Vector meson photoproduction in UPCs with ALICE **Fo**rward **Cal**orimeter

Sasha Bylinkin

The University of Bergen

March 27-31, 2023, DIS 2023, MSU, East Lansing, Michigan, USA

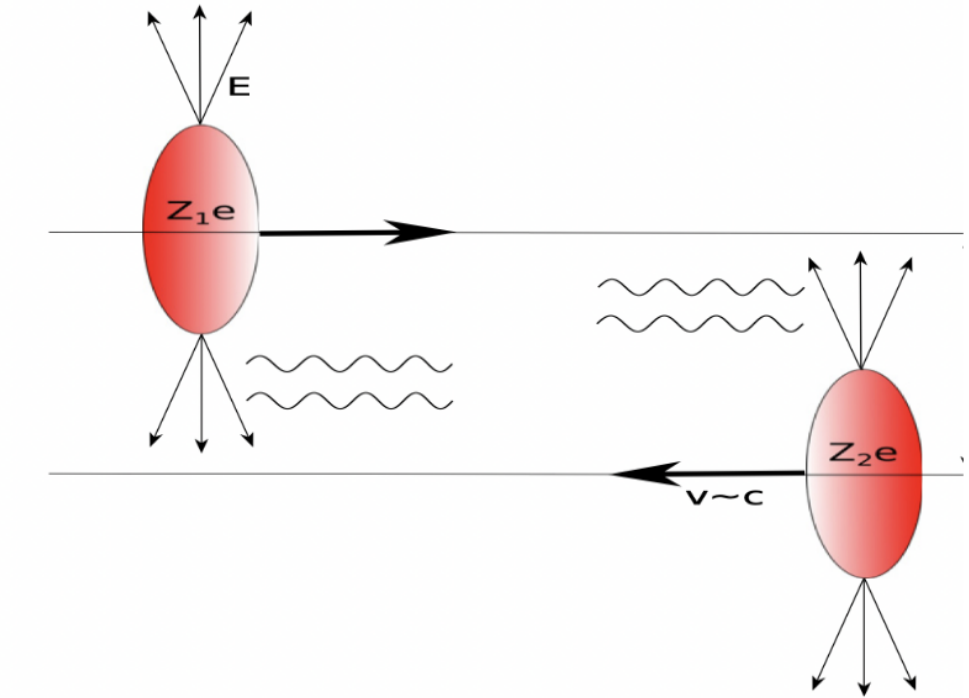
Outline

- Introduction
  - Ultra-Peripheral Collisions
  - ALICE FoCal Detector
  - Run 4 program and luminosity
- Prospects of UPC measurements with FoCal
  - A. Bylinkin, J. Nystrand and D. Tapia Takaki ***(2023)*** **J. Phys. G**

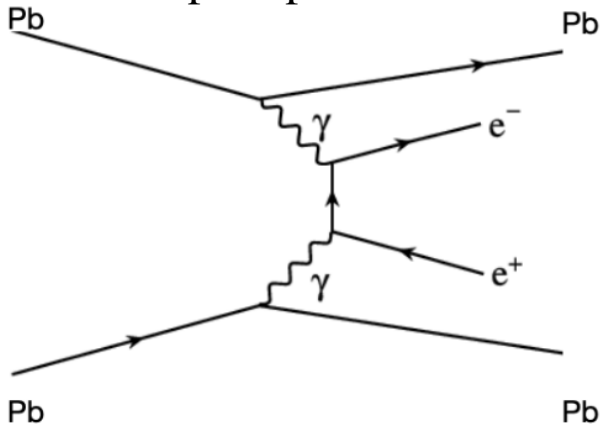
    https://doi.org/10.1088/1361-6471/acc419
- Summary

Photon induced processes in heavy ion collisions

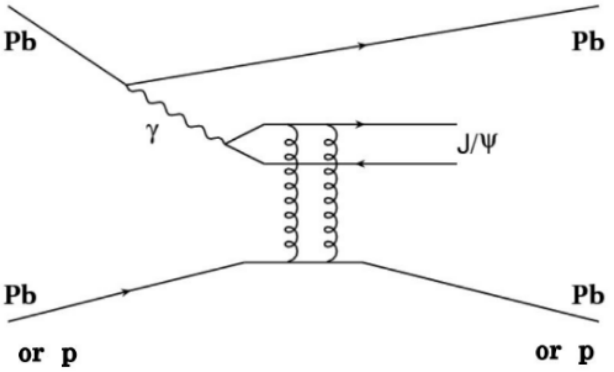
- Nuclei “miss” each other (b > 2R)
- Electromagnetic interaction dominates over strong
- Photon flux grows with the square of the charge, Z^2



