Coherent $J/\Psi$ photoproduction in Pb-Pb collisions with nuclear overlap with ALICE at the LHC

L. Massacrier for the ALICE team

Laboratoire de Physique des 2 infinis Irène Joliot Curie (IJCLab)
Open questions and basics of Quantum ChromoDynamics

Quantum ChromoDynamics

Nucleon and hadron structure

How do the mass and spin of the nucleon arise from its constituents? What are the static and dynamical properties of hadrons?

Medium effects

What are the modification of the quark and gluon structure of a nucleon when it is immersed in a nuclear medium?

Quark Gluon Plasma

What are the properties of nuclei and strongly-interacting matter as encountered shortly after the Big Bang, in catastrophic cosmic events and in compact stellar objects?

- Confinement:
  - For $d \sim 1 \text{fm}$ (typical size of hadrons), $Q^2 < 1 \text{ GeV}$

- Asymptotic freedom:
  - At short distances quarks and gluons quasi-free
Probing QCD under extreme conditions: the QGP

Phase diagram of nuclear matter

- QGP: Deconfined state of nuclear matter predicted by QCD: quarks and gluons no longer confined in hadrons
- Formed from ordinary nuclear matter provided that temperature and/or energy density is high enough
- Open questions: nature of the phase transition, existence of a critical point, EoS of nuclear matter?
Heavy ion collisions to recreate the QGP in the lab

- In the early stages of the Universe (few μs after Big Bang), quarks and gluons were evolving freely due to the large temperature.

- As the universe cooled down, they were confined inside the hadrons.

- To study confinement, recreate this stage of matter in the lab.

- From lattice QCD: $T_c \sim 170$ MeV ($10^5$ times $t^\circ$ inside sun) $\Rightarrow \varepsilon_c \sim 1$ GeV/fm$^3$ (5 times ordinary matter).

How to reach those conditions in lab?

Collisions of High-Energy Ultra-Relativistic Heavy Nuclei

→ Vary type of nuclei and energy to explore different regions of the phase diagramme of nuclear matter.
Probing the Quark Gluon Plasma with HI

- QGP not « directly » accessible to observation (last only few fm/c!)
- Need a combination of several probes and good reference system(s) (without QGP formation)

- Radiation of thermal photons
- Azimuthal asymmetry and radial expansion
- Energy loss by quarks, gluons and other particles
- Suppression of quarkonia

Coherent J/Ψ photoproduction in Pb-Pb collisions with nuclear overlap in ALICE – Laure Massacrier
Quarkonia as probe of the QGP in AA collisions

- Quarkonia are heavy quark bound states
- $c\bar{c}$ pairs produced at the initial stages of the collision via hard scattering of partons → experience full evolution of the system

Hot medium effects: Debye screening

- High color density in the medium induces a screening of the «Coulombian» term of the inter-quark potential
  $$V(r) = -\frac{\alpha}{r} + kr$$  $$\rightarrow$$  $$V(r) = -\frac{\alpha}{r} e^{-r/T_D}$$

- Debye screening condition occurs at different temperature for the different quarkonium species

- Sequential suppression of quarkonia states is a priori a thermometer of the medium temperature

<table>
<thead>
<tr>
<th>Bound state</th>
<th>$X_c$</th>
<th>$\Upsilon'$</th>
<th>$J/\psi$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(1S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_D/T_c$</td>
<td>$\leq 1$</td>
<td>$\leq 1$</td>
<td>1.2</td>
<td>1.2</td>
<td>2</td>
</tr>
</tbody>
</table>


**Important to know feed-down!**

Coherent $J/\psi$ photoproduction in Pb-Pb collisions with nuclear overlap in ALICE – Laure Massacrier
Quarkonia as probe of the QGP in AA collisions

Hot medium effects: Charmonium recombination (at LHC energy and low $p_T$)

- Central Pb-Pb collisions at LHC: large number of $c\bar{c}$ pairs produced ($\times 10$ w.r.t RHIC)
- Uncorrelated $c\bar{c}$ pairs can recombine to form charmonia

- Two main models: Statistical Hadronization versus transport models

The importance of reference measurements to interpret AA data

- Understand quarkonium «normal» suppression in Cold Nuclear Matter in pPb collisions (CNM also present in PbPb!)
- Understand quarkonium production mechanisms in pp collisions (CS, CEM, NRQCD…)

