Experimental insights from CMS in ultra-peripheral collisions

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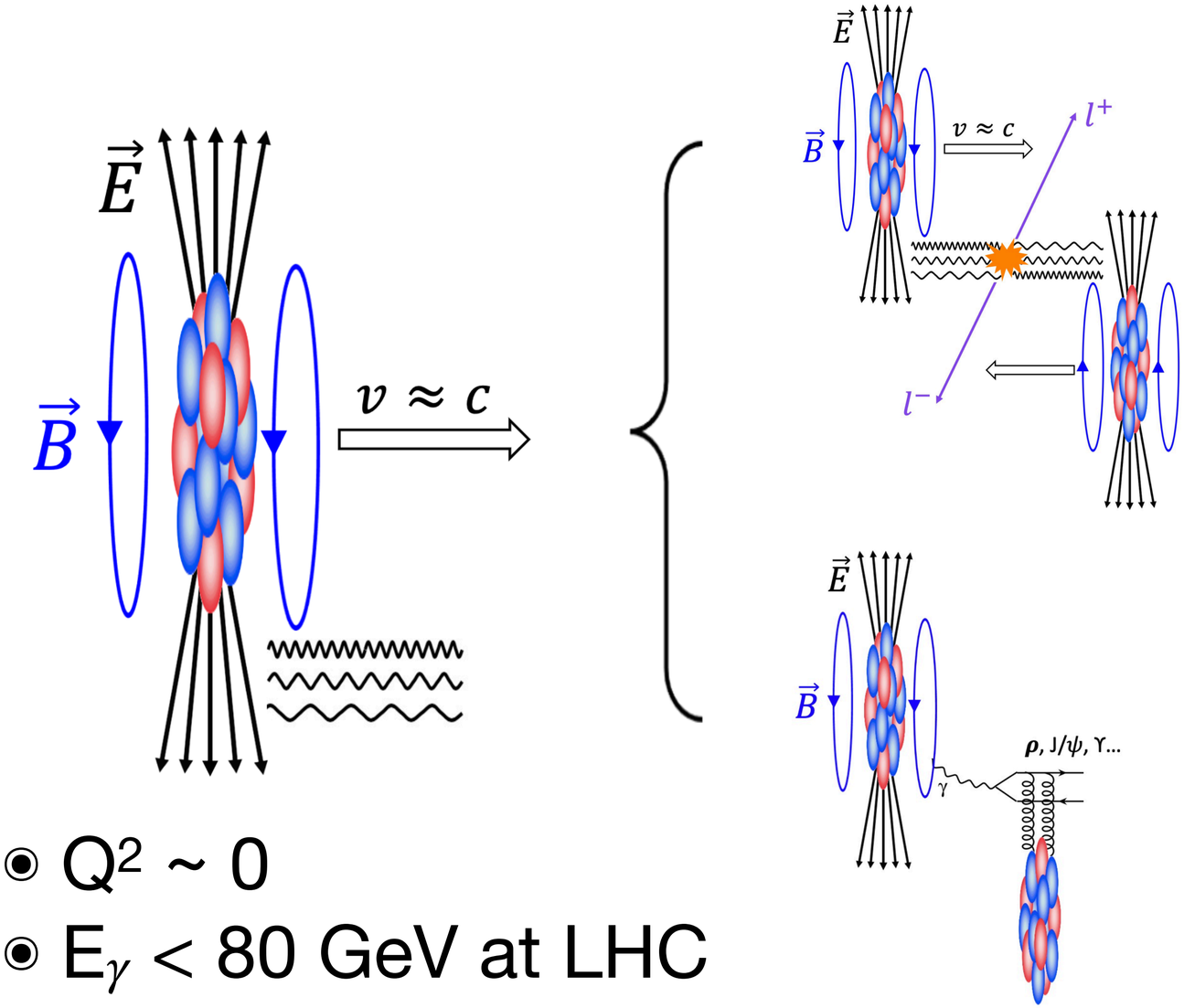
Advances, Innovations, and Prospects in High-Energy Nuclear Physics,
Wuhan, Oct 19-24, 2024

Photon-induced interactions

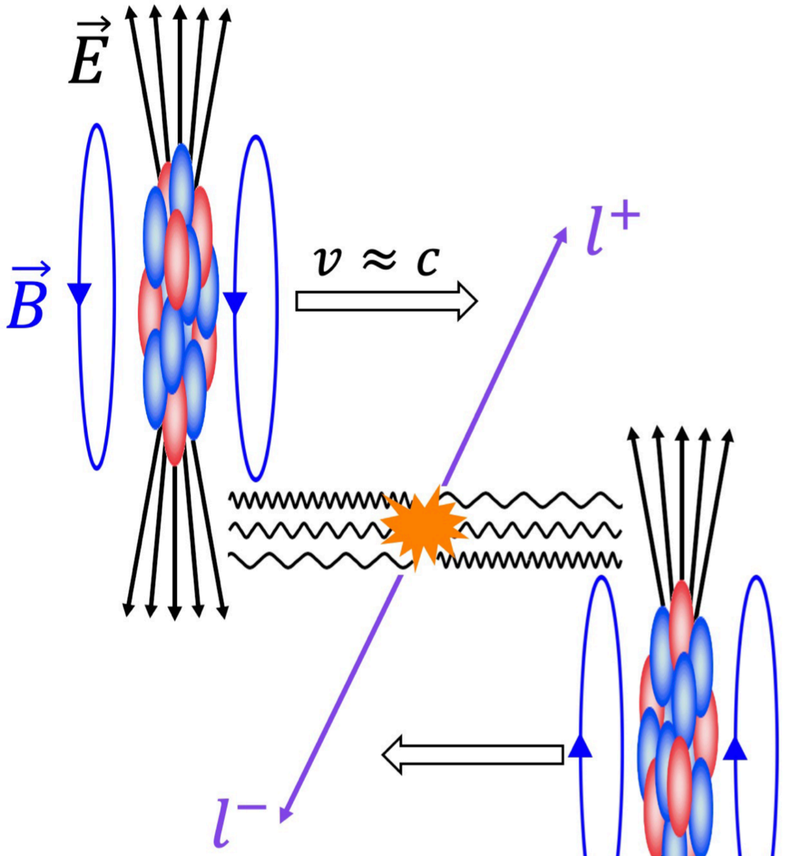


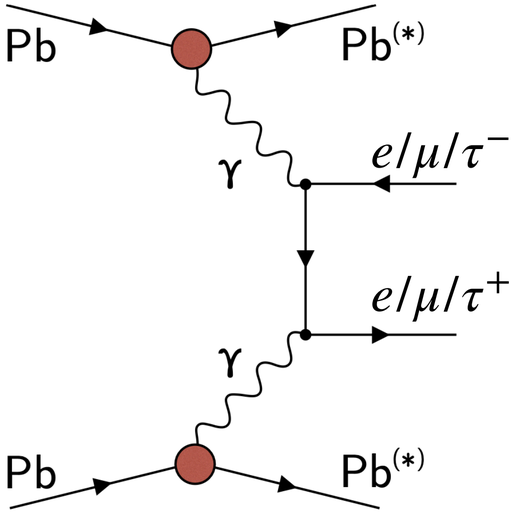
- $Q^2 \sim 0$
- $E_\gamma < 80$ GeV at LHC

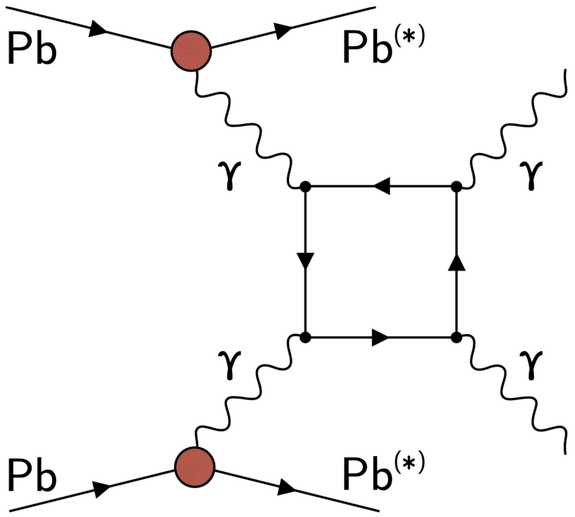
- Photon-photon interactions
  - QED
  - BSM physics

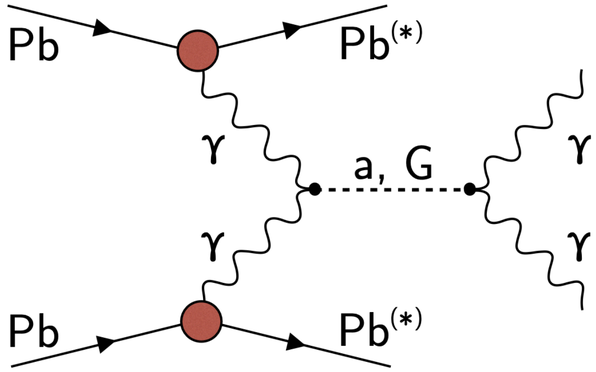
- Photon-nuclear interactions
  - Little “EIC”: gluonic structure

