Exploring the nuclear structure with vector mesons in UPCs

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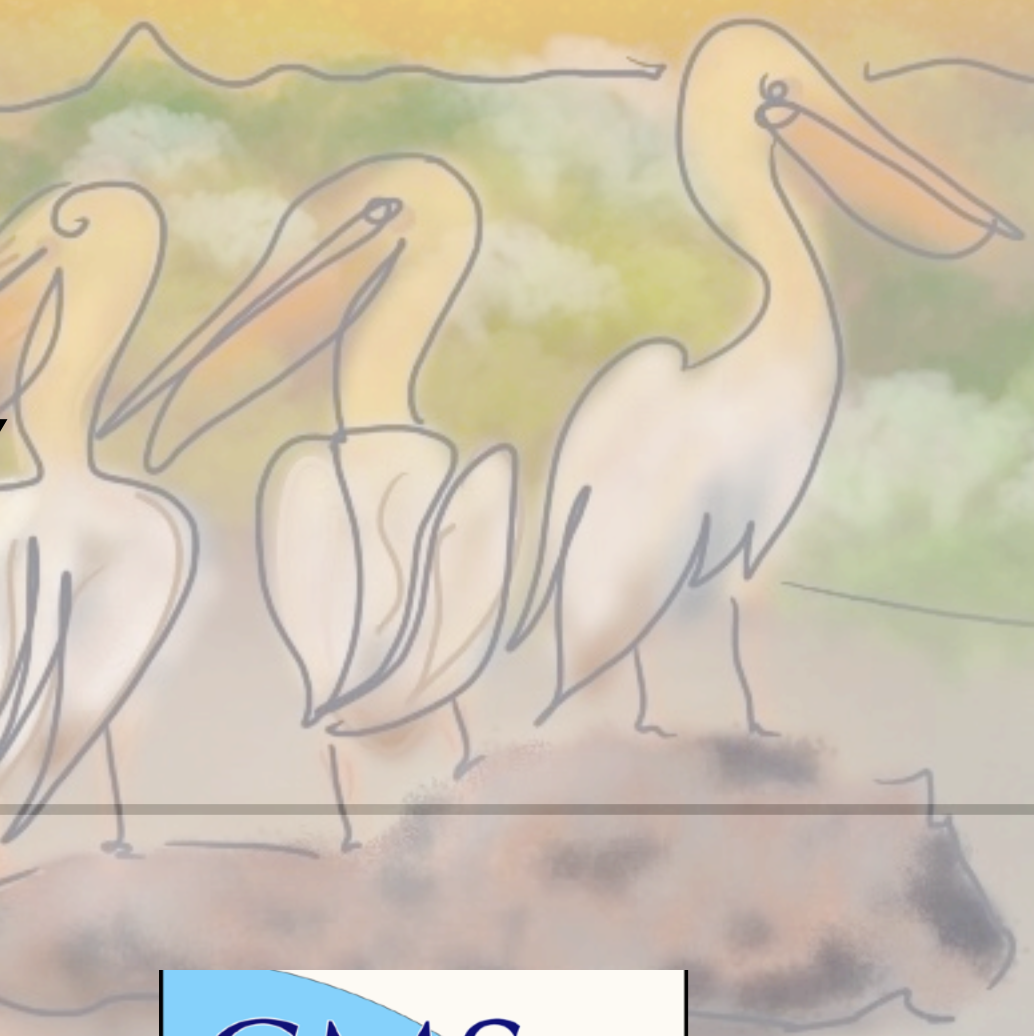


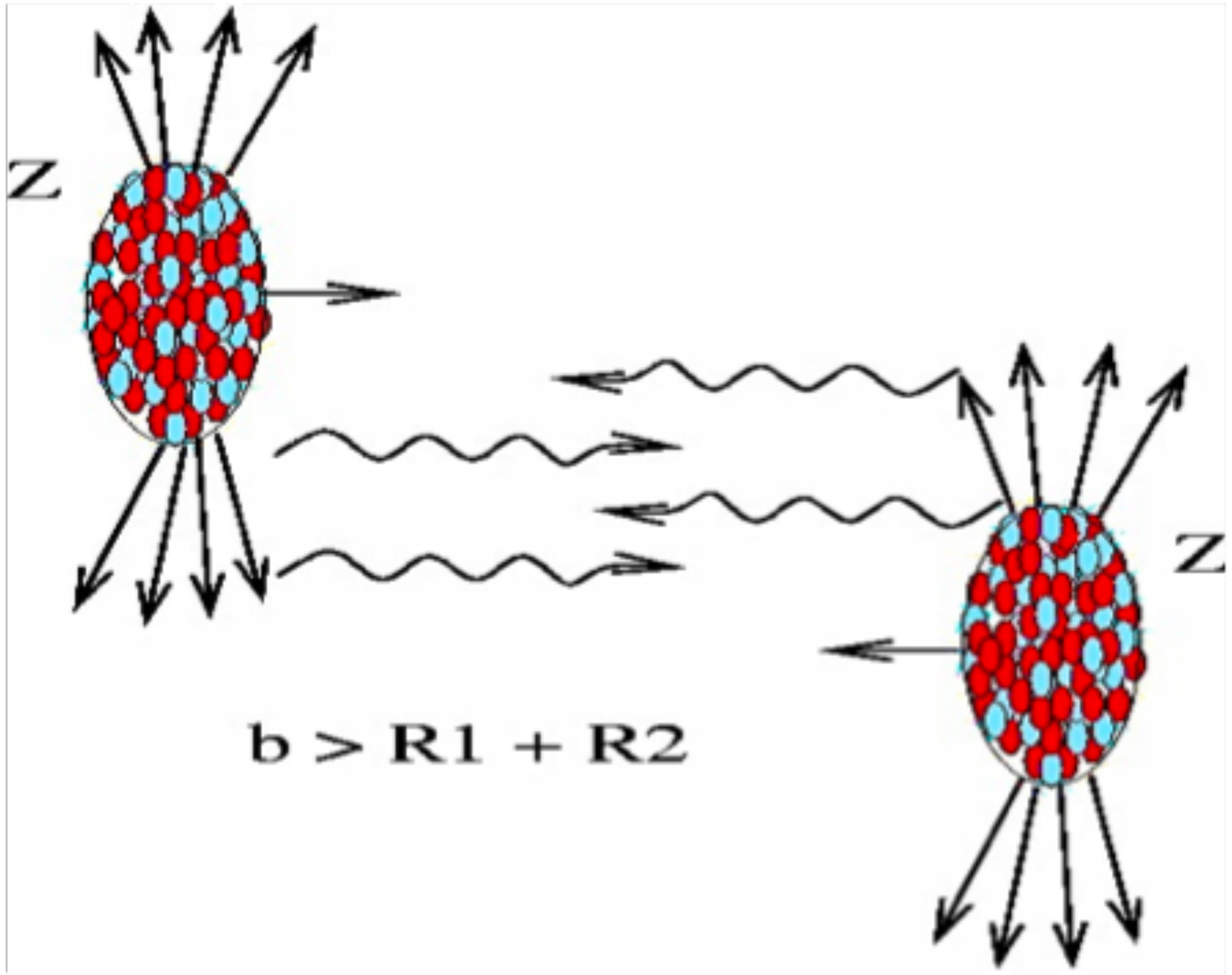
New trends in HEP and low-x physics
Sfantu Gheorghe, Romania
Sept. 3, 2024

OUTLINE

- **Ultraperipheral collisions**
- **Vector meson photoproduction**
- **Heavy quarkonia**
- **Light vector mesons**
- **Summary**

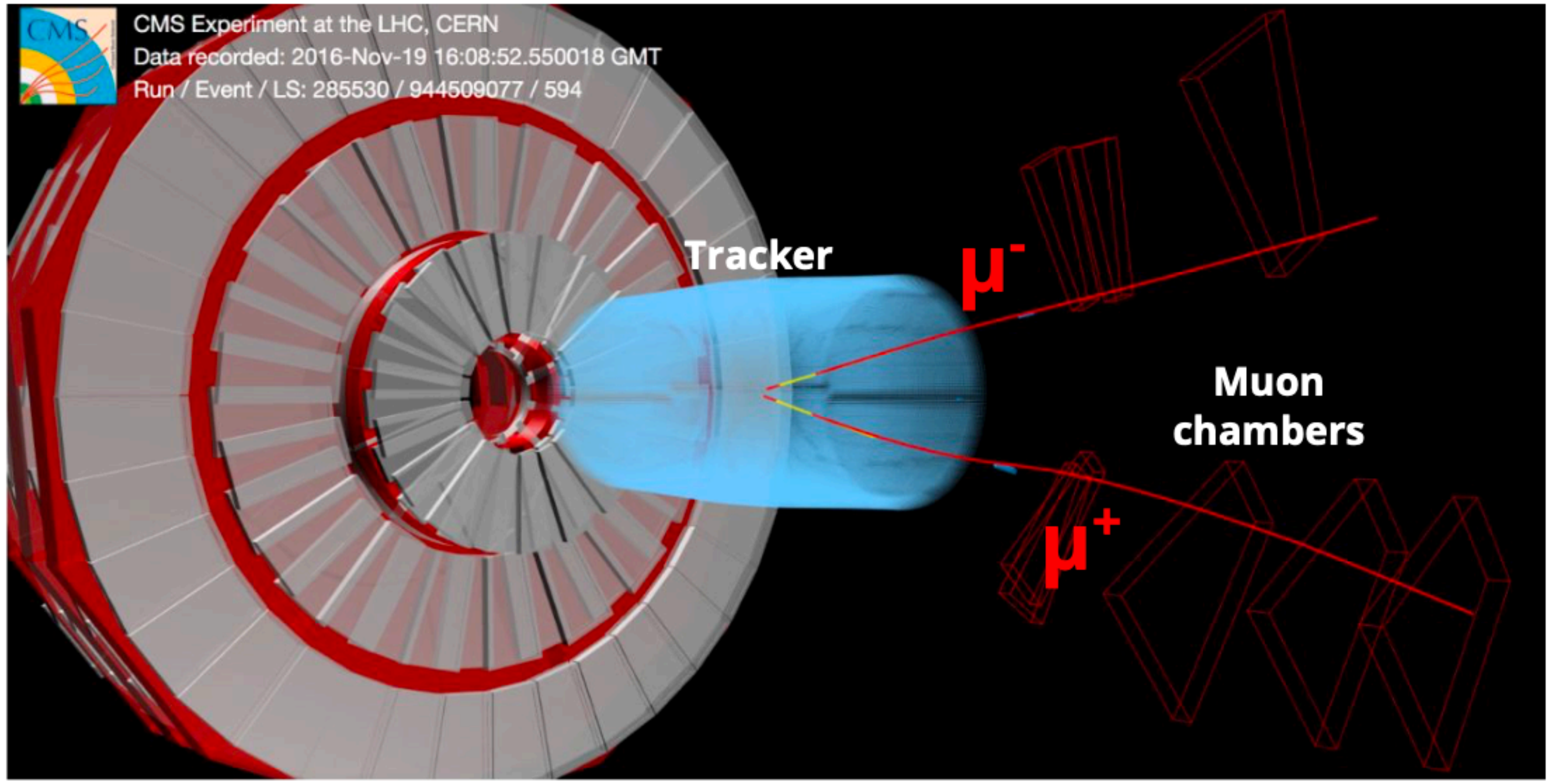
Ultrapheripheral collisions (UPCs)

- When ions don't "touch" each other: Impact parameter $b > R_1 + R_2$:
- These processes dominate nucleus-nucleus cross section.
- Electromagnetic (photon) interactions dominate.
- Photons are quasi-real: $Q^2 \lesssim 1/R_A^2$
- Large photon flux $\sim Z^2$ (Fermi/Weizsacker-Williams). In the case of Pb, probability 82^4 larger than proton!

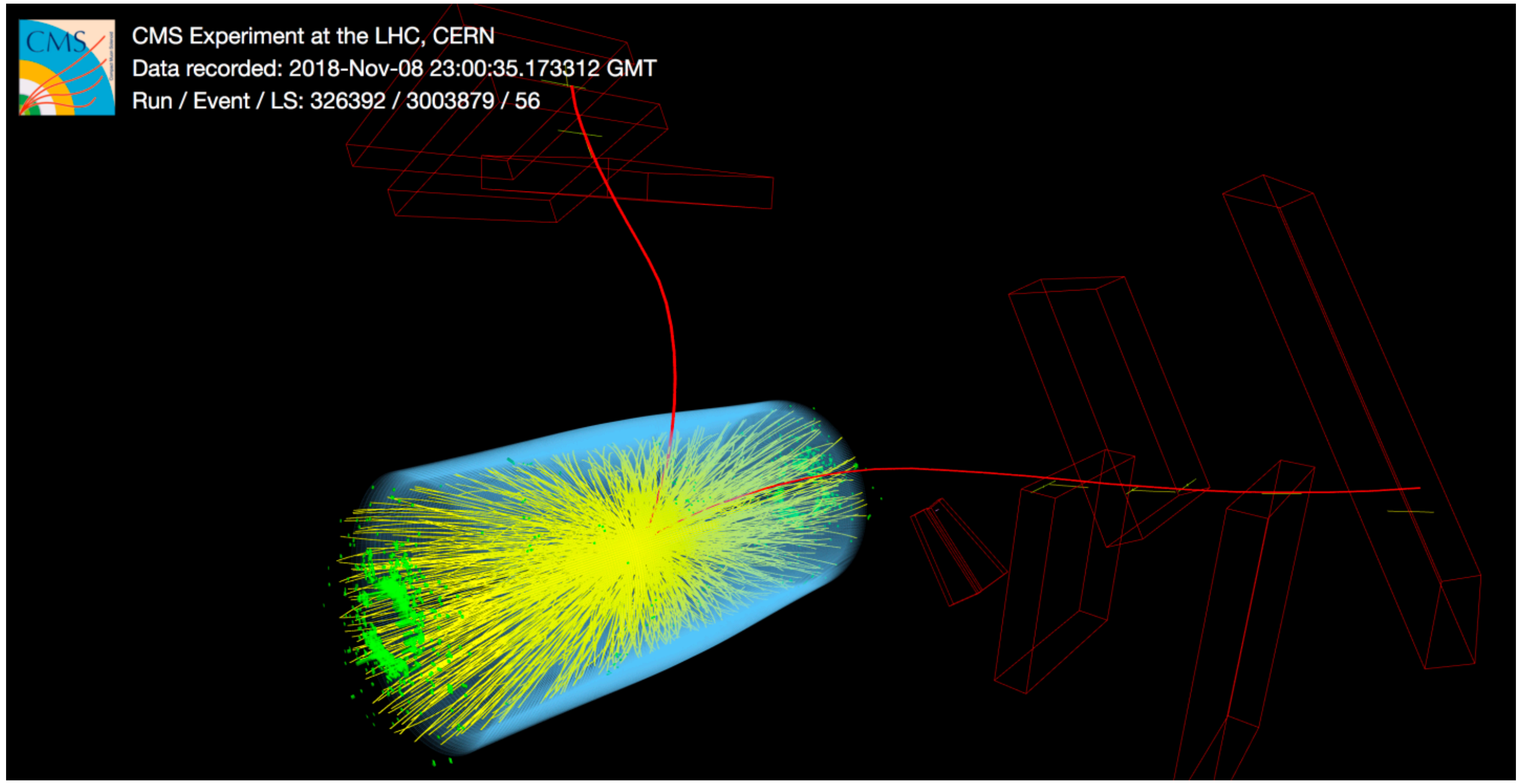


Ultraperipheral collisions (UPCs)

UPC



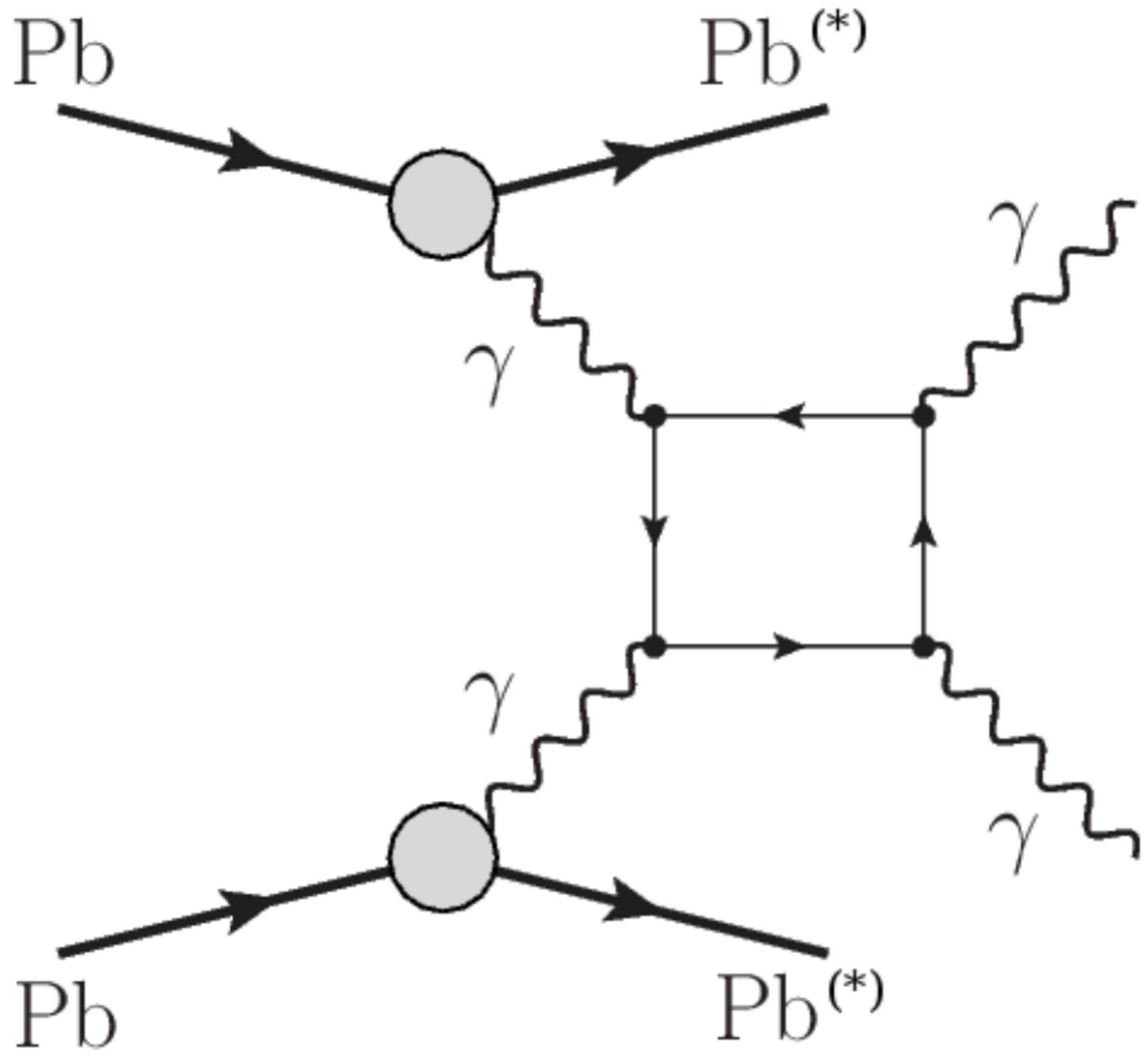
Central



Experimentally very clean events !

