# Heavy-quark photoproduction in ultra-peripheral collisions and the connection to the Parton Distribution Functions

HF2022: Heavy Flavours from small to large systems

Institut Pascal, Université Paris-Saclay,
3-21 October 2022

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# Outline

- Short introduction to ultra-peripheral collisions.

- Exclusive photonuclear and photon-proton vector meson production.

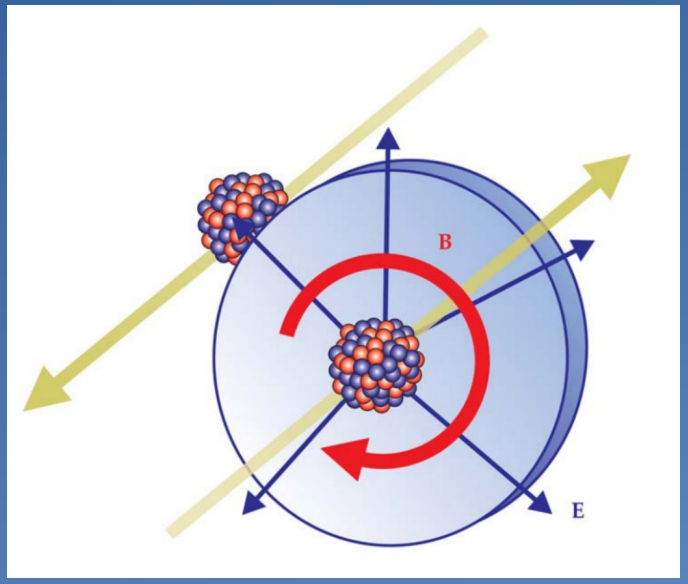
- Connection to the parton distribution functions - what has to be done, what can be done.

- Production of heavy flavour quarks through photon-gluon fusion.

# What are Ultra-peripheral Collisions?

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.




The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

# The first hadron collider

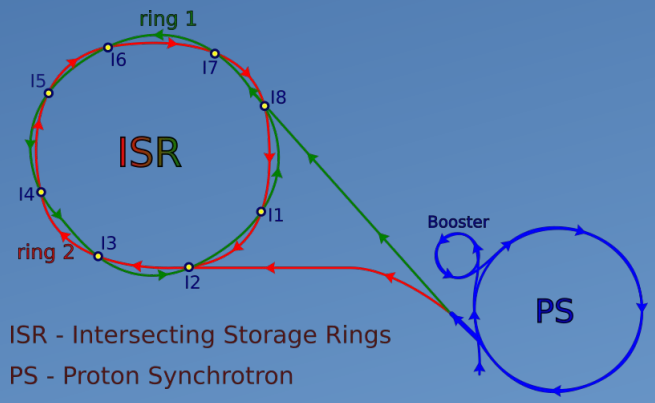
First obeservation of particle production in an ultra-peripheral collision between protons:

$p+p \rightarrow p+p+\mu^{+}\mu^{-}$

at the ISR in 1980 (by the CERN-Harvard-LAPP-MIT-Pisa Collaboration, CERN-EP/80-82, a conference proceeding, never published).

ISR: Intersecting Storage Ring – A collider at CERN for protons and $\alpha$-particles, in operation 1971 – 1984, maximu energy $\sqrt{s}$ = 62 GeV.

The world's first hadron collider.

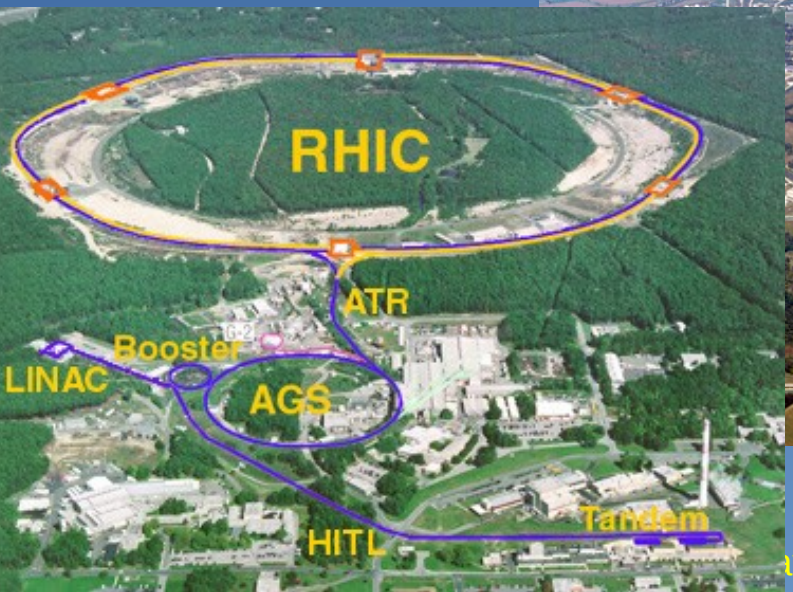



# The Hadron Colliders RHIC, Tevatron and LHC

Tevatron at Fermilab (1987 - 2011):
$p+\bar{p}$ at $\sqrt{s}$ = 1.96 TeV

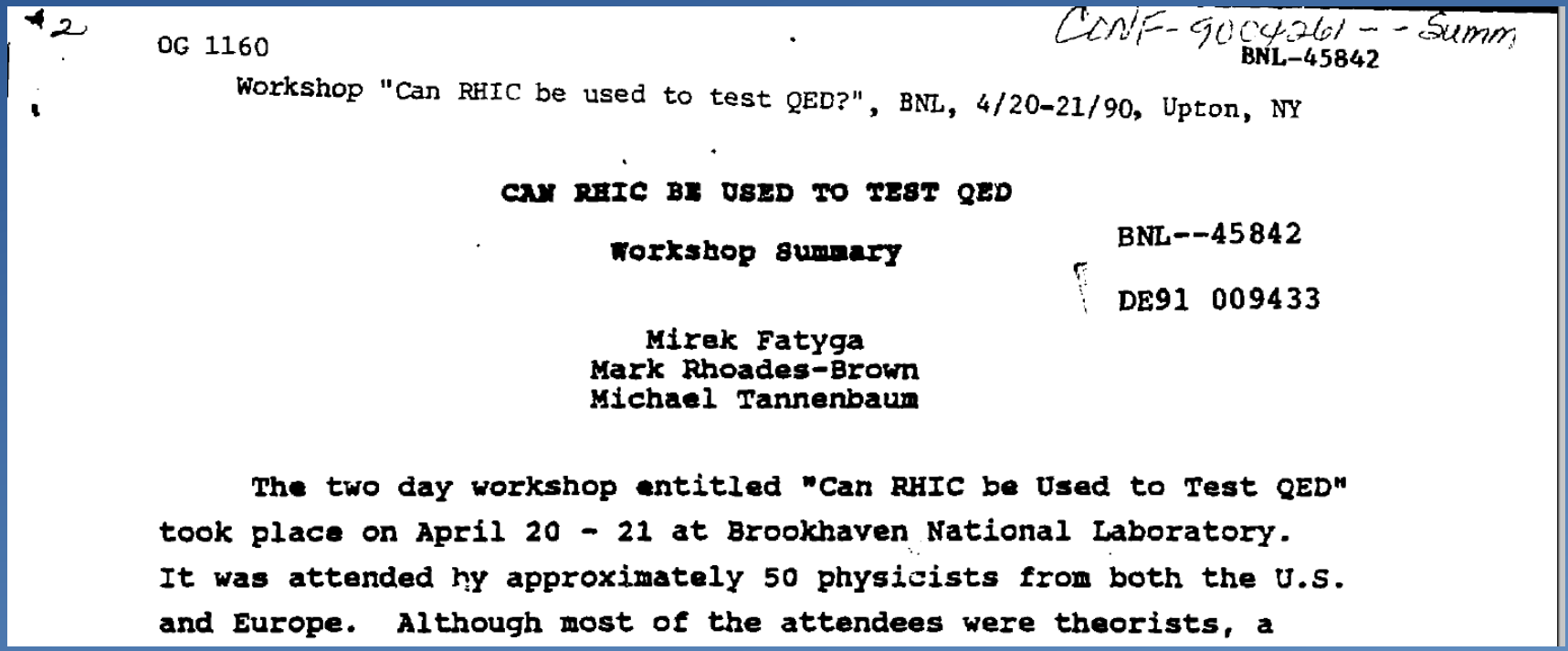
RHIC at Brookhaven National Laboratory (2000 -):
Au+Au at $\sqrt{s_{nn}}$ = 200 GeV; p+p at $\sqrt{s}$ = 200 and 500 GeV.

LHC at CERN (2009 - ):
Pb+Pb at $\sqrt{s_{nn}}$ = 5 TeV; p+Pb at $\sqrt{s_{nn}}$ = 8 TeV; p+p at $\sqrt{s}$ = 13 TeV.




# Ultra-relativistic heavy-ion collisions

## A workshop held at BNL 1990 ”Can RHIC be Used to Test QED”



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BNL-45842

Workshop "Can RHIC be used to test QED?", BNL, 4/20-21/90, Upton, NY

**CAN RHIC BE USED TO TEST QED**

**Workshop Summary**

BNL--45842

DE91 009433

Mirek Fatyga
Mark Rhoades-Brown
Michael Tannenbaum

The two day workshop entitled "Can RHIC be Used to Test QED" took place on April 20 - 21 at Brookhaven National Laboratory. It was attended by approximately 50 physicists from both the U.S. and Europe. Although most of the attendees were theorists, a

- $\gamma\gamma \rightarrow$ e+e- (violation of unitarity, strong field effects)
- $\gamma\gamma \rightarrow$ single (scalar, tensor) mesons.
- $\gamma\gamma \rightarrow$ Higgs (too low energy at RHIC)

# Ultra-relativistic heavy-ion collisions

People also did calculations for various two-photon processes, also for heavy-ions at the LHC.

Volume 223, number 3,4 PHYSICS LETTERS B 15 June 1989

**CAN ONE DETECT AN INTERMEDIATE-MASS HIGGS BOSON IN HEAVY-ION COLLISIONS?**

M. DREES [a], J. ELLIS [a] and D. ZEPPENFELD [b]

[a] *CERN, CH-1211 Geneva 23, Switzerland*

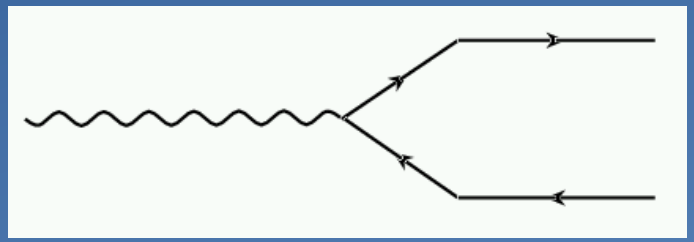
[b] *Physics Department, University of Wisconsin, Madison, WI 53706, USA*

Received 1 March 1989

# Exclusive vector meson production

Initially all the focus was on exclusive two-photon production of some final state: a single meson, a dilepton pair, a Higgs.

