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Probing a new regime of ultra-dense gluonic matter using high-energy photons with the CMS experiment

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OUTLINE

- Ultraperipheral Collisions
- Vector meson Photoproduction
- Motivation
- Signal Extraction
- Results
- Summary

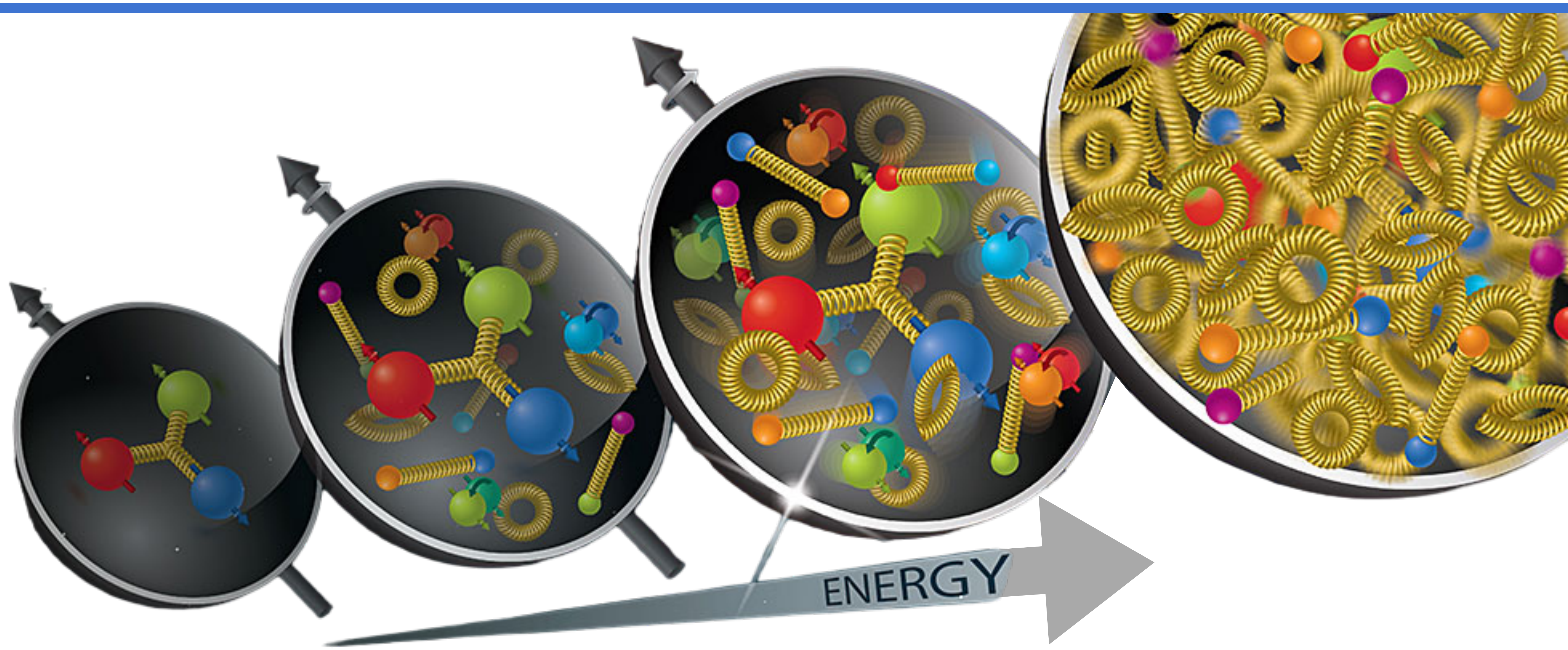
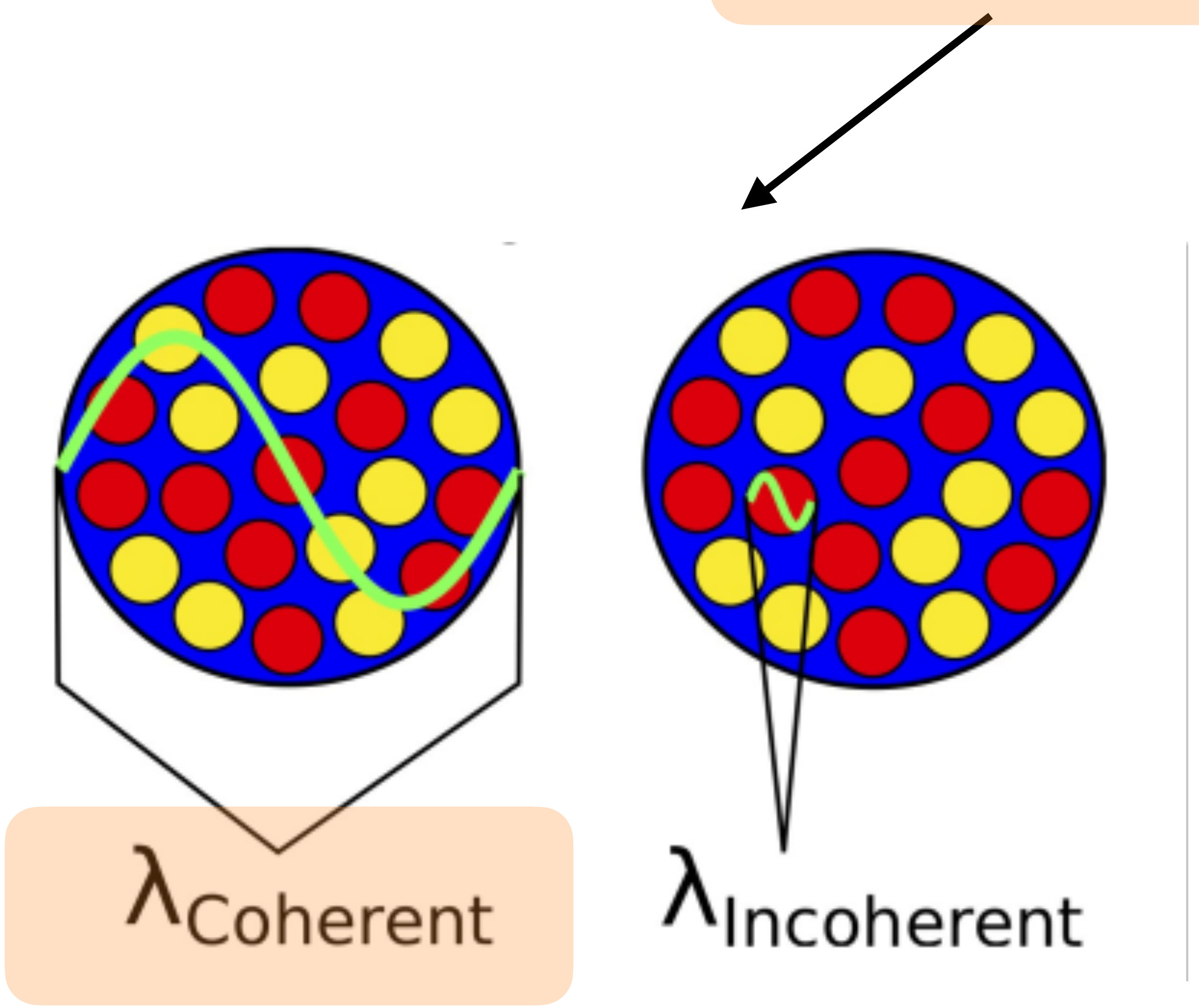
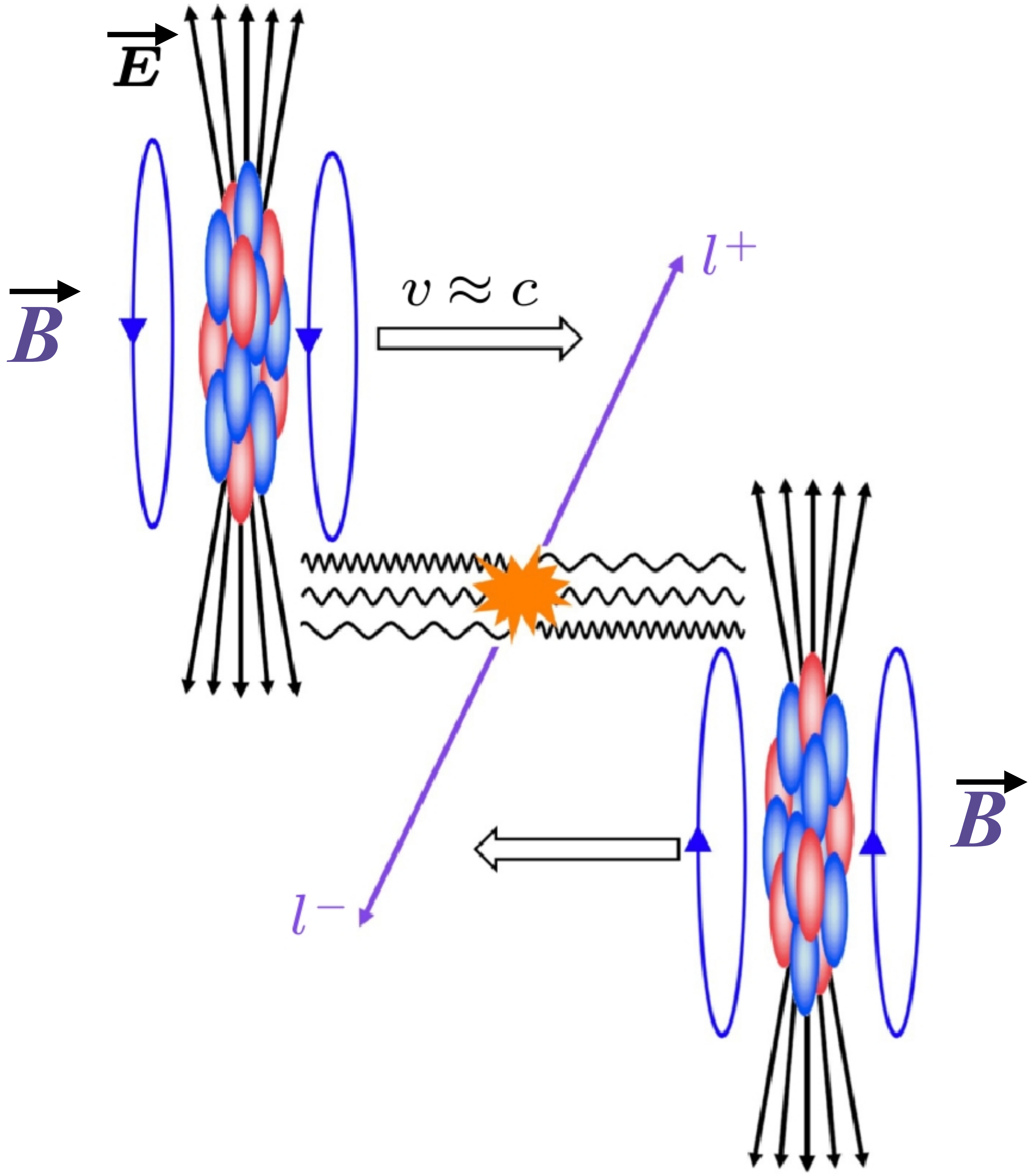


Image credits : EIC, BNL

- Heavy ions moving at ultra relativistic speeds
- Cross each other with an impact parameter b $> R_A + R_B$
- Lorentz contracted EM fields → Flux of quasi-real $\gamma \propto Z^2$ $(Q^2 < \hbar^2/R^2)$
- Interaction via photon- photon or photon-nucleus

