

Transverse single spin asymmetries for very forward neutrons in ultra-peripheral p-A collisions

GM, Phys. Rev. C 95, 044908 (2017).

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(RIKEN BNL Research Center)



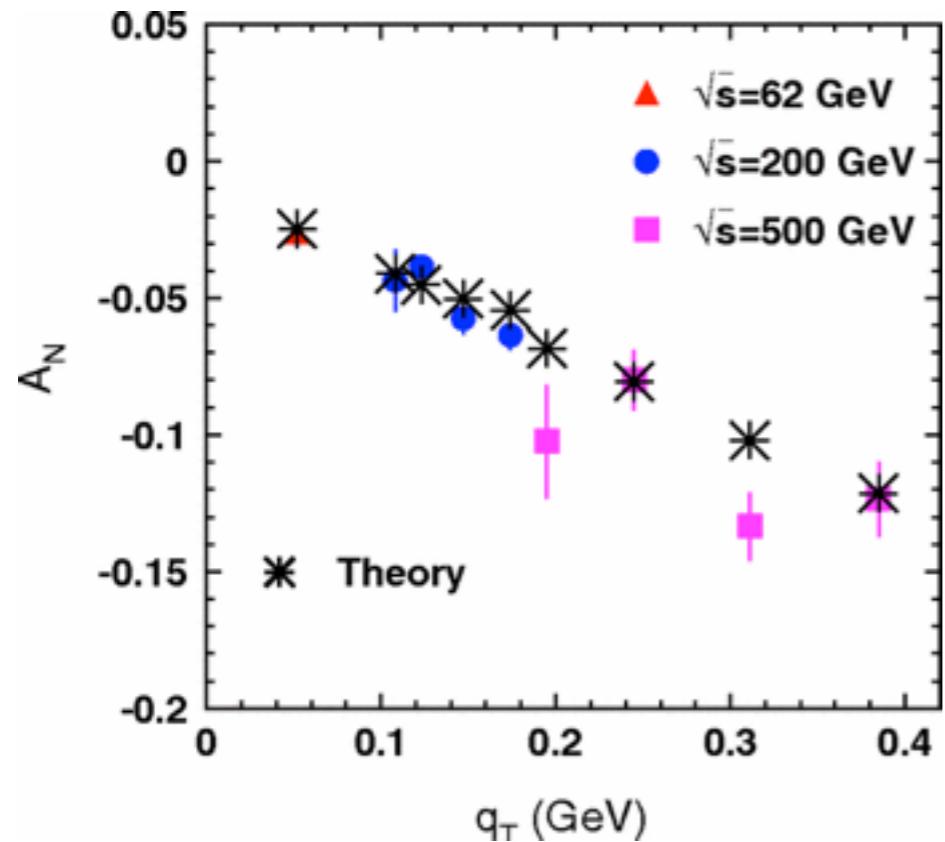
Workshop on forward physics and high-energy scattering at zero degrees 2017
26-29 September 2017, Nagoya University

Outline

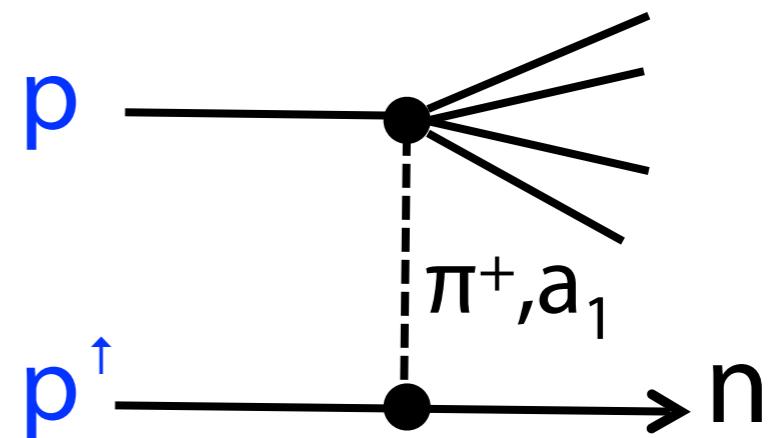
1. Introduction and Physics motivation
 - Large A_N for forward neutrons discovered in pAu collisions
 - Can electromagnetic effects explain positive and large A_N ?
2. Ultra-peripheral collisions (UPCs)
 - Do γ^*p interactions have large A_N ?
 - MC simulations of γ^*p interactions
3. MC simulation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

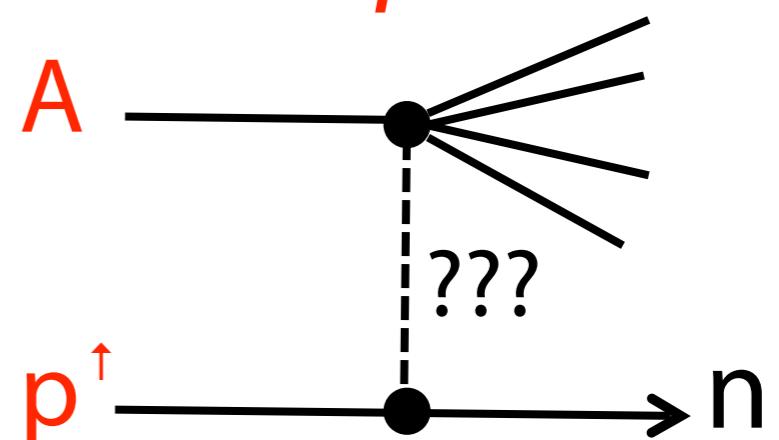


A_N in pp at the RHIC energies are well explained by an one- π /Reggeon exchange model with the interference between π (spin flip) and a_1 (nonflip).

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

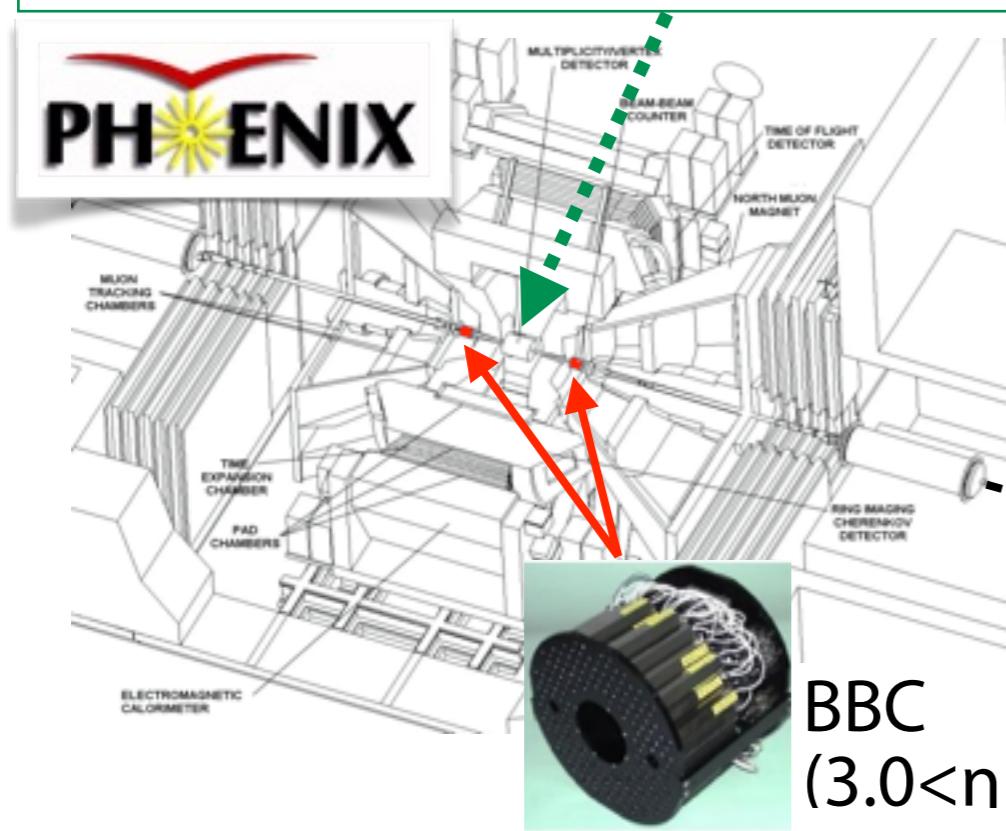
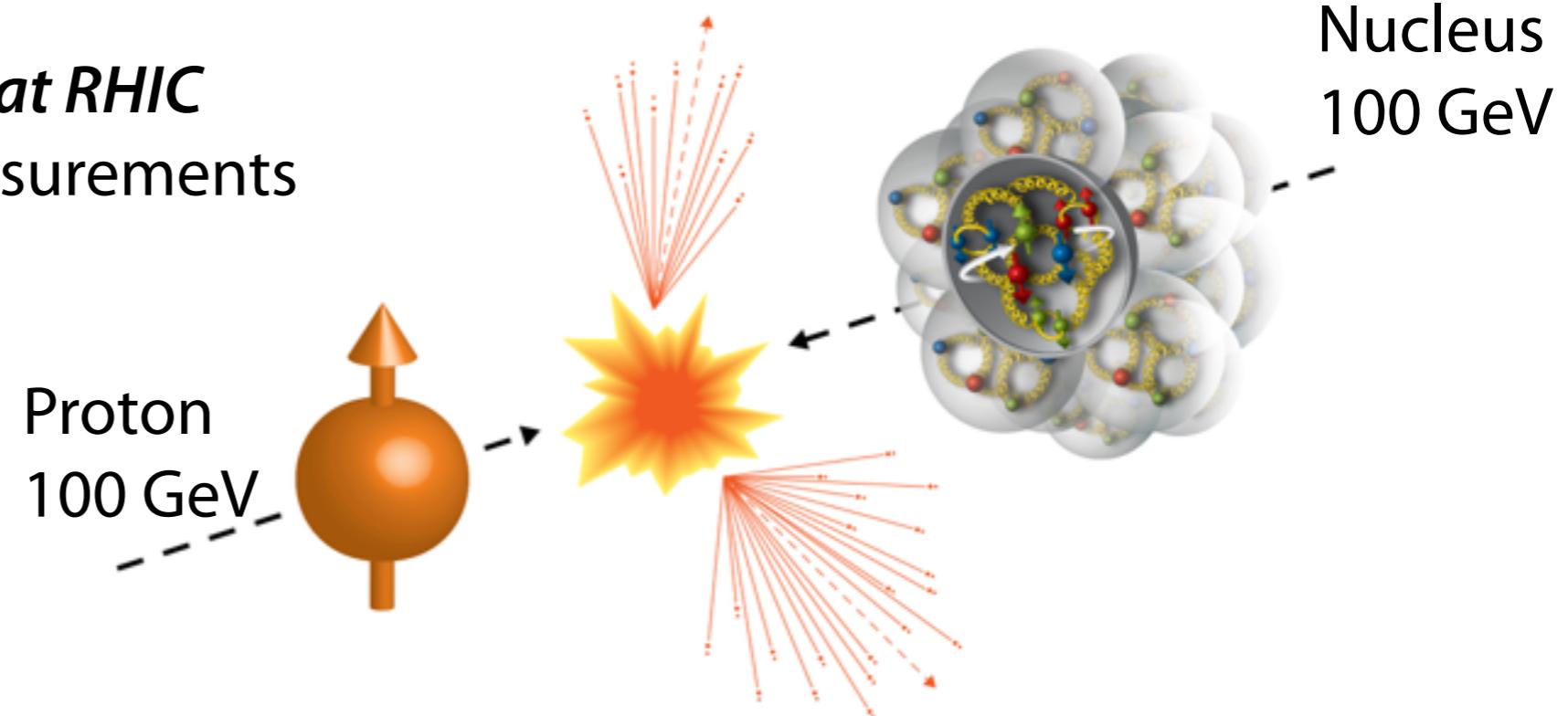


1.1 Transversely polarized pA collisions

Run 15 pAl/pAu collisions at RHIC

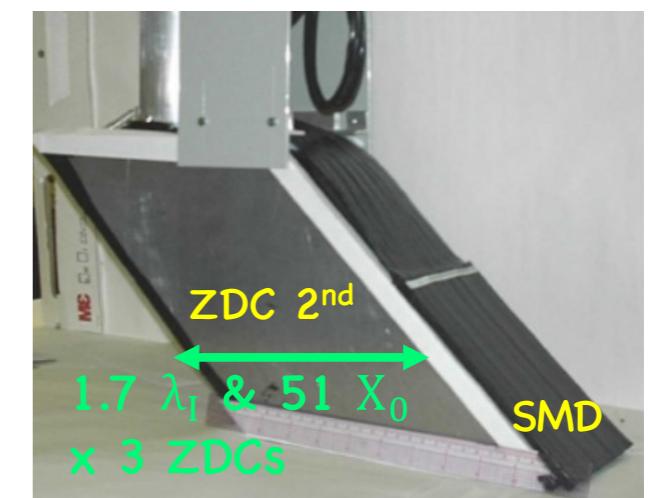
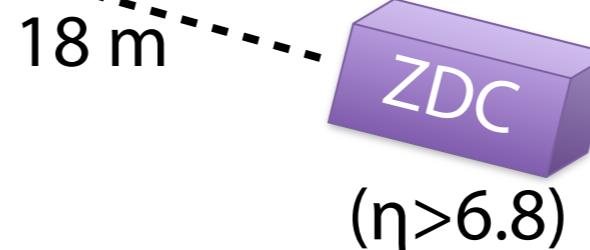
Dedicated run for A_N measurements

Average pol. $\sim 0.5\text{--}0.6$
(syst. uncertainty $\sim 3\%$)



