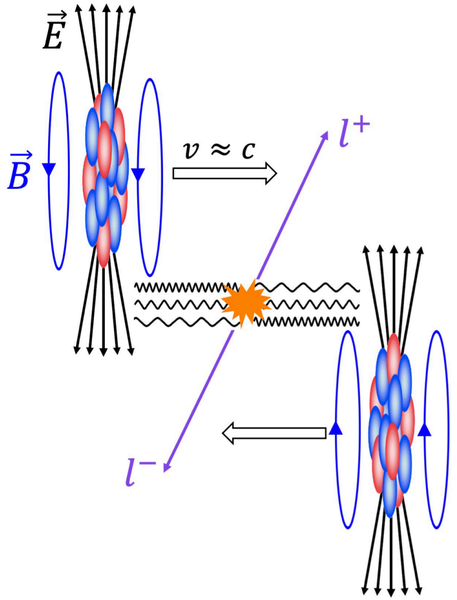
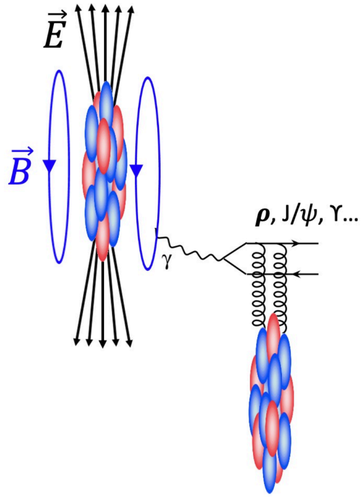
The recent measurements of ultra-peripheral collisions



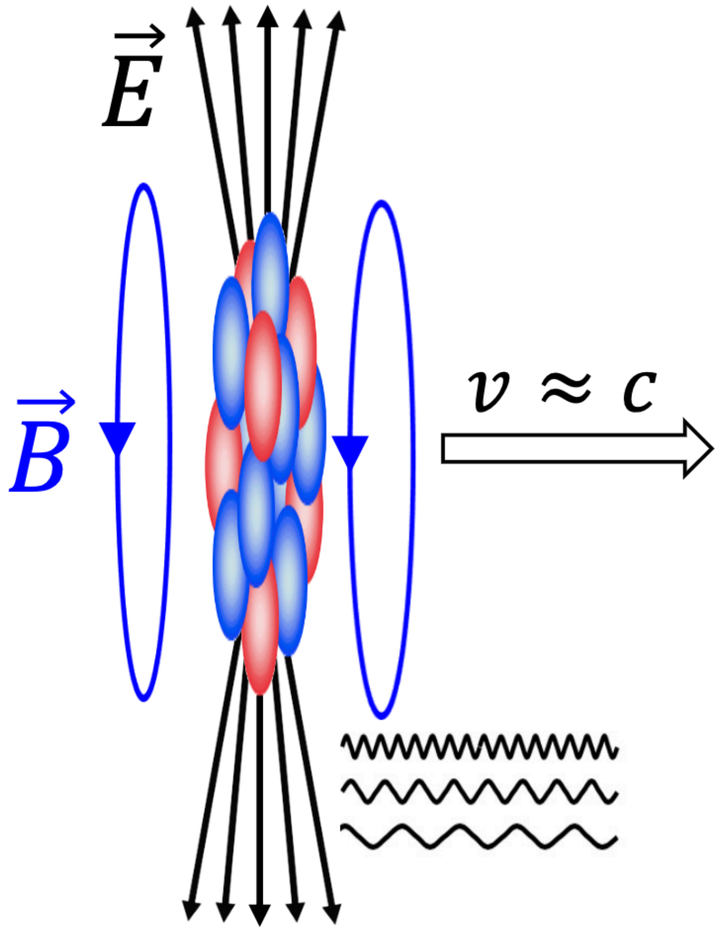
Shuai Yang (杨 帅)

South China Normal University



The 2nd China-Russia Joint Workshop on NICA Facility, Qingdao, Sep 10-13, 2024

Equivalent photon



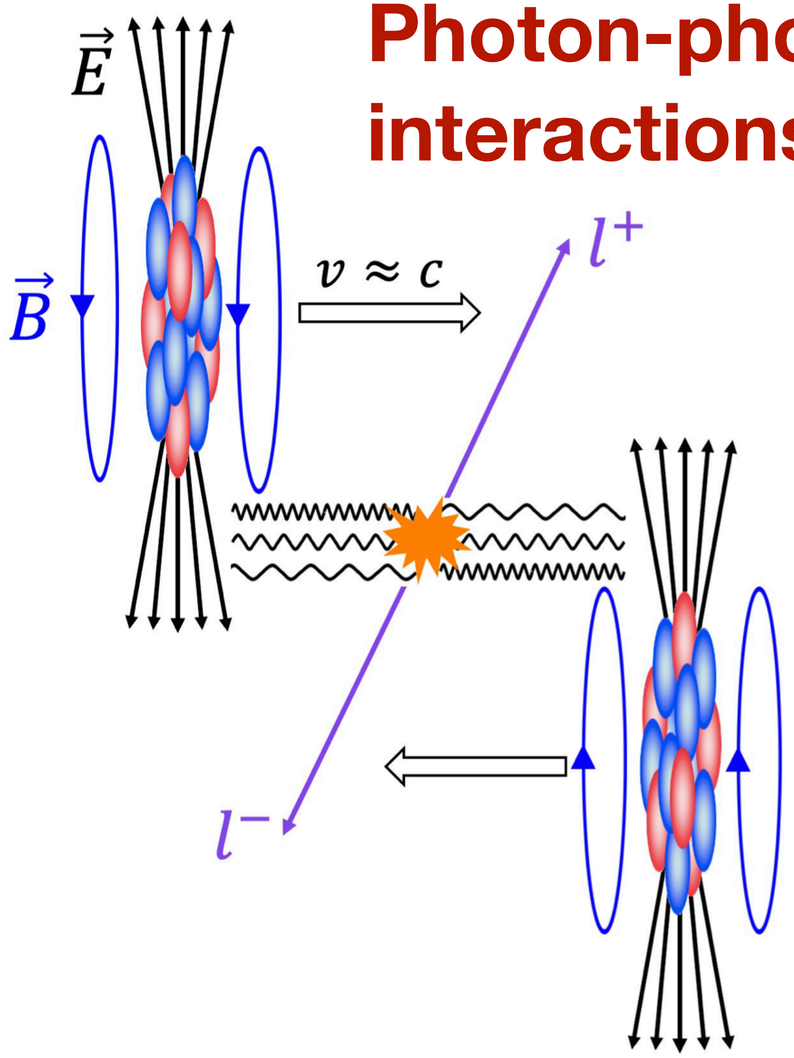
- Equivalent Photon Approximation
  - Photon Flux ∝ Z^2
  - Q^2~0 (quasi real photon)

Fermi, Z. Phys. 29 (1924) 315
Williams, Phys. Rev. 45 (1934) 729
Weizsacker, Z. Phys. 88 (1934) 612

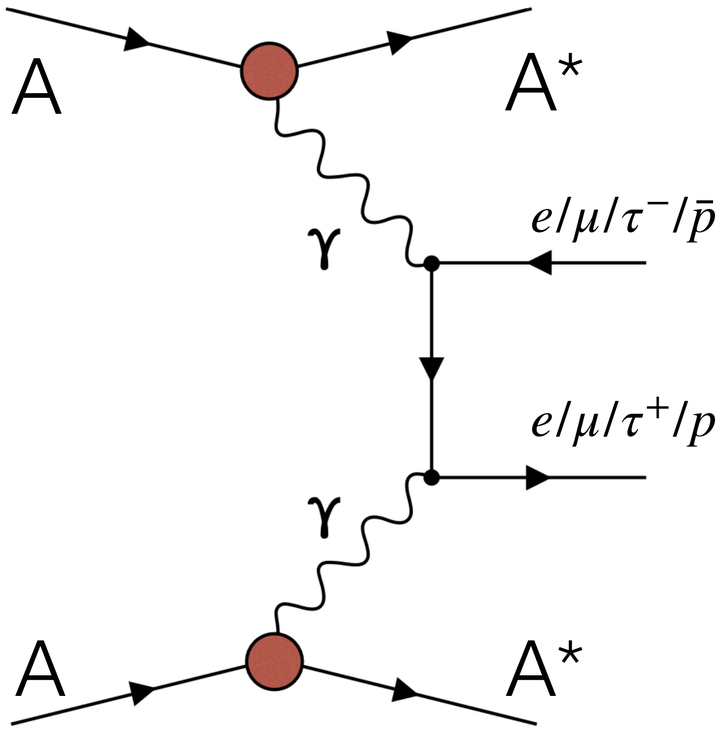
- Photon kinematics

maximum energy $E_{\gamma,max}$~γ($\hbar$c/R)	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) p_{Tmax} ~ $\hbar$c/R	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as **Z^2**: nuclei >> protons	Flux of photons on other nucleus ~ **Z^2**, flux of photons on photons ~ **Z^4 (45M!)**

Photon-photon interactions



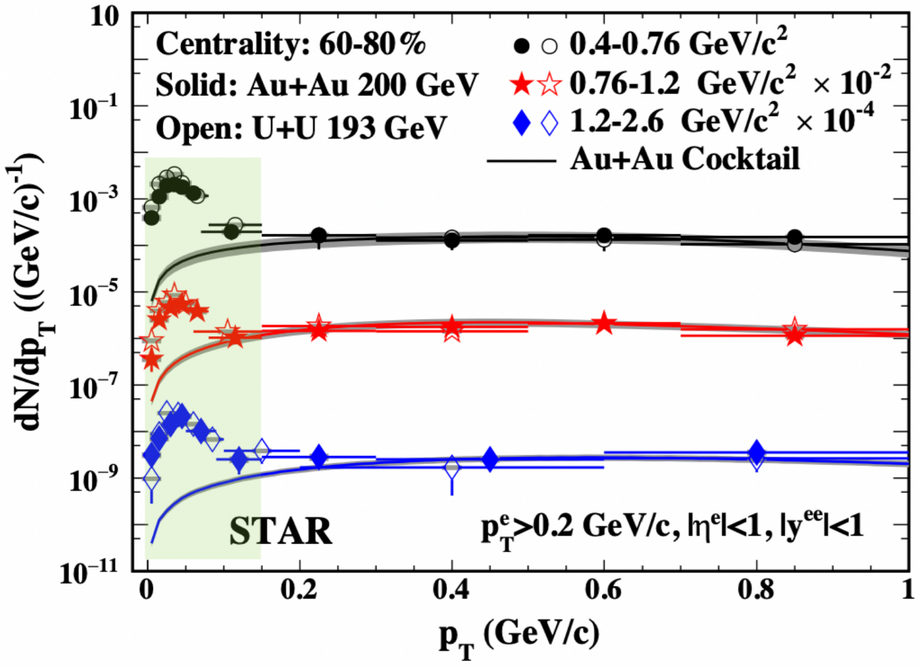
Photon-photon interactions

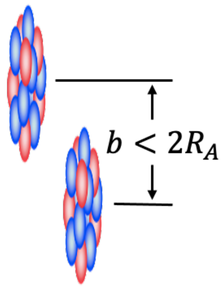


- QED
- BSM physics

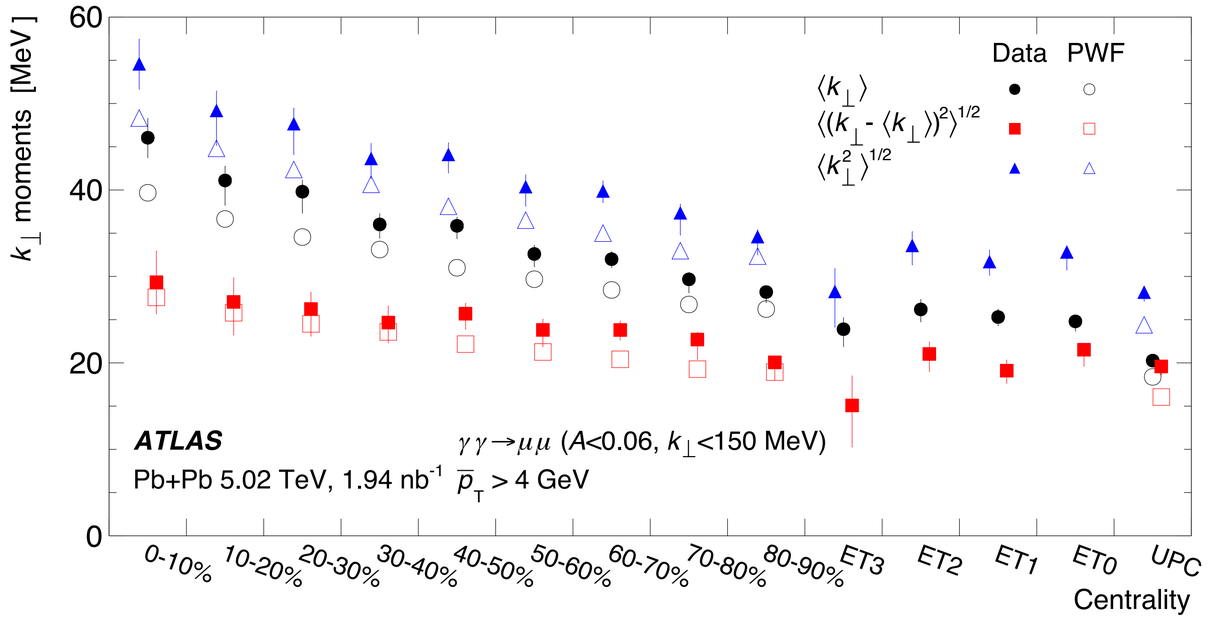
Observed Breit-Wheeler process in non-UPC

