RICE

Exclusive Vector Mesons Photoproduction in PbPb UPCs with CMS

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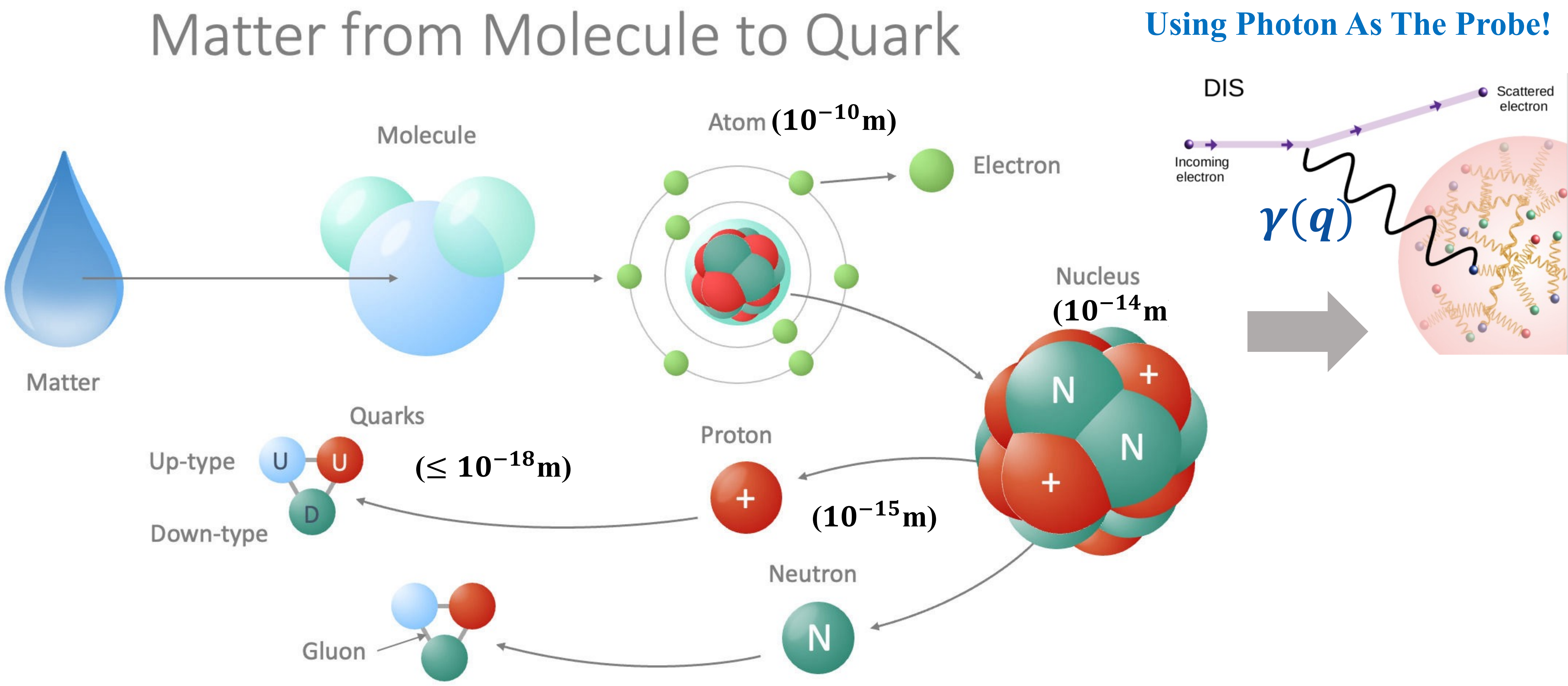
Outline

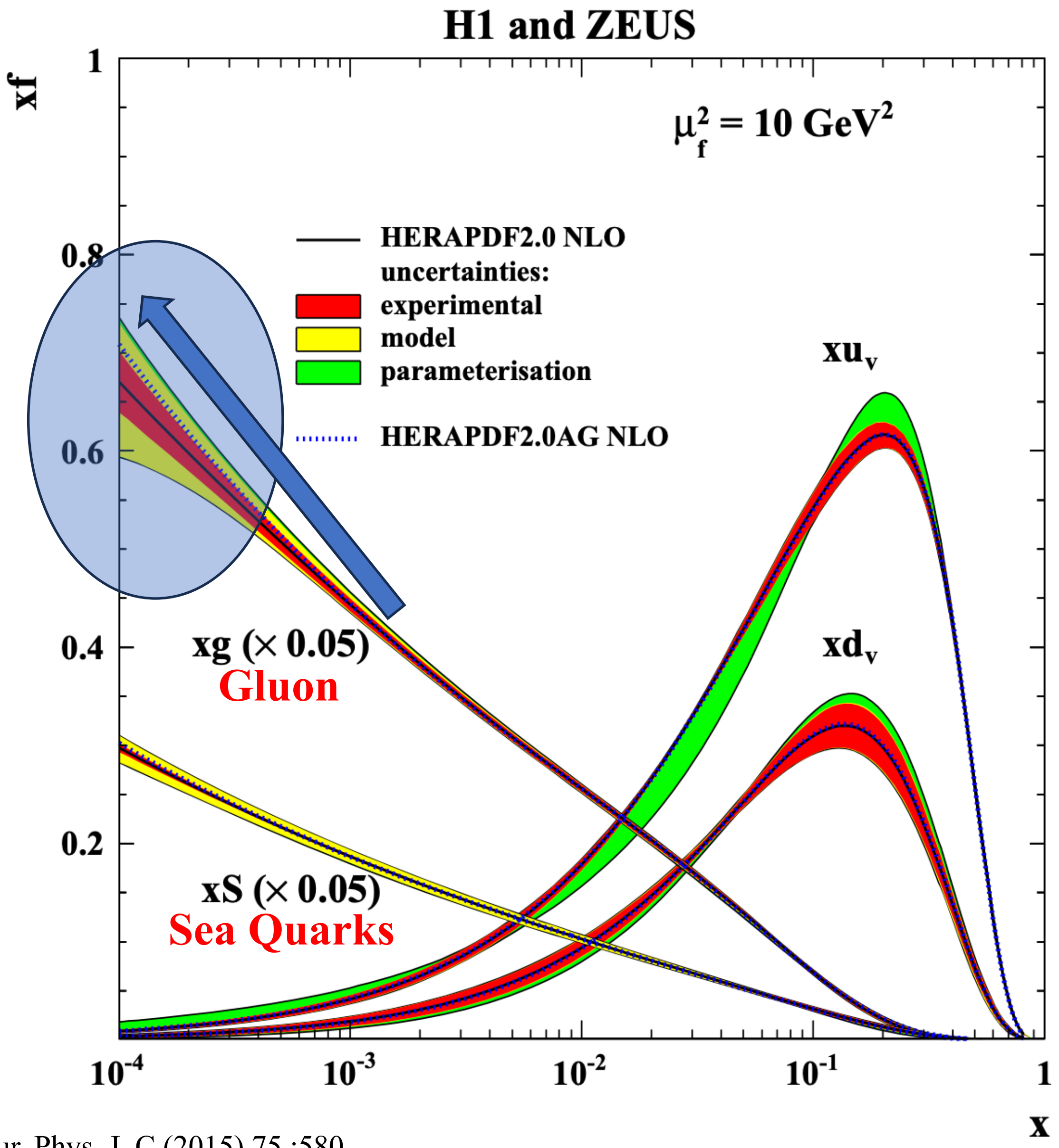
- **Introduction**
- **UPCs and VMs photoproduction**
- **Coherent/Incoherent J/ψ**
- **First Observation of Coherent ϕ**
- **Summary and Outlooks**

Understand the Fundamental Matter

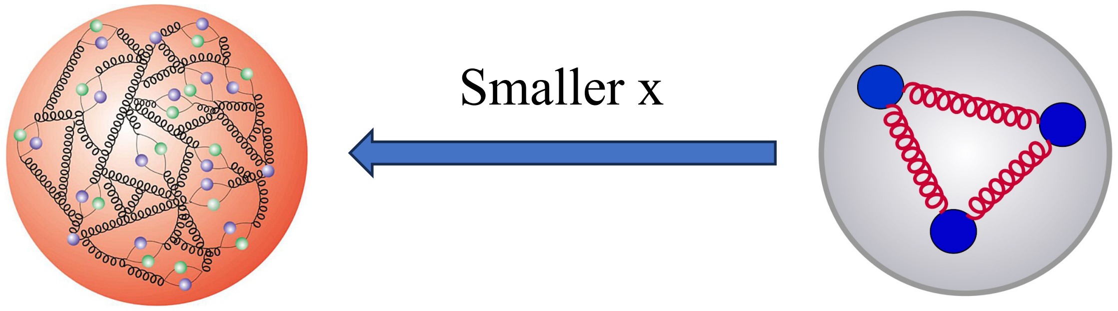
Using Photon As The Probe!



Understand the Gluon That Binds Us All



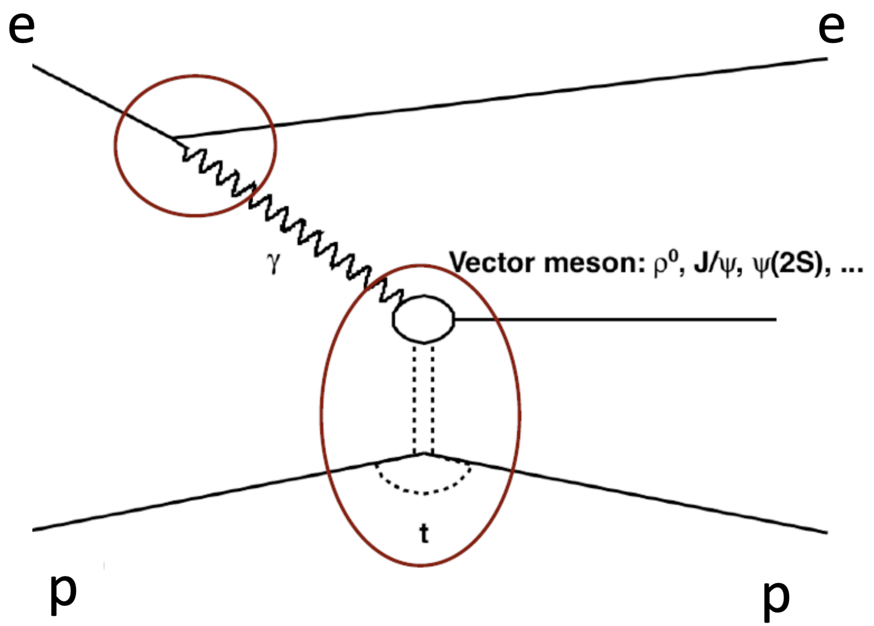
Eur. Phys. J. C (2015) 75 :580



- DIS results show **rapid growth of the gluon PDF** from linear evolution (gluon splitting)
- Unchecked growth of the gluon density at small-x violates unitarity
- What happens to gluons at extreme densities near the unitarity limit?
- How can we experimentally probe this high-density regime at small-x?

Vector Meson (VM) Photoproduction

Using Photon as the Probe!



$$|\gamma\rangle = |\gamma\rangle_{bare} + |q\bar{q}\rangle + |\rho\rangle + |\phi\rangle + |J/\psi\rangle + \cdots$$

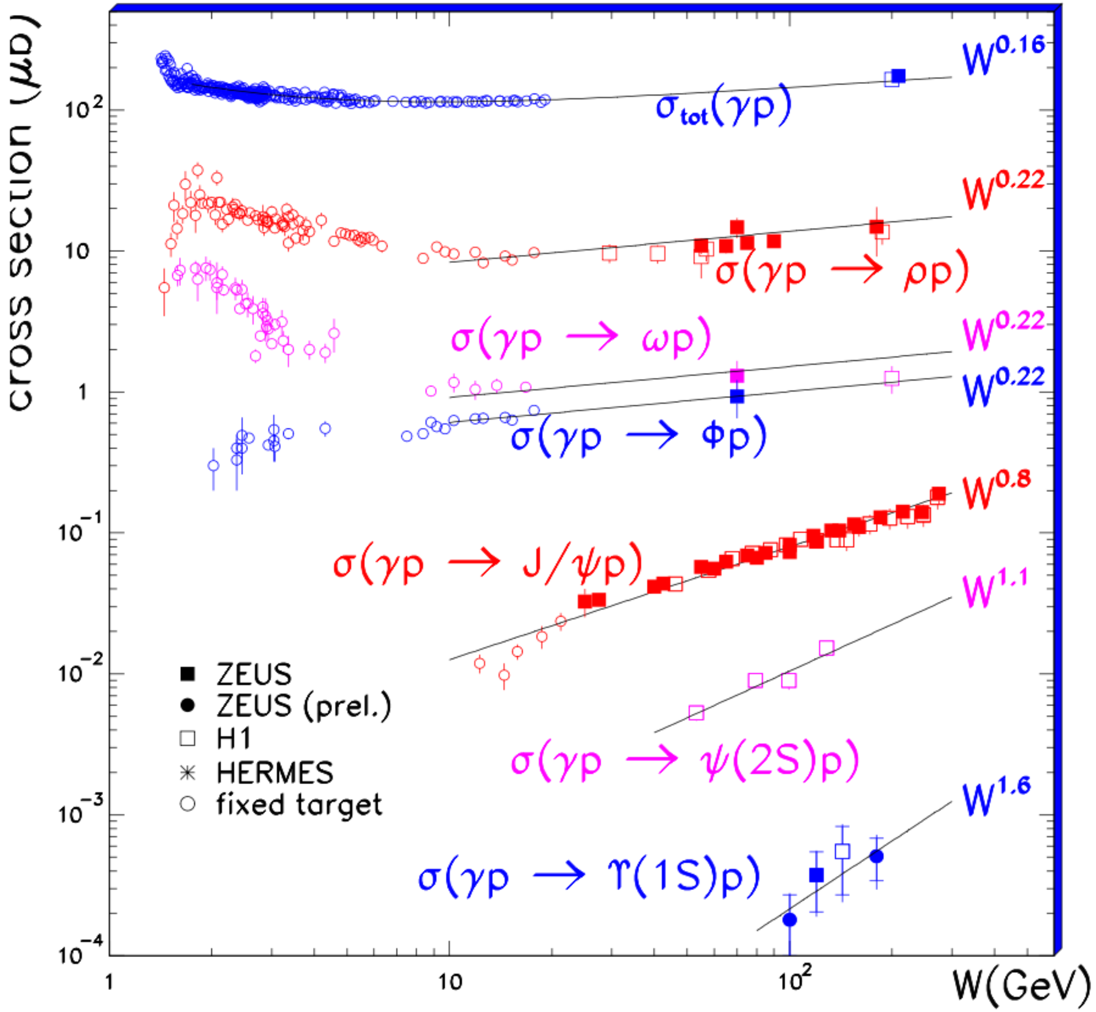
- The photon ($J^{PC} = 1^{--}$) can fluctuate into quark-antiquark pair and various hadronic states
  - VMs share the quantum numbers of the photon
- The $q\bar{q}$ couples to pomeron, two-gluon exchange, via s-channel interactions
- VM photoproduction cross section is **sensitive to the gluon density** in LO pQCD

Probability of interaction (LO in pQCD):

$$\underbrace{P \sim \alpha_s}_{\text{Coupling constant}} \cdot \underbrace{r^2}_{\text{Transverse area (of the probe)}} \cdot \underbrace{\left(xg(x,Q^2)\right)^2}_{\text{Gluon density}}$$

HERA VM Photoproduction

$$\gamma + p \rightarrow \text{VM} + p$$



Prog.Part.Nucl.Phys.61 343,2008

Studied ep collisions at HERA

- Photoproduced VMs at small x probe the gluon content of the target
  - Tests scaling behavior of the gluon density
- H1 and ZEUS measured VM photoproduction cross sections in W, up to ~300 GeV
- Observed power-law growth of cross section with W **consistent with rising gluon density** at high energy

Gluon Dynamics at Extreme Density

How does QCD resolve divergence of extremely high gluon density?

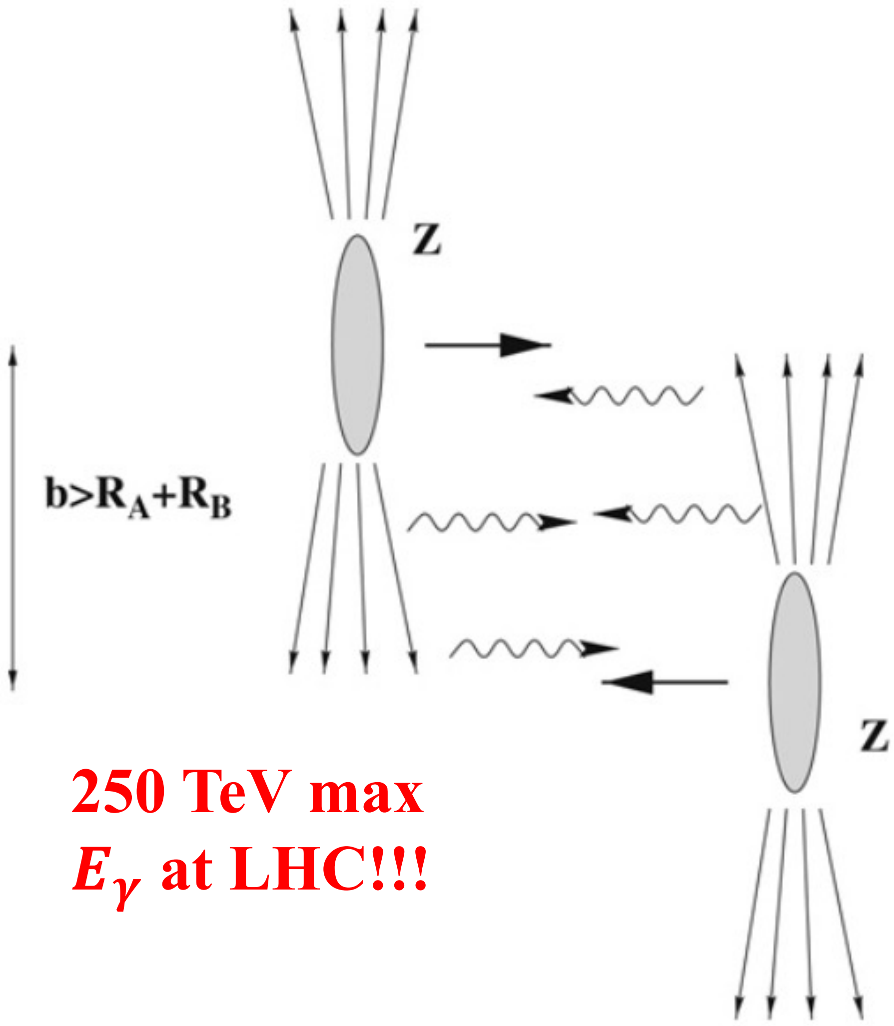
Recombination
Nonlinear evolution

Splitting
Linear evolution

Saturation?

Can we see saturation in LHC experiments?

Ultra-Peripheral Collision (UPC)

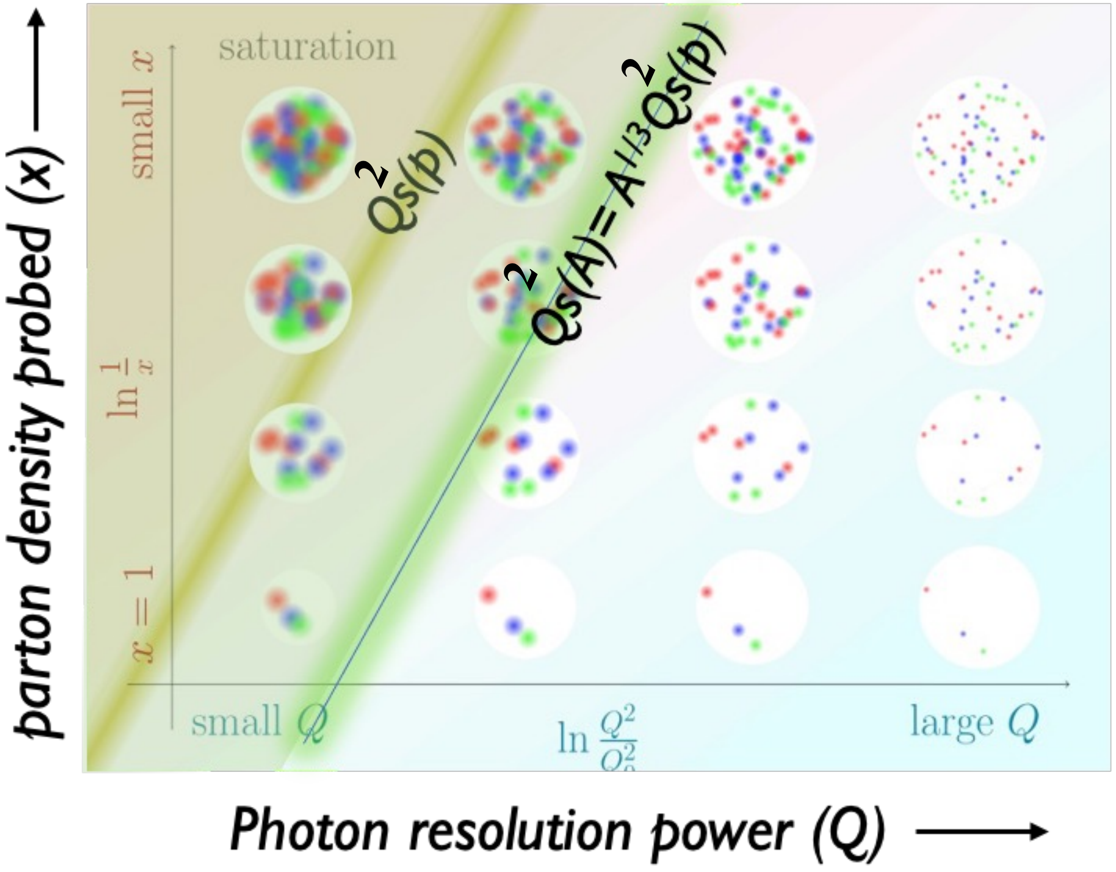


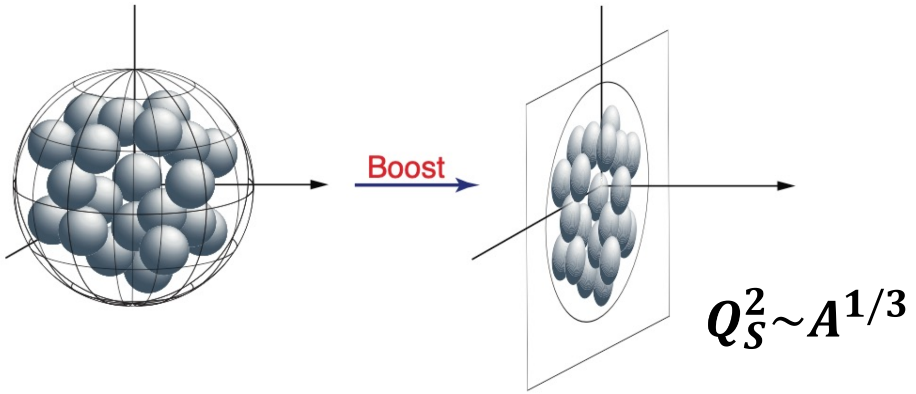
250 TeV max E_γ at LHC!!!

- Nuclei "miss" each other
  - b > $R_A + R_B$
- The Lorentz-boosted EM field of a nucleus acts as a flux of quasi-real photons ($Q^2 \sim 1/R_A^2$)
- Photon flux is intense (~Z^2), energetic, and low virtuality
- Hadronic interactions are strongly suppressed in UPCs

Gluon Dynamics in Nuclei

Can we see saturation in heavy-ion?



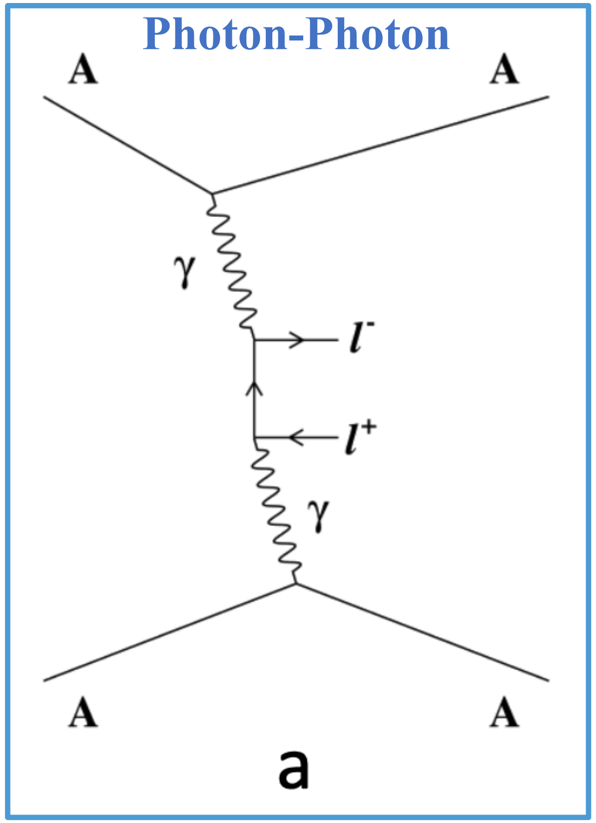


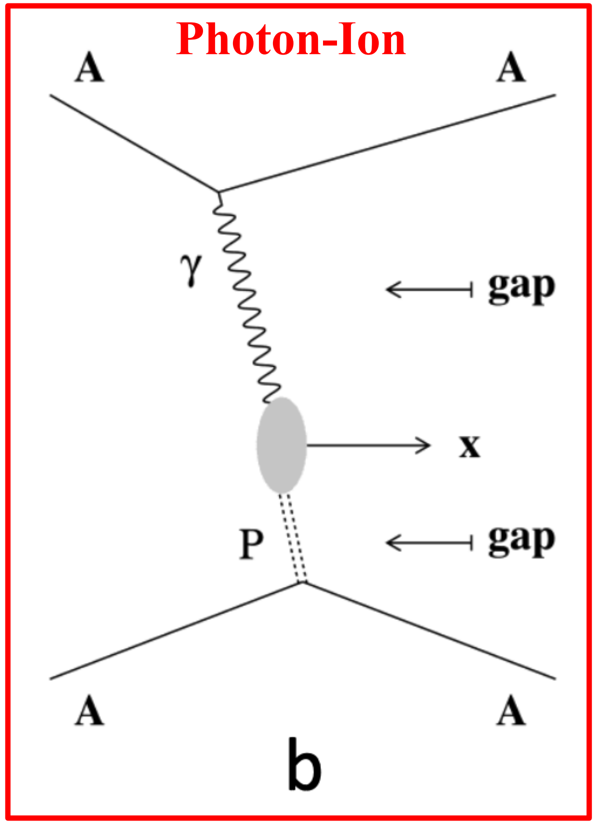
- In nuclei, **gluon density is enhanced** by a factor $A^{1/3}$
- Gluon saturation is expected to be easier to be reached in nuclei!

