# An overview of ultra-peripheral collisions

”Orlando fest”

University of Birmingham, Birmingham, 16 May 2023

Joakim Nystrand
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# Outline

- What are Ultra-Peripheral Collisions (UPCs).

- Early (theoretical) developments in the 1930's.

- Ultra-relativistic heavy-ion collisions.

- Exclusive Vector Meson production.

- Saturation in QCD.

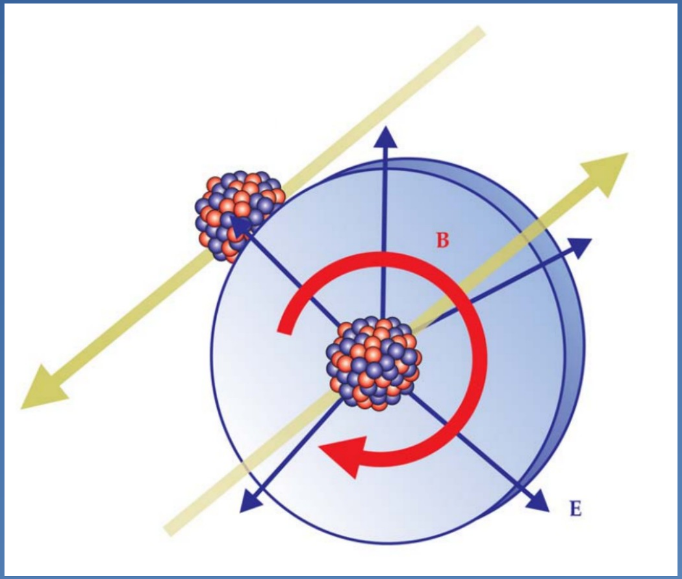
First a note:
I first met Orlando at a conference in Calcutta in 1993.


Since ≈2010 we have both worked on implementing a program for UPC in ALICE.

# What are Ultra-peripheral Collisions?

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

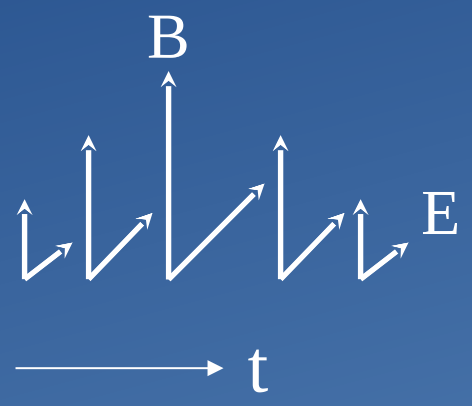
Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.




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

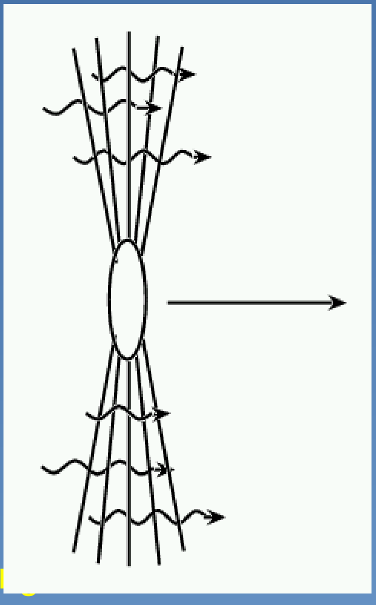
Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

# Electromagnetic fields of a moving charged particle




1) $|E| \approx |B|$ 2) $(E \perp B)$ 3) $\Delta t \sim b/\gamma c$

Fermi 1924: The effect of the field is equivalent to a flux of of photons with a continous energy spectrum. (hep-th/0205086)



Pulse width $b/\gamma c$ $\leftrightarrow$ the spectrum contains photons w/ $\omega < \gamma c/b$

Quantum Mechanical derivation 1934 by Weizsäcker,Williams. $\Rightarrow$ *Weizsäcker-Williams method*

We can calculate $n(\omega)$ through a Fourier transform.

# Early developmens in the 1930's

The origins go back to the Dirac equation, the discovery of the positron, and the rudimentary quantum field theories of the 1930's.

1928: Publication of the Dirac equation.

1932: Discovery of the positron (C.D. Anderson), "predicted" by the Dirac equation.

1934: Calculation of the cross section $\gamma\gamma \rightarrow$ e+e- (Breit-Wheeler).

1935: Calculation of the cross section $\gamma\gamma \rightarrow \gamma\gamma$ (Euler, Kockel, Heisenberg).

1933-1937: Calculation of the cross section for two-photon production of $e^+e^-$ pairs in nucleus-nucleus collisions (Furry, Carlson, Landau, Lifshitz, Bhabha, Racah, Nishina,Tomonaga).

# Early developmens in the 1930's

From the paper by W.H. Furry, J.F. Carlson, Phys. Rev. 44 (1933) 237:

The experimental discovery of the positive electron makes possible, as has recently been observed by Oppenheirner and Plesset, a consistent development of Dirac's theory of the electron, in which the appearance of pairs (electron and anti-electron) plays an important part. *It appears that, in the experimental production of the pairs, the Coulomb fields, especially those of nuclei, are most important.*

**On The Production of Positive Electrons by Electrons**

The experimental discovery of the positive electron makes possible, as has recently been observed by Oppenheimer and Plesset,[1] a consistent development of Dirac's theory of the electron, in which the appearance of pairs (electron and anti-electron) plays an important part. It appears that, in the experimental production of the pairs, the Coulomb fields, especially those of nuclei, are most important. In this case the theory shows that radiation of energy greater than $2mc^2$ is required for their production. Oppenheimer and Plesset have made a preliminary study of the production of pairs by $\gamma$-rays; we have carried through the analogous work for their production by high energy electrons (and positives). For $\gamma$-rays it appears, both from OP and from the experiments of Anderson, that the production of pairs becomes increasingly important as the energy of the $\gamma$-rays is increased; we have wanted to see whether this

[1] J. R. Oppenheimer and M. S. Plesset, Phys. Rev. **44**, 53 (1933) (hereafter referred to as OP).

