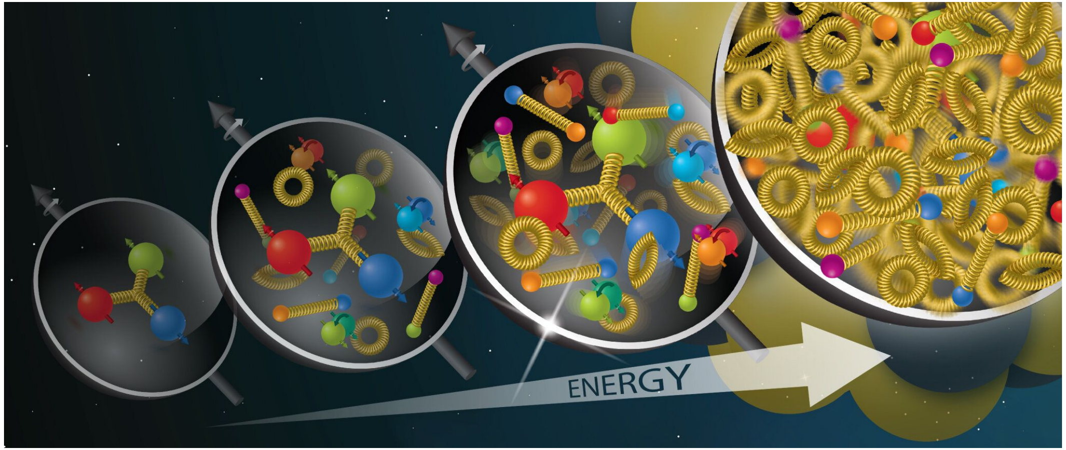
Probing gluon PDF at x⟶0 with Ultraperipheral PbPb collisions at 5.02 TeV in CMS

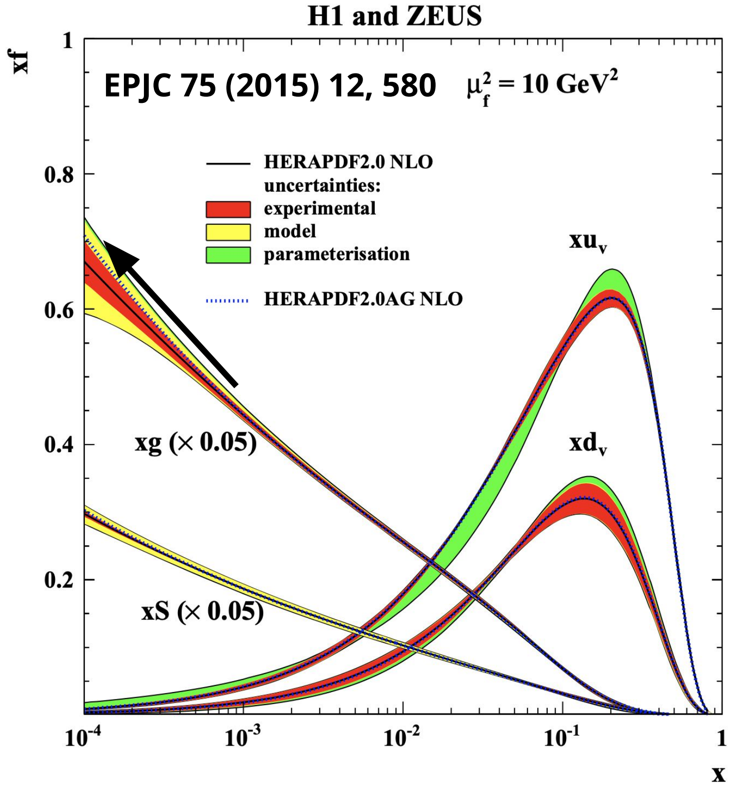
André Ståhl
on behalf of the CMS Collaboration

European Organisation for Nuclear Research

LPCC CERN Seminar

Understand the Glue that binds us all

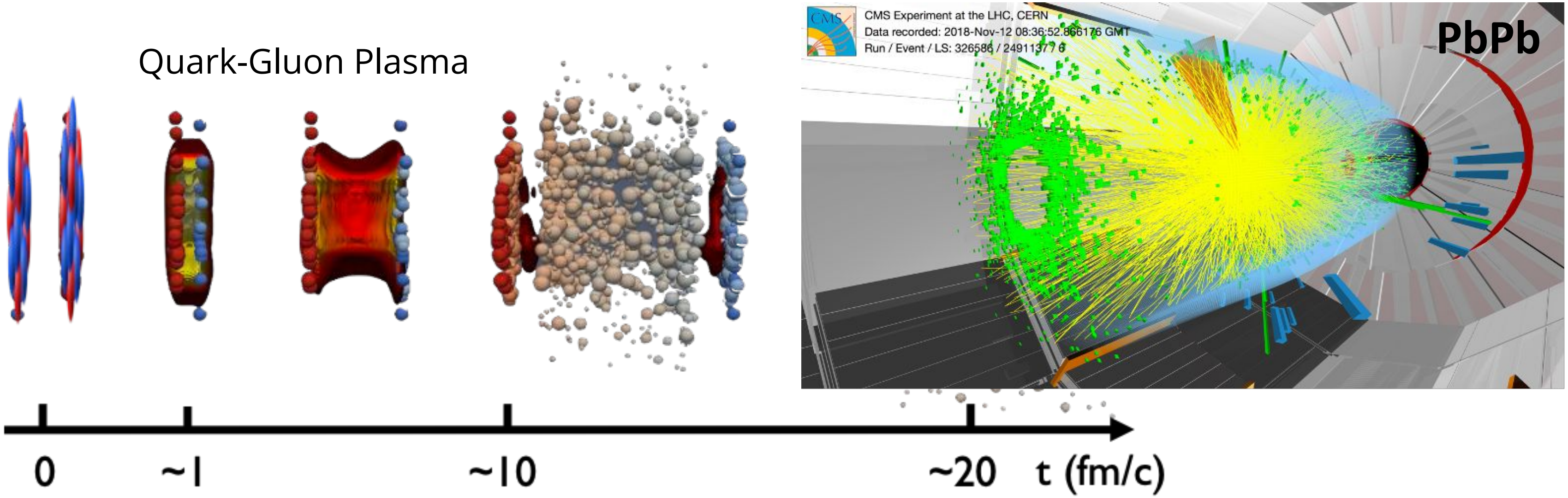




- DIS results show a rapid increase of gluon density towards small x, by gluon splittings.
- Indefinite growth at small-x violates unitarity → mechanism beyond gluon splitting expected.

What is the fate of gluons at extreme densities toward the unitary limit?

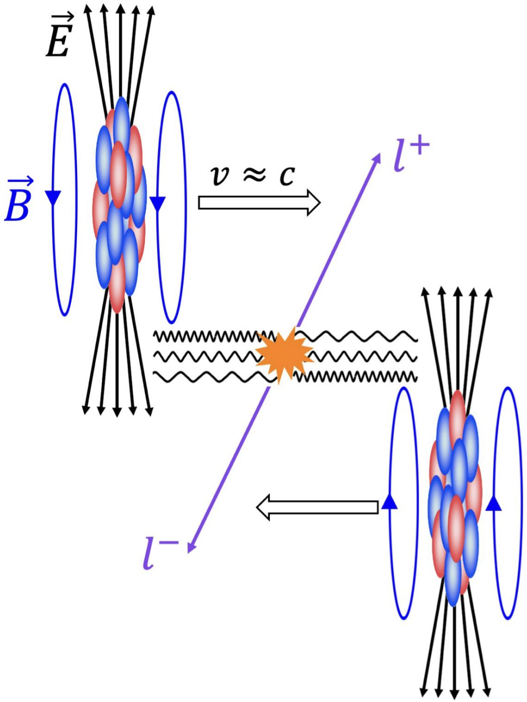
Heavy ion collisions and Hot Quark-Gluon Matter



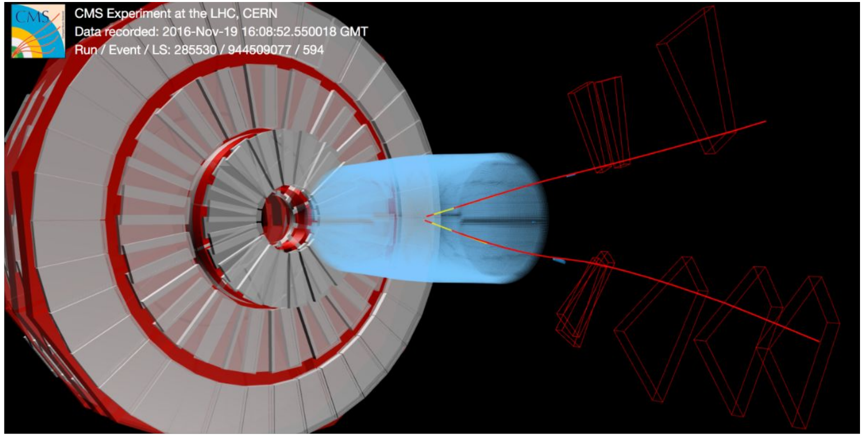
A comprehensive program of investigating novel properties of quark-gluon plasma created at highest temperatures with the CMS experiment, using a multitude of probes in large (PbPb) and small (pp, pPb) systems

Ultra-peripheral nuclear collisions

When two ions "miss" each other, no QGP is created but,



- Strong EM fields generated by relativistic ions (B ~ 10^{16} T).
- Lorentz contracted EM fields → flux of quasi-real γ ($Q^2<\hbar^2/R^2$). The photon flux ∝ Z^2.
- Photon kinematics: $p_T < \hbar/R_A$ ~ 30 MeV (E_{max} ~ 80 GeV) at LHC.

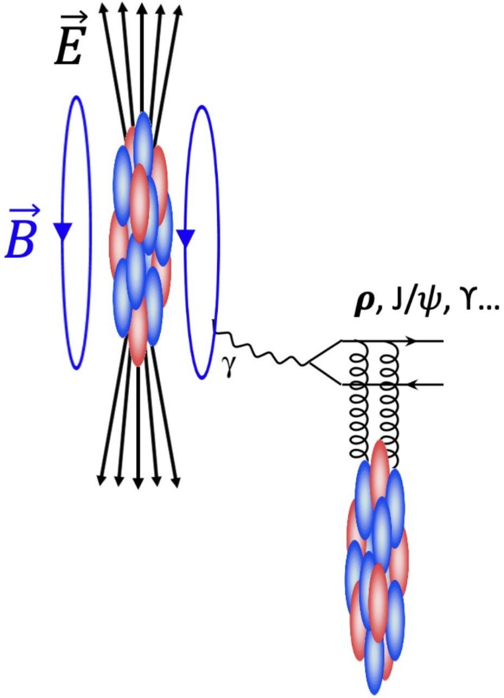


- light-light and light-Nucleus collider
- BSM searches (ALP, g_τ-2).

Ultra-peripheral nuclear collisions: photon-nuclear interactions

Vector meson (e.g., J/Ψ) photoproduction directly probes gluonic structure of nucleus and nucleon.

At LO in pQCD, cross section ~ photon flux ⊗ $[xG(x)]^2$ (gluon PDFs)



Coherent production:

- Photon ($\hbar/k_L$ > 2R) couples coherently to whole nucleus.
- Vector Meson (VM) $\langle p_T \rangle$ ~ 50 MeV.
- Target nucleus usually remains intact.

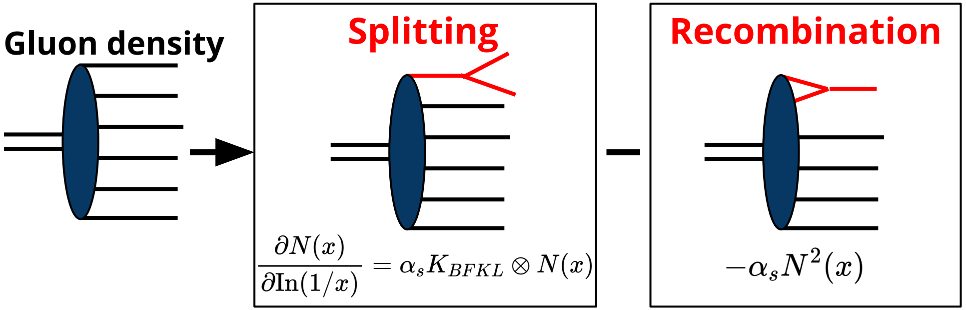
Incoherent production:

- Photon couples to part of nucleus.
- VM $\langle p_T \rangle$ ~ 500 MeV.
- Target nucleus usually breaks.

Final state kinematics directly map to:

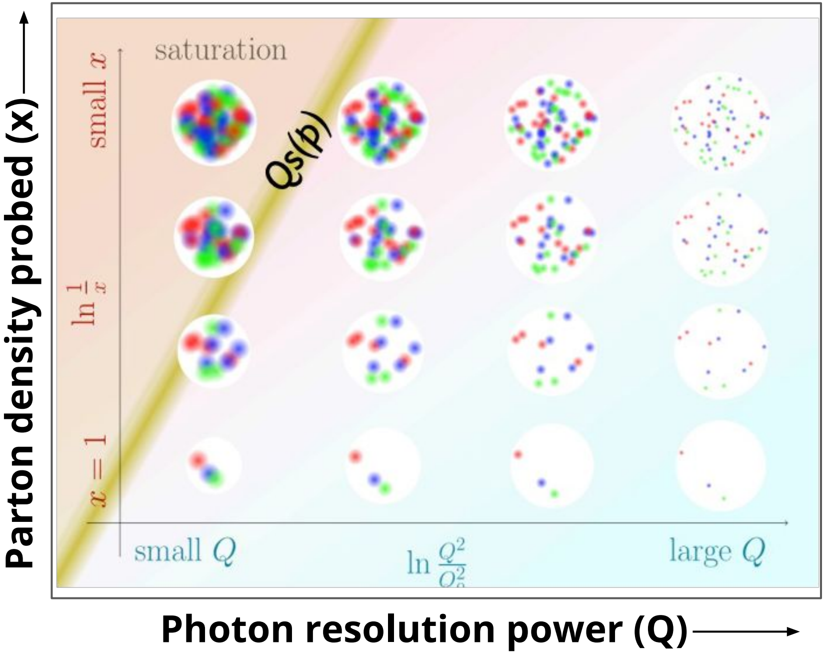
- Photon energy: $\omega = \frac{M_{VM}}{2} e^{\pm y}$
- ***Bjorken-x*** of gluons: $x = \frac{M_{VM}}{\sqrt{s_{\rm NN}}} e^{\mp y}$

Gluon Saturation and Non-linear QCD regime

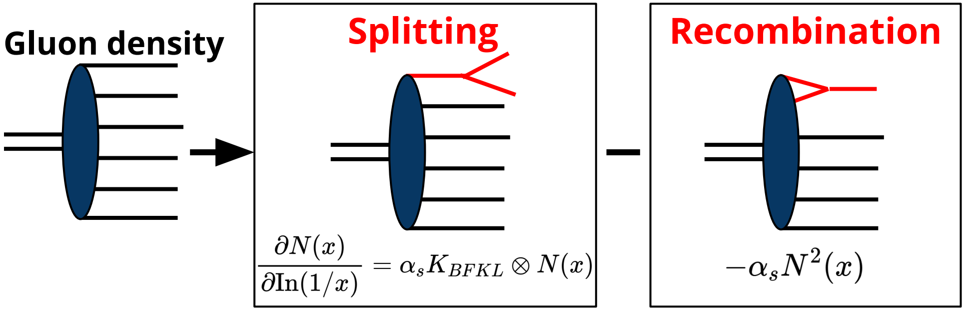


Linear evolution

Non-Linear evolution



- A new regime of QCD: gluon saturation ($Q^2 < Q^2_s$) at gluon recom. = gluon splitting.



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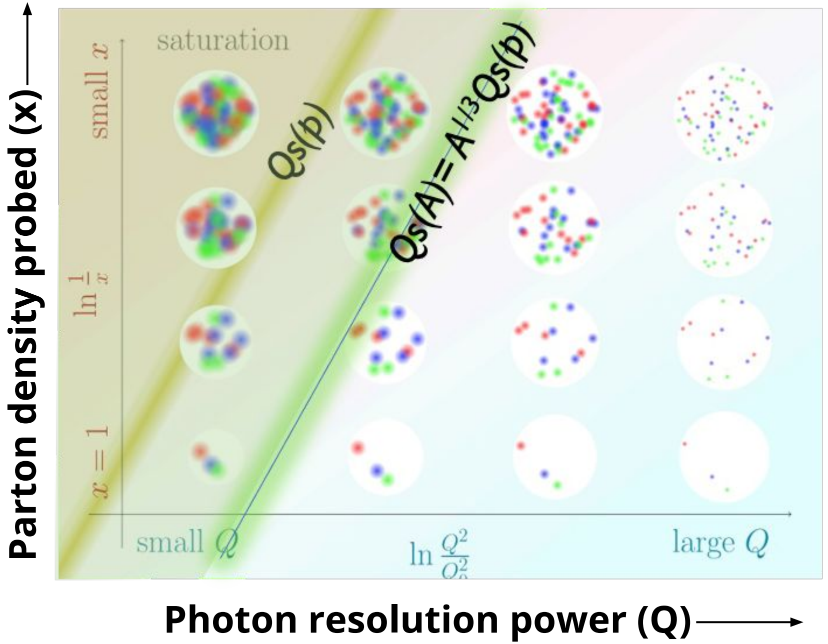
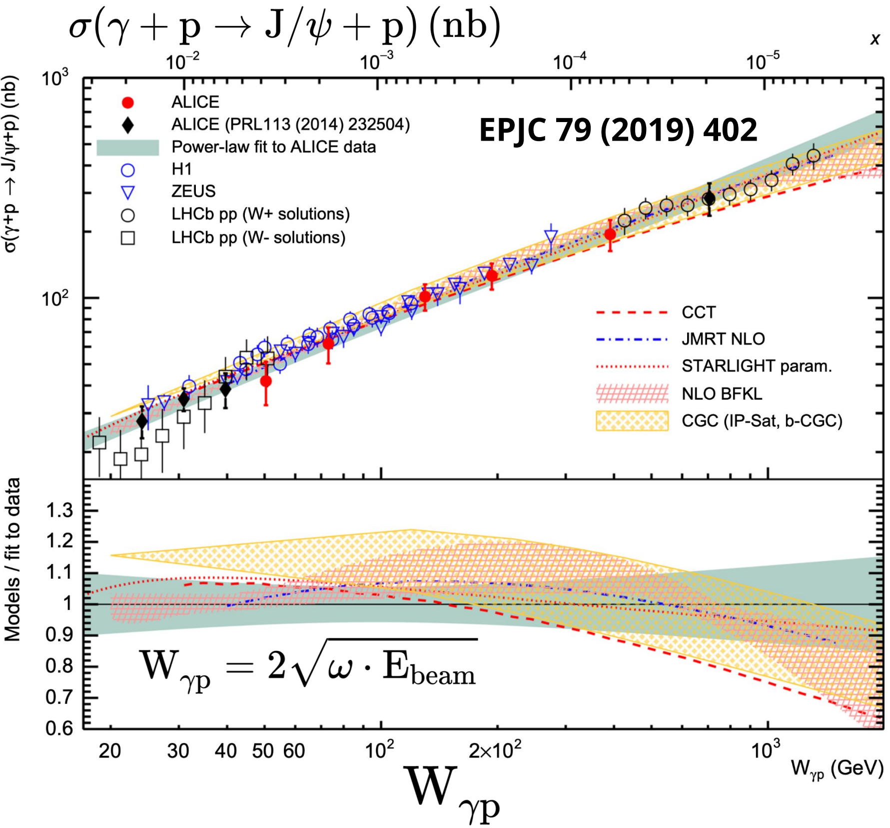


- A new regime of QCD: gluon saturation ($Q^2 < Q^2_s$) at gluon recom. = gluon splitting.
- **Saturation region is expected to be easier to be reached in nuclei: $Q_s \propto A^{1/3}$**

Search for gluon saturations in nucleons



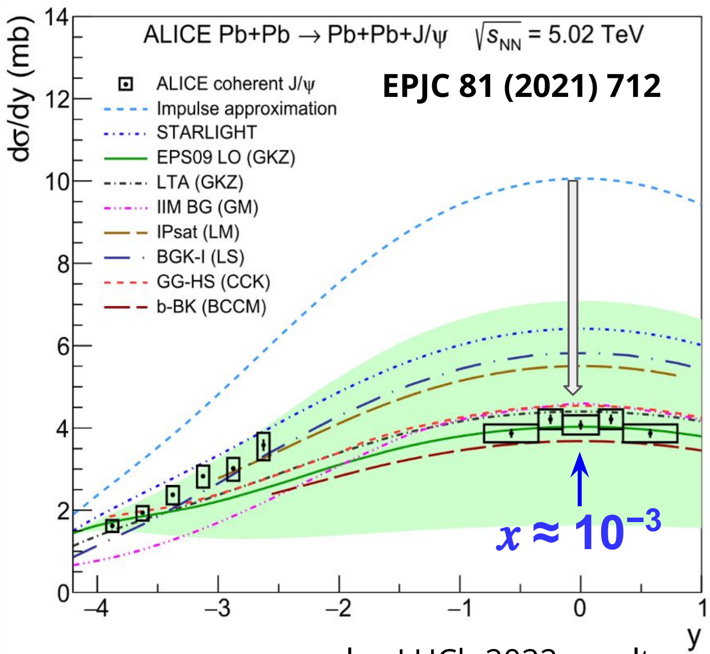
J/Ψ photoproduction from **photon-proton** interactions in ep, pPb and pp collisions

❖ Data follow a power-law trend, consistent with expectation from the rapidly increasing gluon density in a proton.