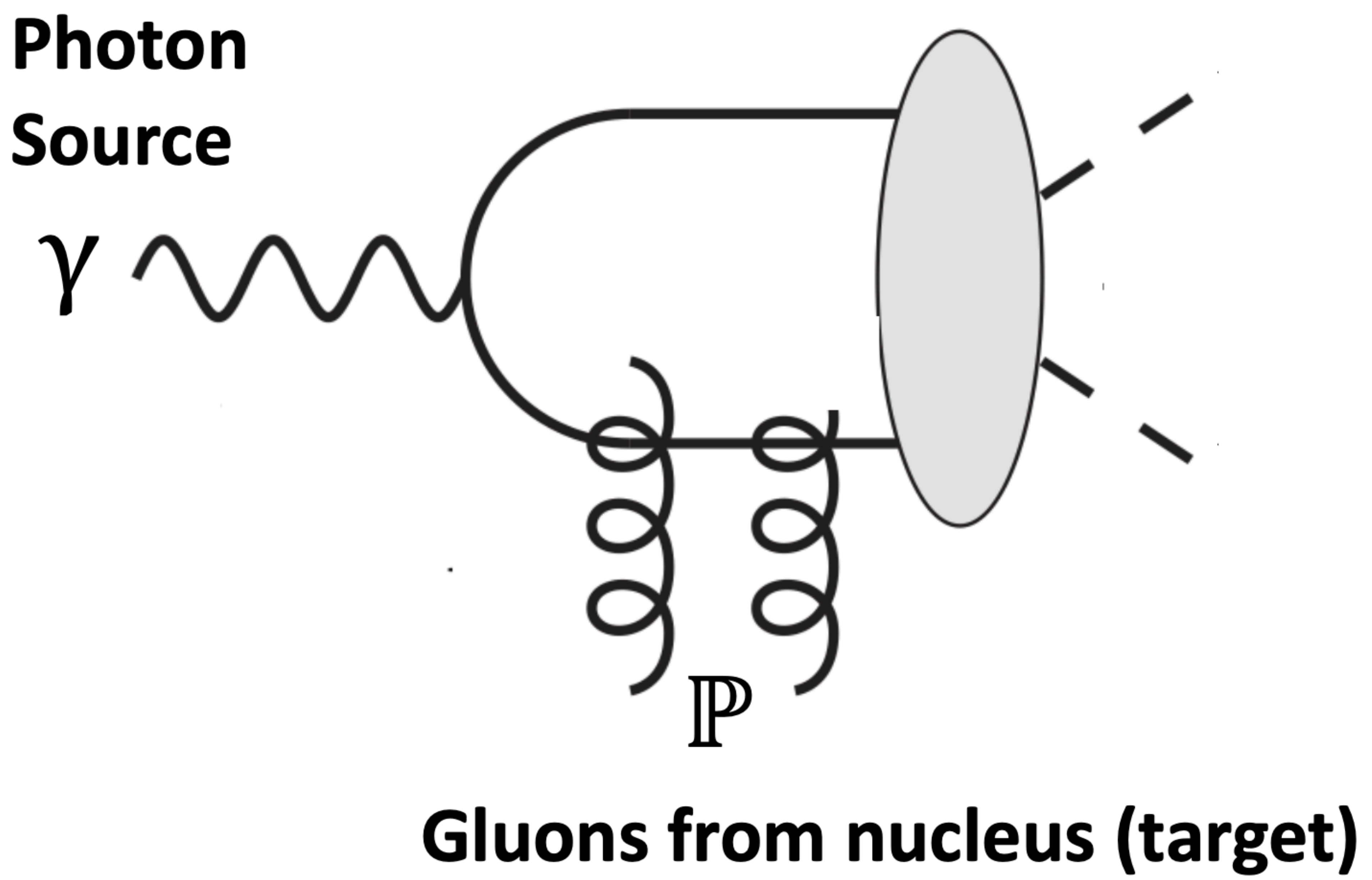
Types of processes in UPCs

Photon - photon:



- BSM physics
- QED precision tests
- …

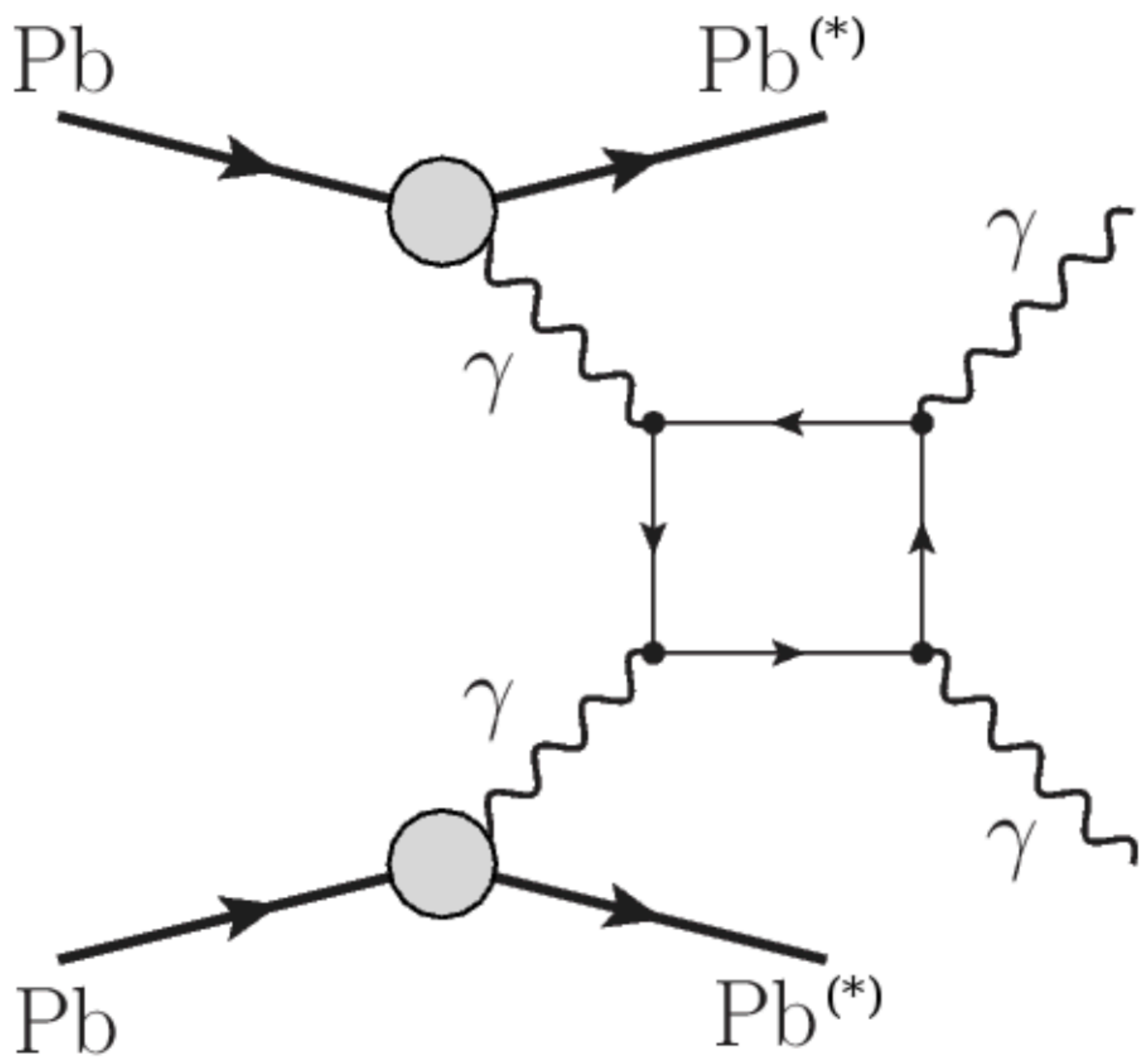
Photon - target:



- Sensitive to saturation gluon saturation
- Test nuclear PDFs
- …

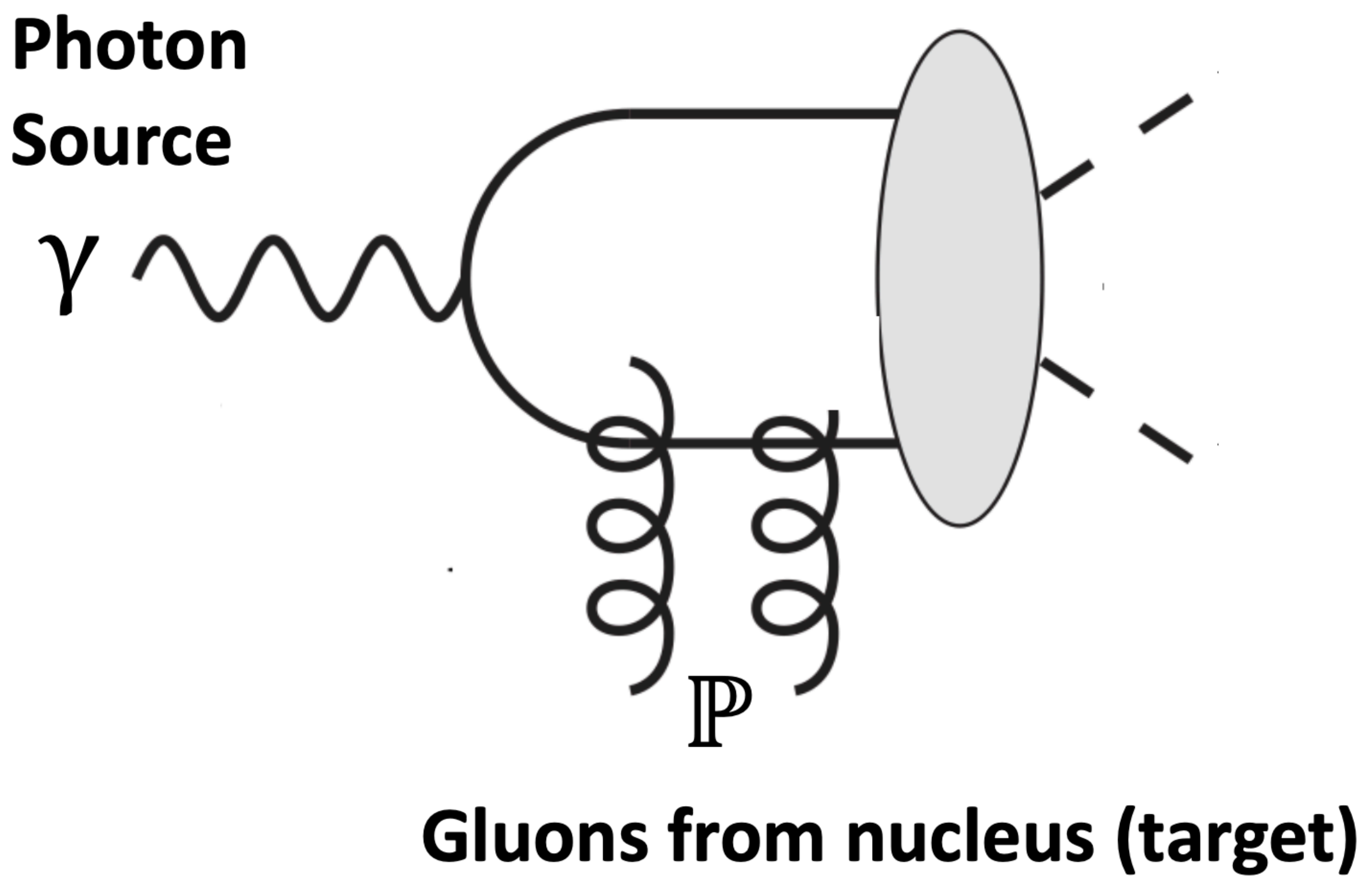
Types of processes in UPCs

Photon - photon:



- BSM physics
- QED precision tests
- …

Photon - target:

