Disentangling transverse single spin asymmetries for very forward neutrons in polarized p-A collisions using ultra-peripheral collisions

PHENIX, arXiv:1703.10941, submitted to PRL
GM, arXiv:1702.03834, accepted in PRC

Gaku Mitsuka (RIKEN BNL Research Center)
for the PHENIX Collaboration

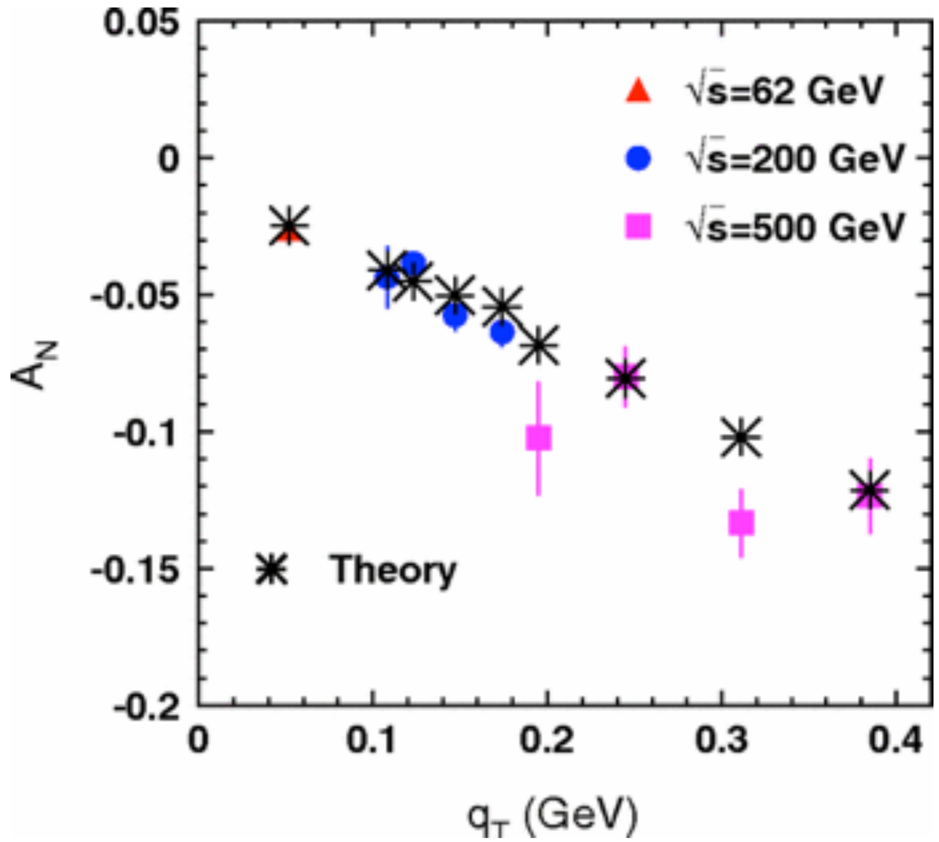
25th International Workshop on Deep Inelastic Scattering and Related Topics
3-7 April 2017, Birmingham, UK

Outline

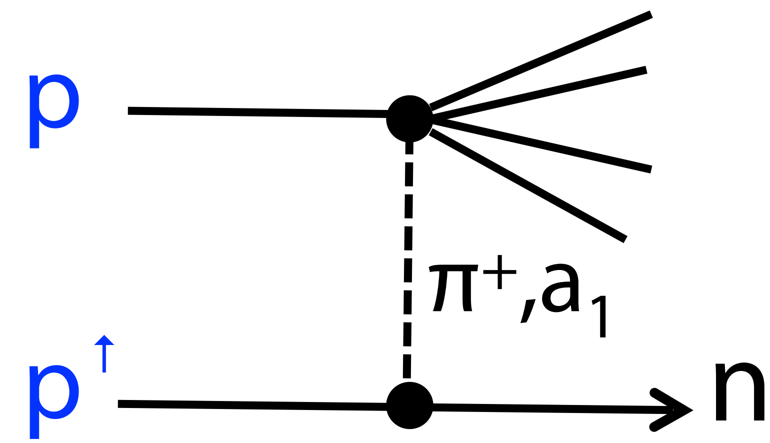
1. Introduction and Physics motivation
    - Large A_N for forward neutrons discovered in pAu collisions
    - Can electromagnetic effects explain positive and large A_N?
2. Ultra-peripheral collisions (UPCs)
    - Do γ^*p interactions have large A_N?
    - MC simulations of γ^*p interactions
3. MC simulation results
    - UPCs vs. hadronic interactions
    - MC simulations vs. the PHENIX measurements
4. Summary and Future prospects

1. Introduction and Physics motivations

Single spin asymmetry A_N for very forward neutrons in pp



Kopeliovich et al.
PRD. 84.114012 (2011)

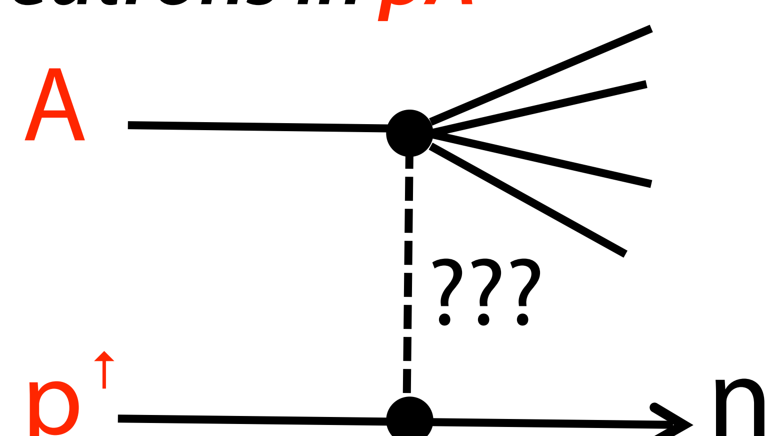


A_N in pp at the RHIC energies are well explained by an one-Reggeon exchange model with the interference between π (spin flip) and a_1 (nonflip).

Single spin asymmetry A_N for very forward neutrons in pA

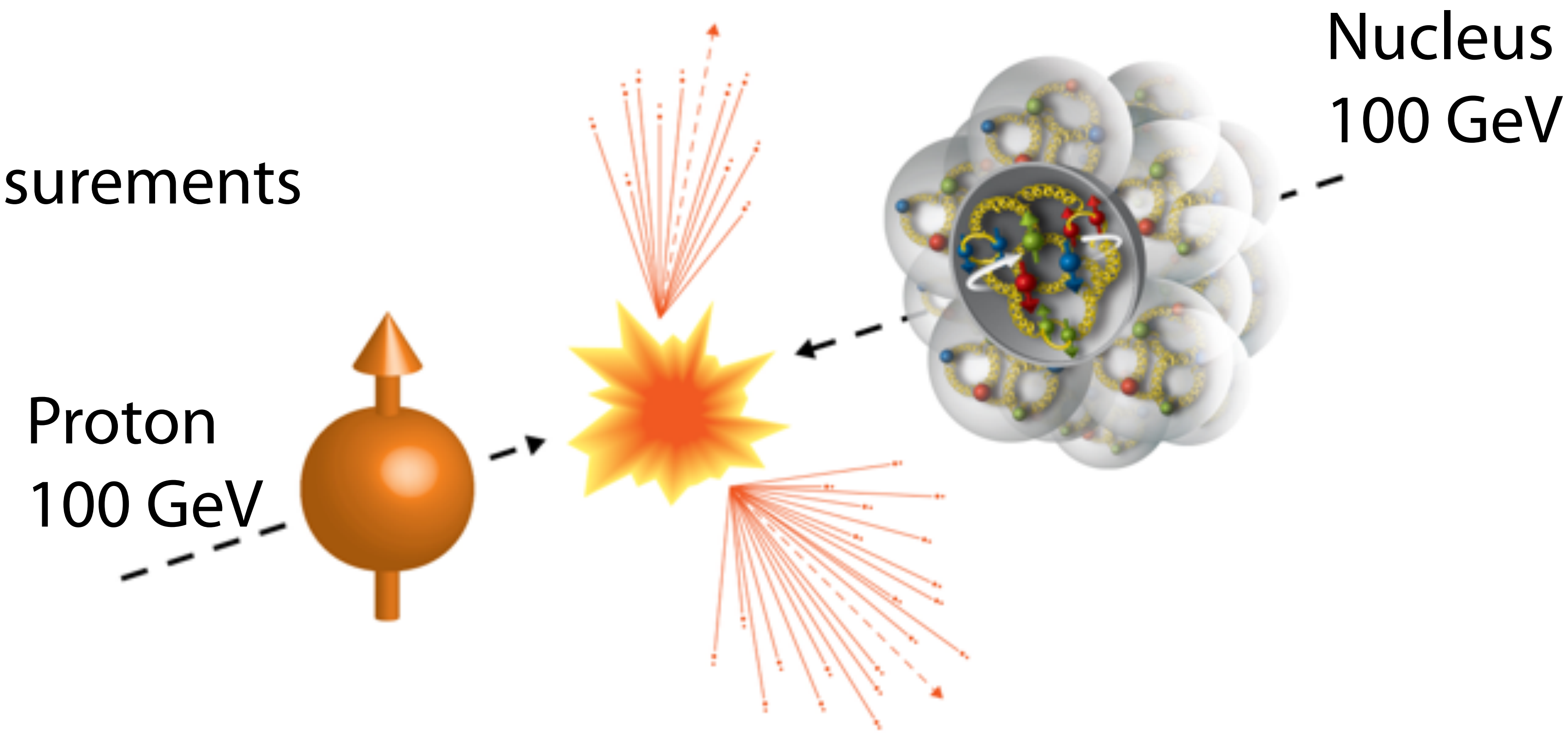
Can A_N in pA be successfully explained by the π-a_1 interference? or by other mechanisms?

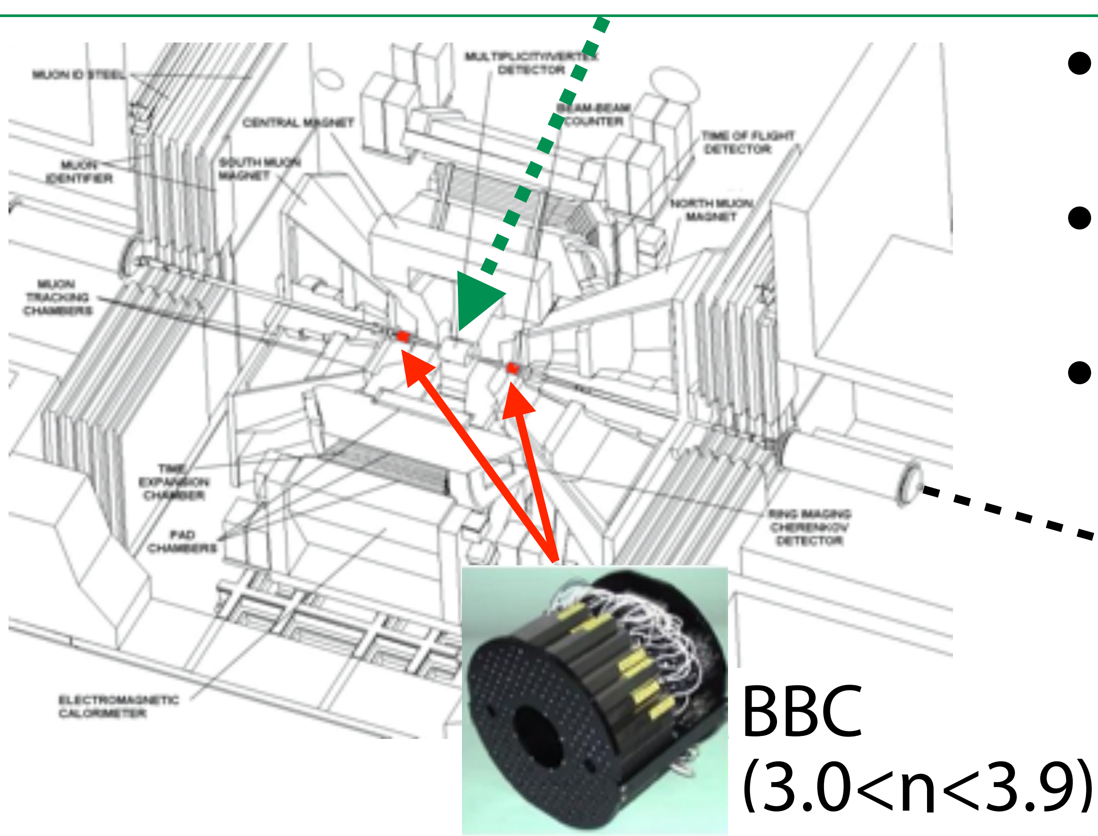
→ understand forward neutron production in pA



