

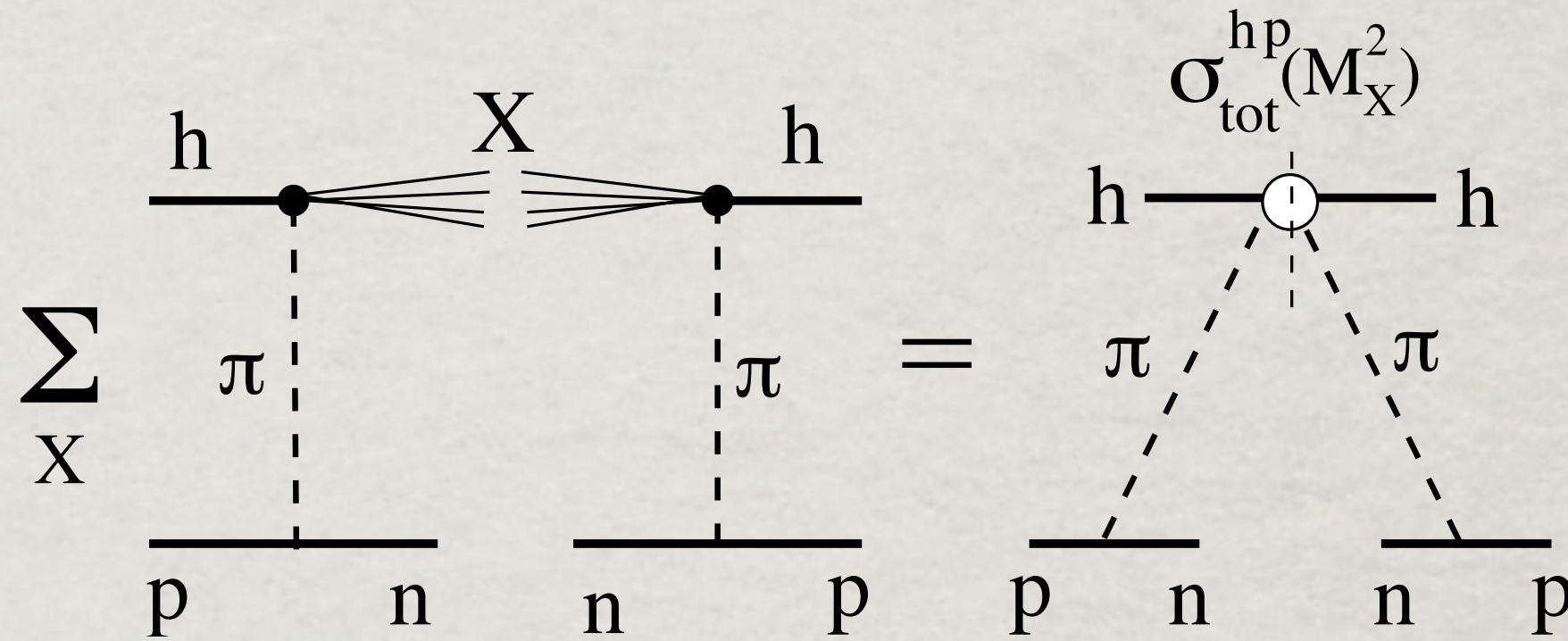
Forward neutrons from polarized pA collisions

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Neutron production in the vicinity of pion pole

$$p + p \rightarrow n + X$$

$$z = \frac{p_n^+}{p_p^+} \rightarrow 1 ; \quad M_X^2 = (1 - z)s$$



$$A_{p \rightarrow n}^B(\tilde{\mathbf{q}}, z) = \bar{\xi}_n \left[\sigma_3 \mathbf{q}_L + \frac{1}{\sqrt{z}} \tilde{\sigma} \cdot \tilde{\mathbf{q}}_T \right] \xi_p \phi^B(\mathbf{q}_T, z)$$

$$\phi^B(\mathbf{q}_T, z) = \frac{\alpha'_\pi}{8} G_{\pi+pn}(t) \eta_\pi(t) (1 - z)^{-\alpha_\pi(t)} A_{\pi+p \rightarrow X}(M_X^2)$$

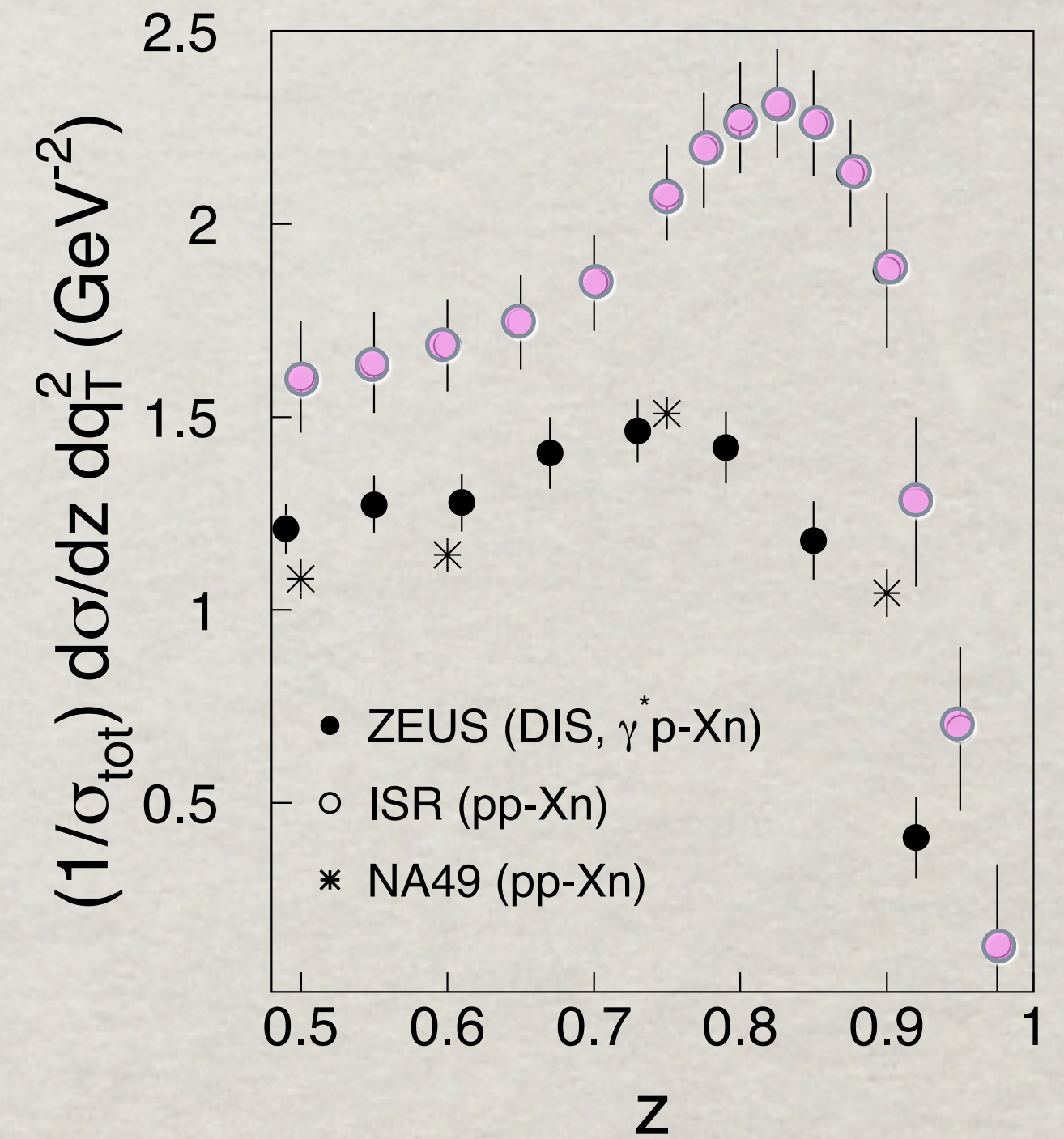
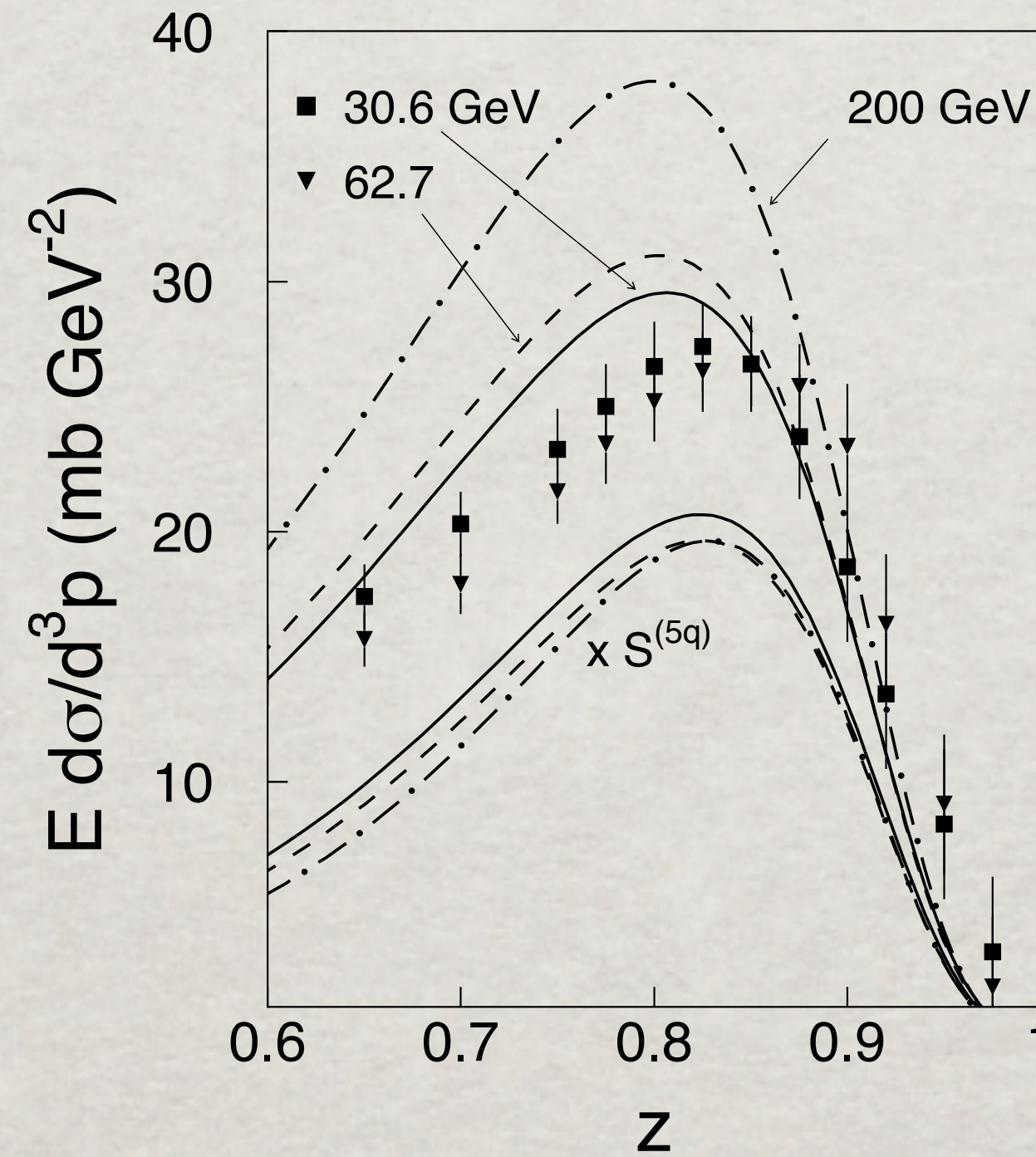
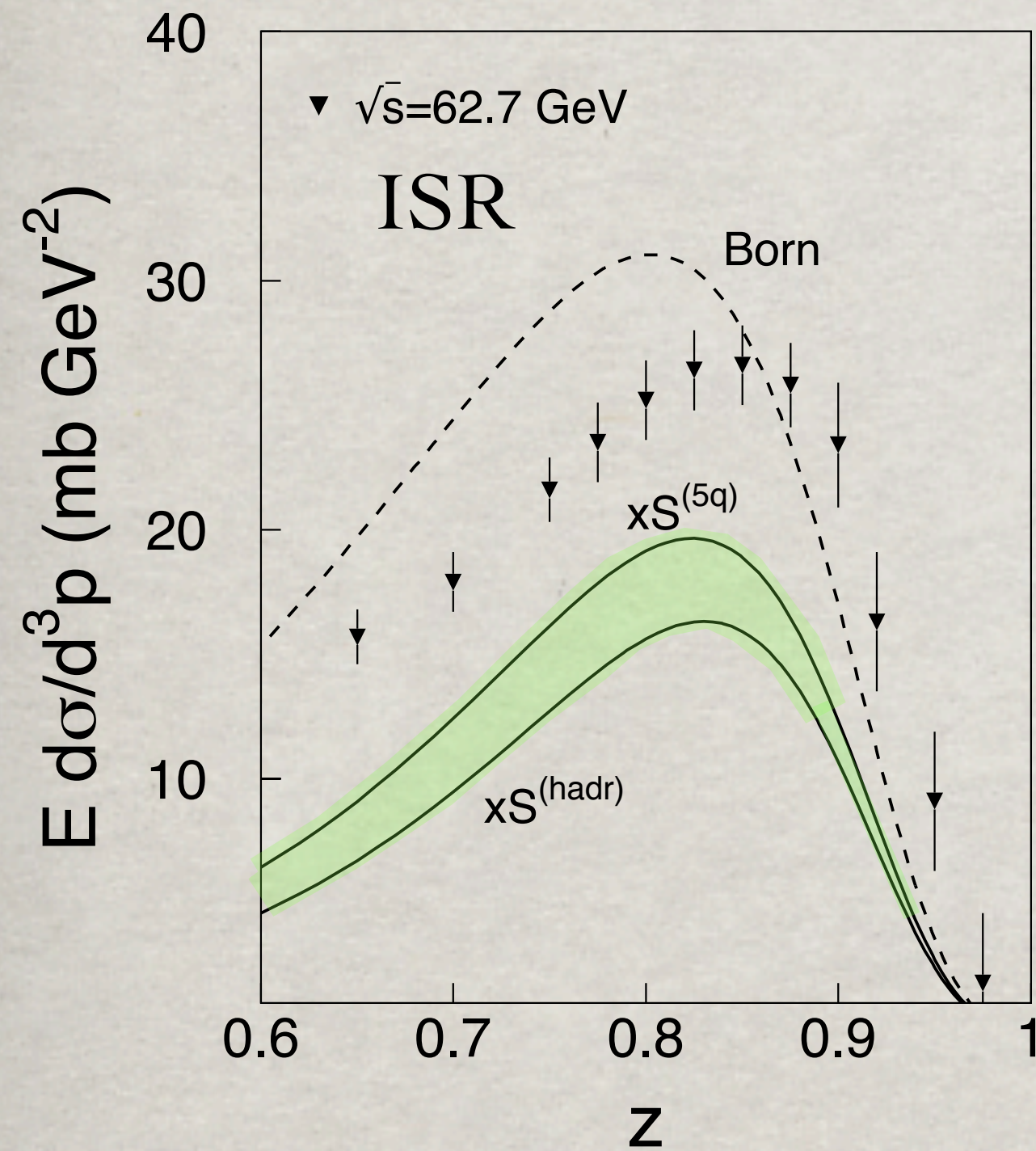
$$q_L = \frac{1 - z}{\sqrt{z}} m_N$$

