Single spin asymmetries for π^0s and neutrons in pp and pA

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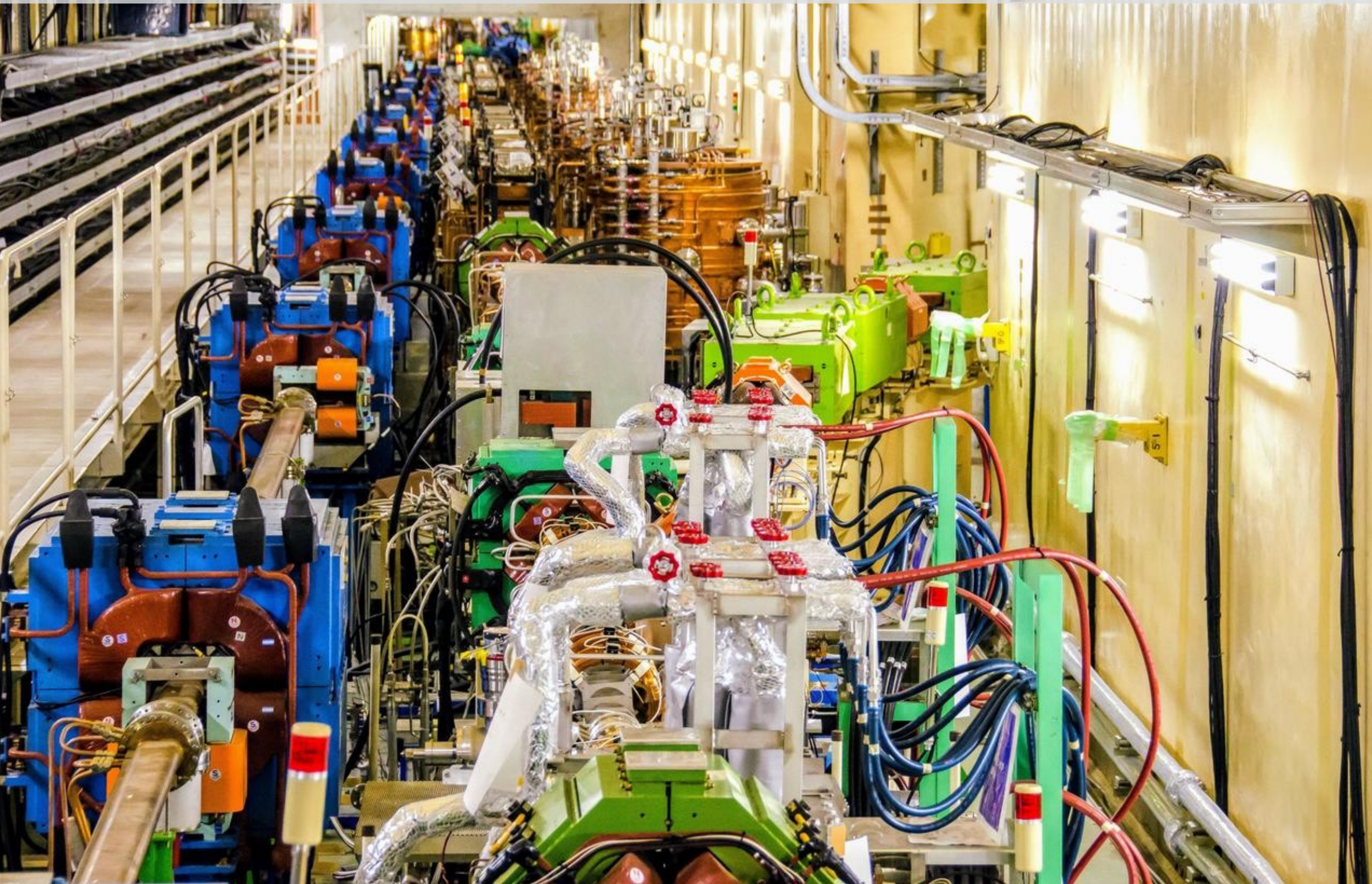
LHCf-RHICf Joint meeting
(Villa Ruspoli, Firenze)

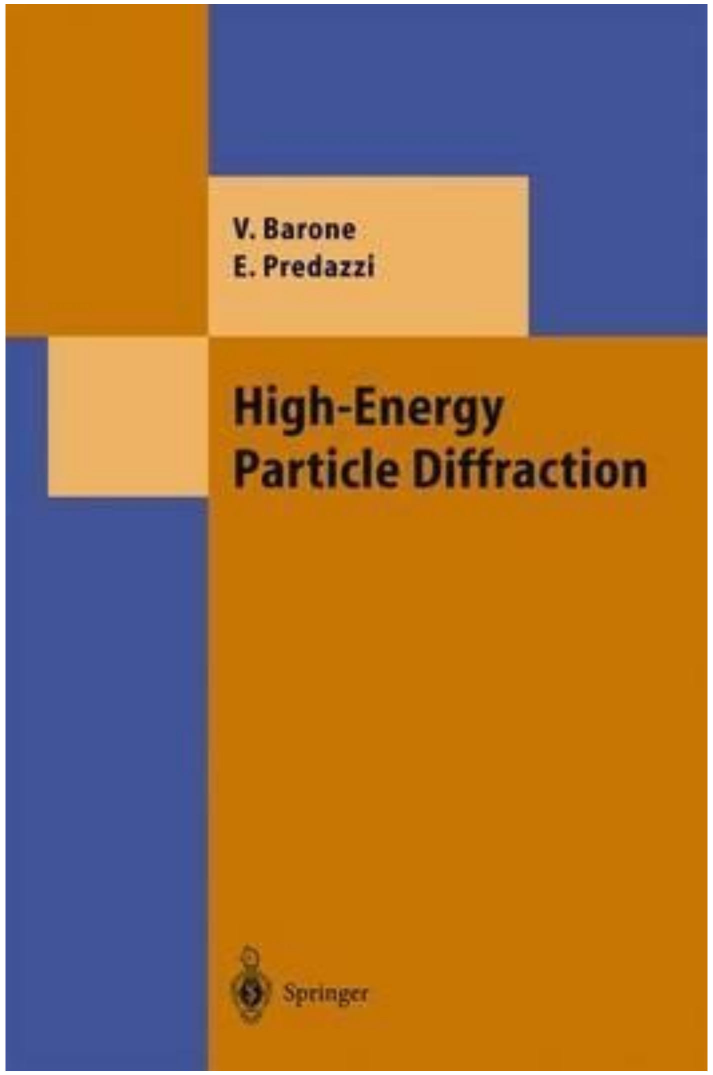
The SuperKEKB e^+e^- accelerator



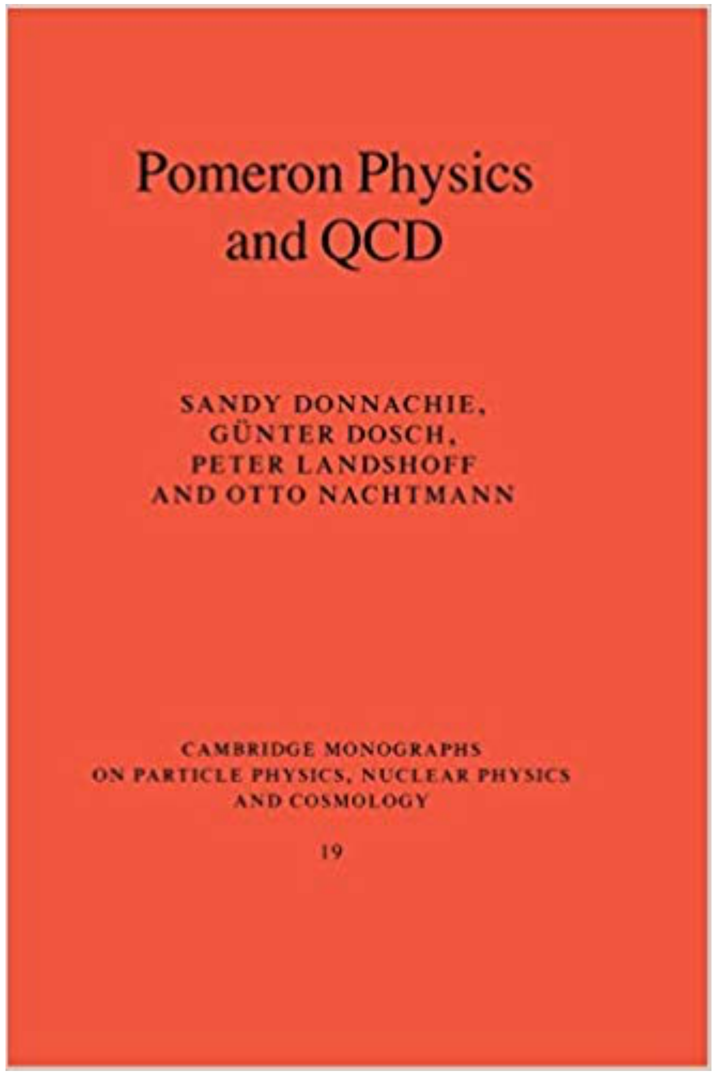
Outline

- Single π^0 asymmetry in pp collisions at $\sqrt{s} = 510$ GeV
  - Trial and error…
- Single neutron asymmetry in pA collisions at $\sqrt{s} = 200$ GeV
  - Ultraperipheral collisions at the LHC and RHIC
  - Photon + polarized proton scatterings
  - UPC with polarized protons
- My thoughts on future RHICf

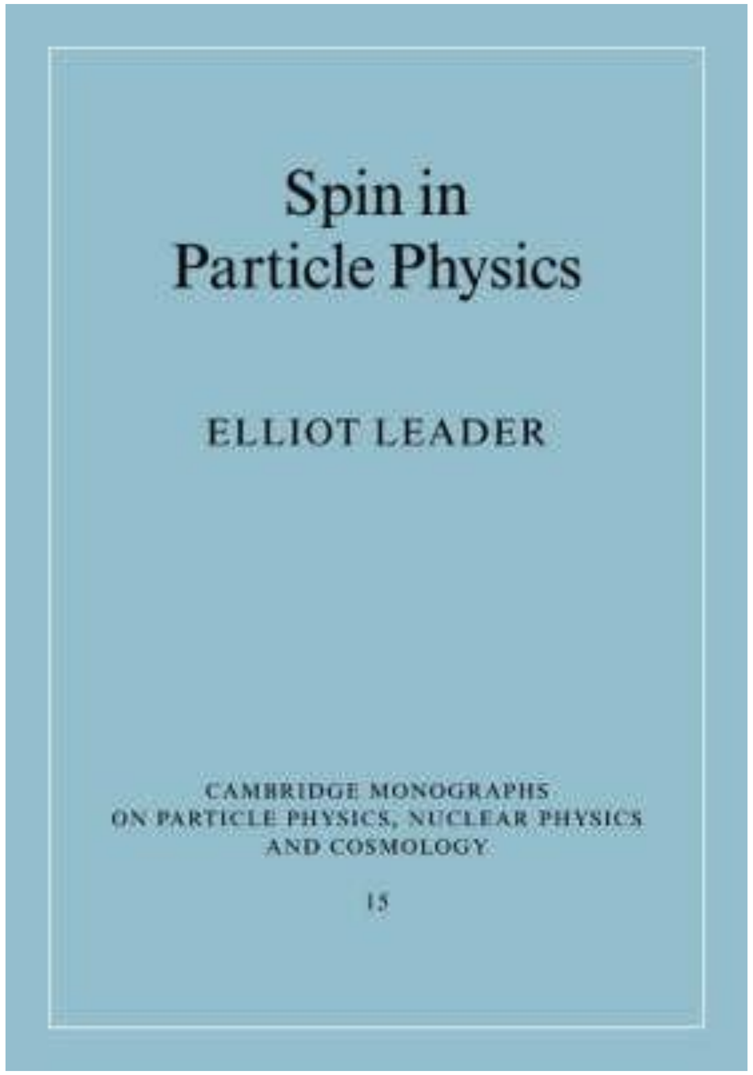
References



Rigorous

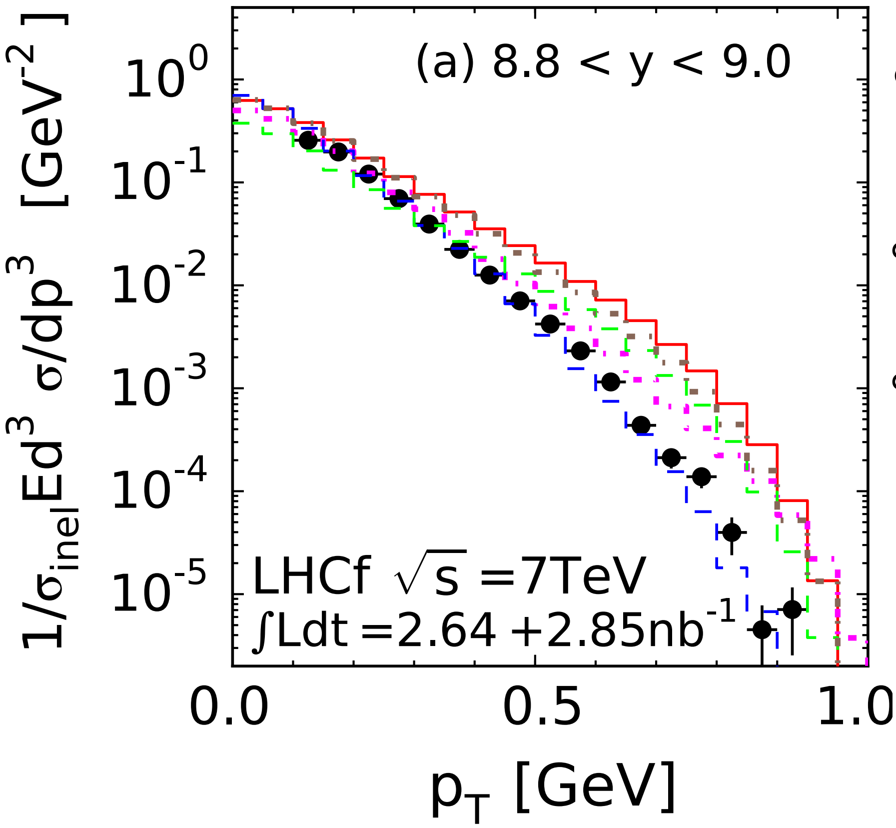


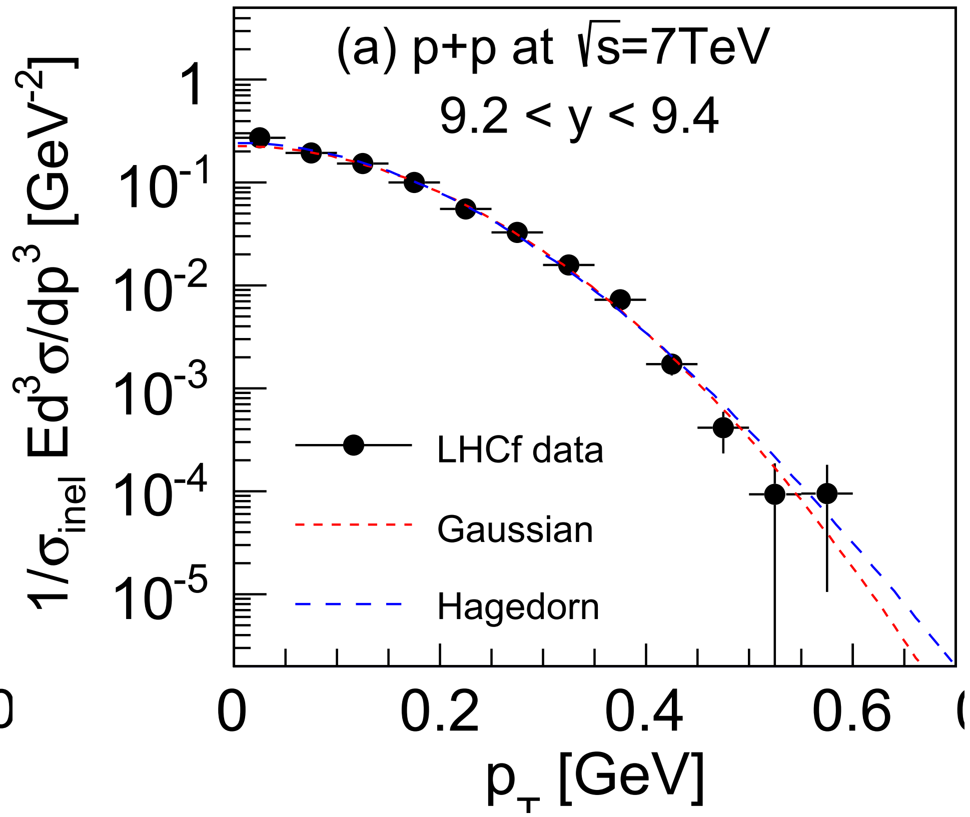
Variety of topics

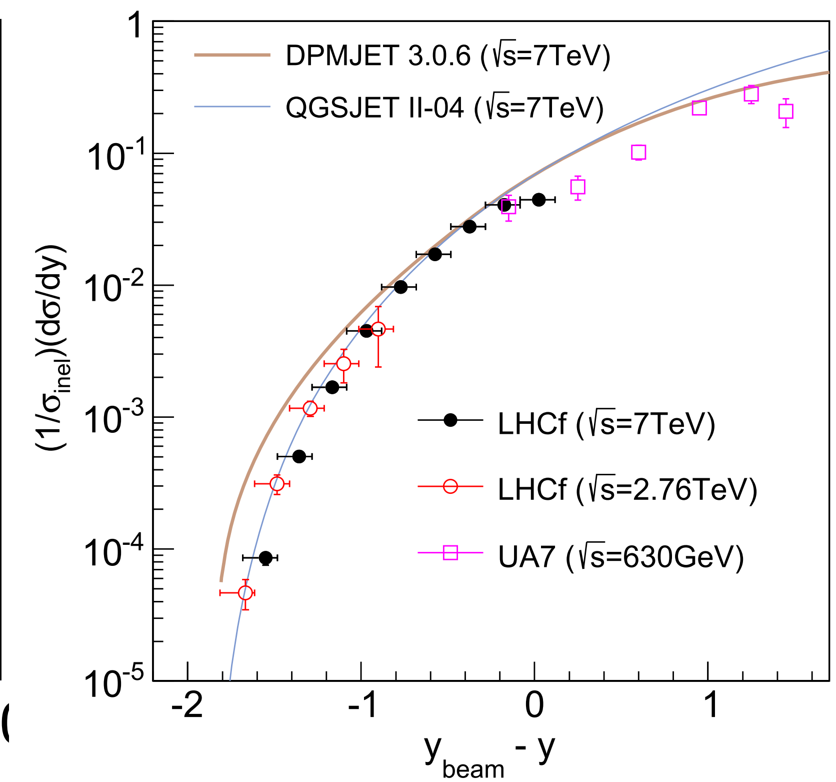


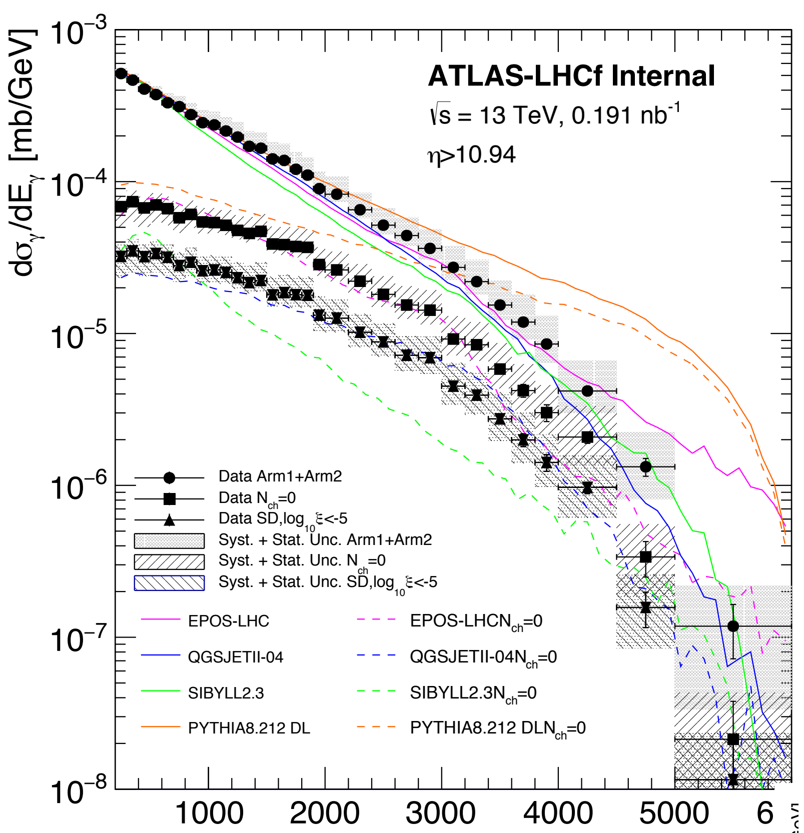
Rigorous

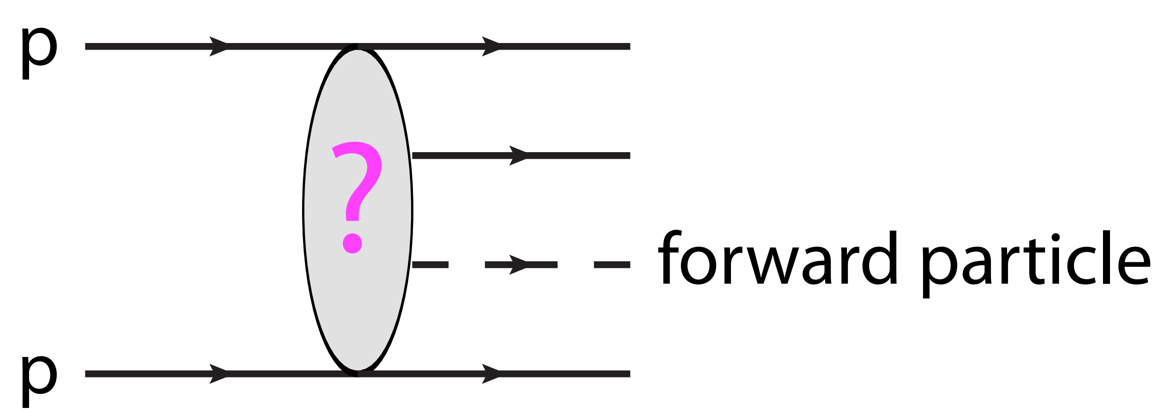
Why is spin important?