Photon-photon interactions





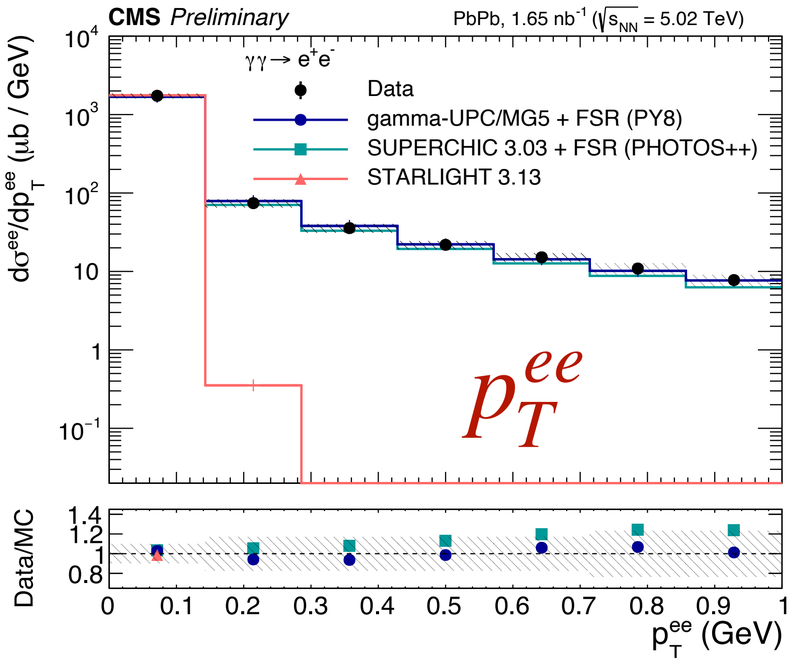


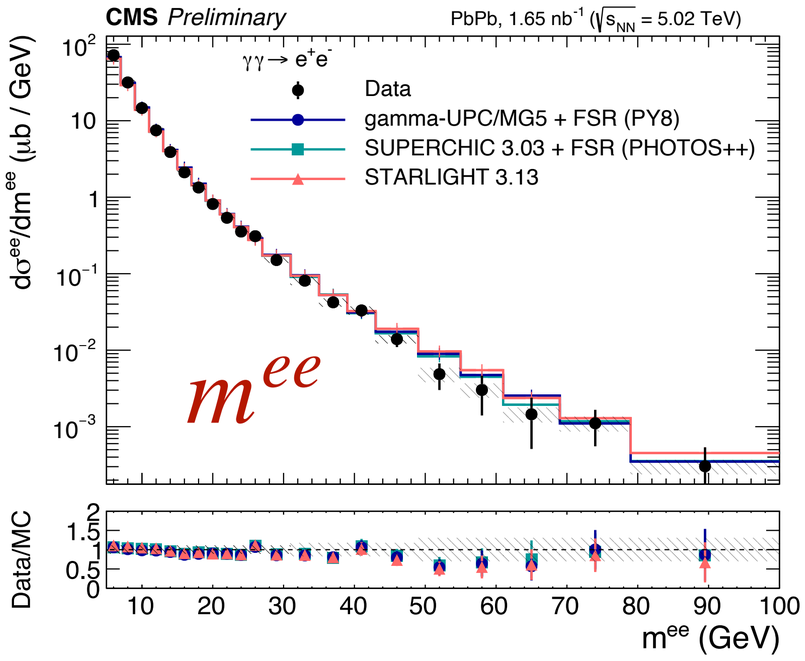


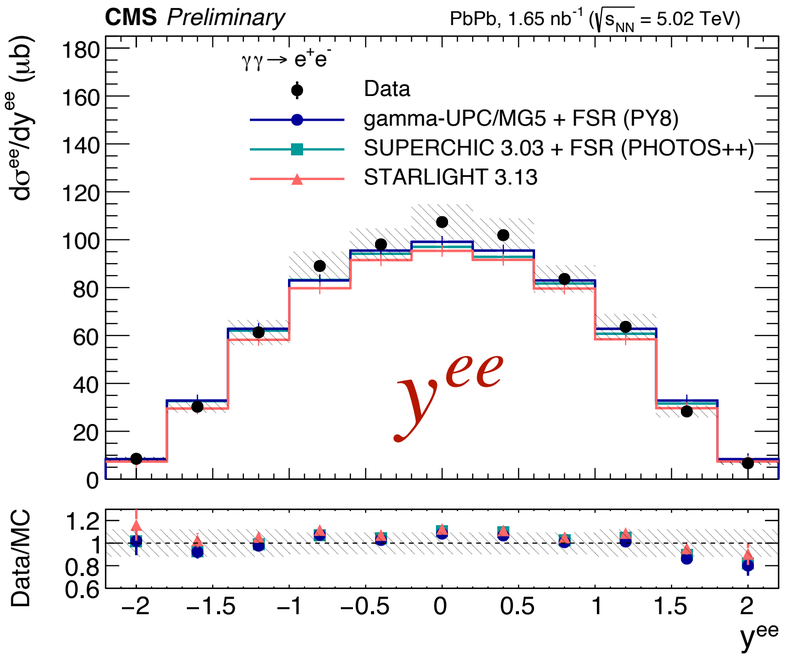
ATLAS, Nat. Phys. 13 (2017) 852
ATLAS, PRC 104 (2021) 024906
ATLAS, JHEP 03 (2021) 243
ATLAS, PRL 131 (2023) 151802
CMS, PLB 797 (2019) 134826
CMS, PRL 127 (2021) 122001
CMS, PRL 131 (2023) 151803
CMS, ROPP 87 (2024) 107801
CMS-PAS-HIN-21-015
CMS-PAS-HIN-24-011

Breit-Wheeler process

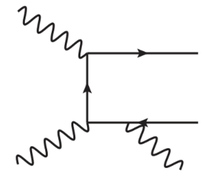
CMS-PAS-HIN-21-015







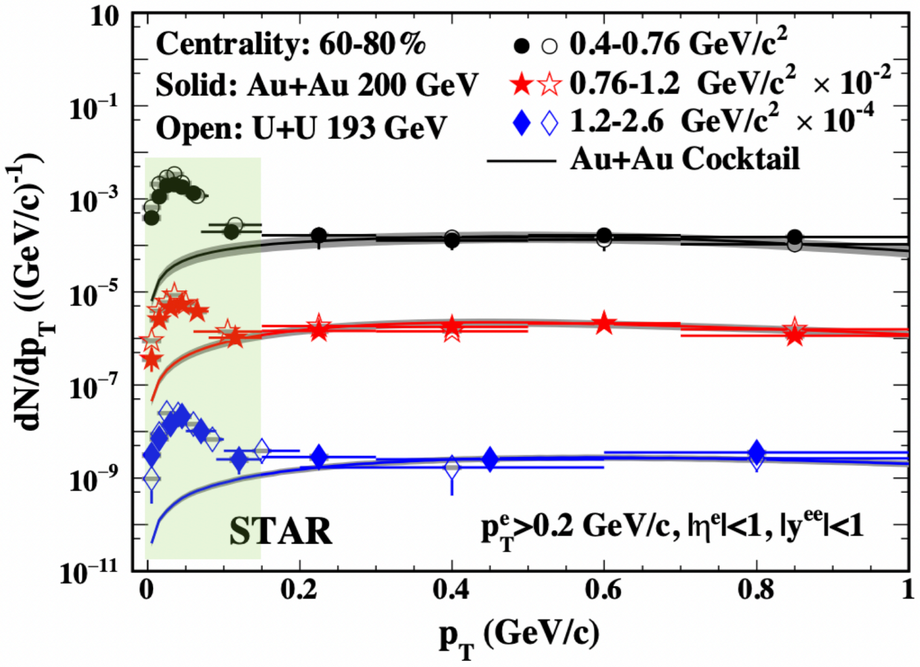
- Cross section vs. p_T, mass, and rapidity
- Good agreement with between data and model predictions
  - FSR is critical to describe pair p_T distribution at LHC

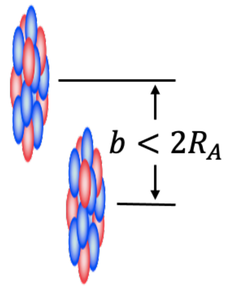


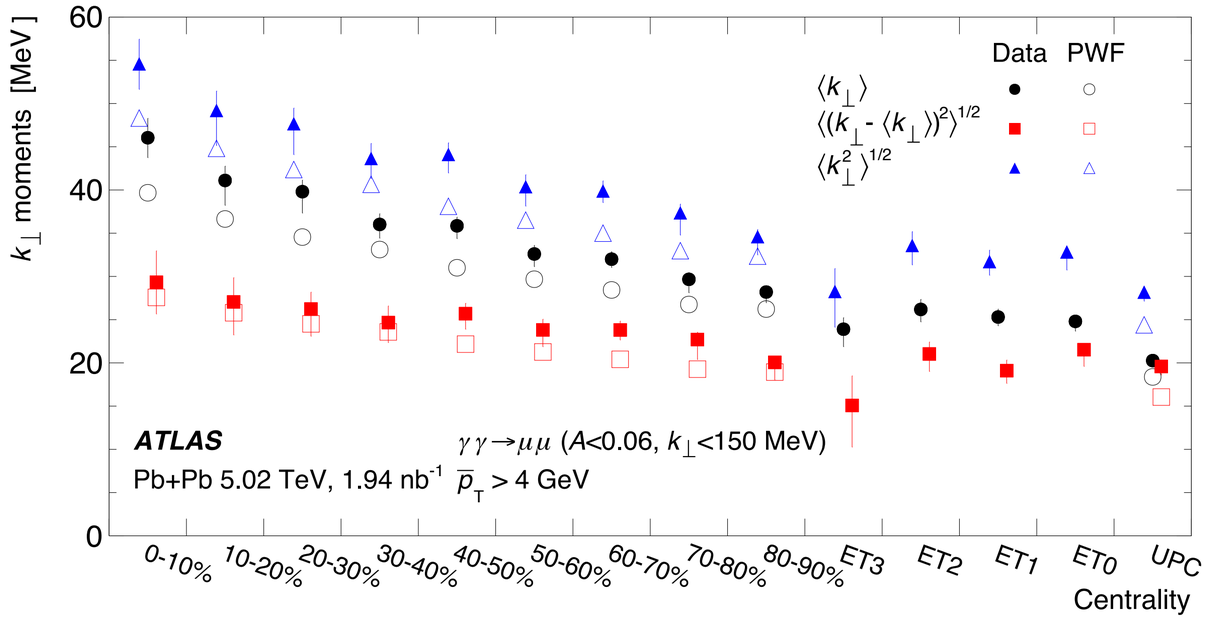
p_T broadening of $\gamma\gamma \rightarrow l^+l^-$ in non-UPC

STAR, PRL 121 (2018) 132301

ATLAS, PRL 121 (2018) 212301
ATLAS, PRC 107 (2023) 054907



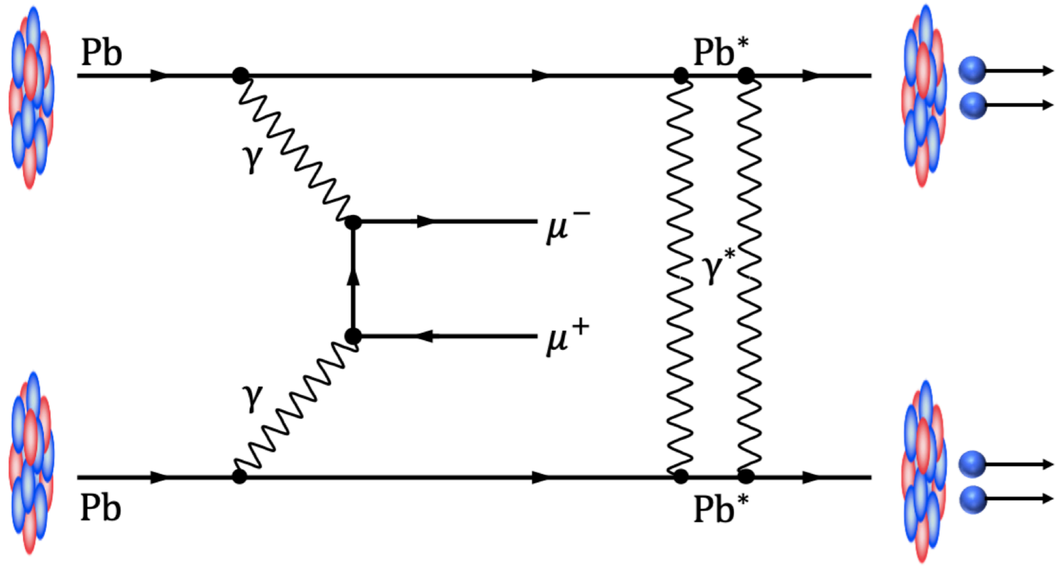


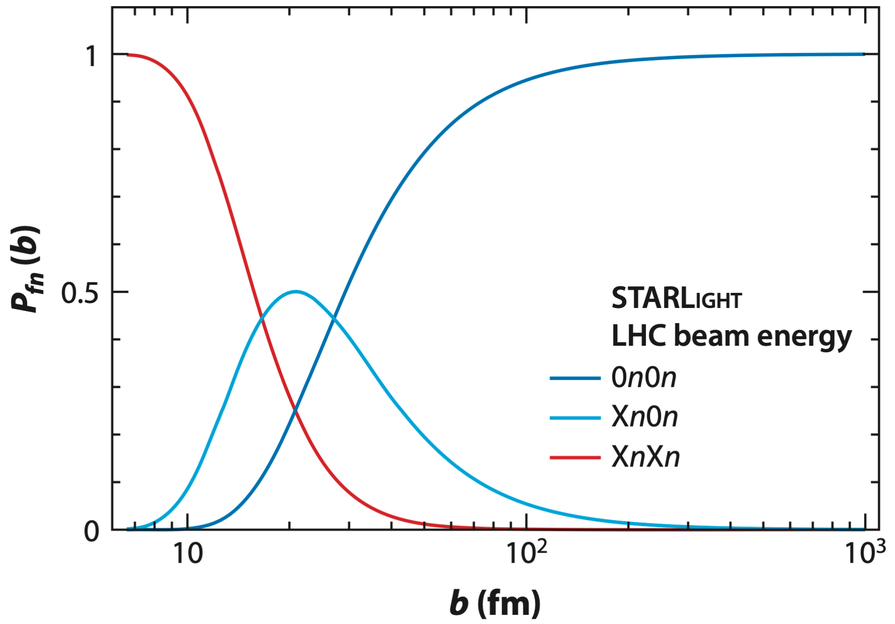


smaller *b* ← **larger *b***

- Observed Breit-Wheeler process in non-UPC
- Broadening of pair p_T towards central collisions
  - QGP EM properties vs. initial photon p_T broadening