# Early developmens in the 1930's

Also the idea to study photonuclear interactions is from these times

*Charged particles are able to excite nuclei without penetrating into the nucleus by means of the action of the their electric field upon the nucleus when they pass nearby.*
V.F. Weisskopf, Physical Review, 1938.

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This was the basis for several nuclear structure experiments in the 1950’s and 1960’s, where one bombarded a target nucleus with another nucleus with an energy below the Coulomb barrier.

But for a long time, the energy of hadronic/nuclear beams were not high enough to investigate particle production.

⇨ The energy frontier of electromagnetic (and weak) interactions used to be with lepton beams.

# The first hadron collider

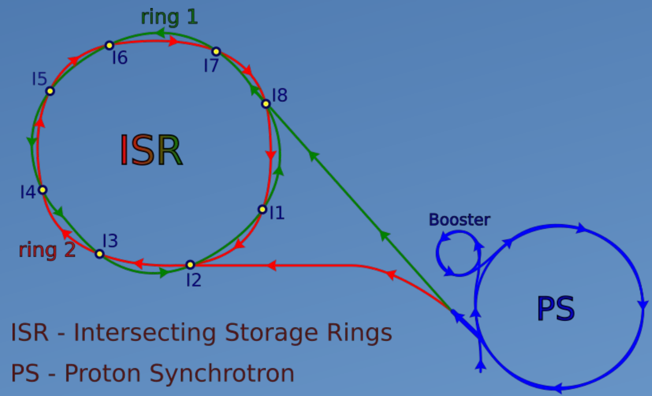
First obeservation of particle production in an ultra-peripheral collision between protons:

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

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 α-particles, in operation 1971 – 1984, maximu energy $\sqrt{s}$ = 62 GeV.

The world's first hadron collider.



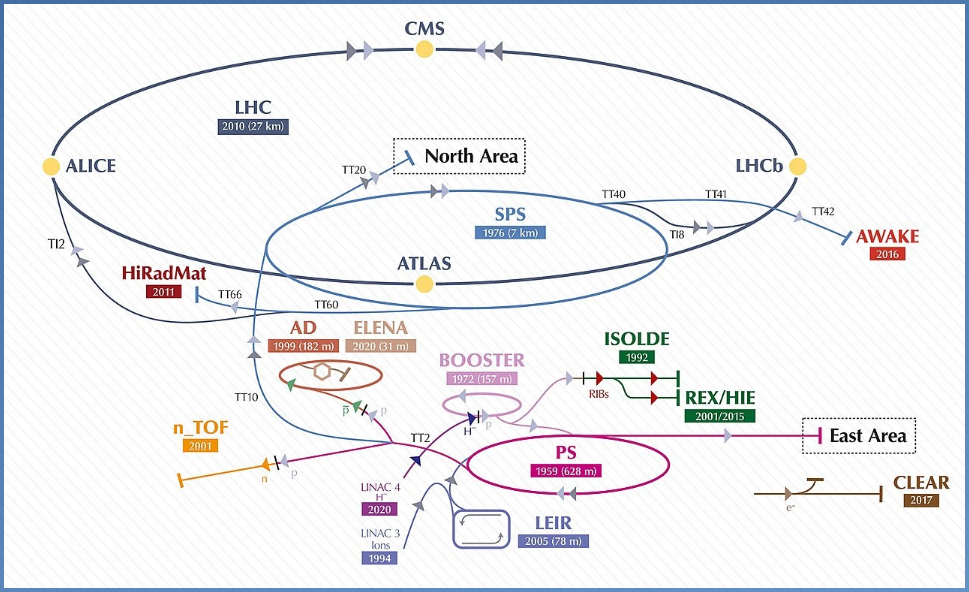

# Ultra-relativistic heavy-ion collisions

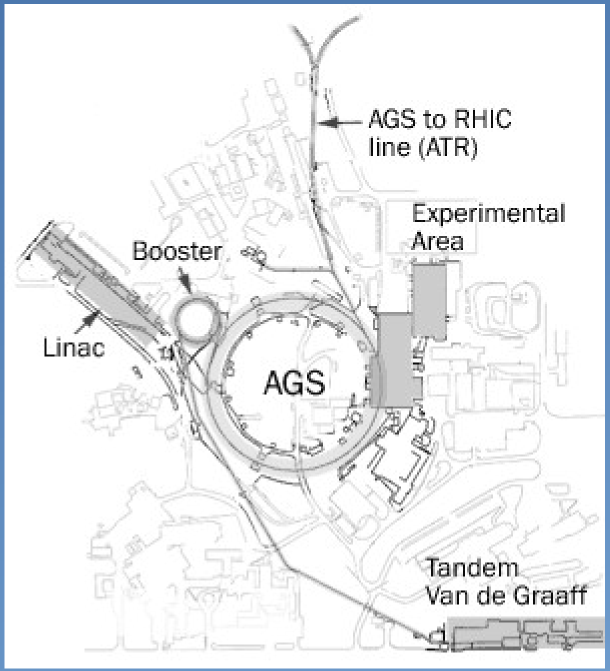
Start of the utlra-relativistic heavy-ion program in 1986:

Acceleration of oxygen ions at the AGS and SPS (followed, respectively, by Au in 1992 and Pb in 1994).