$$t = -q_L^2 - q_T^2/z$$

$$z \frac{d\sigma_{p \rightarrow n}^B}{dz dq_T^2} = \frac{g_{\pi+pn}^2}{(4\pi)^2} \frac{|t| F^2(t)}{(m_\pi^2 - t)^2} (1 - z)^{1-2\alpha_\pi(t)} \sigma_{\text{tot}}^{\pi^+p}(M_X^2)$$

Results

I.Potashnikova, I.Schmidt, J.Soffer & B.K. Phys.Rev. D78 (2008)014031



Underestimated theory,
or overestimated data?

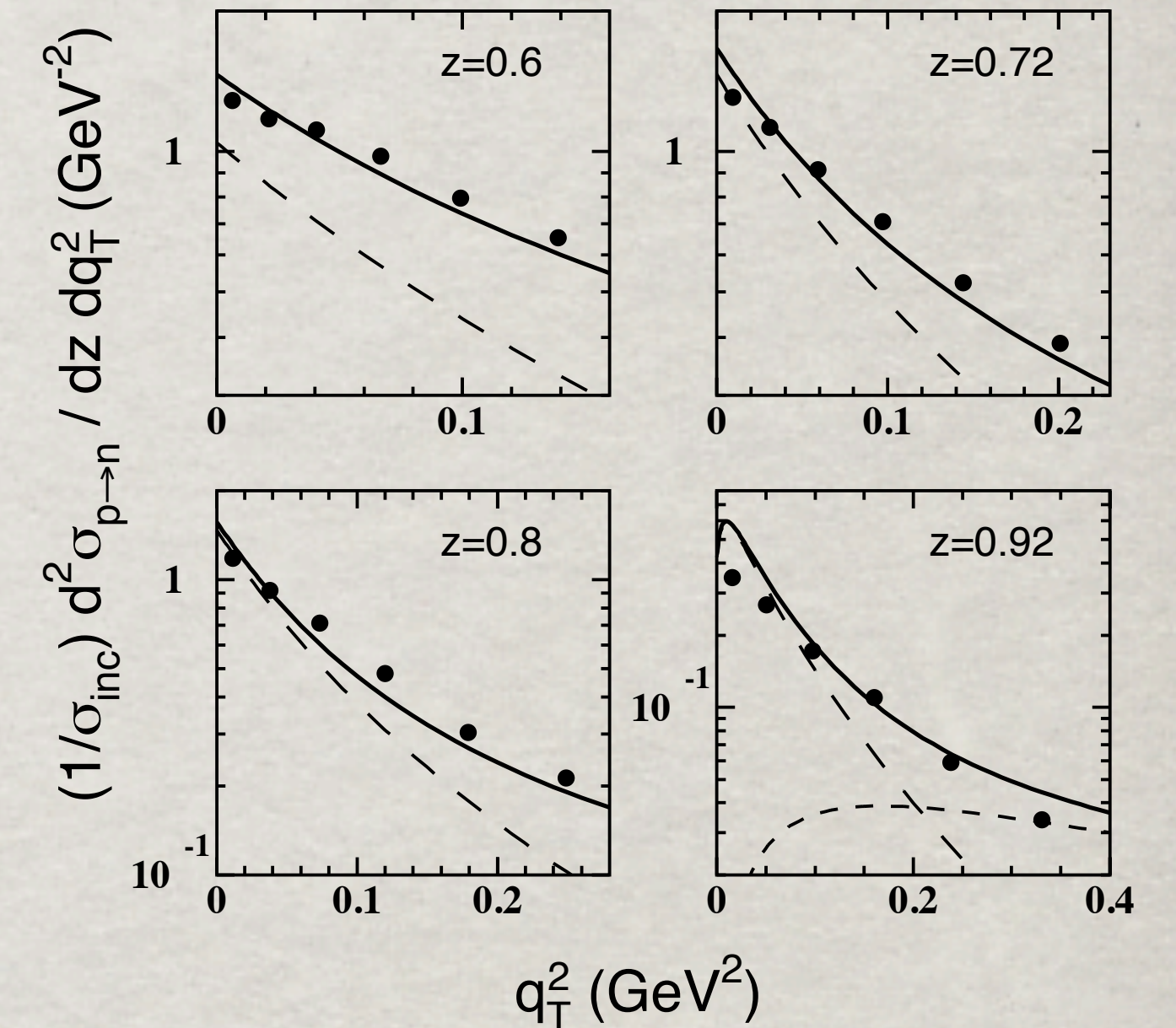
The main suspect is the
normalization of the ISR data.

