



# Investigação da fotoprodução de $J/\psi$ em diferentes geometrias de colisão no experimento ALICE

Investigation in the  $J/\psi$  Photoproduction in Different Collision Geometries in ALICE Experiment

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- Physics Motivation
- Ultraperipheral Collisions
- Peripheral Collisions
- Simulations using the FoCal Calorimeter
- Conclusion and Look Ahead

# Physics Motivation

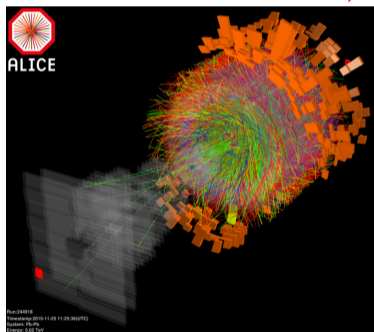
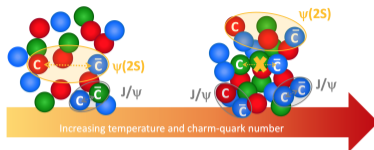
The background of the slide features a complex, abstract pattern. On the right side, there is a dense, fan-like structure composed of numerous thin, overlapping lines in various colors including green, yellow, red, and purple. This structure is partially overlaid by several larger, semi-transparent orange rectangular blocks. The overall effect is a textured, multi-layered composition that suggests a scientific or mathematical theme.

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Part I

# The Quark-Gluon Plasma

- **The QGP:**
  - It is an **extremely** hot and dense state of matter.
  - Quarks and gluons **are not confined** into hadrons → they are free!
  - It was present in the first millionths of a second after the Big Bang.
- **The Large Hadron Collider (LHC):**
  - The QGP state can be recreated in heavy-ion collisions at the LHC.
  - The ALICE experiment collides lead nuclei that form **charmonia states**.
  - These bound states are affected by the quark-gluon plasma.
- **Motivation:**
  - The study of quarkonia production provides insight into the QGP.
  - $J/\Psi$  suppression is one of the key signatures of deconfinement.



Lead-lead collisions by ALICE (Images: ALICE Collaboration)

# Parton Model

The *Parton Model*, proposed in 1969 by Richard Feynman.

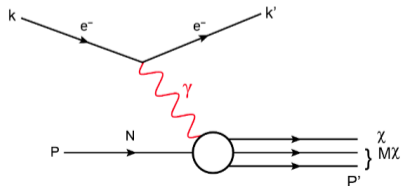
R. P. Feynman, "The behavior of hadron collisions at extreme energies," vol. 690905, pp. 237–258, 1969

- At high energy, the hadrons behave like a group of punctual particles called partons;
- These partons carry a small fraction  $x$  of their total momentum ( $P$ ), which is  $\sum_i x_i P = P$ .

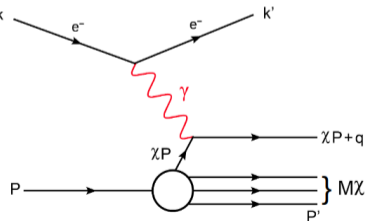
$$Q^2 \equiv -q^2 = -(k - k')^2$$

$$x \equiv \frac{Q^2}{2M\nu} \qquad \nu = \frac{P \cdot q}{M}$$

(a)

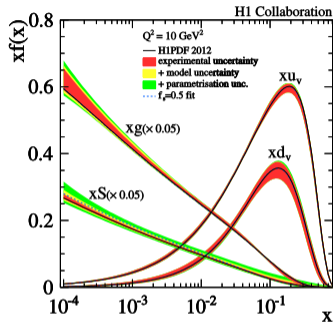
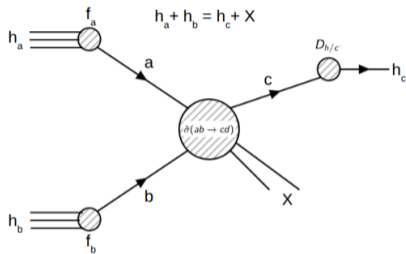


(b)



a) Feynman diagram of deep inelastic scattering (DIS). b) Feynman diagram of DIS in the parton model.

