Color screening in Quark Gluon Plasma (QGP): A new experiment to measure charm production in PbPb collisions at the CERN SPS

CHIC: Charm in Heavy Ion Collisions

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Heavy quarks and Quark Gluon Plasma (QGP)

Heavy quarks are "special" QGP probes : m_Q >> QGP critical temperature T_C (~170 MeV),

→ Heavy quarks should be produced in initial hard nucleon-nucleon collisions only, the **QGP phase shouldn't modify the overall heavy quark yields**,

→ ***QGP phase should modify relative heavy quark (open/hidden) bound state yields***

Heavy quark hadronization ($c\bar{c}$ example):

- ~90% of $c\bar{c}$ pairs → open charm
- ~10% of $c\bar{c}$ pairs → hidden charm (charmonia)

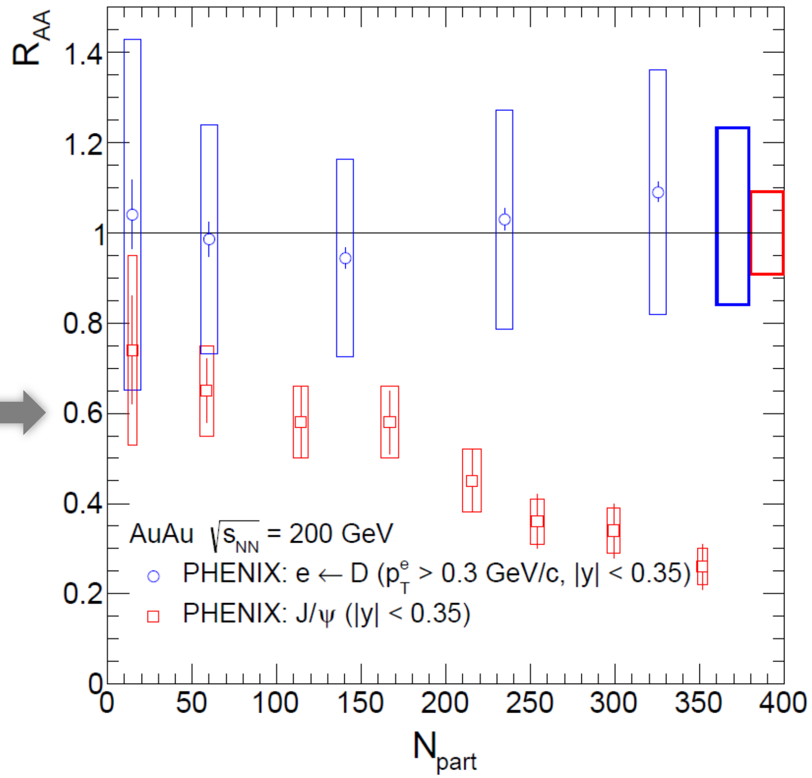
Since most of the produced $c\bar{c}$ pairs hadronize into open charm (~90%), **open charm production reflects the original charm quark yield.**

PHENIX Au+Au collisions @ $\sqrt{s_{NN}}$ = 200 GeV

Blue = open charm

Red = hidden charm

- no (little) modification of open charm yield
- modification of J/Ψ (*$c\bar{c}$ bound state*) yield



- # Heavy quarks and Quark Gluon Plasma

Heavy quarks are "special " QGP probes : m_Q >> QGP critical temperature T_C (~170 MeV),

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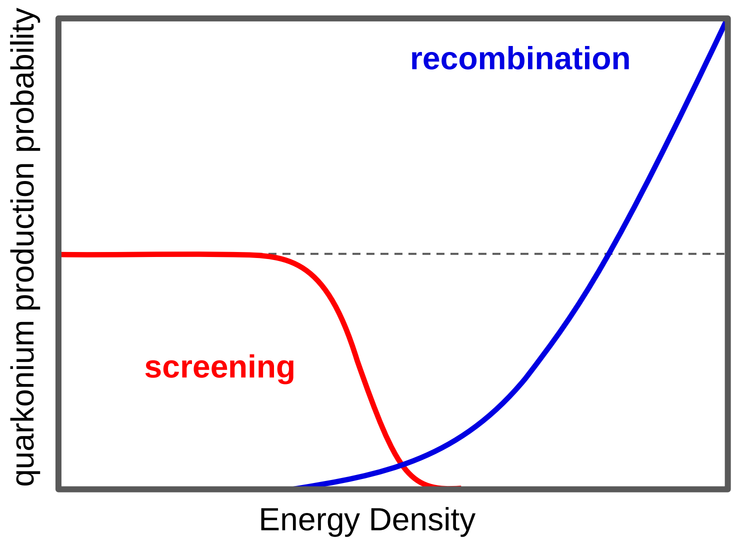
➔ ***QGP phase should modify relative heavy quark (open/hidden) bound state yields***

– Possible QGP effects on quarkonium:

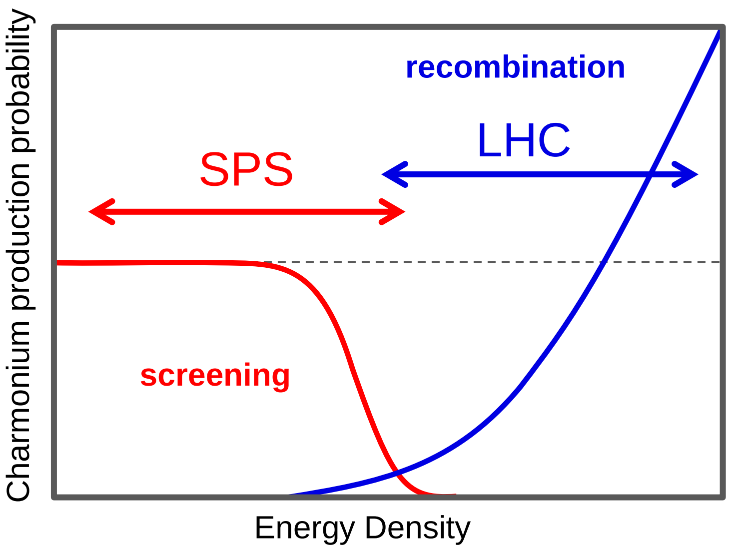
- **Color screening:** ***$Q\bar{Q}$ bound states suppression***
  - Color screening in a QGP decreases quarkonium binding
  - Color screening should lead to a suppression of quarkonium production yields
- **Recombination:** ***$Q\bar{Q}$ bound states enhancement***
  - at sufficiently high $\sqrt{s_{NN}}$, heavy quarks are abondantly produced.
  - After thermalisation, statistical combination can lead to an enhancement of quarkonium production yields



The Physics case

- **Experimentally, charmonium is a priviledged probe**
  - Charmonium production in A+A collisions studied at:
    - CERN-SPS (√s=17 GeV) NA38, NA50, NA60 experiments
    - BNL-RHIC (√s=200 GeV) PHENIX, STAR experiments
    - CERN-LHC (√s=2.76 TeV) ALICE, CMS experiments
  - Short summary for J/Ψ:
    - NA50 (PbPb@SPS) observed an *anomalous* J/Ψ suppression
    - PHENIX (AuAu@RHIC) observed a similar suppression (than NA50)
    - ALICE (PbPb@LHC) observed a smaller suppression (than PHENIX)

➔Possible Color screening starting at SPS
➔Possible recombination occuring at LHC



  - **Within the SPS+RHIC+LHC energy range, charm seems to be the adequate probe to investigate both screening and recombination.**

What next to be done with charmonium

To confirm (and study) charmonium color screening and enhancement, one must compare charmonium and open charm production in A+A collisions

- Since most of the produced $c\bar{c}$ pairs hadronize into open charm (~90%), open charm production reflects the original $c\bar{c}$ pair production
- Open charm is therefore an (the?) appropriate reference to calibrate charmonium screening/recombination studies.

– Study charmonium recombination

- Both J/Ψ and open charm will be measured in PbPb at large energy densities at LHC

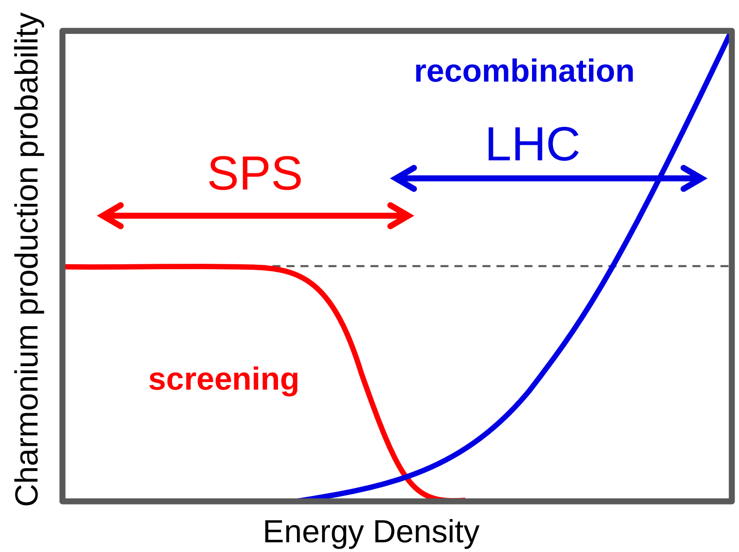
➔ **LHC is the best place to study charmonium recombination**

– Study charmonium color screening

- At SPS energies, in Pb+Pb collisions, J/Ψ suppression occurs in the middle of the accessible energy density range

➔ **SPS is the best place to study color screening**

- ***Need measurement of open charm yields***
- ***Need precise measurements of several $c\bar{c}$ states to test if color screening leads indeed to a sequential suppression***



Color screening

- **Quarkonium sequential suppression**
  - **Quarkonium sequential suppression** in a Quark Gluon Plasma is a prediction of **lattice QCD**, for instance :

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

$\frac{\text{quarkonium dissociation temperature}}{\text{critical QGP temperature}}$ →

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

  - Because of feed-downs and different T_d, **sequential suppression** should show up.

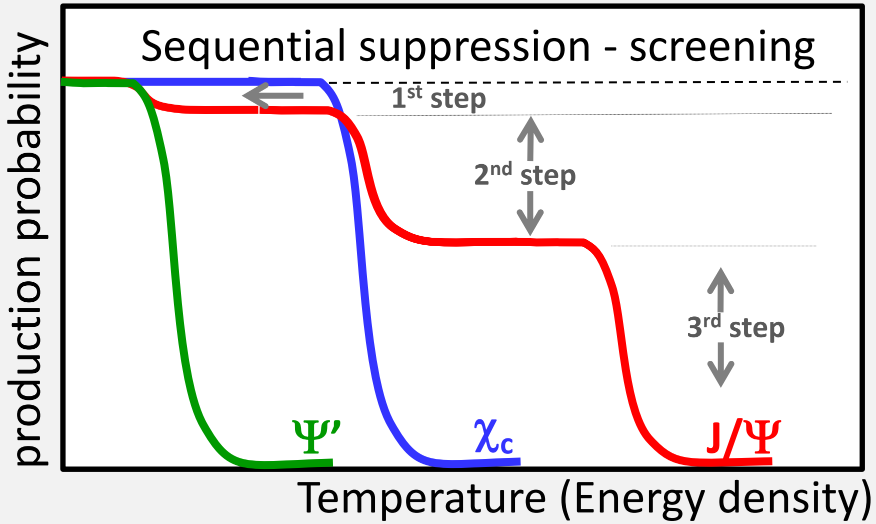
Feed-downs contributing to J/Ψ inclusive yield

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

Inclusive J/Ψ yield

According to lattice calculations,
$T_d\,(\Psi') < T_d\,(\chi_c) < T_d\,(J/\Psi)$

➔ **One should observe a step-like suppression pattern**



NA50 results

- **Anomalous suppression at SPS**

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

L = length of nuclear matter seen by quarkonium state

Expected = measured yields in p+A extrapolated to large L

Color screening ?