Vector Meson Dominance (VMD): The quantum numbers of the Photon $J^{PC} = 1^{--}$ are the same as for a Vector Meson ⇒ High probability for fluctuation to Vector Meson.



While in the vector meson state, the photon can interact hadronically. It can, for example, scatter coherently and elastically off the other nucleus and emerge as a real vector meson.

$$V^* + A \rightarrow V + A$$

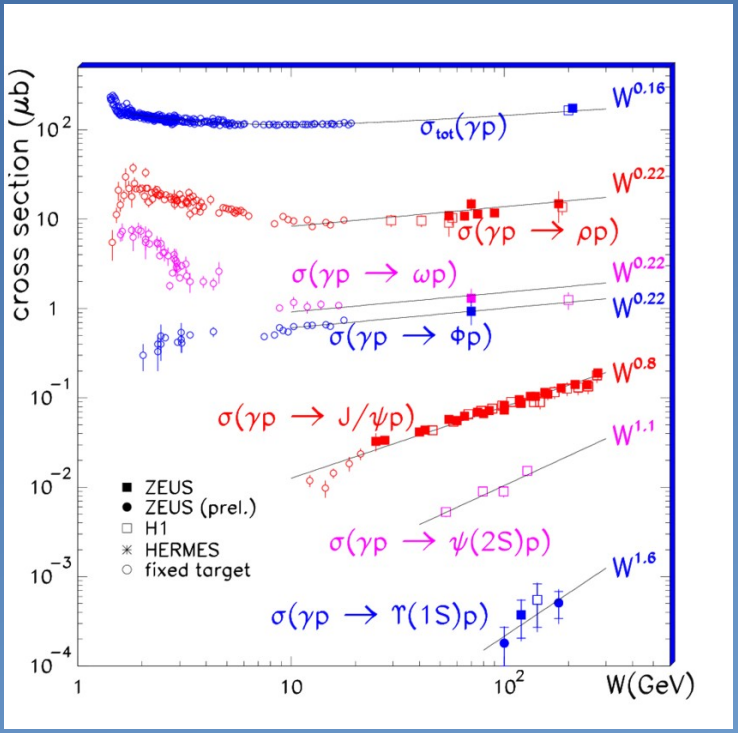
The scattering can be seen as mediated by a Pomeron.

# Exclusive vector meson production

These types of interactions have been studied in fixed target experiments with muon beams with proton targets and a few (usually light) nuclear targets.

They have also been rather extensively studied with proton targets at the electron-proton collider HERA.

Compilation of results on exclusive vector meson production on proton targets at HERA and in fixed target experiments.



# Exclusive vector meson production

How to scale these results to $\gamma$+A?

- Use the experimental $\sigma(\gamma+p \rightarrow J/\psi+p)$ and scale them from $\gamma$+proton to $\gamma$+nucleus using the Glauber model.

- Combine the photonuclear cross section with the appropriate photon flux at hardon colliders.

- Thus obtain the cross sections/rates for exclusive vector meson production in Au+Au collisions at RHIC and Pb+Pb collisions at the LHC.

# Exclusive vector meson production

PHYSICAL REVIEW C, VOLUME 60, 014903

**Exclusive vector meson production in relativistic heavy ion collisions**

Spencer R. Klein and Joakim Nystrand
*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
(Received 8 February 1999; published 16 June 1999)

The production rates are large enough that heavy ion colliders could be used as vector meson factories. The $\phi$ and $J/\psi$ production rates at LHC are comparable to those at existing or planned meson factories based on $e^+e^-$ annihilation.

For mesons of comparable masses, the cross sections are a factor 100 higher for exclusive photonuclear production compared with two-photon production.

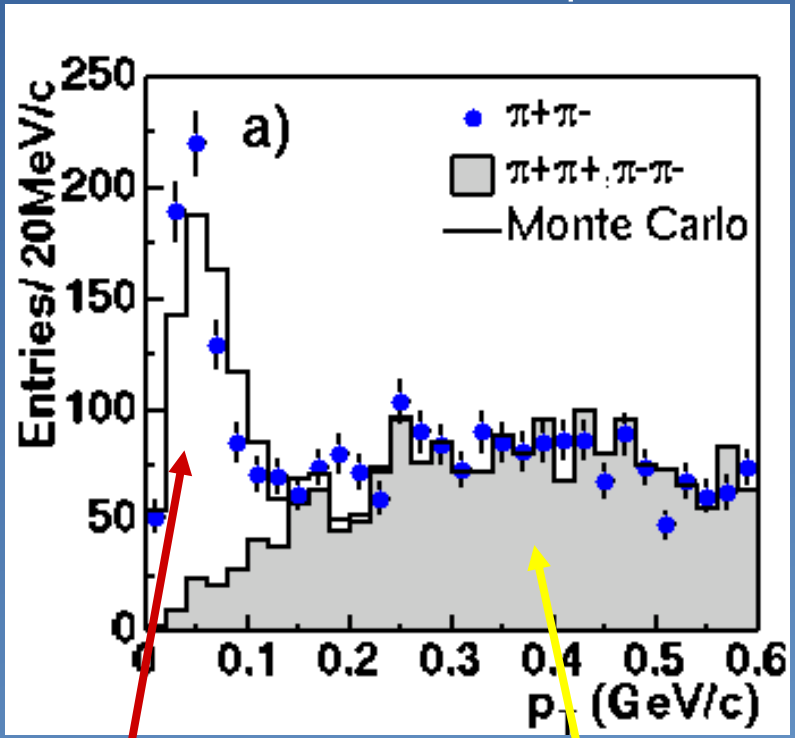
# The first UPC result from RHIC

Exclusive $\rho^0$-production, Au+Au→Au+Au+$\rho^0$
(C. Adler et al. (STAR Collaboration) PRL 89(2002)272302).

Run 1 $\sqrt{s_{NN}}$ = 130 GeV –
Identification of coherent $\rho^0$.

"Two charged particles in an otherwise empty detector"

Clear signal for coherent production seen in $p_T$ distribution.

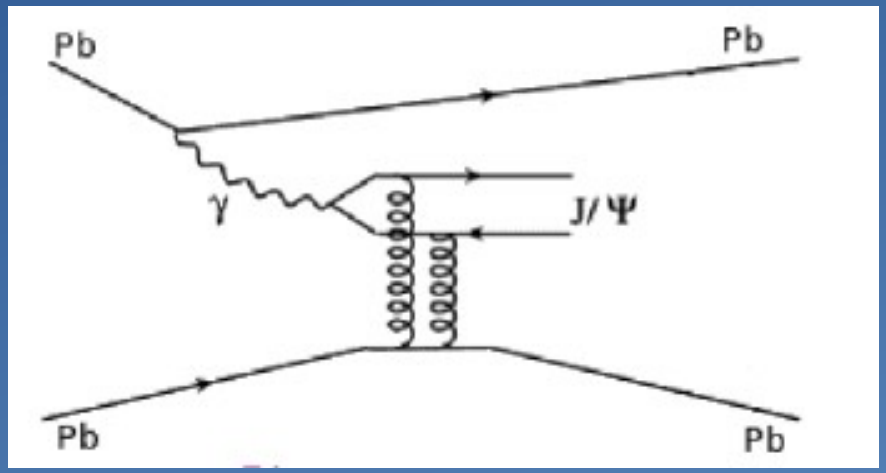



Signal+background, unlike-sign pairs

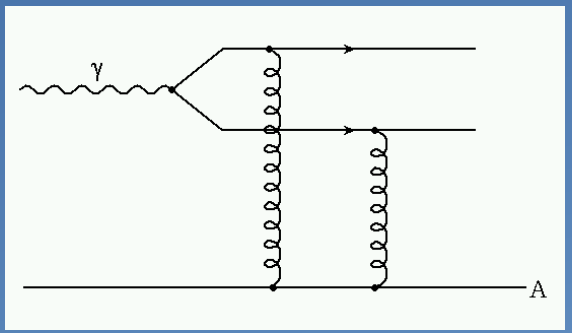
background, like-sign pairs

# Exclusive vector meson production

In perturbative QCD, the Pomeron can be treated as the exchange of two gluons, if the scale - determined by the mass of the vector meson - is high enough.




The cross section $\sigma(\gamma+p \rightarrow J/\psi+p)$ can thus be calculated




$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

Ryskin 1993

Leading Order.

"Sensitive probe of gluon distribution", $[g(x)]^2$.

# Exclusive vector meson production

Assuming a power law for the gluon PDF

$$x \cdot g(x, \mu^2) = N x^{-\lambda}$$

$$\lambda = a + b \ln\left(\frac{\mu^2}{0.45 GeV^2}\right)$$

This implies

$$\left.\frac{d\sigma}{dt}\right|_{t=0} \propto x^{-2\lambda}$$

$$\sigma(\gamma + p \rightarrow J/\psi + p) \propto x^{-2\lambda}$$

The kinematics gives for the Bjorken-x

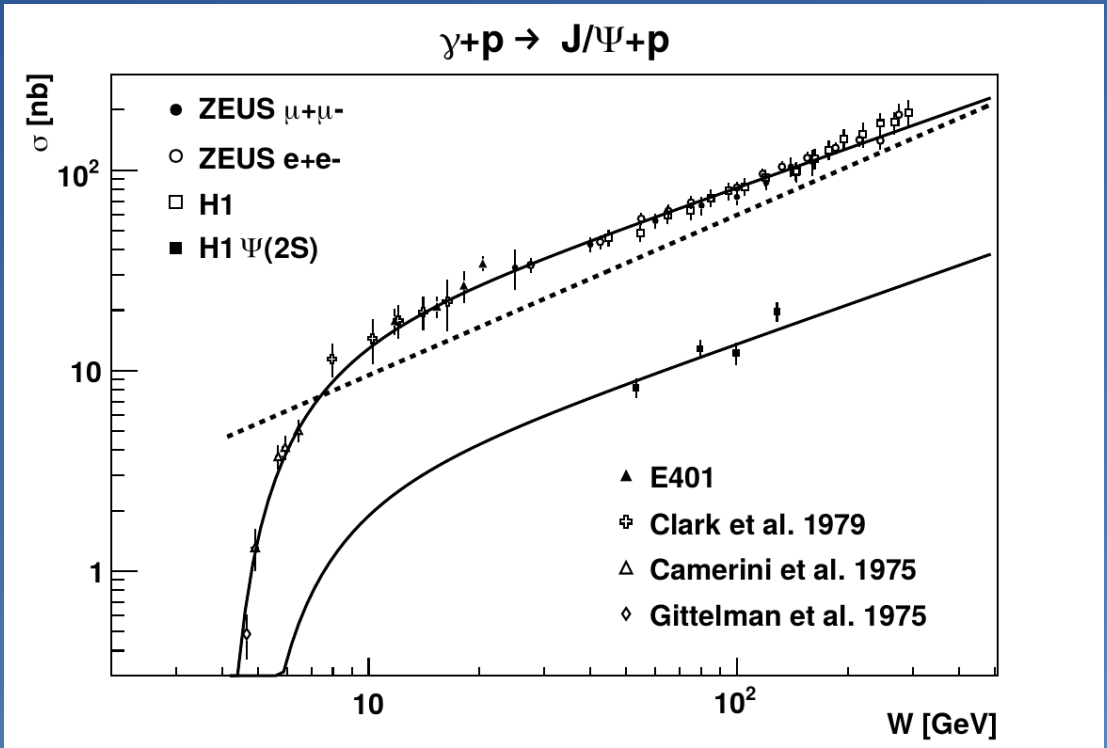
$$x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}}$$

And thus

$$\sigma(\gamma + p \rightarrow J/\psi + p) \propto W^{4\lambda}$$

# Exclusive vector meson production

Data from HERA and fixed target experiments consistent with a power law:




$\sigma(\gamma+p \rightarrow J/\psi+p)$ well described by such a parameterization - experimental uncertainties small.