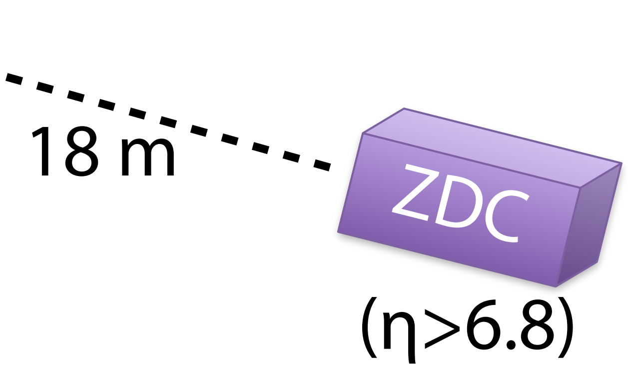
1.1 Transversely polarized pA collisions

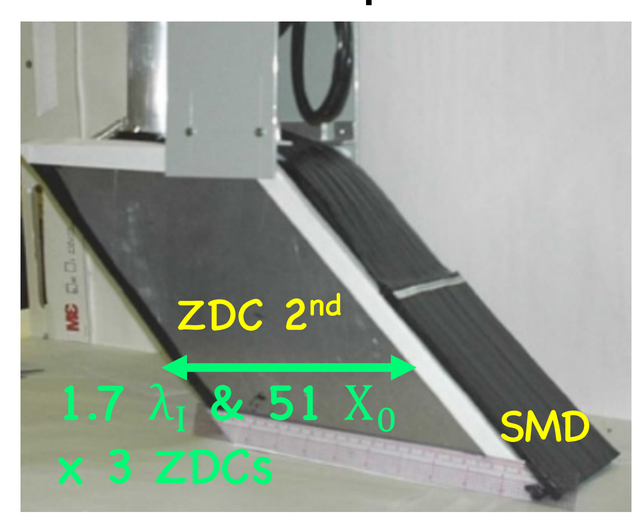
Run15 pAl/pAu collisions
Dedicated run for A_N measurements
Average pol. ~ 0.5-0.6
(syst. uncertainty ~ 3%)





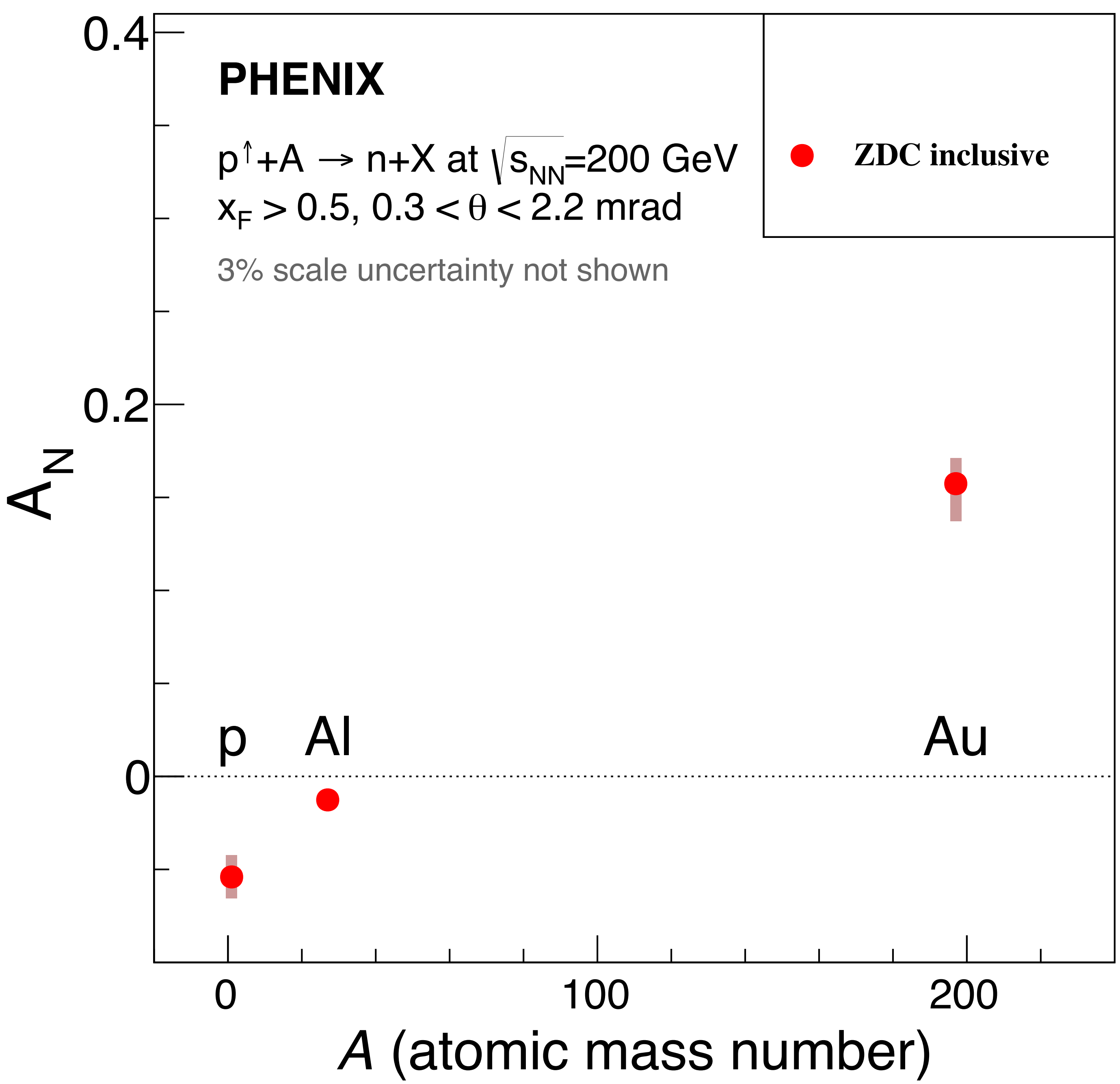
- ZDC (Zero Degree Calorimeter): hadron calorimeter with a 10 x 10 cm^2 area ($\Delta E/E$ ~ 20–30 %)
- SMD (Shower Max Detector): X-Y plastic scintillator hodoscope (Δx, Δy ~ 1 cm)
- Charge veto counter: plastic scintillator pad at front





1.2 *Inclusive* A_N for forward neutrons

PHENIX, arXiv:1703.10941



Prediction before the measurement:
weak A-dependence
(Reggeon exc. and/or nuclear effects)

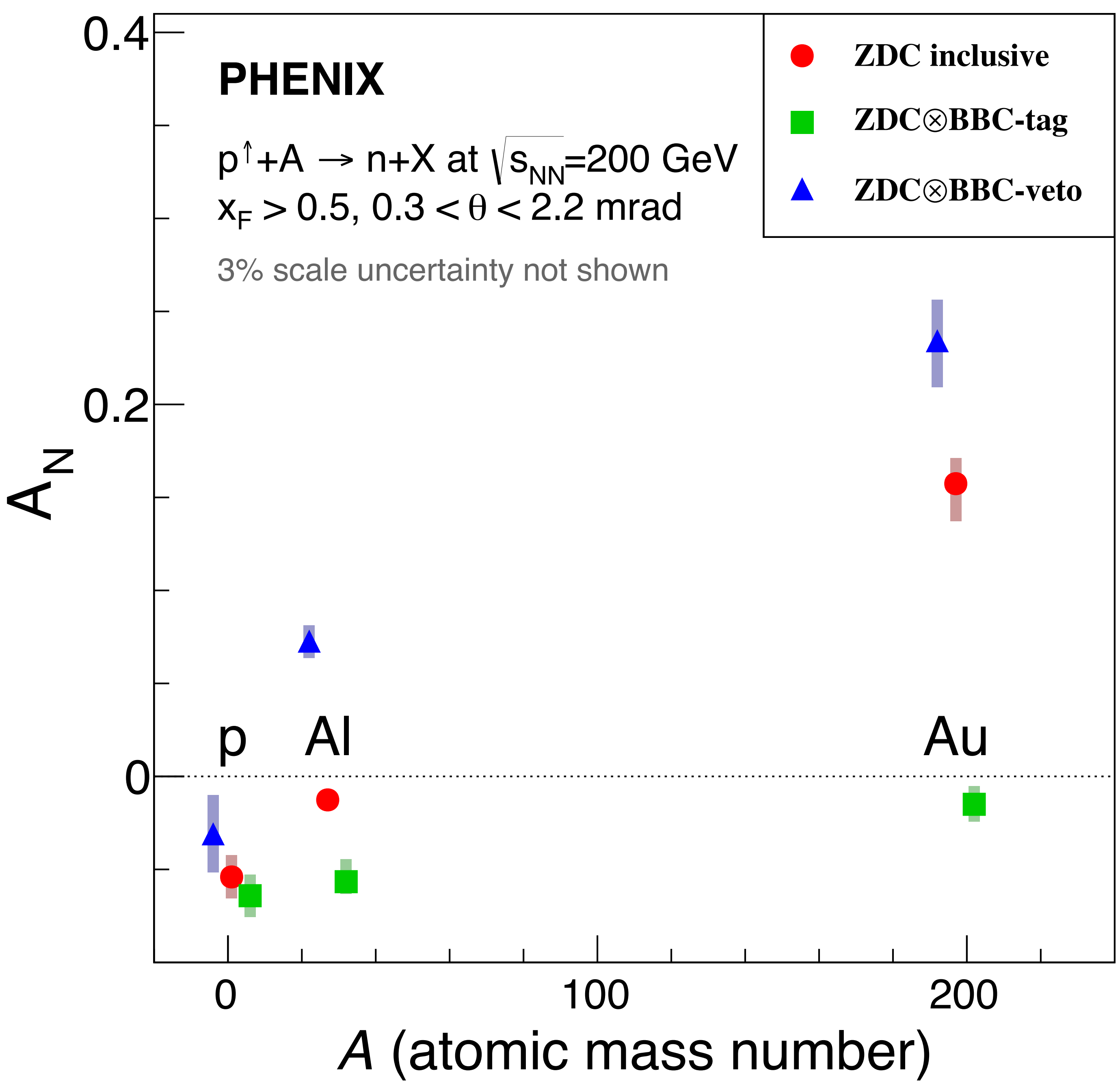
Surprisingly strong A-dependence

→ whats mechanisms do produce such strong A-dependence?