STAR, PRL 121 (2018) 132301





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

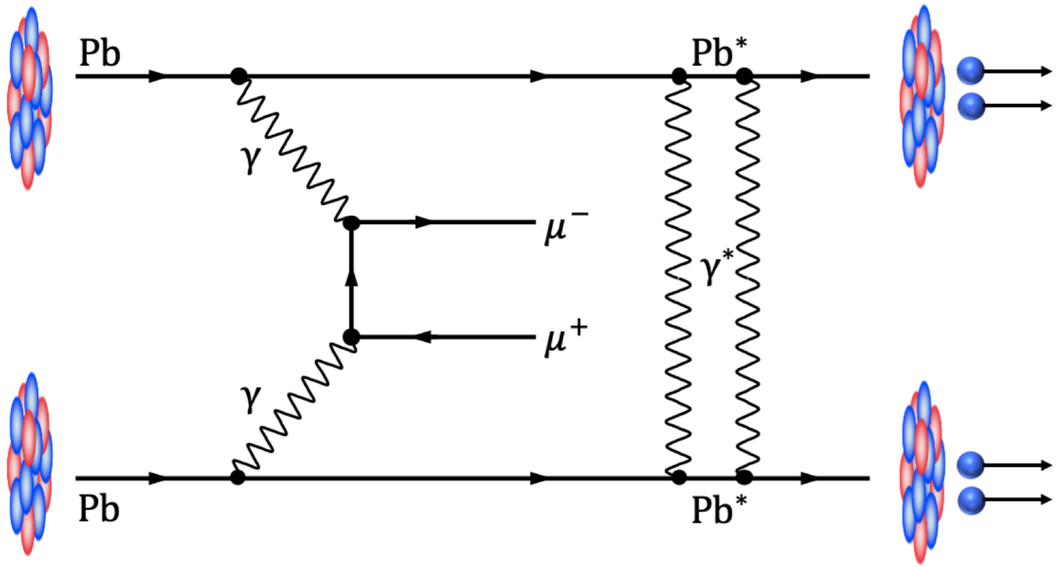


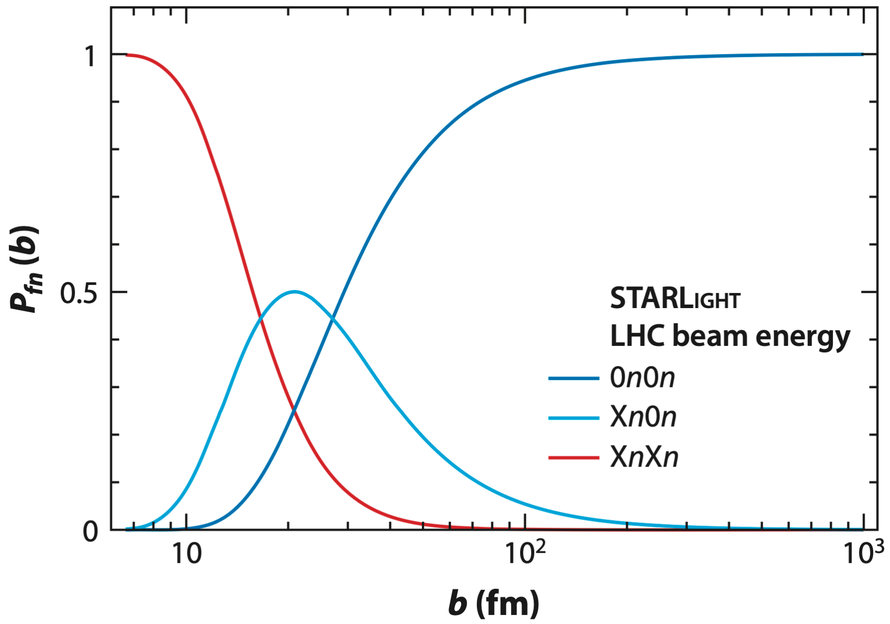
smaller *b* ← **larger *b***

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

Control impact parameter in UPC

Nuclei **may** exchange soft photon(s) ⟹ nuclear dissociation

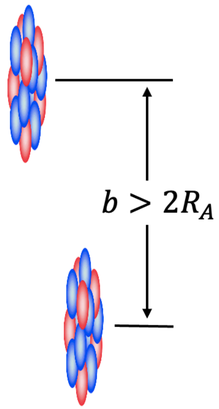


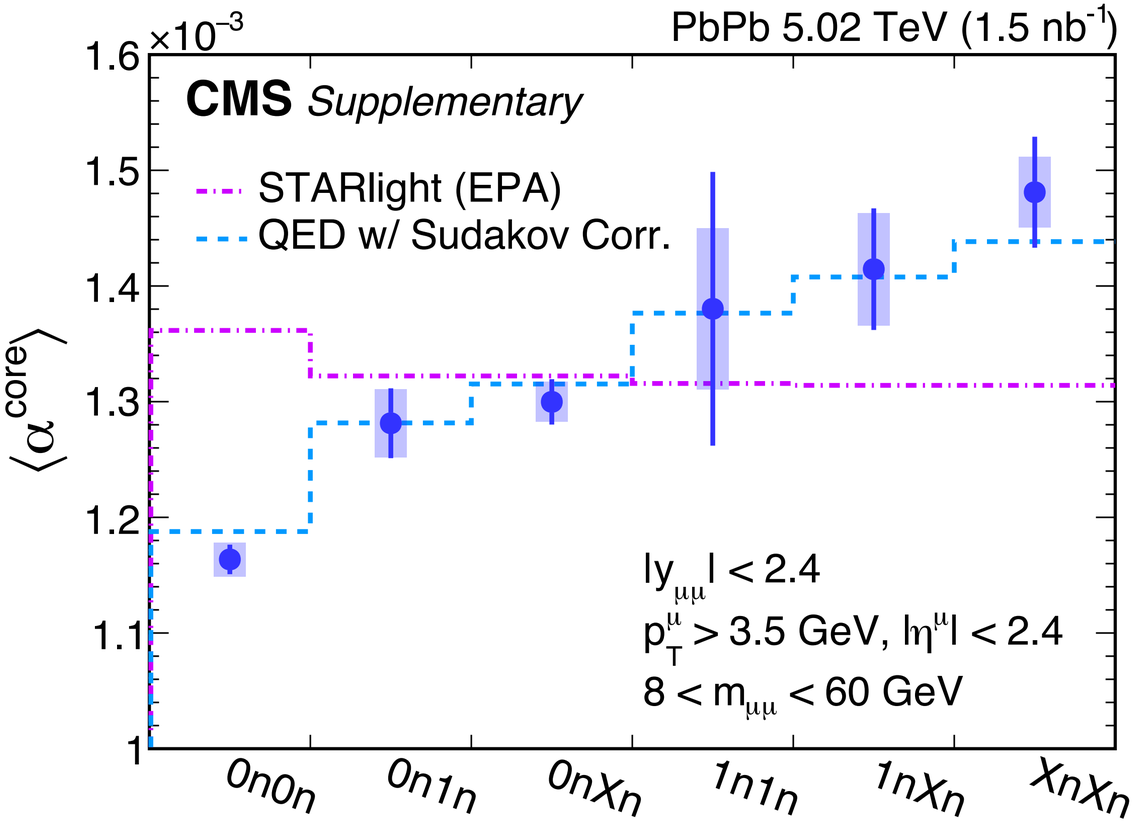


Klein and Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

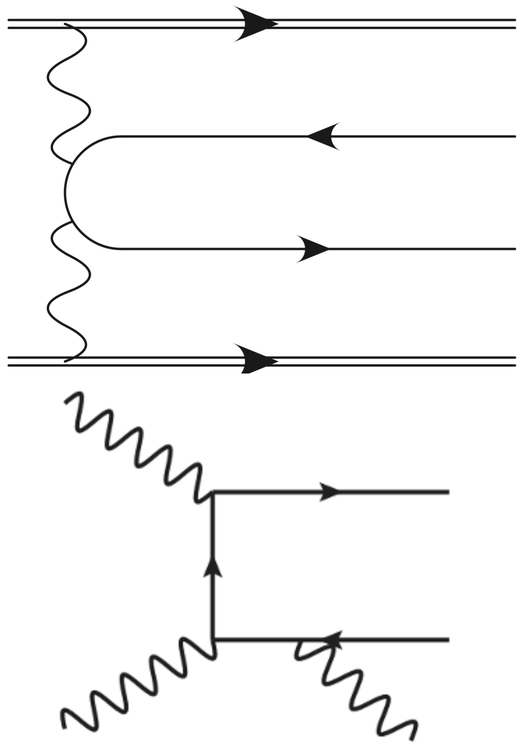
- Control the impact parameter via forward neutron multiplicity
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

Concluded the *b* dependence of photon p_T





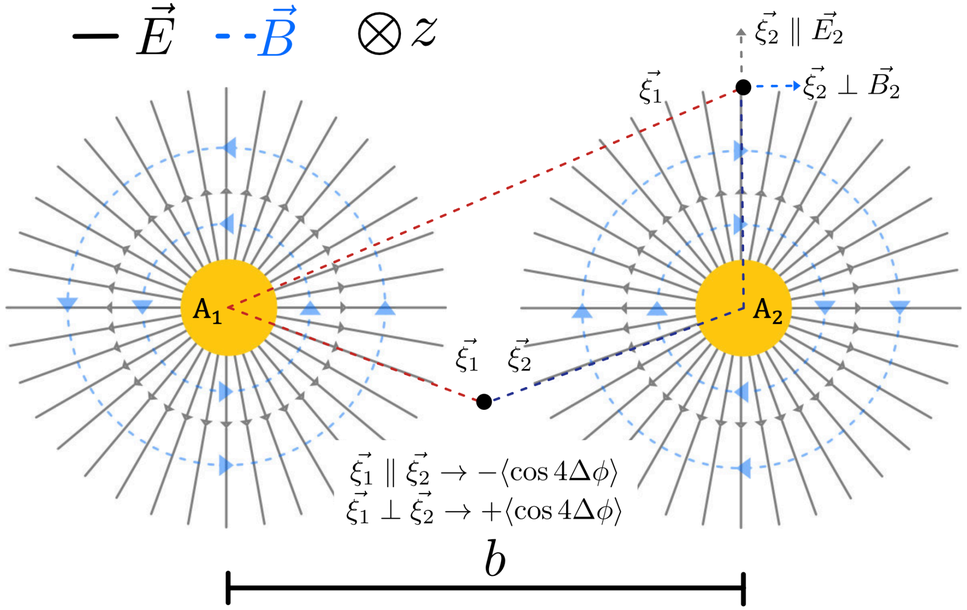
CMS, PRL 127 (2021) 122001
Brandenburg et al., arXiv:2006.07365