Increase Energy (lowering x) → More Gluon
Decrease Resolution (Q^2) → Larger Overlap

UPC Processes

Heavy ion collider is also a Photon-Photon and Photon-Ion collider!

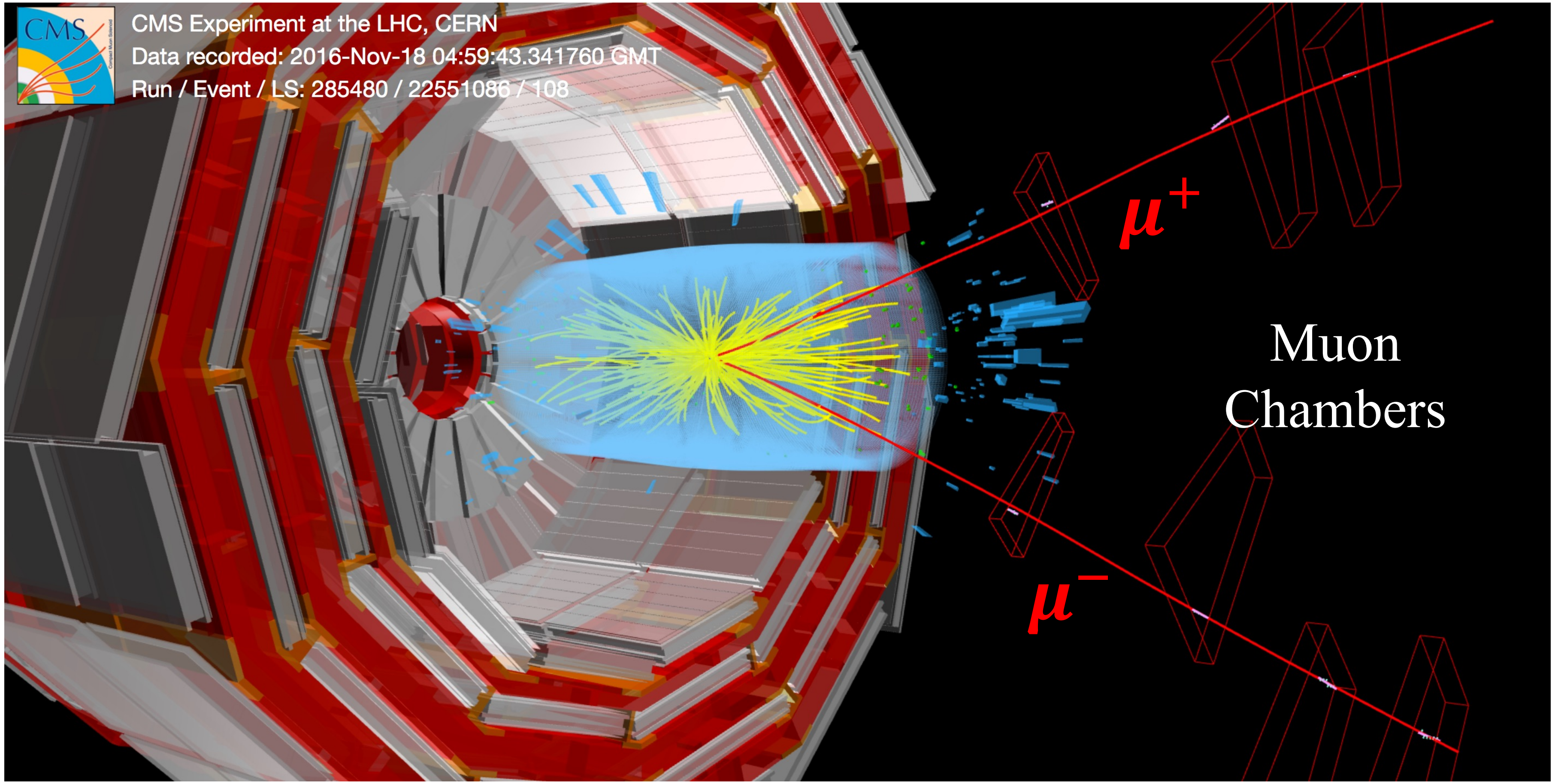




- Pure QED processes: $\gamma\gamma \rightarrow l+l-$
- Sensitive to photon flux modeling and QED precision observables (e.g., anomalous magnetic moment)

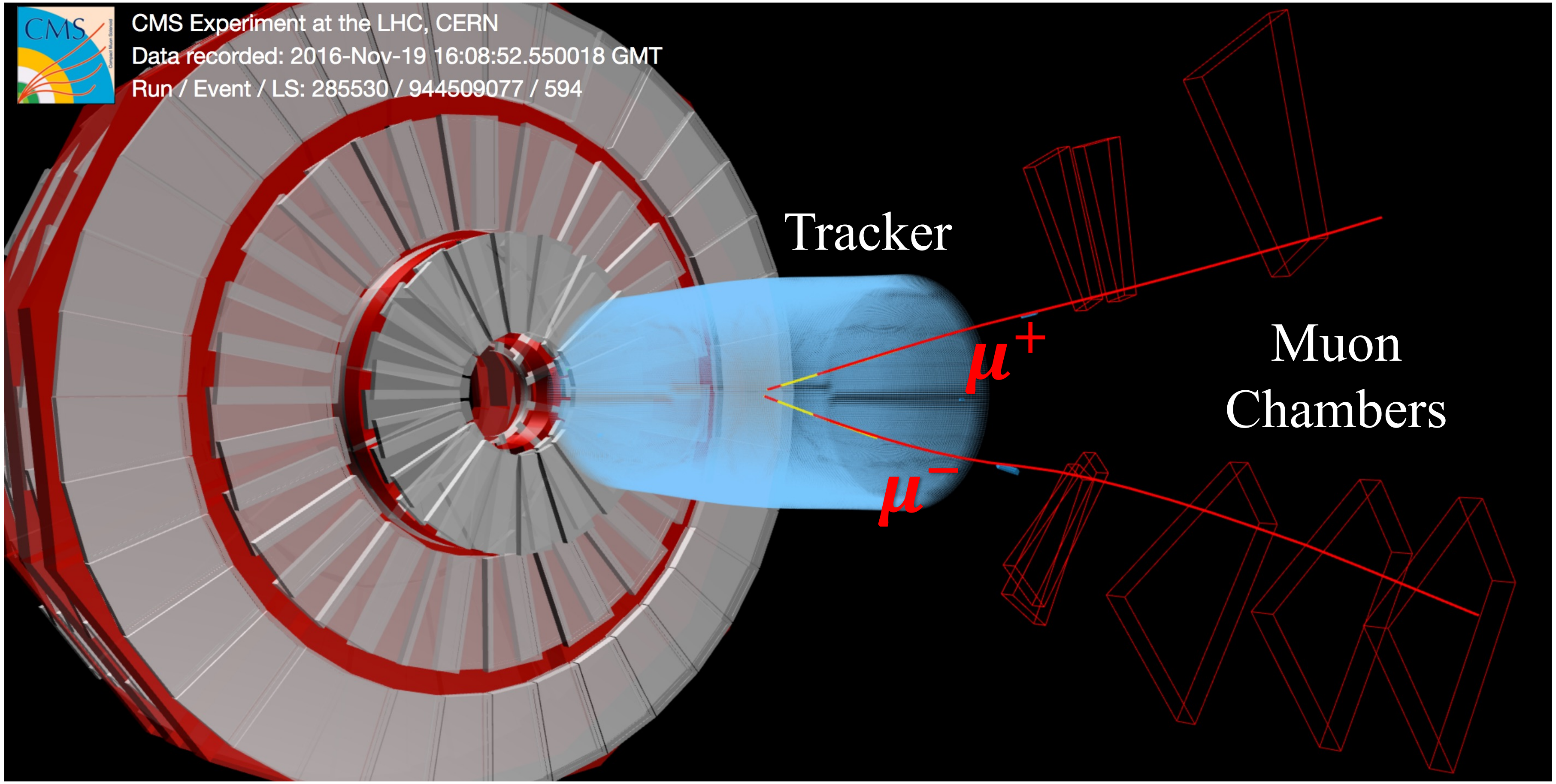
- Exclusive VM Photoproduction (e.g., J/ψ)
- Interaction via color-singlet exchange (two gluons), no net color is transferred
- Probes gluon at small-x, $Q^2 \sim 0$

J/ψ Event at CMS



- A typical heavy ion event where a candidate J/ψ particle is produced and decays to two muons
- A lot of detector activities, **high-multiplicity environments**

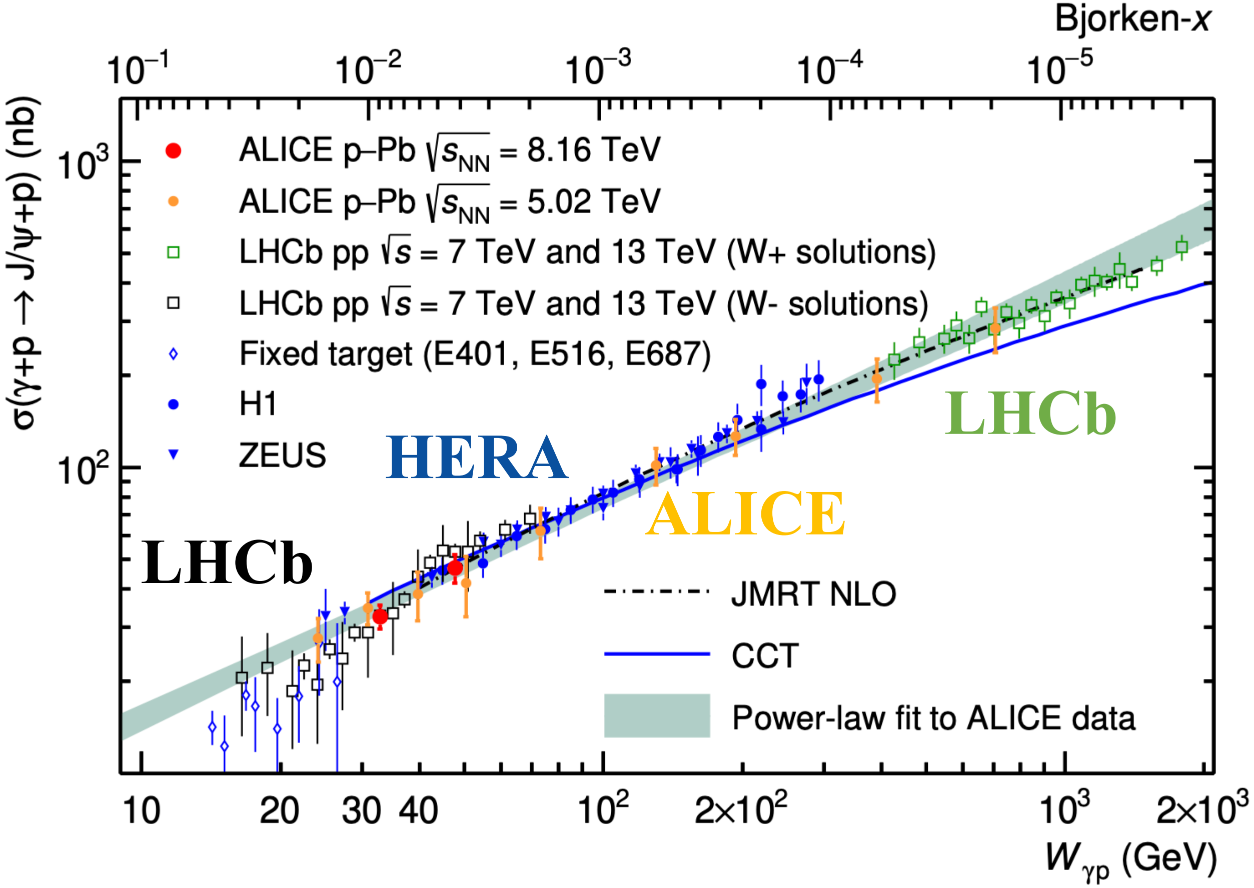
Exclusive J/ψ Event at CMS



- UPCs are distinct: few produced particles → **very clean signatures**
- Require low energy in forward calorimeters to suppress hadronic background
- Select events with exactly two reconstructed tracks, both identified as muons

Exclusive J/ψ in pPb UPC

$$\boldsymbol{\gamma + p \rightarrow \mathrm{J}/\psi + p}$$



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

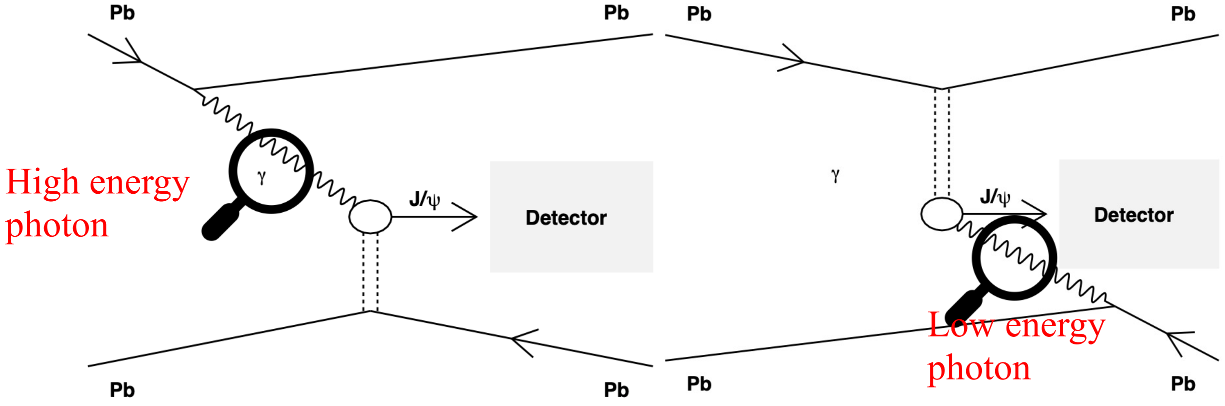
- LHC experiments measured exclusive J/ψ in **pp/pPb UPCs** probes gluons up to x~10^{-5}
- Power-law growth persists with no deviation up to LHC energies
- No significant change in gluon PDF behavior between HERA and LHC
- **No clear evidence for gluon saturation** in the proton

$W_{\gamma p}$ up to ~ 1000 GeV

Phys. Rev. D 108 (2023) 112004

The Two-way Ambiguity

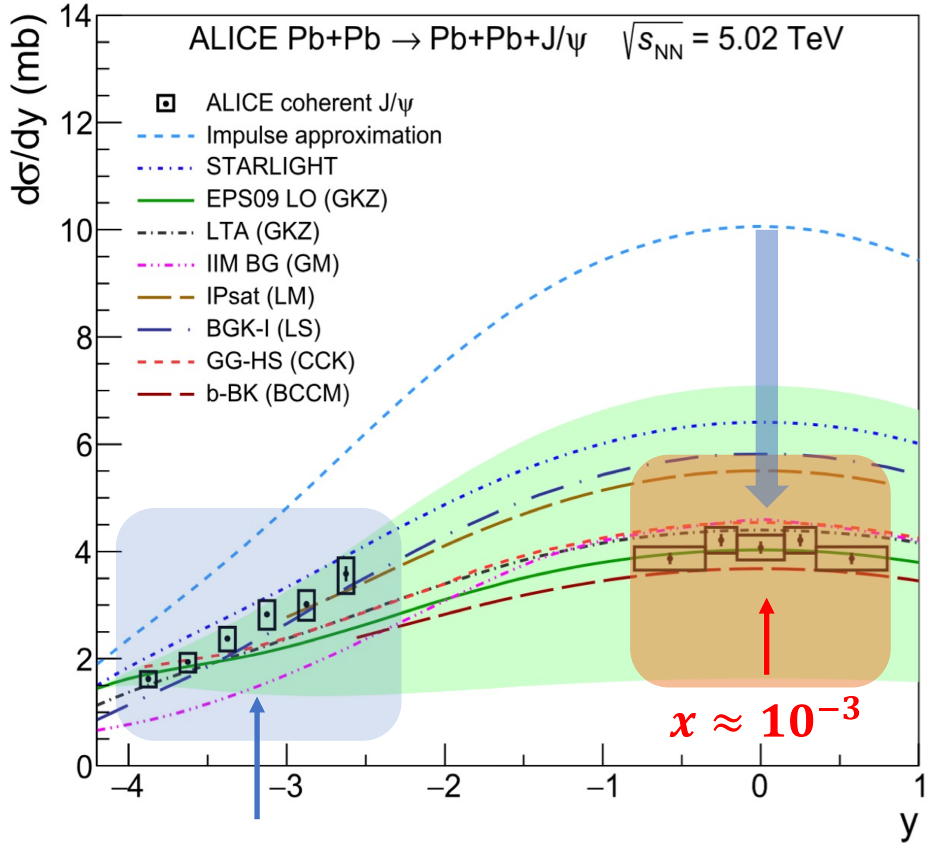
- **Symmetric systems** (e.g., PbPb): both nuclei act as photon source and target
- Each data point includes contributions from both low-energy and high-energy photons
- Differential cross section is sum of the two terms: photon flux × single photonuclear cross section



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

No easy access to x ~ 10^{-5} in Pb

Eur. Phys. J. C (2021) 81:712

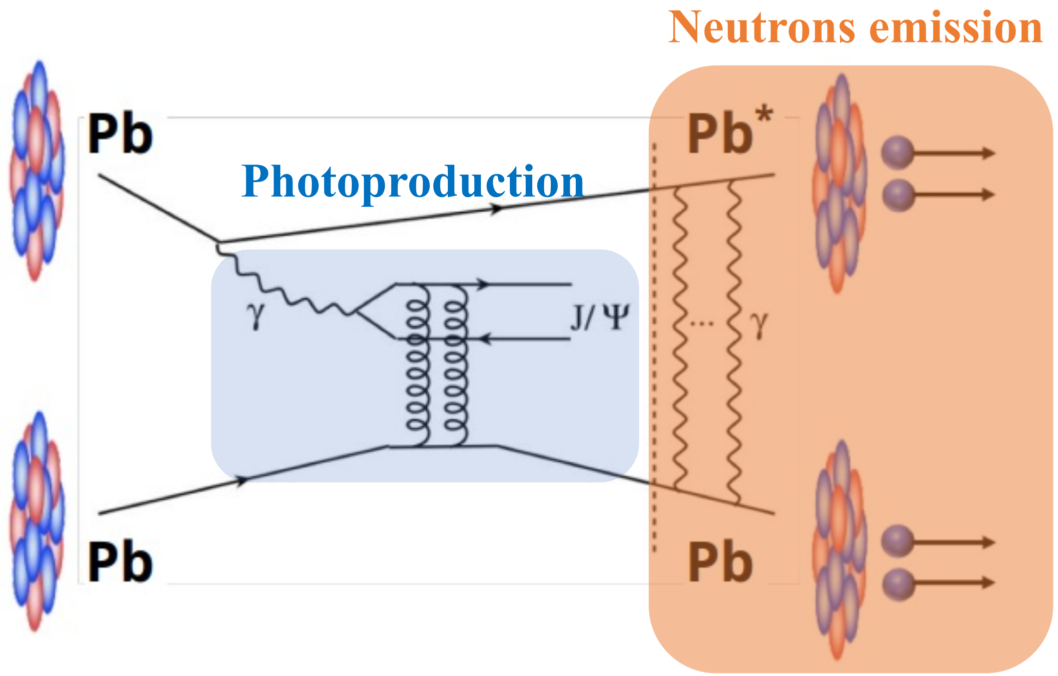


$x \approx 10^{-5}$ *or* 10^{-2}

(~95% high x)

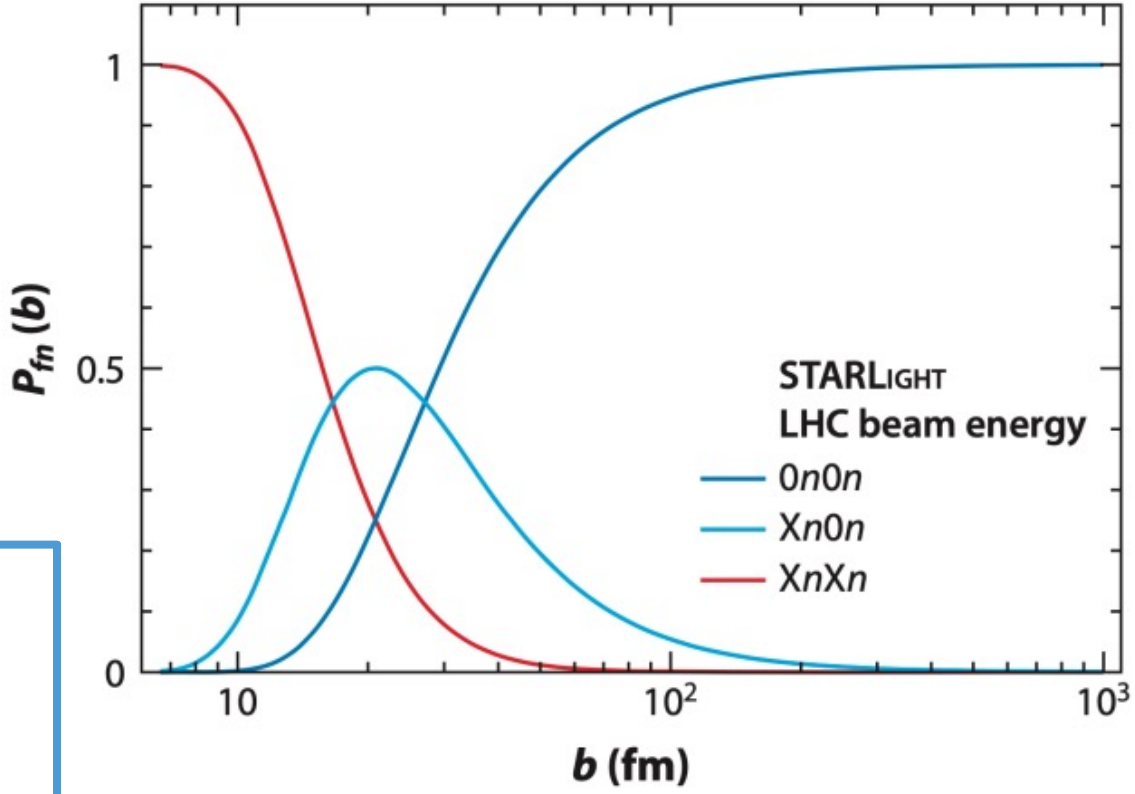
$$x = \left(\frac{M_{VM}}{\sqrt{s_{NN}}}\right)e^{\mp y}$$

A Solution To The Two-way Ambiguity Puzzle



- Tag the impact parameter in UPCs by measuring forward neutrons from Electromagnetic Dissociation (EMD)
- EMD triggered by soft photons (~10 MeV)
- Occurs **independently of the main physics process**
- Enables impact-parameter-dependent studies without biasing the hard probe