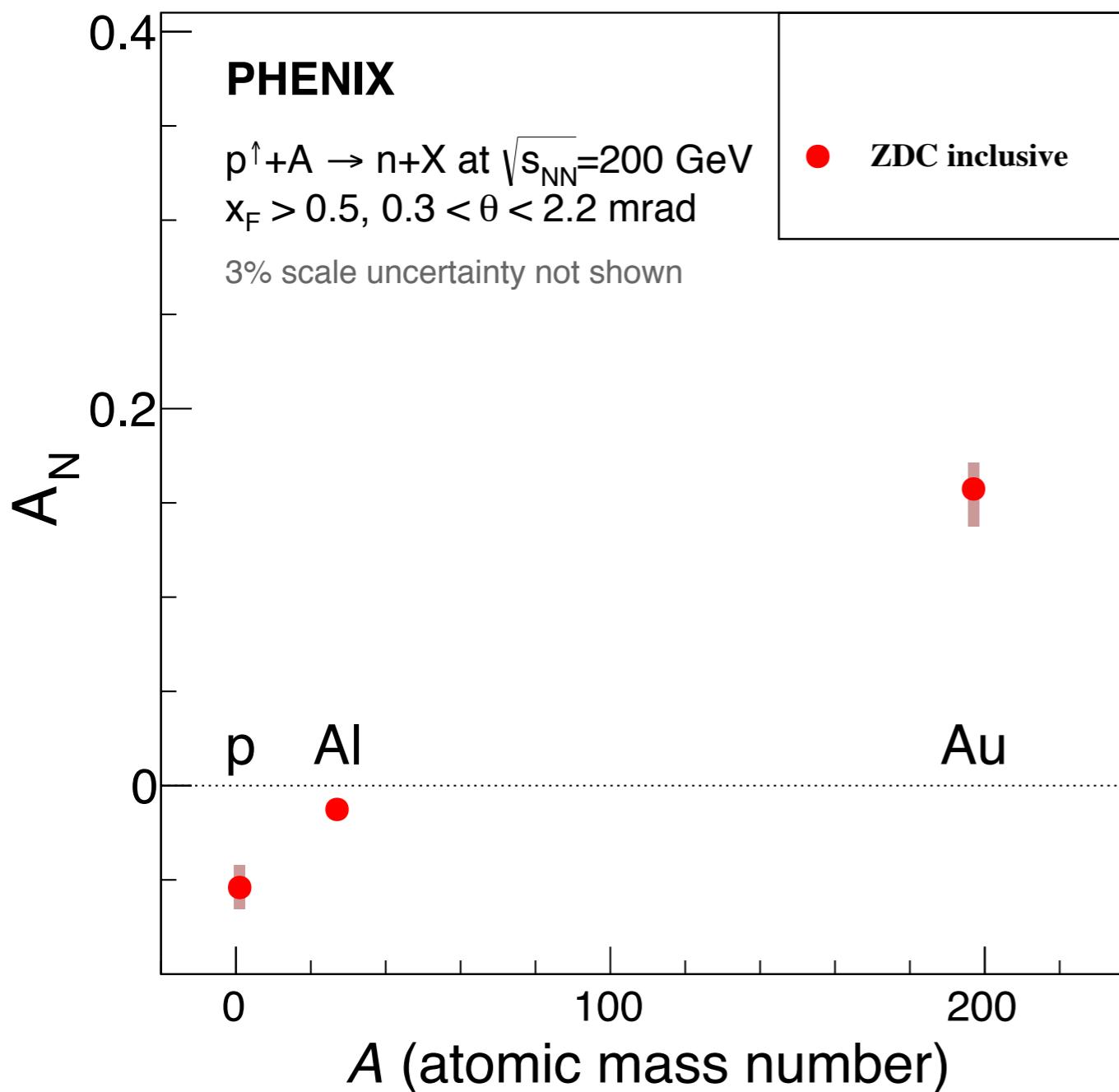
BBC
($3.0 < n < 3.9$)

- ZDC (Zero Degree Calorimeter): hadron calorimeter with a $10 \times 10 \text{ cm}^2$ area ($\Delta E/E \sim 20\text{--}30\%$)
- SMD (Shower Max Detector): X-Y plastic scintillator hodoscope ($\Delta x, \Delta y \sim 1 \text{ cm}$)
- 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)

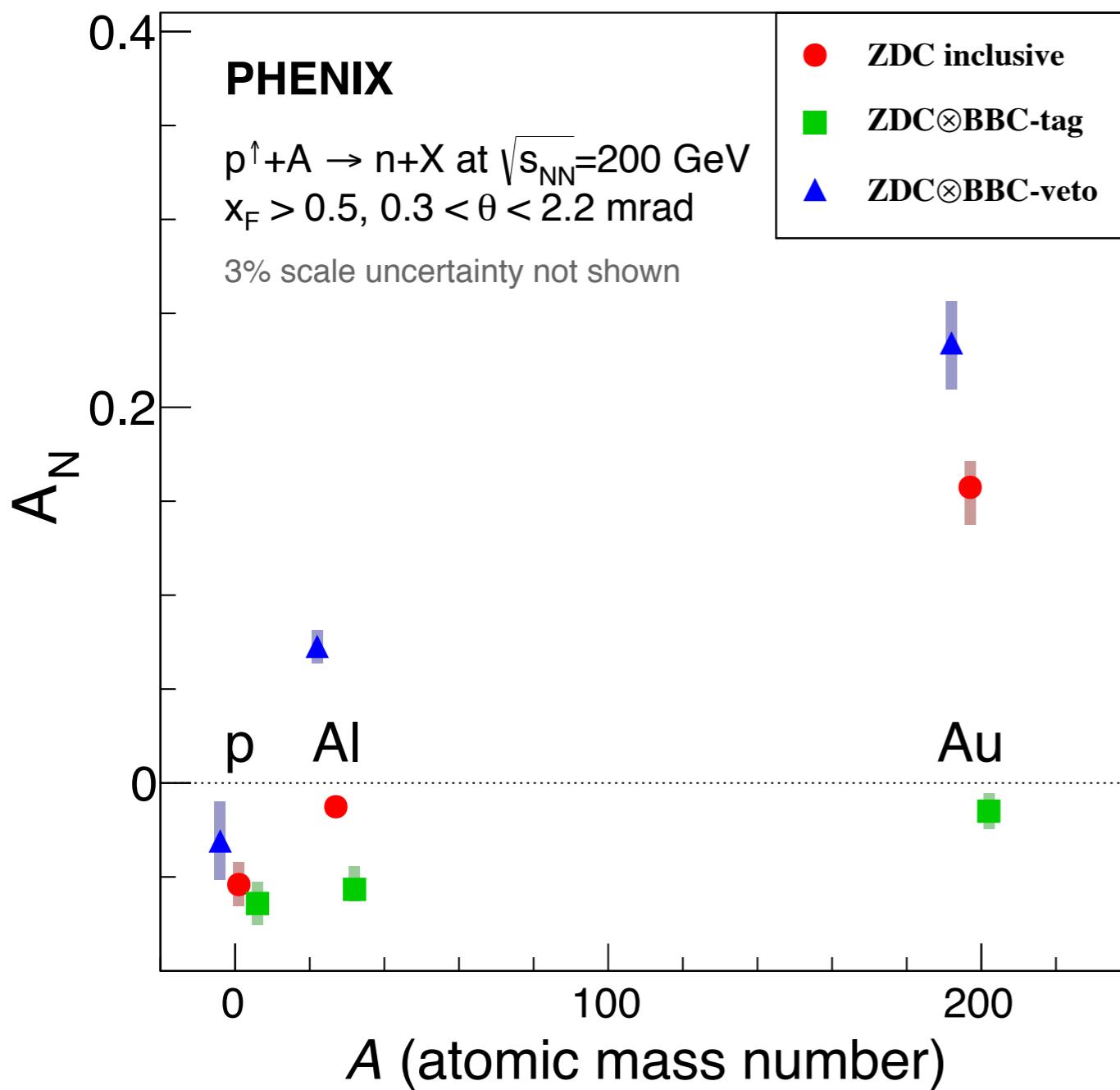


Surprisingly strong A -dependence

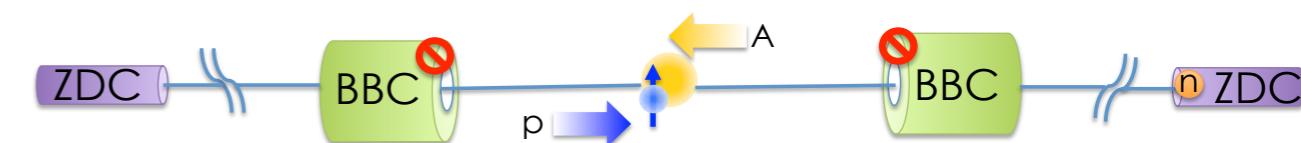
→ what mechanisms do produce such strong A -dependence?
→ *hint: how does A_N behave with the other triggers?*

1.3 BBC correlated A_N for forward neutrons

PHENIX, arXiv:1703.10941



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

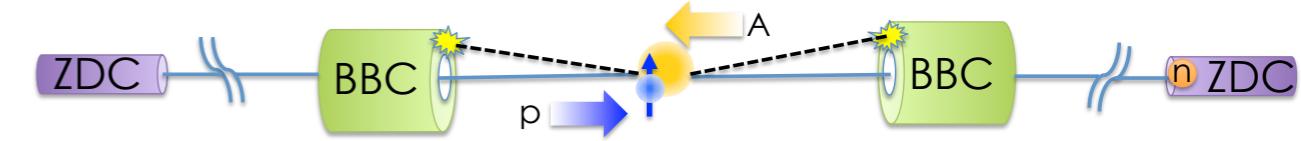


→ much stronger A-dependence



BBC
($3.0 < \eta < 3.9$)

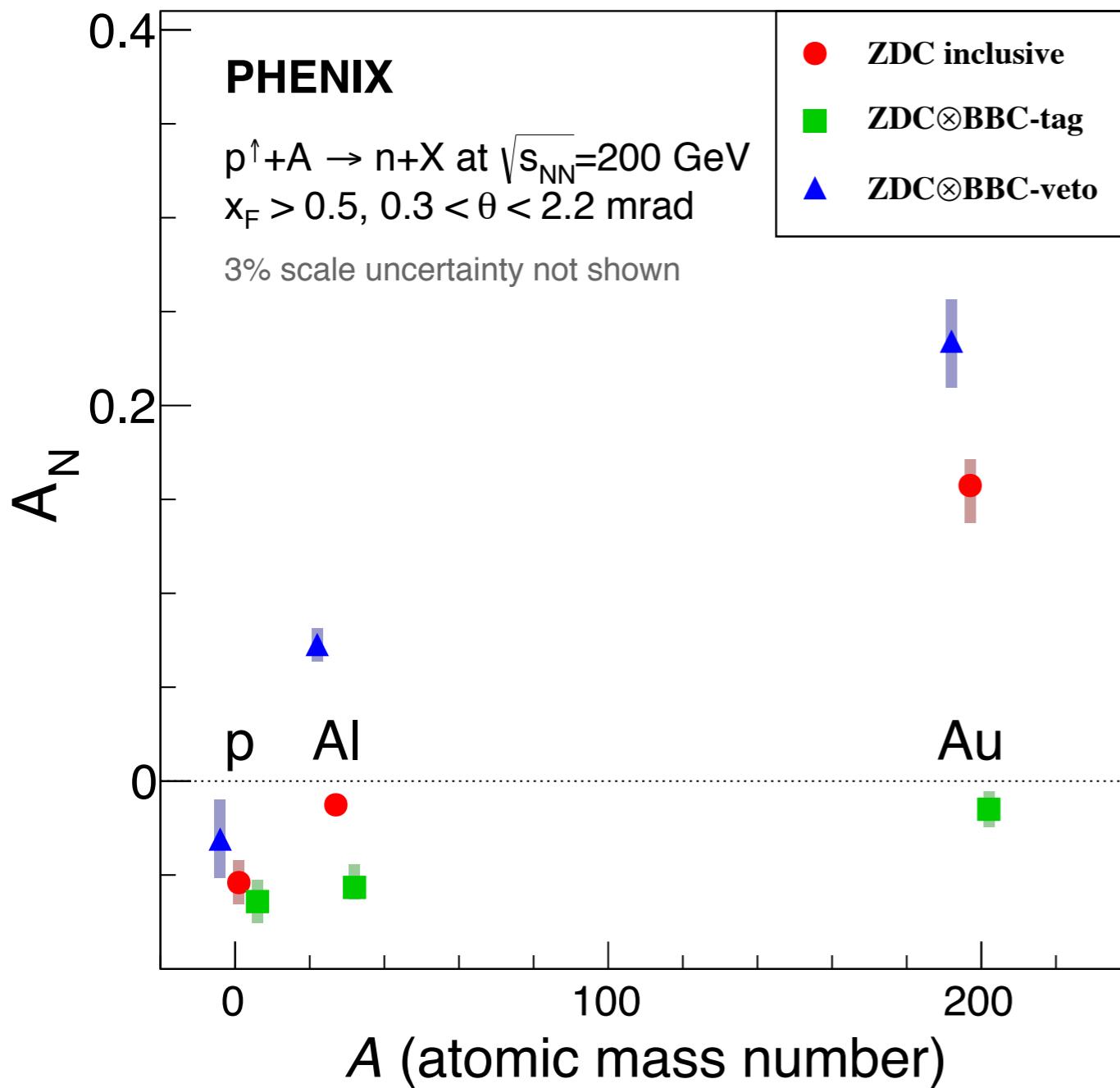
Particle hits at lower rapidities: **BBC-TAG**



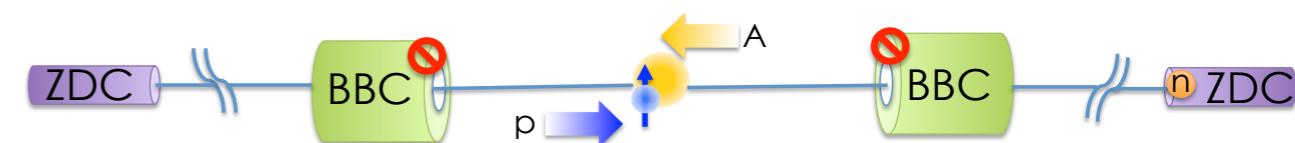
→ weak A-dependence

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

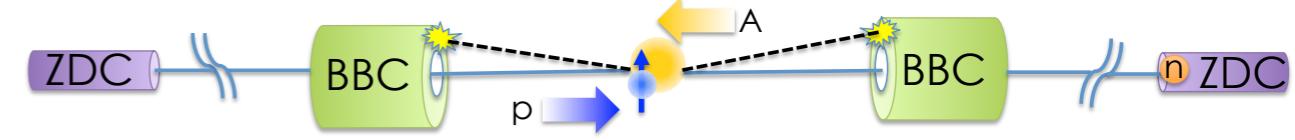


→ much stronger A-dependence

*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-TAG**

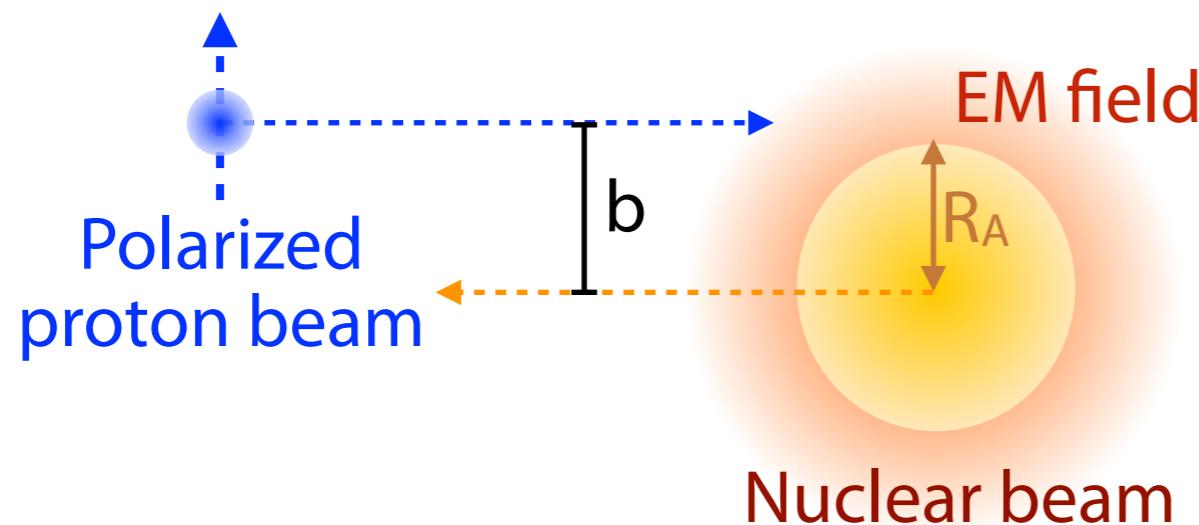


→ weak A-dependence

2. Ultra-peripheral collisions (UPCs)

UPCs (aka Primakoff effects);