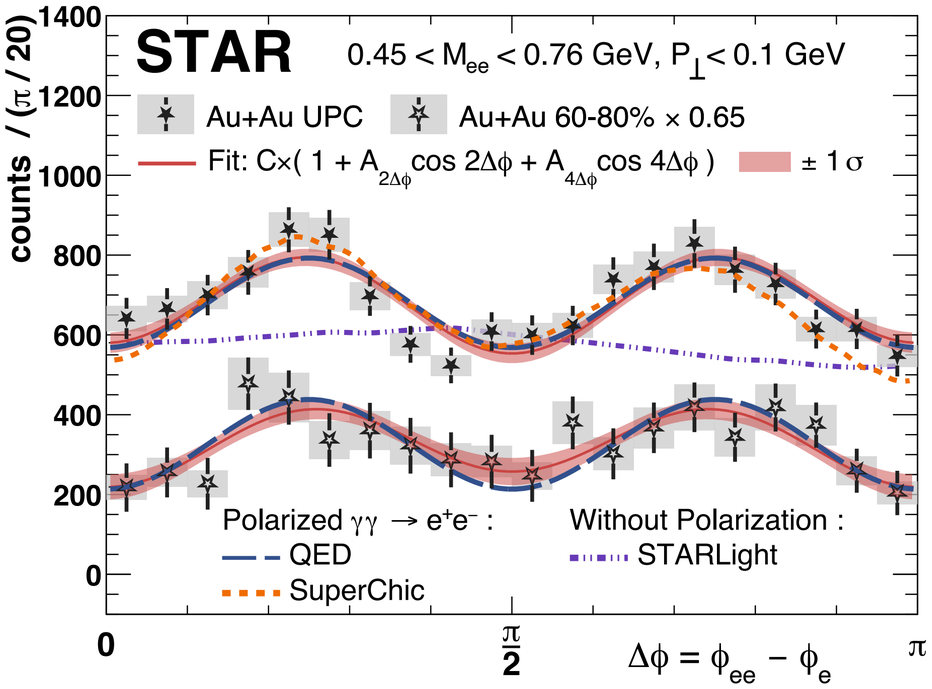
- Qualitatively described by a leading order QED model
- Demonstrated the b dependent of photon p_T
  - Precise reference for probing QGP EM effects

Experimental signature of linearly polarized photons

Li, Zhou, and Zhou, PLB 795 (2019) 576



STAR, PRL 127 (2021) 052302



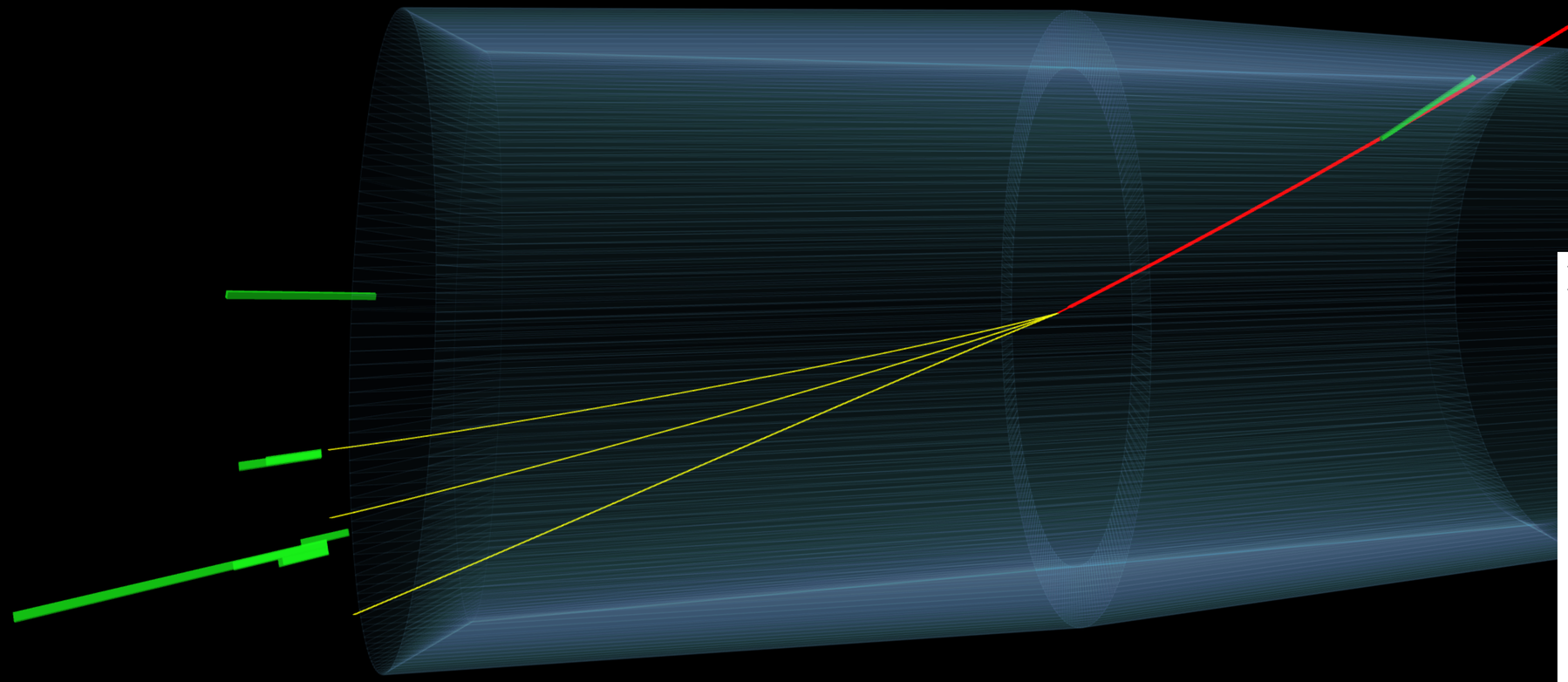
- Different helicity amplitude combinations for linearly polarized photons lead to a splitting of angular modulation
- Experimentally observe that photons are linearly polarized
  - UPC: $A_{4\Delta\phi}$ observed with > 6σ
  - non-UPC: $A_{4\Delta\phi}$ observed with > 4σ

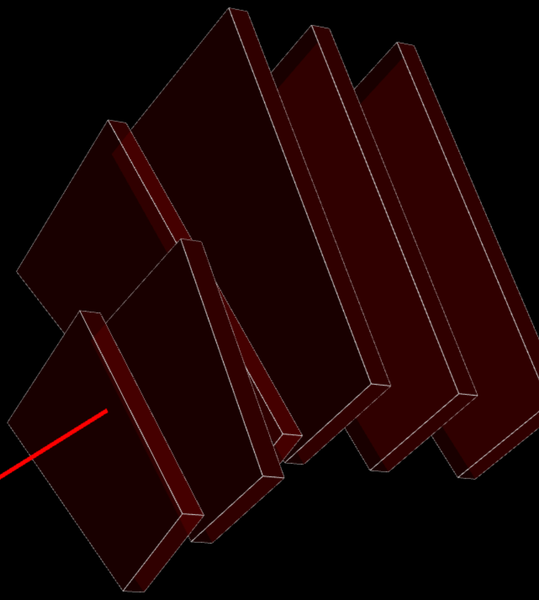
Observation of $\gamma\gamma \to \tau\tau$ in AA

CMS Experiment at the LHC, CERN

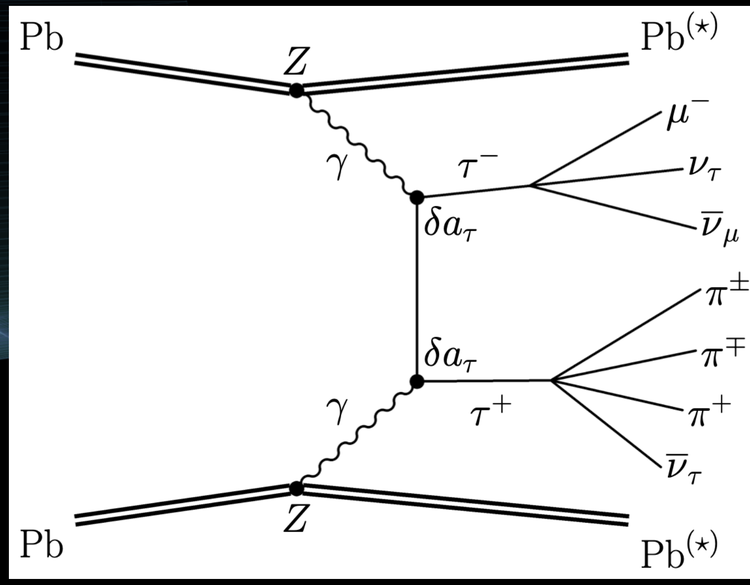
Data recorded: 2015-Dec-06 21:41:27.033612 GMT

Run / Event / LS: 263400 / 88515785 / 849



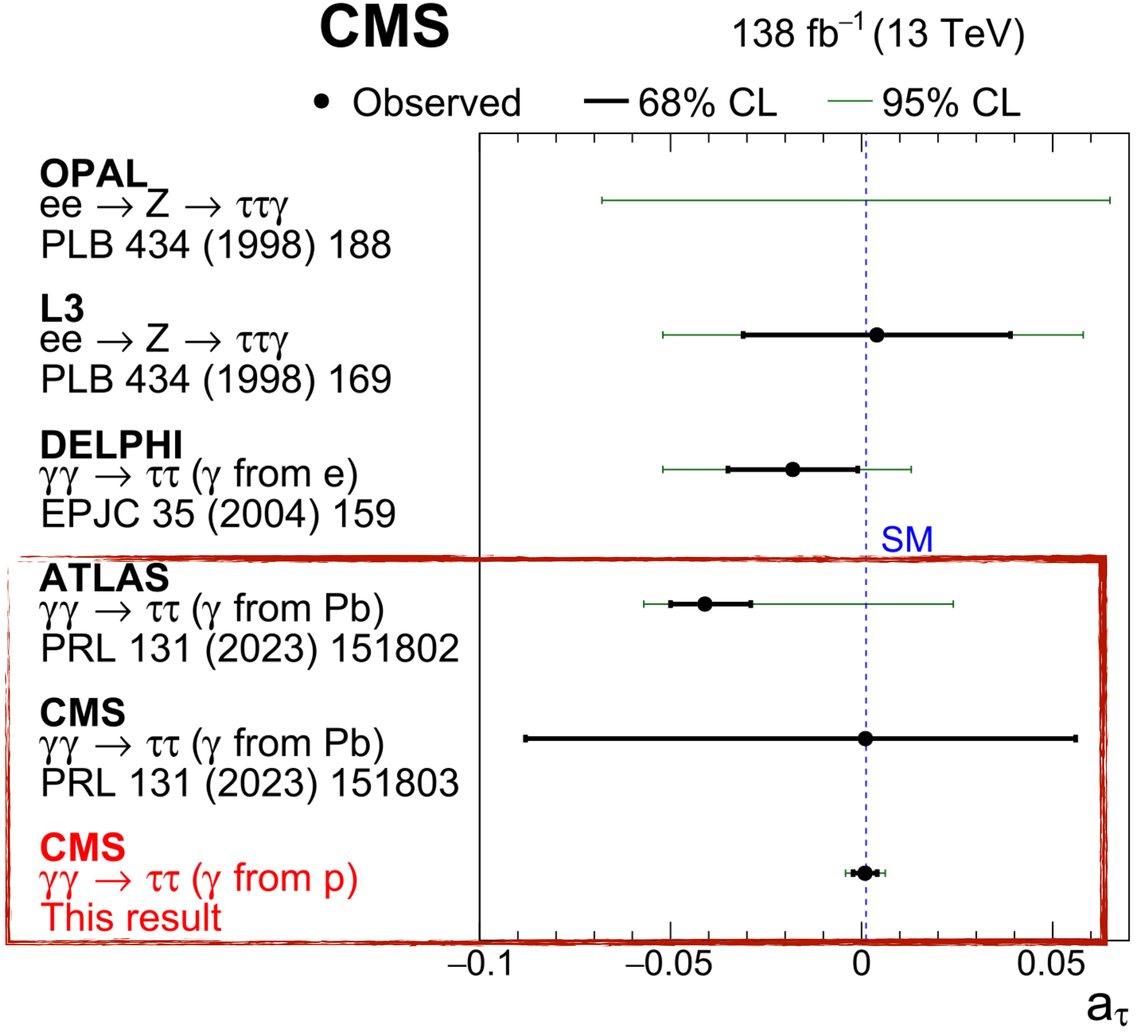


ATLAS, PRL 131 (2023) 151802
CMS, PRL 131 (2023) 151803



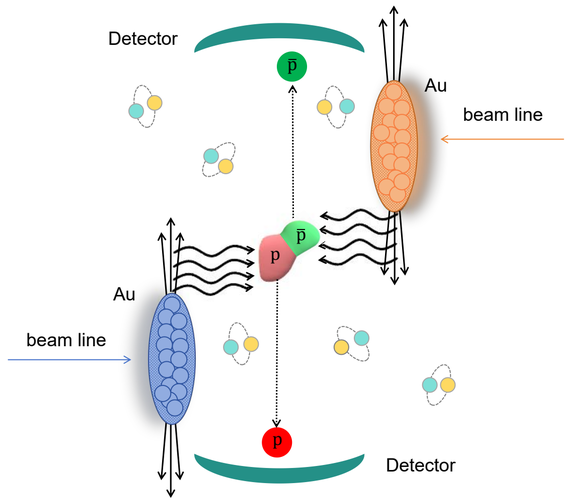
Constrain $a_\tau = (g_\tau - 2)/2$

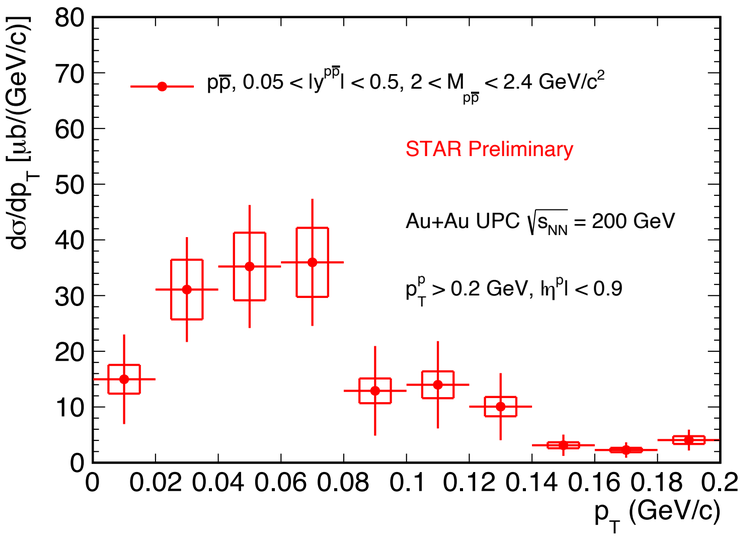
ATLAS, PRL 131 (2023) 151802
CMS, PRL 131 (2023) 151803
CMS, ROPP 87 (2024) 107801