No clear indication of gluon saturation down to x ~ 10^{-5} in a free nucleon.

Search for gluon saturations in heavy nuclei

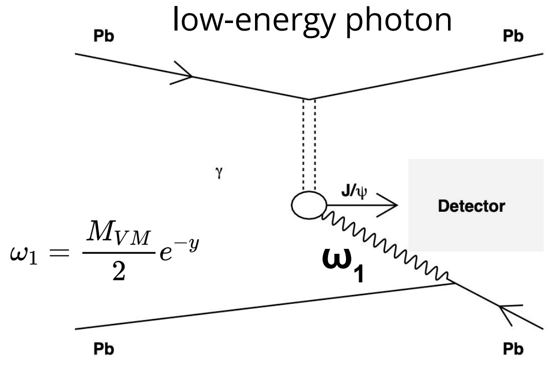
- Coherent Vector Meson production extensively measured at LHC.
- $\sigma(J/\Psi) \propto [xG(x)]^2 \rightarrow \sigma(J/\Psi) <$ I.A. (no nuclear effects) → evidence for strong nuclear modification in heavy nuclei.
- No theory calculations (e.g., shadowing, saturation) can simultaneously predict mid- and forward rapidity data!?

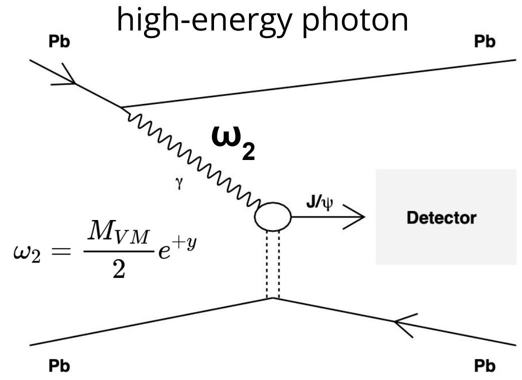


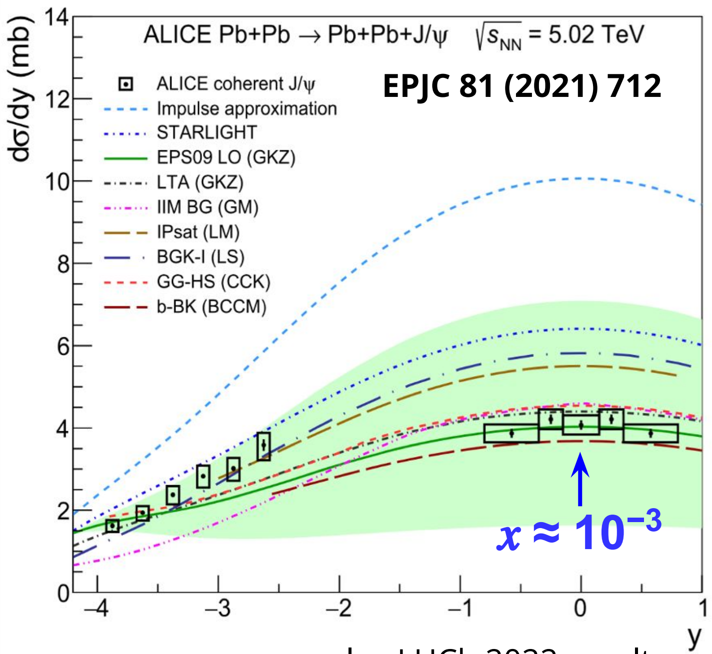
also LHCb 2022 results
arXiv:2206.08221

Symmetric system: either ion can serve as the photon source or target nucleus

- A two-way ambiguity!







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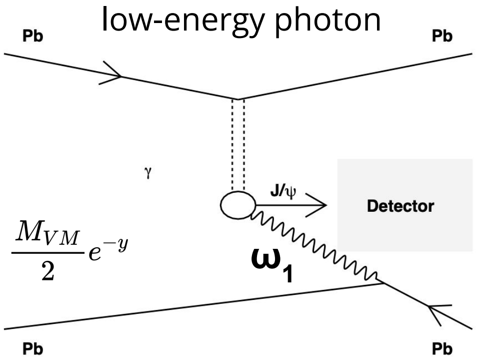
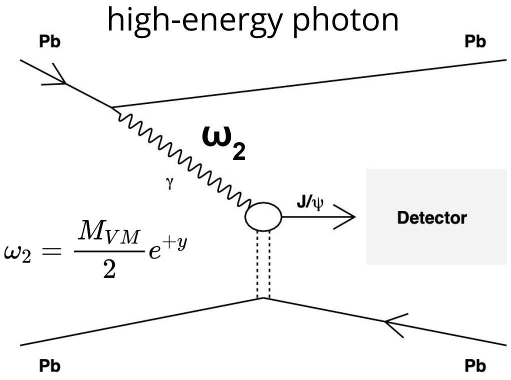


$$\omega_1 = \frac{M_{VM}}{2} e^{-y}$$

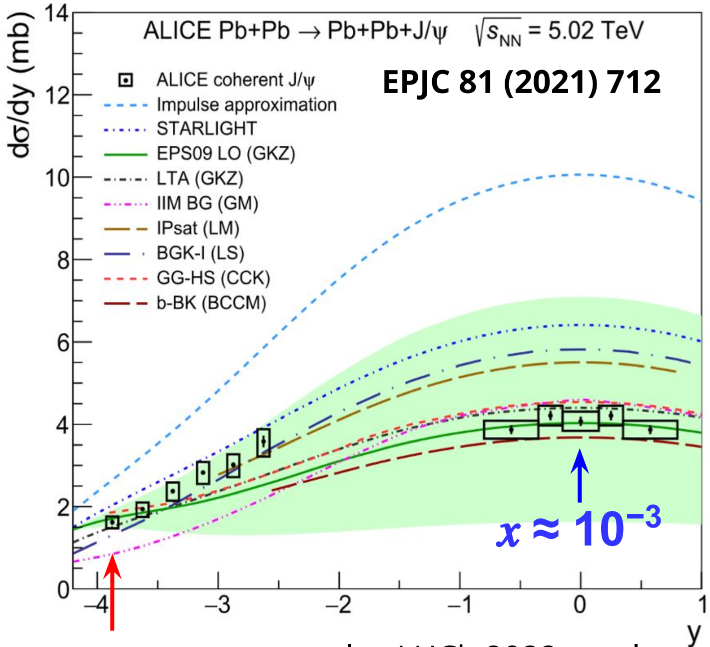


$$\omega_2 = \frac{M_{VM}}{2} e^{+y}$$

$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A\to J/\psi A'(\omega_1)} + N_{\gamma/A}(w_2) \cdot \sigma_{\gamma A\to J/\psi A'(w_2)}$$

The cross section at a given *y* consists of low- and high-x gluon contributions (except for y=0)

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



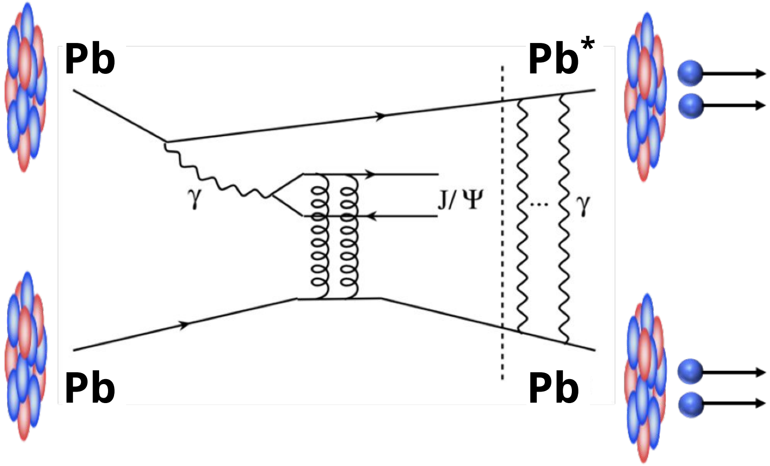
$x_1 \approx 10^{-5}$
or $x_2 \approx 10^{-2}$
(~95% high-x)

also LHCb 2022 results
arXiv:2206.08221

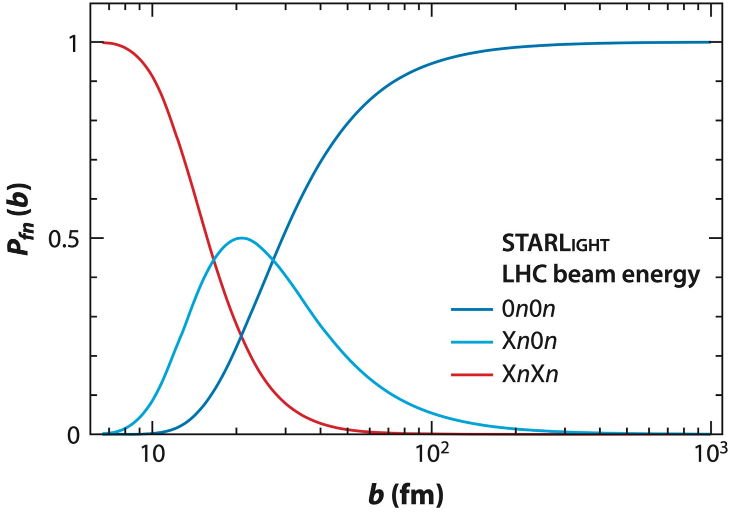
$$x_{1,2} = \frac{1}{\omega_{1,2}} \cdot \frac{M_{VM}^2}{2\sqrt{s_{NN}}}$$

A solution to the two-way ambiguity puzzle

Control the impact parameter or “centrality” of UPCs via forward emitted neutrons



Klein & Steinberg,
Ann. Rev. Nucl. Part. Sci. 70 (2020) 323



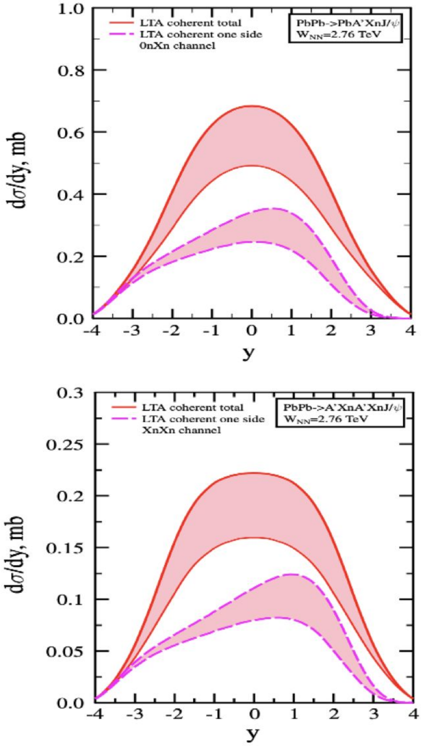
Nucleus excitation probability:

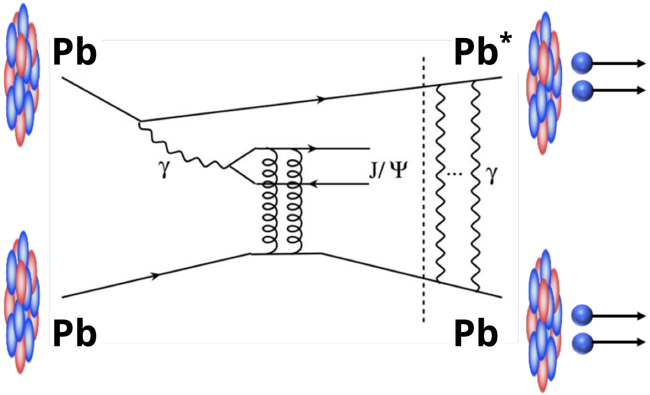
$$P_i(b) \propto 1/b^2$$

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

A solution to the two-way ambiguity puzzle

Guzey et al., **EPJC 74 (2014) 2942**





$$w_1 = \frac{M_{VM}}{2} e^{-y}$$

$$w_2 = \frac{M_{VM}}{2} e^{+y}$$

What is measured **Photon flux from theory** **What we want to extract**

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

⟶ Solve for $\sigma_{\gamma A\to J/\psi A'(\omega_1)}$ and $\sigma_{\gamma A\to J/\psi A'(w_2)}$

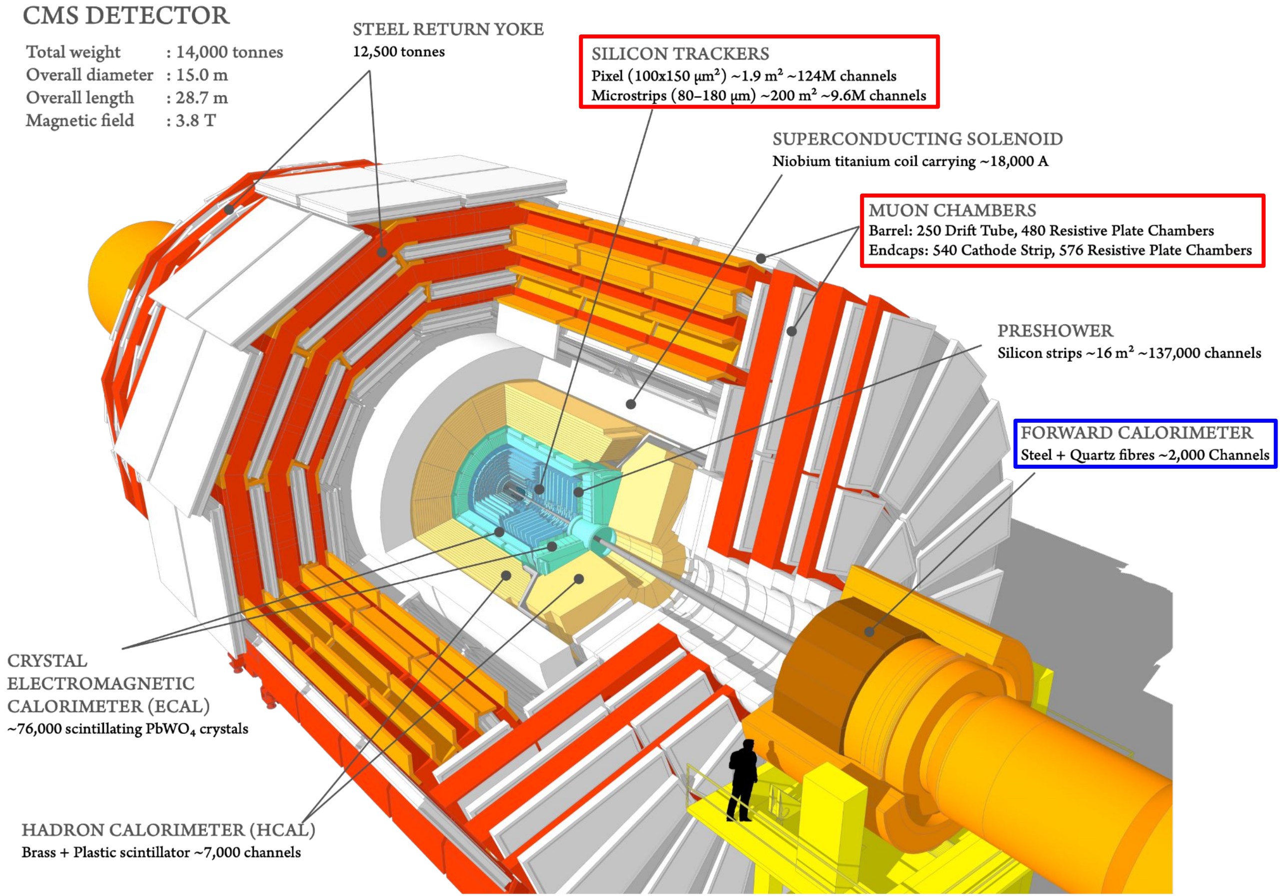
Entering a new regime of small x ~ 10^{-4}-10^{-5} in nuclei!

Outline

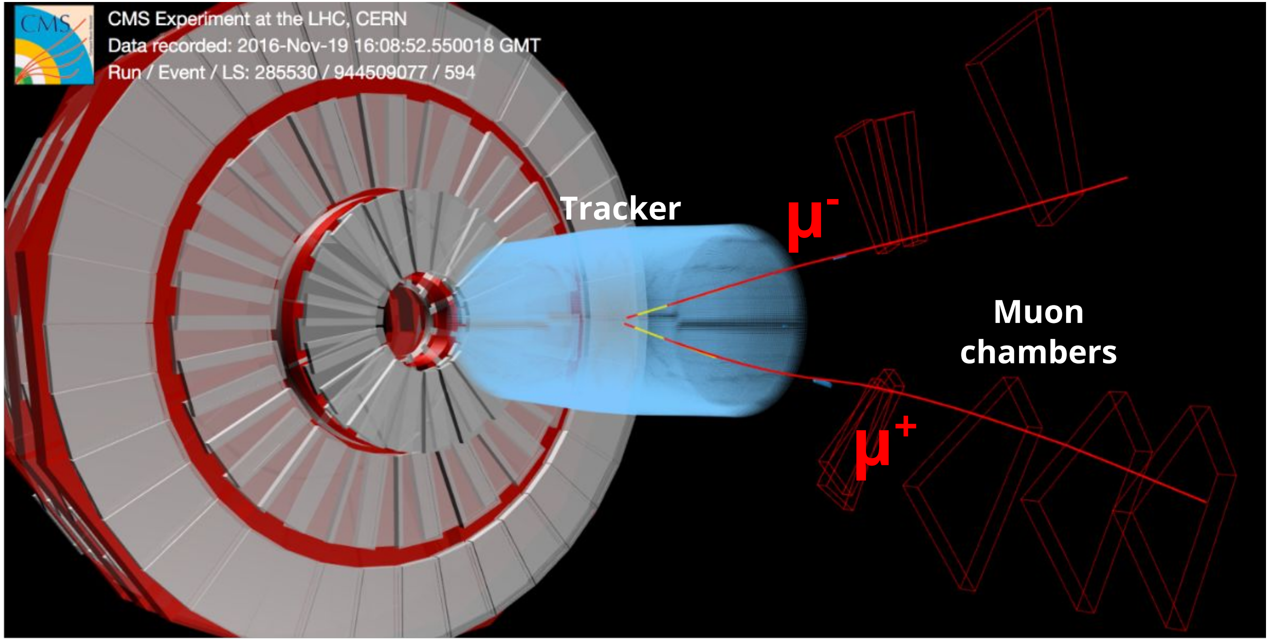
- **Introduction:**
  - General introduction to heavy ion physics and ultra-peripheral collisions.
  - State-of-the-art measurements and physics of interest.
- **Experimental setup:**
  - Compact Muon Solenoid detector.
  - Event selection and muon reconstruction.
  - Zero Degree Calorimeter and neutron multiplicity classification.
- **Controlling impact parameter dependence in UPC PbPb at 5.02 TeV:**
  - Neutron multiplicity dependence of $\mu^+\mu^-$ acoplanarity.
- **Coherent J/Ψ photoproduction in UPC PbPb at 5.02 TeV**
  - Results and discussion on new CMS result (CMS-PAS-HIN-22-002).
- **Future prospects**
- **Summary**

Compact Muon Solenoid Detector

SketchUpCMS

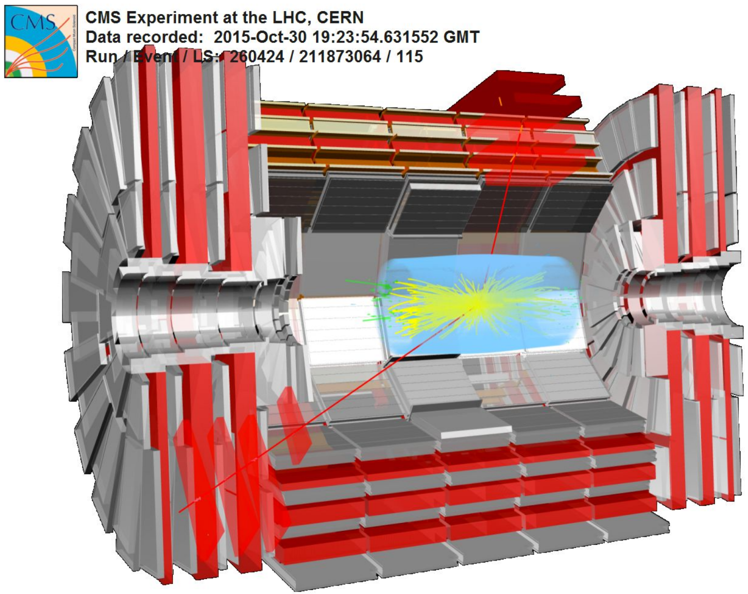


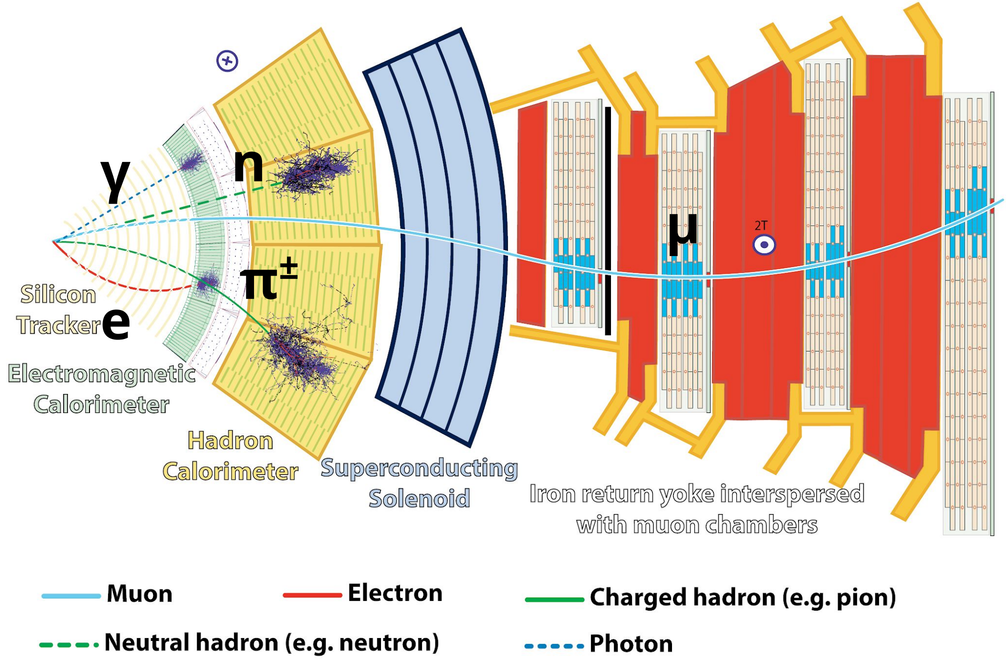
Event selection



- UPC collisions produce few particles:
  - Require low energy measured in HF to suppress hadronic collisions.
- Select events with exactly two reconstructed tracks identified as muons.