Dilepton production

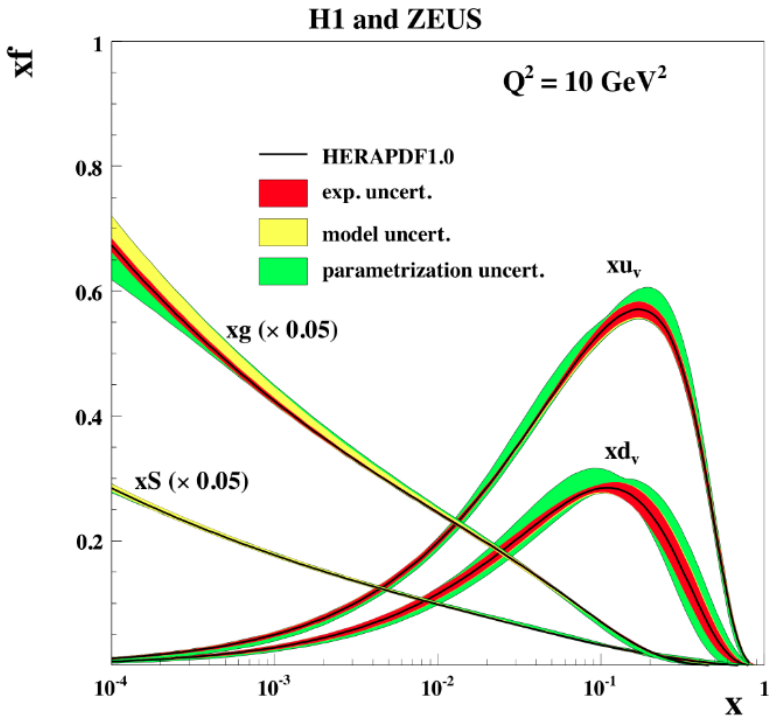


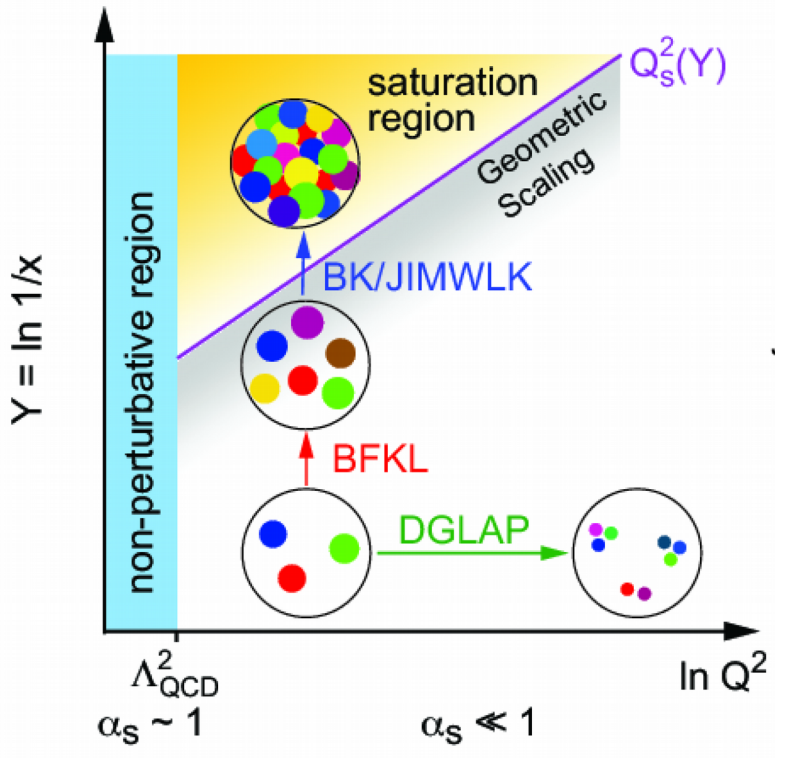
Vector meson production



Probes of nuclei in UPC

- UPCs at LHC: the most energetic photon-nuclei interactions
- Low-x physics and search for the nonlinear parton dynamics (saturation regime)





Exclusive vector meson photoproduction

- Photoproduction is sensitive to the gluon density at LO (NLO calculations are already available)

$$\left.\frac{d\sigma_{\gamma p, A\to V p, A}}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xG(x,Q^2)]^2$$

K.J. Eskola et. al

Phys. Rev. C 106 (2022) 035202

$$\sigma_{\gamma p\to VMp} = \frac{1}{b}\frac{d\sigma_{\gamma p, A\to VM\, p, A}}{dt}|_{t=0}$$