NA50 measured J/Ψ and Ψ’, but,

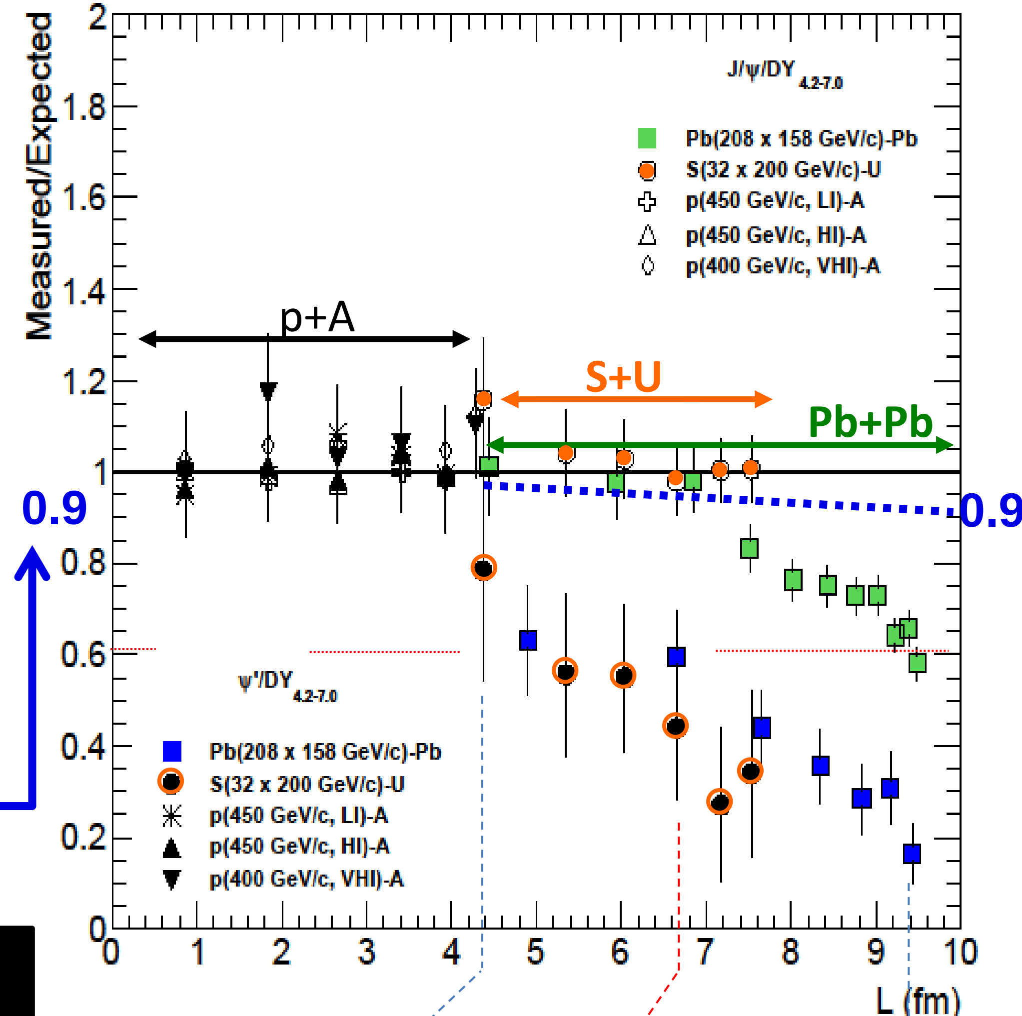
- **too small *Ψ’→ J/Ψ feed-down***
- **too fragile Ψ’**

to answer the question

→ need of a larger feed-down fraction

→ Need of a stronger bound state

→ Need to measure χ_c yield !



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

Suppression patterns

- **Anomalous suppression at SPS**

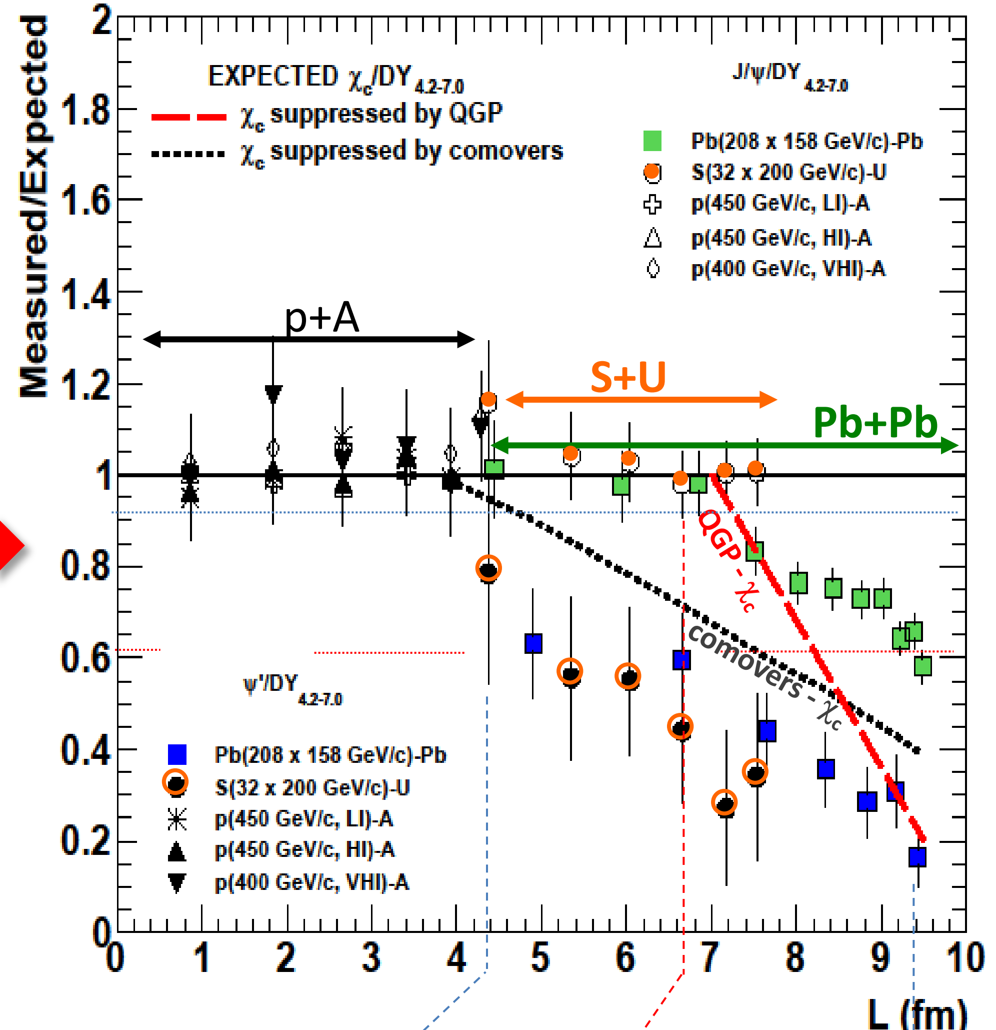
Eur.Phys.J.C49:559-567,2007

Color screening ?

Take advantage of large $\chi_c \rightarrow J/\Psi$ feed-down fraction

$$\frac{60\%\ \text{direct}\ J/\Psi + 30\%\ \chi_c \rightarrow J/\Psi+\gamma + 10\%\ \Psi' \rightarrow J/\Psi + X}{\text{Inclusive}\ J/\Psi\ \text{yield}}$$

Measuring J/Ψ, Ψ' and χ_c suppression patterns will give the answer



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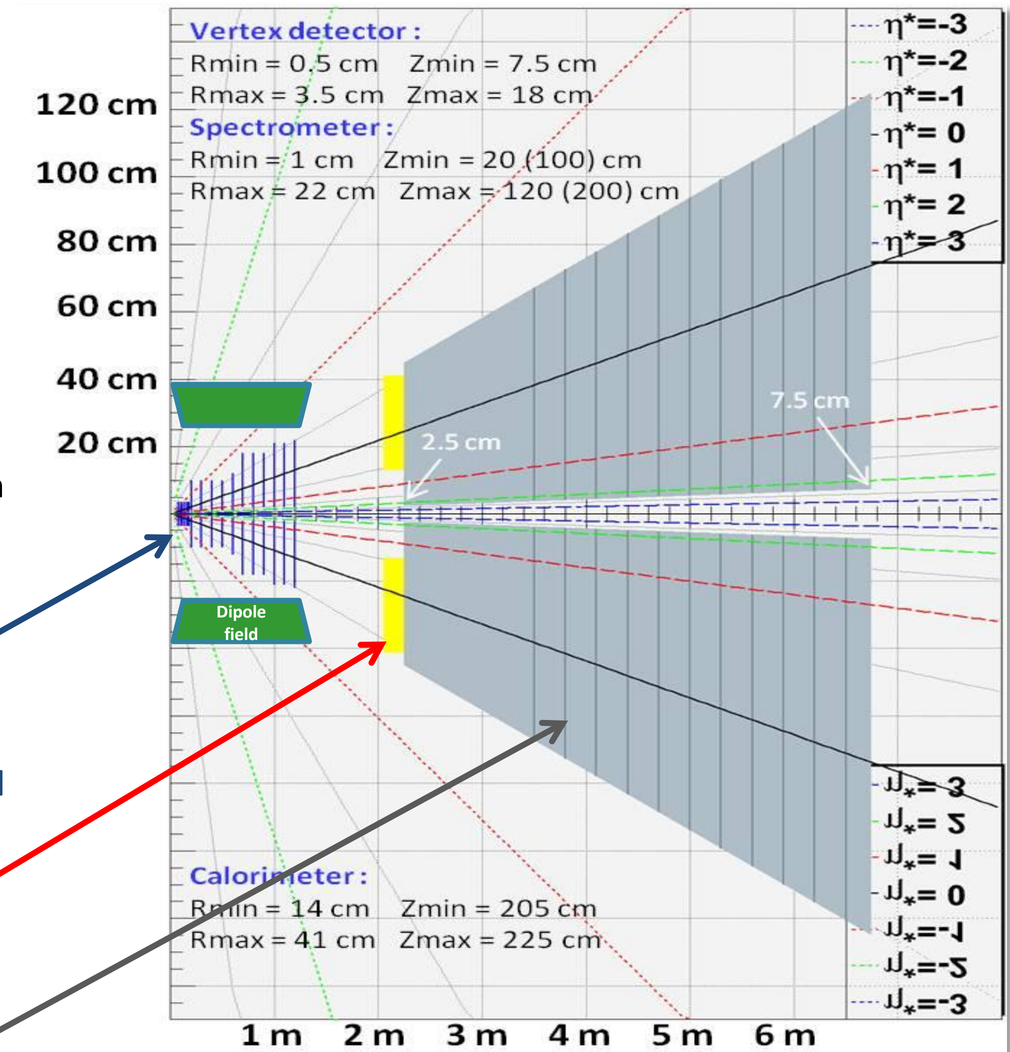
ε (GeV/fm³)	1.04	1.24	2.04	2.53	3.19	3.76

- ***Alternative (no QGP) scenario: suppression by comoving hadrons***
  - *Smooth suppression*
  - *Same suppression-starting point*
  - *Slopes related to binding energy :* $S_{\Psi'} > S_{\chi} > S_{J/\Psi}$

