CHIC

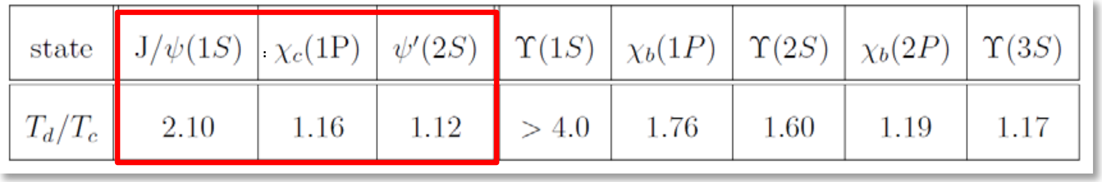
Charmonia in Heavy Ion Collisions should we go **back to SPS ?**

– charmonia in A+A : the current (simplified) picture –

– back to SPS : the CHIC picture –

Reminder

- **Motivations**
  - Quarkonia suppression is a prediction of lattice QCD calculations, for instance :



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

H. Satz, J. Phys. G 32 (2006)

- **Experimental setups**

SPS/CERN – NA38, NA50, NA60 ($\sqrt{s_{NN}}$ = 17 – 30 GeV): fixed target experiments

- **Statistic :100 000's J/ψ**
- **Data sets : p+A w/ A=p, d, Be, Al, Cu, Ag, W, Pb; S+U, In+In, Pb+Pb**
- **Small rapidity coverage (typically $y_{CMS} \in [0,1]$)**

RHIC/BNL – Phenix experiment ($\sqrt{s_{NN}}$ = 200 GeV): collider experiments

- **Statistic : 1000's J/ψ (10000's since 2007)**
- **Data sets : p+p, d+Au, Cu+Cu, Au+Au**
- **Large rapidity coverage ($y_{CMS} \in [-0.5,0.5]$, $y_{CMS} \in [-2.2,-1.2]$ and $y_{CMS} \in [1.2,2.2]$)**

LHC/CERN experiments ($\sqrt{s_{NN}}$ = 5,5 TeV): collider experiments

- **Collider experiments**
- **Statistic : 100000's J/ψ**
- **Data sets : p+p, Pb+Pb, p+Pb**
- **Large rapidity coverage ($|y_{CMS}|<2.5$ ATLAS/CMS, $|y_{CMS}|<0.9$ and $-4.0 < y_{CMS} < -2.5$ ALICE)**

Envisionned mechanisms

- **Sequential suppression in a QGP**

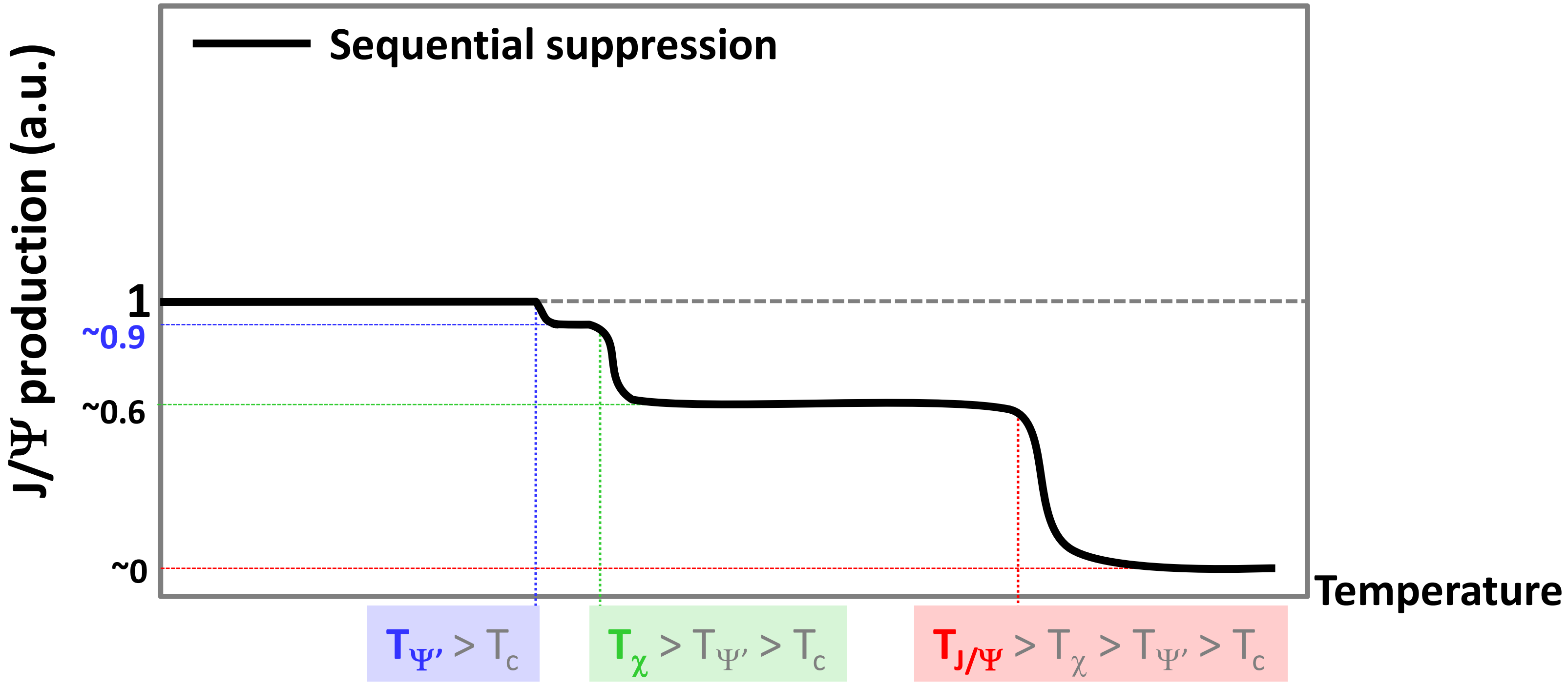
inclusive J/Ψ yield ~ 60% direct J/Ψ **+ 30%** $\chi_c \rightarrow J/\Psi + \gamma$ **+ 10%** $\Psi' \rightarrow J/\Psi + X$

Charmonium temperatures of dissociation

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

H. Satz, J. Phys. G 32 (2006)

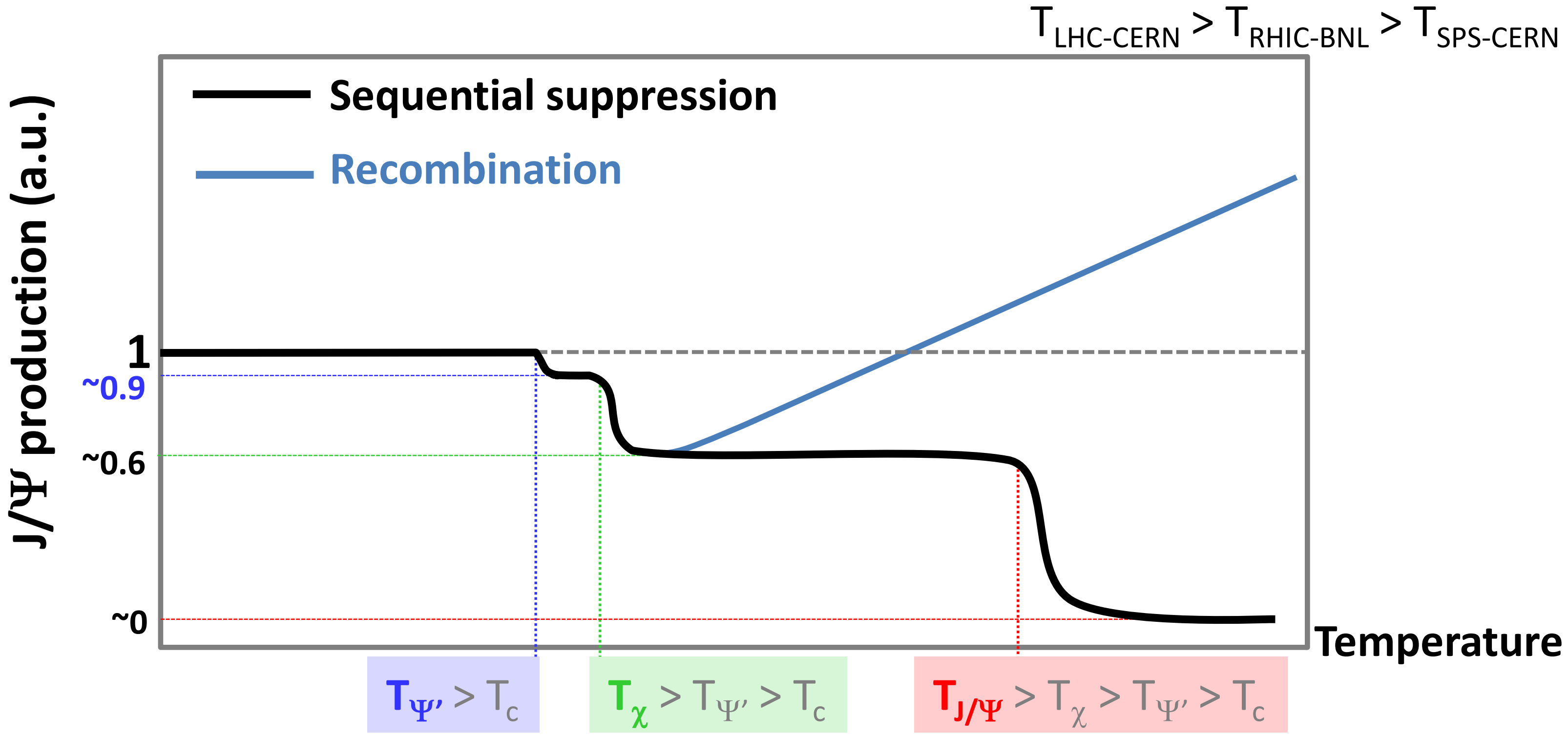
$T_{LHC\text{-}CERN} > T_{RHIC\text{-}BNL} > T_{SPS\text{-}CERN}$



Envisionned mechanisms

- **Recombination in a QGP**

If QGP at work ➔ c and $\bar{c}$ quarks can combine to form a J/Ψ
(require a large number of $c\bar{c}$ pairs → RHIC ? LHC ?)