AGS – The Alternating Gradien Synchroton at Brookhaven National Laboratory, fixed target experiment, √s = 4.9 GeV.

SPS – The Super Proton Synchrotron at CERN, fixed target experiments,√s = 17.4 GeV.



# Ultra-relativistic heavy-ion collisions

Energy too low for any significant particle production in UPC. But two-photon proudction of e+e- pairs could, and was, studied resulting in a few paper.

AGS: A. Belkacem, N. Claytor, T. Dinneen, B. Feinberg, and H. Gould, Phys. Rev. A 58 (1998) 1253.

SPS: C. R. Vane, S. Datz, P. F. Dittner, H. F. Krause, C. Bottcher, M. Strayer, R. Schuch, H. Gao, and R. Hutton Phys. Rev. Lett. 69 (1992) 1911 S-beams at SPS
R. Baur et al. [CERES/NA45 Collaboration], Phys. Lett. B 332 (1994) 471.

Rather hard to compare to measurements at colliders because of the analysis methods and variables used. The general conclusion is “the results are in agreement with QED calculations”.

# Ultra-relativistic heavy-ion collisions

To maintain coherence, the maximum photon energy with a hadronic/nuclear beam will be ~$\gamma\hbar c/R$
$\gamma$ – Lorentz factor of the beam
R – Hadron/nuclear radius

At RHIC $\sqrt{s}$ = 200 GeV ==> $\gamma \approx 100$ with R = 7 fm ==> $E_{max} \approx 3$ GeV.

Final states with $m_{inv} \leq \sim 6$ GeV can be studied.

At LHC $\sqrt{s}$ = 5 TeV ==> $\gamma \approx 2700$ with R = 7 fm ==> $E_{max} \approx 75$ GeV.

Final states with $m_{inv} \leq \sim 150$ GeV can be studied.

# Ultra-relativistic heavy-ion collisions

There was a workshop at BNL in 1990 ”Can RHIC be Used to Test QED”

CONF-9004261--Summ
BNL-45842

OG 1160

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**

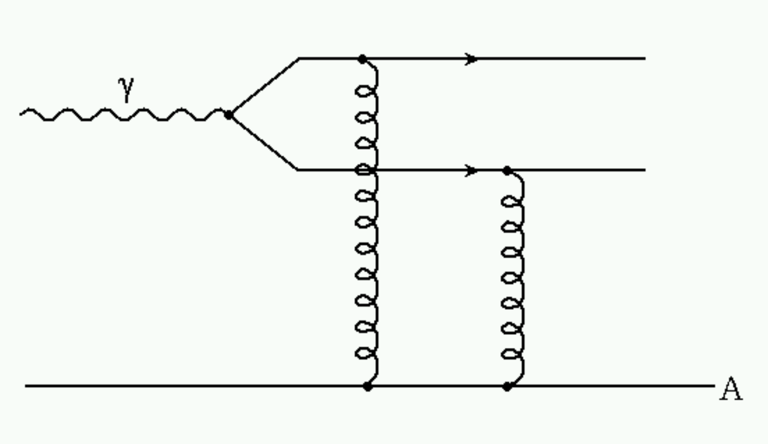
**The two day workshop entitled "Can RHIC be Used to Test QED" took place on April 20 - 21 at Brookhaven National Laboratory. It was attended by approximately 50 physicists from both the U.S. and Europe. Although most of the attendees were theorists, a**

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

# Exclusive vector meson production

An alternative method (to γγ) to produce a final state is through an exclusive photonuclear interaction, in particular exclusive vector meson production.

Both nuclei remain intact - a vector meson is produced, Pb+Pb → Pb+Pb+V.




Two gluons can be exchanged without color transfer ↔ exchange of a Pomeron

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

Ryskin 1993

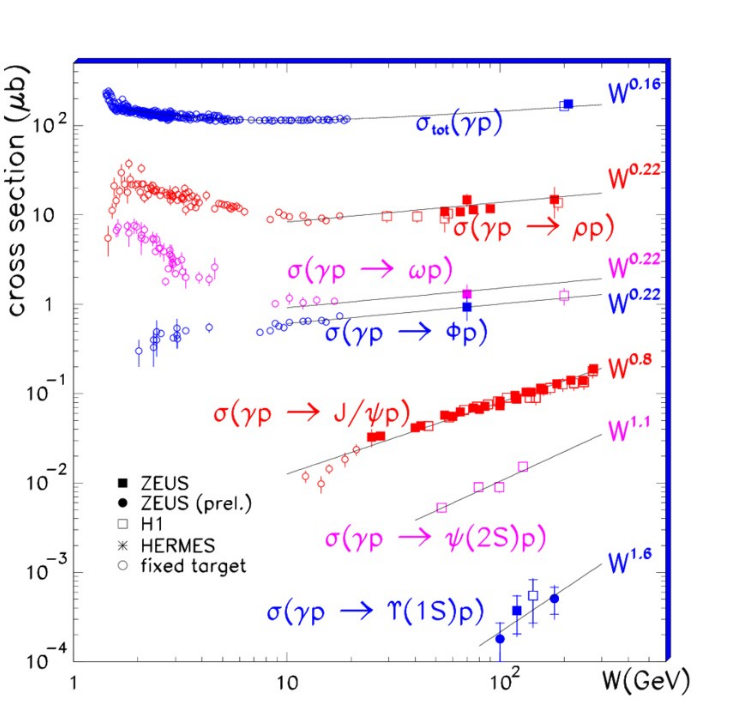
⇒ Sensitive probe of g(x), $[(g(x))^2]$

# Exclusive vector meson production

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

They had 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.



