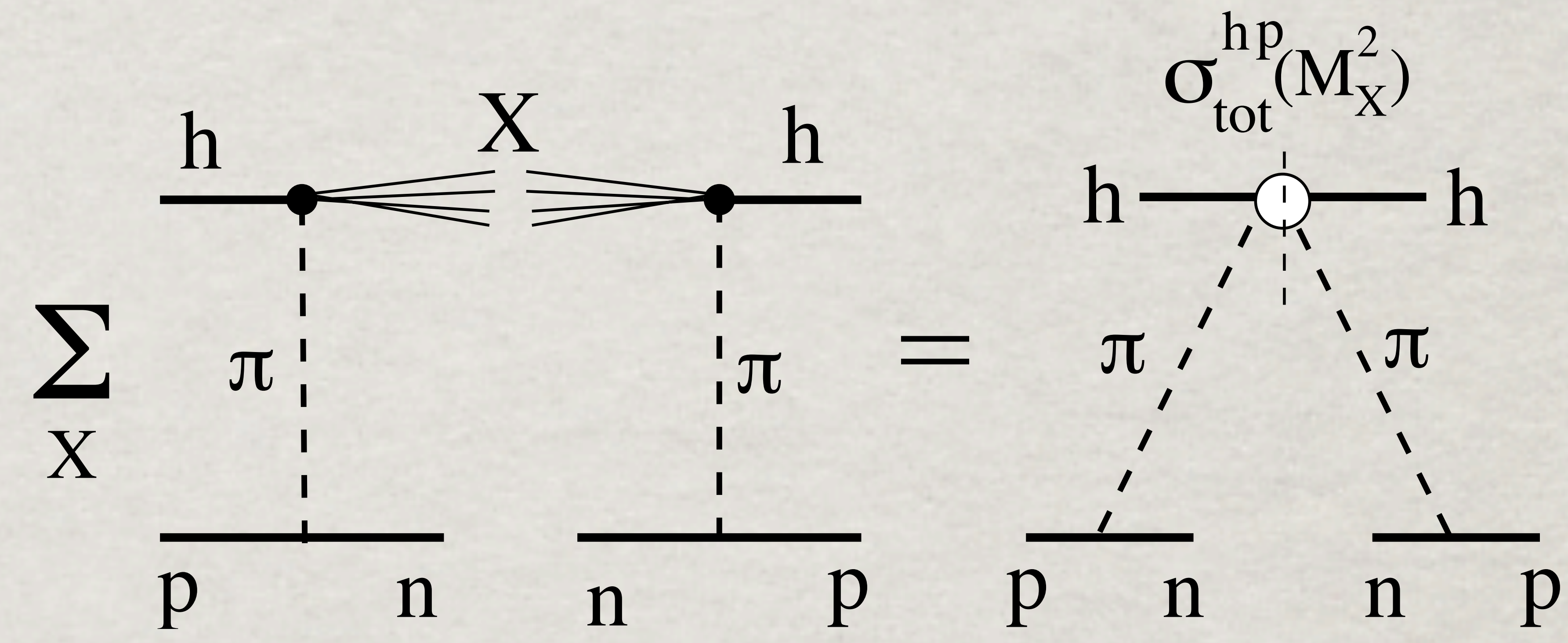
Leading neutrons from polarized pA collisions

Boris Kopeliovich
Valparaiso, Chile

Neutron production in the vicinity of pion pole

$$\mathbf{p + p \to n + X}$$

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



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

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

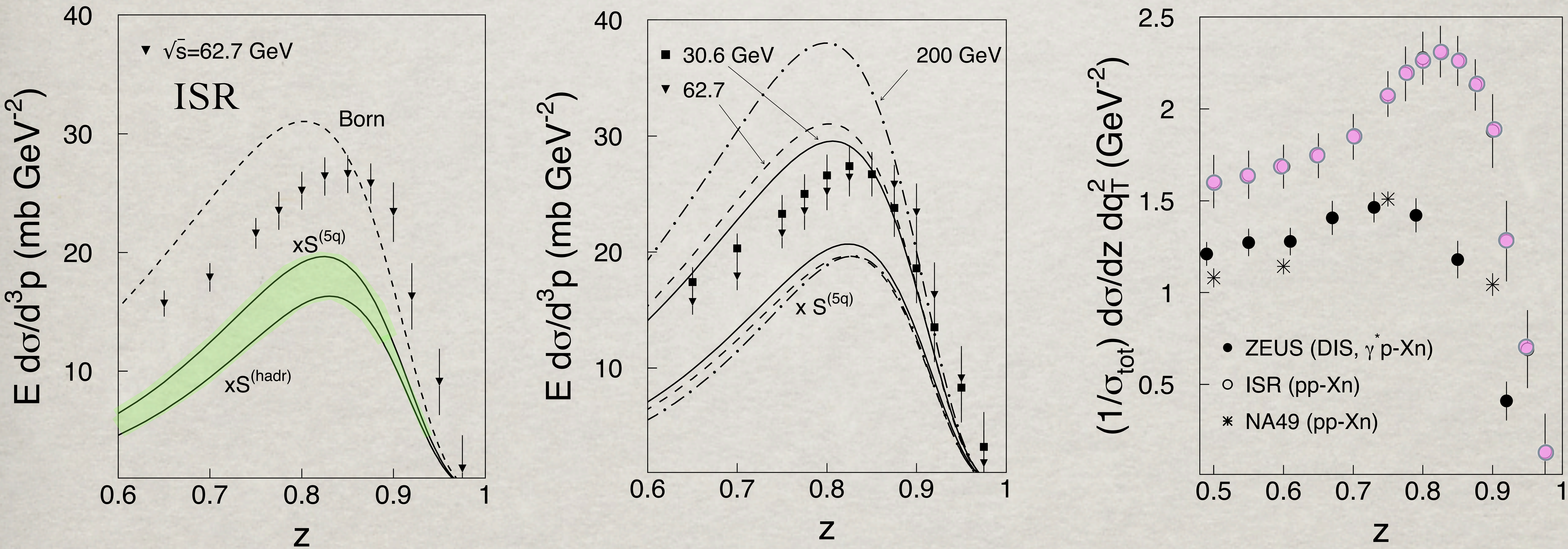
$$\mathbf{t = -q_L^2 - q_T^2/z}$$

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

$$\mathbf{z\frac{d\sigma^B_{p\to n}}{dz dq_T^2} = \frac{g^2_{\pi^+ pn}}{(4\pi)^2}\, \frac{|t|\, F^2(t)}{(m_\pi^2 - t)^2} (1 - z)^{1 - 2\alpha_\pi(t)} \sigma_{tot}^{\pi^+ p}(M_X^2)}$$

Results

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



Underestimated theory, or overestimated data?