Envisionned mechanisms

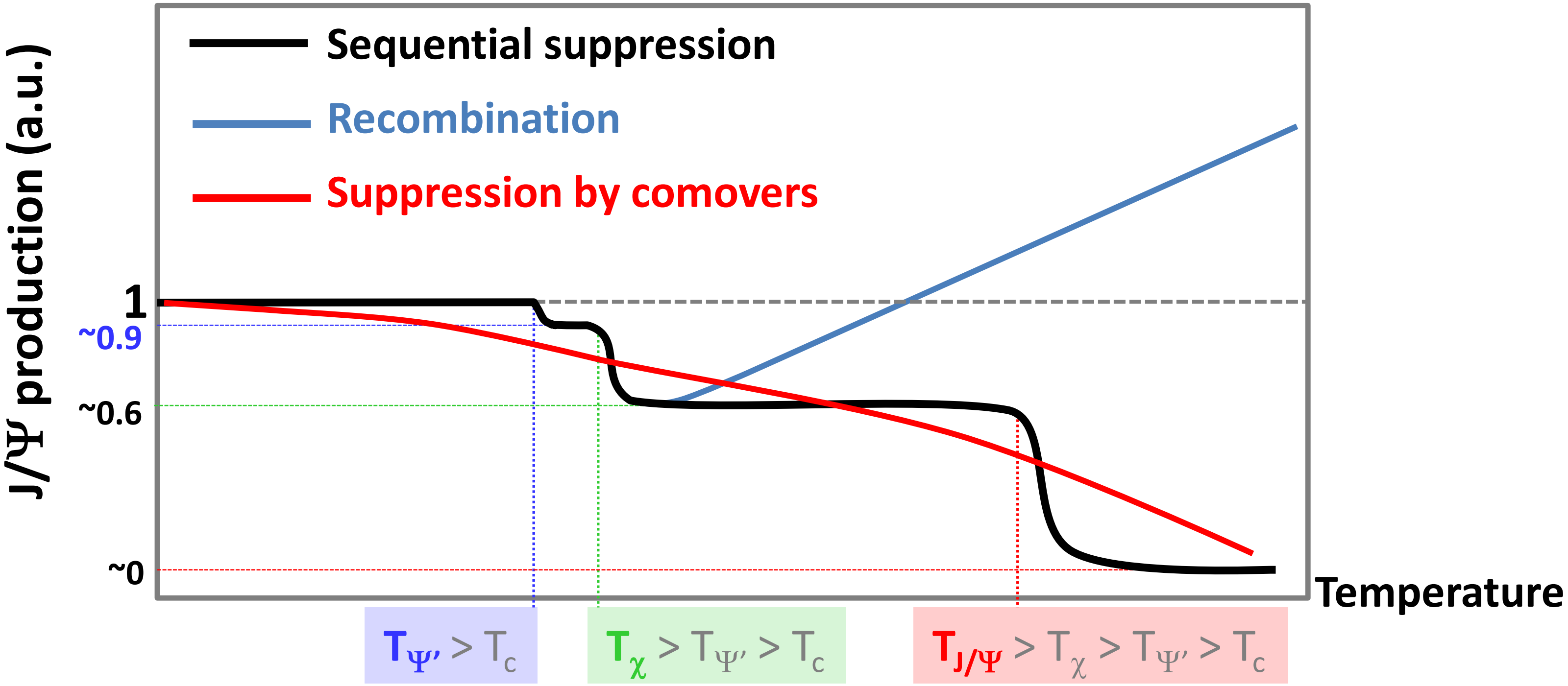
- **Suppression by comovers (Alternative scenario)**
  - Suppression by comovers: (Eur.Phys.J.C58:437-444,2008)
    - quarkonia can be broken by interaction with comoving hadrons

Two parameters

Interaction cross section σ_{co}

Hadron density N^{co}

$$\tau \frac{\mathrm{d}N_{J/\psi}}{\mathrm{d}\tau}(b,s,y) = -\sigma_{co} N^{co}(b,s,y) N_{J/\psi}(b,s,y)$$



Experimental highlights

- **SPS (17 GeV): NA38, NA51, NA50, NA60**

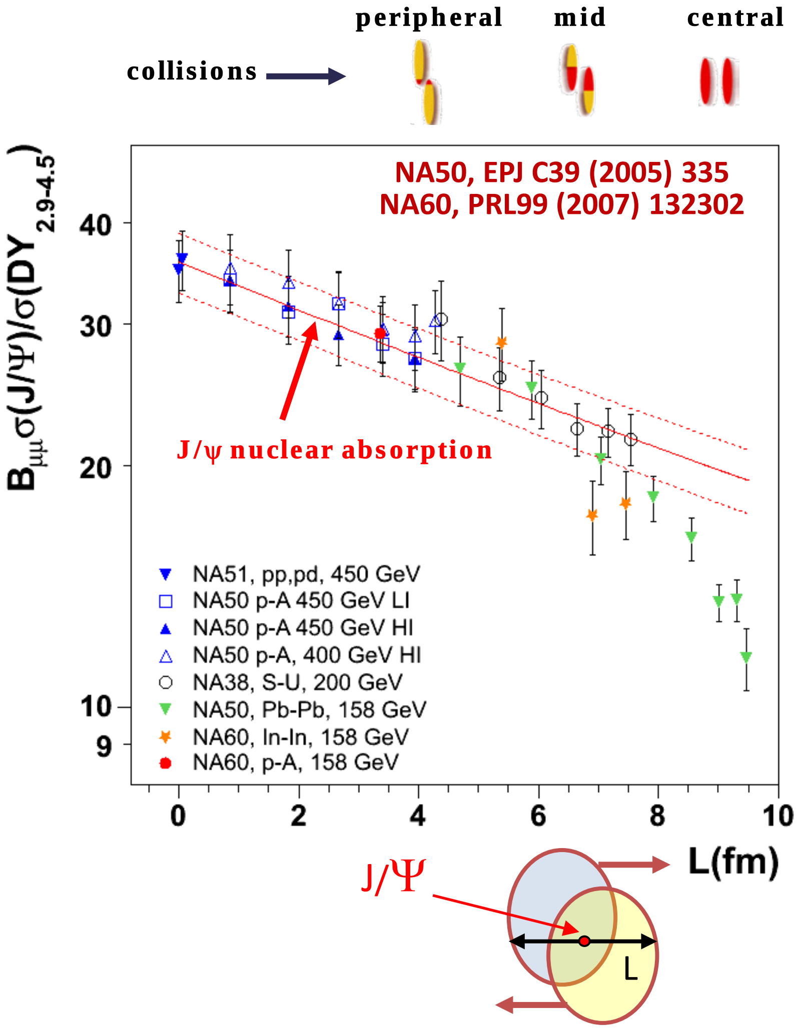
Two major results :

1. Observation of **Cold Nuclear Matter effects :** Absorption by nuclear matter
    - Suppression observed from p+p to peripheral Pb+Pb
    - J/ψ survival probability :

$$S(J/\Psi) \propto e^{-\rho\sigma_{abs}L}$$

    - Fit to data: **σ_{abs}=4.18 ±0.35 mb**

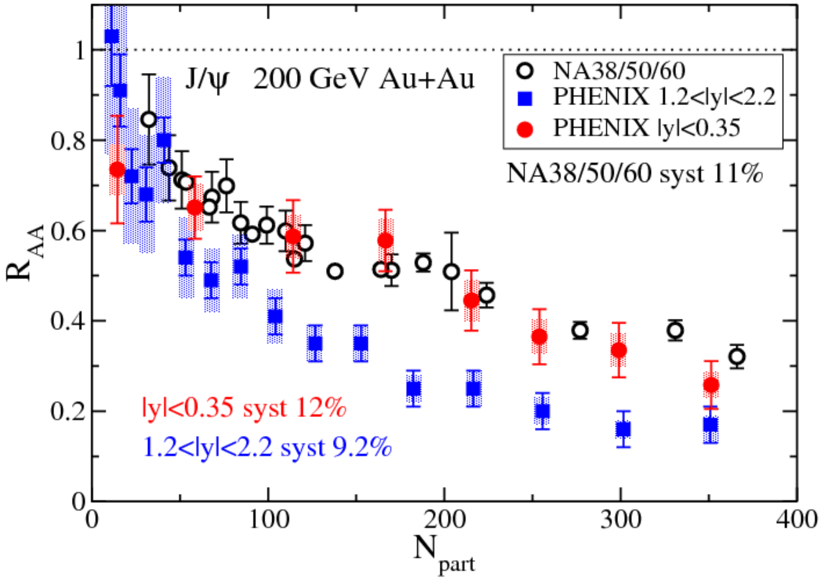
1. Observation of **Anomalous suppression** in Pb+Pb (NA50) central collisions when compared with Cold Nuclear Matter effects.

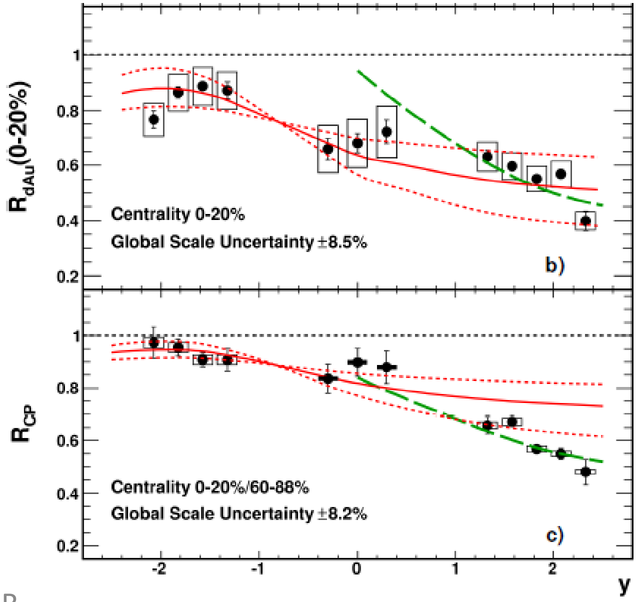


NA50, EPJ C39 (2005) 335
NA60, PRL99 (2007) 132302

Experimental highlights

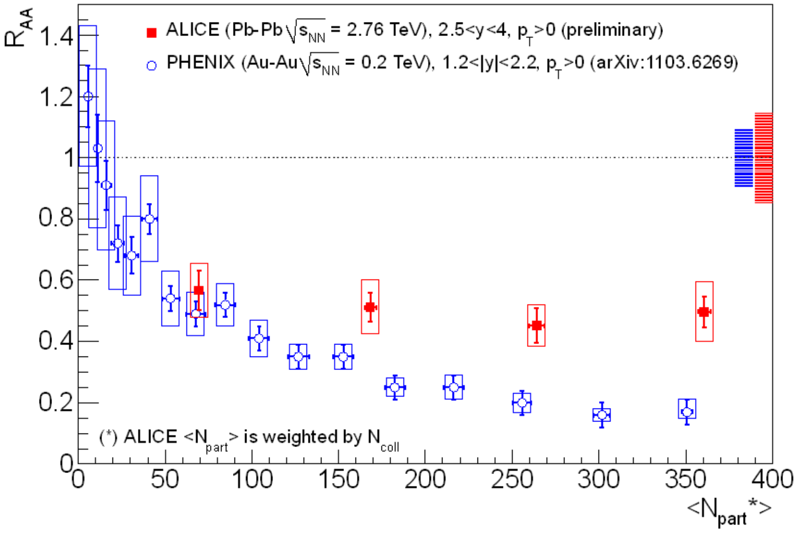
- **RHIC (200 GeV) .vs. SPS (17 GeV)**
  1. **Hot and dense matter** effects
     - Measure J/Ψ in Au+Au (RHIC) Pb+Pb (SPS)
     - Compare at same rapidity (same y ~ same x_F)
       - 0<y<1 at SPS **(NA50/NA60)**
       - |y|<0.35 at RHIC **(PHENIX)**
     - Expected larger suppression at RHIC due to larger energy density
     - observe **SIMILAR SUPPRESSION at mid rapidity**
     - Observe **LARGER SUPPRESSION at forward rapidity**
  2. **Cold Nuclear Matter** effects at RHIC
     - Measure J/Ψ production in d+Au collisions
     - Observe **LARGER SUPPRESSION at forward rapidity (small x_2)**
     - Pattern still not fully understood
     - Difference forward.vs.mid rapidity may explain larger suppression observed in forward Au+Au