Results

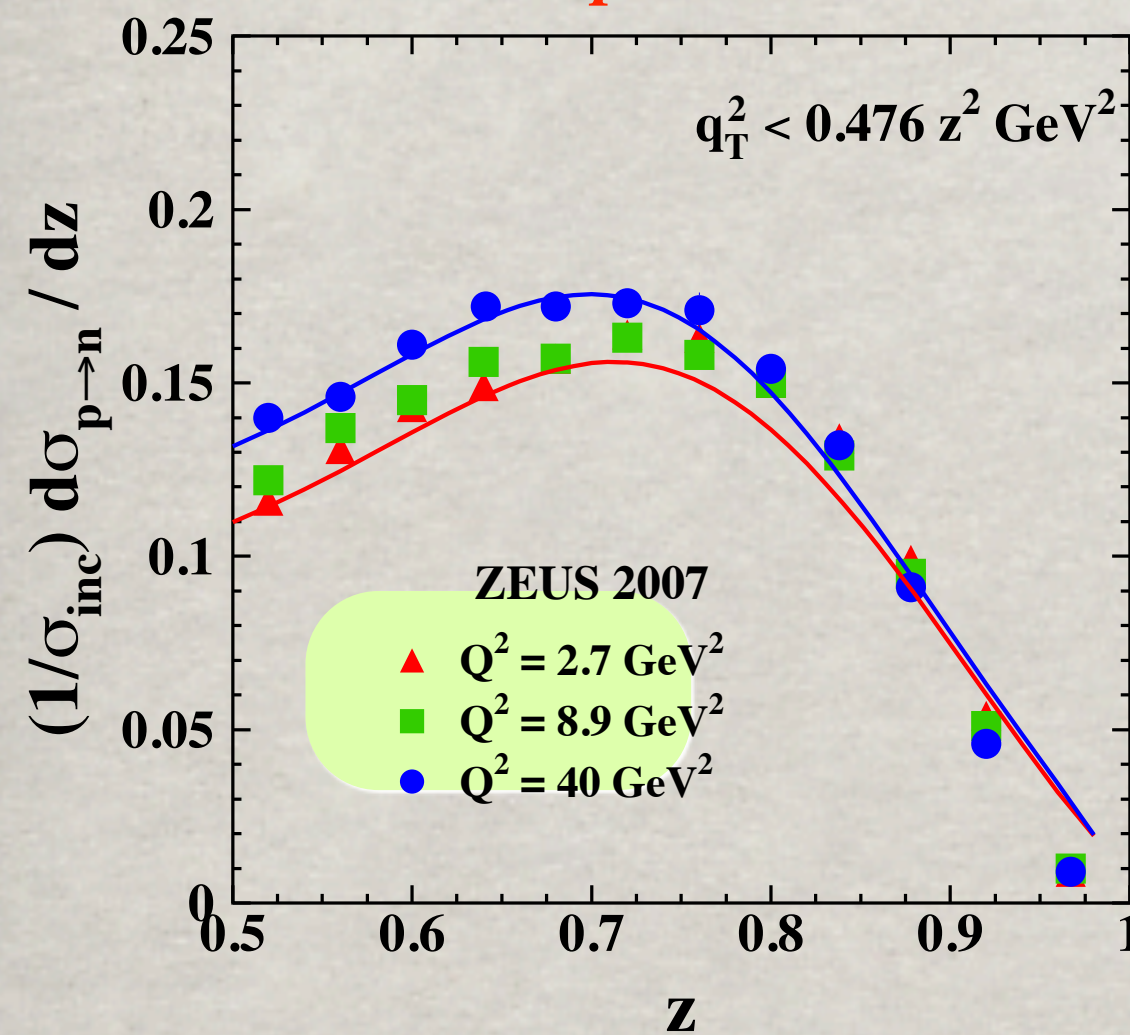
Leading neutrons from DIS on protons $\gamma^* p \rightarrow nX$ offer a unique way to measure the pion structure function at small x .

I.Potashnikova, I.Schmidt, B.Povh & B.K. Phys.Rev. D85 (2011)114025

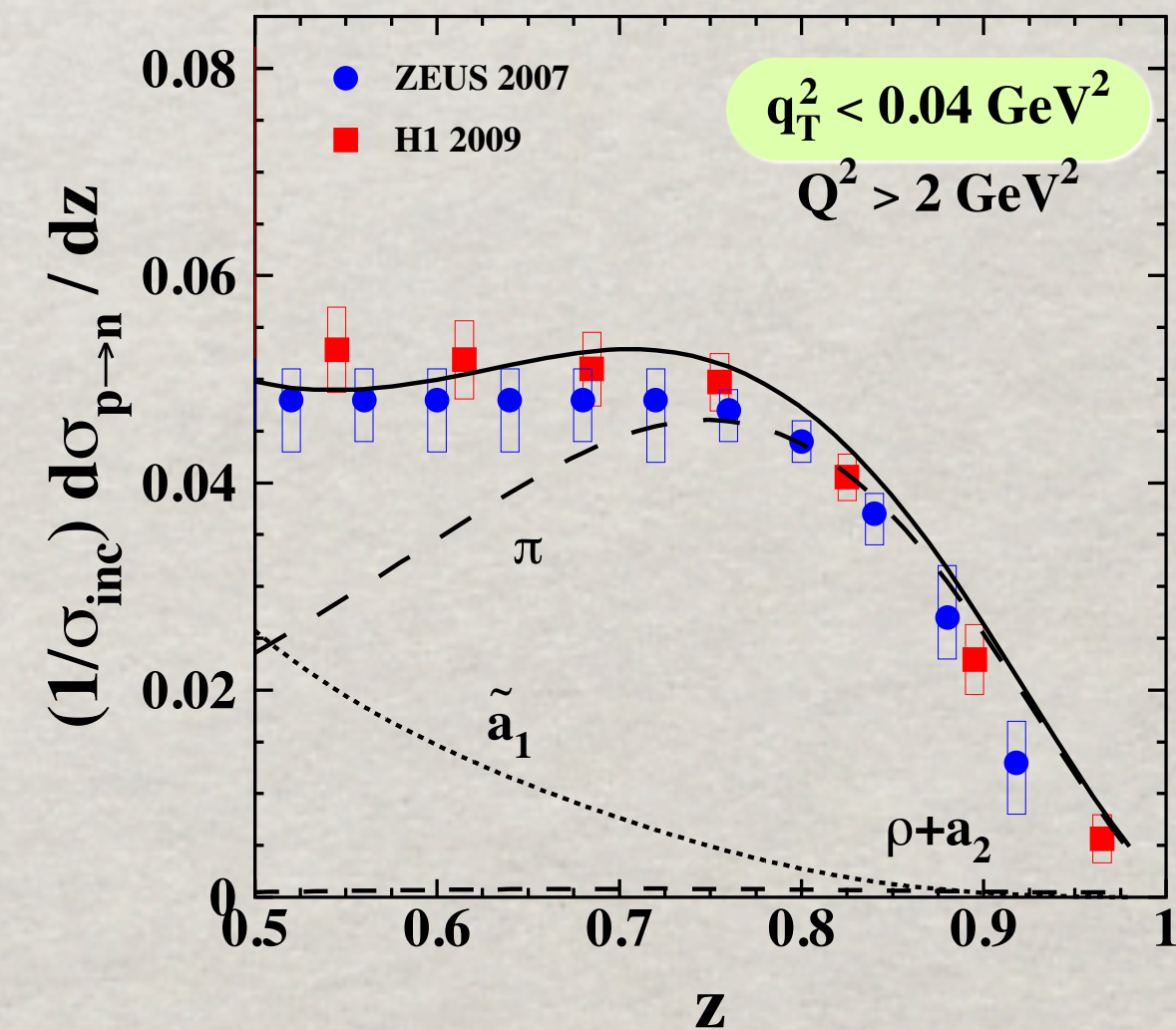
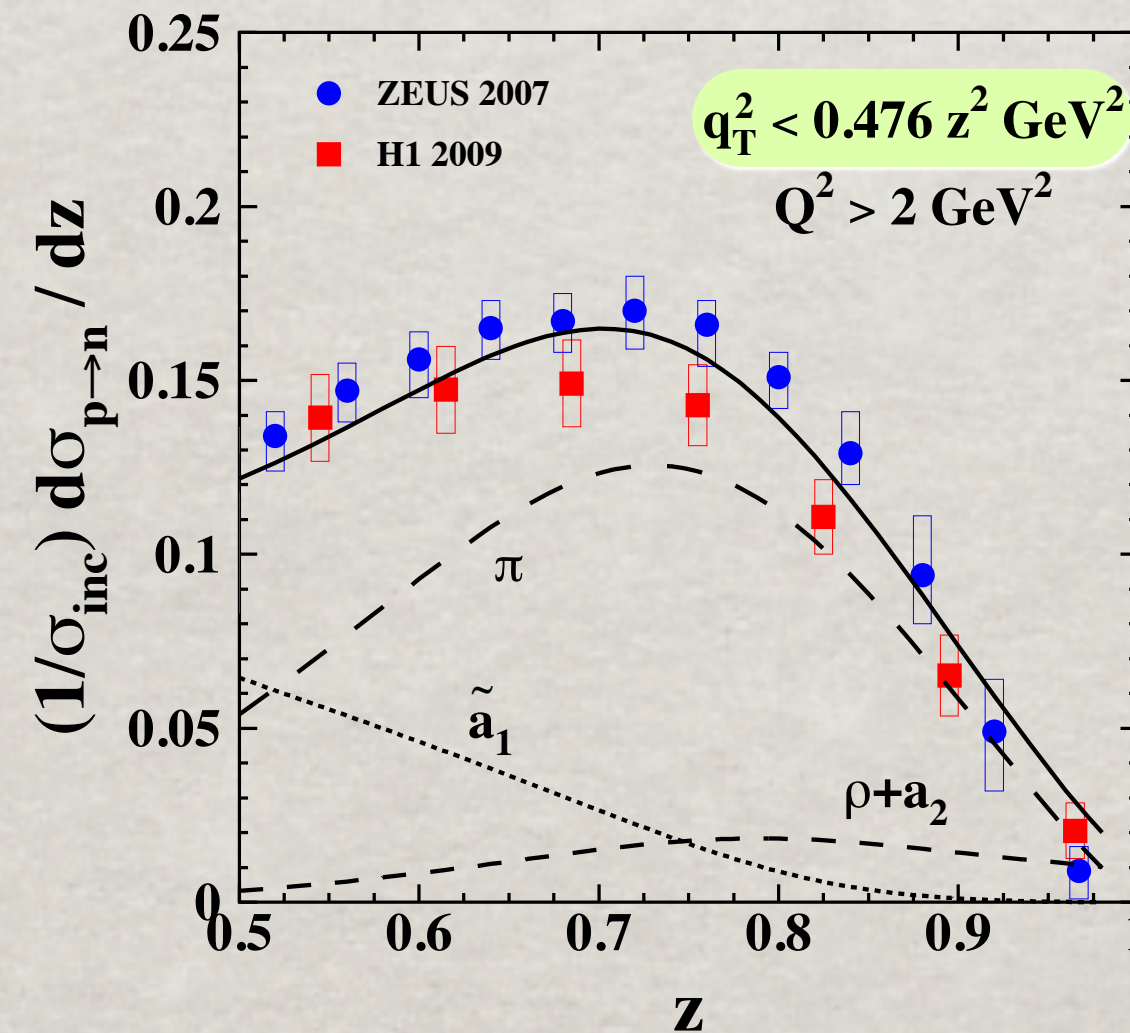
qT-dependence