# Hadronic Process - Factorization



<https://arxiv.org/abs/1506.06042>

$$\sigma_{hh \rightarrow hx} \propto f_{a/h}(x_1, Q^2) \otimes f_{b/h}(x_2, Q^2) \otimes \hat{\sigma}(ab \rightarrow cd) \otimes D_{h/c}(z_c, \hat{Q}^2)$$

$f_p(x, Q^2) \rightarrow$  Parton Distribution Functions (PDFs)

$\hat{\sigma}(ab \rightarrow cd) \rightarrow$  partonic subprocesses:  $qq \rightarrow qq$ ,  $q\bar{q} \rightarrow gg$ ,  $gg \rightarrow gg$ , ...

$D_{h/c}(z_c, \hat{Q}^2) \rightarrow$  hadronization function of hadron  $h$  from parton  $c$ .

# PDFs Evolution Equations

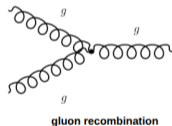
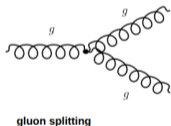
- Evolution equations:

- Linear equations

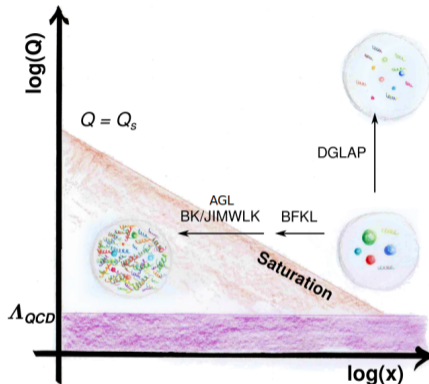
  - DGLAP
  - BFKL

- Non-linear equations

  - AGL
  - JIMWLK
  - BK



At **small-x** the gluon **recombination process** is important.

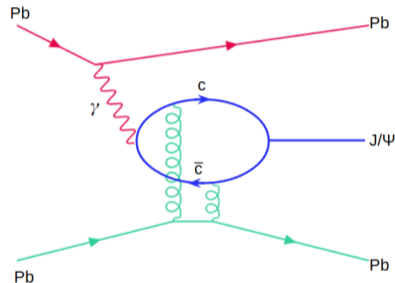


Adapted from <https://cds.cern.ch/record/2719928>

**No model proposes an analytical gluon distribution function valid for the entire spectrum of  $x$  and  $Q^2$ .**

## Exclusive Vector Meson Production at Small- $x$

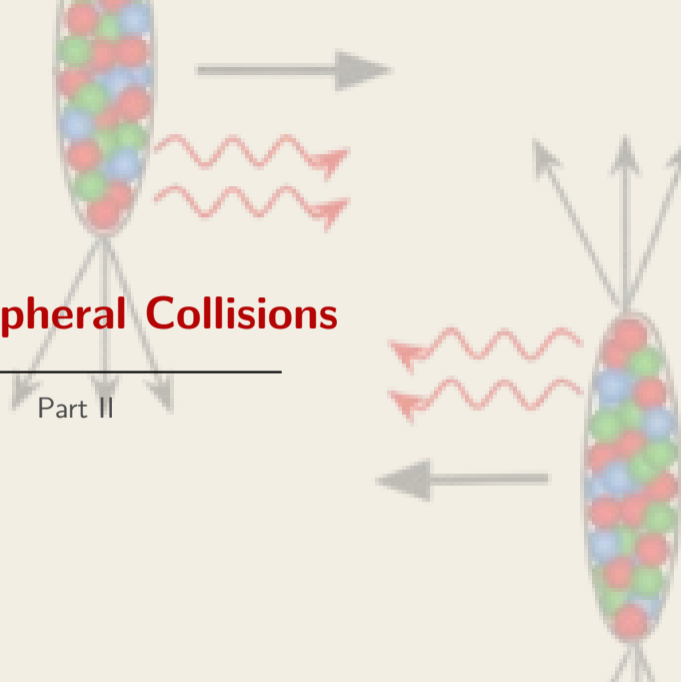
- Exclusive **vector meson** production **provides access to the PDFs** and allows for **checking the gluon density**.
- At **small- $x$** , **gluons** play an **important role** in describing **structure functions**.
- Currently, there is a **lack of information** for  $x < 10^{-6}$ .
- Understanding how  $J/\psi$  mesons are **produced** and **suppressed** provides insight into **color screening** and **deconfinement** in the **Quark-Gluon Plasma (QGP)**.
- Studying **different centrality classes** helps explore the **transition** from **hadronic** to **electromagnetic** dominated production **regimes**.
- In high-energy heavy-ion collisions, the production of  $J/\psi$  can occur through:
  - Hadronic interactions in the QGP phase.
  - Photoproduction processes induced by intense electromagnetic fields.