- Sensitivity to the BSM physics
  - Model-dependent value of a_τ
  - Much better precision compared to DELPHI result

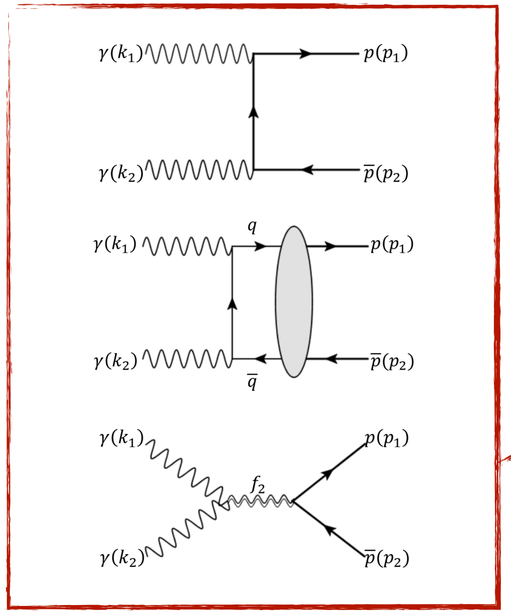
Higher excitation of QED vacuum

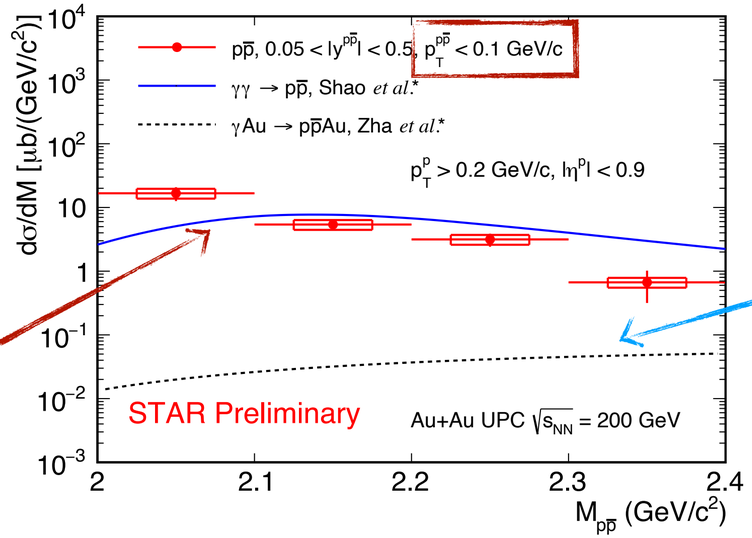


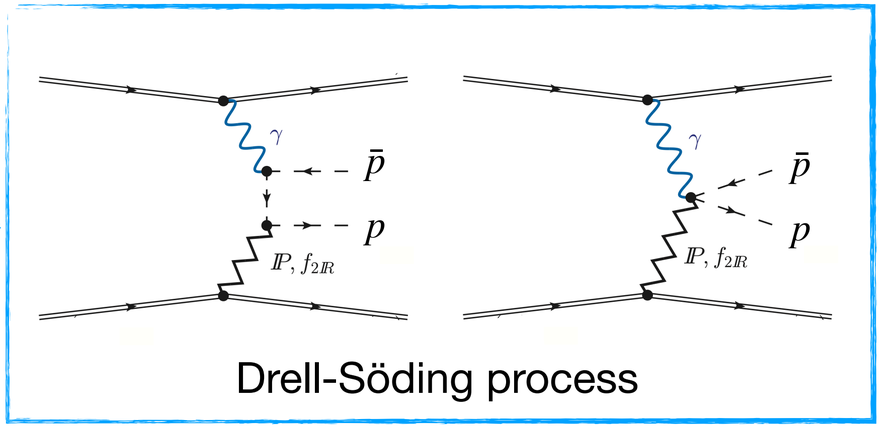


Zhang, Zhang, and Shao, arxiv: 2406.05618

- First observation of $\gamma\gamma \rightarrow$ dibaryon production in UPC
  - Contribution of Drell-Söding process is significantly lower than data
  - Consistent with $\gamma\gamma \rightarrow p\bar{p}$ production

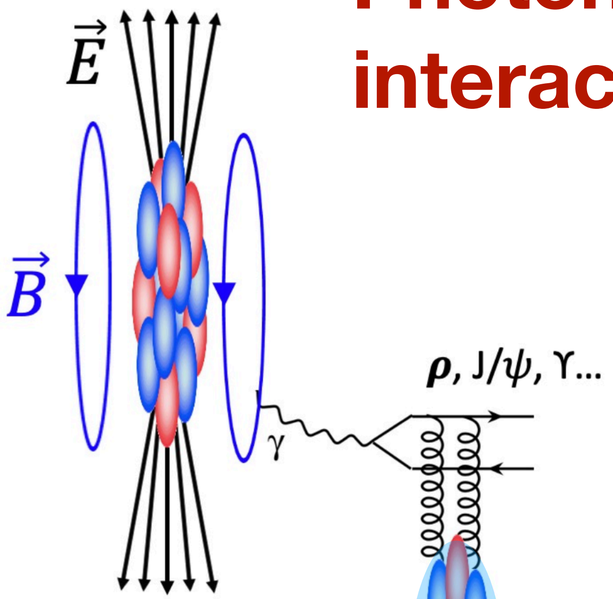






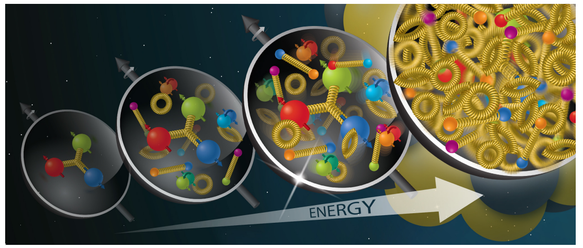
Photon-nuclear interactions

Photon-nuclear interactions



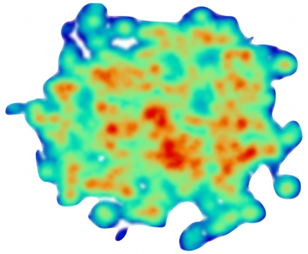
- Little “EIC”

Coherent (nuclear keeps intact)



gluonic structure

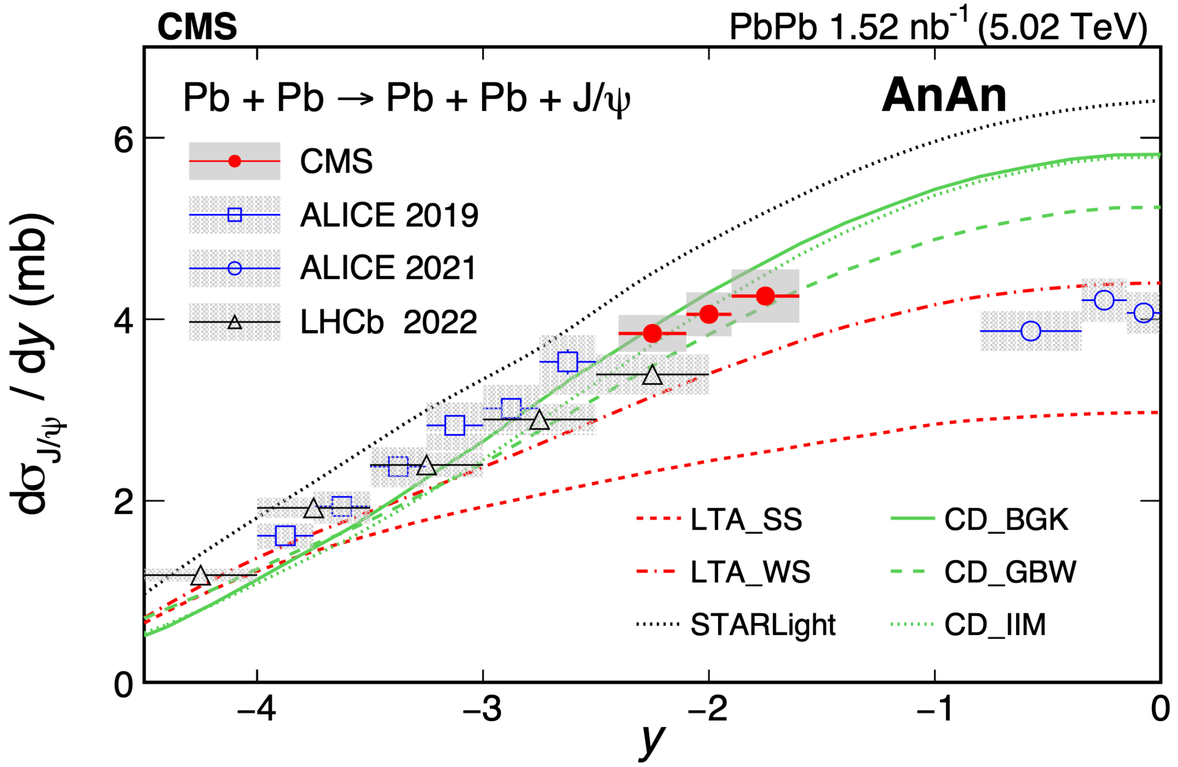
Incoherent (nuclear breaks up)



sub-nucleon fluctuation

Imaging heavy nuclear with coherent J/ψ

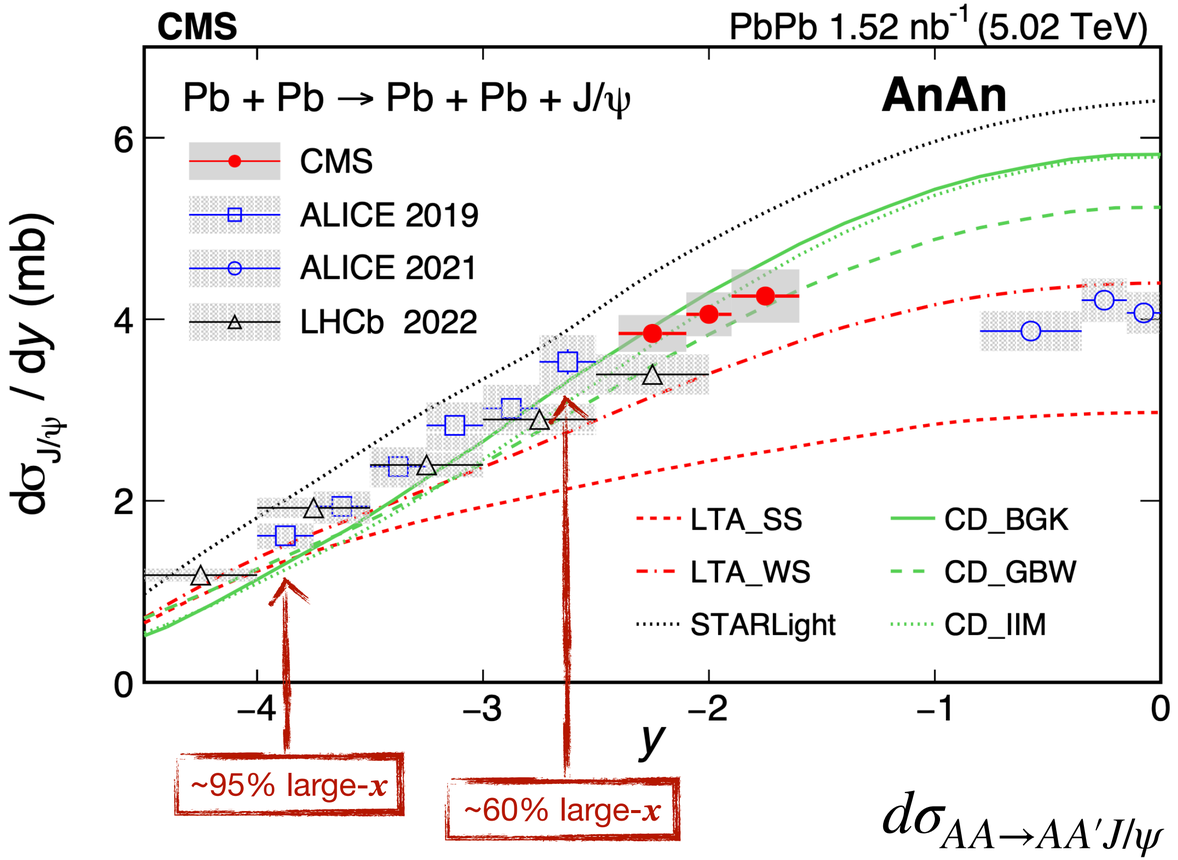
ALICE, EPJC 81 (2021) 712
CMS, PRL 131 (2023) 262301
LHCb, JHEP 06 (2023) 146