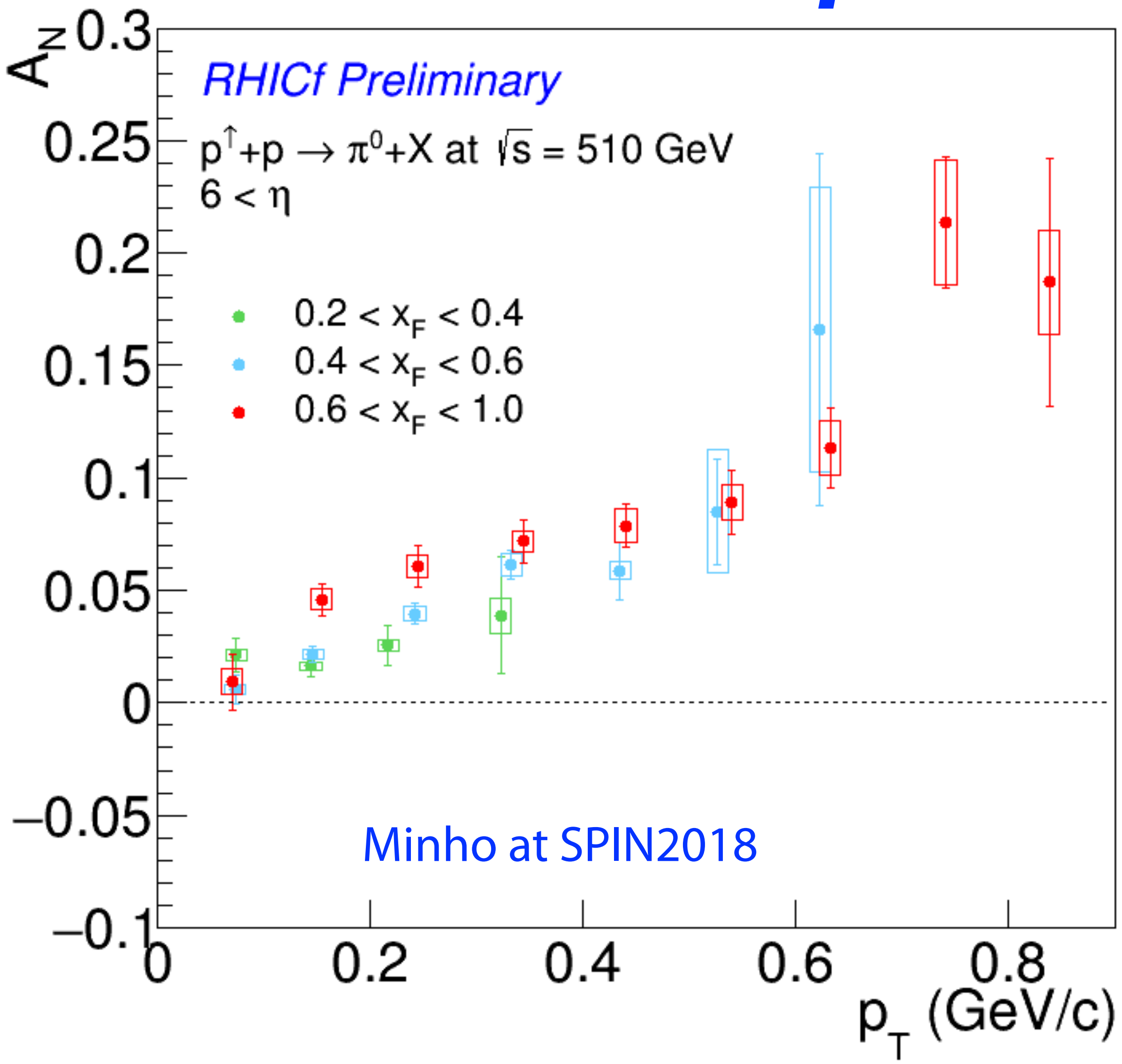
Revealing what's happening in particle production

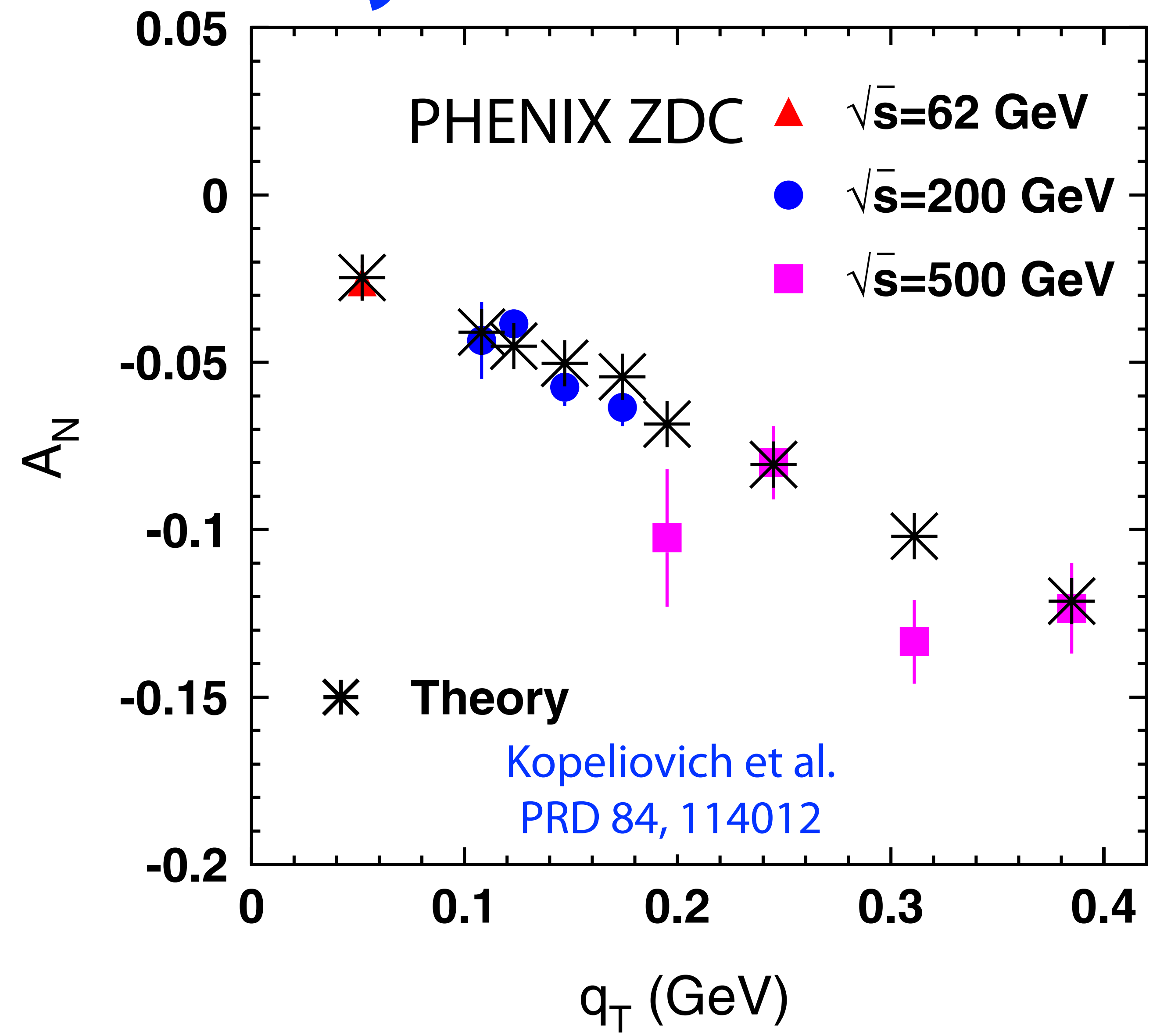
→ many observables as much as possible

- Publications so far: cross section, scaling, p_T, y, and x_F
- Preliminary: N_{ch}, double arm correlation, and <u>A_N</u>

Neutron and π^0 asymmetries in pp

Motivation of this talk is to find a mechanism that can explain forward asymmetries.



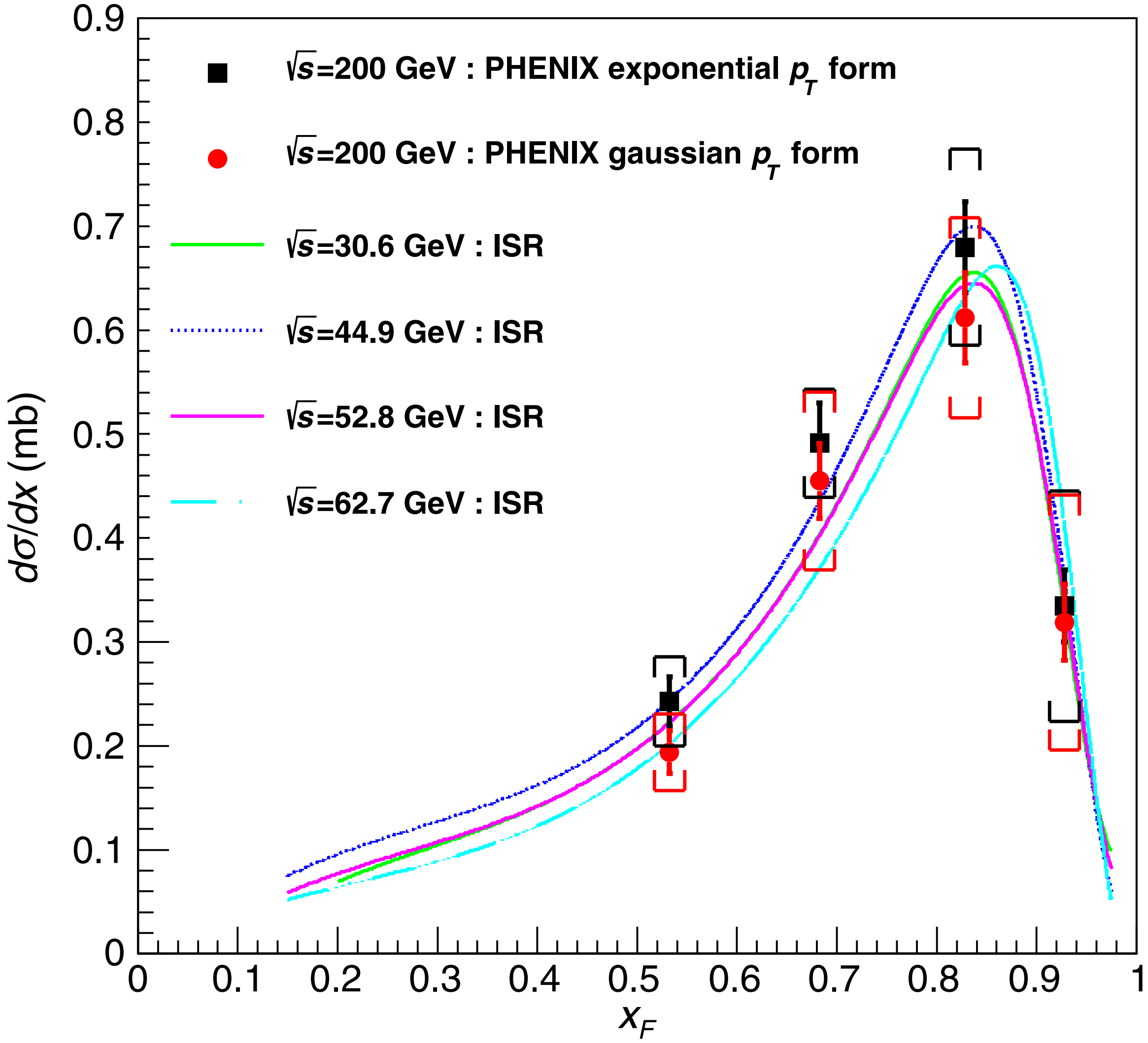


- π^0 asymmetry increases ~ 16%/GeV, instead of neutron asymmetry ~ -32%/GeV.
- π^0/neutron is ~ -1/2. Could π^0s be understood by a similar manner as neutrons?

Looking at only A_N is insufficient

$$A_N^{incl} = \frac{A_N^{SD}\sigma^{SD} + A_N^{DD}\sigma^{DD} + A_N^{ND}\sigma^{ND} + A_N^{pQCD}\sigma^{pQCD}}{\sigma^{SD} + \sigma^{DD} + \sigma^{ND} + \sigma^{pQCD}}$$

$$\sigma^{incl} = \sigma^{SD} + \sigma^{DD} + \sigma^{ND} + \sigma^{pQCD}$$

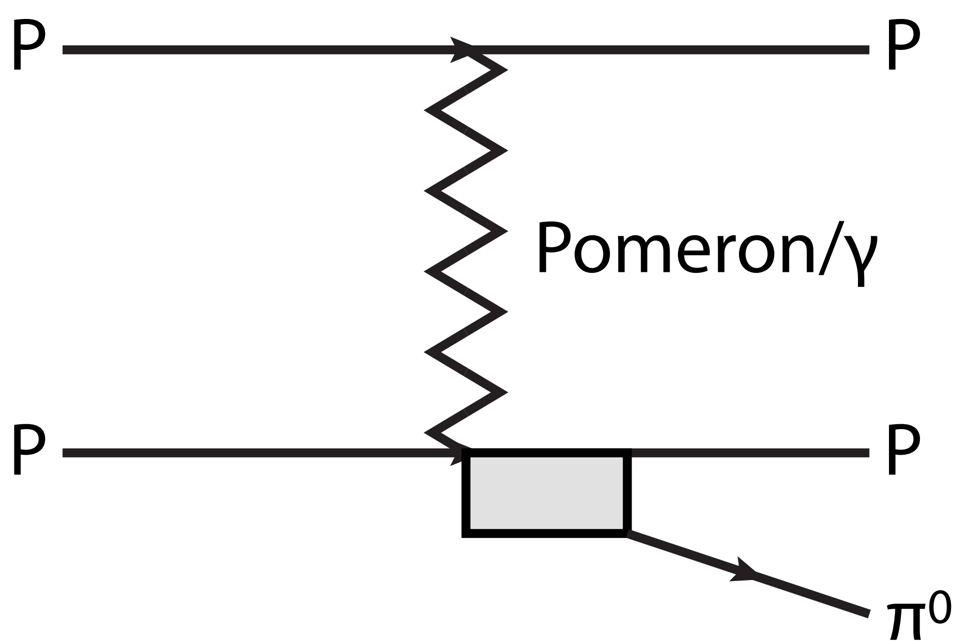


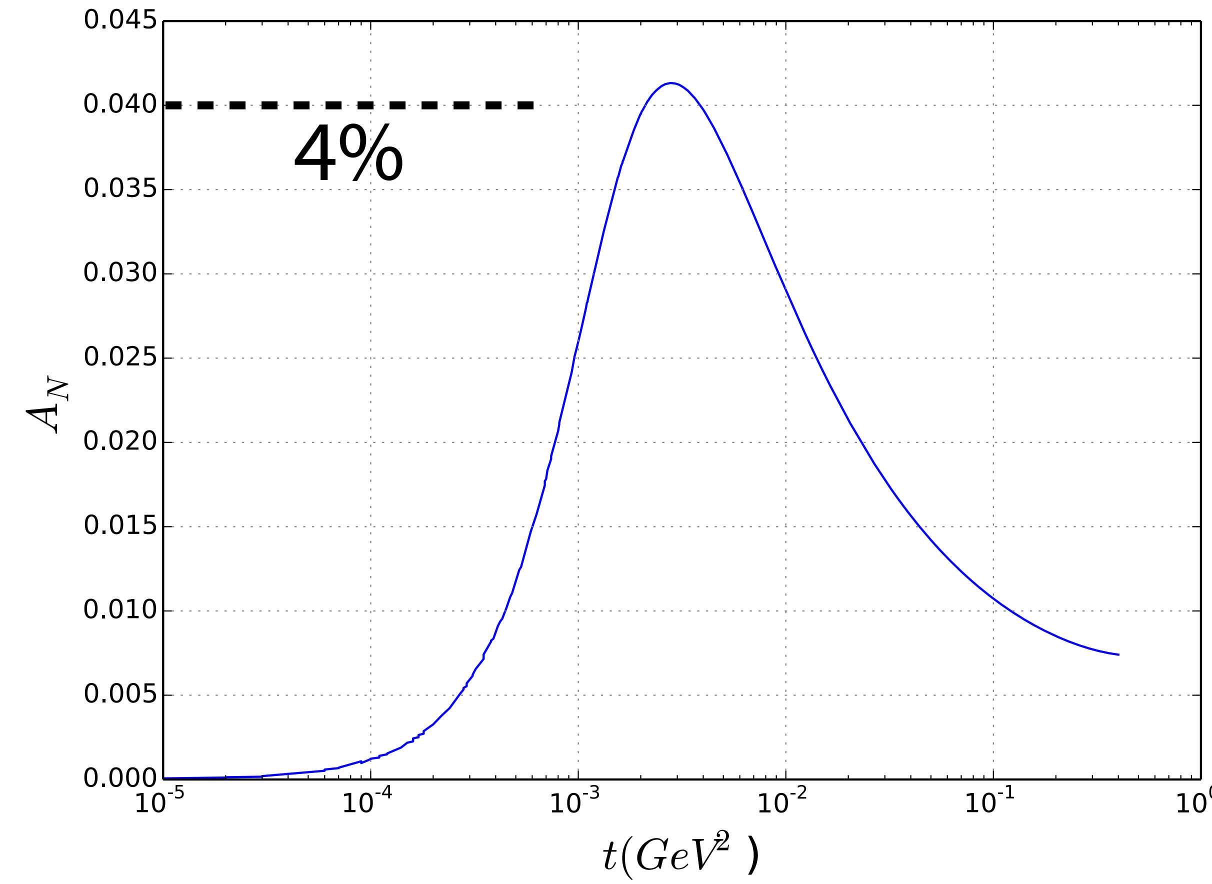
Very forward neutrons are exceptionally lucky; we can focus on only one-π exchange.

It is not true for forward π^0s.

Let's see what's happening in π^0 production

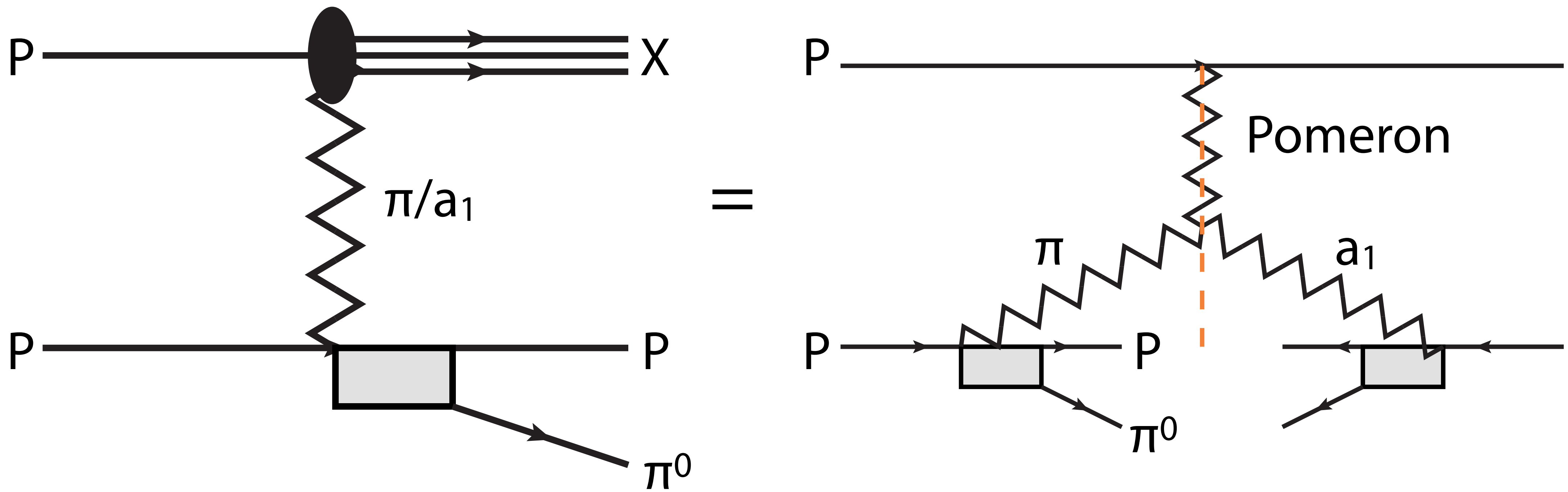
Elastic-like π^0 asymmetry (P and γ)





- Well known Coulomb-nuclear interference (CNI) gives a few % asymmetry.
- In fact, the RHIC polarimeter ($p^{\uparrow}$+C) is based on this mechanism.
- Calculated asymmetry of an intermediate state is far smaller than the RHICf data.
  - A_N < 5% and rapidly decreases as $|t| > 10^{-2}$ GeV^2.

Diffractive-like π^0 asymmetry (π and a_1)

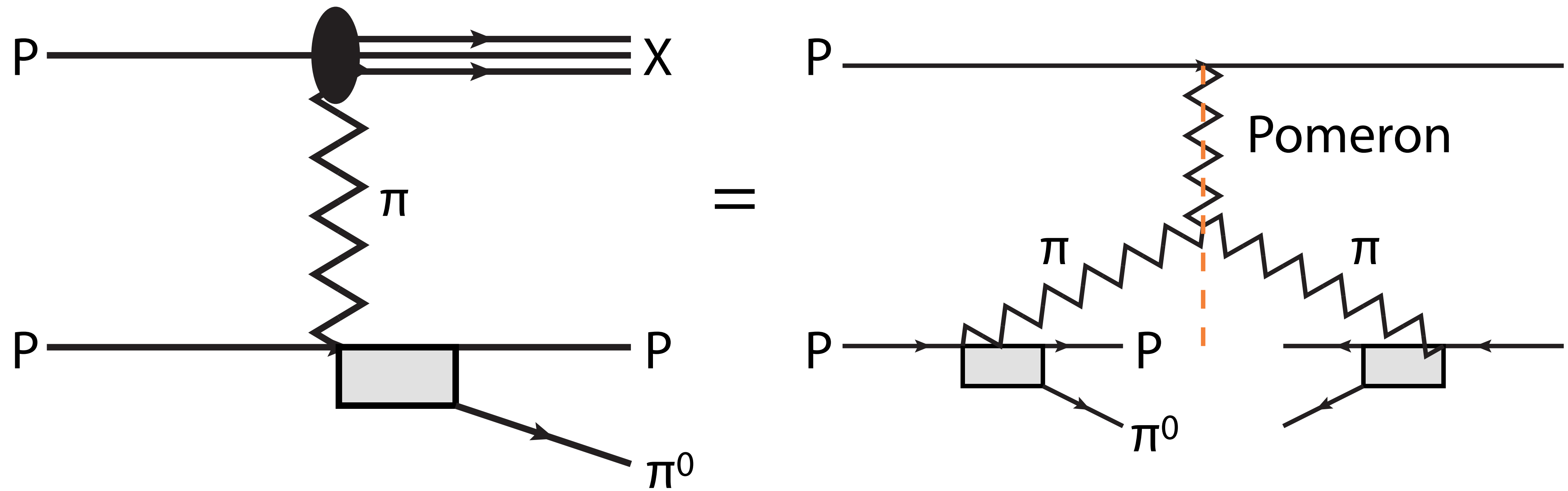


- High energy single diffraction is represented by a triple-reggeon diagram.
- Interference between π (spin-flip) and a_1 (nonflip) gives nonzero asymmetry.
  - Kopeliovich et al reproduced the PHENIX forward neutron asymmetry ~ -5%.
- I tried to apply Kopeliovich's idea to π^0 asymmetry;
  - so sensitive to the a_1 parameters (some parameter choices seem biased.)
  - turned out few % asymmetry for π^0s, as expected by neutron asymmetry
- But few % asymmetry only from a single diffraction should be insufficient to explain the RHICf *inclusive* measurements.

$$A_N = \frac{A_N^{diff}\sigma^{diff} + A_N^{non\text{-}diff}\sigma^{non\text{-}diff}}{\sigma^{diff} + \sigma^{non\text{-}diff}}$$

$$A_N^{non\text{-}diff} \sim 0?$$

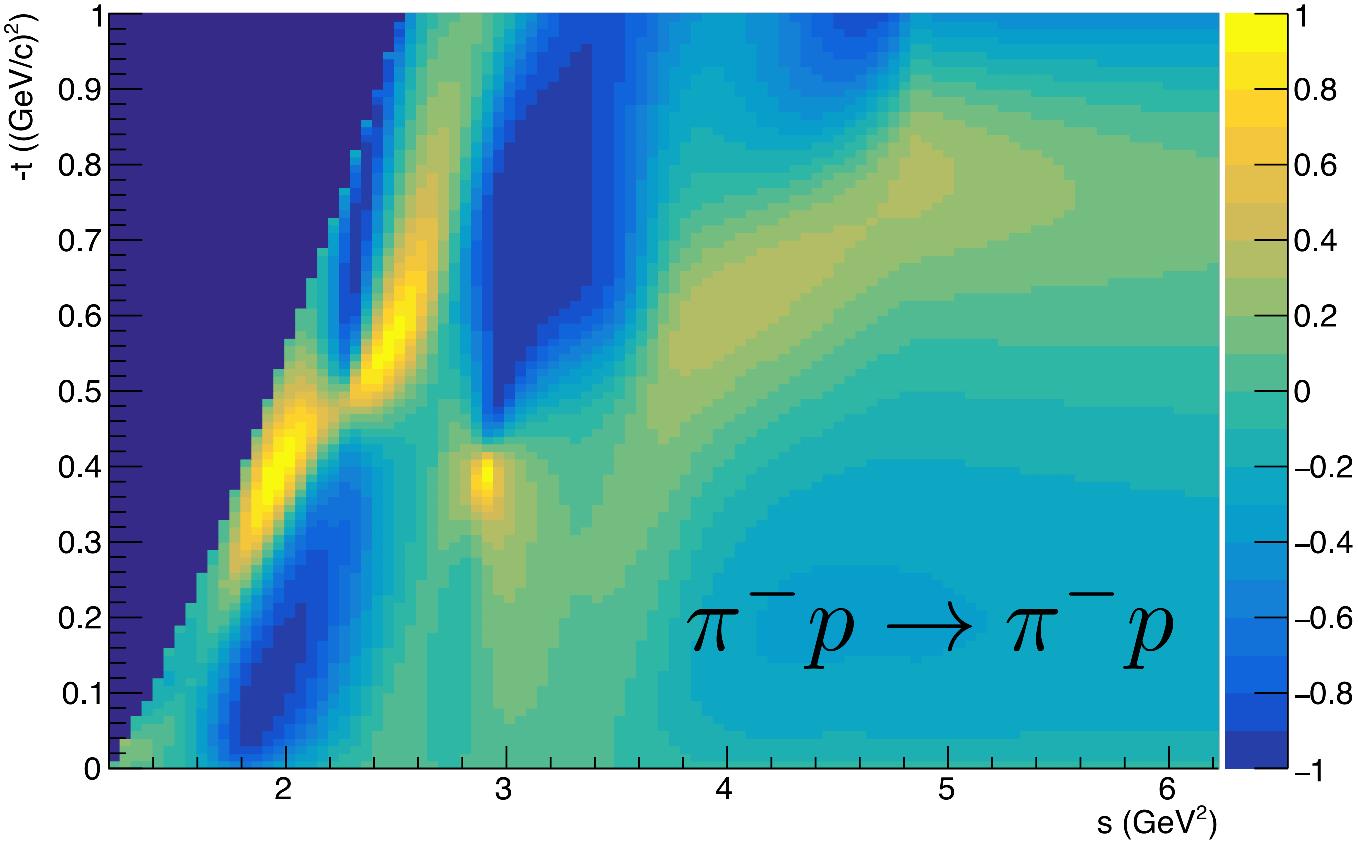
Diffractive-like π^0 asymmetry (πN)