Coherent $J/\psi$ photoproduction in Pb+Pb collisions with nuclear overlap in ALICE – Laure Massacrier
The ALICE apparatus (Run-II)

Central barrel :
$J/\psi \rightarrow e^+e^-$
$|y| < 0.9$

2015 Pb-Pb (Run-II)
$\sqrt{s_{NN}} = 5.02$ TeV
$L_{\text{int}} \sim 10 \mu b^{-1}$

ITS : tracking
TPC : tracking, PID

Muon spectrometer :
$J/\psi \rightarrow \mu^+\mu^-$
$2.5 < y < 4$

2011 Pb-Pb (Run-I)
$\sqrt{s_{NN}} = 2.76$ TeV
$L_{\text{int}} \sim 70 \mu b^{-1}$

2015 Pb-Pb (Run-II)
$\sqrt{s_{NN}} = 5.02$ TeV
$L_{\text{int}} \sim 200 \mu b^{-1}$

2015 +2018 Pb-Pb (Run-II)
$\sqrt{s_{NN}} = 5.02$ TeV
$L_{\text{int}} \sim 700 \mu b^{-1}$

Muon tracker : tracking
Muon trigger : triggering

Coherent $J/\psi$ photoproduction in Pb-Pb collisions with nuclear overlap in ALICE – Laure Massacrier

Présentation au pôle PHE, JJCLab
The ALICE apparatus (Run-III)

- New Inner Tracking System:
  - 7 layer pixel detector
  - First layer closer to IP
  - Beam pipe with reduced radius (~ 2cm)
  - Improved resolution, smaller material budget, faster readout

- A New Muon Forward Tracker (MFT):
  - -3.6 < η < -2.3

- TPC readout via GEM

- Fast Interaction Trigger (FIT)

- Continous readout (50 kHz in Pb-Pb):
  - Upgrade of the electronics of several detectors (including the muon spectrometer)
  - New integrated online-offline system (O₂)
Upgrade of the front-end electronics of the Muon Spectrometer

- LHC run 3 (> 2021) : expected muon trigger rate in Pb-Pb beyond 10 kHz for $p_T > 1$ GeV/c.
- Current MS readout cannot cope with this data taking rate → Upgrade of MS readout (together with other ALICE detectors)
- Design, production and integration of a new readout electronic for the Muon Tracker:
  - DualSampa technology (20000 under production), Large PCB (links DualSampa to DAQ), renewal of High Voltage boards, Commissioning of the “upgraded” detector
  - Major involvement of lab electronics and detector division

DS12: 23 mm x 63 mm

DS345: 32 mm x 50 mm
**Definition of key heavy-ion observables**

The Collision centrality: a key quantity related to the initial overlap region of the colliding nuclei

- **Glauber model**: a geometrical picture of the AA collisions
- **Nucleon density**: Wood Saxon, nucleons travel in straight-line, nucleon-nucleon interaction according to $\sigma_{NN}$
- **Permit to relate impact parameter $b$, nuclear overlap function $T_{AA}$, $N_{\text{part}}, N_{\text{coll}}$ with observables (e.g., multiplicity)**
- **Many quantities scale with $N_{\text{part}}$ (particle multiplicity) or $N_{\text{coll}}$ (hard probe yields)**
- **Centrality is expressed in terms of percentage of the total nuclear inelastic cross section**

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The Nuclear Modification factor $R_{AA}$

$$R_{AA}^i = \frac{Y_{J/\psi}^i(\Delta p_T, \Delta y)}{\langle T_{AA}^i \rangle \times \sigma_{J/\psi}^{pp}(\Delta p_T, \Delta y)}$$

- $J/\psi$ invariant yield in PbPb collisions
- $J/\psi$ cross section in pp collisions

If $R_{AA} \neq 1$

- Medium effects (Hot or Cold)

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**Coherent $J/\psi$ photoproduction in Pb-Pb collisions with nuclear overlap in ALICE – Laure Massacrier**
J/ψ production results in hadronic Pb-Pb collisions (run1 & 2)