Feynman diagram for  $J/\psi$  photoproduction process.

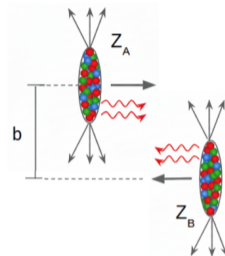
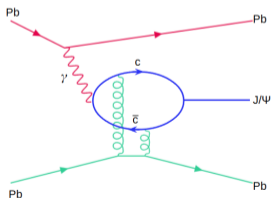
## Ultraperipheral Collisions

Part II



## Production of $J/\psi$ meson: Ultraperipheral Collision (UPC)

- An UPC occurs when the **impact parameter**  $b$  is **larger** than the **sum of its radii** ( $R_A$  and  $R_B$ ).
- UPC process can be described as a **purely electromagnetic** process because there is **no direct hadronic collision** involved



$$\frac{d\sigma_{J/\psi}}{dy} \propto N_\gamma(y)\sigma_{J/\psi}^{\gamma H}(y) + (y \rightarrow -y)$$

where

- Photon flux  $N_\gamma(y)$
- Nuclear photoproduction  $\sigma_{J/\psi}^{\gamma H}(y)$

M. B. Gay Ducati; F. Kopp; M. V. T Machado; S. Martins. Physical Review D, nov. 2016. DOI: 10.1103/PhysRevD.94.094023.

# The Photoproduction Cross section

$$\frac{d\sigma_{J/\psi}}{dy} \propto N_\gamma(y)\sigma_{J/\psi}^{\gamma H}(y) + (y \rightarrow -y)$$

- **The photon flux**

(Weinszäcker-Williams Method)

$$\frac{dN(\omega)}{d\omega} = \frac{2q^2}{\omega\pi} \left[ \chi_{\min} K_0(\chi_{\min}) K_1(\chi_{\min}) - \frac{1}{2} \chi_{\min}^2 (K_1^2(\chi_{\min}) - K_0^2(\chi_{\min})) \right]$$

with the  $K_1$  and  $K_0$  as the Bessel functions,  $\omega$  the photon energy and  $\chi_{\min} = \omega R_A / \gamma$

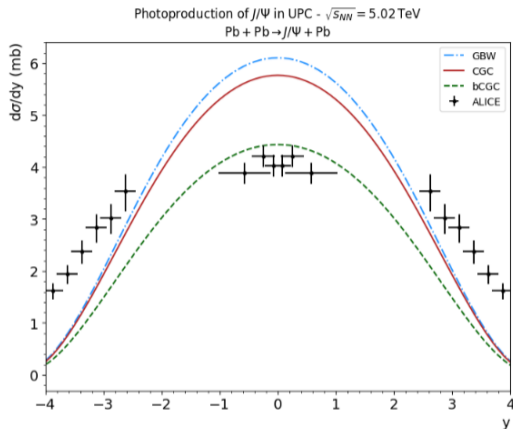
- **The photonuclear cross section**

(Dipole Formalism)

$$ImA(x, t = 0) = \int \int \frac{d^2 r dz}{4\pi} (\Psi_V^* \Psi_\gamma)_T \sigma_{dip}^{nuc}(x, r)$$

$$\sigma_{dip}^{nuc}(x, r) = 2 \int d^2 b' \left[ 1 - \exp\left(-\frac{1}{2} T_A(b') \sigma_{dip}^{proton}(x, r)\right) \right]$$