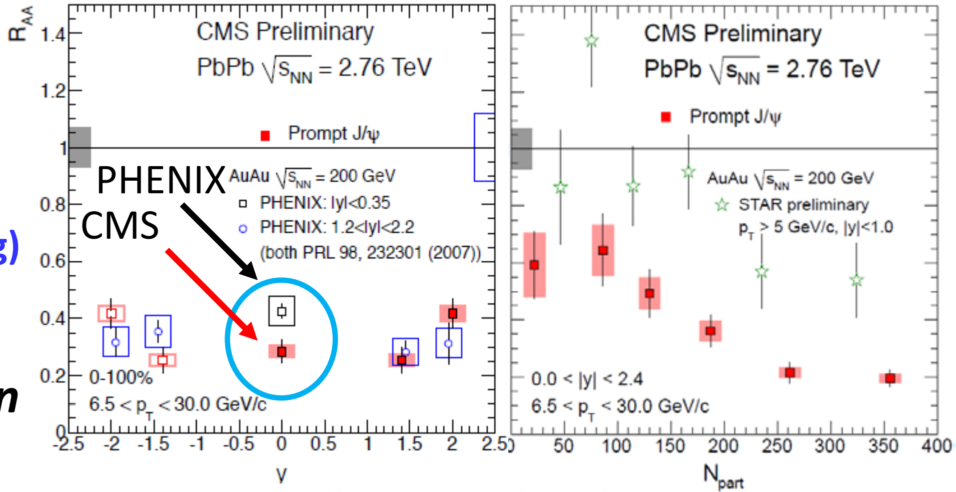
Experimental highlights

- **RHIC (200 GeV) .vs. LHC (2.76 TeV) at forward rapidity**
  - Compare PHENIX vs ALICE
    - 1.2 < $|y|$ < 2.2 at RHIC/**PHENIX**
    - 2.5 < y < 4 at LHC/**ALICE**
  - **LESS SUPPRESSION** at LHC .vs. RHIC
  - Could be due to **recombination** effects



- **RHIC (200 GeV) .vs. LHC (2.76 TeV) at mid-rapidity**
  - Compare PHENIX, STAR vs CMS
    - $|y|$<0.35 at RHIC/**PHENIX**
    - $|y|$<1 at RHIC/**STAR**
    - $|y|$<1 at LHC/**CMS**
  - **MORE SUPPRESSION** at LHC .vs. RHIC
    - p_T>6.5 GeV/c → in principle no recombination applies
    - larger suppression due to **QGP effects ?**
  - Hint of **sequential suppression ? (J/Ψ melting)**

Caution : Need CNM effects comparison



http://cdsweb.cern.ch/record/1353586

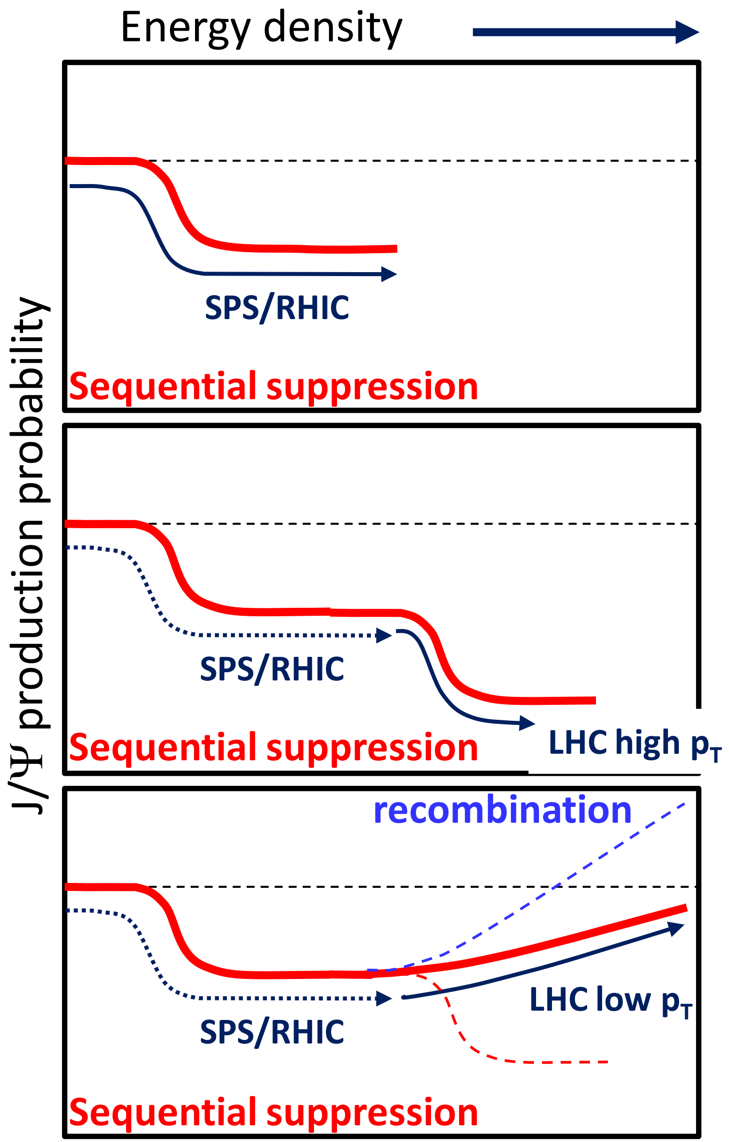
The current picture

- **Overall possible J/Ψ (simplified) picture**

1. ***Similar suppression* at SPS.vs.RHIC**
   Ψ' and χ_c suppression only ?

2. ***CMS: Larger suppression* at LHC**
   pT>6.5 GeV/c ➔ « outside » recombination regime ?
   Hint of sequential suppression ?
   (assuming CNM effects are the same or smaller)

3. ***ALICE |y|>2.5: Smaller suppression* at LHC**
   « inside » recombination regime ?
   Hint of recombination ?
   (assuming CNM effects are the same of larger)



Key questions

- **Answers to these questions are mandatory :**
  - *What are CNM effects at LHC ?* ➔ p+Pb run
    - *Shadowing should be large at forward rapidity*
    - *Shadowing should be small at high p_T*
    - *Resonance break-up cross section should be small*
  - *Is recombination mechanism at work ?* ➔ ALICE.vs.CMS at $|y|=0$
    - *If smaller suppression observed at mid-rapidity and low p_T*
  - *Is sequential suppression at work ?*
    - *Need several (at least two) resonances*
    - *Ψ' is not a good probe because of comovers*
    - *Should measure χ_c* ➔ unreachable

Back to SPS ? Sequential suppression ?

- **Measuring χ_c in A+A:**
  - test charmonia sequential suppression
  - How χ_c is suppressed relative to J/Ψ ? Dependence with y, p_T, centrality?
  - ➡ *Mandatory to draw the whole picture (SPS .vs. RHIC .vs. LHC)*

- **Should measure χ_c at SPS. Why at SPS ?**
  - ***If we understand SPS, we understand RHIC (same suppression)***
  - Anomalous suppression has been seen at SPS
  - Appropriate range of energy density: can investigate Ψ', χ_c and J/Ψ suppression
  - **On average, 0.1 $c\bar{c}$ pair/event**
    - ➡ *No recombination at SPS*

- **Fixed target experiment ?**
  - Can operate many target species
  - ➡ ***Better control of CNM effects***

Charmonia suppression

- **Charmonia suppression**

At SPS

60% direct J/Ψ
+ 30% $\chi_c \rightarrow J/\Psi+\gamma$
+ 10% $\Psi' \rightarrow J/\Psi + X$

Inclusive J/Ψ yield

Two possible scenarios:

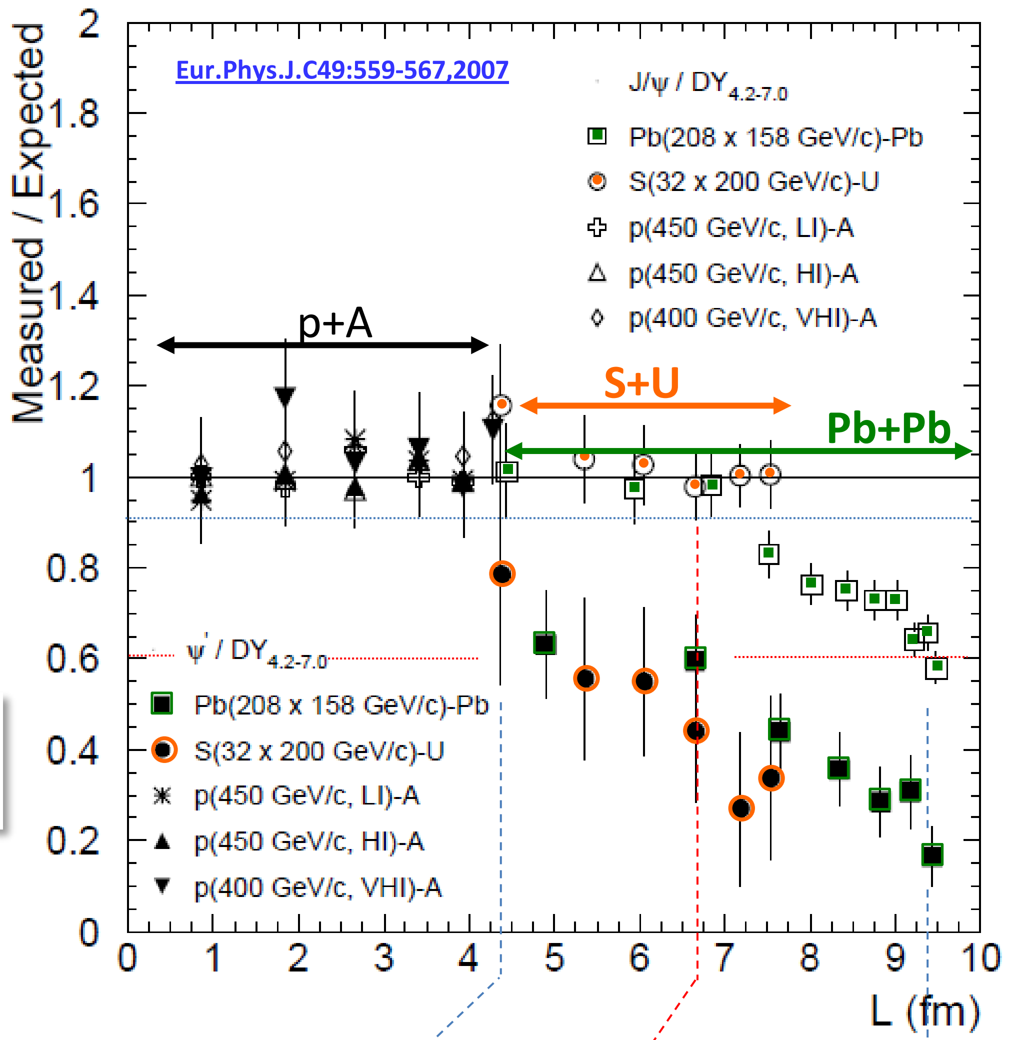
- **sequential suppression (QGP)**
- **comovers (no QGP)**