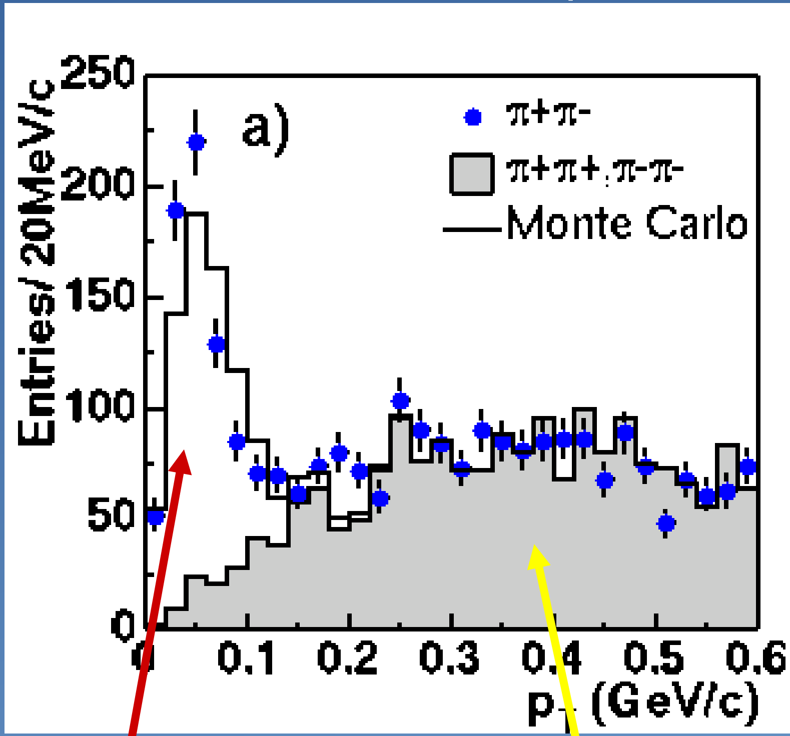
# The first UPC result from RHIC

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.



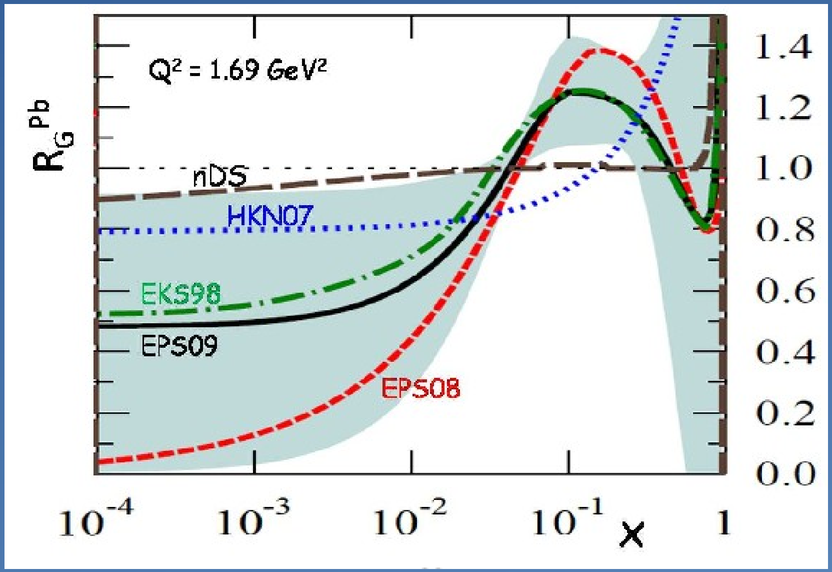

Signal+background, unlike-sign pairs

background, like-sign pairs

# Exclusive vector meson production

How do the cross sections scale from γ+p to γ+A?

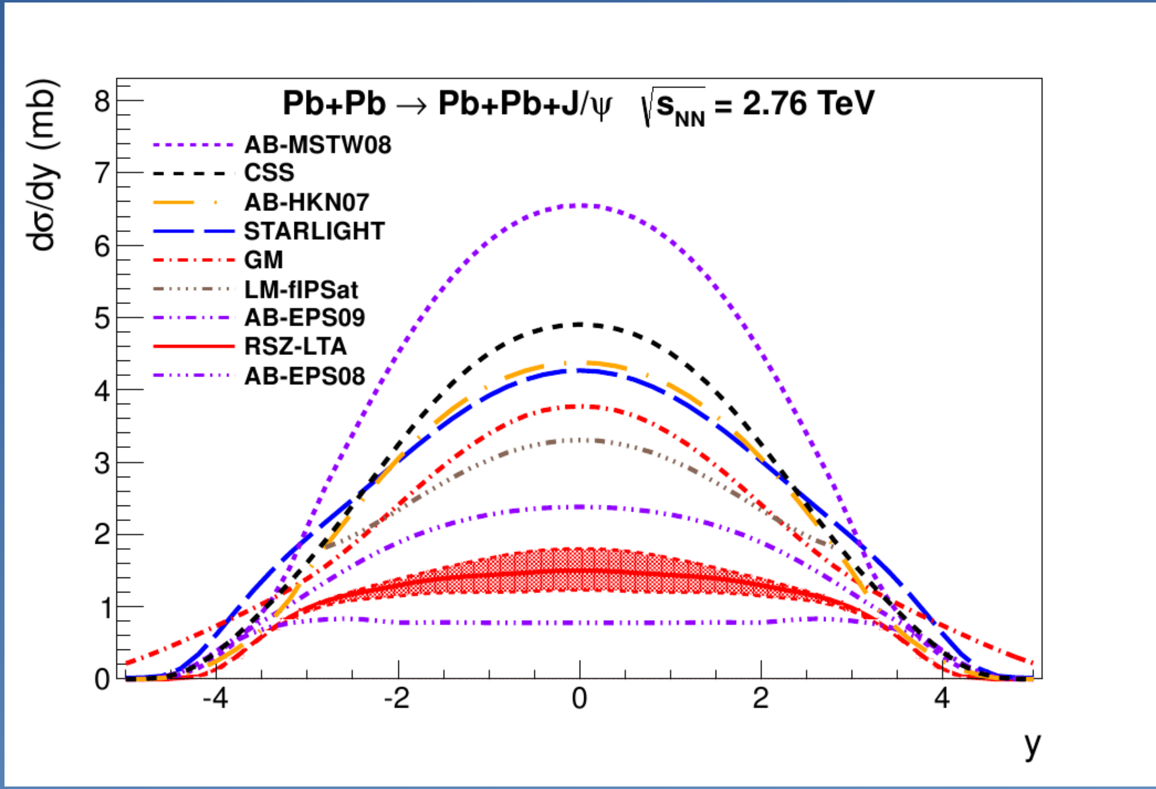
Big uncertainties in the nuclear gluon distributions.