Muon reconstruction

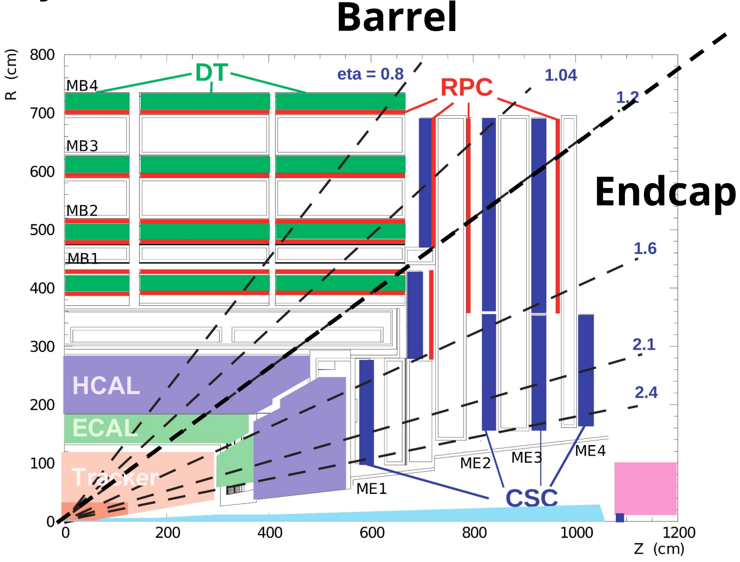




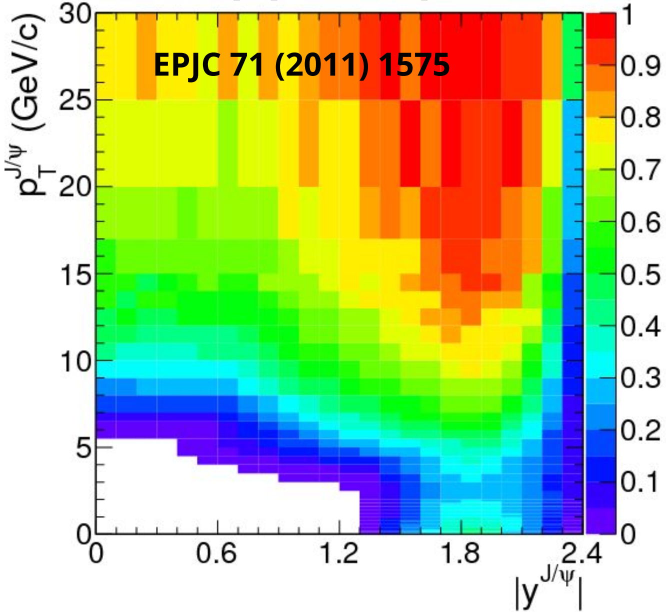
- Tracker and muon detectors used to reconstruct/identify muons.

Muon reconstruction

JINST 7 (2012) P10002

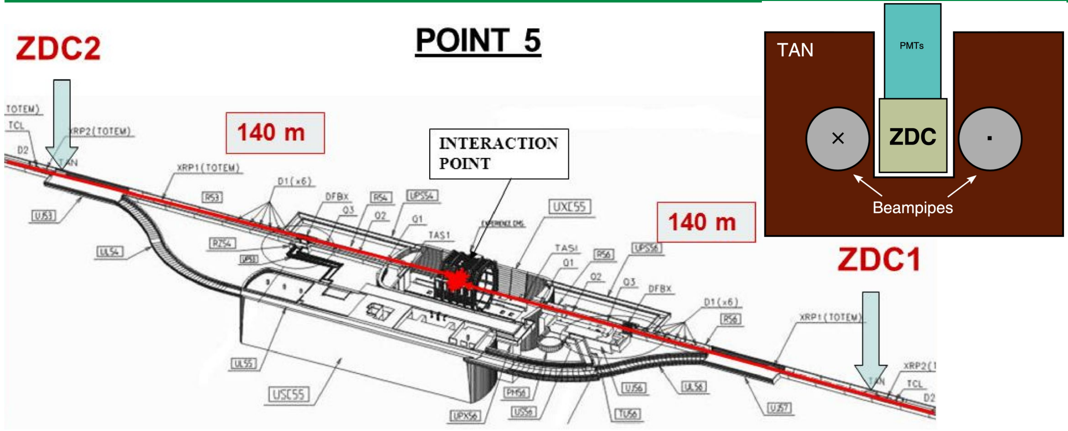


$J/\Psi \rightarrow \mu^- \mu^+$ acceptance



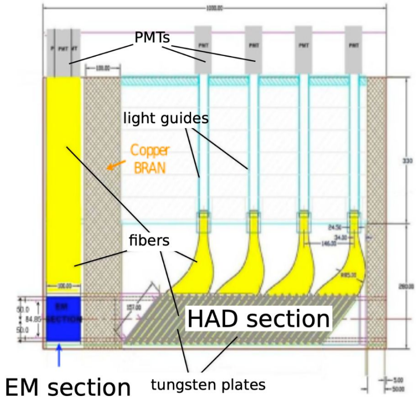
- Tracker and muon detectors used to reconstruct/identify muons.
- CMS able to reconstruct muons down to muon p_T~ 1 GeV in forward region.
    - Key to identify J/Ψ mesons down to 0 GeV.

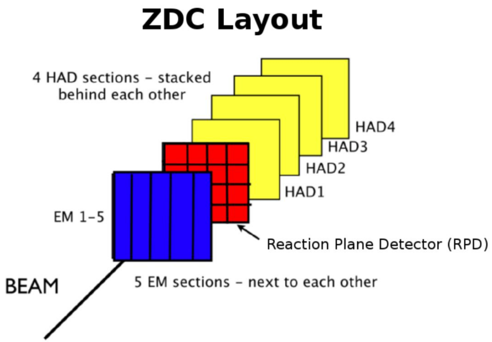
Zero Degree Calorimeter

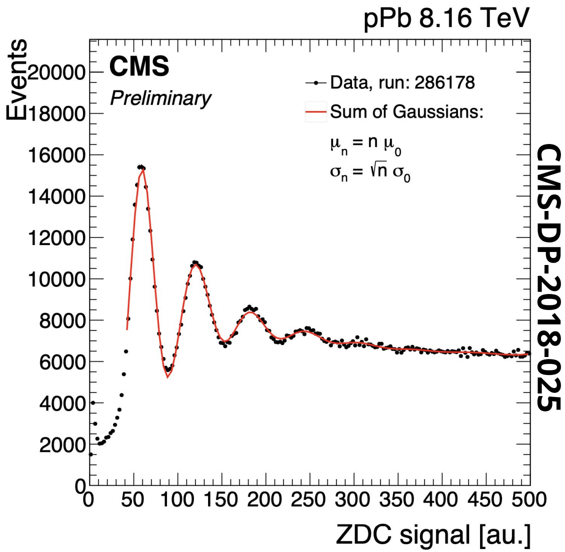


- Located ~ 140 m from IP5, between the two beam pipes.
- Measures forward neutral particles at |η|>8.5.
- Used for neutron detection.

Universe 5 (2019) 210



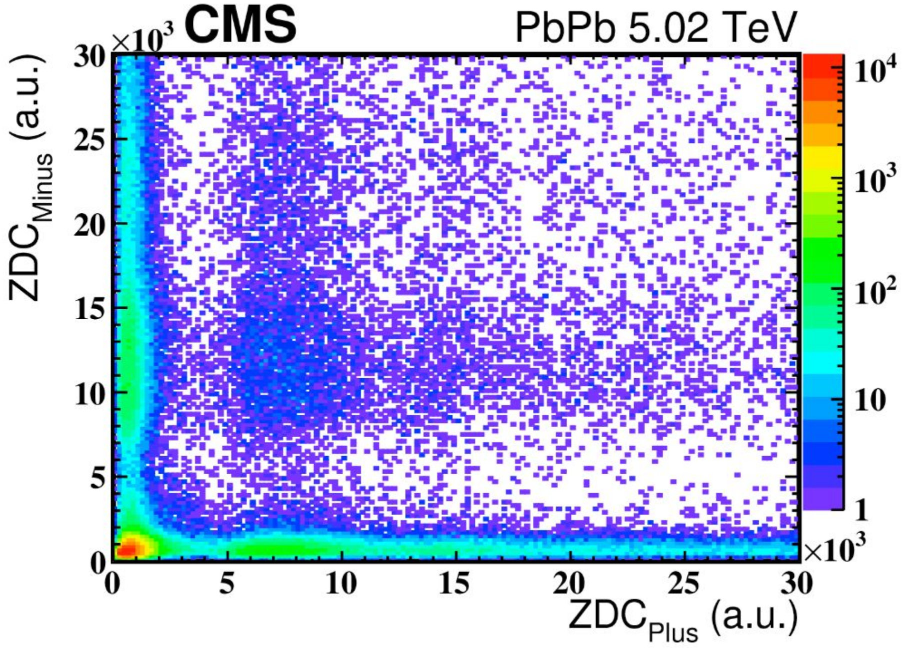


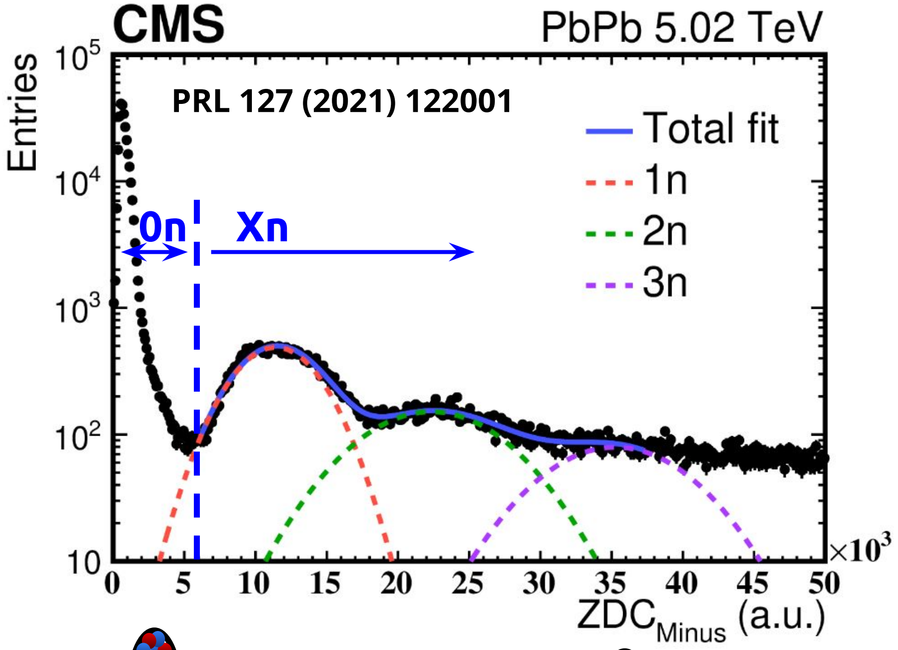


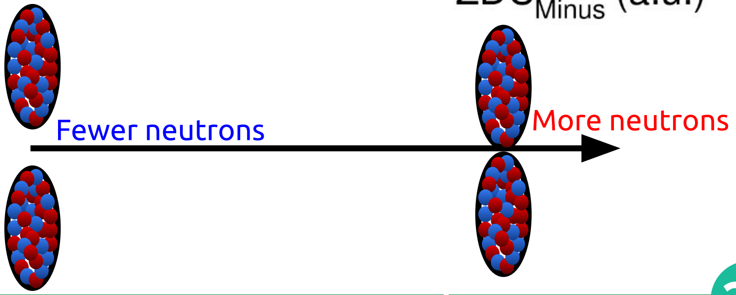
CMS-DP-2018-025

- Segmented in 1 RPD, 5 EM and 4 hadronic channels.

Event classification via neutron multiplicity

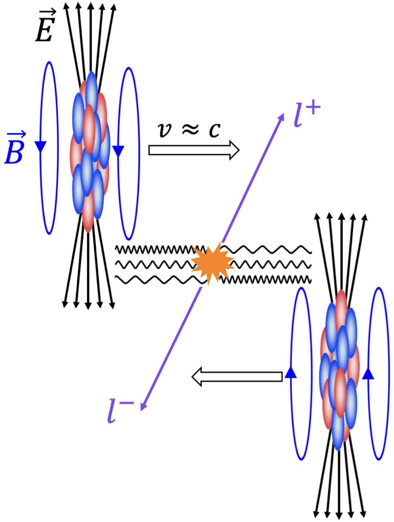




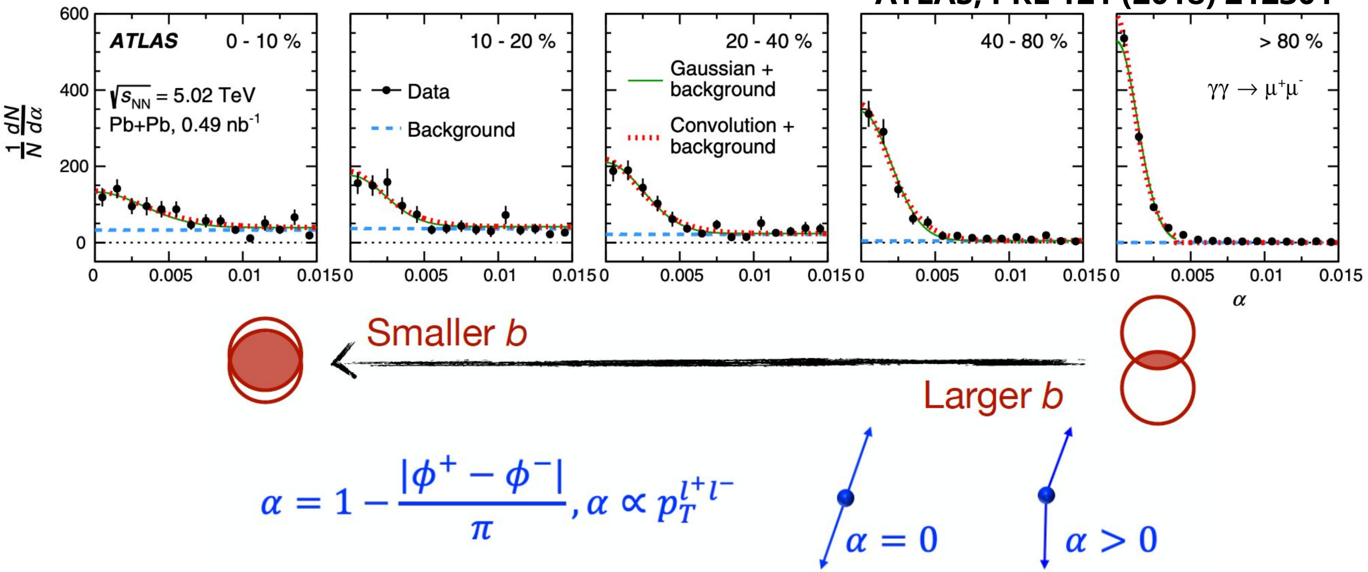


- Straight cut to disentangle neutrons:
  - 0n0n, 0nXn, XnXn (X: ≥1)

Strong-field QED processes with impact parameter dependence



ATLAS, PRL 121 (2018) 212301



$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+l^-}$$

Back-to-back correlation becomes weaker towards central events

Final-State Effect?

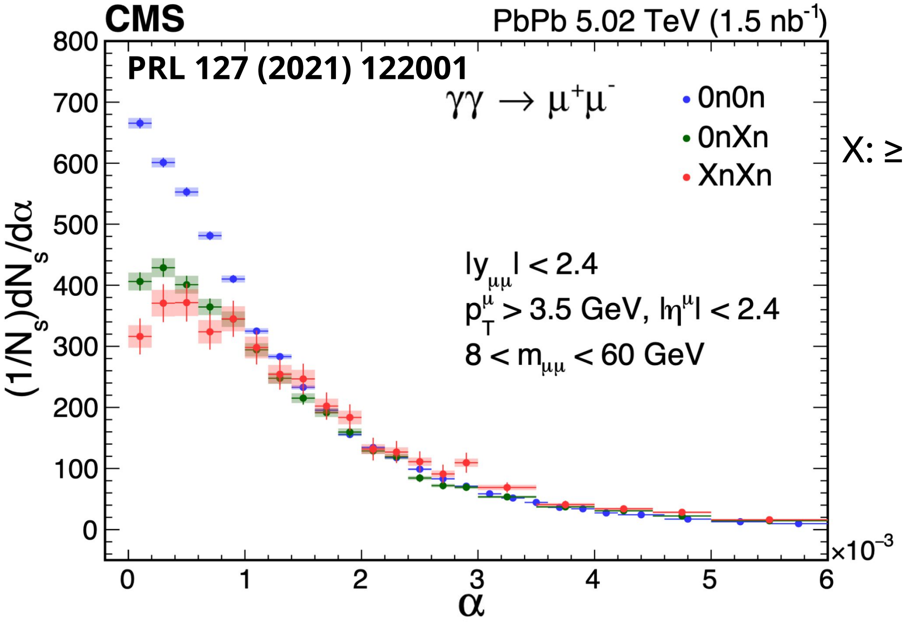
- EM rescatterings by the QGP medium?

OR

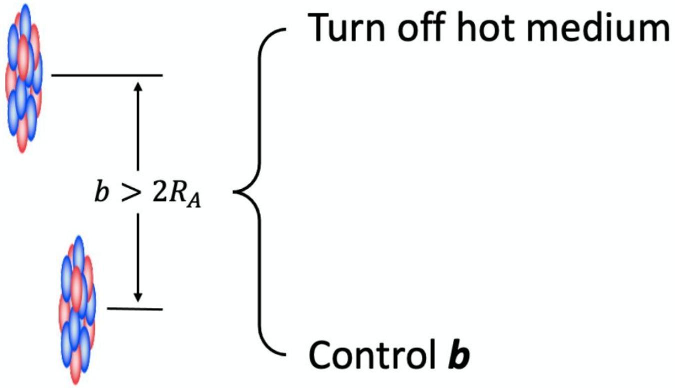
Initial-State Effect?

- Initial photon p_T varies with b?