- $(\Psi_V^* \Psi_\gamma)_T$  is the overlap photon-meson wave function
- $T_A(b')$  the nuclear profile function;
- $\sigma_{dip}^{proton}(x, r)$  the dipole cross section
  - ▶ GBW - Golec-Biernat and Wüsthoff
  - ▶ CGC - Color Glass Condensate
  - ▶ bCGC - b-dependence CGC



Results for the photoproduction of the  $J/\psi$  and  $\Psi(2s)$  compared with ALICE data  
*Acharya et al.*, Phys. Lett. B798 (2019) 134926; *Acharya et al.*, Eur. Phys. J. C 81 (2021) 712.

All models **underestimate** the data, nevertheless, they are able to **reproduce** the **overall trend**.

# Peripheral Collisions

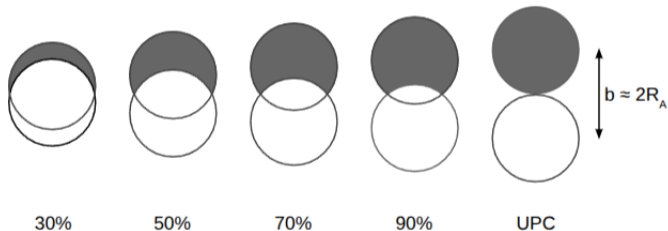
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Part III



## Centralities

$$c = \frac{b^2}{4R_A^2}$$



- $b$  the impact parameter and  $R_A$  the nuclear radius.

## Peripheral Collisions

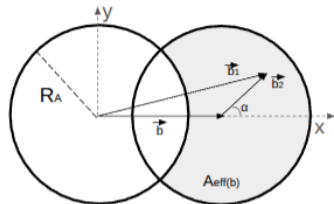
- In peripheral collisions the **impact parameter**  $b$  is not **larger** than the **sum of its radii** ( $R_A$  and  $R_B$ ).

- Centrality classes:
  - 30% - 50% → close to a central collision
  - 70% - 90% → almost an ultra-peripheral collision

$$\frac{d\sigma_{J/\psi}}{dy} \propto N_\gamma(y)\sigma_{J/\psi}^{\gamma H}(y) + (y \rightarrow -y)$$

- The cross section investigated in **three scenarios**
- Hypothesis:** Only spectators interact coherently with the photon.

M. B. Gay Ducati and S. Martins, Phys. Rev. D97, 116013, (2018).



### Scenarios:

- Scenário 1 (S1):**  $b$ -dependence in the photon flux;
- Scenário 2 (S2):** Effective photon flux;

$$N^{eff}(\omega, b) \propto \int N^{usual}(\omega, b_1)\theta(b_1 - R_A)\theta(R_A - b_2)d^2b_2$$

- Scenário 3 (S3):** Effective photon flux + effective photonuclear cross section.

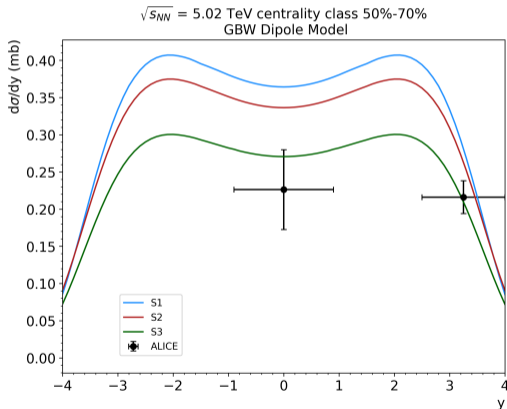
$$\sigma_{dip}^{nuc}(x, r) \propto \int d^2b_2\theta(b_1 - R_A) \left[ 1 - \exp\left(-\frac{1}{2}T_A(b_2)\sigma_{dip}^{proton}\right) \right]$$