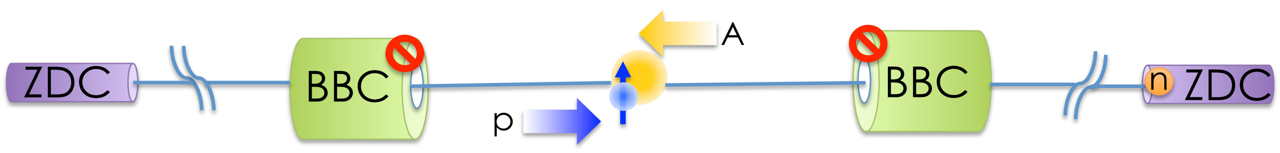
→ ***hint: how does A_N behave with the other triggers?***

1.3 *BBC correlated* A_N for forward neutrons

PHENIX, arXiv:1703.10941

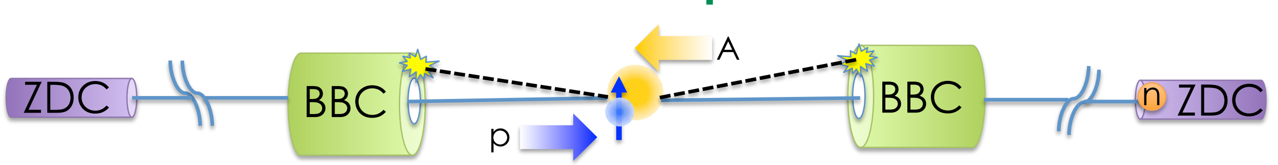


Particle veto at lower rapidities: ***BBC-VETO***



→ much stronger A-dependence

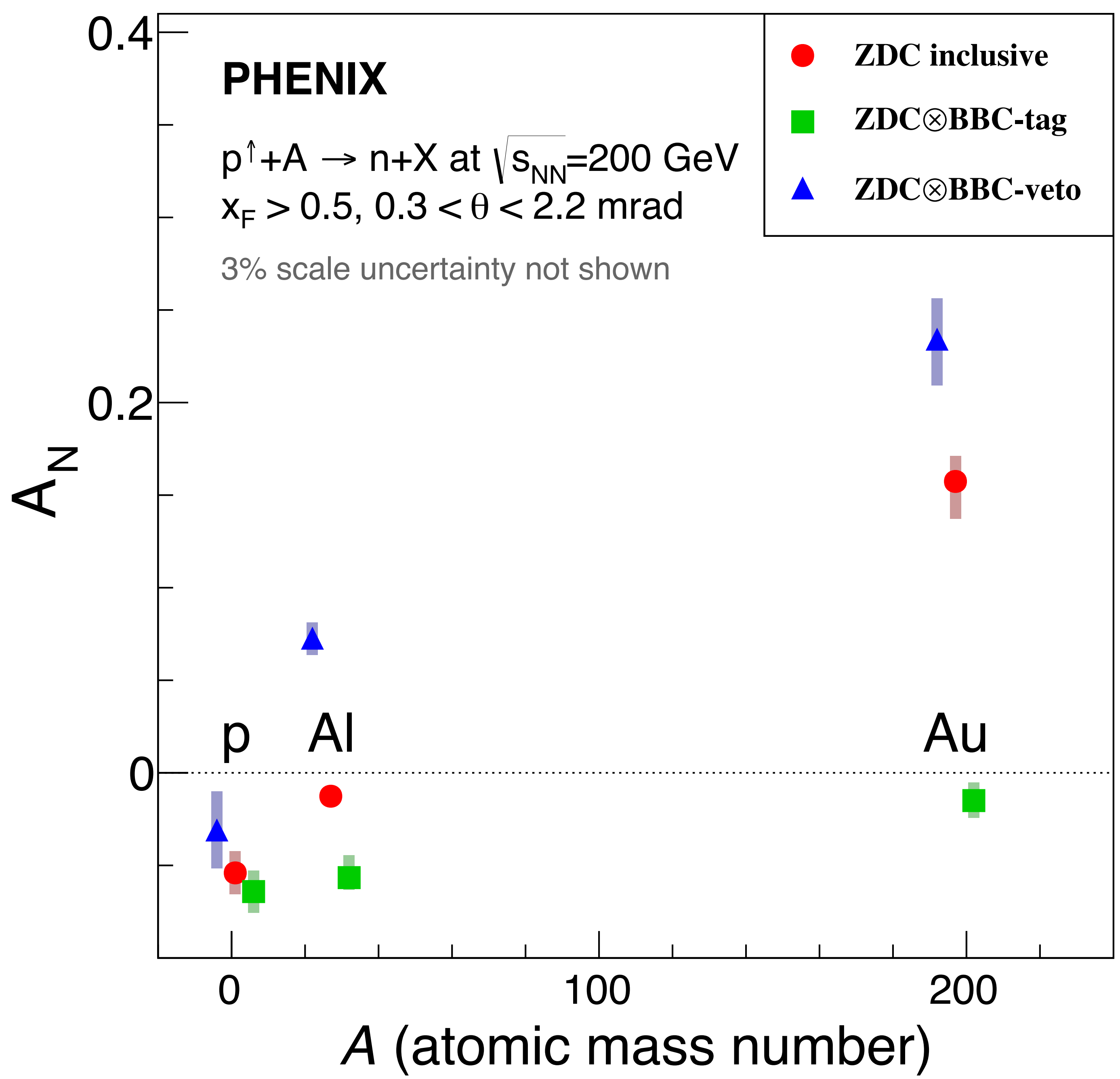
Particle hits at lower rapidities: ***BBC-TAG***



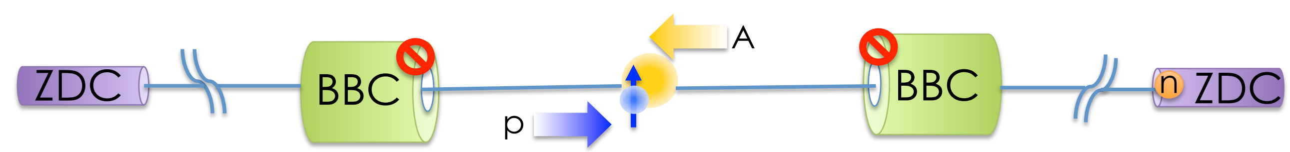
→ weak A-dependence

1.3 *BBC correlated* A_N for forward neutrons

PHENIX, arXiv:1703.10941



Particle veto at lower rapidities: ***BBC VETO***

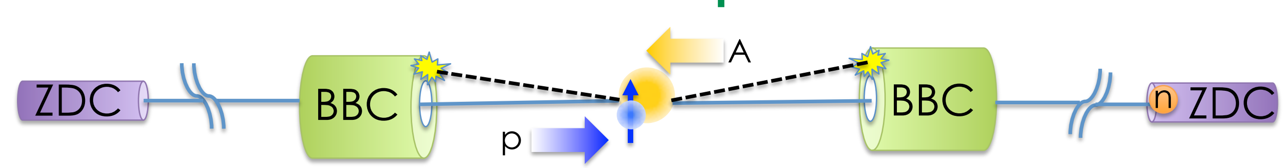


→ much stronger A-dependence

Large A_N when ***fewer*** underlying particles
Small A_N when ***ample*** underlying particles

Do not only hadronic interactions but also electromagnetic interactions play a crucial role in pA?

Particle hits at lower rapidities: ***BBC HIT***

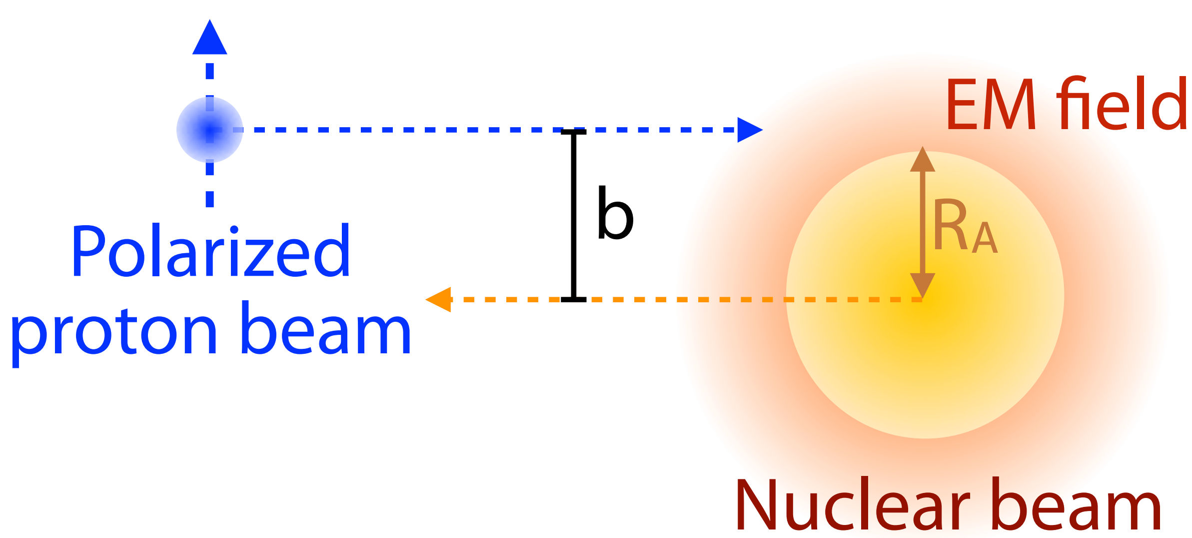


→ weak A-dependence

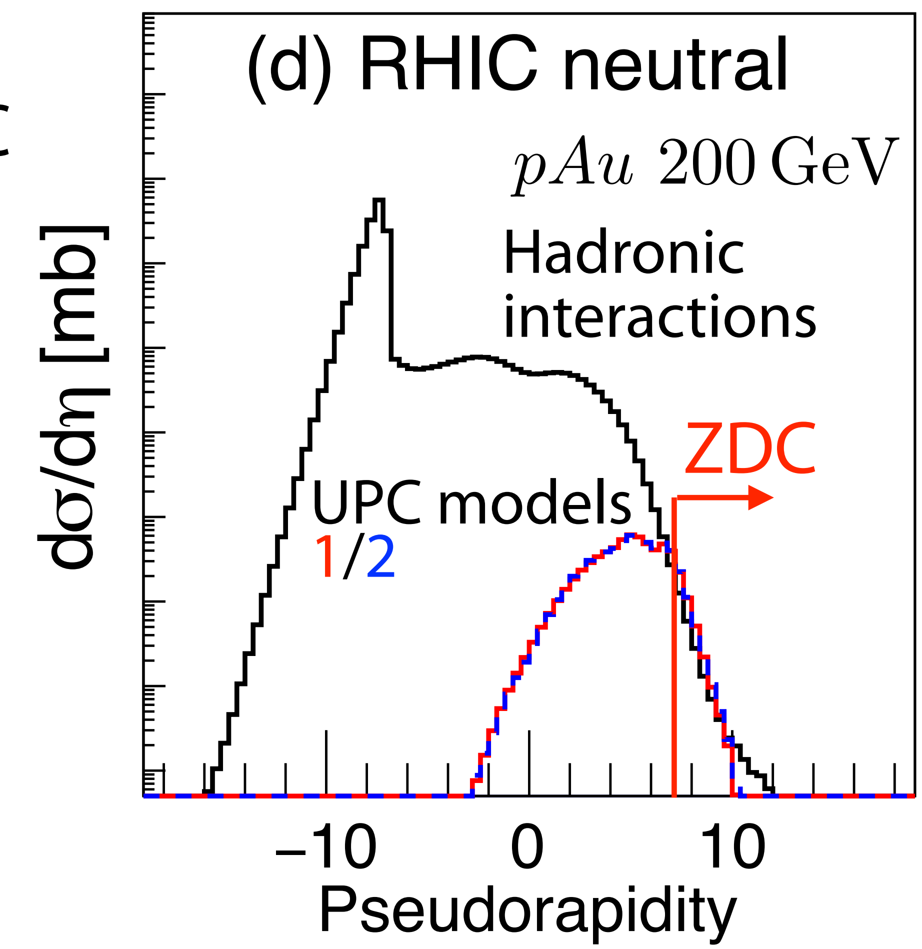
2. Ultra-peripheral collisions (UPCs)

UPCs (aka Primakoff effects);

- a collision of a proton with the EM field made by a relativistic nucleus when the impact parameter b is larger than R_A+R_p
- fewer underlying particles unlike in hadronic interactions → smaller activity at BBC



GM, EPJ. C **75**, 614 (2015)



UPC cross section

γ* flux $\propto Z^2$

Does γ*p→π⁺n lead to large A_N?