Temperature of dissociation

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

Binding energy

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05



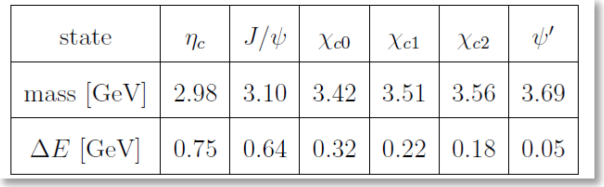
Eur.Phys.J.C49:559-567,2007

L (fm)	4.37	4.90	6.65	7.65	8.83	9.43
ε (GeV/fm^3)	1.04	1.24	2.04	2.53	3.19	3.76

Back to SPS ? Charmonia suppression

- **Two possible scenarios**

1. QGP (sequential suppression)



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ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Because ΔE (Ψ’) ~50 MeV

- **Ψ’ easily suppressed by comovers**

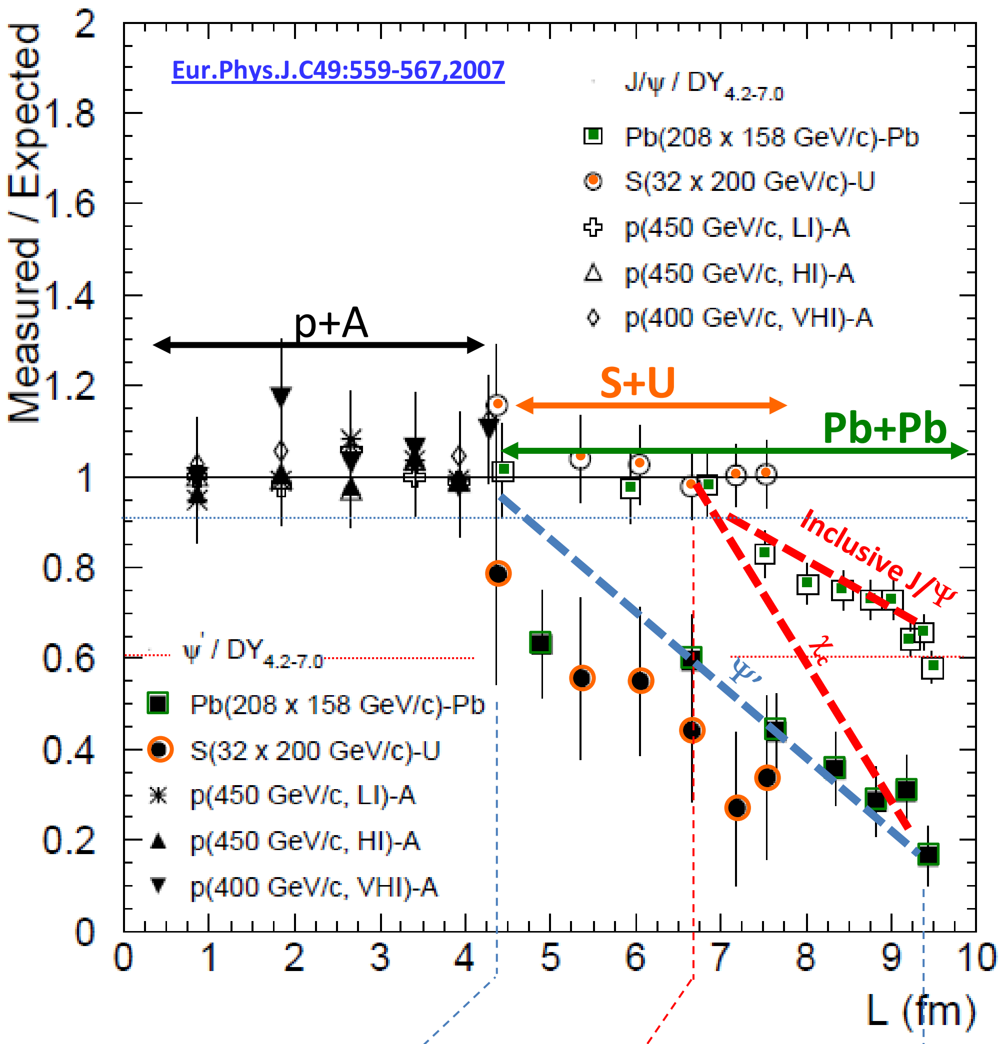
Because ΔE(χ_c)~200 MeV and ΔE(J/Ψ)~600 MeV

- **χ_c and J/Ψ hardly suppressed by comovers**

If χ_c suppressed by **QGP**,

- **χ_c slope strongly steeper than J/Ψ and Ψ’**

Measuring *χ_c suppression pattern will (in)validate this*



L (fm) ε (GeV/fm³)	4.37 1.04	4.90 1.24	6.65 2.04	7.65 2.53	8.83 3.19	9.43 3.76

Note that direct J/Ψ can be experimentally estimated

$\text{Yield}_{\text{incl.J}/\Psi} - \text{Yield}_{\chi c \to J/\Psi + \gamma} - \text{Yield}_{\Psi'} \sim \text{Yield}_{\text{direct J}/\Psi}$

Back to SPS ? Charmonia suppression

- **Two possible scenarios**

2. No QGP (full comovers)

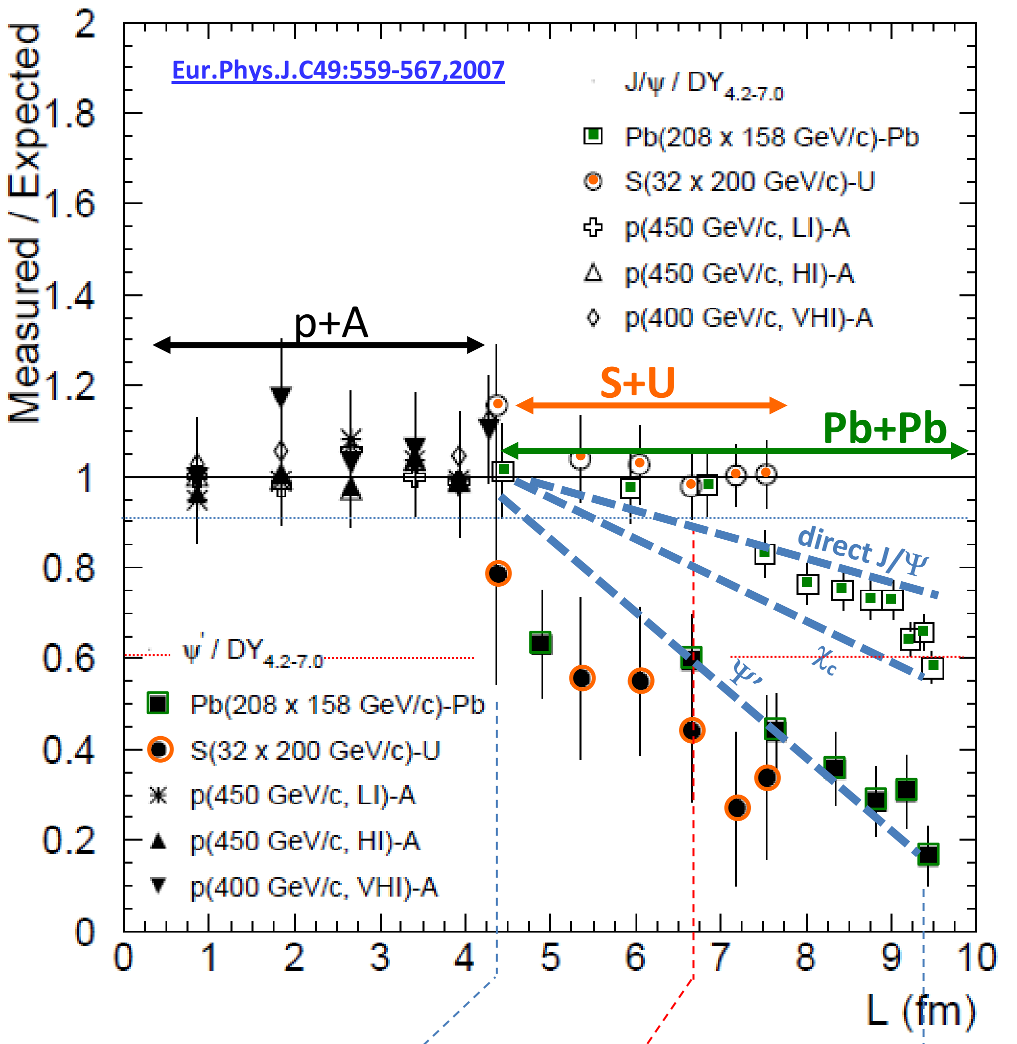
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Because $\sigma_{J/\Psi\text{-co}} \le \sigma_{\chi c\text{-co}} \le \sigma_{\Psi'\text{-co}}$

- **Ψ' slope slightly steeper than χ_c**
- **χ_c slope slightly steeper than J/Ψ**

Measuring

χ_c suppression pattern will (in)validate this



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Note that direct J/Ψ can be experimentally estimated

$$\text{Yield}_{\text{incl.}J/\Psi} - \text{Yield}_{\chi c \rightarrow J/\Psi+\gamma} - \text{Yield}_{\Psi'} \sim \text{Yield}_{\text{direct } J/\Psi}$$