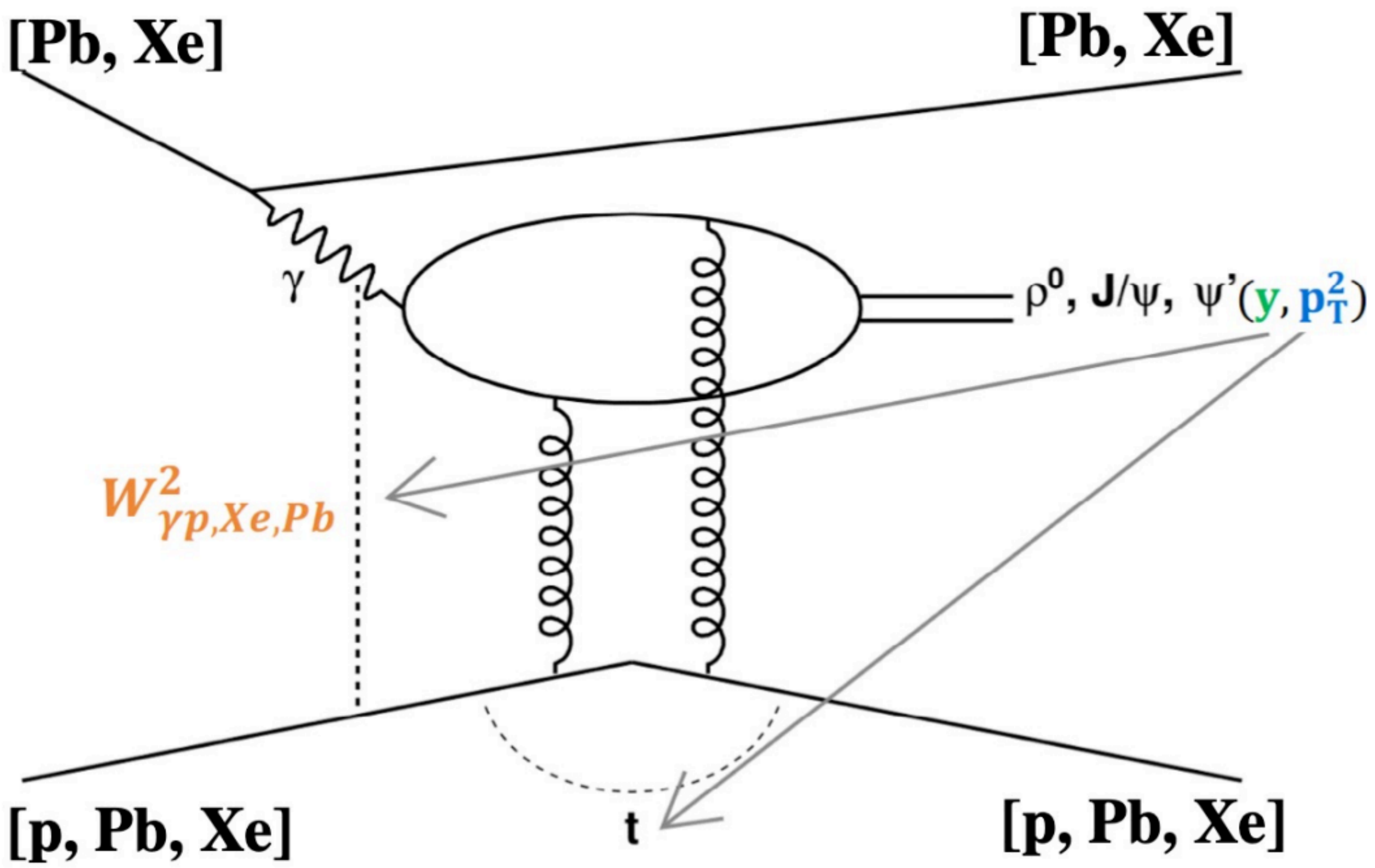


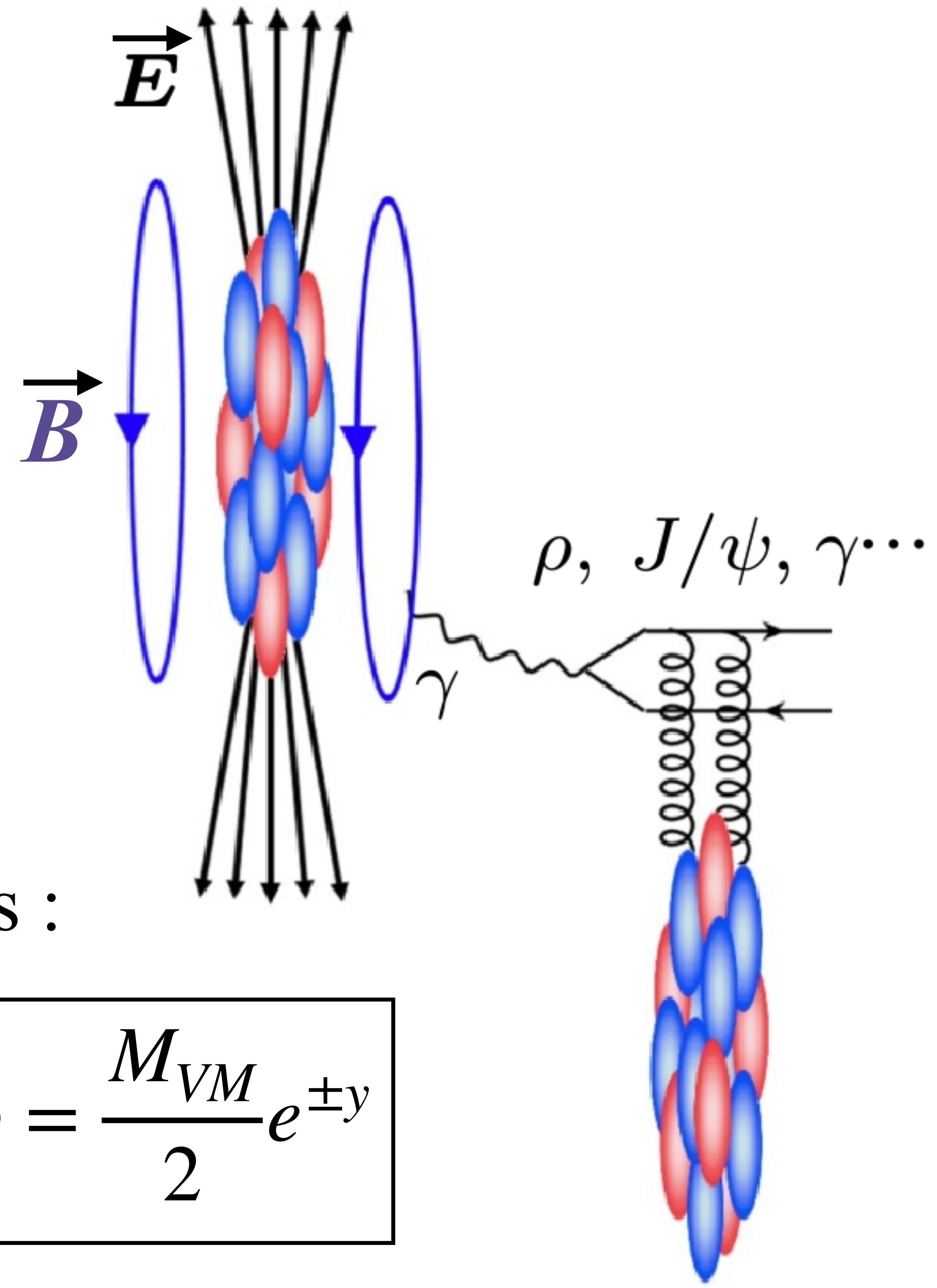


How can photons probe the gluonic structure ?

Vector Meson Photoproduction

- Vector meson photo production directly probes gluonic structure.
- Quasi-real γ fluctuates to a q$\bar{q}$ pair
- q$\bar{q}$ scatters elastically → J/Ψ
- Coherent vector mesons photo-production ∝ $(xg(x, Q^2))^2$
- Final state : Vector mesons (ρ^0, J/Ψ, ϕ….)





Final state kinematics :

$$x = \frac{M_{VM}}{\sqrt{S_{NN}}} e^{\mp y}$$

$$\omega = \frac{M_{VM}}{2} e^{\pm y}$$

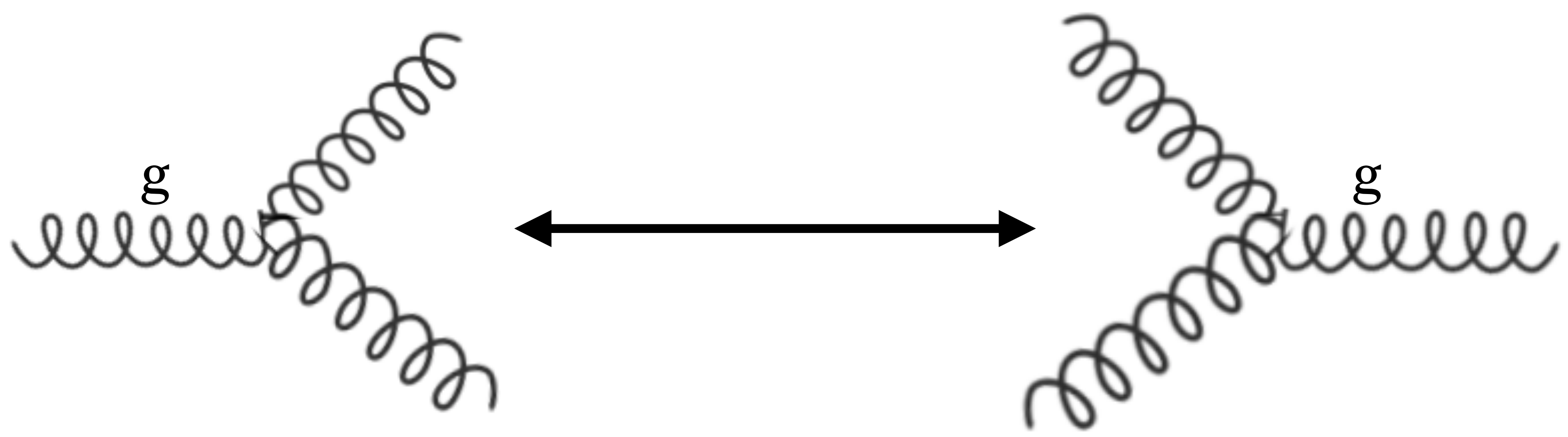
$$W^2 = M_{VM}\sqrt{S_{NN}} \, . \, e^{\pm y}$$

Gluon Density

EPJC 75, 580 (2015)

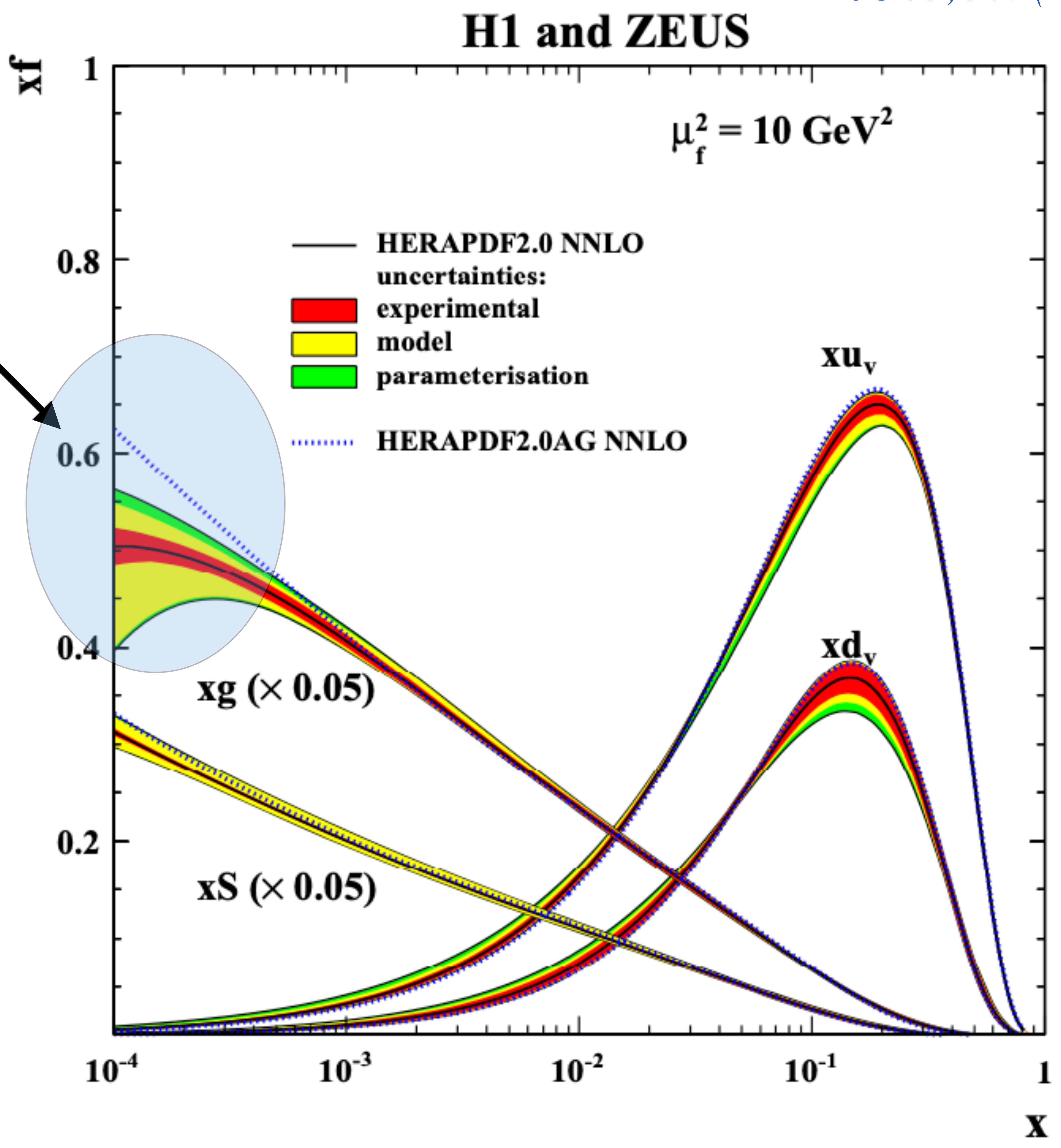
- Low x : Gluon dominance
- High x : Quark dominance
- Indefinite growth at small-x region