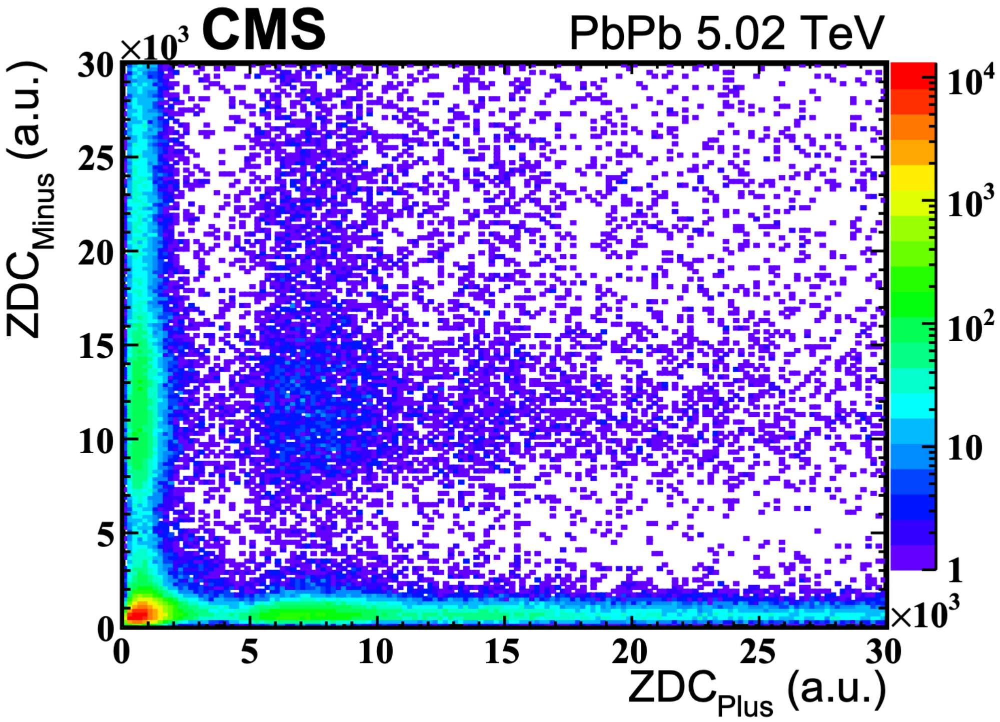
$$P_i(b) \propto 1/b^2$$

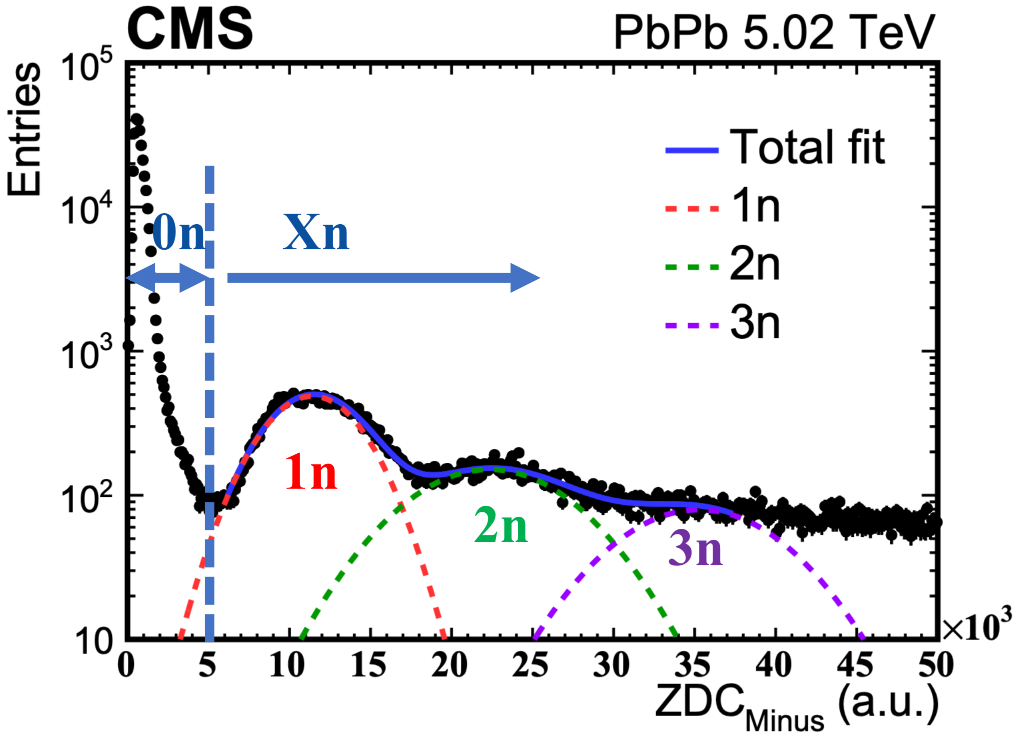


Spencer Klein & PAS, Ann Rev Nucl Part Sci Vol. 70:323-354

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

Event Classification via Neutron Multiplicity



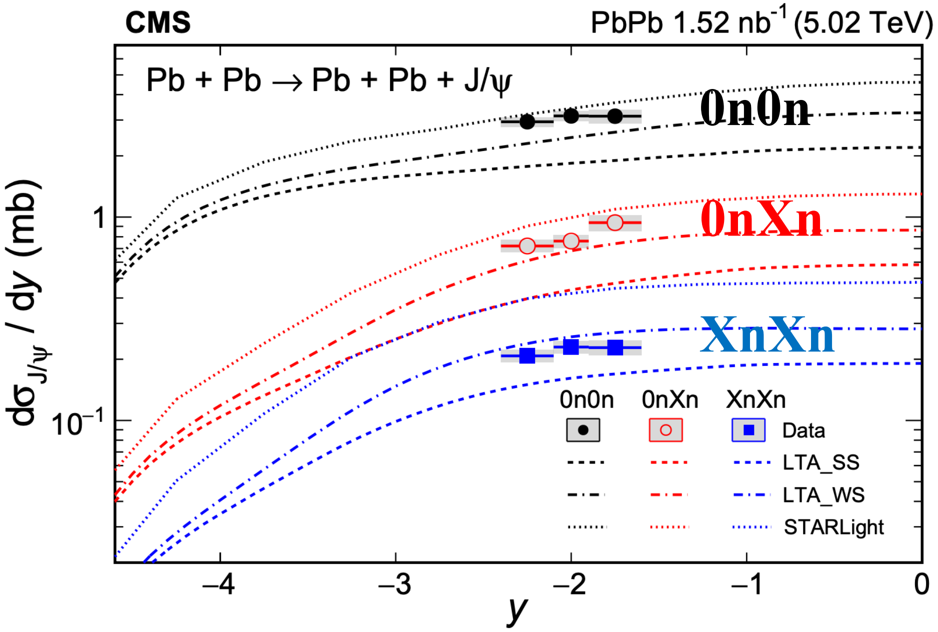


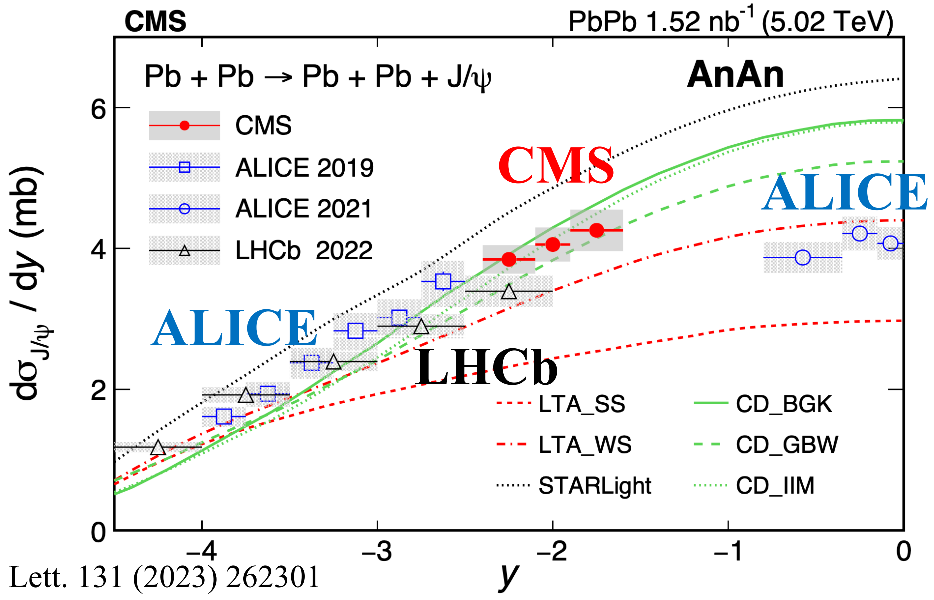
0n0n → Larger b **XnXn → Smaller b**

- Forward neutrons can be detected using the Zero Degree Calorimeter (ZDC) in the CMS detector.
- Applying a simple threshold-based selection (straight cut) on the ZDC signal effectively disentangles neutron emission classes (e.g., 0n0n, XnXn)

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

Coh. J/ψ in Neutron Configurations





Phys. Rev. Lett. 131 (2023) 262301

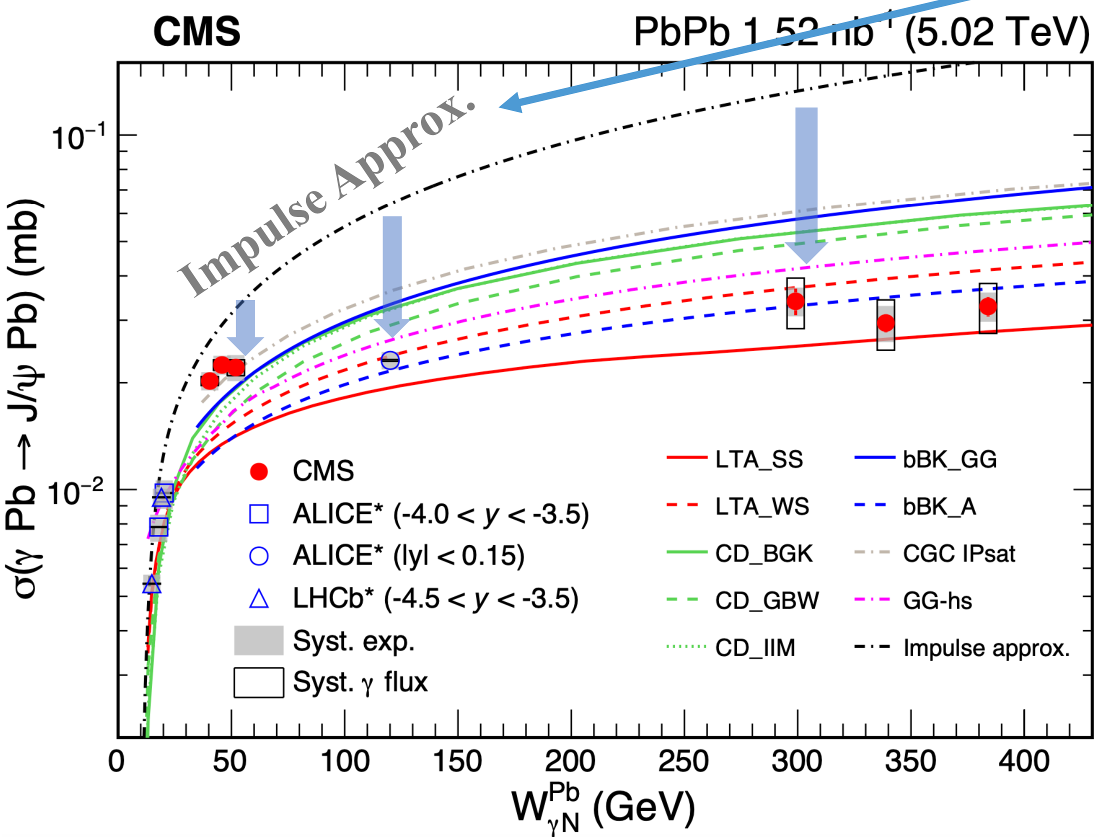
- First differential separation of VM production by neutron emission class (e.g., 0n0n, XnXn)
- LTA fails to describe all neutron classes simultaneously
- **Toward a Clearer Picture**: Focusing on production from γPb without “two-way ambiguity”
- Could provide deeper insight into nuclear gluon dynamics

$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(y)\cdot\sigma_{\gamma A\to J/\psi A'}(y) \quad \text{High x}$$

$$+N_{\gamma/A}(-y)\cdot\sigma_{\gamma A\to J/\psi A'}(-y) \quad \text{Low x}$$

Coh. J/ψ in $\gamma + Pb$

After decomposing the two-way ambiguity, coherent J/ψ photoproduction cross section as a function of W



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

Impulse Approximation (IA)

- Treats interaction as with a free nucleon, neglecting nuclear effects
- Valid when photon wavelength is large → coherent interaction with the whole nucleus

- Low W: Good agreement with IA.
  - Consistent with steep gluon density rise at small x
- High W: Deviation from IA
  - Cross section exhibits only slow, linear growth. Suggests increased nuclear suppression at high energy

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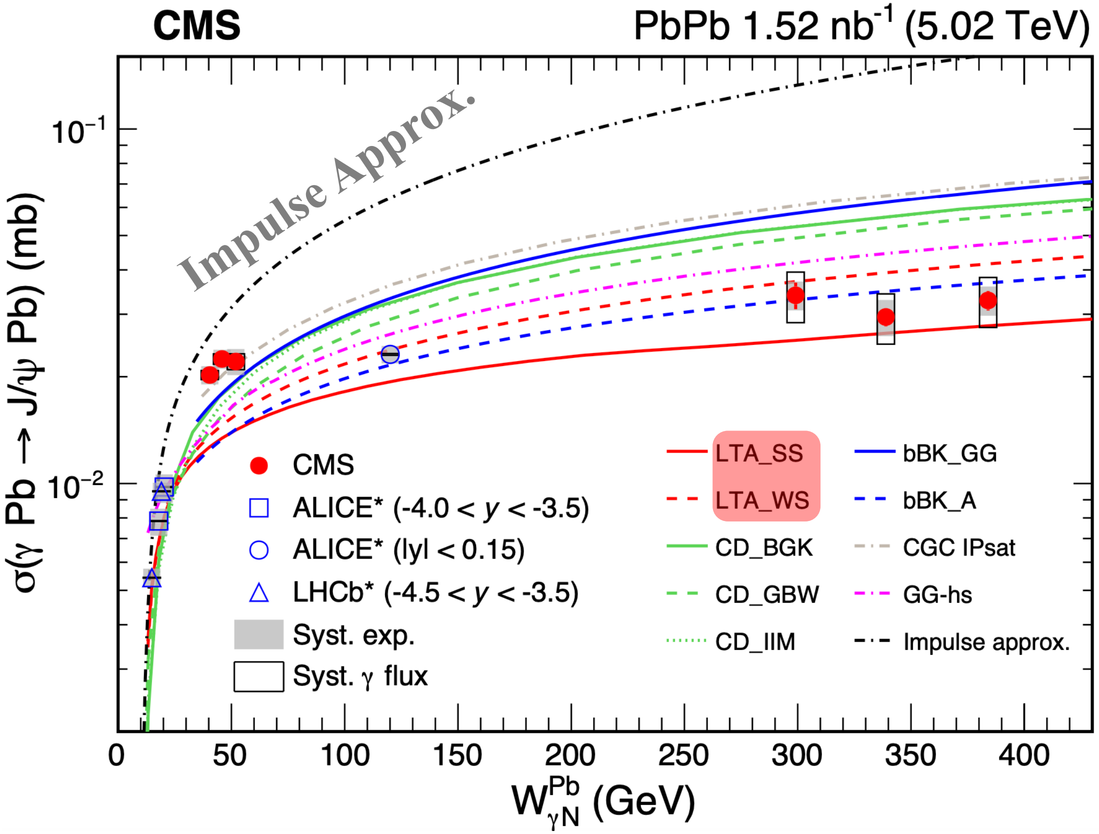
Coh. J/ψ in $\gamma + Pb$

$\gamma + Pb \rightarrow \mathrm{J}/\psi + Pb$



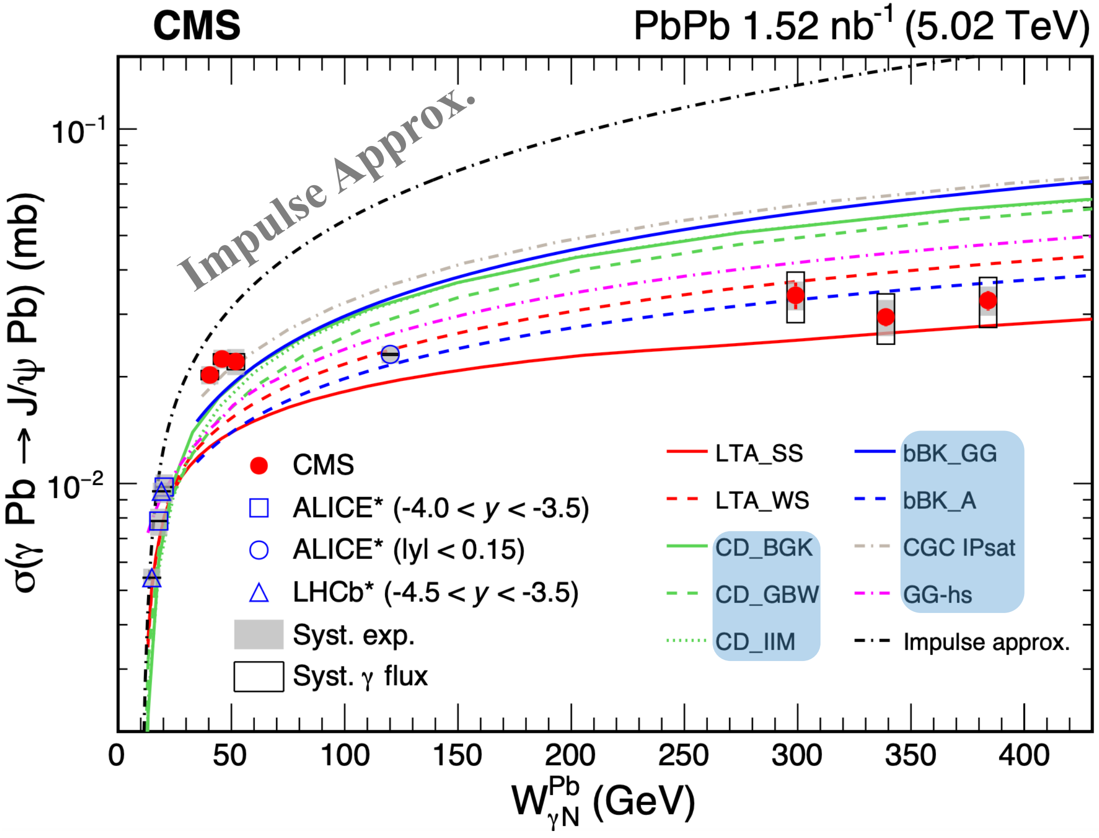
Shadowing

- Suppression arises from multiple coherent scatterings within the nucleus. Reduces the effective number of interacting nucleons
- Analogy: more layers in a curtain → fewer photons transmitted
- Not saturation: Suppression originates from destructive interference in multi-nucleon amplitudes.

Phys. Rev. Lett. 131 (2023) 262301

Coh. J/ψ in $\gamma + Pb$

$\gamma + Pb \rightarrow \mathrm{J}/\psi + Pb$



Gluon Saturation

- Suppression arises from saturation: nonlinear gluon recombination balances splitting, limiting density growth
- Analogy: keep throwing tennis balls at a wall → eventually, there's no space left to stick more
- Models include saturation effects but differ in: Treatment of the vector meson wavefunction. Modeling of the dipole–nucleus interaction

Both models fail to describe data trend! Not clear what's the underlying physics processes.

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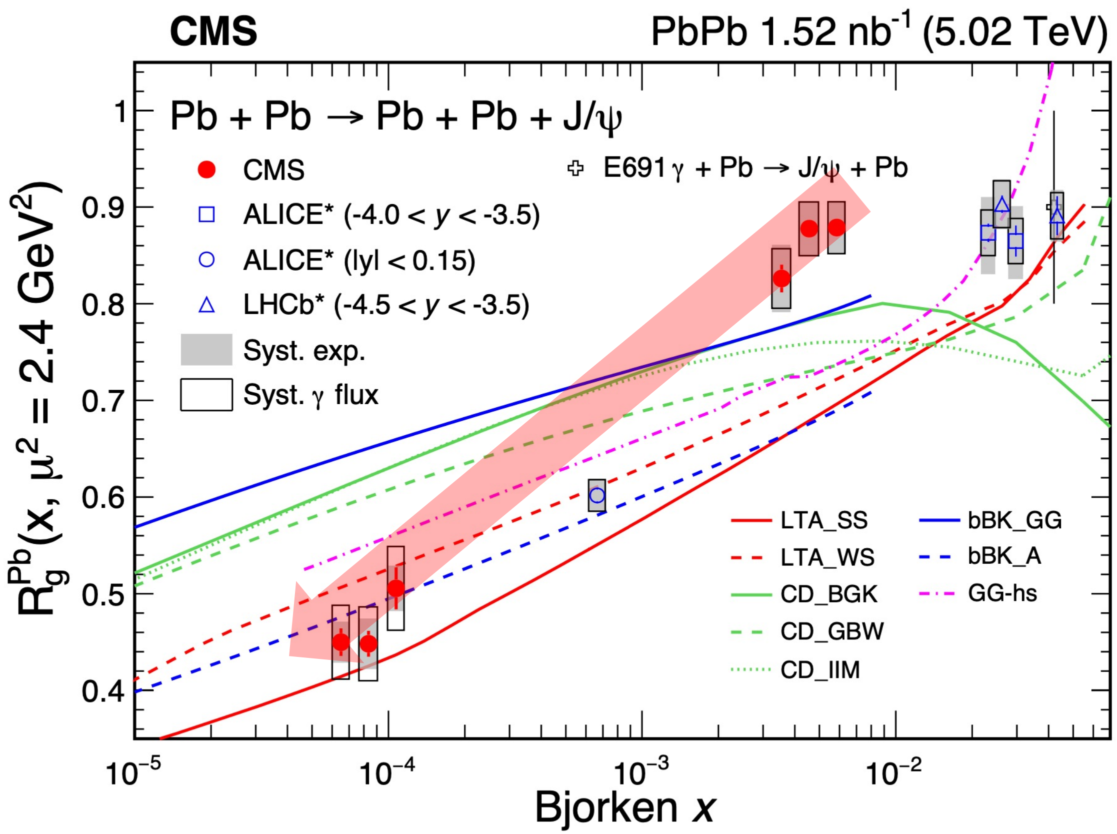
Nuclear Suppression Factor



- Suppression factor (at LO) quantifies the suppression
  - $$R_g^A = \frac{g_A(x,Q^2)}{A \cdot g_p(x,Q^2)} = \left(\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}}\right)^{1/2}$$
- At low-x data consistent with both saturation and shadowing models

Indicates Stronger-than-expected suppression in Pb, spanning a broad energy range

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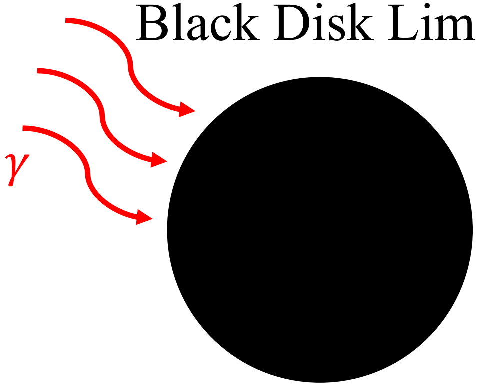
What Physics is Behind?

How does one resolve convoluted effects at small x?

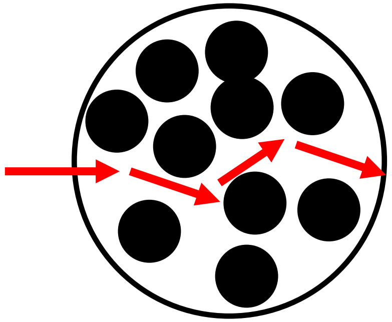
Linear QCD

Non-Linear QCD

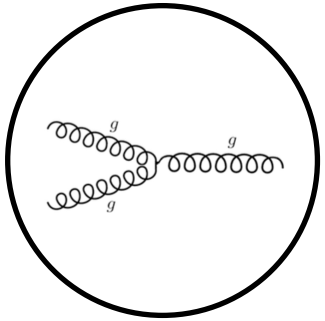
Geometric
Black Disk Limit



Shadowing
Multiple scatterings
Multi-nucleon interactions



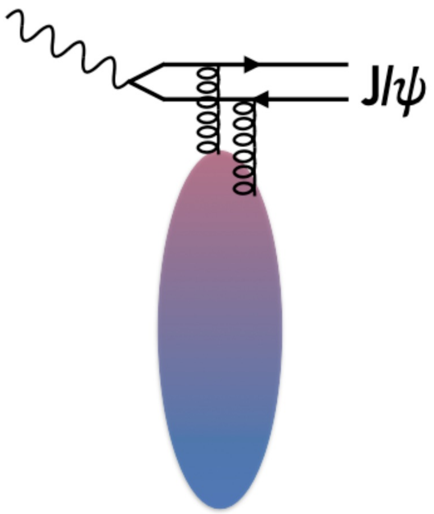
Saturation
First Principles QCD



Have we reached BDL?