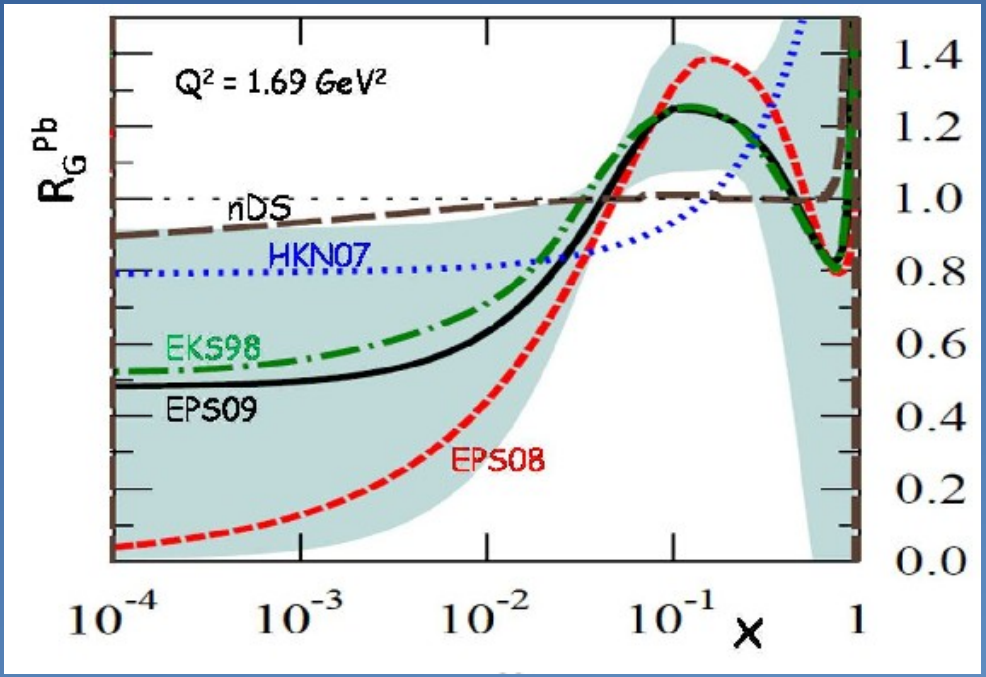
Fit with 2 parameters gives $\sigma_p$ = 4.06 nb, $\epsilon$ = 0.65.

$$\sigma(\gamma + p \rightarrow V + p) = \sigma_P \cdot \left[1 - \frac{(m_p + m_V)^2}{W_{\gamma p}^2}\right]^2 \cdot W_{\gamma p}^{\epsilon}.$$

# Exclusive vector meson production

What to expect for the nuclear case, $\sigma(\gamma+\mathrm{Pb} \rightarrow J/\psi+\mathrm{Pb})$?

Big uncertainties in the nuclear gluon distribution. Different parameterizations available.




Measuring exclusive vector meson production at the LHC can Improve this for $Q^2 \sim M_V^2$ and $x \approx 10^{-2} - 10^{-4}$ (x range is rapidity dependent).

# Exclusive vector meson production

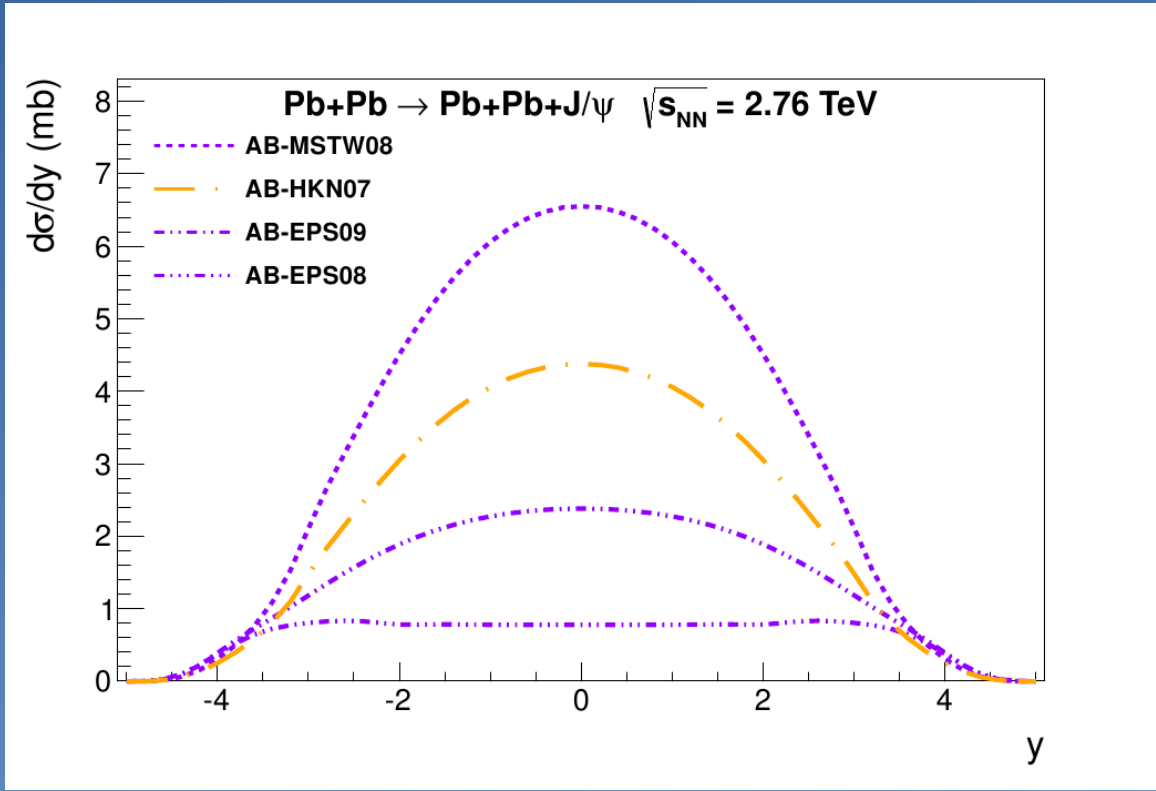
Calculation by Adeluyi and Bertulani assuming $\sigma \propto (g(x))^2$.
(Phys. Rev. C 85 (2012) 044904)

Normalizing to $\gamma$p data from HERA.

MSTW08 – no nuclear effects ($A^2$ scaling)

HKN07, EPS09, EPS08 - different nuclear g(x).

Leads to very different cross sections for J/$\psi$, especially at midrapidity!




An experimentalist's dream!

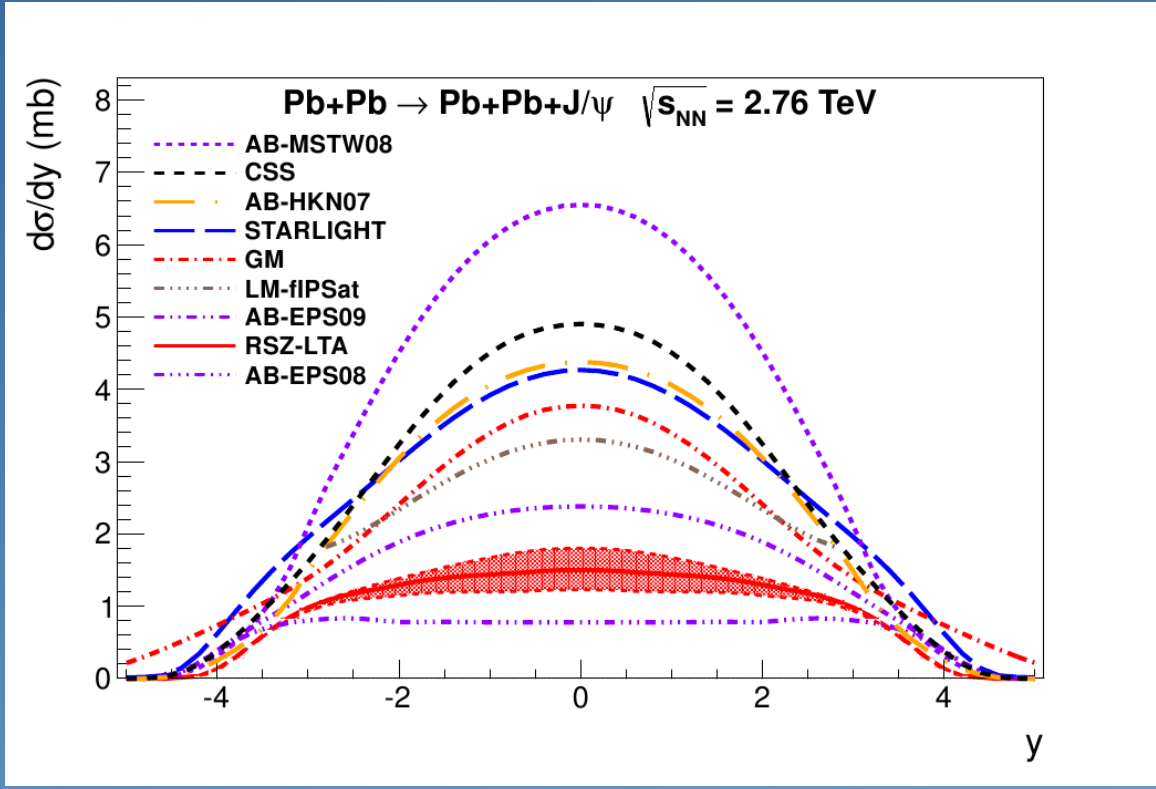
# Exclusive vector meson production

Also other models on the market

Many based on the Color Dipole Model (CSS, GM, LM-fIPSat).