Rather than using directly the leading order calculation, other calculations start from the color dipole model.

# Exclusive vector meson production

This was the situation before LHC.



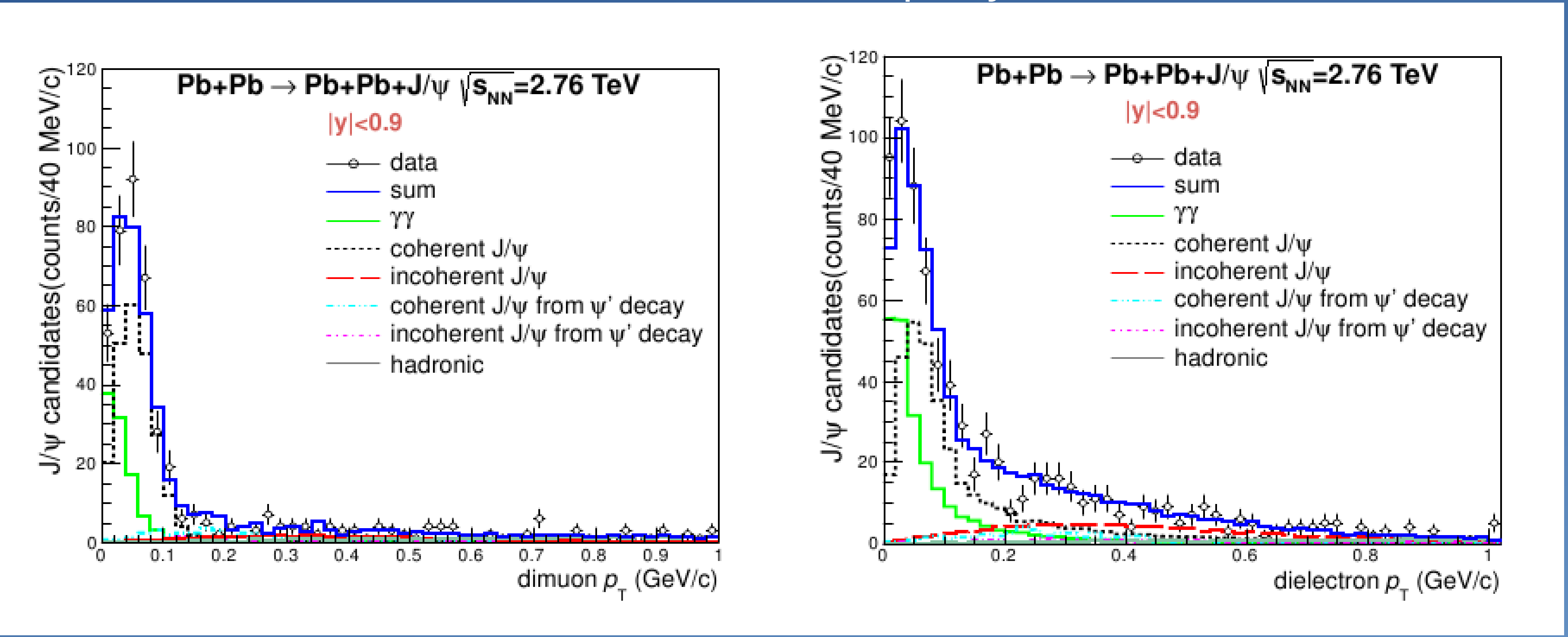
# Exclusive vector meson production

Results from ALICE

$J/\psi \to ee/\mu\mu$

*Two tracks in an otherwise empty detector*

Transverse momentum distributions – midrapidity

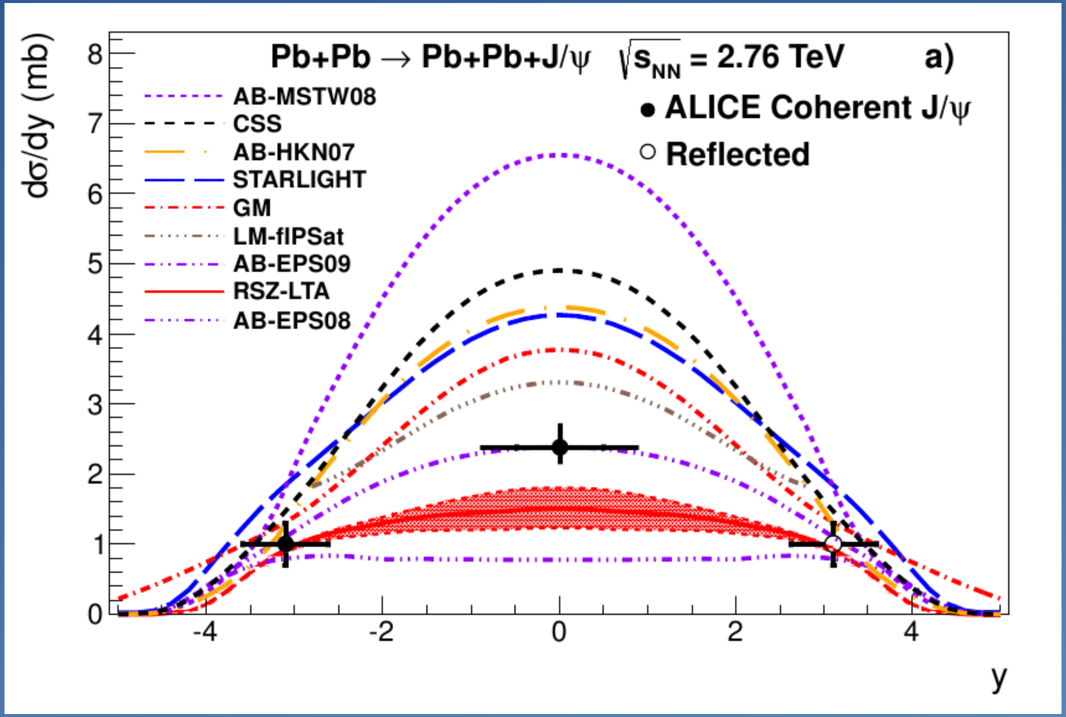



Clear coherent peak from J/ψ and continuum $\gamma\gamma \to l^+l^-$ observed at low $p_T$.