Control impact parameter in UPC

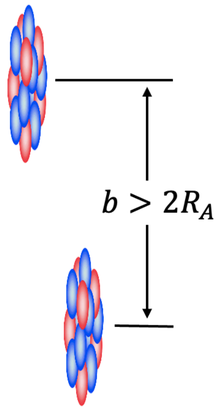


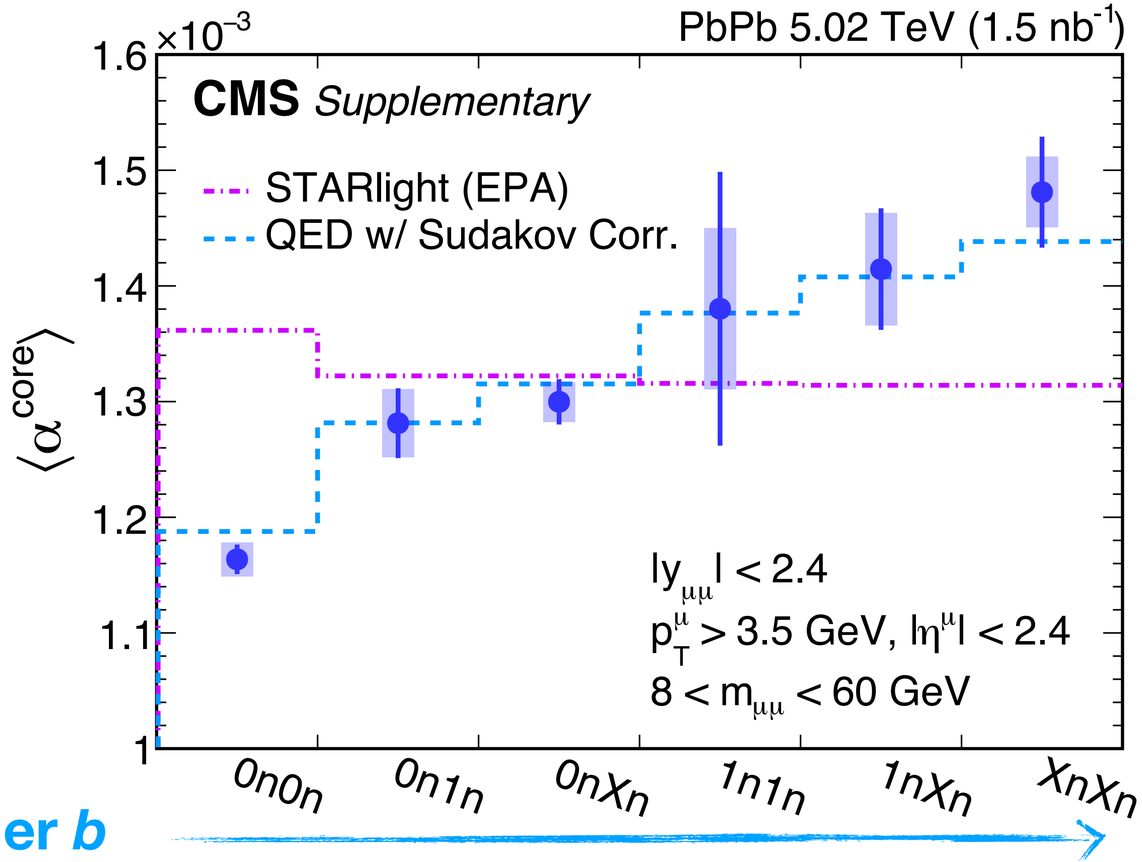


Klein and Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

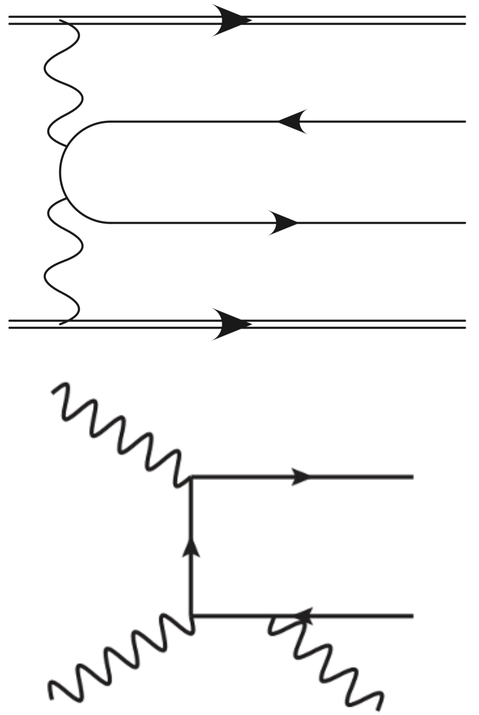
- Control the impact parameter via forward neutron multiplicity
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

Concluded the *b* dependence of photon p_T





CMS, PRL 127 (2021) 122001
Brandenburg et al., arXiv:2006.07365



larger *b* → smaller *b*

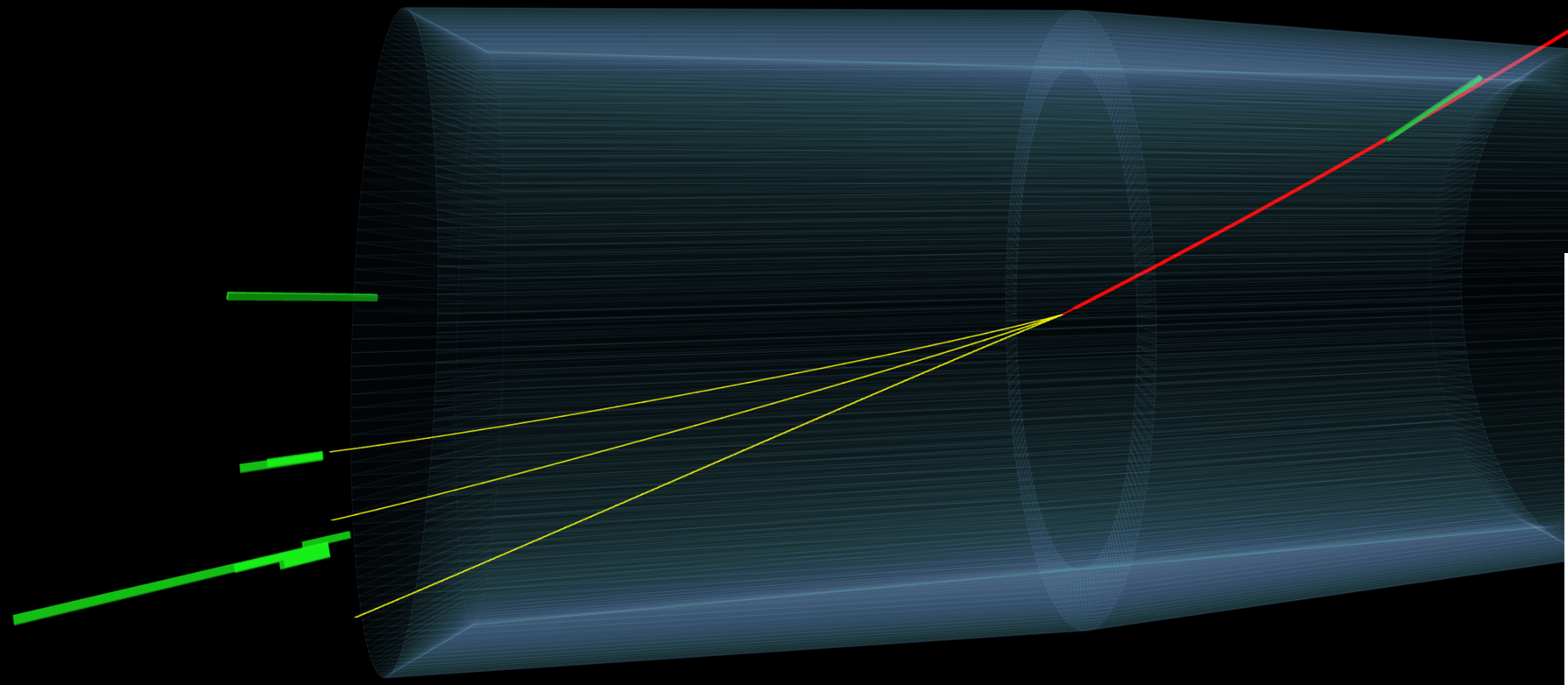
- Qualitatively described by a leading order QED model
- Demonstrated the b dependent of photon p_T
  - Precise reference for probing QGP EM effects

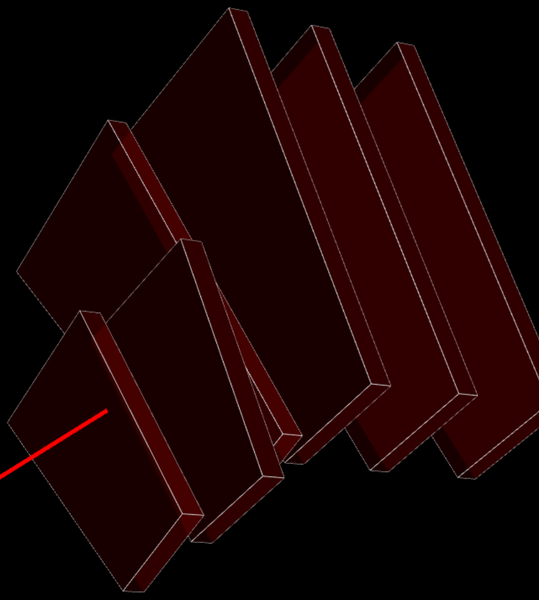
Observation of $\gamma\gamma \to \tau\tau$ in AA

CMS Experiment at the LHC, CERN

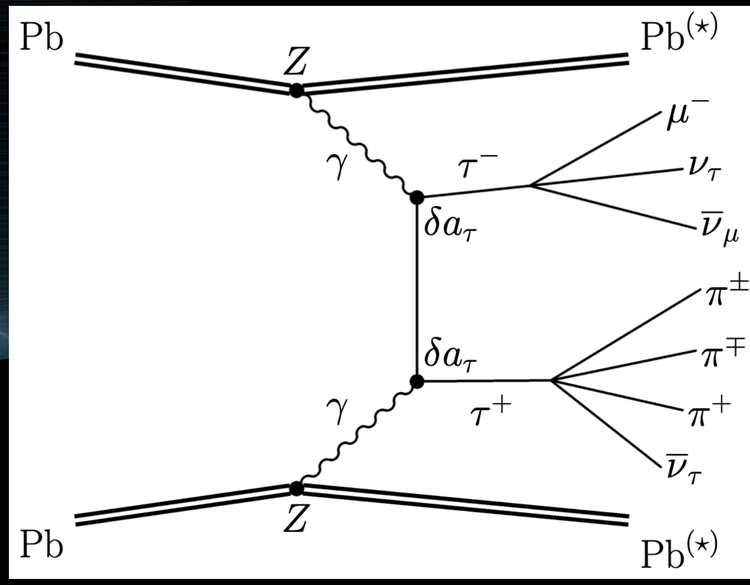
Data recorded: 2015-Dec-06 21:41:27.033612 GMT