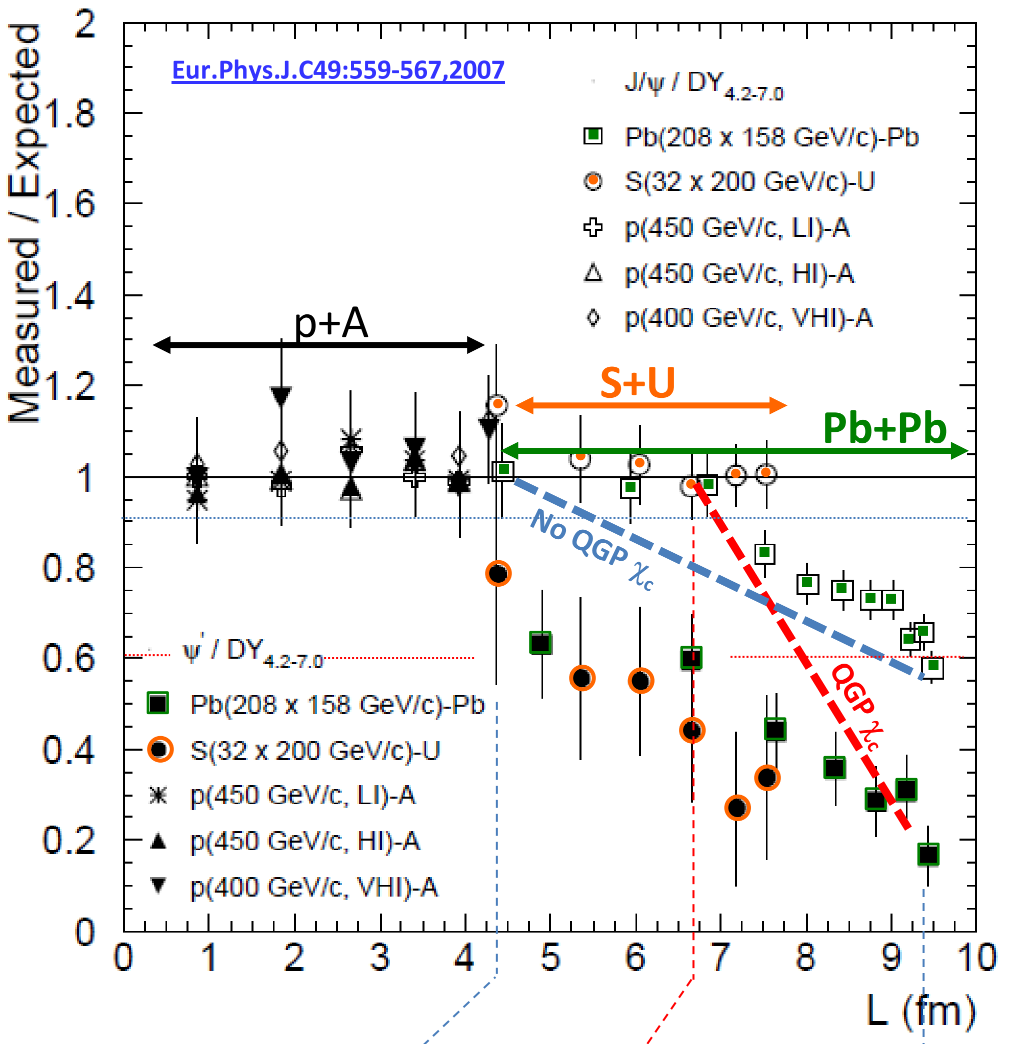
Measuring χ_c

- **Conclusion :**

measuring
Ψ', J/Ψ and χ_c suppression pattern

will answer the question

------ QGP
------ no QGP



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Note that direct J/Ψ can be experimentally estimated

$$\text{Yield}_{\text{incl.J}/\Psi} - \text{Yield}_{\chi c\rightarrow \text{J}/\Psi+\gamma} - \text{Yield}_{\Psi'} \sim \text{Yield}_{\text{direct J}/\Psi}$$

Back to SPS **Charm In Heavy Ion Collisions**

- **Primary goals :**
  - $\chi_c \rightarrow J/\Psi + \gamma \rightarrow \mu^+\mu^-\gamma$ at $y_{CMS} = 0$
  - $J/\Psi \rightarrow \mu^+\mu^-$ in large y_{CMS} range
- **Detector features : very compact**

1. **Spectrometer**
   - Measure tracks before absorber ➔ σ_M~20 MeV/c²
   - Covers y_{CMS} [-0.5, 2] ➔ need high segmentation

   ➔ Silicon technologies
2. **Calorimeter**
   - Measuring γ in high π^0 multiplicity environment

   ➔ ultra-granular EMCal (Calice)
3. **Absorber/trigger**
   - Using 4.5 m thick Fe to absorb π/K and low P $\mu^{+/-}$
   - Can use smaller absorber if Fe magnetized
   - Trigger to be defined (expected rate = 0.3 kHz)

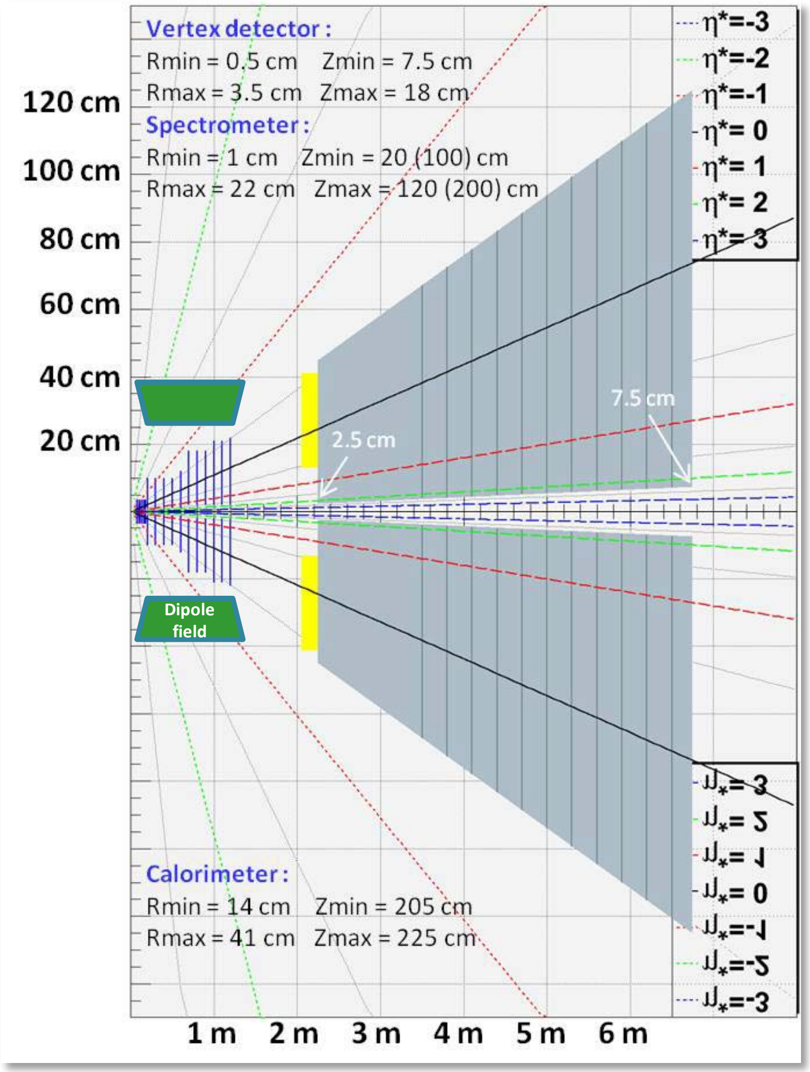
- **Expected performances**

1. **tracking :**

$$\frac{\Delta P}{P} \sim 1\% \text{ within 1m long 2.5T } \vec{B}$$

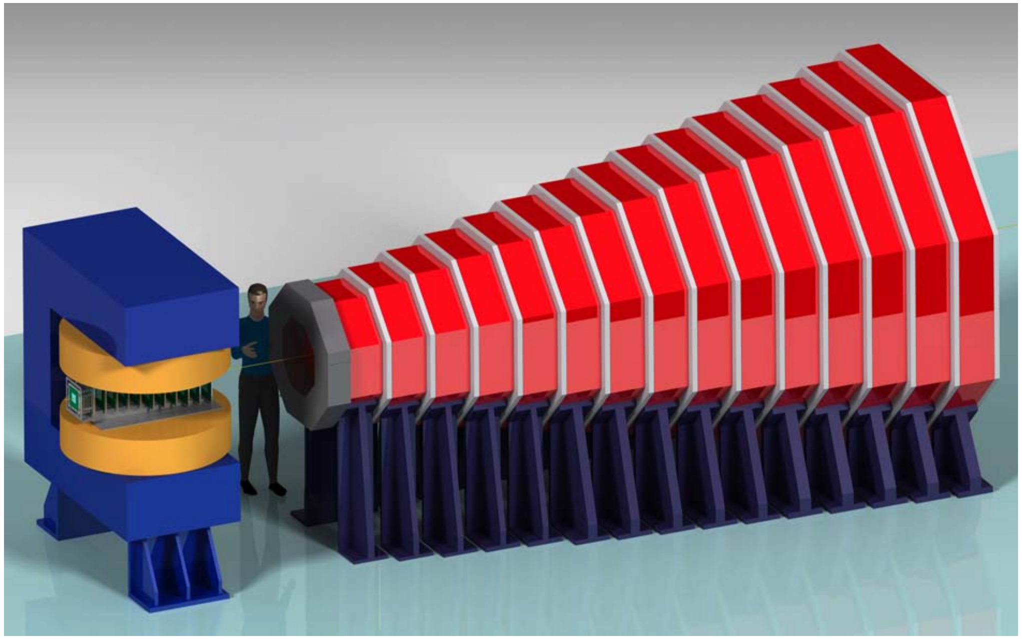
2. **Calorimetry :**

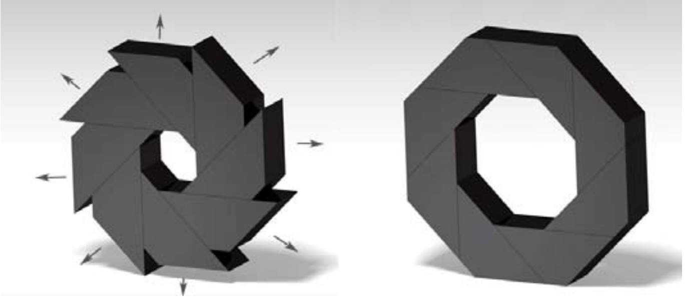
$$\frac{\Delta E}{E} \sim \frac{20\%}{\sqrt{E}}$$