Increasing gluon density due to Gluon splitting



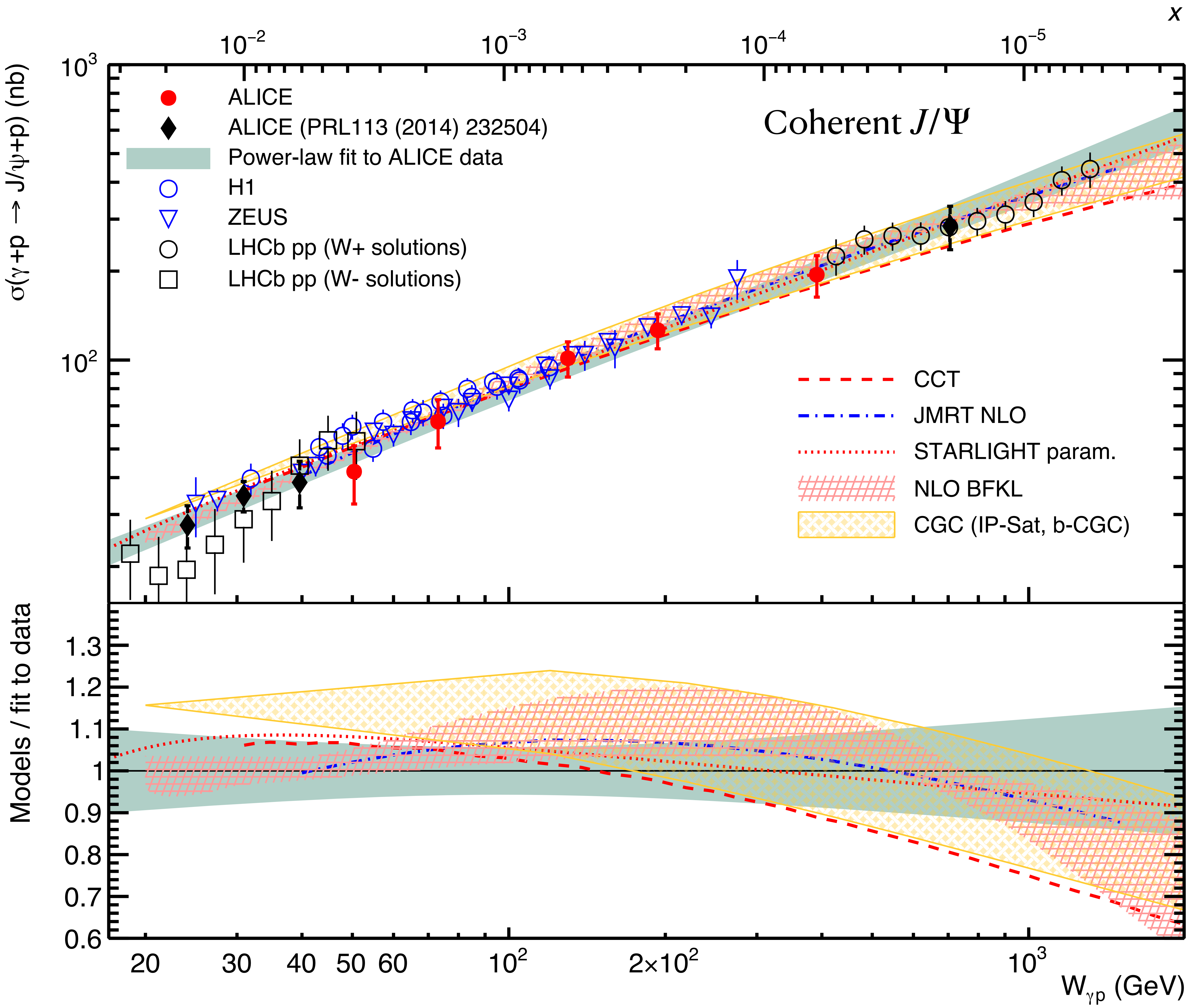
"Gluon starts to overlap and recombine"

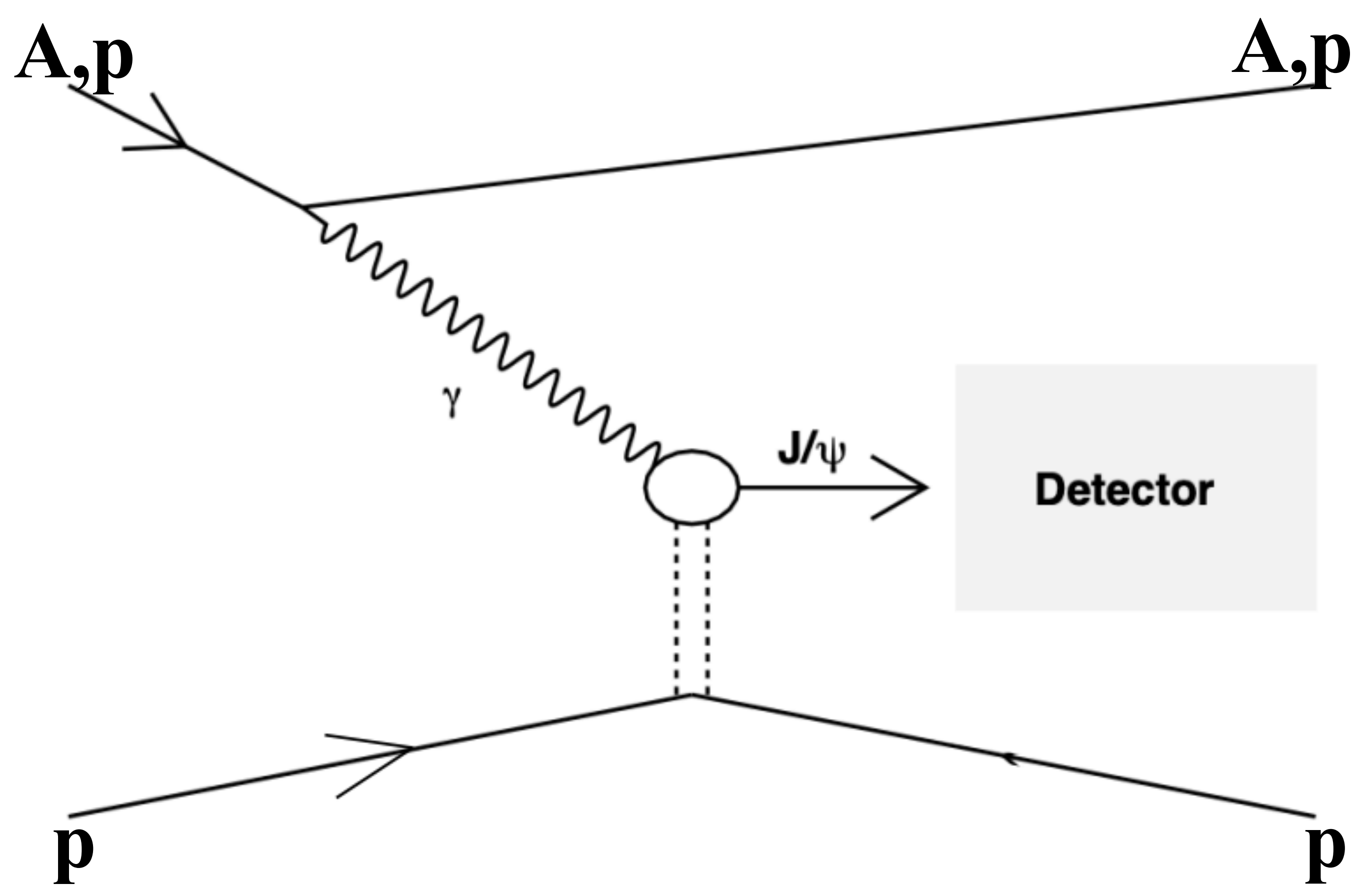
SATURATION ?