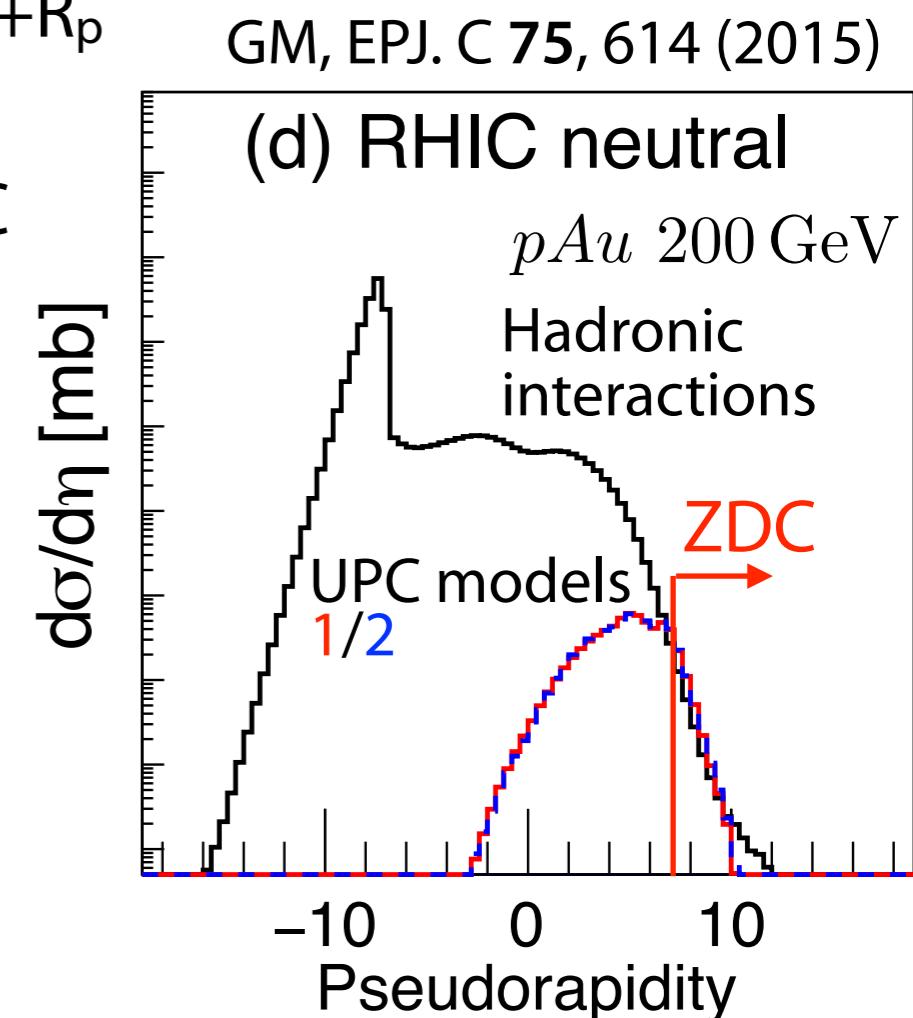
- a collision of a proton with the EM field made by a relativistic nucleus when the impact parameter b is larger than $R_A + R_p$
- fewer underlying particles unlike in hadronic interactions → smaller activity at BBC



UPC cross section

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

γ^* flux Does $\gamma^* p \rightarrow \pi^+ n$
 $\propto Z^2$ lead to large A_N ?



2. Virtual photon flux

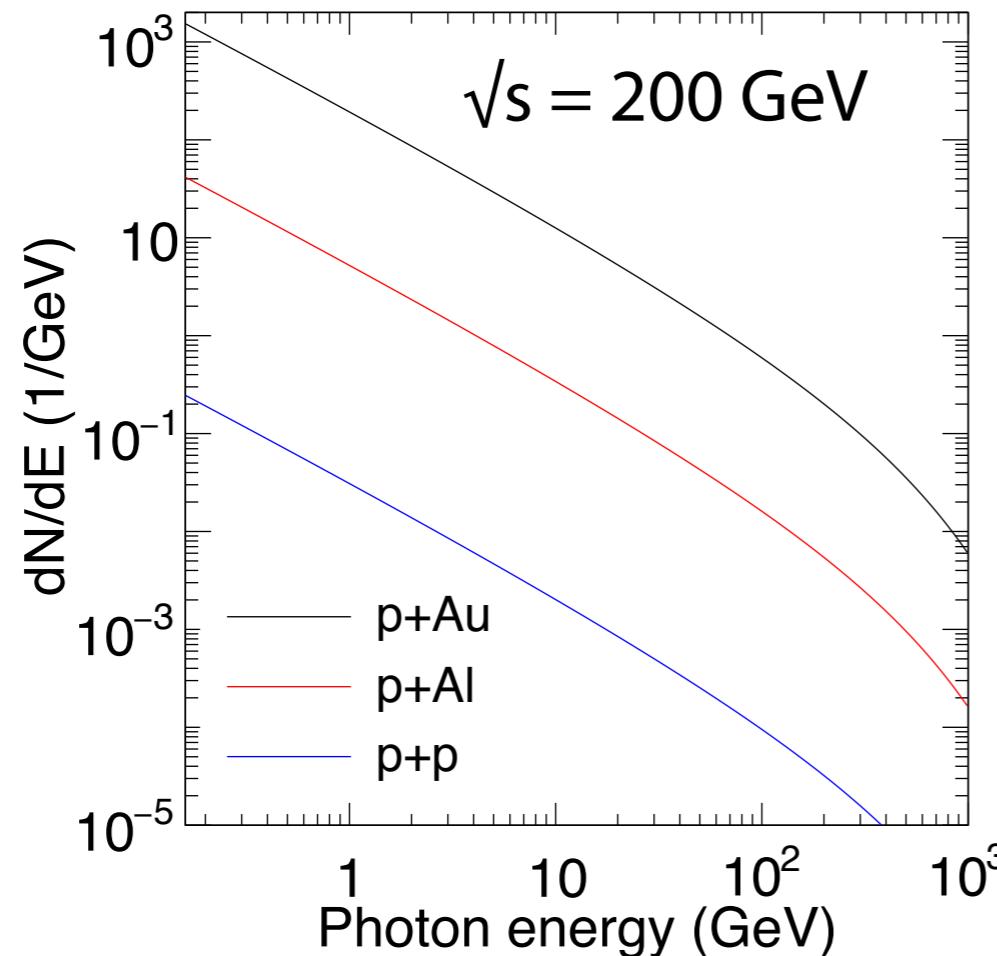
The number of virtual photons per energy and b is formulated by the Weizsäcker-Williams approximation (Phys. Rep 364 359 '02, NPA 442 739 '85, etc...):

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

Proportional to Z^2

where $x = \omega_{\gamma^*}^{rest} b / \gamma$ and ω^{rest} 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, $Q^2 < 10^{-3} \text{ GeV}^2$

2.1 Do $\gamma^* p$ interactions have large A_N ?

Polarized $\gamma^* p$ cross sections

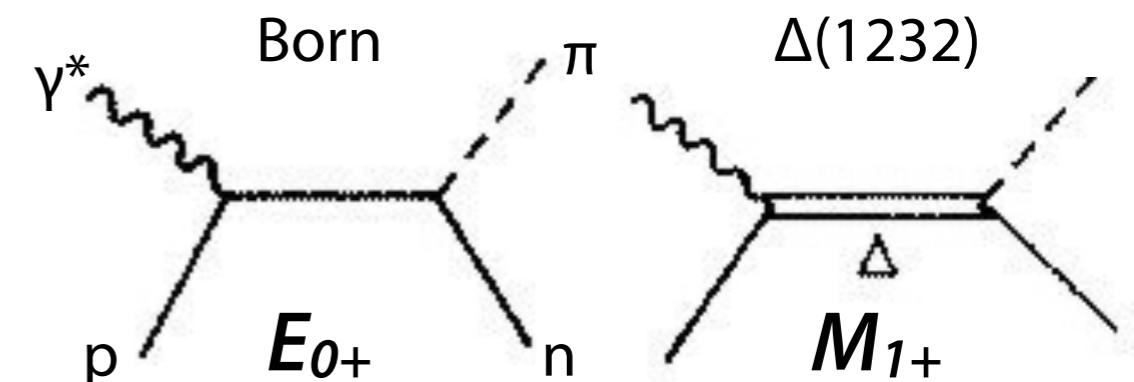
$$\frac{d\sigma_{\gamma^* p \uparrow \rightarrow \pi^+ n}}{d\Omega_\pi} = \frac{|q|}{\omega_{\gamma^*}} (R_T^{00} + P_y R_T^{0y}) \quad \text{Equivalent to } A_N$$

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

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

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

$$T(\theta_\pi) = \frac{R_T^{0y}}{R_T^{00}} \propto \text{Im}\{E_{0+}^*(E_{1+} - M_{1+}) - 4 \cos \theta_\pi (E_{1+}^* M_{1+})\dots\}$$



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

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

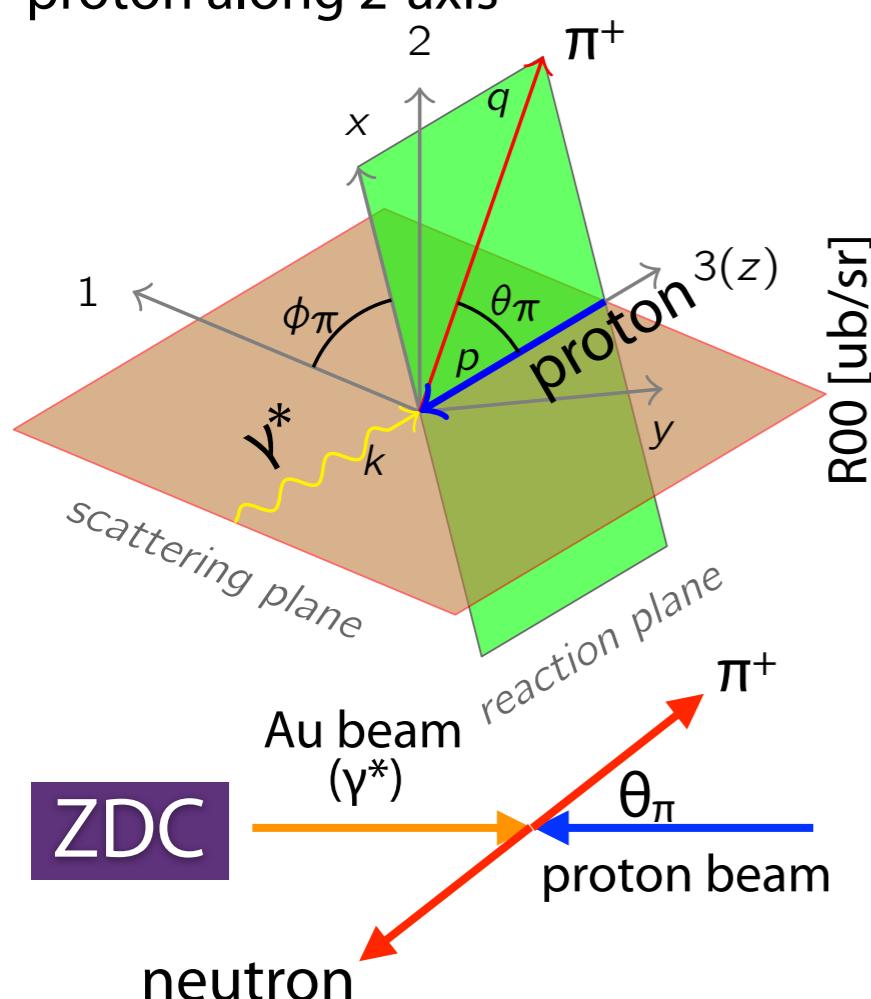
2.2 MC simulations for γ^*p interactions

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

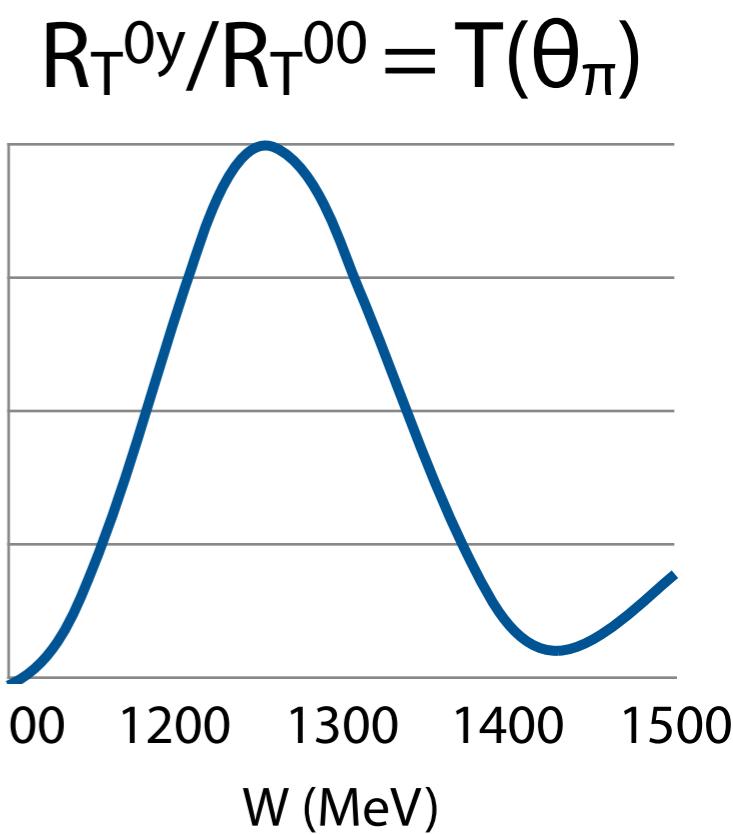
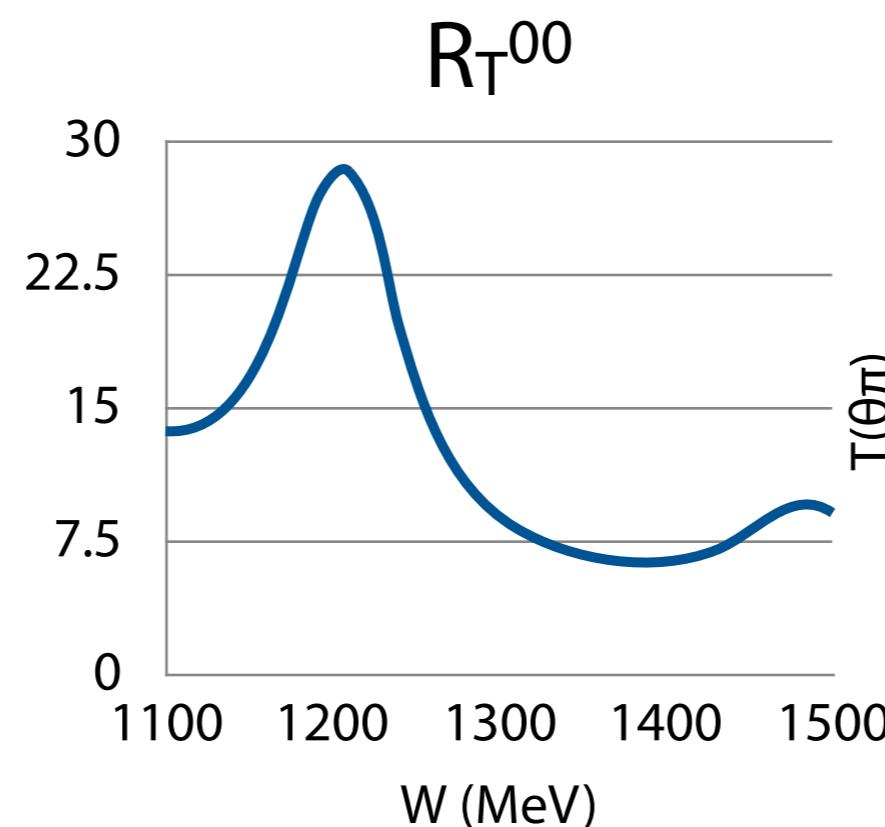
γ^*p center-of-mass system