RSZ-LTA – calculates nuclear shadowing from Leading Twist Approximation

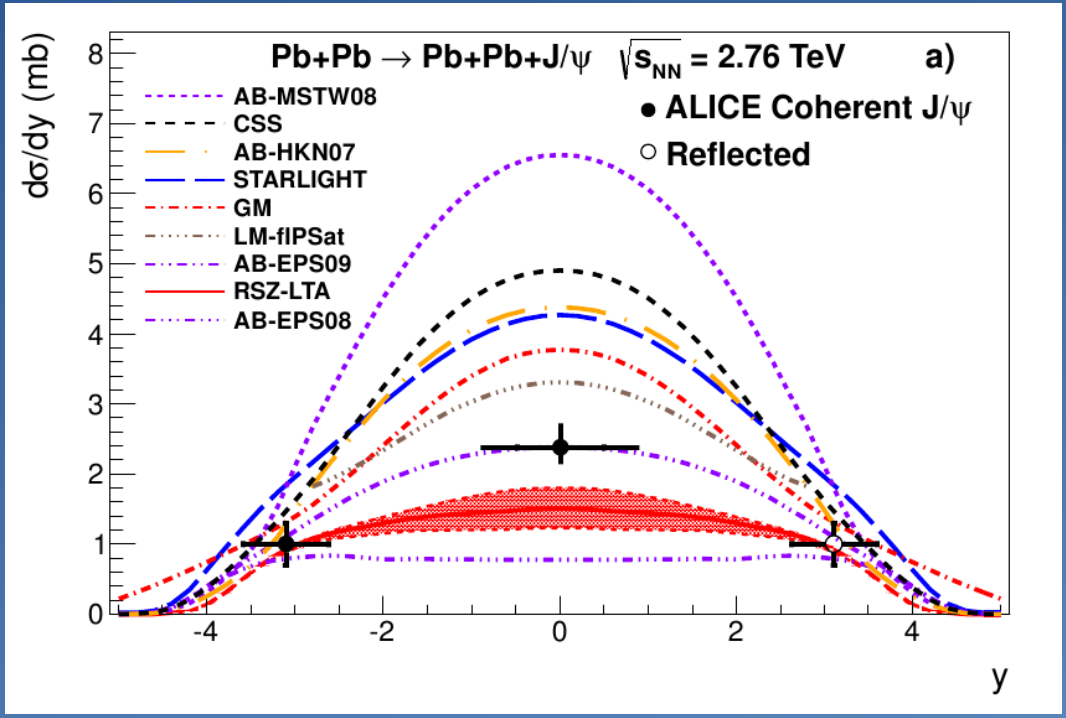
STARLIGHT – scales the measured $\gamma$p cross section using a Glauber Model.




For exact references, see Eur. Phys. J 73 (2013) 2617.

# Exclusive vector meson production

First results on UPC at the LHC from ALICE




ALICE Collaboration

Phys. Lett. B 718 (2013) 1273

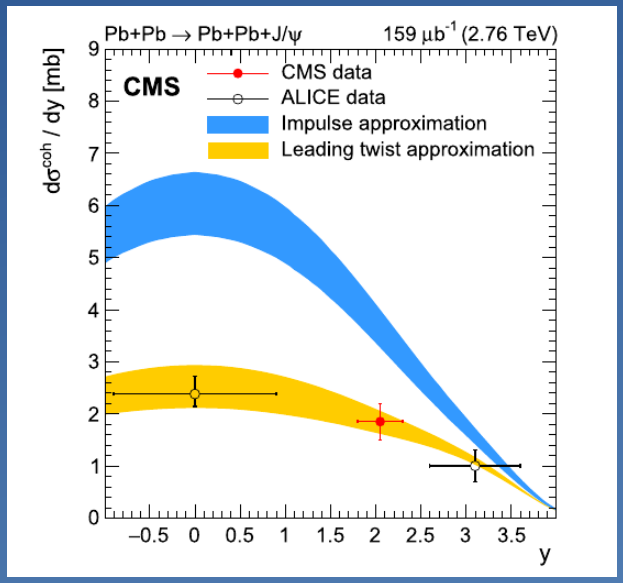
and

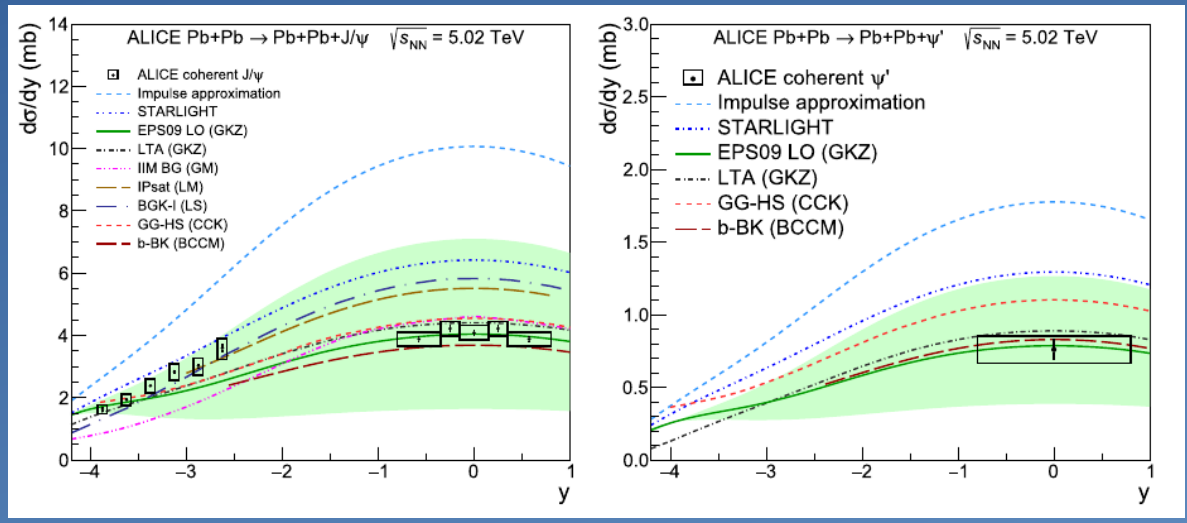
EPJ C 73 (2013) 2617.

This result from ALICE shows that the distribution in the x $\approx 10^{-2} - 10^{-3}$ range is consistent with the EPS09 parameterization.

# Exclusive vector meson production

These results have been updated with higher statistics and also CMS has measured the same thing with similar conclusions.



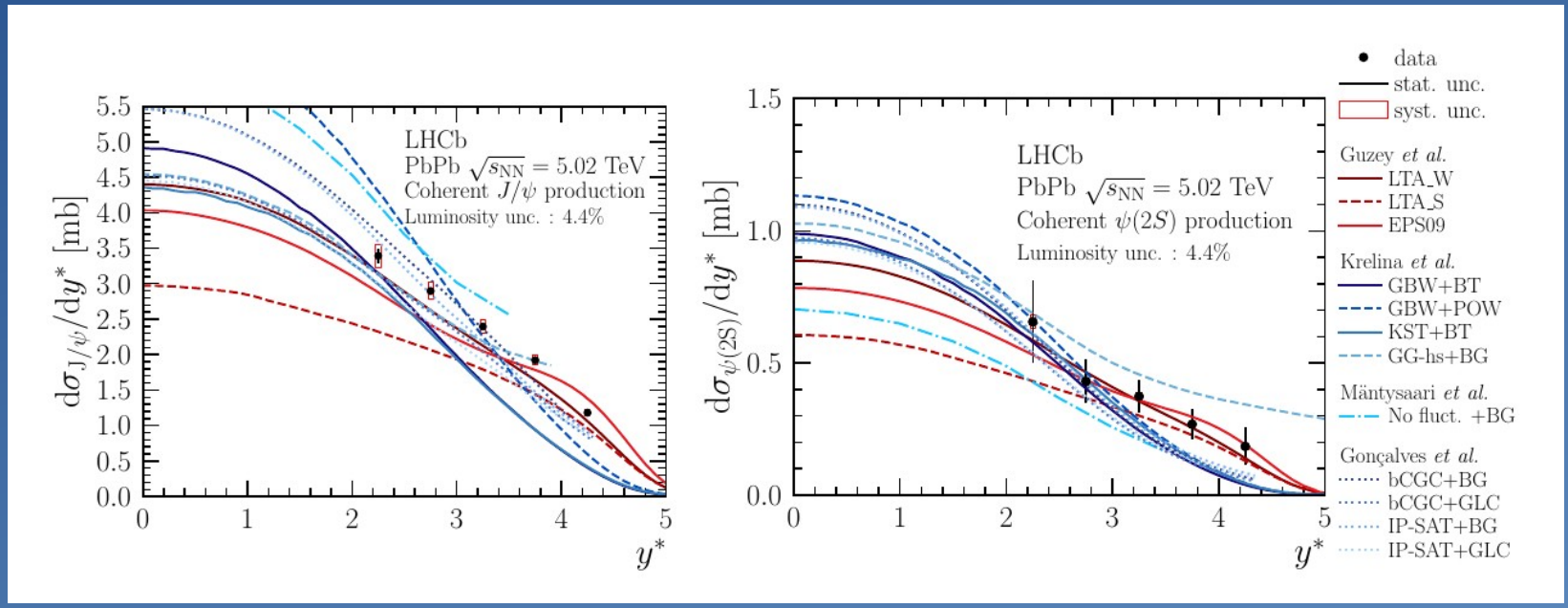




CMS Collaboration Phys. Lett. B 772 (2017) 489.

ALICE Collaboration Phys. Lett. B 798 (2019) 134926; Eur. Phys. J. C 82 (2021) 712

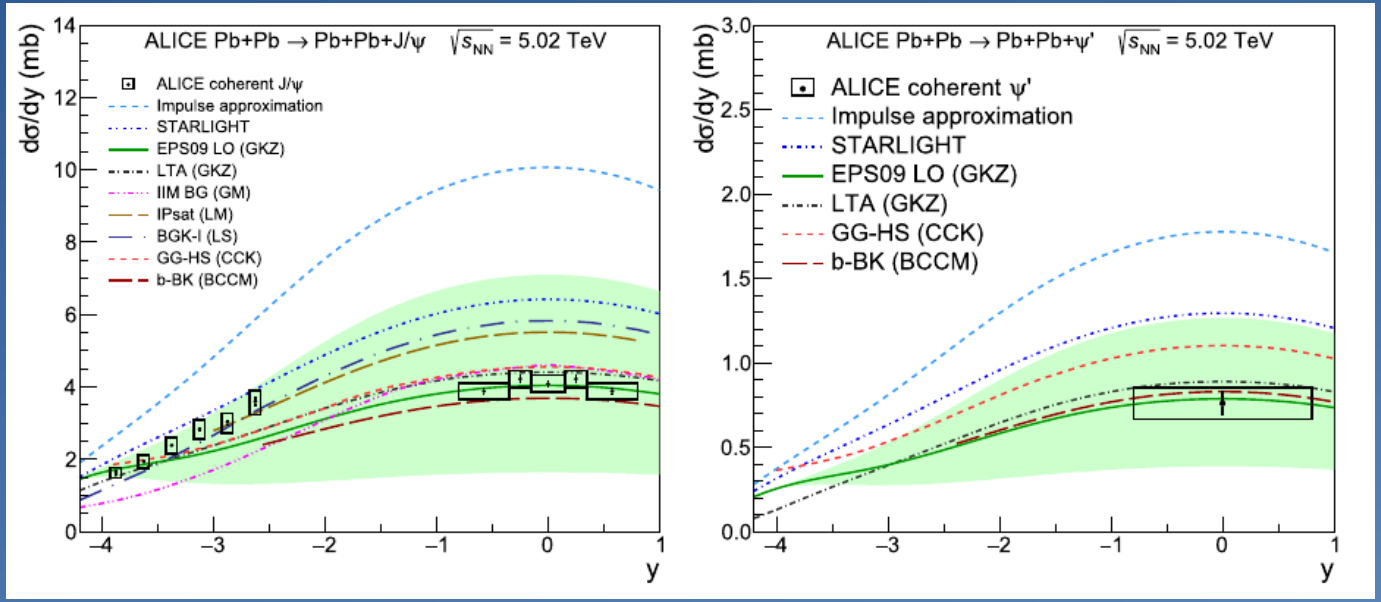
# Exclusive vector meson production

Recent results also released by LHCb (arxiv:2206.08221).