J/Ψ Photoproduction in γp

Alice, EPJC 79 (2019) 5, 402

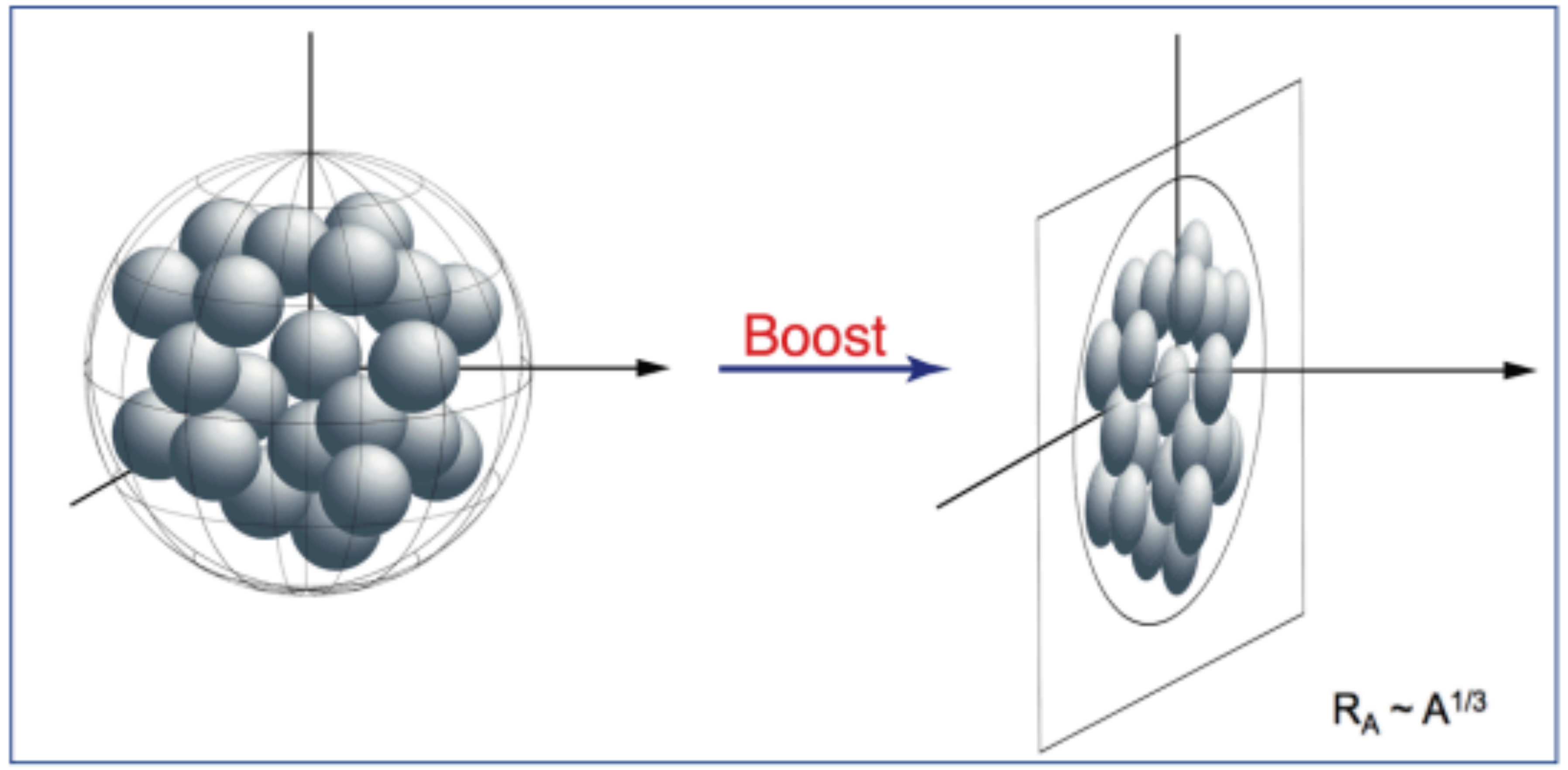




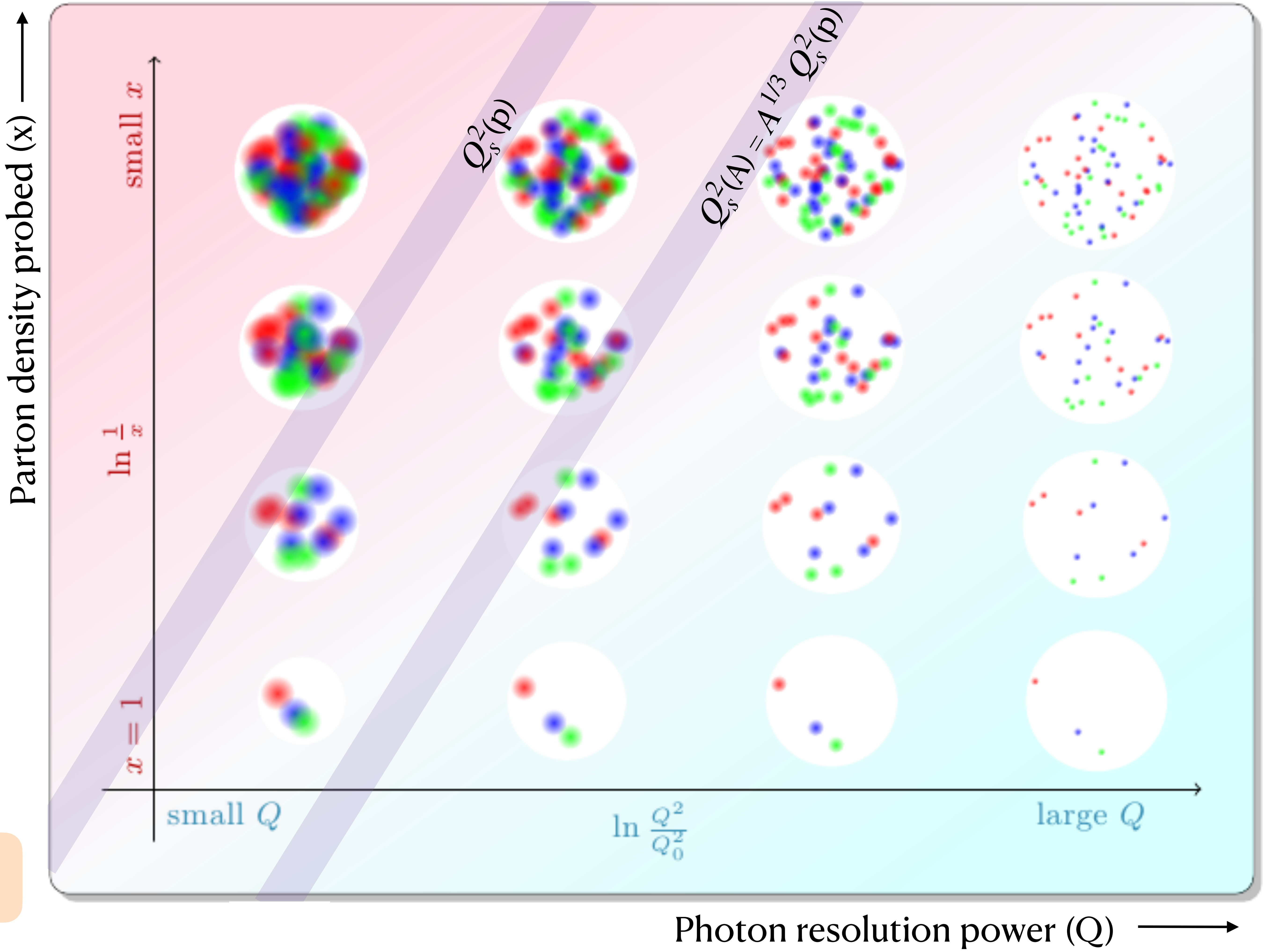
$\sigma(W_{\gamma p})$ follows a universal power law rise from HERA to the LHC.

No clear sign of gluon saturation !

Advantages of Gluon Saturation Search in Nucleus



Gluon density is enhanced by a factor of $A^{1/3}$ in nucleus compared to what in free nucleon
Saturation scale: $Q_s^2 \propto A^{1/3}$

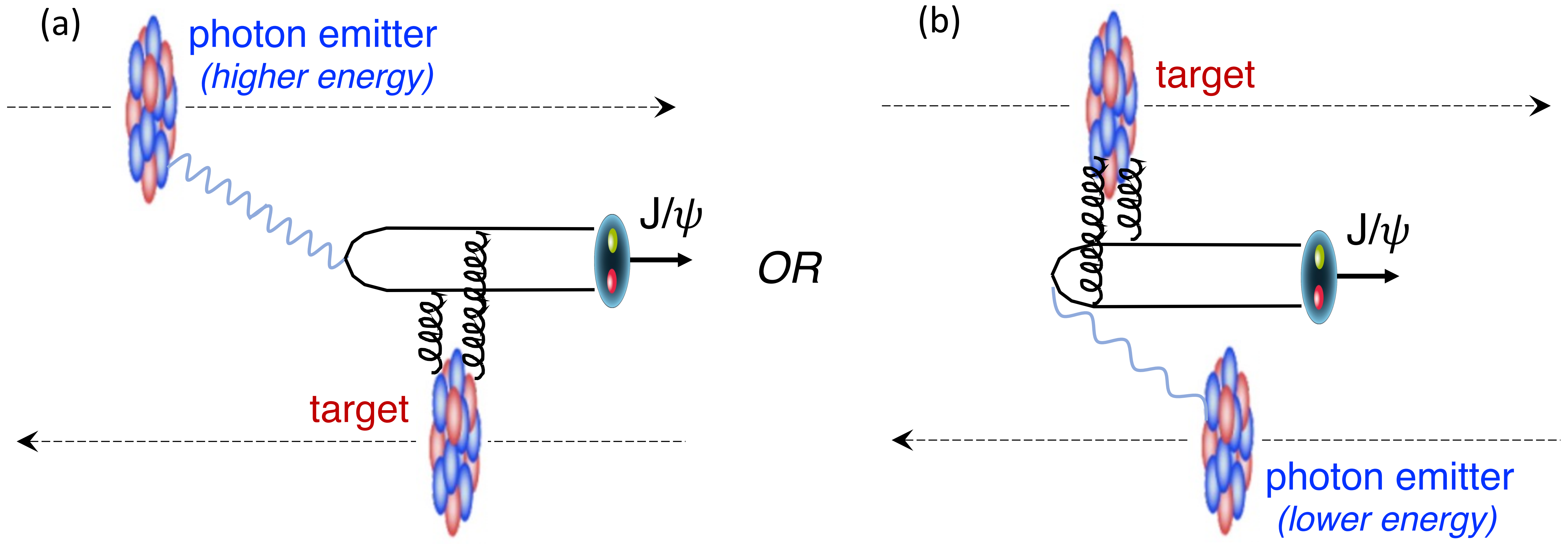


Easier to reach gluon saturation in the case of Nuclei

Two way ambiguity in A-A UPC

CMS, Phys. Rev. Lett. ***131*** *(2023) , 262301*

$$\frac{d\sigma_{AA\to AA'J/\Psi}}{dy} = N_{\gamma/A}(\omega_1)\,.\,\sigma_{\gamma A\to J/\Psi A'}(\omega_1) + N_{\gamma/A}(\omega_2)\,.\,\sigma_{\gamma A\to J/\Psi A'}(\omega_2)$$



Can we solve this two way ambiguity?

↓

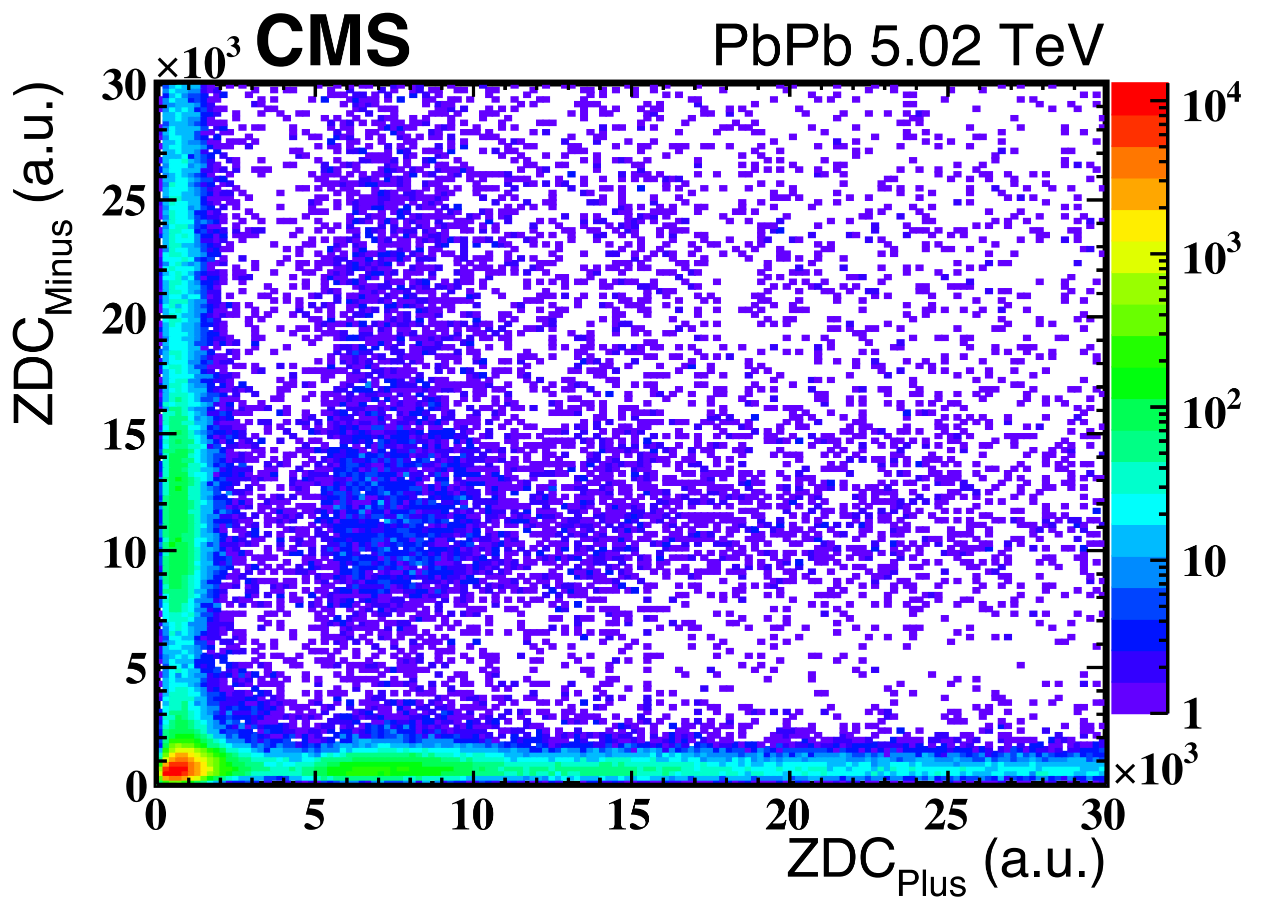
Impact parameter dependence:

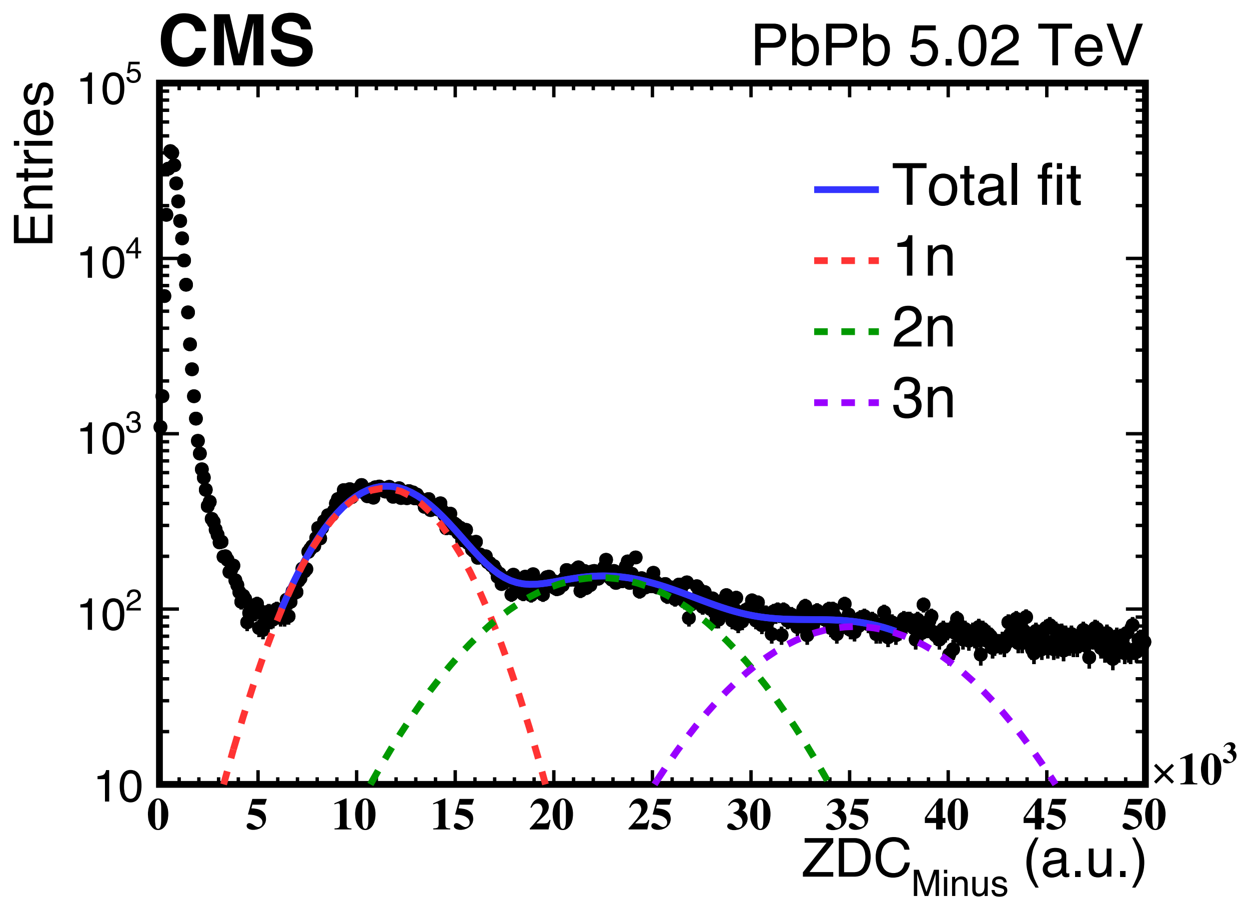
$$b_{XnXn} < b_{Xn0n} < b_{0n0n}$$

(Zero Degree Calorimeter)