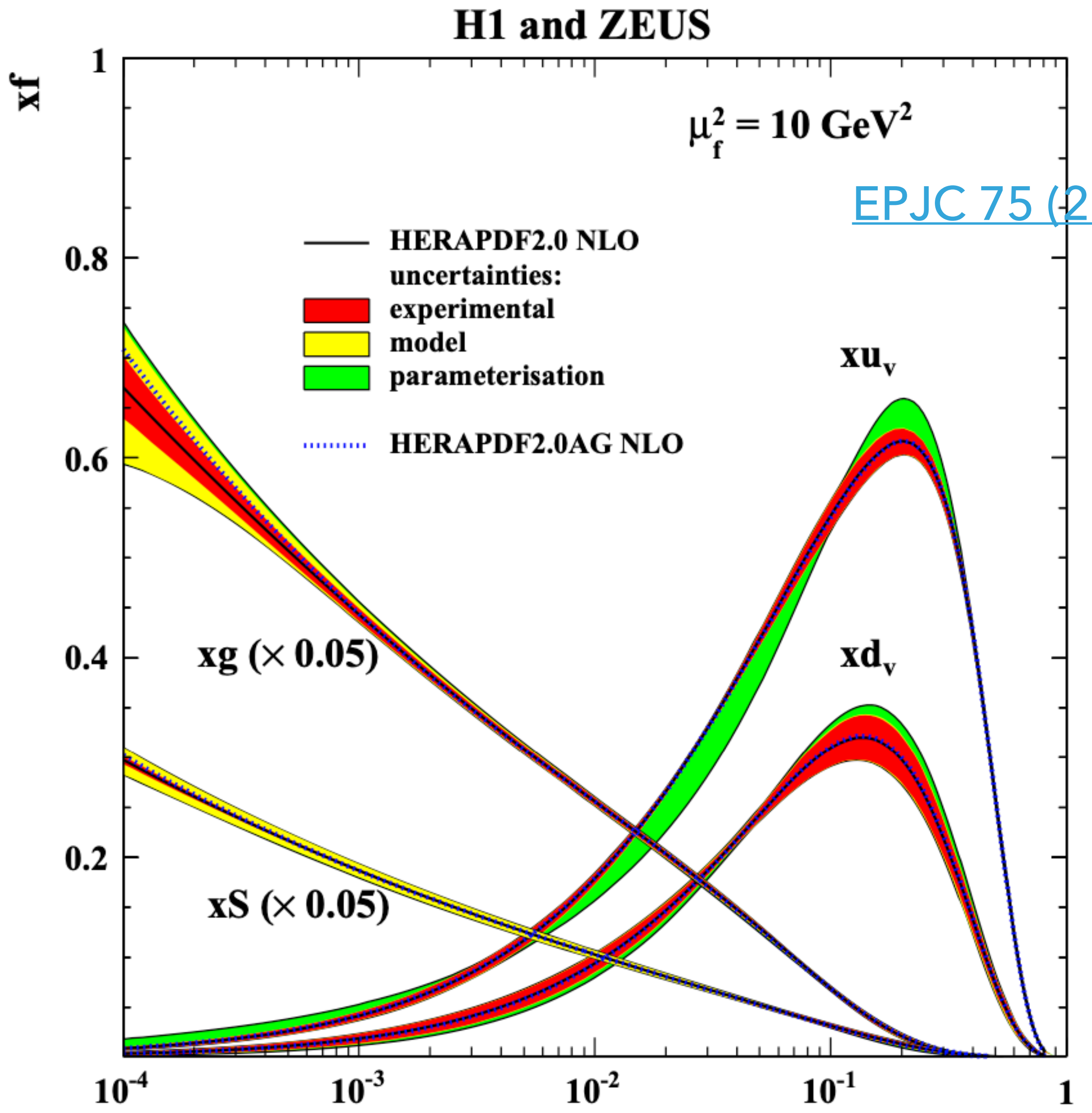


- Sensitive to saturation gluon saturation
- Test nuclear PDFs
- …

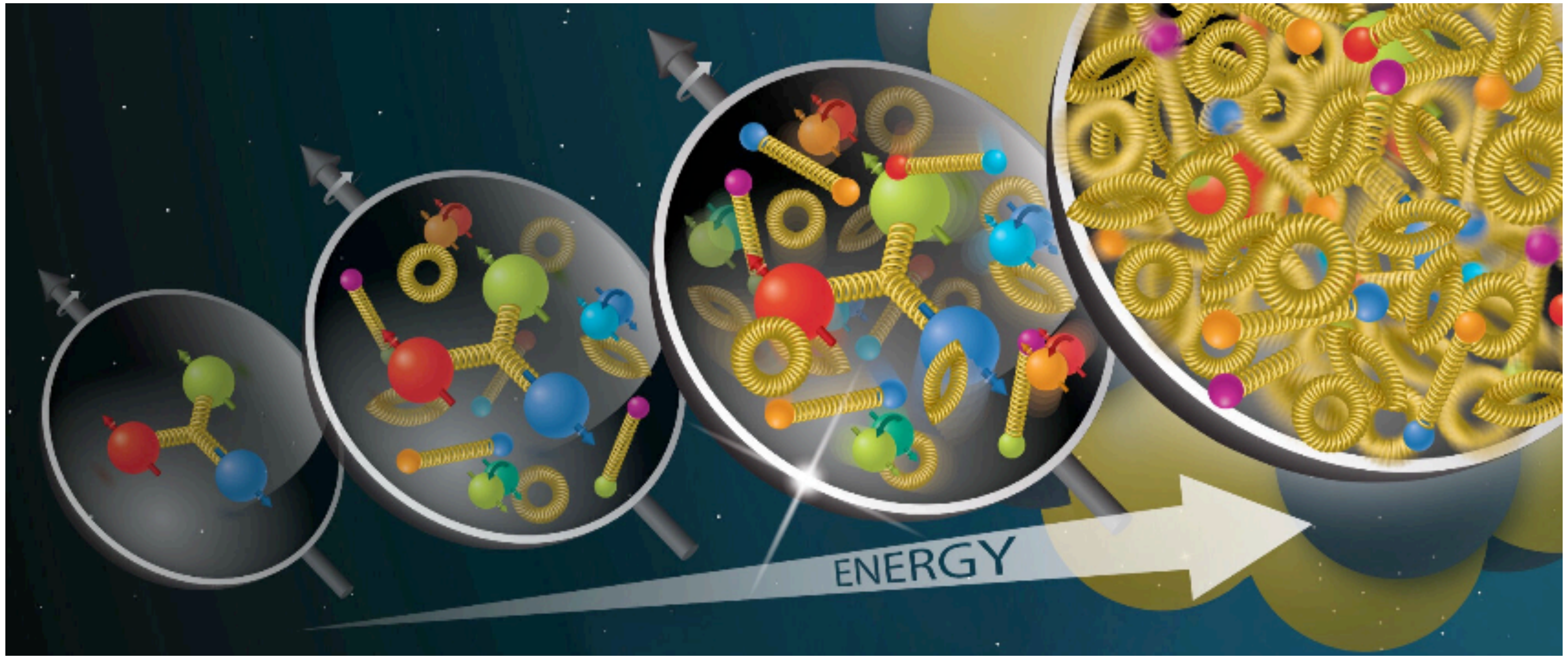
UPCs and saturation

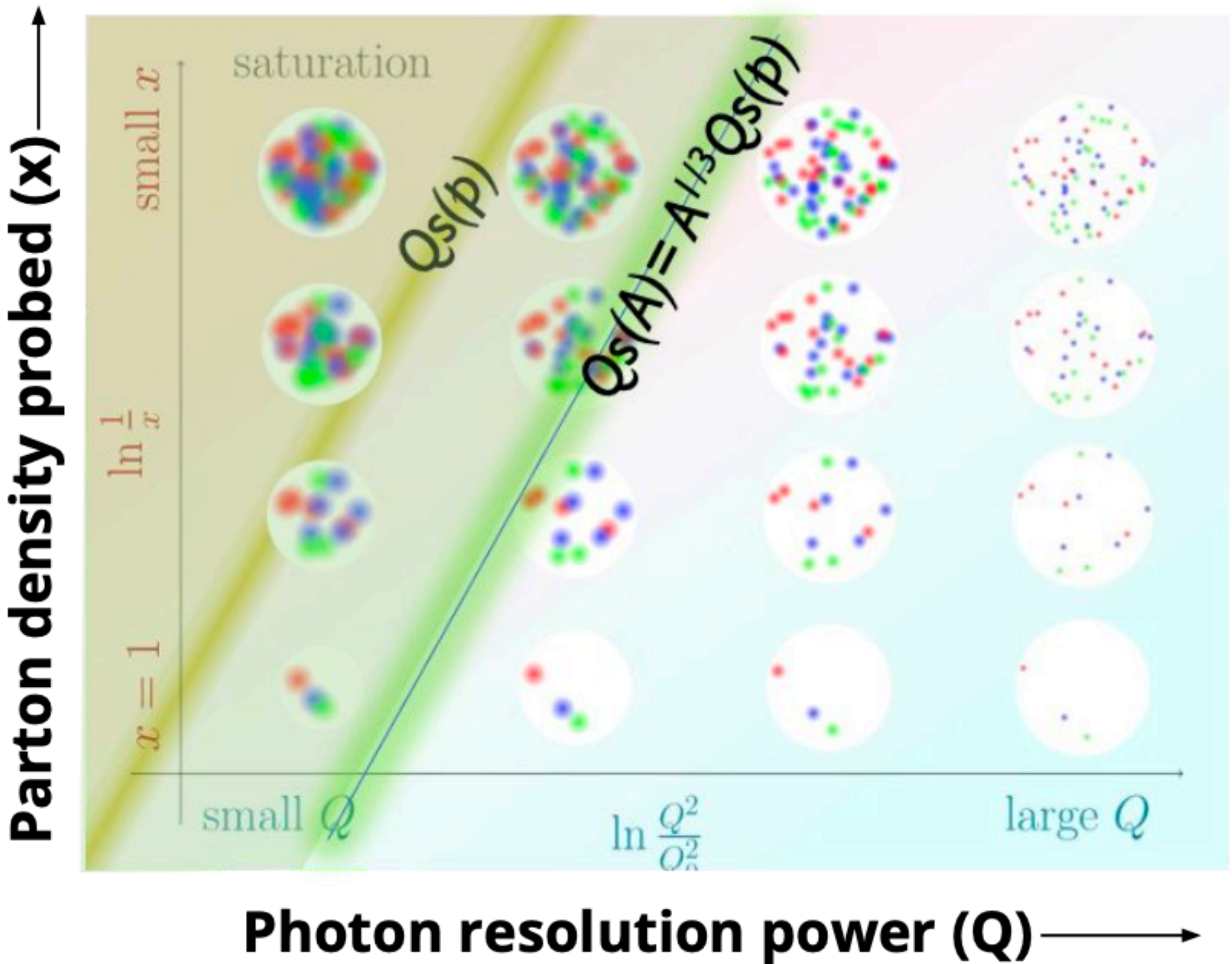
- DIS experiments show gluons become rapidly dominant at high energies.
- Unitarity: This behavior cannot go forever!
- New QCD regime: compensation between gluon splittings and recombinations.
- No conclusive evidence of saturation to date!
- Saturation region is expected to be easier to be accessed in UPCs

$Q_S \propto A^{1/3}$



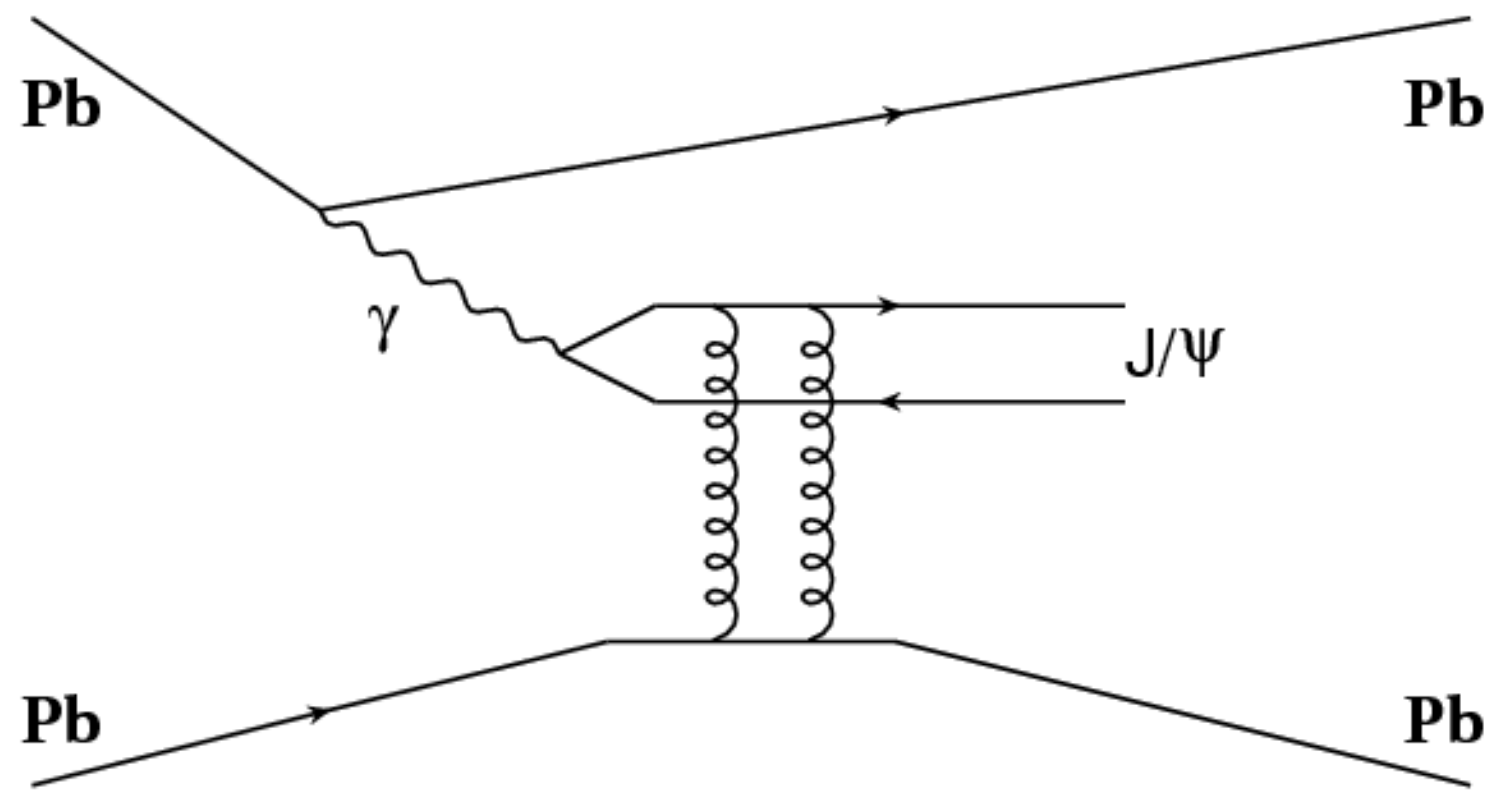
EPJC 75 (2015) 12, 580

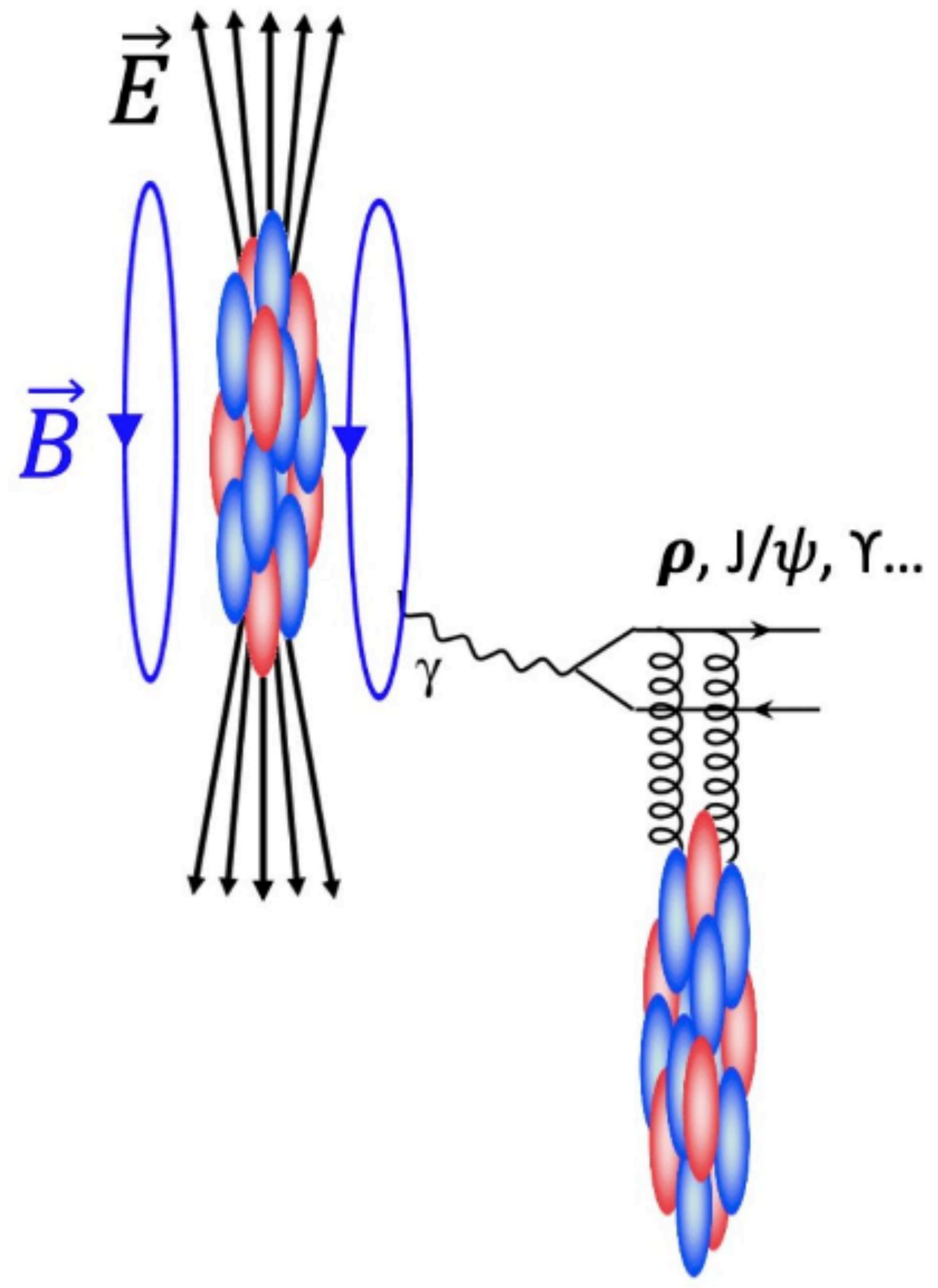




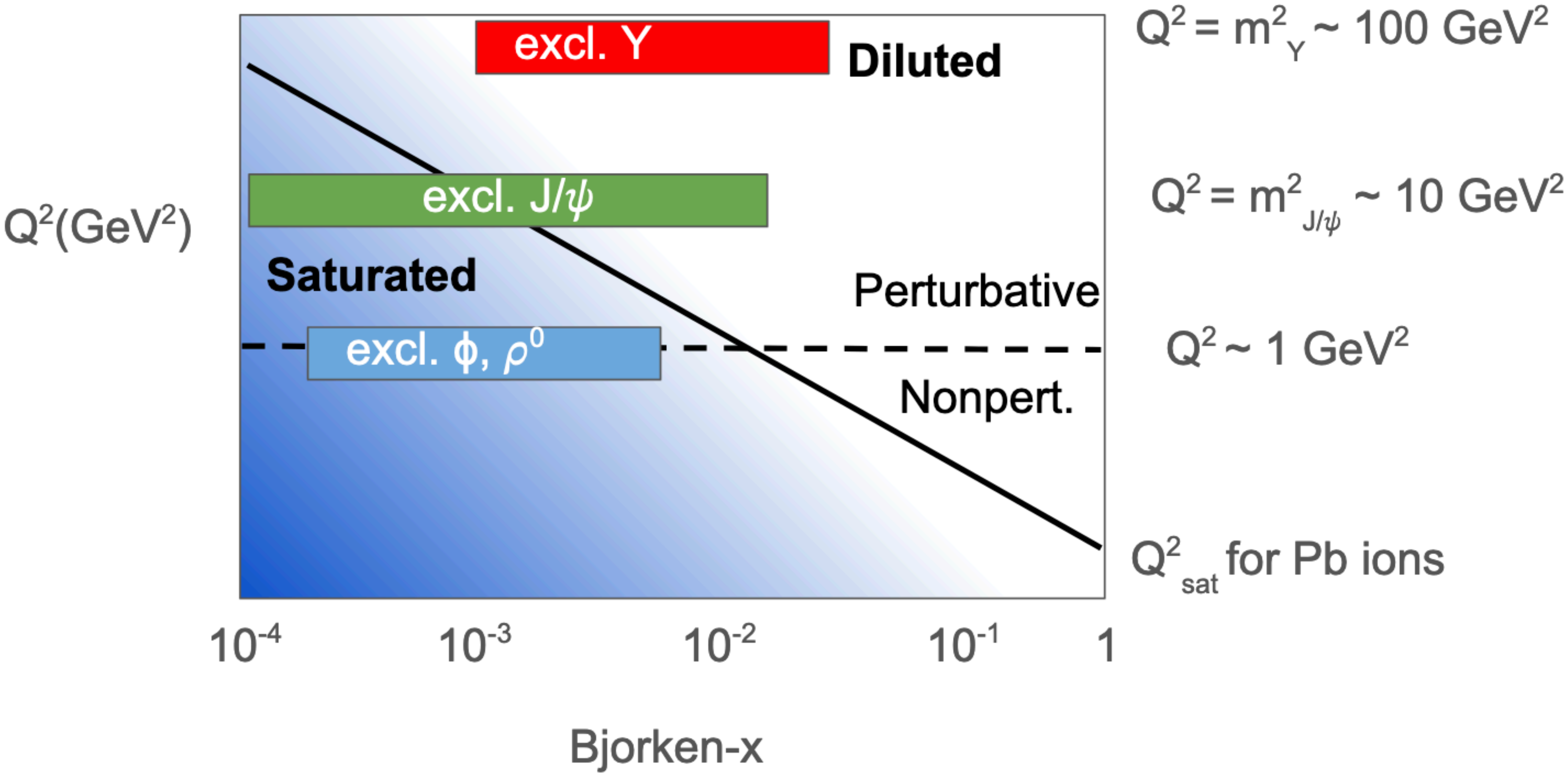
Vector meson photoproduction

- Vector mesons: particles with spin 1 and odd parity.
- Photon quantum numbers ($J^{PC} = 1^{--}$) same for VM → highly likely a photon will fluctuate into a VM !
- VM photoproduction cross section $\propto (xg(x, Q^2))^2$ at LO → sensitive to saturation
- Photoproduced VM cross section at small x can test gluon density