Experimental design

A new experiment @ SPS

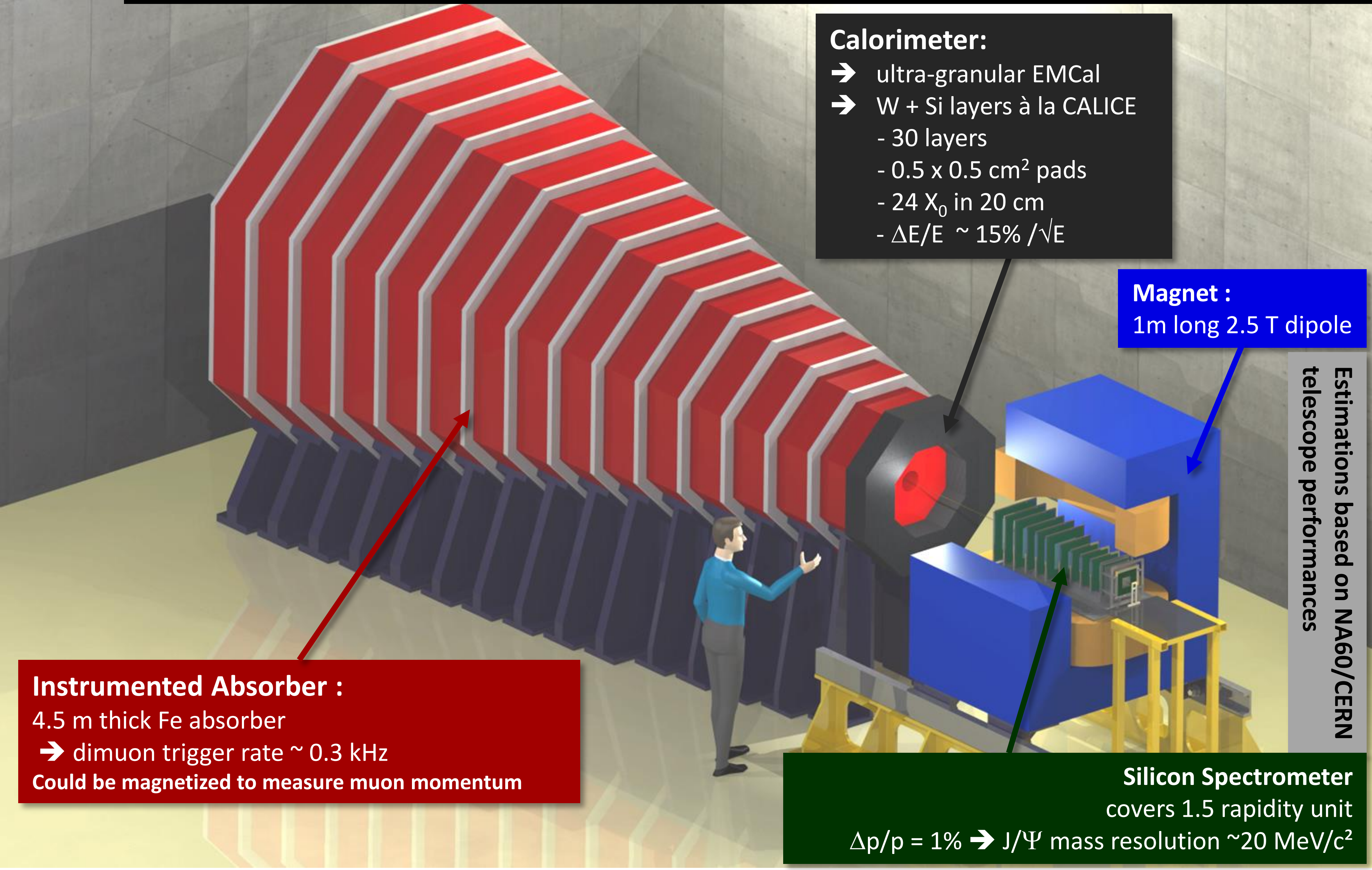
- **Must measure :**
  - Charmonia : J/Ψ, Ψ', χ_c
  - open charm (for reference)
- **Beam:fixed-target experiment**
  - high-intensity 158 GeV/c Pb beam
  - high-intensity 158/450 GeV/c *p* beam
- **Experimental constraints**
  - Measure muons from charmonia and open charm decays
  - Measure photon from χ_c decay ($\chi_c \rightarrow J/\Psi+\gamma$)
- **Detector main components :**
  1. **Vertex detector + Spectrometer**
     - **Measures tracks before absorber ➔ very good mass resolution**
     - **Measure muon vertex offset ➔ open charm**
  2. **Ultra-granular calorimeter**
     - **Measure γ in high π^0 multiplicity environment**
  3. **Absorber/ muon trigger**
     - **Absorb π/K**
     - **Minimize fake triggers from π/K decays**



CHIC

Apparatus artist view

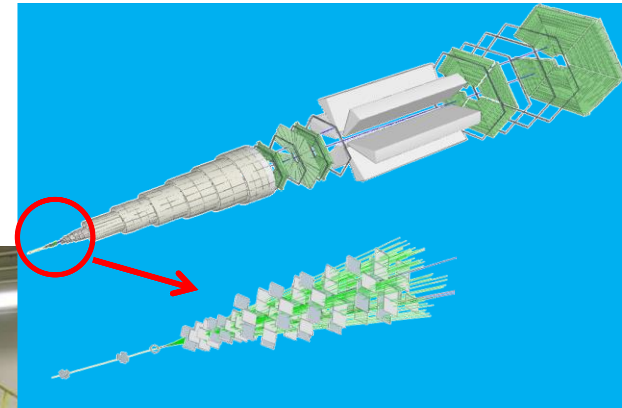
A new experiment @ SPS

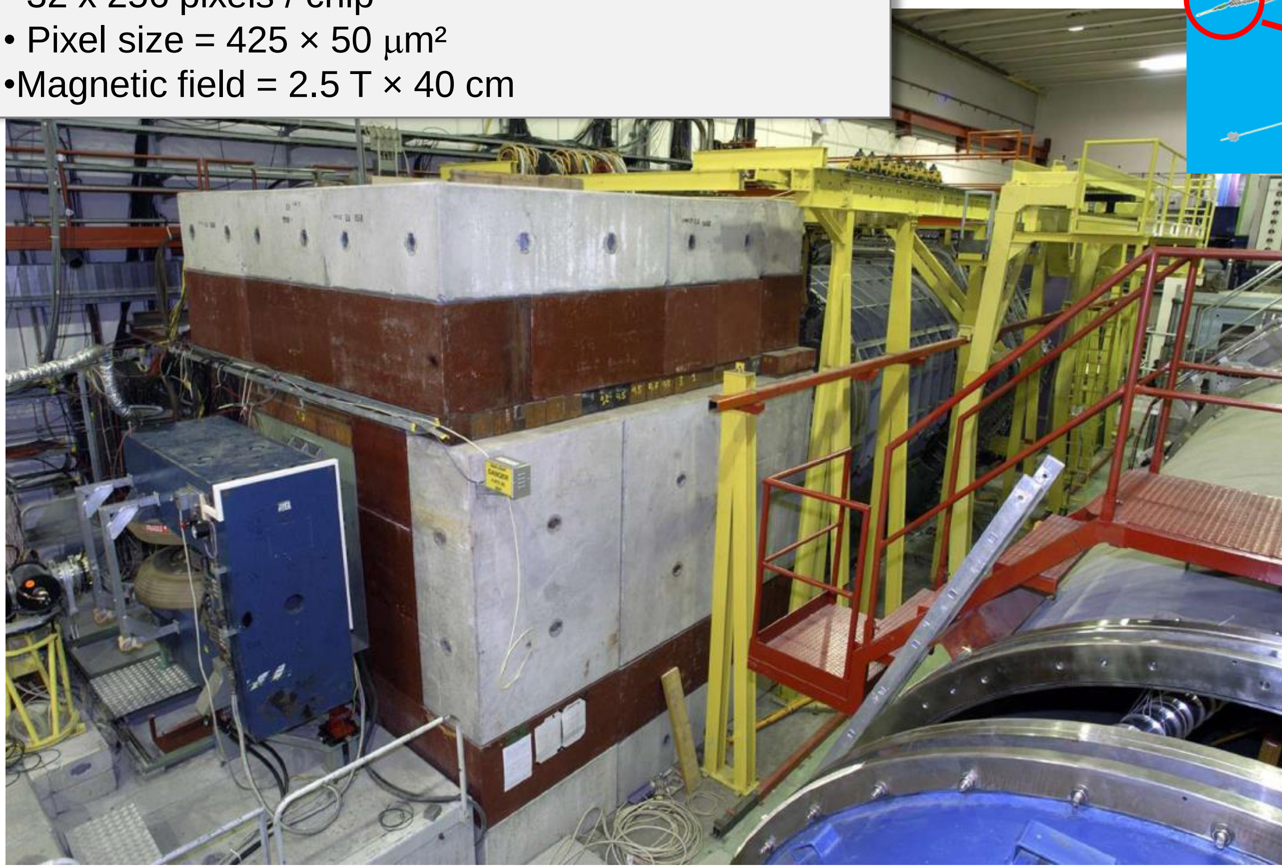


Silicon spectrometer

- **The NA60 example**

Pixel detector
- 16 planes – 96 chips total
- 32 x 256 pixels / chip
- Pixel size = 425 × 50 μm²
- Magnetic field = 2.5 T × 40 cm





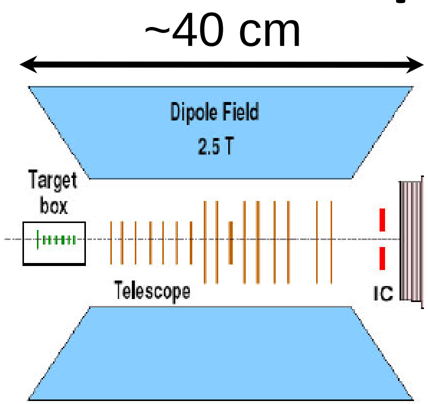
Momentum resolution
@J/Ψ mass
(typical p_μ ~ 15 GeV/c)

$$\boxed{\frac{\Delta P}{P} \sim 6\%}$$

(R. S. priv. Comm.)

Magnetic field

- **The NA60 pixel detector**



$$\boxed{\frac{\Delta P}{P} = 6\% \Rightarrow \frac{\Delta M}{M} = \frac{\Delta P}{\sqrt{2}P} = 4.2\% \Rightarrow \Delta M_{J/\Psi} \sim 130\ \mathrm{MeV}}$$

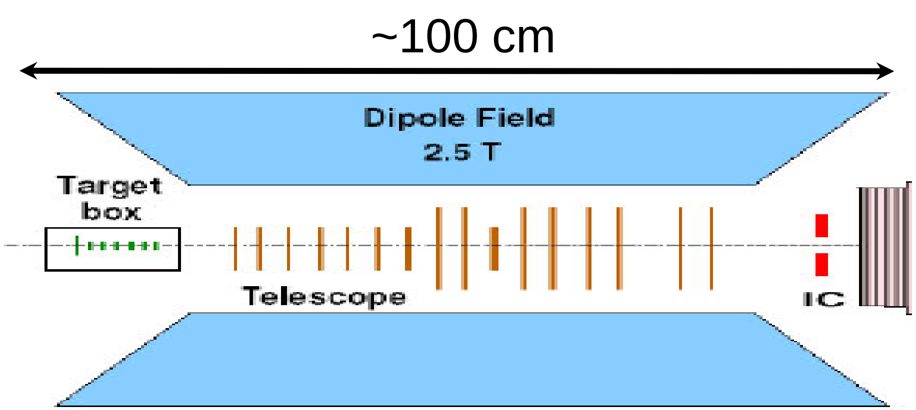
$\Downarrow$ ***L*** **= 0.4 m**

$$\boxed{\frac{\Delta P}{P} \propto \frac{1}{BL^2} P}$$

$\Downarrow$ ***L*** **= 1 m**

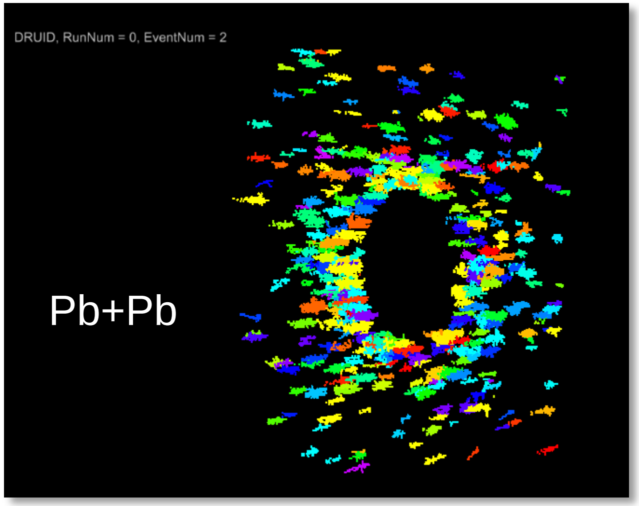
$$\boxed{\frac{\Delta P}{P} = 1\% \Rightarrow \Delta M_{J/\Psi} \sim 20\ \mathrm{MeV}}$$