Full spectrum explained by, in addition, incoherent J/ψ, J/ψ from feed down from ψ', and some hadronic contribution at high $p_T$.

# Exclusive vector meson production

First results on UPC at the LHC from ALICE




ALICE Collaboration

Phys. Lett. B 718 (2013) 1273

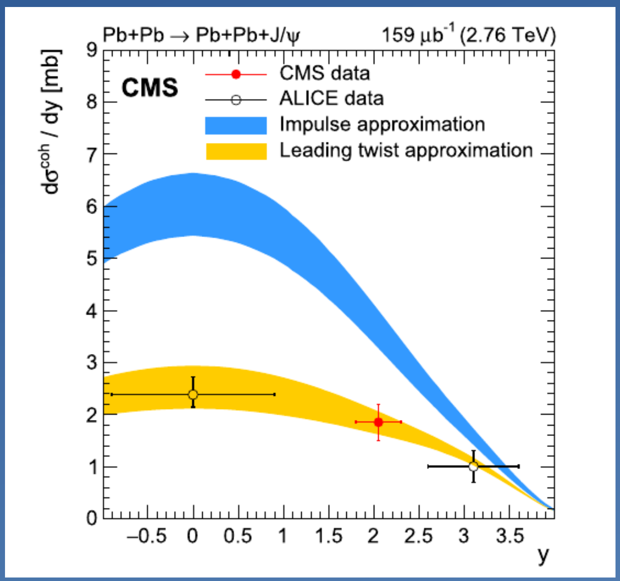
and

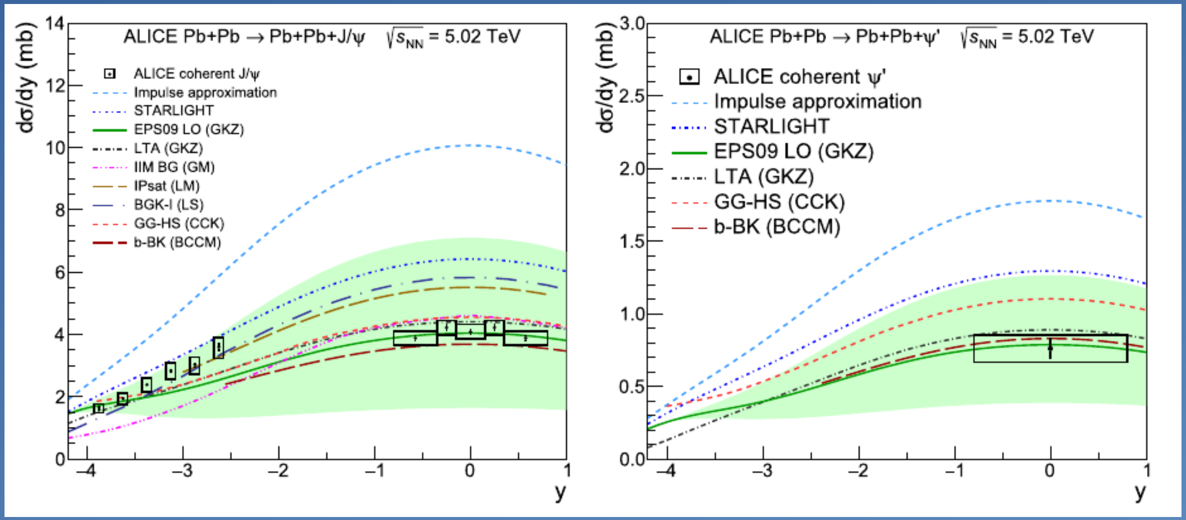
EPJ C 73 (2013) 2617.

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 Eur. Phys. J. C 82 (2021) 712

# Exclusive vector meson production

The results have also triggered new theoretical developments.

**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)

Phys. Rev. C 106 (2022) 035202.