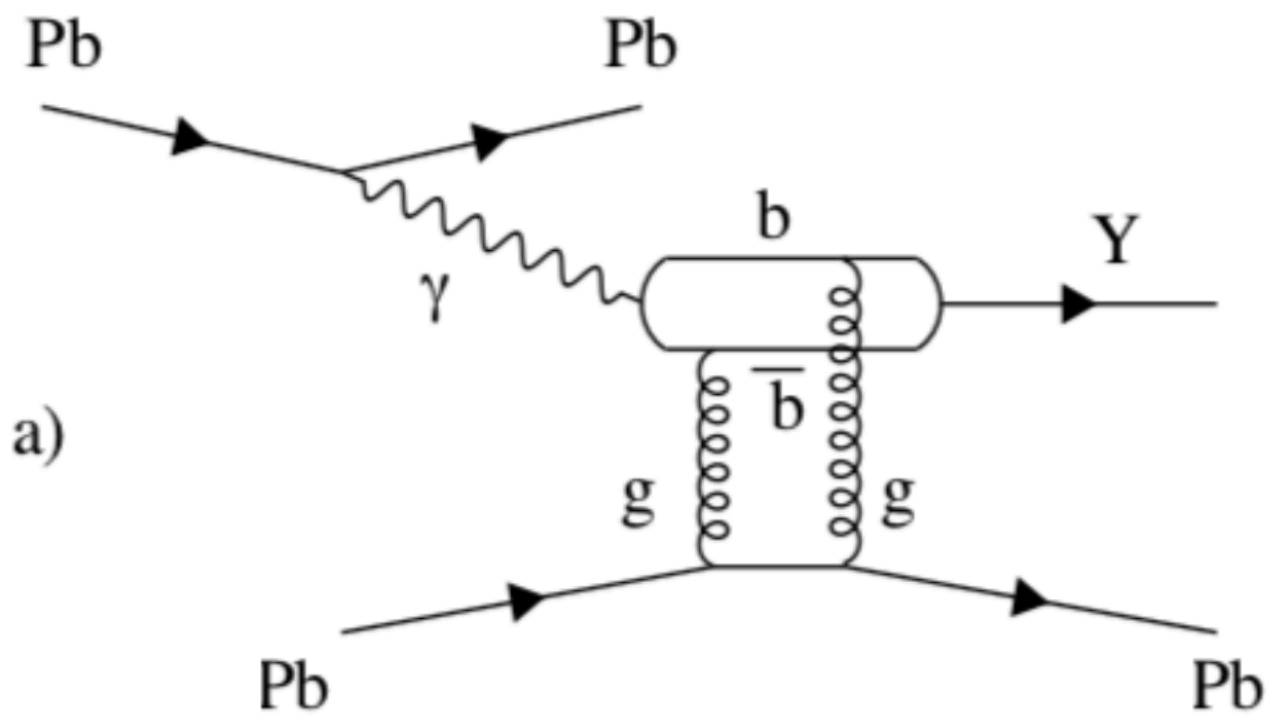


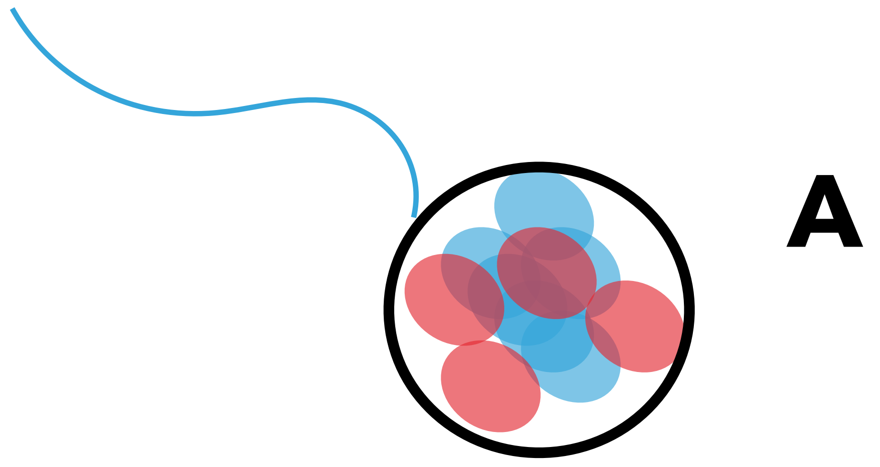
Vector meson photoproduction

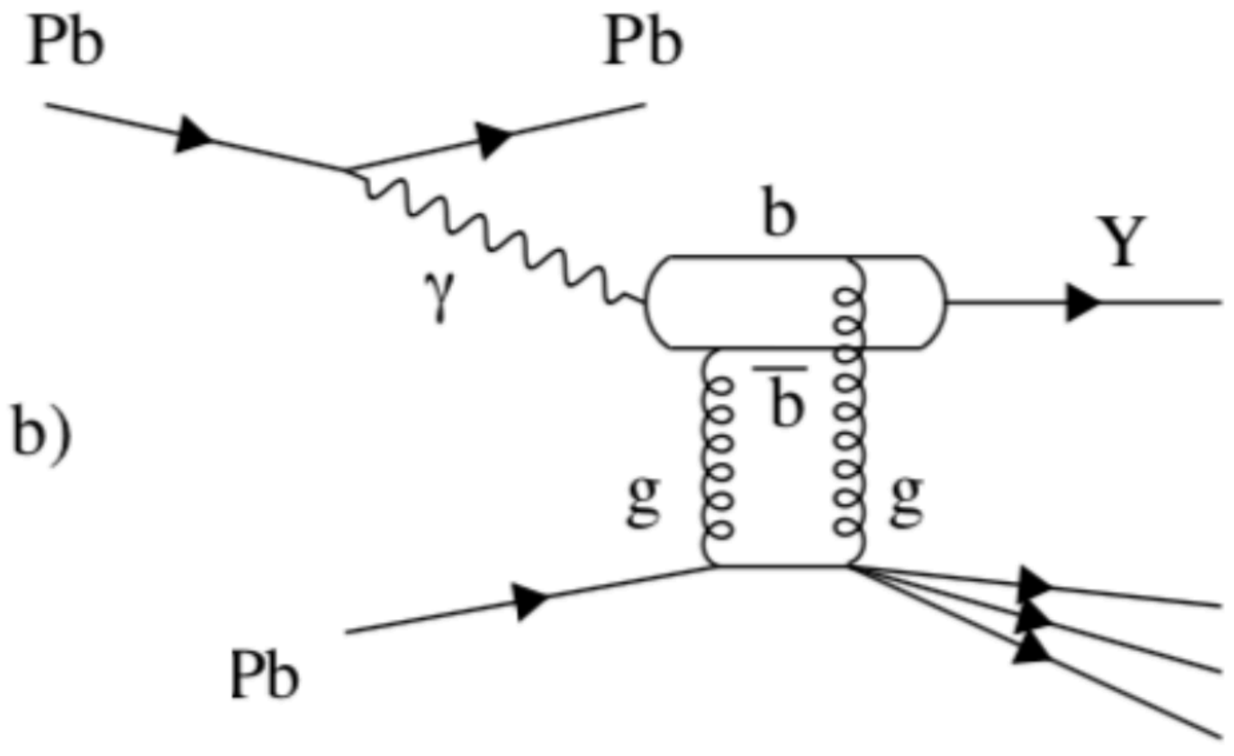


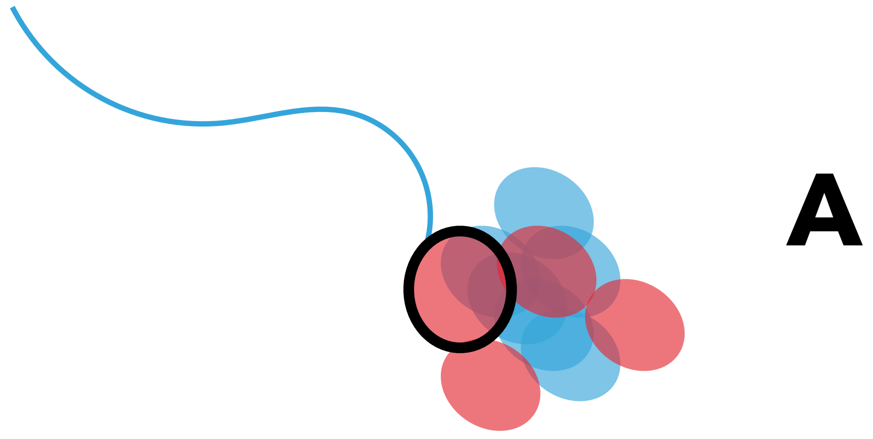
Coherent and Incoherent VM production

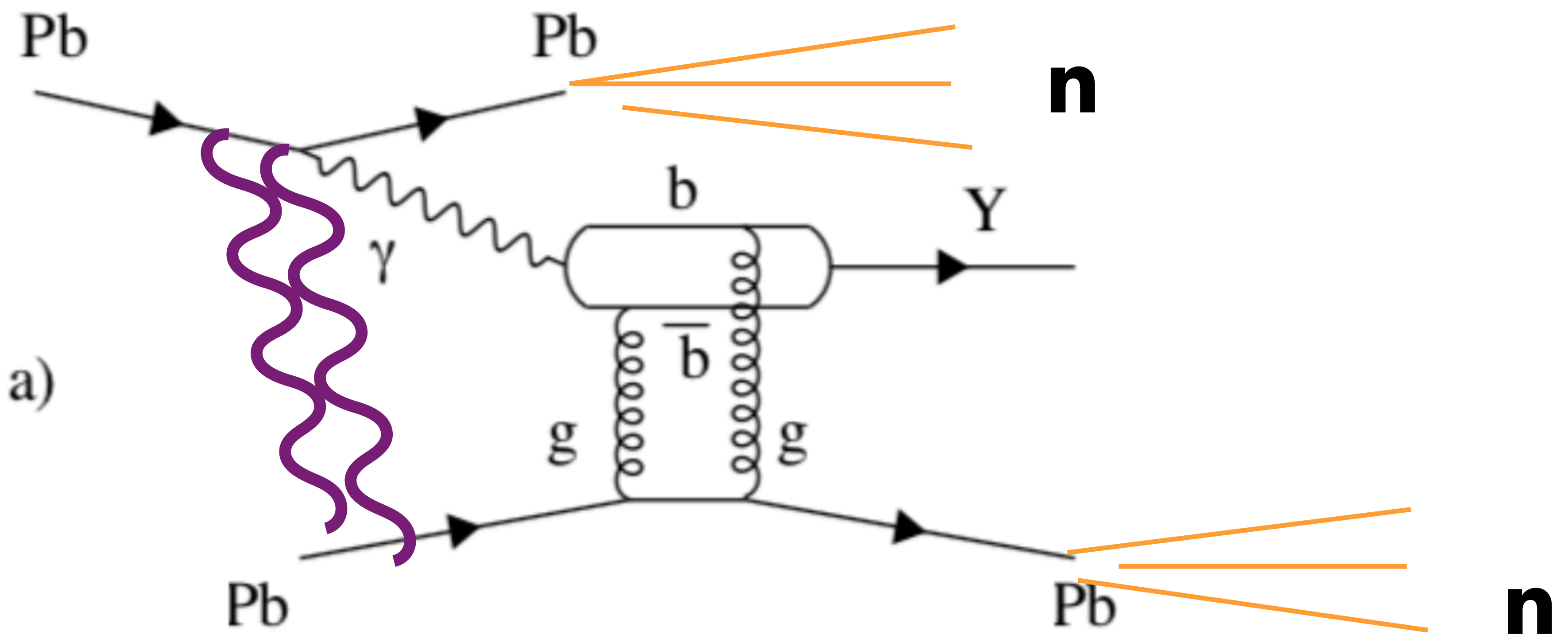
- Coherent:
  - Photon couples with the nuclei as a whole
  - Nuclei usually remains intact
- Incoherent:
  - Photon couples to single nucleons
  - Nuclei usually breaks
- In both cases we can have additional photon exchanges:
  - Nuclei collective excitation
  - Neutron emission as de-excitation processes.



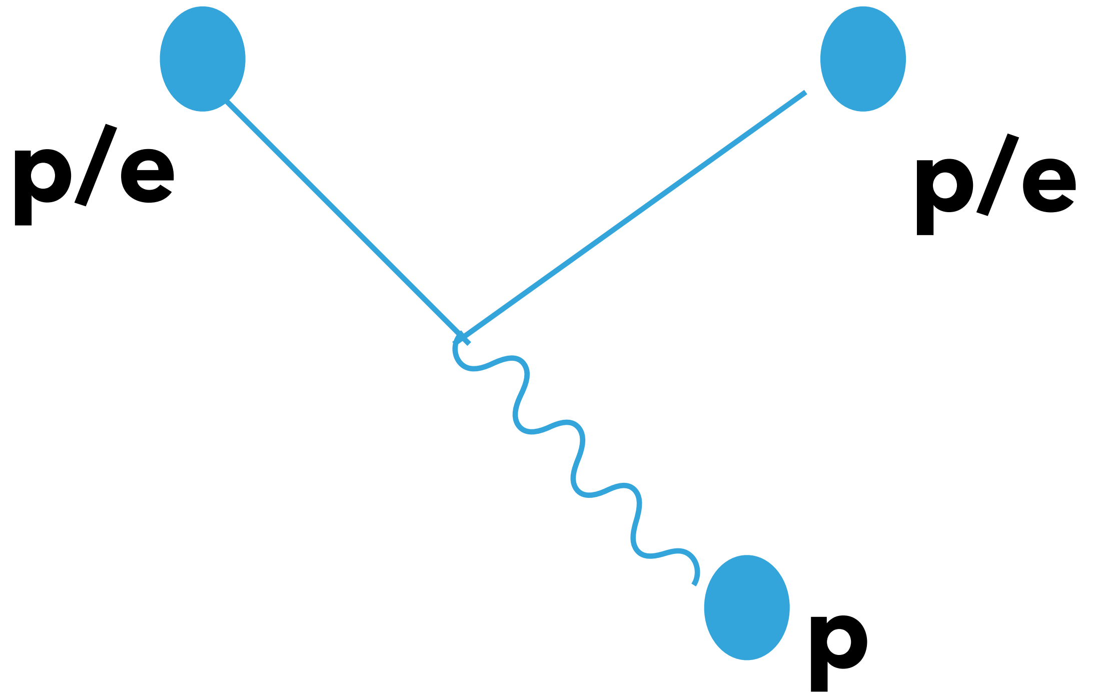






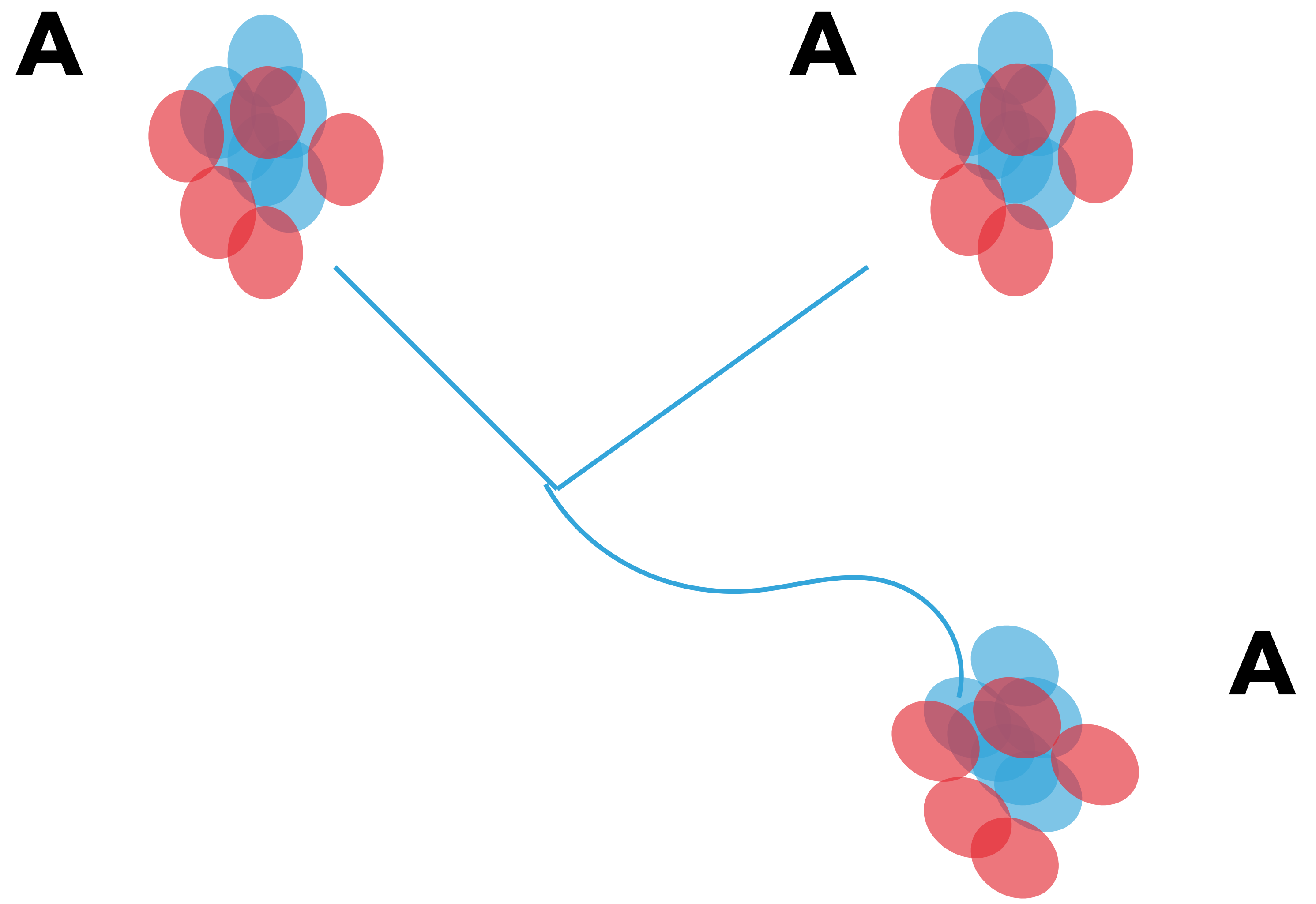


Photoproduction in pp/ep vs. AA



- Advantage:
- Wavelength $\lambda \propto R_{\text{proton}}$, then higher photon virtualities (better "resolution power".).

- Disadvantage:
- Low photon flux

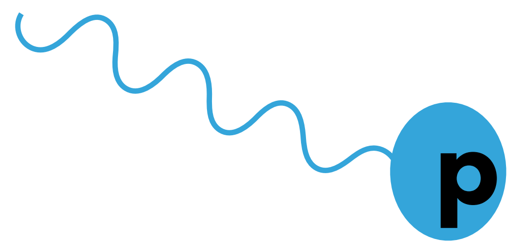


- Disadvantage:
- Wavelength $\lambda \propto R_{\text{Ion}}$, then lower photon virtualities (worse "resolution power").

