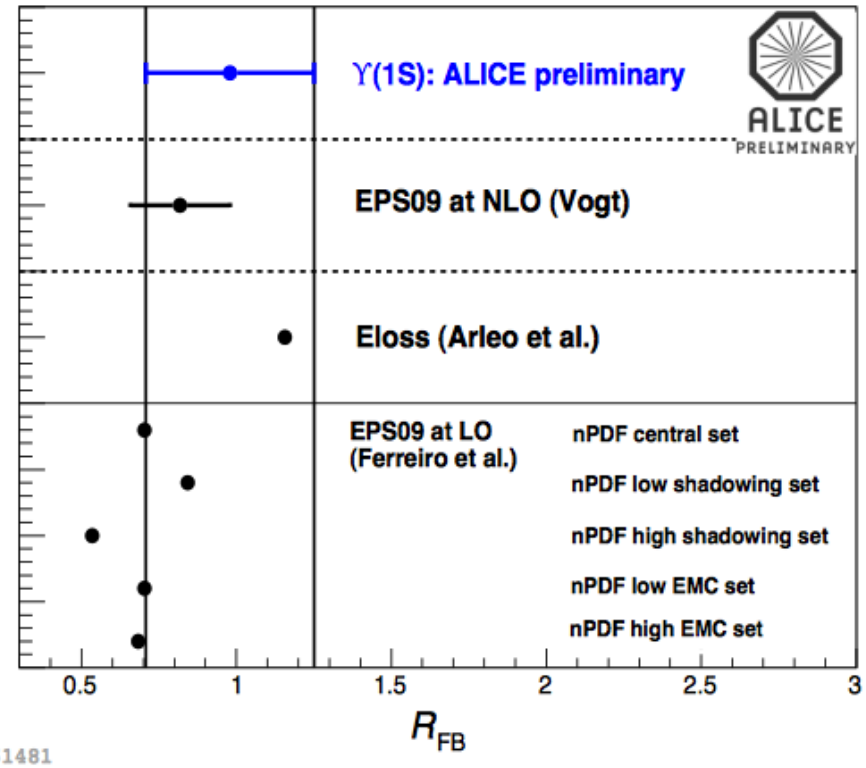
J/ψ and ϒ(1S) in p-Pb (2)

Forward-Backward ratio cancels the pp reference cross section and <N_{coll}>

$$R^{\Upsilon}_{FB}(2.96<|y_{CMS}|<3.54)=\frac{Y_{pA}(3.47<|y_{LAB}|<4)}{Y_{Ap}(2.5<|y_{LAB}|<3.07)}$$







- J/ψ R_{FB} significantly lower than ϒ one
- ϒ R_{FB} in agreement with all models
- J/ψ R_{FB} lower at low p_T than at high p_T where better agreement to models is observed

And then …

Hergé, *Les aventures de Tintin*, *Le trésor de Rackham le rouge*

Main observations

pp collisions

- polarization of quarkonia still puzzling

Charmonia

- J/ψ suppression in A-A more important at RHIC than at LHC energy
- J/ψ suppression in A-A more important at forward than at mid rapidity, both at RHIC and LHC
- evidence of non zero J/ψ elliptic flow in Pb-Pb at LHC