- Energy of the γp collision

$$W_{\gamma p}^2 = 2 \cdot E_p \cdot M_{VM} \cdot \exp(-y)$$

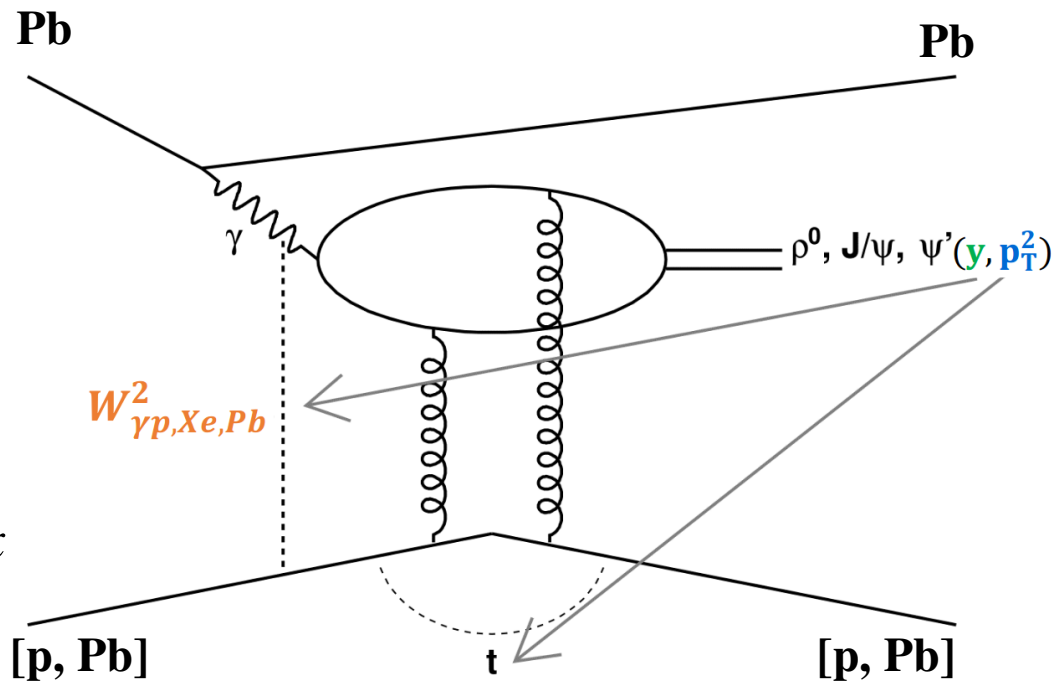
E_p – proton beam energy

M_{VM} – mass of the vector meson

y – rapidity of the vector meson

- Probe gluon distributions in the proton at low-x

$x = (M_{VM}/W_{\gamma p})^2$

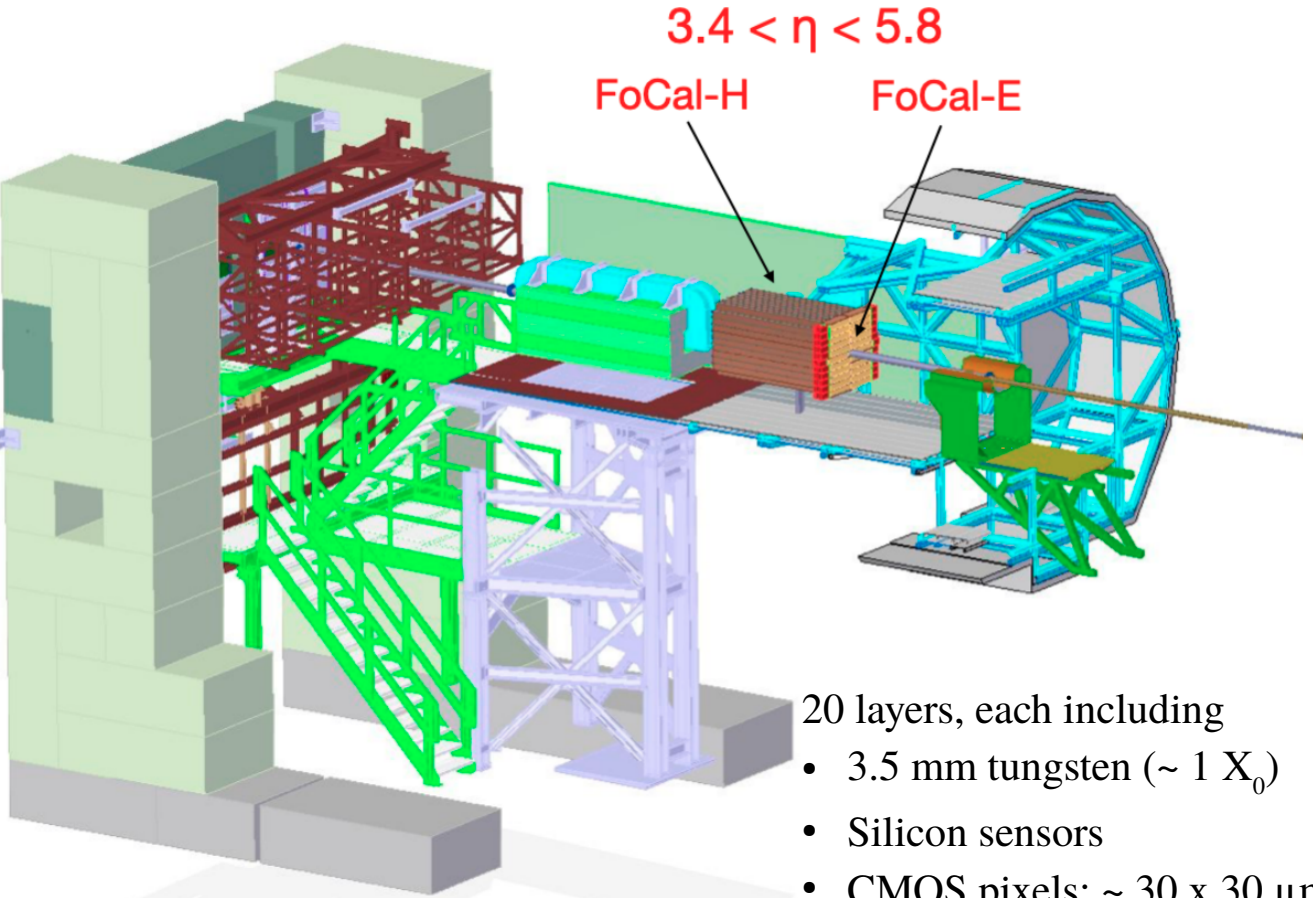


Measurements in the forward region are needed to probe lowest possible x values

FoCal in ALICE Run 4

FoCal is a new high granularity calorimeter to be installed in the very forward region.

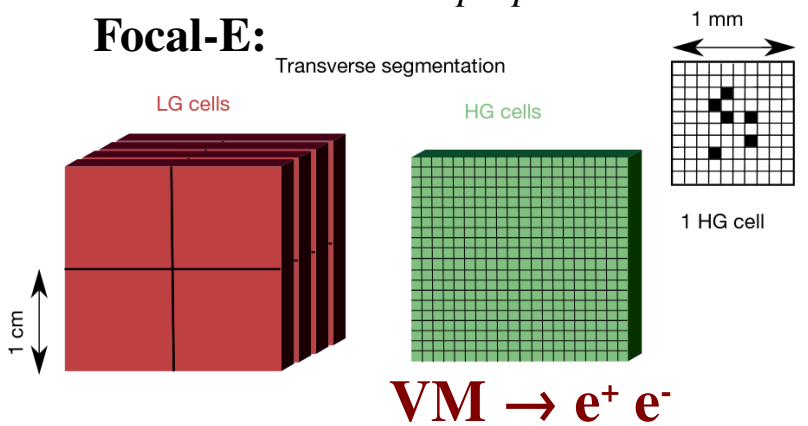
HP 2023: Talk by Tatsuya Chujo *https://wwuindico.uni-muenster.de/event/1409/contributions/2152/*



ALICE, LHCC-I-036 (2020)

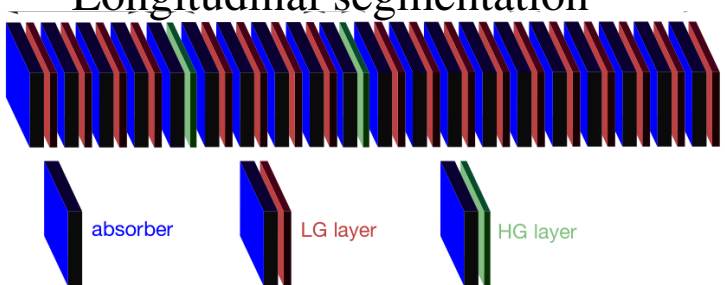
TDR in preparation

Focal-E:



VM → $e^+ e^-$

Longitudinal segmentation



20 layers, each including

- 3.5 mm tungsten (~ 1 X_0)
- Silicon sensors
- CMOS pixels: ~ 30 x 30 μm²

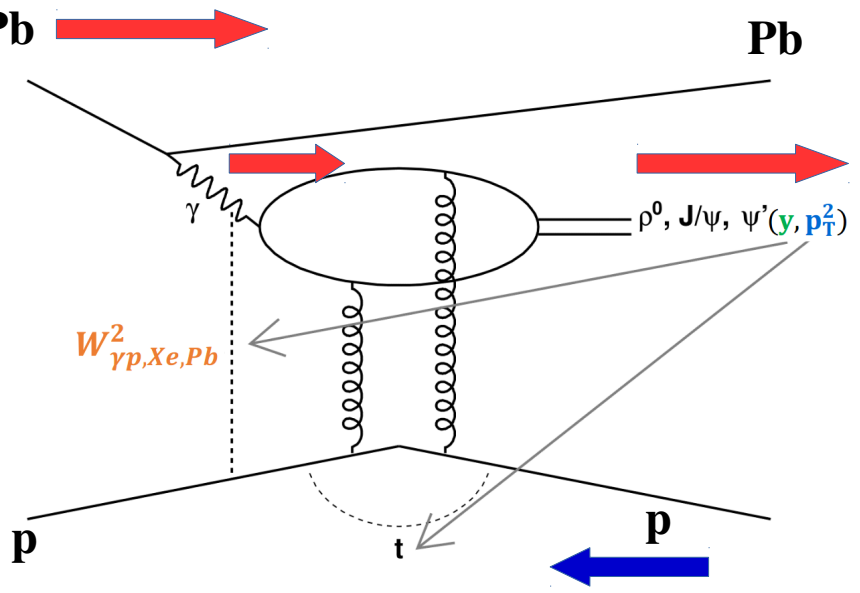
Exclusive vector meson photoproduction with FoCal

- Energy of the γp collision $W_{\gamma p}^2 = 2 \cdot E_p \cdot M_{VM} \cdot \exp(-y)$
- Probe gluon distributions in the proton at low-x $x = (M_{VM}/W_{\gamma p})^2$

$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma p, +y) + n(-y)\sigma(\gamma p, -y)$$

- Two possible cases:

Pb → FoCal **VM→ FoCal**	**p → FoCal** **VM→ FoCal**
High energy γ	Low energy γ
Small photon flux	Large photon flux
Large Wγp	Small Wγp
Small x	Large x



- The same for PbPb collisions
  - Can be distinguished with the help of ZDCs

Projected statistics in Run 4

- **VM → e^+ e^-** from *STARlight* with both electrons reconstructed in the FoCal acceptance
- 150 + 150 nb^{-1} for p-Pb and Pb-p, respectively

VM	$\sigma(p + Pb \to p + Pb + VM)$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$ p → FoCal	Yield p → FoCal
ρ^0	35 mb	140 nb	21,000
ϕ	1.7 mb	51 nb	7,700
J/ψ	98 μb	400 nb	60,000
$\psi(2S)$	16 μb	8.9 nb	1,300
$\Upsilon(1S)$	220 nb	0.38 nb	60
		Pb → FoCal	Pb → FoCal
ρ^0	35 mb	17 nb	2,600
ϕ	1.7 mb	5.3 nb	800
J/ψ	98 μb	36 nb	5,400
$\psi(2S)$	16 μb	0.53 nb	80
$\Upsilon(1S)$	220 nb	0.67 pb	~ 0