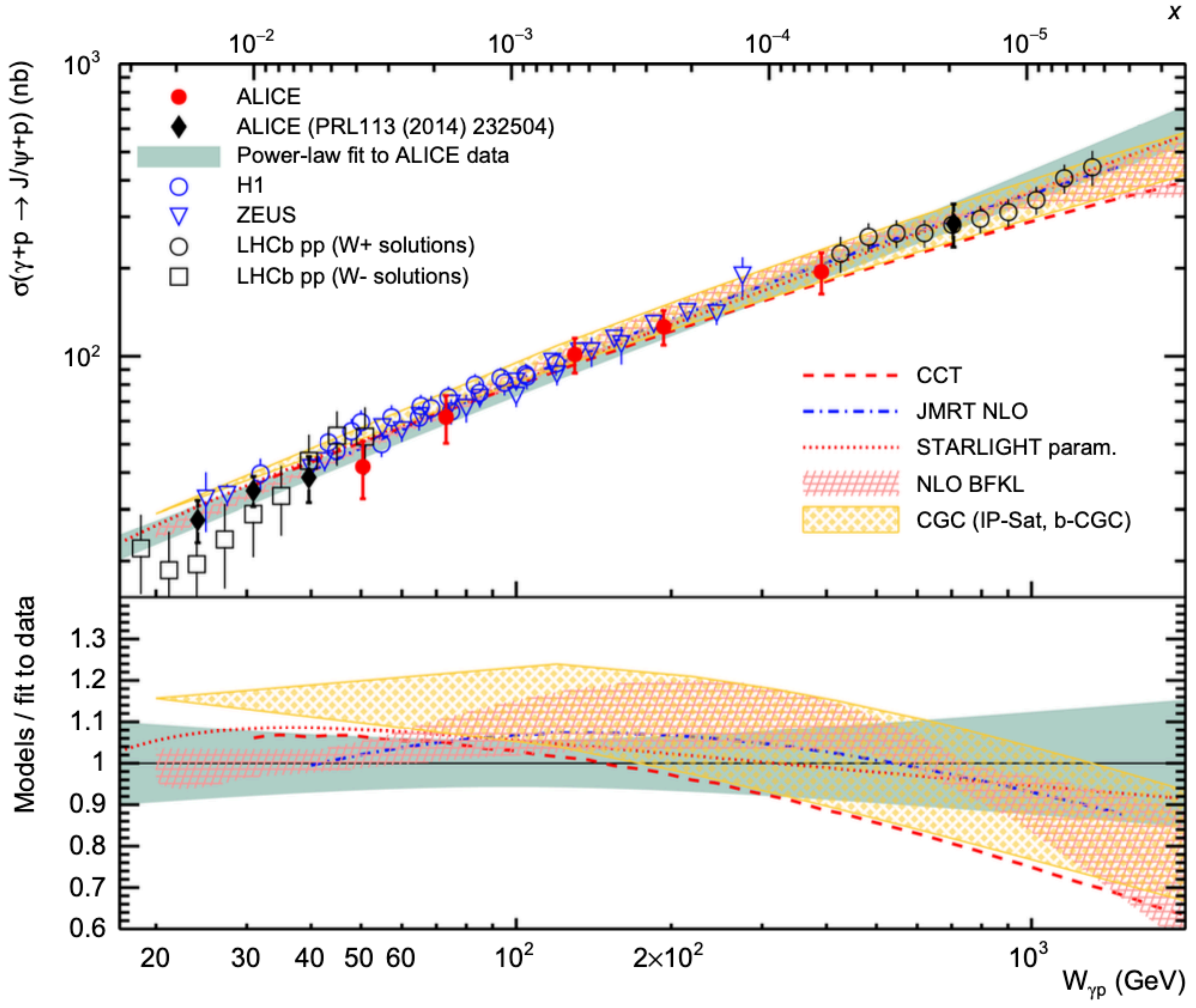
- Advantages:
- High photon flux (enhanced by Z^2).
- Saturation scale easier to be accessed (scale by $A^{1/3}$).

Looking inside protons...

$$\gamma + p \rightarrow J/\psi + p$$



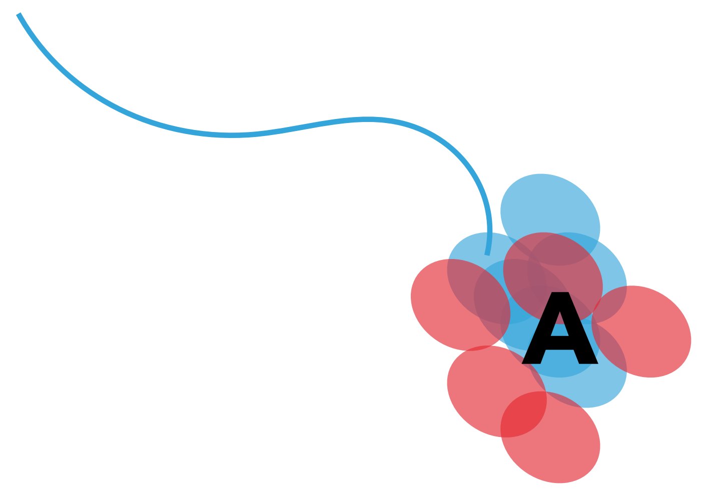
- Gluons inside a proton:
  - Investigated with ep, pPb and pp collisions by HERA and LHC
  - Consistent results between HERA and LHC data.
  - Data follow a power-law trend, consistent with the rapidly increasing gluon density.
  - No evidence for saturation !



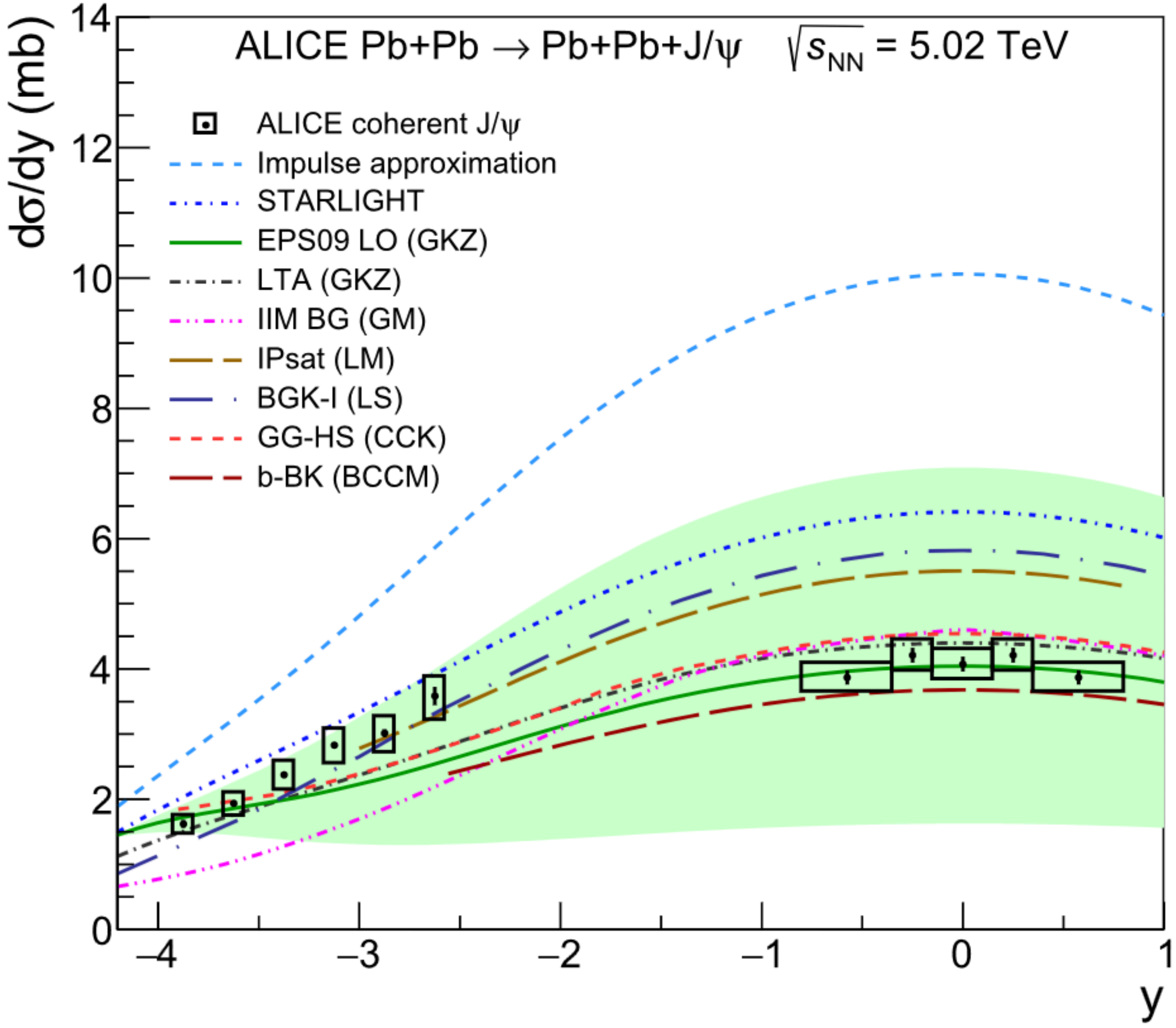
EPJC 79 (2019) 402

Looking inside Pb…

$$\gamma + Pb \rightarrow J/\psi + Pb$$



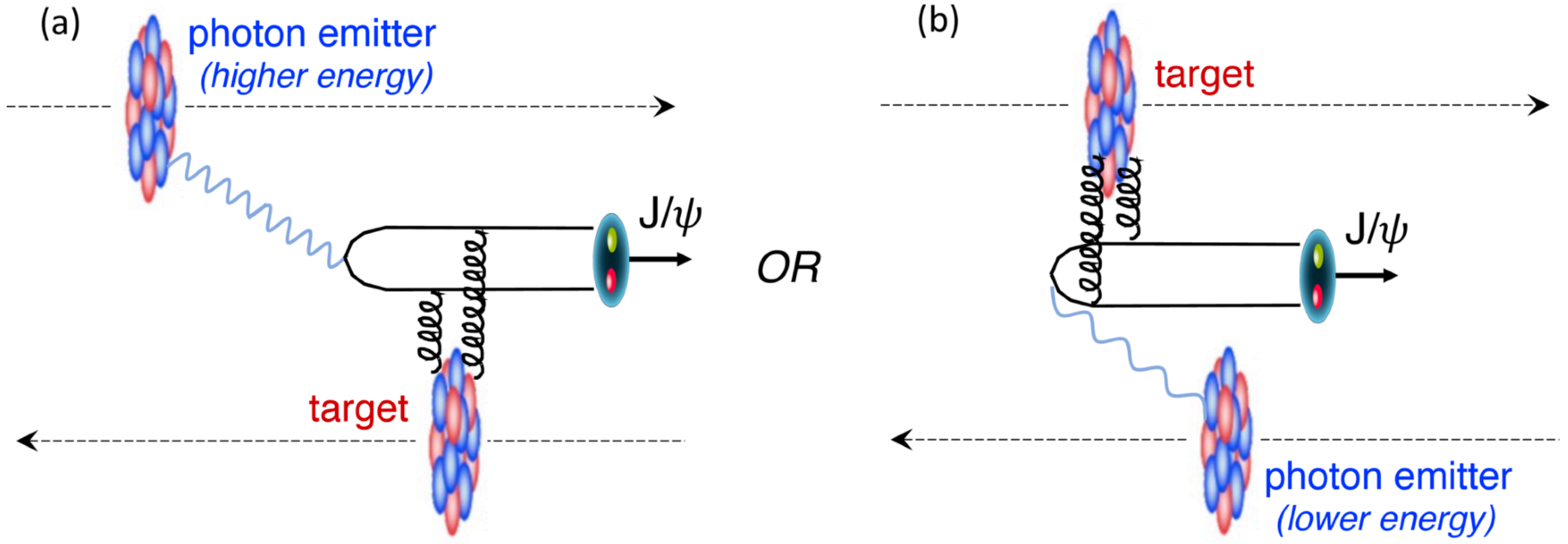
- Gluons inside Pb:
  - $\sigma(J/\psi)$ < Impulse Approximation(simplest model only putting protons and neutrons together) → strong nuclear modification in nuclei.
  - No theory model can describe data at both forward and central rapidities.



EPJC 81 (2021) 712

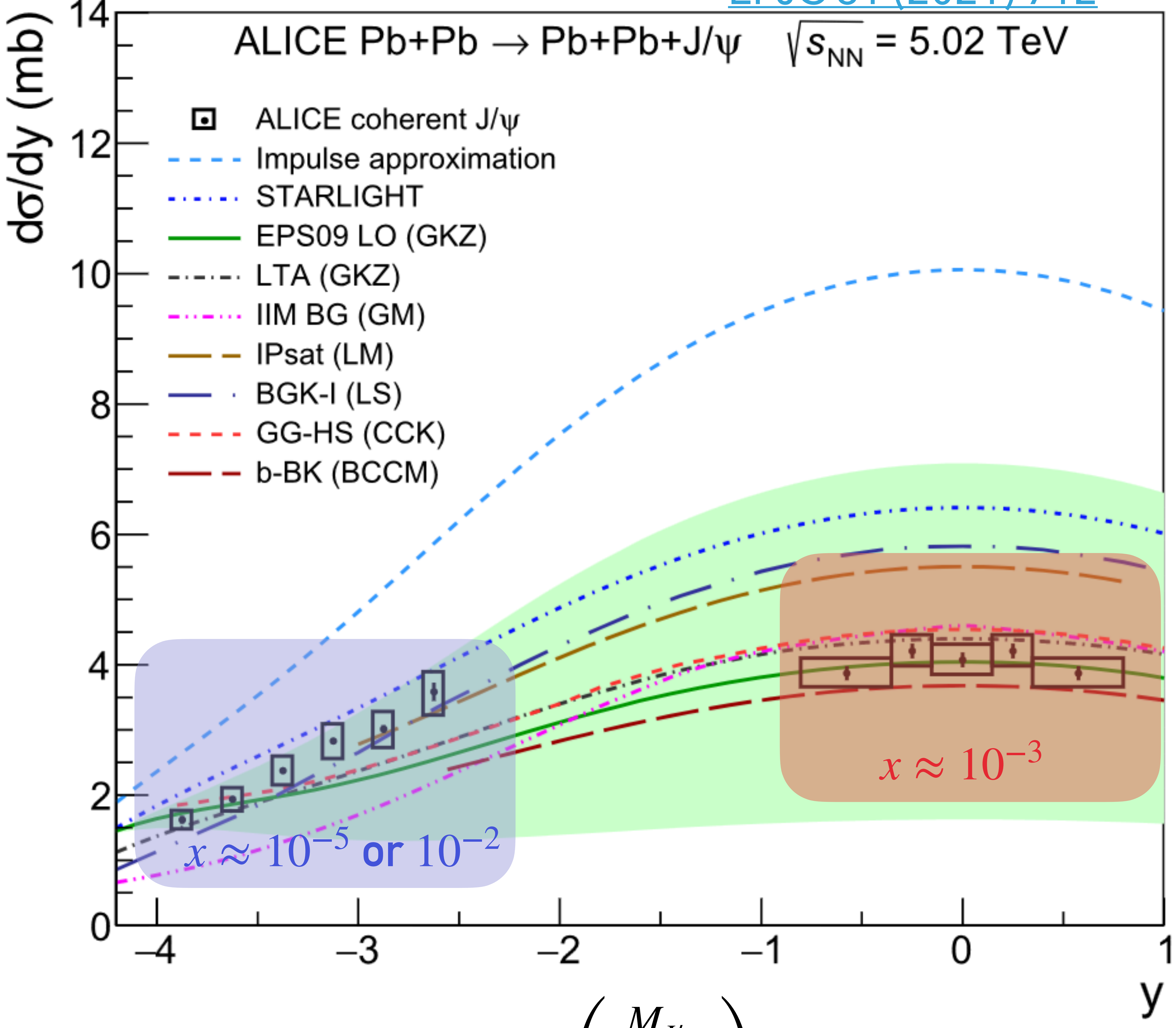
Looking inside Pb…

- **Ambiguity in symmetric collisions:** either ion can serve as the emitter or target.
- Each data point has contributions from low and high energy photons.



$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(y)\cdot\sigma_{\gamma A\to J/\psi A'}(y) + N_{\gamma/A}(-y)\cdot\sigma_{\gamma A\to J/\psi A'}(-y)$$