# $d\sigma/dy$ in different scenarios

**S1:** b-dependence

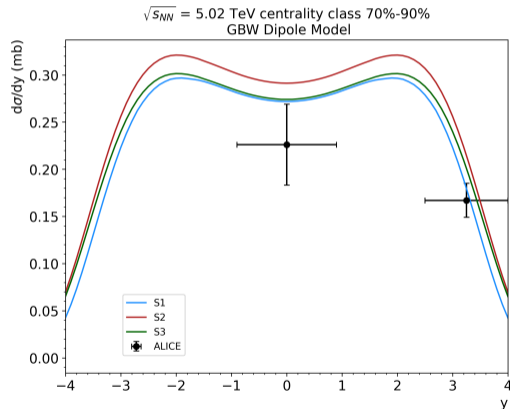
**S2:** Effective photon flux

**S3:** Effective photon flux + Effective photonuclear cross section



ALICE Collaboration, Phys. Lett. B 871, 139952, (2025).

ALICE Collaboration, Phys. Lett. B 846, 137467, (2023).

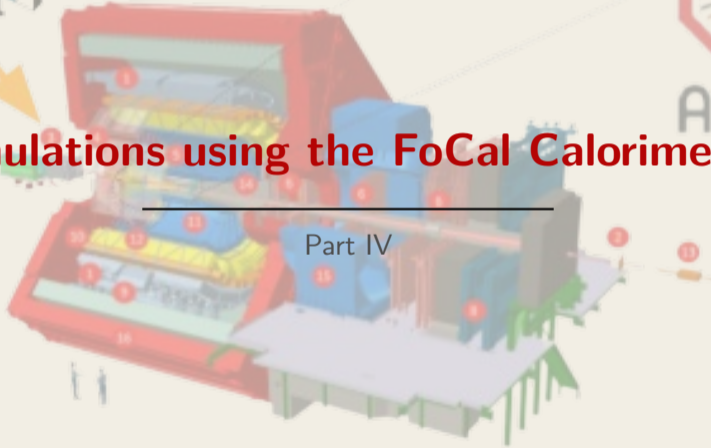




ALICE

# Simulations using the FoCal Calorimeter

Part IV



# The ALICE experiment (Run 4)

- **Physics motivation:**

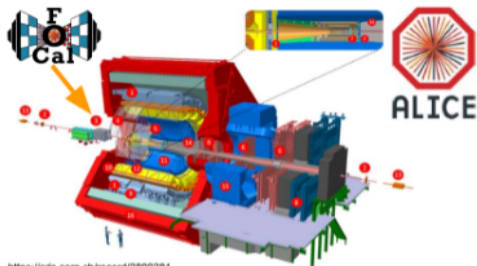
- $J/\Psi$  photoproduction in ultra-peripheral Pb-Pb collisions reveals important insights into nuclear effects, gluon saturation, and non-perturbative QCD at very low Bjorken- $x$  values.

- **ALICE experiment:**

- ALICE (A Large Ion Collider Experiment) is designed to study the properties of the QGP.

- **New detector:**

- FoCal, the new ALICE detector, will be used to extend heavy quarkonia studies to ultra-peripheral Pb-Pb collisions and lower  $x$ -values  $x < 10^{-6}$ .



<https://ods.cern.ch/record/2890281>

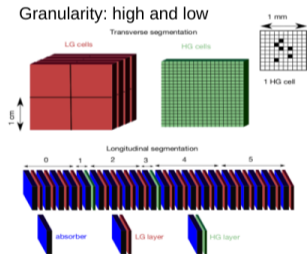
- |   |  |
|---|--|
| 1 EMCAL   Electromagnetic Calorimeter                             | 9 PHOS/CPV   Photon Spectrometer       |
| 2 FIT   Fast Interaction Trigger                                  | 10 TOF   Time Of Flight                |
| 3 FoCal   Forward Calorimeter<br>(in front of compensator magnet) | 11 TPC   Time Projection Chamber       |
| 4 HMPID   High Momentum Particle<br>Identification Detector       | 12 TRD   Transition Radiation Detector |
| 5 ITS   Inner Tracking System                                     | 13 ZDC   Zero Degree Calorimeter       |
| 6 MCH   Muon Tracking Chambers                                    | 14 Absorber                            |
| 7 MFT   Muon Forward Tracker                                      | 15 Dipole Magnet                       |
| 8 MID   Muon Identifier   | 16 L3 Magnet                           |