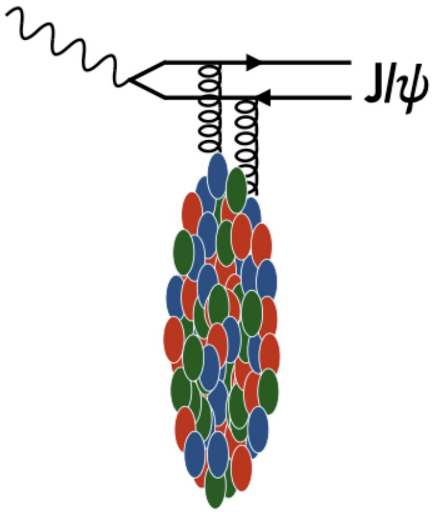
Incoh. J/ψ

Incoh. J/ψ Photoproduction



Coherent

Probes the average gluon configuration

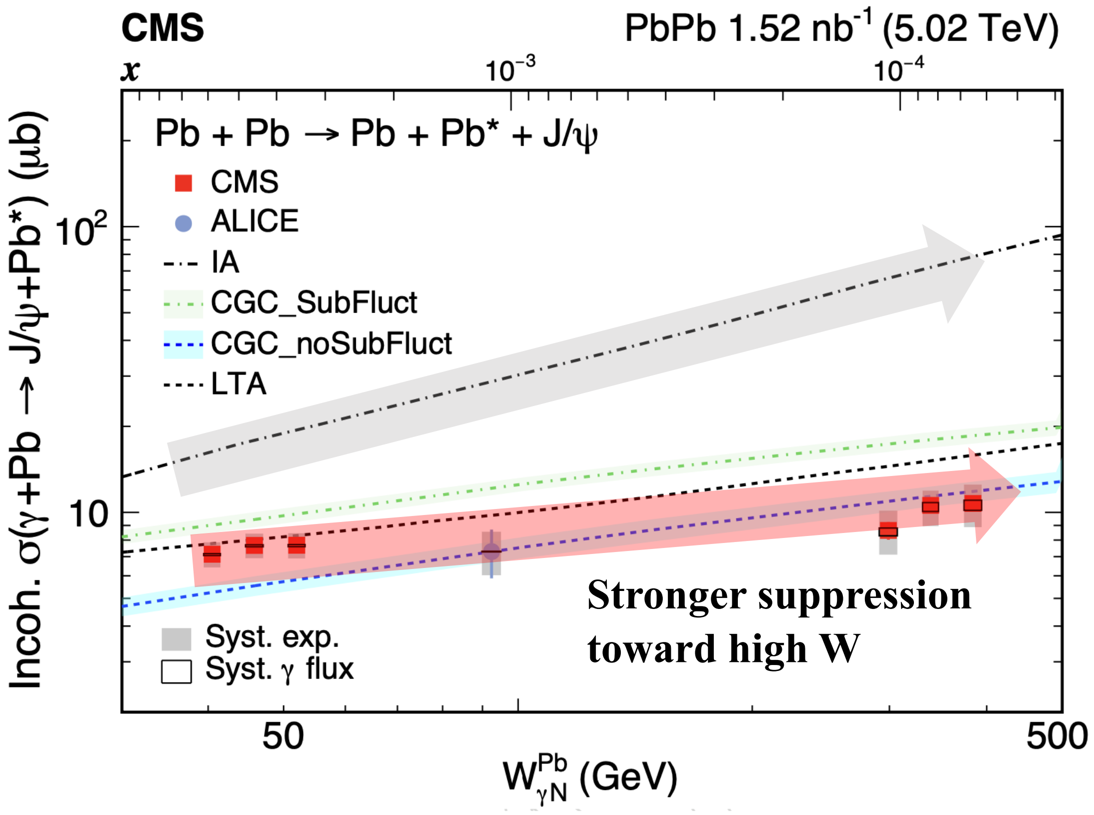


Incoherent

Probes the variances of the gluon configurations

- For incoh. production, the photon couples to a single nucleon within the nucleus
  - Signature: $< p_T^{VM} > \sim 500$ MeV
  - Typically accompanied by nucleon dissociation
- At low energies -> variance grows with gluons
- If the BDL is reached the gluon distributions largely overlap across nucleons, which reduces the variance in configurations

Incoh. J/ψ



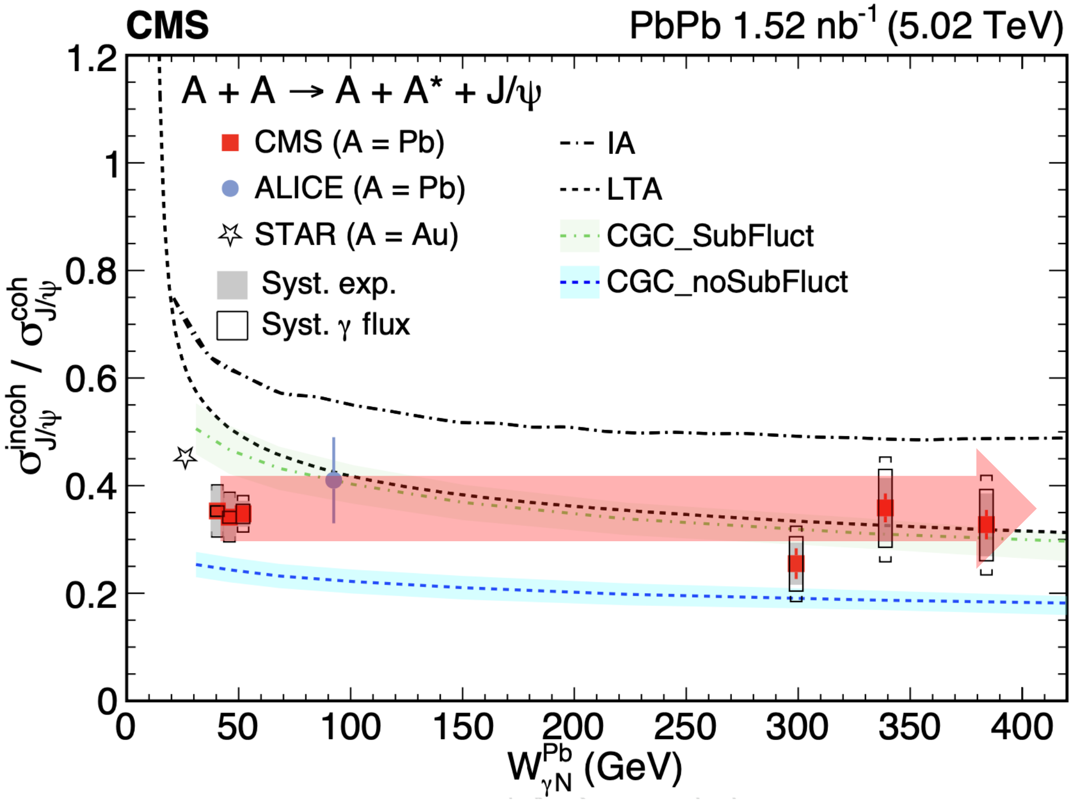
Stronger suppression toward high W

- CMS disentangled the energy dependent incoh. J/ψ cross section
- A strong suppression is observed relative to the IA prediction
  - Comparing incoh. production in heavy ions is effectively comparing the parton structure of bound versus free nucleons
- At W< 50 GeV, the LTA model describes the data
- At higher energies (W > 90 GeV), the CGC framework provides a better description of the data

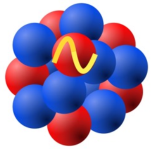
arXiv:2503.08903

Incoh. to Coh. Ratio

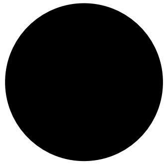
Cleanest test since many theorical uncertainties cancelled



- The data lies below the IA prediction,
  - Stronger suppression compared to the coh. process
- The nearly flat ratio: **does not support reaching the BDL**
  - If it was, the ratio would decrease at higher W, since the inner structure of the nucleus becomes invisible
- Both saturation and shadowing models qualitatively capture the observed data trends
- However, the current measurements **do not clearly distinguish between the two frameworks**



Approaching the BDL?

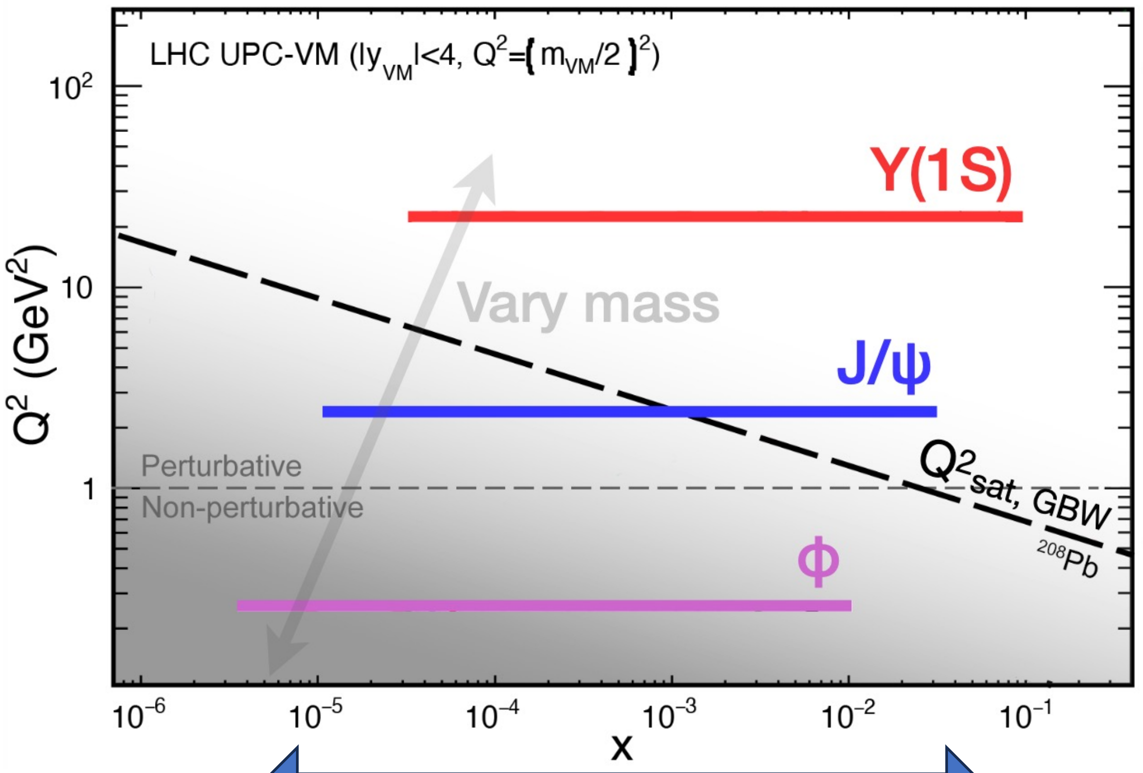


NOT supported by the data!

arXiv:2503.08903

What’s the Path to Nonlinear Evolution

Results from J/ψ highlights unresolved aspects of the underlying physics



Wider rapidity coverage

VM Mass

$Q^2 \sim M_{VM}^2/4$

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

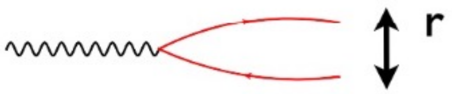
Can we conduct a 2D scan to search for Nonlinear evolution?

Amplify the nonlinear effects by lowering Q^2

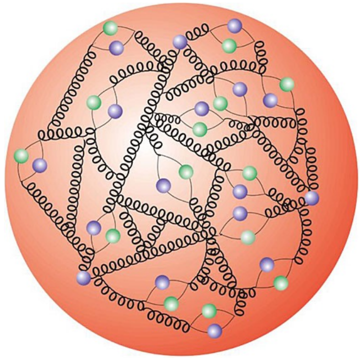
Coh. ϕ

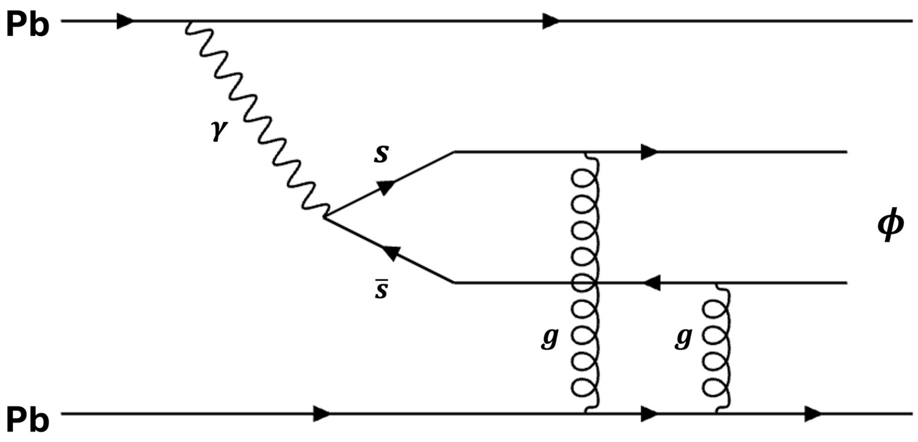
Amplifying the Nonlinear Effects with ϕ Meson

Larger dipole size



Gluon interaction

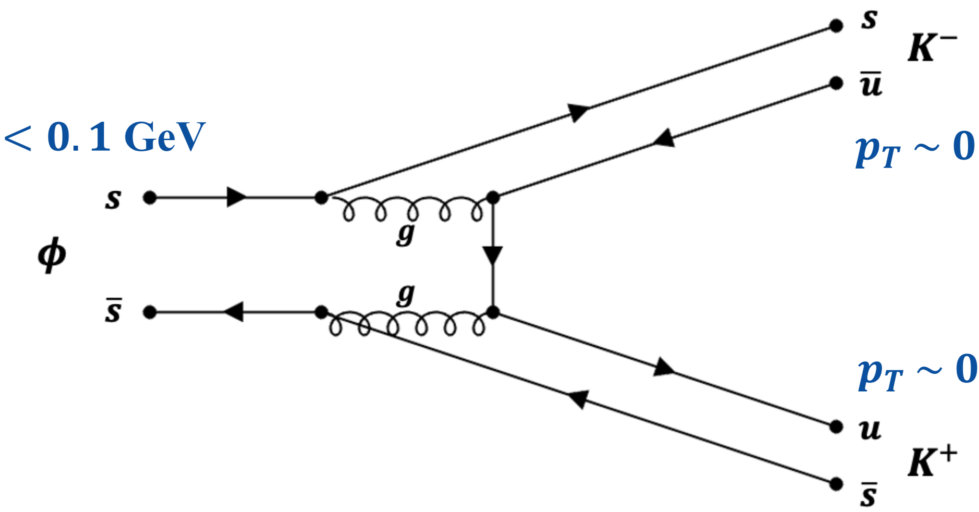




$$r^2 \sim \frac{1}{Q^2} \sim \frac{1}{M_{VM}^2}$$

- VM mass → one of the primary determinant of the energy scale in QCD calculations.
- Larger dipole size (lighter mass) than J/ψ
- **Enhanced sensitivity to saturation** and non-pert. effects
- Probes the transition region between pQCD and non-pQCD dynamics

Experimental Challenges



$\boldsymbol{p_T < 0.1}$ **GeV**

$\boldsymbol{p_T \sim 0.1}$ **GeV**

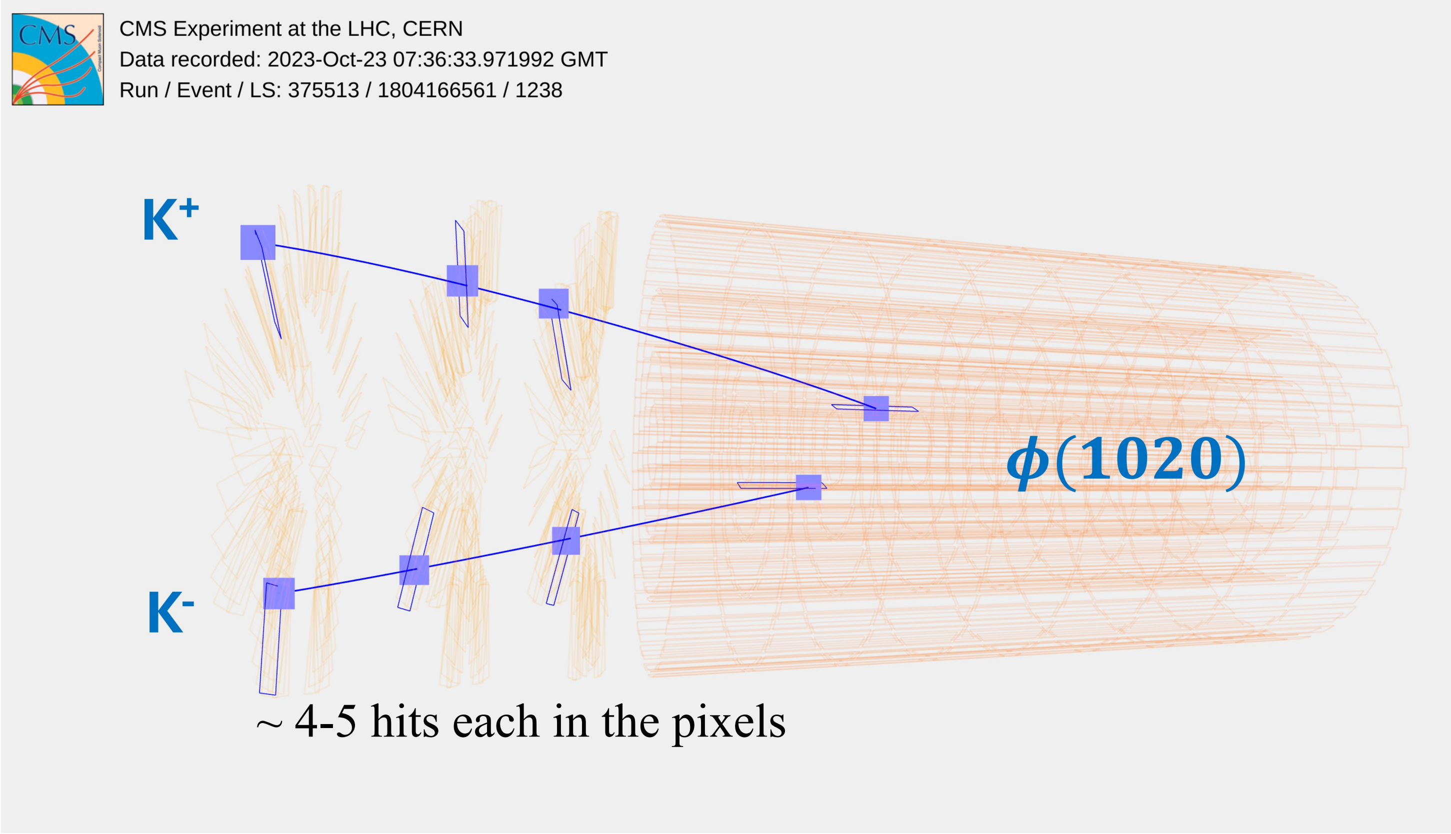
$\boldsymbol{p_T \sim 0.1}$ **GeV**

Never been observed before in UPCs!

- ϕ (1020) primarily decay through K^+K^- channel
  - $BR(\phi \to K^+K^-) = 49.1 \pm 0.1$ %
- $M_\phi \sim 2 \cdot M_K$: coherent ϕ mesons have low transverse momentum, leading to decay kaons with low pT
- Difficult to reconstruct experimentally

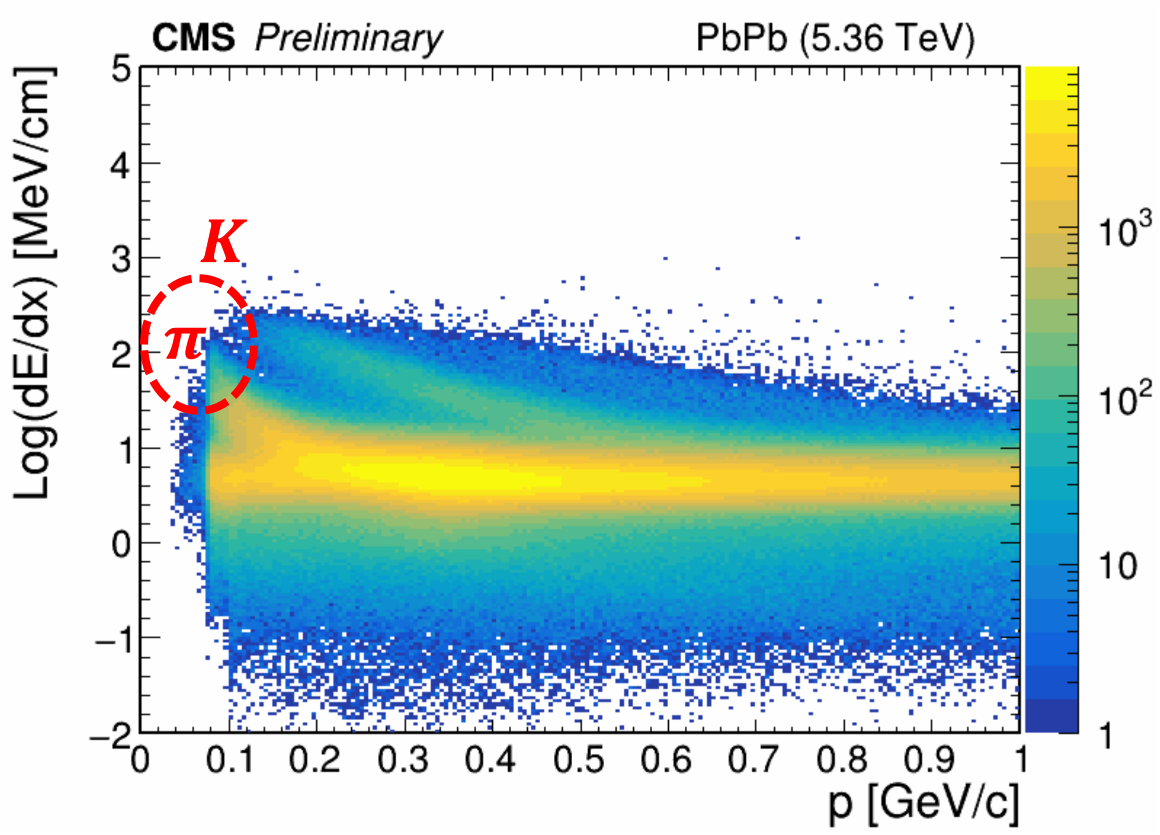
Searching for ϕ Meson in UPCs

Need to rely on CMS pixel tracking detectors



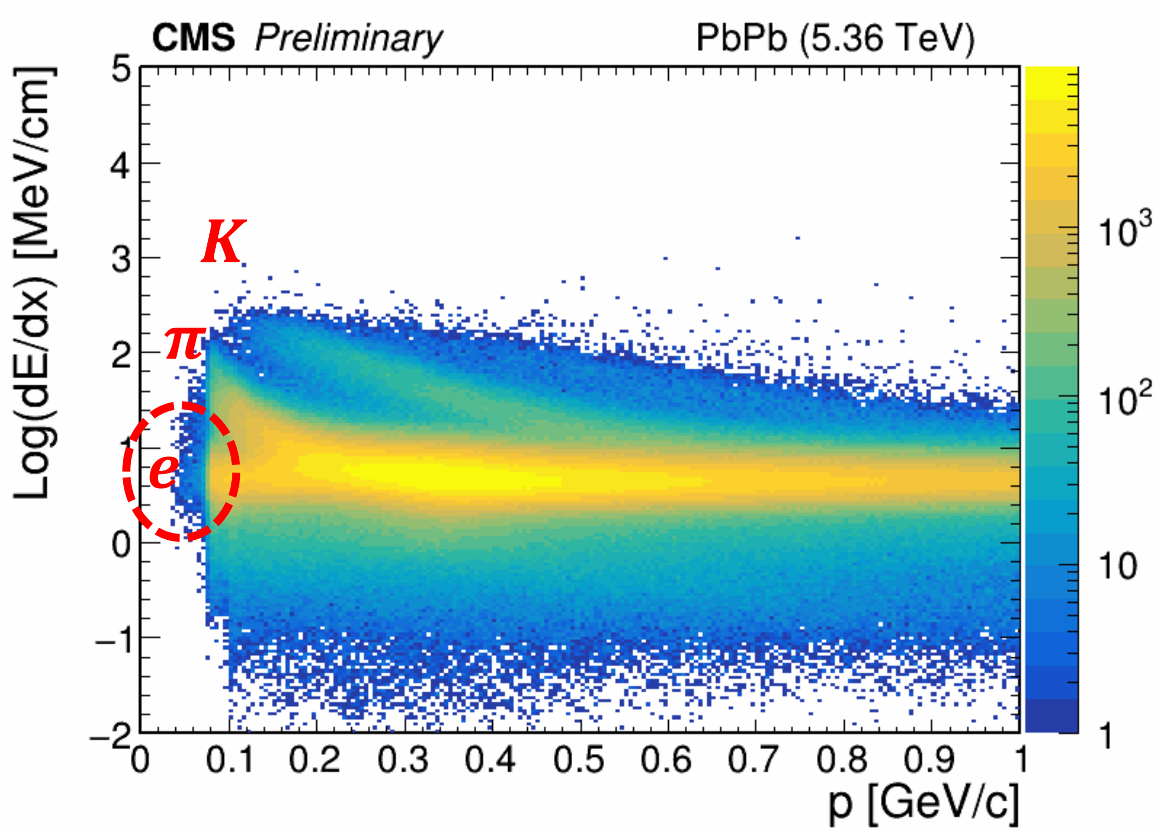
- Events are selected using a zero-bias trigger
  - Online requirement of at least one track detected in the pixel tracker
  - A minimum pT threshold of 0.05 GeV is applied
- Largest energy deposits in both the +/- sides HFs must fall below thresholds
- A primary interaction vertex is required, formed by two oppositely charged tracks

Kaon Selection Strategy



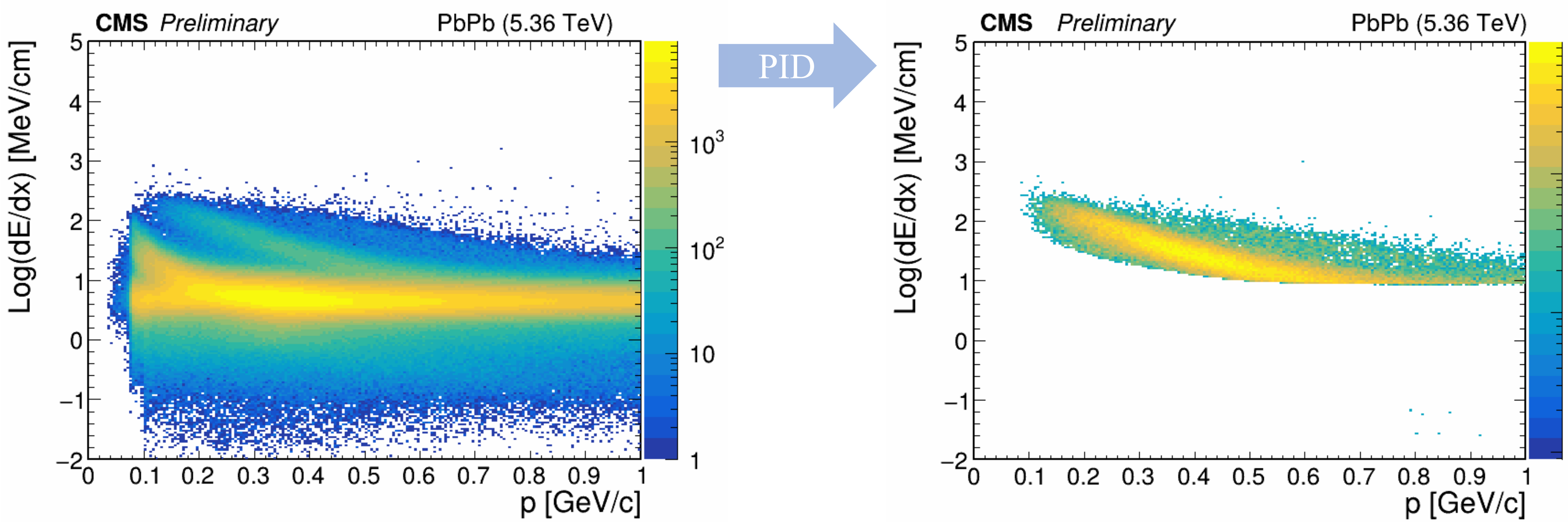
- In offline analysis, kaon identification is performed using dE/dx measurements from the energy deposited in the pixel detector
- The kaon band in dE/dx is clearly separated from the pion and electron bands at low momentum
- Misidentified pion pairs from coherent ρ production
  - Contribute to a broad mass peak around 1.2 GeV