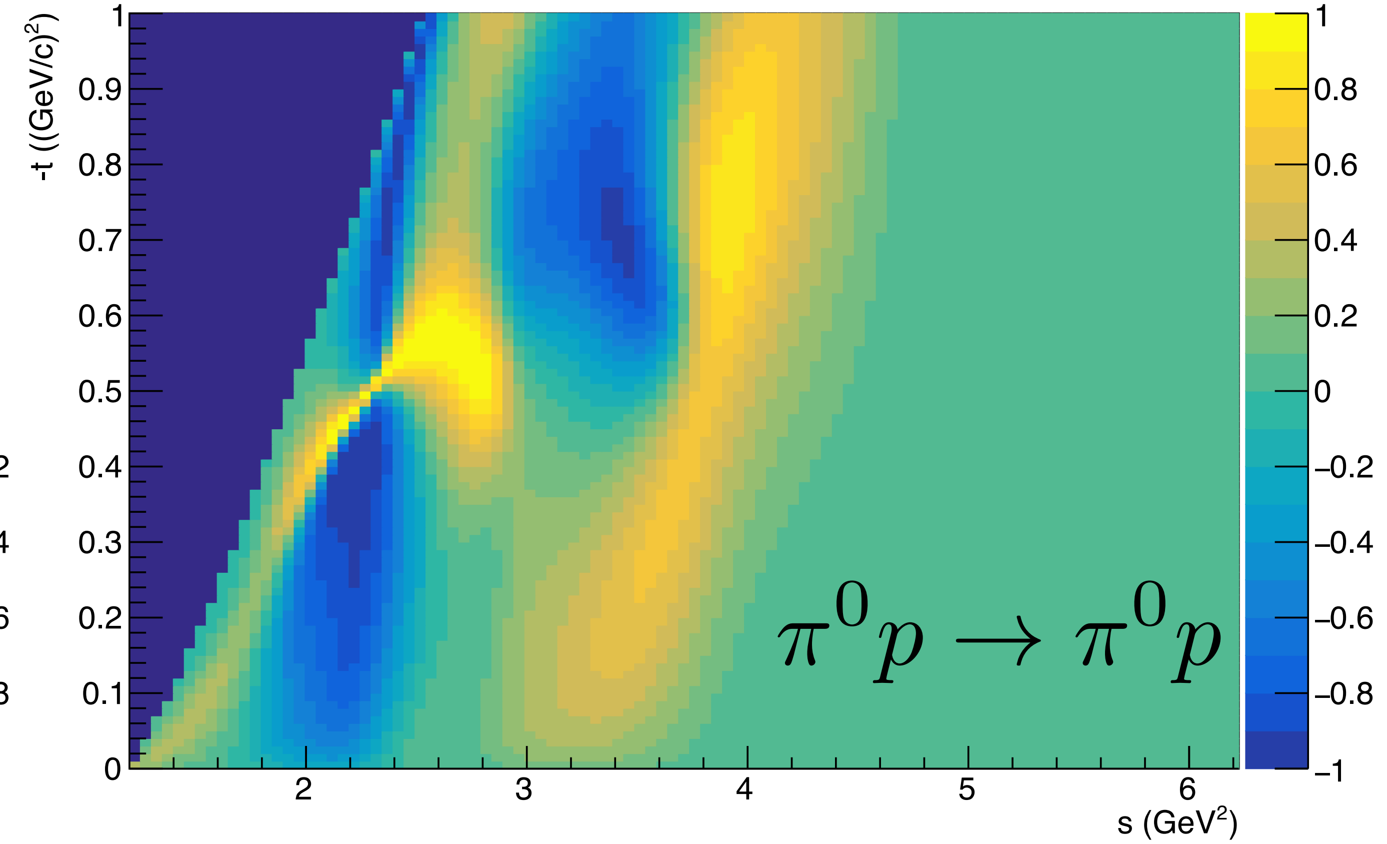


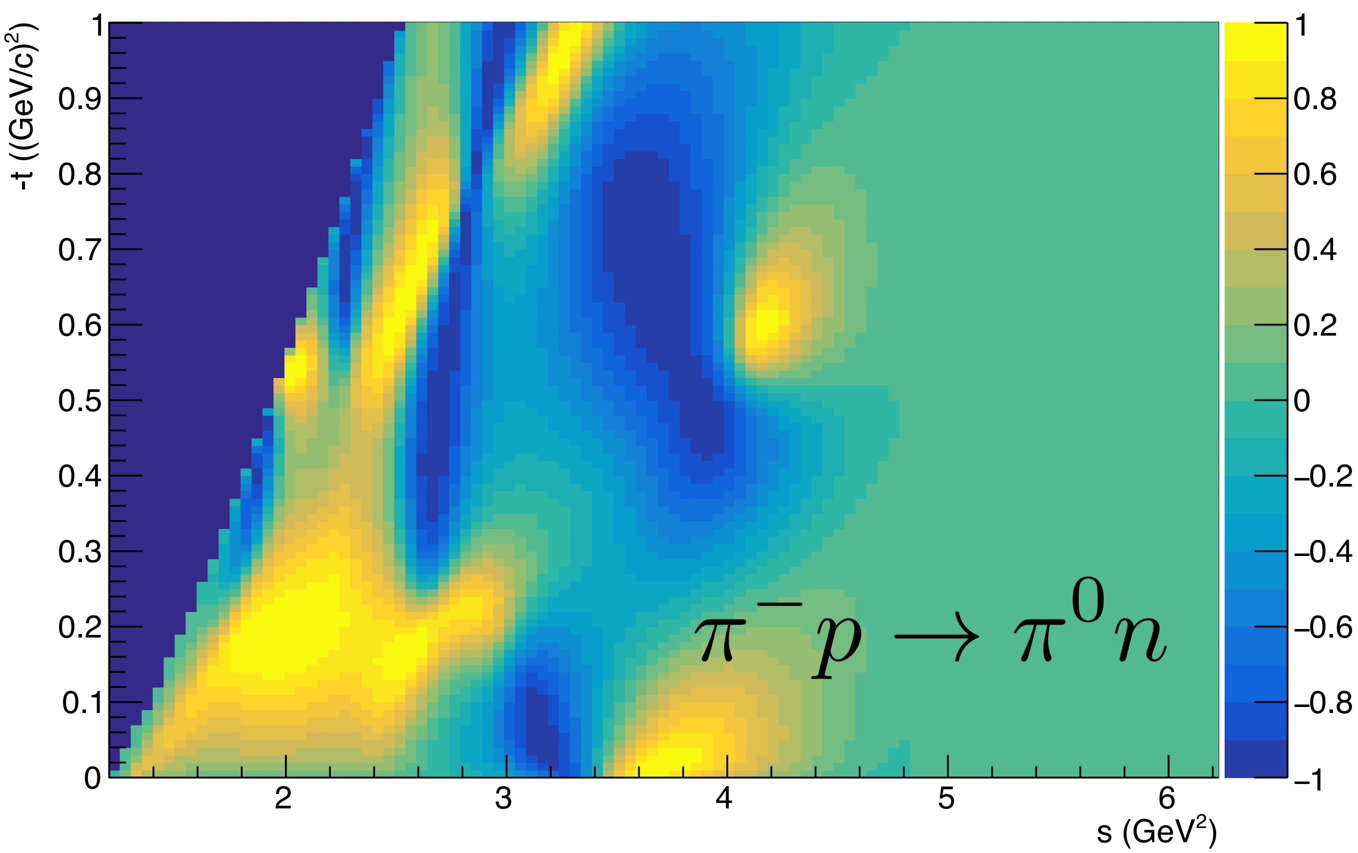
- Amplitude of π-exchange dominates other mesons/reggeons.
- $\pi+p^{\uparrow}$ is known to give sizable (+ and -) asymmetries for outgoing particles.

Large A_N^{diff} may compensate small σ^{diff} → $A_N = \dfrac{A_N^{diff}\sigma^{diff} + A_N^{non\text{-}diff}\sigma^{non\text{-}diff}}{\sigma^{diff} + \sigma^{non\text{-}diff}}$

- Low energy $\pi+p^{\uparrow}$ scatterings are parametrized by partial wave amplitudes:
  - Kamano et al, Ronchen et al, SAID, etc…







- Exchanged πs have small momenta, so the invariant πp↑ mass W (= √s) can be down to the Δ(1232) mass.
- Present asymmetries for outgoing πs are predicted by SAID.
- SAID papers say similar results can be obtained by other models as well.
- Large π^0 asymmetries either in positive and negative

Fraction of diffraction among inelastic σ

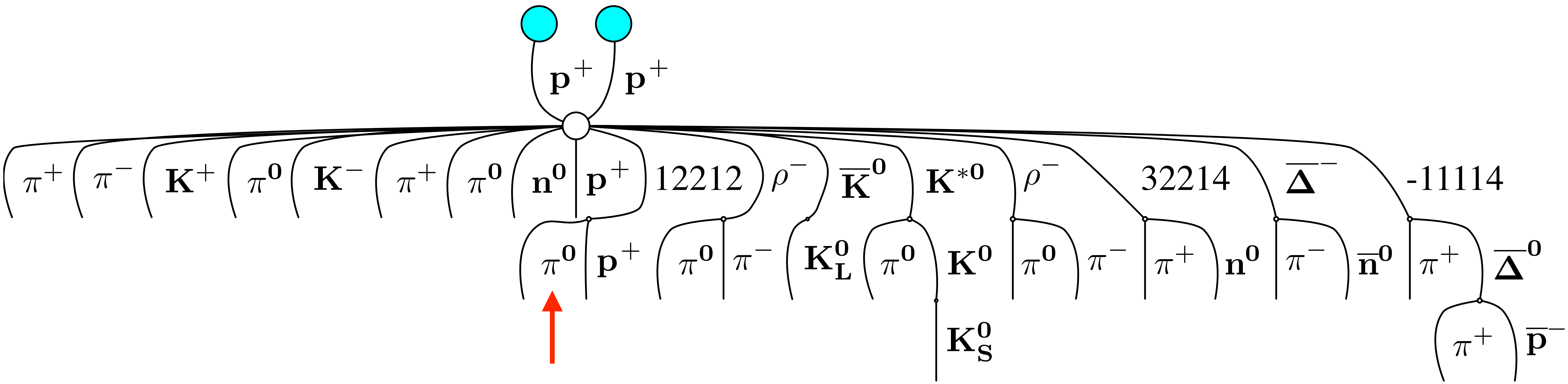
$$A_N = \frac{A_N^{diff}\sigma^{diff} + A_N^{non\text{-}diff}\sigma^{non\text{-}diff}}{\sigma^{diff} + \sigma^{non\text{-}diff}}$$

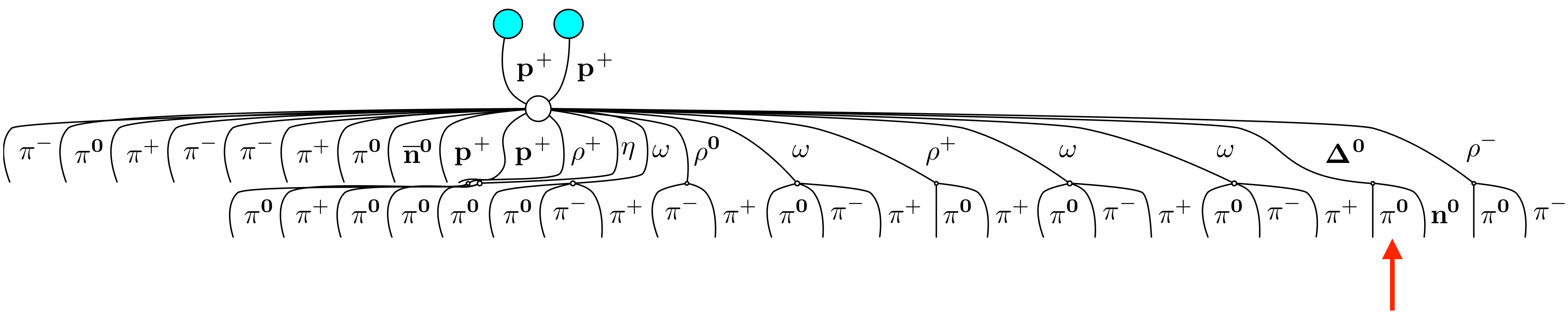
- We see large π^0 asymmetries emerge in low energy $\pi+p^\uparrow$ scatterings.
- Next step is an estimation of π^0 production cross sections σ^{diff} and $\sigma^{\mathrm{non\text{-}diff}}$.
- Diffractive cross section is calculated using the discontinuity in M_x^2.
  (I learned it from text books. Please forgive unintentional misunderstandings.)

$$E_p E_{\pi^0} \frac{d^6\sigma^{diff}}{d^3p_p d^3p_{\pi^0}} = \frac{1}{s}\mathrm{disc}_{M_X^2} A_{pp\to Xp\pi^0}$$

- I did such cumbersome calculations for x_F, p_T, and φ <u>distributions</u>.
- But at this time, I used a shortcut to use Monte Carlo simulations, PYTHIA8 and EPOS, to get overall <u>normalization</u> of diffraction relative to inelastic events.
- Only in PYTHIA8 and EPOS (via HEPMC), we can trace given particles' parents and children.

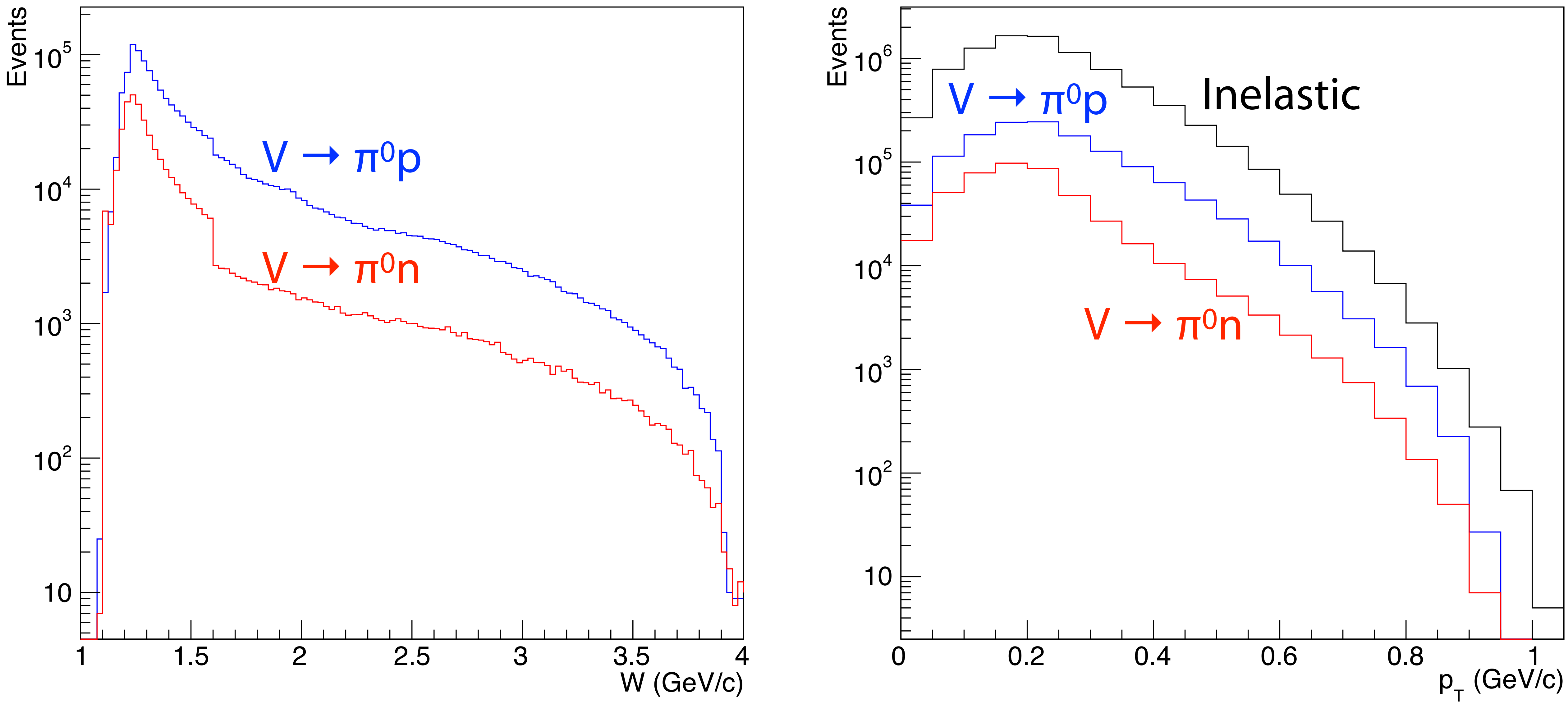
Highest energy π^0 (EPOS LHC via HEPMC)