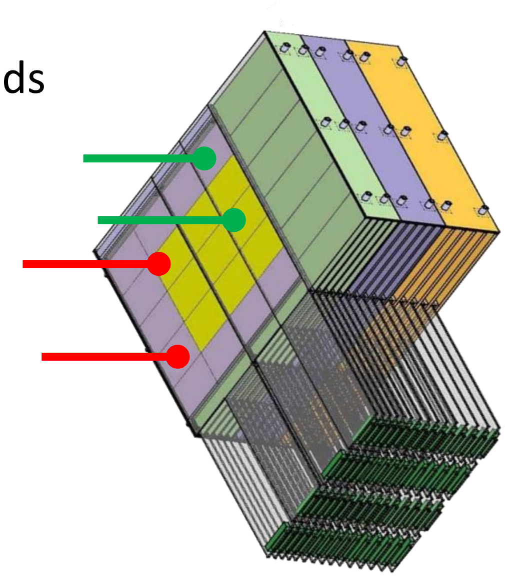
- **The CHIC pixel detector**

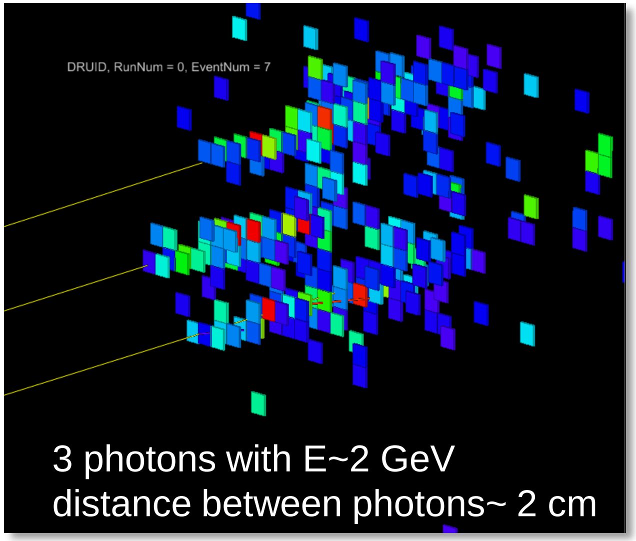


Calorimetry

- **Need to measure low energy photon (~3 GeV in lab) in high π^0 multiplicity environment → need very high segmentation**
    - To separate electromagnetic showers
    - To isolate photons from $\pi^{+/-}$ contamination
- **W + Si calorimeter à la Calice**
    - 30 layers
    - 0.5 x 0.5 cm^2 pads
    - 24 X_0 in 20 cm







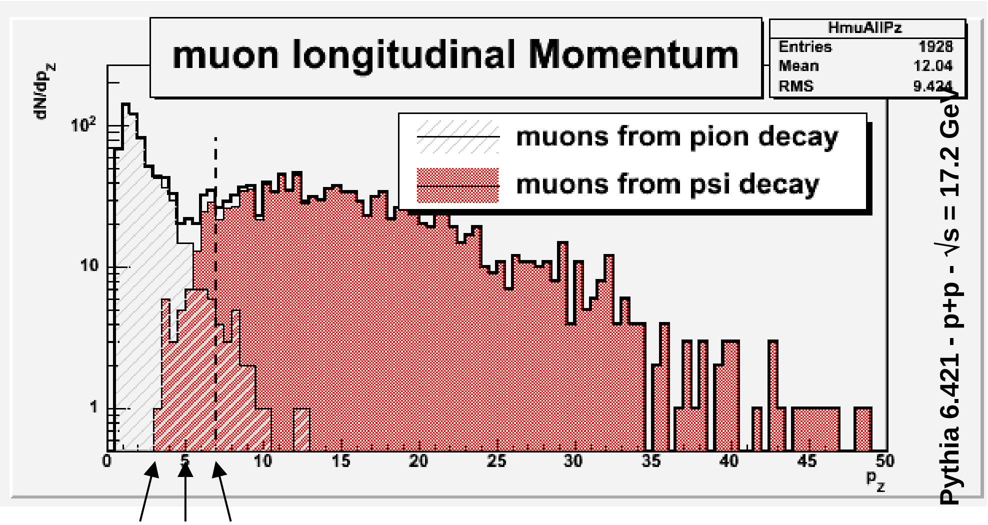
(full simu made by D. Jeans - LLR - Calice collab.)

Absorber

- **Absorber size and muon energy loss**

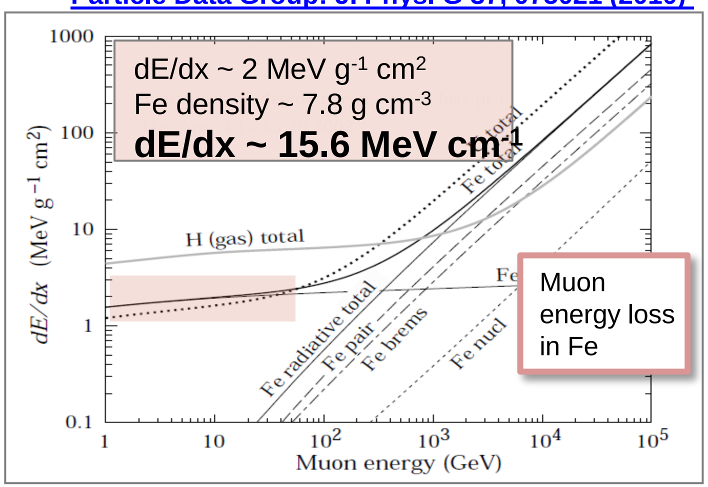
All $\pi^{+/-}$ stopped with a 2.0 m Fe

➔ but need more Fe to stop muons from pion decay



3 5 7 GeV/c

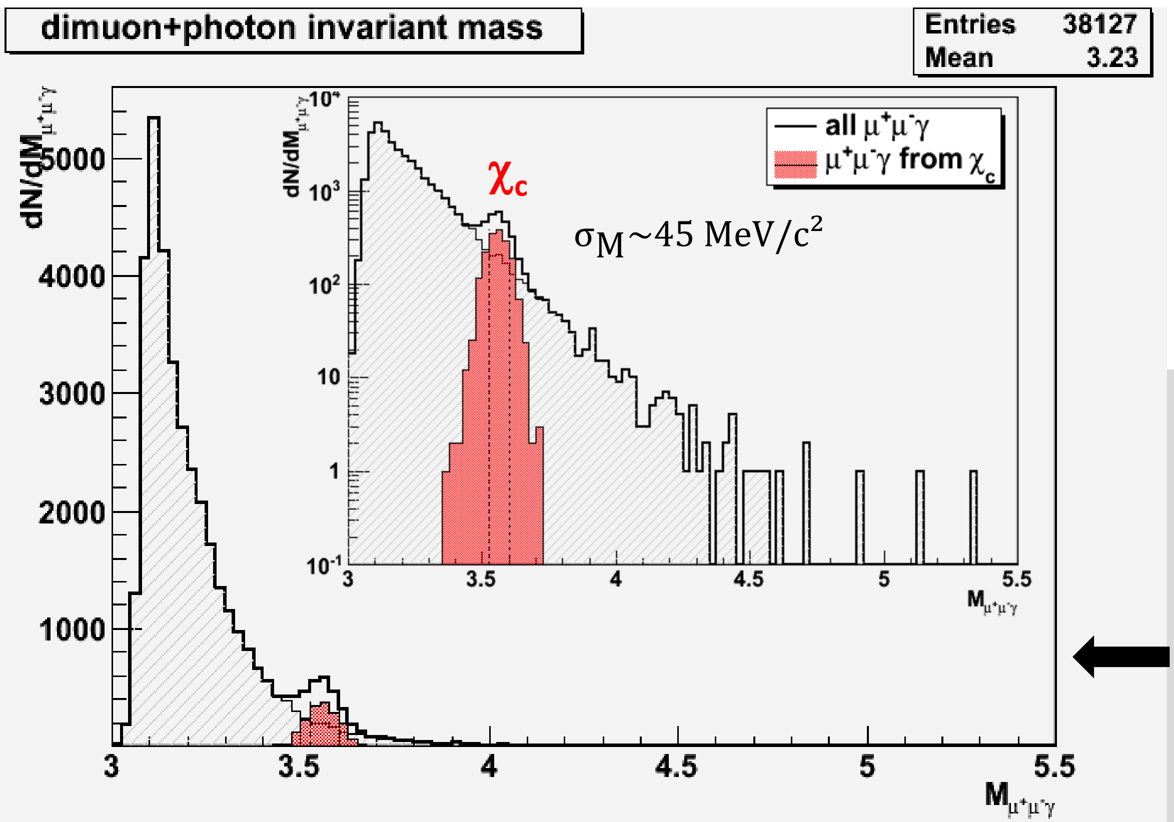
Particle Data Group: J. Phys. G 37, 075021 (2010)

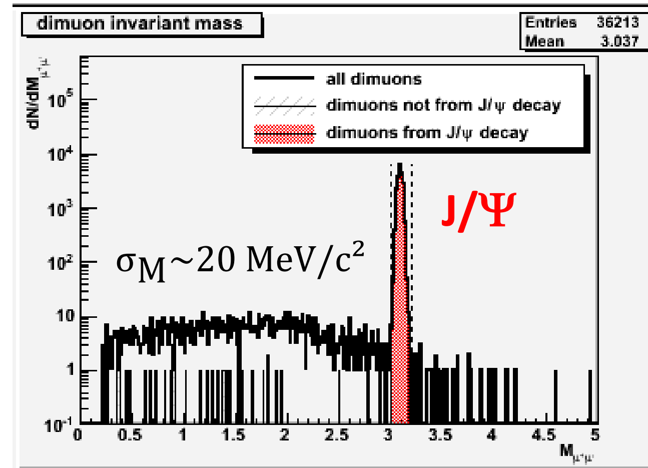


➔ 2.0 m Fe ➔ $\Delta E/\Delta x$ ~ 15.6 x 200 ~ 3 GeV
➔ 3.2 m Fe ➔ $\Delta E/\Delta x$ ~ 15.6 x 320 ~ 5 GeV
➔ 3.8 m Fe ➔ $\Delta E/\Delta x$ ~ 15.6 x 380 ~ 6 GeV
➔ 4.5 m Fe ➔ $\Delta E/\Delta x$ ~ 15.6 x 450 ~ 7 GeV

Expected performances **Signal extraction**

- **Typical mass plots (~1 week data taking w/ a 10% λ_I Pb target)**
  - 200 000 J/Ψ embedded in Pb+Pb Minbias events produced w/ EPOS
    - 140 000 direct J/Ψ→ $\mu^+\mu^-$ (70%)
    - 60 000 χ_c → J/Ψ γ → $\mu^+\mu^-$ γ (30%)





After acceptance/selection cuts
within $y_{CMS}\in$[-0.5;0.5]
35 000 **J/Ψ→$\mu^+\mu^-$**
→ acc x eff = 17.4%

Including
1700 **χ_c → J/Ψ γ → $\mu^+\mu^-$ γ**
→ acc x eff = 2.8 %

Expected number of events

Statistics

- **Typical 40-day Pb+Pb run** **($10^7.s^{-1}$ Pb beam → 10% λ_I Pb target)**
  - ~ 180 000 $J/\Psi \rightarrow \mu^+\mu^-$ recorded
  - 2 extreme *numerical* scenarios:
    - If χ_c suppressed as J/Ψ $\quad \dfrac{\chi_c \text{ yield}}{J/\Psi \text{ yield}} \sim 4\%$

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

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

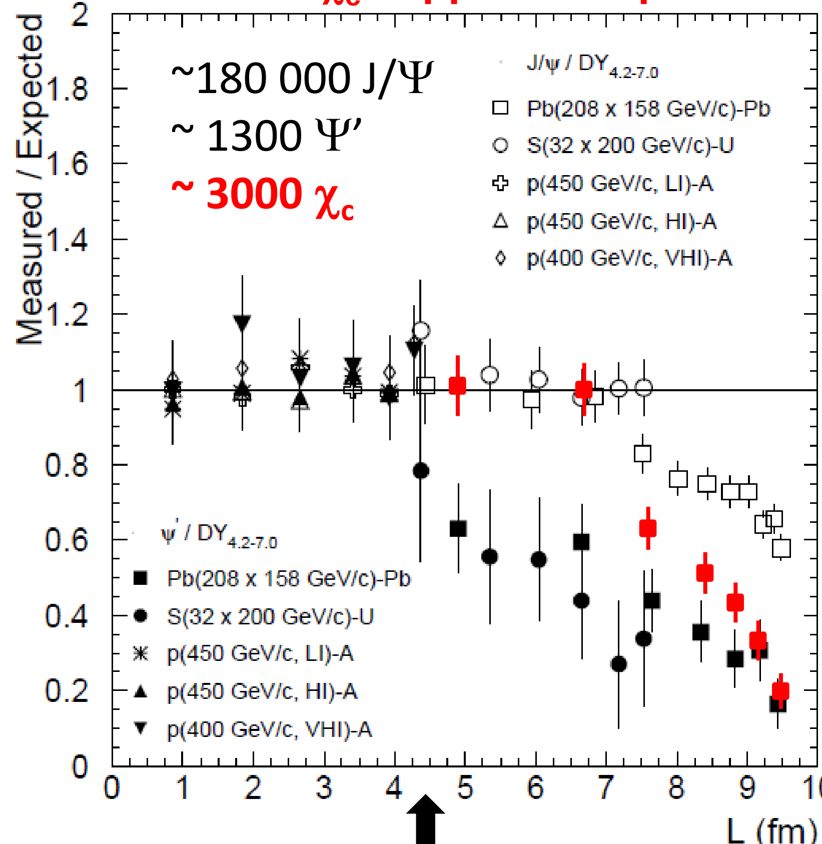
$$\begin{pmatrix}\text{most periph.}\\ \chi_c \text{ yield}\end{pmatrix} = 16942 \times 4\% \times 0.6 = 406$$