α spectrum vs. neutron multiplicity class

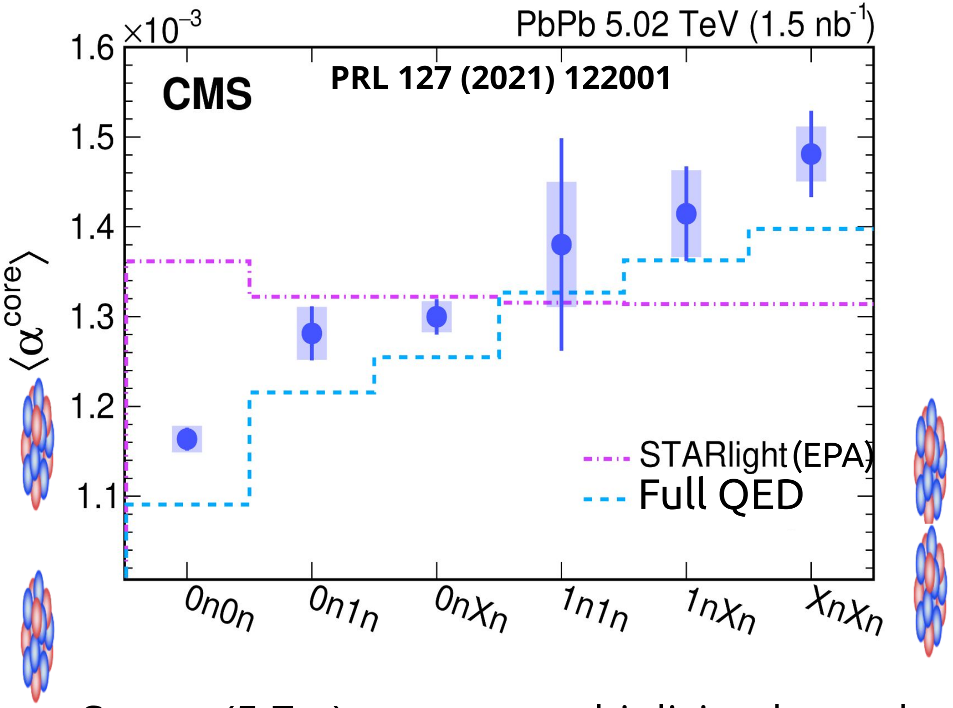


X: ≥2



Significant broadening of back-to-back correlations toward smaller b still observed when final effects are turned off, which must be related to the initial photon p_T

⟨α^{core}⟩ vs. neutron multiplicity class



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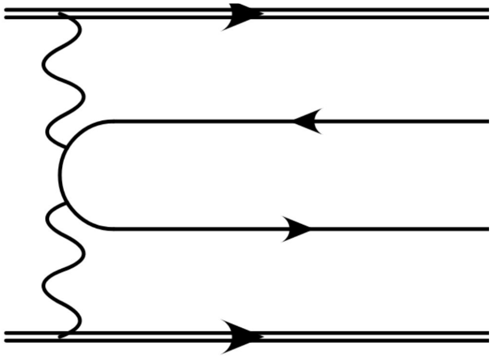
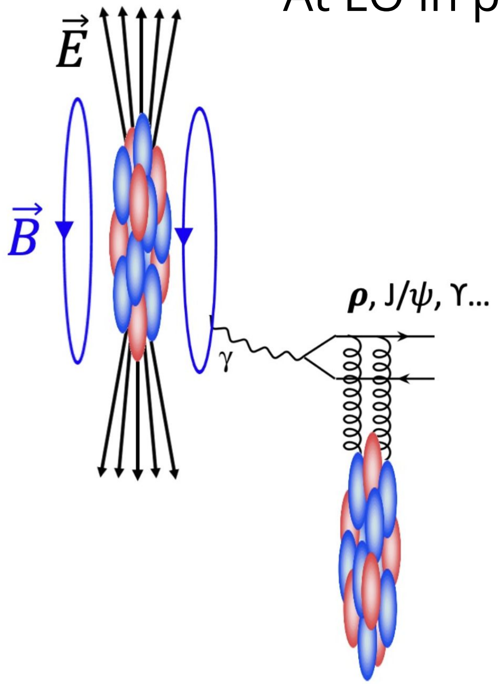


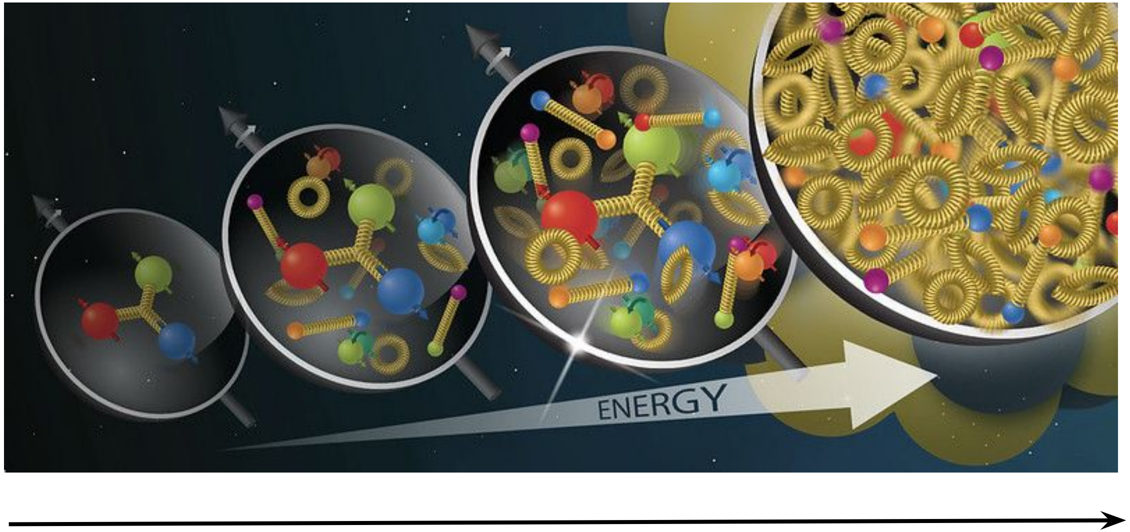
Strong (5.7 σ) neutron multiplicity dependence of ⟨α^{core}⟩ ∝ $\gamma\, p_T$

- b dependence of initial photon p_T, not captured by STARLight
- **Described by a leading order QED calculation with b dependence.**

Imaging the gluonic structure of nuclei

At LO in pQCD, cross section ~ photon flux ⊗ $[xG(x)]^2$ (gluon PDFs)

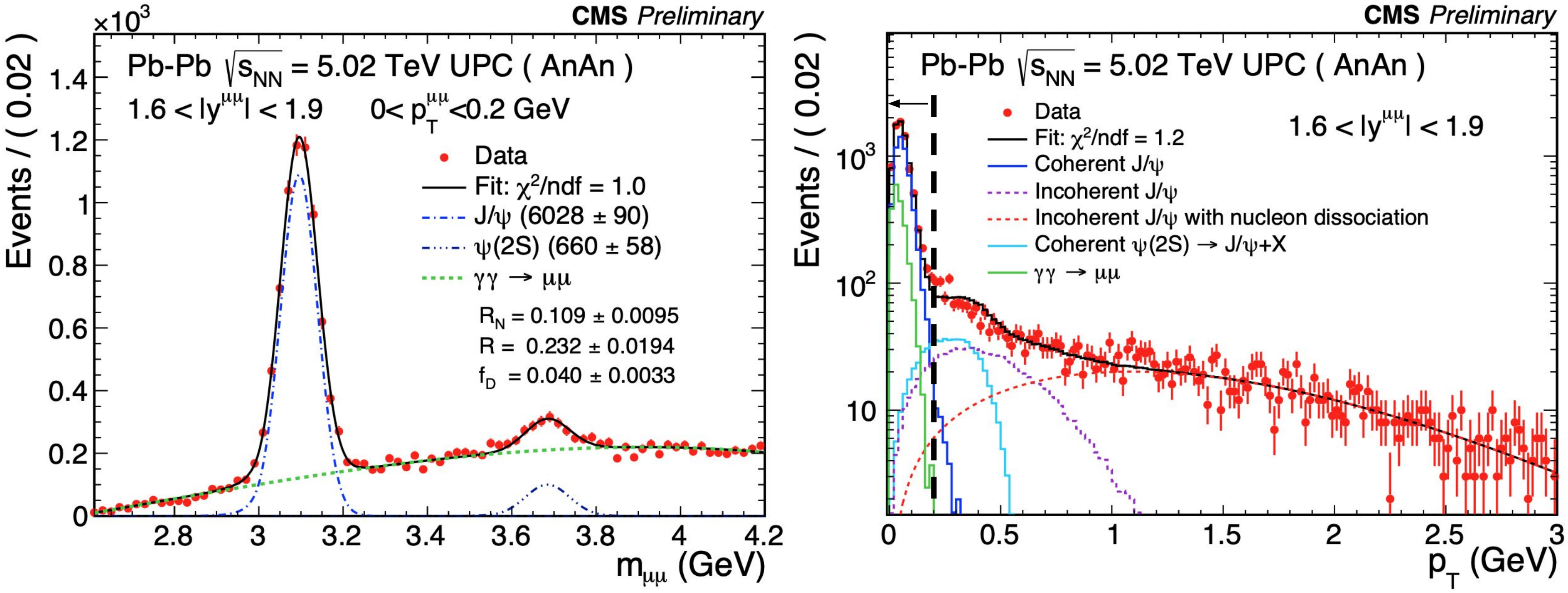




Smaller x

Signal extraction

CMS-PAS-HIN-22-002

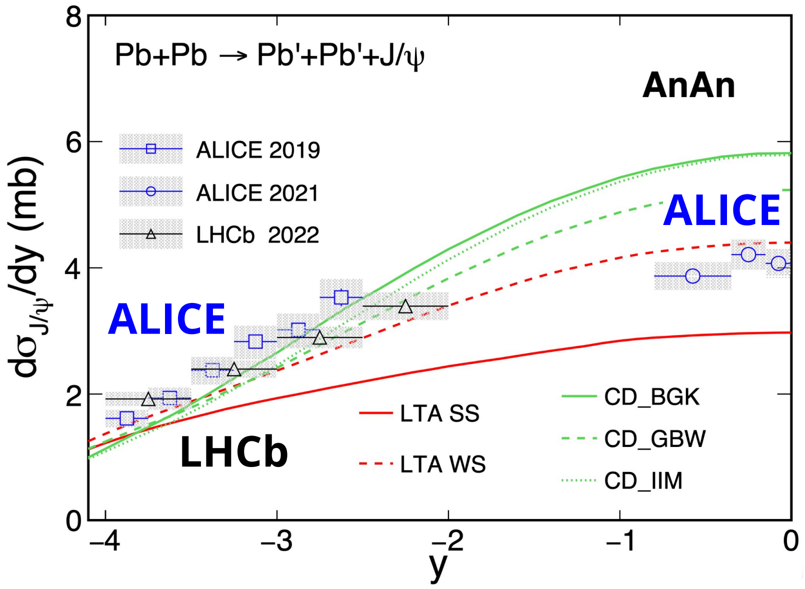


Signal yields are extracted by fitting the mass and transverse momentum spectra.

AnAn: All possible neutron emissions

Coherent J/Ψ in AnAn

ALICE, **EPJC 81 (2021) 712**
LHCb, **arXiv:2206.08221**



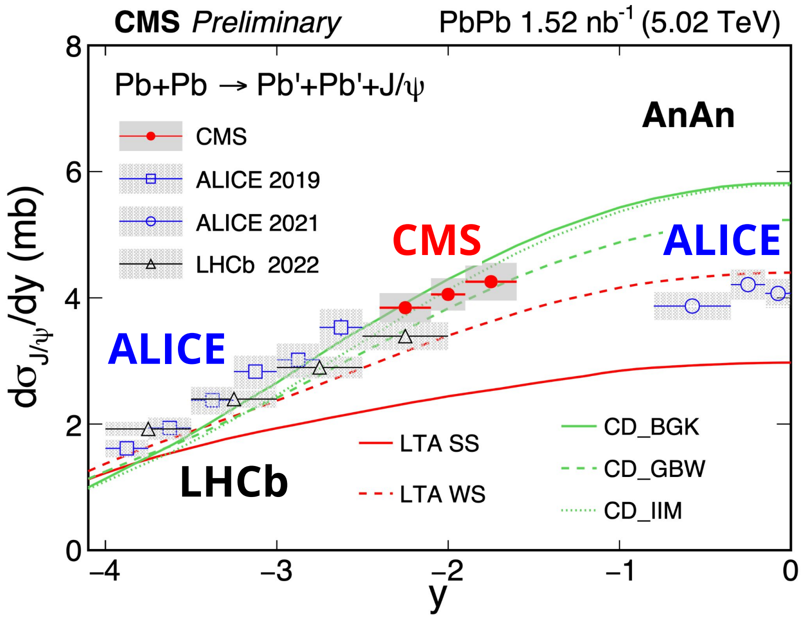
AnAn: All possible neutron emissions

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

- A tension between ALICE forward and mid rapidity data?
- LHCb data seems to better connect to ALICE mid rapidity data.

Coherent J/Ψ in AnAn

CMS-PAS-HIN-22-002



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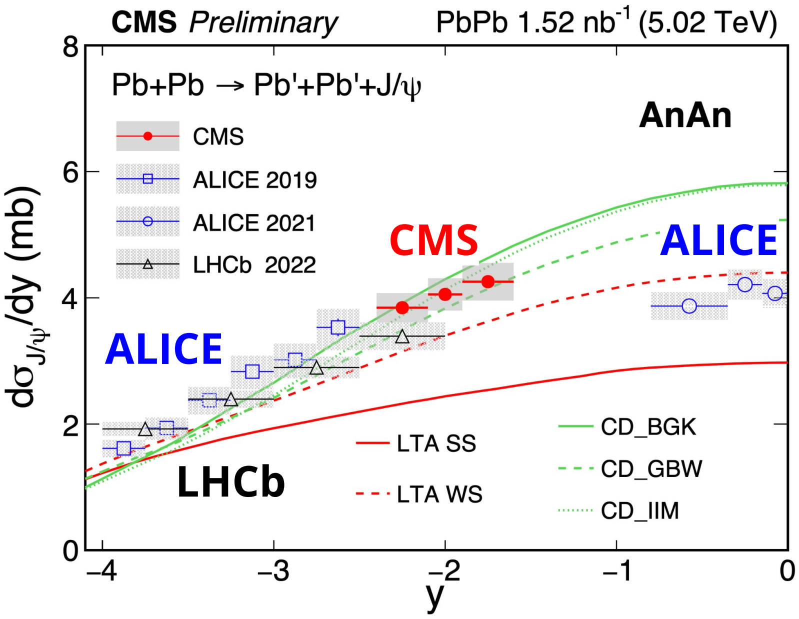
- **CMS data cover a unique rapidity region.**

Coherent J/Ψ in AnAn

CMS-PAS-HIN-22-002



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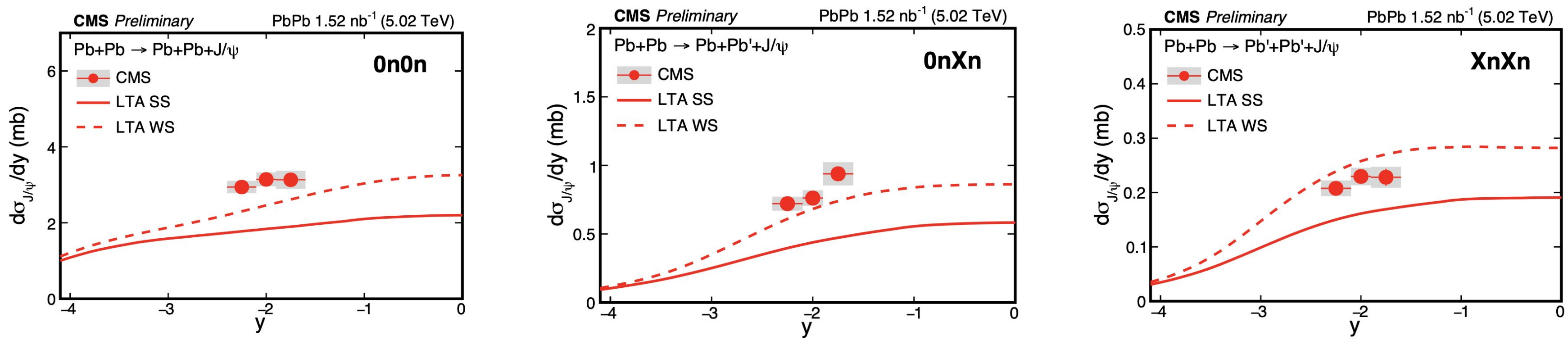
- LHCb data seems to better connect to ALICE mid rapidity data.
- **CMS data cover a unique rapidity region.**

$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot \boxed{\sigma_{\gamma A\to J/\psi A'}(\omega_1)} + N_{\gamma/A}(\omega_2)\cdot \boxed{\sigma_{\gamma A\to J/\psi A'}(\omega_2)}$$

- A deeper look at J/Ψ production from γ+Pb at a given **ω** without the “two-way ambiguity” may tell more.

Coherent J/Ψ in 0n0n, 0nXn, XnXn

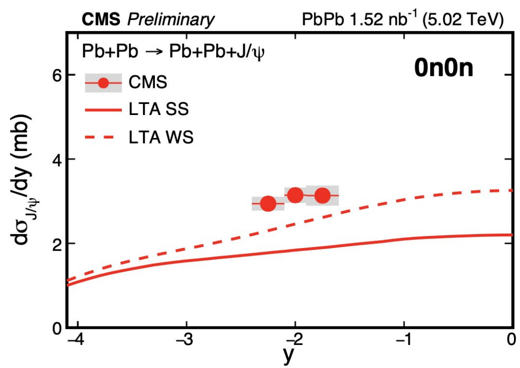
CMS-PAS-HIN-22-002

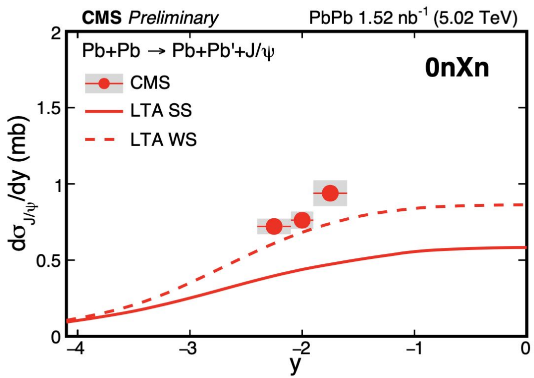


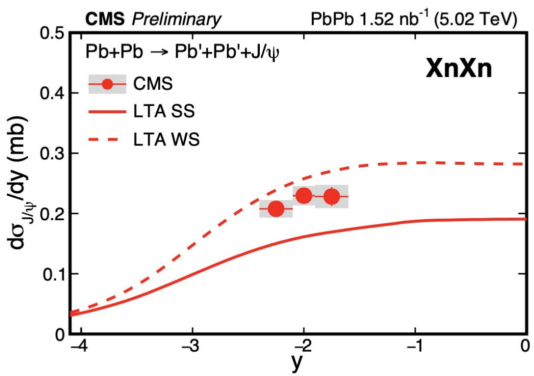
- Data in 0n0n and 0nXn are higher than Leading Twist Approximation (LTA) prediction.
- Data in XnXn stay in between LTA weak suppression (WS) and strong suppression (SS) assumptions.

Coherent J/Ψ in 0n0n, 0nXn, XnXn help to disentangle

CMS-PAS-HIN-22-002







$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

⇒

$$\sigma_{\gamma A\to J/\psi A'}(w_1)$$

$$\sigma_{\gamma A\to J/\psi A'}(w_2)$$

Low-energy γ

$$w_1 = \frac{M_{VM}}{2}e^{-y}$$

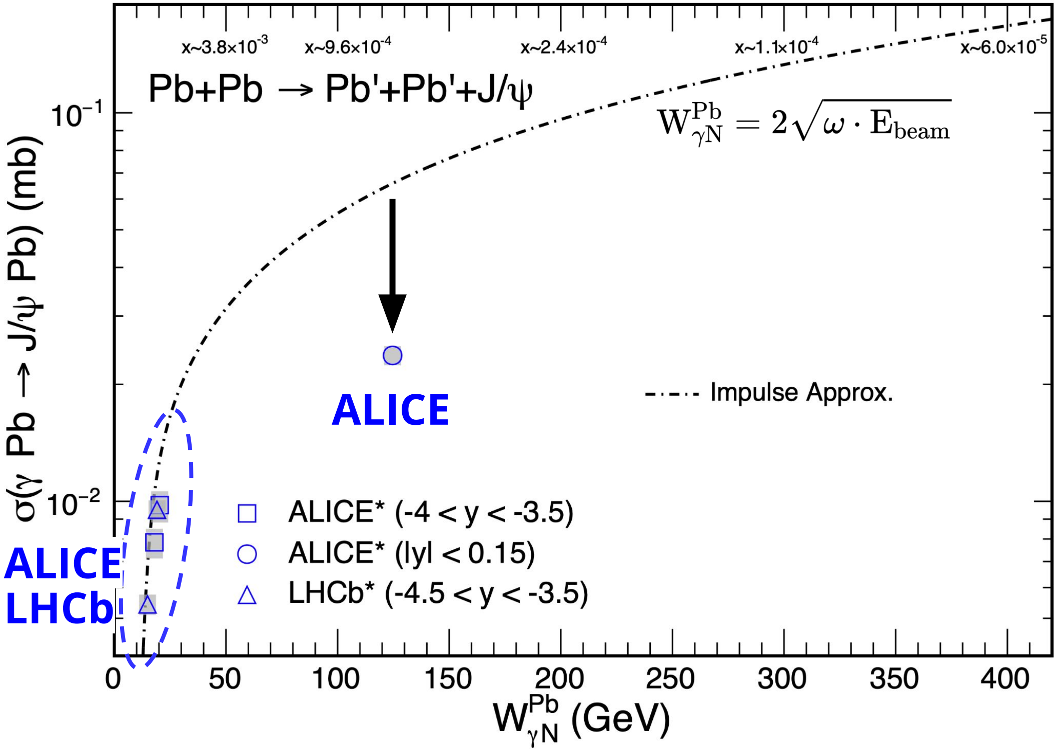
High-energy γ

$$w_2 = \frac{M_{VM}}{2}e^{+y}$$

- Disentangle the low- and high- energy photon-nucleus contributions of a single γ+Pb.