transversely polarized

proton along 2-axis



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

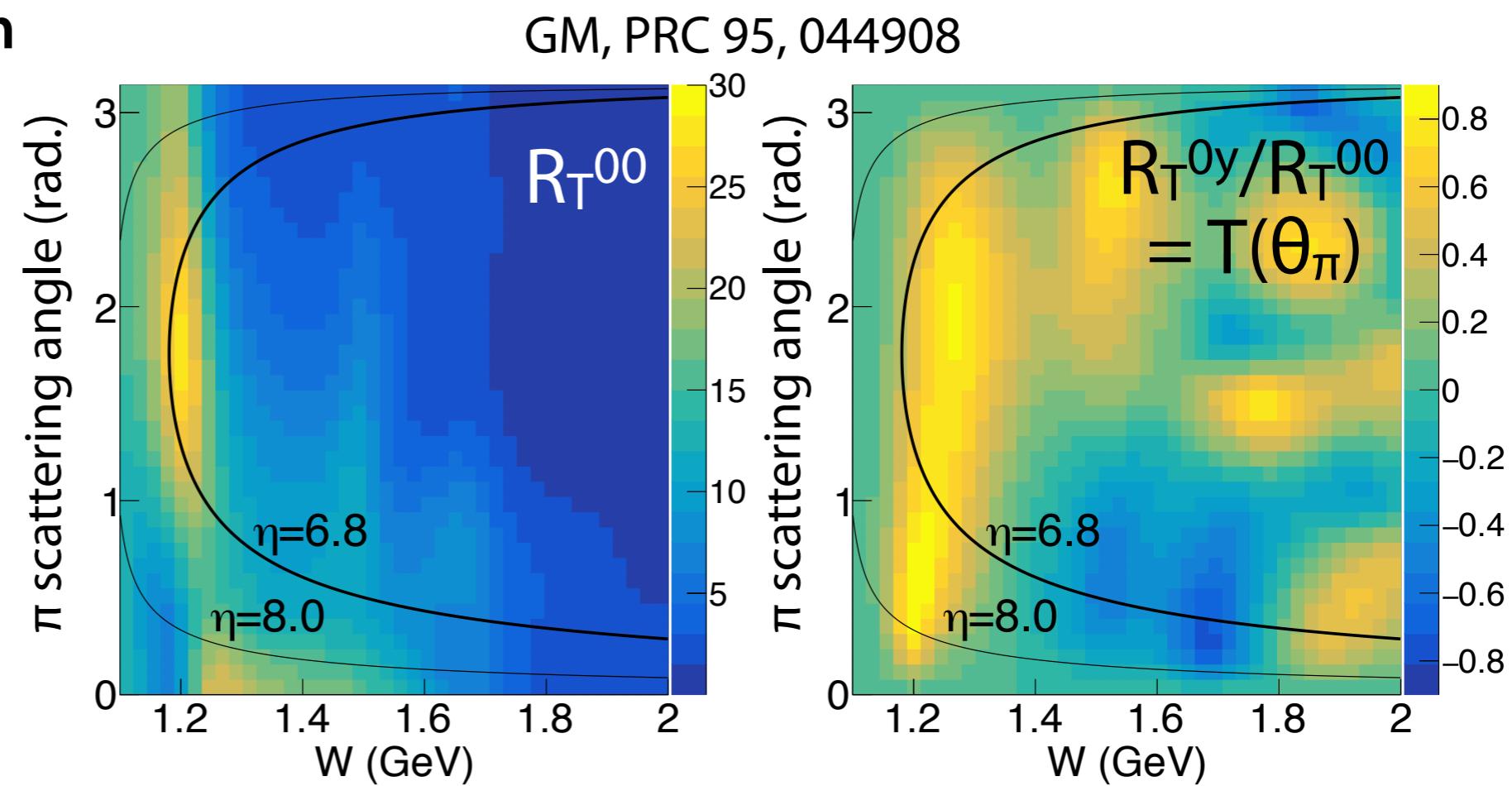
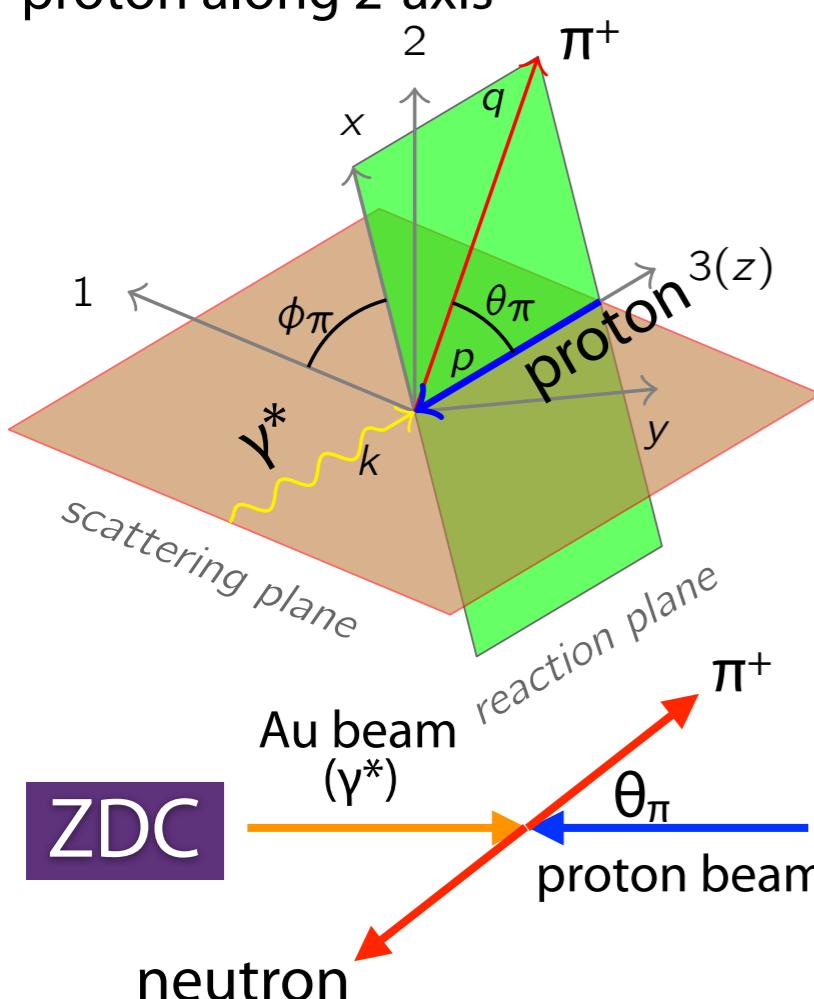


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γ^*p center-of-mass system

transversely polarized
proton along 2-axis



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

2.2 UPC cross sections as a function of W

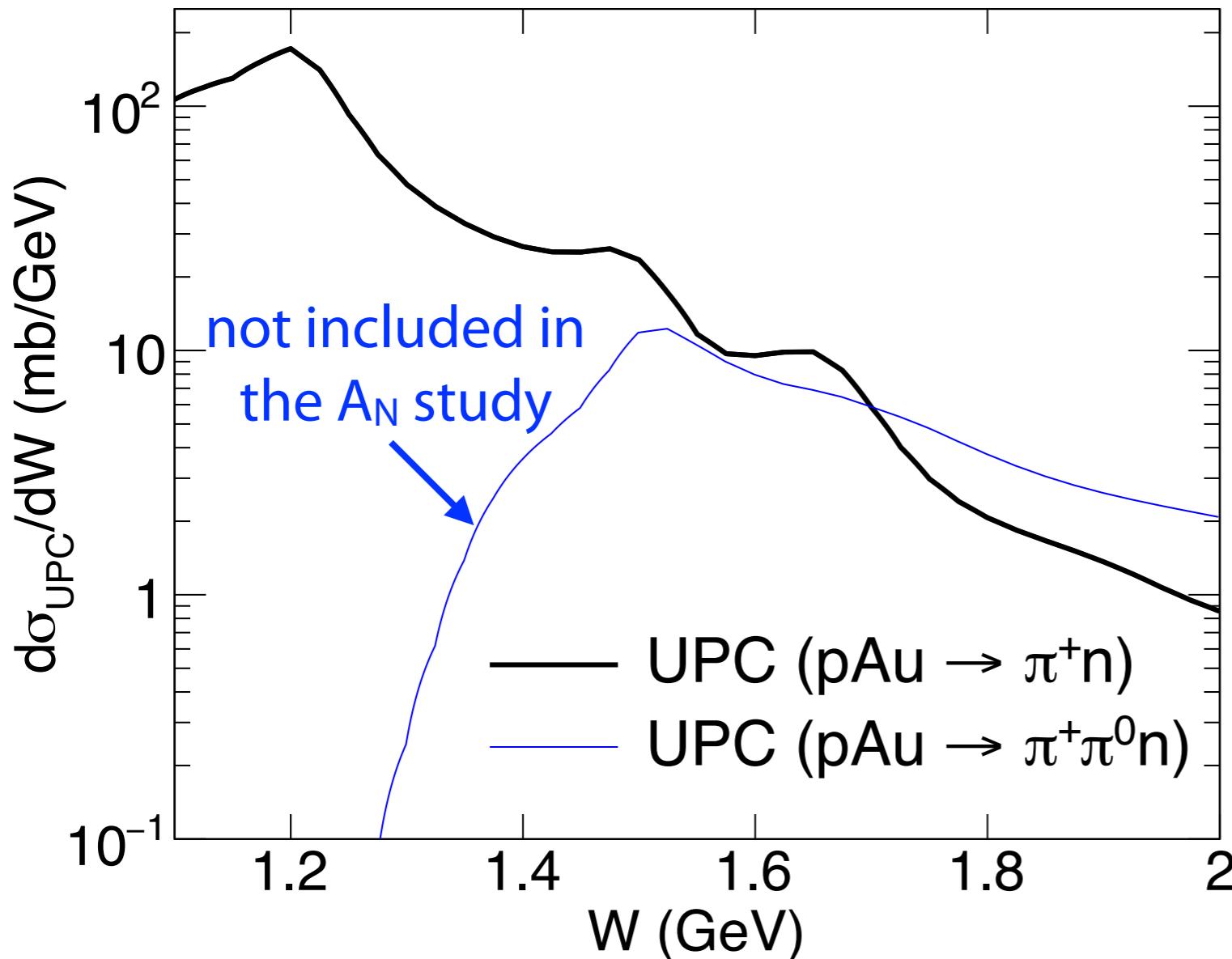


TABLE I. Cross sections for neutron production in ultraperipheral collisions and hadronic interactions at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$. Cross sections in parentheses are calculated without η and z limits.

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

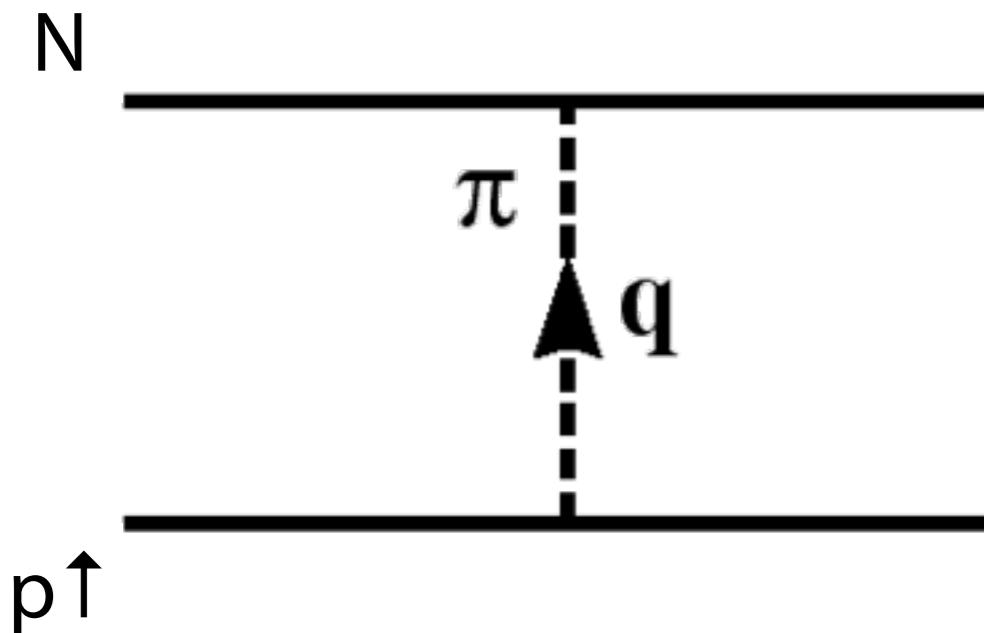
$$\frac{d\sigma_{\text{UPC}(p^\uparrow\text{A} \rightarrow \pi^+n)}^4}{dW db^2 d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW db^2} \frac{d\sigma_{\gamma^* p^\uparrow \rightarrow \pi^+ n}(W)}{d\Omega_n} P_{\text{had}}(b)$$

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

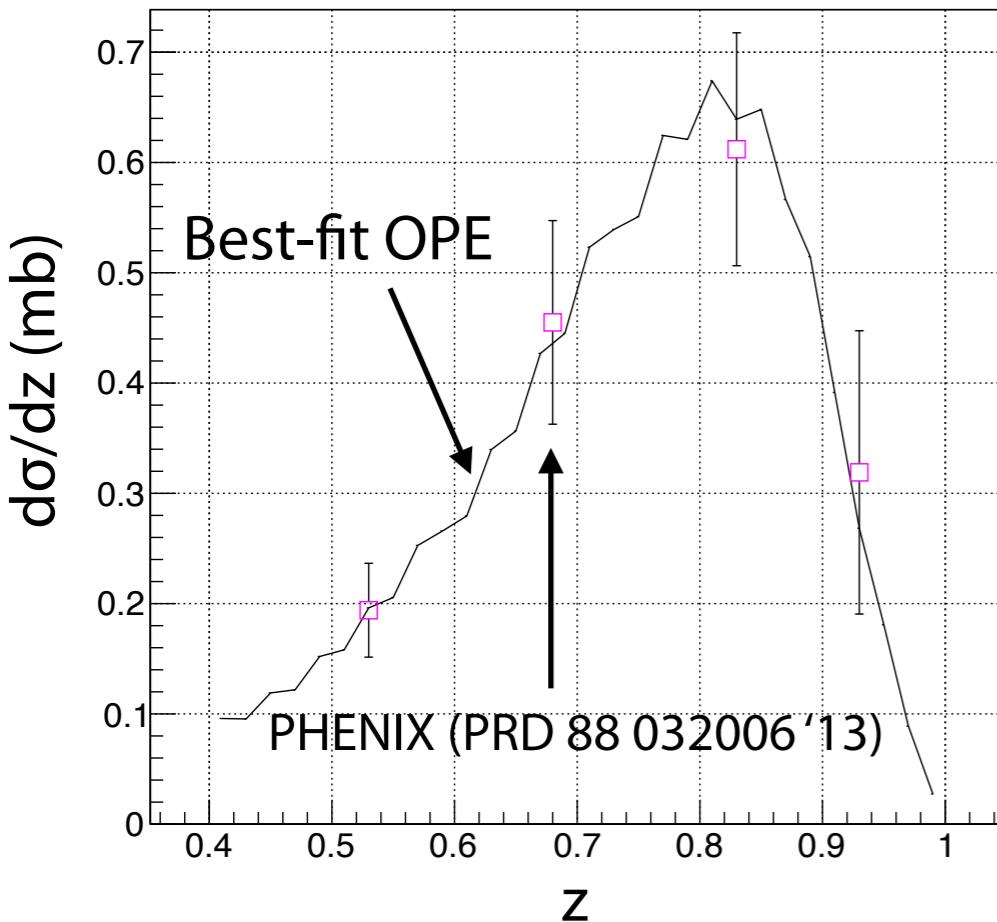
TABLE II. Cross sections in ultraperipheral $p\text{Au}$ collisions at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$.