Run / Event / LS: 263400 / 88515785 / 849

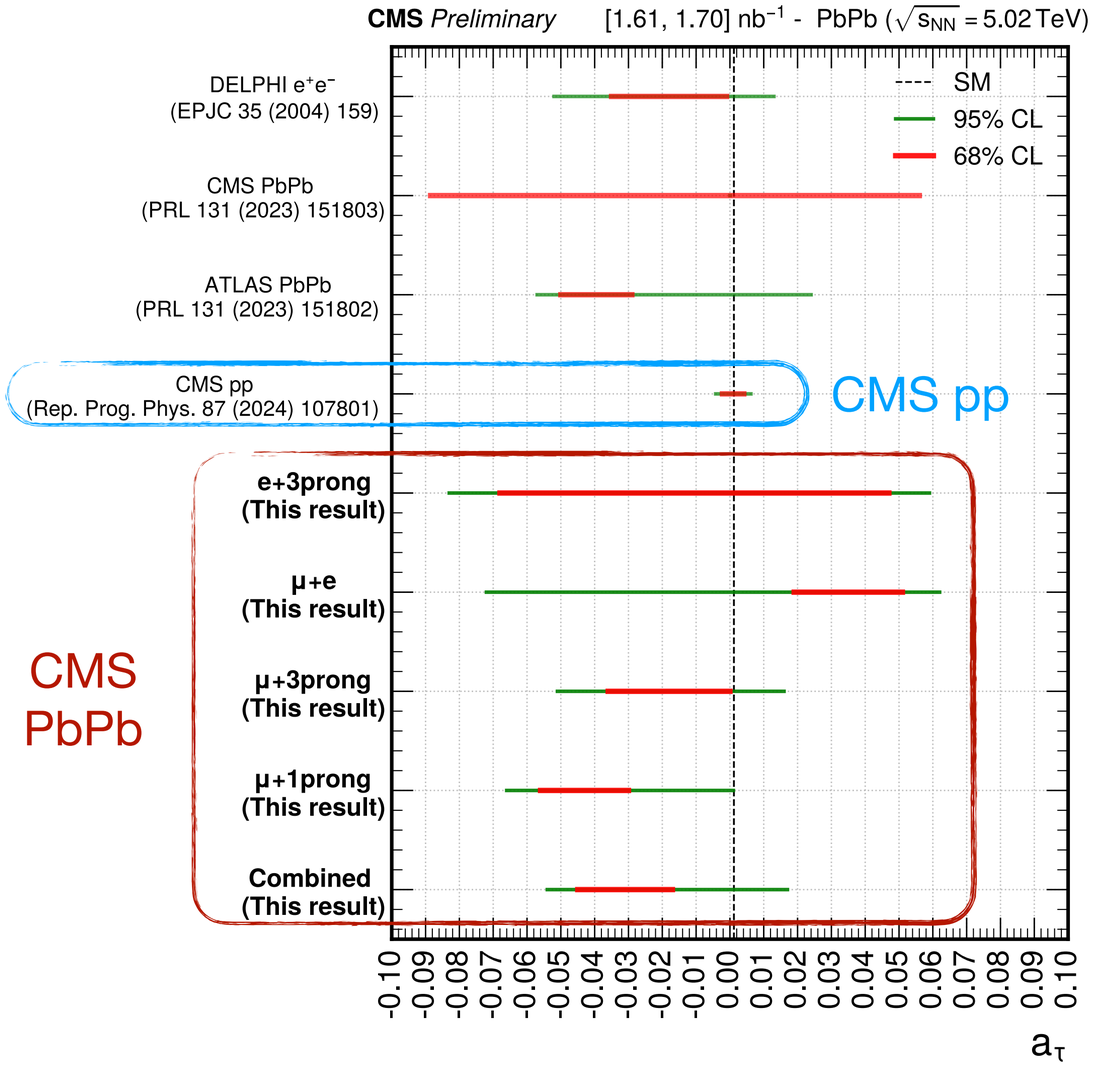




CMS, PRL 131 (2023) 151803



Constrain $a_\tau = (g_\tau - 2)/2$



ATLAS, PRL 131 (2023) 151802
CMS, PRL 131 (2023) 151803
CMS, ROPP 87 (2024) 107801
CMS-PAS-HIN-24-011

- Sensitivity to the BSM physics
  - Much better precision compared to DELPHI result
  - Model-dependent value of a_τ
  - Consistent results between ATLAS and CMS in PbPb UPC

Differential $\gamma\gamma \rightarrow \gamma\gamma$ fiducial cross sections

CMS-PAS-HIN-21-015

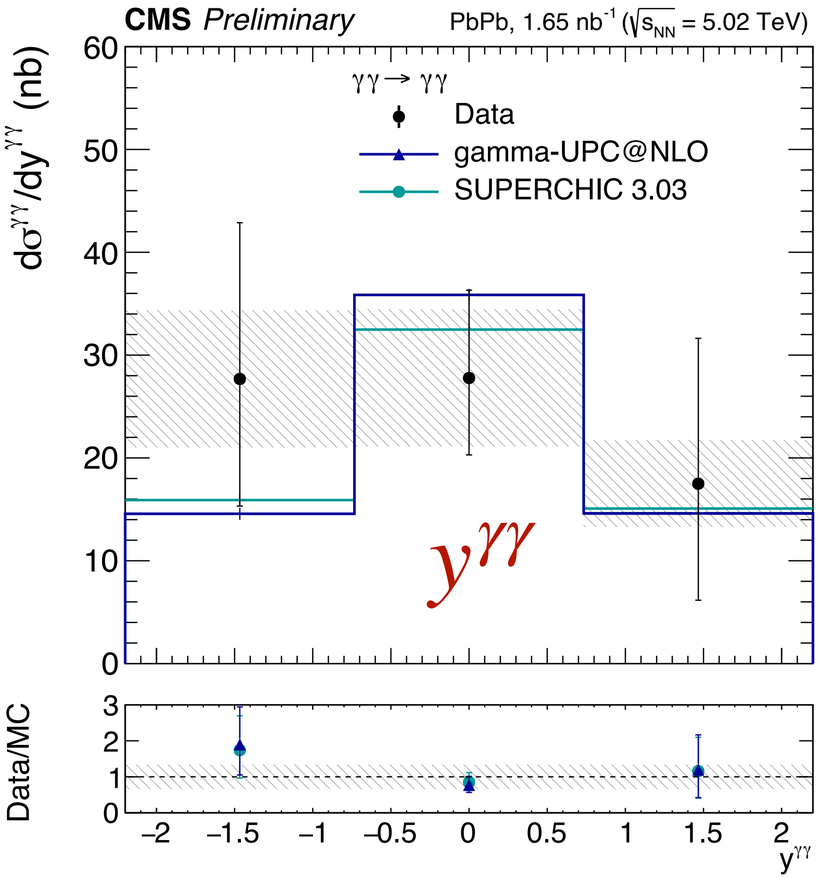
$E_T^{\gamma} > 2$ GeV

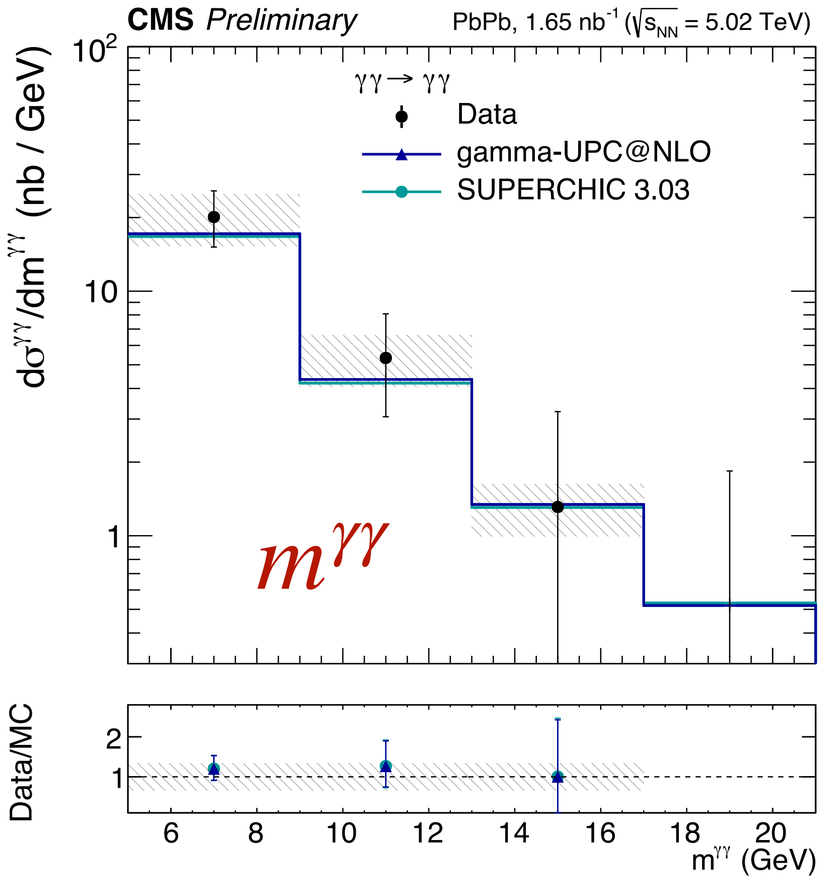
$|\eta^{\gamma}| < 2.2$

$m^{\gamma\gamma} > 5$ GeV

$p_T^{\gamma\gamma} < 1$ GeV

$A_{\phi}^{\gamma\gamma} < 0.01$





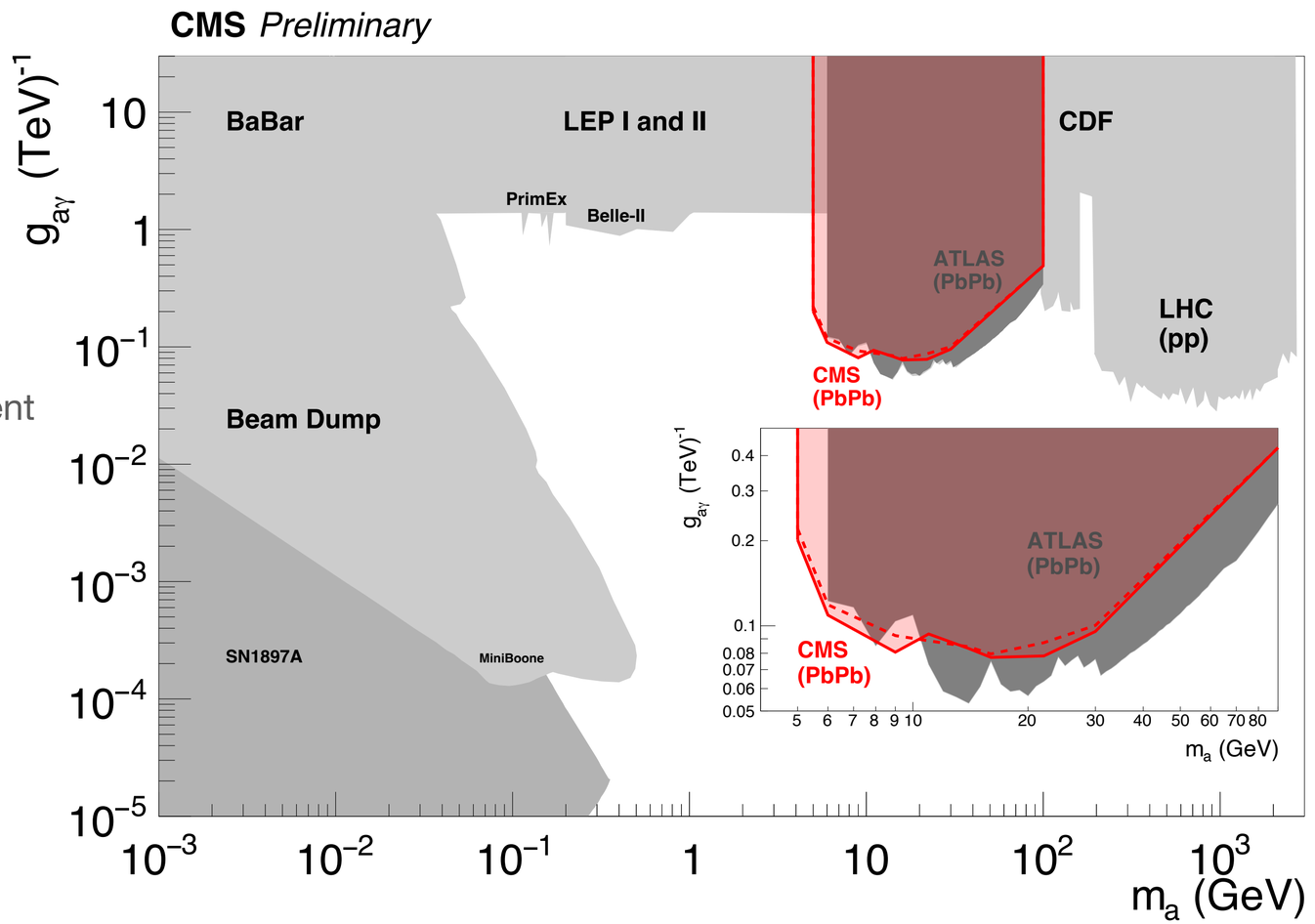
- Fiducial cross sections measured w.r.t. mass and rapidity
  - Consistent with gamma-UPC and SuperChic prediction

Constraints on axion-like particles

CMS-PAS-HIN-21-015

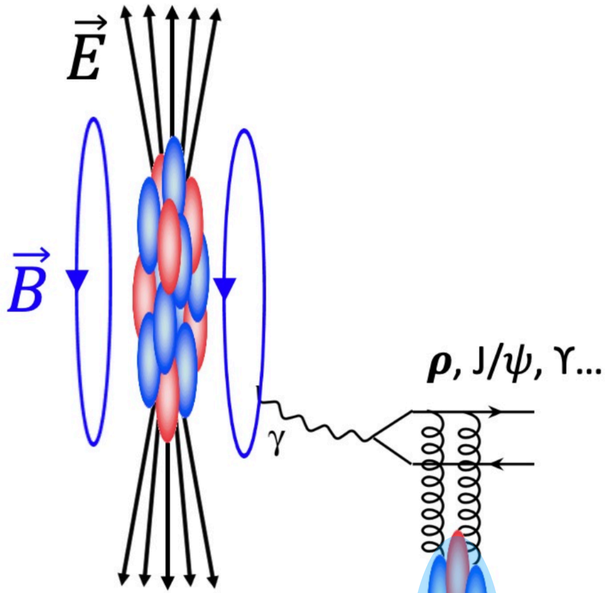
$$g_{a\gamma} = C_{\gamma\gamma}/\Lambda$$