- 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



- LHC experiments complement each over a wide range of y region
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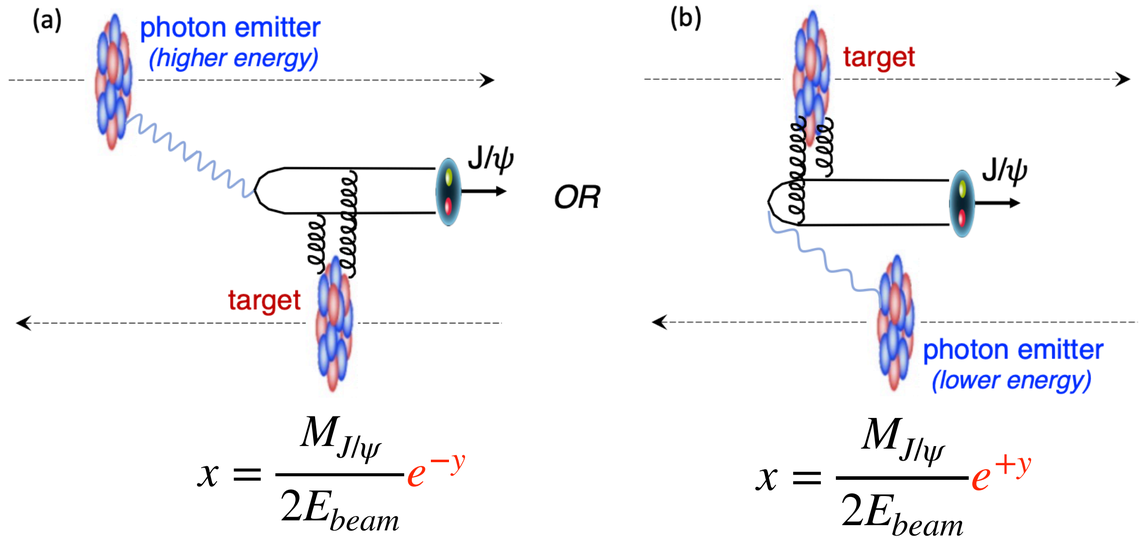


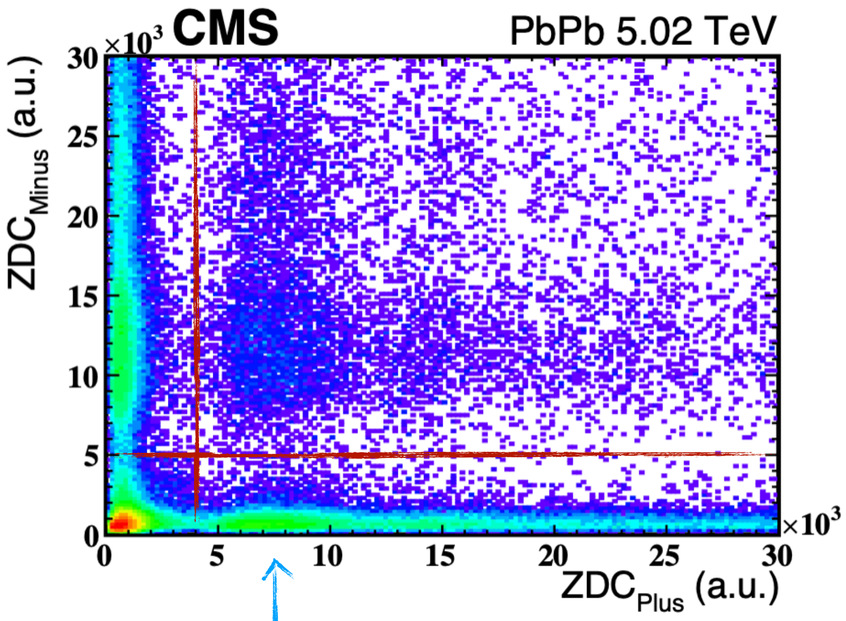
$$x = \frac{M_{J/\psi}}{2E_{beam}} e^{-y} \qquad x = \frac{M_{J/\psi}}{2E_{beam}} e^{+y}$$

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

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”

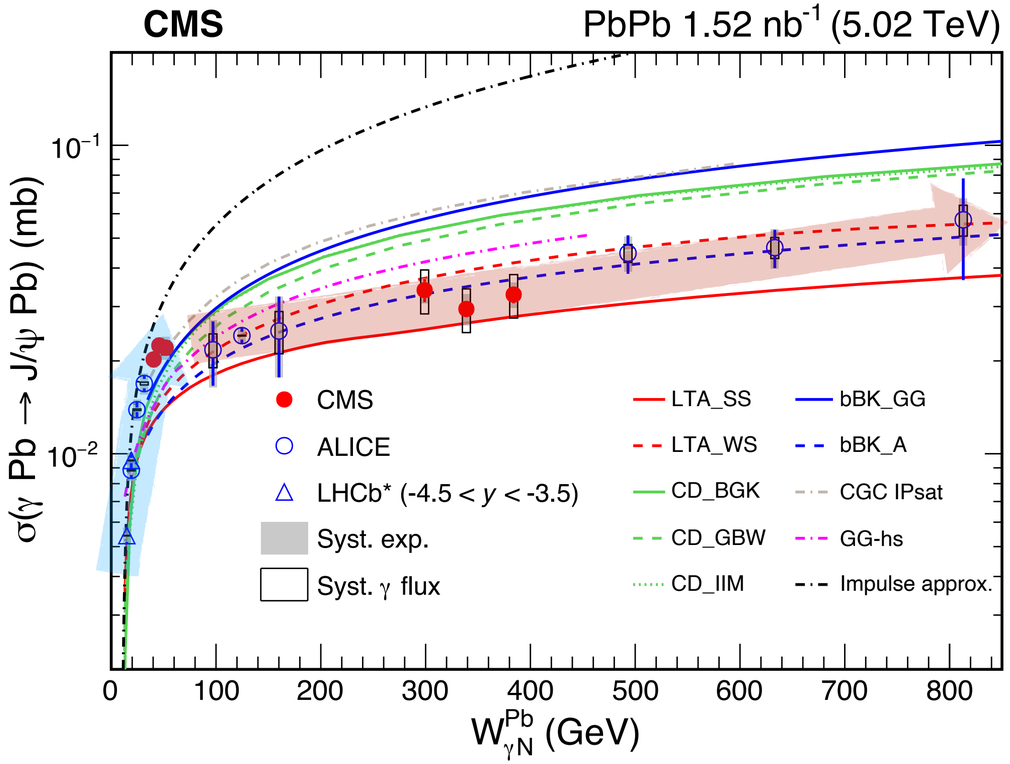
↓

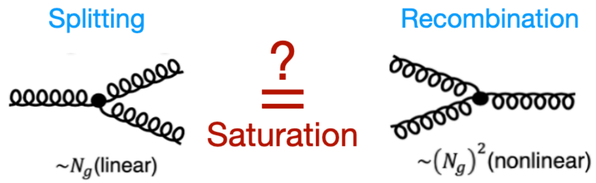
Probe gluons at x~10^{-5}-10^{-4} in heavy nucleus!

Imaging heavy nuclear with coherent J/ψ

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

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

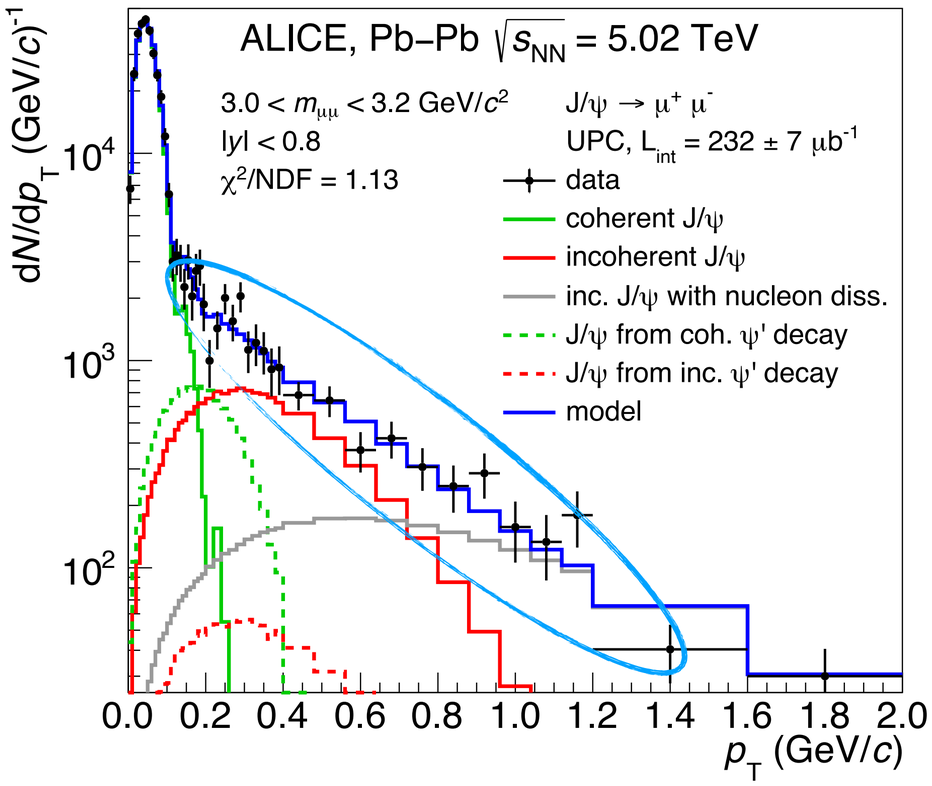


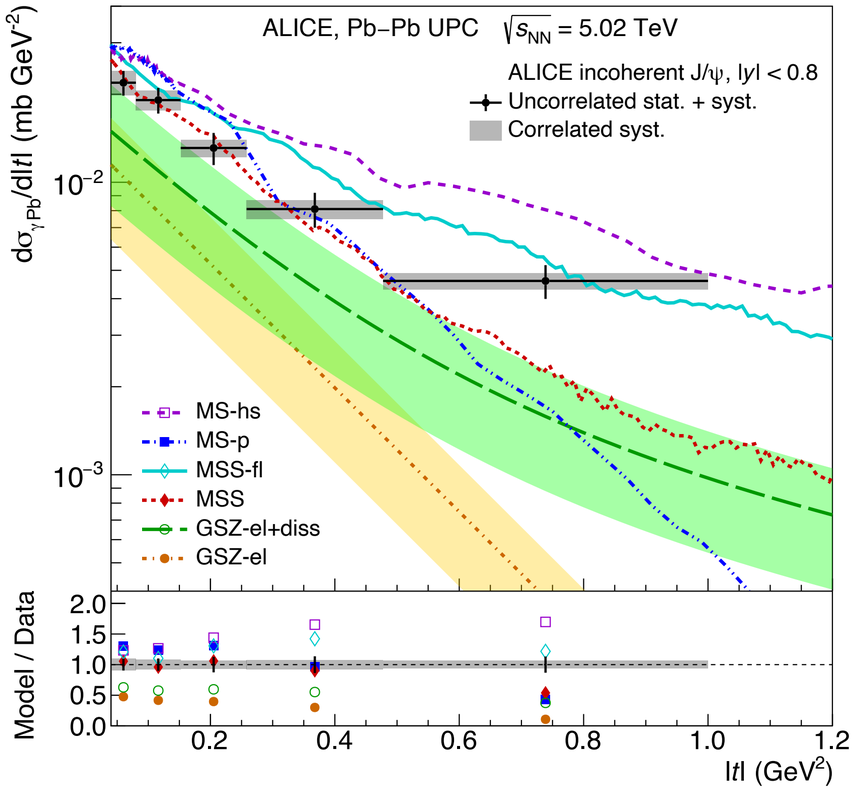


- Forward neutron tagging is employed to solve the “two-way” ambiguity
- Direct evidence of gluon saturation inside heavy nuclei?
  - $W^{Pb}_{\gamma N} < 40$ GeV: rapidly rising
  - $40 < W^{Pb}_{\gamma N} < 800$ GeV: nearly flat with a much slower rising