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

3.1 Hadronic interactions (one- π exchange)



$$\begin{aligned}
 X & z \frac{d\sigma_{pp \rightarrow nX}}{dz dp_T^2} = S^2 \left(\frac{\alpha'_\pi}{8} \right)^2 |t| G_{\pi^+ pn}^2(t) |\eta_\pi(t)|^2 \\
 & \times (1-z)^{1-2\alpha_\pi(t)} \sigma_{\pi^+ + p}^{\text{tot}}(M_X^2), \\
 & z \frac{d\sigma_{p^\uparrow A \rightarrow nX}}{dz dp_T^2} = z \frac{d\sigma_{pA \rightarrow nX}}{dz dp_T^2} (1 + \cos \Phi A_N^{\text{HAD}(pA)}) \\
 & = z \frac{d\sigma_{pp \rightarrow nX}}{dz dp_T^2} A^{0.42} (1 + \cos \Phi A_N^{\text{HAD}(pA)})
 \end{aligned}$$

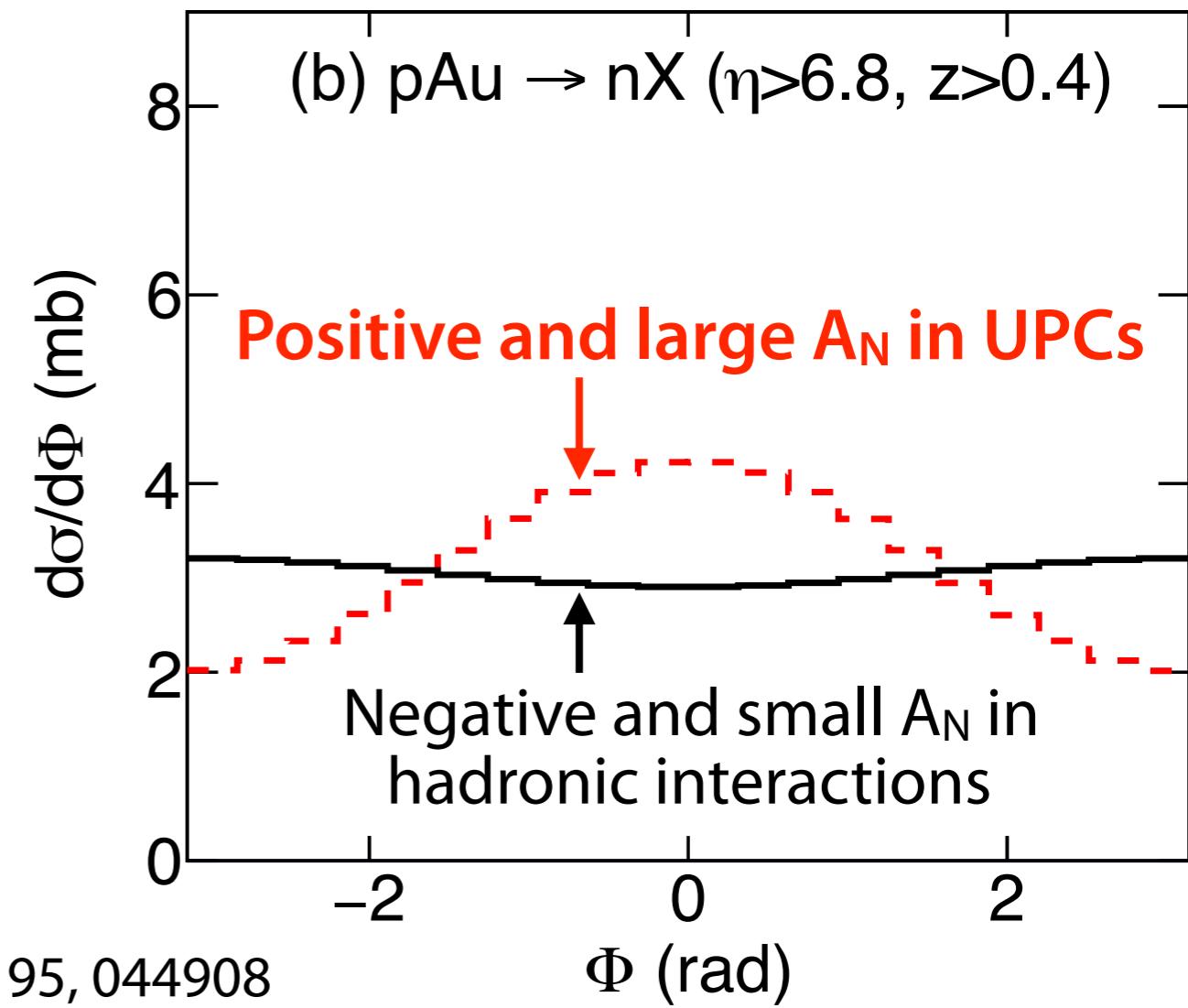
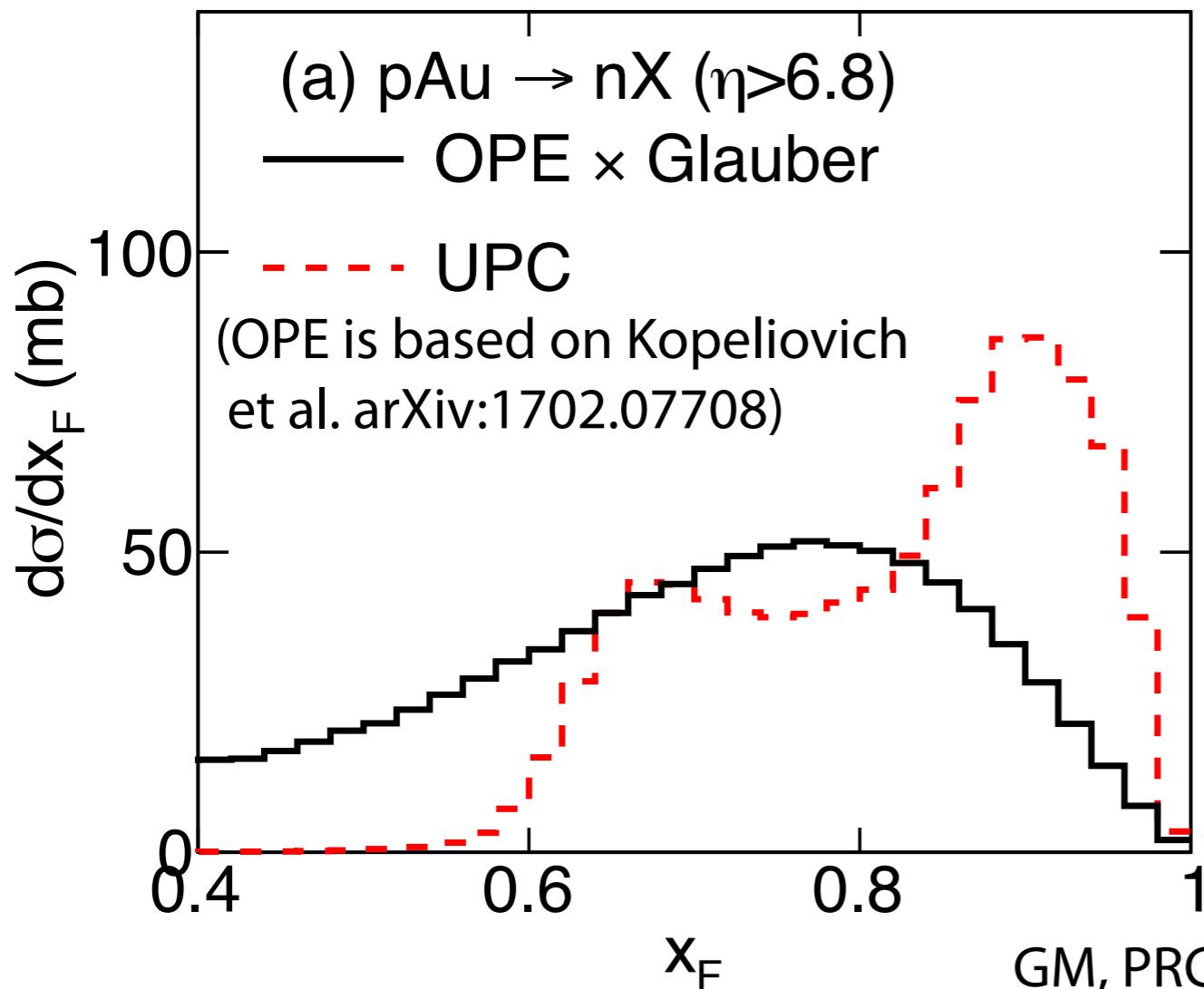


- Kopeliovich et al. propose an interference between π and a_1 -Reggeon leading to negative asymmetry in p-p and p-A.
- In this study, due to a technical difficulty, I omit an implementation of the interference. Alternatively, I apply $(1+\cos\Phi A)$ to the differential cross section of unpolarized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

3.1 UPCs vs. hadronic interactions

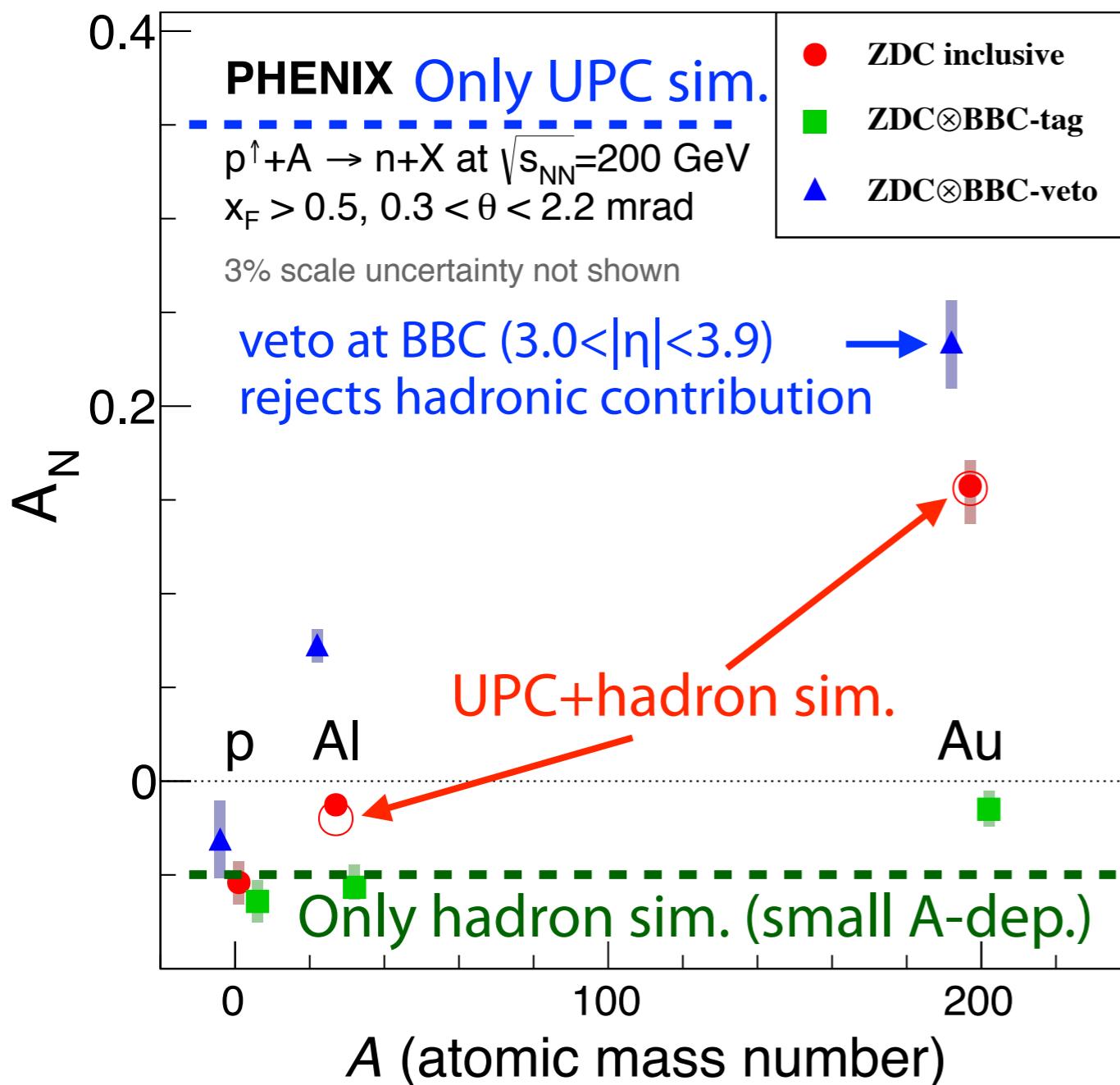
- Neutron cross section in pAu UPCs ($\propto Z^2$) is comparable with hadronic interactions, while $\sigma_{\text{UPC}} \sim \sigma_{\text{HAD}} \times 0.1$ in pAl.
- **UPC-induced A_N is positive and large in both pAl and pAu.**

Expected X_F and Φ distributions for forward neutrons in pAu



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, PRC 95, 044908

If we omit an interference between EM and hadronic amplitudes, total A_N can be written as

$$A_N^{\text{UPC+OPE}} = \frac{\sigma_{\text{UPC}} A_N^{\text{UPC}} + \sigma_{\text{OPE}} A_N^{\text{OPE}}}{\sigma_{\text{UPC}} + \sigma_{\text{OPE}}}$$

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

- Nuclear effects to A_N
- 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 compare 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.
- Future prospects:
 - Missing 2π -production will contribute by $\sim 10\%$ at $W > 1.25$ GeV.
 - Coulomb-Nuclear interference?