Q²-dependence



z-dependence



Neutron production off nuclei

At first glance, is sufficient to replace $\sigma_{\text{tot}}^{\pi p}$ by $\sigma_{\text{tot}}^{\pi A}$

$$z \frac{d\sigma_{pA \rightarrow nX}^B}{dz dq_T^2} = \frac{g_{\pi^+ pn}^2}{(4\pi)^2} \frac{|t| F^2(t)}{(m_\pi^2 - t)^2} (1 - z)^{1-2\alpha_\pi(t)} \sigma_{\text{tot}}^{\pi A}(M_X^2)$$

However, absorption is order of magnitude stronger, compared with $pp \rightarrow nX$

$$\frac{\sigma(pA \rightarrow nX)}{A \sigma(pp \rightarrow nX)} = \frac{2}{\sigma_{\text{tot}}^{\pi p}} \int d^2b \left[1 - e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi N} T_A(b)} \right] e^{-\sigma_{\text{in}}^{\pi N} T_A(b)}$$

absorption

$$T_A(b) = \int_{-\infty}^{\infty} dz \rho_A(b, z)$$

★ If BBC are **fired** detecting multiparticle production, one should replace

$$2 \left[1 - e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi N} T_A(b)} \right] \Rightarrow 1 - e^{-\sigma_{\text{in}}^{\pi N} T_A(b)}$$

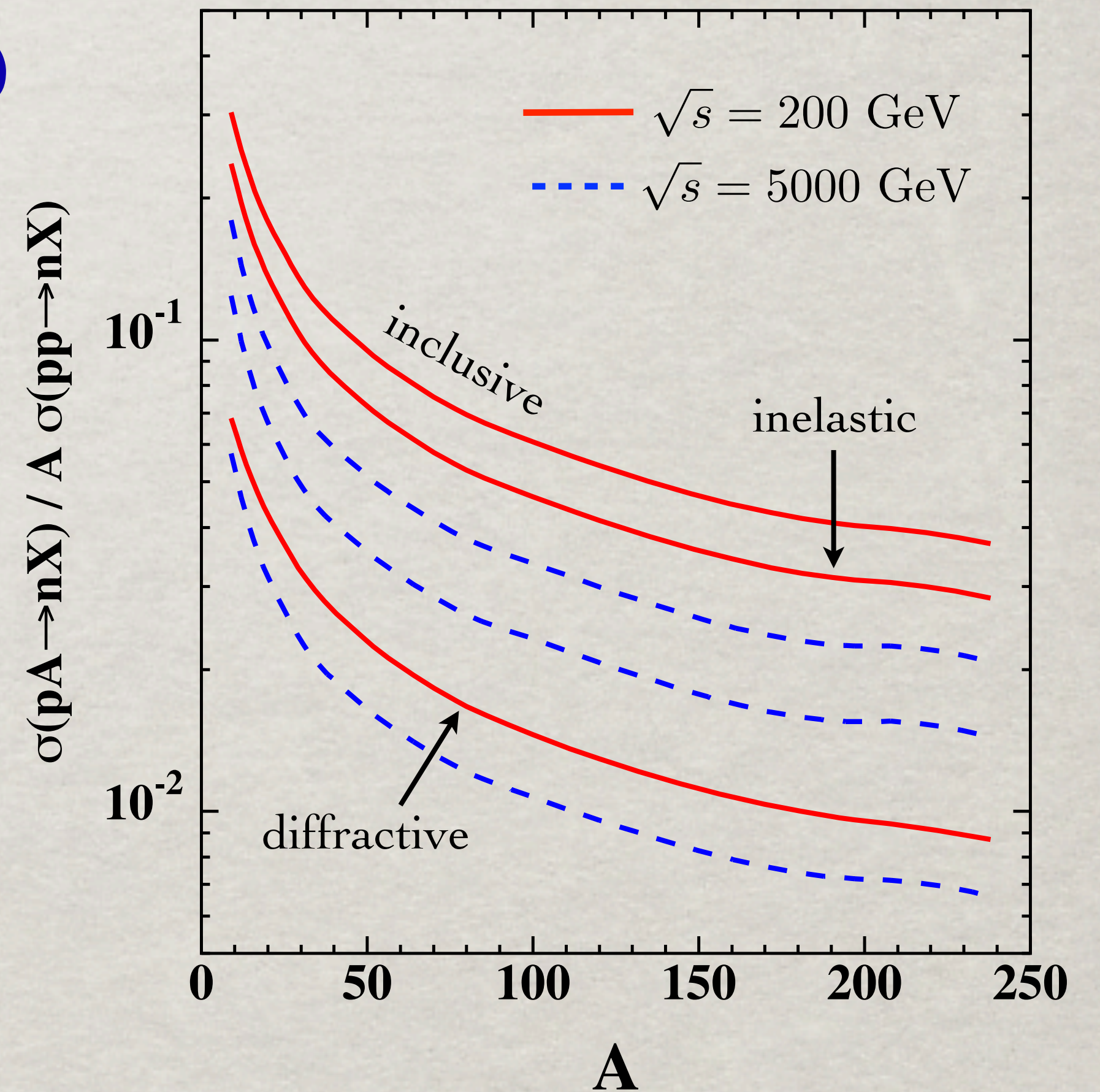
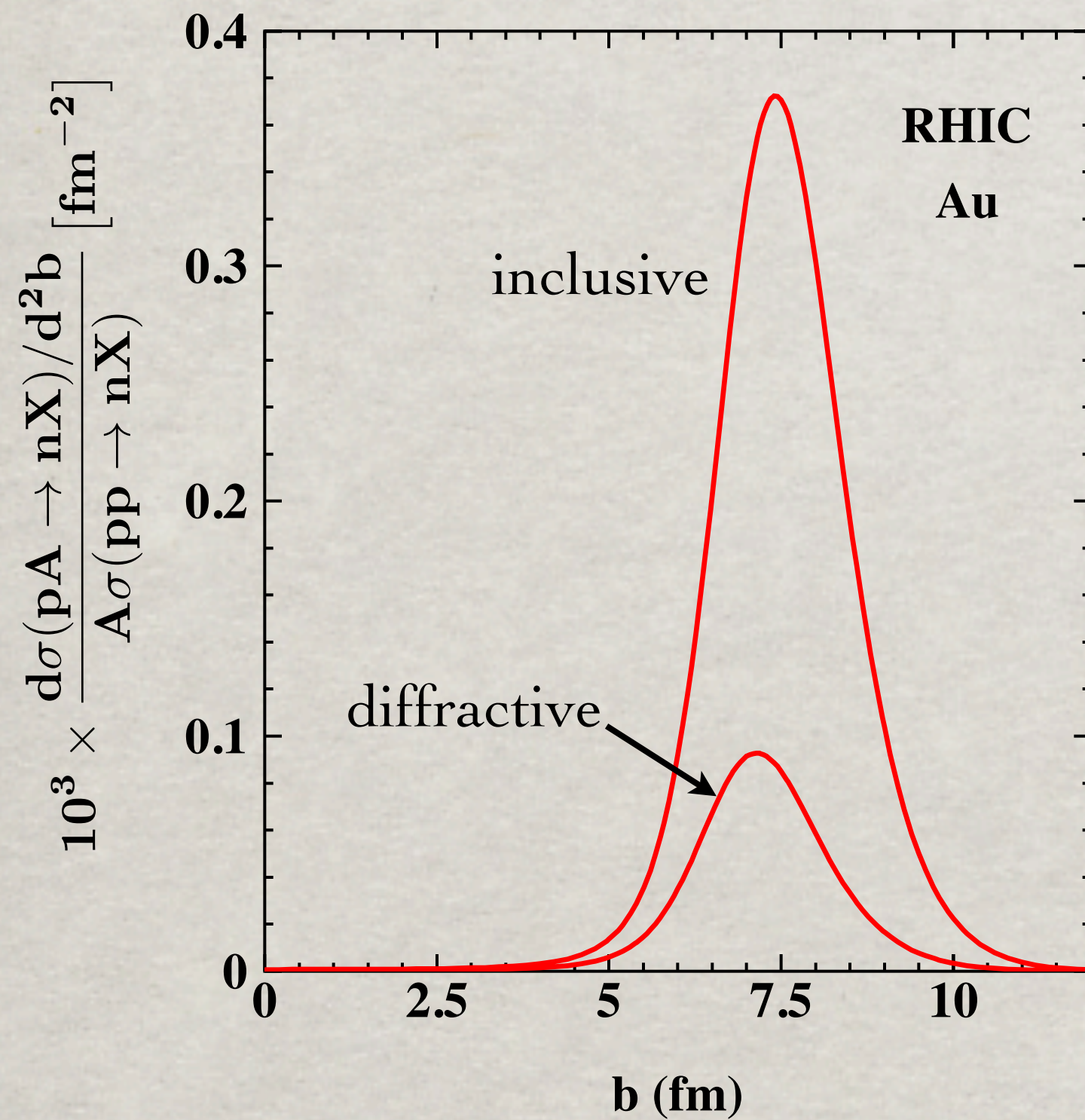
★ If BBC are **vetoed**, the diffractive channels $p + A \rightarrow n\pi^+ + A^*$ dominate, i.e. $\pi A \rightarrow X$ should be replaced by elastic and quasielastic cross sections,

$$2 \left[1 - e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi N} T_A(b)} \right] \Rightarrow \underbrace{\left[1 - e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi N} T_A(b)} \right]^2}_{\text{elastic } \pi A} + \underbrace{\sigma_{\text{el}}^{\pi N} T_A(b) e^{-\sigma_{\text{in}}^{\pi N} T_A(b)}}_{\text{quasielastic } \pi A}$$