Incoherent J/ψ production at LHC

ALICE, PRL 132 (2024) 162302

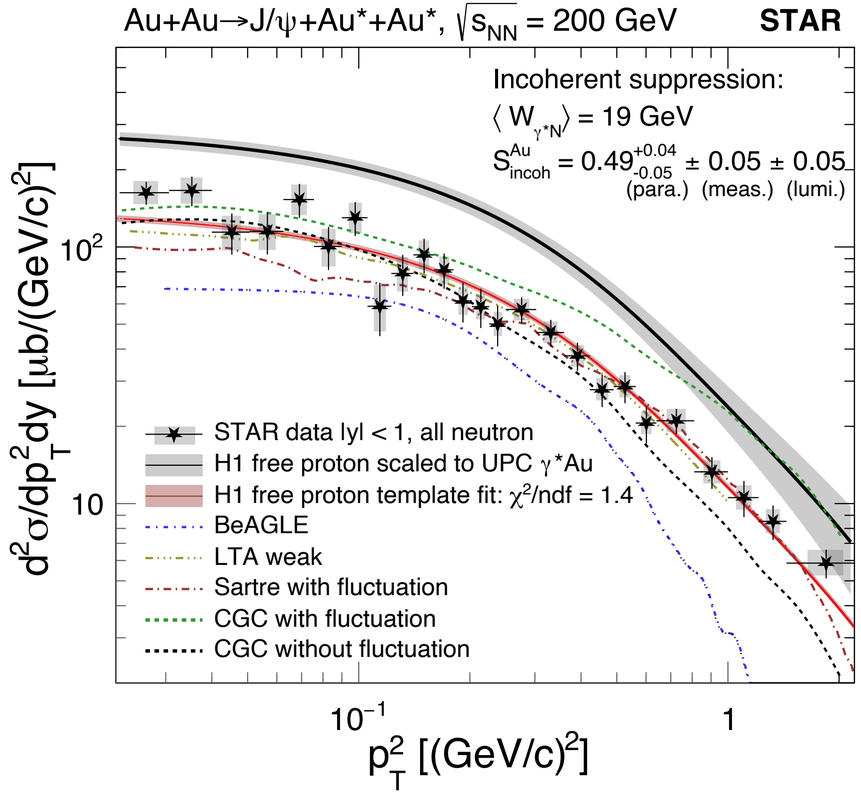




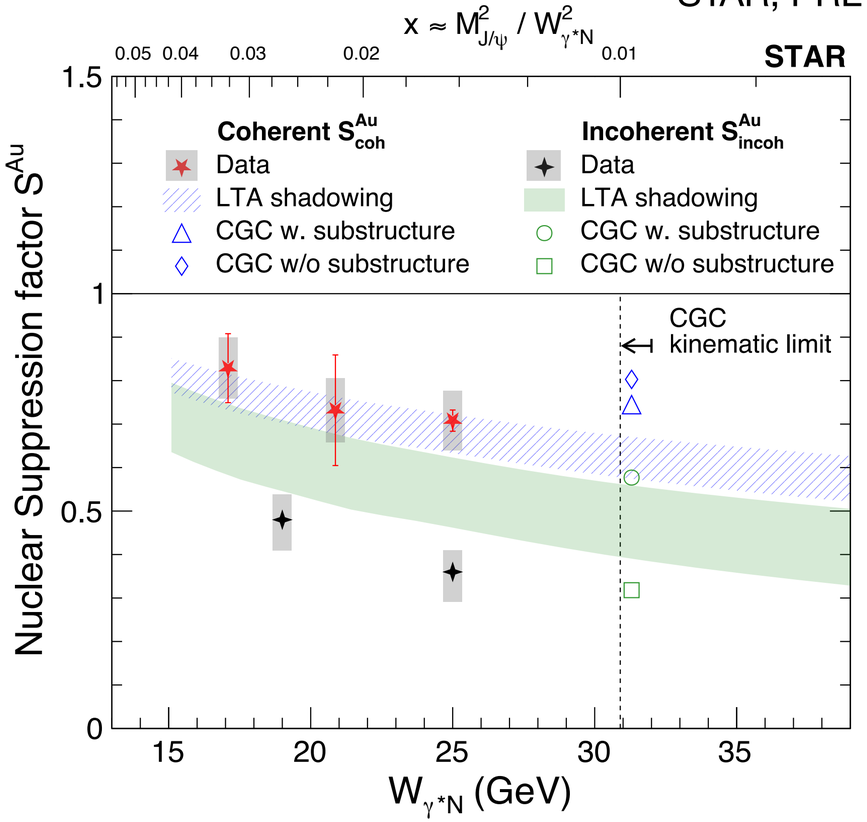
- The first measurement of |t| spectrum of incoherent J/ψ
  - No model describes both the absolute yield and the shape of |t| spectrum
  - A reasonably good description of the |t| spectrum is achieved when models incorporate sub-nucleon fluctuation

Incoherent J/ψ production at RHIC

STAR, PRC 110 (2024) 14911



STAR, PRL 133 (2024) 523



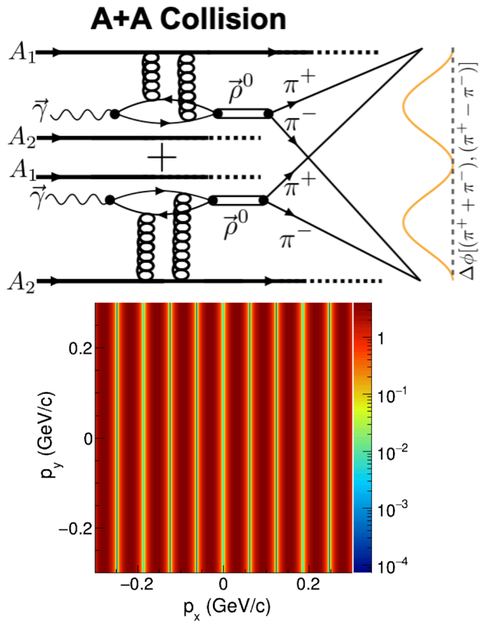
- The |t| shapes of incoherent J/ψ are similar between bound and free nucleons
- The incoherent suppression factor is less than that of the coherent production
  - Cannot conclude if sub-nucleon fluctuation is present in the incoherent photoproduction

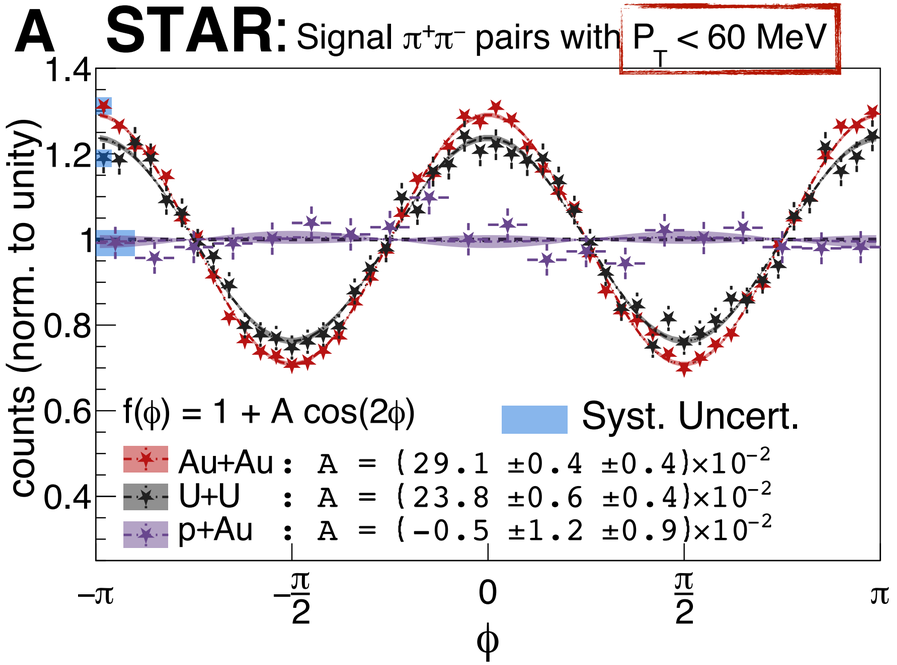
Spin-interference for photoproduced ρ^0

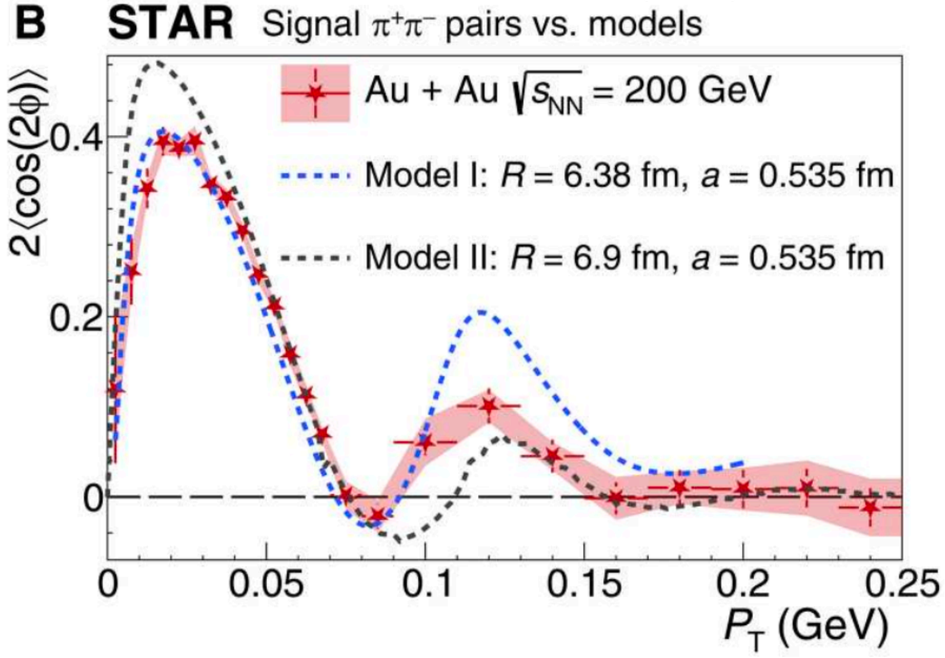
STAR, Sci. Adv. 9 (2023) eabq3903

$$\Delta\phi = \phi(\vec{e}^{+} + \vec{e}^{-}) - \phi(\vec{e}^{+} - \vec{e}^{-})$$