Coherent J/Ψ cross section of single γ+Pb vs. W

ALICE, **EPJC 81 (2021) 712**
LHCb, **arXiv:2206.08221**

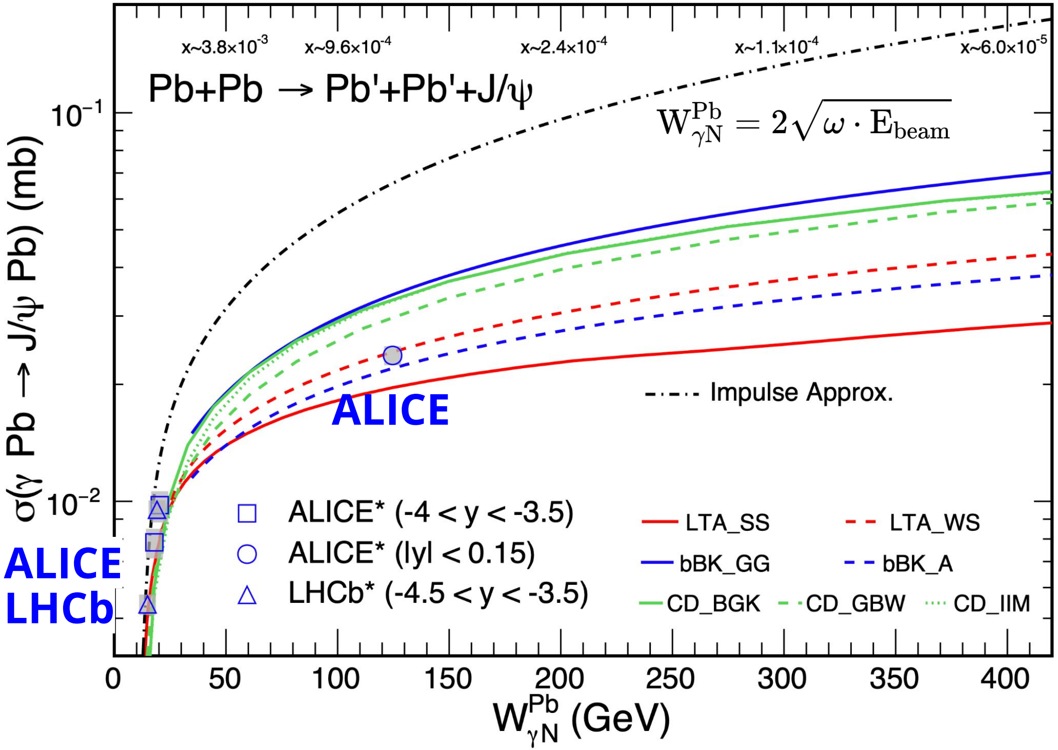


ALICE, LHCb vs. IA:

- Data is close to IA at low W.
- Data is significant lower than IA at W~125 GeV.

Coherent J/Ψ cross section of single γ+Pb vs. W

ALICE, **EPJC 81 (2021) 712**
LHCb, **arXiv:2206.08221**



ALICE, LHCb vs. IA:

- Data is close to IA at low W.
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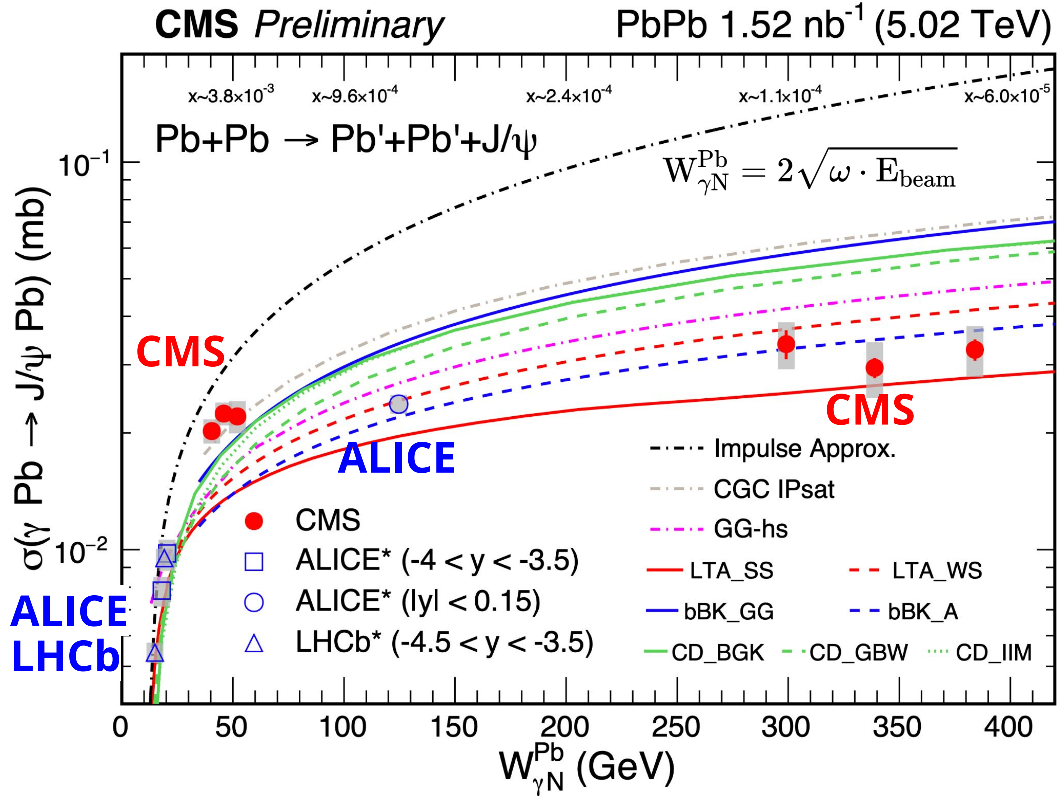
Coherent J/Ψ cross section of single γ+Pb vs. W

CMS-PAS-HIN-22-002



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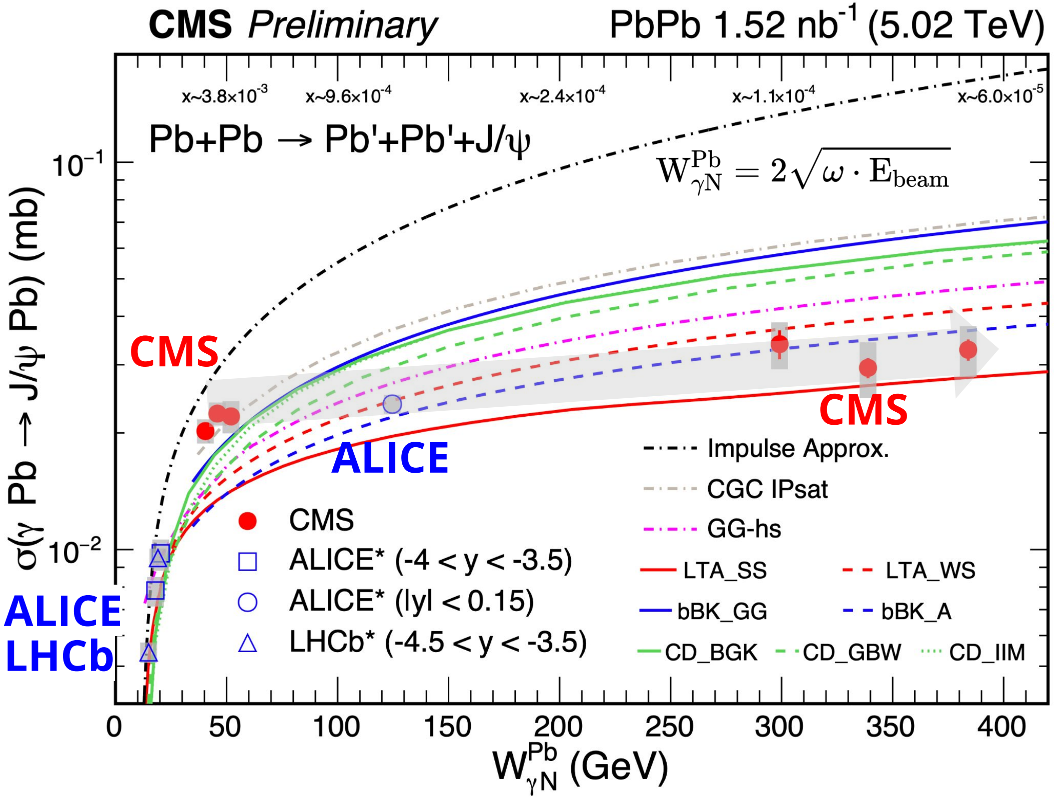
New data from CMS:

- Rapid increase at W<40 GeV.

Coherent J/Ψ cross section of single γ+Pb vs. W

CMS-PAS-HIN-22-002



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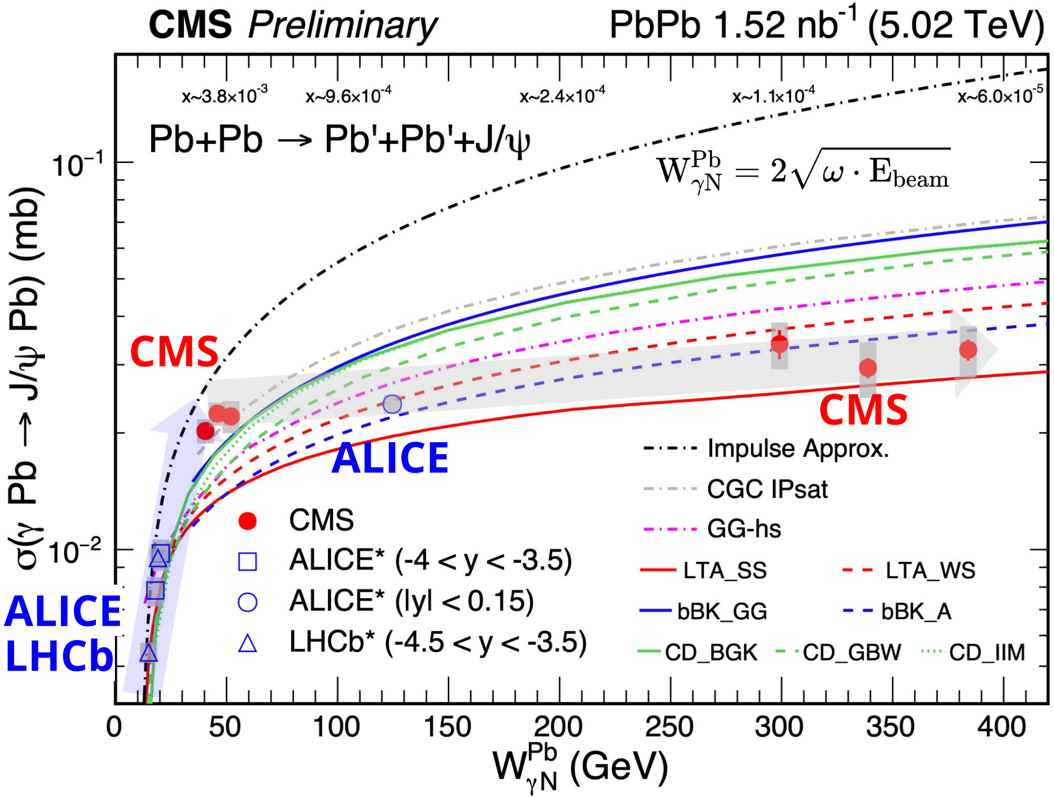
- Rapid increase at W<40 GeV.
- Turn into a nearly flat trend for W>40 GeV.

Slope = 2.98 ± 0.42 (stat.) ±1.06 (syst.)×10^{-5} mb/GeV

Coherent J/Ψ cross section of single γ+Pb vs. W

CMS-PAS-HIN-22-002



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- Rapid increase at W<40 GeV.
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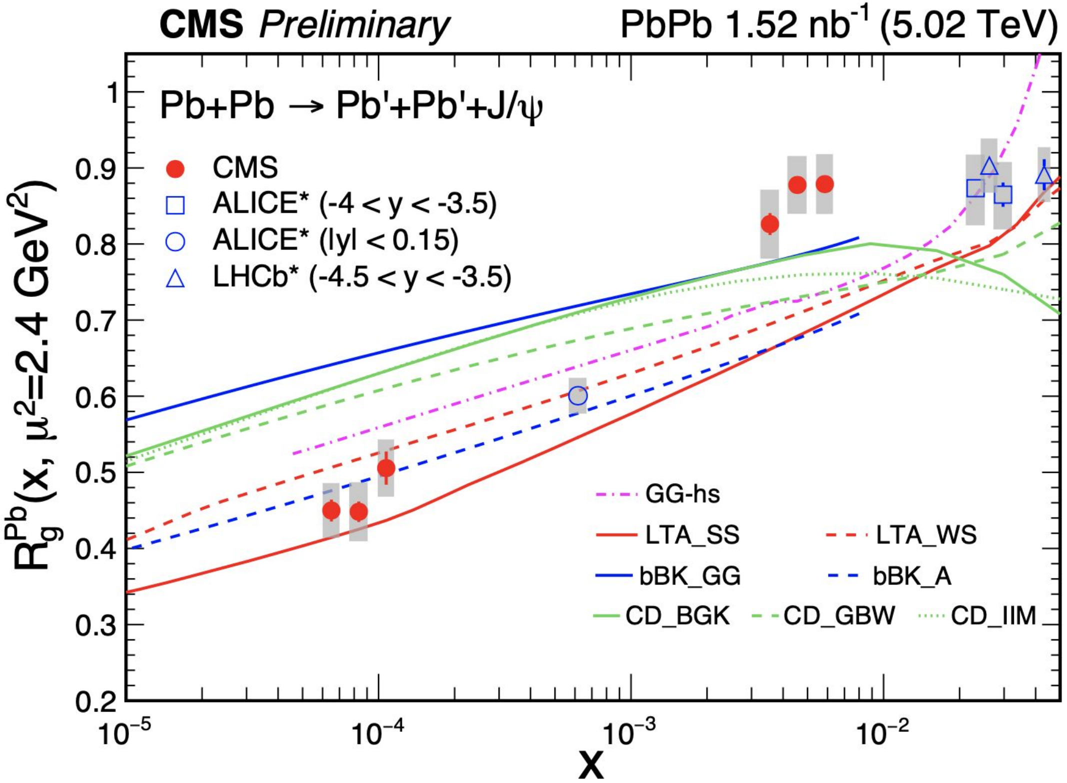
Slope = 2.98 ± 0.42 (stat.) ±1.06 (syst.)×10^{-5} mb/GeV

No models can describe the entire data distribution.

Nuclear gluon suppression factor

CMS-PAS-HIN-22-002



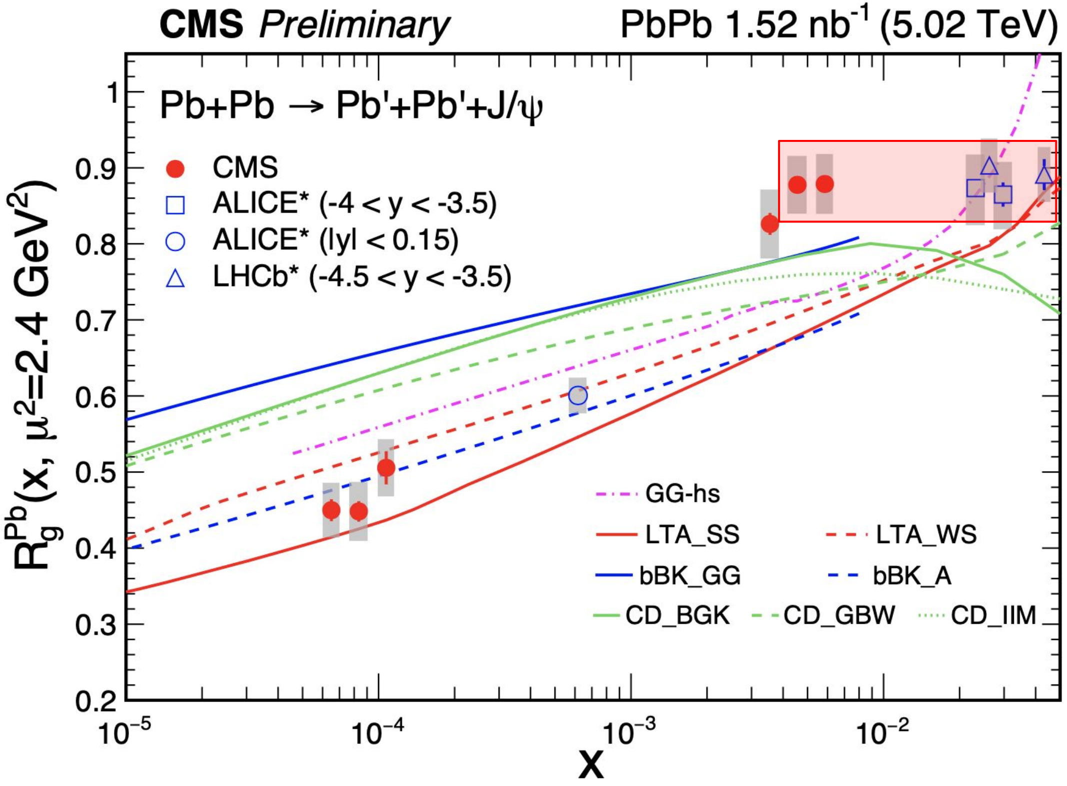
$$R_g^A = \left(\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}}\right)^{1/2}$$

Impulse approx. (IA) neglects all nuclear effects.

- Rg represents nuclear gluon suppression factor at LO.

Nuclear gluon suppression factor

CMS-PAS-HIN-22-002



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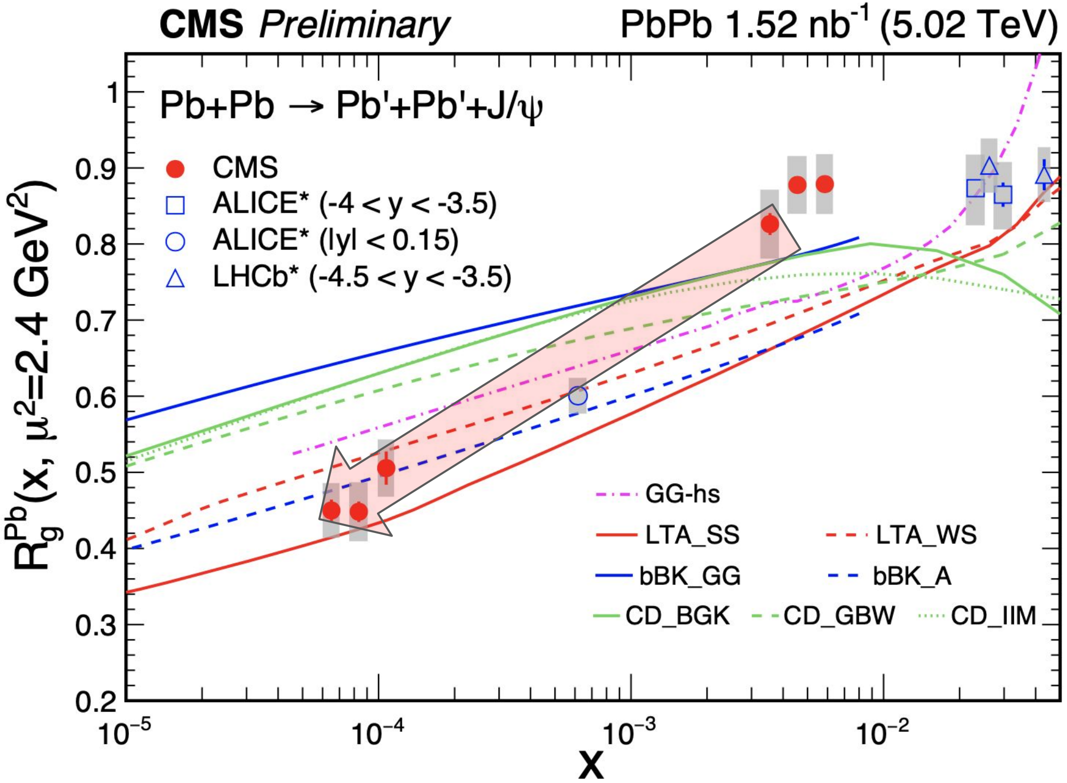
- $x \sim 10^{-3}$ - 10^{-2}: flat trend.