$$\frac{d\sigma^4_{\mathrm{UPC}(p^\uparrow \mathrm{A}\to\pi^+ n)}}{dW\,db^2\,d\Omega_n} = \frac{d^3N_{\gamma^*}}{dW\,db^2}\,\frac{d\sigma_{\gamma^* p^\uparrow\to\pi^+ n}(W)}{d\Omega_n}\,\overline{P_{\mathrm{had}}}(b)$$

2.1 Do γ*p interactions have large A_N?

Polarized γ*p cross sections

(Drechsel and Tiator, J. phys. G 18, 449 (1992))

$$\frac{d\sigma_{\gamma^* p^\uparrow \to \pi^+ n}}{d\Omega_\pi} = \frac{|q|}{\omega_{\gamma^*}}(R_T^{00} + P_y R_T^{0y})$$

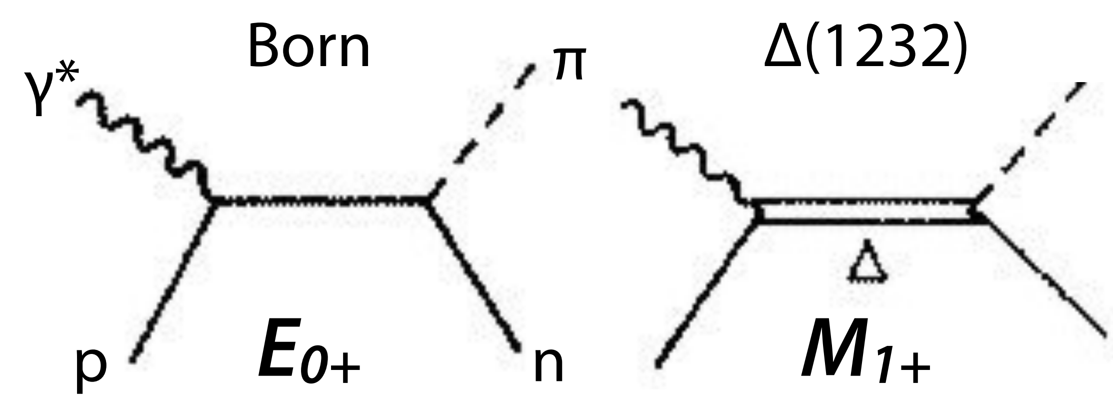
$$= \frac{|q|}{\omega_{\gamma^*}} R_T^{00}(1 + P_2 \cos\phi_\pi T(\theta_\pi))$$

Equivalent to A_N

$T(\theta_\pi)$ is decomposed into multipoles:

$$T(\theta_\pi) \equiv \frac{R_T^{0y}}{R_T^{00}} \propto \mathrm{Im}\{E_{0+}^*(E_{1+} - M_{1+})$$

$$-4\cos\theta_\pi(E_{1+}^* M_{1+})\ldots\}$$



Interference between E_{0+} and M_{1+} leads to large $T(\theta_\pi)$ in the Δ(1232) region

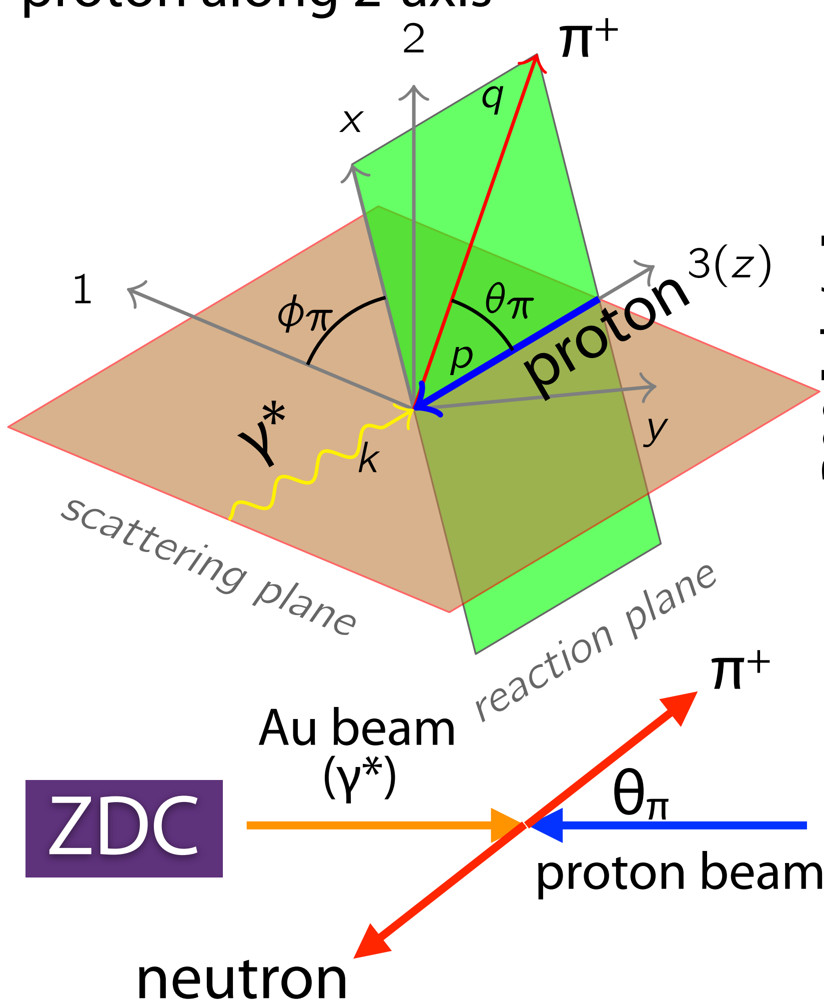
MC simulations of the polarized γ*p interactions are developed for testing $T(\theta_\pi)$, i.e. A_N in pA collisions.

2.2 MC simulations for γ*p interactions

- MC simulations based on the MAID2007 model (Drechsel et al. EPJ A 34, **69** (2007)) are performed for R_T^{00} and $T(\theta_\pi)$.
- $T(\theta_\pi)$~0.8 at Δ(1232), ~-0.5 at N(1680) → large A_N!!

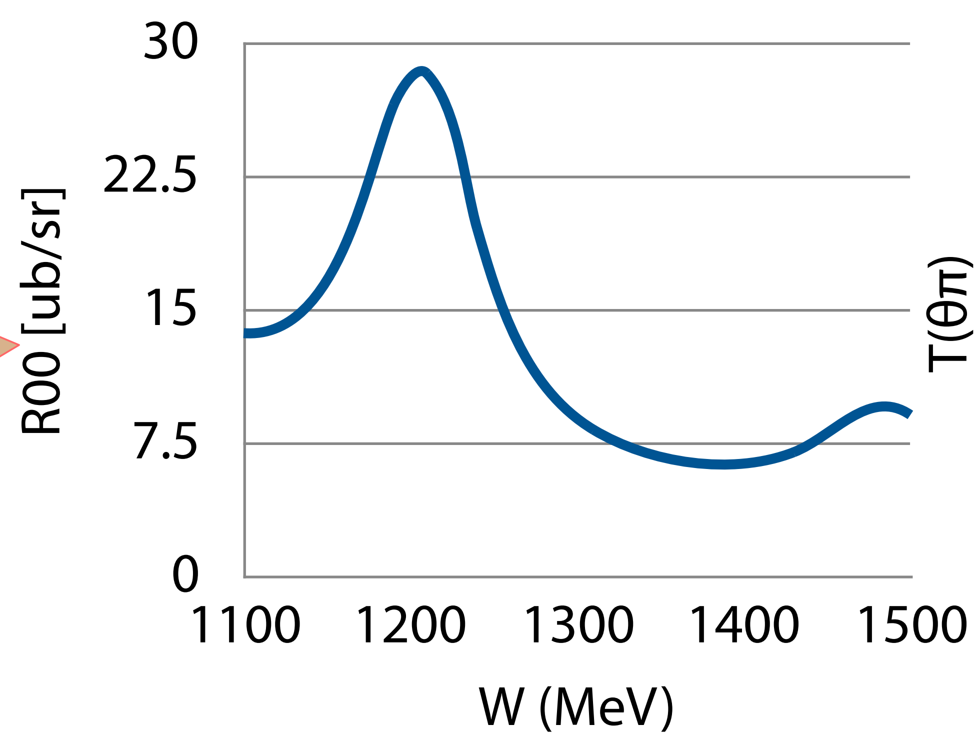
γ*p center-of-mass system

transversely polarized proton along 2-axis

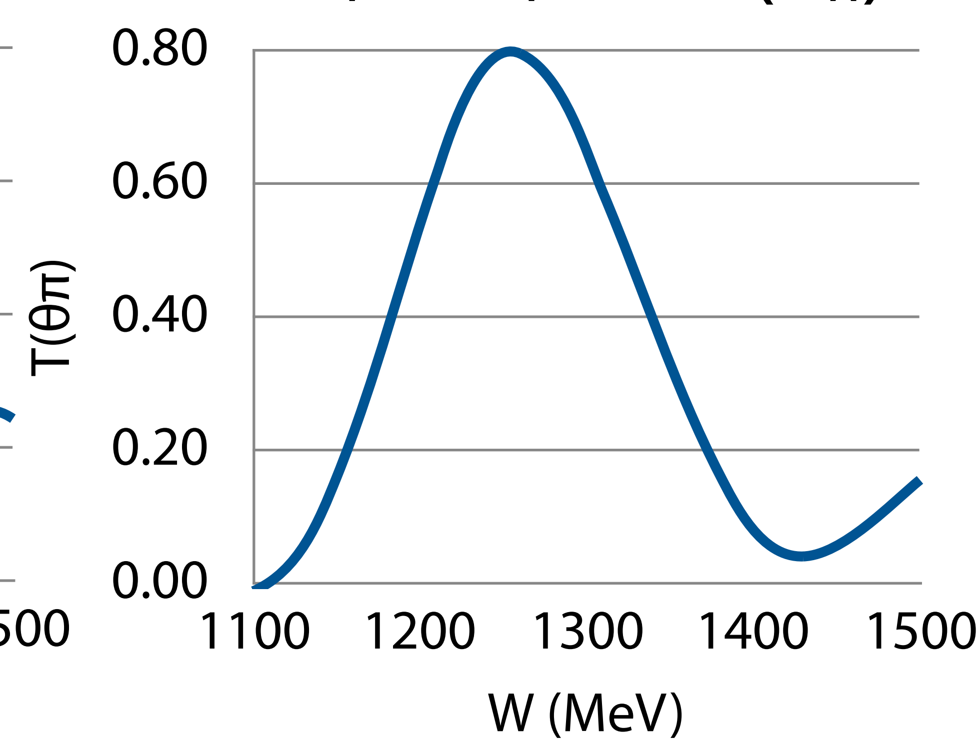


Numerical data from MAID 2007 ($Q^2 = 0$, θπ = 90 degree)