# Exclusive vector meson production

Here we are after 10 years of heavy-ion data from the LHC



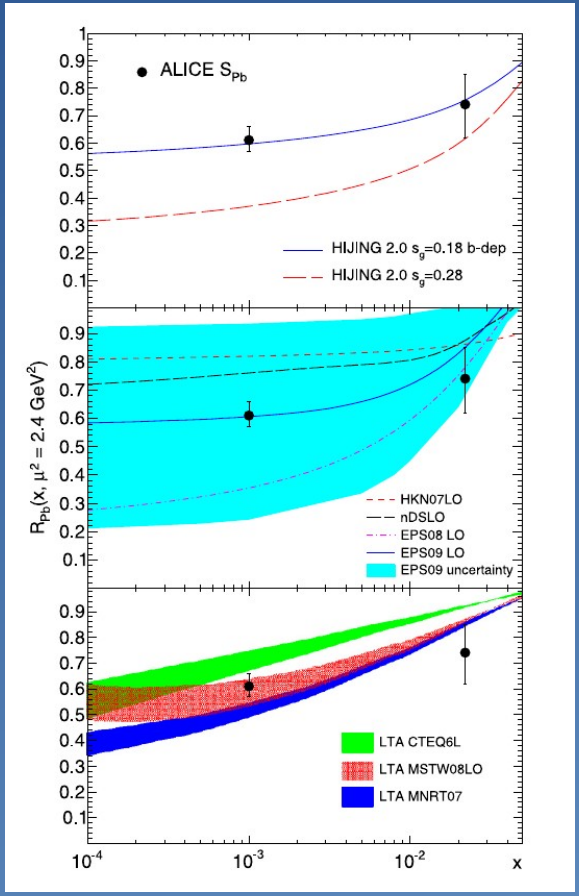

High statistics measurements of exclusive photoproduction of J/ψ, rapidity and $p_T$ distributions well constrained.

The baseline, $\sigma(\gamma+p \rightarrow J/\psi+p)$, well constrained.

But what have we learnt about the nuclear gluon distributions?

# Exclusive vector meson production

Some attempts have been made to convert the exclusive J/ψ measurements into a shadowing function.




But the results have not been used by the "well established" parameterizations of the nuclear PDFs (EPPS16 and 21).

V. Guzey, E. Kryshen, M.Strikman, M. Zhalov, Phys. Lett. B 726 (2013) 290.

# Exclusive vector meson production

Recent calculation from (some of) the EPPS authors:

**Exclusive $J/\psi$ photoproduction in ultraperipheral Pb+Pb collisions at the LHC to next-to-leading order perturbative QCD**

K. J. Eskola,[1,2] C. A. Flett,[1,2] V. Guzey, T. Löytäinen,[1,2,*] and H. Paukkunen[1,2]

[1] *University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*

[2] *Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*

(Dated: March 23, 2022)

arxiv:2203.11613

There are big differences between LO and NLO calculations and uncertainties on the relevant scale.

Quarks seems to give a very significant contribution in addition to gluons.

# Exclusive vector meson production

What could improve the situation?

1) More statistics? For J/ψ, I think no!

2) Heavier vector mesons, ψ(2S), ϒ(1S), ϒ(2S), ϒ(3S)?

3) Increased rapidity range, for example with FoCal in ALICE Run 4 ($3.4 < y < 5.8$)?

# Exclusive vector meson production

Statistics from Run 2 ($\int Ldt \approx 230\ \mu b^{-1}$):

| | ALICE $\lvert y\rvert<0.9$ | ALICE $2.5<y<4.0$ |
|---|---|---|
| Coherent J/ψ: | ≈5 000 | ≈22 000 |
| Coherent ψ(2S): | ≈200 | ≈500 |

| | LHCb $2.0<y<4.5$ |
|---|---|
| Coherent J/ψ: | ≈20 000 |
| Coherent ψ(2S): | ≈500 |

# Exclusive vector meson production

Expected statistics from Run 3 ($\int Ldt \approx 7$ nb$^{-1}$):

| | ALICE $\|y\|<0.9$ | ALICE $2.5<y<4.0$ |
|---|---|---|
| Coherent J/ψ: | ≈150 000 | ≈200 000 |
| Coherent ψ(2S): | ≈6 000 | ≈5 000 |
| Coherent ϒ(1S)*: | ~1 000 | ~300 |

Can expect similar numbers from LHCb (I suppose).

Will it help?

*Calculated from STARLIGHT + geometrical acceptance.

# Photoproduction in p+Pb Collisions at the LHC

Dominated by γp interactions, where the Pb-ion emits the photon (≈95% of cases). Advantage compared with p-p.

For a γ+p→V+p interaction, the center of mass energy given by

$$W_{\gamma p} = \sqrt{2E_p M_V e^y}$$

Here, $E_p$ is the proton energy ($E_p$ = 6.5 TeV) and y the rapidity of the Vector Meson.

ALICE muon arm at forward rapidities ($-4.0 < \eta < -2.5$). Kinematics depends on beam direction

Pb-p ==> $550 < W < 1160$ GeV

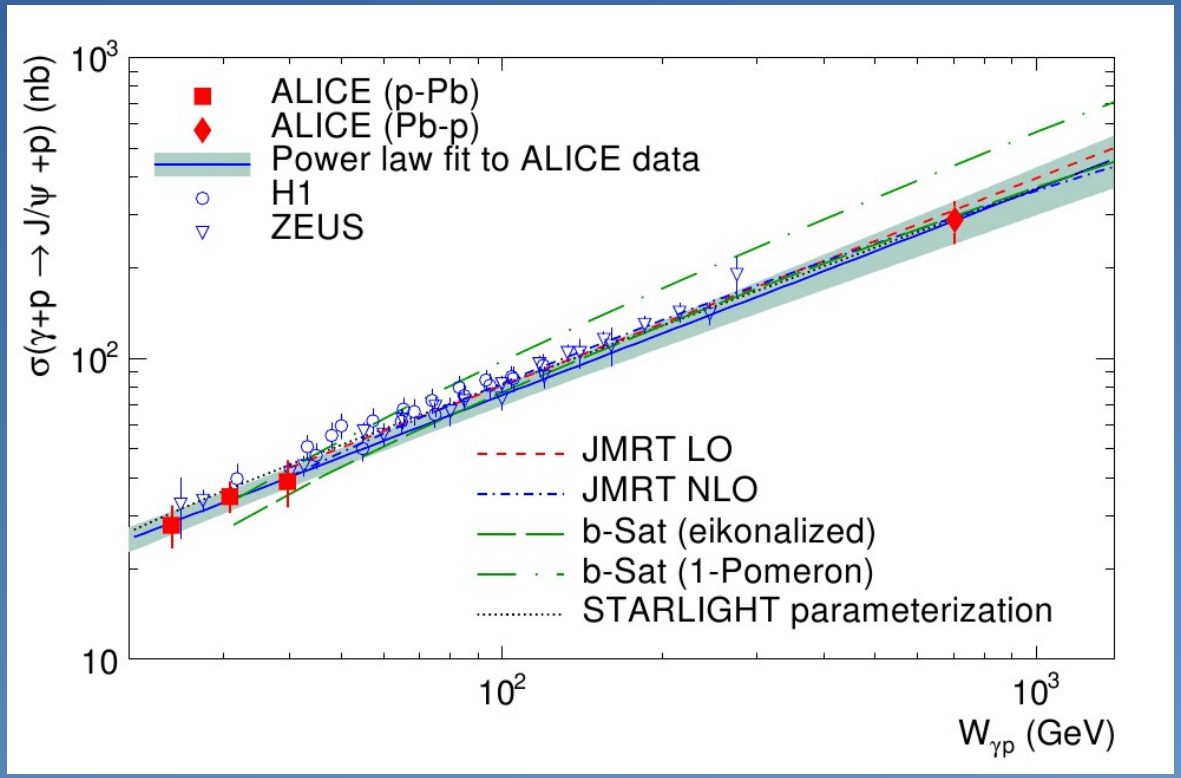
P-Pb ==> $21 < W < 45$ GeV

Measurements at HERA up to W = 300 GeV.

# Photoproduction in p+Pb Collisions at the LHC

Extracted cross section in $21 \leq W \leq 45$ GeV (p-Pb) range in good agreement with previous measurements.

New measurement in $580 \leq W \leq 950$ GeV (Pb-p) in good agreement with a power law.

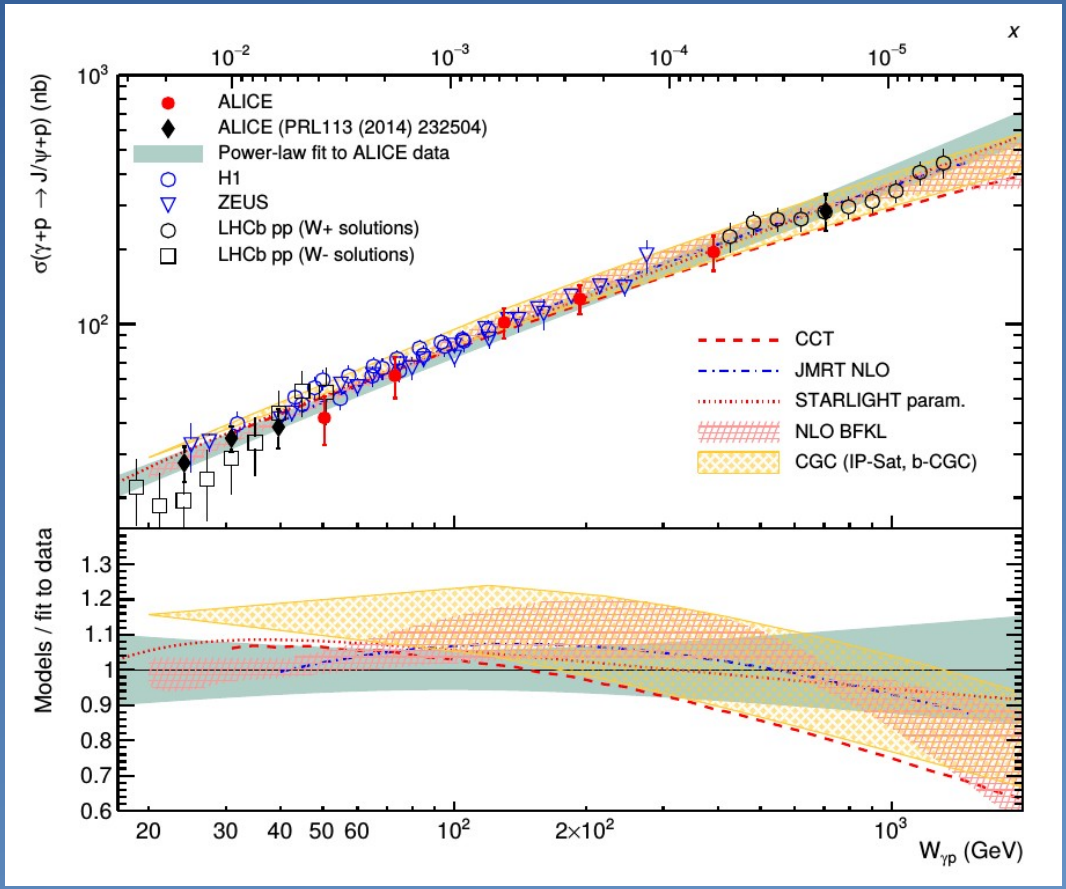



From Run 1.
$\sqrt{s}$ = 5 TeV.