Kaon Selection Strategy



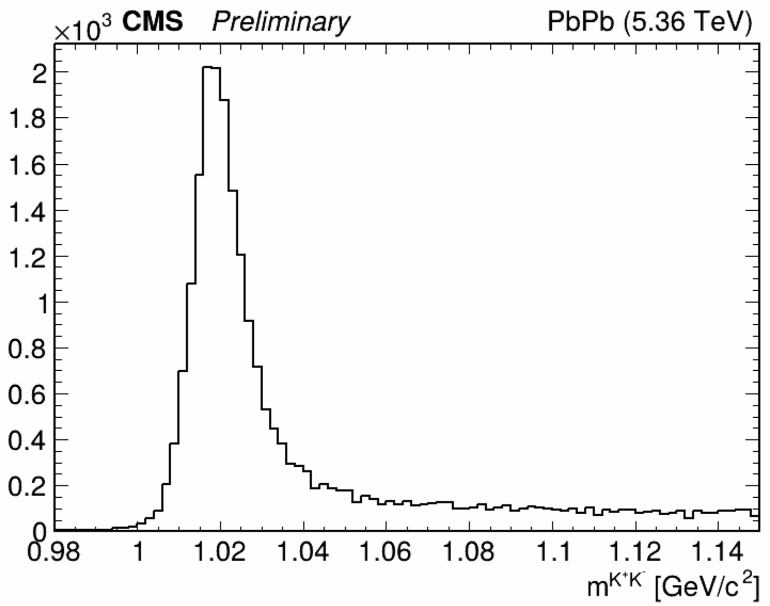
- Electron-positron pairs originating from photon conversions
  - Mass distribution peaking in the low-mass region
- The production of $p\bar{p}$ pairs is strongly suppressed due to the lack of coupling to VM photoproduction in UPCs
  - Making this background negligible

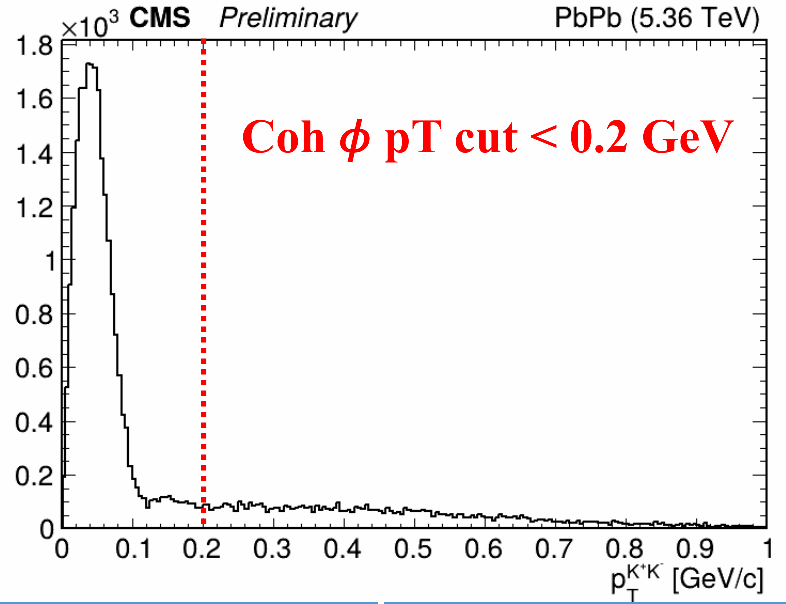
Particle Identification (PID)



- A probability-based method is used to discriminate kaon
- Effectively separated the kaon band

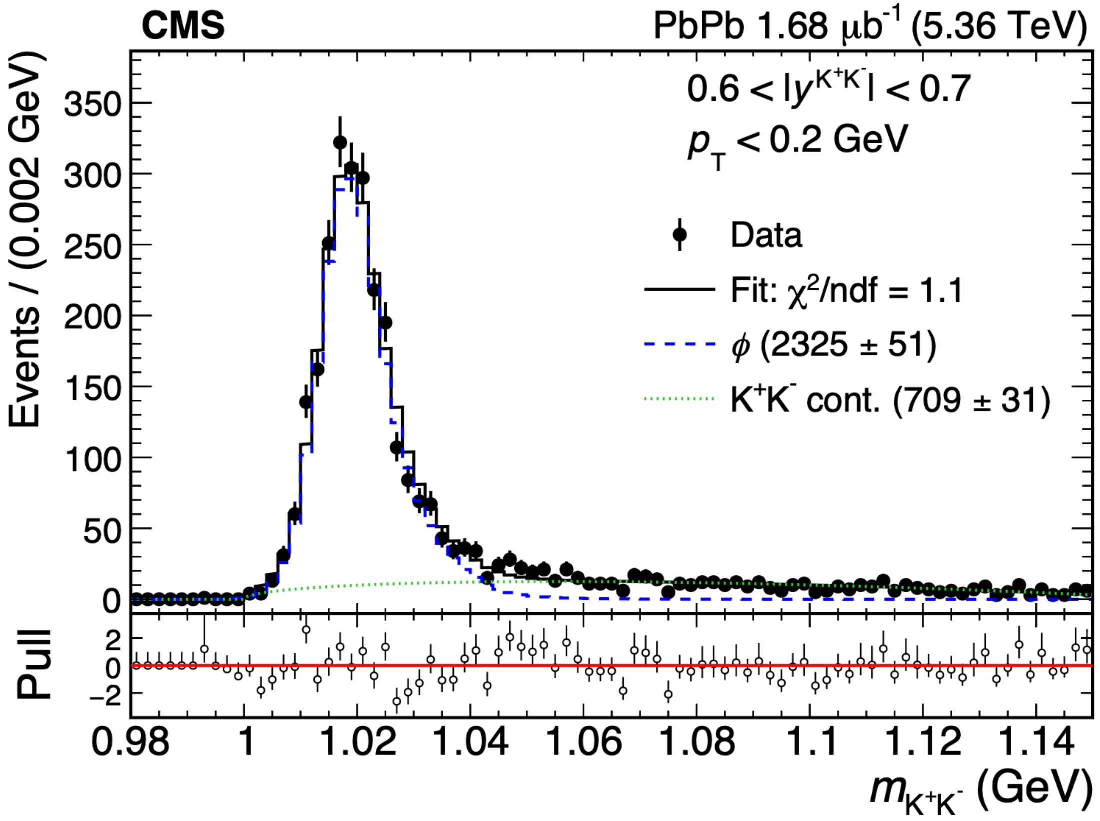
Selected Candidate After PID





- Kaon pairs with an invariant mass in the range $0.98 < m < 1.15$ GeV are selected
- A primary source of background arises from direct K^+K^- production
  - A photon fluctuates into a virtual kaon pair and elastically scatters off the target nucleus.
  - A smooth continuum in the invariant mass distribution
- Additional contamination from misidentified pion pairs, especially from coherent ρ decays or direct pion production
  - Estimated using MC simulations by assigning the kaon mass to pion tracks
  - Negligible after selection cuts

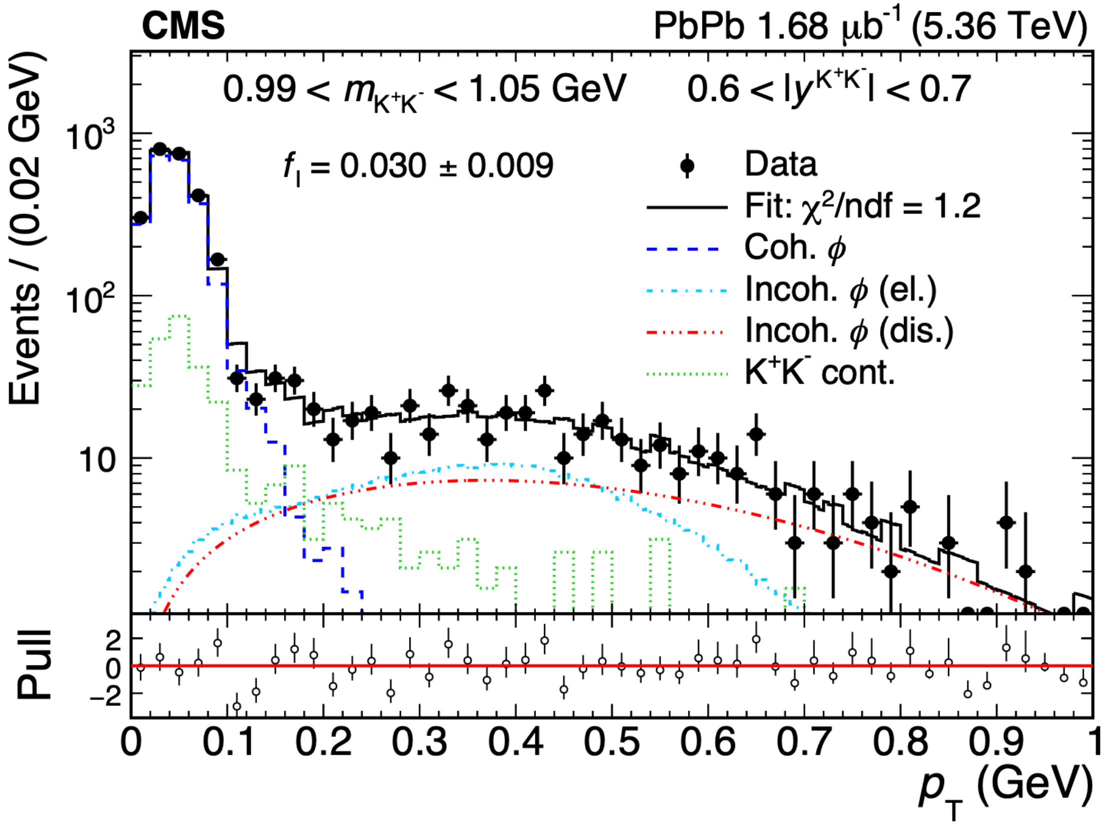
ϕ Signal Extraction



- A $\chi 2$ template fit to the mass distribution of K^+K^- pairs is done to extract the raw yield of the ϕ meson
- Fit is performed in the low-pT (< 0.2 GeV) region, where coherent production dominates
- The continuum background from direct K^+K^- production
  - Modeled using an empirical function that accounts for threshold effects near twice the kaon mass

arXiv:2504.05193

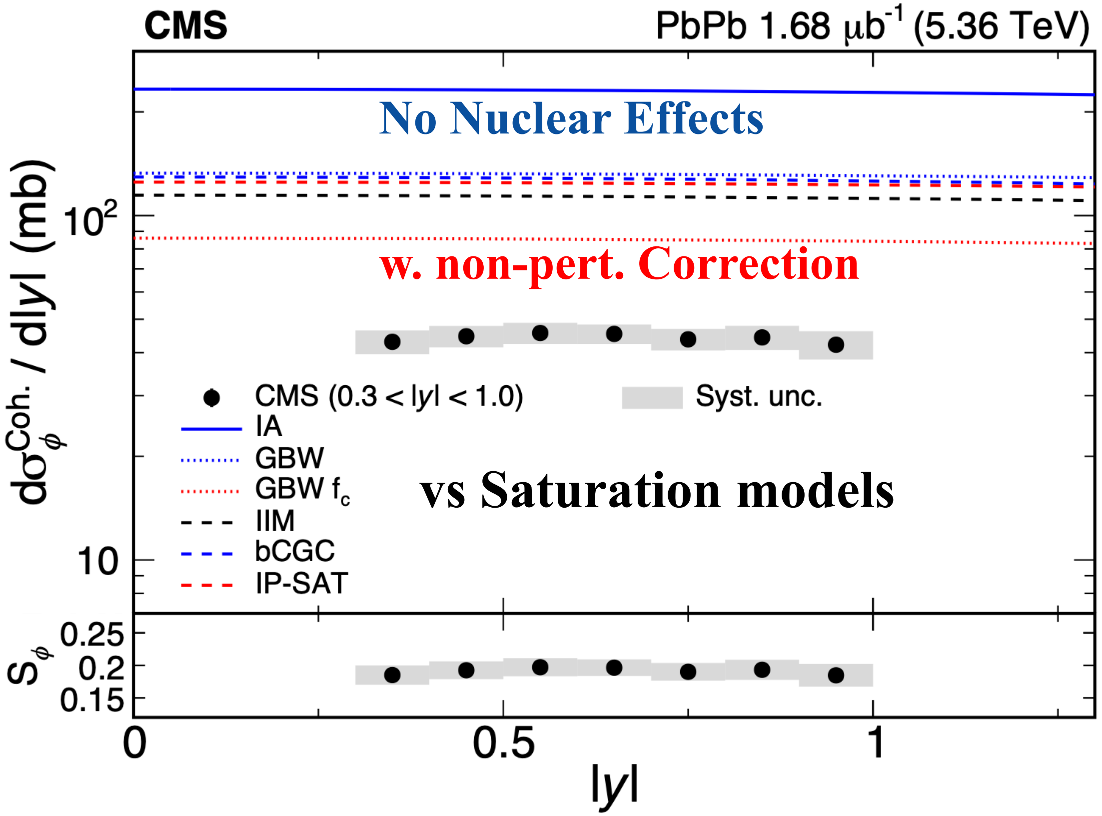
Incoherent Fraction



- There is a small incoherent contribution in the signal region
- Determined by fitting the pT distribution of kaon pairs within the mass window
- Exploiting the characteristic difference in pT between coherent and incoherent production mechanisms

arXiv:2504.05193

First Observation of Coh. ϕ



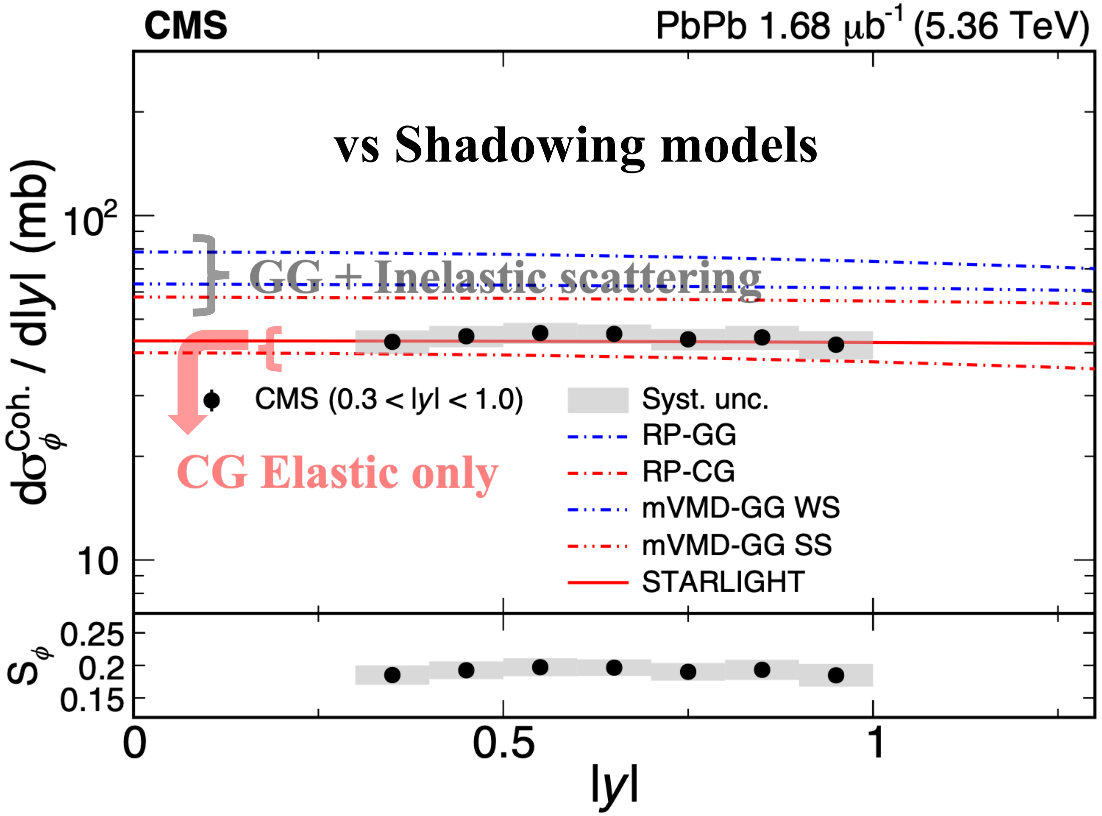
$$x = \frac{M_{VM}}{\sqrt{s_{NN}}} \cdot \exp(\pm y_{VM})$$

- **First measurement** of coherent ϕ meson photoproduction off a heavy nucleus
- The cross section is found to be **significantly suppressed by a factor of ~5 compared to an IA model**
- Saturation-based models tend to **overpredict** the cross section
- Even after including non-pQCD corrections, which reduce the predictions by about 40%
  - Still overestimate the data by roughly a factor of 2,

arXiv:2504.05193

First Observation of Coh. ϕ

classical Glauber (CG)
Gribov–Glauber (GG)

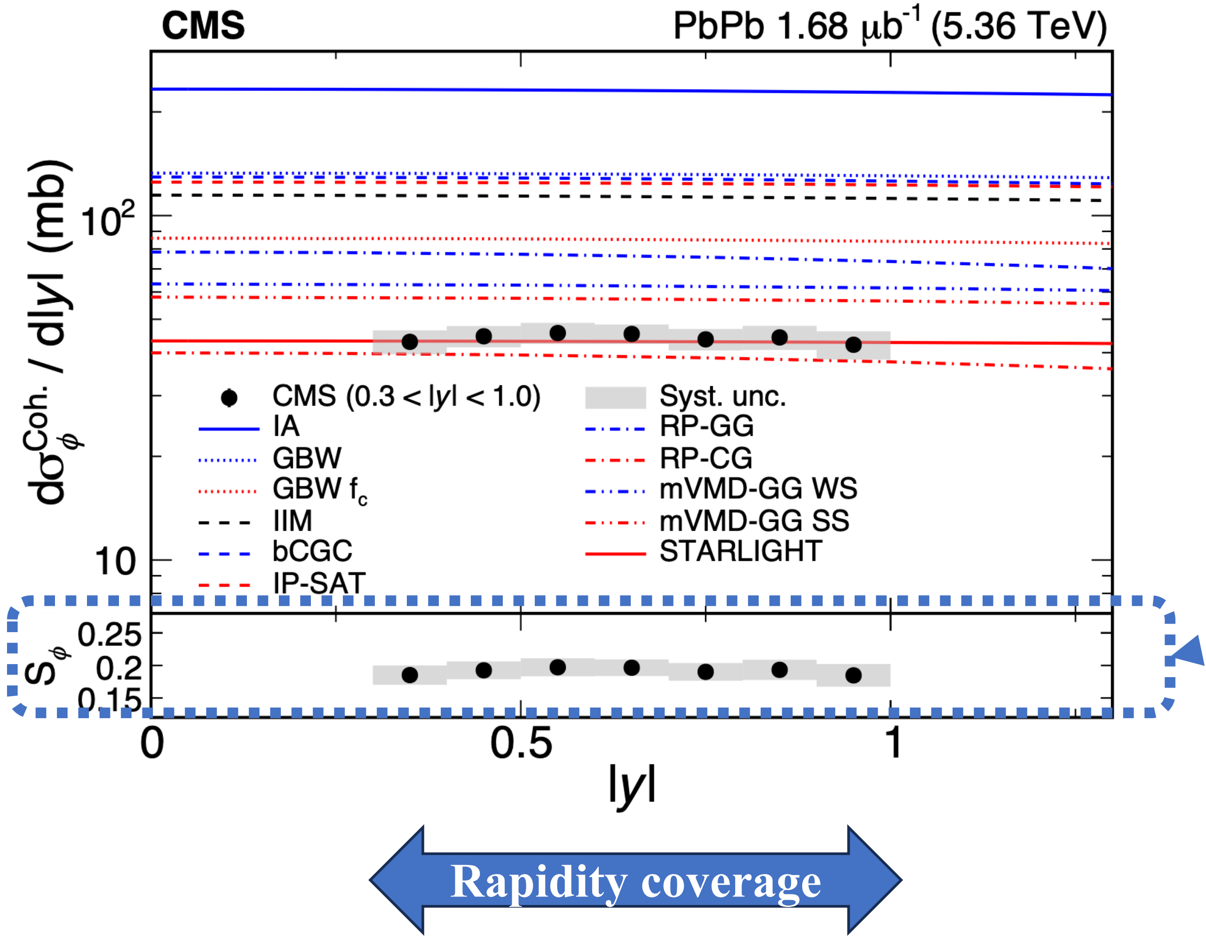


$$x = \frac{M_{VM}}{\sqrt{s_{NN}}} \cdot \exp(\pm y_{VM})$$

- Models incorporate nuclear shadowing within the vector meson dominance (VMD) framework **predict an even stronger suppression**
  - Multiple scatterings of the virtual VM as it traverses the nucleus
- The STARLIGHT model (VDM+CG) is found to be **consistent with the measured data** within a few percent
  - Note that the STARLIGHT model fails to describe recent measurements of coherent ρ(770) and J/ψ, highlighting its limited applicability across different mass regimes

arXiv:2504.05193

Summary



arXiv:2504.05193

- Establishes a powerful new tool for exploring nuclear effects and the gluon structure of nuclei in the small-x (~10^{-4}) regime at a unique energy scale
    - Bridging the perturbative and nonperturbative QCD domains
- Provides strong evidence that coherent ϕ meson undergoes **significant nuclear suppression (S~0.18–0.20)**
- Provides additional constraints on existing theoretical models

What Have We Learned So Far?

Coh. J/ψ

Models with saturation or shadowing effects have all **failed to fully describe the data**

BDL?

Incoh. J/ψ

Suppression is more pronounced than coh. production. However the **data disfavor reaching the BDL**

Amplify the nonlinear effects?

Coh. ϕ

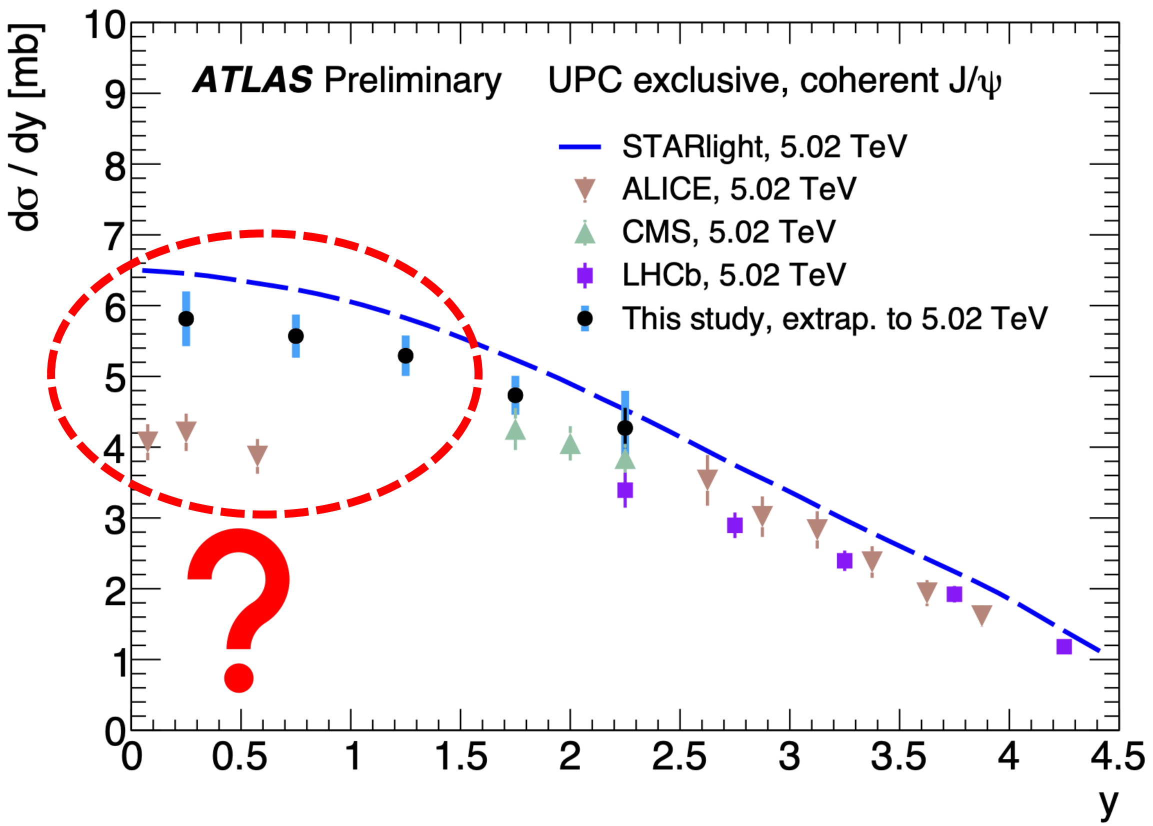
Strong suppression observed. Data seem to favor shadowing models for ϕ meson

Take Away

Strong Suppression observe across all measurement.
Robus nuclear effects but unclear underlying physics.

What’s Next?