- $C_{\gamma\gamma}$ = 1: dimensionless coefficient
- Assume $\mathcal{B}(a \to \gamma\gamma) = 100\,\%$
- ALP simulated with SuperChic



- Limits on ALP coupling to photon with $5 < m_a < 100$ GeV
  - Most straight limits for $5 < m_a < 10$ GeV

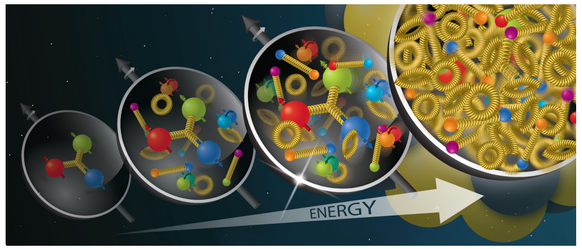
Photon-nuclear interactions



Coherent (nuclear keeps intact)

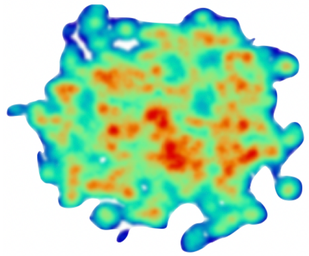
$\langle p_T \rangle \sim 50$ MeV

Average gluonic structure



Incoherent (nuclear breaks up)

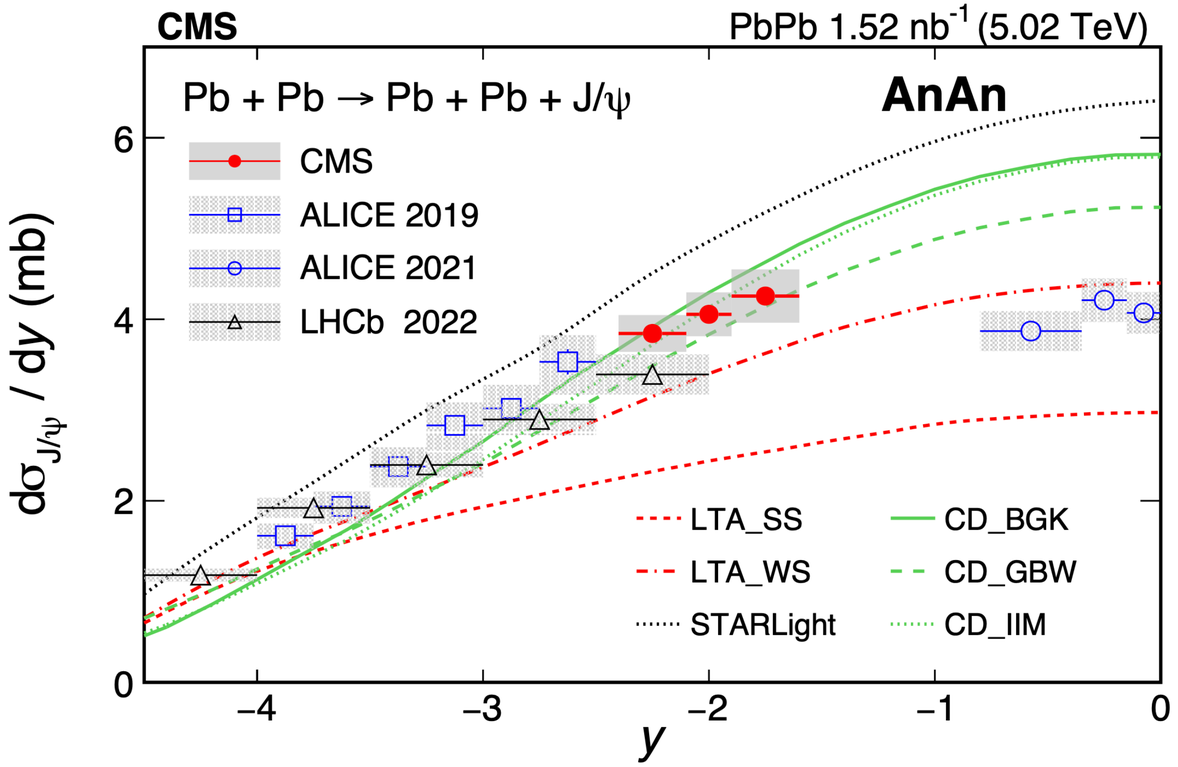
$\langle p_T \rangle \sim 500$ MeV



Sub-nucleon fluctuation

Imaging heavy nuclear with coherent J/ψ

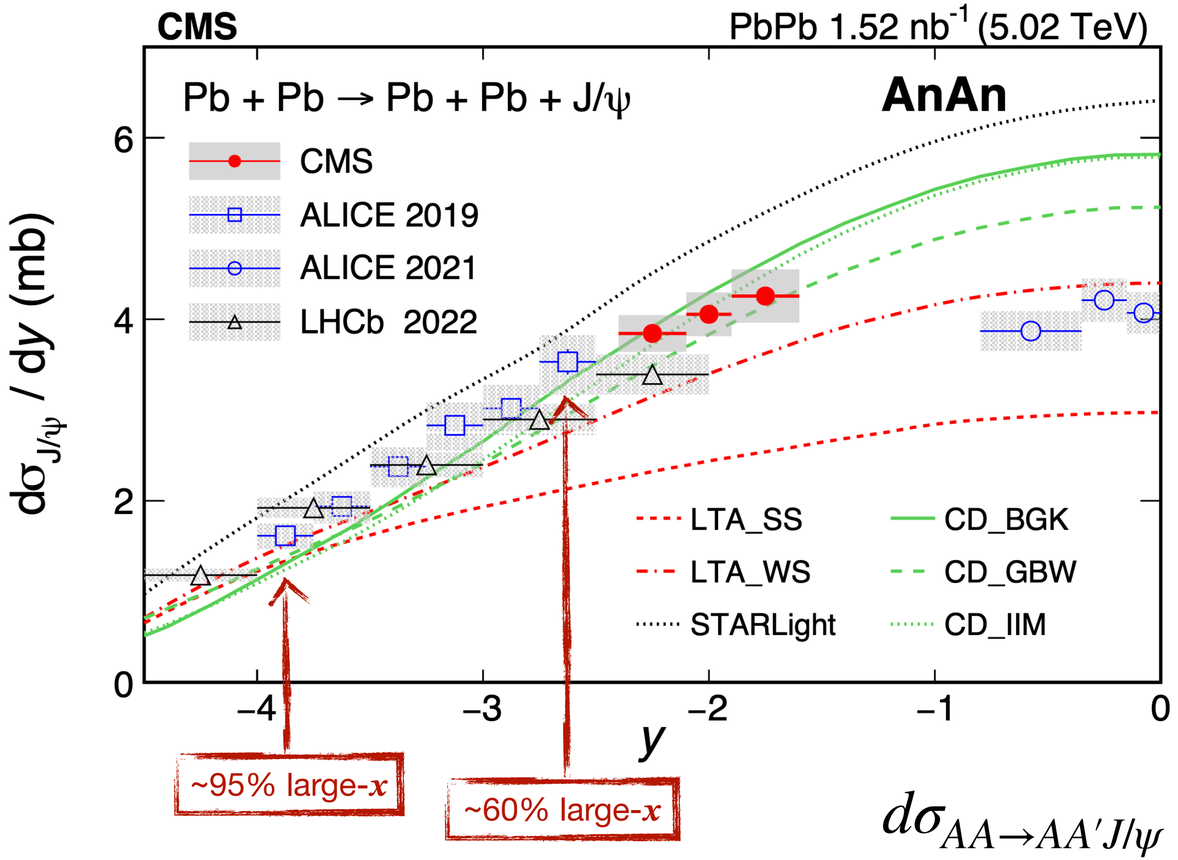
ALICE, EPJC 81 (2021) 712
CMS, PRL 131 (2023) 262301
LHCb, JHEP 06 (2023) 146



- LHC experiments complement each over a wide range of y region
  - $R_g^{Pb} = 0.64 \pm 0.04$ at x~10^{-3} (y=0)

Imaging heavy nuclear with coherent J/ψ

ALICE, EPJC 81 (2021) 712
CMS, PRL 131 (2023) 262301
LHCb, JHEP 06 (2023) 146



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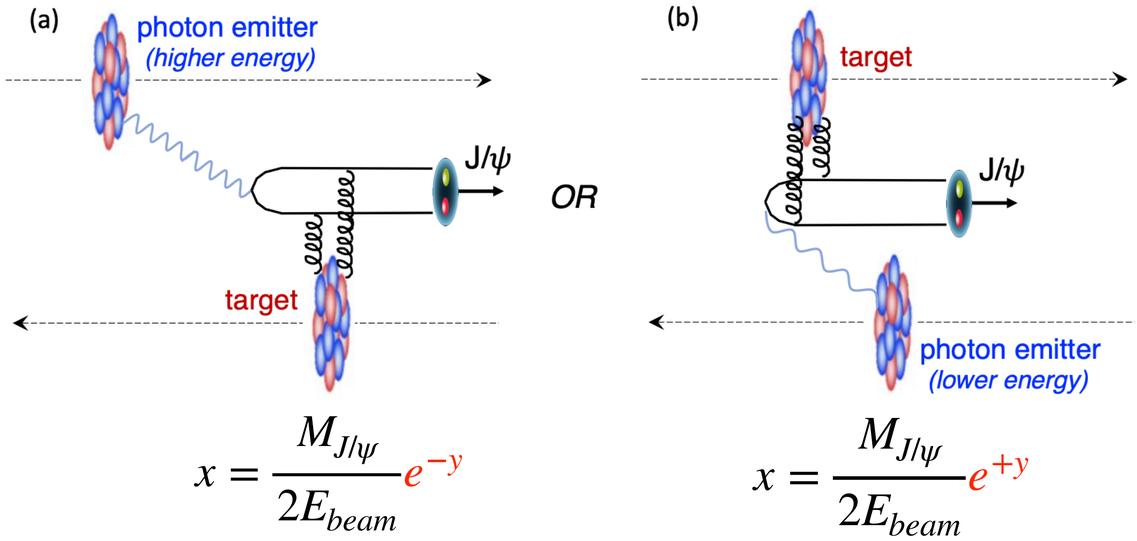


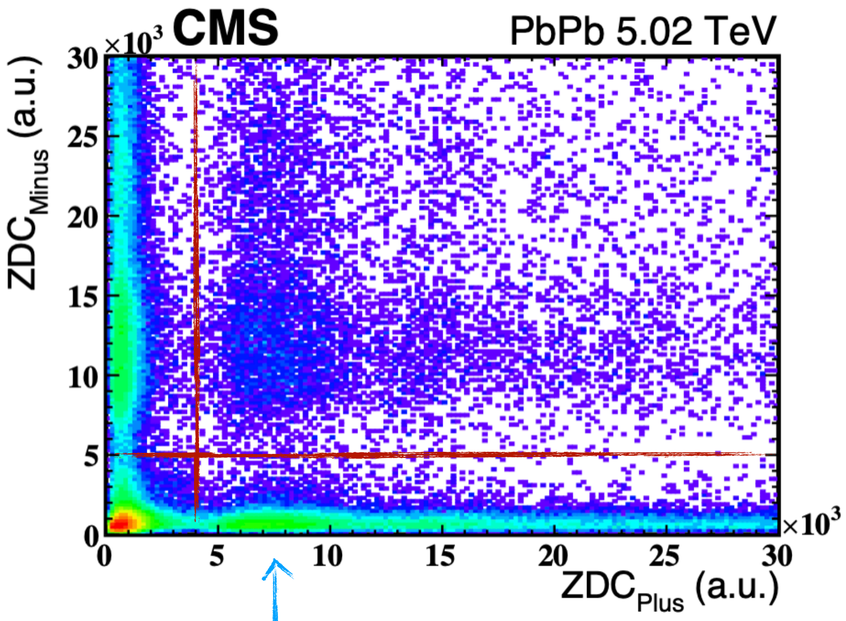
$$x = \frac{M_{J/\psi}}{2E_{beam}} e^{-y} \qquad x = \frac{M_{J/\psi}}{2E_{beam}} e^{+y}$$

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

A solution to the “two-way ambiguity”

CMS, PRL 127 (2021) 122001

Guzey et al., EPJC 74 (2014) 2942



Single neutron peak

Experimental measurements

Photon flux from theory

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

What we need!