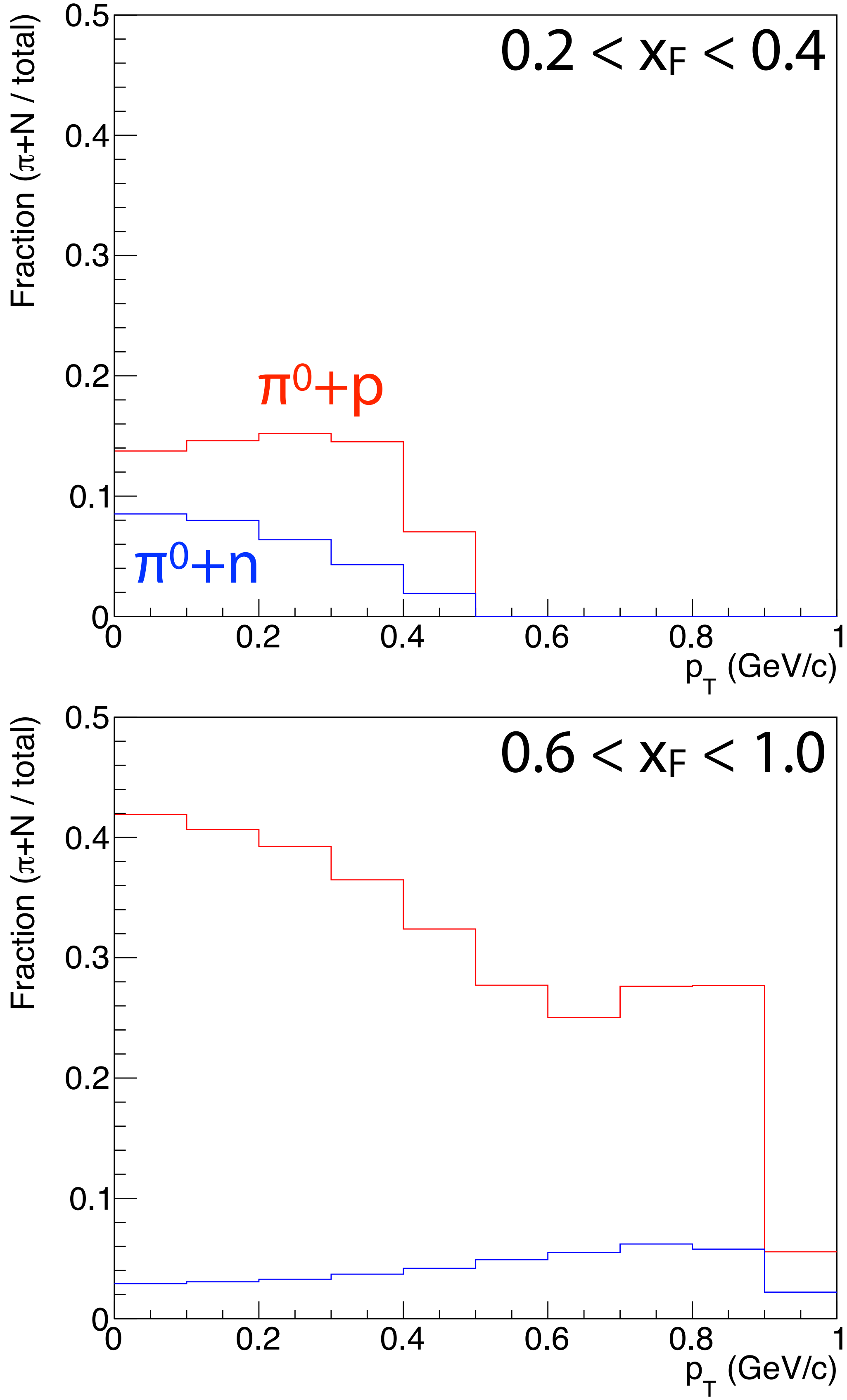


Fraction of diffraction among inelastic σ

PYTHIA8.235 default tune

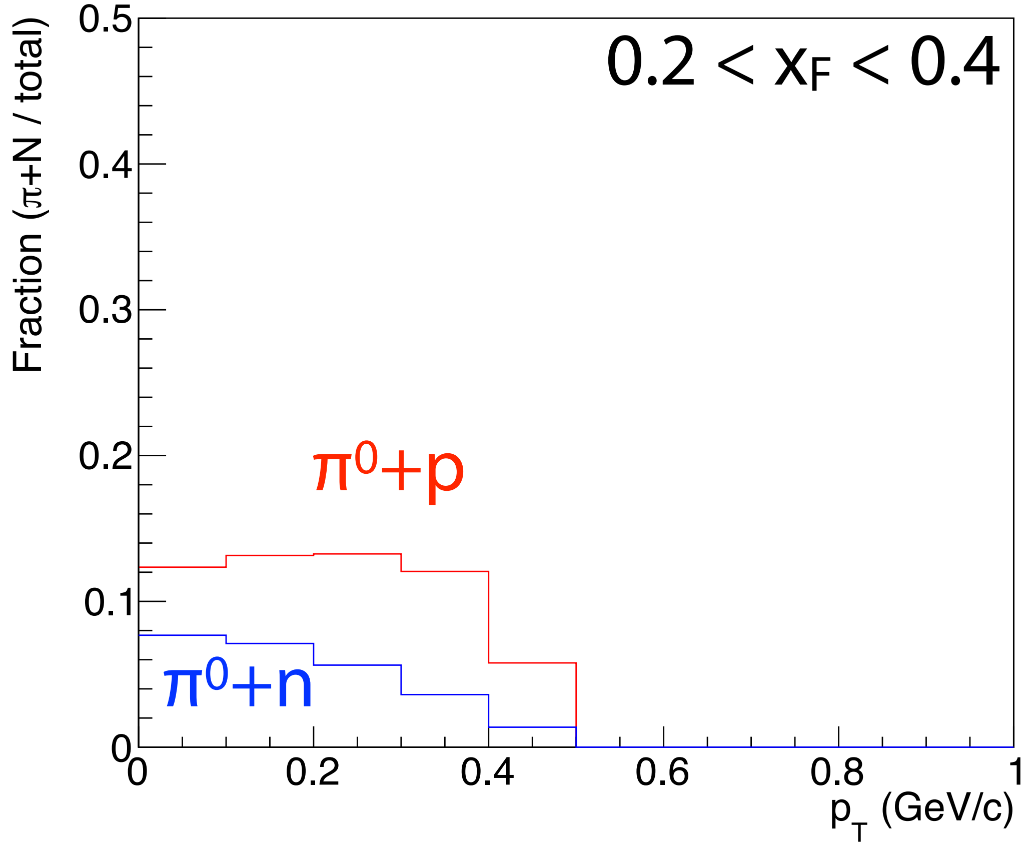


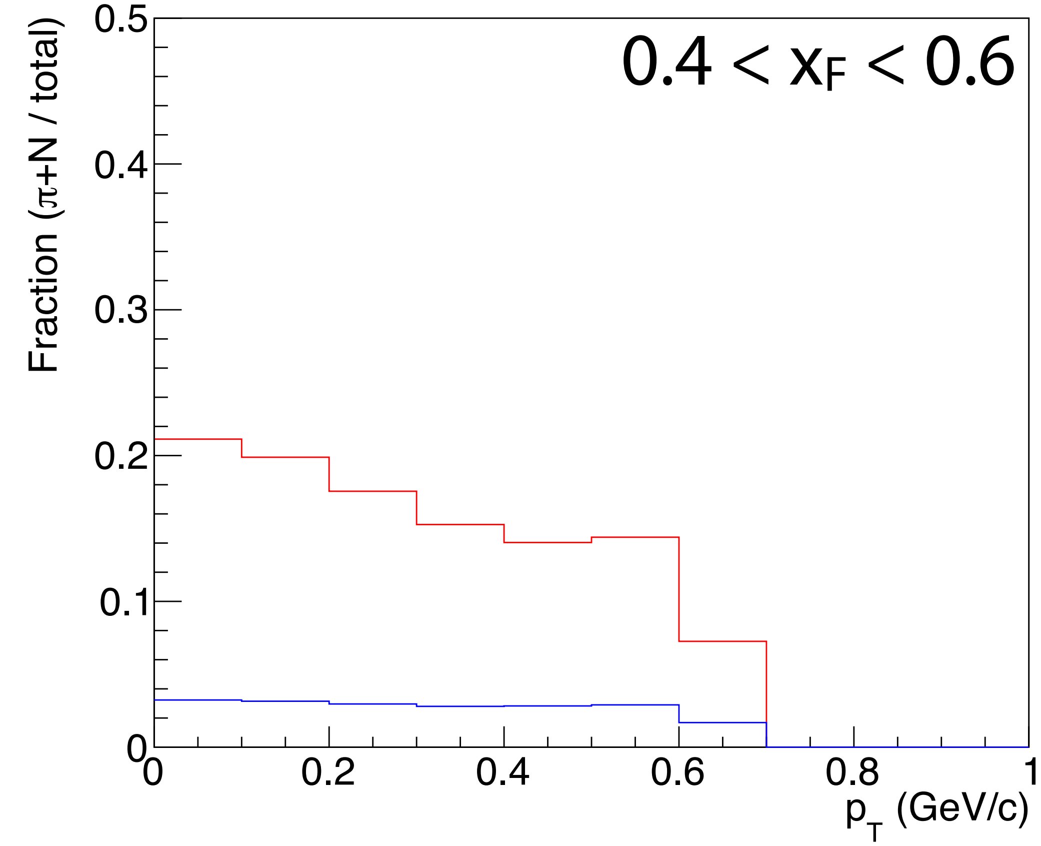
πN/total fraction by PYTHIA8 default

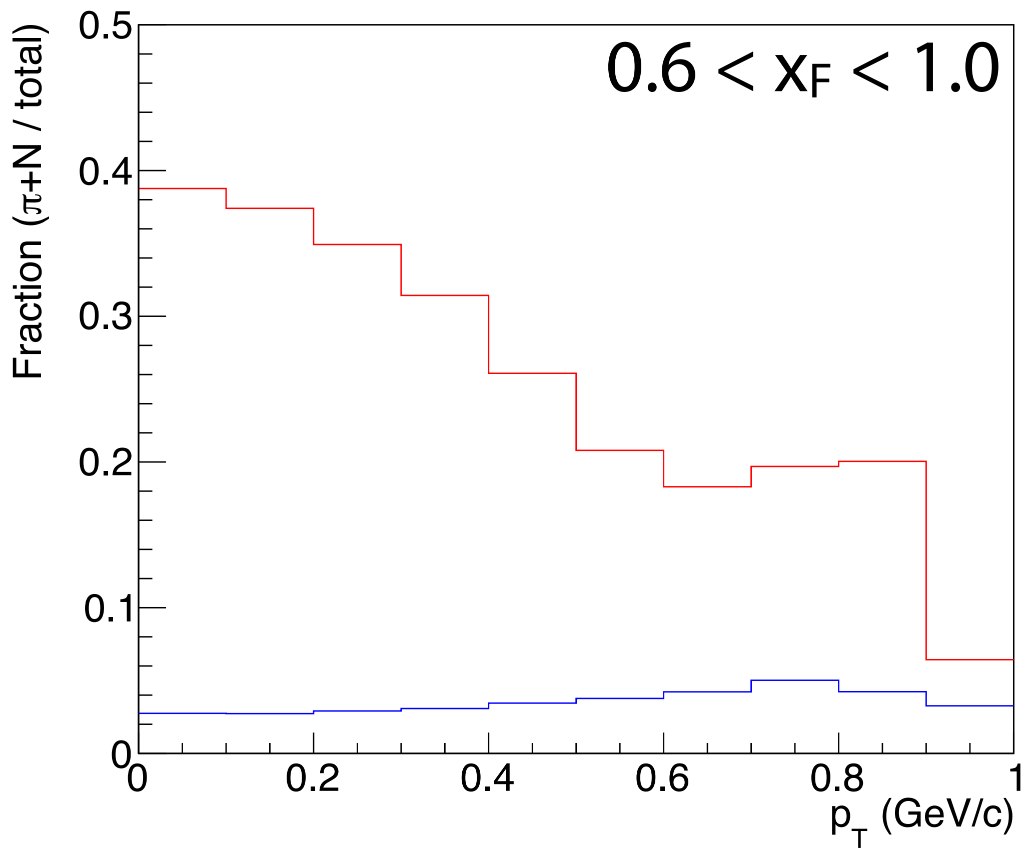


Consistent with the well known PYTHIA8's tendency:
large fraction of diffraction at high x_F

πN/total fraction by PYTHIA8 Tune4C



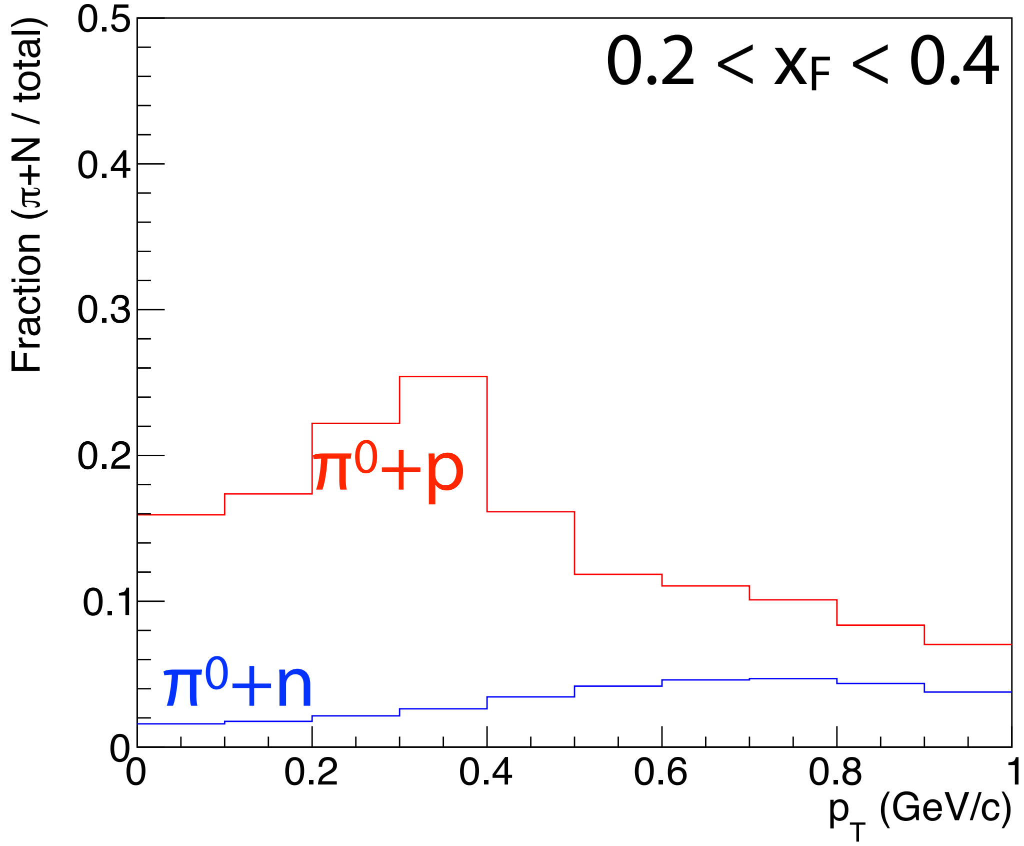


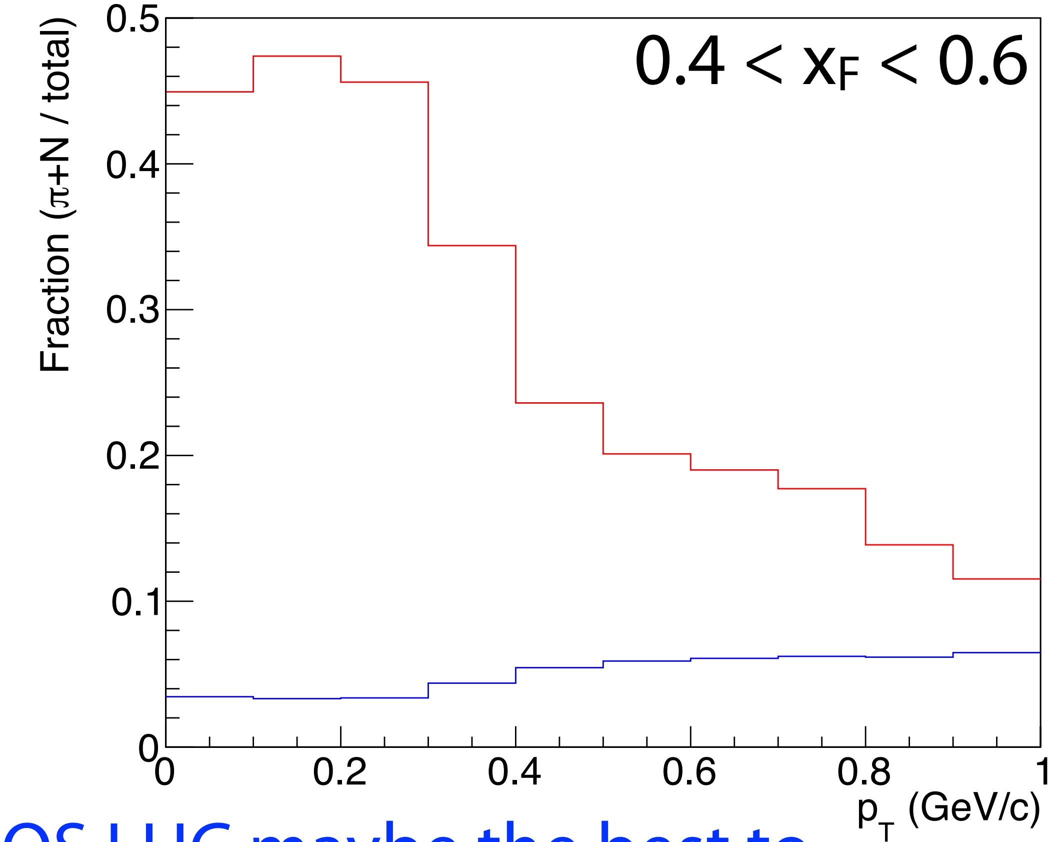


Tune4C is tuned by the Tevatron diffraction data.

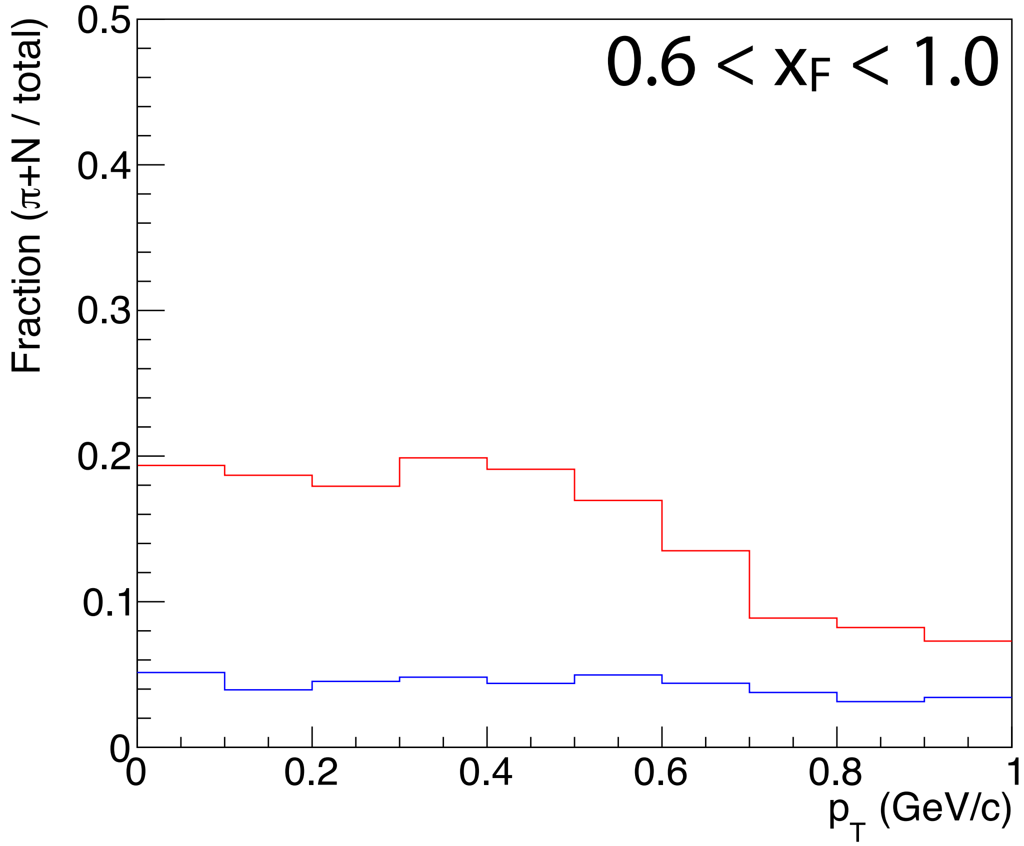
Consistent with the well known PYTHIA8's tendency:
large fraction of diffraction at high x_F

πN/total fraction by EPOS LHC

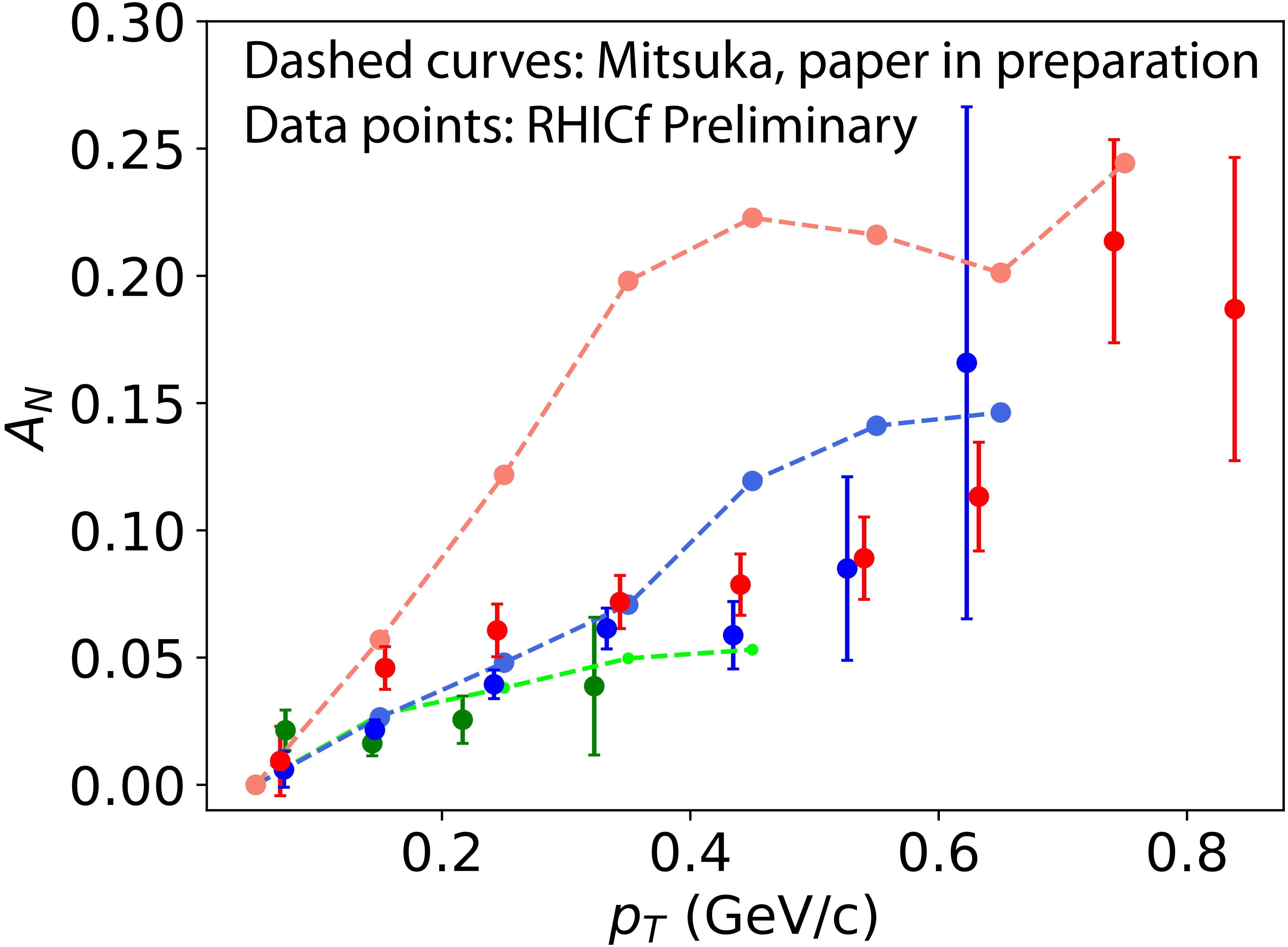




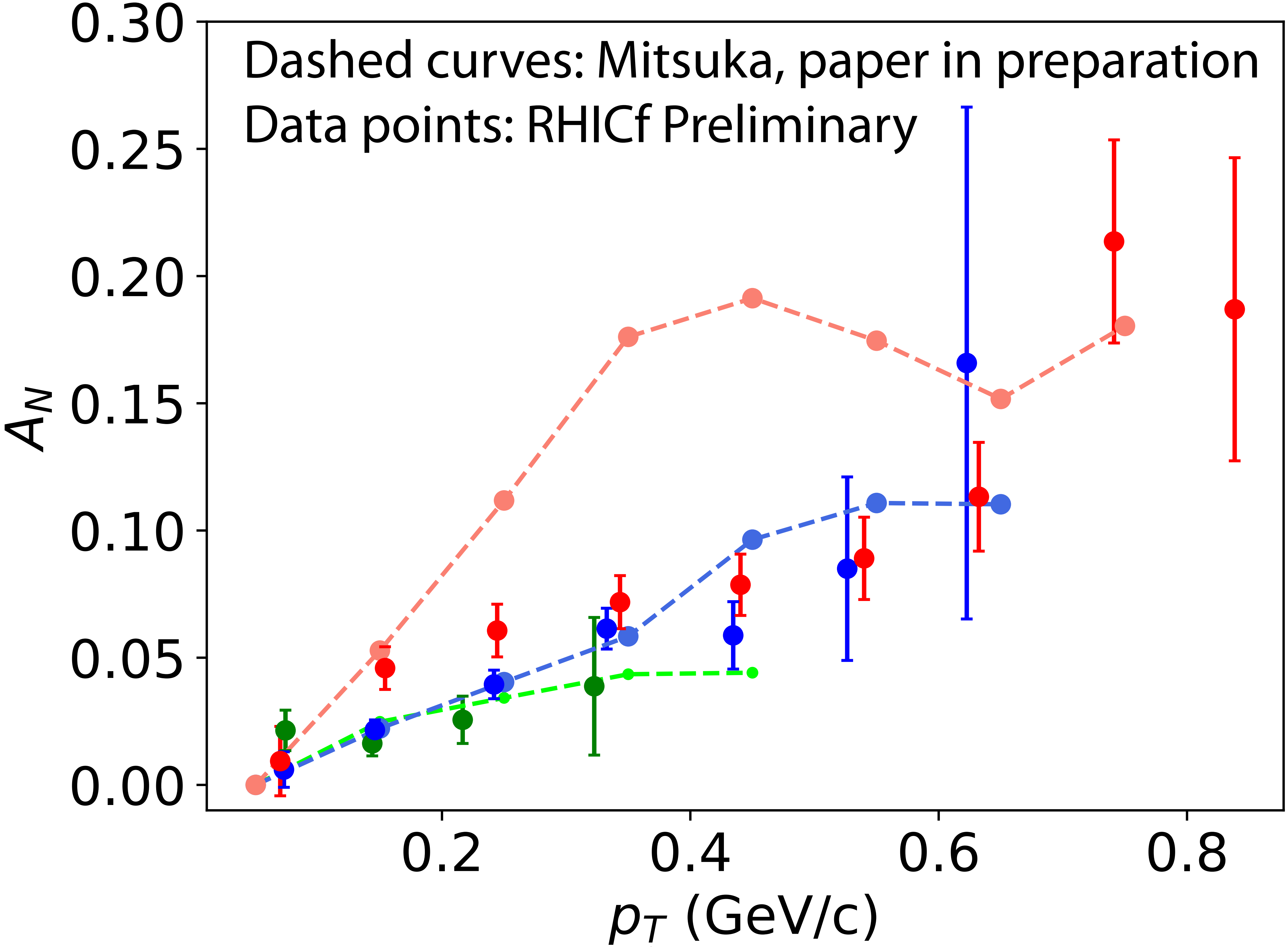
EPOS LHC maybe the best to reproduce the ATLAS-LHCf data.