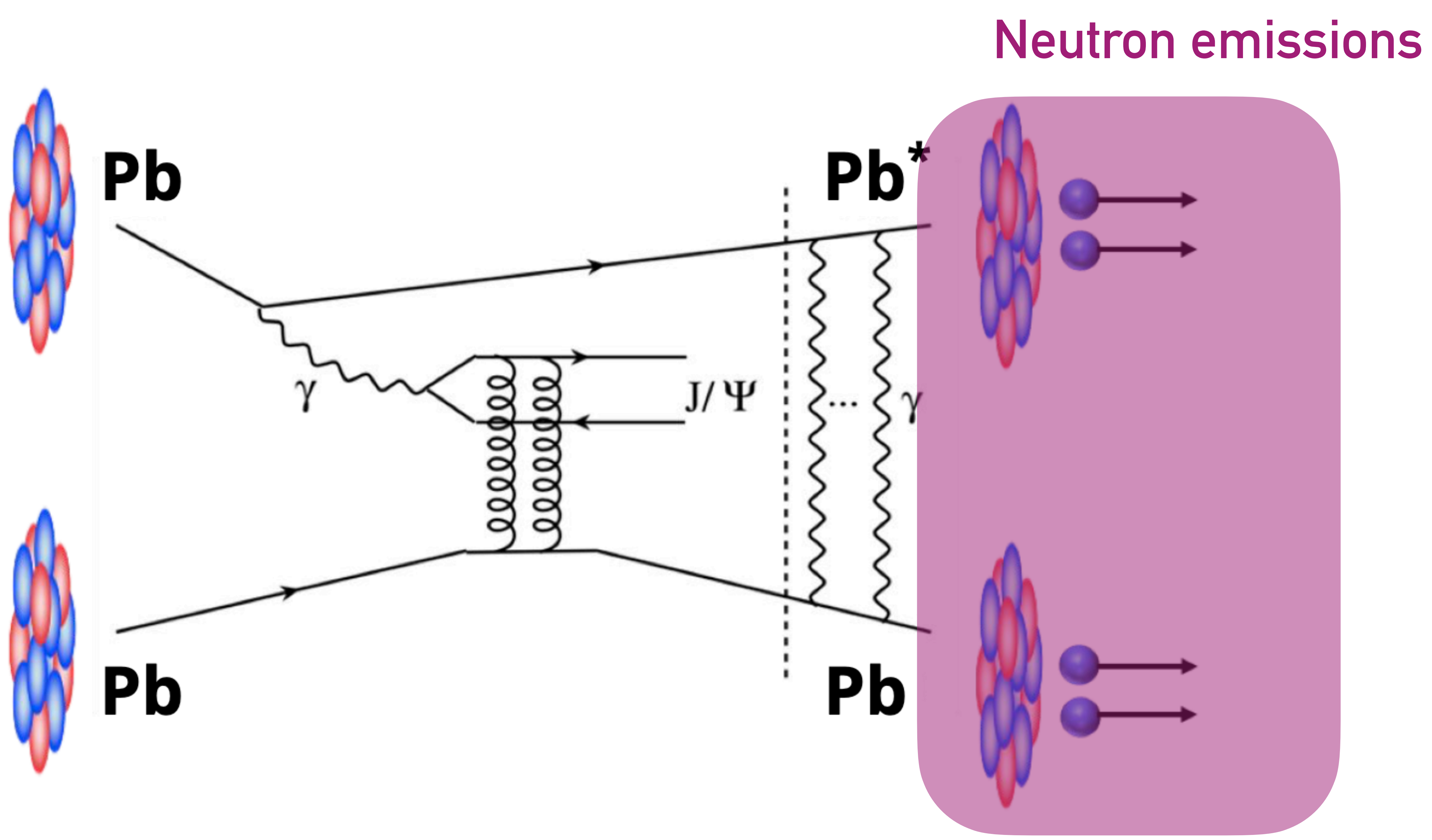
EPJC 81 (2021) 712

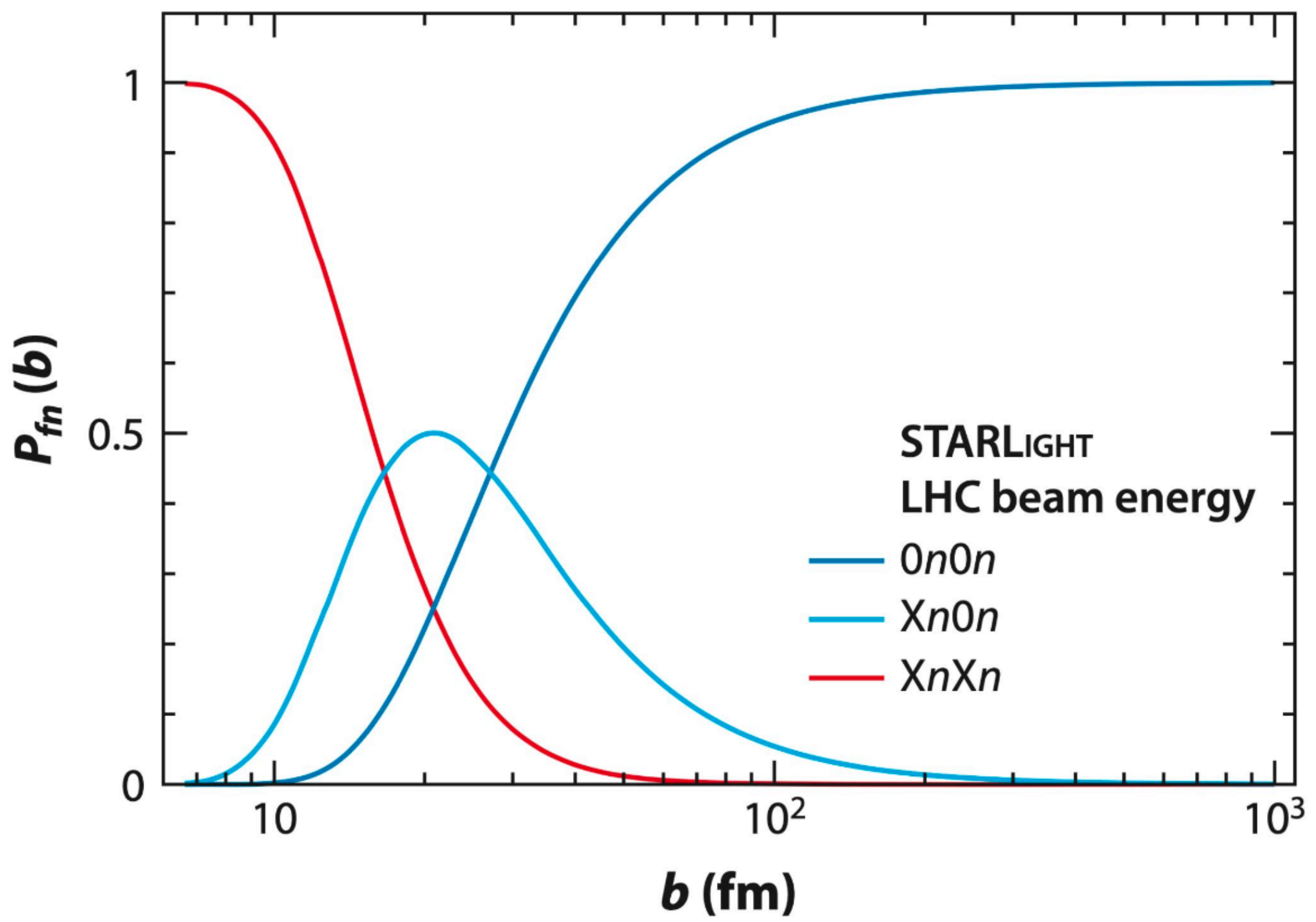


$$x = \left(\frac{M_{J/\psi}}{\sqrt{s_{NN}}}\right) e^{\mp y}$$

A solution to the two-way ambiguity puzzle

Control impact parameter of UPCs via forward neutron emissions Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

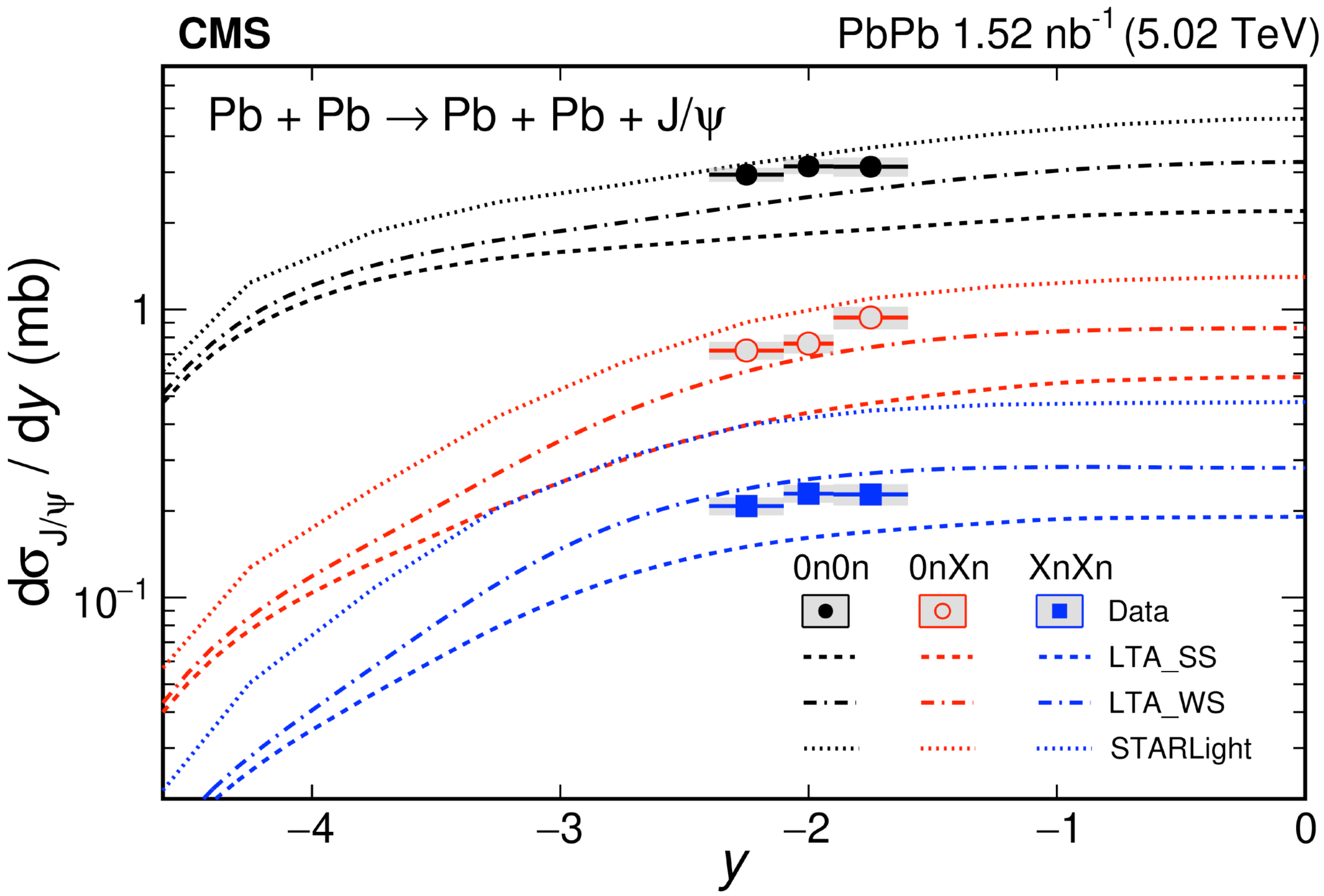




- Additional photon exchanges lead to neutron emissions via EMD.

- Analogous to centrality:
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

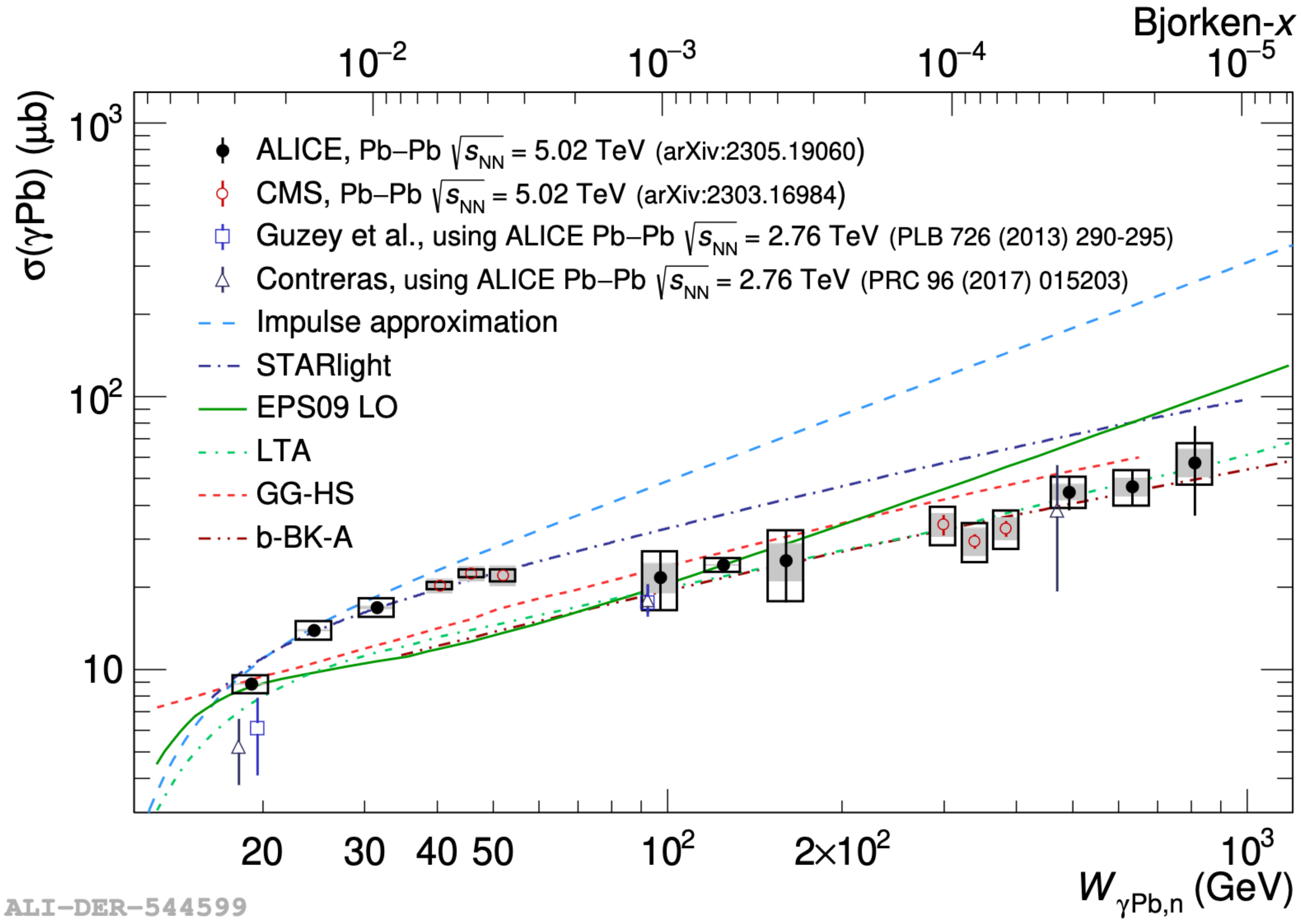
Total Coh. J/ψ cross section in neutron categories



- ZDC allows to classify events in neutron categories.
- **First separation in different neutron categories.**

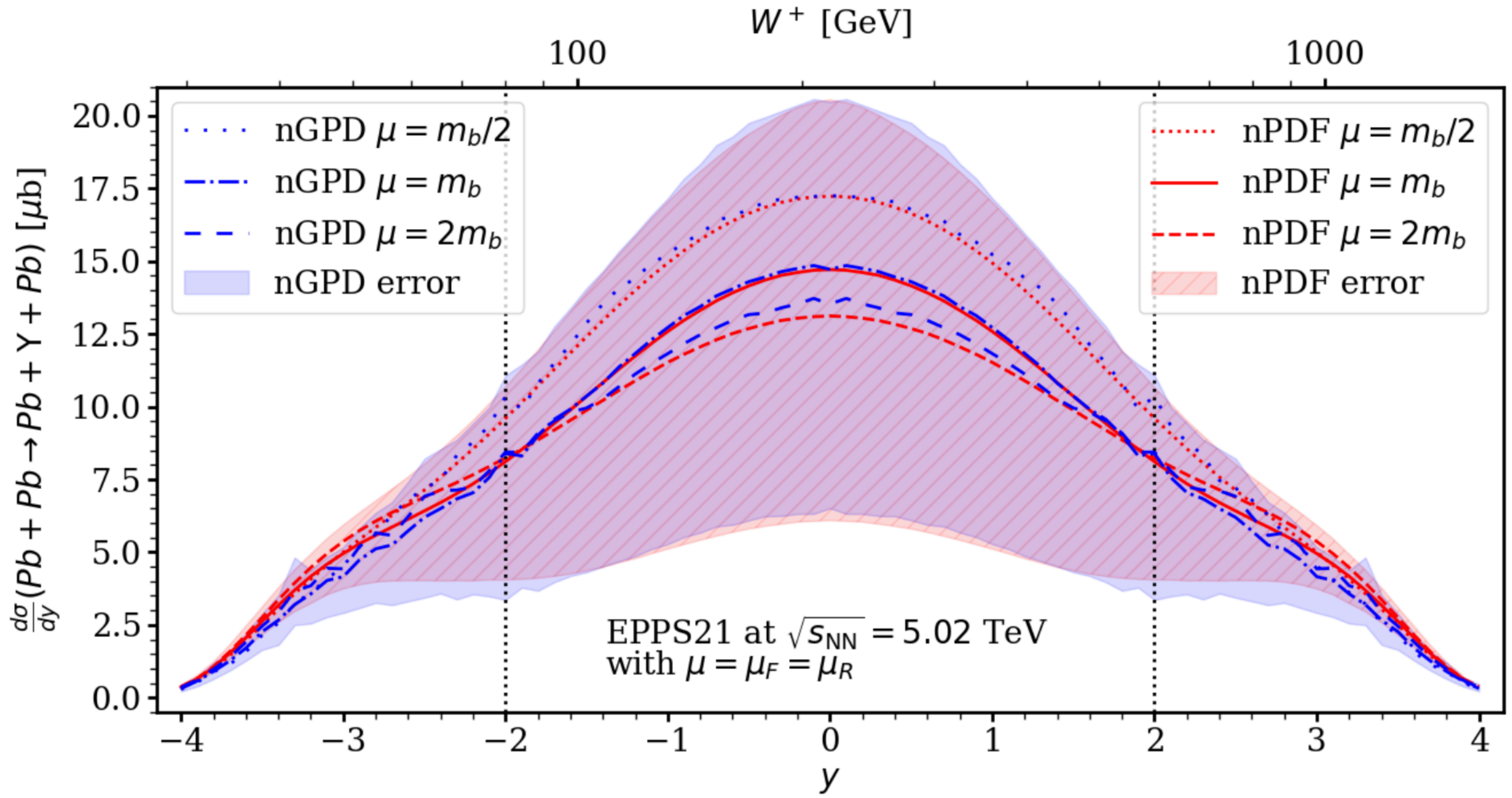
arXiv:2303.16984

Coh. J/ψ photo nuclear cross section vs W



- ZDC categories allow us to obtain the W dependence.
- W< 40 GeV: rapidly increasing
- Higher W: slow rise → underlying physics changed!
- First evidence of saturation?
- No models can describe the entire data distribution!

What about even higher mass ?