*"A natural explanation is that no change in the behaviour of the gluon PDF in the proton is observed between HERA and LHC energies"* PRL 113 (2014) 232504.

# Photoproduction in p+Pb Collisions at the LHC

More results from ALICE in Run 2 using both the central barrel and muon arm (Eur. Phys. J C 79 (2019) 402).
Results from LHCb from p+p collisions. There is an ambiguity in the extraction of the low energy/high energy component.




But no deviation from a power law seen!

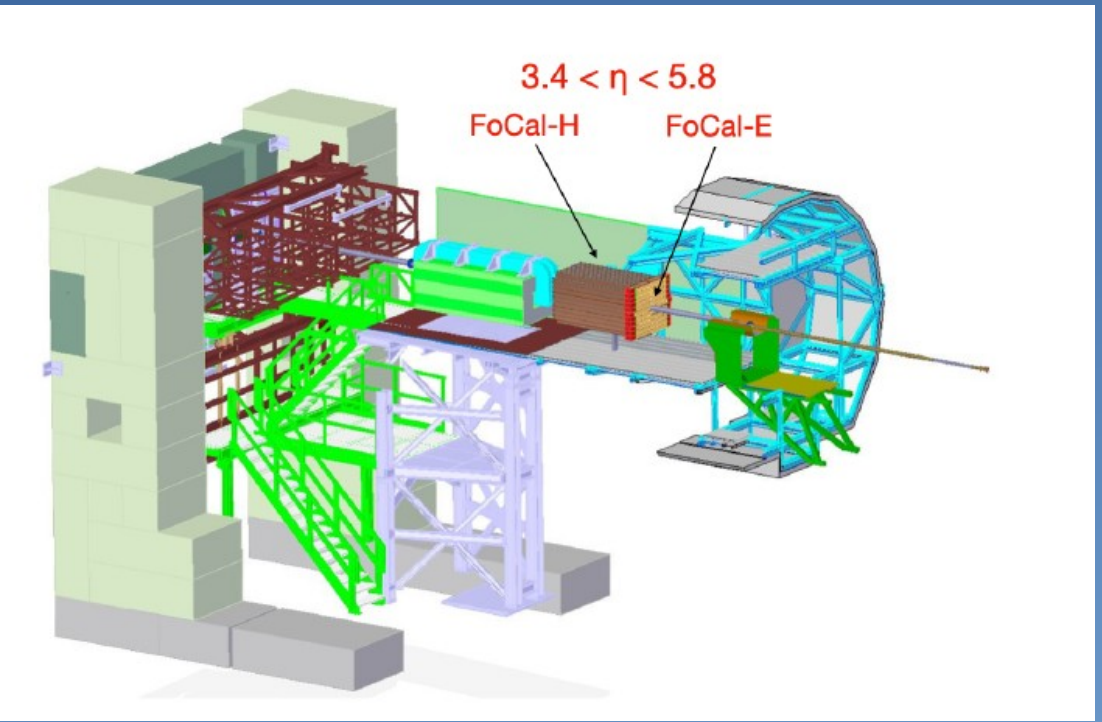
Here, an extension in acceptance to forward rapidities might help.

# Vector meson photoproduction in the forward direction

The Forward Calorimeter (FoCal) in ALICE.

A highly granular Si+W electromagnetic calorimeter combined with a conventional sampling hadronic calorimeter covering pseudorapidities of $3.4 < \eta < 5.8$.

Optimized to measure isolated photon spectra at forward rapidity in the range of about $4 < p_T < 20$ GeV/c.




- Located 7 m from the primary vertex.

- Radial distance from the beam 4 – 45 cm.

- To be installed in Run 4 (2029).

# Vector meson photoproduction in the forward direction

The Forward Calorimeter (FoCal) in ALICE. Main physics goals:

- Measure the gluon distribution functions at low x in protons and heavy nuclei.

- Investigate the suppression of high-$p_T$ hadrons in an unexplored region of phase space.

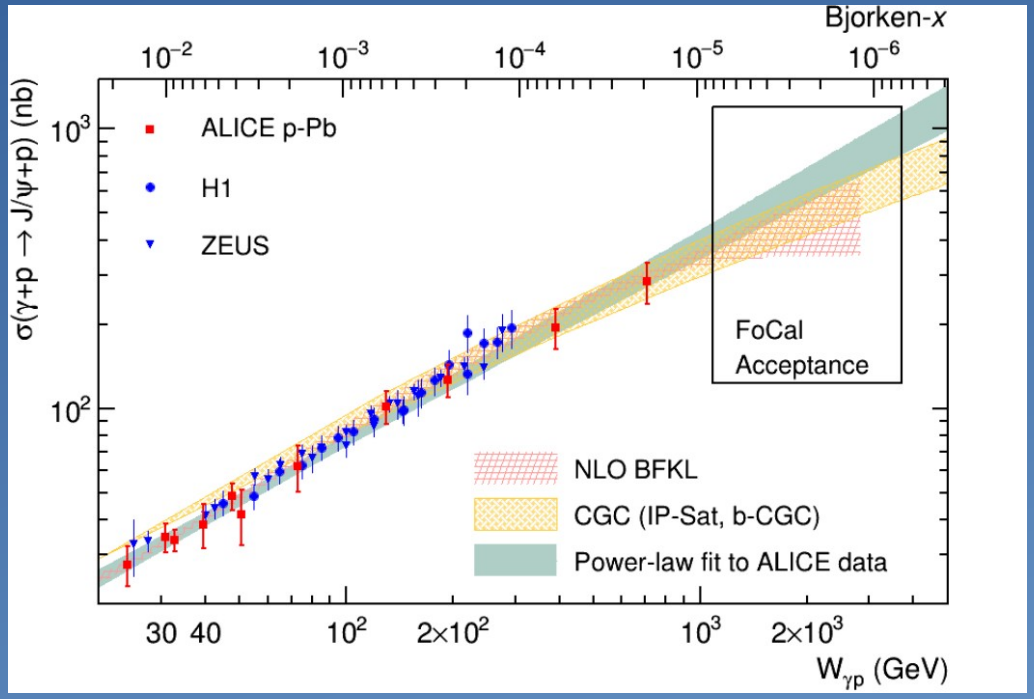
- Investigate long range correlations in $\eta$ - the so called “ridge effect” - by combining measurements in FoCal and the central barrel.

- Exclusive Vector Meson production in the forward region in p+Pb and Pb+Pb interactions.

# Vector meson photoproduction in the forward direction

Starting with p+Pb collisions: Reaching rapidities y = 5.8 corresponds to a $W_{\gamma p}$ = 3.6 TeV!

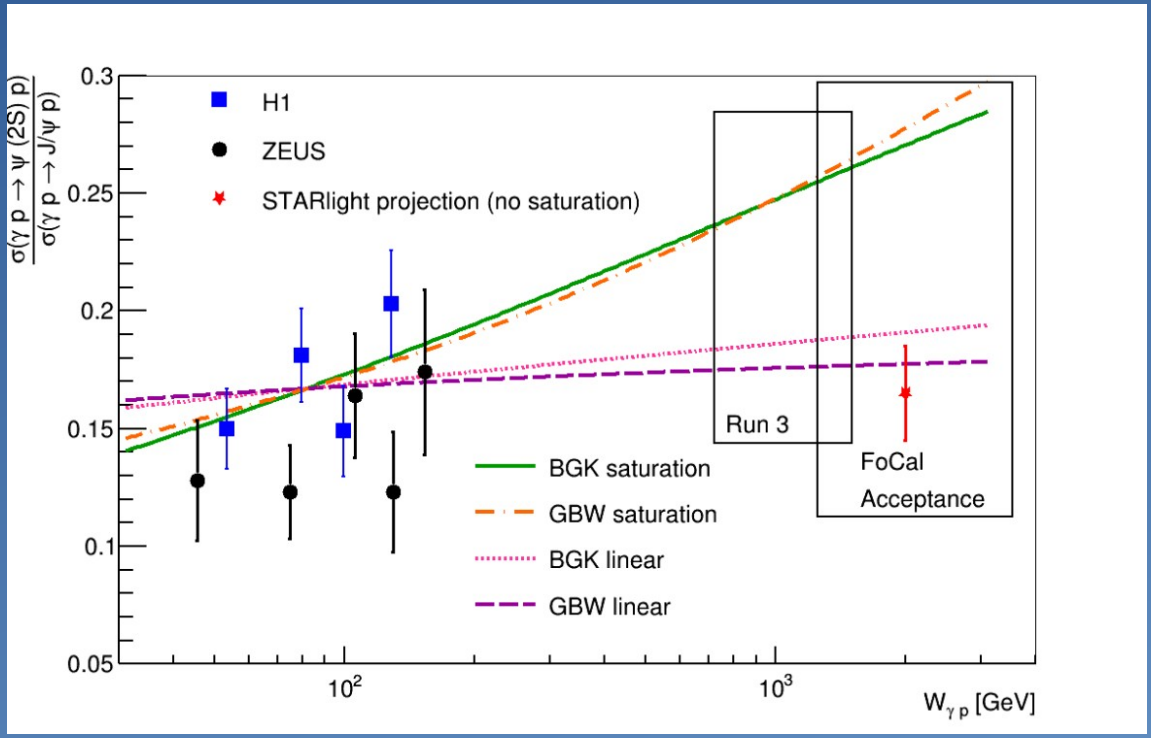
FoCal will thus provide a significant increase in energy!




Work done together with Daniel Tapia Takaki and Alexander Bylinkin.

# Vector meson photoproduction in the forward direction

Measuring the ratio $\sigma(\gamma+p \rightarrow \psi'+p)/\sigma(\gamma+p \rightarrow J/\psi+p)$ might improve the sensitivity to saturation.




M. Hentschinski et al., arxiv:2203.08129.

The STARlight point includes the expected statistical error.