R_T^{00}



$R_T^{0y}/R_T^{00} = T(\theta_\pi)$

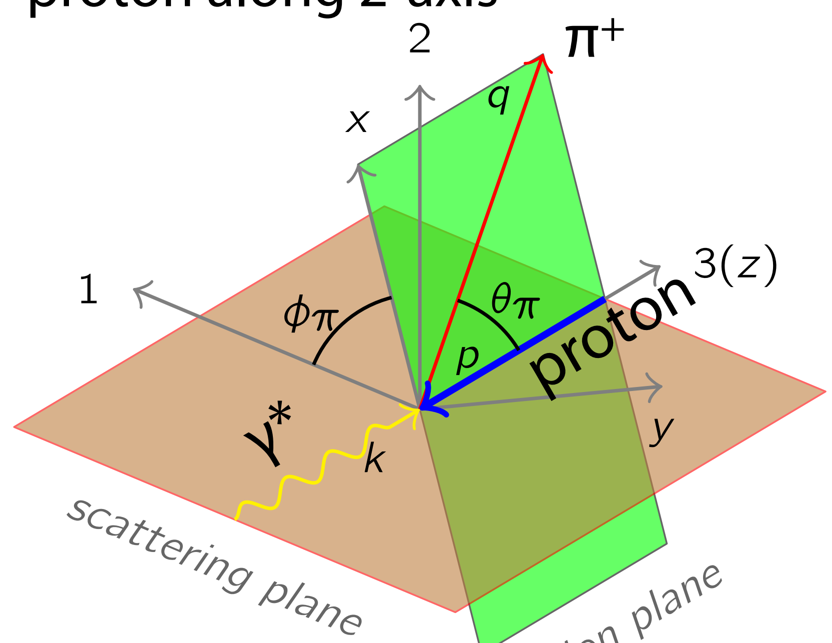


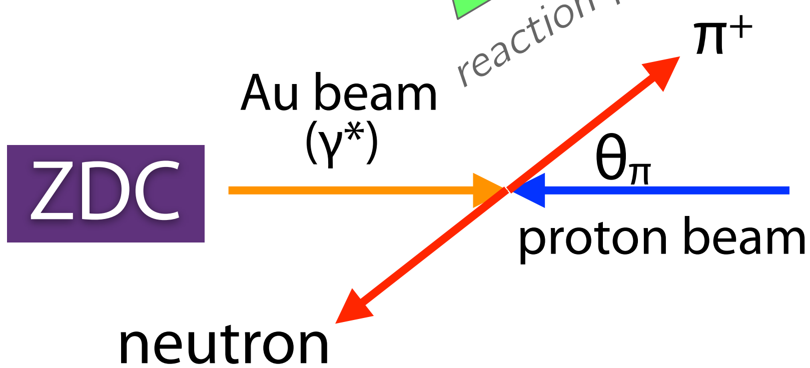
2.2 MC simulations for γ*p interactions

- MC simulations based on the MAID2007 model (Drechsel et al. EPJ A 34, **69** (2007)) are performed for R_T^{00} and $T(\theta_\pi)$.
- $T(\theta_\pi)$~0.8 at Δ(1232), ~-0.5 at N(1680) → large A_N!!

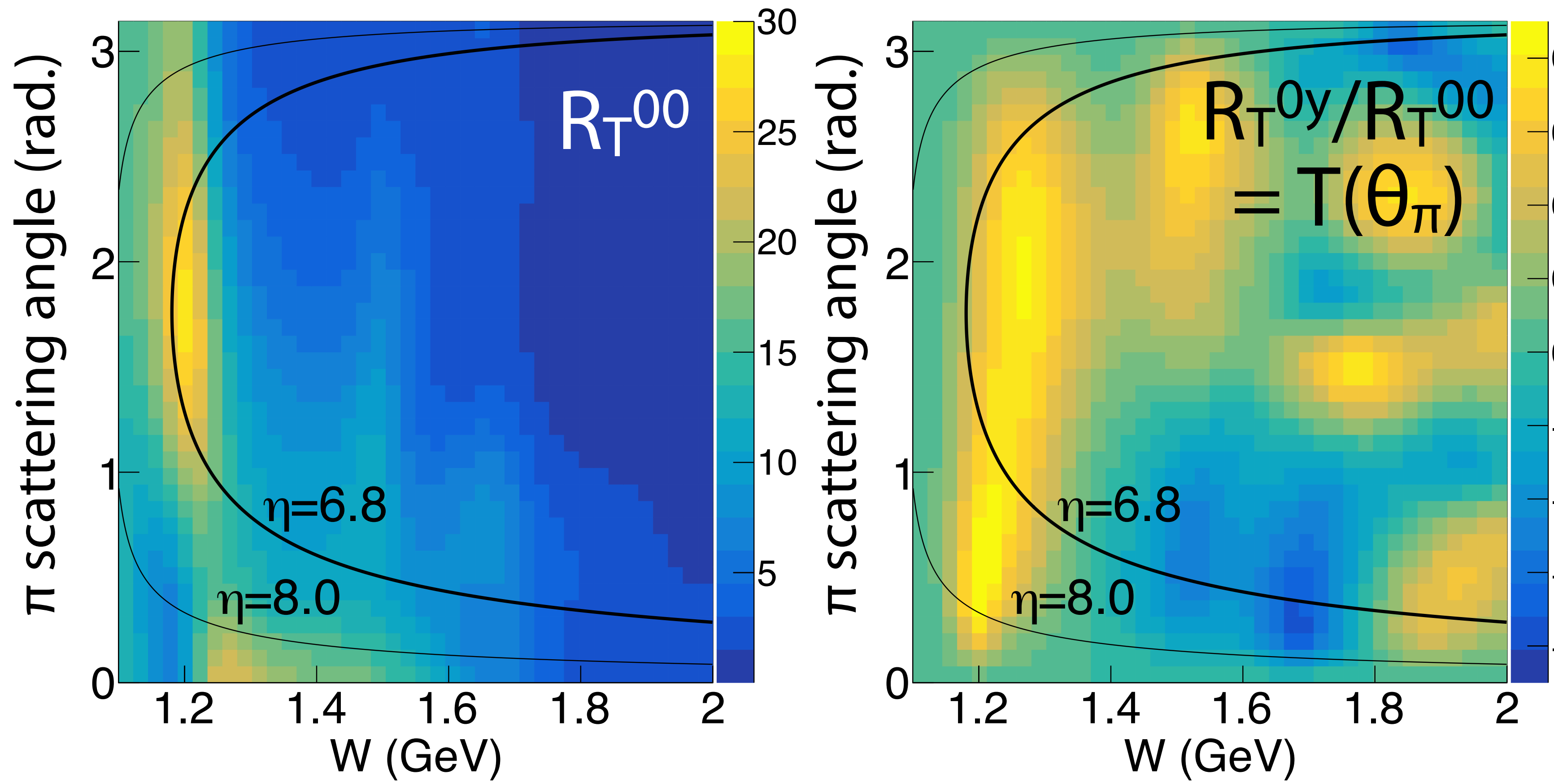
γ*p center-of-mass system

transversely polarized proton along 2-axis





GM, arXiv:1702.03834

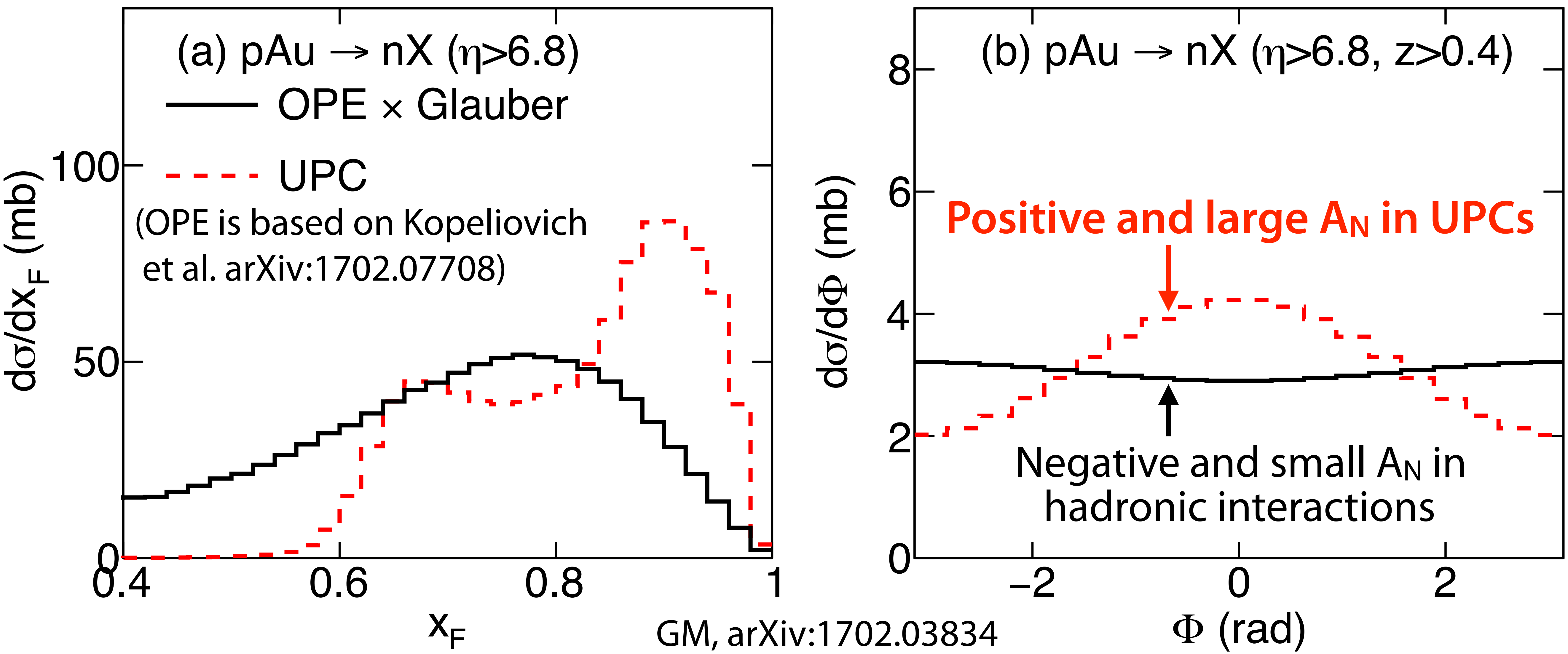


- Solid curves indicate the ZDC acceptance.
- $T(\theta_\pi)$ with the weight of γ* flux = A_N

3.1 UPCs vs. hadronic interactions

- Neutron cross section in pAu UPCs ($\propto Z^2$) is comparable with hadronic interactions, while $\sigma_{\mathrm{UPC}} \sim \sigma_{\mathrm{HAD}} \times 0.1$ in pAl.
- UPC-induced A_N is positive and large in both pAl and pAu.

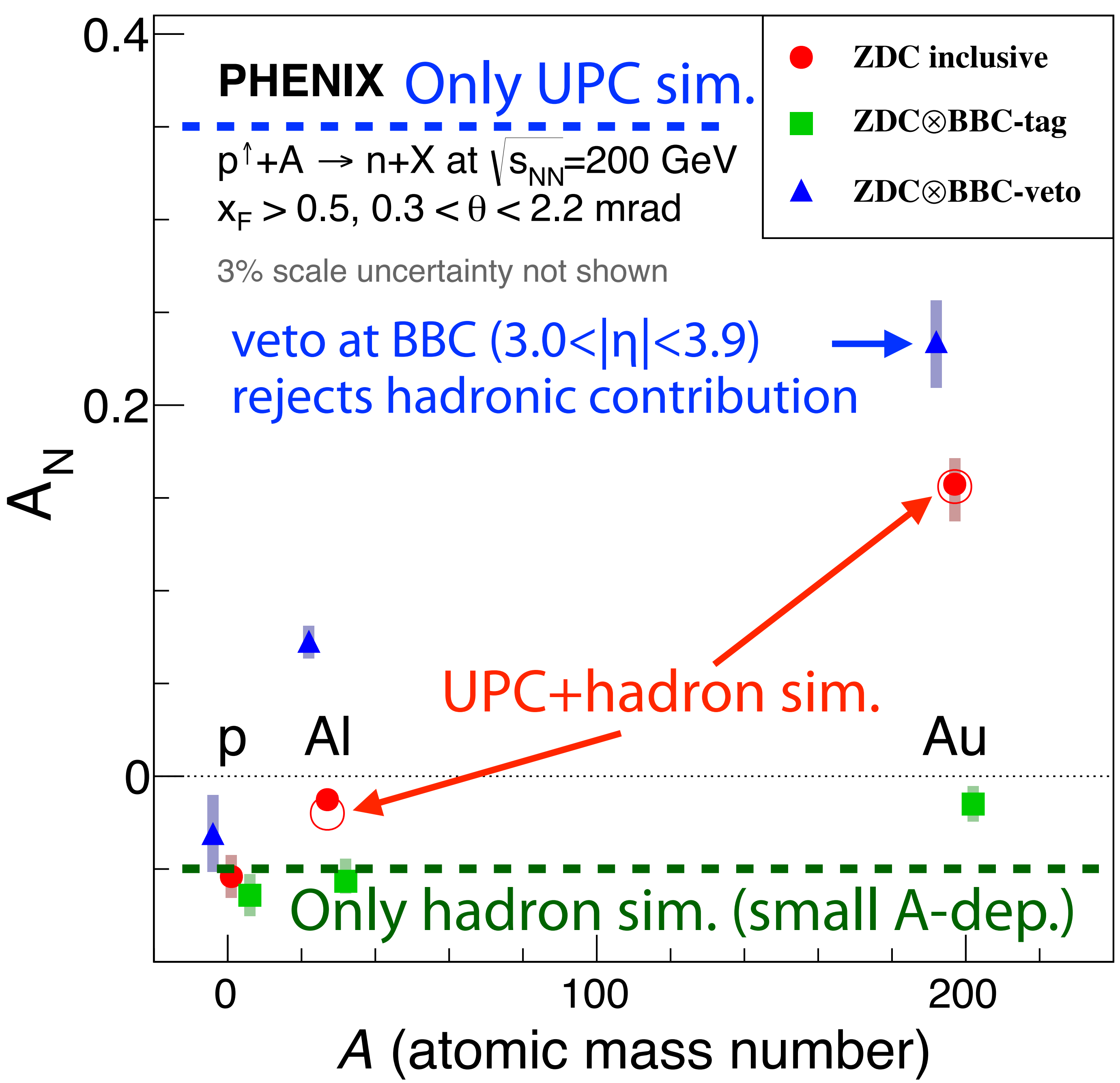
Expected X_F and Φ distributions for forward neutrons in pAu



GM, arXiv:1702.03834

3.2 MC sim. vs. the PHENIX measurements

- PHENIX measurements are well explained by the sum of UPCs and hadronic interactions.
- BBC-veto can be reasonably understood by the enhanced UPC fraction.