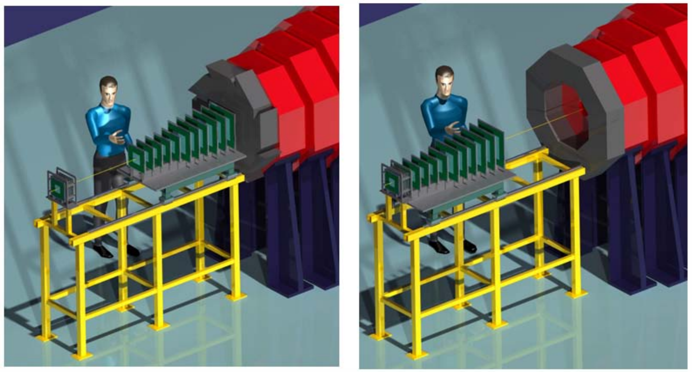
CHIC: Experimental setup flexibility

Very compact detector
(full detector simulation ongoing) ➡





Forward rapidity **Mid rapidity**

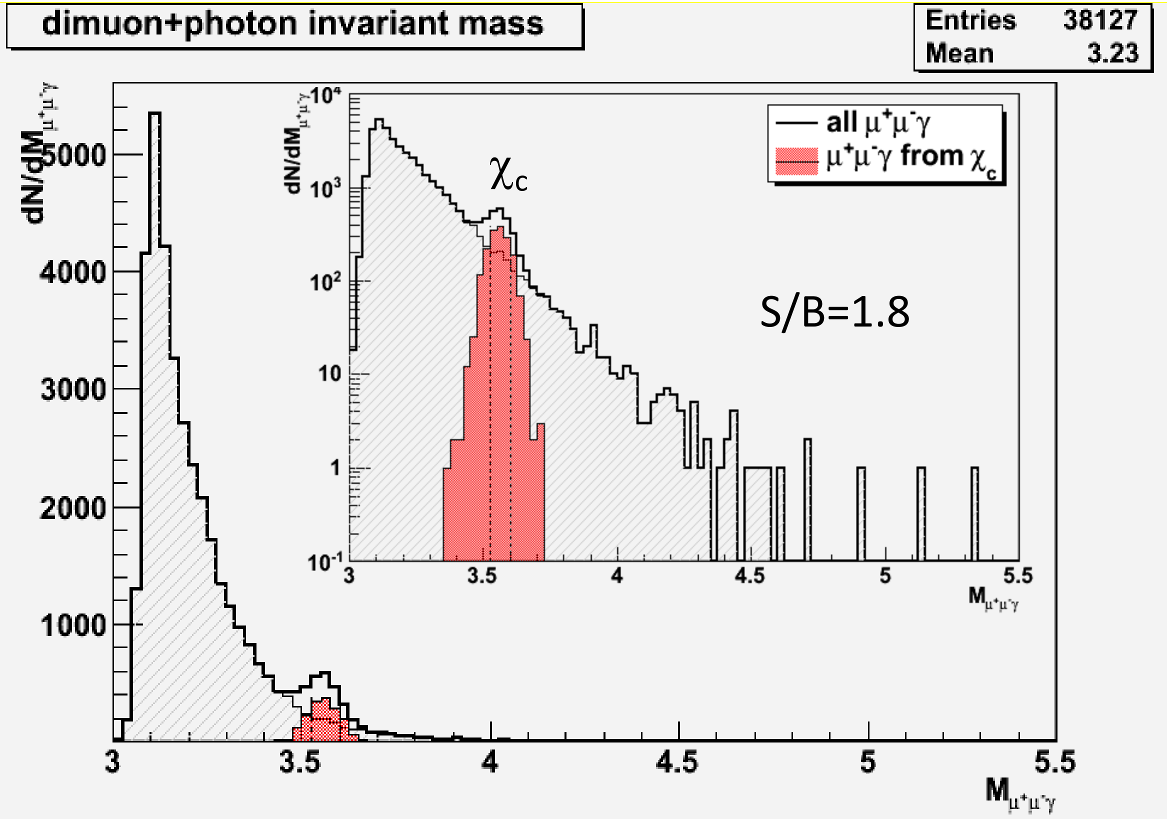


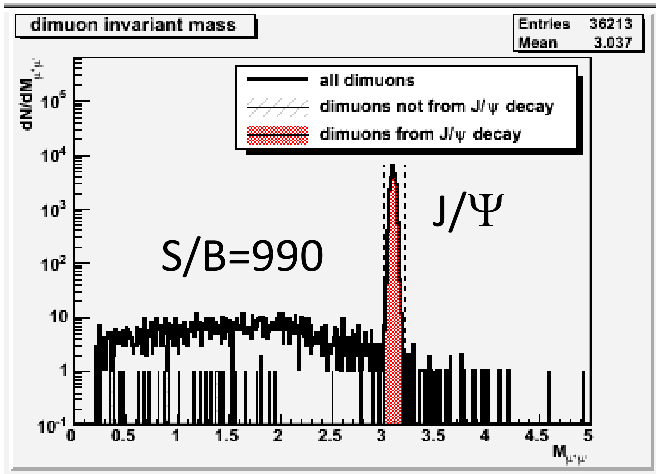
Large rapidity coverage

- fixed target mode → high flexibility
- displace tracker to access large rapidity
- modify calorimeter to access large rapidity

Signal extraction

- **Typical mass plots**
  - 200 000 Pb+Pb minBias EPOS events
    - 140 000 events with J/Ψ embedded (70%)
    - 60 000 events with χ_c embedded (30%)





After acceptance and selection cuts:

- 35 000 **J/Ψ**

➔ **acc x eff = 17.4%**

- 1700 χ_c

➔ **acc x eff = 2.8 %**

Figure of Merit

- **Typical one month Pb+Pb run with a 4mm thick target**
  - ~ 200 000 inclusive $J/\Psi \rightarrow \mu^+\mu^-$ expected
  - 2 extreme scenarios:
    - If χ_c suppressed as J/Ψ $\quad \frac{\chi_c \text{ yield}}{J/\Psi \text{ yield}} \sim 4\%$

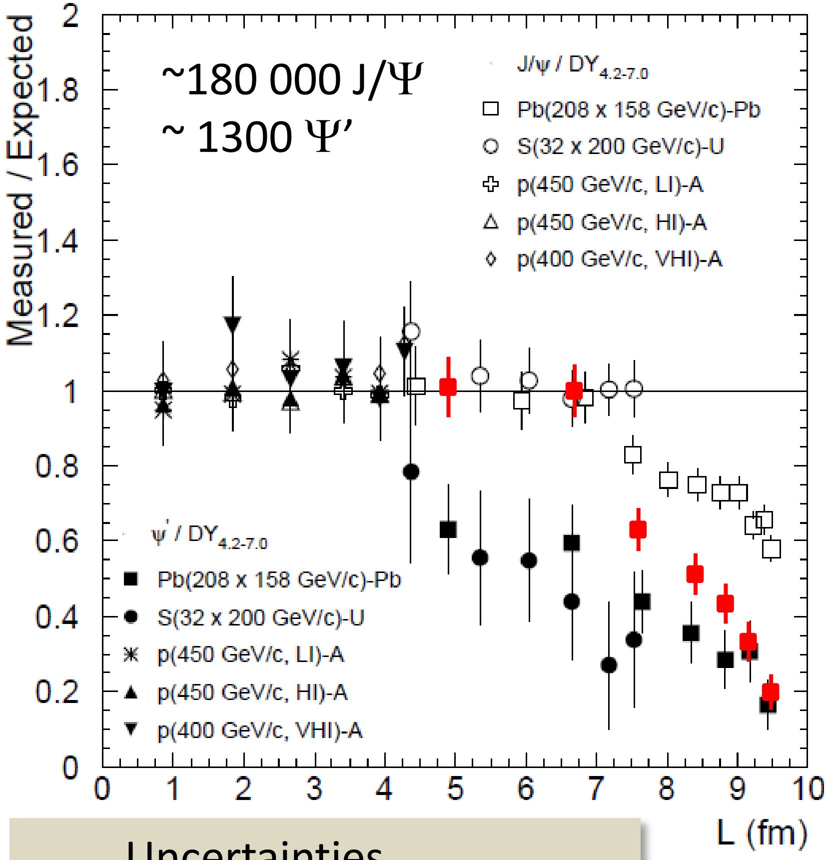
$$\begin{pmatrix}\text{most periph.}\\ \chi_c \text{ yield}\end{pmatrix} = 16942 \times 4\% = 677$$

- If χ_c suppressed as Ψ' $\quad \frac{\chi_c \text{ yield}}{\Psi' \text{ yield}} = 2.18$

$$\begin{pmatrix}\text{most periph.}\\ \chi_c \text{ yield}\end{pmatrix} = 16942 \times 4\% \times 0.6 = 406$$

Eur.Phys.J.C49:559-567,2007

E_T range (GeV)	ψ'	J/ψ	χ_c as J/Ψ	χ_c as Ψ'
3–20	186 ± 25	16942 ± 146	677	406
20–35	243 ± 31	25229 ± 181	1010	530
35–50	227 ± 35	27276 ± 192	1091	495
50–65	193 ± 36	27681 ± 196	1107	421
65–80	154 ± 36	27315 ± 200	1093	336
80–95	159 ± 37	25111 ± 193	1004	347
95–150	110 ± 40	28570 ± 209	1143	240
			7125	**2775**



~180 000 J/Ψ

~ 1300 Ψ'

Uncertainties

χ_c stat > 2 x Ψ' stat

→ χ_c error < Ψ' error/$\sqrt{2}$

Back to SPS Charm In Heavy Ion Collisions

- **Conclusion**
  - Core benchmark : **unique test of χ_c in heavy ion collisions**
  - What we didn't discuss :
    - **CHIC p+A program**
      - **9 months of proton beam available** – to be compared to the usual one month
      - **capability to access $x_F = 1$**
      - physics of saturation : shadowing, CGC, energy loss (Arléo, Peigné)
      - charmonium hadronisation time
      - charmonium absorption cross section
    - **Drell-Yan studies**
    - **Open charm studies**
    - **Charged/neutral hadrons studies**
    - **Photons studies**
    - **Low mass dileptons**

Backup slides

Backup

Physics motivations

- **Sequential suppression in a QGP**

If QGP at work ➔ threshold effect

Above threshold $\frac{\varepsilon}{T^4} = cte$

$$\Rightarrow \frac{\varepsilon_d^{\Psi'}}{\left(T_d^{\Psi'}\right)^4} = \frac{\varepsilon_d^{\chi_c}}{\left(T_d^{\chi_c}\right)^4}$$

Temperatures of dissociation :

H. Satz, J. Phys. G 32 (2005)

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
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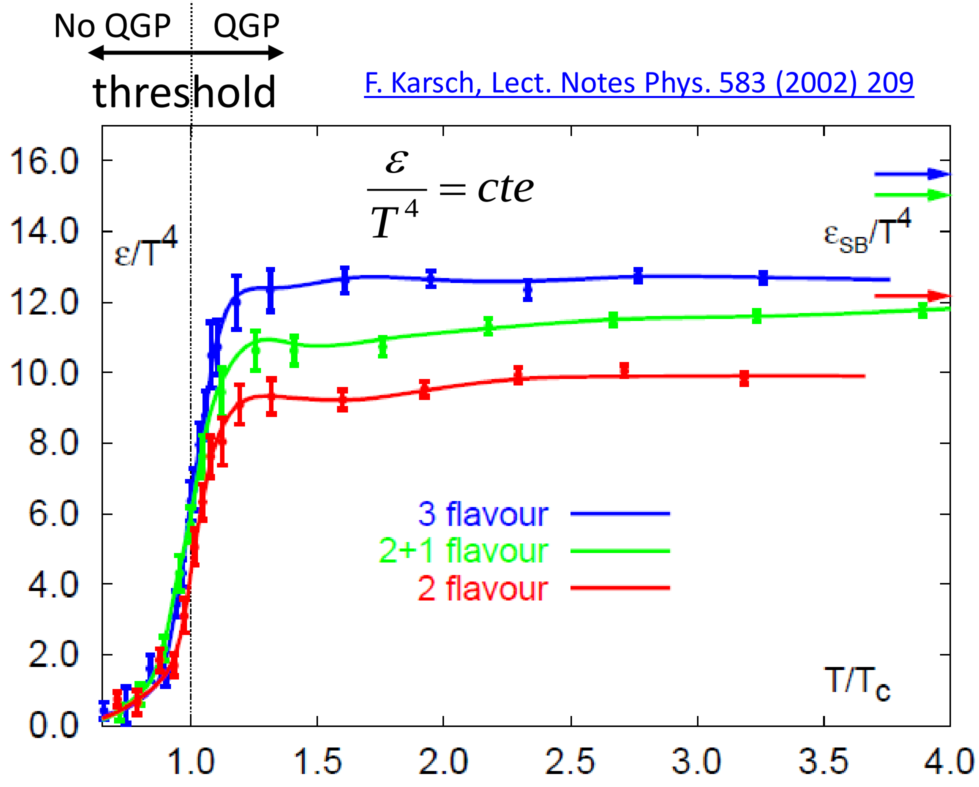