Asymmetries for forward π^0 at FNAL...

$$A_N^{\text{UPC}} \sim T(\theta_\pi) \equiv \frac{R_T^{0y}}{R_T^{00}} \propto \text{Im}\{E_{0+}^*(E_{1+} - M_{1+}) - 4 \cos \theta_\pi (E_{1+}^* M_{1+})\}$$

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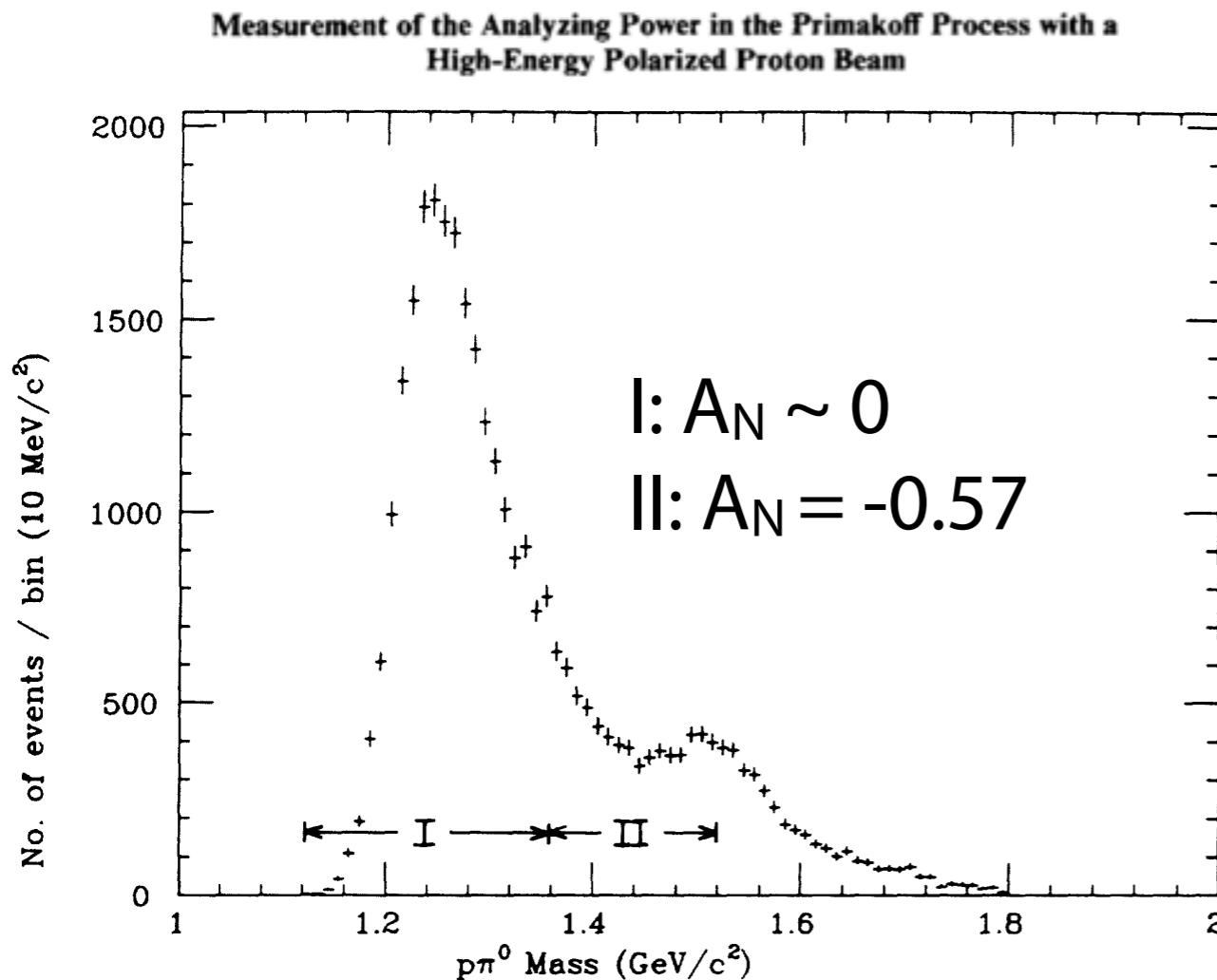
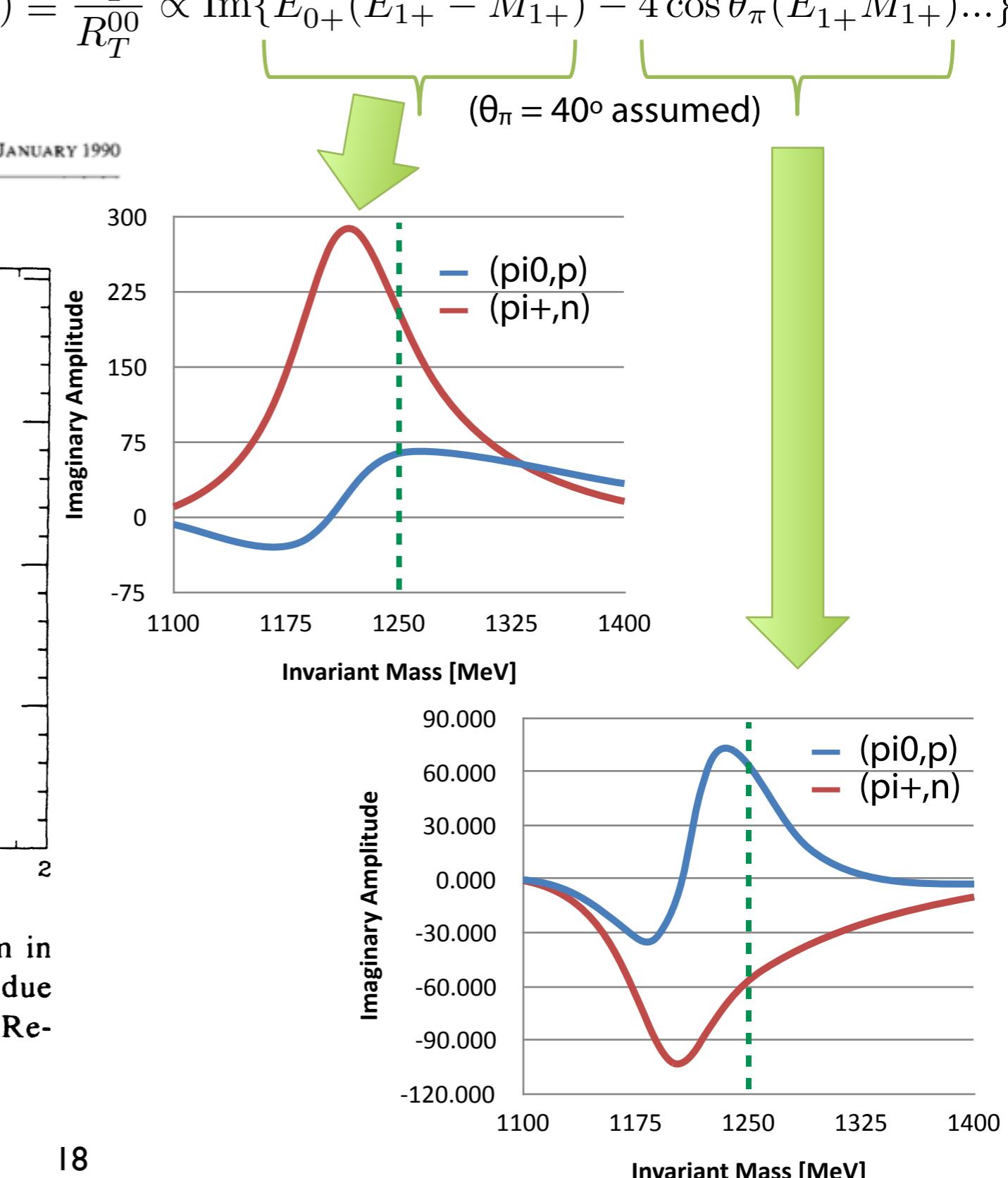


FIG. 2. The invariant-mass spectrum of the π^0 - p system in $p + \text{Pb} \rightarrow \pi^0 + p + \text{Pb}$ for $|t'| < 1 \times 10^{-3} (\text{GeV}/c)^2$. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.



Asymmetries for forward π^0 at FNAL...

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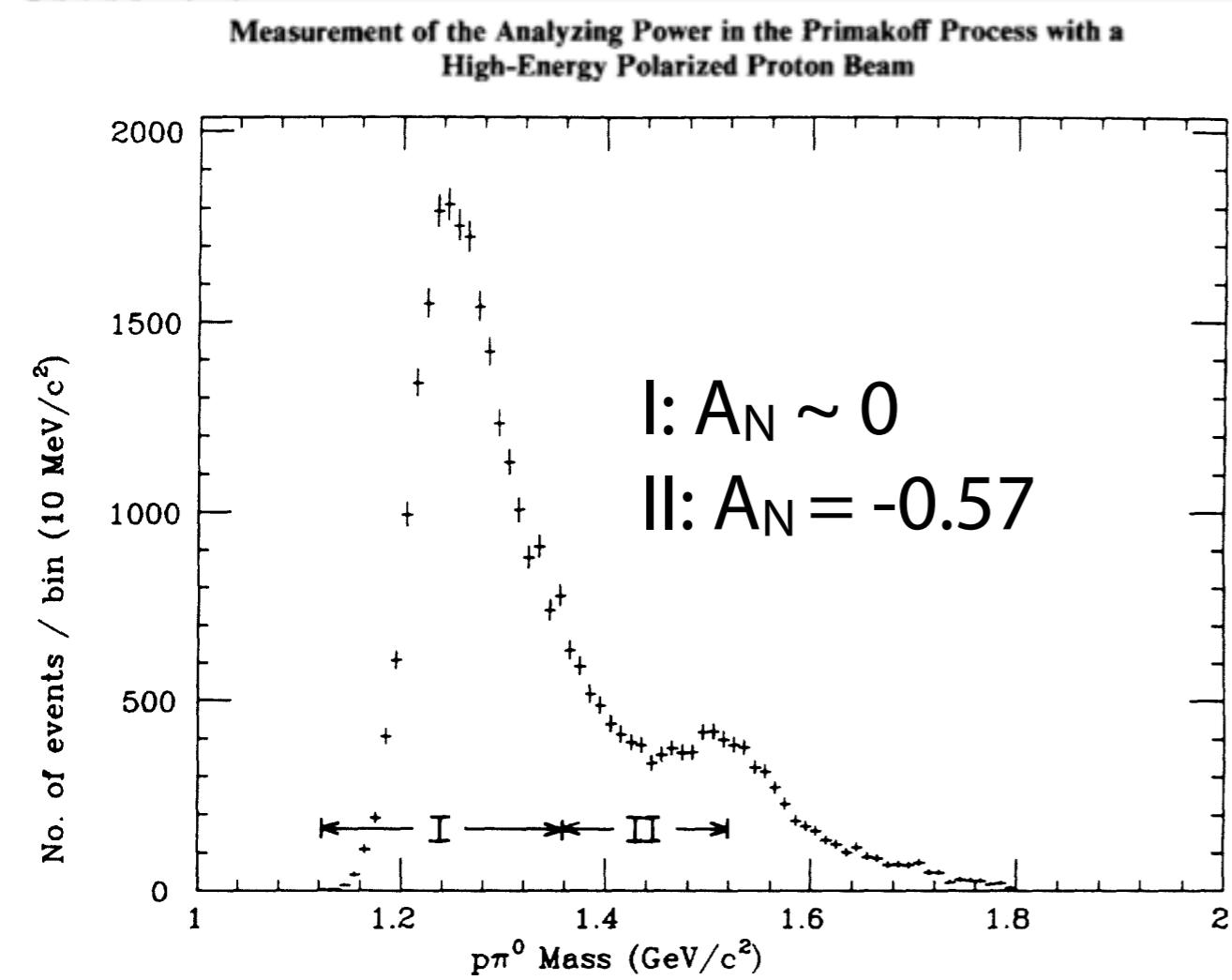
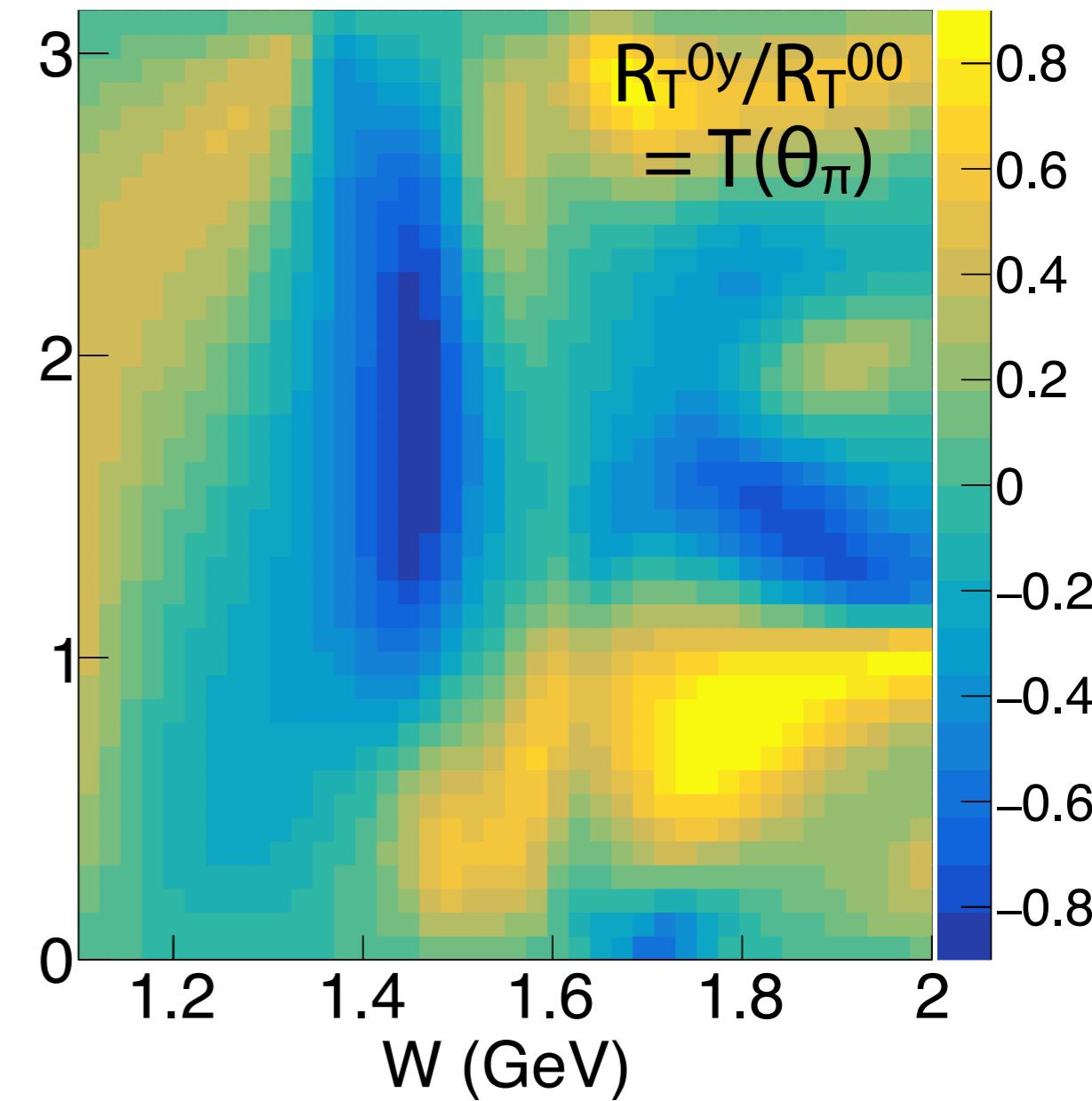