PHENIX, arXiv:1703.10941
GM, arXiv:1702.03834

The subtraction of UPCs (sys.~10%) from the PHENIX measurements enables discussions on

- nuclear effects
- Coulomb-Nuclear Interference

4. Summary and Future prospects

- Large A_N for forward neutrons in polarized pAu collisions and its A-dependence are discovered by PHENIX.
- To compared with the PHENIX data, we developed the MC simulations involving UPCs and hadronic interactions in polarized pA collisions.
- UPCs has large A_N and the cross section is proportional to Z^2.
- Simulation results well explain the PHENIX inclusive measurements.
  → Large A_N in pAu collisions originates in UPCs.

- <u>Future prospects</u>: p_T- and X_F-dependent A_N is under analysis
  - detailed understanding in UPCs→ reduction of UPC sys. errors.
  - UPC subtracted A_N in pA enables (almost) model-independent discussion on hadronic contribution to A_N.

Backup

UPC formalism

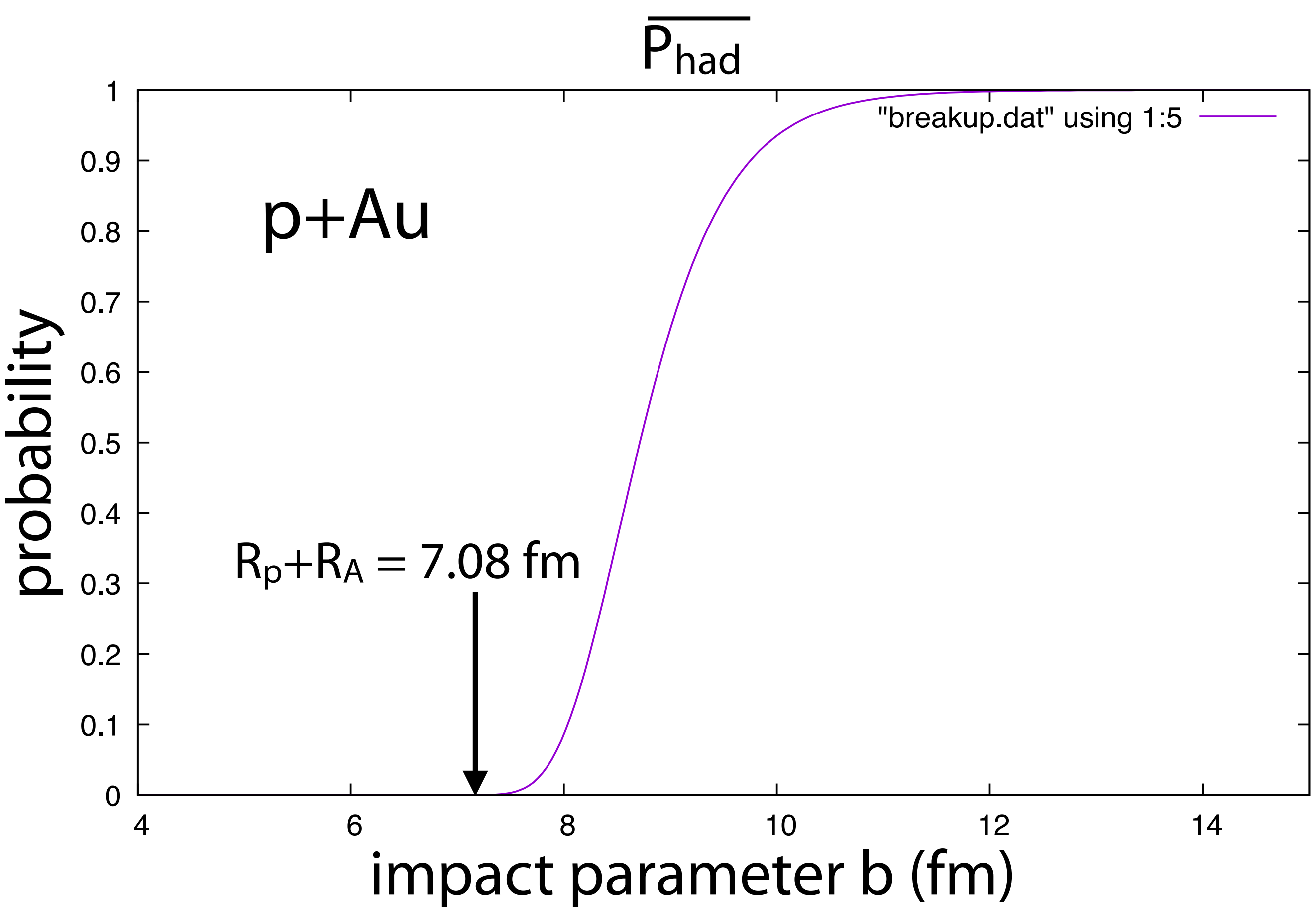
The UPC cross section is factorized as

$$\frac{d\sigma^4_{\mathrm{UPC}(p^\uparrow \mathrm{A}\to\pi^+ n)}}{dW\,db^2\,d\Omega_n} = \frac{d^3N_{\gamma^*}}{dW\,db^2}\,\frac{d\sigma_{\gamma^* p^\uparrow\to\pi^+ n}(W)}{d\Omega_n}\,\overline{P_{\mathrm{had}}}(b)$$

photon flux (N): quasi-real photons produced by a relativistic nucleus

$\sigma_{\gamma+p\to X}$: inclusive cross sections of γ+p interactions

$\overline{P_{had}}$: a probability not having a p+A hadronic interaction.



- ***$\overline{P_{had}}$ is calculated by using a Glauber MC simulation.***
- ***UPCs occur only if the impact parameter b is larger than the sum of radii R_p and R_A.***
- ***$\overline{P_{had}}(b)$ distribution is important not only for the cross section but also for the energy distribution.***

Virtual photon flux

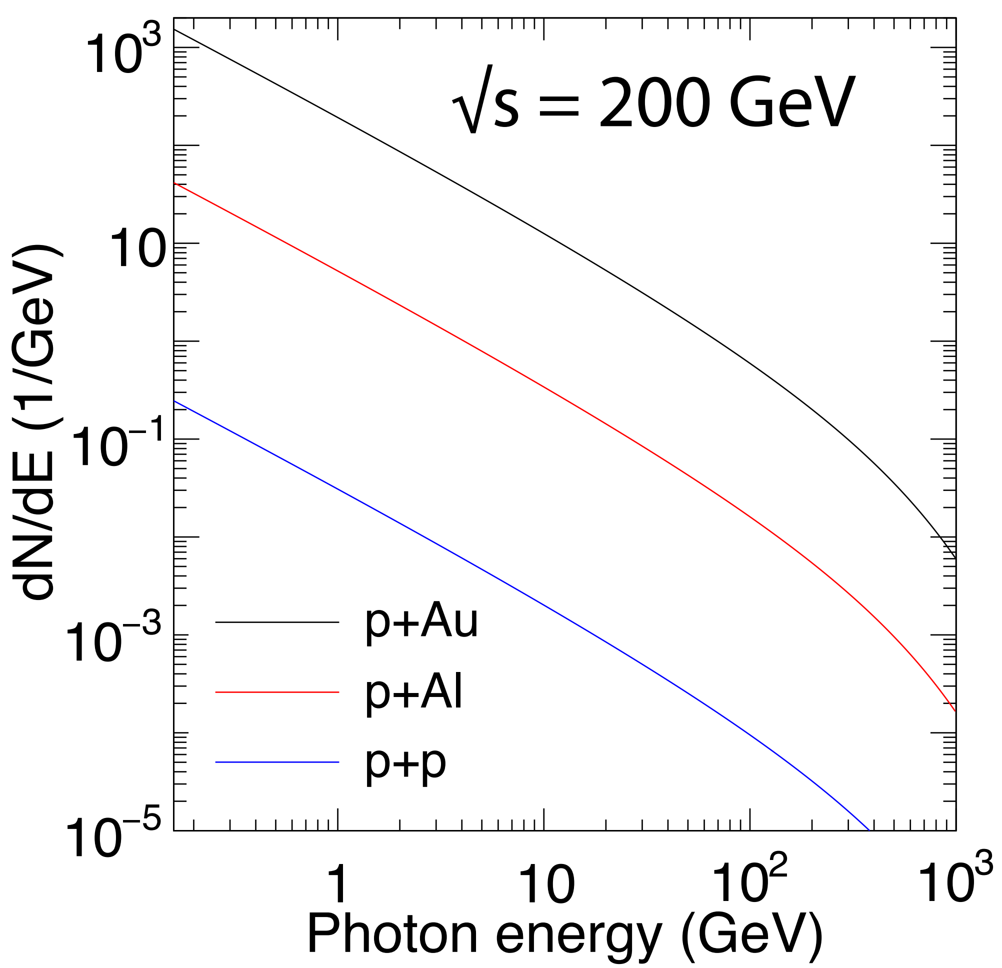
The number of virtual photons per energy and b is formulated by the Weizsacker-Williams approximation or QED (Phys. Rep 364 359 '02, NPA 442 739 '85, etc…):

$$\frac{d^3N_{\gamma^*}}{d\omega_{\gamma^*}^{rest}db^2} = \frac{Z^2\alpha}{\pi^2}\frac{x^2}{\omega_{\gamma^*}^{rest}b^2}\left(K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right)$$

Proportional to Z^2

where $x = \omega_{\gamma^*}^{rest}b/\gamma$ and ω^{rest}_{γ} is the virtual photon energy in the proton rest frame.