Xing et al., JHEP 10 (2020) 064
Zha et al., PRD 103 (2021) 033007



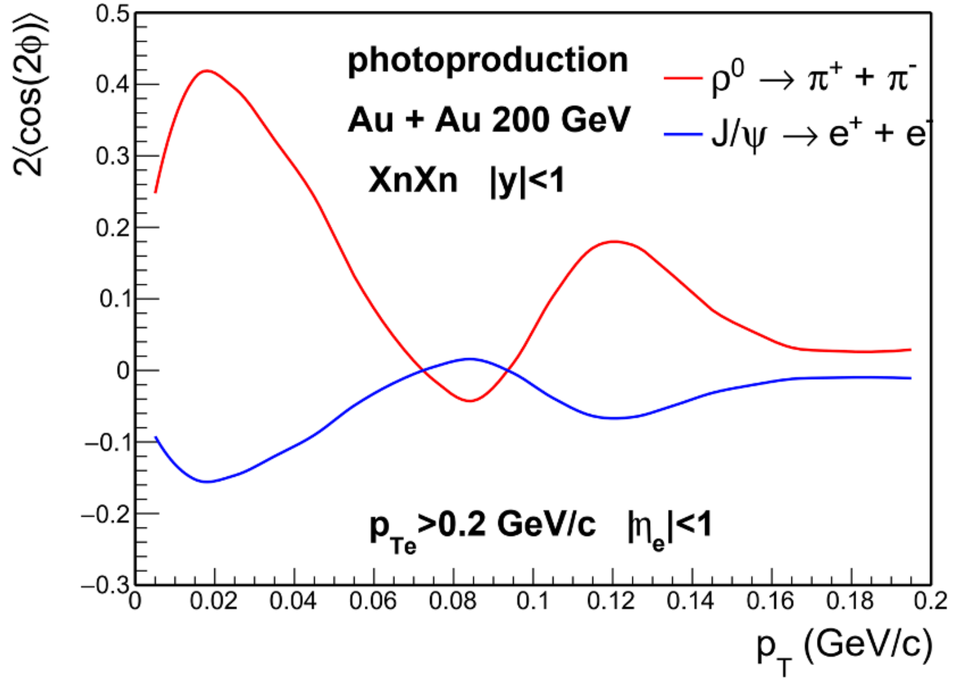




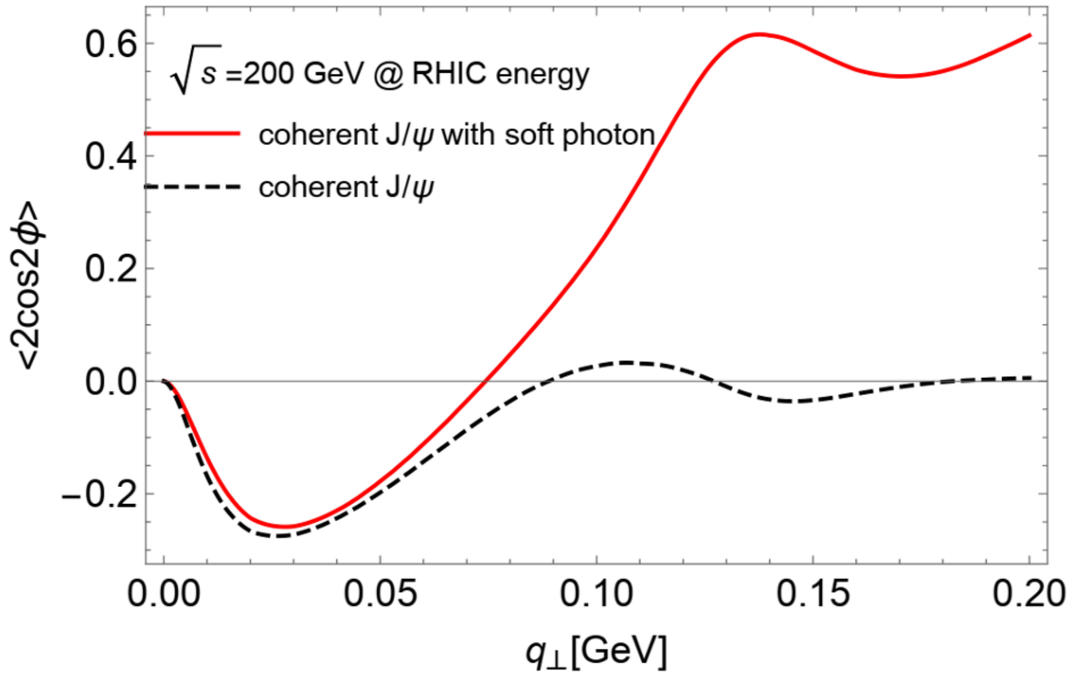
- Strong cos2Δϕ modulations due to photon polarization
  - "Double-slit" interference is critical to this observable
- Sensitive to nuclear geometry → strong interaction radius
  - New techniques for multidimensional imaging of nuclei

Spin-interference for photoproduced J/ψ

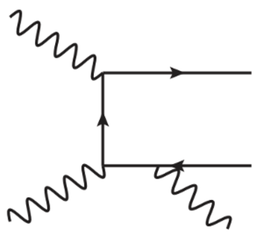
Zha et al., PRD 103 (2021) 033007



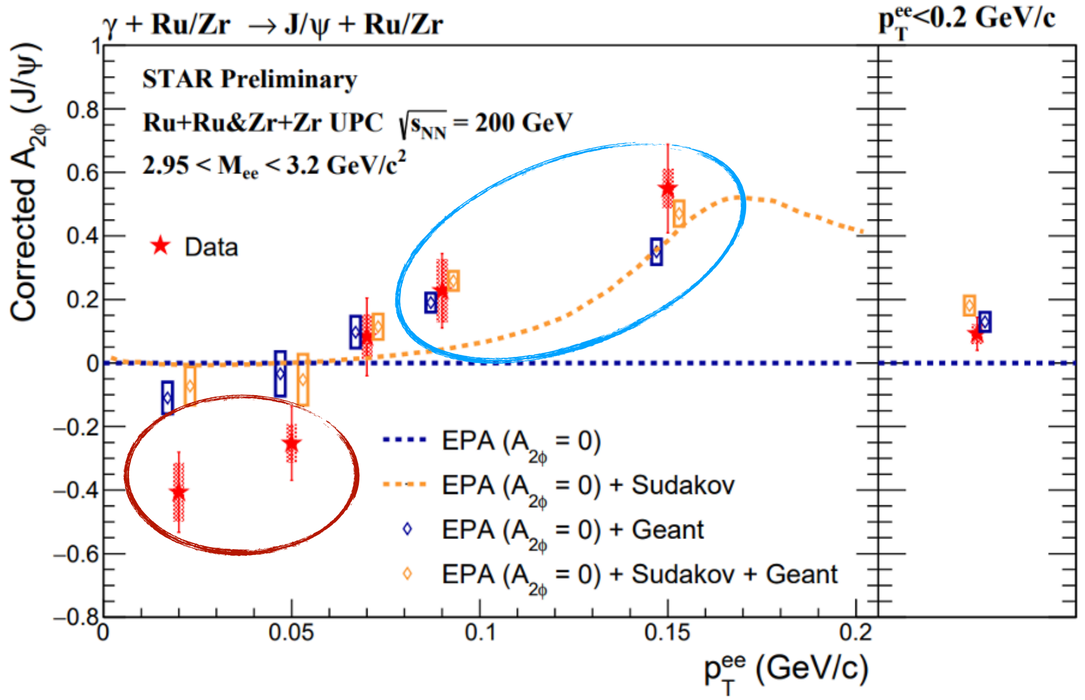
Brandenburg et al., PRD 106 (2022) 074008



- Negative modulation predicted for J/ψ
  - Decay daughters are fermions → different angular momentum projection along z-axis
- Need to consider the effect of soft photon radiation



Spin-interference for photoproduced J/ψ



- Experimental challenges of photoproduced J/ψ
  - $\gamma\gamma \rightarrow e^+e^-$ background
  - Soft photon radiation
  - Bremsstrahlung & detector effects
- Indication of negative spin interference of photoproduced J/ψ at low p_T

Summary

- Significant experimental progress of two-photon interactions
  - Demonstrated the *b*-dependence of photon p_T → baseline to probe QGP EM effects
  - Experimental signal of linearly polarized photon → new techniques to image nuclear
  - Observed $\gamma\gamma \to \tau\tau$ in UPC and showed the sensitivity to BSM physics
  - Observed $\gamma\gamma \to p\bar{p}$ production → higher excitation of QED vacuum

- Multidimensional imaging of nuclei with photon-nuclear interactions
  - Direct experimental evidence of gluon saturation?
  - Observed spin interference of photoproduced vector meson → strong interactions radius
  - First measurement of the |t|-spectra of incoherent J/ψ → sub-nucleon fluctuation

Summary

- Significant experimental progress of two-photon interactions
  - Demonstrated the *b*-dependence of photon p_T → baseline to probe QGP EM effects
  - Experimental signal of linearly polarized photon → new techniques to image nuclear
  - Observed $\gamma\gamma \to \tau\tau$ in UPC and showed the sensitivity to BSM physics
  - Observed $\gamma\gamma \to p\bar{p}$ production → higher excitation of QED vacuum

- Multidimensional imaging of nuclei with photon-nuclear interactions
  - Direct experimental evidence of gluon saturation?
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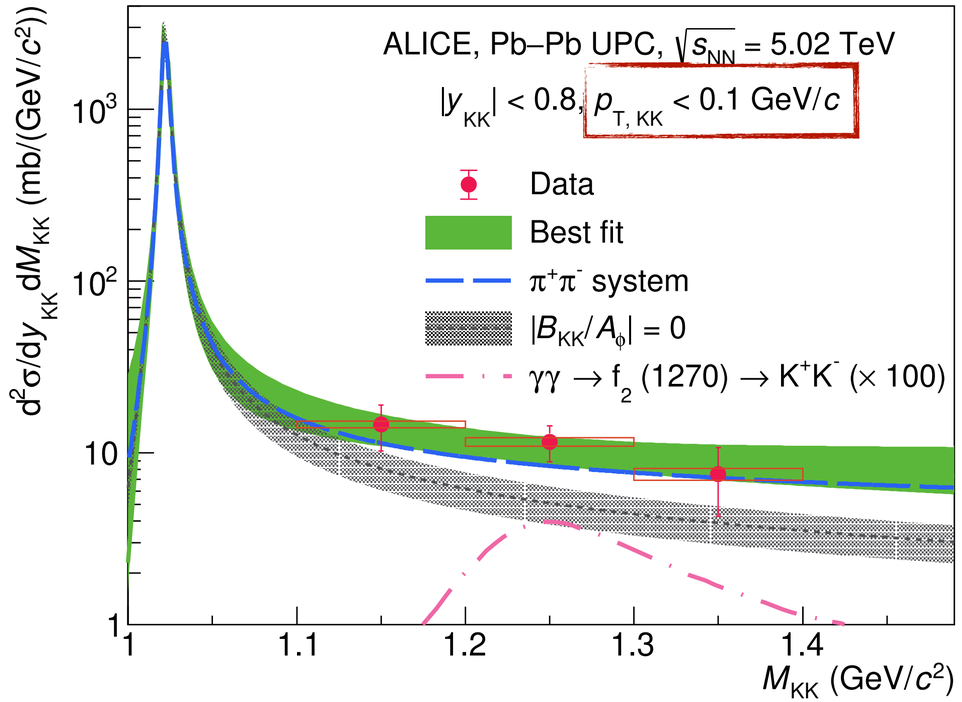
  - First measurement of the |t|-spectra of incoherent J/ψ → sub-nucleon fluctuation

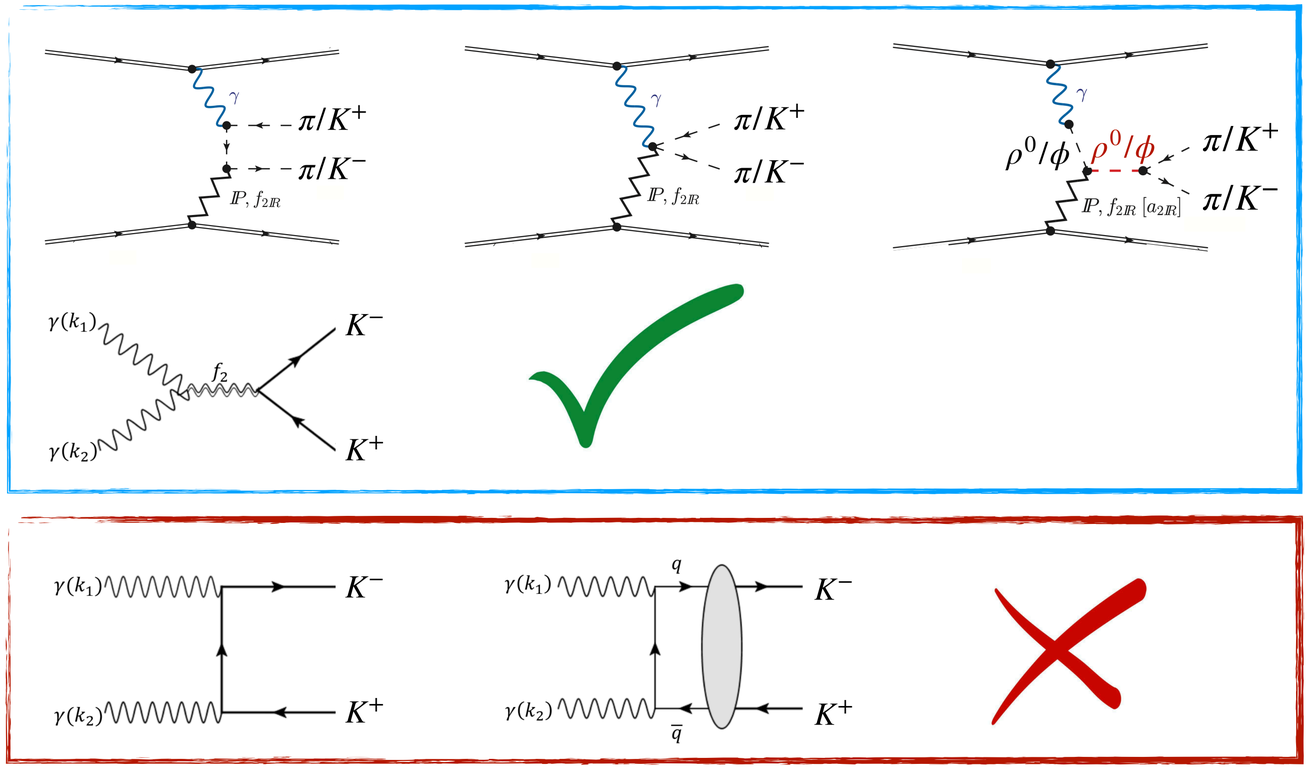
Thank you for your attention!