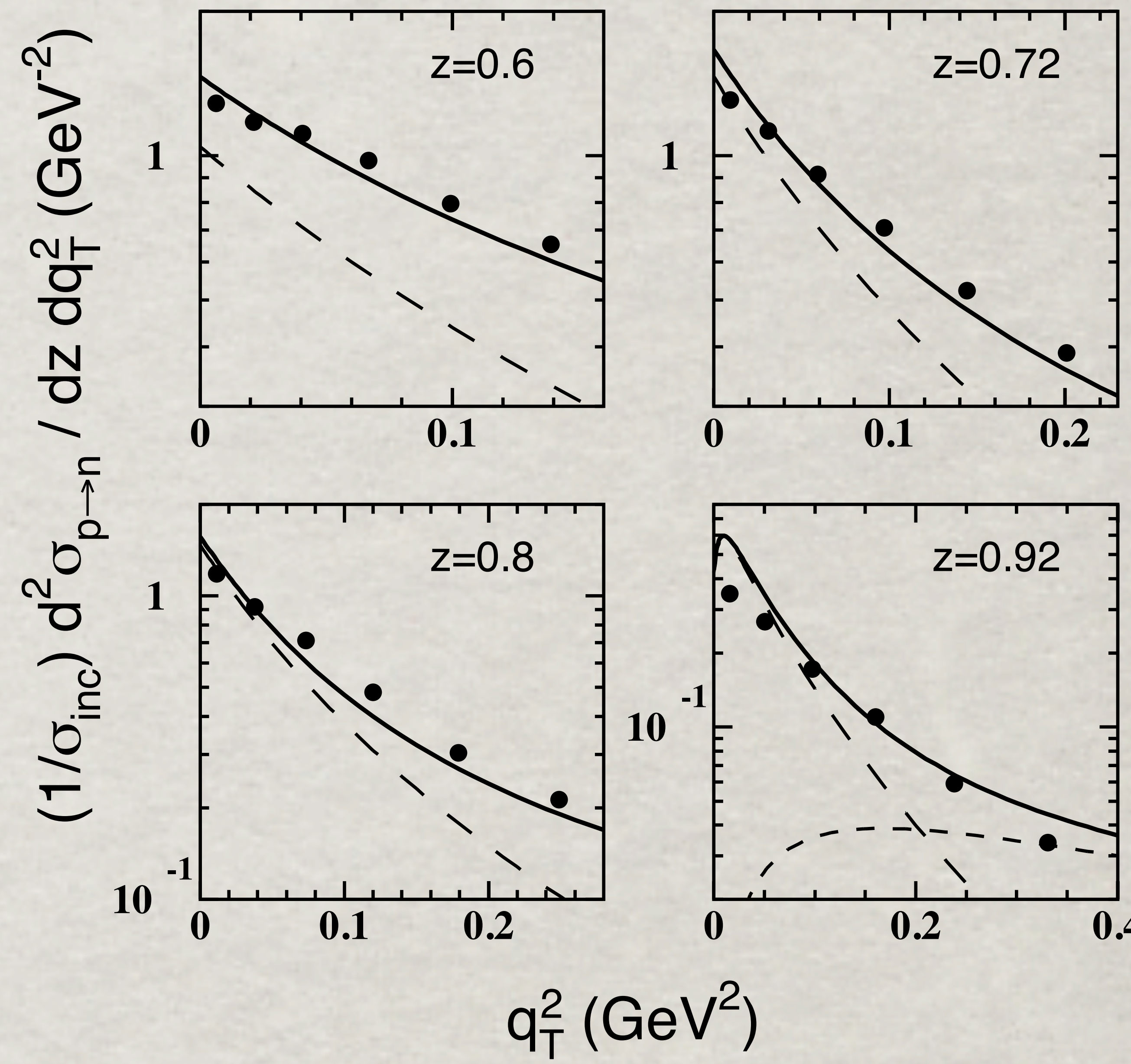
The main suspect is the normalization of the ISR data.