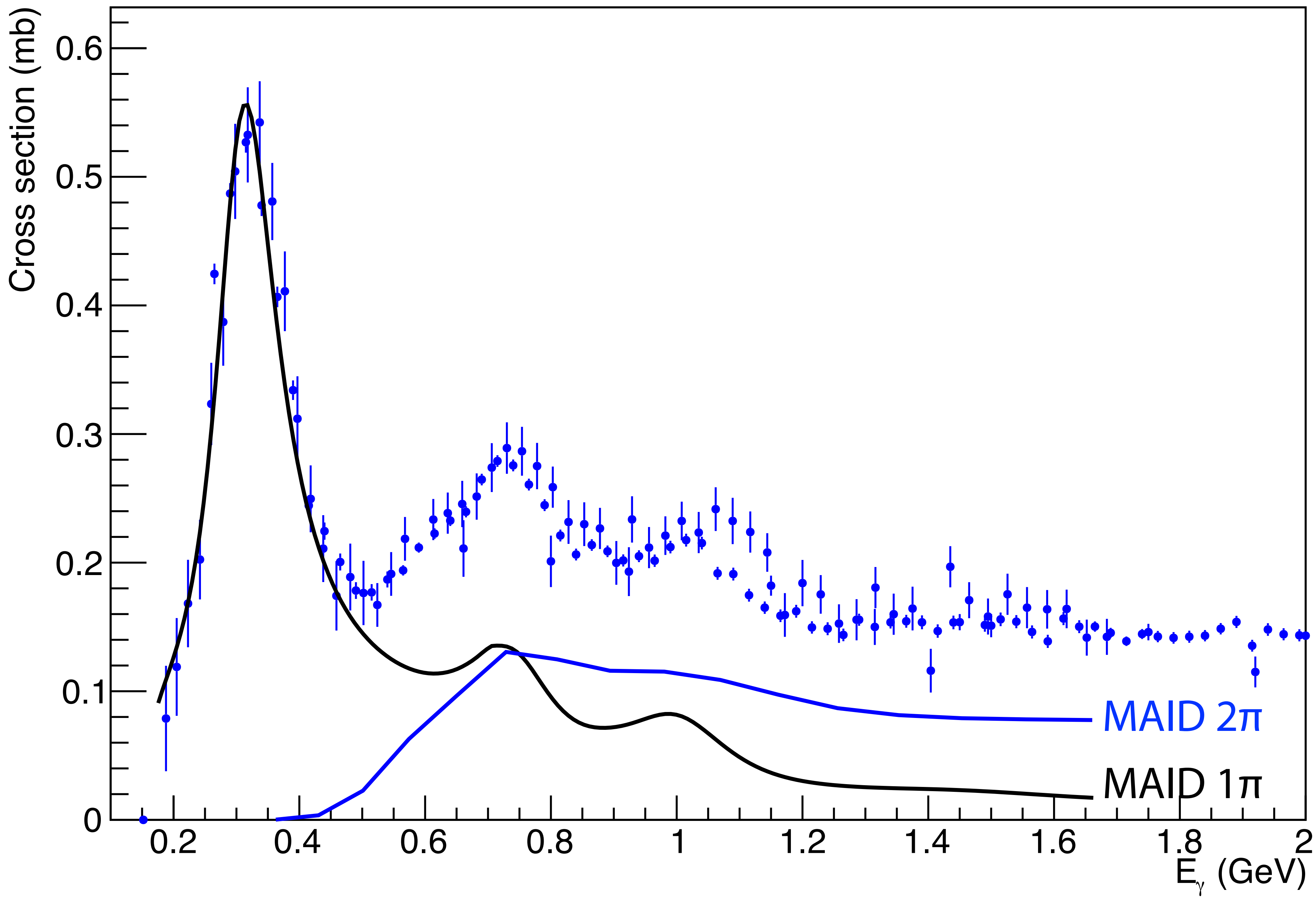
Note that the virtual photon flux depends on the charge of photon source as Z^2.



- ***From the virtual photon flux, we see that low-energy photons dominate UPCs.***

Photon virtuality is limited by $Q^2 < \frac{1}{R^2}$. So, $Q^2 < 10^{-3}\,\mathrm{GeV}^2$

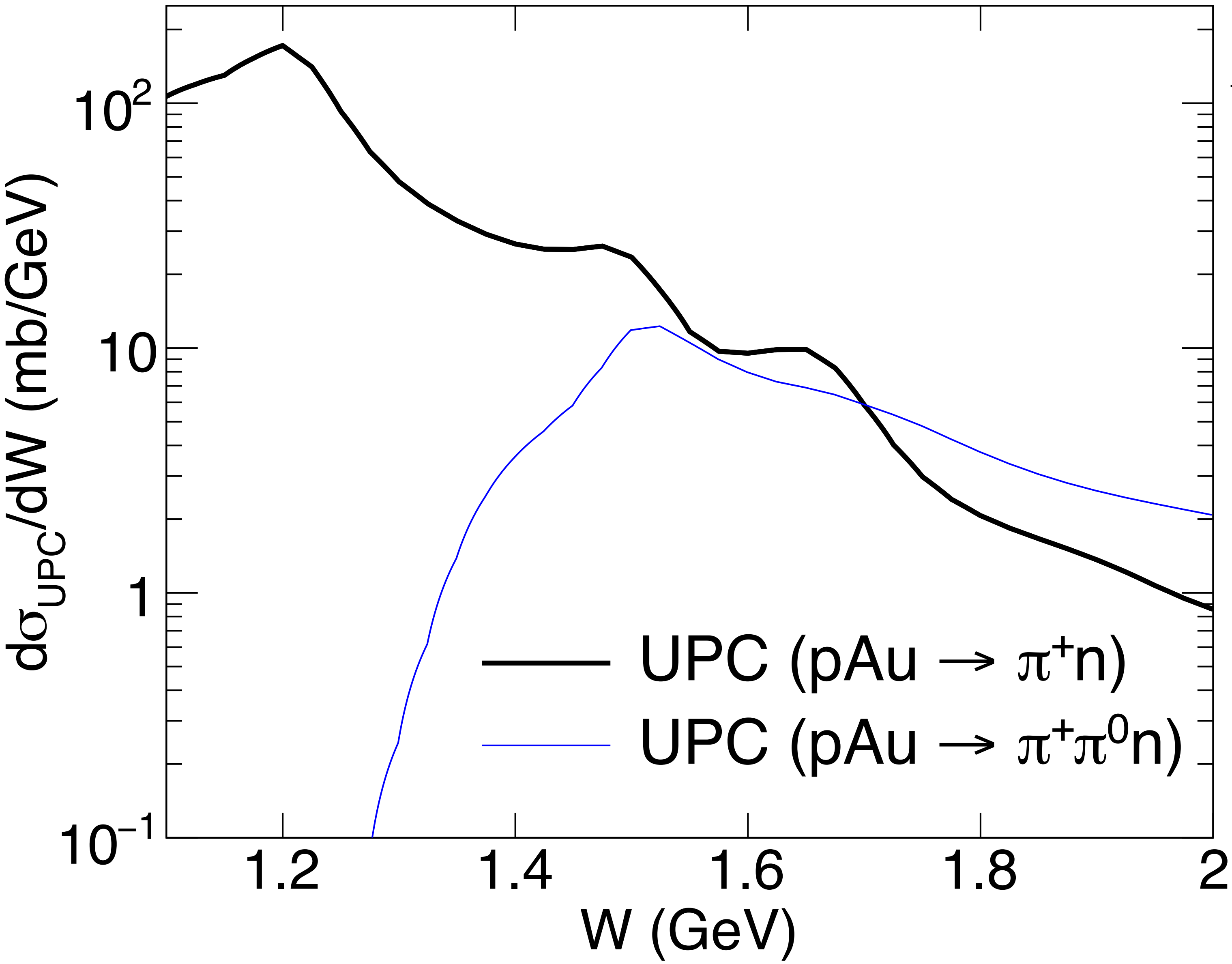
Inclusive cross sections of γ+p interactions



Only 1π channel is simulated in this study.

It is hard to simulate neutron momenta in 2π channels (future study?).

UPC cross sections as a function of W



$$\frac{d\sigma^4_{\mathrm{UPC}(p^\uparrow \mathrm{A}\to\pi^+ n)}}{dW\, db^2 d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW\, db^2} \frac{d\sigma_{\gamma^* p^\uparrow \to \pi^+ n}(W)}{d\Omega_n} \overline{P_{\mathrm{had}}}(b)$$

- ***2π channels are anyway subdominant in UPCs.***
- ***Table I and II show the total cross sections in UPCs and hadronic interactions.***

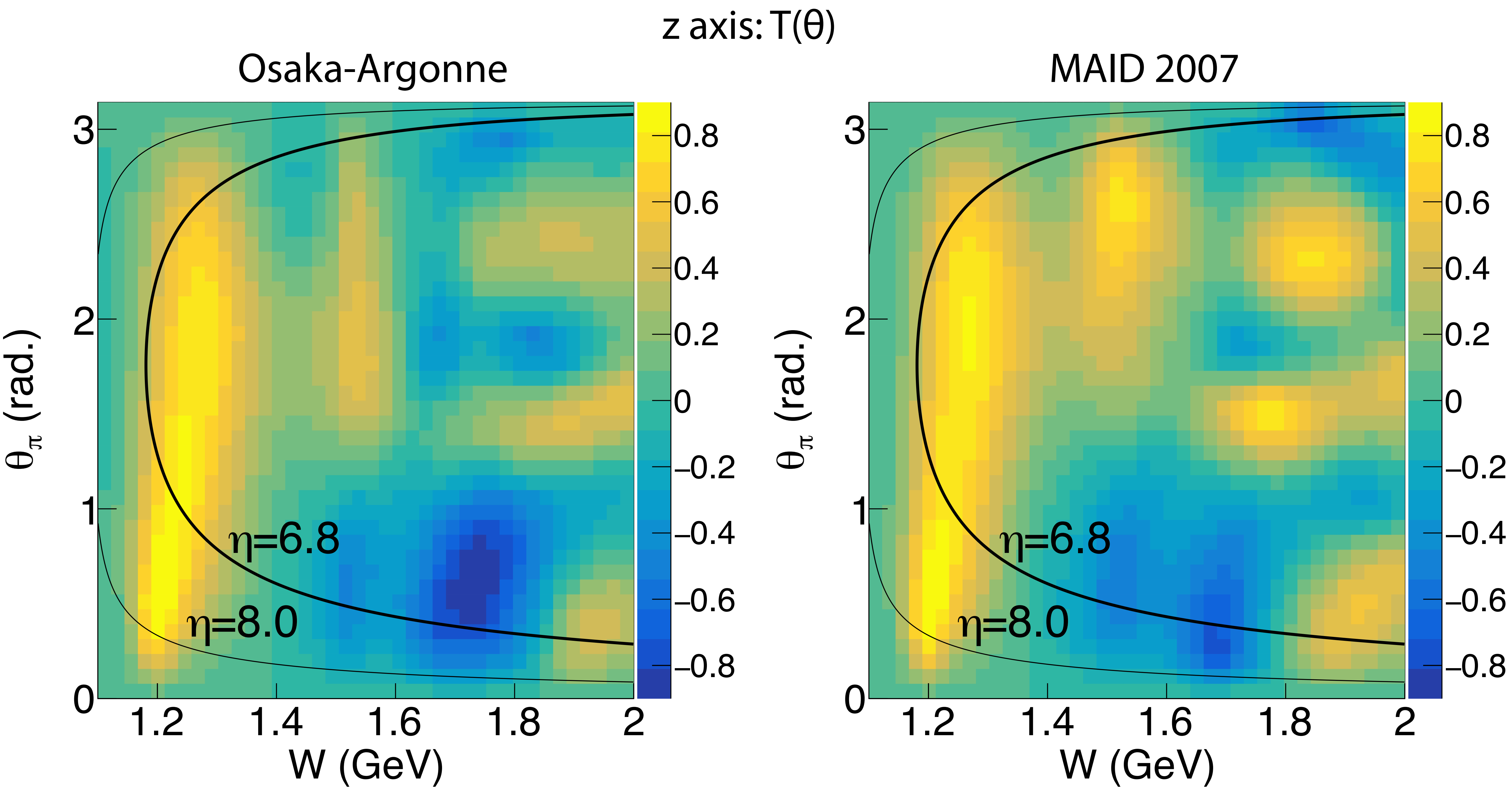
TABLE I. Cross sections for neutron production in ultraperipheral collisions and hadronic interactions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$. Cross sections in parentheses are calculated without η and z limits.