↓

Solve the “two-way ambiguity”

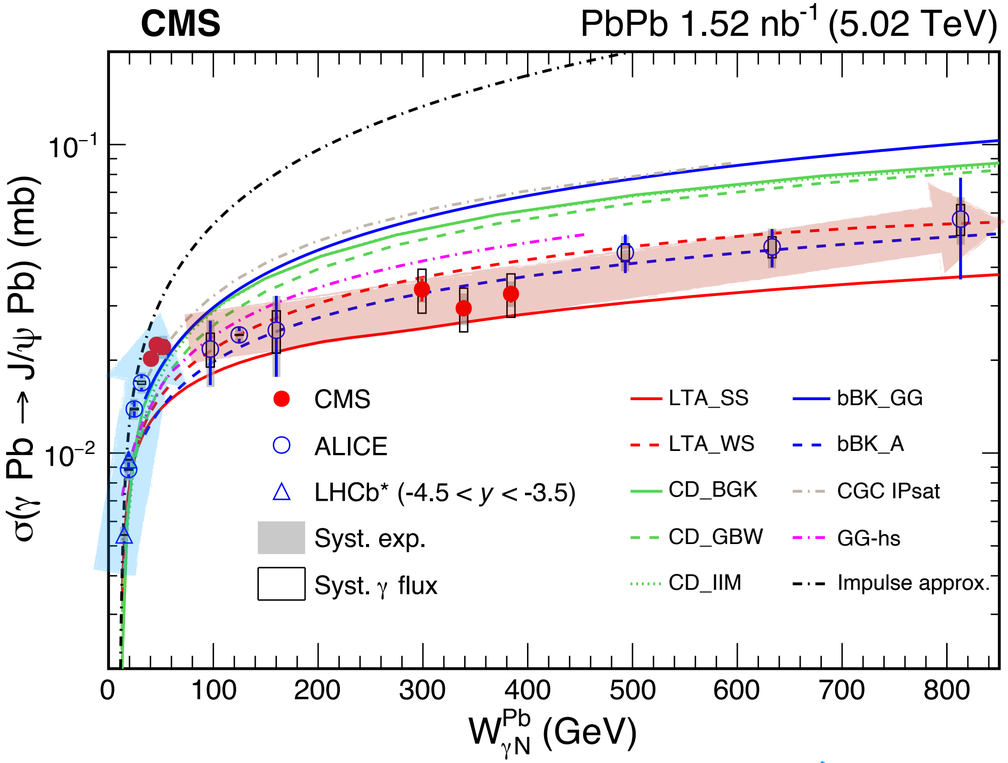
↓

Probe gluons at x~10^{-5}-10^{-4} in heavy nucleus!

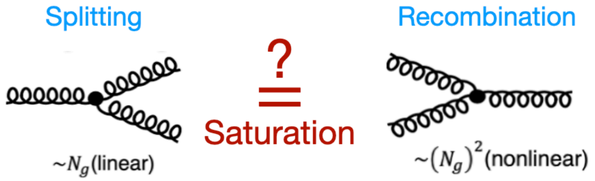
Imaging heavy nuclear with coherent J/ψ

CMS, PRL 131 (2023) 262301
ALICE, JHEP 10 (2023) 119

LO pQCD:
$\sigma^{VM} \propto [xG(x)]^2$



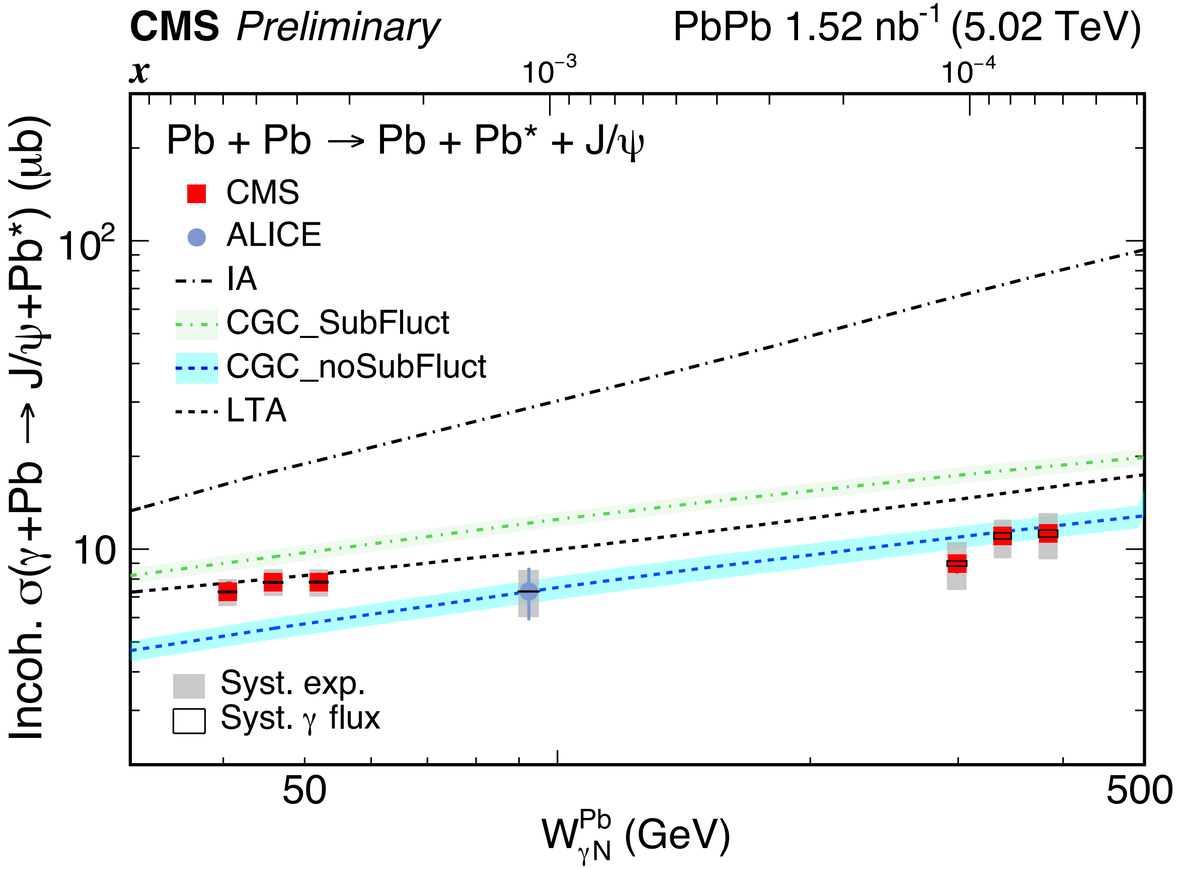
larger x → **smaller x**



- Direct evidence of gluon saturation inside heavy nuclei?
  - $W^{Pb}_{\gamma N} < 40$ GeV: rapidly rising
  - $40 < W^{Pb}_{\gamma N} < 800$ GeV: nearly flat with a much slower rising

Probing gluon fluctuations with incoherent J/ψ

CMS-PAS-HIN-23-009

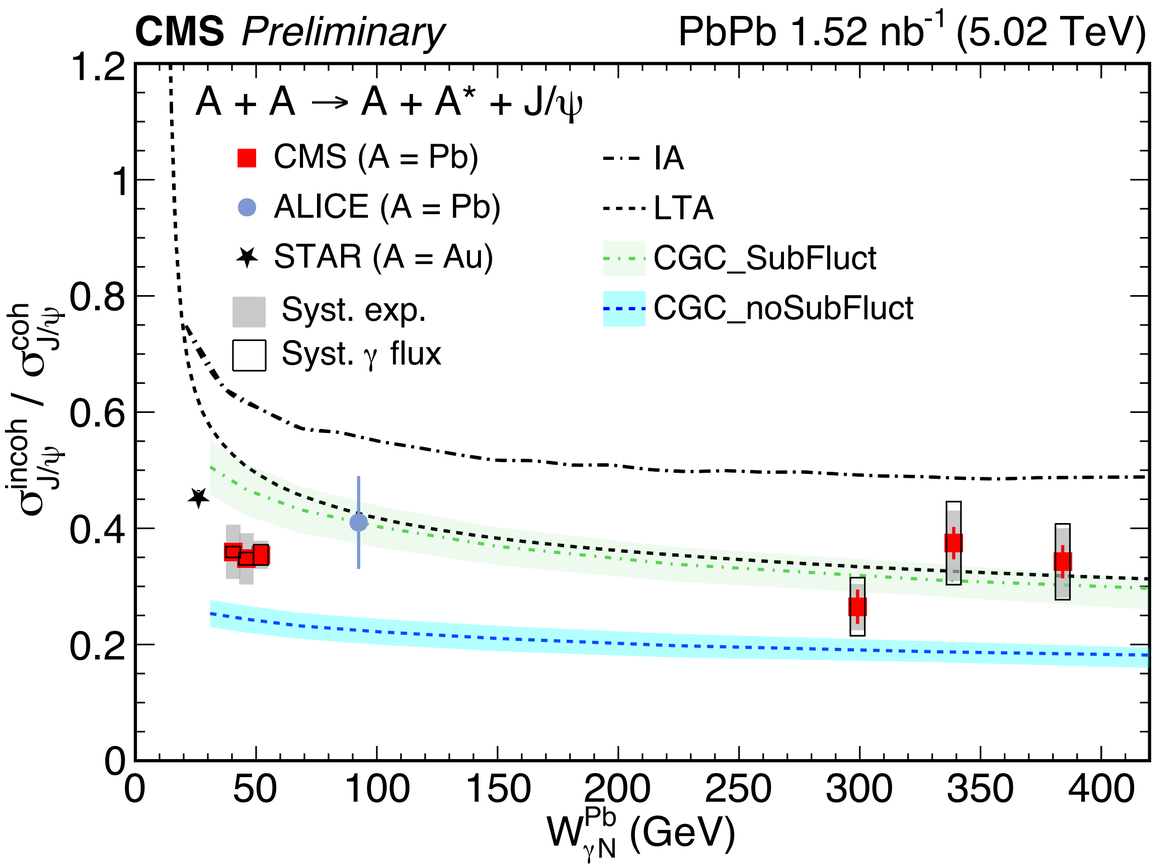


larger x → **smaller x**

- First measurement of incoherent J/ψ as a function of energy
- Strong suppression compared to impulse approximation model
- LTA describe the data with $W_{\gamma N}^{Pb} < 60$ GeV, while CGC without gluon fluctuations is consistent with data with $W_{\gamma N}^{Pb} > 90$ GeV

Comparisons of coherent and incoherent J/ψ

CMS-PAS-HIN-23-009

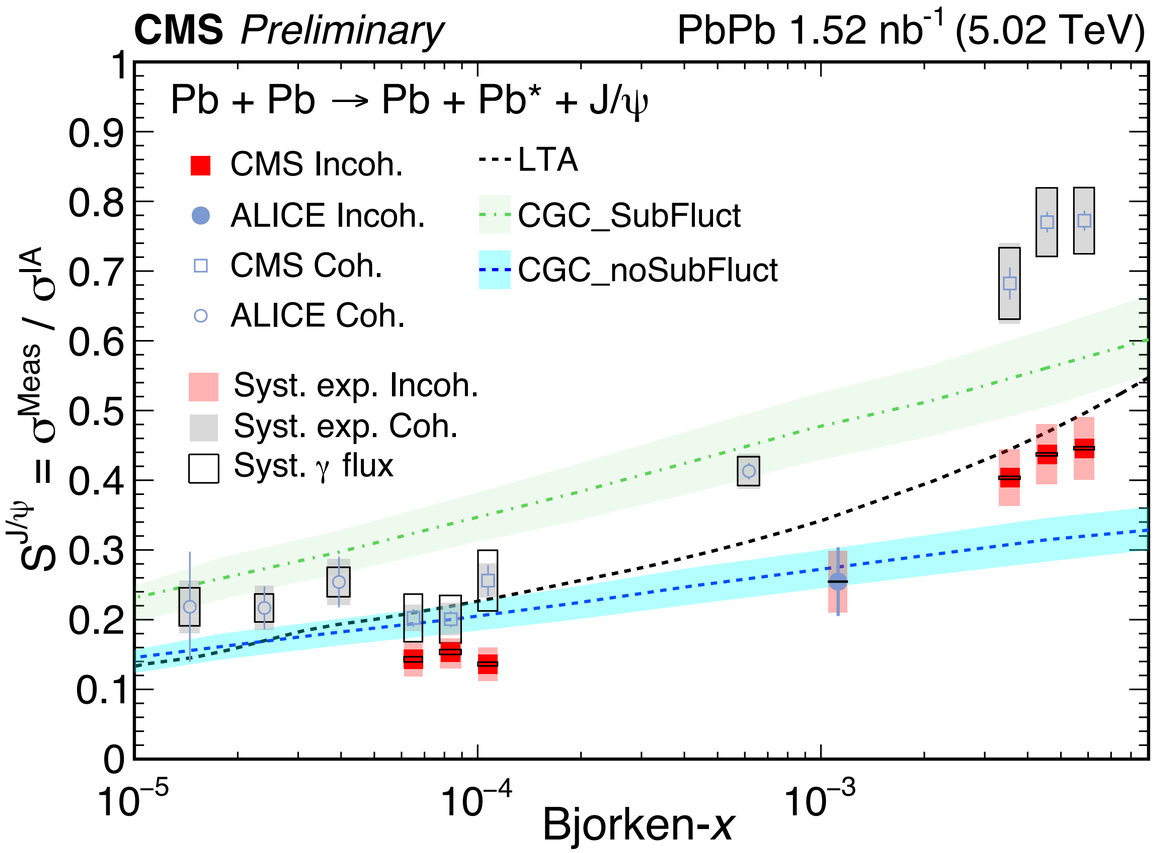


larger x → **smaller x**

- Uncertainties are largely cancelled
  - Experimental wise: Correlated systematic uncertainties
  - Theoretical wise: VM wave function, nucleon PDFs, photon flux, nuclear shape etc
- Incoherent J/ψ is more suppressed compared to coherent J/ψ
- Data are consistent CGC incorporating gluon fluctuations
  - Overestimates data at low energy