# The FoCal calorimeter

The FoCal implementation will be installed in the **ALICE Experiment** during the **LS3 (2027–2029)**.  
CERN. *Technical Design Report of the ALICE Forward Calorimeter (FoCal)*. CERN, Geneva, 2024. CERN-LHCC-2024-004, ALICE-TDR-022.

- **FoCal-E:**

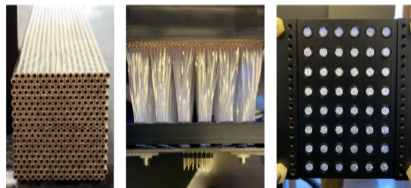
- Sampling calorimeter with tungsten absorber
- Pad and pixel layers



FoCal-E scheme.

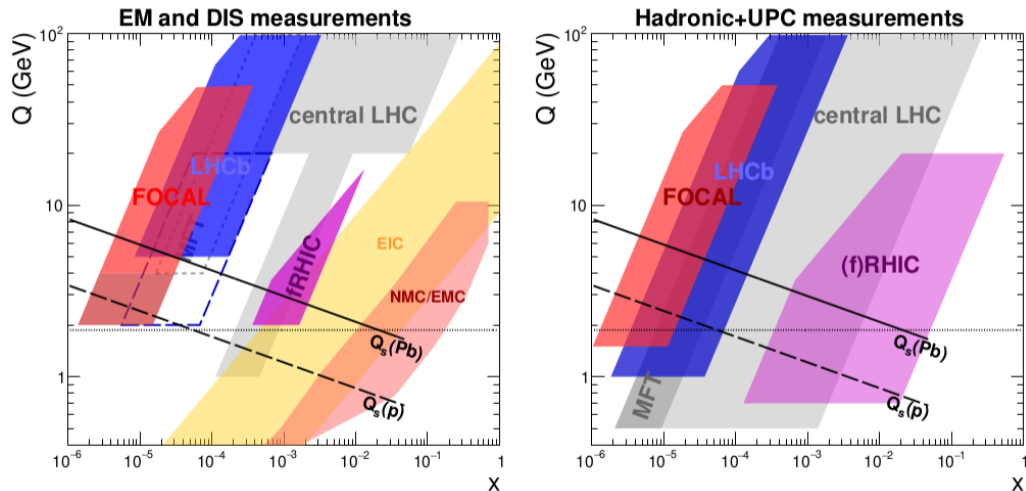
- **FoCal-H:**

- Sampling calorimeter
- Spaghetti type



FoCal-H prototype.

## The FoCal calorimeter: Performance



The FoCal  $xQ$  coverage compared with others detectors.

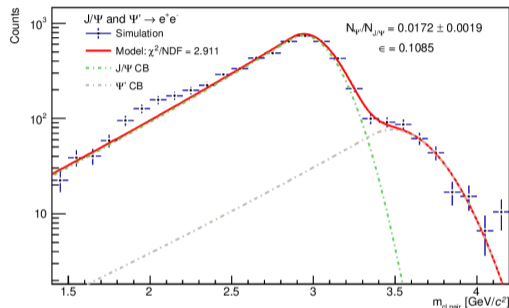
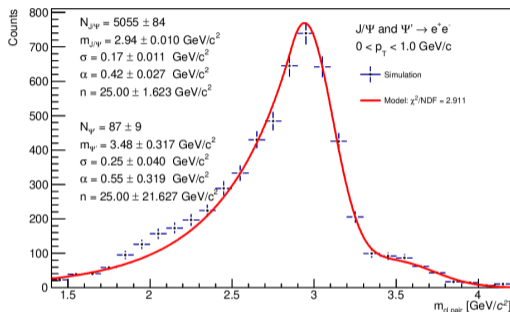
## Simulations of $J/\psi$ and $\psi'$ production