UPCs		Hadronic interactions	
$p^\uparrow$Al	$p^\uparrow$Au	$p^\uparrow$Al	$p^\uparrow$Au
0.7 mb (2.2 mb)	19.6 mb (41.7 mb)	8.3 mb	19.2 mb

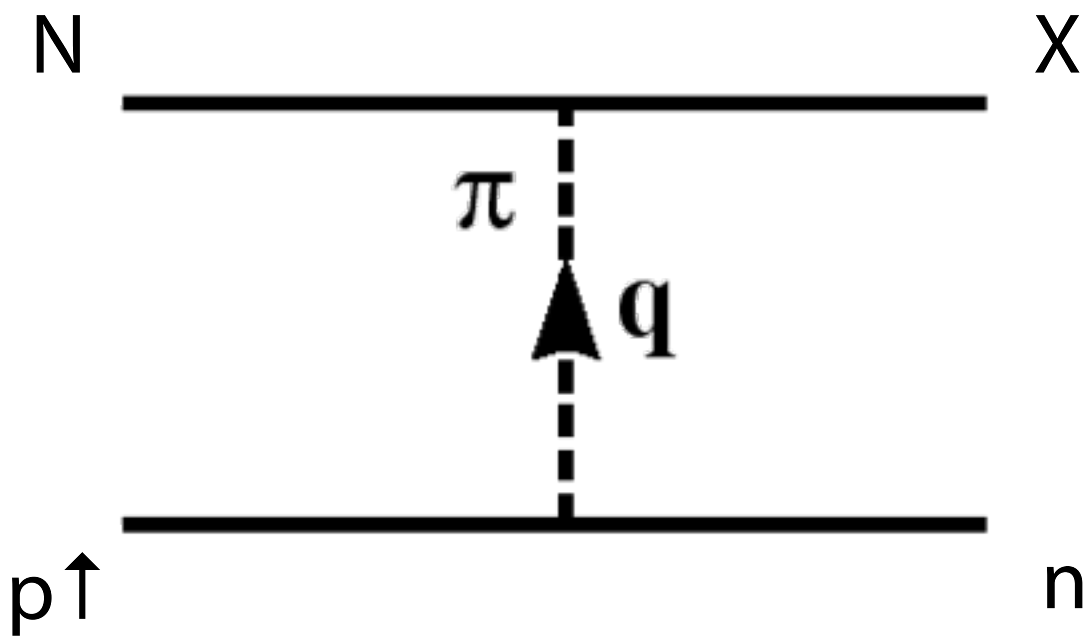
TABLE II. Cross sections in ultraperipheral pAu collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$.

$p\mathrm{Au} \to nX$ ($\eta > 6.9$ and $z > 0.4$)			$p^\uparrow\mathrm{Au} \to \pi^+\pi^0 n$
< 1.1 GeV	1.1–2.0 GeV	> 2.0 GeV	1.25–2.0 GeV
0.6 mb	27.4 mb	1.8 mb	6.2 mb

Target asymmetry as a function of W

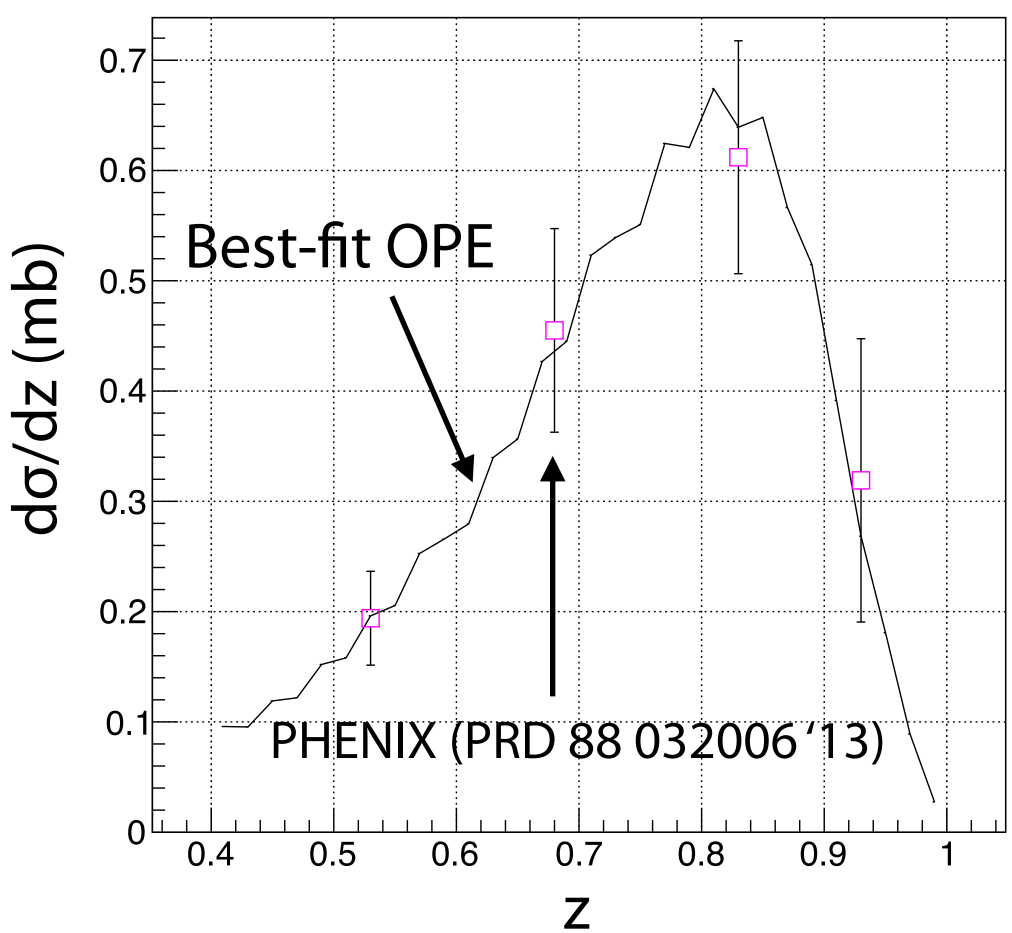


Hadronic interactions (one-π exchange)



$$z\frac{d\sigma_{pp\to nX}}{dzdp_{\mathrm{T}}^2} = S^2\left(\frac{\alpha'_\pi}{8}\right)^2 |t|G^2_{\pi^+pn}(t)|\eta_\pi(t)|^2 \times (1-z)^{1-2\alpha_\pi(t)}\sigma^{\mathrm{tot}}_{\pi^++p}(M_X^2),$$

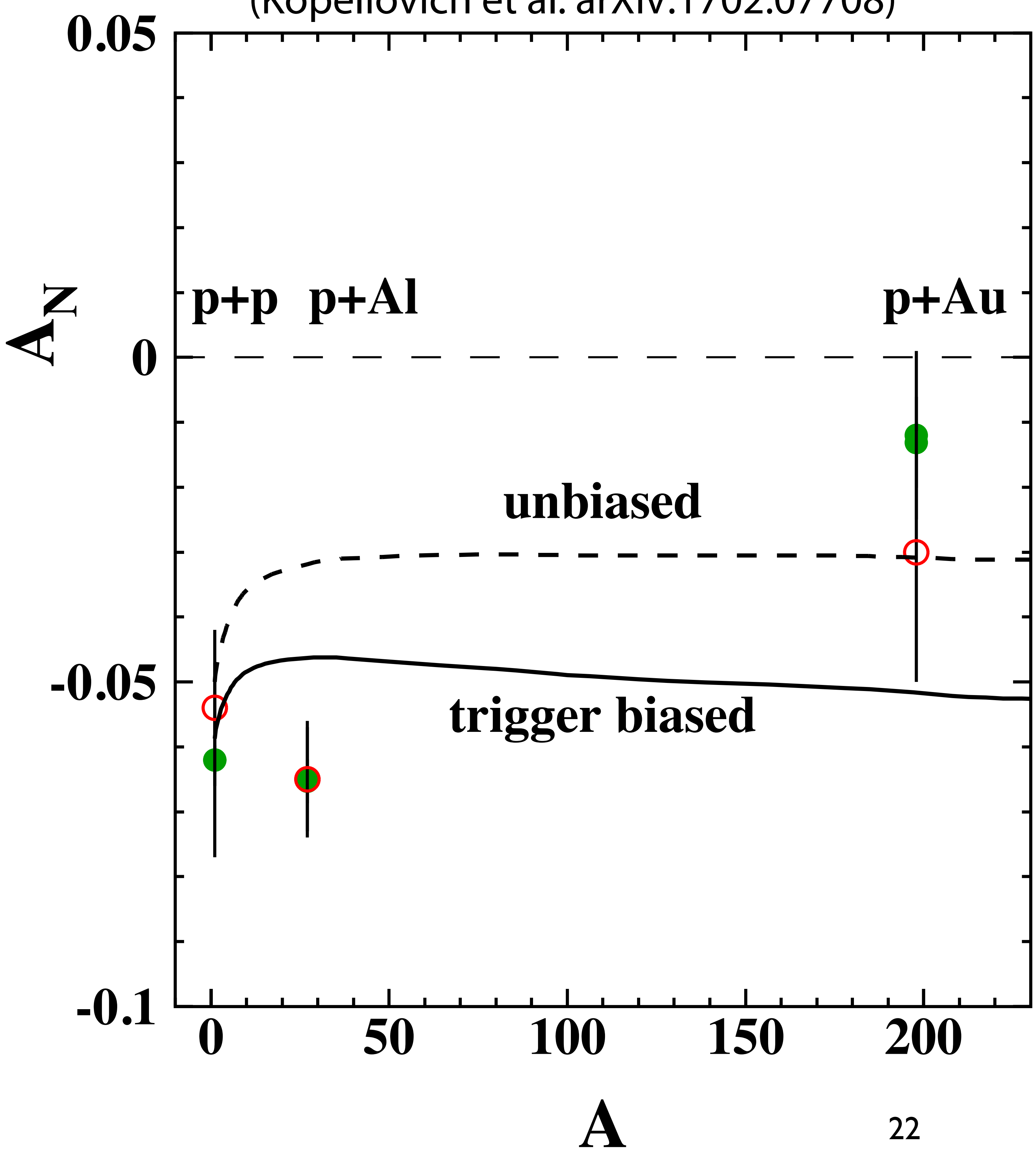
$$z\frac{d\sigma_{p^\uparrow A\to nX}}{dzdp_{\mathrm{T}}^2} = z\frac{d\sigma_{pA\to nX}}{dzdp_{\mathrm{T}}^2}(1+\cos\Phi A_{\mathrm{N}}^{\mathrm{HAD}(pA)}) = z\frac{d\sigma_{pp\to nX}}{dzdp_{\mathrm{T}}^2}A^{0.42}(1+\cos\Phi A_{\mathrm{N}}^{\mathrm{HAD}(pA)})$$



- *Kopeliovich et al. propose an interference between π and a_1-Reggeon leading to negative asymmetry in p-p and p-A.*
- *In this study, due to a technical difficulty, I omit an implementation of the interference. Alternatively, I apply (1+cosΦA) to the differential cross section of unpolarized proton and then effectively obtain the differential cross section of polarized proton.*
- *The coupling $G_{\pi+pn}$ is chosen so that the calculated dσ/dz gives the best-fit to the PHENIX result.*

Hadronic interactions (one-π exchange)

(Kopeliovich et al. arXiv:1702.07708)



$$A_N^{(\pi-\tilde{a}_1)}(q_T, z) = q_T \, \frac{4m_N \, q_L}{|t|^{3/2}} \, (1-z)^{\alpha_\pi(t)-\alpha_{\tilde{a}_1}(t)} \quad (12)$$

$$\times \; \frac{\mathrm{Im}\; \eta_\pi^*(t)\, \eta_{\tilde{a}_1}(t)}{|\eta_\pi(t)|^2} \left(\frac{d\sigma_{\pi p \to \tilde{a}_1 p}(M_X^2)/dt|_{t=0}}{d\sigma_{\pi p \to \pi p}(M_X^2)/dt|_{t=0}} \right)^{1/2} \frac{g_{\tilde{a}_1^+ pn}}{g_{\pi^+ pn}}.$$

$$A_N^{pA\to nX} = A_N^{pp\to nX} \boxed{\times \frac{R_1}{R_2} R_3}$$

Nuclear effects:
no significant effect to A_N