<u>Symmetric Collisions</u> :
Both ions can be photon emitter or target

Each point have a contribution of:
low and high energy photon

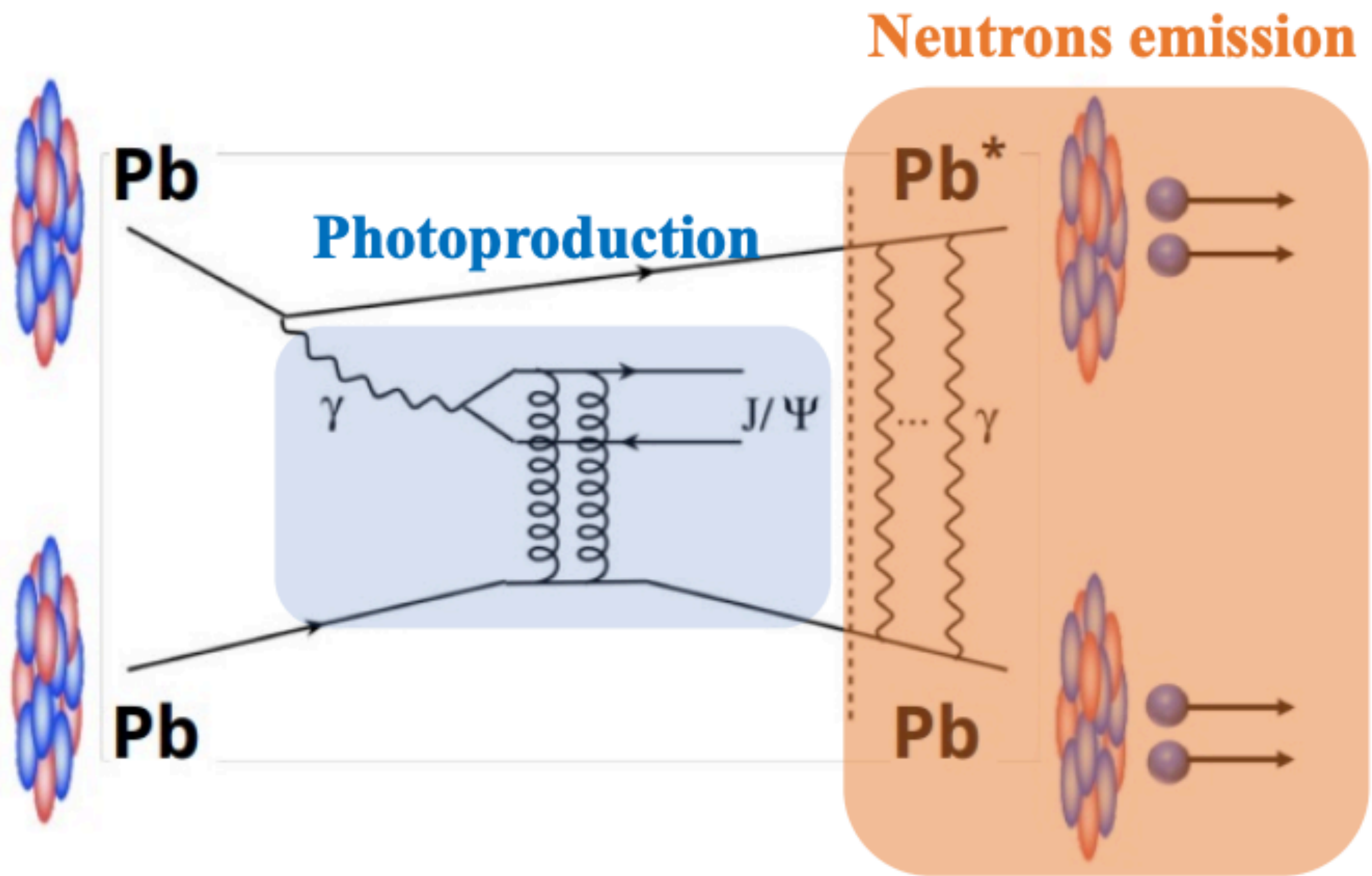




Phys. Rev. Lett. 127, 122001 (2021)

Solution to two way ambiguity in A-A UPC

$$\frac{d\sigma_{AA\to AA'J/\Psi}}{dy} = N_{\gamma/A}(\omega_1)\,.\,\sigma_{\gamma A\to J/\Psi A'}(\omega_1) + N_{\gamma/A}(\omega_2)\,.\,\sigma_{\gamma A\to J/\Psi A'}(\omega_2)$$



Controlling the impact parameter

↓

Impact parameter dependence:

$$b_{XnXn} < b_{Xn0n} < b_{0n0n}$$

↓

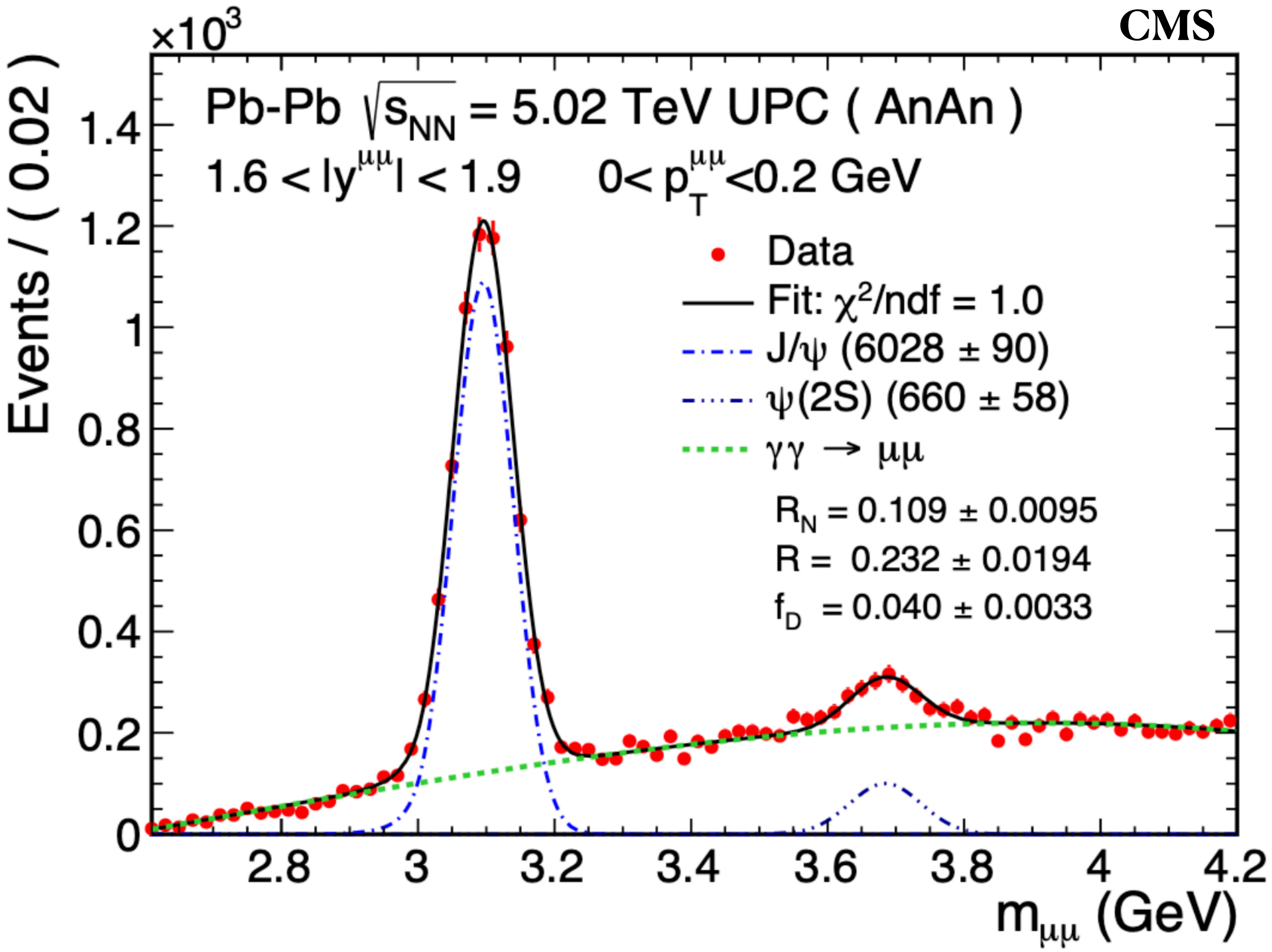
Quantity measured		Photon flux from theory		Want to measure		Photon flux from theory		Want to measure
$\frac{d\sigma^{0n0n}_{AA\to AA'J/\Psi}}{dy}$	=	$N_{\gamma/A}(\omega_1)^{0n0n}$	.	$\sigma_{\gamma A\to J/\Psi A'}(\omega_1)$	+	$N_{\gamma/A}(\omega_2)^{0n0n}$	.	$\sigma_{\gamma A\to J/\Psi A'}(\omega_2)$
$\frac{d\sigma^{0nXn}_{AA\to AA'J/\Psi}}{dy}$	=	$N_{\gamma/A}(\omega_1)^{0nXn}$	.	$\sigma_{\gamma A\to J/\Psi A'}(\omega_1)$	+	$N_{\gamma/A}(\omega_2)^{0nXn}$	.	$\sigma_{\gamma A\to J/\Psi A'}(\omega_2)$
$\frac{d\sigma^{XnXn}_{AA\to AA'J/\Psi}}{dy}$	=	$N_{\gamma/A}(\omega_1)^{XnXn}$	.	$\sigma_{\gamma A\to J/\Psi A'}(\omega_1)$	+	$N_{\gamma/A}(\omega_2)^{XnXn}$	.	$\sigma_{\gamma A\to J/\Psi A'}(\omega_2)$