We focus on J/ψ production in present studies

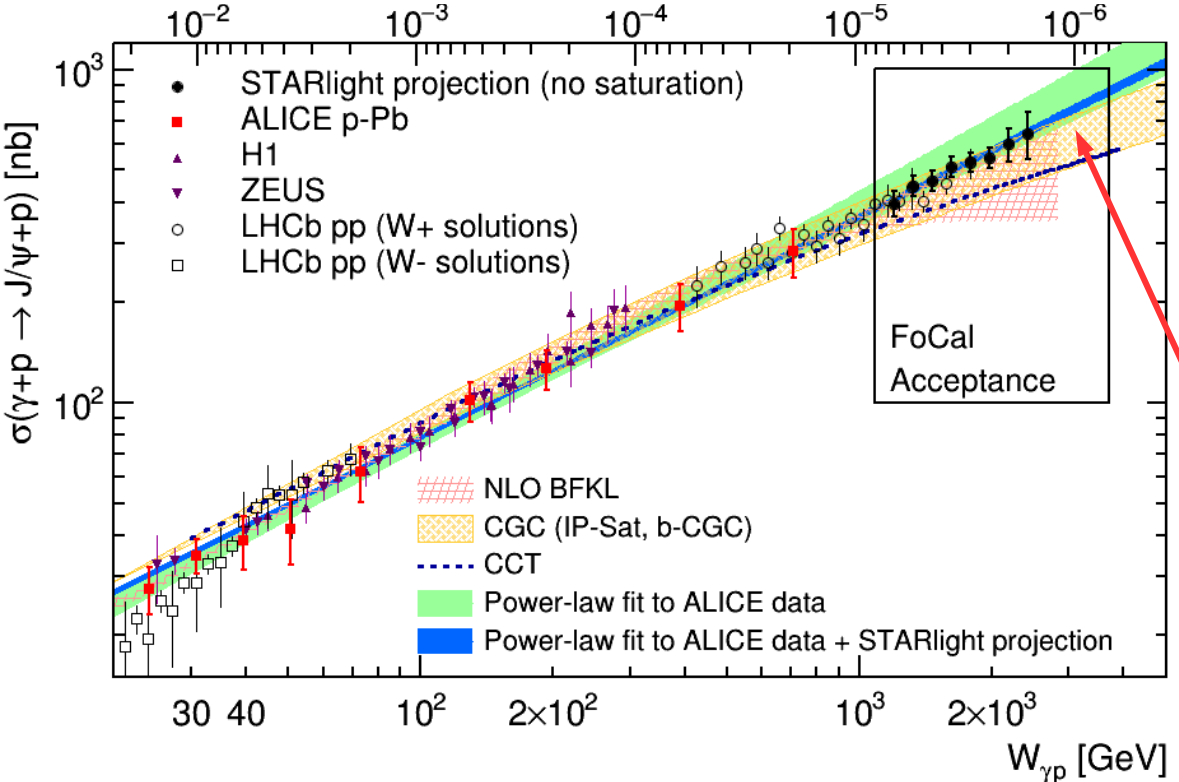
** 1 MHz interaction rate considered*

Exclusive J/ψ in p-Pb

VM	$\sigma(\mathrm{p+Pb \to p+Pb+VM})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
J/ψ	98 μ	36 nb	5,400

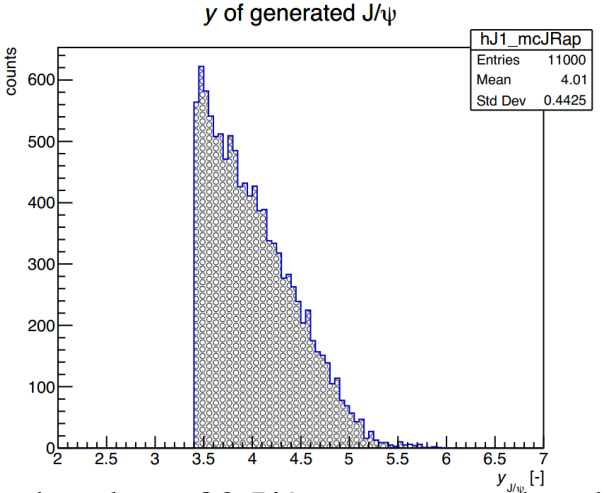
A **J/ψ → e⁺ e⁻** detected in FoCal within **3.4 < *y* < 5.8**:

1.1 < $W_{\gamma p}$ < 3.6 TeV, ↔ 8·10⁻⁶ > *x* > 7·10⁻⁷



The only measurement going up to 3 TeV in the foreseen future

Projection uncertainty: Run 2 systematics (7%) + projected statistics*(60% efficiency)



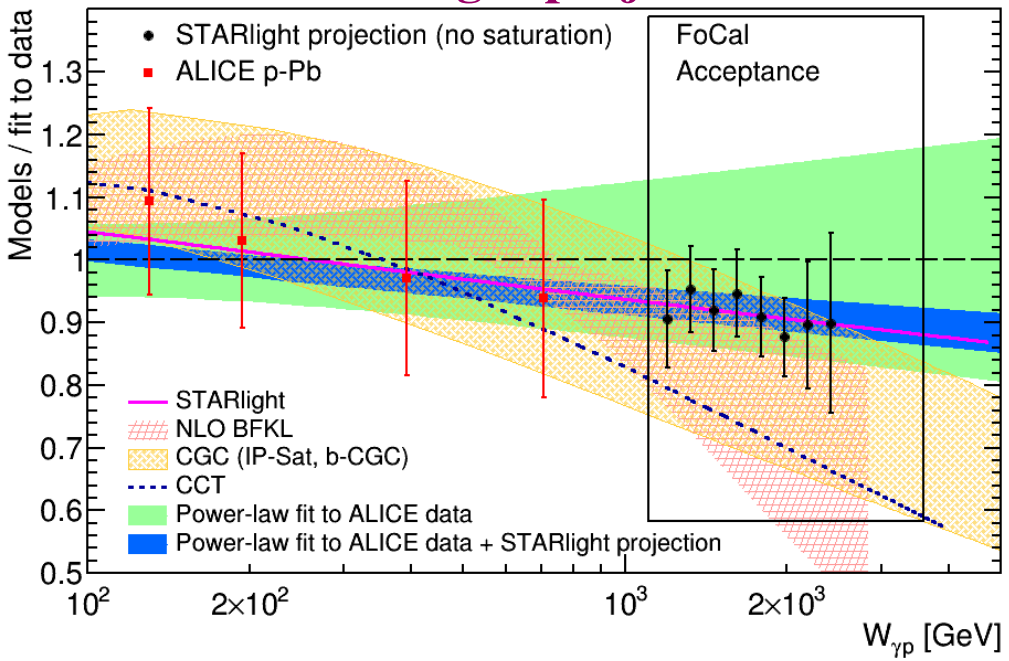
*Only bins with at least 80 J/ψ-s are considered