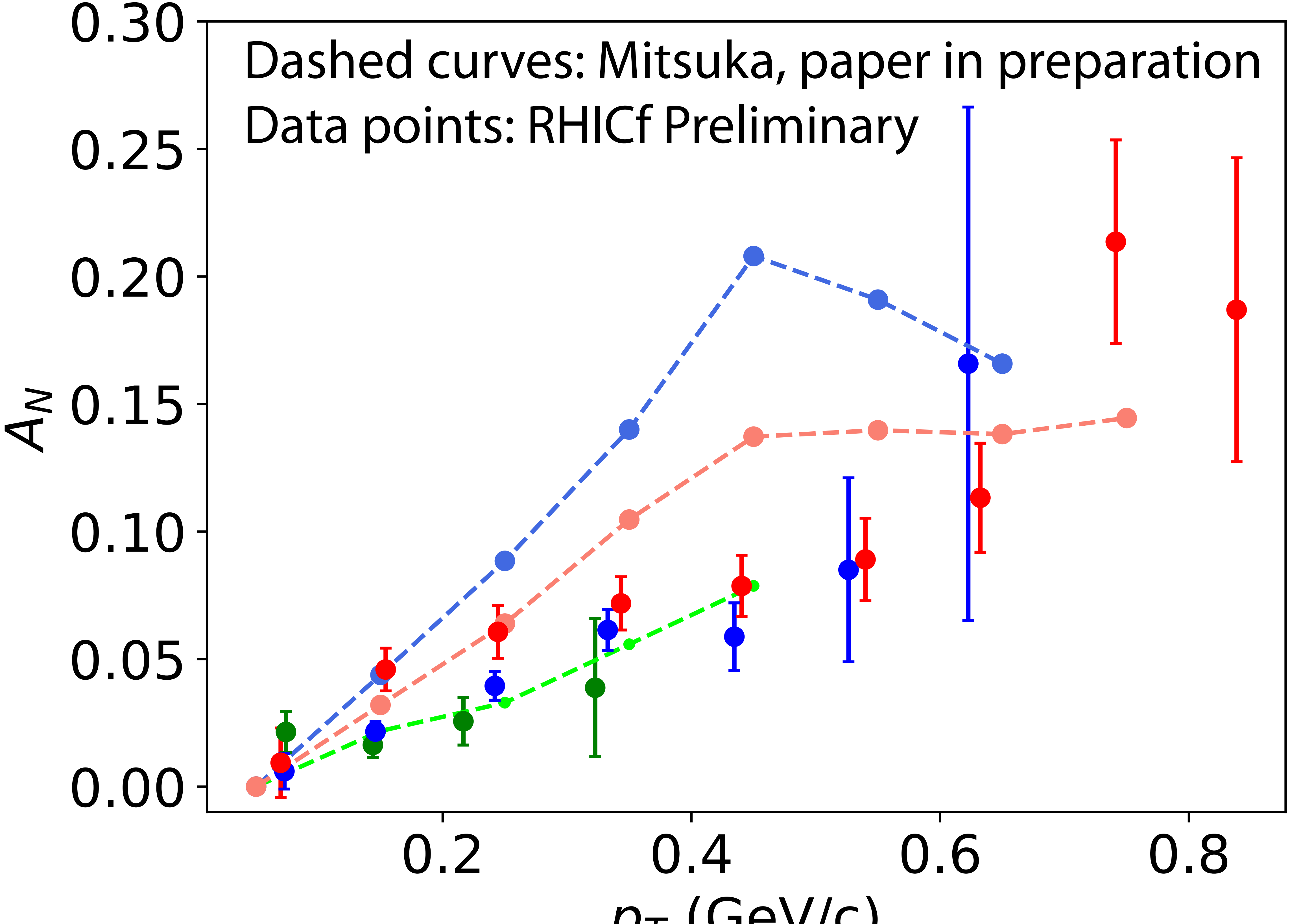
π^0 A_N (fraction by PYTHIA8 default)



π^0 A_N (fraction by PYTHIA8 Tune4C)

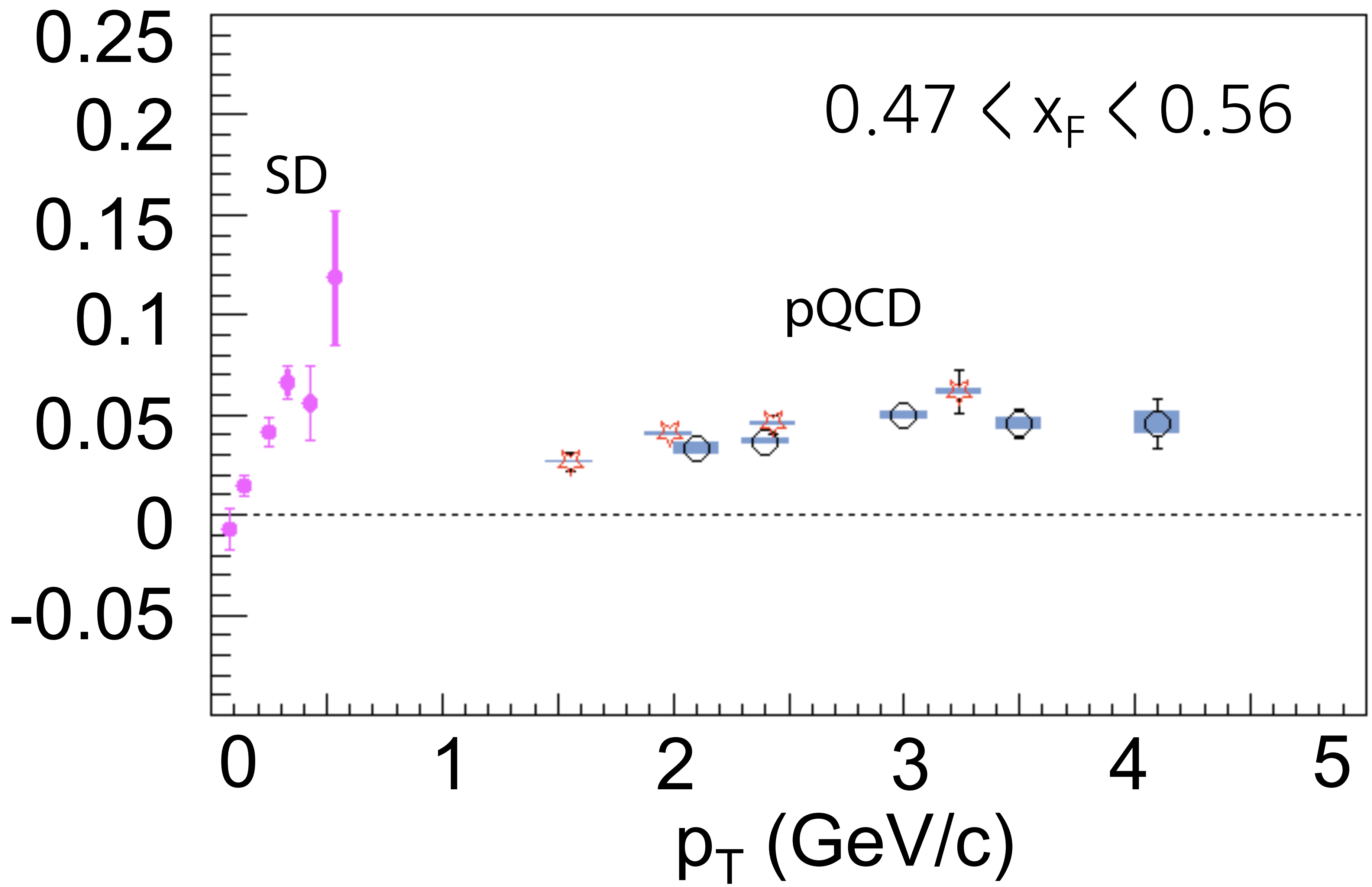


π^0 A_N (fraction by EPOS LHC)



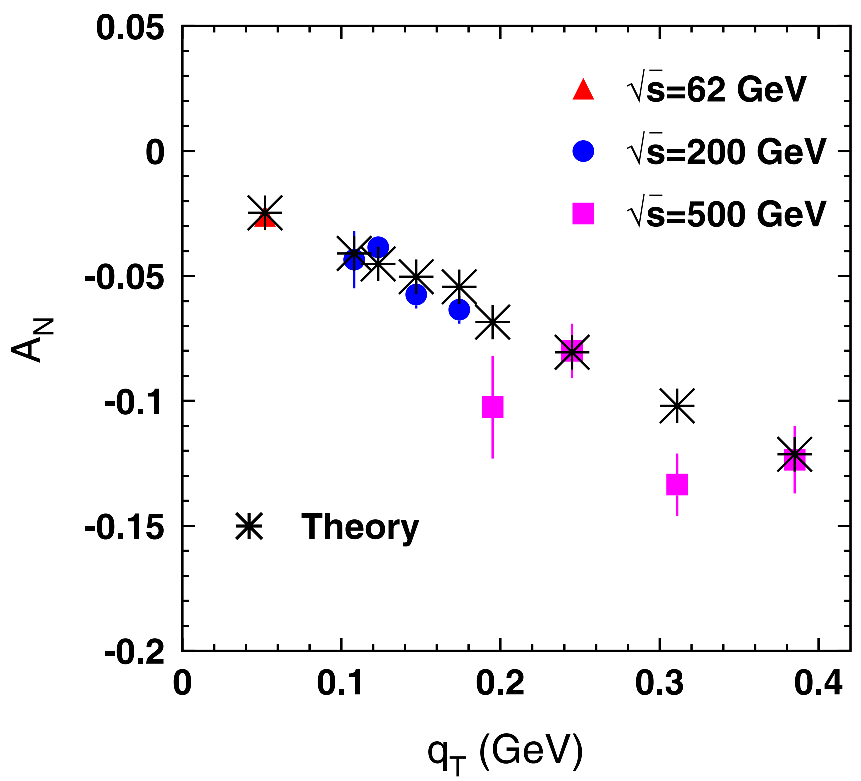
On Minho's plot

$$A_N^{incl} = \frac{A_N^{SD}\sigma^{SD} + A_N^{DD}\sigma^{DD} + A_N^{ND}\sigma^{ND} + A_N^{pQCD}\sigma^{pQCD}}{\sigma^{SD} + \sigma^{DD} + \sigma^{ND} + \sigma^{pQCD}}$$



Summary of asymmetries in pp

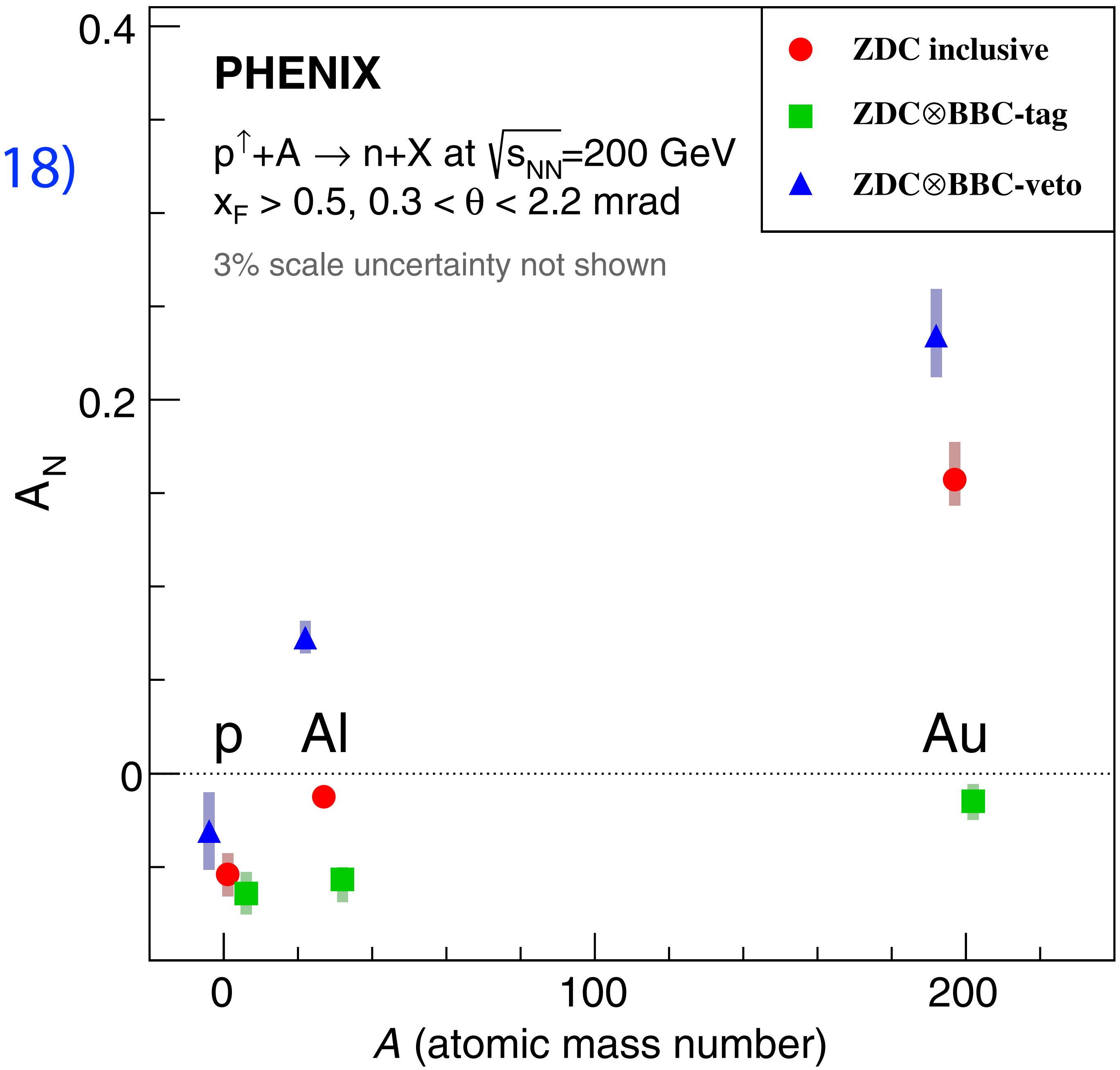
- As presented by Minho, the RHICf preliminary data indicated large and positive asymmetries for forward π^0s.
- I calculated π^0 asymmetries assuming three scenarios: elastic, π/a_1 interference, and low energy πN scatterings.
- Large asymmetries induced by πN scatterings can reproduce the RHICf data in some x_F regions.
- But, if this scenario is true, how can we understand neutron asymmetries that were successfully reproduced by π/a_1 interference??



Neutron asymmetries in pAl and pAu

- Large A_N of ZDC inclusive in pAu may indicate
  1) substantial nuclear effects in nuclear targets
  2) effects of electromagnetic (EM) field produced by relativistic A targets

PRL 120, 022001 (2018)

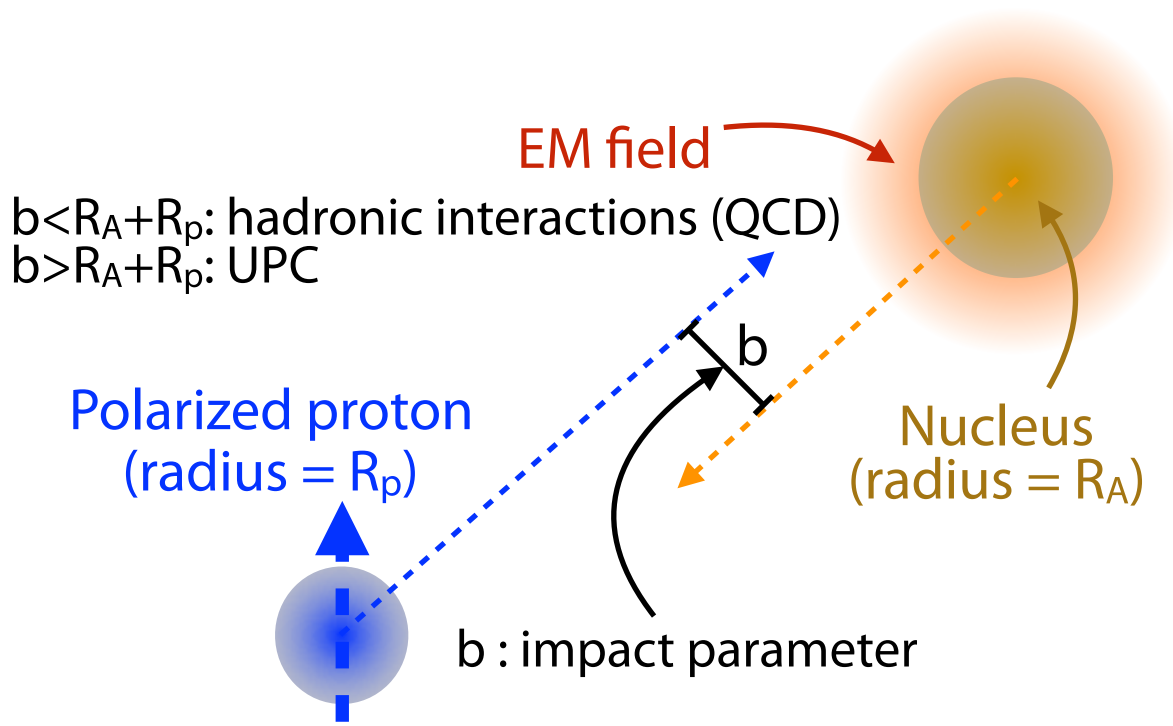



Accelerator
Detector

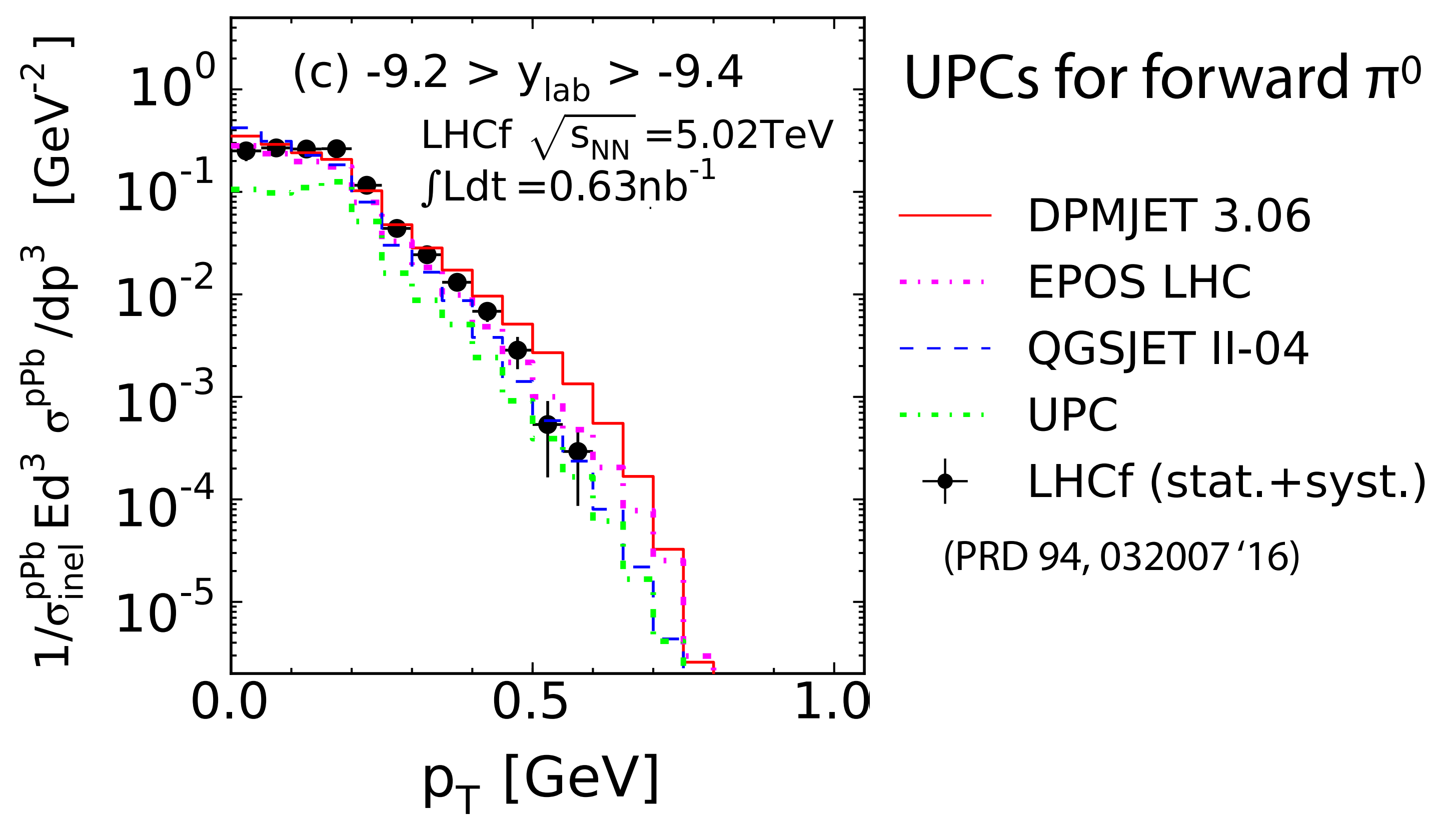
Ultra-peripheral collisions (UPCs)

- In order to test the EM field scenario, I developed the MC simulation framework that took into account the both ***hadronic interactions*** and ***ultra-peripheral collisions***.

- Ultra-peripheral collisions (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.

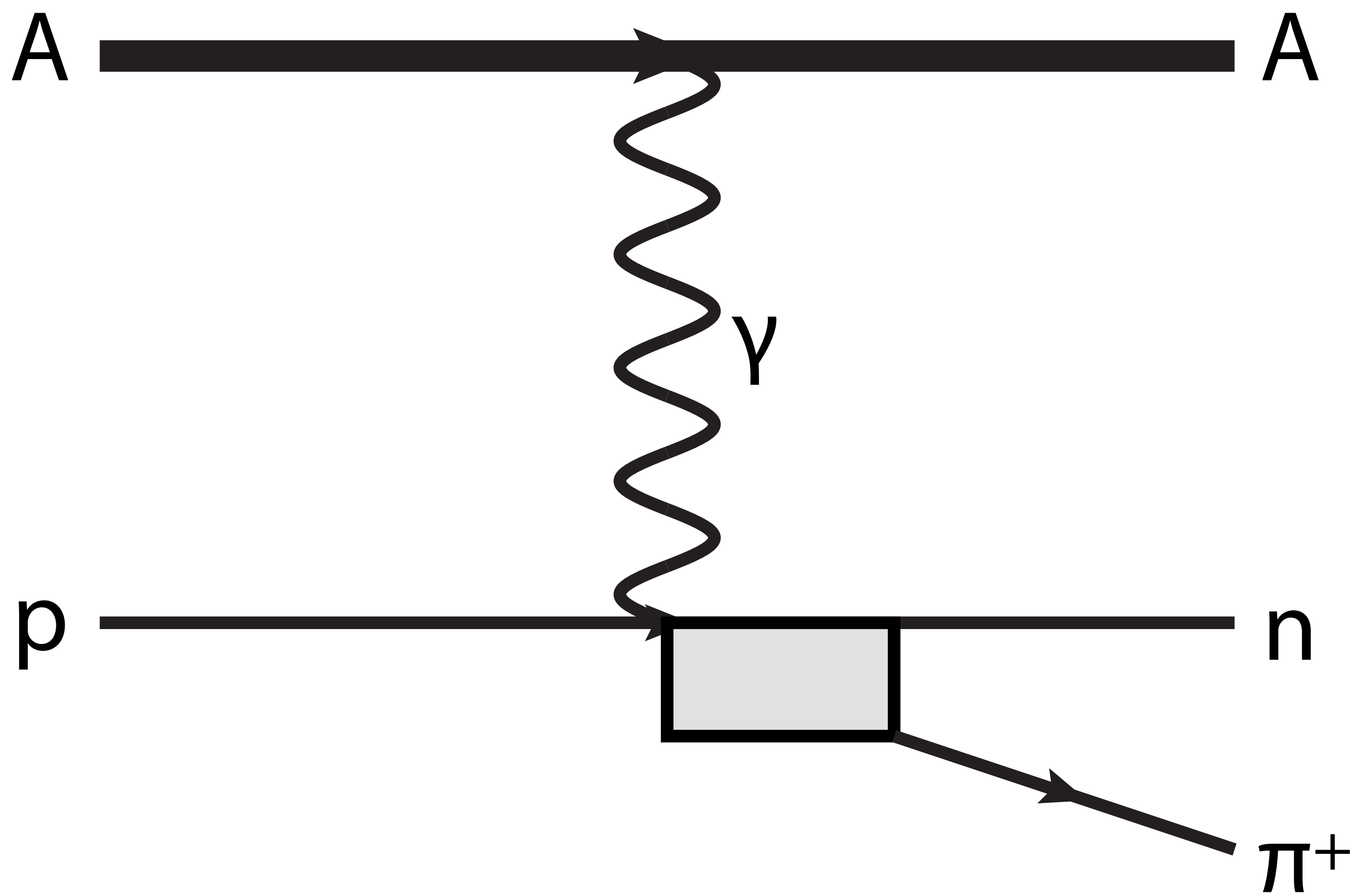


Please see my papers for details:
GM, EPJ C **75**, 614 (2015) and
GM, PRC **95**, 044908 (2017).