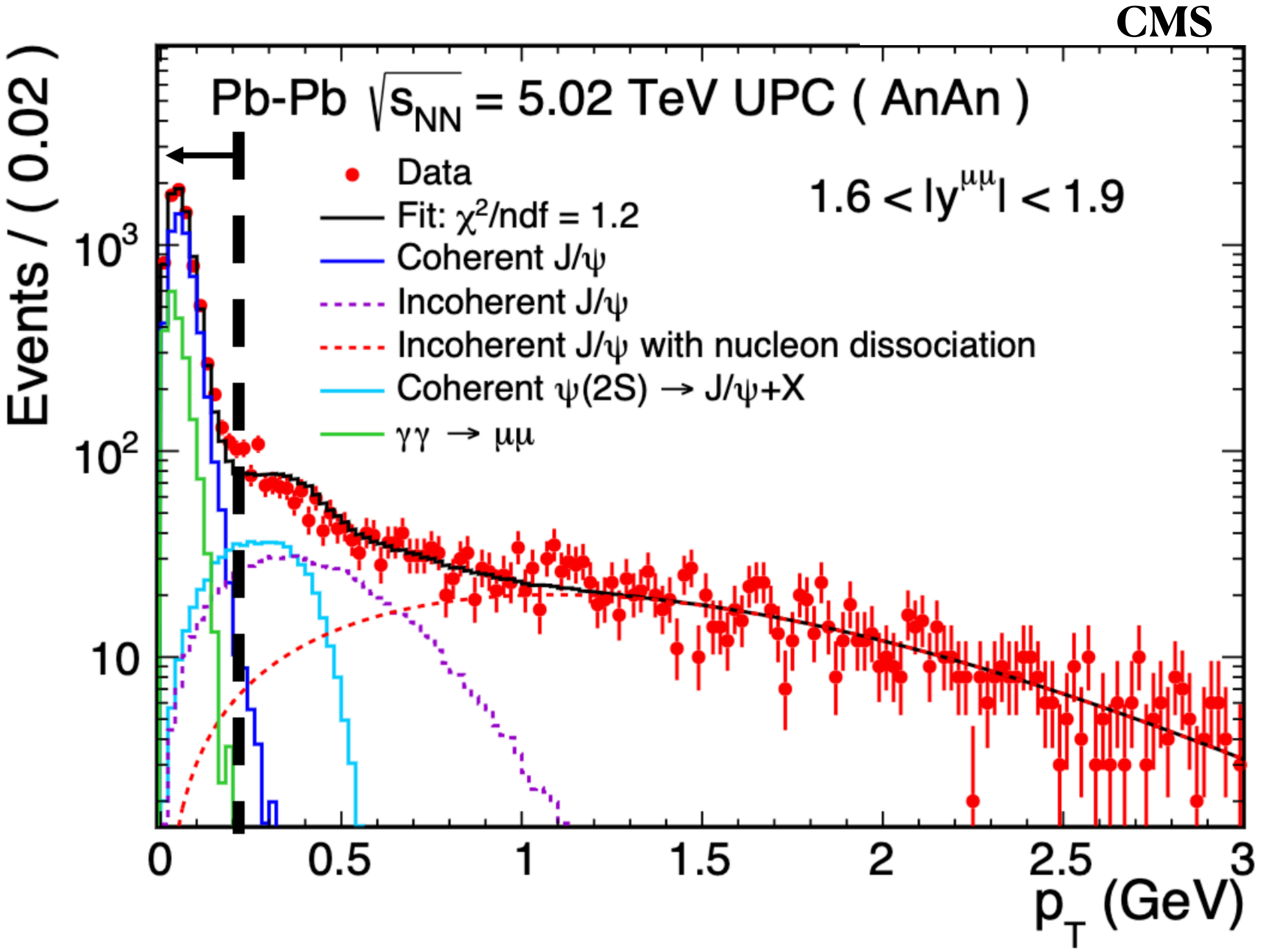
CMS Detector

Signal selection:
Primary Vertex and Cluster Compatibility Filters
Low activity in forward calorimeters
Exactly two high purity tracks identified as muons

Signal Extraction

CMS, Phys. Rev. Lett. ***131*** *(2023), 262301*





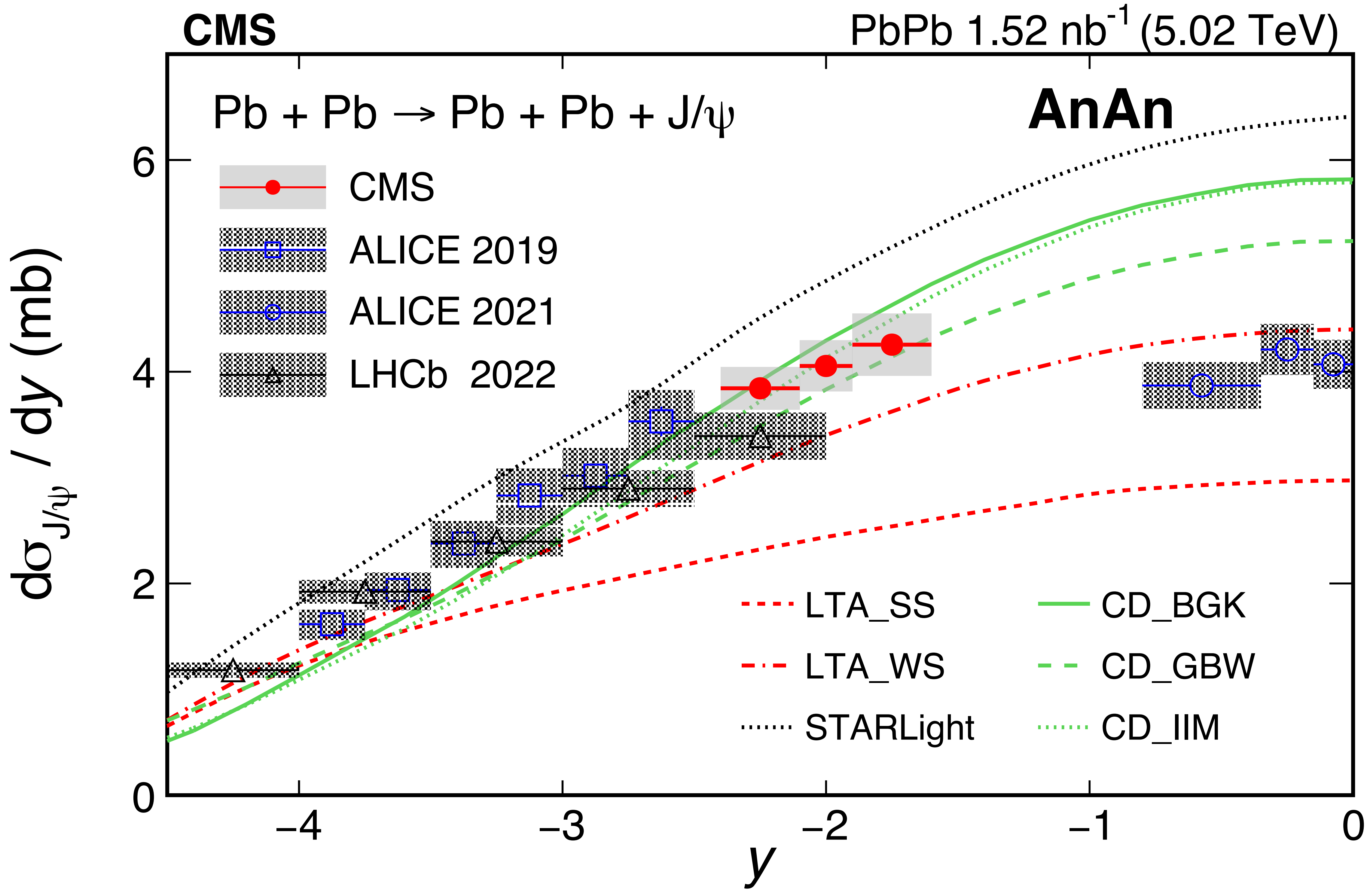
Yields extracted by fitting mass peak in the range $p_T < 0.20$ GeV/c

AnAn : All possible neutron emissions

J/Ψ Photoproduction in γPb

*CMS, Phys. Rev. Lett. **131** (2023), 262301*
ALICE, EPJC 81 (2021) 712
LHCb, JHEP 06 (2023) 146

$$\frac{d\sigma^{coh}_{J/\Psi}}{dy} = \frac{N_{J/\Psi}}{(1+f_I+f_D)\,.\,\epsilon_{J/\Psi}\,.\,Acc_{J/\Psi}\,.\,BR_{J/\Psi->\mu\mu}\,.\,L_{int}\,.\,\Delta y}$$



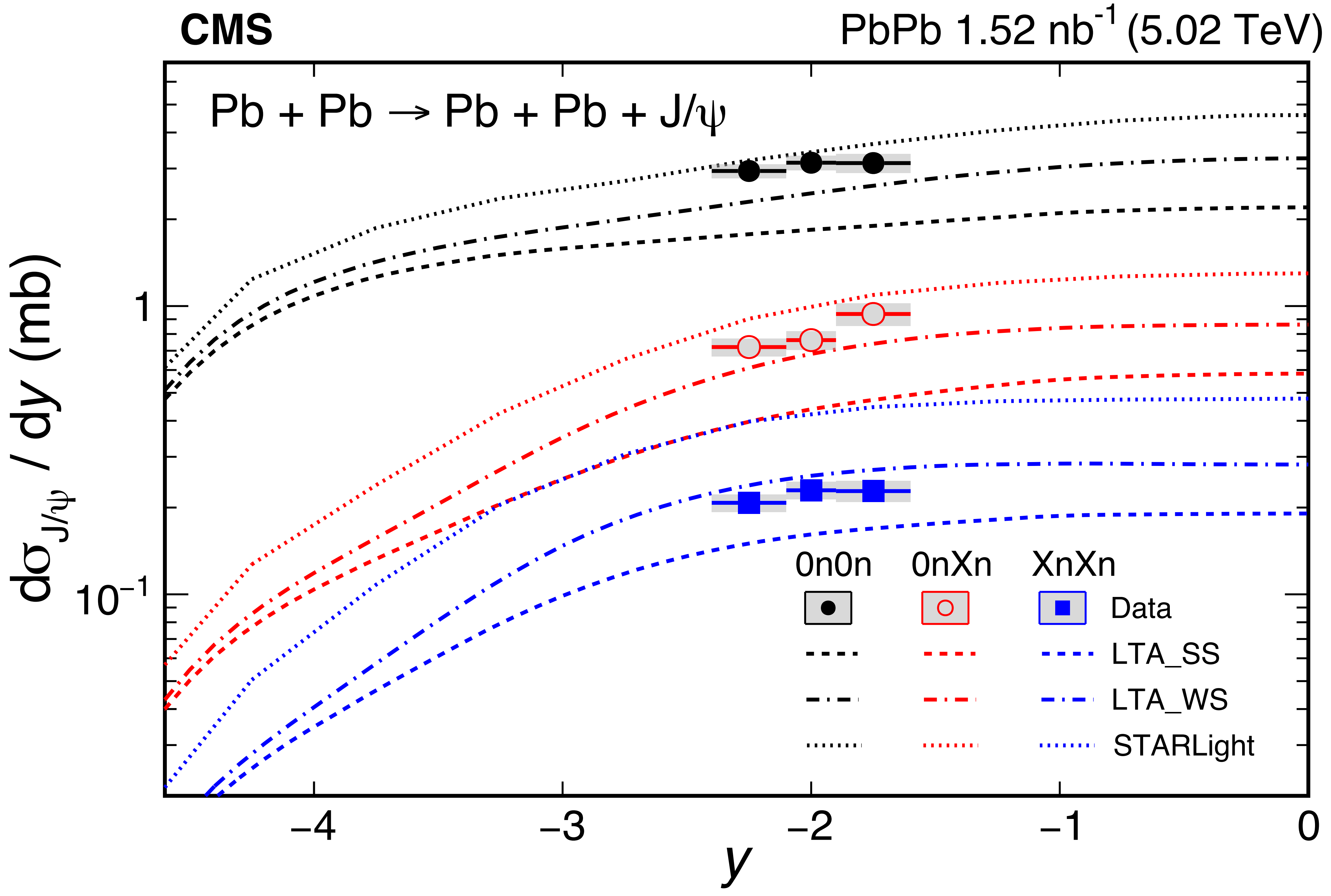
$$f_I = \text{incoherent fraction} = \frac{N(Incoh_{J/\Psi})}{N(Coh_{J/\Psi})}$$

$$f_D = \text{Feed down ratio} = \frac{N(Feeddown_{J/\Psi})}{N(Primary_{J/\Psi})}$$

- CMS data cover a unique rapidity region and follows ALICE forward rapidity trend
- No theory can describe data over full y range

CMS, Phys. Rev. Lett. **131** (2023), 262301
ALICE, EPJC 81 (2021) 712
LHCb, JHEP 06 (2023) 146