Results

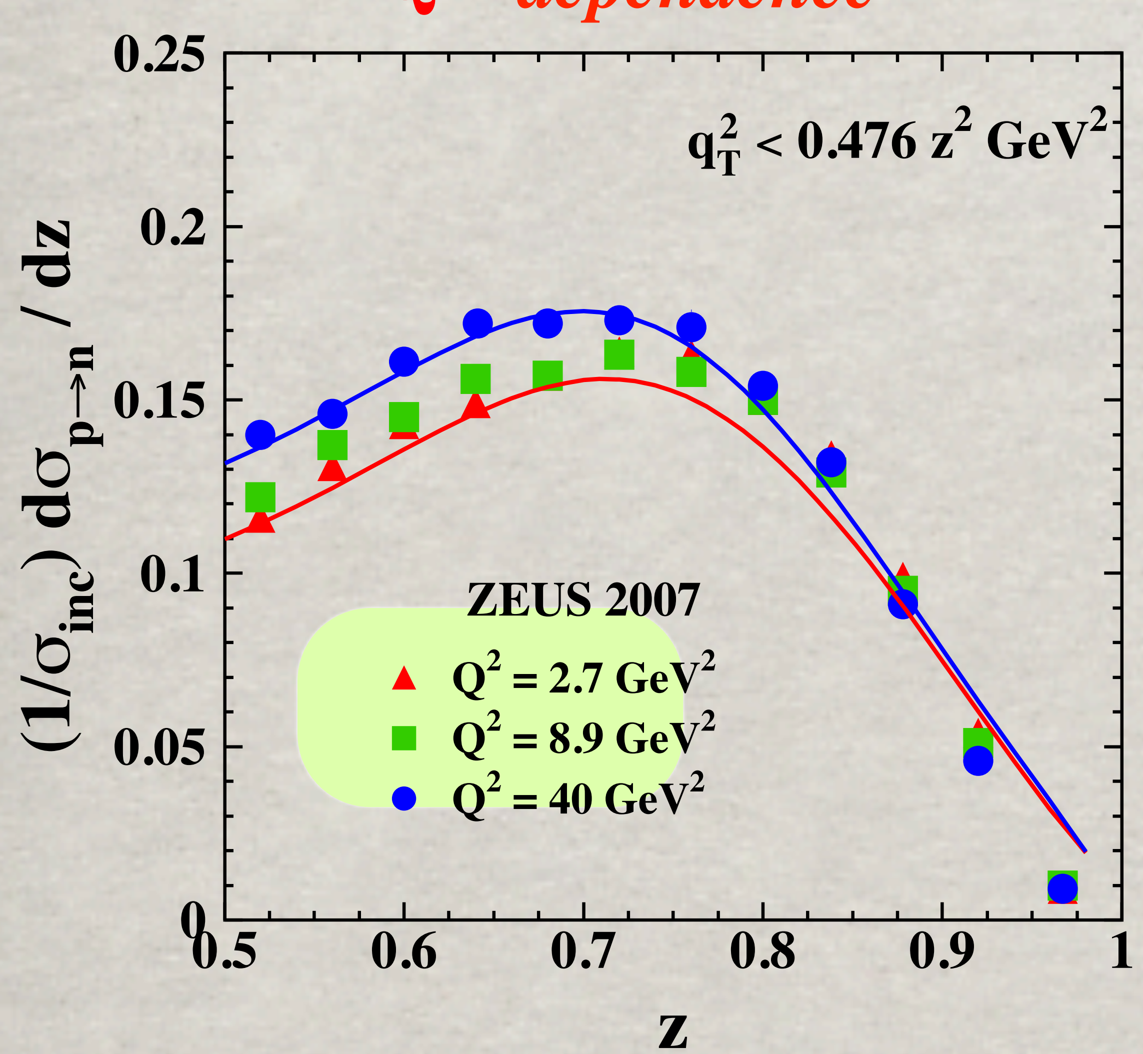
Leading neutrons from DIS on protons $\gamma^* \mathbf{p} \to \mathbf{nX}$ offer a unique way to measure the pion structure function at small x.