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Backup

UPC formalism

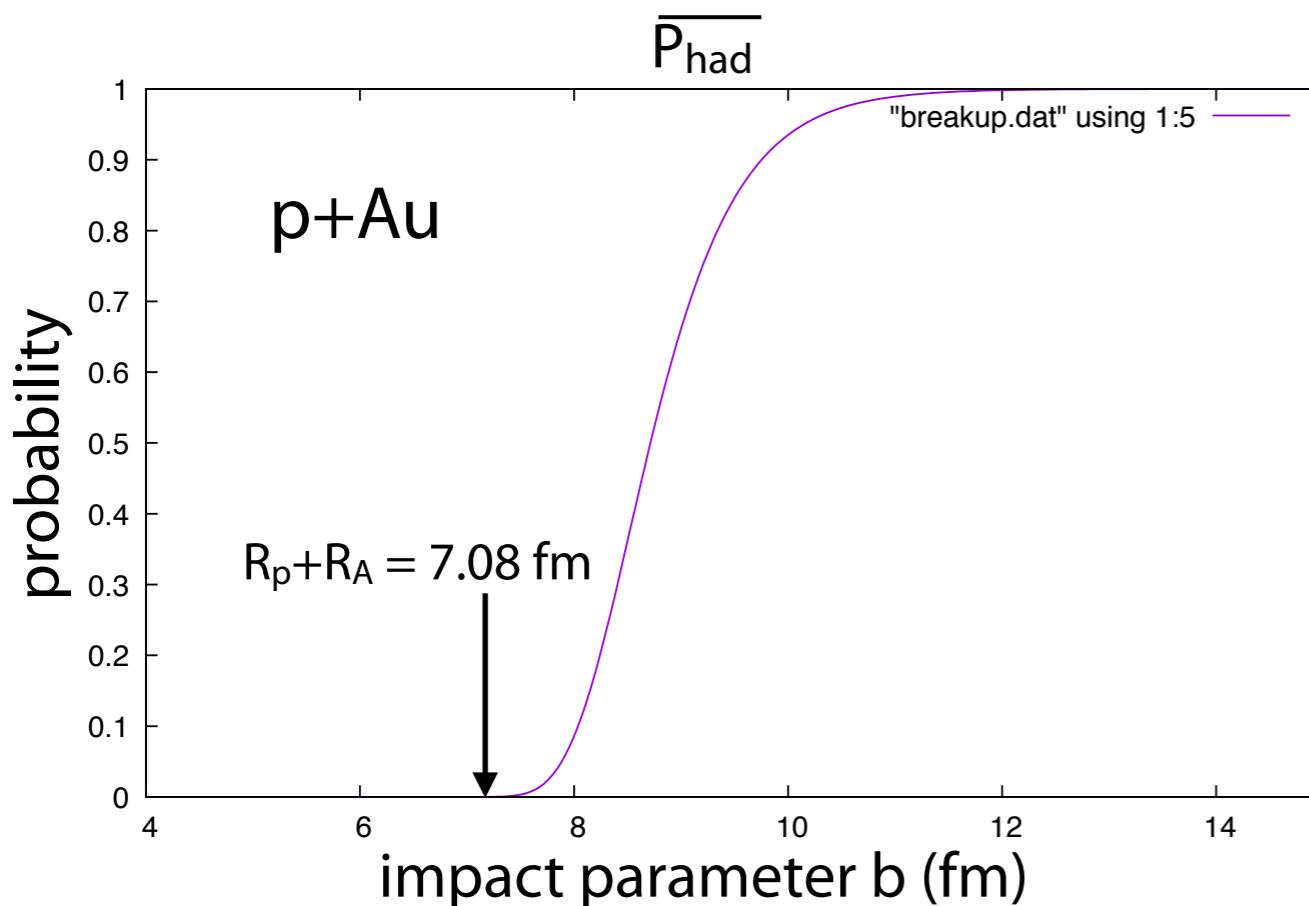
The UPC cross section is factorized as

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

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

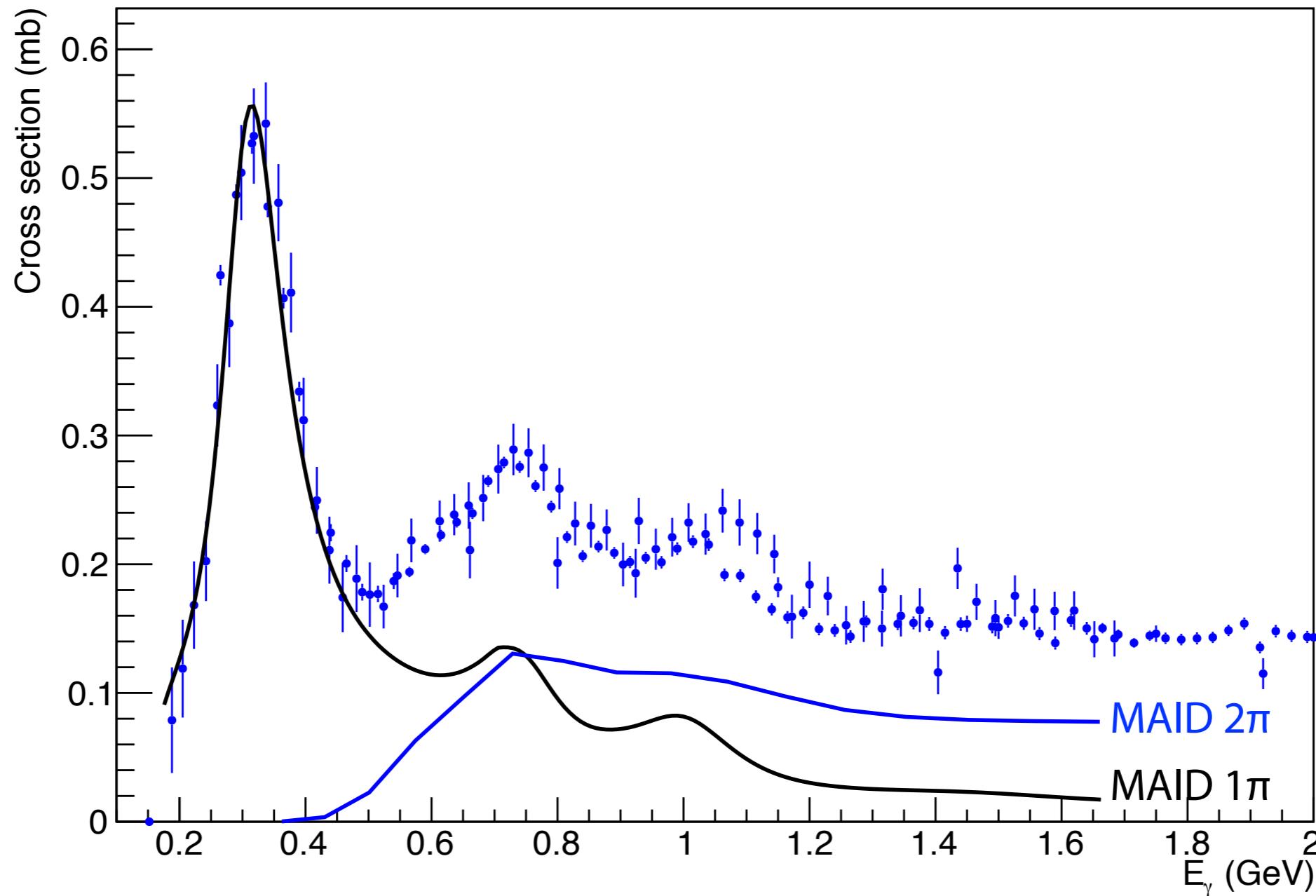
$\sigma_{\gamma+p \rightarrow x}$: inclusive cross sections of $\gamma+p$ interactions

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



- $\overline{P}_{\text{had}}$ 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 .
- $\overline{P}_{\text{had}}(b)$ distribution is important not only for the cross section but also for the energy distribution.

Inclusive cross sections of $\gamma + p$ interactions



Only 1π channel is simulated in this study.

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

Photopion production formalism

(Berends et al. NPB 4, 1 '67)

$$\frac{d\sigma}{d\Omega} = \frac{q}{k} |\langle \chi_f | \mathcal{F} | \chi_i \rangle|^2, \quad (\text{A.1})$$

where

$$\mathcal{F} = i\sigma \cdot \epsilon \mathcal{F}_1 + \sigma \cdot \hat{q} \sigma \cdot (\hat{k} \times \epsilon) \mathcal{F}_2 + i\sigma \cdot \hat{k} \hat{q} \cdot \epsilon \mathcal{F}_3 + i\sigma \cdot \hat{q} \hat{q} \cdot \epsilon \mathcal{F}_4. \quad (\text{A.2})$$

$$\sum_f \langle \chi_f | \mathcal{F} | \chi_i \rangle^\dagger \langle \chi_f | \mathcal{F} | \chi_i \rangle = \langle \chi_i | \mathcal{F}^\dagger \mathcal{F} | \chi_i \rangle$$

$$\langle \chi_i | \mathcal{F}_\pm^\dagger \mathcal{F}_\pm | \chi_i \rangle = (1 \mp \hat{k} \cdot \mathbf{P}) \alpha + \beta \pm \sin \theta \hat{e}_1 \cdot \mathbf{P}_\gamma + \sin \theta \hat{e}_2 \cdot \mathbf{P}_\delta, \quad (\text{A.7})$$

where

$$\alpha = |\mathcal{F}_1|^2 + |\mathcal{F}|^2 - 2 \cos \theta \operatorname{Re}(\mathcal{F}_1^* \mathcal{F}_2) + \sin^2 \theta \operatorname{Re}\{\mathcal{F}_1^* \mathcal{F}_4 + \mathcal{F}_2^* \mathcal{F}_3\}, \quad (\text{A.8})$$

$$\beta = \frac{1}{2} \sin^2 \theta \{|\mathcal{F}_3|^2 + |\mathcal{F}_4|^2 + 2 \cos \theta \operatorname{Re}(\mathcal{F}_3^* \mathcal{F}_4)\}, \quad (\text{A.9})$$

$$\gamma = \operatorname{Re}\{\mathcal{F}_1^* \mathcal{F}_3 - \mathcal{F}_2^* \mathcal{F}_4\} + \cos \theta \operatorname{Re}\{\mathcal{F}_1^* \mathcal{F}_4 - \mathcal{F}_2^* \mathcal{F}_3\}, \quad (\text{A.10})$$

$$\begin{aligned} \delta = \operatorname{Im}\{\mathcal{F}_1^* \mathcal{F}_3 - \mathcal{F}_2^* \mathcal{F}_4\} + \cos \theta \operatorname{Im}\{\mathcal{F}_1^* \mathcal{F}_4 - \mathcal{F}_2^* \mathcal{F}_3\} \\ - \sin^2 \theta \operatorname{Im}(\mathcal{F}_3^* \mathcal{F}_4). \end{aligned} \quad (\text{A.11})$$

Polarized nucleon, unpolarized photon

$$\frac{d\sigma(\mathbf{P})}{d\Omega} = \frac{1}{2} \left\{ \frac{d\sigma_+(\mathbf{P})}{d\Omega} + \frac{d\sigma_-(\mathbf{P})}{d\Omega} \right\}$$

$$= \frac{q}{k} \left\{ \alpha + \beta + \sin \theta \hat{e}_2 \cdot \mathbf{P} \delta \right\} \rightarrow \frac{d\sigma_0}{d\Omega} = \frac{q}{k} (\alpha + \beta), A_N = \frac{\sin \theta \delta}{\alpha + \beta}$$

Photopion production

(Berends et al. NPB 4, 1 '67)

Eq. (A.2)

$$\tilde{\mathcal{F}}(s, t) = \sum_{l=0}^{\infty} \begin{bmatrix} G_l(x) & 0 \\ 0 & H_l(x) \end{bmatrix} \tilde{M}_l(s), \quad \tilde{M}_l =$$

$$\begin{bmatrix} E_{l+} \\ E_{l-} \\ M_{l+} \\ M_{l-} \\ S_{l+} \\ S_{l-} \end{bmatrix}$$

G_l and H_l are Legendre polynomials, and \tilde{M}_l are multipoles.

(Drechsel and Tiator, JphysG 18, 449 '92)

Multipole decomposition:

$$R_T = |E_{0+}|^2 + \frac{1}{2} |2M_{1+} + M_{1-}|^2 + \frac{1}{2} |3E_{1+} - M_{1+} + M_{1-}|^2 + 2 \cos \Theta \operatorname{Re}\{E_{0+}^*(3E_{1+} + M_{1+} - M_{1-})\} + \cos^2 \Theta (|3E_{1+} + M_{1+} - M_{1-}|^2 - \frac{1}{2} |2M_{1+} + M_{1-}|^2 - \frac{1}{2} |3E_{1+} - M_{1+} + M_{1-}|^2)$$

$$R_T(n_i) = 3 \sin \Theta \operatorname{Im}\{E_{0+}^*(E_{1+} - M_{1+}) - \cos \Theta (E_{1+}^*(4M_{1+} - M_{1-}) + M_{1+}^* M_{1-})\}$$