(PRD 94, 032007 '16)

UPC diagram (very simplified)



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

photon flux (N): virtual 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

Virtual photon flux

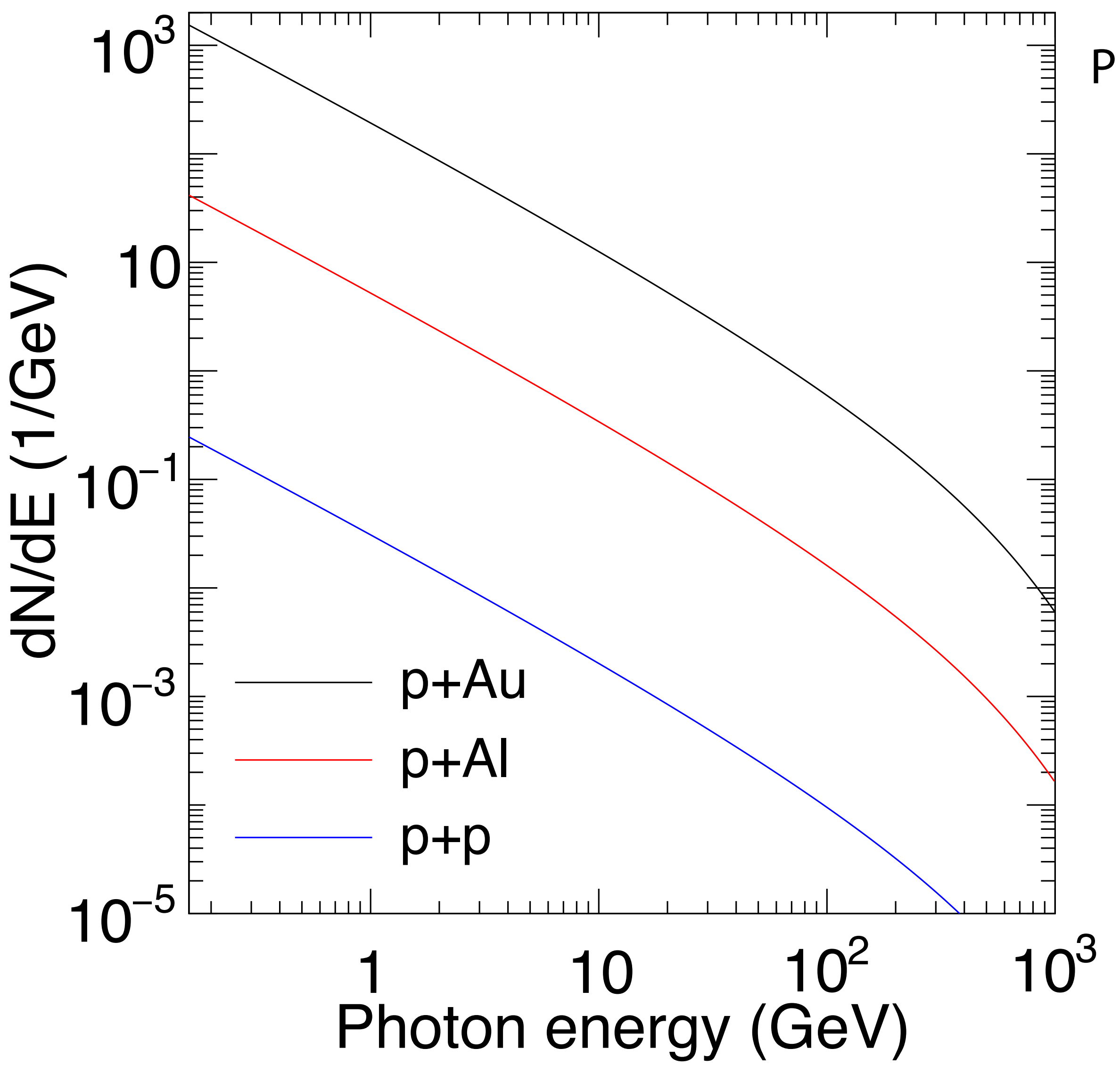
The number of virtual photons per energy and b is formulated by the Weizsacker-Williams approximation or QED (Phys. Rep 364 359 '02, NPA 442 739 '85, etc…):

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

Proportional to Z^2

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

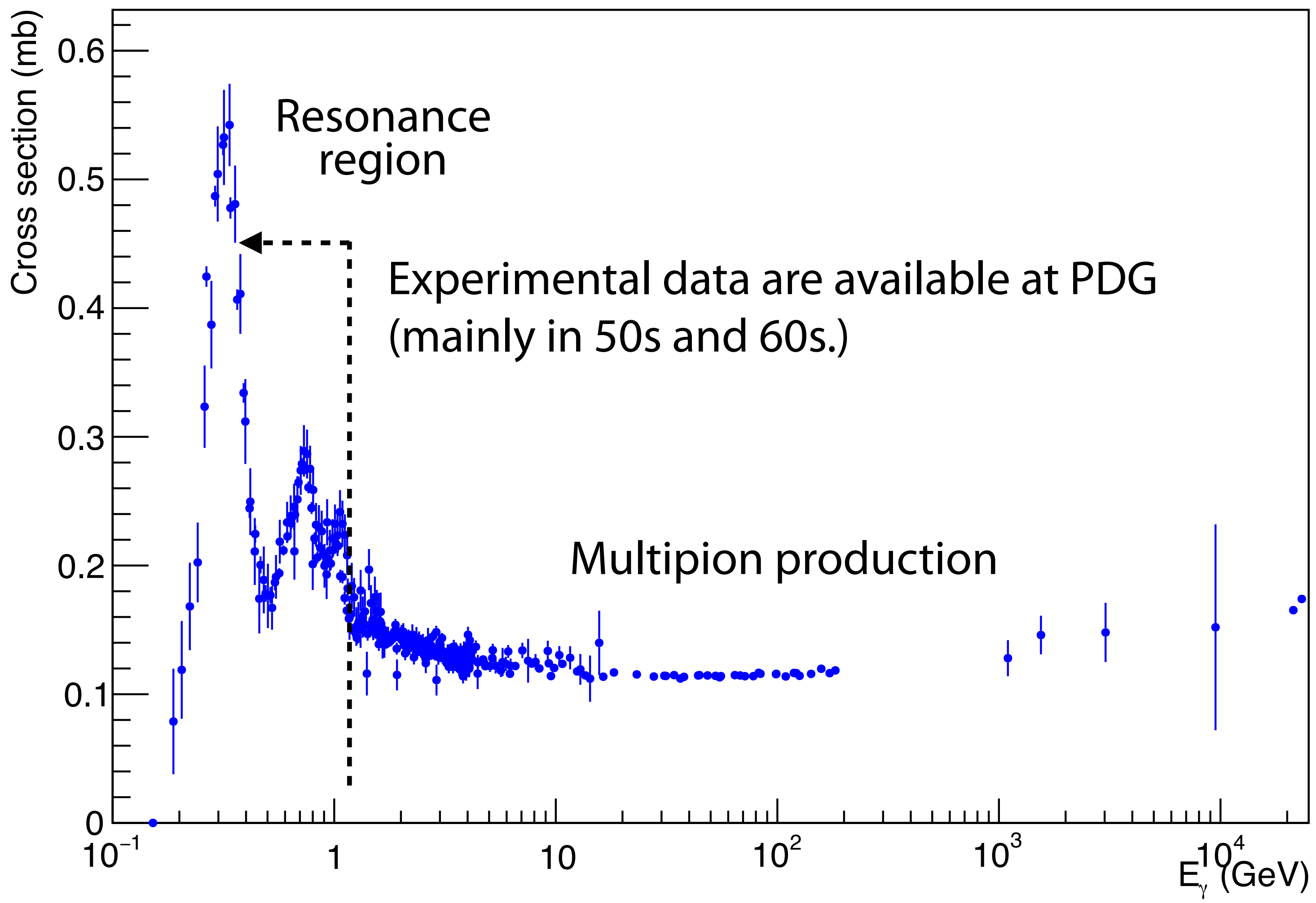
Note that the virtual photon flux depends on the charge of photon source as Z^2.



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

γ+p interactions

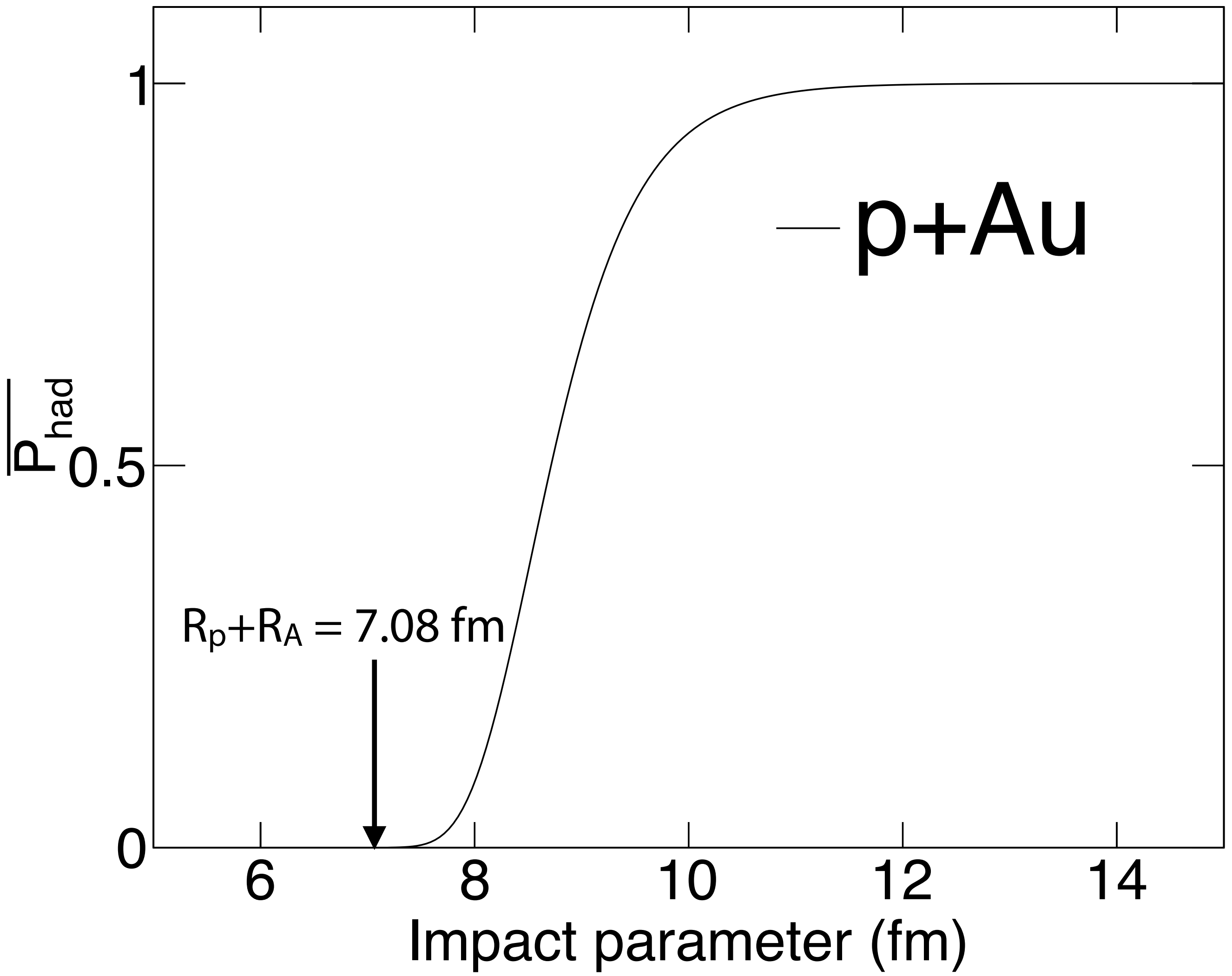
$$\frac{d\sigma^4_{\mathrm{UPC}(p^\uparrow \mathrm{A}\to\pi^+ n)}}{dW\,db^2\,d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW\,db^2}\frac{d\sigma_{\gamma^* p^\uparrow \to \pi^+ n}(W)}{d\Omega_n}\overline{P_{\mathrm{had}}}(b)$$



- Recalling the virtual photon flux and dominance of low-energy photons, most UPCs occur at the baryon resonance region.
- Namely, low-energy γ+p interactions ($\omega^{\mathrm{rest}}_\gamma < 1.5$ GeV) play major role in UPCs.

Impact parameter (~A) dependence

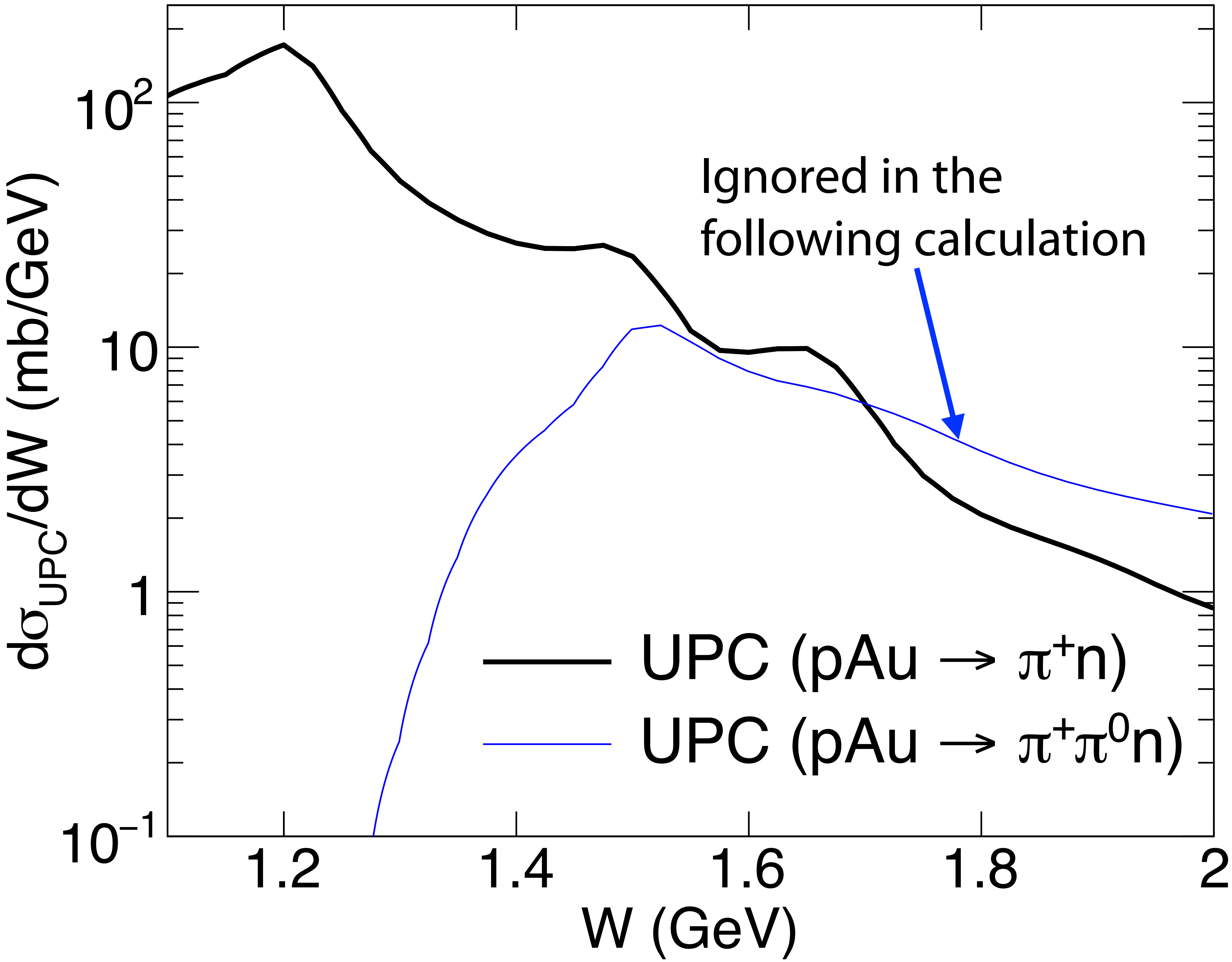
$$\frac{d\sigma^4_{\mathrm{UPC}(p^\uparrow \mathrm{A} \to \pi^+ n)}}{dW\, db^2\, d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW\, db^2} \frac{d\sigma_{\gamma^* p^\uparrow \to \pi^+ n}(W)}{d\Omega_n} \overline{P_{\mathrm{had}}}(b)$$



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

UPC cross sections as a function of W

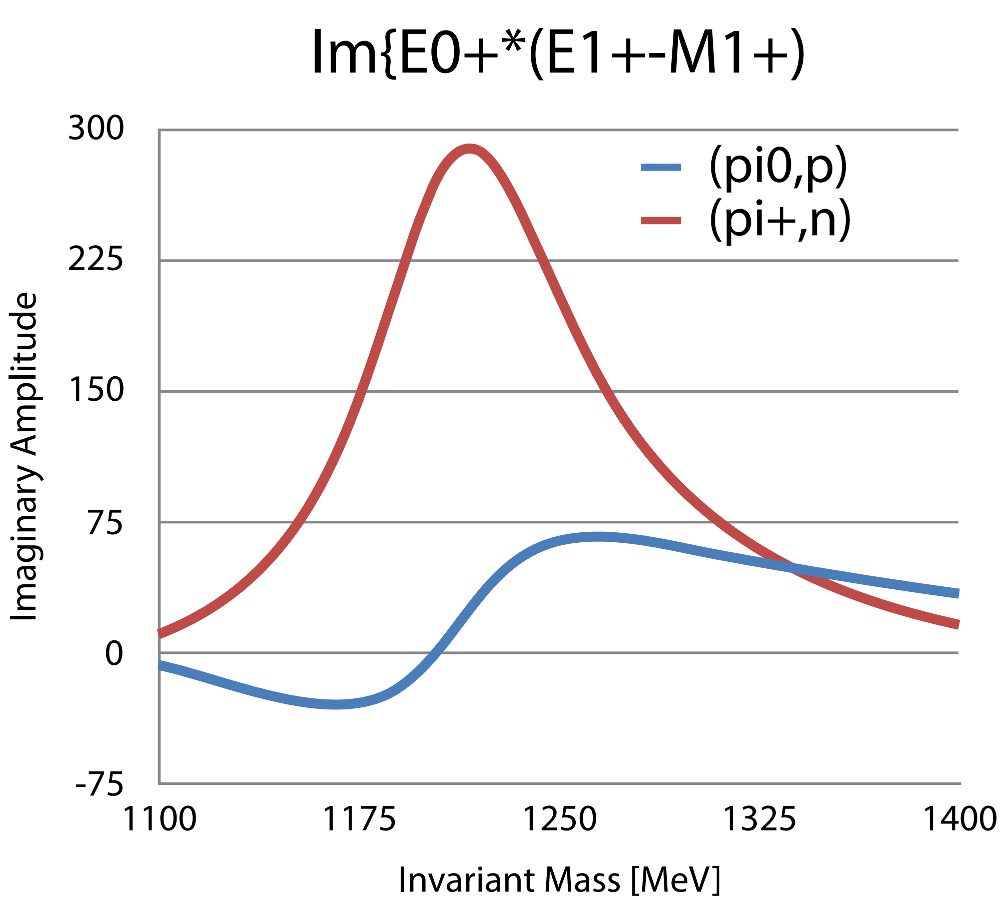
$$\frac{d\sigma^4_{\mathrm{UPC}(p^\uparrow \mathrm{A}\to\pi^+ n)}}{dW\,db^2\,d\Omega_n} = \frac{d^3 N_{\gamma^*}}{dW\,db^2}\,\frac{d\sigma_{\gamma^* p^\uparrow\to\pi^+ n}(W)}{d\Omega_n}\,\overline{P_{\mathrm{had}}}(b)$$

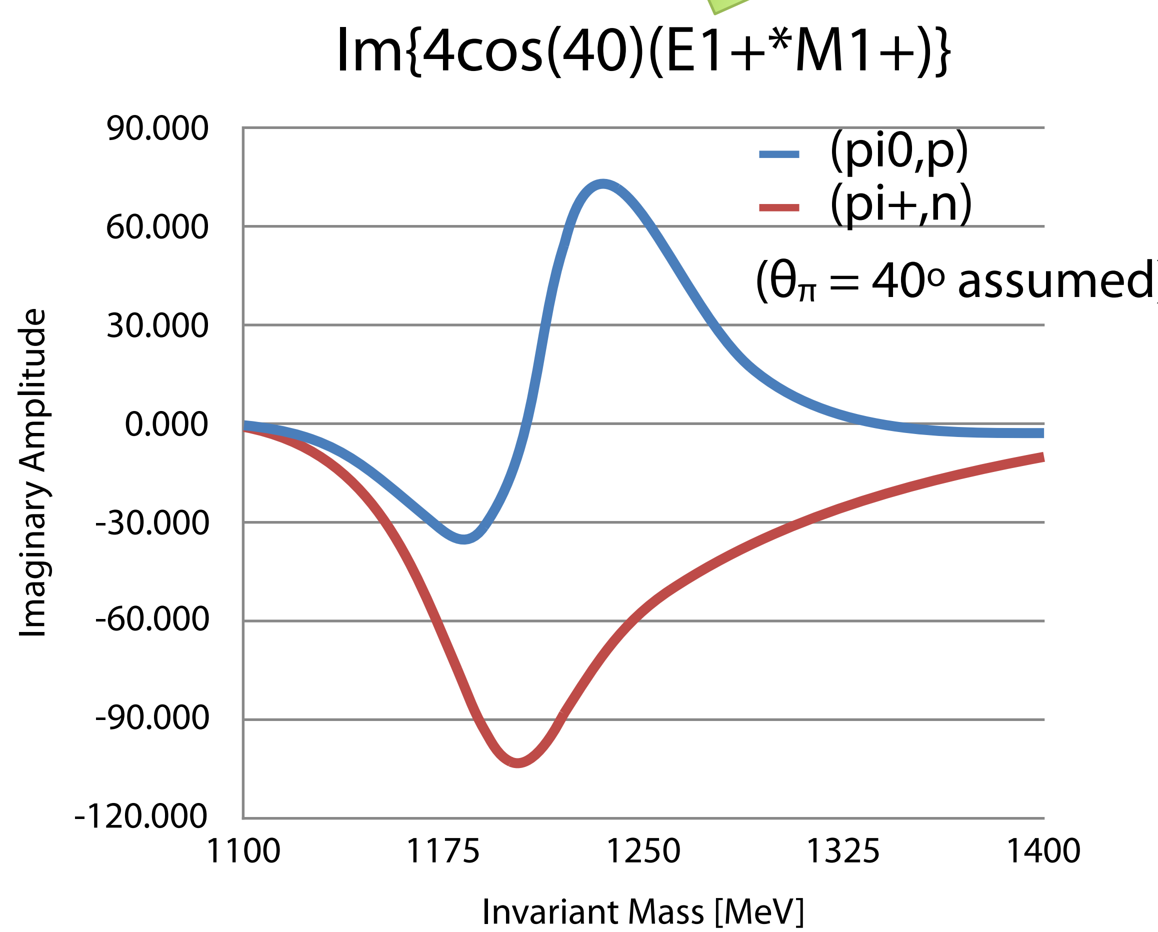


Origin of asymmetries in UPCs

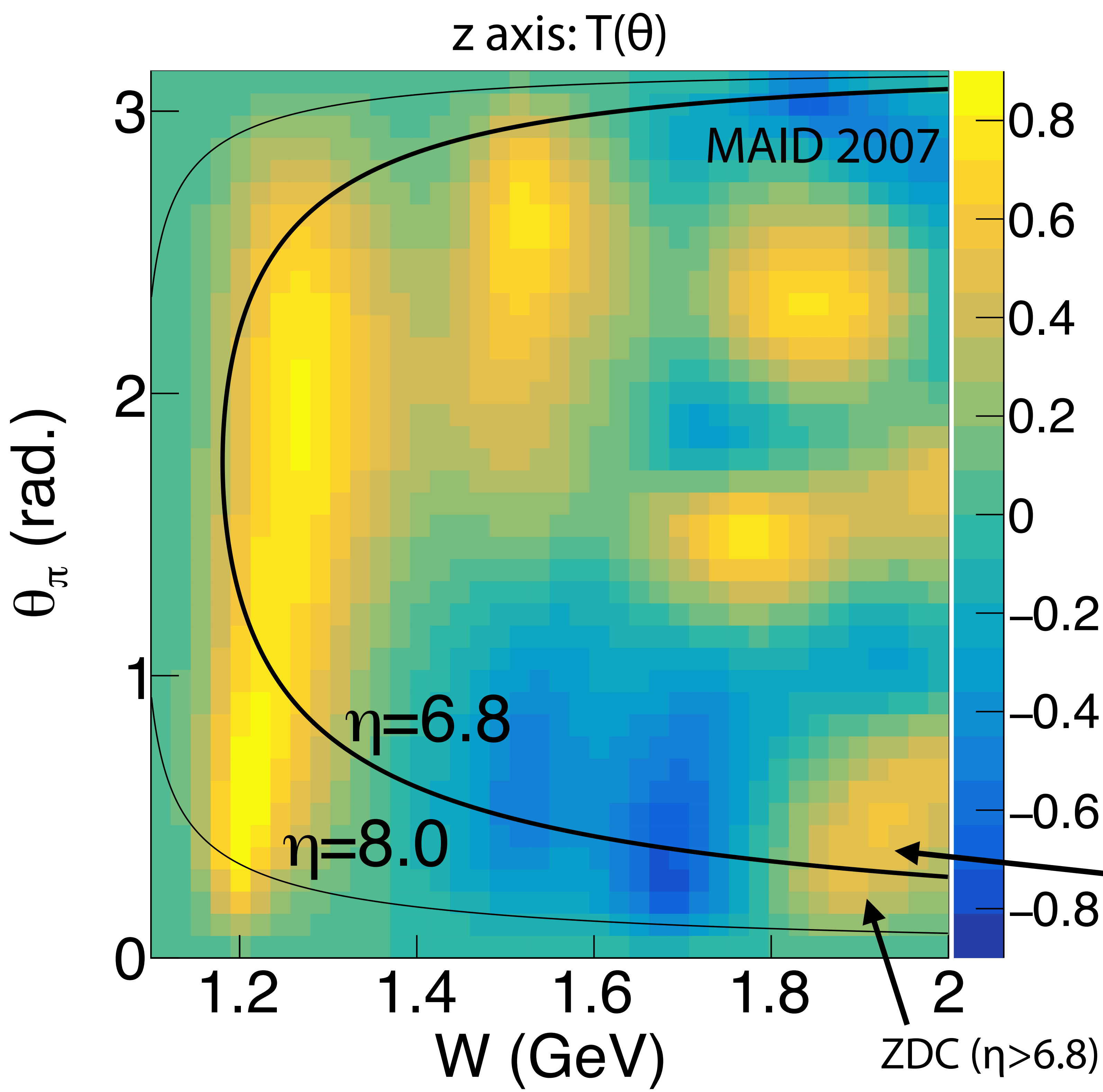
(courtesy of I. Nakagawa)