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

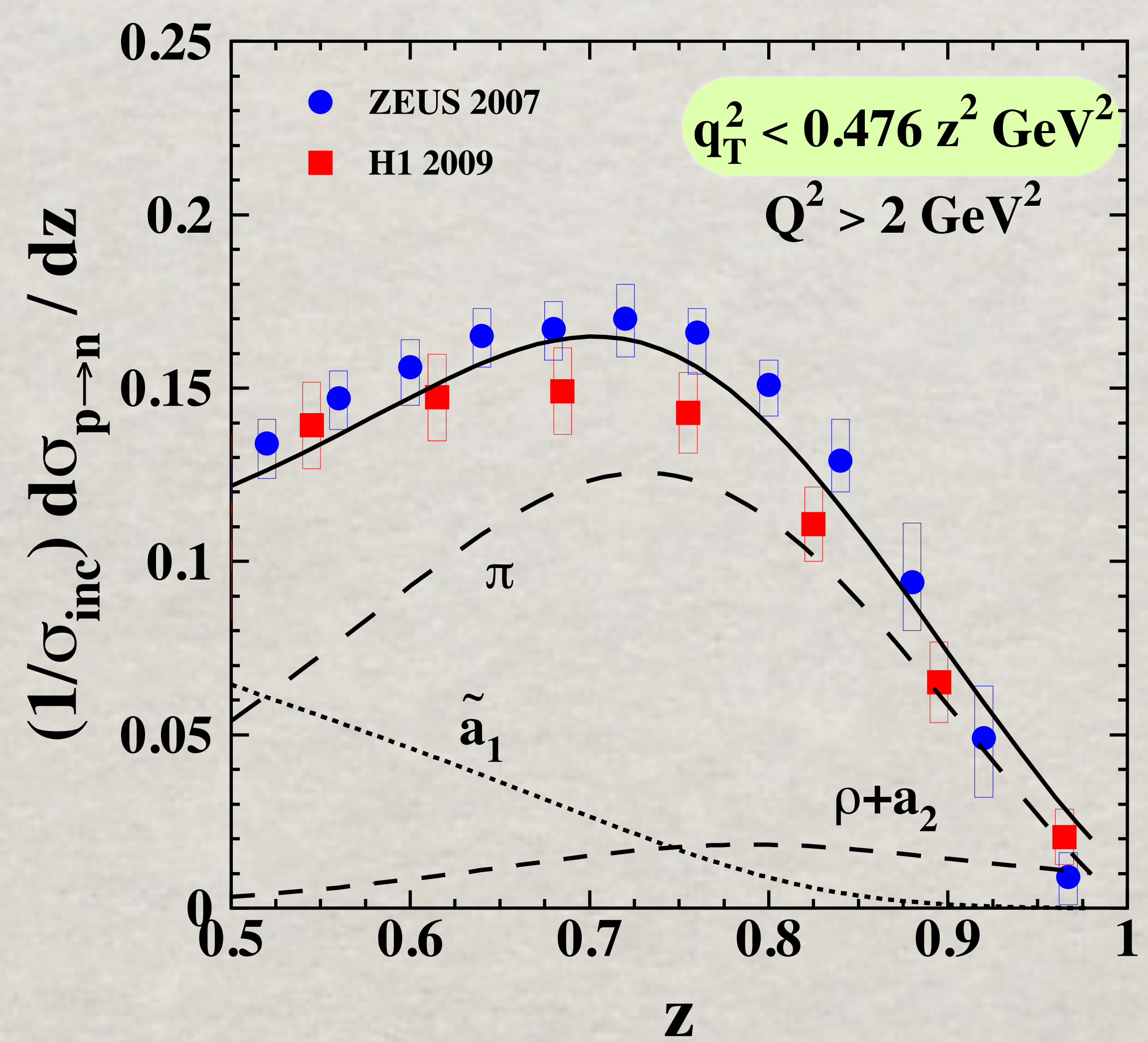
qT-dependence

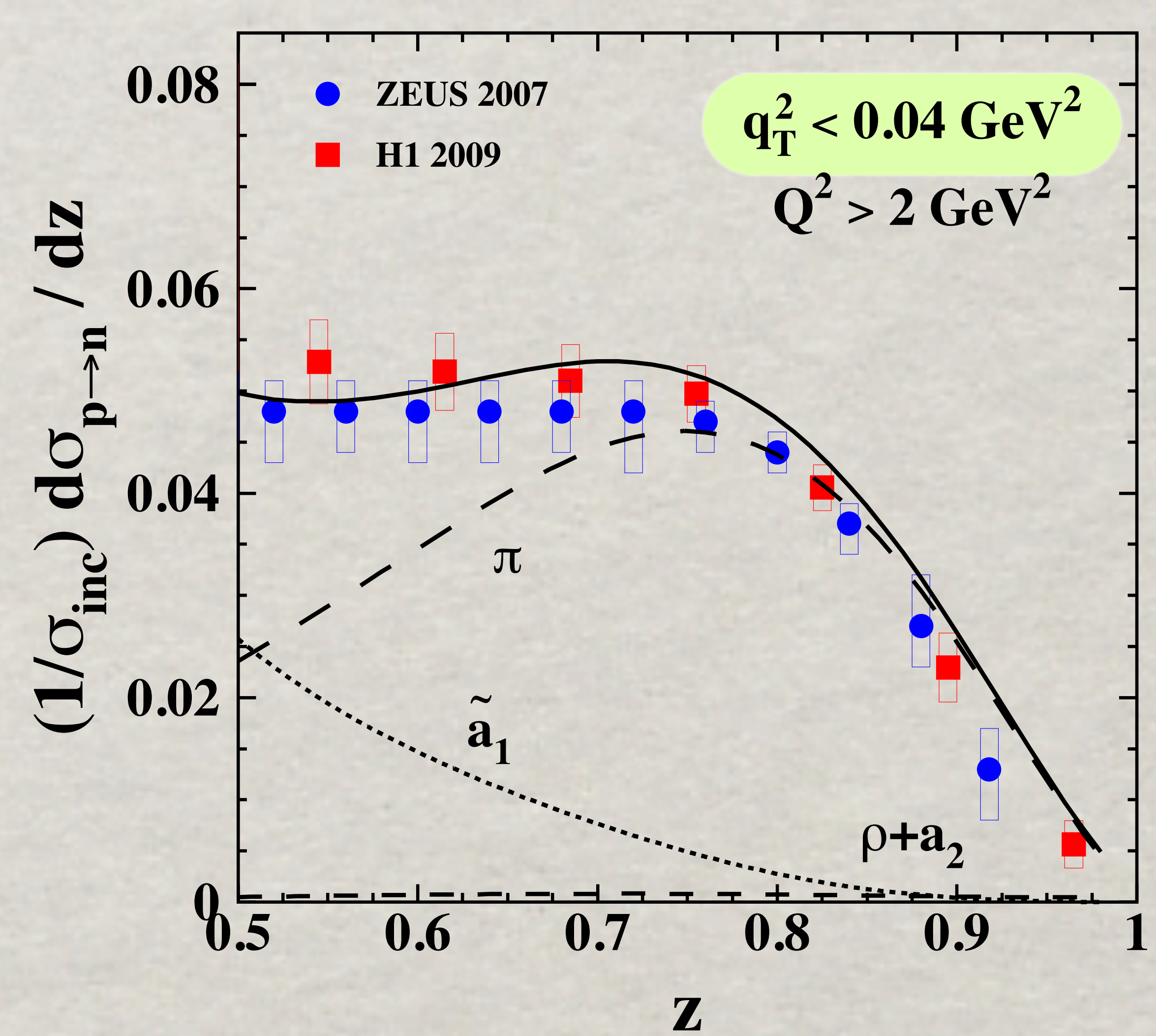


Q^2 -dependence



z-dependence





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Neutron production off nuclei

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

$$z\frac{d\sigma^B_{pA\to nX}}{dz\,dq_T^2} = \frac{g^2_{\pi^+pn}}{(4\pi)^2}\,\frac{|t|\,F^2(t)}{(m_\pi^2-t)^2}\,(1-z)^{1-2\alpha_\pi(t)}\,\sigma^{\pi A}_{tot}(M_X^2)$$