- Inclusive J/ψ measurements in the dimuon decay channel in hadronic Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV and 5.02 TeV
- Run-1 data: first evidence of charmonium regeneration at the LHC (\( \sqrt{s_{NN}} = 2.76 \) TeV)
- Run-2 data (2015): Confirmation of charmonium regeneration at \( \sqrt{s_{NN}} = 5.02 \) TeV
  - Slight increase of the regeneration with energy in line with model expectations
  - \( R_{AA} \) differential measurements versus centrality, \( p_T, y \)
- Run-2 data (2015+2018): More precise differential (+ double differential) \( R_{AA} \) measurements
  - Extension of the \( p_T \) reach to ~ 20 GeV/c (study interplay between color screening and eloss)

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L. Valencia thesis

M. Tarhini thesis

C-L Huang thesis

Coherent J/ψ photoproduction in Pb-Pb collisions with nuclear overlap in ALICE – Laure Massacrier

Présentation au pôle PHE, JCLab
**J/Ψ photoproduction and Ultra-Peripheral collisions (UPC)**

- The EM field of Pb nuclei can be described as beam of quasi-real photons (number of photons proportional to $Z^2$).

- **UPC**: interactions with $b$ larger than the sum radii of the incoming nuclei
  - Involves at least one photon
  - Hadronic interaction strongly suppressed, Electromagnetic interactions dominant

- Photoproduction of vector meson (VM) in UPC has a clean experimental signature:
  - Very low $p_T$ production
  - Large rapidity gaps

- Exclusive quarkonium production in UPC probes gluon GPDs
  - approx : at LO probes gluon nPDFs squared

- Coherent photoproduction of VM
  - $γ$ couples coherently to all nucleons
  - $<p_T>_{J/Ψ} \sim 50$ MeV
  - No breaking of target nucleus

- Incoherent photoproduction of VM
  - $γ$ couples to part of nucleus
  - $<p_T>_{J/Ψ} \sim 500$ MeV
  - Usually target nucleus breaks
First observation of \( J/\Psi \) photoproduction in peripheral AA collisions?

- Exclusive event
- Only vector meson decay detected

Coherent J/\( \Psi \) photoproduction in Pb-Pb collisions with nuclear overlap in ALICE – Laure Massacrier

Clear excess at low \( p_T \) in the J/\( \Psi \) yield with respect to hadronic production expectations, in peripheral Pb-Pb collisions
First observation of J/Ψ photoproduction in peripheral AA collisions?

- Exclusive event
- Only vector meson decay detected

J/Ψ very low p_T excess observed for the first time in peripheral Pb-Pb collisions (Run-1 data)
Interpreted as coherent J/Ψ photoproduction for b < 2 x R_Pb !
What can we learn from coherent J/Ψ photoproduction in AA collisions with nuclear overlap?

- Affects the J/Ψ $R_{AA}$ measurement at very low $p_T$ and therefore the study of hot nuclear matter effects in Pb-Pb collisions.

- Opens new theoretical challenges:
  - How can the coherence condition survive when the nuclei is broken during the hadronic interaction? Do only spectator nucleons participate to the coherence?

- A potential new probe of charmonium color screening in the QGP?
  - Could be formed at the early stages of the collisions
  - Could be dissociated by color screening
  - Recombination of $c\bar{c}$ pairs would not contribute significantly to the extremely low $p_T$ J/Ψ yield

- A novel way to access $\sigma_{\gamma p}\gamma$ when combined to UPC measurement

Coherent J/Ψ photoproduction in Pb-Pb collisions with nuclear overlap in ALICE – Laure Massacrier
Coherent $J/\Psi$ photoproduction at forward rapidity in peripheral Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

- **Effect of the observed very low $p_T$ $J/\Psi$ excess on the hadronic $R_{AA}$**
  - For $p_T < 0.3$ GeV/c, $J/\Psi$ $R_{AA}$ as large as 7
  - None of the recombination models predict such a pattern at LHC energies
  - Model with photoproduction + hadroproduction with QGP effects can reproduce the $R_{AA}$ (W. Shi, PLB 777 (2018) 399-405)

- **Measured coherent cross section**

- **Significance of the excess yield** :
  - In centrality 70-90% : 5.4$\sigma$
  - In centrality 50-70% : 3.4$\sigma$
  - In centrality 30-50% : 1.4$\sigma$
Coherent $J/\Psi$ photoproduction at forward rapidity in peripheral Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV and model comparisons

- Vector dominance model
  - Standard photon flux (UPC)
  - Effective photon flux (considering nuclear overlap) / upper limit
  - Effective photon flux (considering spectator nucleons only) / lower limit
  - ALICE data
  - ALICE exp uncertainties
- Best agreement with « lower limit » photon flux