- Simulation of the coherent  $J/\psi$  production in proton-lead, lead-proton and lead-lead collisions;
- $J/\psi$  reconstruction in the electronic channel ( $J/\psi \rightarrow e^+ e^-$ );
- It was also simulated the production of  $\psi'$ ;
- The electromagnetic shower will be absorbed by FoCal, and the data collected will be used for its reconstruction.
- With the kinematics of the simulation the invariant mass is reconstructed;
  - **Simulation:** Employing STARlight to generate  $J/\psi$  and  $\psi'$  events.
  - **Clusterization of Data:** The data are grouped into superclusters and matched with the physical primary particles.
  - **Kinematics:** the data distribution is plotted into histograms.
  - **Invariant Mass:** Reconstruction of the invariant mass using the superclusters data by

$$m = \sqrt{(\vec{p}_{e^-} + \vec{p}_{e^+})^2 - (p_{e^-} + p_{e^+})_x^2 - (p_{e^-} + p_{e^+})_y^2 - (p_{e^-} + p_{e^+})_z^2}.$$

- **Fit function:** Crystal-ball function used to fit the invariant mass data.

## Simulations: Invariant mass for lead-proton collisions

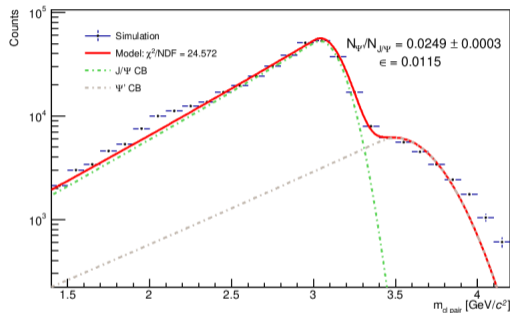
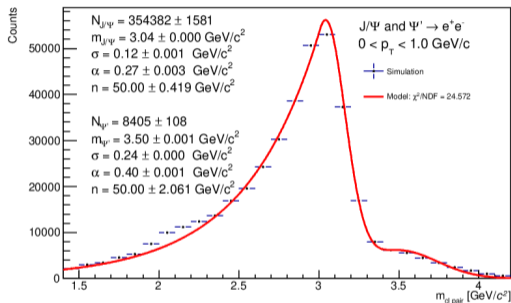


- In lead-proton collisions, as the Pb nucleus moves toward FoCAL, the **calorimeter** can still **distinguish** between both **particles**.

CERN. *Technical Design Report of the ALICE Forward Calorimeter (FoCal)*. CERN, Geneva, 2024. CERN-LHCC-2024-004, ALICE-TDR-022.

LUZ, Paulo Henrique Fetter da. *Use of FoCal to constrain gluons distribution on ALICE*. Master dissertation, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, 2023.

## Simulations: Invariant mass for lead-lead collisions



- For Pb-Pb collisions, the **two peaks** are even more **distinct** than in proton-lead collisions.

**CERN.** *Technical Design Report of the ALICE Forward Calorimeter (FoCal).* CERN, Geneva, 2024. CERN-LHCC-2024-004, ALICE-TDR-022.

**LUZ,** Paulo Henrique Fetter da. *Use of FoCal to constrain gluons distribution on ALICE.* Master dissertation, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, 2023.

# Conclusion and Look Ahead

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Part VI

## Conclusion and Look Ahead

- **UPC and peripheral results** show that the dipole formalism **reproduces** the overall shape and trend of the cross sections.
- **Geometric constraints** introduced in Scenarios 2 and 3 **reduce** the **results**.
- **Simulations using the FoCal calorimeter:** Invariant mass reconstruction successfully distinguish  $J/\psi$  and  $\psi'$  resonances.
- **Future prospects:** Perform ALICE data analysis covering different centrality classes (Run 3).

**Thank you for listening!**

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