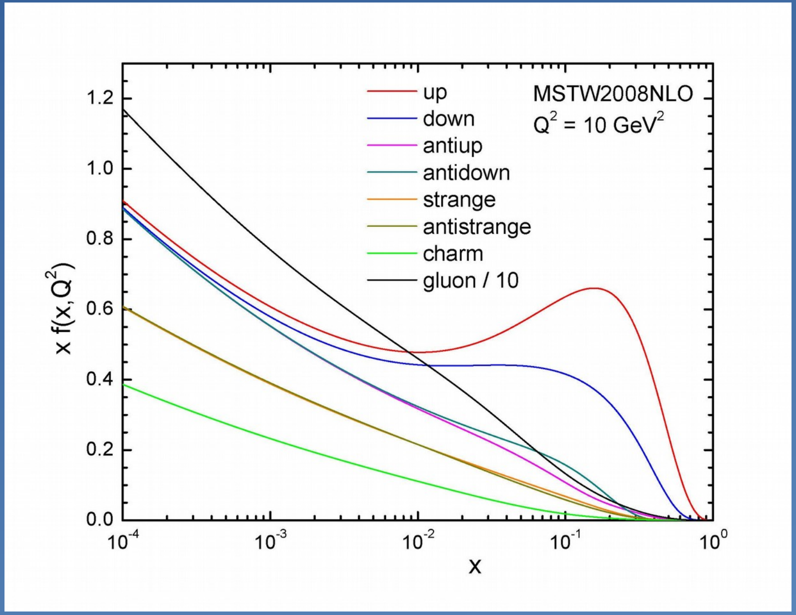
There are big differences between LO and NLO calculations and uncertainties on the relevant scale.

An ongoing development to understand these interactions and how they probe QCD.

# Saturation in QCD

Back to the $\gamma + p \rightarrow p + V$ results.

The proton gluon distribution exhibits a rise with 1/*x* for low values of Bjorken-x.




This rise cannot continue to arbitrary small *x* as it would violate unitarity.

# Saturation in QCD

Before the start up of HERA, one had expected to see a deviation from the $1/x$ behaviour at low values of $x$.

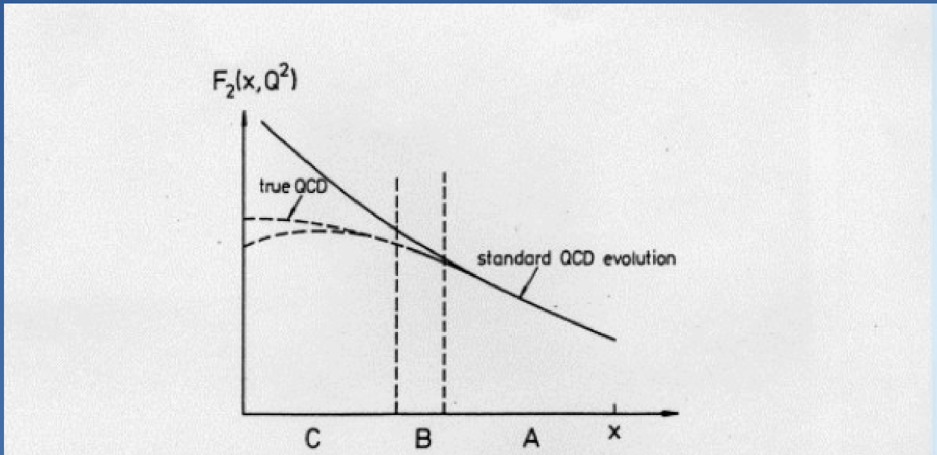
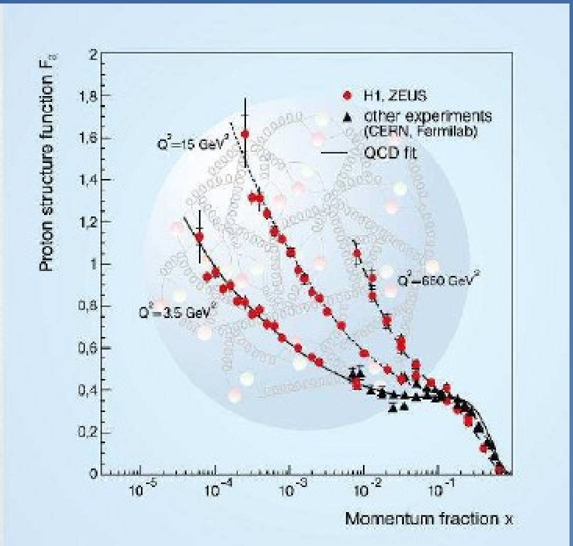



**Figure 2:** *Small-x behavior of the structure function: standard QCD evolution versus "true QCD" evolution. A is the perturbative region, B the transition region, C the nonperturbative region.*




R. Yoshia, Proc. XXXVIII Intl. Symp. Mult. Particle Dynamics (http://dx.doi.org/10.3204/DESY-PROC-2009-01/67).

But after 15 years of data taking at HERA there were no unambigous signs of such a deviation.

The effect is expected to set in at higher values of x in nuclei (which were never studied at HERA), roughly at a scale $Q_s^2 \sim A^{1/3} x_p$.

# Probing low-x PDFs in protons in ultra-peripheral p-Pb

Exclusive photoproduction of J/ψ measured by ALICE in p-Pb collisions (Eur. Phys. J C 79 (2019) 402).

The photon flux scales as $Z^2$, so the photons are predominantly emitted by the Pb-nucleus and the proton is the target.