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

E_T range (GeV)	ψ'	J/ψ	χ_c as Ψ'	χ_c as J/Ψ
3–20	186 ± 25	16942 ± 146	406	677
20–35	243 ± 31	25229 ± 181	530	1010
35–50	227 ± 35	27276 ± 192	495	1091
50–65	193 ± 36	27681 ± 196	421	1107
65–80	154 ± 36	27315 ± 200	336	1093
80–95	159 ± 37	25111 ± 193	647	1004
95–150	110 ± 40	28570 ± 209	240	1143
			3075	**7125**

$\underbrace{\hspace{4em}}_{\text{NA50 data}}$

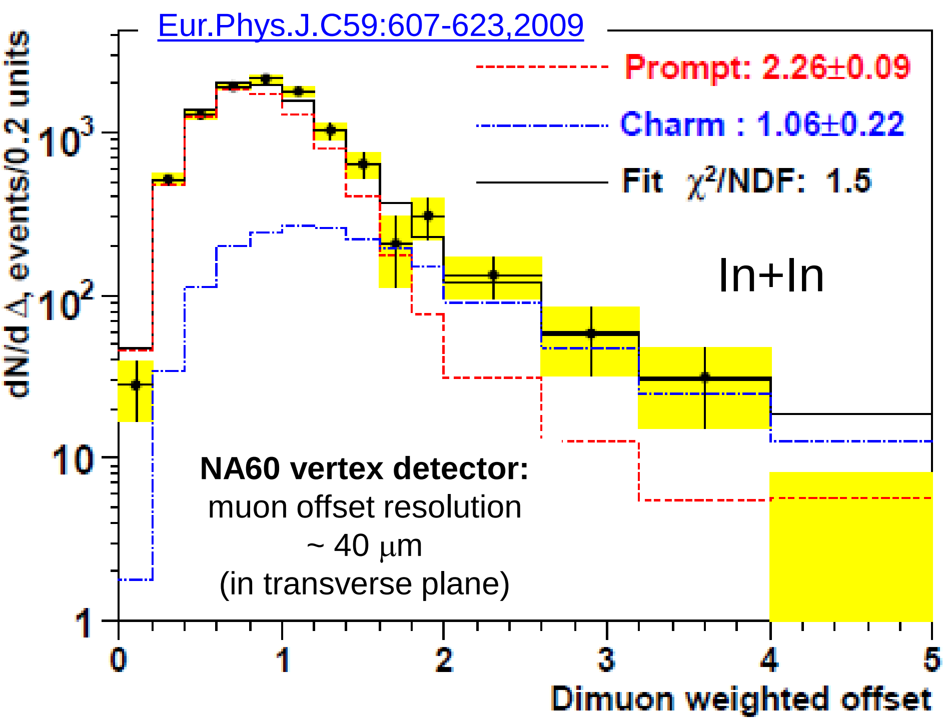
Possible χ_c suppression pattern

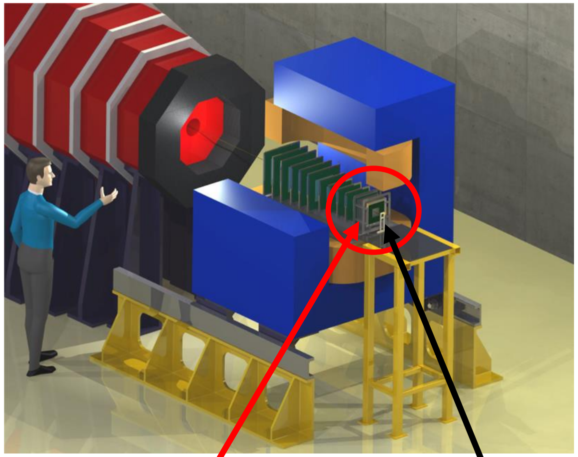


Expect 3000 < N_{χ_c} < 7000

Measuring muon offset

- **Use same Strategy as NA60: measure muon vertex**
  - Open charm decay length: $\begin{cases} D^{+/-}: c\tau = 311.8\ \mu m \\ D^{0}: c\tau = 122.9\ \mu m \end{cases}$





target

CHIC: Vertex detector located 7.5 cm downstream of the target (7 cm for NA60)

- **CHIC is able to measure open charm yields.**
- Detailed simulations needed to estimate performances

- **NA60 has separated prompt (red) from charm (blue) contribution in In+In**
- **NA60 has found an excess of prompt dimuons in Intermediate Mass Region**
- **NA60 has measured open charm cross-section: compatible with p+A results**

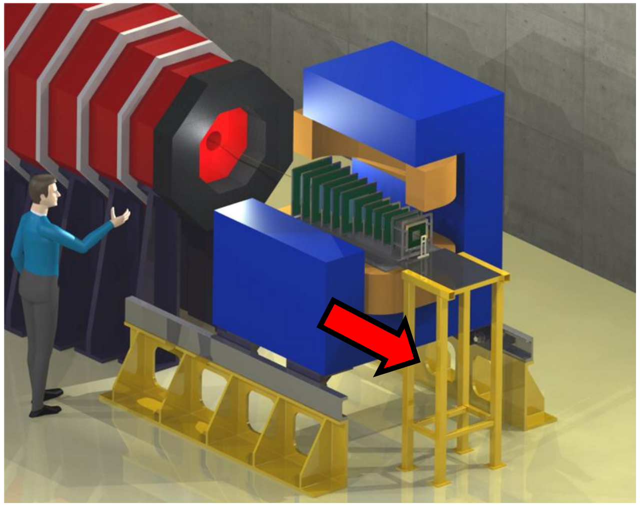
Cold Nuclear Matter

A thorough p+A program is mandatory to study Cold Nuclear Matter effects as a reference to study Hot Nuclear Matter effects

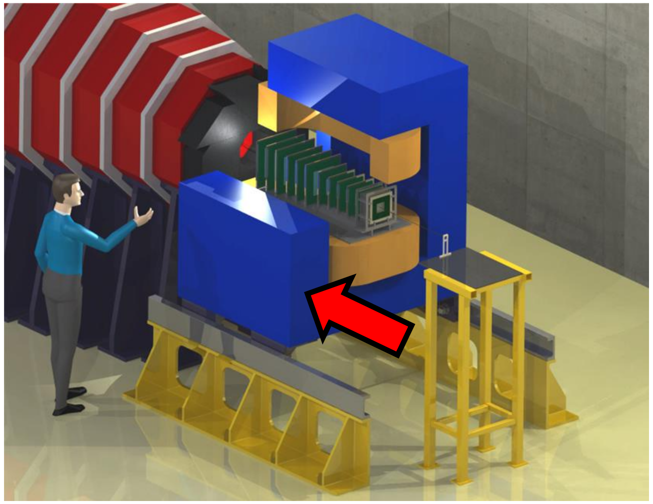
- **Must control (understand) :**
  - charmonium absorption by cold nuclear matter ➔ A dependence
  - Shadowing/anti-shadowing (x_2 scaling)
  - Energy loss, formation time (x_F scaling)

➔ **Need large y_{CMS} range**

Mid-rapidity : $y_{CMS} \in$ [-0.5 ; 1]

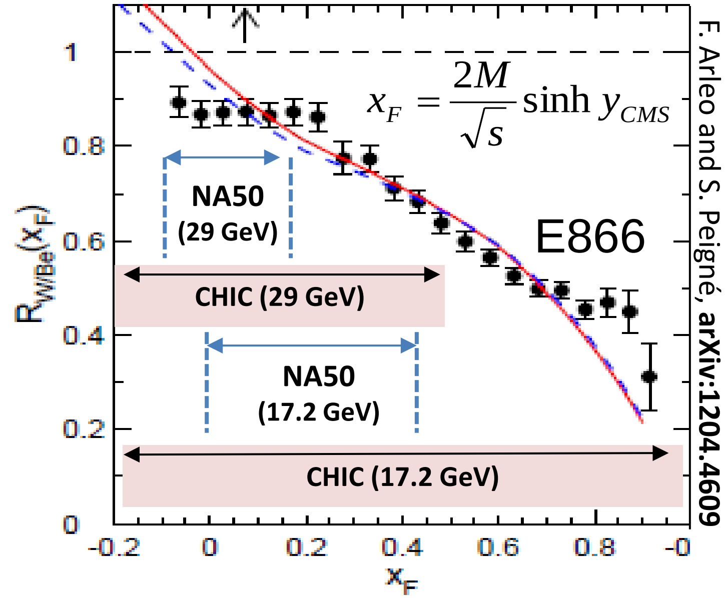


Forward-rapidity : $y_{CMS} \in$ [0.5 ; 2]



Detector capabilities

- **Large rapidity range**
  - Significantly Larger rapidity range for CHIC ($y_{CMS}\in$[-0.5;2]).vs. NA50 ($y_{CMS}\in$[0;1])
- **Precise A dependence (thanks to fixed-target mode)**
  - NA50 samples : p+Be, p+Al, p+Cu, p+Ag, p+W, p+Pb
- **Large amount of data (thanks to fixed-target mode)**
  - Large statistics required to study J/Ψ, Ψ', χ_c and open charm differential yields as a function of y, p_T.
  - **Current SPS operation: Delivering proton beam to the LHC several months per year**
  - **Significantly larger (than NA50) amount of data available for CHIC.**



Typical 1week/target NA50 data taking
(EPJ C33 (2004) 31-40)

Target	size (λ_I)	$< I_{protons} >$ ($\times 10^8$)	Total $N_{protons}$ ($\times 10^{12}$)	$N_{\mu\mu}^{+-}$ (2.7 - 3.5)
Be	60 %	21.7	50.7	368 000
Al	52 %	23.0	63.4	602 000
Cu	28 %	27.0	45.5	762 000
Ag	30 %	24.8	43.8	821 000
W	19 %	23.5	28.5	524 000

Project status

- **EoI submitted to the SPS Committee (oct. 2012)**

Expression of Interest
Submitted to SPSC – oct.2012
CERN-SPSC-2012-031

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

Expression of Interest

for an experiment to study charm production with proton and heavy ion beams

(CHIC: Charm in Heavy Ion Collisions)

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MINUTES of the 108th Meeting of the SPSC
15-16 January 2013
CERN-SPSC-2013-008

The SPSC has received an expression of interest to study charm production with proton and heavy ion beams. The SPSC recognizes the **strong physics motivation** of a study that addresses **central open questions** about the **color screening** of charmonium in heavy ion collisions and about **cold nuclear matter effects**. For a comprehensive investigation, an extension including open charm production would be desirable.

For further review, the SPSC would require a letter of intent with information about the experimental implementation and the **collaboration** pursuing it.