$W_{\gamma p}$ < 2.4 TeV, ↔ *x* > 1.5·10⁻⁶

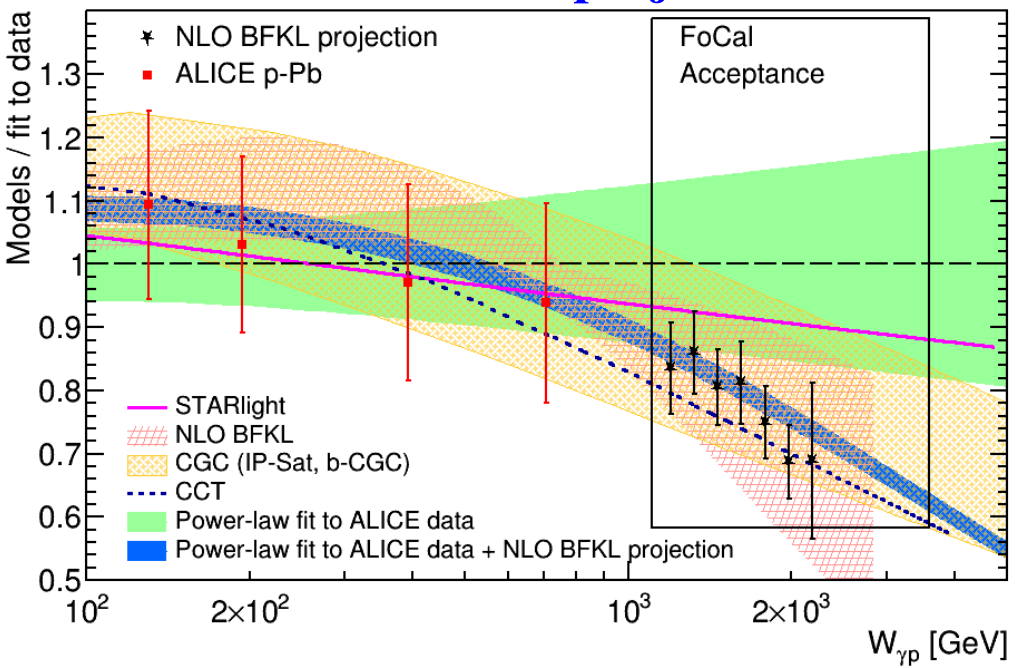
Exclusive J/ψ in p-Pb

VM	$\sigma(\mathrm{p+Pb \to p+Pb+VM})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
J/ψ	98 μ	36 nb	5,400

STARlight projection



NLO BFKL projection

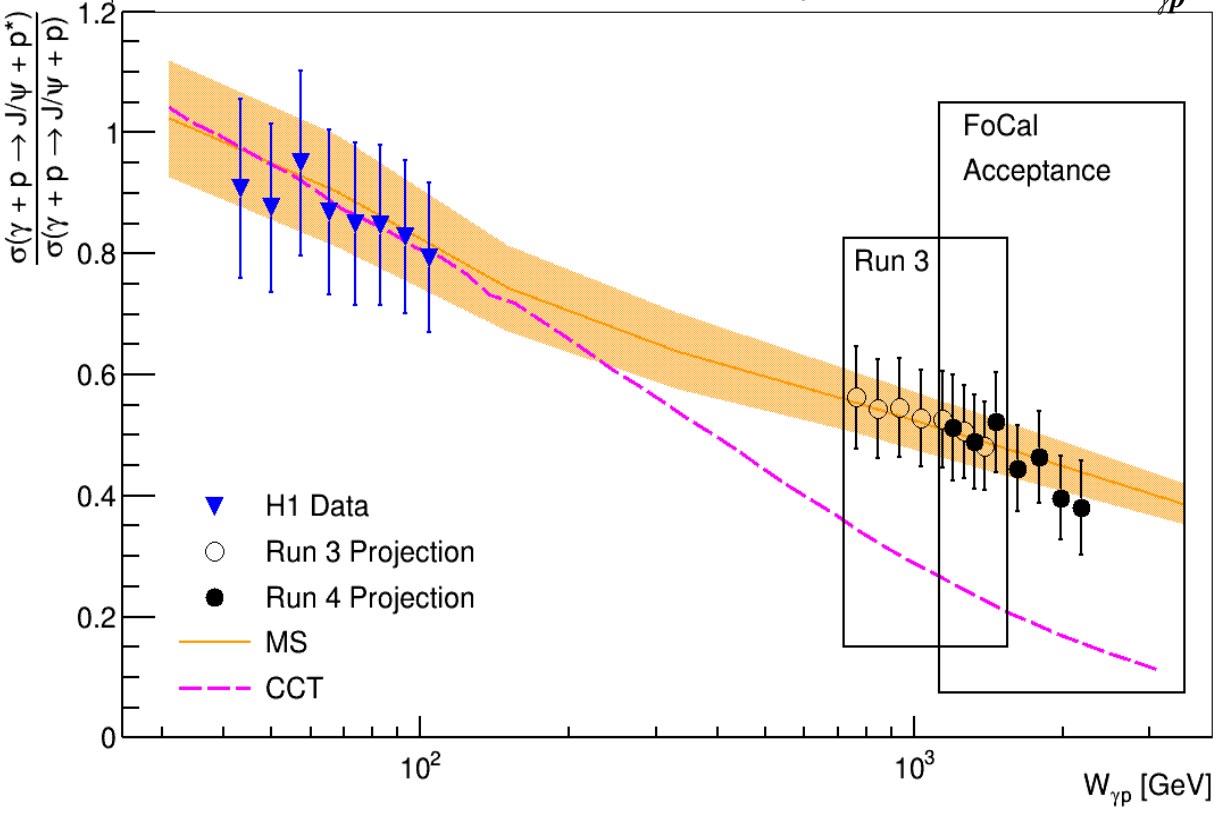


Measurement at unprecedentedly high energies will allow to distinguish between the theoretical models and significantly improve the precision

Proton-dissociative J/ψ in p-Pb

VM	$\sigma(\mathrm{p}+\mathrm{Pb}\to\mathrm{p}+\mathrm{Pb}+\mathrm{VM})$	$\sigma(3.4\leq\eta_{1,2}\leq 5.8)$	Yield
J/ψ	98 μ	36 nb	5,400

A J/ψ detected in FoCal within **3.4 < *y* < 5.8**: **1.1 < $W_{\gamma p}$ < 3.6 TeV, ↔ $8\cdot10^{-6} > x > 7\cdot10^{-7}$**



Projection uncertainty:

Run 2 systematics (**15%**) +

Projected statistics*(60% efficiency)

The MS model is used for the projection.