Cross sections

Three different channels of neutron production:

- (i) inclusive neutrons;
- (ii) multi-particle production (BBC fired);
- (iii) rapidity gap diffractive events (BBC vetoed)



Single-spin asymmetry

The pion-exchange amplitude includes both non-flip and spin-flip terms

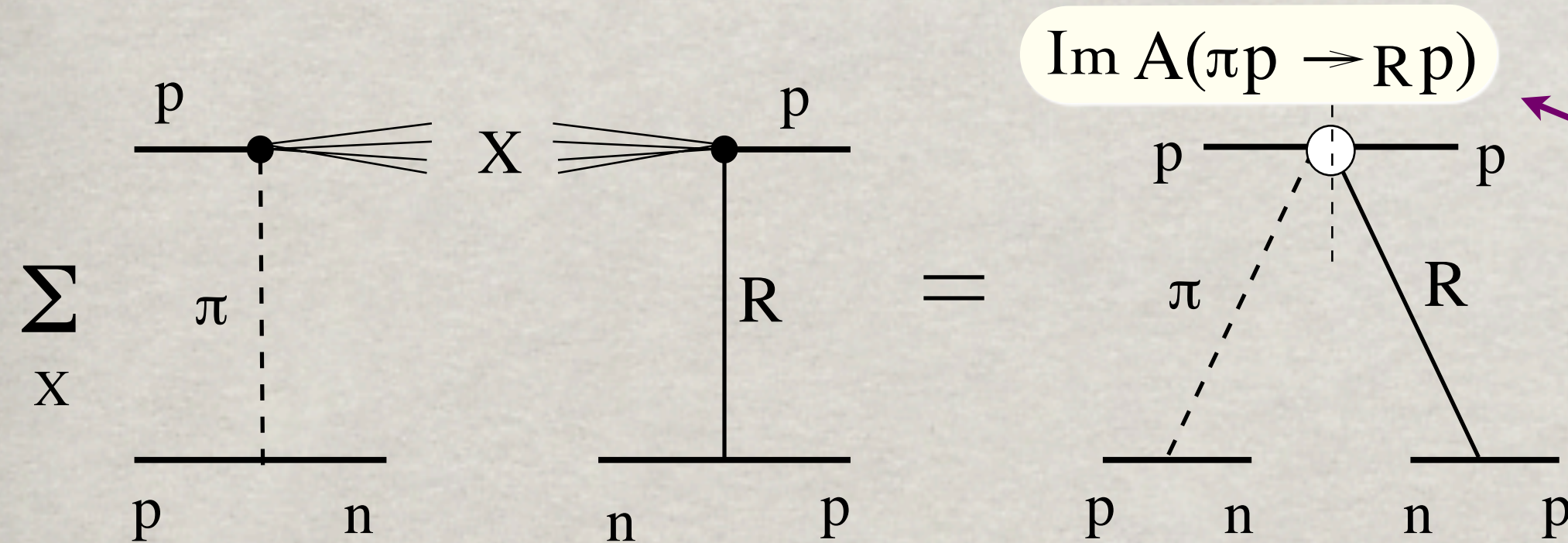
$$A_{p \rightarrow n}^B(\tilde{\mathbf{q}}, \mathbf{z}) = \bar{\xi}_n \left[\sigma_3 \mathbf{q}_L + \frac{1}{\sqrt{z}} \tilde{\boldsymbol{\sigma}} \cdot \tilde{\mathbf{q}}_T \right] \xi_p \phi^B(\mathbf{q}_T, \mathbf{z})$$

Both amplitudes have the same phase

$$\eta_\pi(t) = i - \text{ctg} \left[\frac{\pi \alpha_\pi(t)}{2} \right]$$

No single-spin asymmetry is possible

Interference with other Reggeons



Only unnatural parity states can be produced diffractively

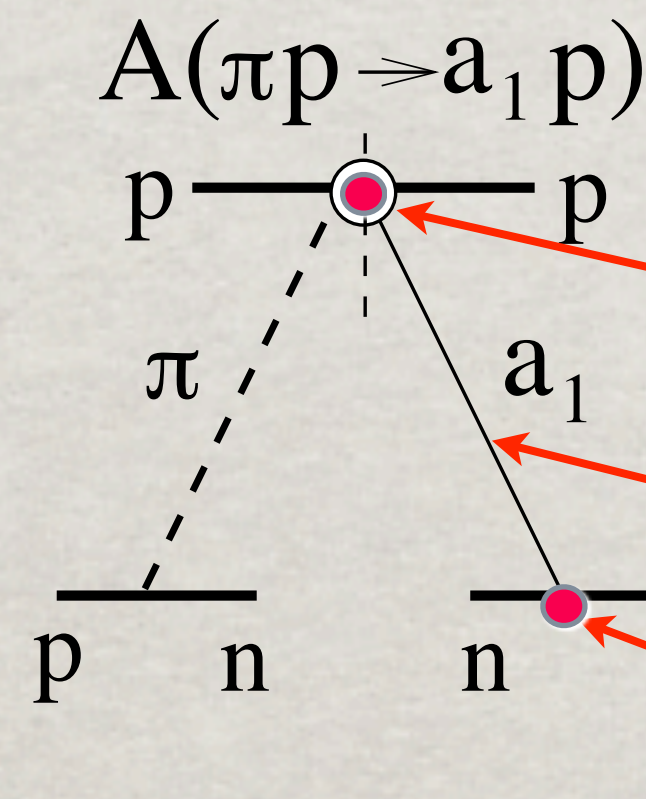
$$A(\pi p \rightarrow \tilde{a}_1 p) \approx \text{const}$$

$$\tilde{a}_1 = a_1, \rho\pi, \dots$$

π - a_1 interference

$$A_N^{(\pi-a_1)}(q_T, z) = q_T \frac{4m_N q_L}{|t|^{3/2}} (1-z)^{\alpha_\pi(t) - \alpha_{a_1}(t)} \frac{\text{Im } \eta_\pi^*(t) \eta_{a_1}(t)}{|\eta_\pi(t)|^2} \\ \times \left(\frac{d\sigma_{\pi p \rightarrow a_1 p}(M_X^2)/dt|_{t=0}}{d\sigma_{\pi p \rightarrow \pi p}(M_X^2)/dt|_{t=0}} \right)^{1/2} \frac{g_{a_1^+ pn}}{g_{\pi^+ pn}}$$

Three inputs:



From pion diffractive data

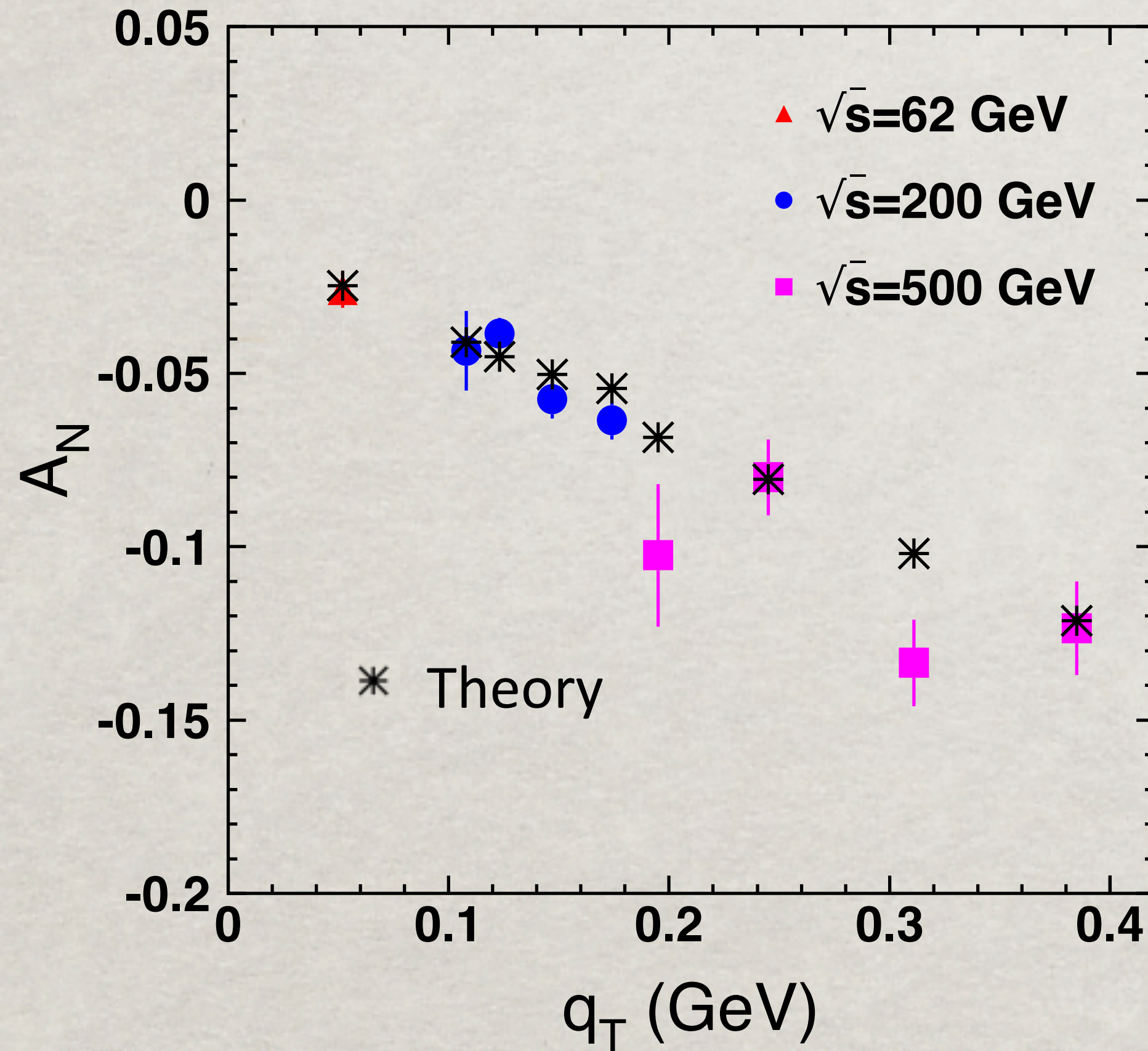
Regge-cut trajectory $\alpha_{\tilde{a}_1}(t)$

a_1 -nucleon coupling $g_{a_1 np}$

PCAC and the 2d Weinberg sum rule: $\frac{g_{a_1 NN}}{g_{\pi NN}} = \frac{m_{a_1}^2 f_\pi}{2m_N f_\rho} \approx 0.5$