Towards a Letter of Intent

- **Green light from CERN SPSC**
  - EoI submitted to SPSC in oct. 2012 : **CERN-SPSC-2012-031**
  - Positive feed-back from SPSC in jan. 2013 : **CERN-SPSC-2013-008**
- **Current think tank**
  - F. Arleo, E.G. Ferreiro, F. Fleuret, P.-B. Gossiaux, S. Peigné
  - **Many opportunities for experimentalists**
- **apparatus**
  - **Tracking**
    - Needs low detector occupancy ➔ silicon technology
    - **Welcomes group with expertise !**
  - **Calorimetry**
    - Need ultragranular calorimetry à la CALICE
    - Expertise at **LLR - Ecole polytechnique (France)**
  - **Trigger**
    - Instrumented (magnetized) Fe Absorber
    - **Welcomes group with expertise !**
- **Expected timeline**
  - From T_0 (3 labs involved): ~ 5 Years for full simulation and final design (2 years), construction and installation (2 years), commisionning (1 year)

Conclusion

- **Measuring J/Ψ, Ψ', χ_c and open charm in A+A collisions at SPS will (dis)prove sequential suppression scenario.**

- **Measuring J/Ψ, Ψ', χ_c and open charm in p+A collisions with several targets will give a thorough control of Cold Nuclear Matter effects**

- **The apparatus is well suited to explore other important physics subjects such as low mass lepton pairs production in heavy ion collisions.**

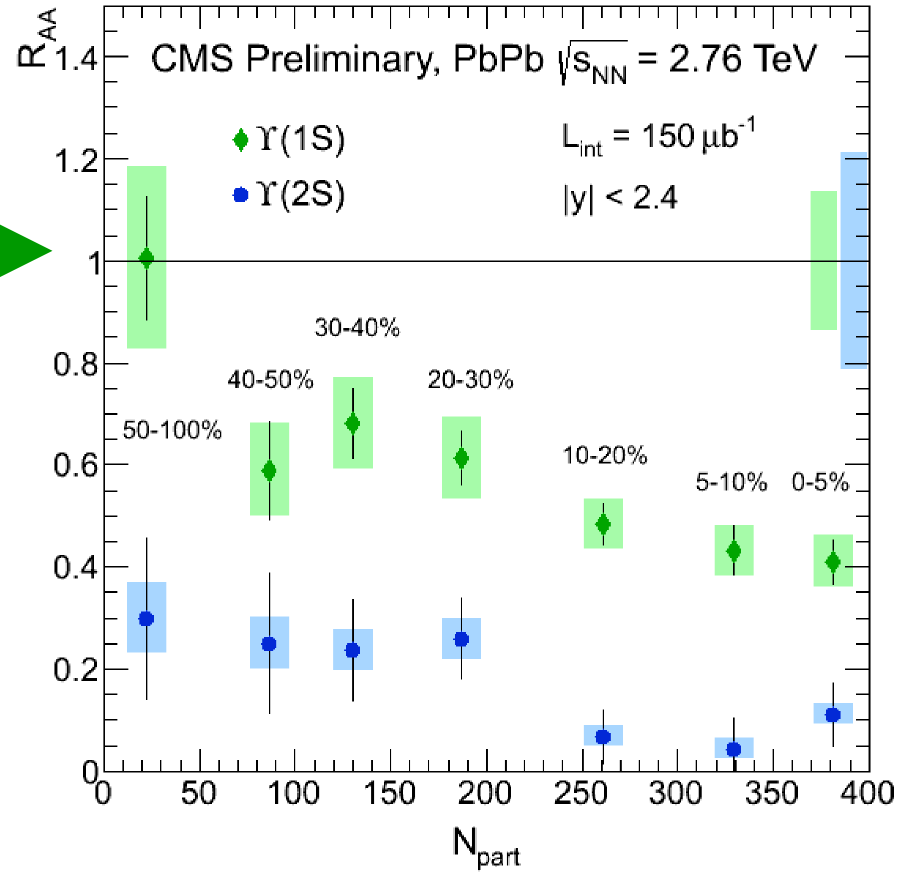
- **Many opportunities to contribute to the project**

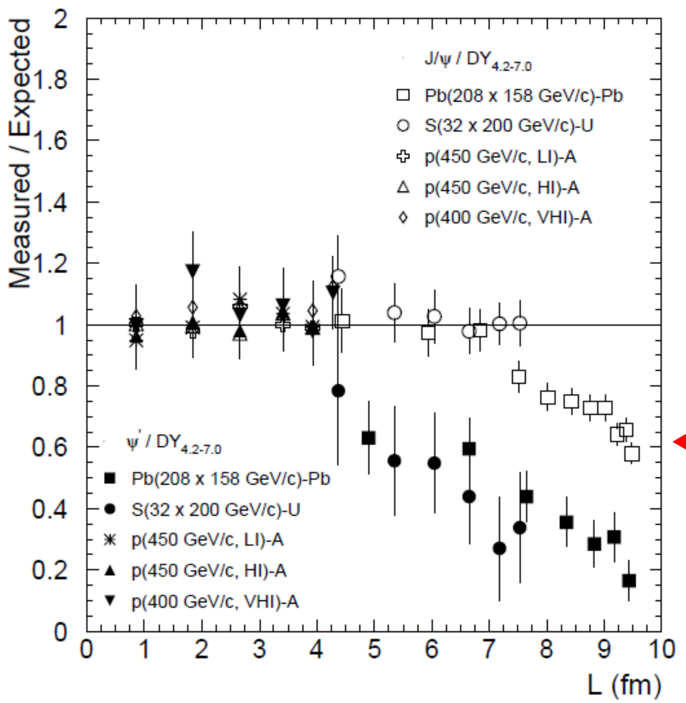
- **Testing sequential suppression scenario at SPS is crucial to fully understand RHIC and LHC results.**

New upsilon results

Results from CMS

"Observation of Sequential Υ Suppression in PbPb collisions" (at LHC)
PRL109, 222301 (2012)

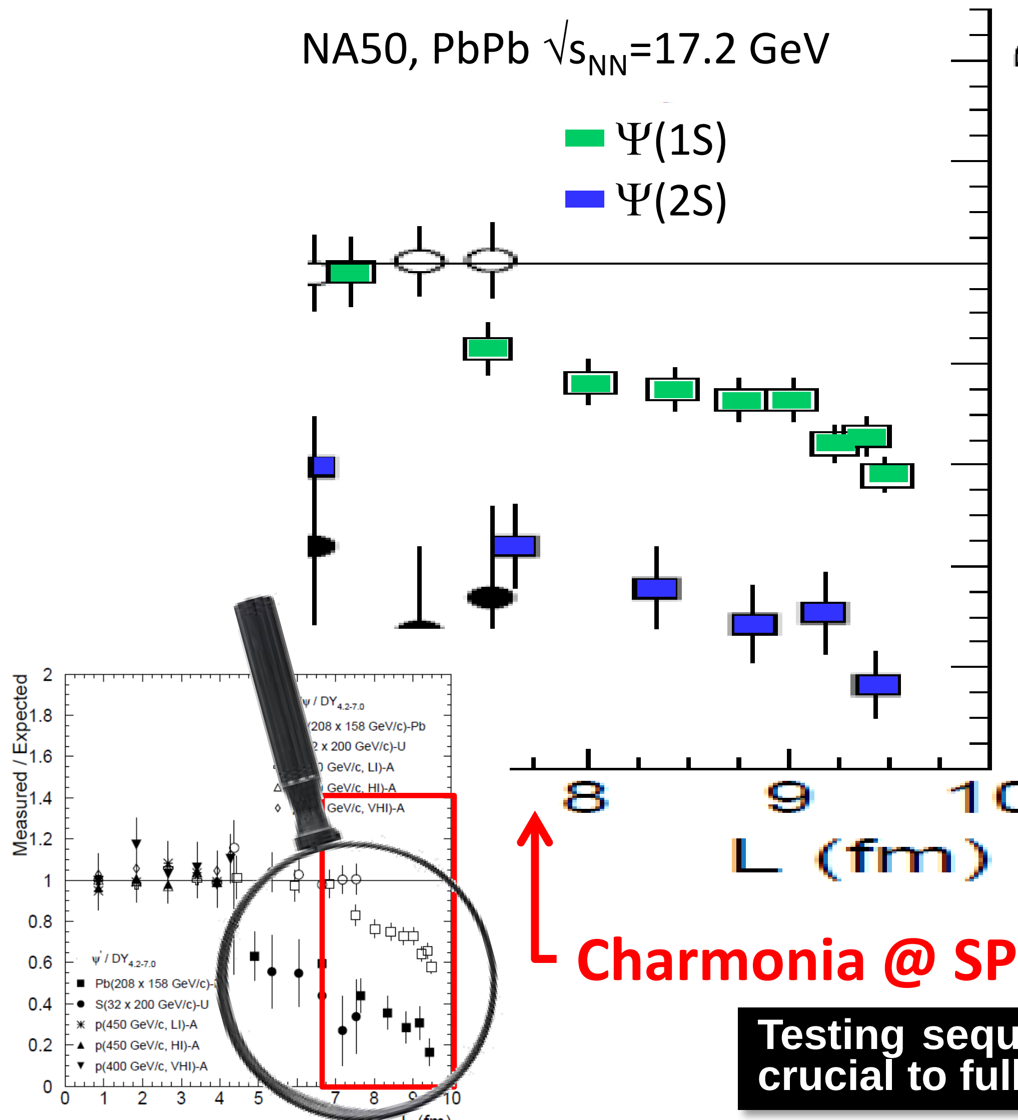


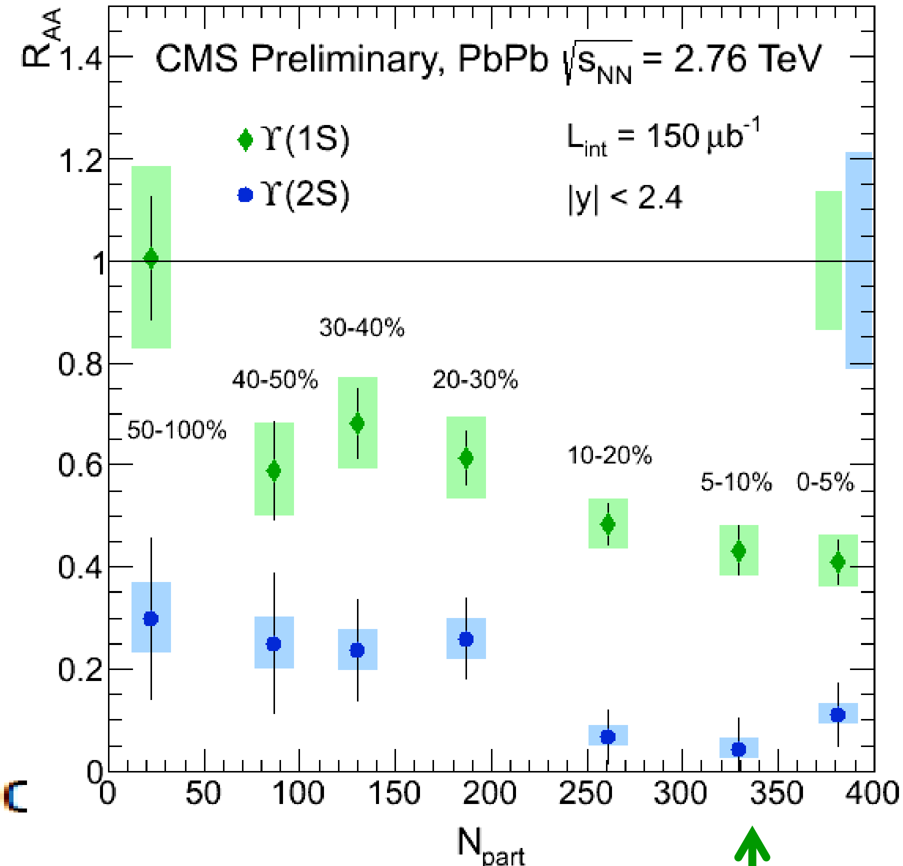


Charmonia @ SPS **bottomonia @ LHC**

Testing sequential suppression scenario at SPS is crucial to fully understand RHIC and LHC results.

J/Ψ@SPS .vs. ϒ@LHC color screening ?





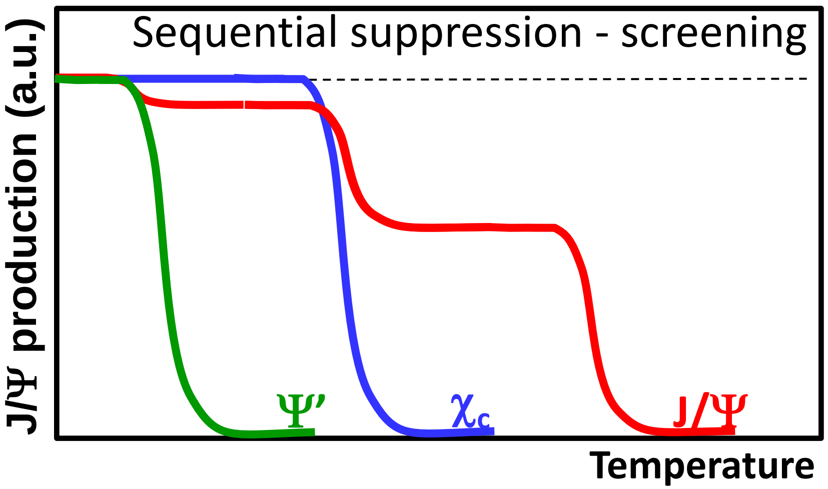
Charmonia @ SPS **bottomonia @ LHC**

Testing sequential suppression scenario at SPS is crucial to fully understand RHIC and LHC results.