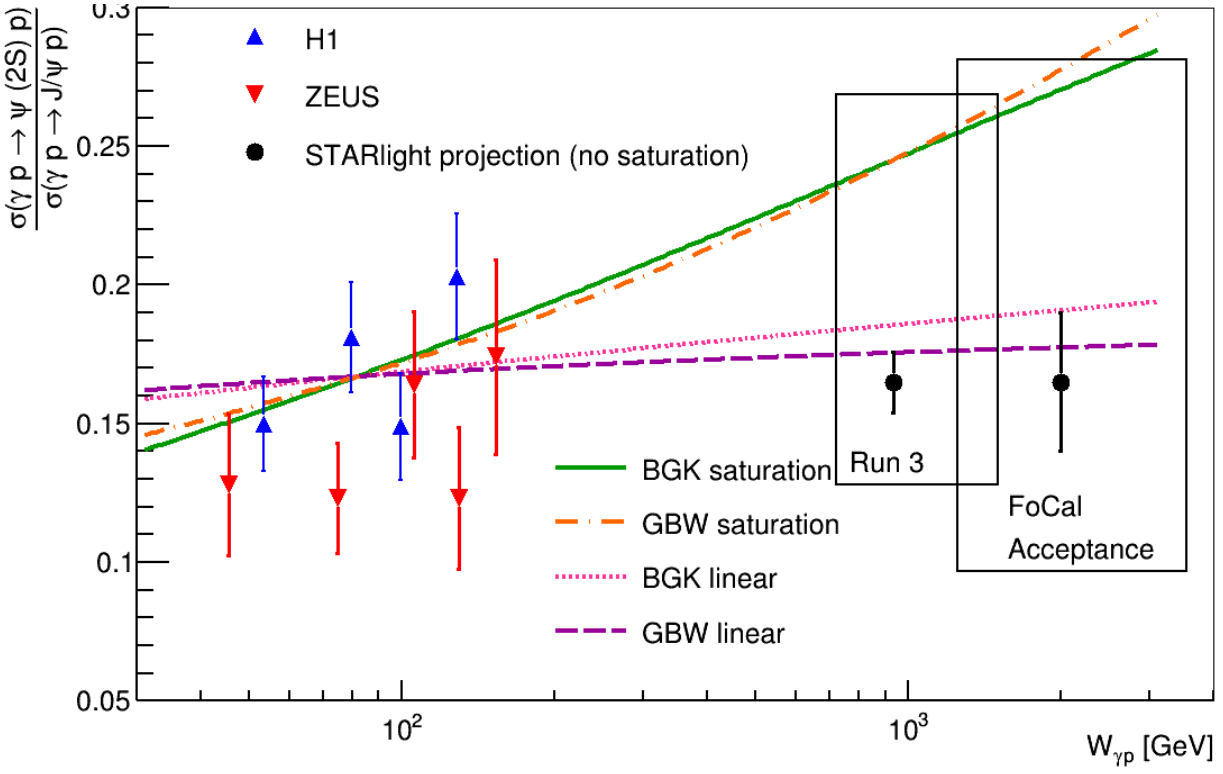
The proton-dissociative cross-sections are sensitive to the saturation effects

***$W_{\gamma p}$ < 2.2 TeV**

(for at least 80 J/ψs)

ψ(2S) to J/ψ cross-section ratio in p-Pb

VM	$\sigma(\mathrm{p}+\mathrm{Pb}\to\mathrm{p}+\mathrm{Pb}+\mathrm{VM})$	$\sigma(3.4\le\eta_{1,2}\le5.8)$	Yield
		Pb → FoCal	Pb → FoCal
J/ψ	98 μb	36 nb	5,400
$\psi(2S)$	16 μb	0.53 nb	80

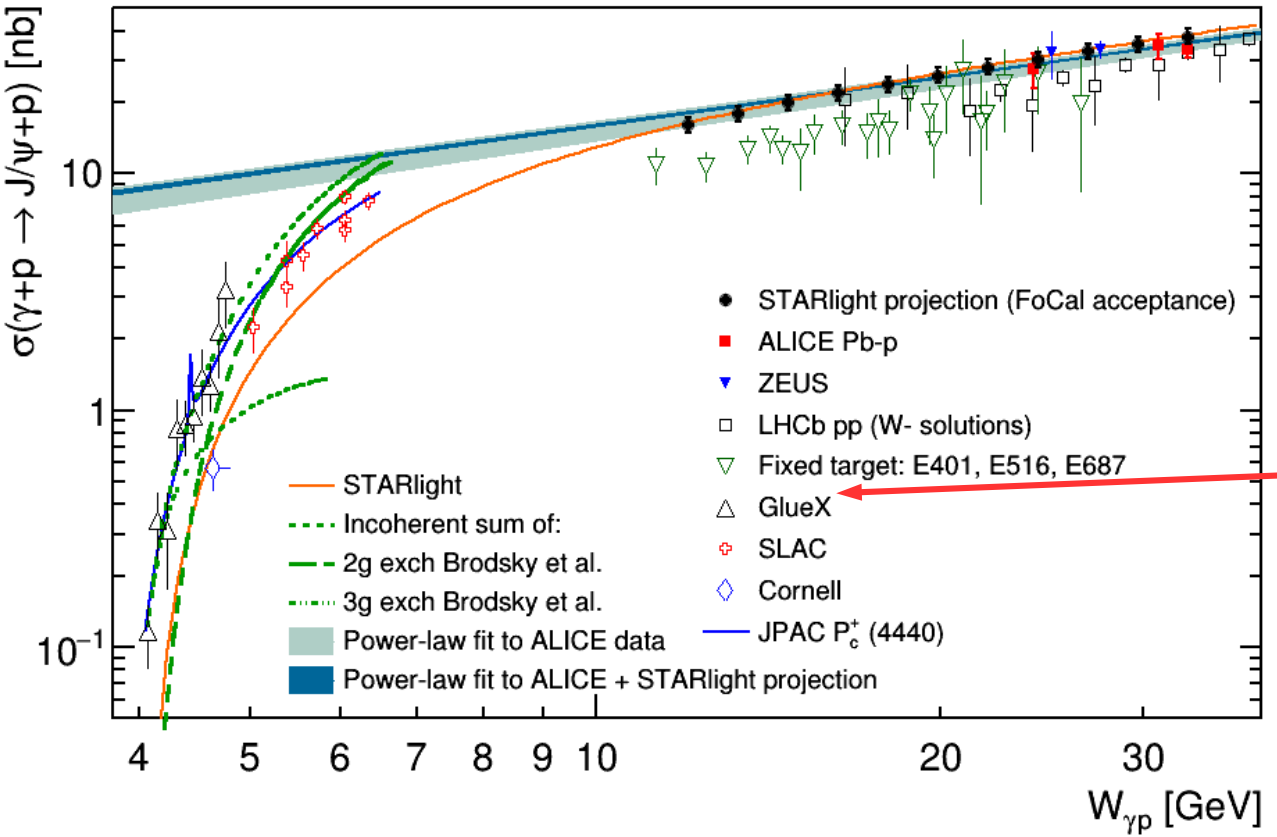


Theoretical studies
(by M. Hentschinski *et.al* [arxiv:2203.08129])
predict a clear onset of saturation effects in the **ψ(2S) to J/ψ** cross section ratios as a function of c.m.s. energy.

Both Run 3 & Run 4 data are important for the energy dependence!

Exclusive J/ψ in Pb-p

$\sigma(p+Pb \to p+Pb+VM)$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$ p → FoCal	Yield p → FoCal
98 μb	400 nb	60,000



Much larger photon flux is expected for the low-energy point.