Nuclear gluon suppression factor

CMS-PAS-HIN-22-002



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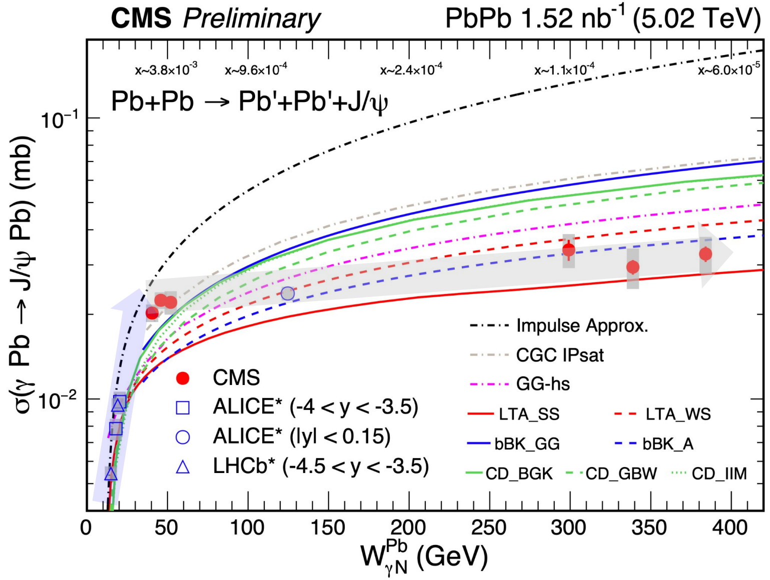
Impulse approx. (IA) neglects all nuclear effects.

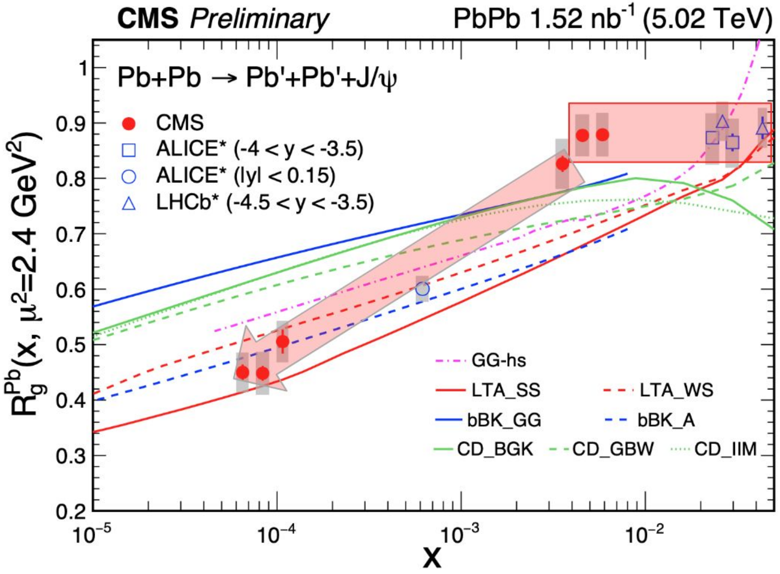
- Rg represents nuclear gluon suppression factor at LO.
- $x \sim 10^{-3}$ - 10^{-2}: flat trend.
- Quickly decrease towards lower x region.

Beyond model expectation

What we learnt

CMS-PAS-HIN-22-002



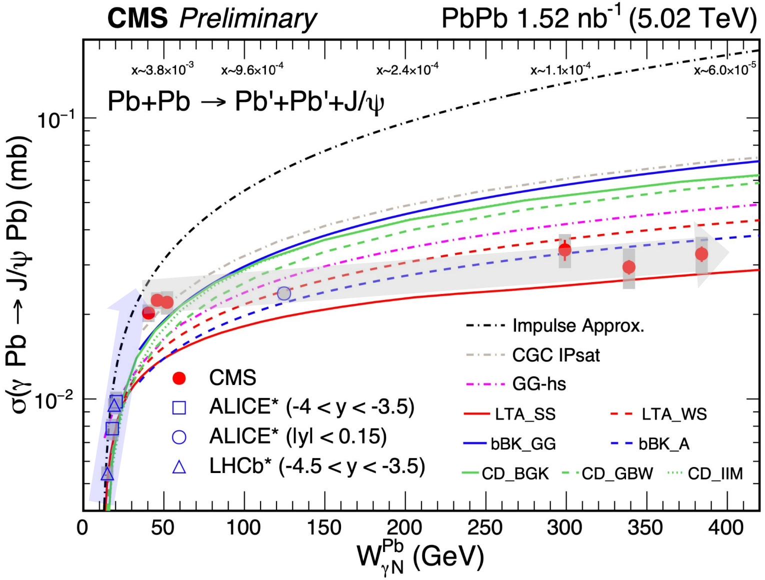


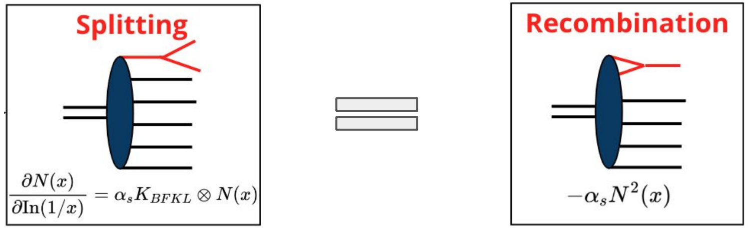
Coherent J/Ψ production vs. W from single γ+Pb:

- At W<40 GeV, quickly rise and the growth slope ~ free nucleons calculation.
- At W>40 GeV, nearly flat with a much smaller increasing trend.
- CMS, ALICE, LHCb data follows the same trend.

What physics behind?

CMS-PAS-HIN-22-002



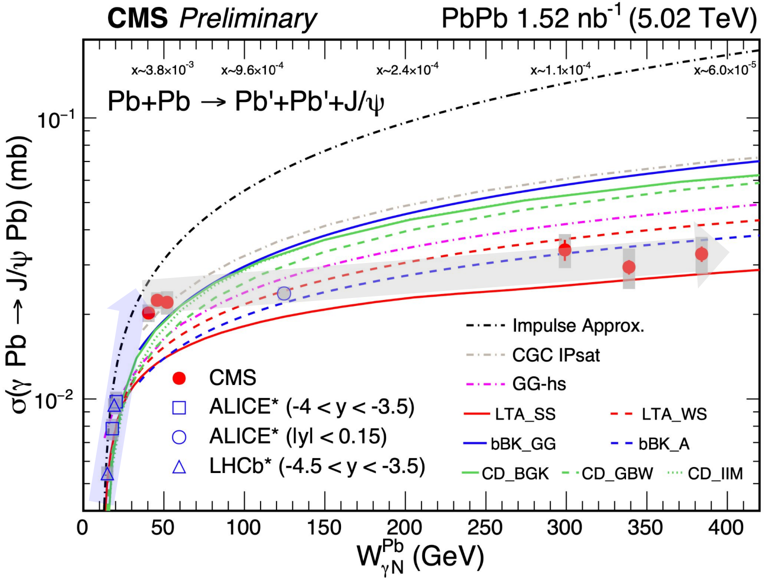


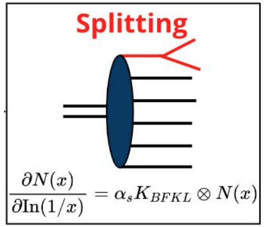
$$\frac{\partial N(x)}{\partial \ln(1/x)} = \alpha_s K_{BFKL} \otimes N(x) \quad = \quad -\alpha_s N^2(x)$$

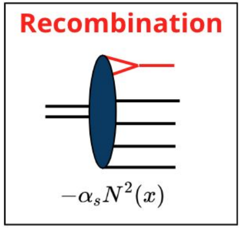
- σ stops rapid rising trend → splitting and recombination of gluons become equal
  - **Clear evidence for gluon saturation!!?**

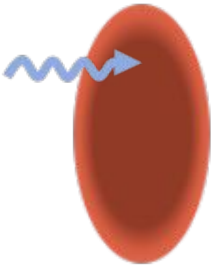
What physics behind?

CMS-PAS-HIN-22-002









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

- σ stops rapid rising trend → splitting and recombination of gluons become equal
  - **Clear evidence for gluon saturation!!?**

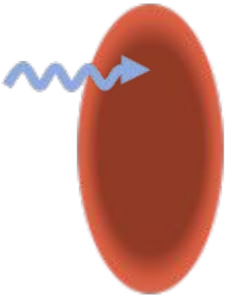
OR

- Nucleus target becomes totally absorptive to incoming photons → **Black Disk Limit!!?**
  - **Nucleus becomes a black disk, internal structure is invisible.**

Another novel regime of QCD: Black Disk Limit

L. Frankfurt, V. Guzey, M. McDermott, M. Strikman **PRL 87 (2001)192301**
L. Frankfurt, M. Strikman, M. Zhalov, **PLB 537 (2002) 51**

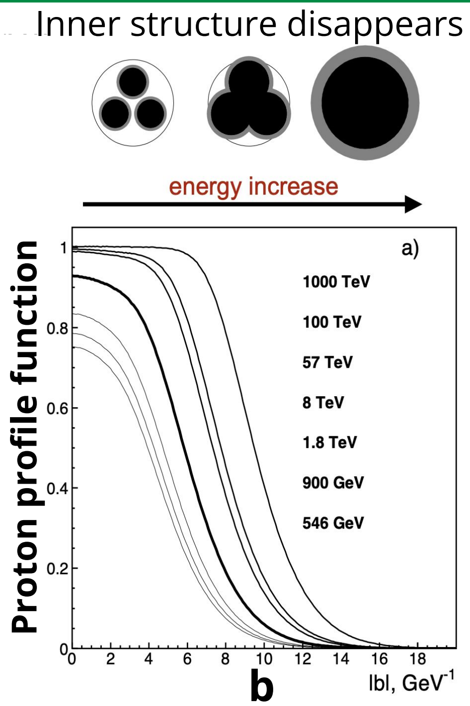
In the *strong absorption scenario*, the interaction probability may reach the unitarity limit. The nucleus target becomes totally absorptive to incoming photons.



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

“Black Disk Limit (BDL)”

- opposite to the “color transparency”

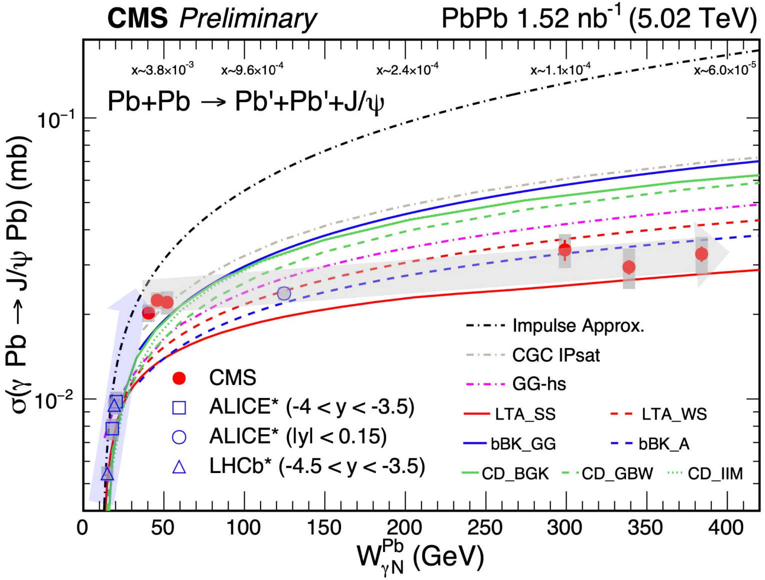


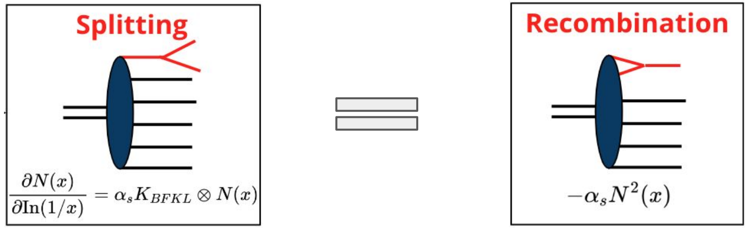
The BDL represents a novel regime at small x when the LO QCD and the notion of the parton distributions becomes inapplicable for describing hard processes .

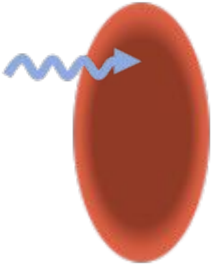
- **New theoretical tools are needed in this regime!**

The slowly increasing trend at high W

CMS-PAS-HIN-22-002





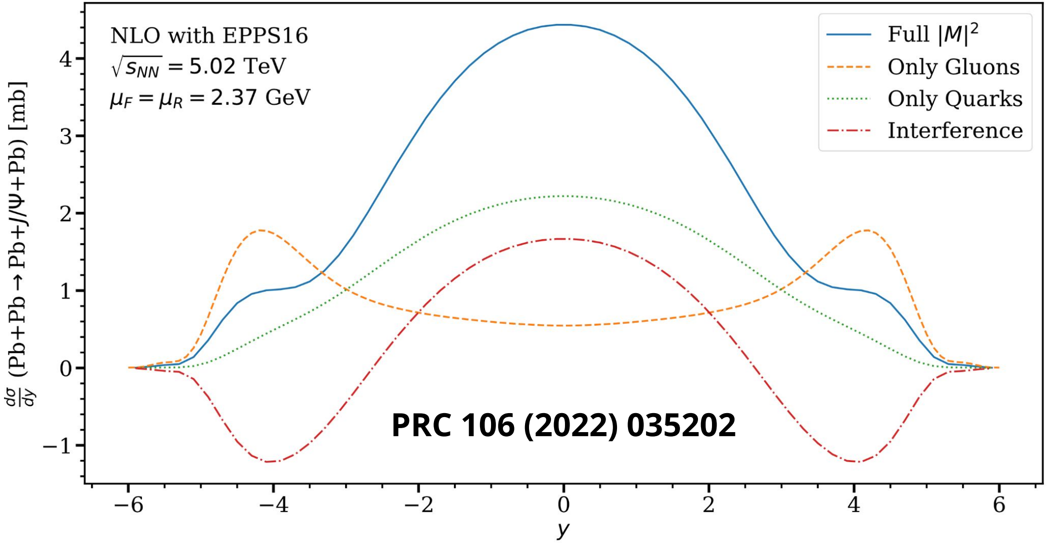


$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

- Periphery of nucleus may not be fully saturated or fully black at W~40 GeV, but gradually turn to saturated or fully black with further increasing of the probing energy.

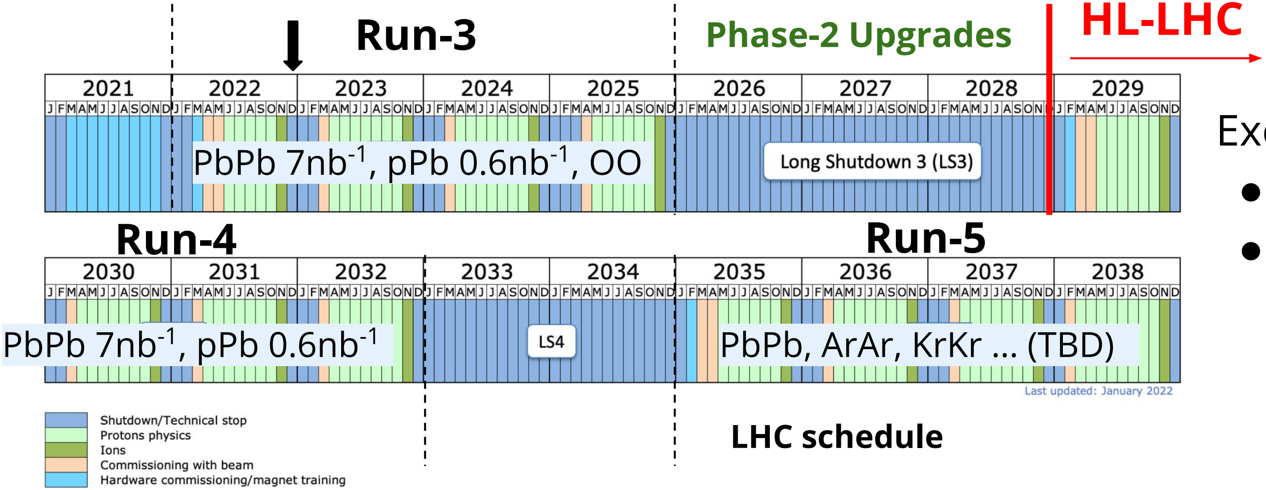
First NLO calculations on exclusive J/Ψ production

- First NLO pQCD calculations published recently (Eskola et al).
- Quark contributions at NLO + strong cancellations between LO and NLO gluons → ***dominance of quark contribution at central rapidities.***



- Needs careful attention when interpreting the data.
- “σ ∝ (gluon PDF)^2” not true at NLO.

Future opportunities



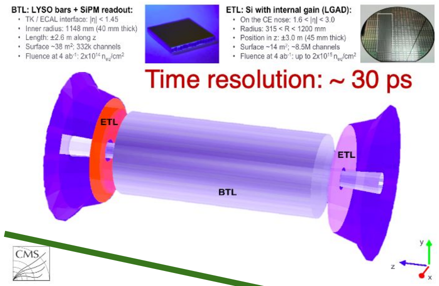
LHC schedule

Exciting opportunities ahead by:

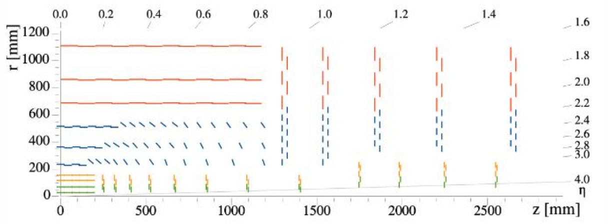
- Higher luminosities.
- A variety of ion species.

Future opportunities

MIP Timing Detector for PID

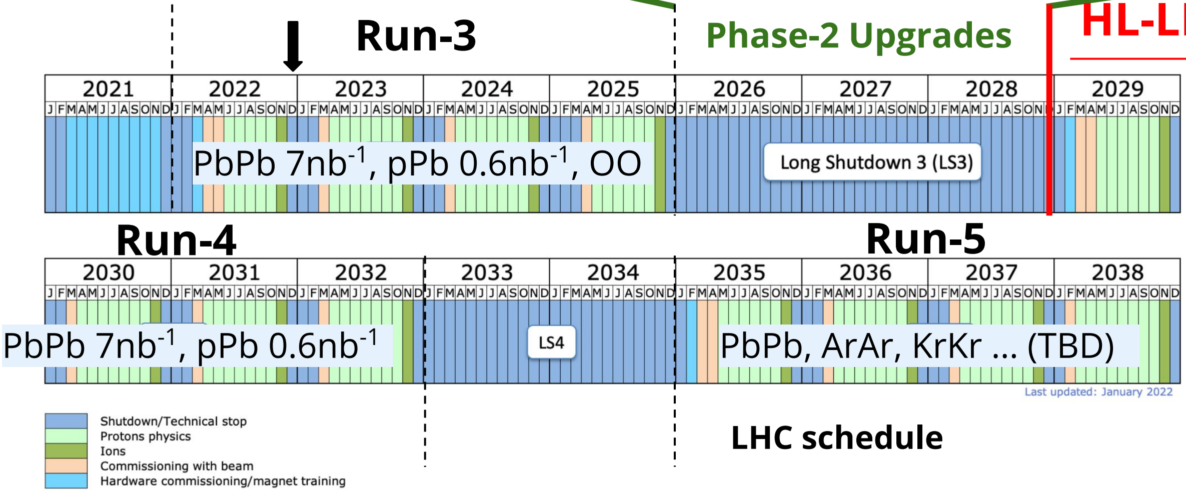


Tracker with |η|<4 and better resolution, lighter materials



- Muon systems with |η|<2.8
- Trigger and DAQ rate: ~10x

……

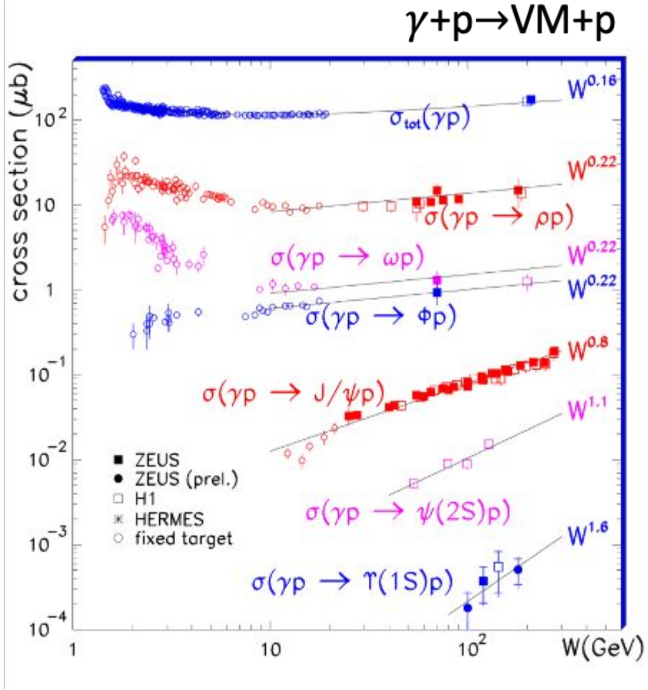


LHC schedule

Exciting opportunities ahead by:

- Higher luminosities.
- A variety of ion species.
- Upgrades enabled by new technologies!