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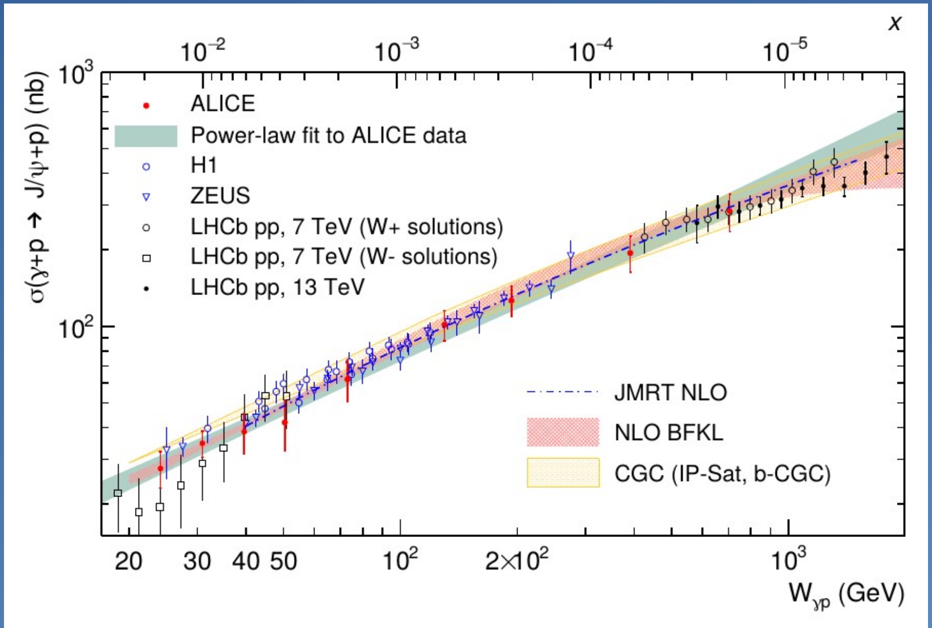



ALICE Collaboration, arxiv:2211.04384.

ALICE results follow the same trend as seen at HERA.

No deviation from a power law seen for energies up to $W_{\gamma p}$ = 700 GeV ($x \approx 2\cdot10^{-5}$).

*"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).

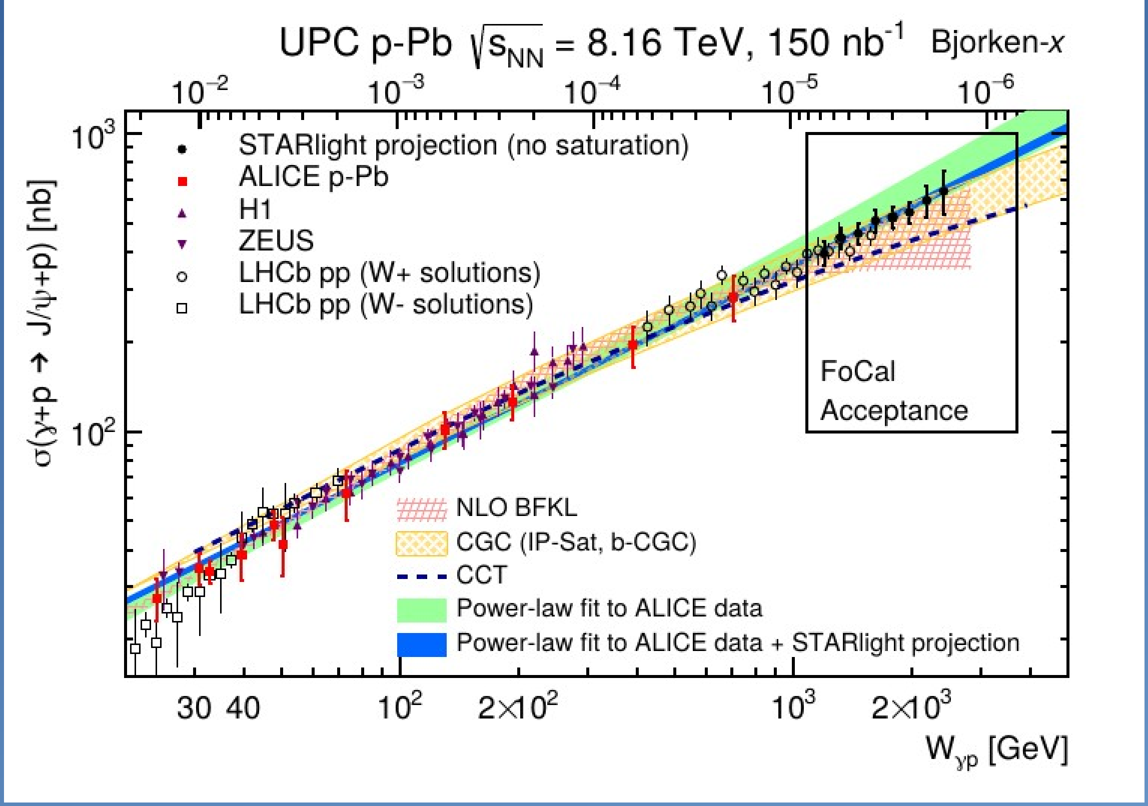
Results from LHCb from p+p collisions. There is an ambiguity in the extraction of the low energy/high energy component.

# Probing low-x PDFs in protons in ultra-peripheral p-Pb

The situation can be improved in Run 4 with the Forward Calorimeter (FoCal) in ALICE.

FoCal acceptance: $3.8 < \eta < 5.8$

The most forward rapidities correspond to x-values below $10^{-6}$.




A. Bylinkin, J. Nystrand, D. Tapia Takaki, arxiv:2211.16107.

# Summary

- Ultra-peripheral collisions is currently the energy frontier for photon-induced interactions.

- An essential element to study them has been to have a working trigger.

- Exclusive vector meson production probes the proton/nuclear gluon structure.

- May reveal the presence of gluon saturation.