A J/ψ within **-5.8 < *y* < -3.4**:

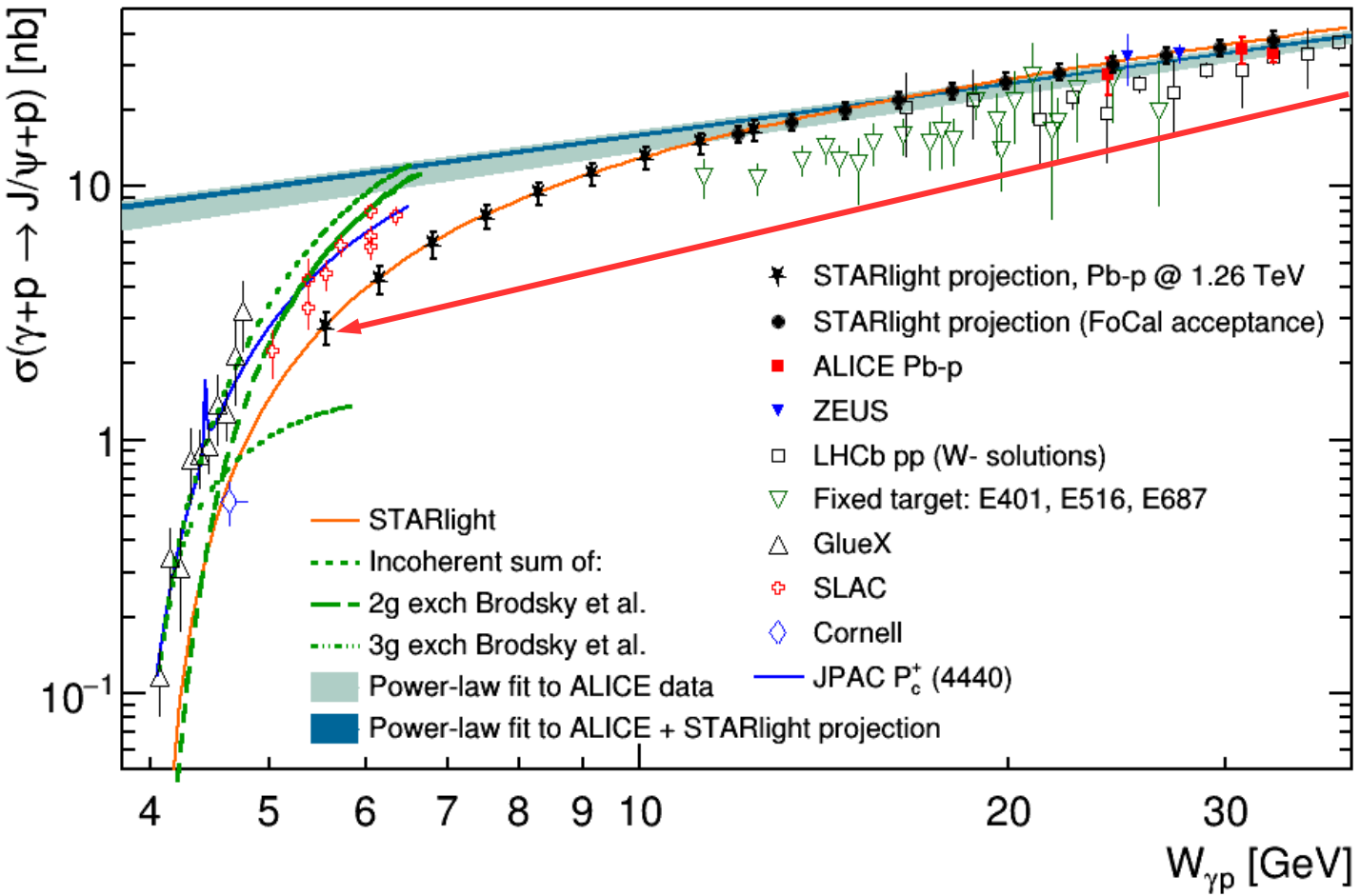
12 < $W_{\gamma p}$ < 36 GeV

Recent precise measurements of near-threshold J/ψ production by GlueX Experiment @ JLab.

FoCal will provide a unique kinematic coverage between the JLab experiments and present LHC data before the EIC.

J/ψ cross-section in Pb-p: special Run?

pPb special run @ $\sqrt{s} = 1.3$ TeV



Only 2 days of pPb @ 1.3 TeV with 20 nb^{-1} will allow to map the whole kinematic region from 4.5 to 12 GeV with high precision.

This low energy pPb run might be interesting for other processes:

- Not only UPCs
- Not only Exclusive production

- due to the huge gap between RHIC and LHC energies.

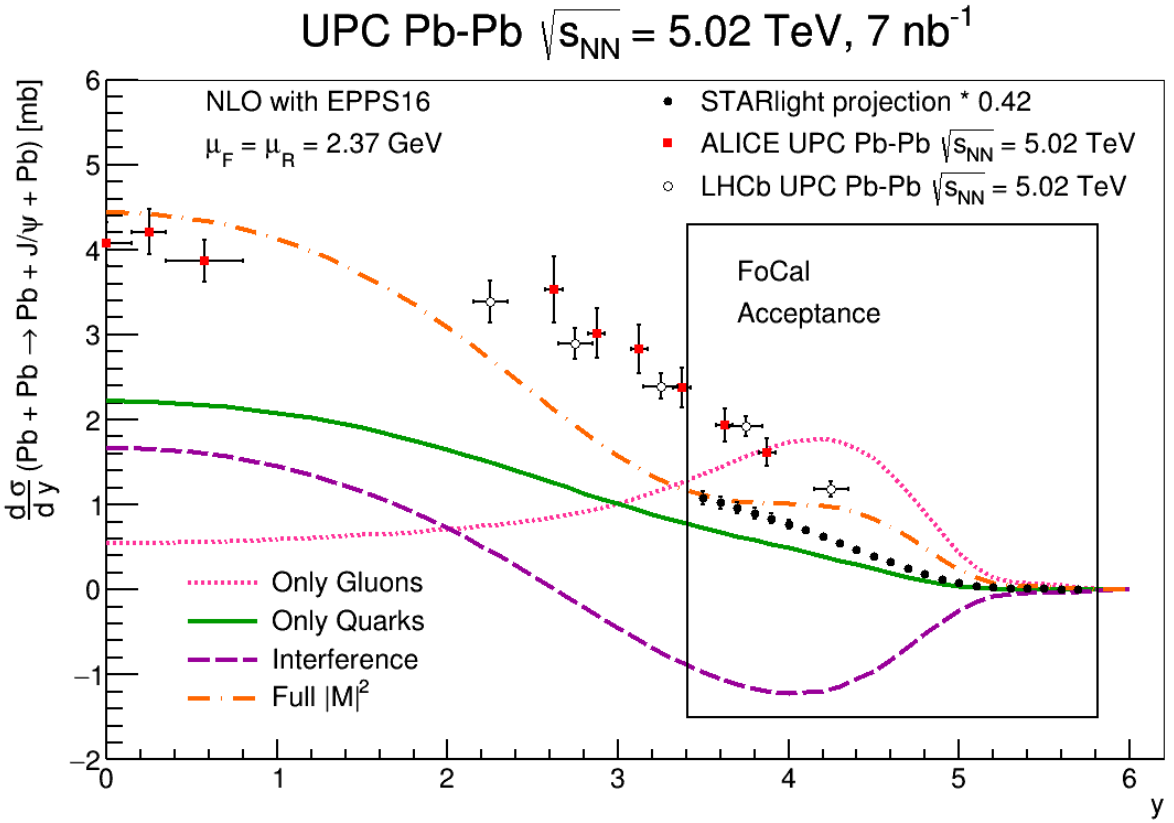
Projected statistics in Run 4

- **VM → e^+ e^-** from *STARlight* with both electrons reconstructed in the FoCal acceptance
- 7 nb^{-1} for Pb-Pb