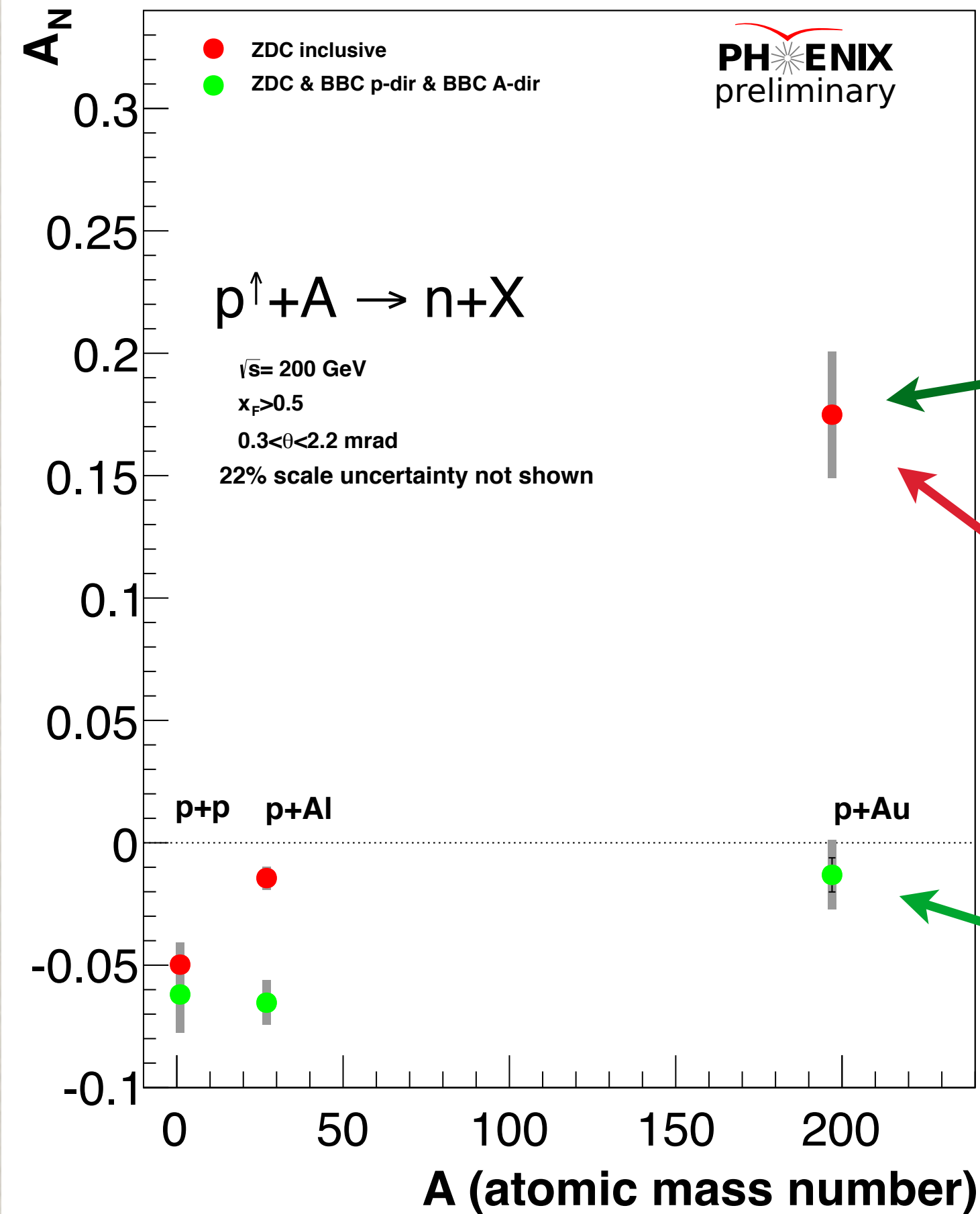
I.Potashnikova, I.Schmidt, J.Soffer & B.K. Phys.Rev. D84(2011)114012

Results



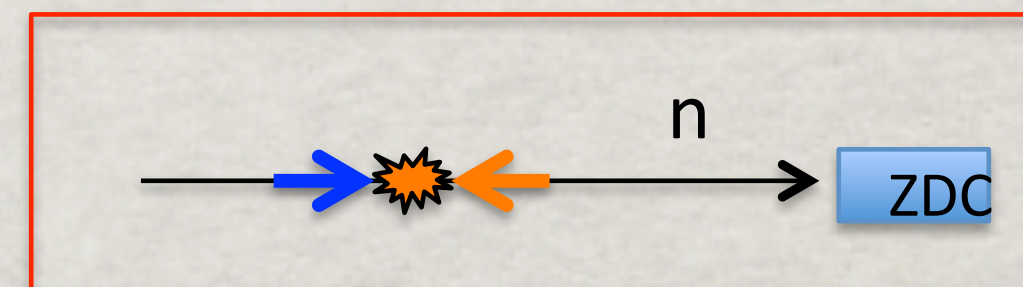
The parameter-free calculations agree with the PHENIX data.

Astonishing spin effects in $pA \rightarrow nX$

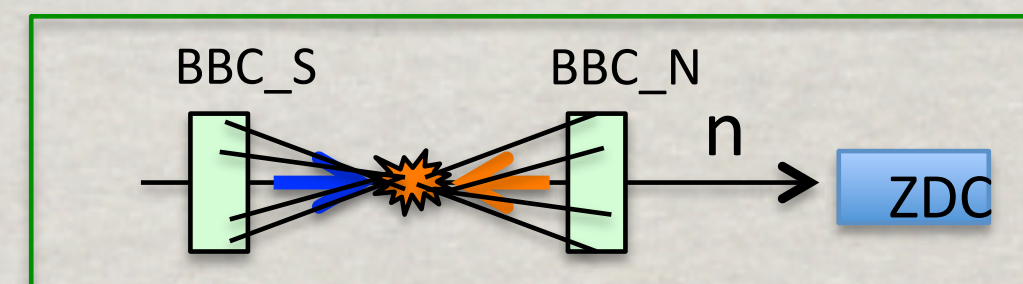


Recent measurements by PHENIX of the single-spin asymmetry of neutrons from polarized pA collisions revealed a weird A-dependence

BBC triggering sheds light on this mystery



inclusive production



inelastic events

A_N in $pA \rightarrow nX$

$$A_N^{pA \rightarrow nX}(q_T, z) = q_T \frac{4m_N q_L}{|t|^{3/2}} (1 - z)^{\alpha_\pi(t) - \alpha_{\tilde{a}_1}(t)} \frac{\text{Im } \eta_\pi^*(t) \eta_{\tilde{a}_1}(t)}{|\eta_\pi(t)|^2}$$

The only difference
with $pp \rightarrow nX$

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

$$A_N^{pA \rightarrow nX} = A_N^{pp \rightarrow nX} \times \frac{R_1}{R_2} R_3 \quad \leftarrow \text{Nuclear and trigger effects}$$

Nuclear effects for coherent $\pi+A \rightarrow \pi p+A$

$$R_1 = \frac{1}{\sigma_{\text{tot}}^{\rho p}} \int d^2b e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi p} T_A(b)} \left[1 - e^{-\frac{1}{2} \sigma_{\text{tot}}^{\rho p} T_A(b)} \right] e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi p} T_A(b)}$$

Nuclear effects for the denominator $\pi A \rightarrow \pi A$

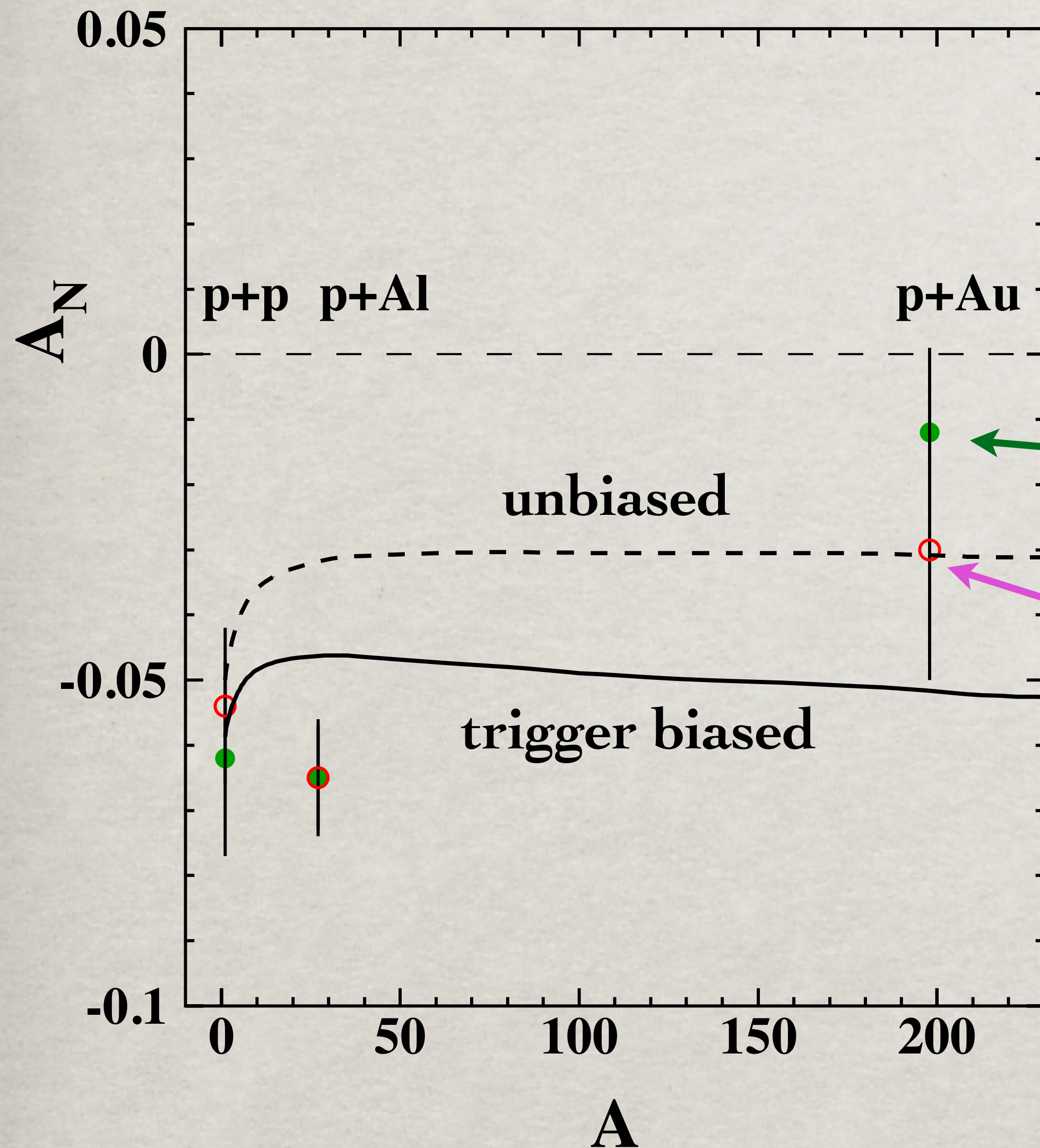
$$R_2 = \frac{2}{\sigma_{\text{tot}}^{\pi p}} \int d^2b \left[1 - e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi p} T_A(b)} \right] e^{-\frac{1}{2} \sigma_{\text{tot}}^{\pi p} T_A(b)}$$