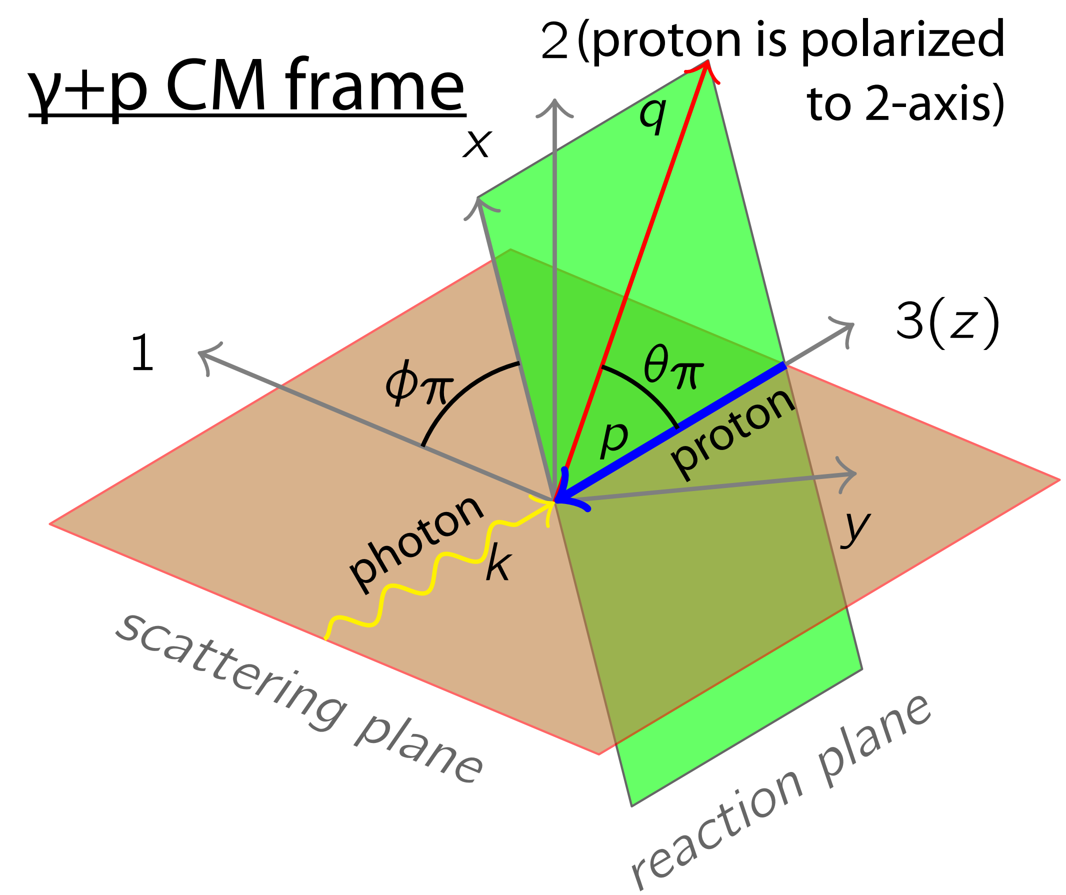
$$A_N^{\mathrm{UPC}} \sim T(\theta_\pi) \equiv \frac{R_T^{0y}}{R_T^{00}} \propto \mathrm{Im}\{\underbrace{E_{0+}^*(E_{1+} - M_{1+})} - \underbrace{4\cos\theta_\pi(E_{1+}^* M_{1+})}...\}$$

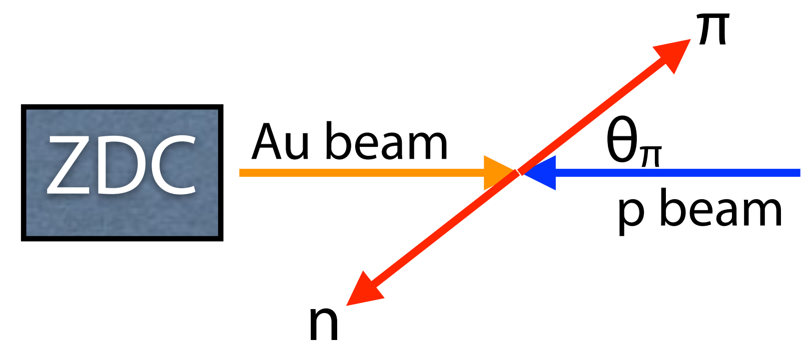




Target asymmetry T(θ) as a function of W



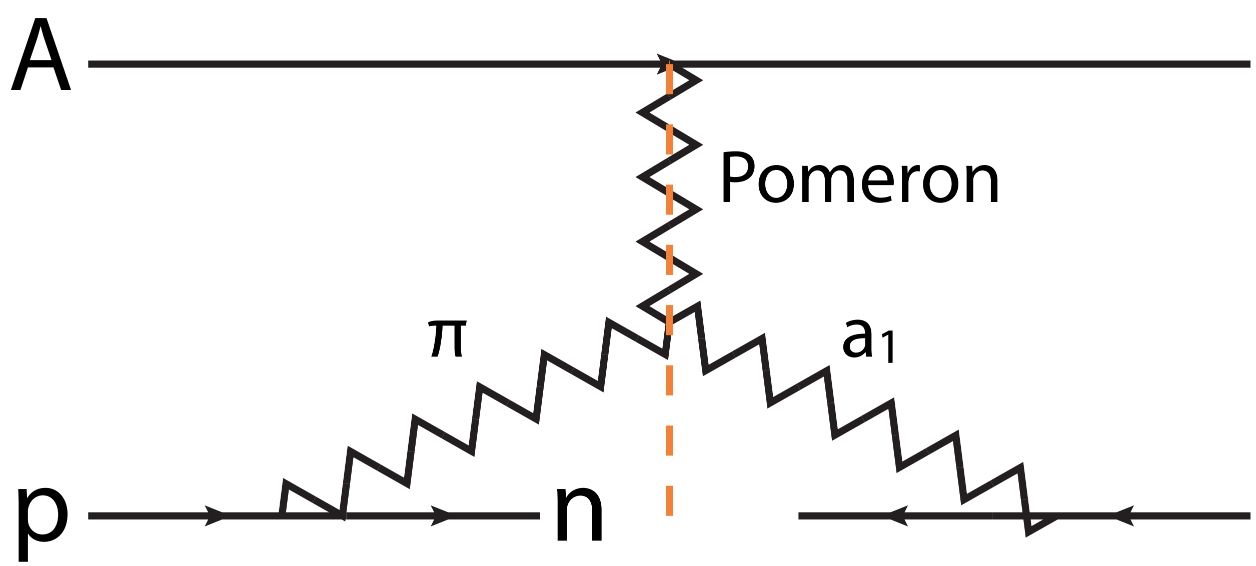




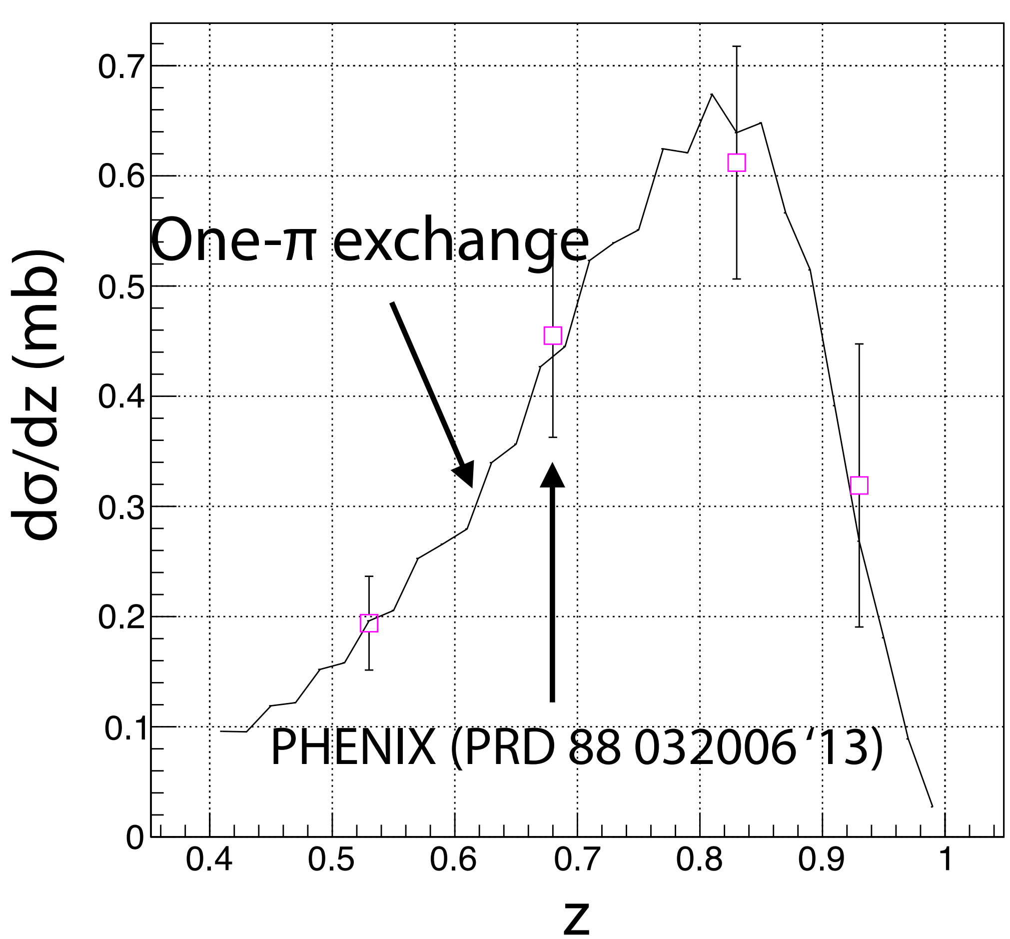
Neutrons emitted at θ_π ($\equiv \theta_n - \pi$) ~ $\pi/2$ have sizable p_T, thus they have larger rapidities.

ZDC (η>6.8) can detect neutrons in this region.

Hadronic interactions (one-π exchange)



- I follow Kopeliovich's idea (π/a_1 interference) for hadronic interactions.
- Calculation of pomeron-nuclear interactions is far beyond my skill!! So, I simply multiply pp cross sections with the A-dependent factors.

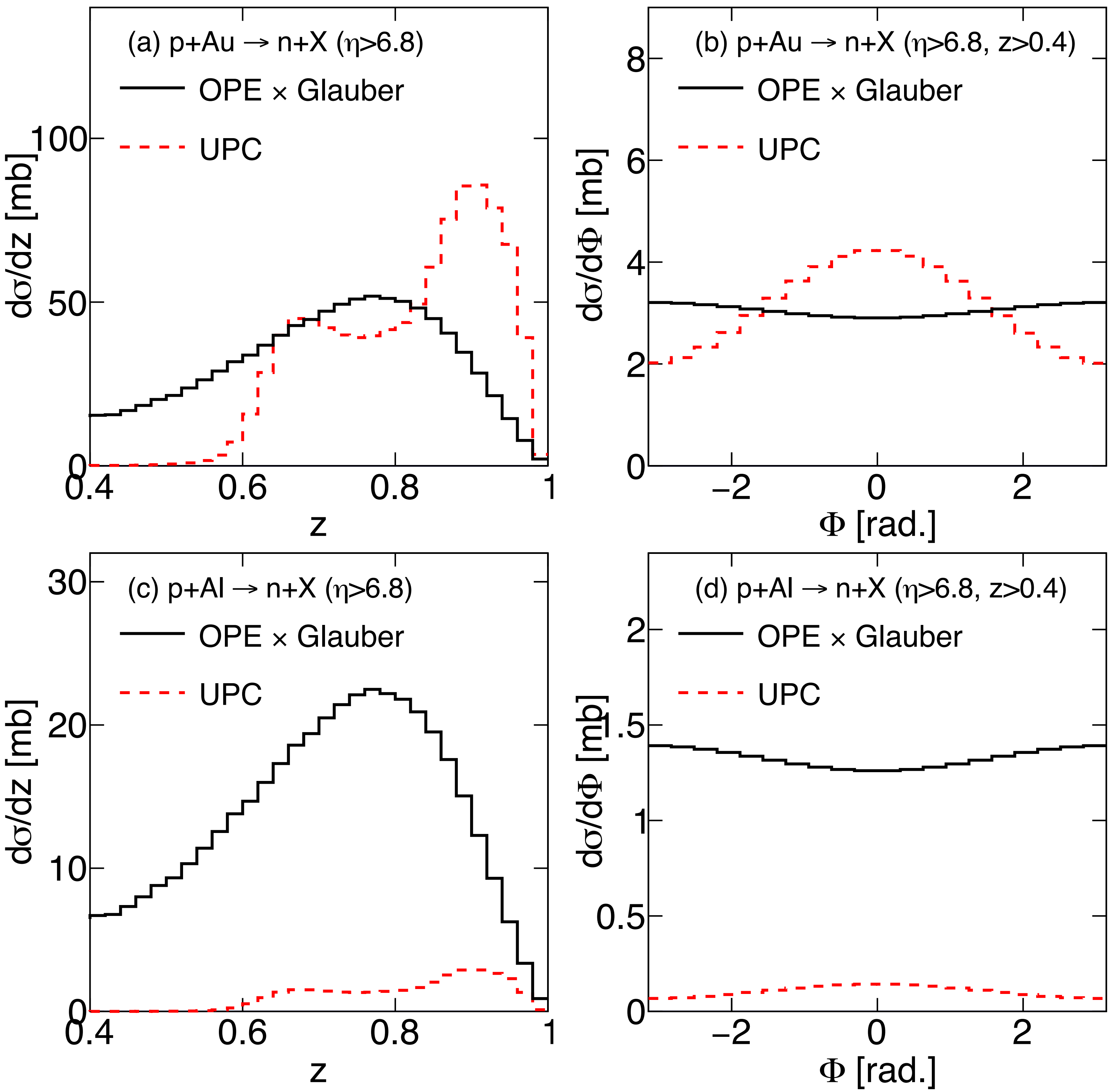


$$z\frac{d\sigma_{pp\to nX}}{dzdp_{\mathrm{T}}^2} = S^2\left(\frac{\alpha'_\pi}{8}\right)^2 |t|G^2_{\pi^+pn}(t)|\eta_\pi(t)|^2 \times (1-z)^{1-2\alpha_\pi(t)}\sigma^{\mathrm{tot}}_{\pi^++p}(M_X^2),$$

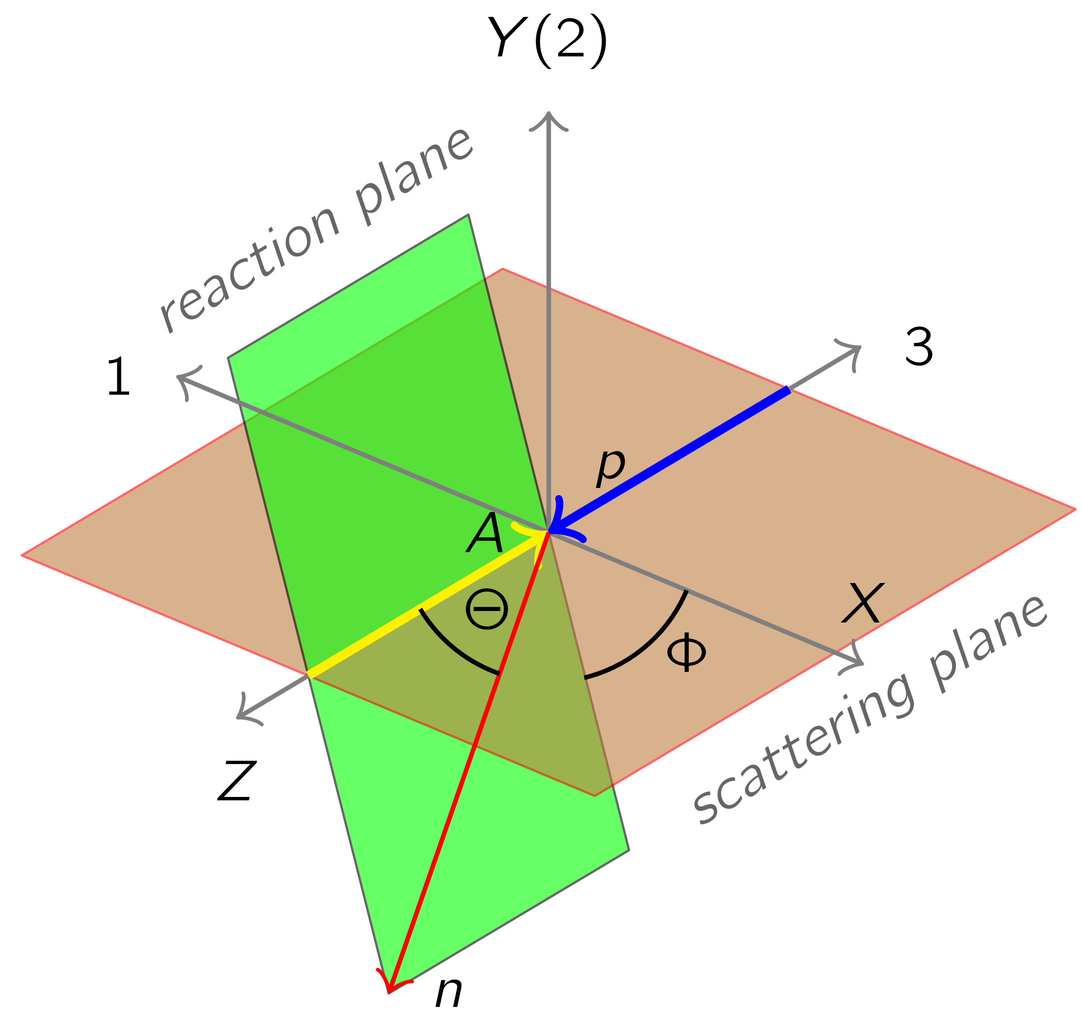
$$z\frac{d\sigma_{p^\uparrow A\to nX}}{dzdp_{\mathrm{T}}^2} = z\frac{d\sigma_{pA\to nX}}{dzdp_{\mathrm{T}}^2}(1+\cos\Phi A_{\mathrm{N}}^{\mathrm{HAD}(pA)})$$

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

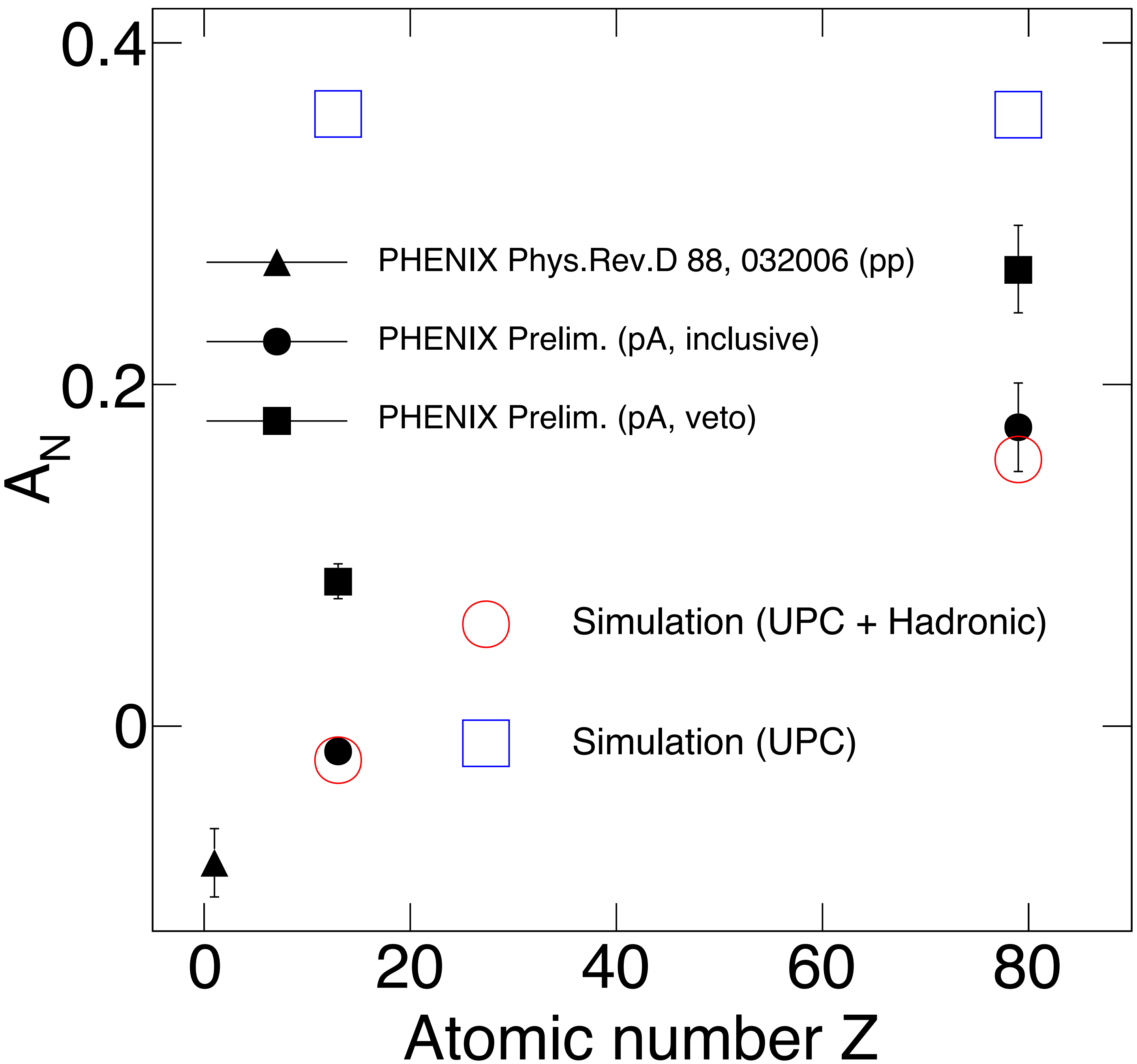
UPCs and OPE at the ZDC acceptance



Detector reference frame



Neutron A_N in pA: data vs. UPC+OPE



Inclusive A_N of the MC simulations can be written as

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

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

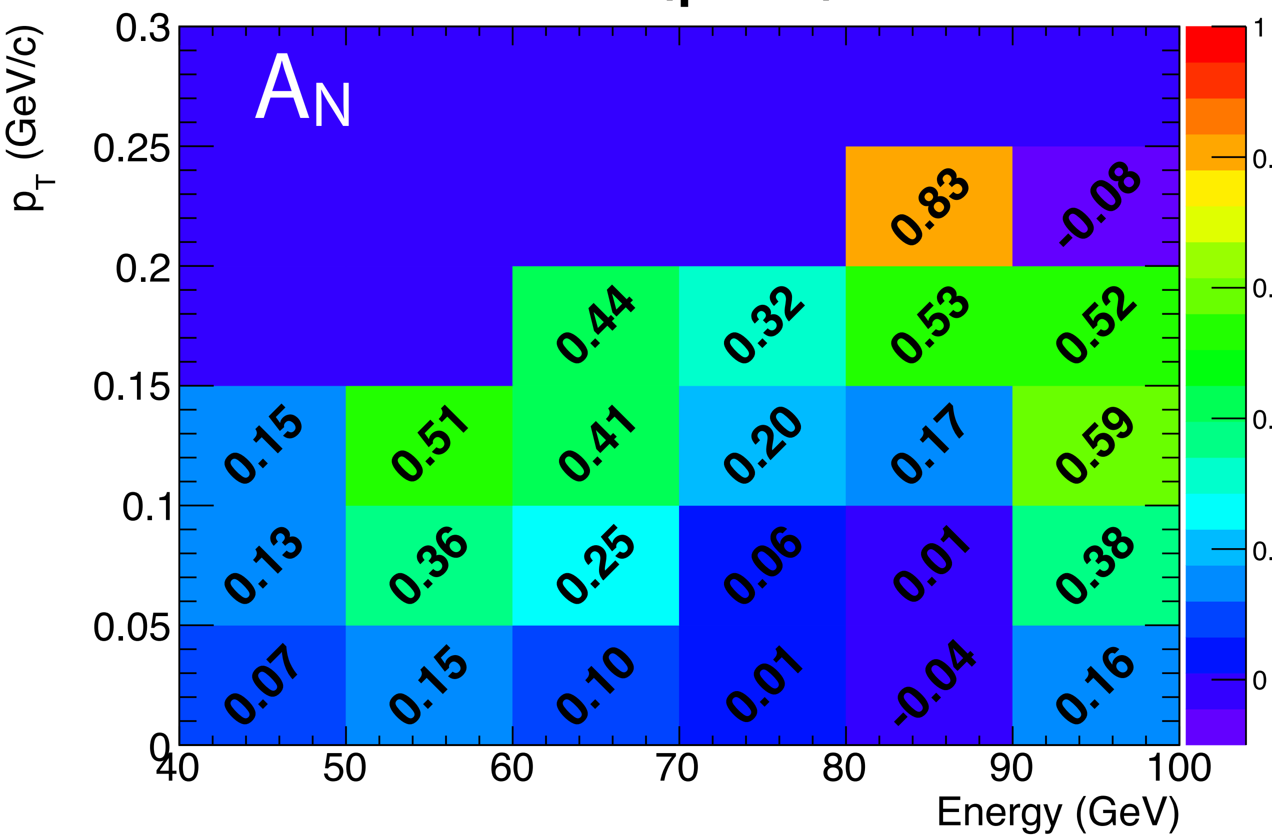
UPCs		Hadronic interactions	
$p^{\uparrow}$Al	$p^{\uparrow}$Au	$p^{\uparrow}$Al	$p^{\uparrow}$Au
0.7 mb (2.2 mb)	19.6 mb (41.7 mb)	8.3 mb	19.2 mb