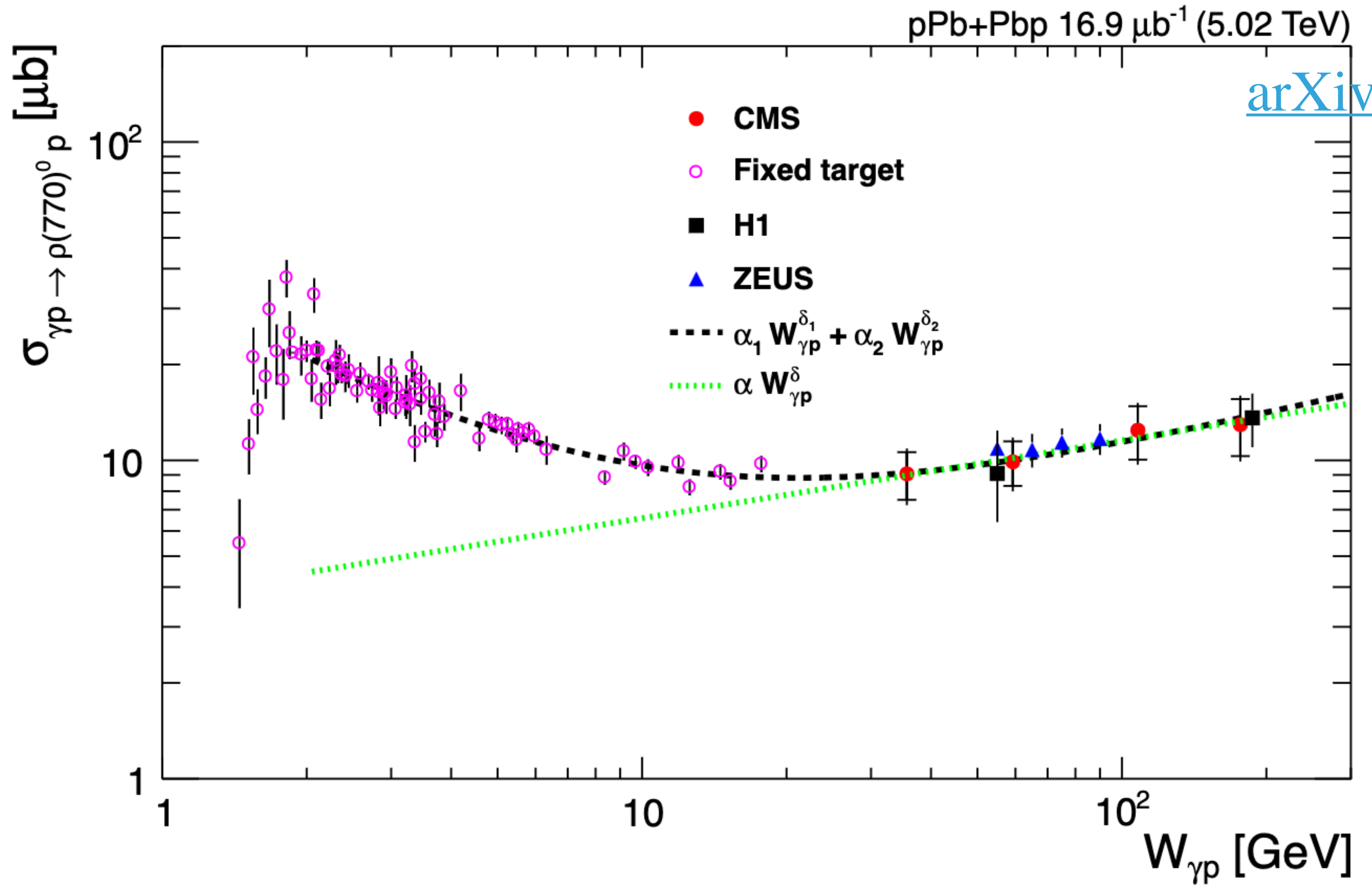


arXiv:2303.03007

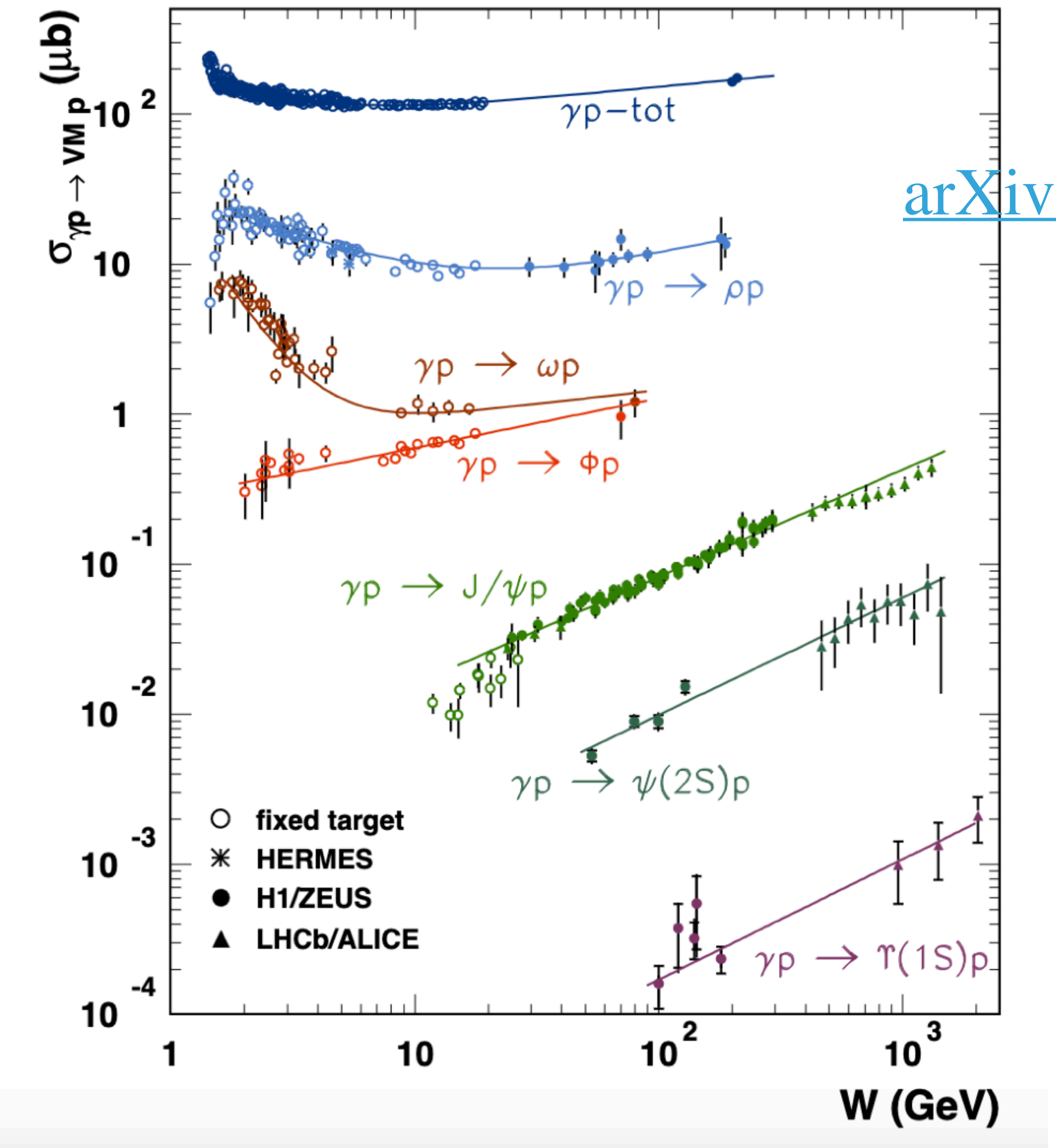
- Photoproduction of Υ (composed of $b\bar{b}$), allows to probe nuclei with a different dipole size.
- The high mass (even higher than J/ψ) sets a sufficiently large scale for pQCD.
- Important to compare with saturation/shadowing models.

Lighter vector mesons

- Lighter VMs more sensitive to saturation, but …
- More challenging for pQCD.
- LHC data complement HERA extensive program.



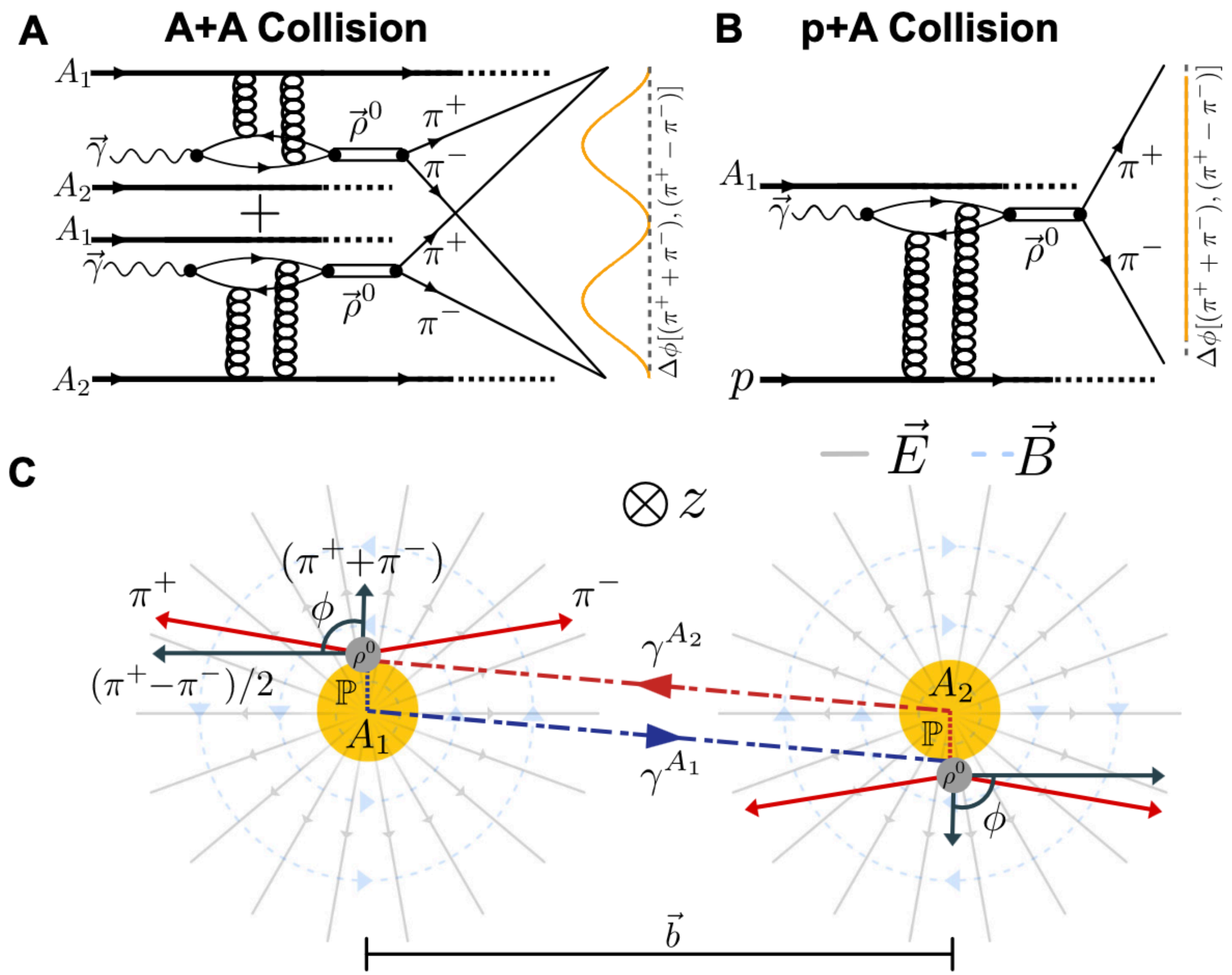
arXiv:1902.01339

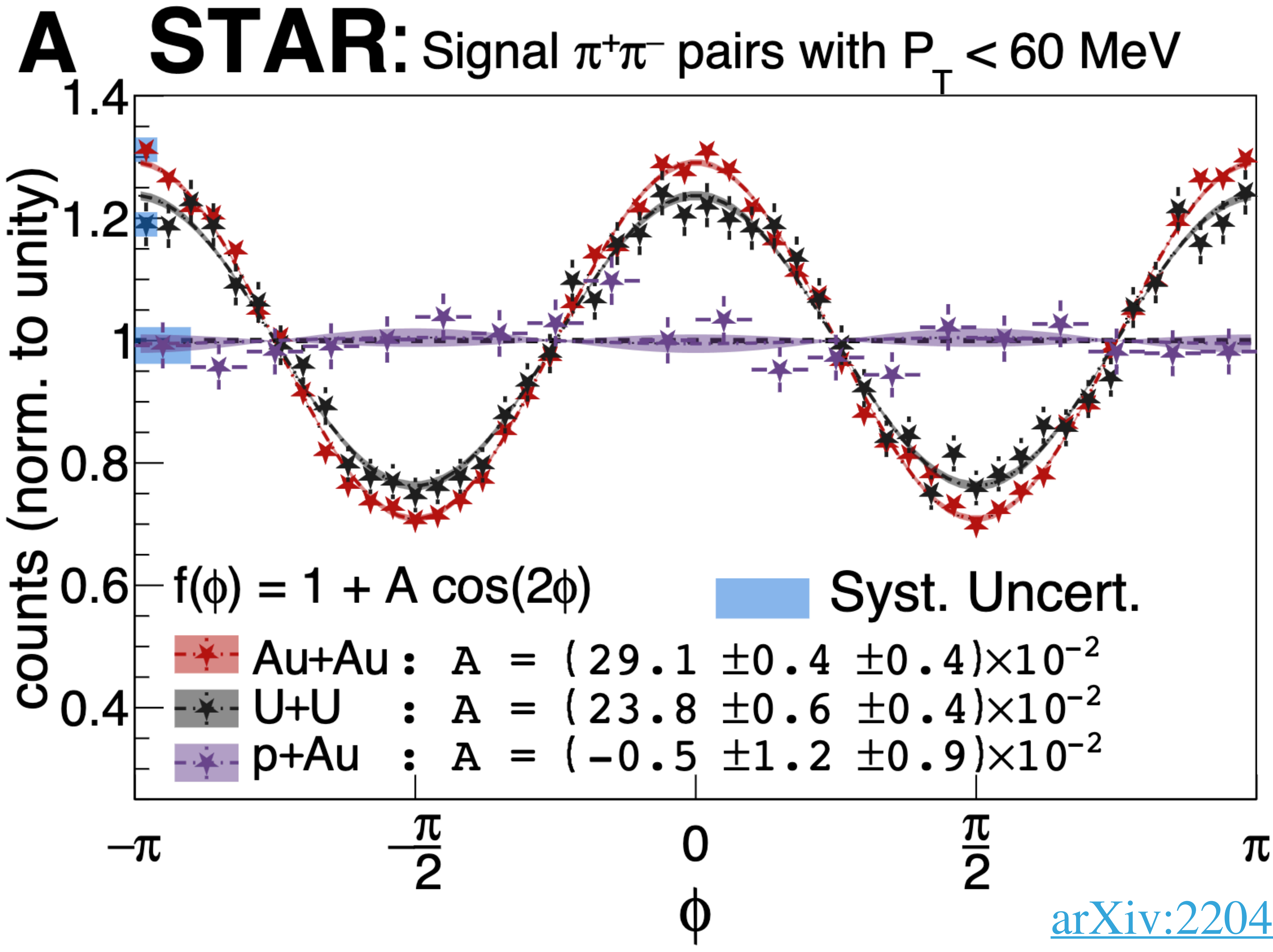


arXiv:1511.04535v2

Lighter vector mesons: quantum interference

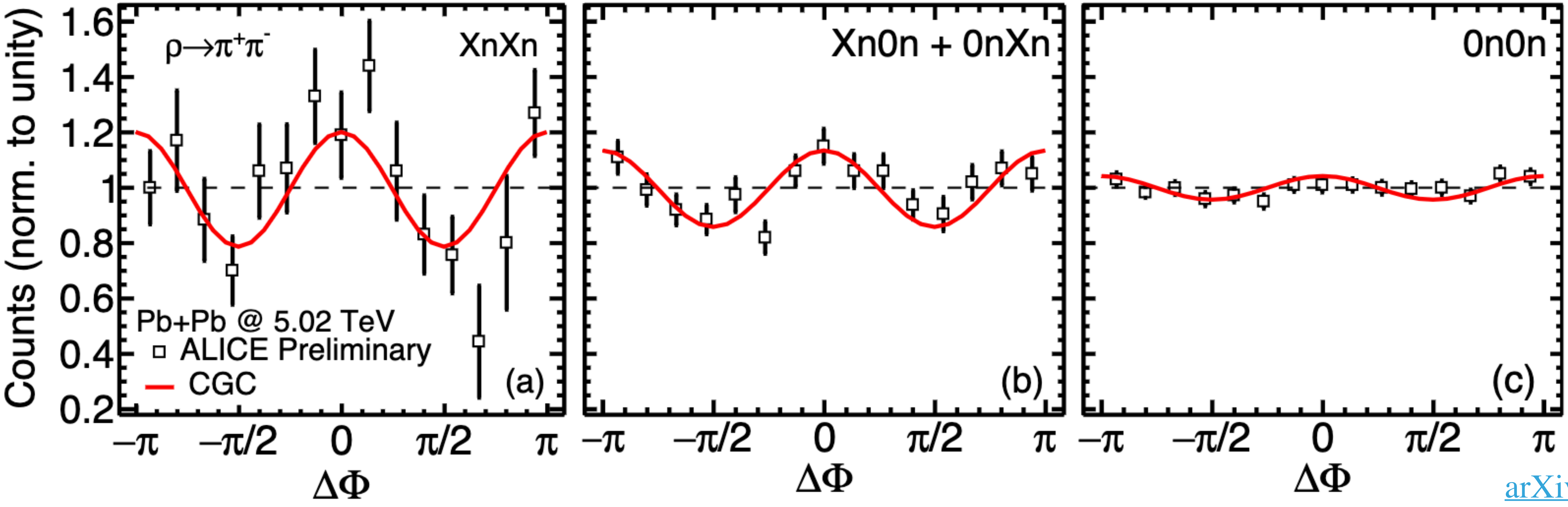
- In symmetric collisions, we have quantum interference.
- Manifested as angular modulations