Absorption factors

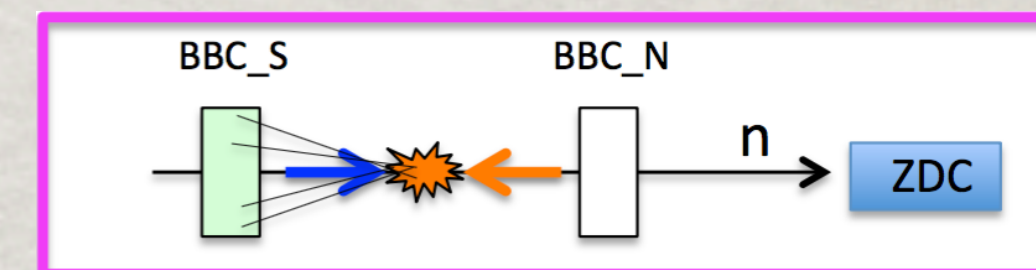
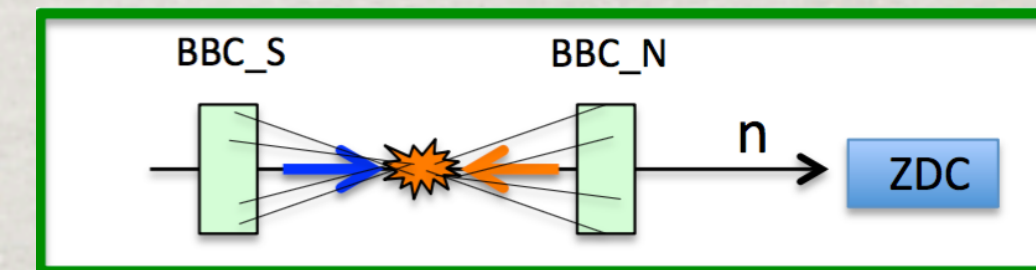
Triggering on nuclear
breaks-up

$$R_3 = \frac{\sigma_{\text{tot}}^{\pi A}}{\sigma_{\text{in}}^{\pi A}}$$

A_N in $pA \rightarrow nX$



Incoherent production:
the nucleus breaks up,
the BBC_S is fired



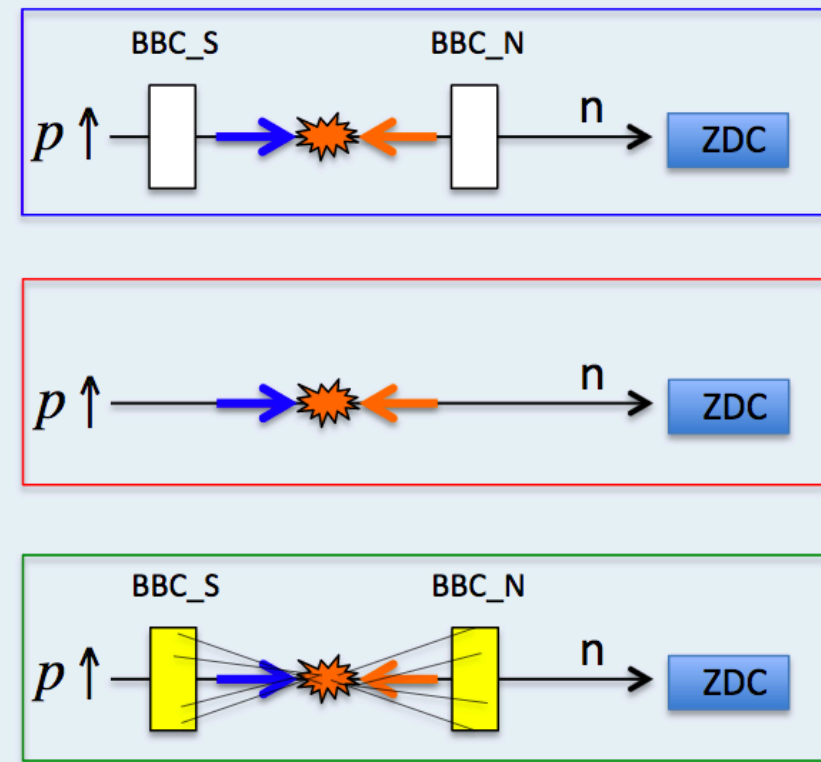
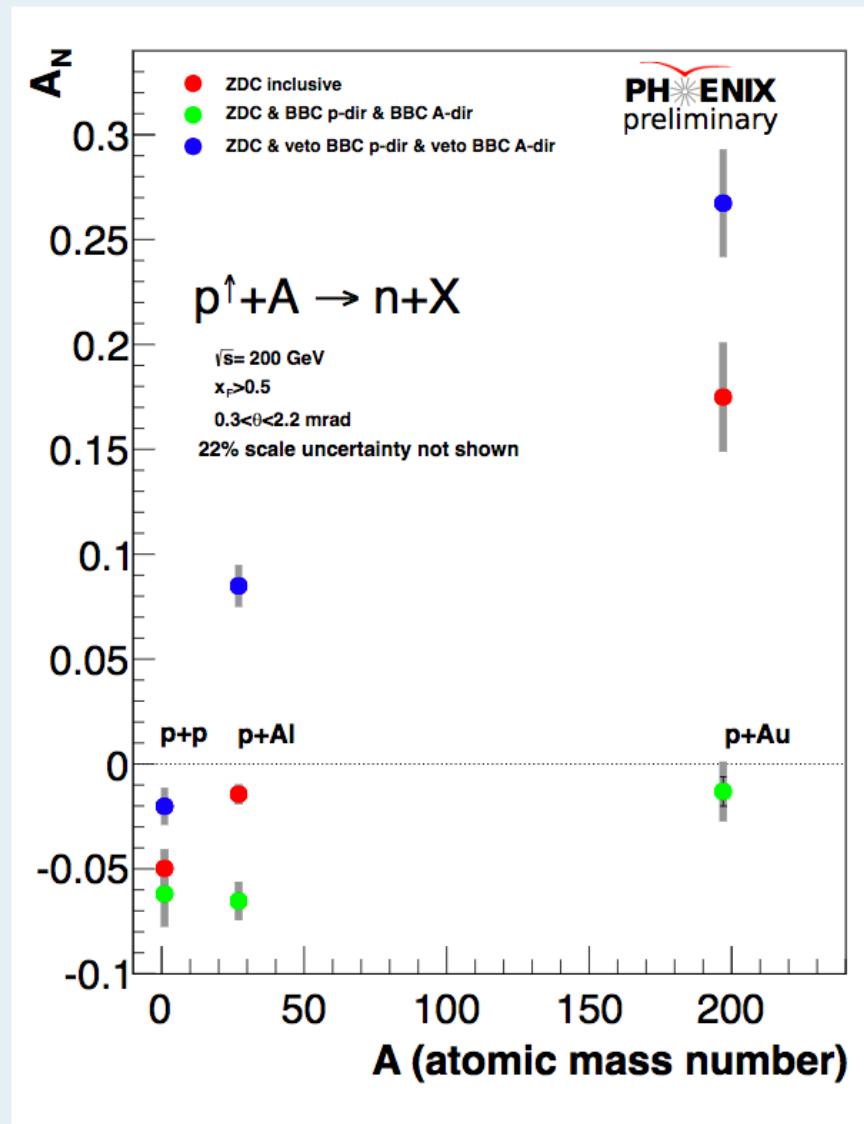
This sample of events with nuclear
break-up is reasonably well explained.

★ However, the large positive values of A_N
in rapidity-gap events remain unexplained.

Rapidity gap vs inclusive channels

A_N vs nucleus mass

ZDC: $\eta > 6.5$
BBC: $3.0 < |\eta| < 3.9$



A. Bazilevsky, Diffraction-2016

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A peculiar feature of the rapidity gap events is the extremely small invariant mass M of the diffractive excitation $p \rightarrow n\pi$.

$$M^2 = \frac{m_n^2}{z} + \frac{m_\pi^2}{1-z} + \frac{q_T^2}{z(1-z)} = (1.15 \text{ GeV})^2$$

The overall momentum transfer in coherent production $p_T^2 \sim 1/R_A^2 = 0.0008 \text{ GeV}^2$ is small compared with the measured neutron $\langle q_T^2 \rangle = 0.013 \text{ GeV}^2$, and is even much less in Coulomb excitation.

Neglecting q_T , and fixing $z=0.75$, the invariant mass is very small, too small to relate to the polarized Primakoff effect.