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

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

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

- If BBC are fired detecting multiparticle production, one should replace

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

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

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

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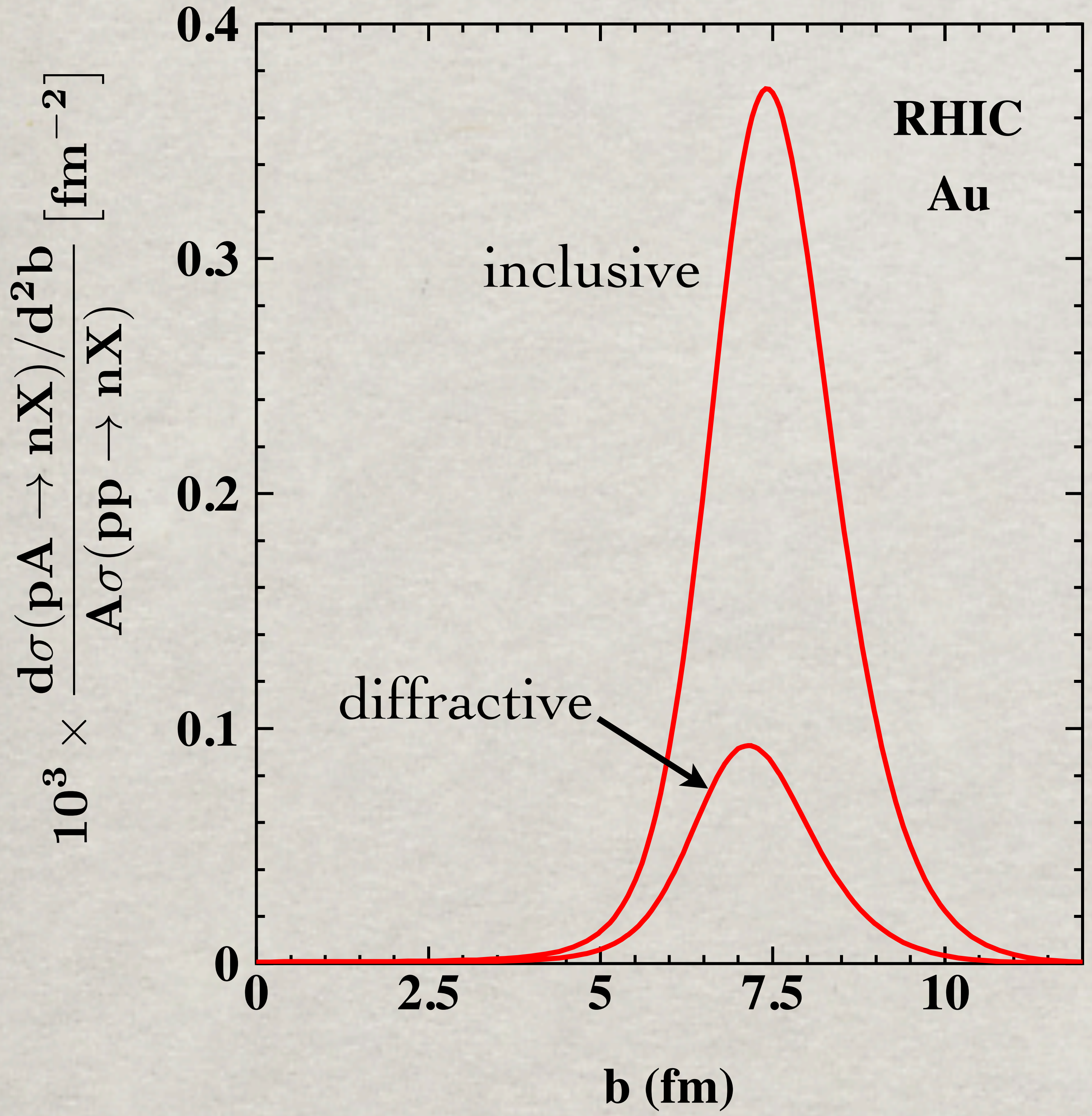
Cross sections

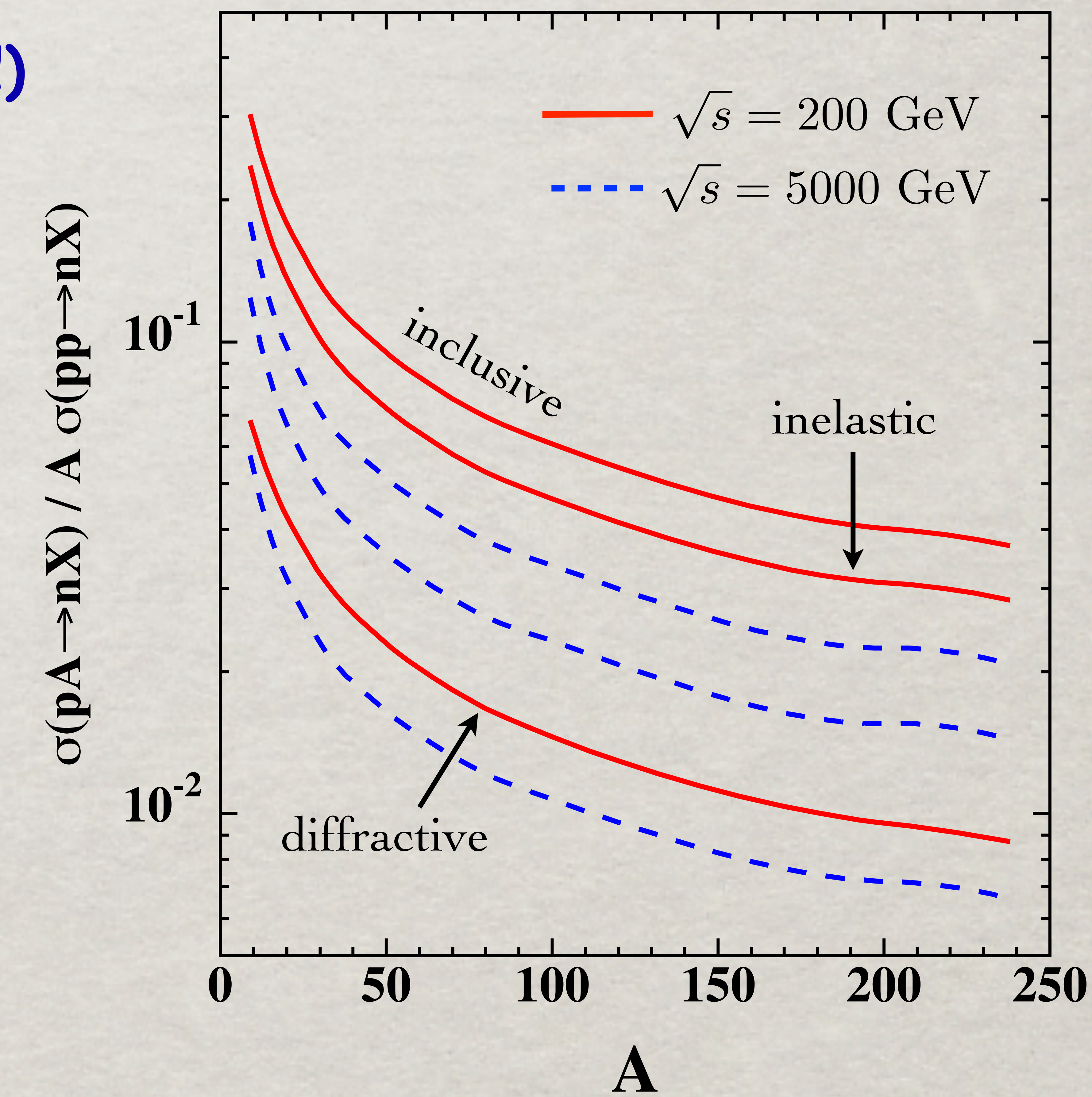
Three different channels of neutron production:

(i) inclusive neutrons;

(ii) multi-particle production (BBC fired);

(iii) rapidity gap diffractive events (BBC vetoed)





Single-spin asymmetry

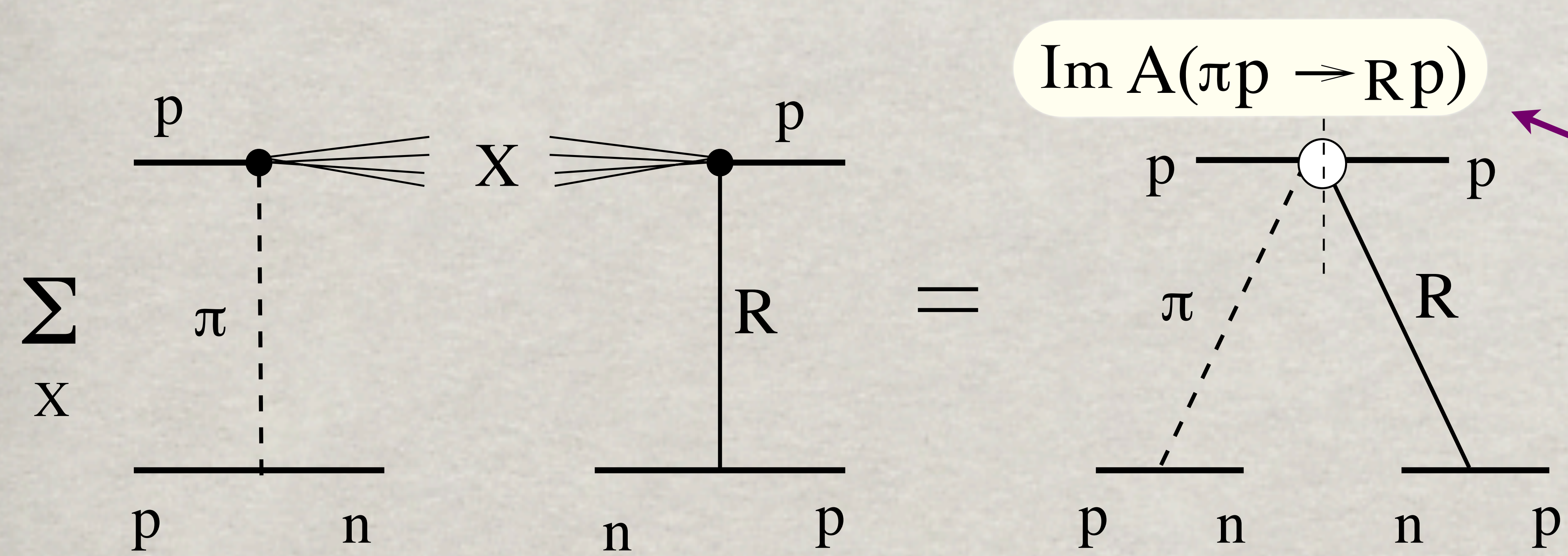
The amplitude includes both non-flip and spin-flip terms

$$A^B_{p\to n}(\tilde{q},z) = \bar{\xi}_n \left[\sigma_3\, q_L + \frac{1}{\sqrt{z}}\,\tilde{\sigma}\cdot\tilde{q}_T\right]\xi_p\,\phi^B(q_T,z)$$

Both amplitudes have the same phase $\eta_\pi(t) = i - ctg\left[\frac{\pi\alpha_\pi(t)}{2}\right]$

No single-spin asymmetry is possible

Interference with other Reggeons



Only unnatural parity states can be produced diffractively

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

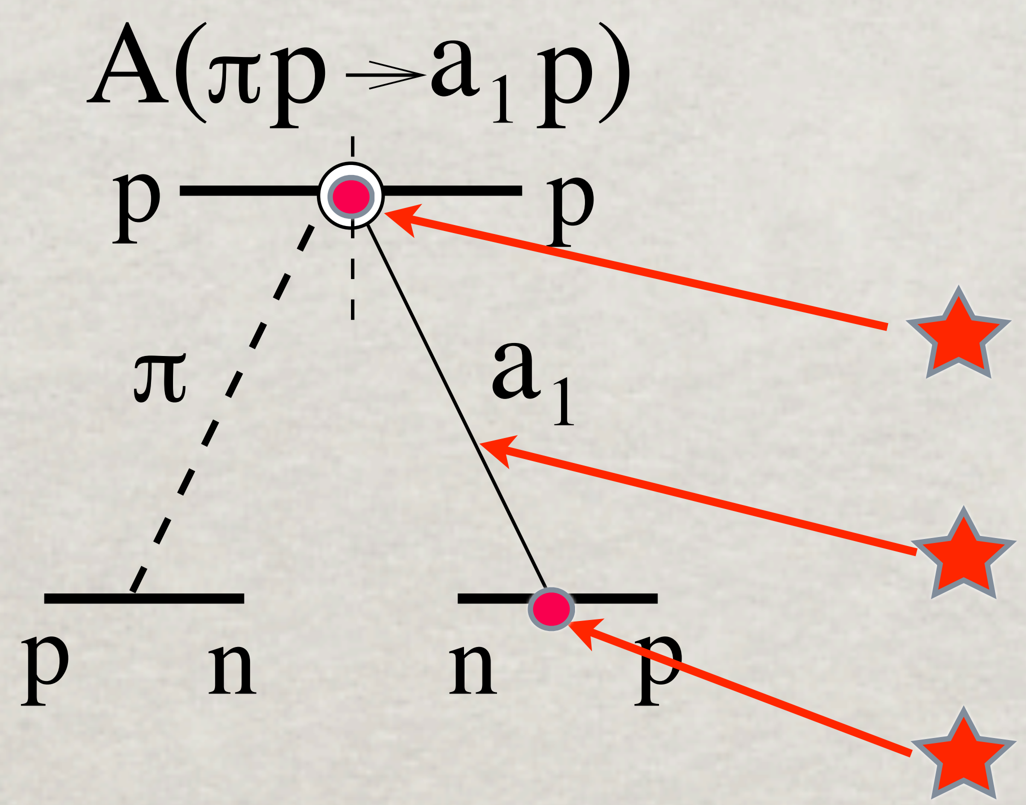
$$\tilde{a}_1 = a_1,\ \rho\pi,\ \ldots$$