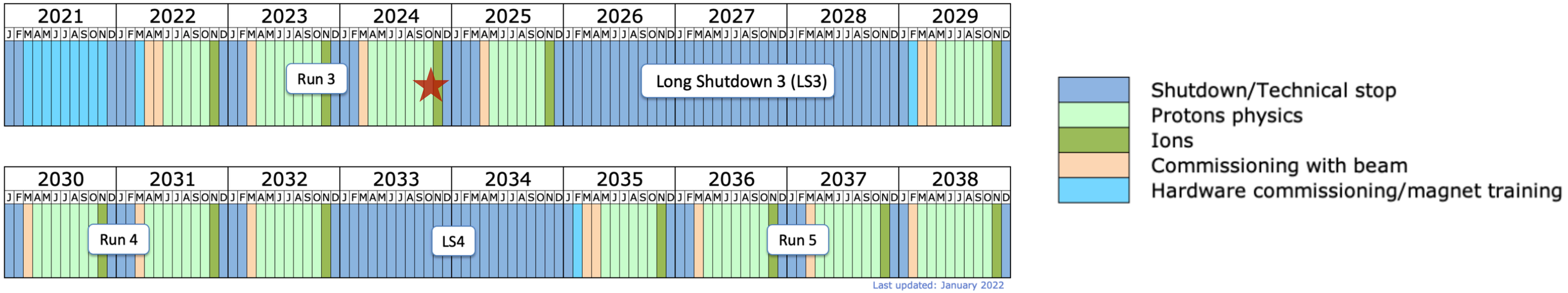
Comparisons of coherent and incoherent J/ψ

CMS-PAS-HIN-23-009

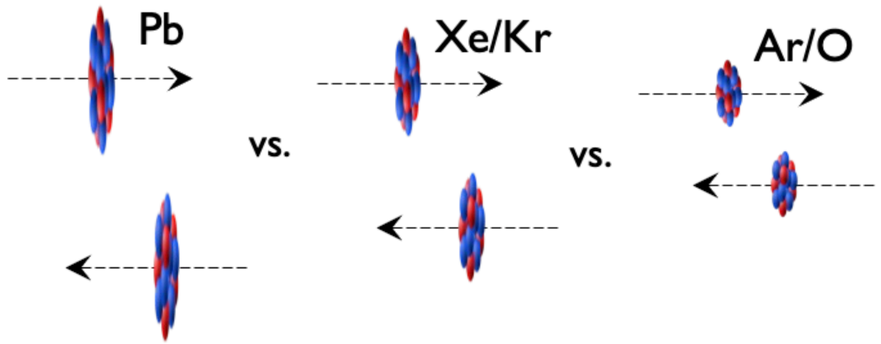


- Strong suppression towards low x region for both coherent and incoherent J/ψ
  - Flatten out at $x < 10^{-4}$
- Compare to coherent J/ψ, incoherent is J/ψ more suppressed at large x but remains consistent at small x
- No theoretical model can consistently describe the whole photoproduced J/ψ measurements

Future opportunities



- Exciting opportunities ahead
  - Higher luminosities
  - System size scan with different ion species
  - Detector upgrade with new technologies
- UPC programs
  - Precise measurements of $\gamma\gamma \rightarrow \gamma\gamma/\tau\tau$
  - Various vector meson photoproductions
  - Open HF and (di-)jet photoproductions



Summary

- Significant experimental progress of two-photon interactions
  - Demonstrated the importance of Sudakov effects at LHC with $\gamma\gamma \rightarrow ee$
  - Concluded the *b*-dependence of photon p_T with $\gamma\gamma \rightarrow \mu\mu$
  - Most precise a_τ measurement with $\gamma\gamma \rightarrow \tau\tau$
  - Constrain the coupling between ALP and photon with $\gamma\gamma \rightarrow \gamma\gamma$

- Multidimensional imaging of nuclei with photon-nuclear interactions
  - Direct experimental evidence of gluon saturation?
  - Energy dependence of the incoherent J/ψ production → sub-nucleon fluctuation

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Thank you for your attention!

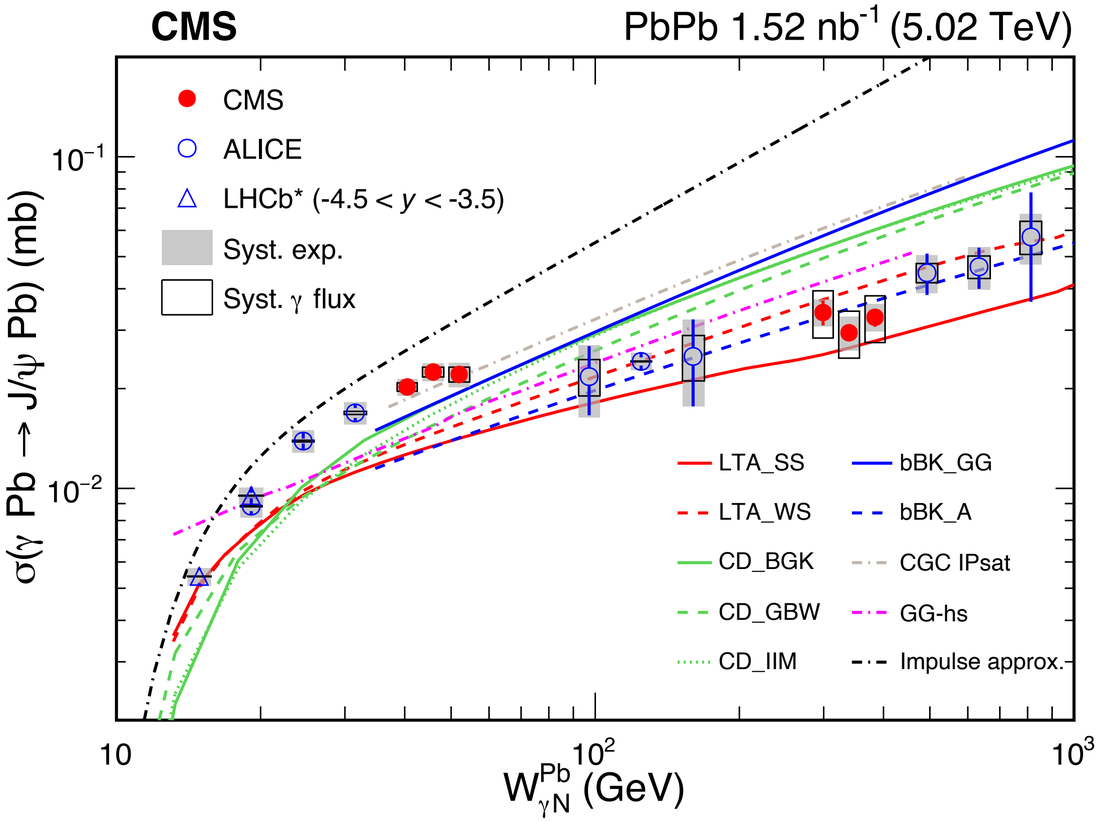
Backups

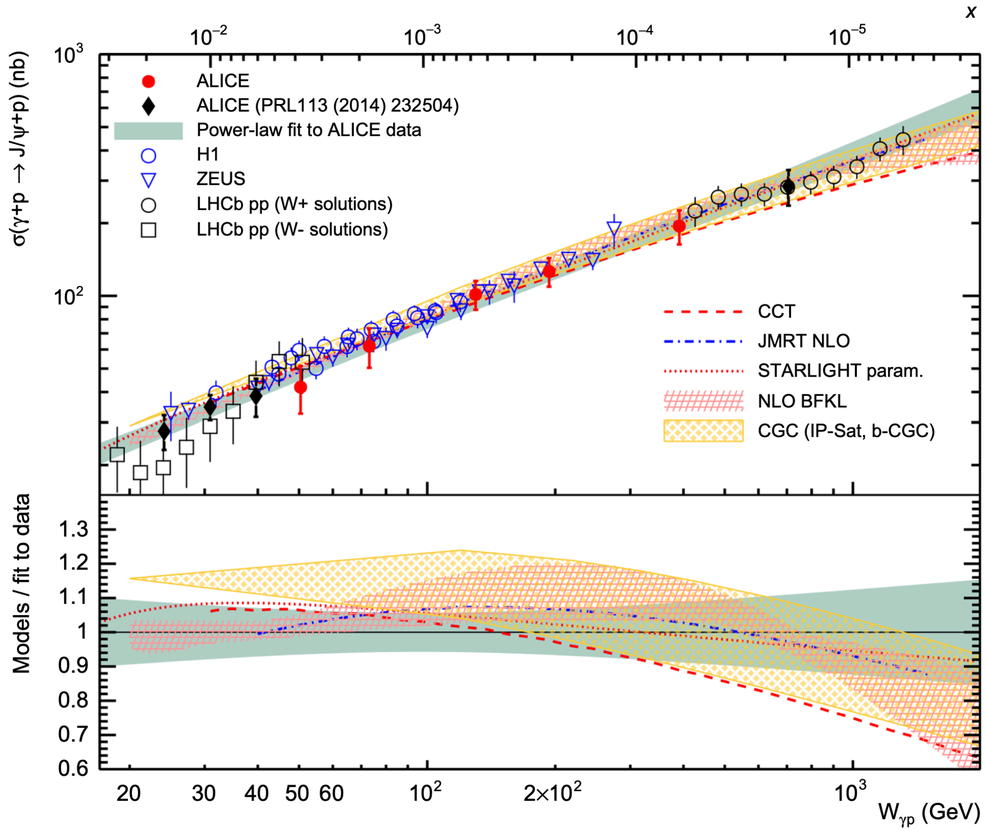
Coherent J/ψ production vs. $W_{\gamma N}^{Pb}$