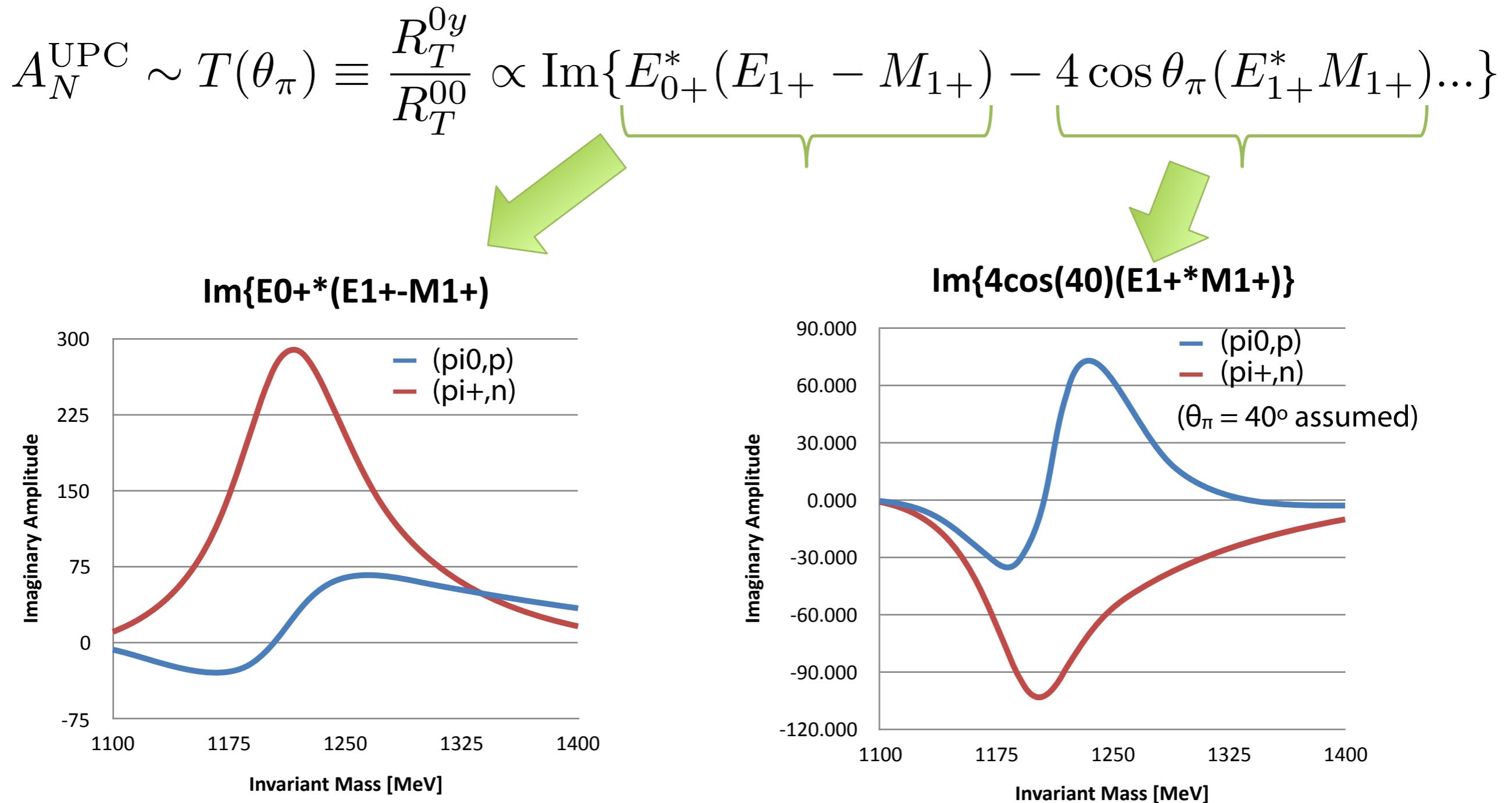
$$R_T^{00} \equiv R_T \text{ and } R_T^{0y} \equiv R_T(n_i) \quad \frac{d\sigma_{\gamma^* p^\uparrow \rightarrow \pi^+ n}}{d\Omega_\pi} = \frac{|q|}{\omega_{\gamma^*}} (R_T^{00} + P_y R_T^{0y})$$

pion and neutron production in UPCs

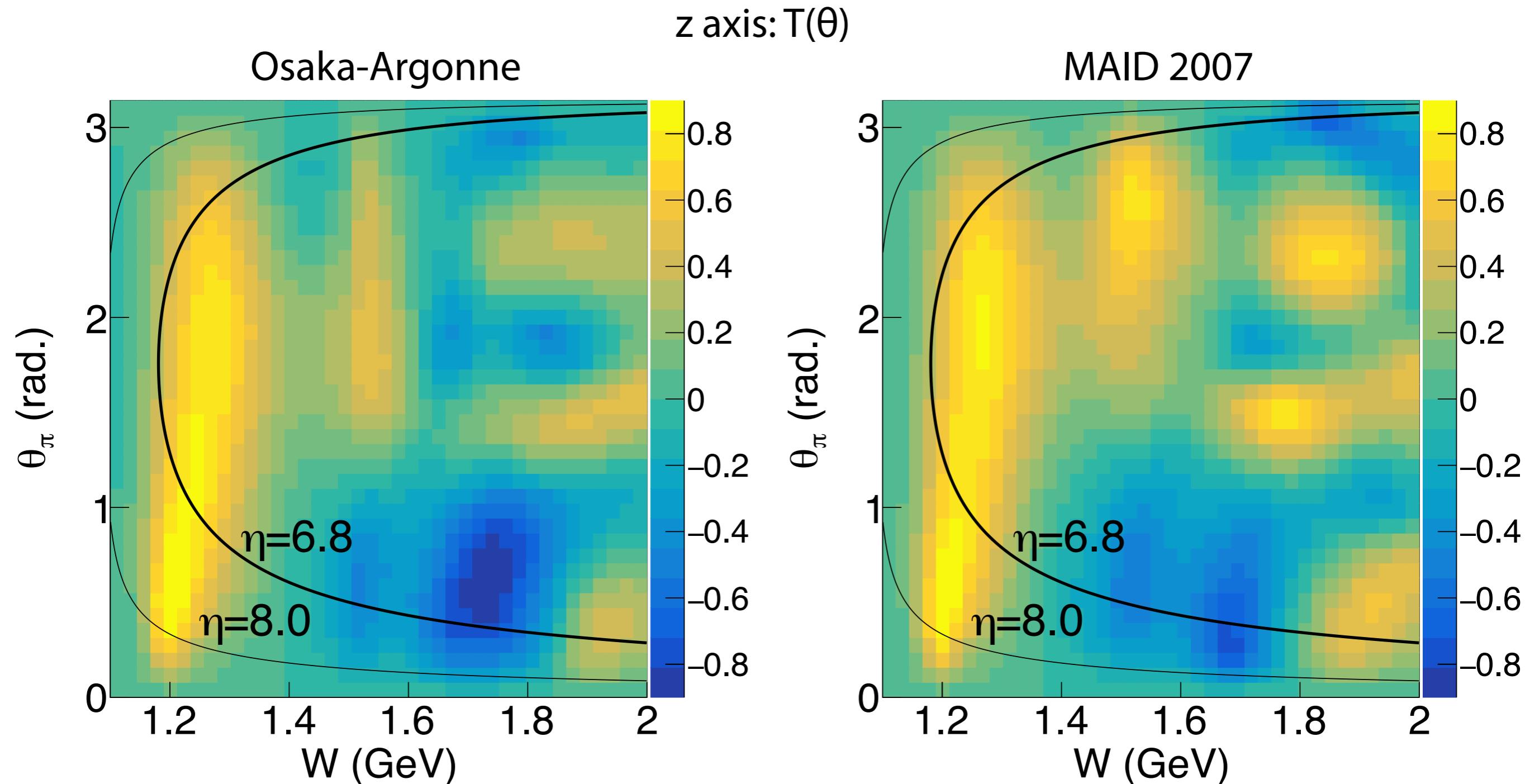
$$= \frac{|q|}{\omega_{\gamma^*}} R_T^{00} (1 + P_2 \cos \phi_\pi T(\theta_\pi))$$

Several models provide their predicted multipoles. MAID2007 is available at <https://maid.kph.uni-mainz.de>.

Multipole decomposition of $T(\theta_\pi)$

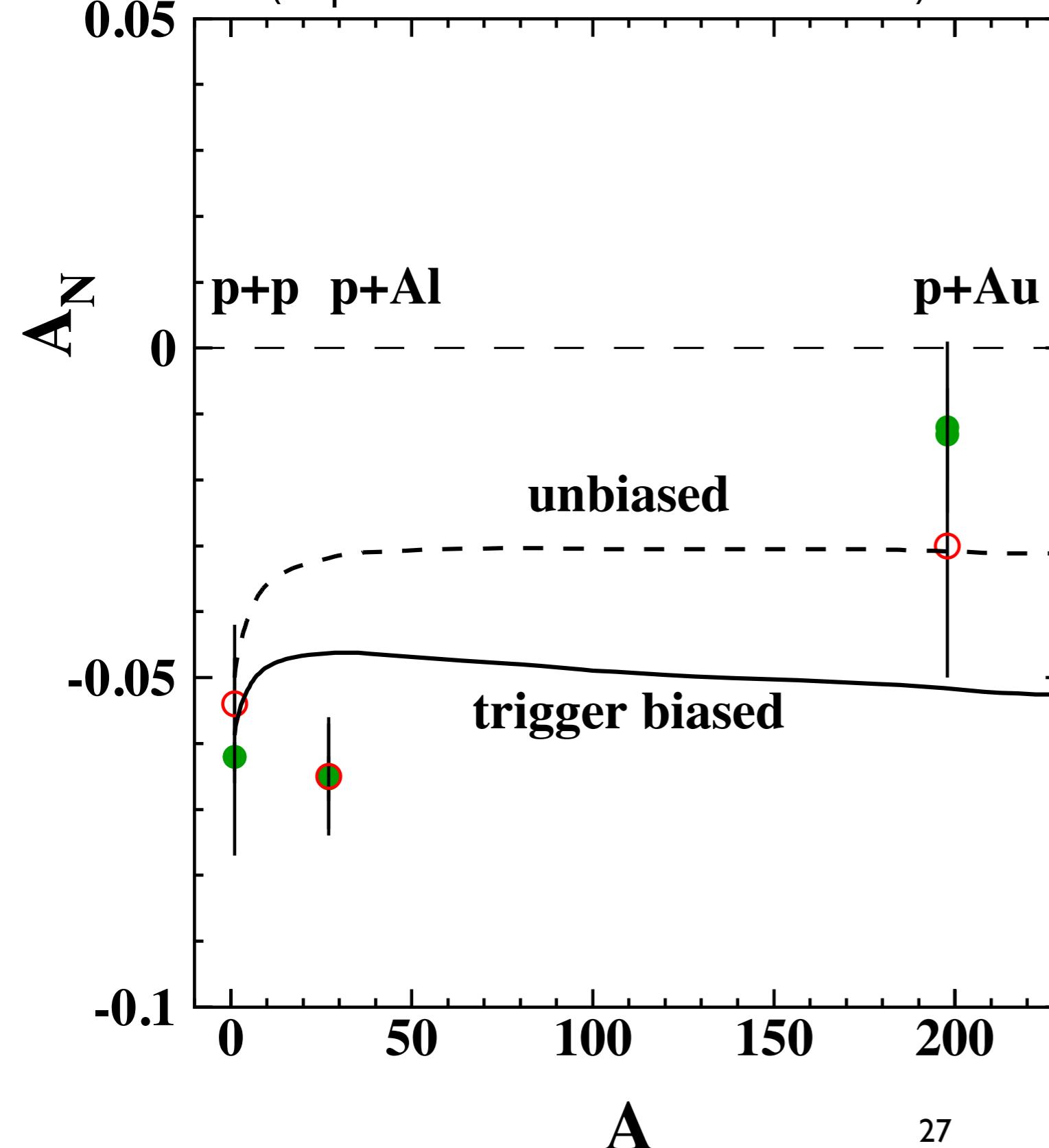


Target asymmetry as a function of W



Hadronic interactions (one- π exchange)

(Kopeliovich et al. arXiv:1702.07708)



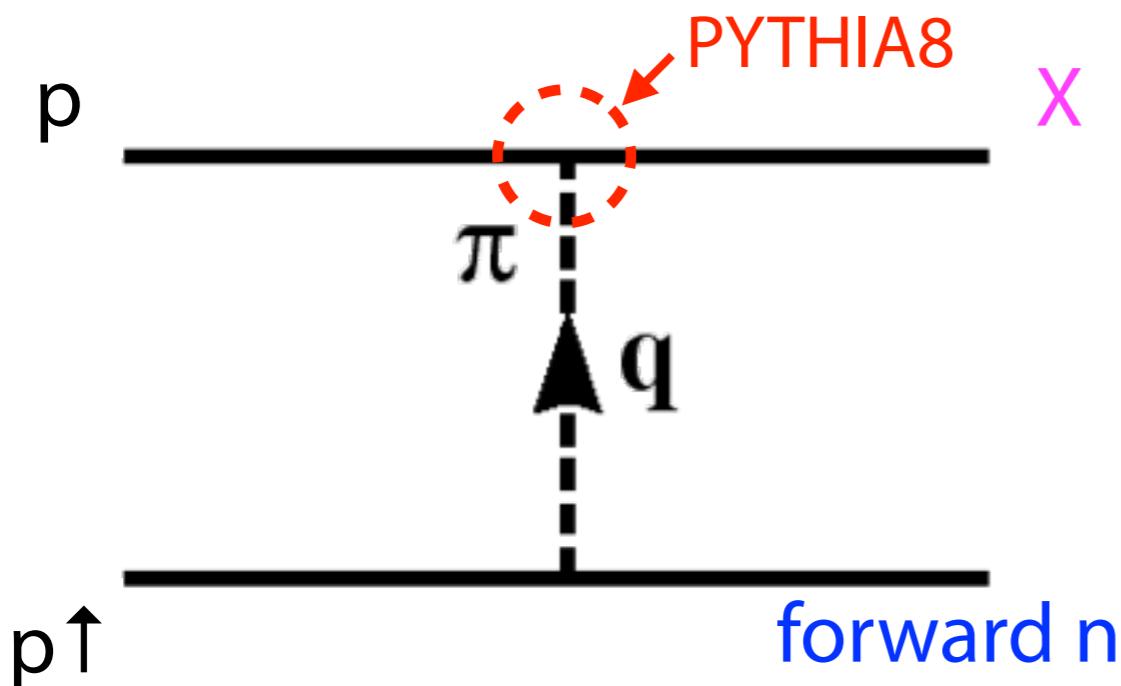
$$A_N^{(\pi-\tilde{a}_1)}(q_T, z) = q_T \frac{4m_N q_L}{|t|^{3/2}} (1-z)^{\alpha_\pi(t)-\alpha_{\tilde{a}_1}(t)} \quad (12)$$

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

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

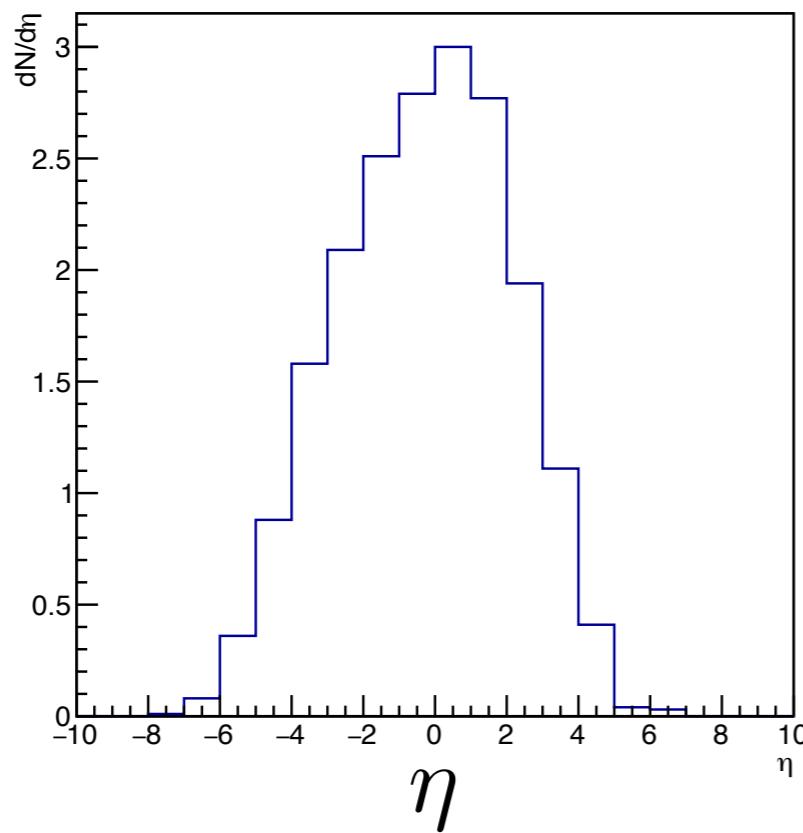
Nuclear effects

OPE with πp scatterings



- A simple OPE model has considered only **forward neutrons** so far.
- Simulation for **$\pi+p$ interactions** via PYTHIA8 is now implemented to simulate the particles **X** which may trigger the BBCs.
- $dN^{ch}_X/d\eta \sim 1.0$ (1.3) at $3 < \eta < 4$ ($3 < -\eta < 4$).

Neutral particles



Charged particles