π-a$_1$ interference

$$A_N^{(\pi-a_1)}(q_T,z) = q_T\,\frac{4m_N\,q_L}{|t|^{3/2}}\,(1-z)^{\alpha_\pi(t)-\alpha_{a_1}(t)}\,\frac{\mathrm{Im}\,\eta_\pi^*(t)\,\eta_{a_1}(t)}{|\eta_\pi(t)|^2}$$

$$\times\left(\frac{d\sigma_{\pi p\to a_1 p}(M_X^2)/dt|_{t=0}}{d\sigma_{\pi p\to \pi p}(M_X^2)/dt|_{t=0}}\right)^{1/2}\frac{g_{a_1^+ pn}}{g_{\pi^+ pn}}$$

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: $\dfrac{g_{a_1 NN}}{g_{\pi NN}} = \dfrac{m_{a_1}^2\,f_\pi}{2m_N\,f_\rho} \approx 0.5$

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

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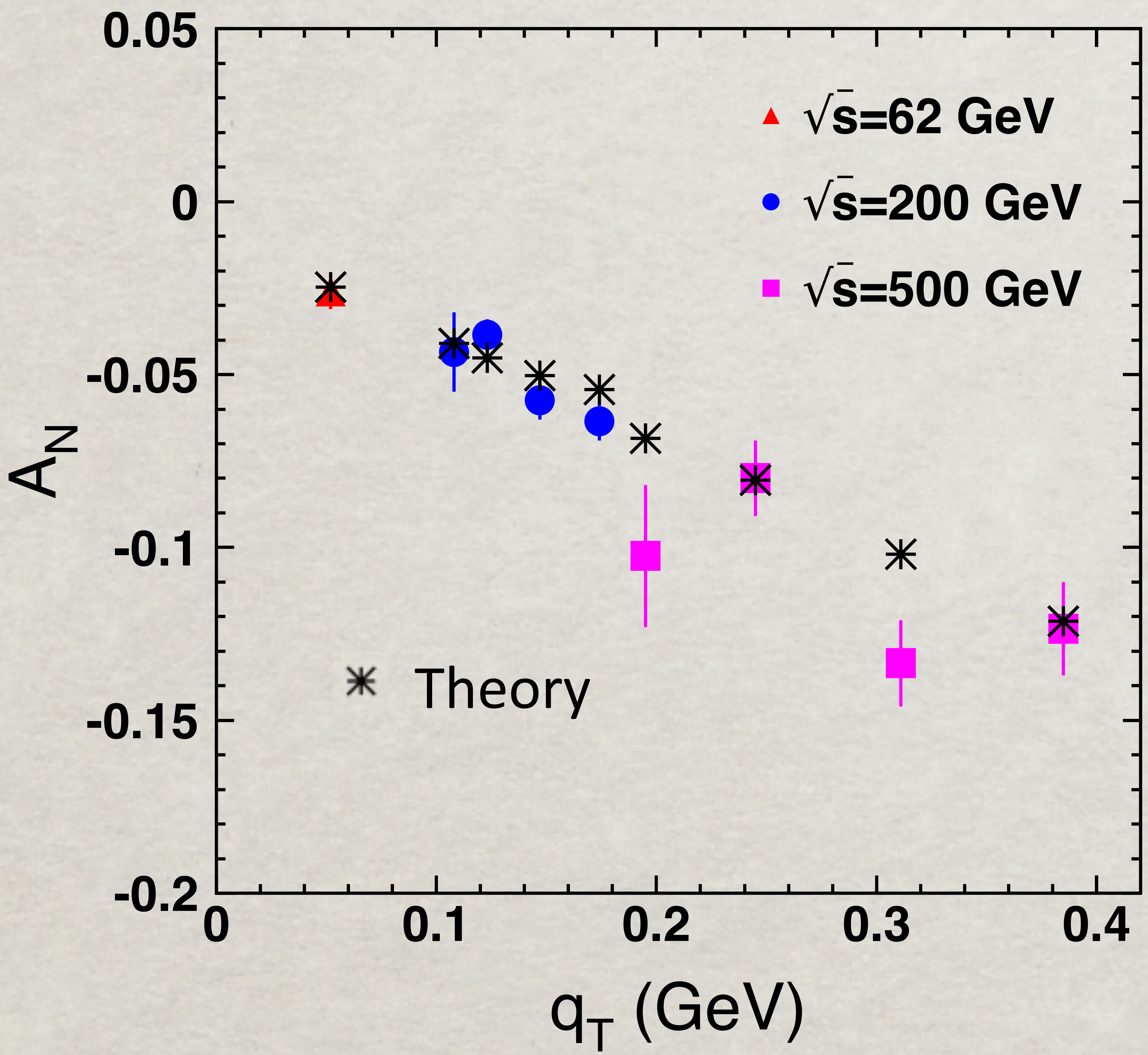
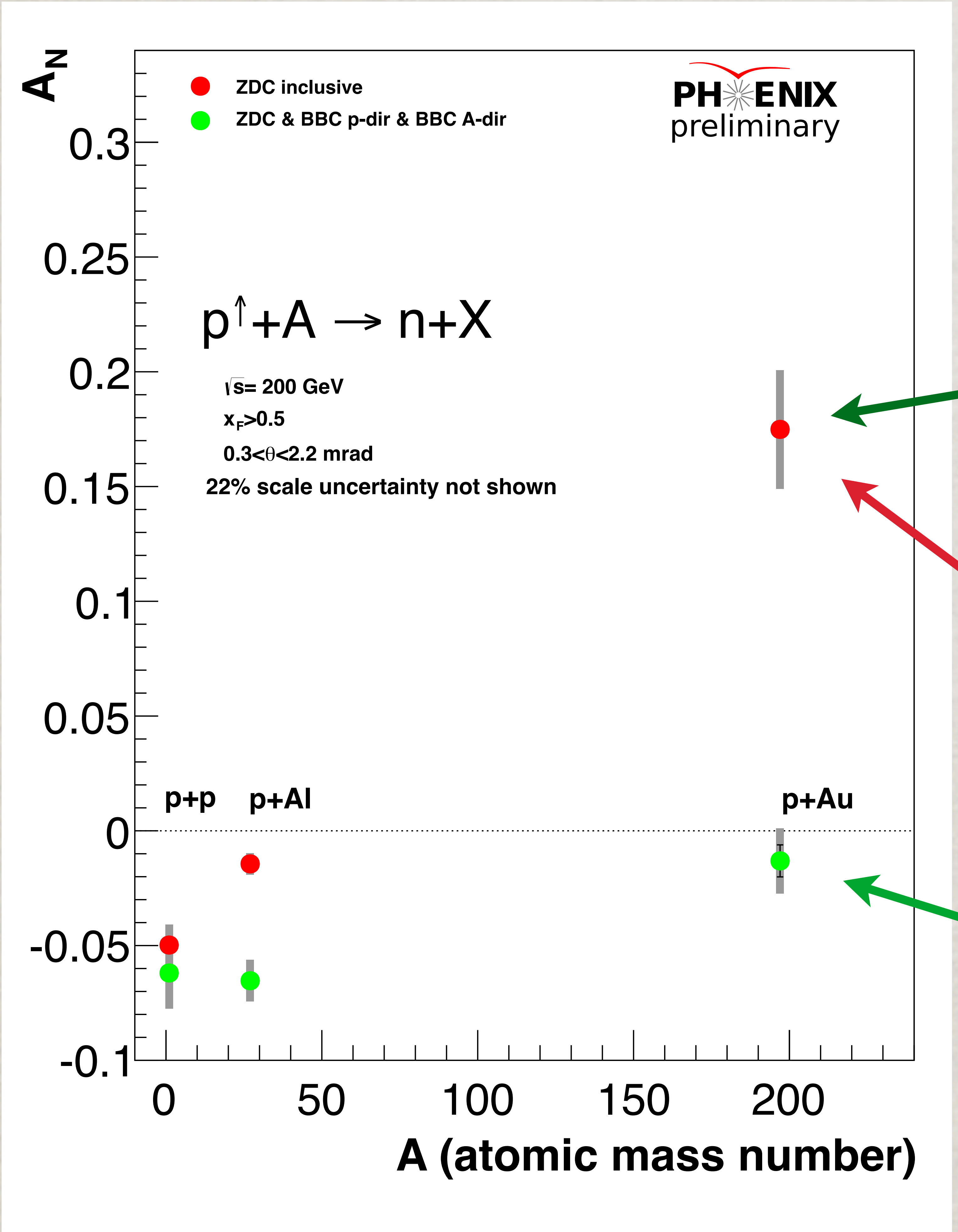
Results