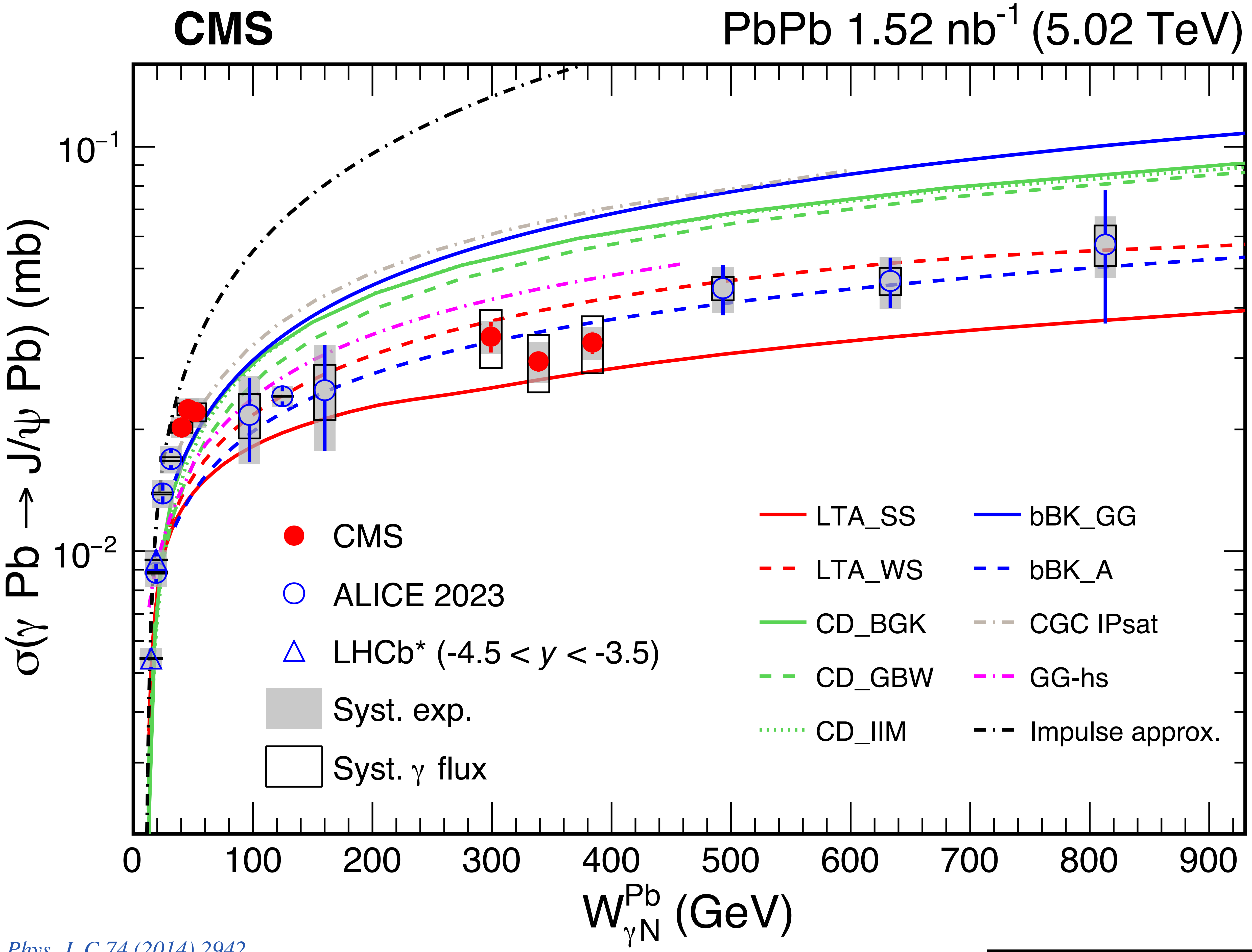
$$\frac{d\sigma^{coh}_{J/\Psi}}{dy} = \frac{N_{J/\Psi}}{(1 + f_I + f_D) \,.\, \epsilon_{J/\Psi} \,.\, Acc_{J/\Psi} \,.\, BR_{J/\Psi->\mu\mu} \,.\, L_{int} \,.\, \Delta y}$$



- First coherent J/Ψ measurement from different neutron classes
- No model can describe the data in different neutron classes
- Allow to disentangle the low- and high-energy photon-nucleus contributions of a single γ+Pb.

Coherent J/Ψ Cross Section in γPb vs. W

*CMS, Phys. Rev. Lett. **131** (2023), 262301*
Alice, JHEP 10 (2023) 119



ALICE, LHCb vs. IA:
- Data is close to IA at low W.
- Data is significant lower than IA at W~125 GeV.

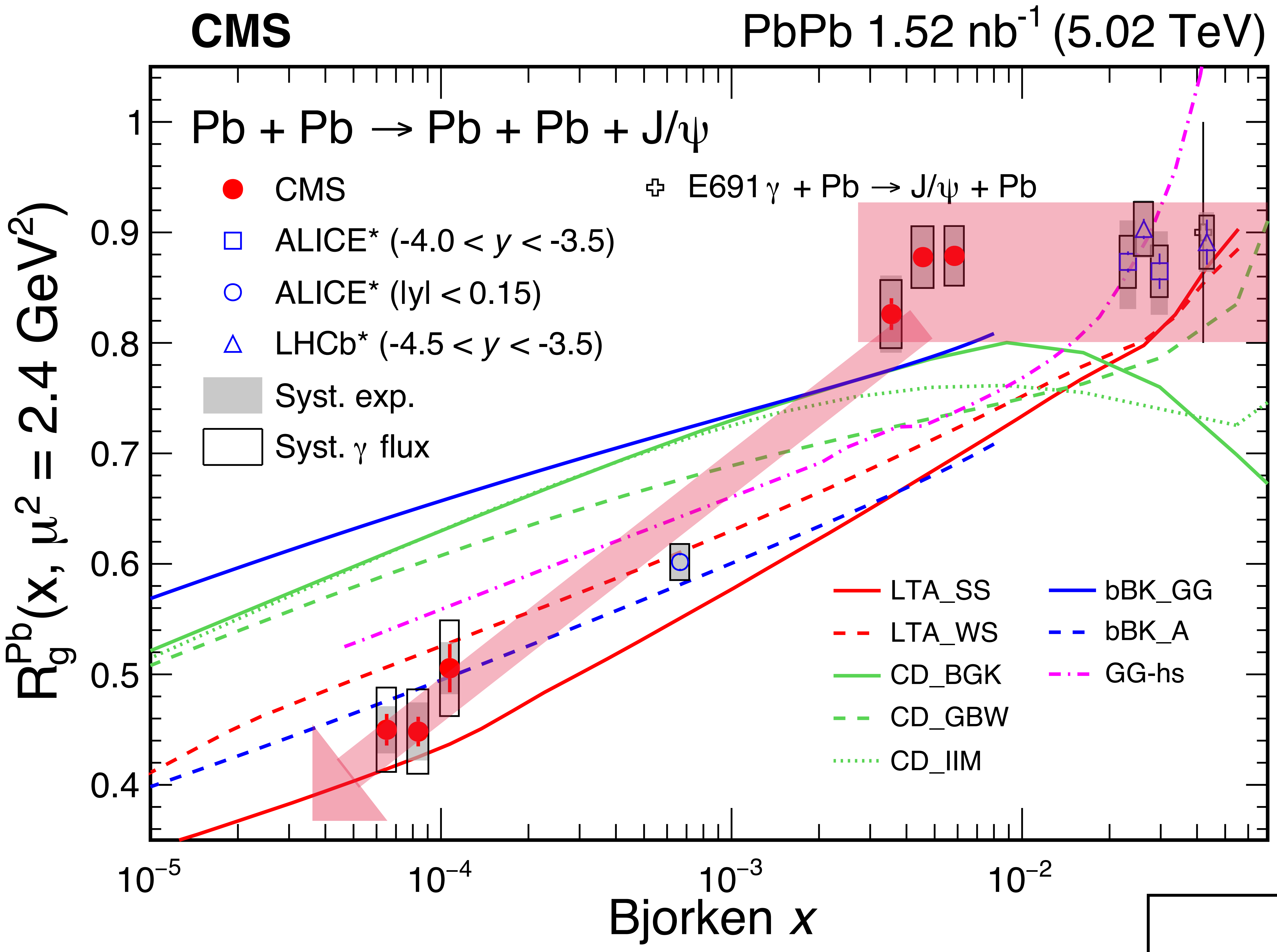
New data from CMS:
- Rapid increase at W<40 GeV.
- Turn into a nearly flat (slower rising) trend for W>40 GeV.

Eur. Phys. J. C 74 (2014) 2942
Phys. Rev. C 93 (2016) 055206
Phys. Rev. C 99 (2019) 044905
Phys. Lett. B 817 (2021) 136306
Phys. Lett. B 772 (2017) 832
Phys. Rev. C 97 (2018) 024901

$$W^2 = M_{VM}\sqrt{S_{NN}}\,.\,e^{\pm y}$$

Nuclear Gluon Suppression Factor

*CMS, Phys. Rev. Lett. **131** (2023), 262301*



$$R_g^A = \left(\frac{\sigma^{exp}_{\gamma A\rightarrow J/\Psi A}}{\sigma^{IA}_{\gamma A\rightarrow J/\Psi A}}\right)^{1/2}$$

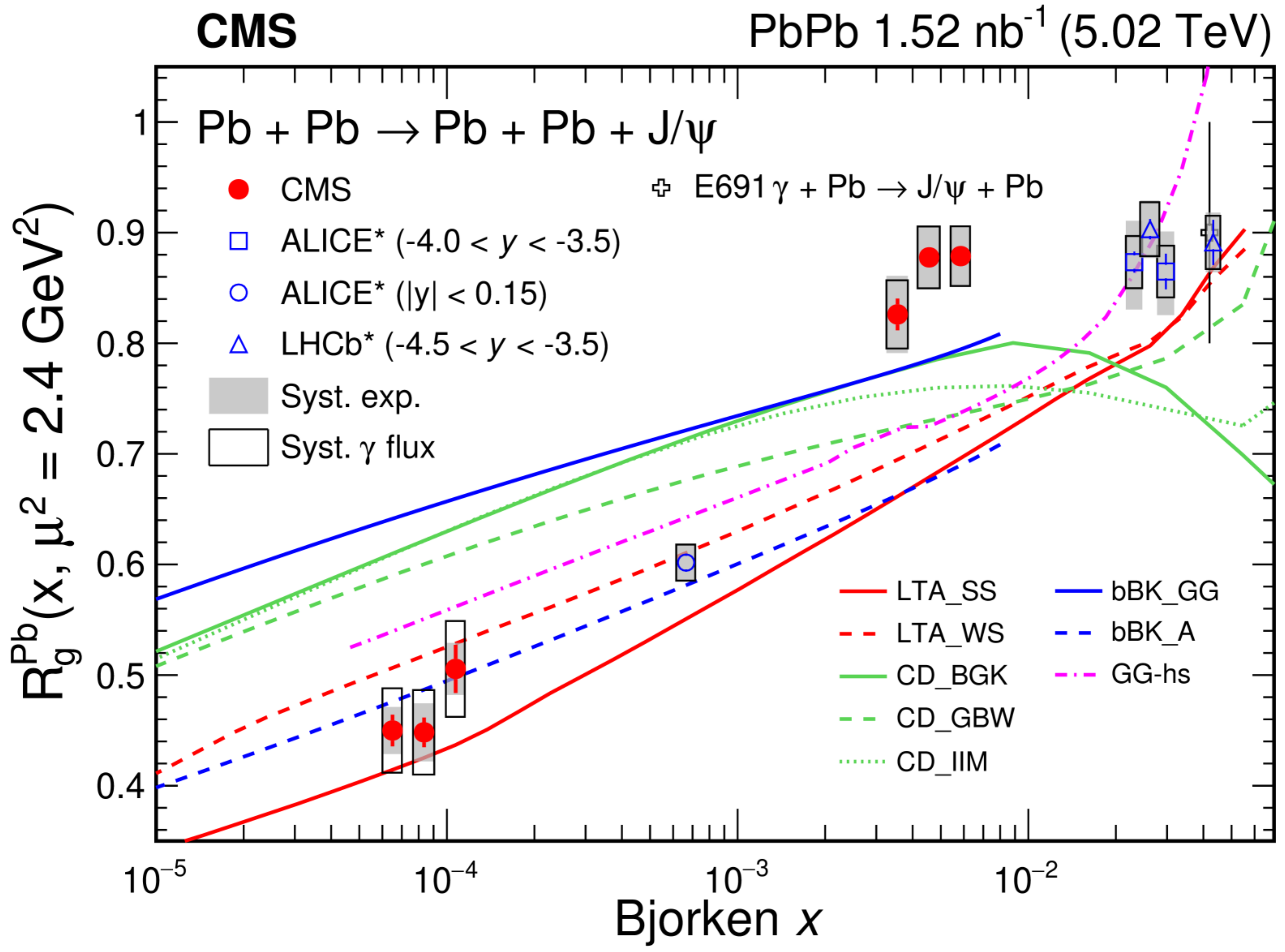
Impulse approx. (IA) neglects all nuclear effects.