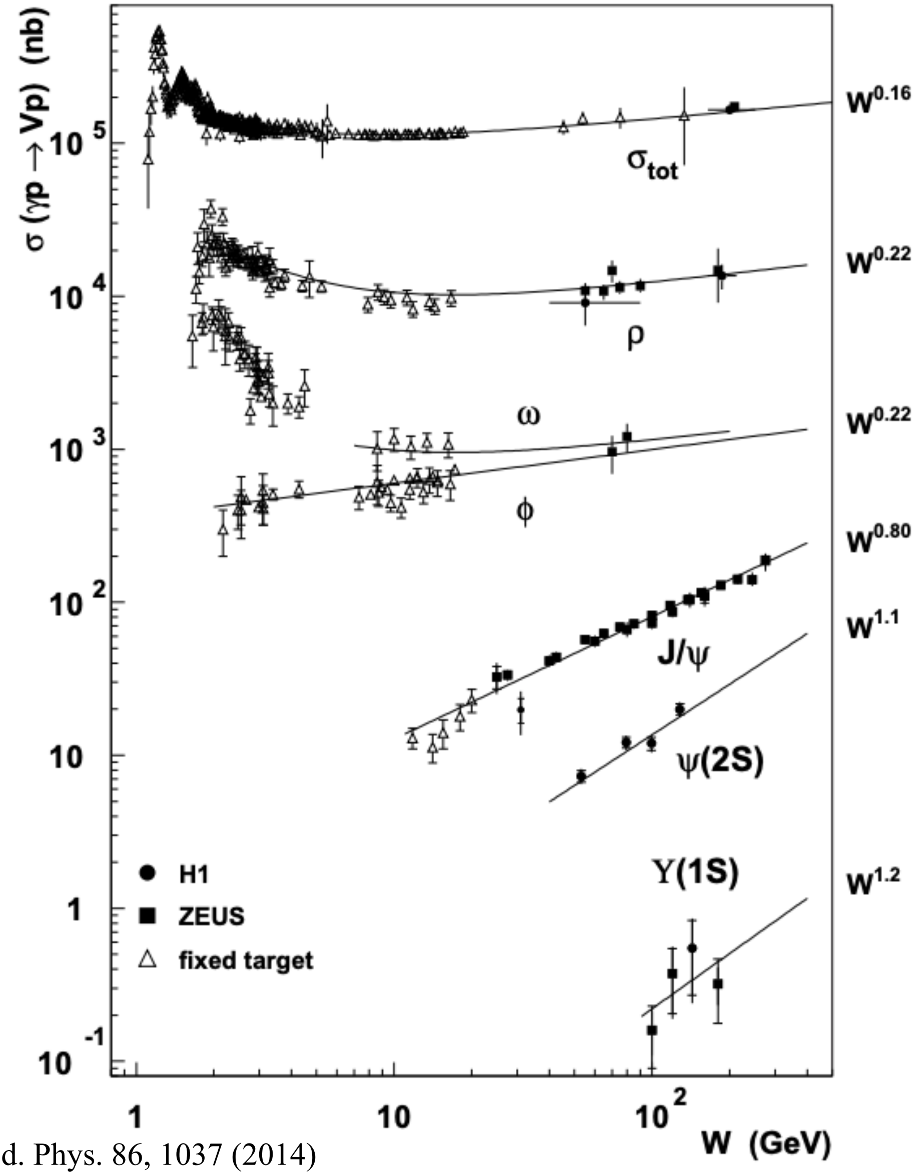
More Coh. J/ψ Measurements



- ATLAS has recently reported new measurements
- These results show tension with previous findings from ALICE!
- No muon ID since muons cannot reach the ATLAS muon detector, they used a track trigger on the inner tracking detector.
  - Two tracks are assumed to be muons, with a low total E_T as an exclusivity requirement.
- CMS is also expected to perform similar measurements in the near future!

ATLAS-CONF-2025-003

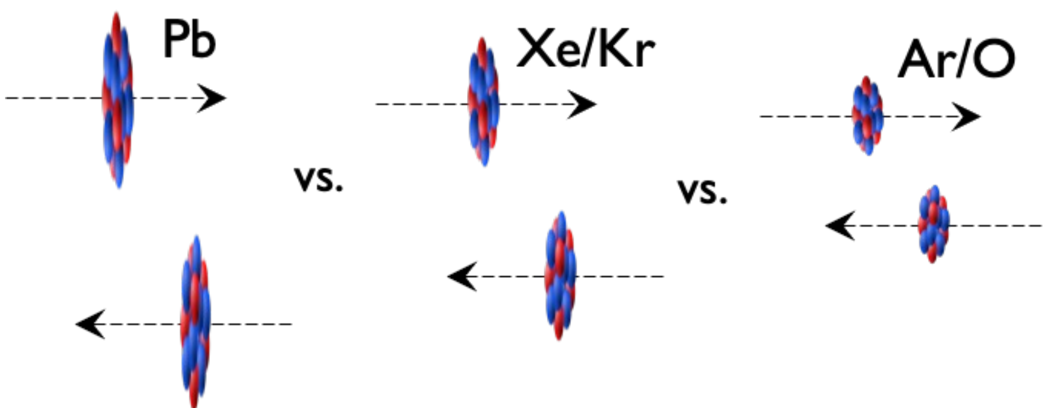
More VMs with Neutron Tagging

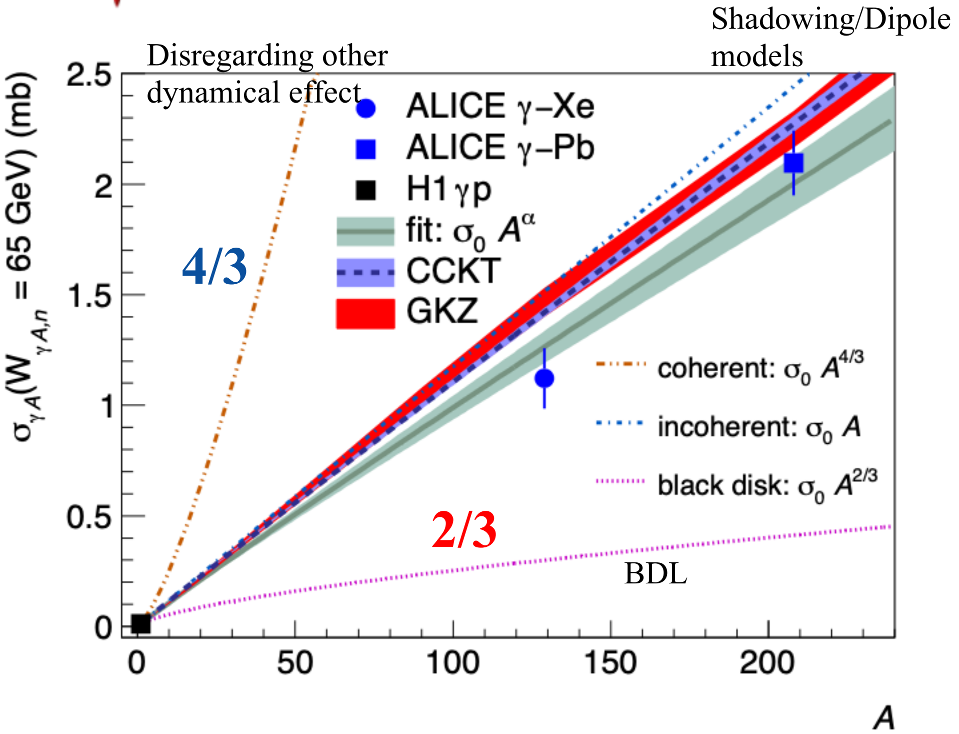


Rev. Mod. Phys. 86, 1037 (2014)

- **Various VM species in coherent/incoherent UPCs can be measured by CMS**
- A similar neutron tagging technique could be used to disentangle energy-dependent cross sections for these species!
  - Phi
  - Psi(2S)
  - Upsilon

A-dependence

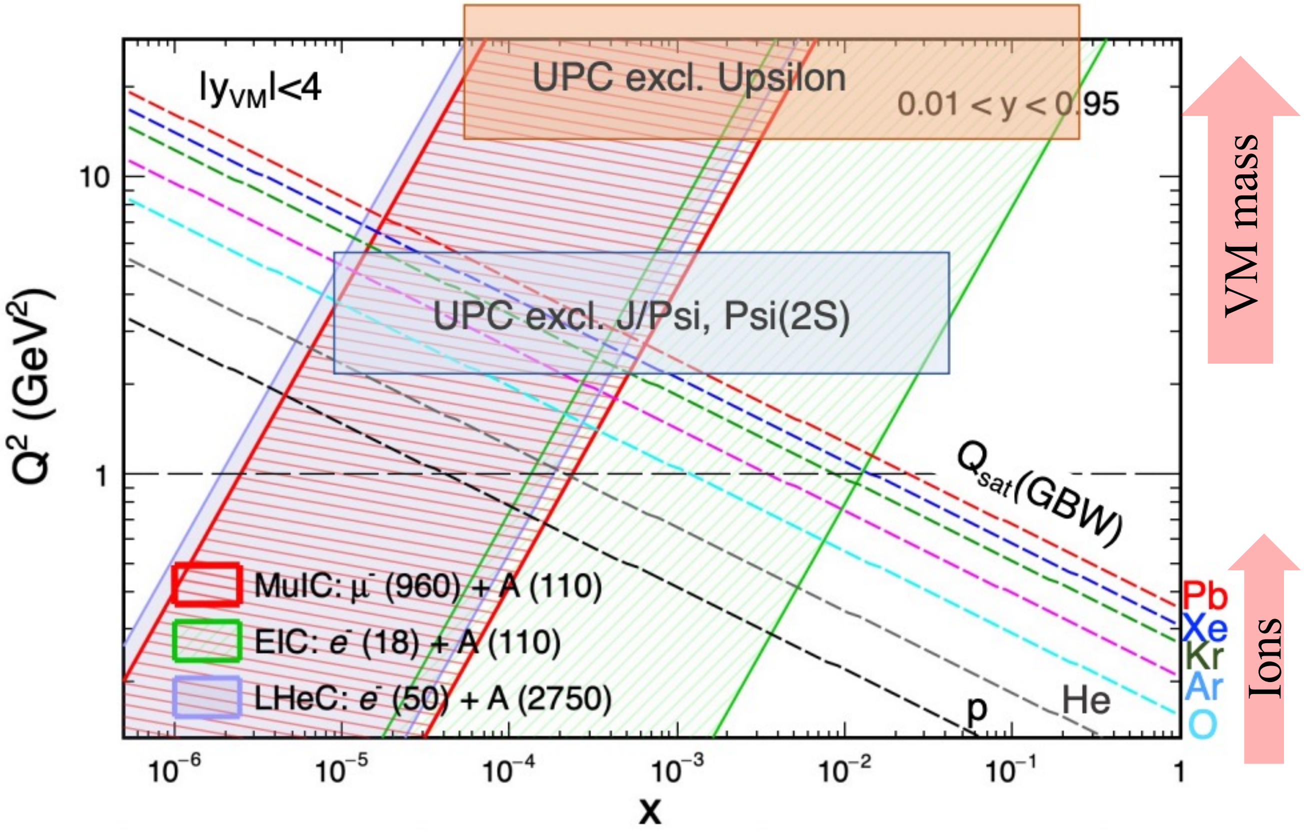




Phys.Lett.B 820 (2021) 136481

- A system size scan with different ion species is essential to better distinguish between various physics processes
  - Sensitive to nuclear shadowing effects and the approach to the BDL
- Some Well-Established Expectations (Not Yet Proven Experimentally):
- Saturation: $Q_s^2(A) \sim Q_s^2(p) \cdot A^{1/3}$
  - A-dependent slope δ :
    - 4/3: Outside the saturation regime
    - 2/3: Deep in the saturation regime, near the BDL
- **LHC OO run is starting this June/July!**

The Future



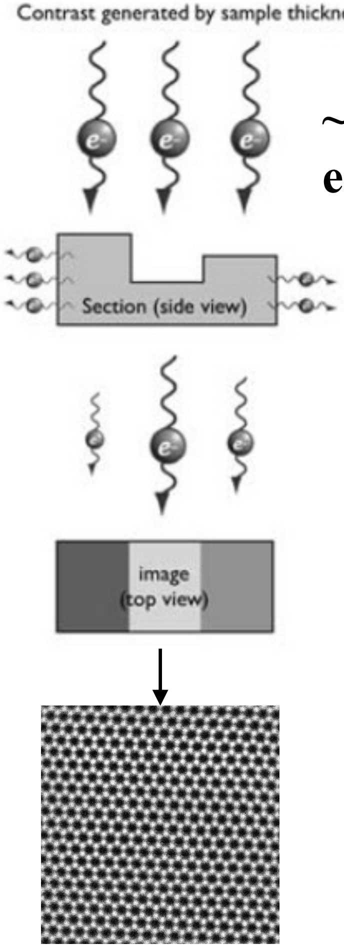
Ultimately, Mapping the Full x, Q^2, A, m_{VM} Dependence!

- x, A, m_{VM} : These variables are accessible through UPCs at the LHC
- Q^2 : A more detailed scan will be possible with future lepton-ion colliders (e.g., EIC),
  - enabling exploration of a more detailed phase space

Thank You!

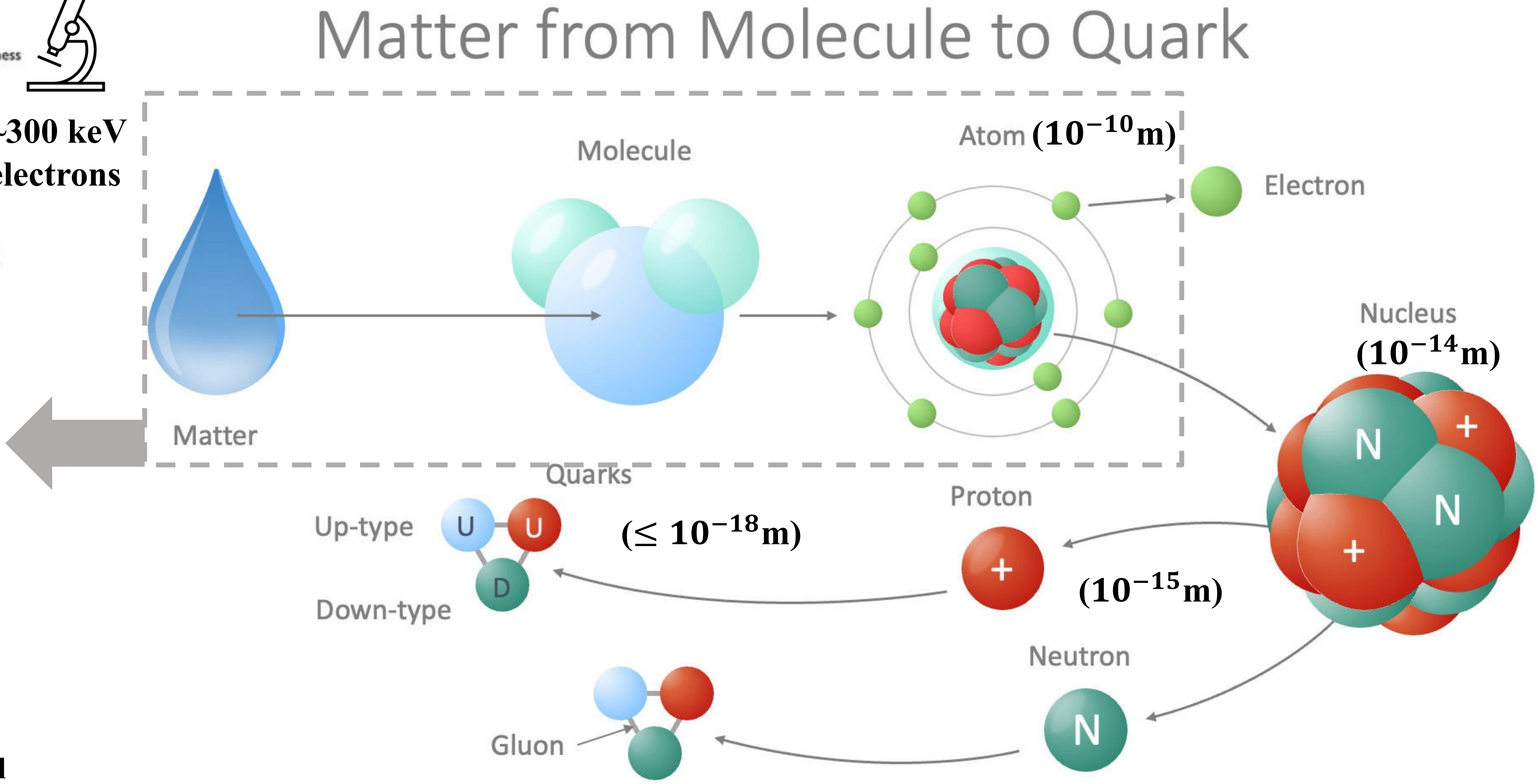
Extra

Understand the Fundamental Matter

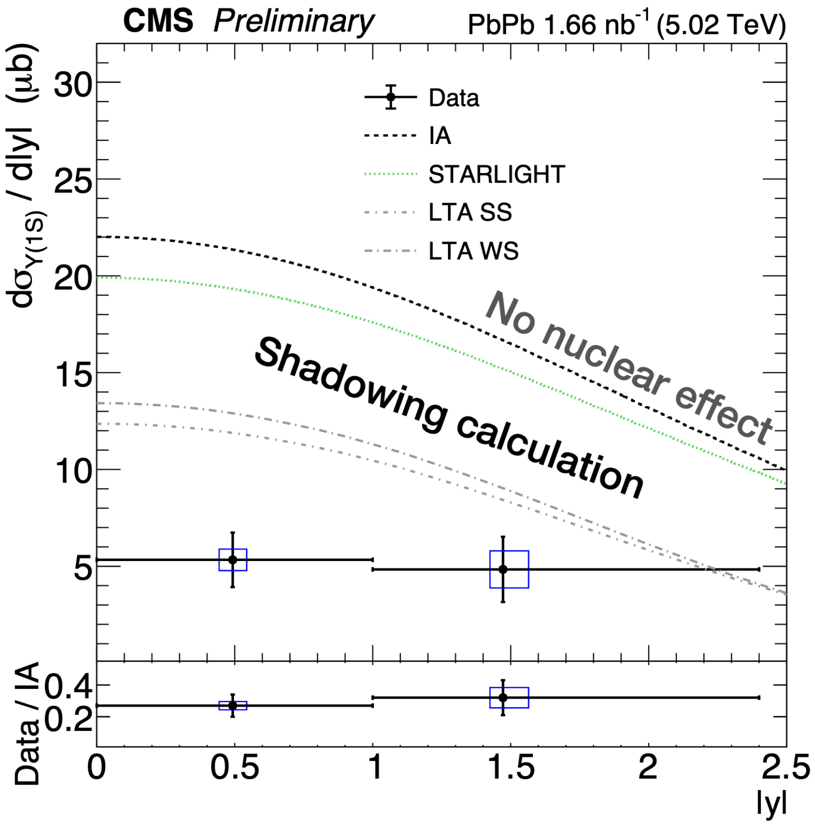


~300 keV electrons

Graphite hexagonal structure under electron microscope

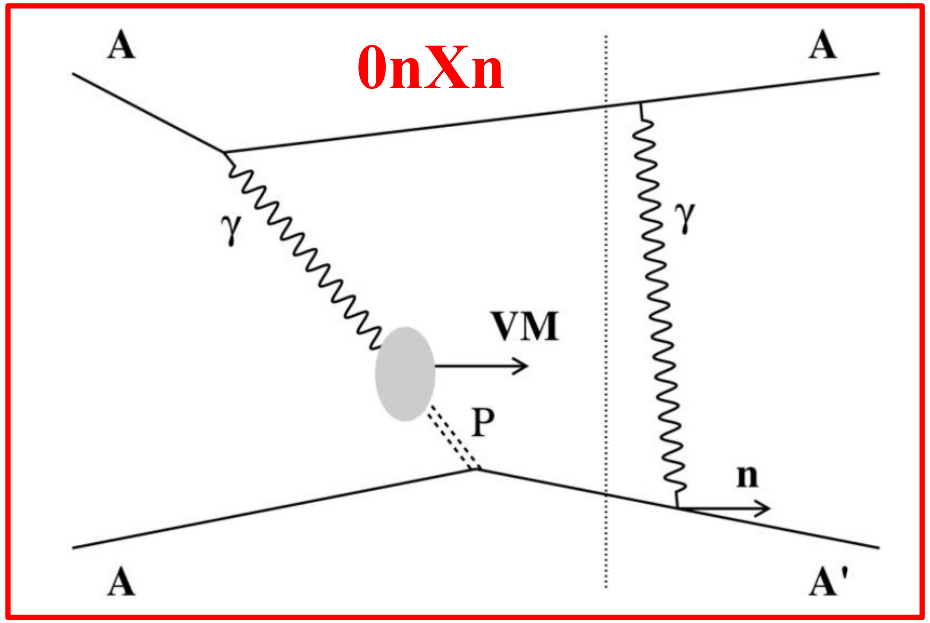


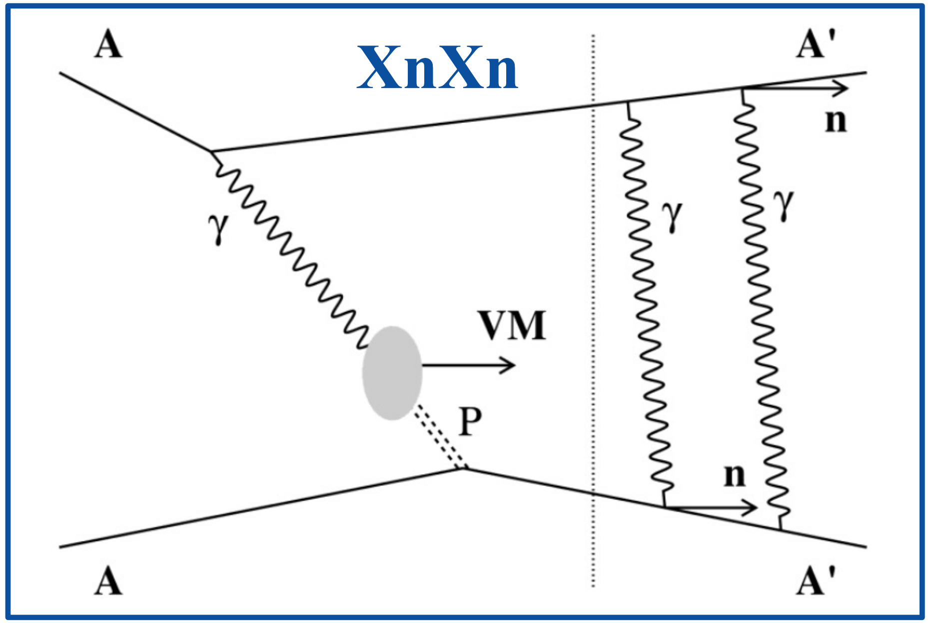
Coh. Υ Photoproduction



- UPC Υ expected to lie far outside the saturation regime
  - Test for the linear QCD evolution at small-x
- Strong nuclear effects have been observed for Y(1S)
  - A suppression factor of approximately 0.3
- Shadowing calculations based on linear evolution alone do not fully describe the data
- This raises the question: could the discrepancy be due to nonlinear evolution for the gluon?
- Alternatively, could it be caused by missing NLO pQCD corrections?

Electromagnetic Dissociation (EMD)





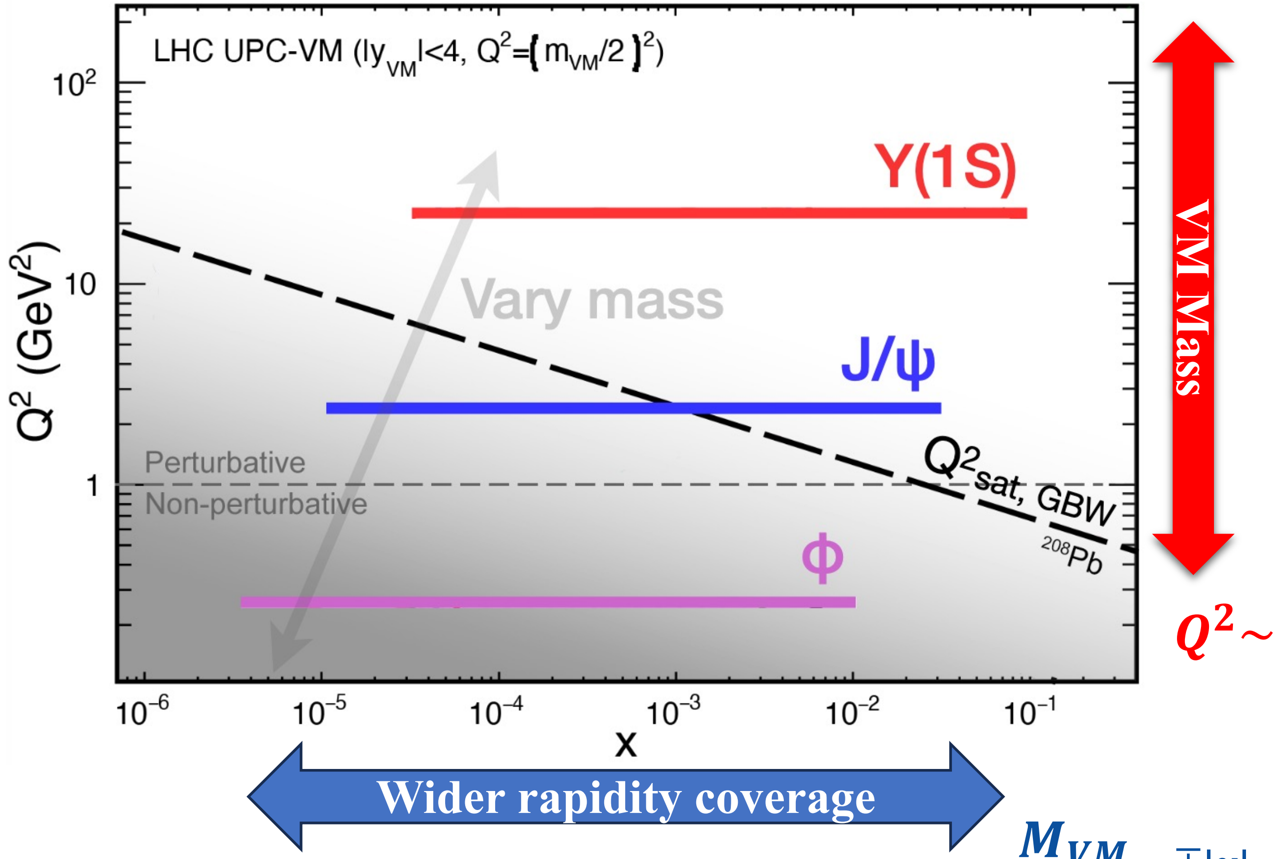
A way to solve the ambiguity puzzle

- In PbPb collision, multiple photon exchange is possible → Neutrons emission with photons absorption
- Total EMD cross section is large (~200 b)
- EMD requires exchange of energetic photons
  - Probability drops with increasing impact parameter

What's the Path to Nonlinear Evolution

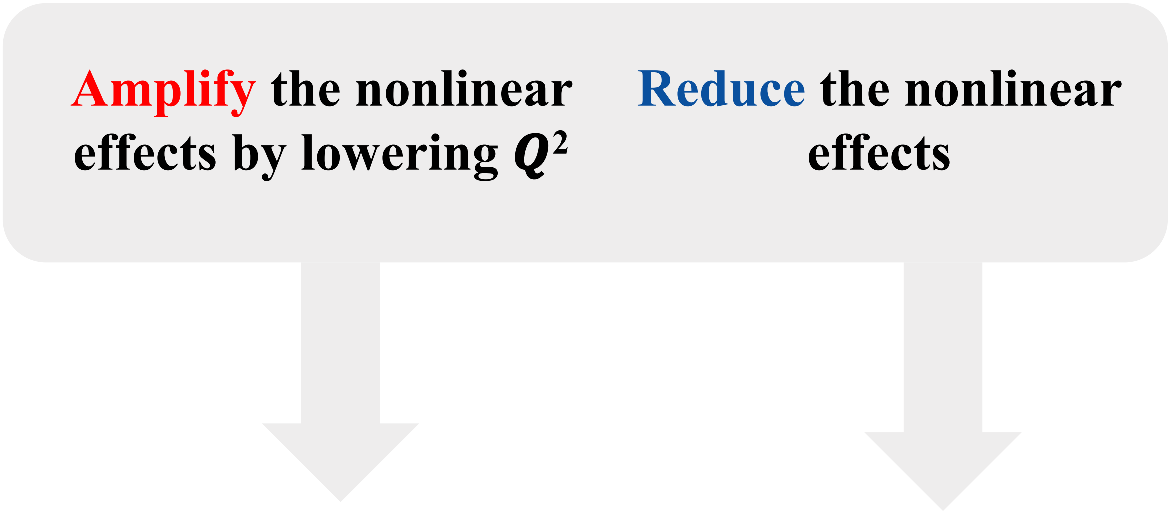
Can we conduct a 2D scan to search for Nonlinear evolution?