F. Karsch, Lect. Notes Phys. 583 (2002) 209

$$\frac{\varepsilon_c^{\chi_c}}{(1.16\times T_C)^4} = \frac{\varepsilon_c^{\Psi'}}{(1.12\times T_C)^4} \Rightarrow \varepsilon_c^{\chi_c} = \left(\frac{1.16}{1.12}\right)^4 \varepsilon_c^{\Psi'} \Rightarrow \boxed{\varepsilon_c^{\chi_c} = 1.15\times\varepsilon_c^{\Psi'}}$$

Physics motivations

- **Sequential suppression in a QGP**

Theoretically, expect

$$\varepsilon_c^{\chi_c} = \left(\frac{1.16}{1.12}\right)^4 \varepsilon_c^{\Psi'} = 1.15\times\varepsilon_c^{\Psi'}$$

data

Experimentally, Ψ' suppression starts at

L (fm)	4.37
ε (GeV/fm³)	1.04

$\varepsilon_c^{\chi_c} = 1.15\times\varepsilon_c$

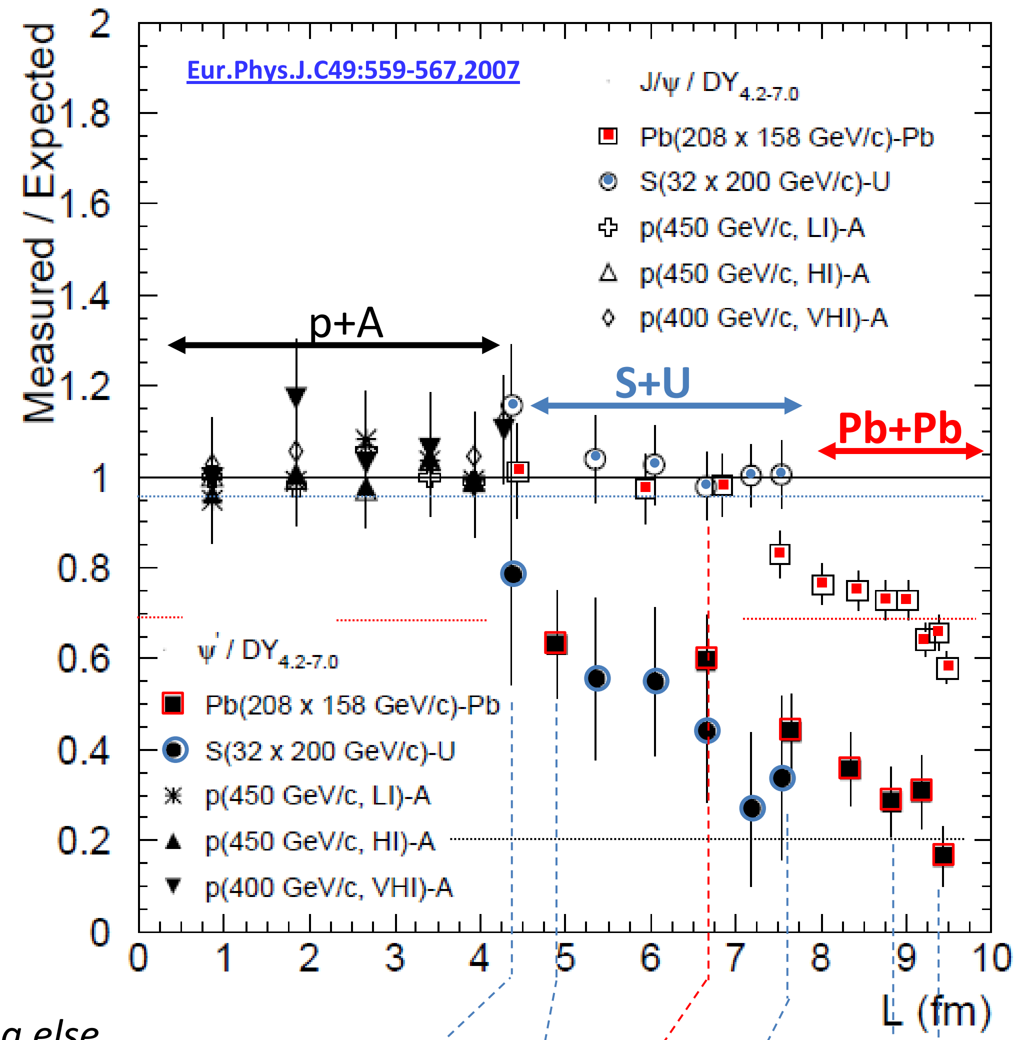
Theoretically, χ_c suppression should start at

L (fm)	4.9
ε (GeV/fm³)	1.2

data

Experimentally, J/Ψ suppression starts at

L (fm)	6.65
ε (GeV/fm³)	2.04



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ε (GeV/fm³)	1.04	1.24	2.04	2.53	3.19	3.76

Conclusion

either theoretical predictions are wrong,

or Ψ' is previously suppressed by something else

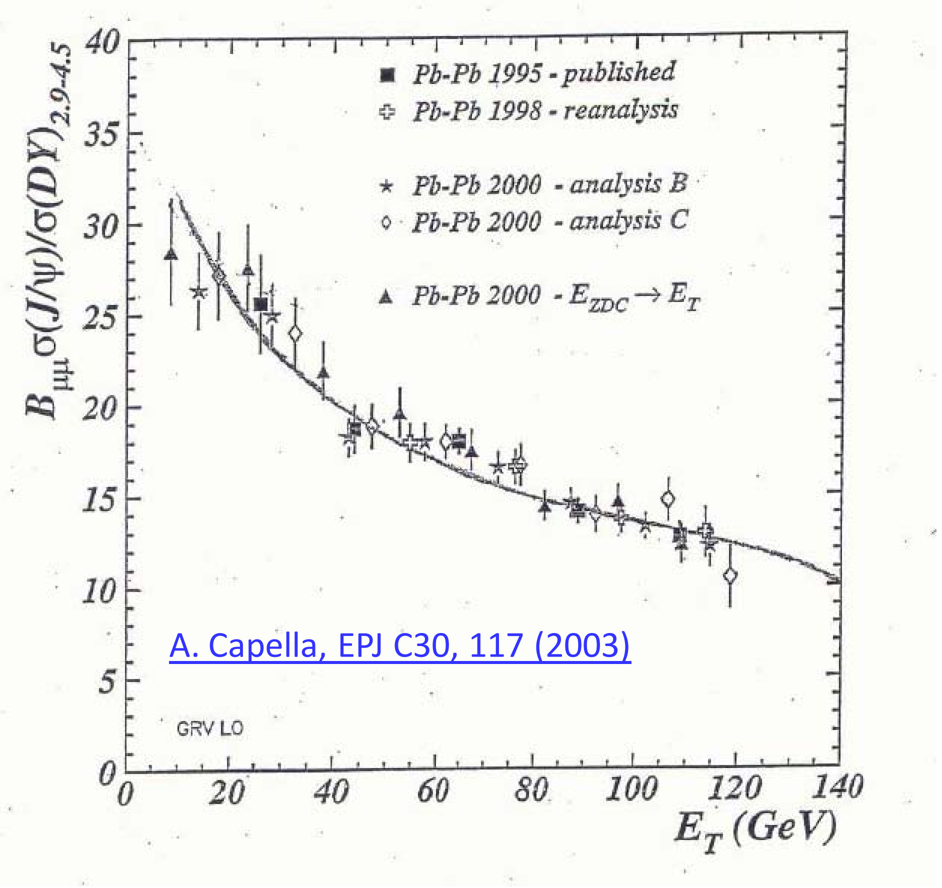
Backup

Physics motivations

- **Sequential suppression by comovers** (Eur.Phys.J.C58:437-444,2008)
  - Suppression by comovers:
    - quarkonia can be broken by interaction with comoving partons/hadrons

$$\tau \frac{\mathrm{d}N_{J/\psi}}{\mathrm{d}\tau}(b,s,y) = -\sigma_{co} N^{co}(b,s,y) N_{J/\psi}(b,s,y)$$

  - Two parameters
    - Hadron density N^{co}
    - Interaction cross section σ_{co}



A. Capella, EPJ C30, 117 (2003)

Backup

Physics motivations

- **Sequential suppression by comovers**

  - Suppression by comovers:
    - quarkonia can be broken by interaction with comoving partons/hadrons
  - Two parameters
    - Hadron density
    - Interaction cross section σ_{co}

$$\tau \frac{dN_{J/\psi}}{d\tau}(b,s,y) = -\sigma_{co} N^{co}(b,s,y) N_{J/\psi}(b,s,y)$$

  - There is a hierarchy in the suppression
    - σ_{co} is linked to the quarkonium binding energy
    - The larger the binding energy, the smaller the σ_{co}
    - But σ_{co} is theoretically unknown (must be fitted on the data)
  - Sequential suppression
    - $\Delta E(J/\Psi) > \Delta E(\chi_c) > \Delta E(\Psi')$

➔ $\sigma_{J/\Psi\text{-co}} \leq \sigma_{\chi c\text{-co}} \leq \sigma_{\Psi'\text{-co}}$

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Quarkonium bindind energy
($\Delta E = M_{quarkonium} - 2M_D$)

Backup

Physics motivations

- **Sequential suppression by comovers**

[Eur.Phys.J.C58:437-444,2008]