# Vector meson photoproduction in the forward direction

Estimates of the yield in FoCal for Pb+p, acceptance for electrons $3.4 < \eta < 5.8$, calculations with Starlight, for 150 $nb^{-1}$:

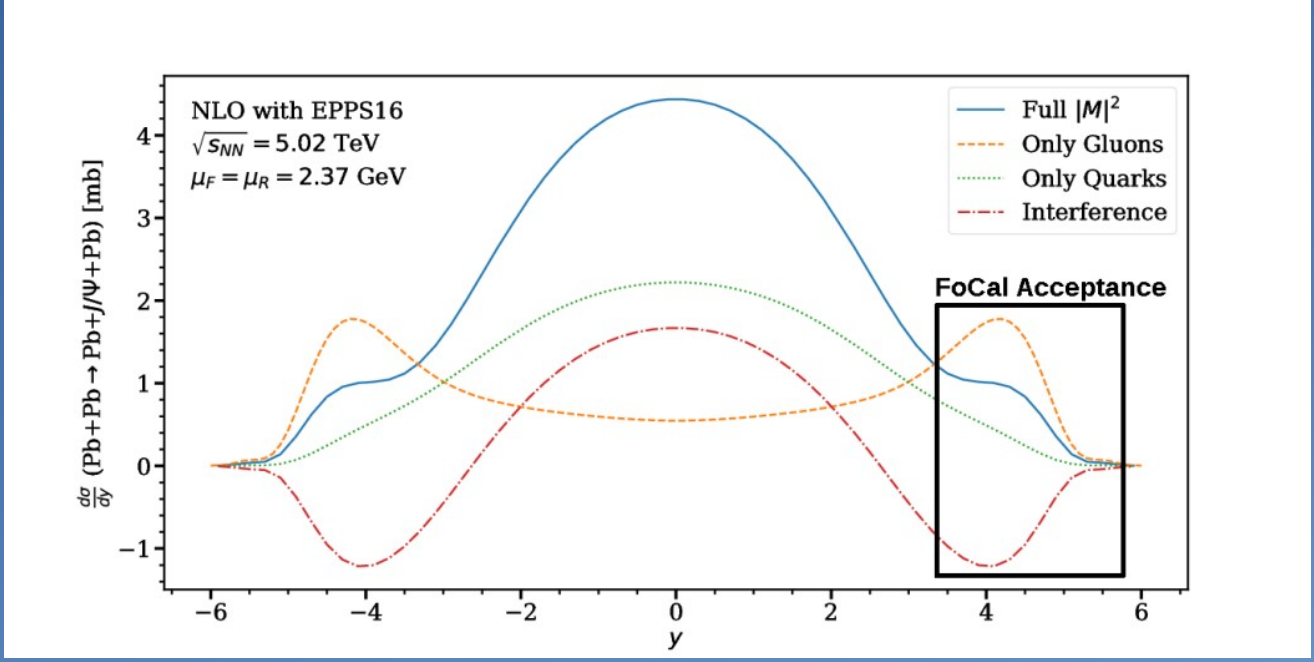
| | |
|---|---|
| J/$\psi$: | 5,400 |
| $\psi$': | 80 |

The uncertainty on the ratio dominated by the statistical error from the $\psi$', $\approx$11%.

# Vector meson photoproduction in the forward direction

FoCal also of interest for J/ψ production in Pb+Pb.

The interference between gluon and quark contributions largest at forward rapidity, right at the acceptance of FoCal.



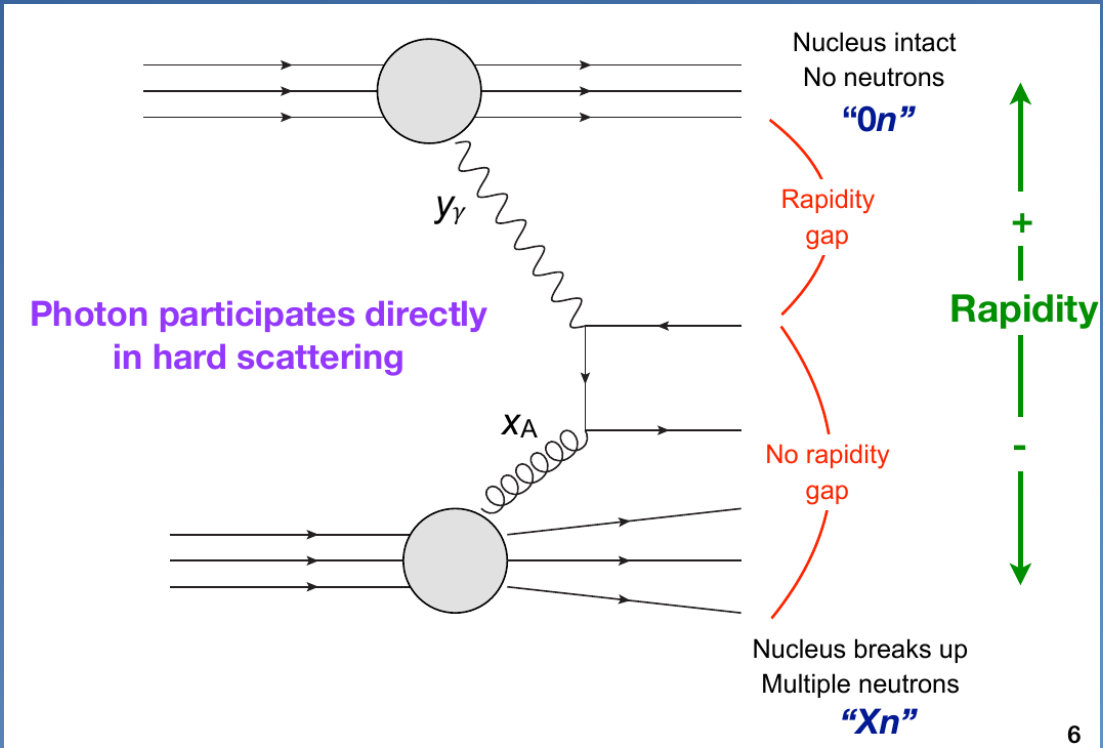

K. Eskola et al., arxiv:2203.11613.

# Photonuclear interactions with nuclear break up

A photon from the field of one nucleus may interact with the other (target) nucleus in several different ways, $\gamma + A \rightarrow X$.

The photon emitting nucleus remains intact, the target nucleus breaks up.

One rapidity gap between photon emitting nucleus and "target" nucleus.

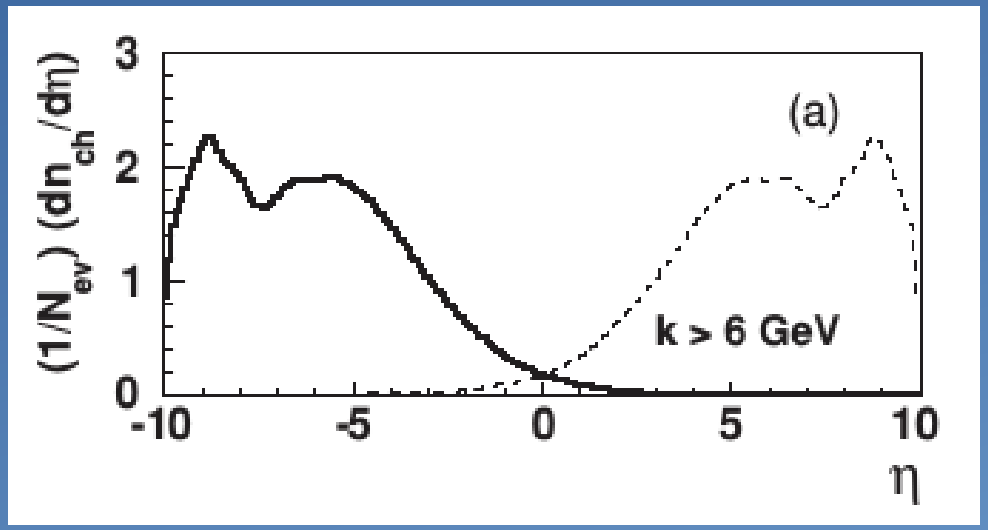


# Photonuclear interactions with nuclear break up

The bulk particle production studied by combining the photon spectrum from starlight with DPMJET to simulate the reaction $\gamma + \mathrm{A} \rightarrow \mathrm{X}$.

The cross sections are huge! The cross section for having at least one charged particle inside $|\eta| < 1$ in a Pb+Pb collision is 4.5 b.

The energy of the photon is always << energy of the beam ==> The production is shifted away from midrapidity

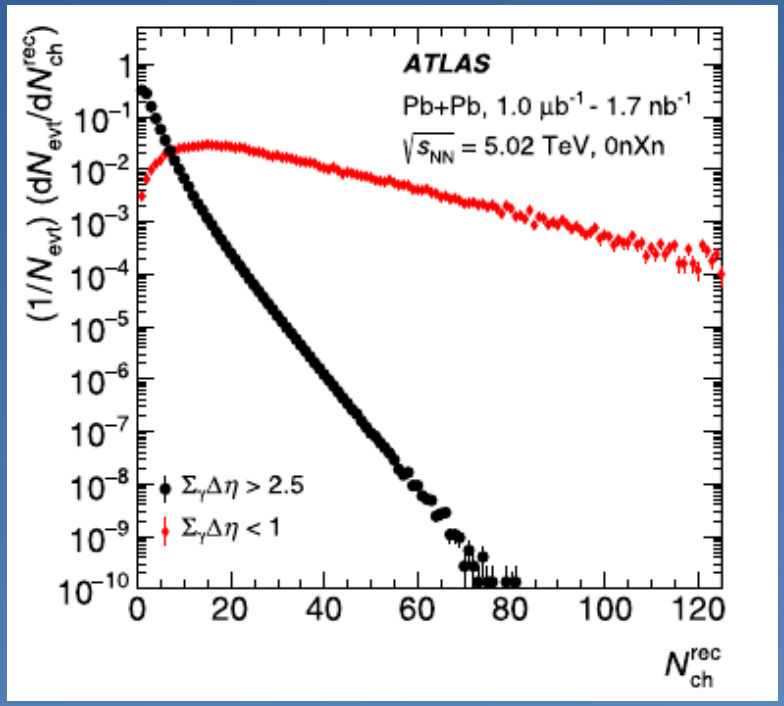



Ø. Djuvsland, J. Nystrand, Phys. Rev. C 83 (2011) 041901).