Future opportunities



Various vector meson species in **γPb** as a function of a broad W range with neutron taggings

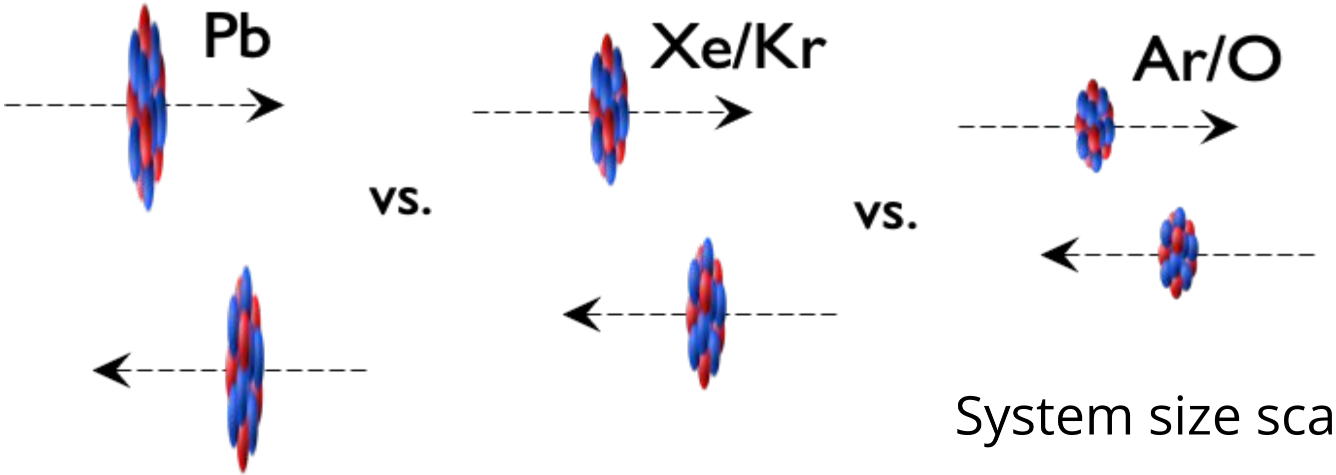
- ➢ e.g., control of dipole sizes and hard scales.

CERN yellow report, **arXiv:1812.06772**

Condition	Tot.	Central 1 Narrow	Central 2 Wide	Forward 1 Narrow	Forward 2 Wide
Rapidity	-	$\lvert y\rvert < 0.9$	$\lvert y\rvert < 2.4$	$2.5 < y < 4.0$	$2 < y < 5$
$e/\pi/\mu$ pseudorapidity	-	$\lvert \eta\rvert < 0.9$	$\lvert \eta\rvert < 2.4$	$2.5 < \eta < 4.0$	$2 < \eta < 5$

PbPb L_{int} = 13 nb^{-1}						
Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$Y(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

Future opportunities



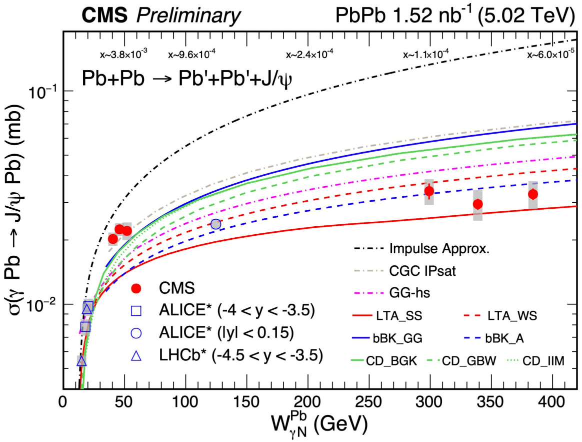
System size scan

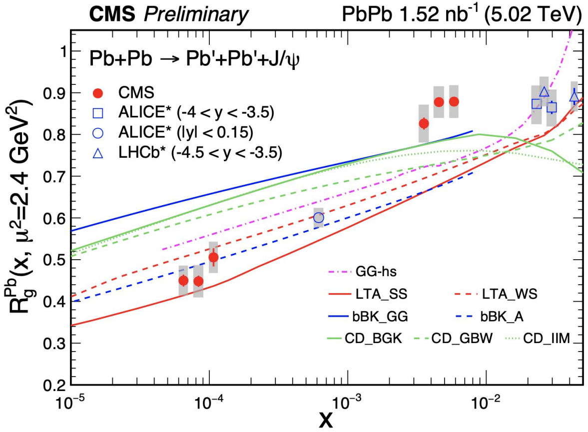
- Variation of saturation scales in search for gluon saturation.
- When approaching the BDL:
  - Coh. cross section scales with $A^{2/3}$
  - Incoh. cross section strongly suppressed, internal substructure becomes invisible

Summary

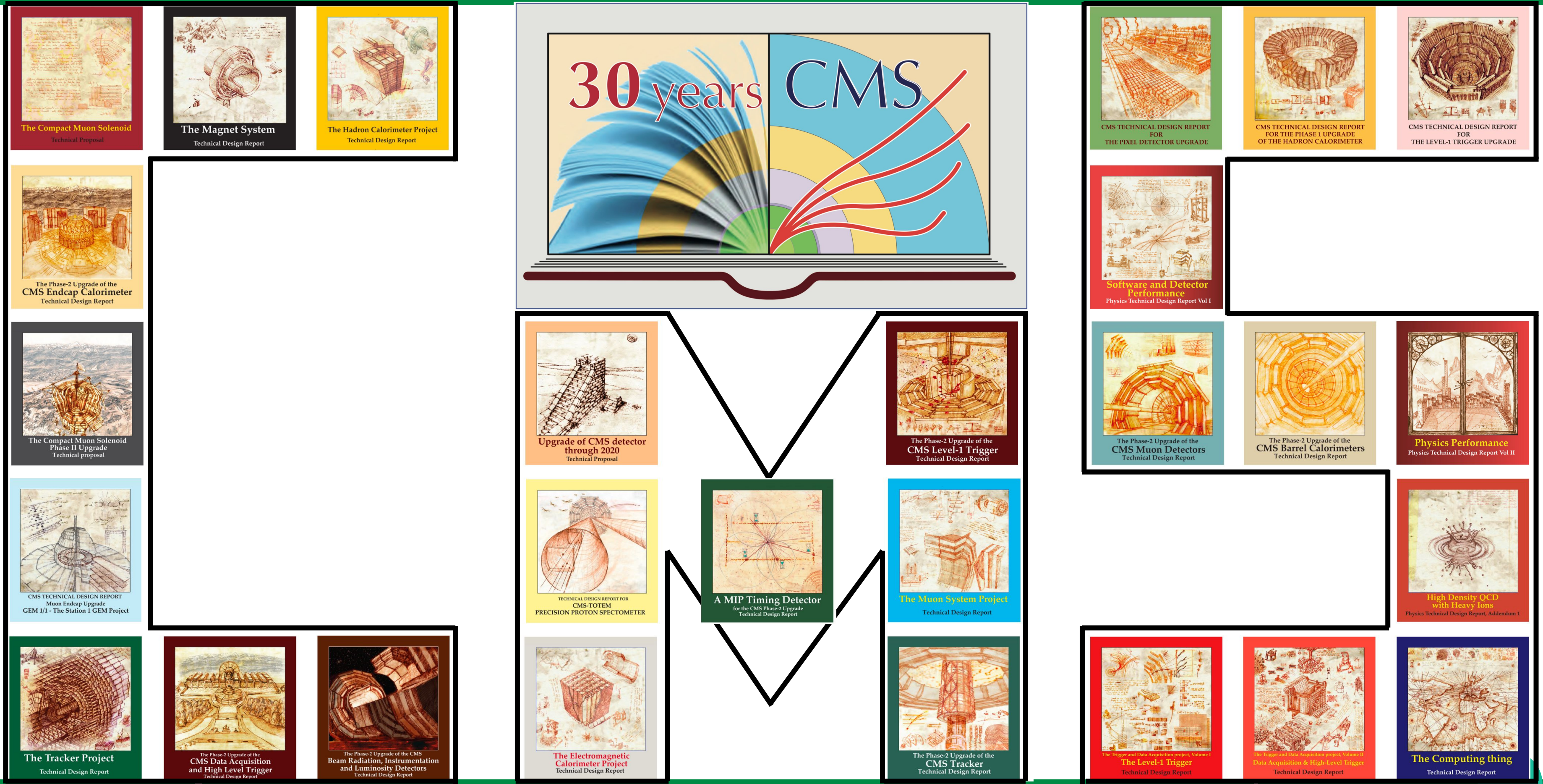
- For the first time, **disentangled the low and high γ energy** contributions to coh. J/Ψ.
- CMS measured coh. J/Ψ at a **new unprecedentedly low-x gluon regime** (10^{-4}-10^{-5}).
- **Flattening** of coh. σ(J/Ψ) vs. W not predicted by state of the art models
  - **Gluon saturation?** or **black disk limit?** or other physic effects?
- HL-LHC including CMS Phase-2 upgrades will bring new exciting opportunities.

CMS-PAS-HIN-22-002





CMS 30 years anniversary

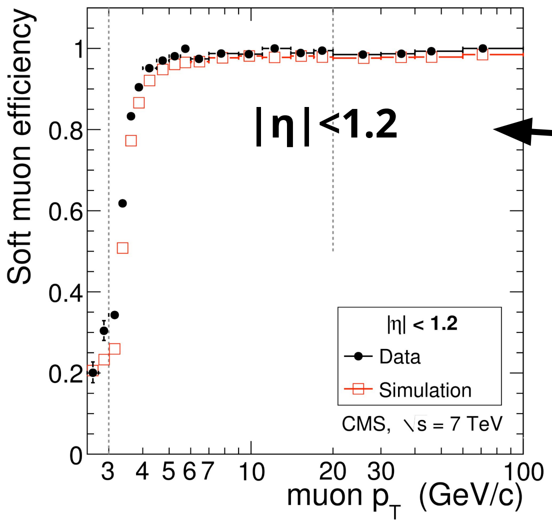


Thank you for your attention!

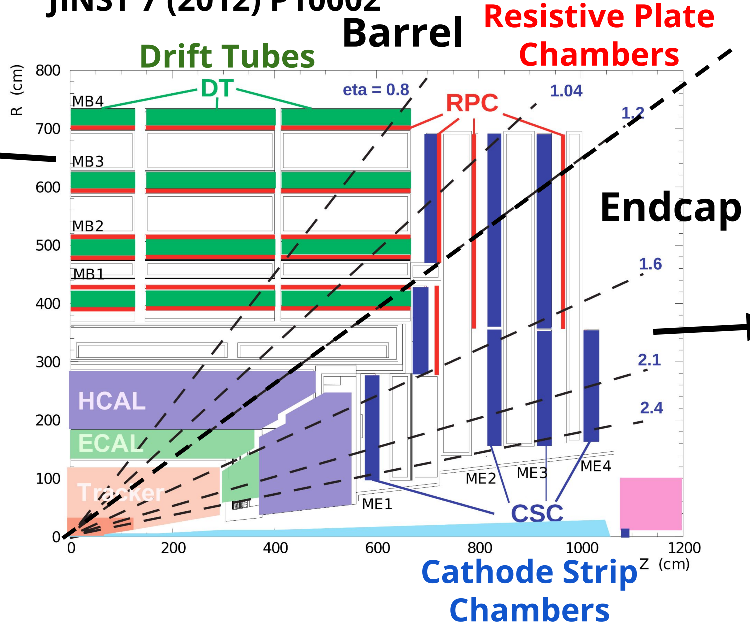
BACKUP

Muon reconstruction

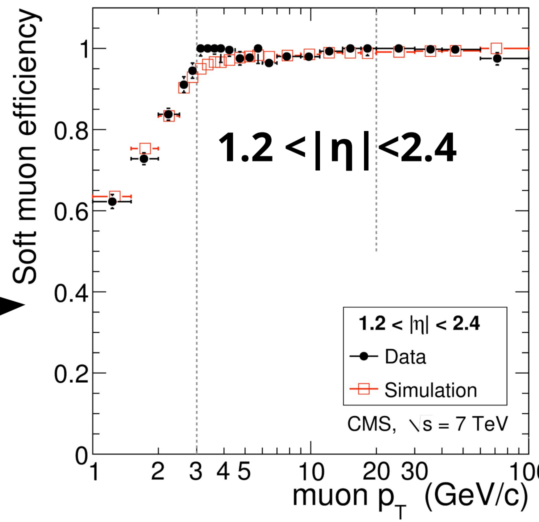
Muon efficiency



JINST 7 (2012) P10002

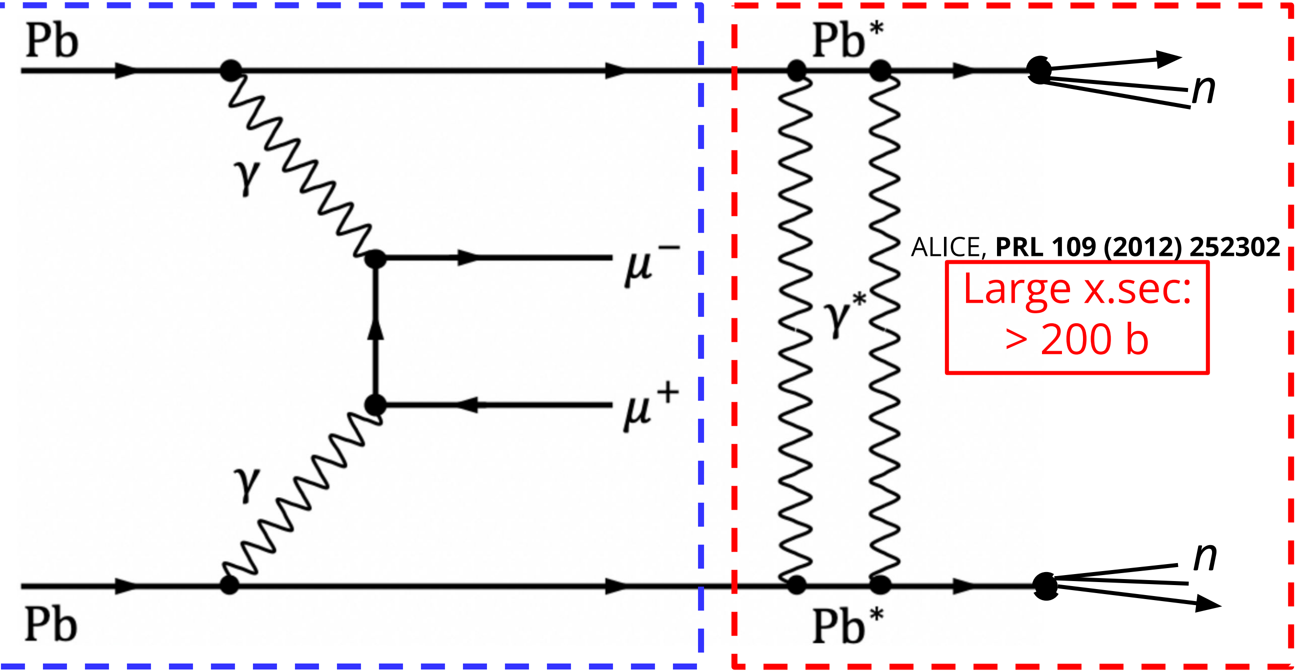


Muon efficiency



- Tracker and muon detectors used to reconstruct/identify muons.
- CMS able to reconstruct muons down to muon p_T~ 1 GeV in forward region.

EM dissociative pileup correction



ALICE, **PRL 109 (2012) 252302**

Large x.sec:
> 200 b

Impact of dissociative PU corrected by measuring neutron multiplicity in events without any activity in CMS tracker.

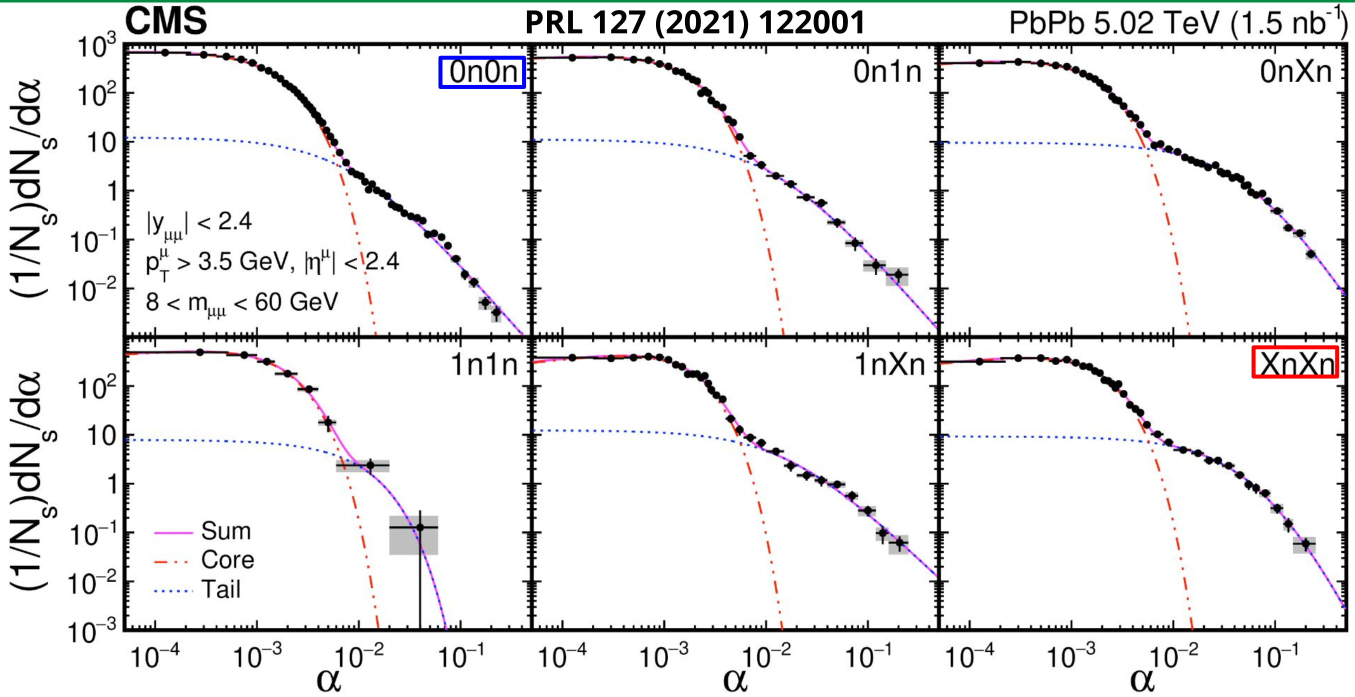
$\gamma\gamma \rightarrow \mu^+\mu^-$ **with/without neutron emitting**

different collisions

EM dissociation **without** any $\gamma\gamma \rightarrow \mu^+\mu^-$

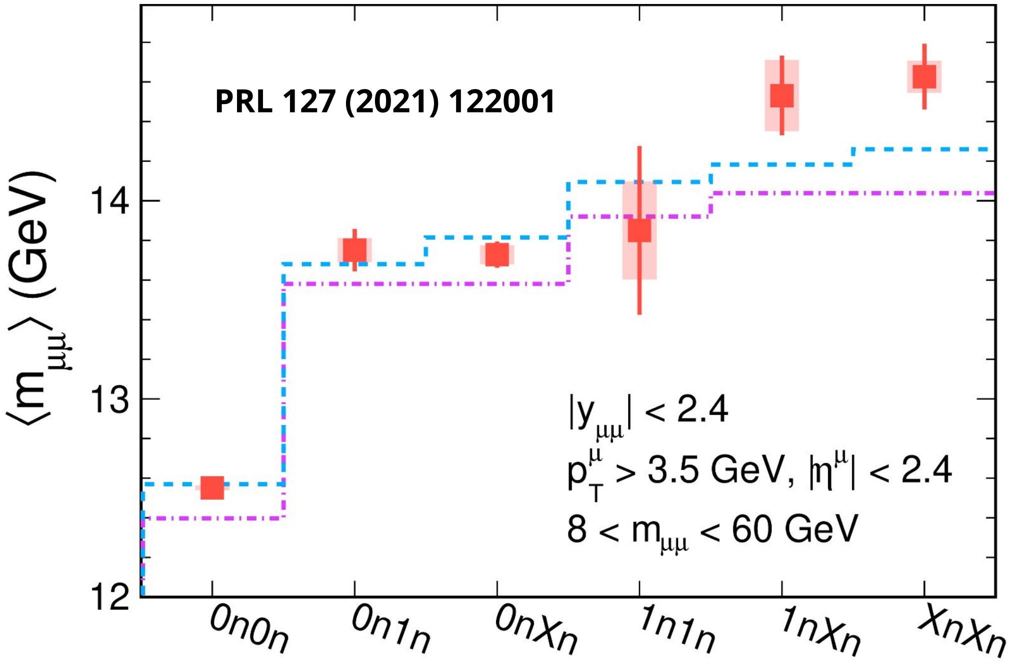
$\gamma\gamma \rightarrow \mu^+\mu^-$ with neutron multiplicity migration

α spectrum vs. neutron multiplicity



- **0n0n (fewer neutrons)** → **XnXn (more neutrons)**
  - Tail contribution becomes larger.
  - Seems has depletion in the very small α.