Yes!



$Q^2 \sim M_{VM}^2/4$

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



Amplify the nonlinear effects by lowering Q^2

Reduce the nonlinear effects

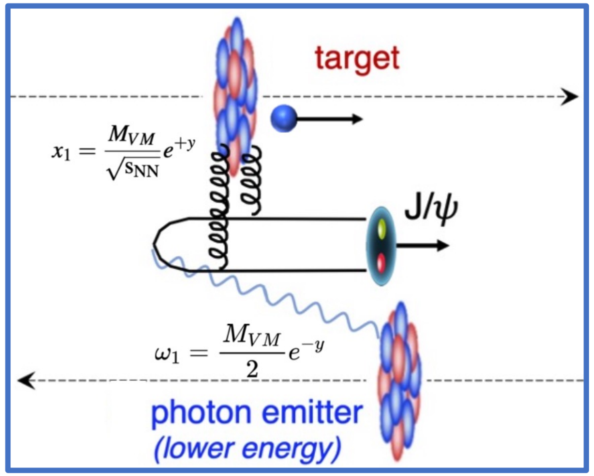
Coh. ϕ

Sensitive to non-pert. effects

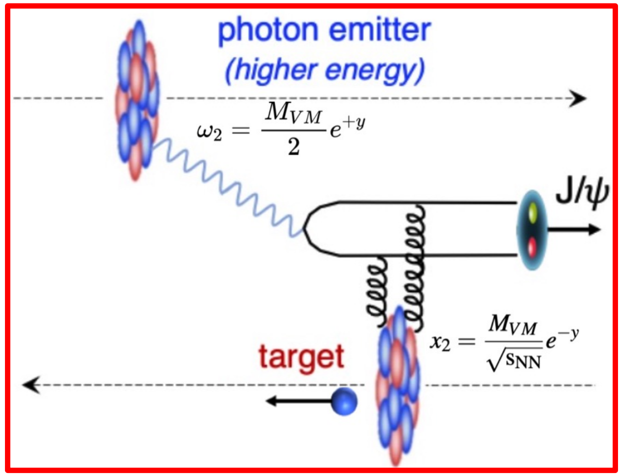
Coh. Υ (briefly)

Testing pQCD and NLO Correction

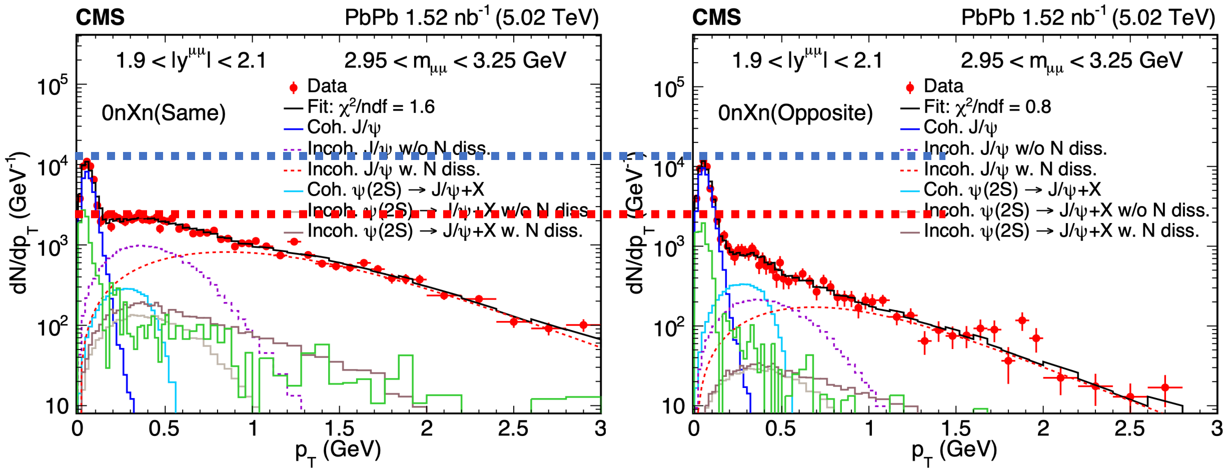
Incoh. J/ψ–Neutron Directional Correlation



Low W



High W



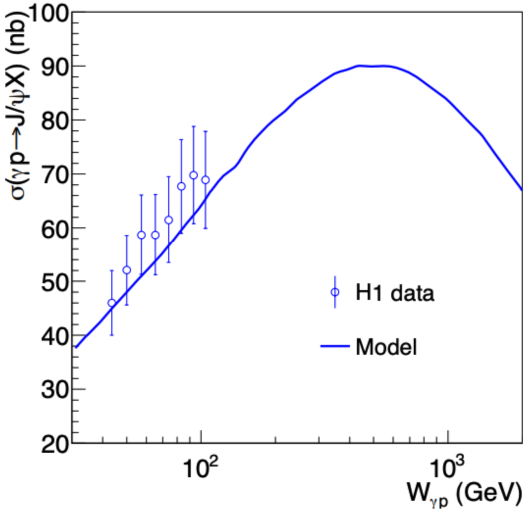
arXiv:2503.08903

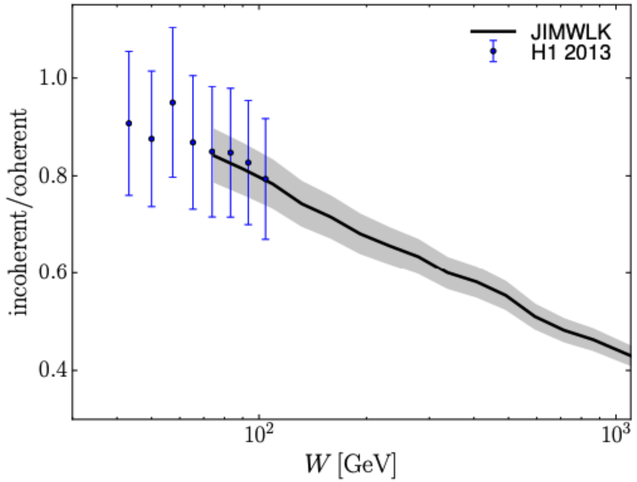
- The first energy dependence of incoh. J/ψ photoproduction was performed by CMS, utilizing forward neutron tagging
- Incoh. : ~85% probability to induce forward neutrons
- Incoh. process is soft compared to the beam energy and the emitted neutron tends to go in the same direction as the J/ψ
  - A strong directional correlation between forward neutrons and incoherent production
- Coh. J/ψ production shows no directional correlation with forward neutrons
  - EMD is an independent process

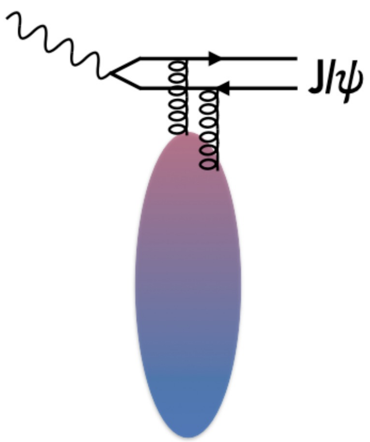
Incoh. J/ψ Photoproduction

- For incoh. production, the photon couples to a single nucleon within the nucleus
  - Signature: $< p_T^{VM} > \sim 500$ MeV
  - Typically accompanied by nucleon dissociation
- Coh. : probes the average gluon configuration
- Incoh. : probes the gluon fluctuations/variances of the gluon configurations

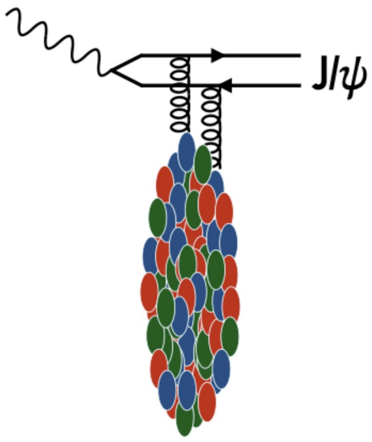
Rept.Prog.Phys. 83 (2020) 8, 082201







Coherent



Incoherent

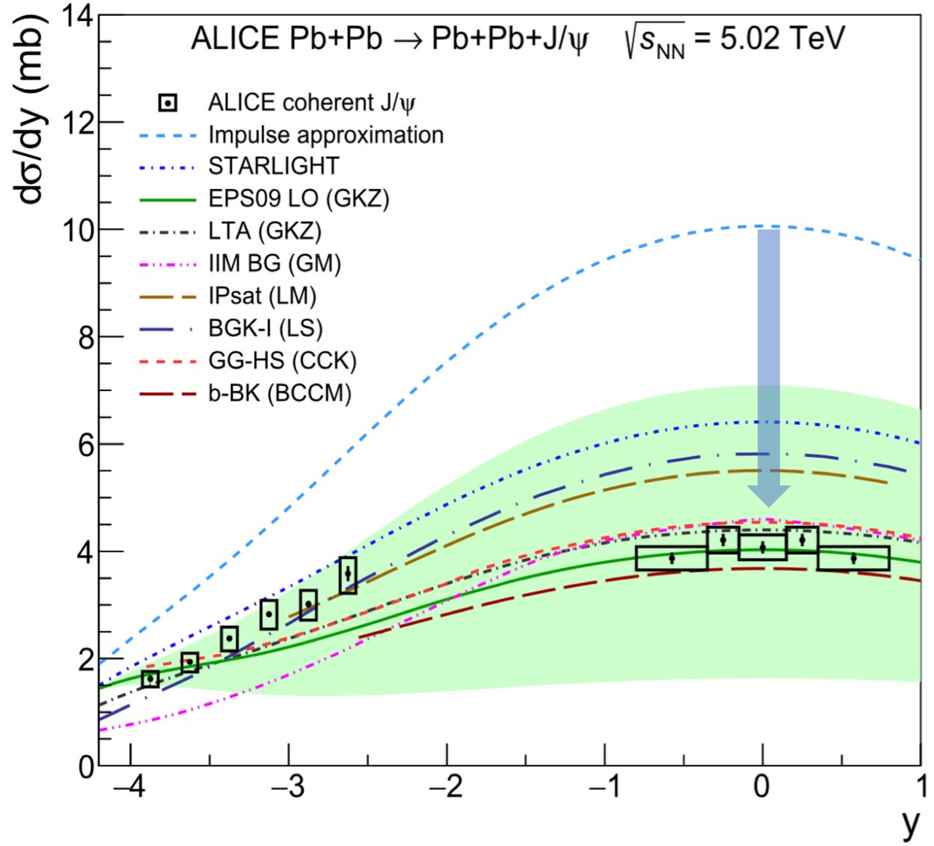
- At low energies, the variance of the gluon field configurations grows with gluon density, rising in the cross section
- If the BDL is reached the gluon distributions largely overlap across nucleons, which reduces the variance in configurations
- This reduction in variance results in a decrease in the cross section compared to coh. production

Exclusive J/ψ in PbPb UPC

Eur. Phys. J. C (2021) 81:712

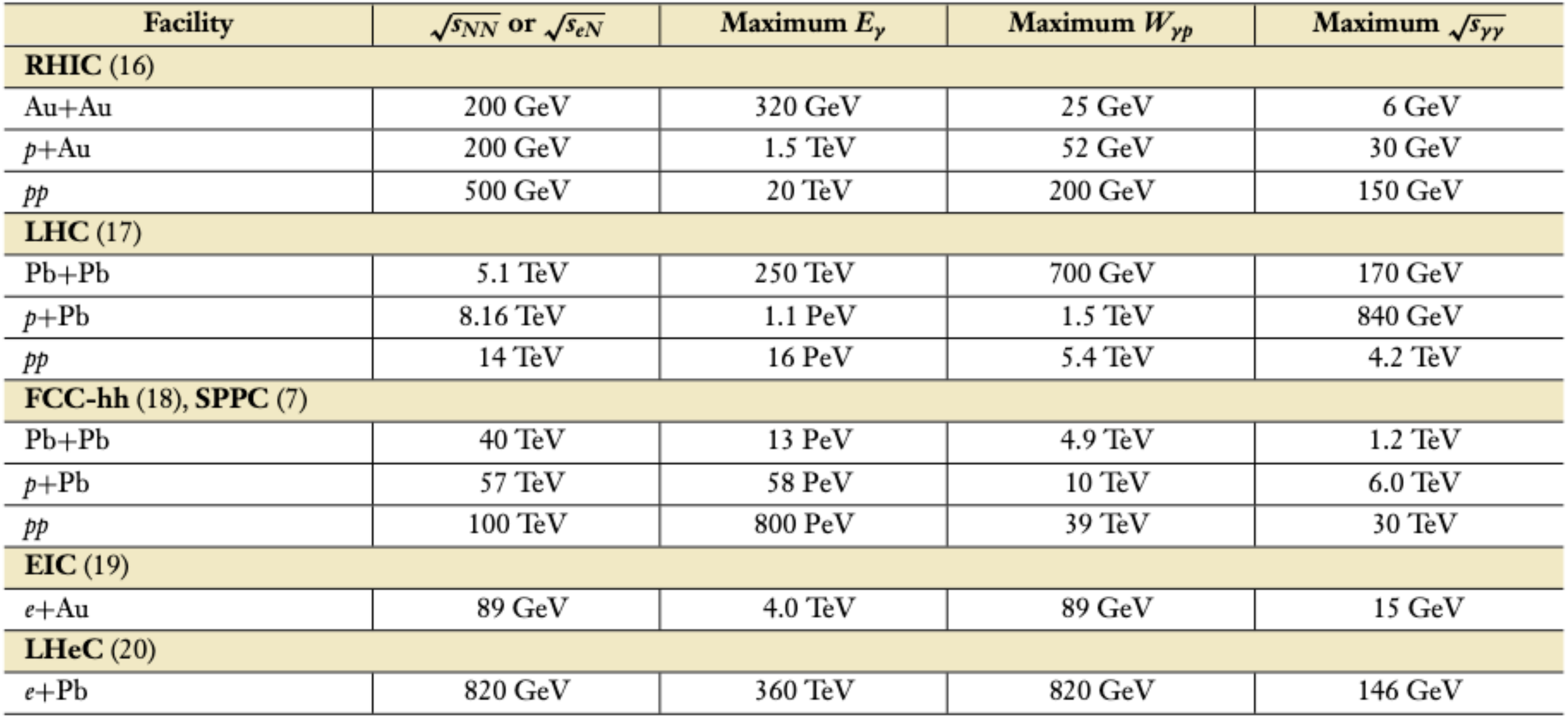
$$\boldsymbol{\gamma + Pb \rightarrow \mathrm{J}/\psi + Pb}$$

- Coherent J/ψ photoproduction in PbPb has also been extensively measured at the LHC.
- ALICE provides measurements
  - both mid and forward rapidity regions.
- Clear evidence for nuclear modification is observed.
- The measured data trends challenge all existing theoretical models
  - none can consistently describe the cross sections across the full rapidity range.



Energy

Annu. Rev. Nucl. Part. Sci. 2020. 70:323–54



Facility	$\sqrt{s_{NN}}$ or $\sqrt{s_{eN}}$	Maximum E_γ	Maximum $W_{\gamma p}$	Maximum $\sqrt{s_{\gamma\gamma}}$
RHIC (16)				
Au+Au	200 GeV	320 GeV	25 GeV	6 GeV
p+Au	200 GeV	1.5 TeV	52 GeV	30 GeV
pp	500 GeV	20 TeV	200 GeV	150 GeV
LHC (17)				
Pb+Pb	5.1 TeV	250 TeV	700 GeV	170 GeV
p+Pb	8.16 TeV	1.1 PeV	1.5 TeV	840 GeV
pp	14 TeV	16 PeV	5.4 TeV	4.2 TeV
FCC-hh (18), **SPPC** (7)				
Pb+Pb	40 TeV	13 PeV	4.9 TeV	1.2 TeV
p+Pb	57 TeV	58 PeV	10 TeV	6.0 TeV
pp	100 TeV	800 PeV	39 TeV	30 TeV
EIC (19)				
e+Au	89 GeV	4.0 TeV	89 GeV	15 GeV
LHeC (20)				
e+Pb	820 GeV	360 TeV	820 GeV	146 GeV

Entering A New Regime Of Small x Gluonic Matter

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

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

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

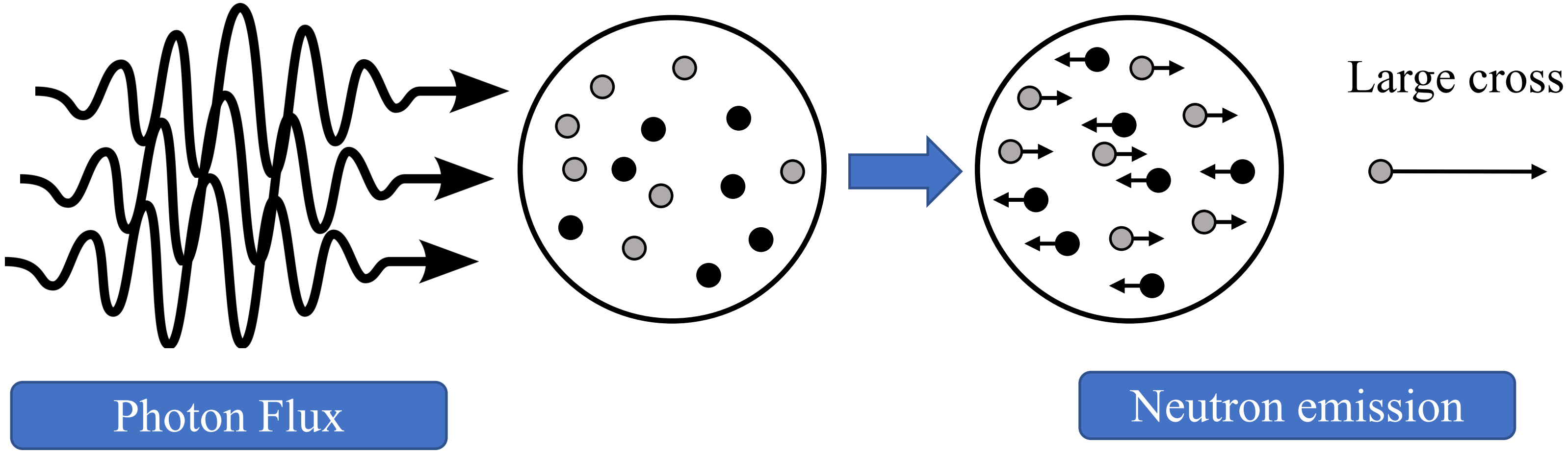
$$\frac{d\sigma^{XnXn}_{AA\rightarrow A'A'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(y)\cdot\sigma_{\gamma A\rightarrow J/\psi A'}(y) + N^{XnXn}_{\gamma/A}(-y)\cdot\sigma_{\gamma A\rightarrow J/\psi A'}(-y)$$

→ Solve for $\sigma_{\gamma A\rightarrow J/\psi A'}(y)$ and $\sigma_{\gamma A\rightarrow J/\psi A'}(-y)$, 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!

Electromagnetic Dissociation (EMD)

- Excitation of nucleons, characterized by the oscillation of the nucleus
- Decay primarily by single neutron emission
- Multiple neutrons emission possible with photons absorption



Large cross section ~200 b

EM Diss. Correction

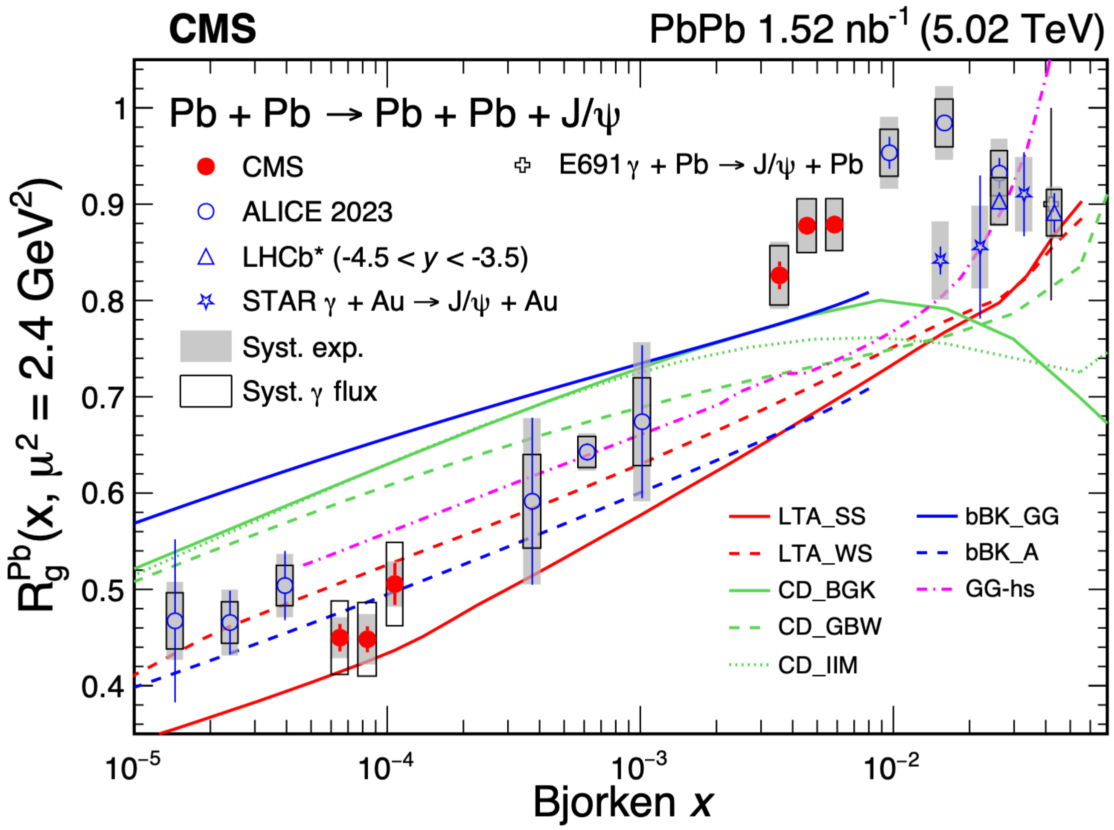
- The correction can be obtained by inverting migration matrix

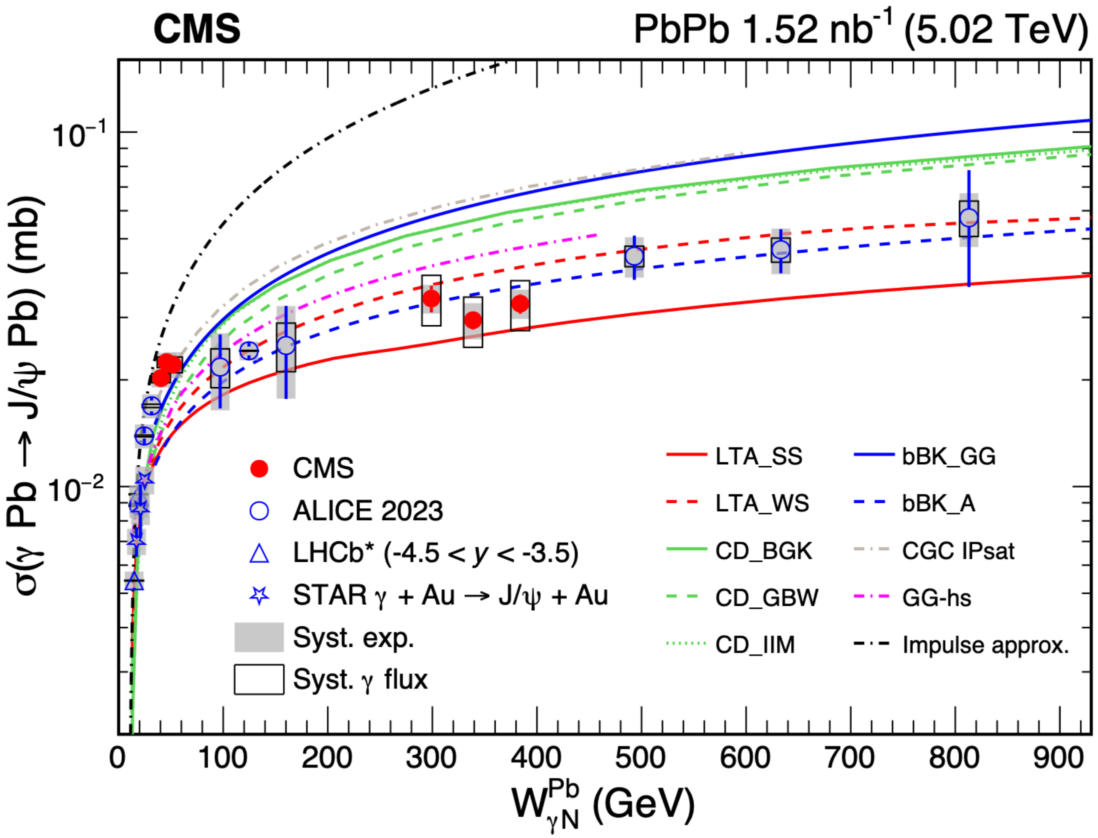
$$\begin{pmatrix} N^{00} \\ N^{0X} \\ N^{X0} \\ N^{XX} \end{pmatrix}^{\text{Obs}} = \begin{pmatrix} P_{00}^{00} & 0 & 0 & 0 \\ P_{00}^{0X} & P_{0X}^{0X} & 0 & 0 \\ P_{00}^{X0} & 0 & P_{X0}^{X0} & 0 \\ P_{00}^{XX} & P_{0X}^{XX} & P_{X0}^{XX} & P_{XX}^{XX} \end{pmatrix} \begin{pmatrix} N_{00} \\ N_{0X} \\ N_{X0} \\ N_{XX} \end{pmatrix}^{\text{True}}$$