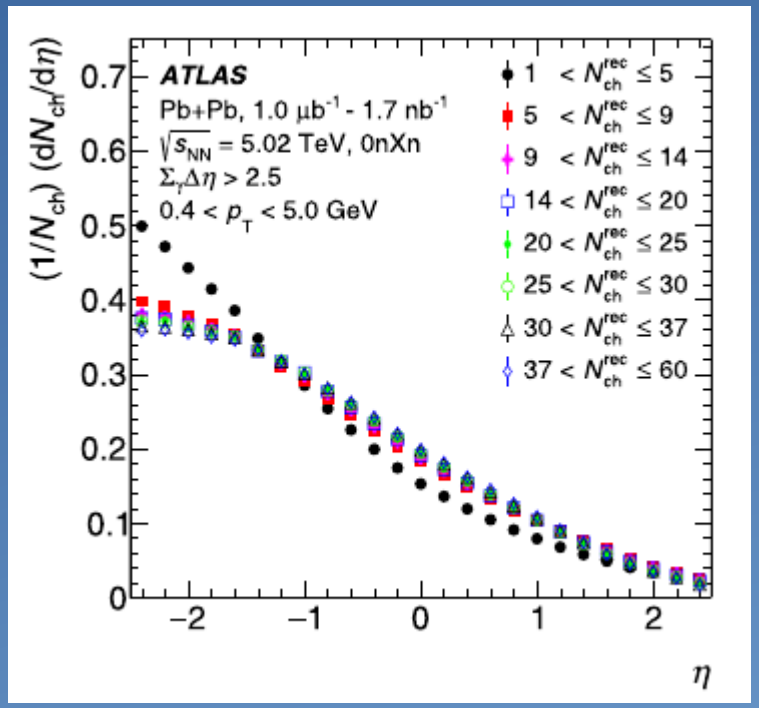
# General photonuclear interactions

A first paper from ATLAS last year on "Two-partical azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS" Phys. Rev. C 104 (2021) 014903.

Multiplicity and pseudo-rapidity distributions for $\gamma$+Pb events.




The multiplicity is generally much lower in photonuclear events (black) than in hadronic Pb+Pb events (red). and pseudo-rapidity distributions for $\gamma$+Pb events.



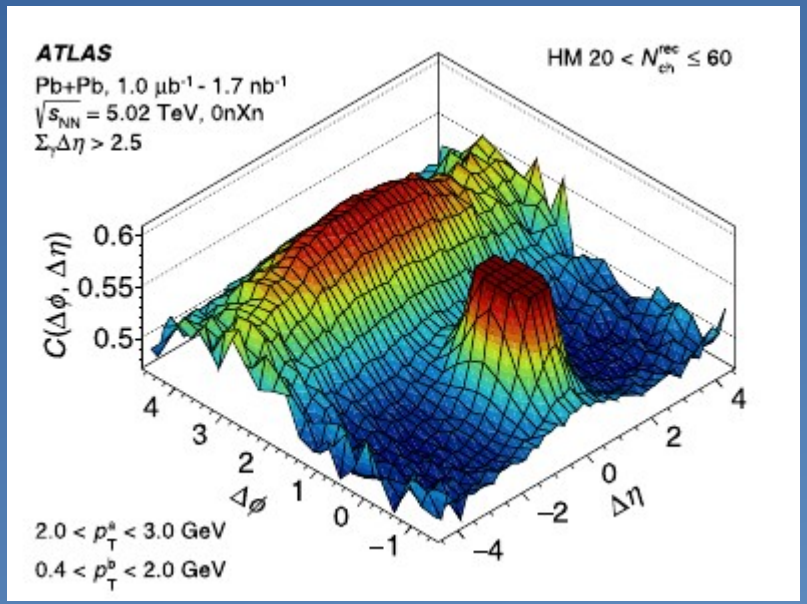

The rapidity distribution of charged particles is shifted away from midrapidity.

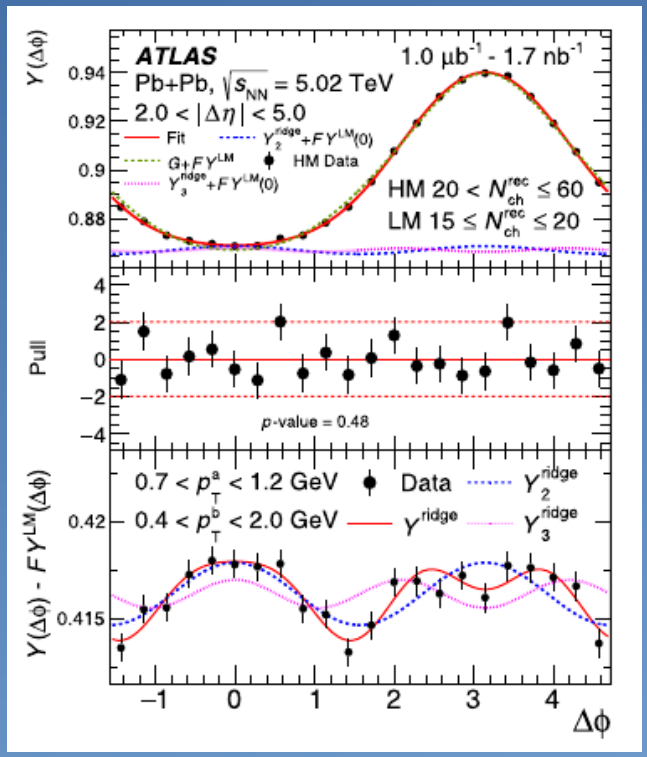
# General photonuclear interactions

Results on flow:

-Use the Fourier coefficients $v_2$ and $v_3$, well known in heavy-ion physics.

Main result: One observes non-zero $v_2$ and $v_3$.

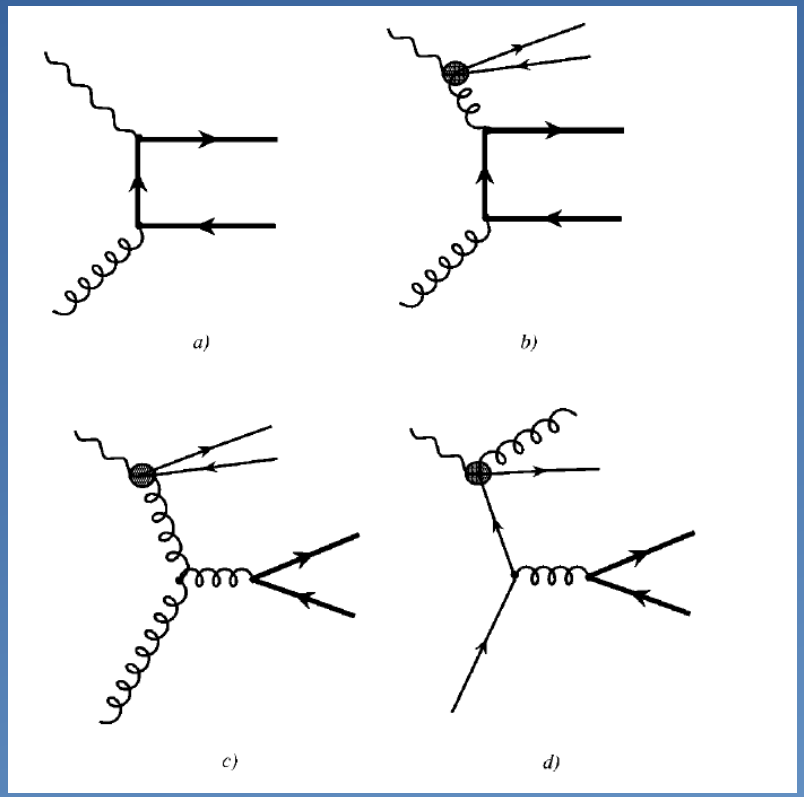


# General photonuclear interactions

Many other processes can be studied as well, for example photoproduction of heavy quarks. See S.R. Klein, J. Nystrand, R. Vogt, Eur. Phys. J C 21 (2001) 563; Phys. Rev. C 66 (2002) 044906.

Cross sections for direct and resolved production of ccbar and bbar pairs calculated.




Total cross sections at the LHC:

$\sigma(Pb+Pb \rightarrow Pb + ccbar + X) = 2\ b$

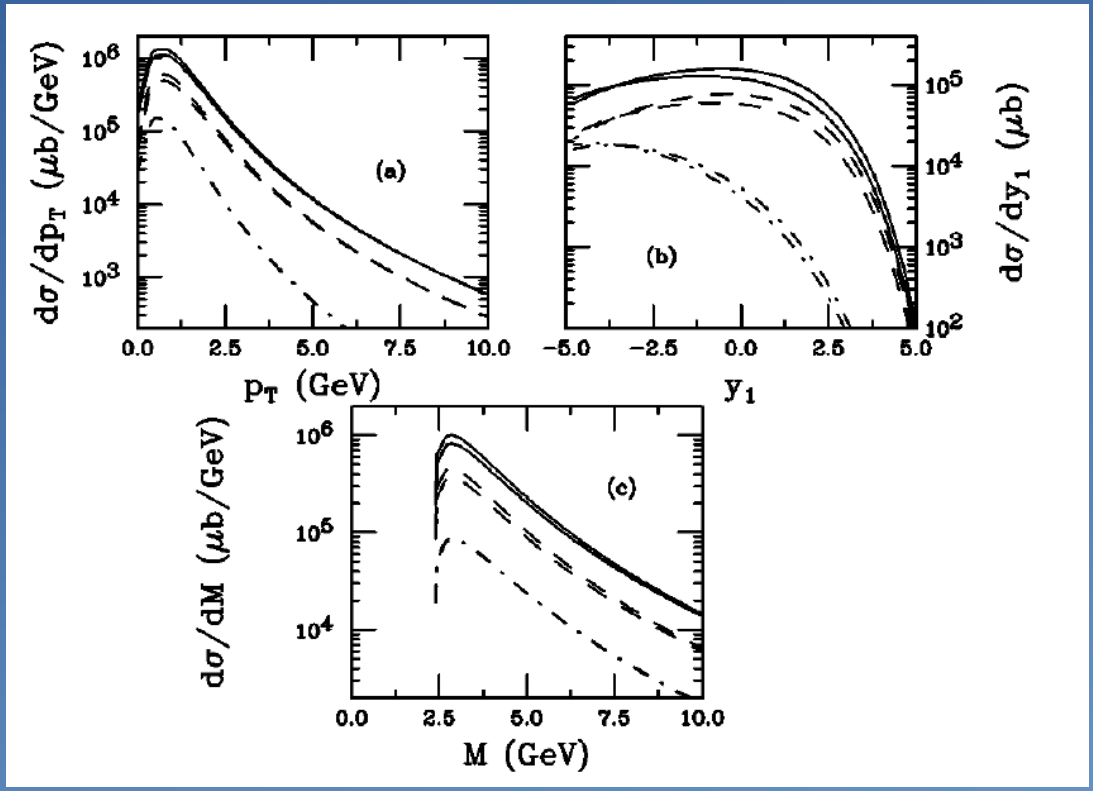
$\sigma(Pb+Pb \rightarrow Pb + bbbar + X) = 830\ \mu b$

A small fraction of the hadroproduction cross sections, but still large.

# General photonuclear interactions

Photoproduction of ccbar in ultra-peripheral Pb+Pb collisions at the LHC.

Single quark $p_T$ and rapidity distributions, $m_{inv}$ distribution of the ccbar pair.




S.R. Klein, J. Nystrand, R. Vogt, Phys. Rev. C 66 (2002) 044906.

# Summary

- After 10 years of data taking at the LHC, high-statistics measurement of exclusive J/ψ photoproduction by several experiments.

- Biggest issue: What is the correct theoretical interpretation of these results (i.e. how do they constrain the nuclear/proton parton distributions).

- Large cross sections for photonuclear production of heavy quarks through γ+gluon fusion. No experimental studies so far.