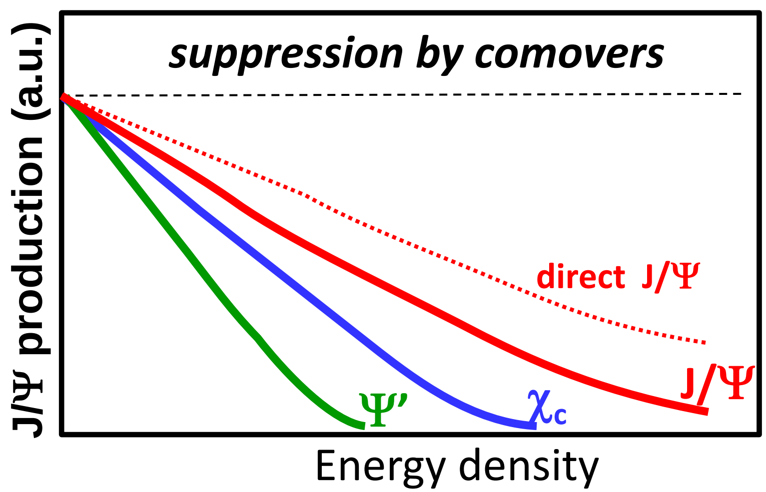
backup

Color screening

- **How to Test sequential suppression with charmonia ?**
  - **must measure J/Ψ, Ψ', χ_c**
  - ~30% (resp. ~10%) of inclusive J/Ψ comes from χ_c (resp. Ψ') decay.
  - According to lattice calculations, T_d (Ψ') < T_d (χ_c) < T_d (J/Ψ)
  - **If screening, one should observe a step-like suppression patterns**



- **Alternative (no QGP) scenario: suppression by comoving hadrons**
  - Smooth suppression
  - Same suppression-starting point
  - Slopes related to binding energy : $S_{\Psi'} > S_{\chi} > S_{J/\Psi}$



Comovers

- **Anomalous suppression at SPS**

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

Expectations in comovers scenario

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

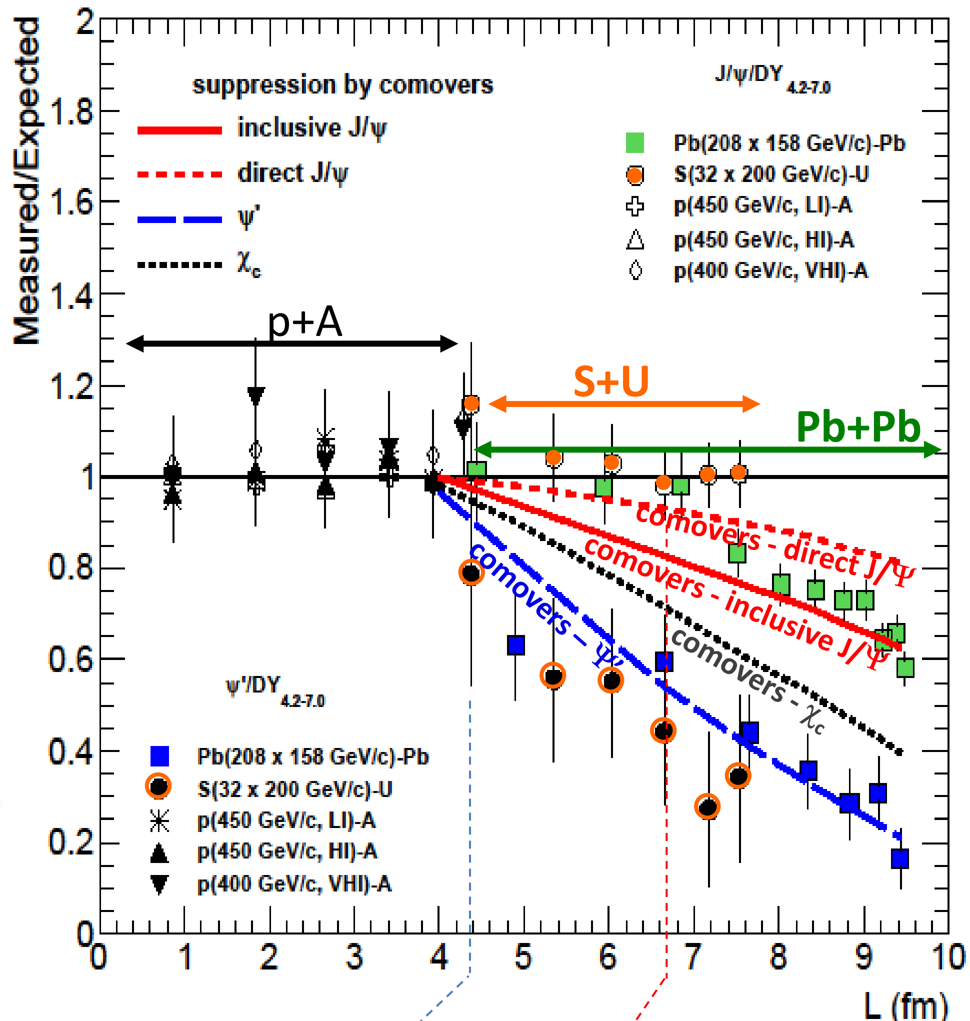
Taking breakup cross-sections:

- **comovers-direct J/Ψ = 0.2 mb**
- **comovers – χ_c = 1.0 mb**
- **comovers – Ψ' = 2.0 mb**

and considering feed-downs

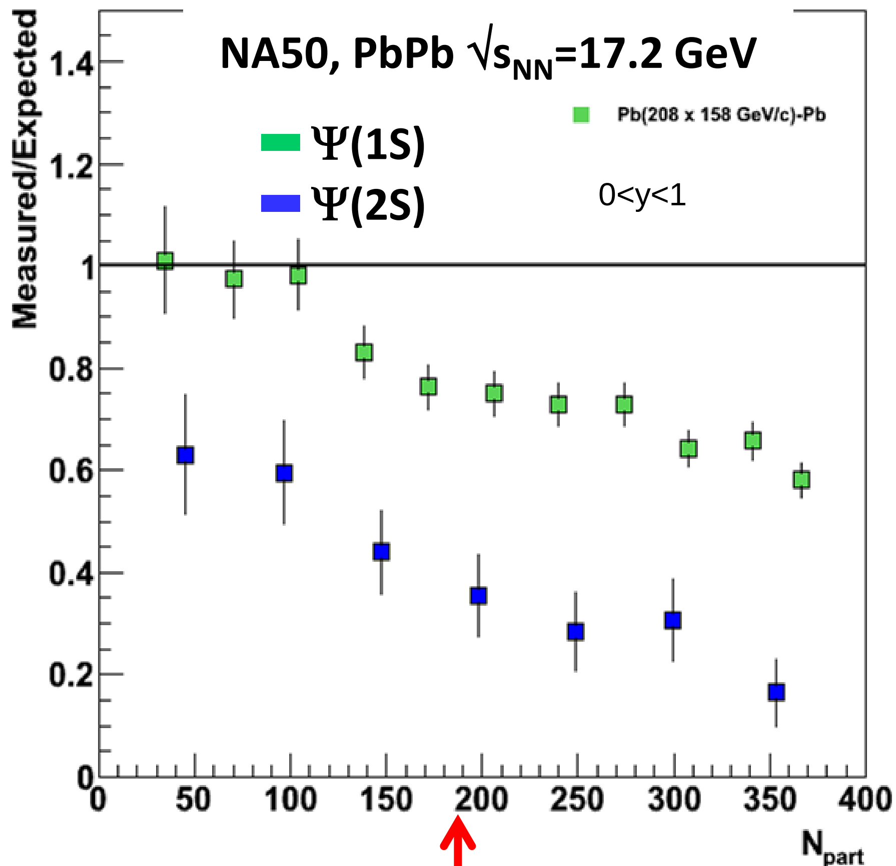
60% direct J/Ψ
+ 30% $\chi_c \rightarrow J/\Psi+\gamma$
+ 10% $\Psi' \rightarrow J/\Psi + X$

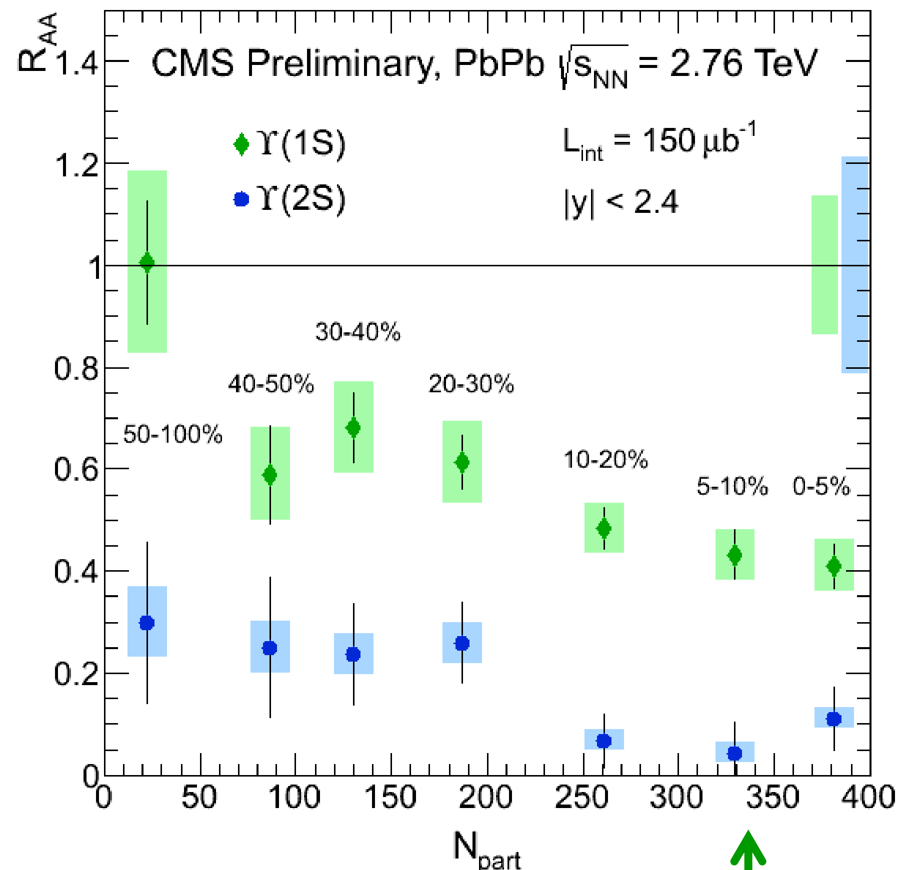
Inclusive J/Ψ yield



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

J/Ψ@SPS .vs. Υ@LHC



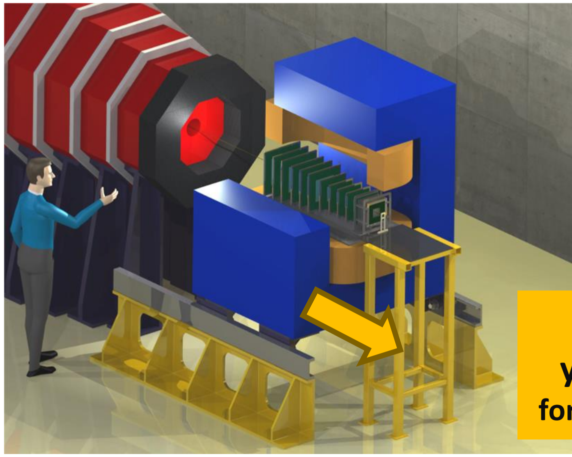


Charmonia @ SPS **bottomonia @ LHC**

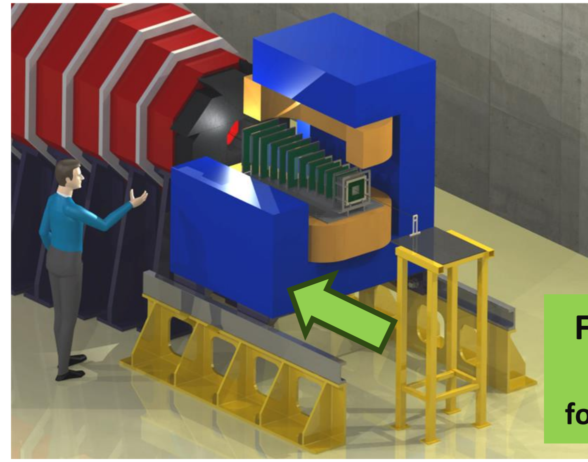
Testing sequential suppression scenario at SPS is crucial to fully understand RHIC and LHC results.