arXiv:2204.01625

Lighter vector mesons: quantum interference

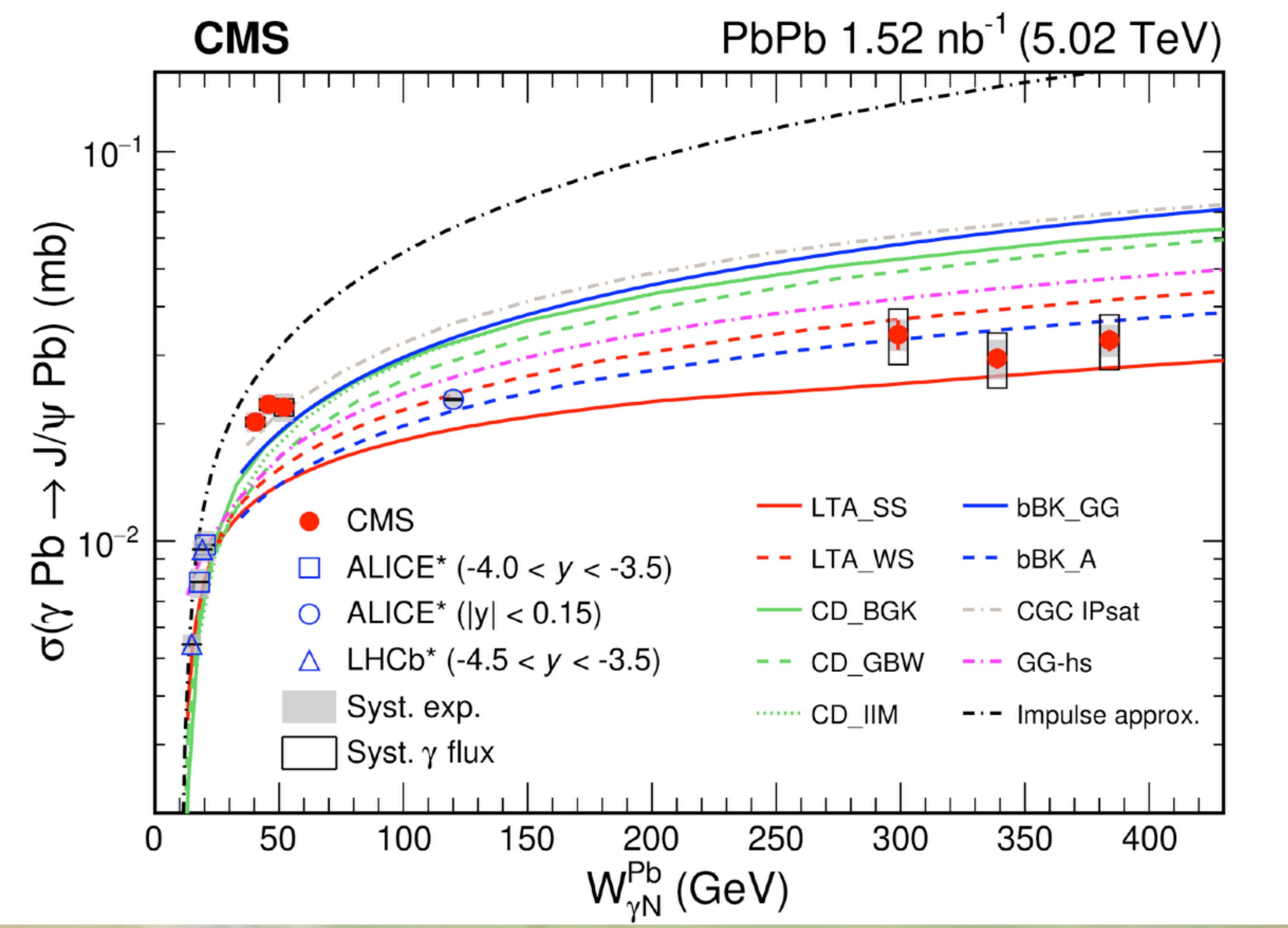


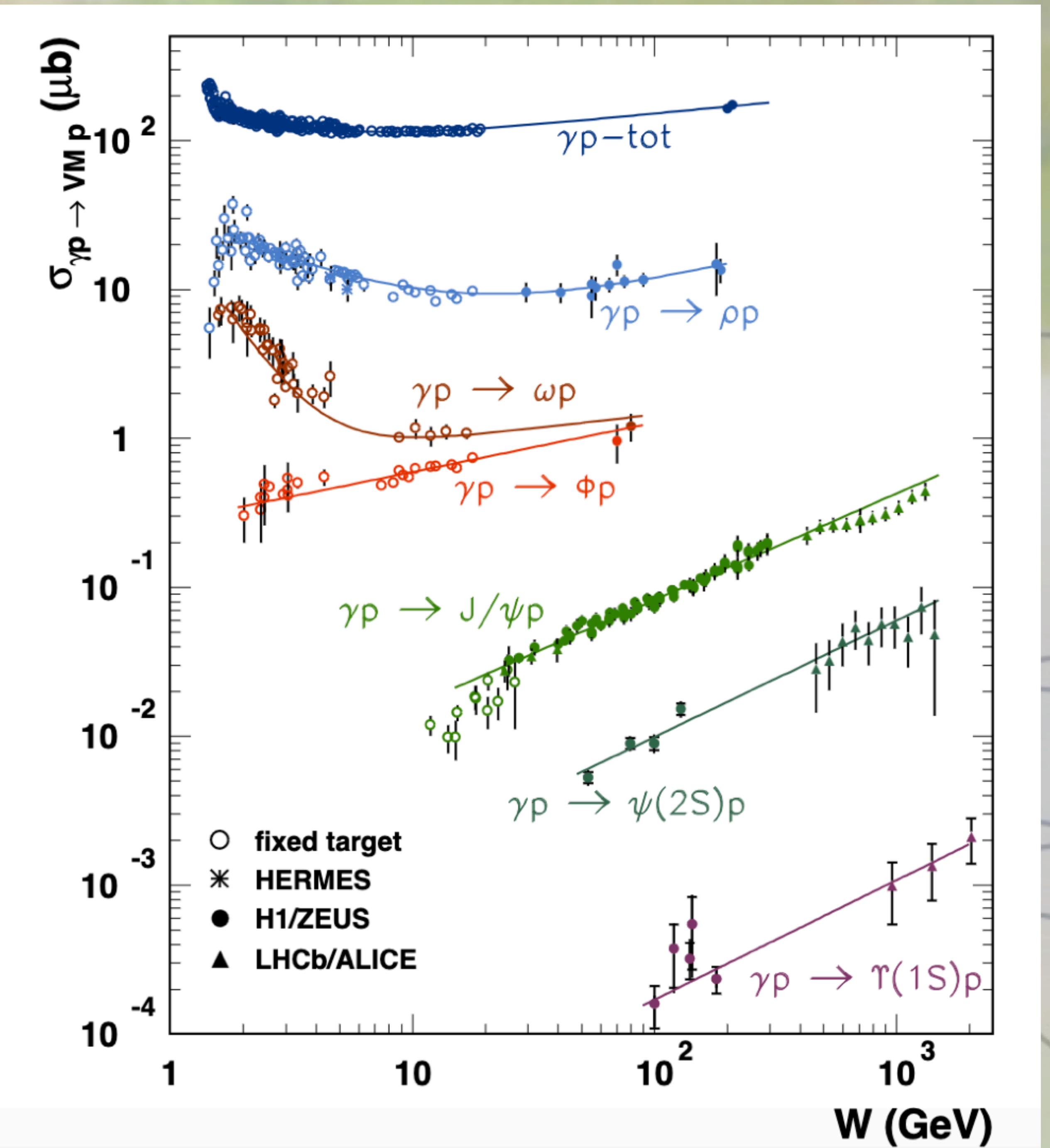
arXiv:2310.15300

- It is expected that interference effects vanish at large impact parameter.
- Effect observed in ALICE data.

Summary

- UPCs are very clean processes to test QED and QCD phenomena.
- Photoproduction of VMs in UPCs are powerful probes to test the gluonic structure of nuclei.
- The topic has brought the attention lately in the LHC community and continues the HERA legacy.
- Many interesting ongoing related studies in CMS, to be unveiled soon !



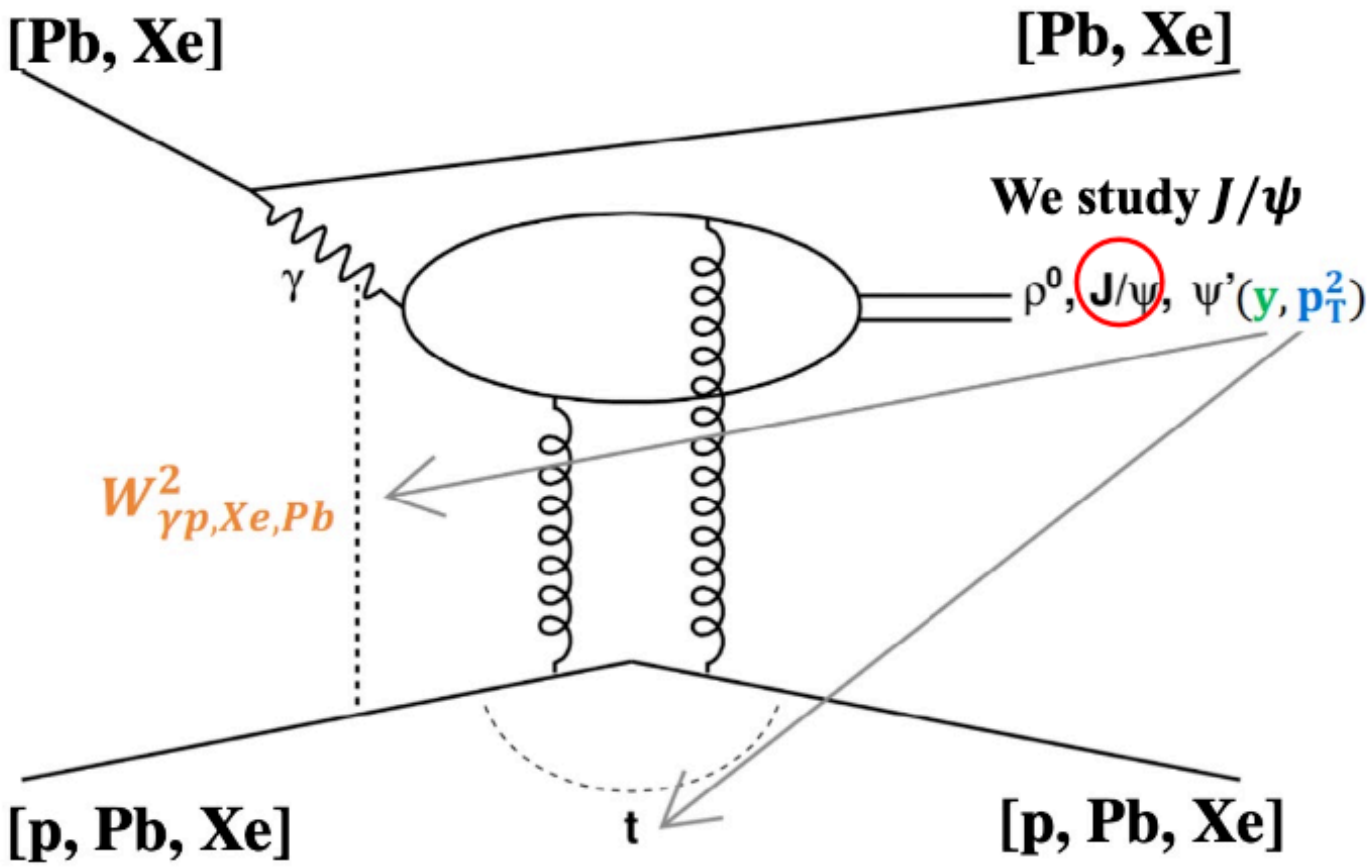


Backup slides

Vector meson photoproduction kinematics

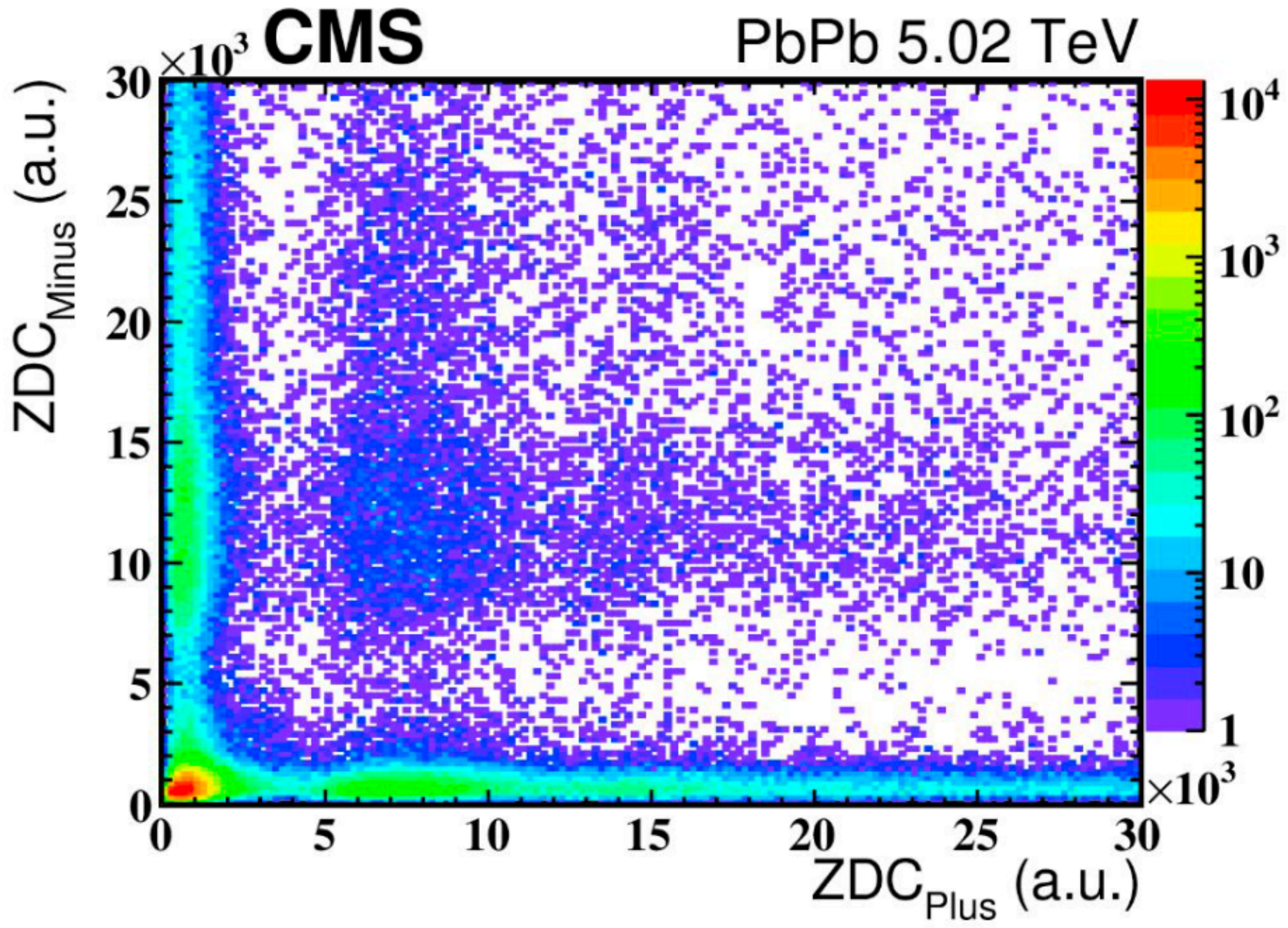
- A given y → Fixes ω, x, W

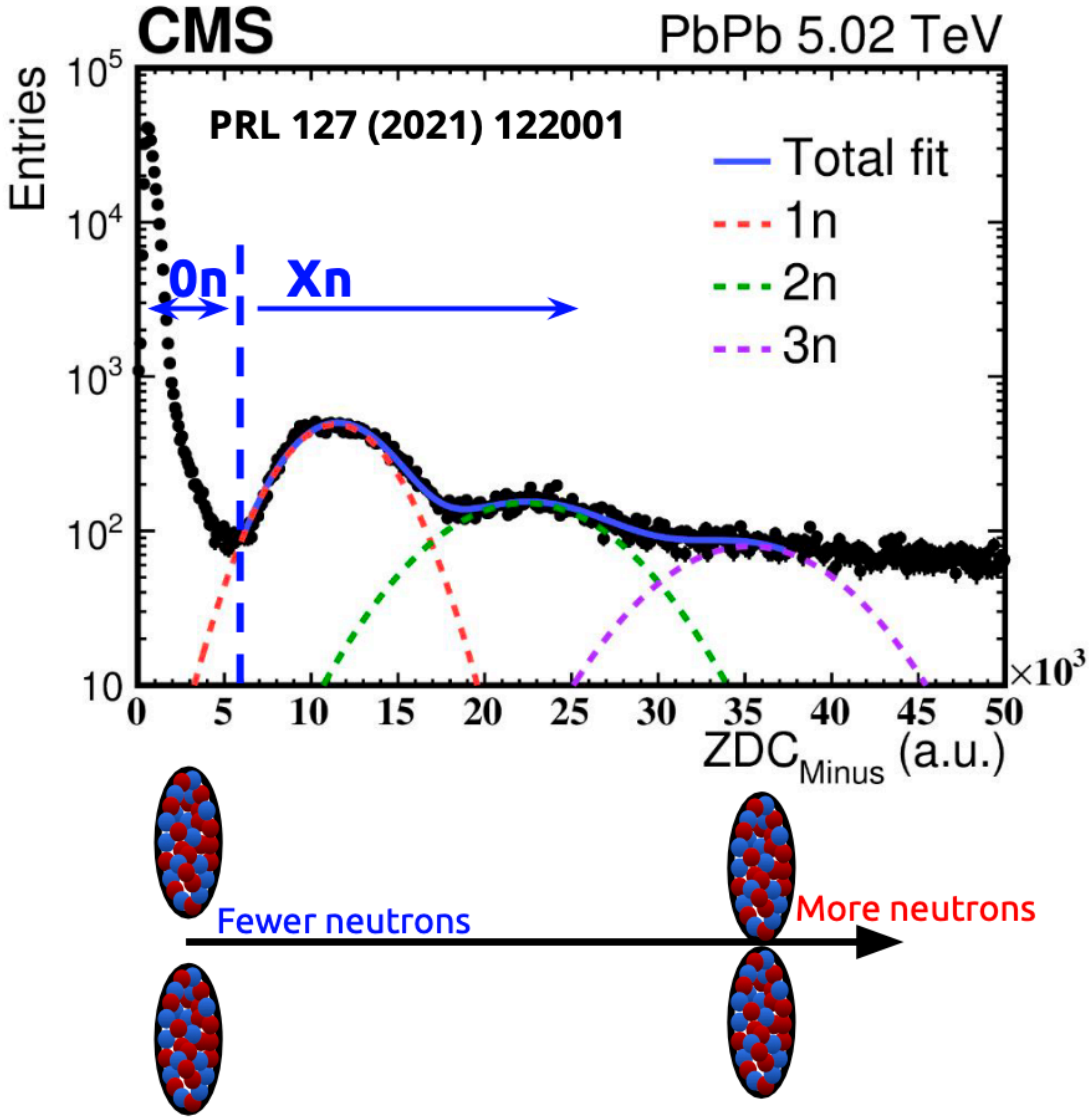
- $\omega = \frac{M_{VM}}{2} e^{\pm y}$
  - y: Rapidity of the VM
  - ω: Photon energy
  - M_{VM}: Mass of the VM
- $x = \left(\frac{M_{VM}}{\sqrt{s_{NN}}}\right) e^{\mp y}$
- $W^2 = M_{VM}\sqrt{s_{NN}} \cdot e^{\pm y}$
  - W: Centre-of-mass energy of the photon–target system



Event classification via neutron multiplicity

- Energy depositions in ZDCs allow to classify events in neutron categories.





- XnXn → smaller b
- 0n0n → larger b

A solution to the two-way ambiguity puzzle

Dominant b ranges of different neutron classes:

- 0n0n: b > 40 fm
- 0nXn: b ~ 20 fm
- XnXn: b < 15 fm

What is measured | Photon flux from theory | What we want

$$\frac{d\sigma^{0n0n}_{AA\to AAJ/\psi}}{dy} = N^{0n0n}_{\gamma/A}(y)\cdot\sigma_{\gamma A\to J/\psi A'}(y) + N^{0n0n}_{\gamma/A}(-y)\cdot\sigma_{\gamma A\to J/\psi A'}(-y)$$

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(y)\cdot\sigma_{\gamma A\to J/\psi A'}(y) + N^{0nXn}_{\gamma/A}(-y)\cdot\sigma_{\gamma A\to J/\psi A'}(-y)$$

$$\frac{d\sigma^{XnXn}_{AA\to A'A'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(y)\cdot\sigma_{\gamma A\to J/\psi A'}(y) + N^{XnXn}_{\gamma/A}(-y)\cdot\sigma_{\gamma A\to J/\psi A'}(-y)$$

→ Solve for $\sigma_{\gamma A\to J/\psi A'}(y)$ and $\sigma_{\gamma A\to J/\psi A'}(-y)$, and $x = \left(\frac{M_{VM}}{\sqrt{s_{NN}}}\right)e^{\mp y}$

Entering a new regime of small x ~ $10^{-4} - 10^{-5}$ in nuclei!