➔ **all observations in agreement with models including regeneration**

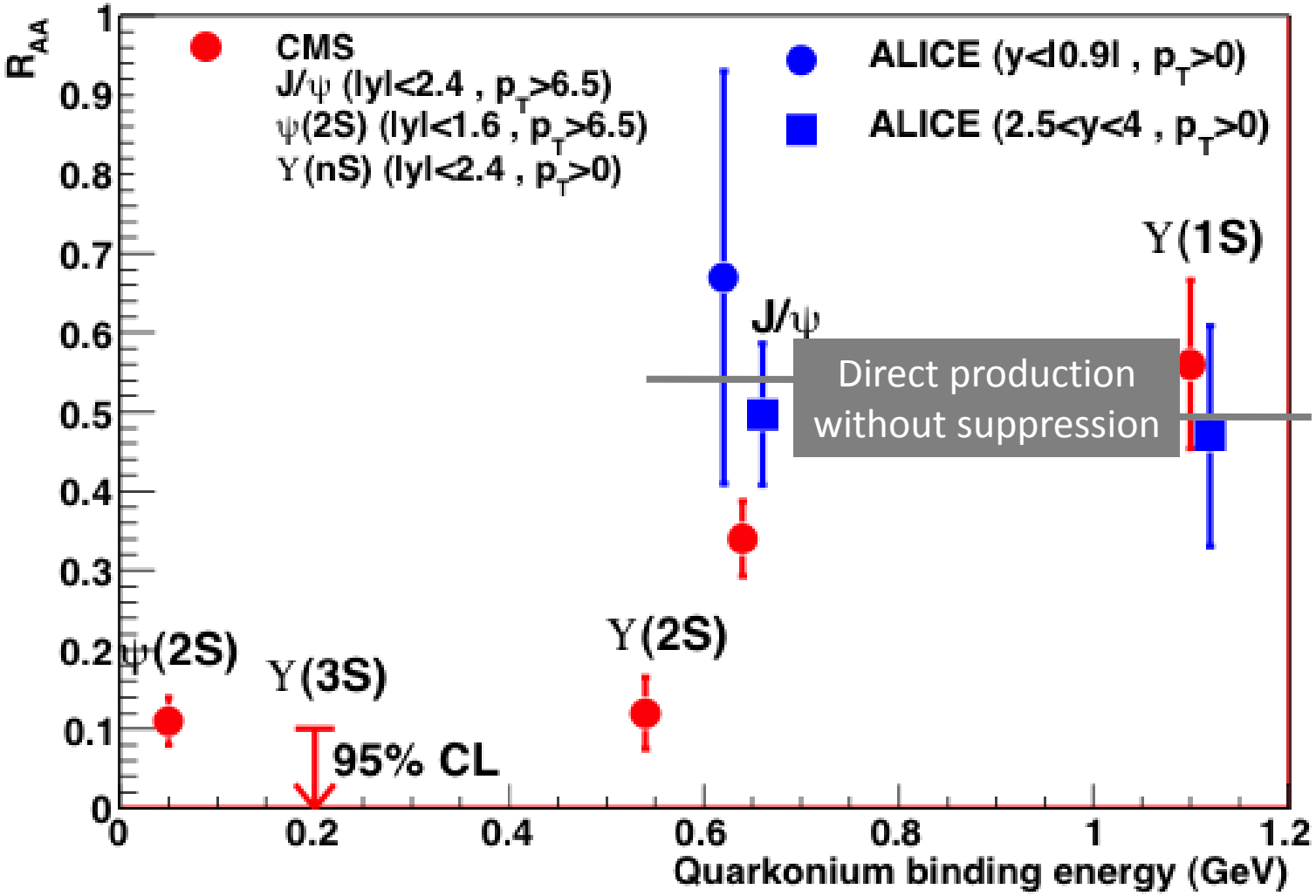
- no evidence of anomalous ψ(2S) suppression in Pb-Pb at LHC
- J/ψ data in p(d)-A seems to require shadowing
  - and nuclear break-up at RHIC ?
  - or energy loss at LHC ?
- ψ(2S) more suppressed than J/ψ in d-Au collisions at RHIC ?

Bottomonia

- observation of ϒ(nS) hierarchy suppression in A-A
- ϒ(1S) suppression in A-A well described by model without (or small) regeneration
- ϒ(1S) suppression in p-Pb at LHC well described by model with shadowing

Summary (Raphaël GdC) plot

Minimum bias Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
with stat and syst uncertainties added in quadrature



Looking forward

❖ Forthcoming running conditions
- with energy × 2
- Pb-Pb luminosity × ~~2~~

➔ still more data where current p-Pb data at 5.02 TeV could be "directly" used for comparison with Pb-Pb

$E_{p\ beam}$	$\sqrt{s}$ in pp	$\sqrt{s_{NN}}$ in Pb-Pb
6.5 TeV	13 TeV	5.1 TeV
7 TeV	14 TeV	5.5 TeV

❖ New ideas needed to disentangled the different scenarii

➔ Satz [ICNFP 2013]: *The correct calibration is hidden to open charm, so that the relevant observable is*

$$S_{J/\psi} = \frac{N_{AA}^{J/\psi} / N_{AA}^{c\bar{c}}}{N_{pp}^{J/\psi} / N_{pp}^{c\bar{c}}}$$

- cancel some errors (pp reference, N_{coll} if same centrality detector)
- cancel a part of cold nuclear matter effects (nPDF if at same Q^2)

❖ A lot of data to be compare to several models: it is times to intensify discussions between theory and experiment

➔ **First SaporeGravis Workshop (SGW 2013)**
2-5 Deember 2013, Nantes

Thanks to all summer Conference speakers for their slides