Summary of asymmetries in pA

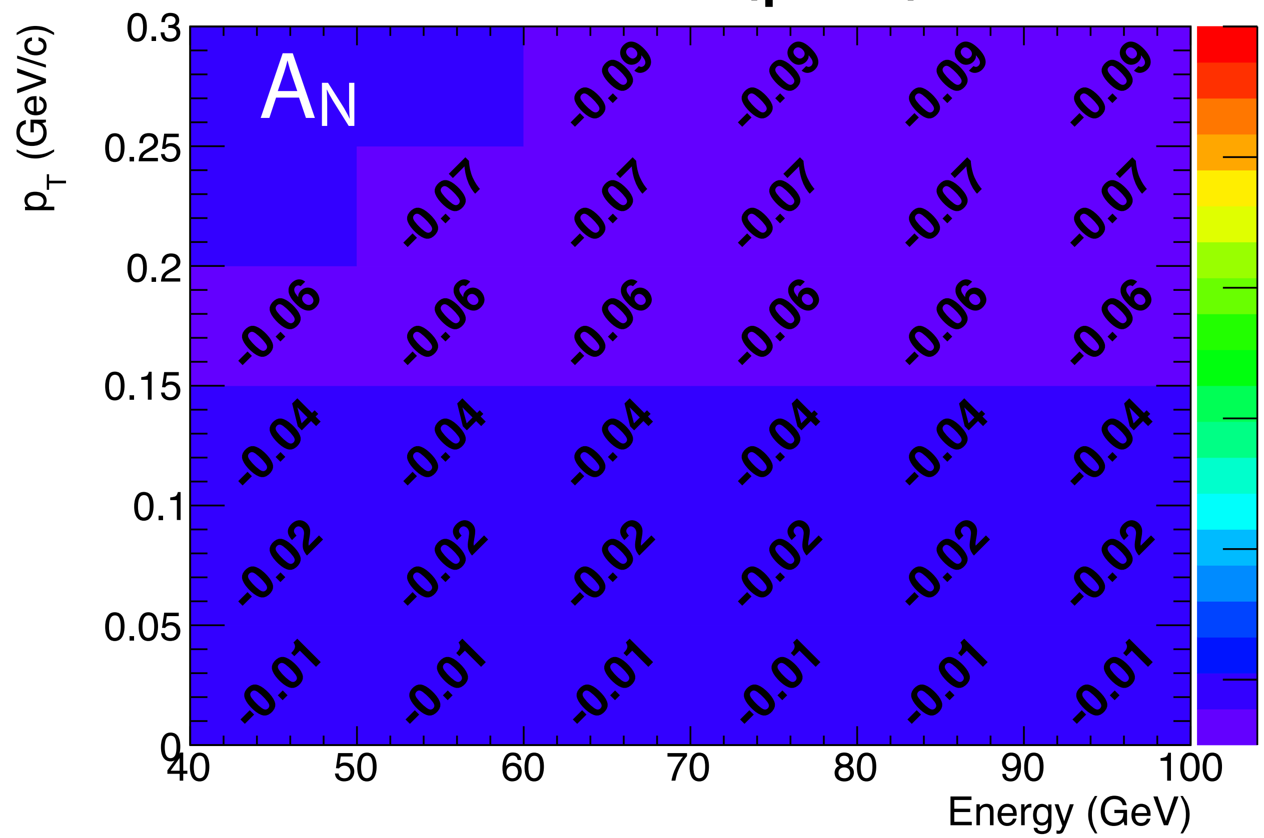
- UPCs and hadronic interactions explain the PHENIX-ZDC data.
  - γp interactions produce large π^0 asymmetries.
  - Photon flux depending on Z^2 enhances asymmetries for heavy nuclei.
  - π-a_1 interference well reproduced the asymmetries in pp.

- x_F and p_T dependent analysis is ongoing at PHENIX.

UPC (pAu)



OPE (pAu)



Comments on π^0 asymmetries in pA

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Measurement of the Analyzing Power in the Primakoff Process with a High-Energy Polarized Proton Beam

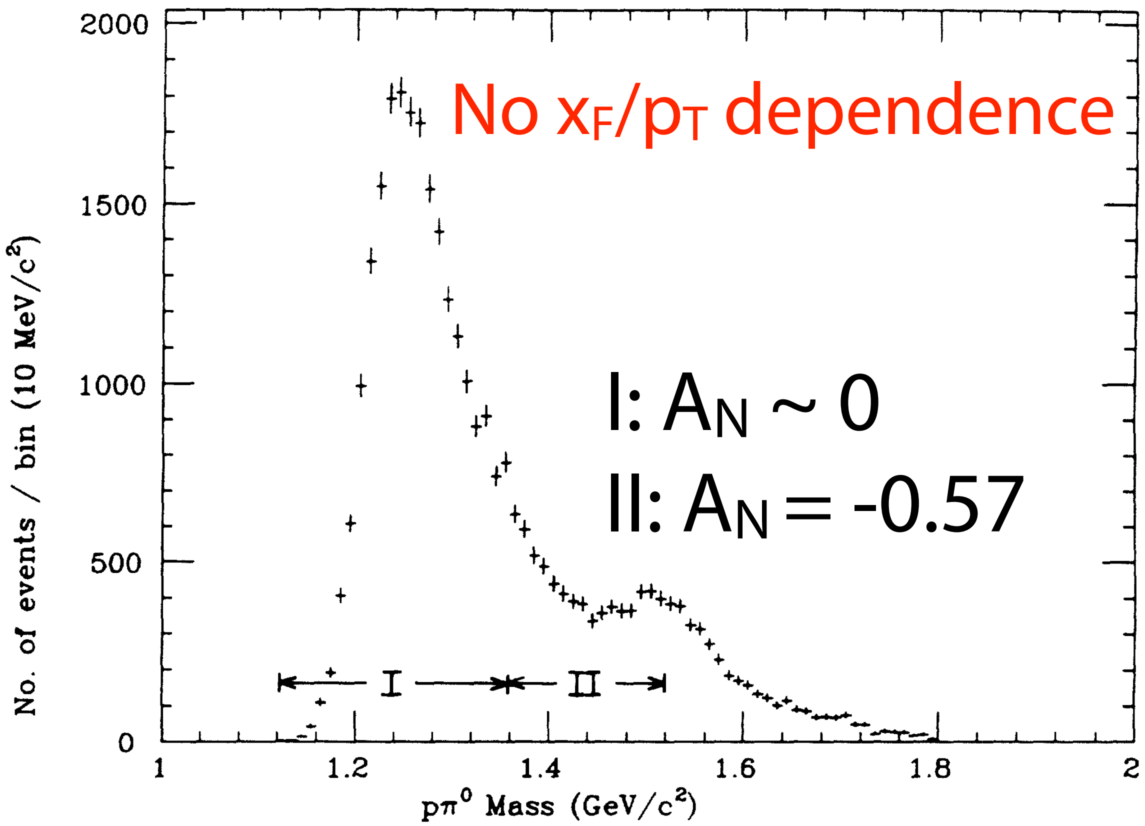
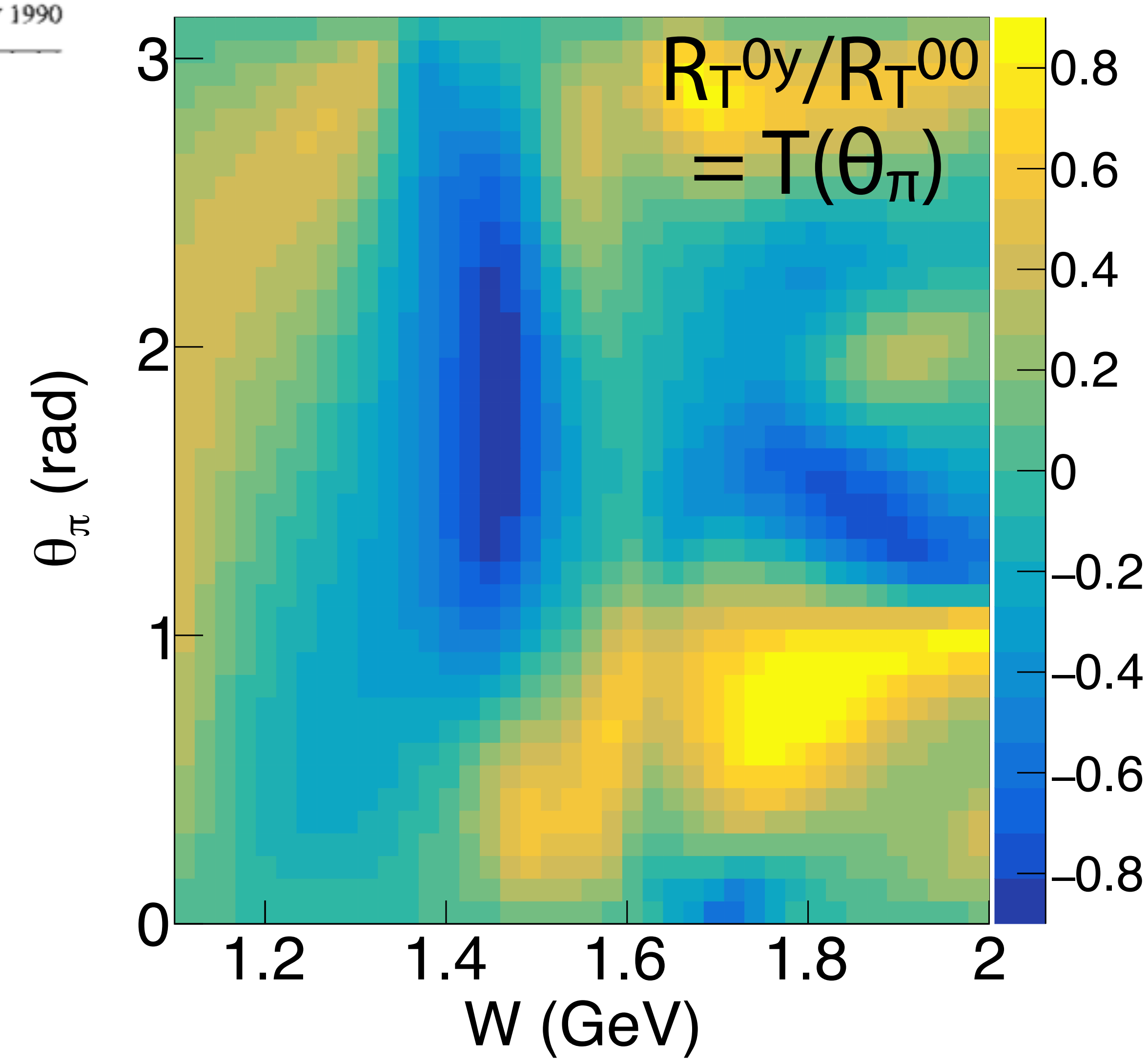


FIG. 2. The invariant-mass spectrum of the π^0-p system in $p+\mathrm{Pb} \to \pi^0+p+\mathrm{Pb}$ for $|t'| < 1\times10^{-3}$ $(\mathrm{GeV}/c)^2$. Peaks due to the $\Delta^+(1232)$ and $N^*(1520)$ resonances are shown. Regions I and II are defined in the text.



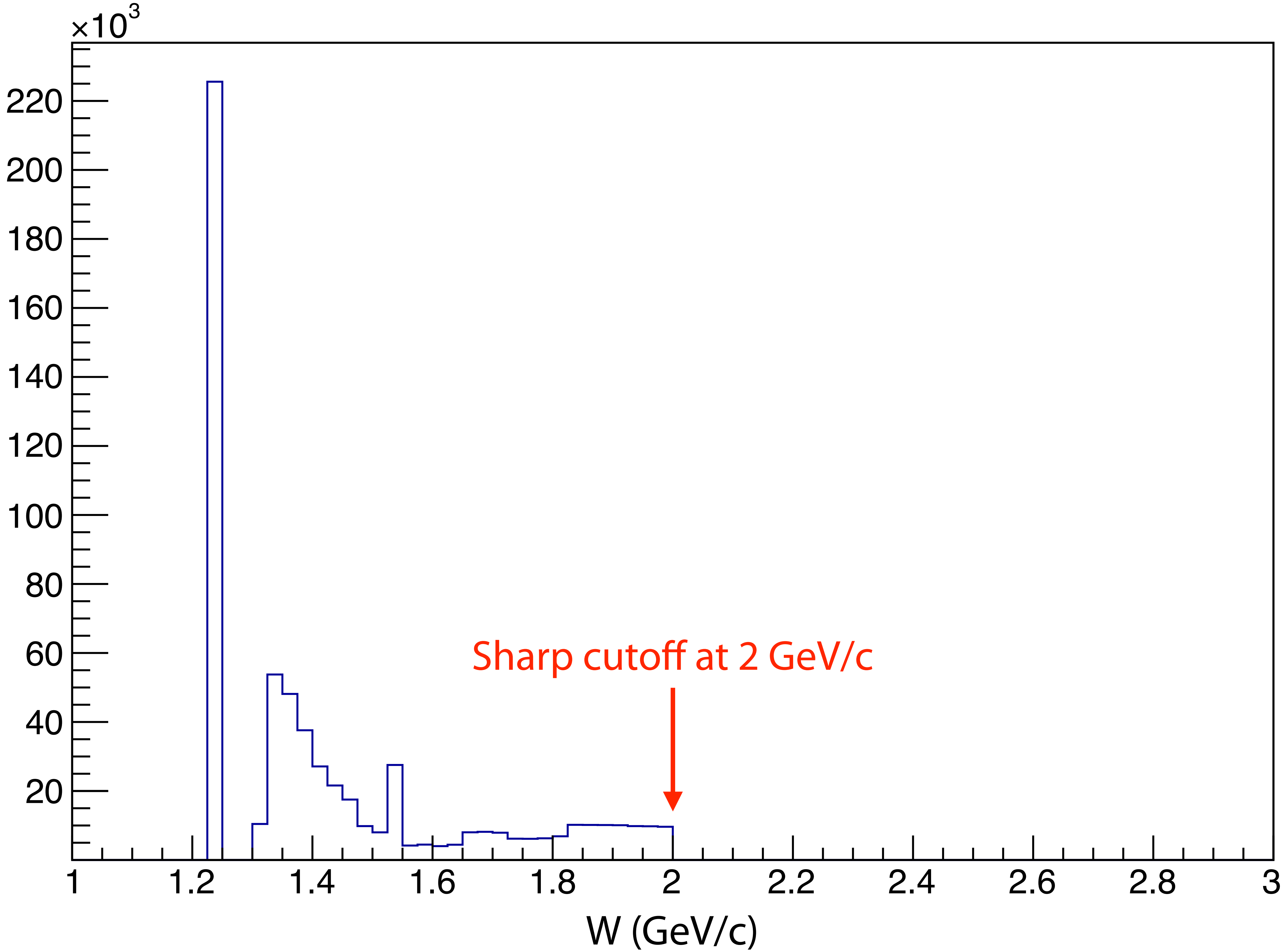
- x_F and p_T dependent π^0 asymmetries in pAl and pAu provide crucial data to disentangle not only single spin but also particle production mechanisms.
  - π/a_1+UPCs or πN+UPCs or $\pi/a_1+\pi$N+UPCs?

A good motivation of the RHICf (hopefully with Si) at sPHENIX

Thank you for attention and invitation!!

Backup

Invariant mass of $\pi^0 p$ of EPOS LHC



Photopion production formalism

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

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

where

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

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

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

where

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

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

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

$$\delta = \mathrm{Im}\{\mathcal{F}_1^*\mathcal{F}_3 - \mathcal{F}_2^*\mathcal{F}_4\} + \cos\theta\,\mathrm{Im}\{\mathcal{F}_1^*\mathcal{F}_4 - \mathcal{F}_2^*\mathcal{F}_3\} - \sin^2\theta\,\mathrm{Im}(\mathcal{F}_3^*\mathcal{F}_4) . \qquad \text{(A.11)}$$

Polarized nucleon, unpolarized photon

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

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

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:

Several models provide their predicted multipoles. I use MAID 2007 available at https://maid.kph.uni-mainz.de.

$$\begin{aligned} R_T = {} & |E_{0+}|^2 + \tfrac{1}{2}\,|2M_{1+} + M_{1-}|^2 + \tfrac{1}{2}\,|3E_{1+} - M_{1+} + M_{1-}|^2 \\ & + 2\cos\Theta\,\mathrm{Re}\{E_{0+}^*(3E_{1+} + M_{1+} - M_{1-})\} \\ & + \cos^2\Theta(|3E_{1+} + M_{1+} - M_{1-}|^2 - \tfrac{1}{2}\,|2M_{1+} + M_{1-}|^2 \\ & - \tfrac{1}{2}\,|3E_{1+} - M_{1+} + M_{1-}|^2) \end{aligned}$$

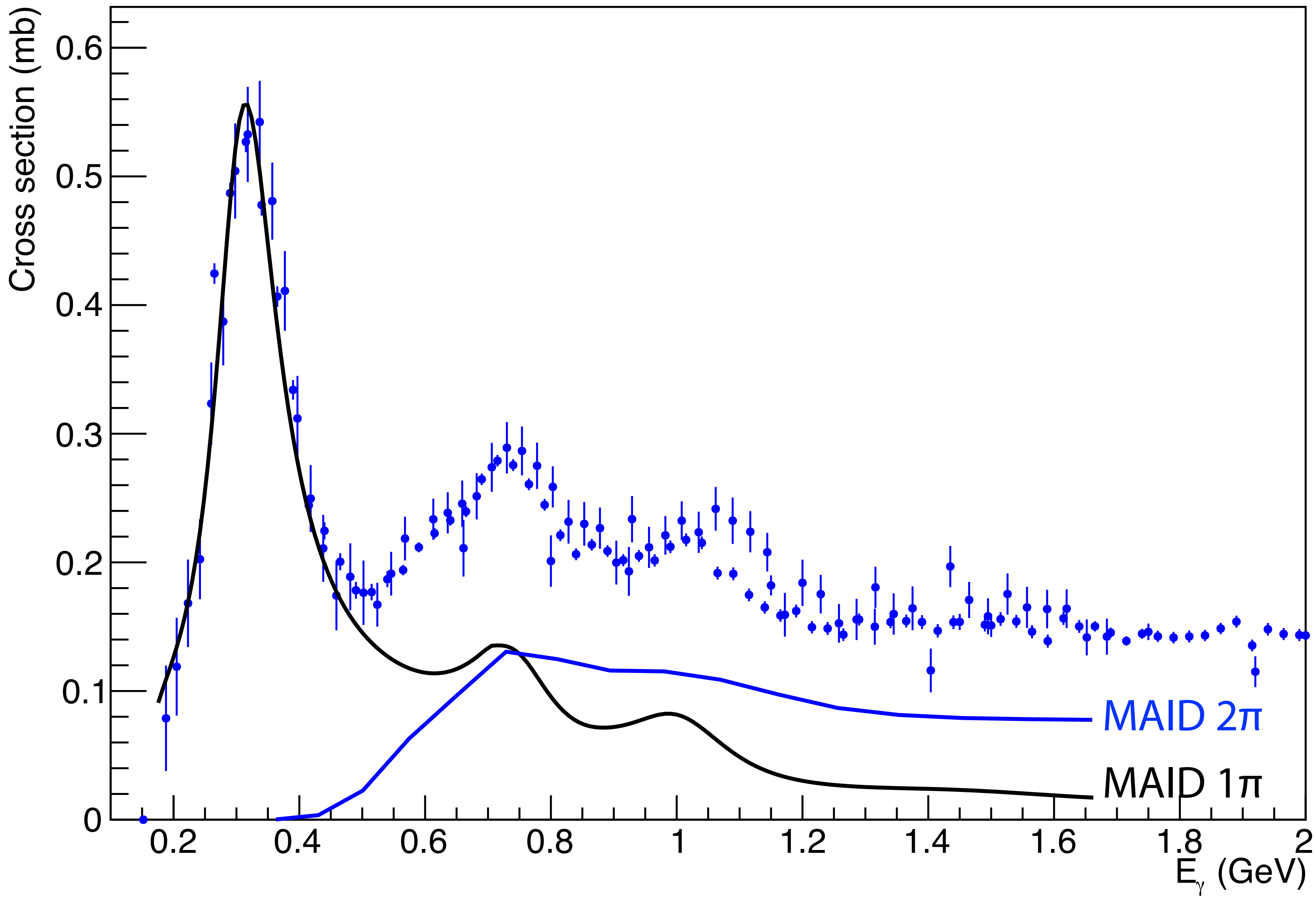
$$R_T(n_i) = 3\sin\Theta\,\mathrm{Im}\{E_{0+}^*(E_{1+} - M_{1+}) - \cos\Theta(E_{1+}^*(4M_{1+} - M_{1-}) + M_{1+}^* M_{1-})\}$$

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

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

pion and neutron production in UPCs

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?)