- Energy dependent hot-spot model calculations
- Extrapolation of $\gamma p$ to $\gamma Pb$ interactions with:
  - Gribov-Glauber calculation (GG)
  - Geometric Scaling (GS)
- Model describes both UPC and peripheral data (better agreement with GS calculation)
Coherent $J/\Psi$ photoproduction at forward rapidity in peripheral Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV and model comparisons

- Strong interactions in the overlapping region of incoming nuclei may disturb the coherent production, leaving room for different coupling assumptions:
  - nucleus – nucleus (no hadronic interaction)
  - nucleus – spectator
  - spectator – nucleus
  - spectator – spectator

- ALICE Run-I data consistent with all 4 scenarios within uncertainties

- Need more precise data and measurement towards most central collisions (challenging!) to be able to disentangle the different scenarios

W. Zha, PRC 97 044910
Coherent J/Ψ photoproduction at mid rapidity in peripheral Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- Very low $p_T$ J/Ψ yield excess also observed at mid-rapidity in the dielectron channel, in peripheral collisions.
- Good resolution at mid-rapidity allows for the excess $p_T$ distribution measurement.

Relative contributions of the various processes are fixed to the UPC measurement values (overall scale is free)

→ Strengthens the hypothesis that the excess origin is coherent photoproduction.
- Differences can be seen at high $p_T$ since contribution from hadronic J/Ψ is not subtracted.
The (A Very) hint decrease Coherent decrease low in 30 –T 50%\) of the \(J/\Psi\) of the background <dimuon excess with respect to the \(\Psi\) photoproduction <p_T > at the \(J/\Psi\) Pb at forward mass centrality range 0-10% is clearly seen at very low \(p_T\) in the centrality ranges 50-70%, 70-90% (hint in 30-50%) with respect to the centrality range 0-10%. The decrease of the background \(<p_T>\) in the centrality range 70-90% could be an indication of the presence of \(\gamma\gamma \rightarrow \mu^+\mu^-\).
Coherent \( J/\Psi \) photoproduction at forward rapidity in peripheral Pb-Pb at \( \sqrt{s_{NN}} = 5.02 \) TeV

- Large \( J/\Psi \) signal almost background free in the centrality range 70-90% and for \( p_T (\mu^+\mu^-) < 0.3 \) GeV/c
- Increase of statistics ~ factor 10 with respect to Run-I analysis
- Hadronic \( J/\Psi \) background subtracted thanks to a modelization which uses as input the \( J/\Psi \) \( p_T \) distribution measurement in pp collisions at 5.02 TeV, the \( J/\Psi \) \( R_{AA} \) measurement in Pb-Pb at 5.02 TeV, and the Axν of hadronic \( J/\Psi \) from MC
- Significance of the raw excess: 14σ (centrality 70-90%), 10σ (centrality 50-70%)

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Raw ( N_{j/\Psi} ) excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-70%</td>
<td>628 ± 39 (stat) ± 46 (syst)</td>
</tr>
<tr>
<td>70-90%</td>
<td>477 ± 26 (stat) ± 21 (syst)</td>
</tr>
</tbody>
</table>
Coherent $J/\psi$ photoproduction at forward rapidity in peripheral Pb-Pb: comparison 2.76 TeV versus 5 TeV

- Coherent $J/\psi$ yield increases by ~ factor 2.5 in centrality range 70-90% between the two energies.
- No strong centrality dependence is observed within uncertainties between 50-70% and 70-90% centrality ranges.
- Coherent $J/\psi$ cross section at 5.02 TeV is extracted from the yield ratio and cross section measurement at 2.76 TeV.
- Cross section increases by ~ a factor 2.5 in the centrality range 70-90% with respect to 2.76 TeV.
Coherent $J/\psi$ photoproduction at forward rapidity in peripheral Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV and comparison with models

- Energy dependent hot-spot model calculations:
  - Gribov-Glauber calculation (GG)
  - Geometric Scaling (GS)

- GBW dipole model (2018)
  - modification of photon flux + photonuclear cross section

- IIM model (Color Glass Condensate Model)

As at $\sqrt{s_{NN}} = 2.76$ TeV, the peripheral coherent $J/\psi$ cross section at $\sqrt{s_{NN}} = 5.02$ TeV agrees qualitatively with the same models.
Coherent $J/\psi$ photoproduction at forward rapidity in peripheral Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV and comparison with models