ALICE, JHEP 10 (2023) 119
ALICE, EPJC 81 (2021) 712
ALICE, PLB 798 (2019) 134926

CMS, PRL 131 (2023) 262301
LHCb, JHEP 06 (2023) 146

ALICE, EPJC 79 (2019) 402



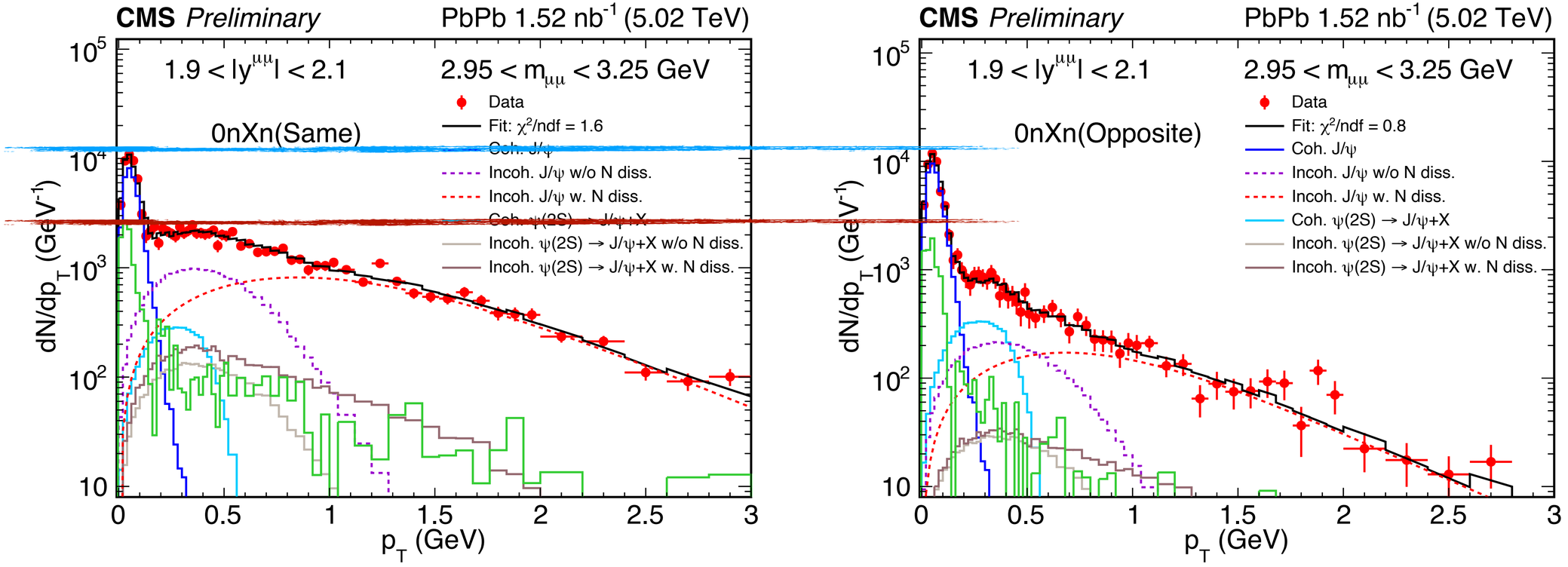


$\gamma A \rightarrow J/\psi A$

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

Incoherent J/ψ signal extraction

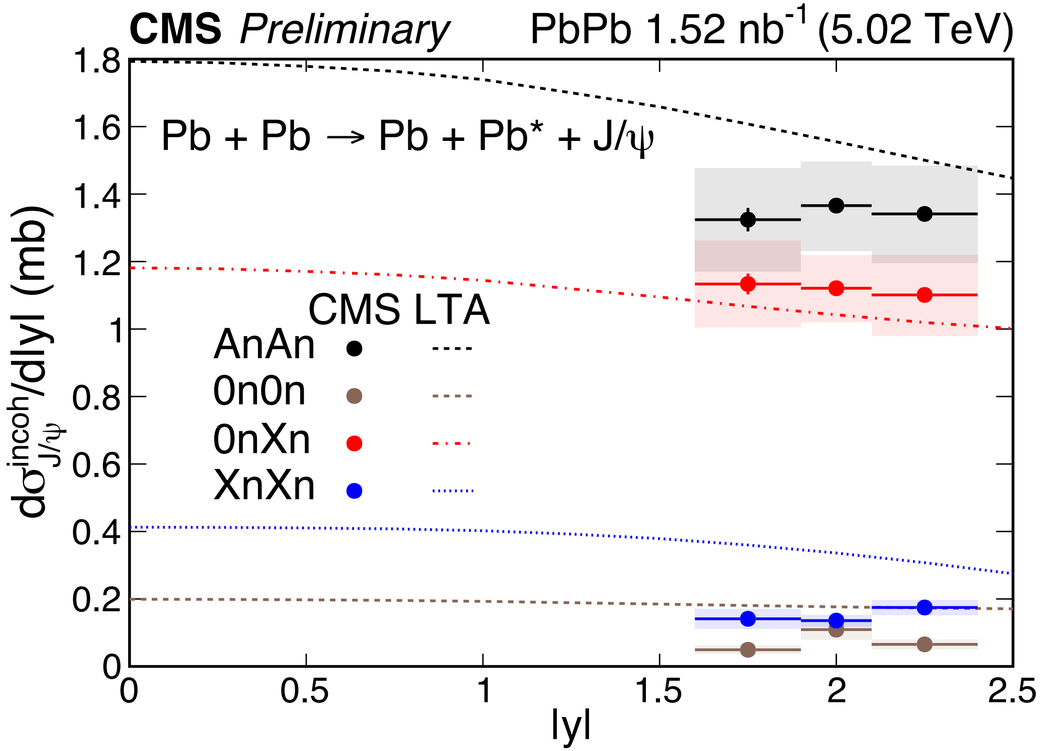
CMS-PAS-HIN-23-009

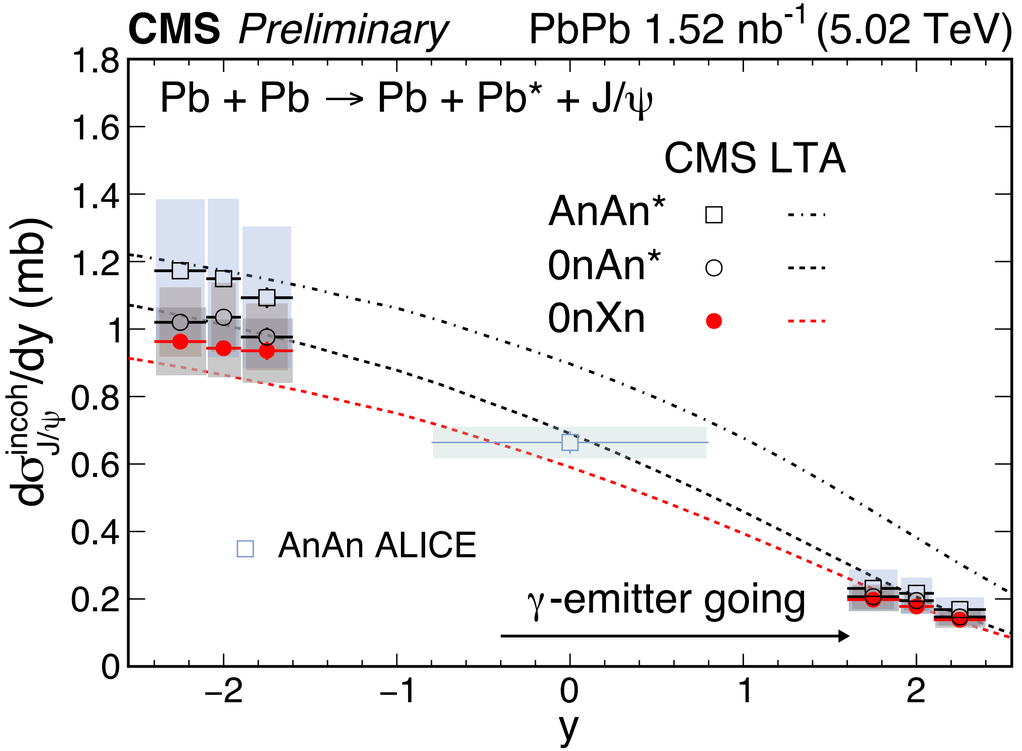


- Coherent J/ψ: no correlation with neutron emissions
- Incoherent J/ψ: strong correlation with neutron emissions

Incoherent J/ψ cross section vs. rapidity

CMS-PAS-HIN-23-009





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

- Relative yield ratio between positive over negative rapidity in 0n0n are assumed to be same as that in 0nXn events

Incoherent J/ψ production at LHC

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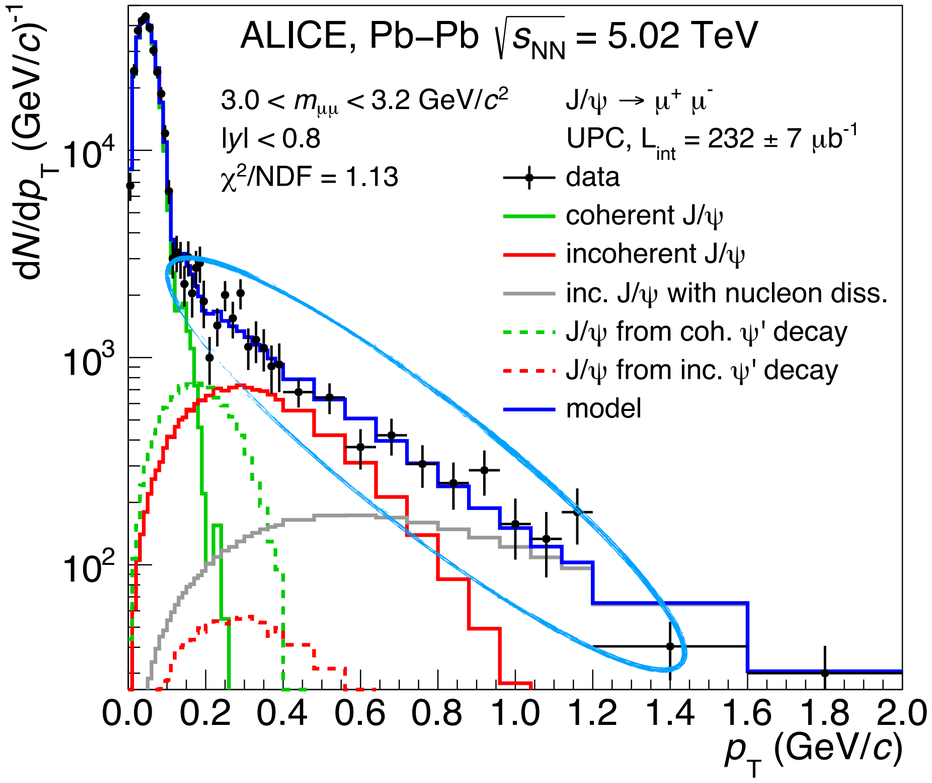

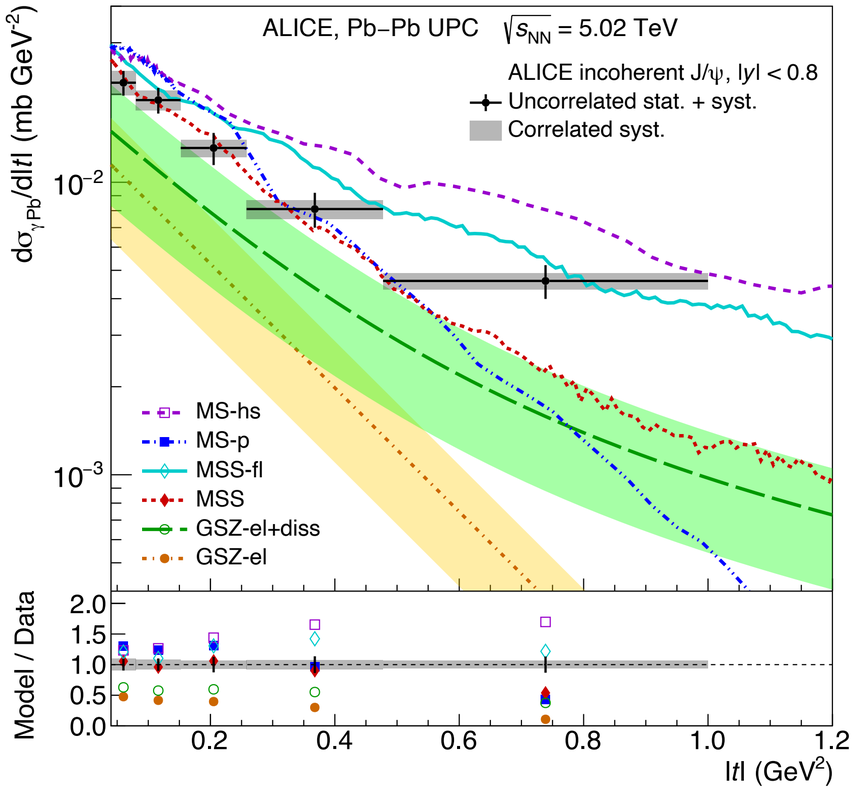

- The first measurement of |t| spectrum of incoherent J/ψ
  - No model describes both the absolute yield and the shape of |t| spectrum
  - A reasonably good description of the |t| spectrum is achieved when models incorporate sub-nucleon fluctuation