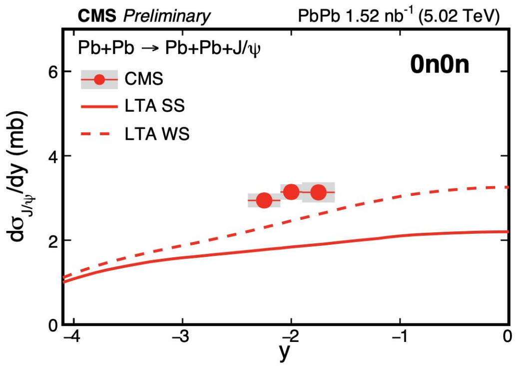
⟨$m^{\mu\mu}$⟩ vs. neutron multiplicity

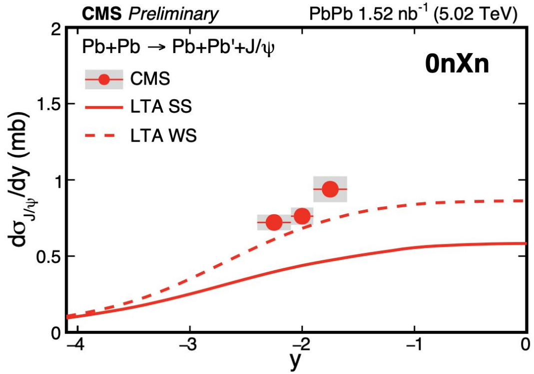


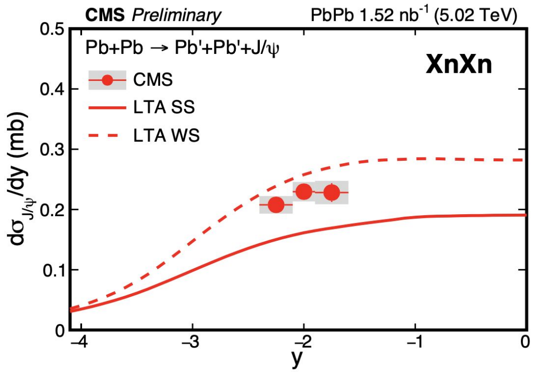
- Strong neutron multiplicity dependence of ⟨$m_{\mu\mu}$⟩
    - Deviation from constant >> 5σ
    - b dependence of initial photon energy.

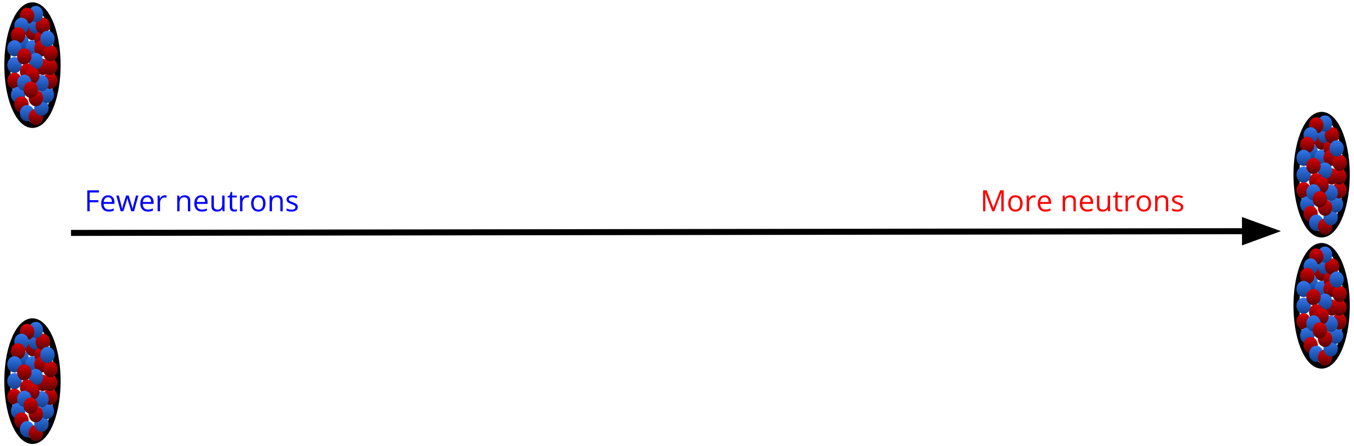
Coherent Jpsi in 0n0n, 0nXn, XnXn

CMS-PAS-HIN-22-002



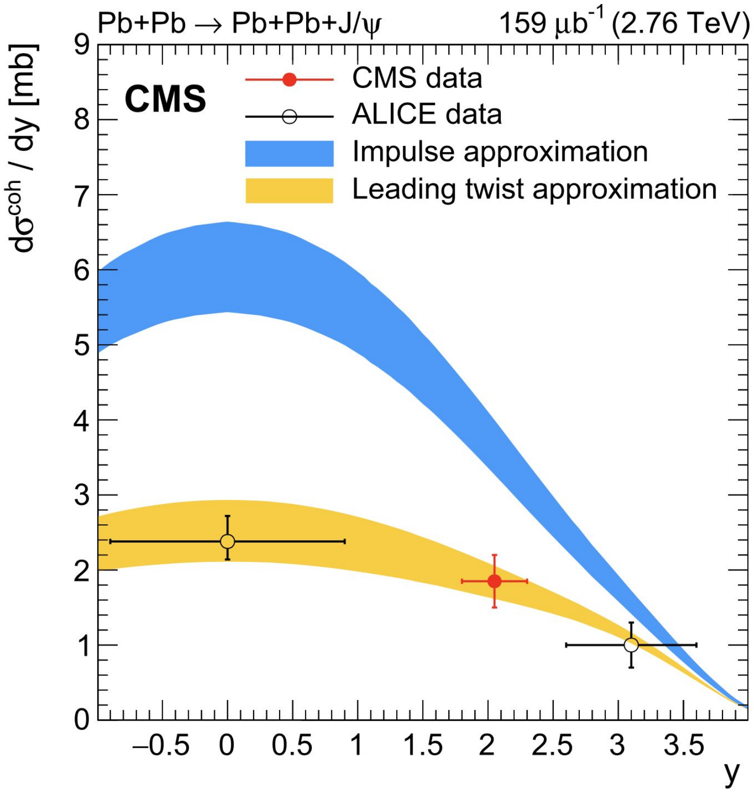






Coherent Jpsi in Run 1

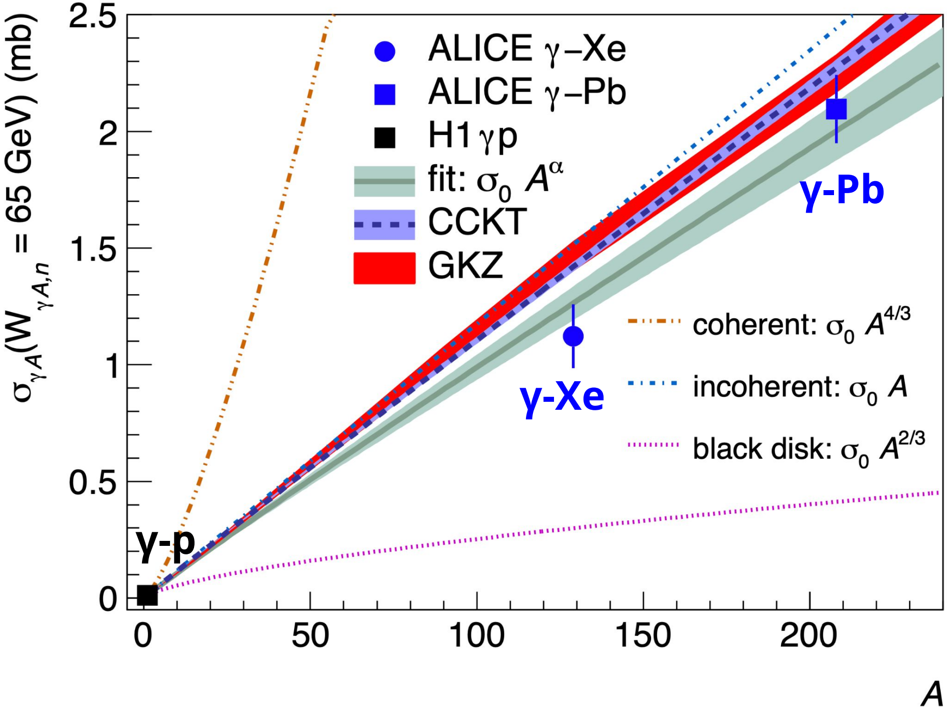
PLB 772 (2017) 489



- Run 1 data from CMS and ALICE well consistent with LTA model calculations
- Large uncertainties and wide y bins

ALICE UPC ρ vs system size

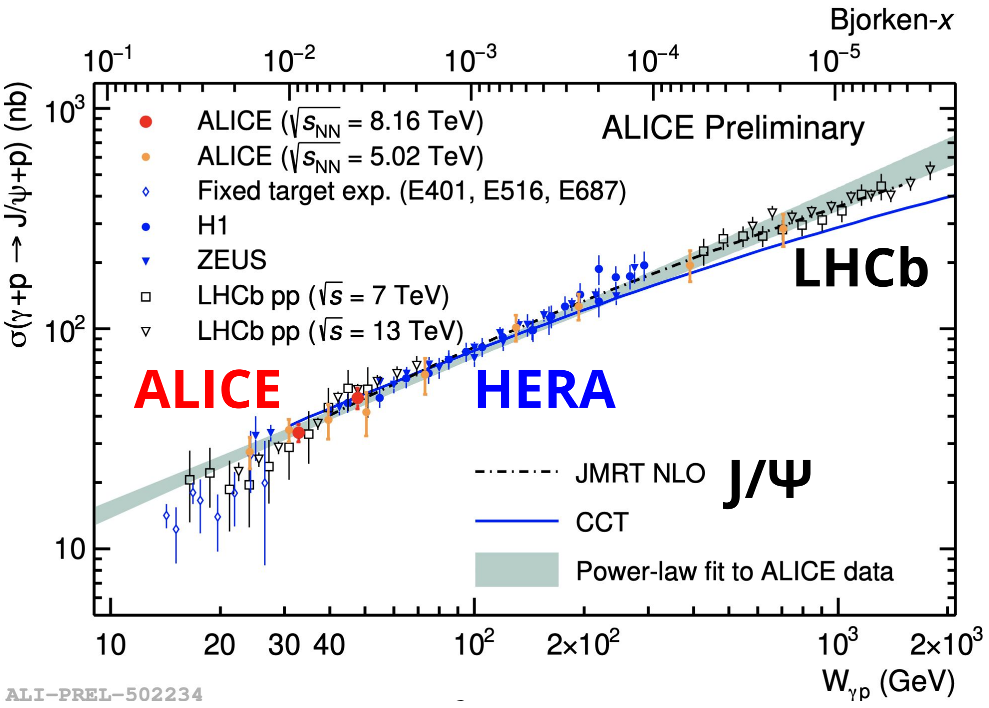
ALICE, **PLB 820 (2021) 136481**



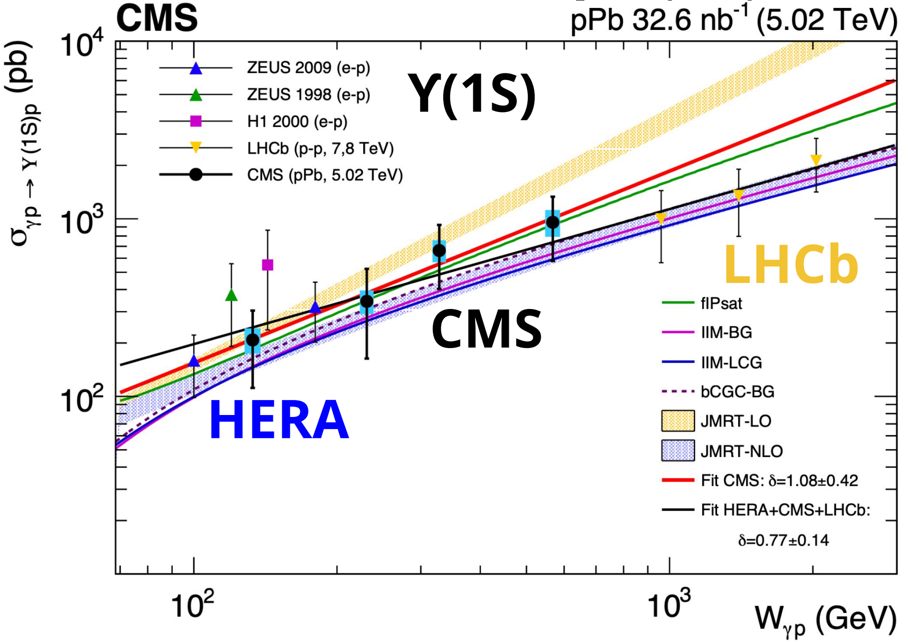
If J/Ψ-nucleus approaches BDL, why ρ-Nucleus does not?

- With A decrease, it is harder to reach BDL → the direct $A^{2/3}$ cannot scale to small A.
- Relation of dipole size vs. M in seen by nucleus is different to what seen by nucleon?

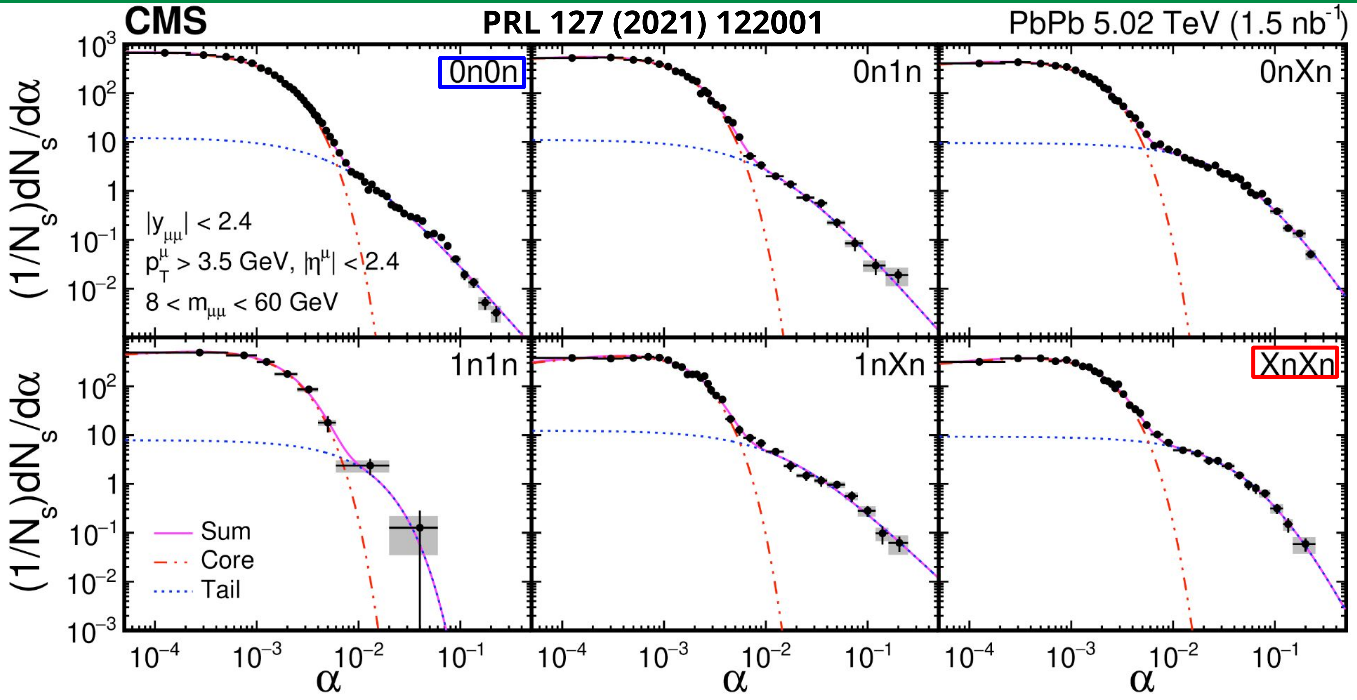
Quarkonium photoproduction in γ-p



CMS, **EPJC 79 (2019) 277**

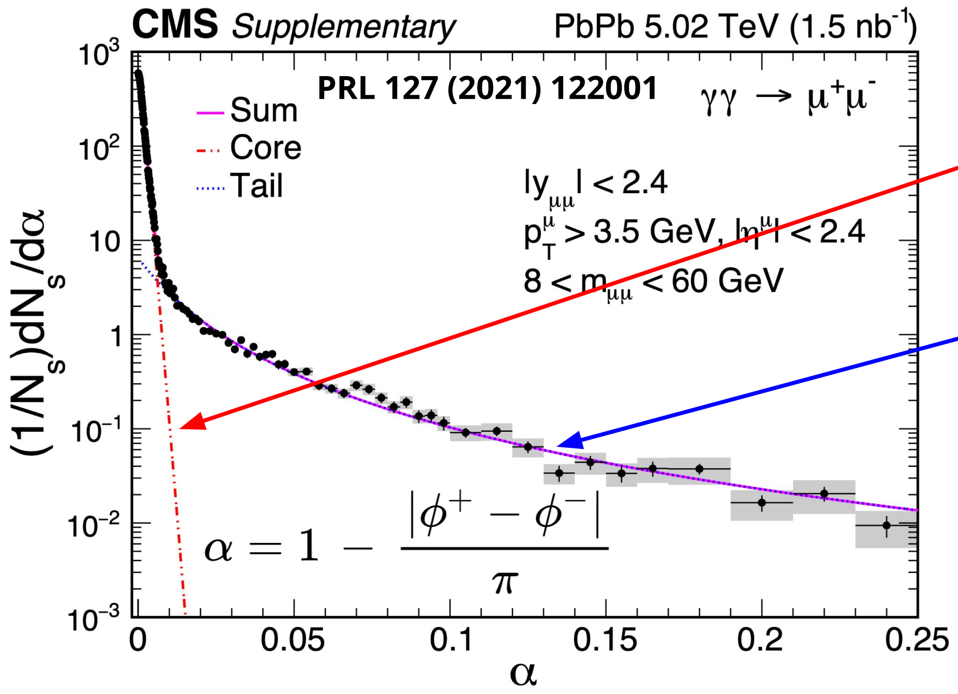


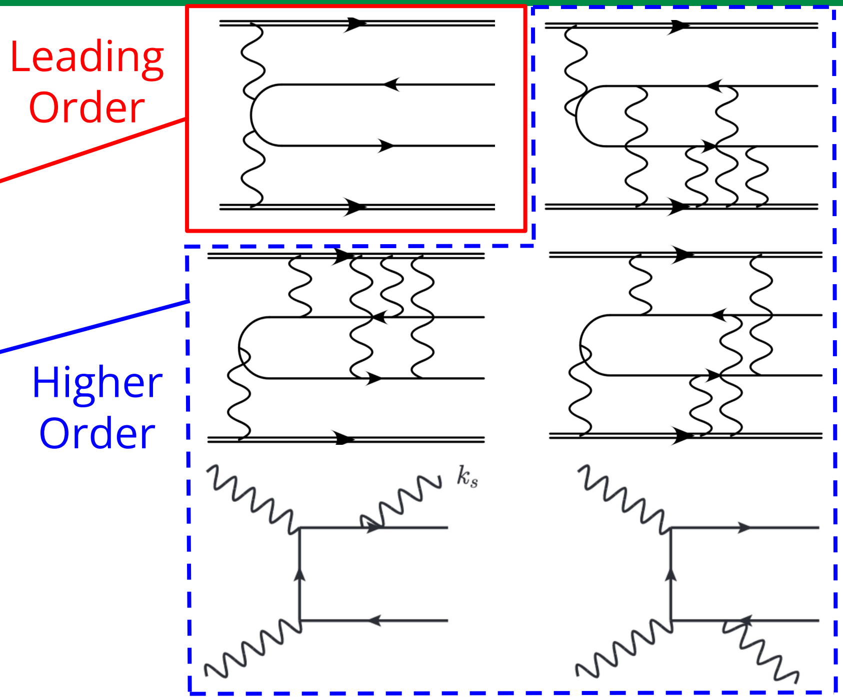
α spectrum vs. neutron multiplicity class



- **0n0n (fewer neutrons)** → **XnXn (more neutrons)**
  - Tail contribution becomes larger.
  - Seems has depletion in the very small α.

Decomposing LO and HO in α spectrum





Zero Degree Calorimeter