- The matrix element can be obtained from ZB fraction

  - $P_{00}^{00} = f_{00}$
  - $P_{00}^{0X} = f_{0X}, P_{0X}^{0X} = f_{00} + f_{0X}$
  - $P_{00}^{X0} = f_{X0}, P_{X0}^{X0} = f_{00} + f_{X0}$
  - $P_{00}^{XX} = f_{XX}, P_{0X}^{XX} = f_{X0} + f_{XX}, P_{X0}^{XX} = f_{0X} + f_{XX}, P_{XX}^{XX} = f_{00} + f_{0X} + f_{X0} + f_{XX} = 1$

Extended Measurement From ALICE



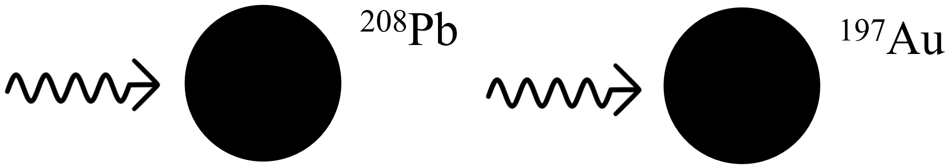


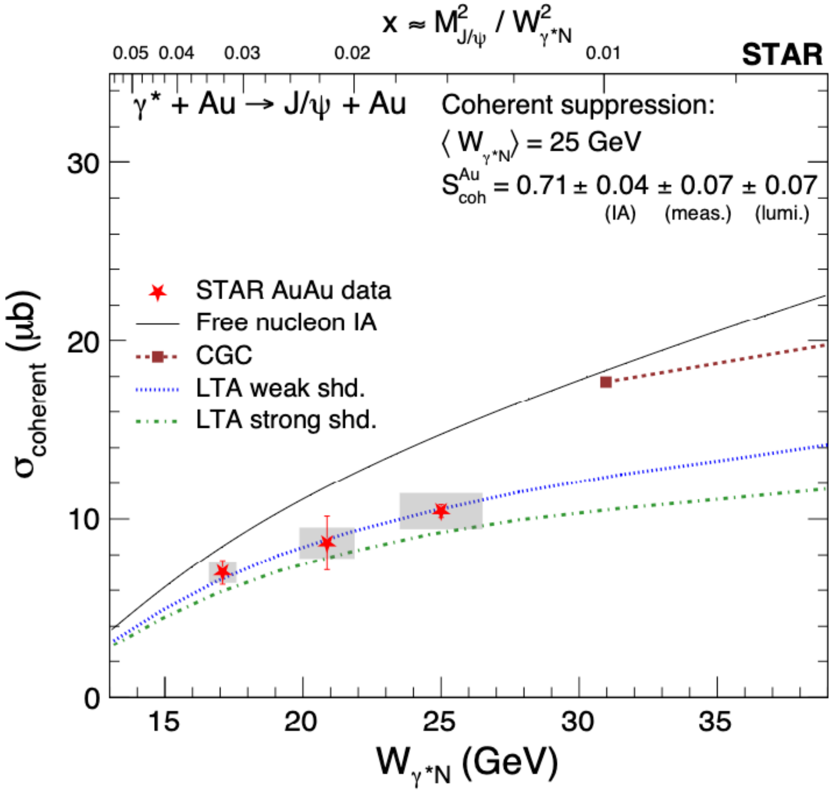
$W_{\gamma N}$ up to ~ 900 GeV

- ALICE: extended the data range for the energy dependence measurement to 17 < W < 920 GeV
- Point to a stronger depletion of the gluon distribution in Pb nuclei over a broad energy range than expected

Coh. J/ψ in $\boldsymbol{\gamma + Au}$

What about the coherent cross section in similar collision systems?





Phys.Rev.C 110 (2024) 1, 014911

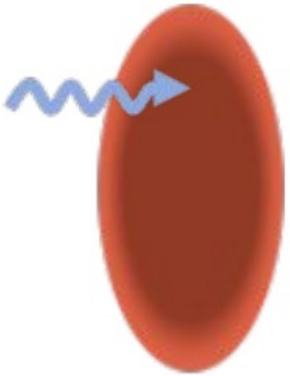
- STAR measured energy dependence of the coherent cross section in γAu
  - Both Au and Pb have similar nuclear sizes
- Probes the **transition region at x ~ 0.01**, between high-x and low-x
- For x > 0.01 (W < 31 GeV), saturation-based models are not applicable.
  - Linear QCD evolution dominates over nonlinear effects
  - Therefore, STAR data can only be meaningfully compared with shadowing models
- Provides a test of shadowing in the absence of saturation
- Observed cross sections are suppressed relative to free proton case and **supports shadowing effects** at lower energies

Another Novel Regime Of QCD: Black Disk Limit

Physics Letters B 537 (2002) 51–61
Phys. Rev. Lett. 87 192301, 2001

In the strong absorption scenario, the interaction probability may reach the unitarity limit. The nucleus target becomes totally absorptive to incoming photons.

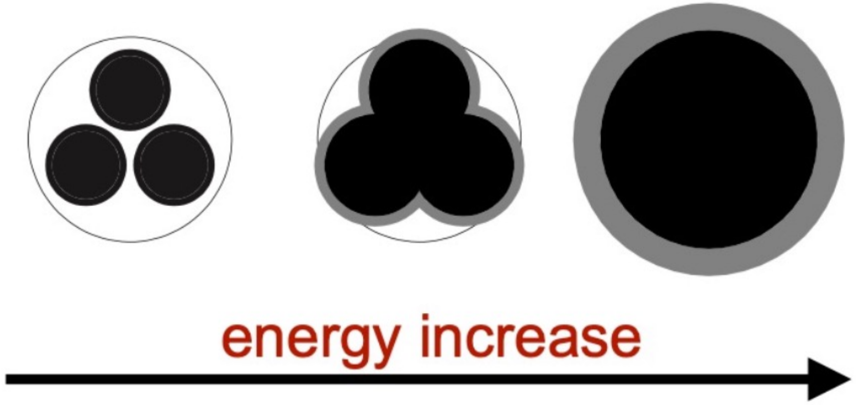
- Total cross section of dipole-nucleus interaction → $2\pi R_A^2$



$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

“Black Disk Limit (BDL)”

- opposite to the “color transparency”

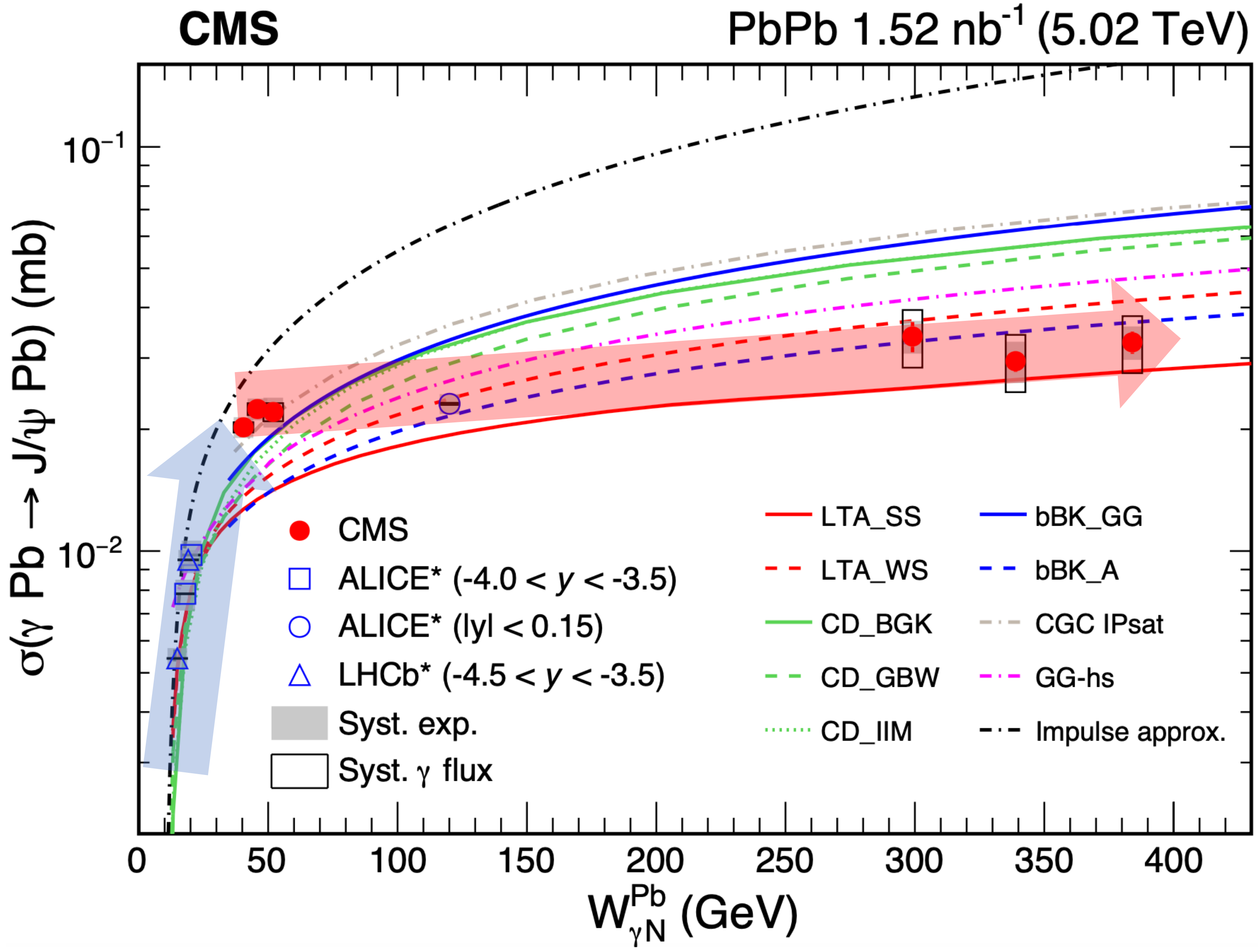


Early onset is possible before gluon saturation if the dipole size is large, for instance. This depends on the weak vs. strongly coupled regime and is not mutually exclusive with gluon saturation.

- New theoretical tools are needed in this regime!

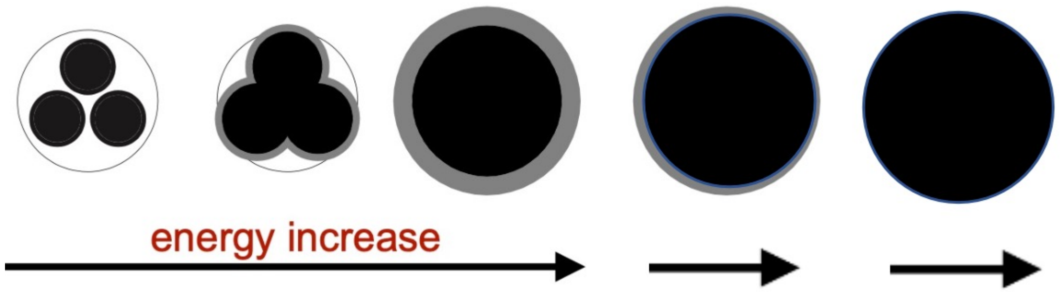
Another Novel Regime Of QCD: Black Disk Limit

arXiv:2303.16984



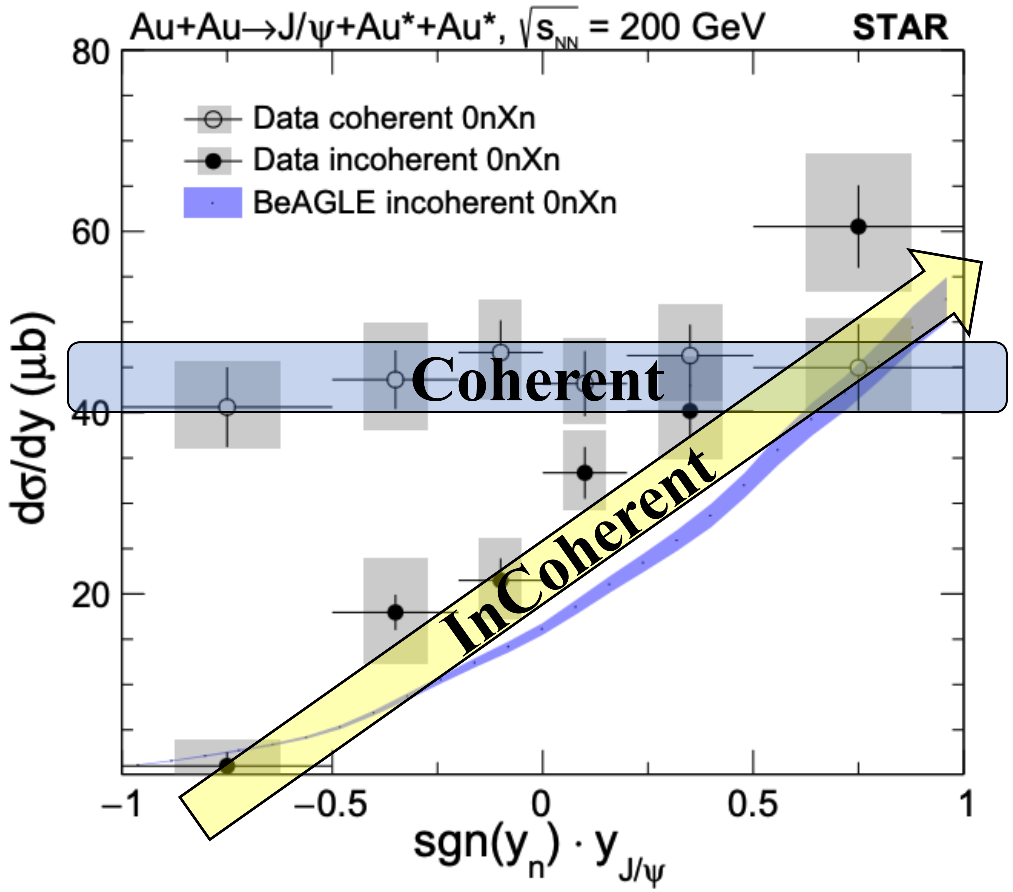
- Rapid grows reflect increased in gluon density
  - Amplitude of interaction is proportional to gluon density

- Slow growth may suggest the periphery of the nucleus has not become fully “black”



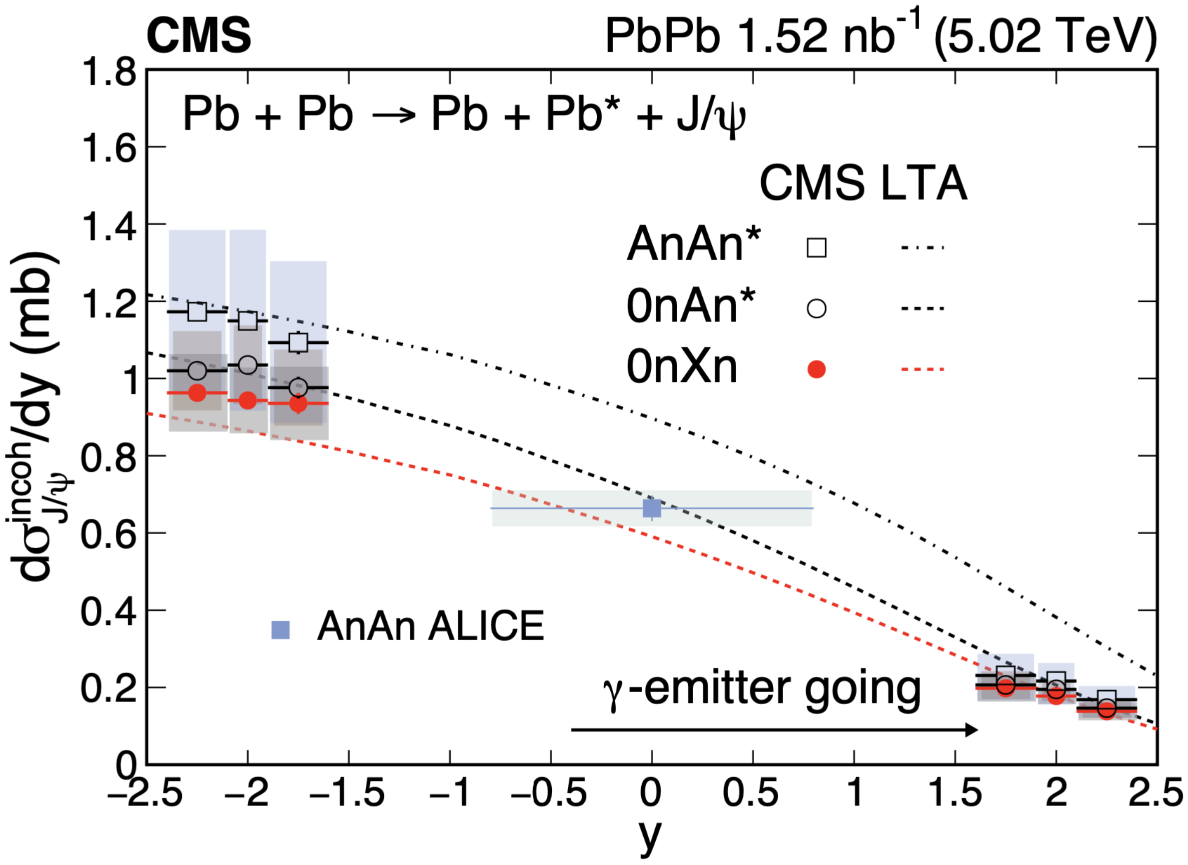
Correlation btw Forward Neutrons and Incoh. J/Psi

STAR: PRC 110 014911 (2024)



- STAR measured rapidity distributions for incoherent J/ψ photoproduction and shows the directional correlation in the 0nXn configuration
- $y > 0$ is chosen as the same direction as the ZDC with a neutron hit in the 0nXn configuration.
- Coherent J/Psi has no direction correlation with the forward neutrons
- Incoherent J/Psi exhabits strong direction correlation with the forward neutrons

Incoh. J/Psi



J/ψ-Xn (Same) **J/ψ-Xn (Opposite)**

- Incoh 0nXn cross sections at (-y) are 5-6 greater than at (+y)
  - Strong incoh. J/ψ-Xn correlation
- 0nAn = 0n0n + 0nXn
- Relative fractions at (+y) and (-y) in 0n0n are assumed to be same as what measured in 0nXn events

Incoh. J/Psi

W Dependent Cross Section Calculation

- Elastic incoherent accounted for in 0nAn*

$$\frac{d\sigma^{\mathrm{0nAn*}}_{\mathrm{PbPb\to PbPb'J/\psi}}}{dy} = \frac{d\sigma^{\mathrm{0nXn}}_{\mathrm{PbPb\to PbPb'J/\psi}}}{dy} + \frac{d\sigma^{\mathrm{0n0n}}_{\mathrm{PbPb\to PbPb'J/\psi}}}{dy}$$

relative fractions at (+y) and (-y) in 0n0n assumed to be same as 0nXn

- Photon flux calculated with STARLIGHT

$$n^{\mathrm{0nAn^*}}_{\gamma/\mathrm{Pb}}(\omega) = n^{\mathrm{0n0n(EMD)}}_{\gamma/\mathrm{Pb}}(\omega) + \frac{1}{2} n^{\mathrm{0nXn(EMD)}}_{\gamma/\mathrm{Pb}}(\omega)$$

$$\sigma_{\gamma\mathrm{Pb\to J/\psi Pb'}}(W) = \frac{d\sigma^{\mathrm{0nAn^*}}_{\mathrm{PbPb\to PbPb'J/\psi}}(y)}{dy} / n^{\mathrm{0nAn^*}}_{\gamma/\mathrm{Pb}}(\omega)$$

Incoh. J/Psi

Photon Flux Calculation

EMD and incoh are independent → 50% align/oppose

$$n_{\gamma/\mathrm{Pb}}^{0\mathrm{nAn}^*}(\omega) = n_{\gamma/\mathrm{Pb}}^{0\mathrm{n}0\mathrm{n}(\mathrm{EMD})}(\omega) + \frac{1}{2} n_{\gamma/\mathrm{Pb}}^{0\mathrm{nXn}(\mathrm{EMD})}(\omega)$$

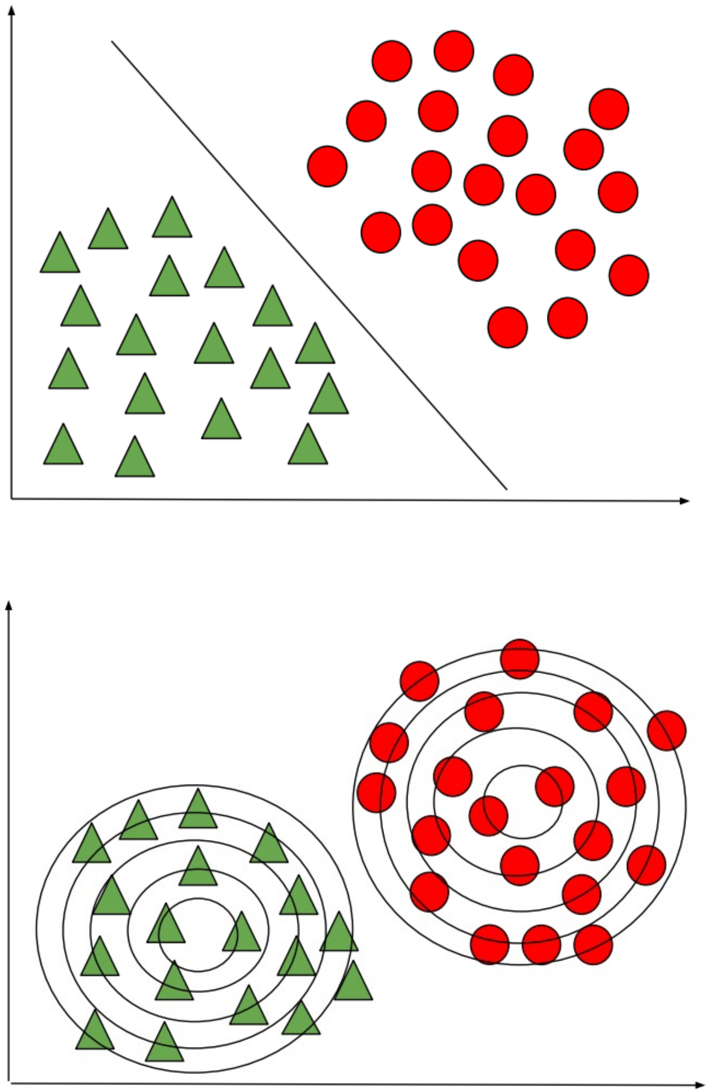
- Photon flux calculated with STARLIGHT: neutron class only includes EMD contribution
  - 0n0n: 0n0n(incoh) + 0n0n(EMD)
  - 0nXn: 1. 0nXn(incoh) + 0n0n(EMD)

    2. 0nXn(incoh) + 0nXn(EMD), Xn aligning in the same direction

Gaussian Discriminator

- Model the probability of a track being a charged particle as a Gaussian
- Calculate the probability P_h that a track would produce the observed **dEdx measurement in the pixels at the given p**

- $P_h = Gauss(\log(dEdx), \ \mu_{\log(dEdx)}, \ \sigma_{\log(dEdx)})$
  - μ and σ are mean and width extracted from fits
- PID Cut:
  - $\boldsymbol{P_{K^+} > 10 \cdot P_{\pi^+}}$ **&&** $\boldsymbol{P_{K^-} > 10 \cdot P_{\pi^-}}$



KK

- The interference effect between direct KK and phi→KK in photon-proton interactions is negligible
  - [Phys.Atom.Nucl. 62 (1999) 980]
- The direct KK (continuum) could dominate the KK yield over phi→KK at the higher mass region (Mass>1.2 GeV) in photon-proton interaction
  - [PRD 98, 014001 (2018)]
- Considering we are extracting the phi signal yield within the mass window of "0.98<M<1.15 GeV" where phi → KK signals are pre-dominated as expected in both theories and shown in our data distributions.

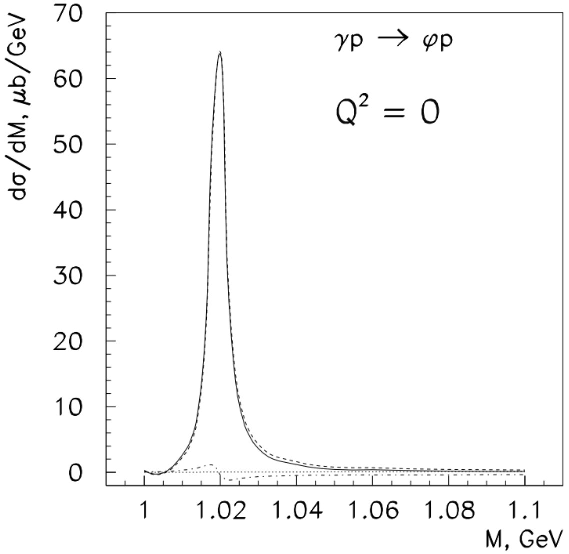


Fig. 5a