- **GBW dipole model (2018)**
  - modification of photon flux + photonuclear cross section

- **IIM model (Color Glass Condensate Model)**

As at $\sqrt{s_{NN}} = 2.76$ TeV, the peripheral coherent $J/\psi$ cross section at $\sqrt{s_{NN}} = 5.02$ TeV agrees qualitatively with the same models
Conclusions and outlook

- Quarkonium are useful tools to study the QGP properties in heavy-ion collisions, and a probe of the gluon GPDs in UPC

- We have indications that quarkonium coherent photoproduction in peripheral to semi-central Pb-Pb collisions has been observed for the first time in ALICE. It opens new theoretical challenges and could potentially become a new way to probe the QGP.

- This excess in the yield of $J/\psi$ at very low $p_T$, observed in peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, was confirmed both at mid and forward at $\sqrt{s_{NN}} = 5.02$ TeV.

- $J/\psi$ coherent photoproduction mechanism seems supported by the measured shape of the excess $p_T$ distribution at mid-rapidity.

- Results from new forward analysis will be extended towards most central events thanks to combination of 2015+2018 data.

- Models used to describe UPC data and modified to account for nuclear overlap region qualitatively reproduce the data.
Gluodynamics P2IO Flagship project

- QCD studies in the funding period 2020-2024 both on experimental and theoretical side
- Explore the key role of gluons in the determination of the properties of hadrons and strongly interacting matter
- Lead French construction contributions to hadron collider projects after 2030: EIC, LHC
- 1010 kEuros received from the labex, 8 laboratories involved
- 4 WG
  - Exp and theo study of nucleon and nuclear geometry at Jlab and LHC
  - Unification of theo framework for the study of hadrons (GPDs, TMD, CGC)
  - Exp investigation of the gluonic force at the LHC (quarkonium, jets)
  - Simu for future QCD exp collider programmes

- 2y postdoc for the ALICE group to work on quarkonium photoproduction in PbPb collision with nuclear overlap
  - Polarization of the \(J/\psi\) excess at forward rapidity
  - Forward and mid-rapidity \(J/\psi\) cross section in most central collisions \(\rightarrow\) QGP-like effects?
  - \(p_T\) distribution of the \(J/\psi\) excess at mid-rapidity (t-slope)
  - Extension of studies to other vector mesons
  - Semi-forward \(J/\psi\) excess analysis
  - Combine UPC and peripheral measurements to extract \(\sigma_{\gamma Pb}(y)\) and \(\sigma_{\gamma Pb}(-y)\)
Charmonium coherent photoproduction and hadroproduction treated consistently with modifications from both cold and hot nuclear matter effects.
## Coherent J/Ψ photoproduction at forward rapidity in peripheral Pb-Pb: systematic uncertainties

### Systematic uncertainties on the yield ratio

<table>
<thead>
<tr>
<th>Source</th>
<th>2.76 TeV</th>
<th>5.02 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extraction</td>
<td>5.9-10%</td>
<td>4.4-7.3%</td>
</tr>
<tr>
<td>Centrality dependence of efficiency loss</td>
<td>0.0-0.5%</td>
<td>0.0-0.5%</td>
</tr>
<tr>
<td>MC input</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>3.6%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Matching efficiency</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Normalisation</td>
<td>3.6%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Uncertainty on the energy dependence of the fraction of incoherent J/Ψ (f_I) and J/Ψ from coherent ψ(2S) decay (f_D)</td>
<td>20%</td>
<td></td>
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### Systematic uncertainties on the cross section

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<tr>
<td>BR</td>
<td>1%</td>
</tr>
<tr>
<td>σ_PbPb</td>
<td>5%</td>
</tr>
</tbody>
</table>

### Dominant uncertainty from unknown energy dependence of f_I+ f_D → will improve thanks to new UPC measurement
Coherent J/Ψ photoproduction at mid rapidity in peripheral Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- Cross section comparison with models

- Energy dependent hot-spot model
  - Gribov-Glauber calculation (GG)
  - Geometric Scaling (GS)

- Color Glass Condensate model

- GBW dipole model
  - modification of photon flux (2017)
  - modification of photon flux + photonuclear cross section (2018)

- Qualitative agreement is found with all models (apart the first version of GBW (2017) in which the modification of the photonuclear cross section was not accounted for)