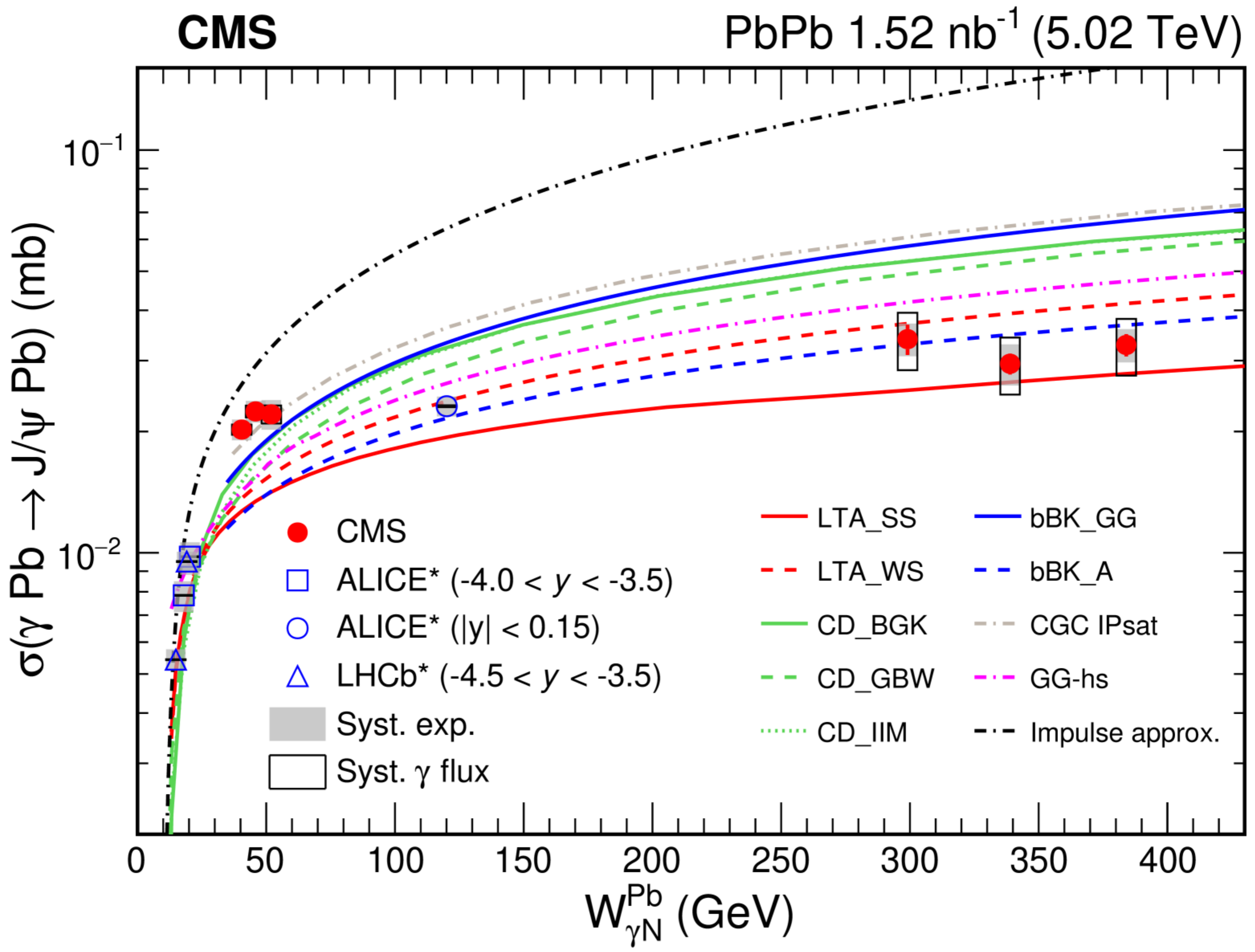
- Rg represents nuclear gluon suppression factor at LO.
- At high-x region: flat trend.Quickly decrease towards lower x region.
- Beyond model expectation in full phase space

$$x = \frac{M_{VM}}{\sqrt{S_{NN}}}e^{y}$$

Summary

- For the first time, directly disentangled coh. $\sigma_{\gamma A->J/\Psi A'}$ (W) in UPC AA.
- CMS measured coh. $\sigma_{\gamma A->J/\Psi A'}$ to a new unprecedentedly low-x gluon regime ($10^{-4} - 10^{-5}$)
- Flattening of coh. $\sigma_{\gamma A->J/\Psi A'}$ → Gluon Saturation / Other effect ?

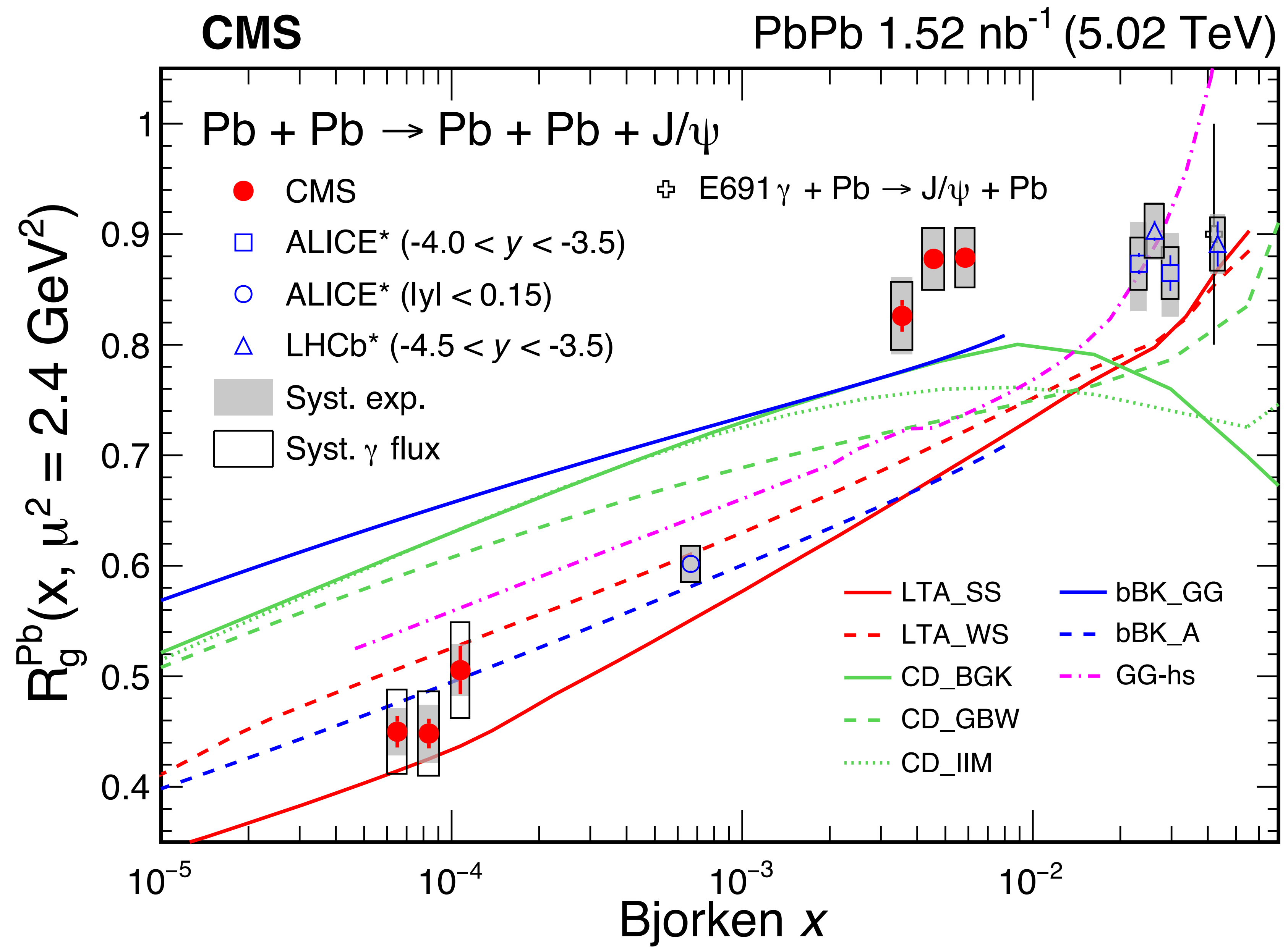




BACKUP

Possibilities

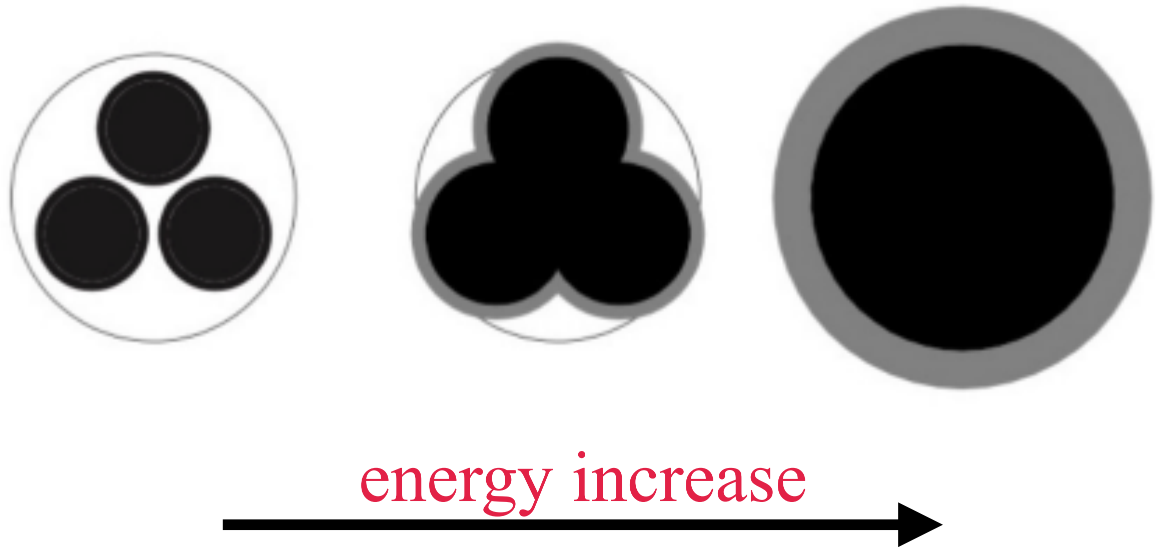
Phys. Rev. Lett. ***131***, *262301*



σ stops rapidly rising → splitting and recombination of gluons become equal

OR

Black Disk Limit ?

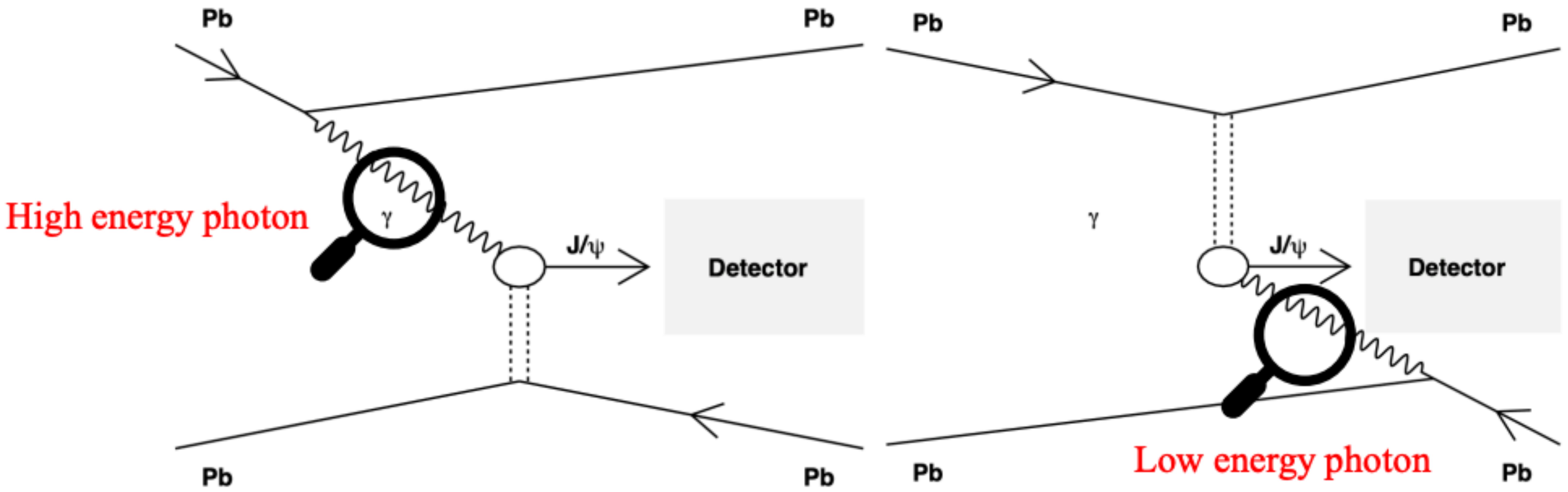


$$\sigma_{PQCD}^{inel} \leq \sigma_{black} = \pi R_{target}^2$$

Nucleus target becomes totally absorptive to incoming photons

- Leading to Black Disk Limit
- Nucleus becomes a black disk
- Internal structure is invisible.

Two way ambiguity in A-A UPC



Measured J/ψ at y

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

Two unknows but **one** equation!

What we measured

Photon flux: **can be precisely determined** from STARLight

What we want: VM cross section of one single γ+Pb at each y

$\frac{d\sigma^{coh}_{J/\Psi}}{dy}$ Explanation

- $\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{N(J/\psi)}{(1+f_I+f_D)\cdot\epsilon(J/\psi)\cdot Acc(J/\psi)\cdot BR(J/\psi\to\mu\mu)\cdot L_{int}\cdot\Delta y}$

Coherent J/ψ yields

- Raw yields within the mass window

Calculated from **mass fit** within pt < 0.2 GeV

Feed down ratio

- $f_D = \frac{N(feed\text{−}down\ J/\psi)}{N(primary\ J/\psi)}$

Incoherent fraction

- $f_I = \frac{N(InCoh\ J/\psi)}{N(Coh\ J/\psi)}$

Calculated from **pt fit**

CMS Detector