VM	$\sigma(\mathrm{Pb}+\mathrm{Pb}\rightarrow\mathrm{Pb}+\mathrm{Pb}+\mathrm{VM})$	$\sigma(3.4\leq\eta_{1,2}\leq5.8)$	Yield
ρ^0	5.0 b	20 μb	140,000
ϕ	440 mb	10 μb	70,000
J/ψ	39 mb	53 μb	360,000
$\psi(2S)$	7.5 mb	1.1 μb	7,500
$\Upsilon(1S)$	94 μb	5.0 nb	35

Coherent J/ψ in Pb-Pb

VM	$\sigma(Pb+Pb \to Pb+Pb+VM)$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
J/ψ	39 mb	53 μb	360,000



Projection uncertainty:

Run 2 systematics (7%) +

Projected statistics (assuming 60% of reconstruction efficiency) and corrected for nPDFs (0.42 for J/ψ)

CERN YR: 1812.06772

Theory:

K.J. Eskola et. Al

arXiv:2203.11613 [hep-ph].

** Efficiency for y>5 might be lower (to be studied).*

Precise mapping of the high-rapidity region where the interference term is important

Neutron dependence in PbPb

- Combined FoCal and ZDC analyses will allow to measure the neutron dependence and thus extract the photo-nuclear cross section as a function of $W_{\gamma Pb}$
- 7 nb^{-1} for Pb-Pb

J/ψ for different breakup scenarios

0n0n	28.8 mb	47 μb	329,000
0nXn	7.3 mb	5.0 μb	35,000
XnXn	3.0 mb	2.0 μb	14,000

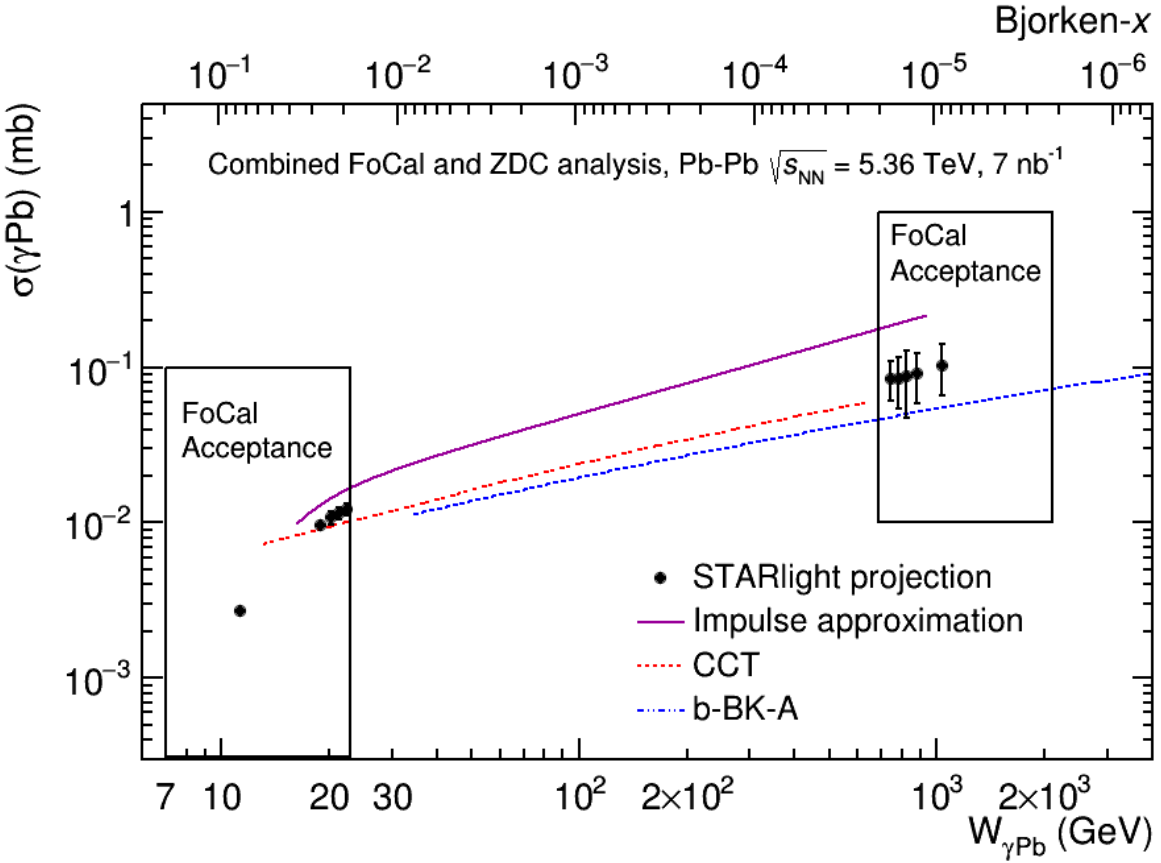
Neutron dependence

$$d\sigma(\text{total})/dy = d\sigma(0\text{n}0\text{n})/dy + 2d\sigma(0\text{n}\text{Xn})/dy + d\sigma(\text{Xn}\text{Xn})/dy$$

Vector meson is accompanied by at least one neutron on one side of the interaction point and no activity on the other side

Coherent J/ψ in Pb-Pb

Extraction made using the SVD approach with 3 breakup scenarios



At least 80 J/ψ-s in each rapidity bin and for each of the scenarios (0n0n, 0nXn, XnXn)

We considered 5%, 6% and 14% systematic uncertainties for the 0n0n, 0nXn and XnXn, respectively. Errors were propagated.

Summary

- Ultra-peripheral collisions with the FoCal are the energy frontier for photon physics probing gluon distributions at Bjorken-x of a few 10^{-6}.
- FoCal electromagnetic calorimeter will allow to measure VM $\rightarrow$ $\mathbf{e^+}$ $\mathbf{e^-}$ decays
- FoCal provides a unique physics program to probe gluons saturation with J/ψ production in UPC Pb-p collisions: cross section, J/ψ to ψ' ratio, dissociative production. (A. Bylinkin, J. Nystrand and D. Tapia Takaki ***(2023)*** **J. Phys. G**)
- Together with the rest of the ALICE detector, including the ZDCs, FoCal will be able to measure the J/ψ cross section in Pb-Pb collisions as a function of energy.
- FoCal can also contribute to many other UPC measurements like dijet production, $\gamma\gamma$ $\rightarrow$ $\mathbf{e^+}$ $\mathbf{e^-}$, near threshold J/ψ production (in case of a special Run).

Thanks to my ALICE Colleagues for fruitful discussions.

Thank you very much for your attention!