If comovers at work ➔ smooth suppression

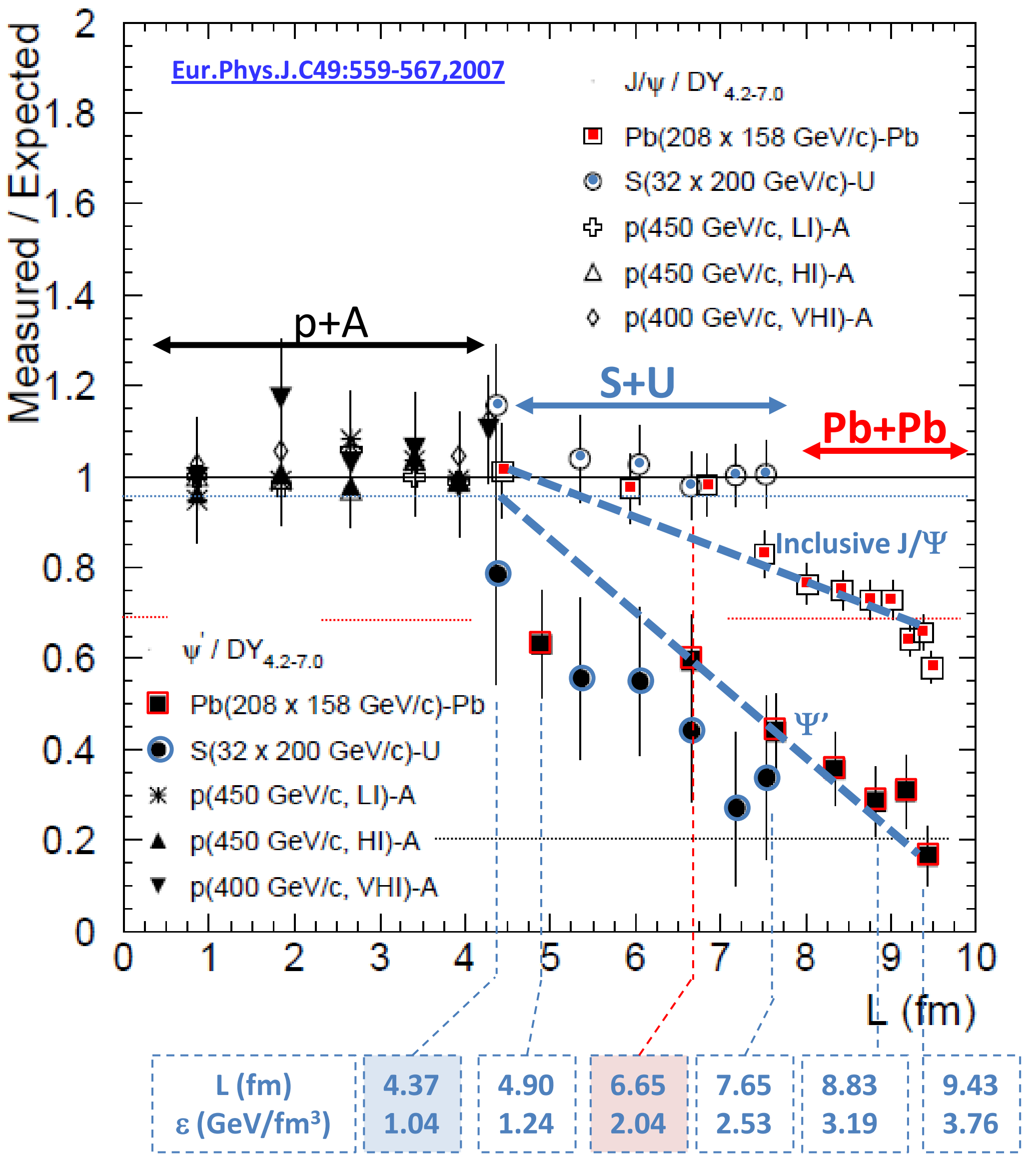
(reminder: If QGP at work ➔ threshold effect)

Experimentally,

- ➢ Ψ’ suppression pattern slightly steeper than J/Ψ one (theoritically $\sigma_{J/\Psi\text{-co}} \leq \sigma_{\Psi'\text{-co}}$)
- ➢ If comovers at work, χ_c suppression pattern should stand within Ψ’ and J/Ψ suppression patterns

Conclusion

Need to measure χ_c pattern to test comovers scenario



Eur.Phys.J.C49:559-567,2007

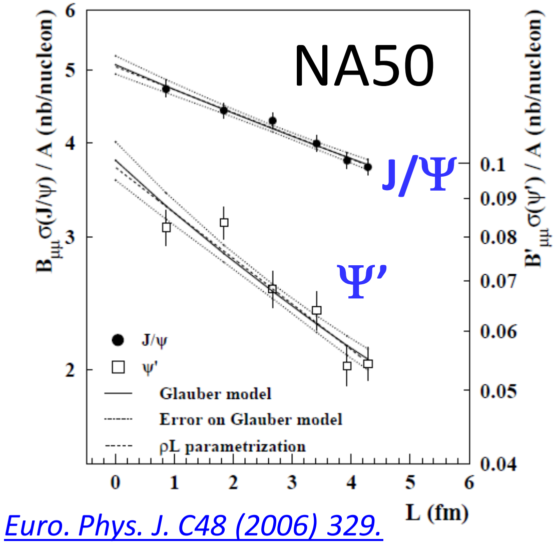
L (fm) ε (GeV/fm³)	4.37 1.04	4.90 1.24	6.65 2.04	7.65 2.53	8.83 3.19	9.43 3.76

Physics motivations

- **Benchmark 2: Measure charmonium in p+A at SPS**

J/Ψ and Ψ' **suppression** in p+A collisions as a function of L

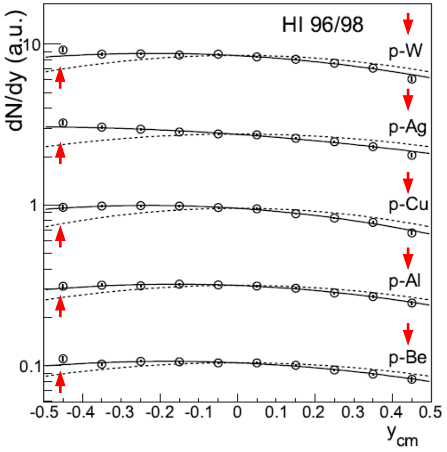
➔ **Measuring different charmonium states gives key information on Cold Nuclear Matter and production mechanism.**



Euro. Phys. J. C48 (2006) 329.

J/Ψ **rapidity distribution** in p+A collisions (asymetry wrt y_{cm}=0)

➔ **Measuring charmonium in a wide x_F range is important to identify possible (anti)shadowing effects**



Backup

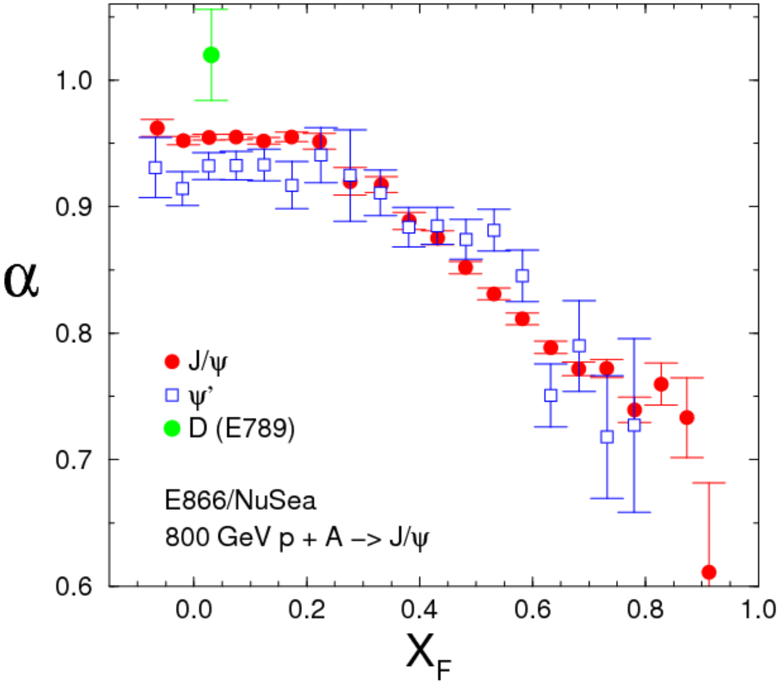
Physics motivations

- **Measure charmonium in p+A at SPS**

➔ **Measuring charmonium in a wide x_F range is important to estimate possible (anti)shadowing effects**

$$\sigma_A = \sigma_p * A^\alpha$$

E866, Phys. Rev. Lett. 84, 3256-3260 (2000)



$$x_F = \frac{2M}{\sqrt{s}} \sinh y_{CMS}$$

With M=3.1 GeV/c² and √**s=17.2 GeV** (158 GeV)

x_F = 1 ➔ y_{CMS} = 1.7

With M=3.1 GeV/c² and √**s=29.1 GeV** (450 GeV)

x_F = 1 ➔ y_{CMS} = 2.2

Y_{CMS}=2 ➔ x_F = 0.8

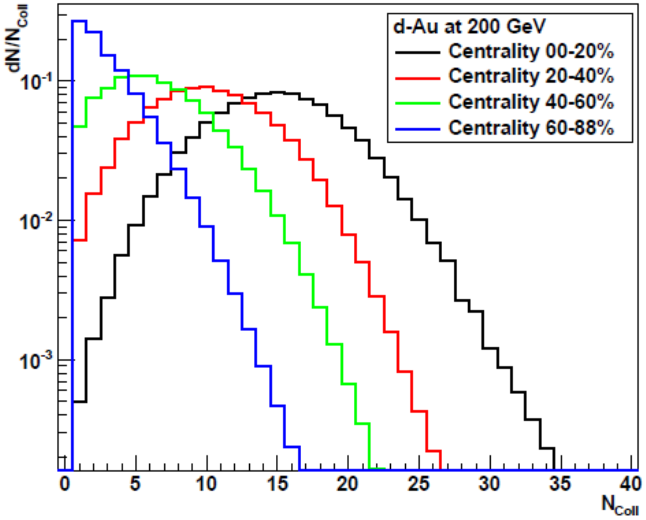
Possible to access large x_F if measuring charmonia at rapidity up to y_{CMS}~2

Backup fixed target.vs.collider mode

- **Cold Nuclear Matter studies**
  - Must be performed in p+A collisions
  - The more A versatility, the better

- **Collider mode**
  - Difficult to operate many A systems (for instance, since 2000, Phenix operated d+Au collisions only) ➔ studies as a function of centrality
  - Constraints:
    1. **Centrality bin limitation**: due to the “small” number of particle produced in p+A, cannot make as many centrality bins as in A+A collisions
    2. **Glauber uncertainty** :

       <N_{coll}>.vs.centrality through Glauber calculation ➔ uncertainty on <N_{coll}> (~7% for Phenix)



Phenix d+Au centrality bins

arXiv:1204.0777

Collider mode:

$$R_{pA} = \frac{dN_{pA}^{J/\Psi}}{\langle N_{coll}\rangle dN_{pp}^{J/\Psi}} \times \frac{dN_{pp}^{MB}}{dN_{pA}^{MB}}$$

centrality	<N_{coll}>
0-20%	15.1 ± 1.0
20-40%	10.2 ± 0.7
40-60%	6.6 ± 0.4
60-88%	3.2 ± 0.2

- **Fixed target mode**
  - **Easy to operate many A systems**
  - **No bin limitation**
  - **No Glauber uncertainties**

Fixed target mode: $R_{pA} = \frac{\sigma_{pA}^{J/\Psi}}{A\,\sigma_{pp}^{J/\Psi}}$