Summary

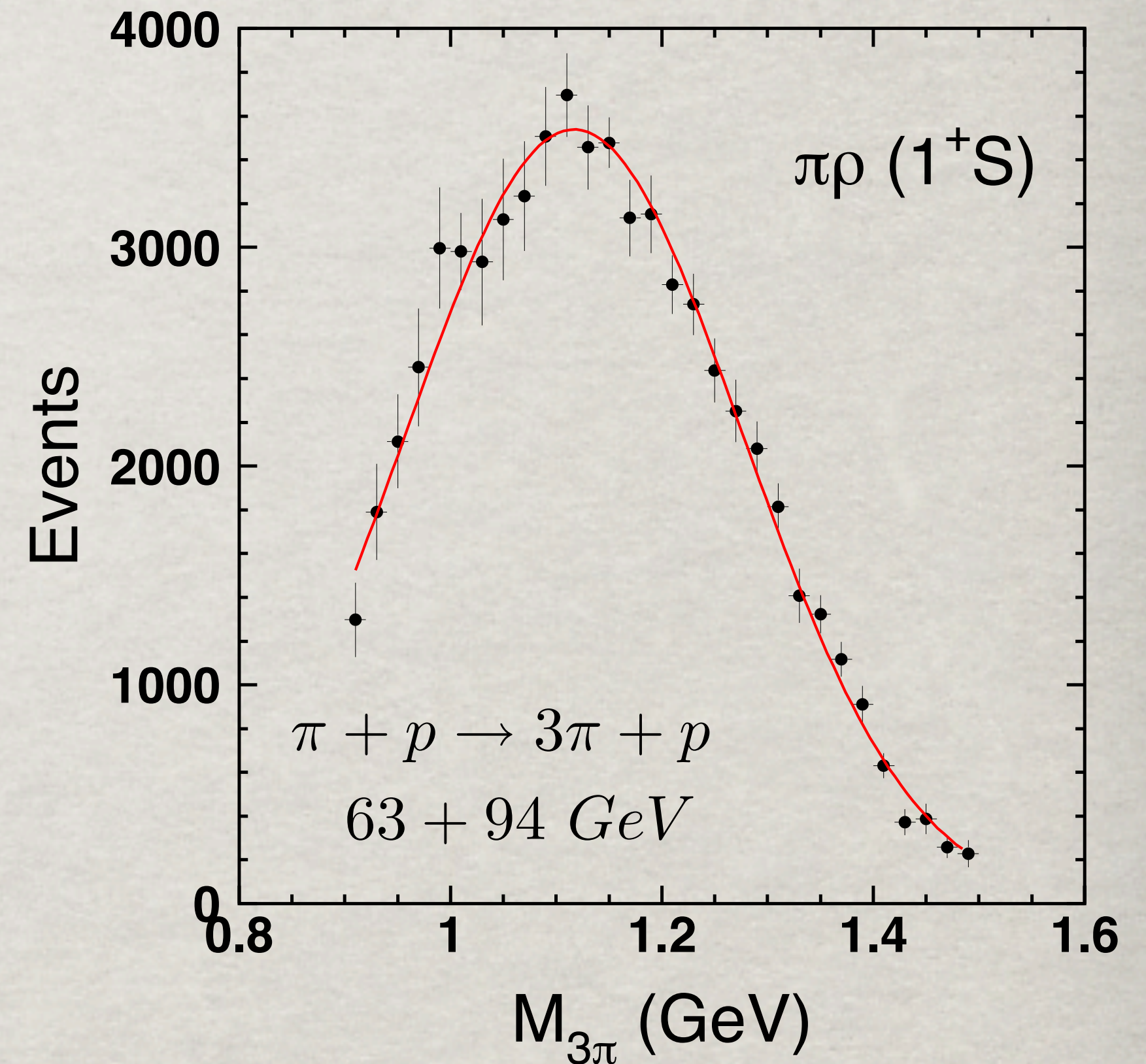
- While the cross section of leading neutron production agree well with the single pion model, the spin effects are more involved and require contribution of other mechanisms, e.g. $\pi - \tilde{a}_1$ interference.
- First calculations of leading neutron production off nuclei are done for coherent, diffractive, and incoherent events. The fraction of rapidity-gap events is found to be 25%, nearly independent of A .
- The nuclear effects for A_N of leading neutrons due to $\pi - \tilde{a}_1$ interference are calculated in good agreement with data for incoherent neutron production, associated with a nuclear break-up.

BACKUPS

a_1 production cross section

The a_1 is a weak pole: no axial-vector dominance for the axial current.

Nevertheless, the invariant mass distribution of diffractively produced $\pi\rho$ in 1^+S state forms a peak, dominated by the Deck mechanism, with a similar position and width as a_1 . This singularity in the dispersion relation can be treated as an effective pole "a" with mass $m_a = 1.1 \text{ GeV}$.



The cross section of $\pi + p \rightarrow (\pi\rho)_{1+S} + p$ was measured up to 94 GeV .

$$\left. \frac{d\sigma_{\pi p \rightarrow a p}(E_{\text{lab}} = 94 \text{ GeV})}{dq_T^2} \right|_{q_T=0} = 0.8 \pm 0.08 \frac{\text{mb}}{\text{GeV}^2}$$

Extrapolated to the RHIC energy range correcting for absorption.

BACKUPS

a_{NN} coupling

PCAC miraculously relates the pion-nucleon coupling with the axial constant

G_A represents the contribution to the dispersion relation of all axial-vector states heavier than pion. Assuming dominance of the 1^+S a -peak, we get

The dispersion integrals for vector and axial currents are related by the 2d Weinberg sum rule

$$g_{\pi NN} = \frac{\sqrt{2}m_N G_A}{f_\pi}$$

Goldberger-Treiman relation

$$G_A = \frac{\sqrt{2}f_a g_{aNN}}{m_a^2}$$

$$f_a = f_\rho = \frac{\sqrt{2}m_\rho^2}{\gamma_\rho}$$

Thus,

$$\frac{g_{aNN}}{g_{\pi NN}} = \frac{m_a^2 f_\pi}{2m_N f_\rho} \approx 0.5$$

BACKUPS

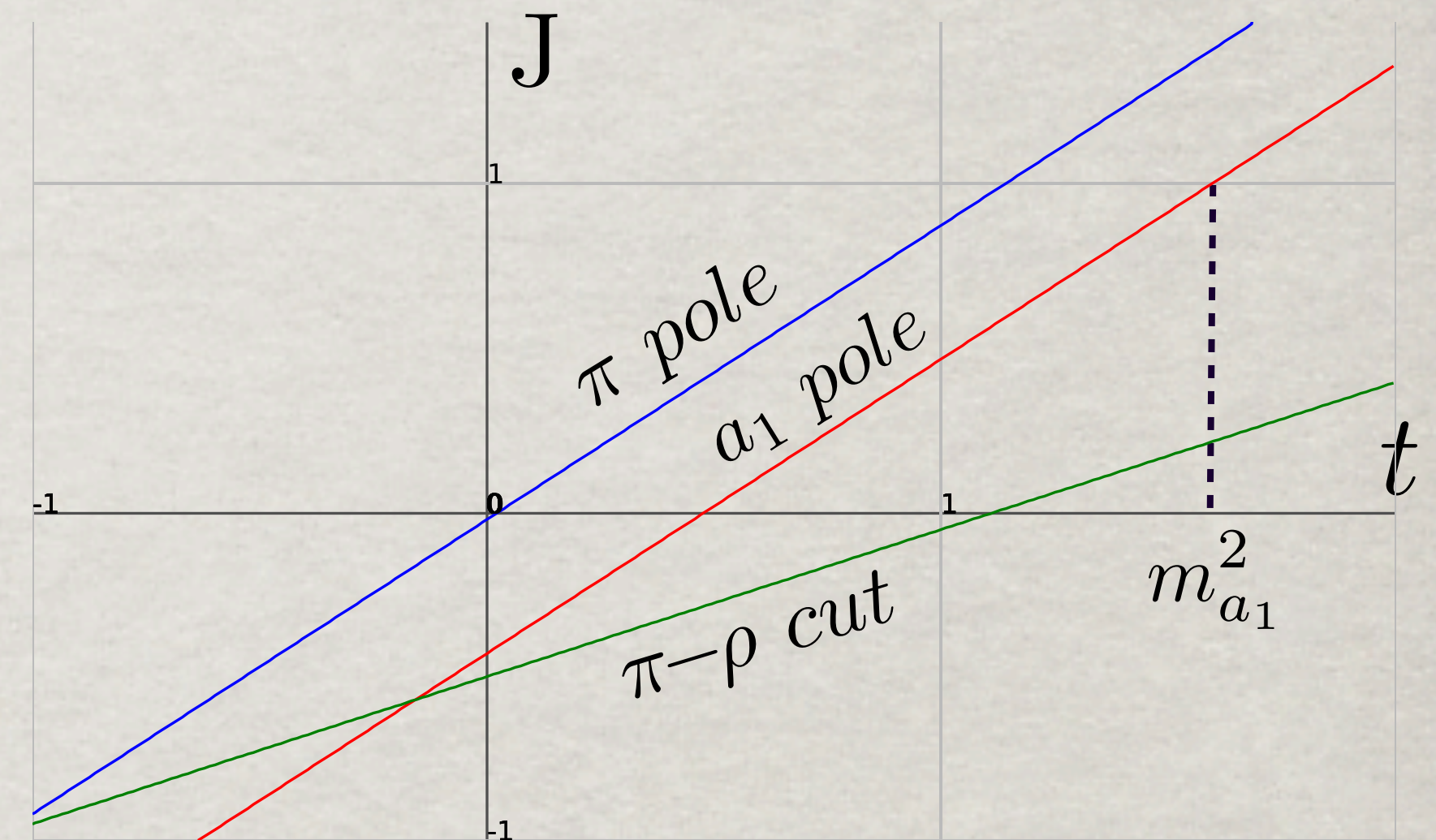
Regge trajectories

Assuming the universal slope of Regge trajectories $\alpha'_{a_1} = 0.9 \text{ GeV}^{-2}$

$$\alpha_{a_1}(t) = -0.43 + 0.9 t$$

The $\pi-\rho$ cut state is more important, it has trajectory

$$\alpha_{\pi-\rho}(t) = \alpha_{\pi}(0) + \alpha_{\rho}(0) - 1 + \alpha'_{\text{R}} t/2$$



The signature factor of the effective 1^+S state

$$\eta_a(t) = -i - t \text{g} [\pi \alpha_a(t)/2]$$

The phase shift relative the pion pole is large

$$\phi_a(t) - \phi_{\pi}(t) \approx \frac{\pi}{2} [1.5 + 0.45 t]$$