Backups

Photoproduction of K^+K^- pairs

ALICE, PRL 132 (2024) 222303

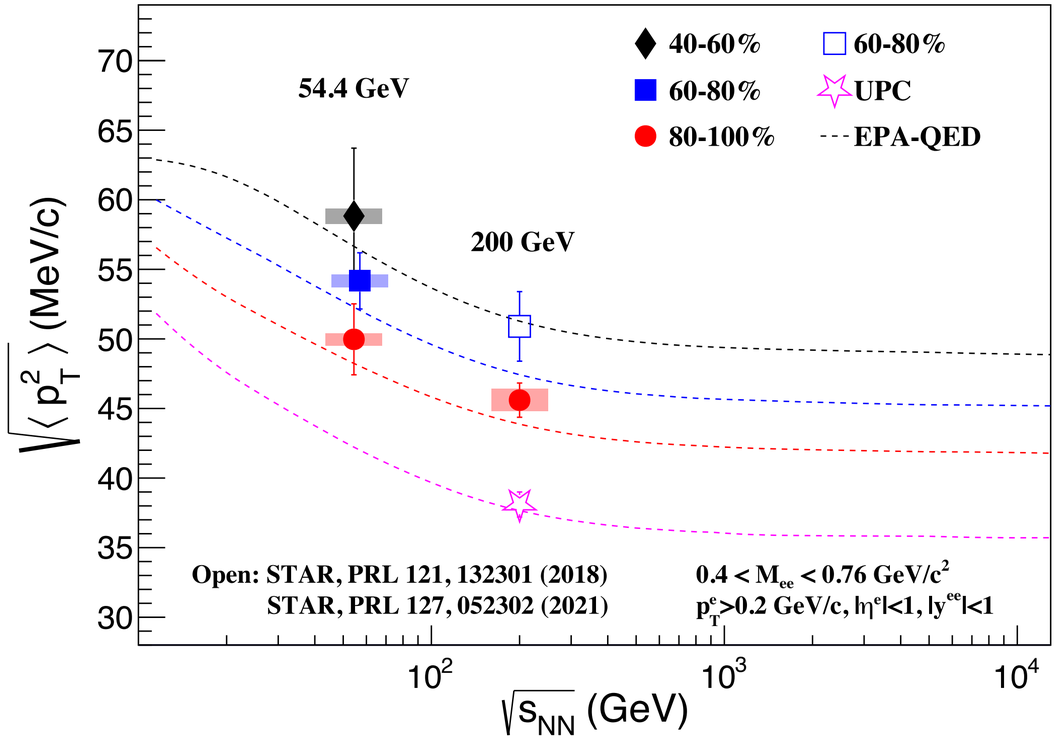


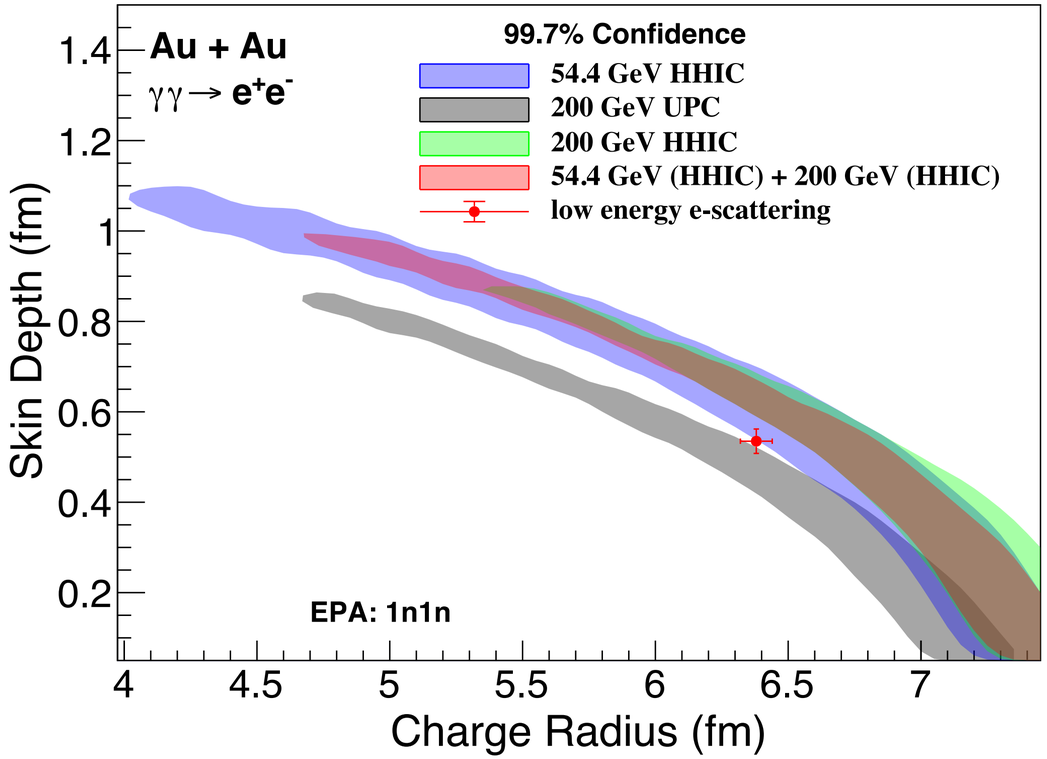


- Data favor the coherent $\phi(1020) \to K^+K^-$ + direct K^+K^- photoproduction, with interference considered
  - The contribution of $\gamma\gamma \to K^+K^-$ is not estimated

Energy dependence of $\gamma\gamma \rightarrow e^+e^-$ production

STAR, arXiv:2407.14821





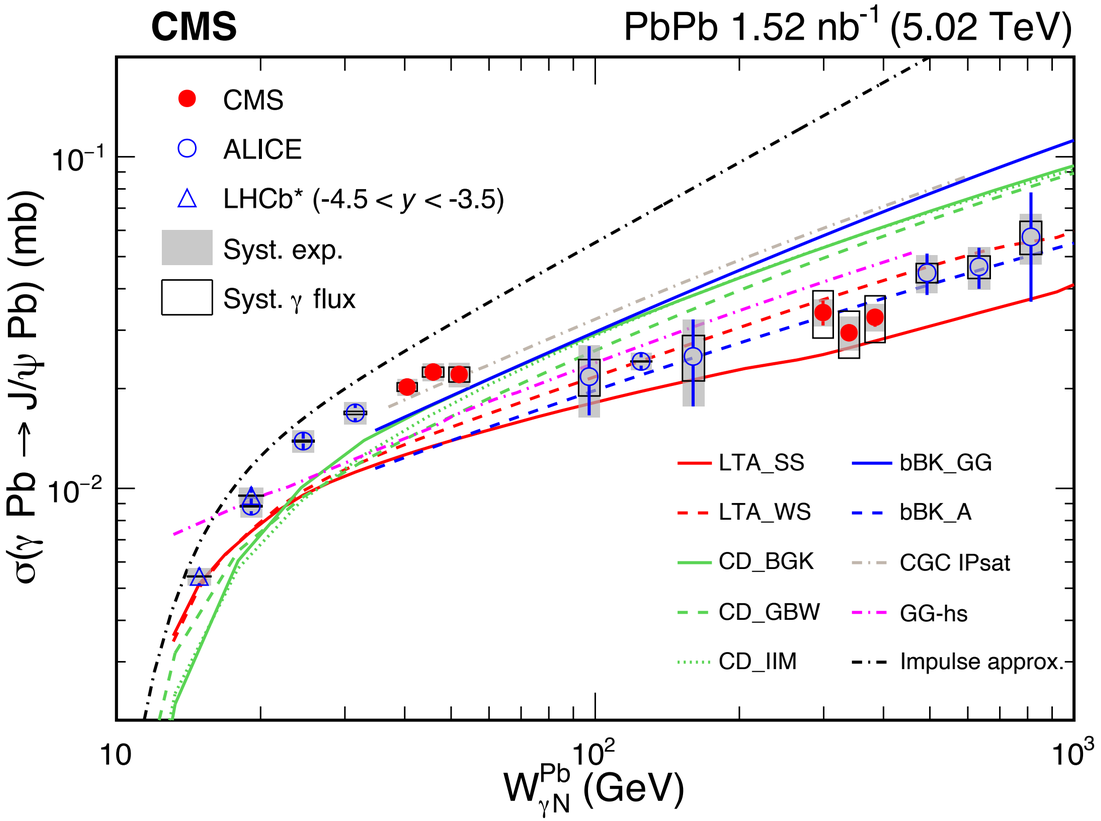
- Clear energy and centrality (*b*) dependence of $\gamma\gamma \rightarrow e^+e^-$ production
  - Consistent with EPA-QED baseline
- Constrain the nuclear charge distribution with $\gamma\gamma \rightarrow e^+e^-$ production

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

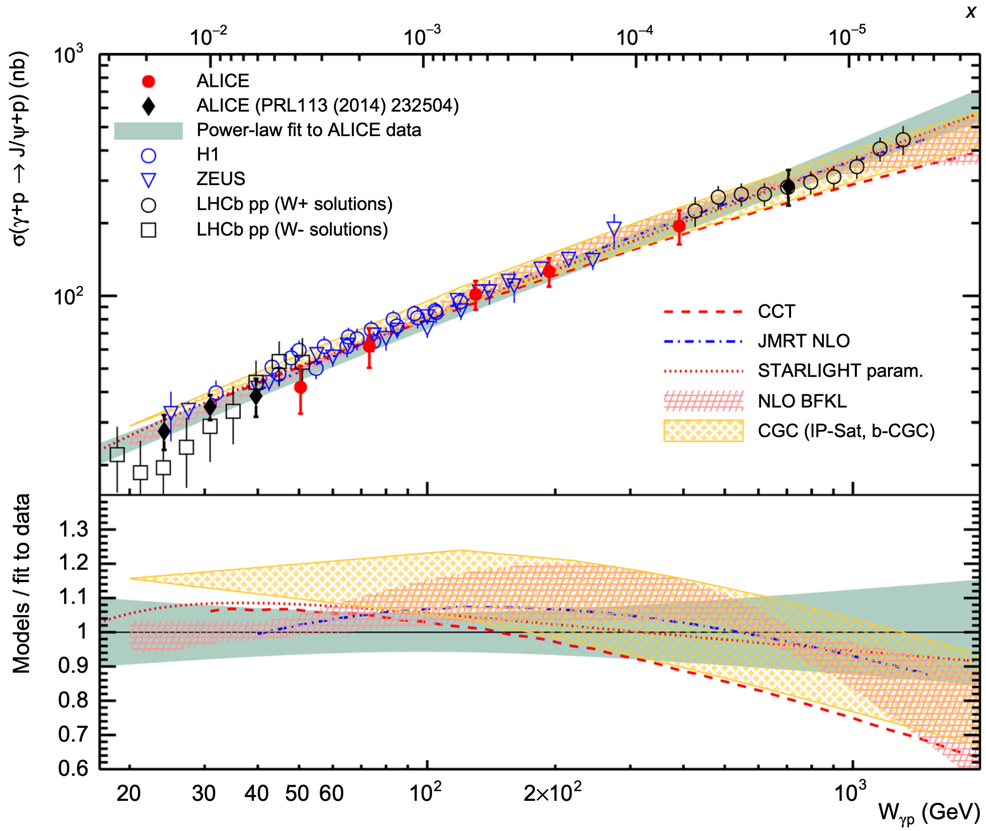
ALICE, JHEP 10 (2023) 119
ALICE, EPJC 81 (2021) 712
ALICE, PLB 798 (2019) 134926

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

ALICE, EPJC 79 (2019) 402



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



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