Energy scan

- **Spectrometer acceptance: two detector configurations**



Mid-rapidity
$y_{CMS} \in [-0.5 ; 1]$
for P_{beam} = 158 GeV/c



Forward-rapidity
$y_{CMS} \in [0.5 ; 2]$
for P_{beam} = 158 GeV/c

Depending on the beam energy, different rapidity ranges accessible

P_{beam} (GeV/c)	$\sqrt{s}$ (GeV)	Rapidity of Center-of-mass	Mid-rapidity		Forward-rapidity	
			y_{CMS} min	y_{CMS} max	y_{CMS} min	y_{CMS} max
158	17.2	2.91	-0.5	1	0.5	2
120	15.1	2.77	-0.36	1.14	0.65	2.14
80	12.3	2.57	-0.16	1.34	0.84	2.34
60	10.7	2.43	-0.02	1.48	0.98	2.48

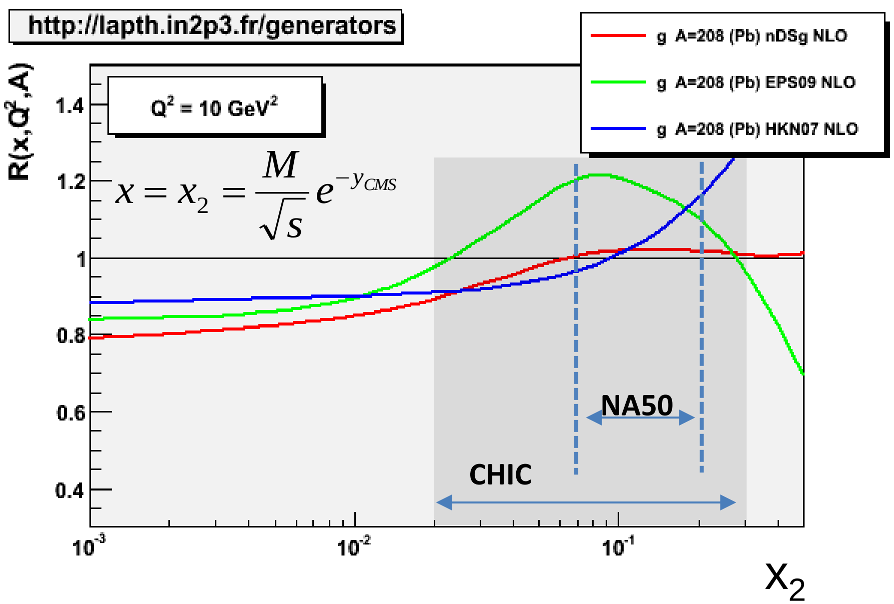
Common coverage: $y_{CMS} \in [0;2]$ **(NA50/NA60 coverage = [0;1])**

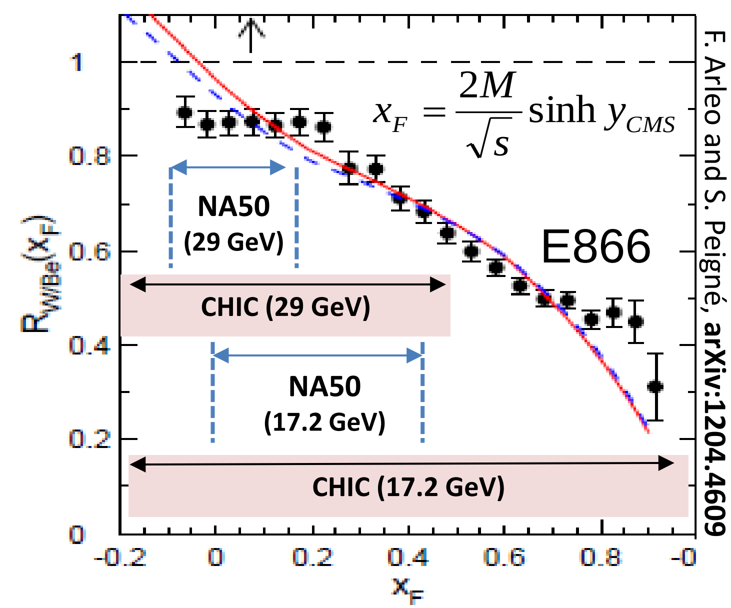
Rapidity coverage

- **A thorough p+A program**
  - **mandatory as reference for hot nuclear matter effects**

J/Ψ, Ψ', χ_c in a large y_{CMS} range
→ Large coverage in x_2
→ Large coverage in x_F

E_{beam} ($\sqrt{s}$)	Exp.	y_{CMS}	x_2	x_F
158 GeV (~17 GeV)	NA50	[0;1]	[0.07;0.18]	[0;0.42]
	CHIC	[-0.5;2]	[0.02;0.30]	[-0.19;1]
450 GeV (~29 GeV)	NA50	[-0.4;0.6]	[0.06;0.16]	[-0.09;0.14]
	CHIC	[-0.9;1.6]	[0.02;0.26]	[-0.22;0.51]





Mass resolution

- **CHIC expected performances for low mass dileptons**
  - Tracking performed upstream to the absorber
    - ➔ no multiple scattering due to absorber
    - ➔ momentum resolution affected by magnetic field only:

$$\frac{\Delta P}{P} \propto \frac{1}{BL^2} P$$

  - Momentum resolution
    - With a 1m long 2.5T dipolar magnetic field
      - $\frac{\Delta P_\mu}{P_\mu}$ = 1% for typical muon from J/Ψ (<P_μ> ~10 GeV/c)
      - $\frac{\Delta P_\mu}{P_\mu}$ = 0.7% for typical muon from ω (<P_μ> ~7 GeV/c)
  - Expected mass resolution:
    - J/Ψ: $\frac{\Delta P_\mu}{P_\mu} = 1\%$ ➔ $\frac{\Delta P_\mu}{\sqrt{2} P_\mu} = \frac{\Delta M_{\mu\mu}}{M_{\mu\mu}} = 0.7\%$
    - ω: $\frac{\Delta P_\mu}{P_\mu} = 0.7\%$ ➔ $\frac{\Delta P_\mu}{\sqrt{2} P_\mu} = \frac{\Delta M_{\mu\mu}}{M_{\mu\mu}} = 0.5\%$

$\Delta M_{\mu\mu}^{J/\Psi} \sim 3.097\ \mathrm{GeV}/c^2 \times 0{,}7\% \sim 20\ \mathrm{MeV}/c^2$
NA50: $\Delta M_{\mu\mu}^{J/\Psi} \sim 90\ \mathrm{MeV}/c^2$

$\Delta M_{\mu\mu}^{\omega} \sim 782.7\ \mathrm{MeV}/c^2 \times 0{,}5\% \sim 4\ \mathrm{MeV}/c^2$
NA60: $\Delta M_{\mu\mu}^{\omega} \sim 20\ \mathrm{MeV}/c^2$

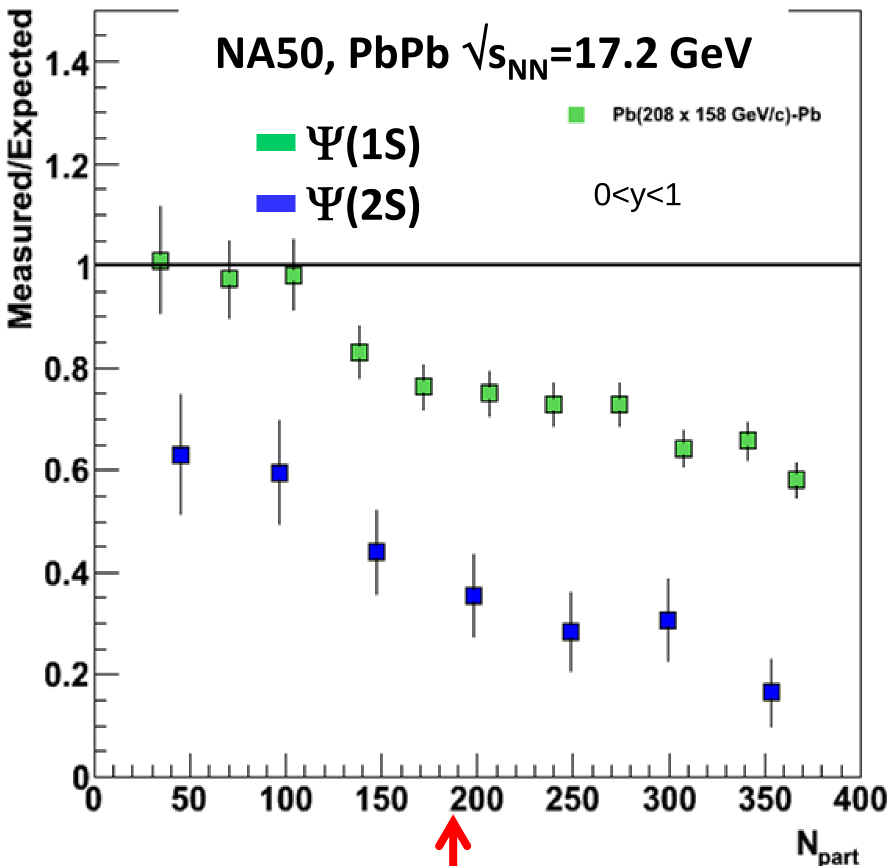
CERN strategy

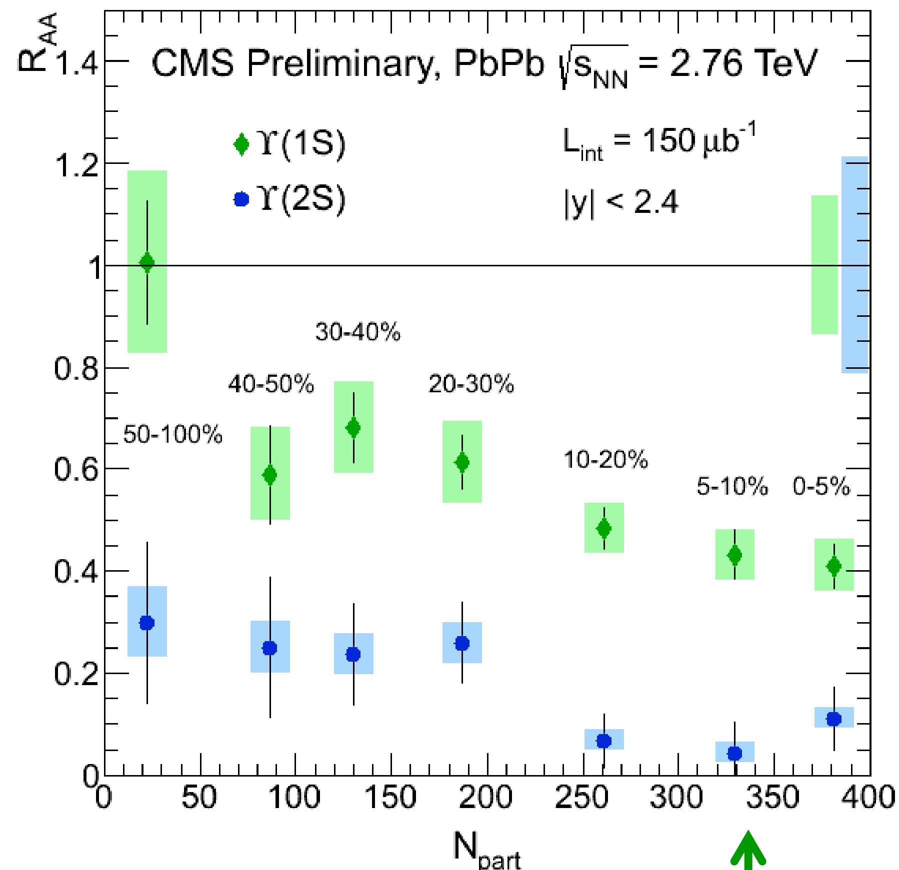
Conclusions of the CERN Town meeting on "Relativistic Heavy-Ion Collisions"

CERN - june 29, 2012

"…The town meeting also observed that the CERN SPS would be well-positioned to contribute decisively and at a competitive time scale to central open physics issues at large baryon density. In particular, the CERN SPS will remain also in the future the only machine capable of delivering, heavy ion beams with energies exceeding 30 GeV/nucleon, and the potential of investigating rare penetrating probes at this machine is attractive."

J/Ψ@SPS .vs. Υ@LHC color screening ?





Charmonia @ SPS

bottomonia @ LHC

On the same axis