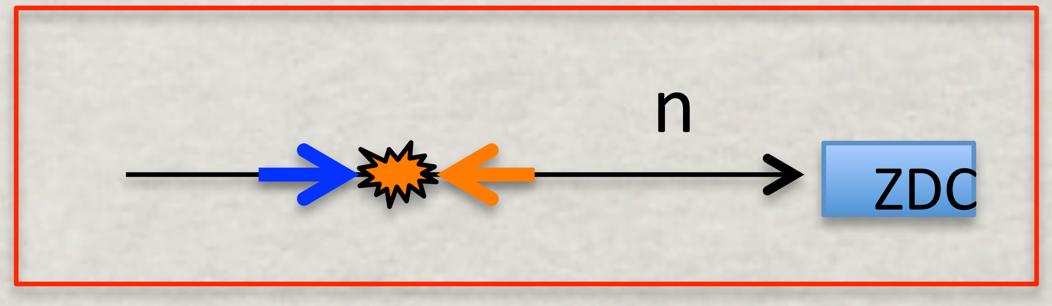
The parameter-free calculations agree with the PHENIX data.

Astonishing spin effects in pA->nX

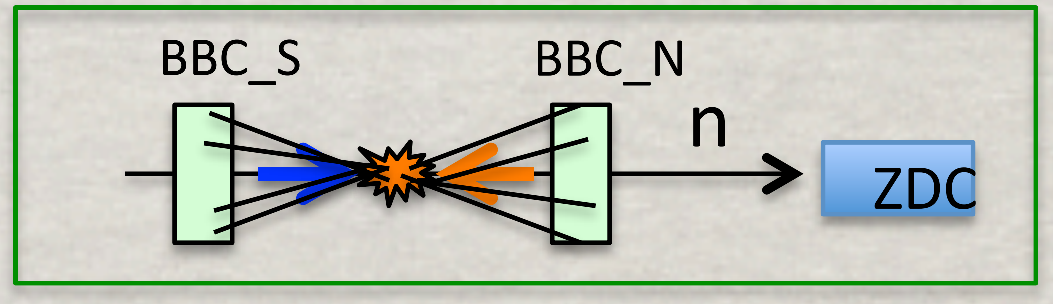


Recent measurements by PHENIX of the single-spin asymmetry of neutrons from polarized pA collisions revealed a weird A-dependence

BBC triggering sheds light on this mistery



inclusive production



inelastic events

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A_N in $pA \to nX$

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

The only difference with pp->nX

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

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

Nuclear and trigger effects

Nuclear effects for coherent π+A-> πρ+A

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

Nuclear effects for the denominator πA-> πA

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

Absorption factors

Triggering on nuclear breaks-up

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

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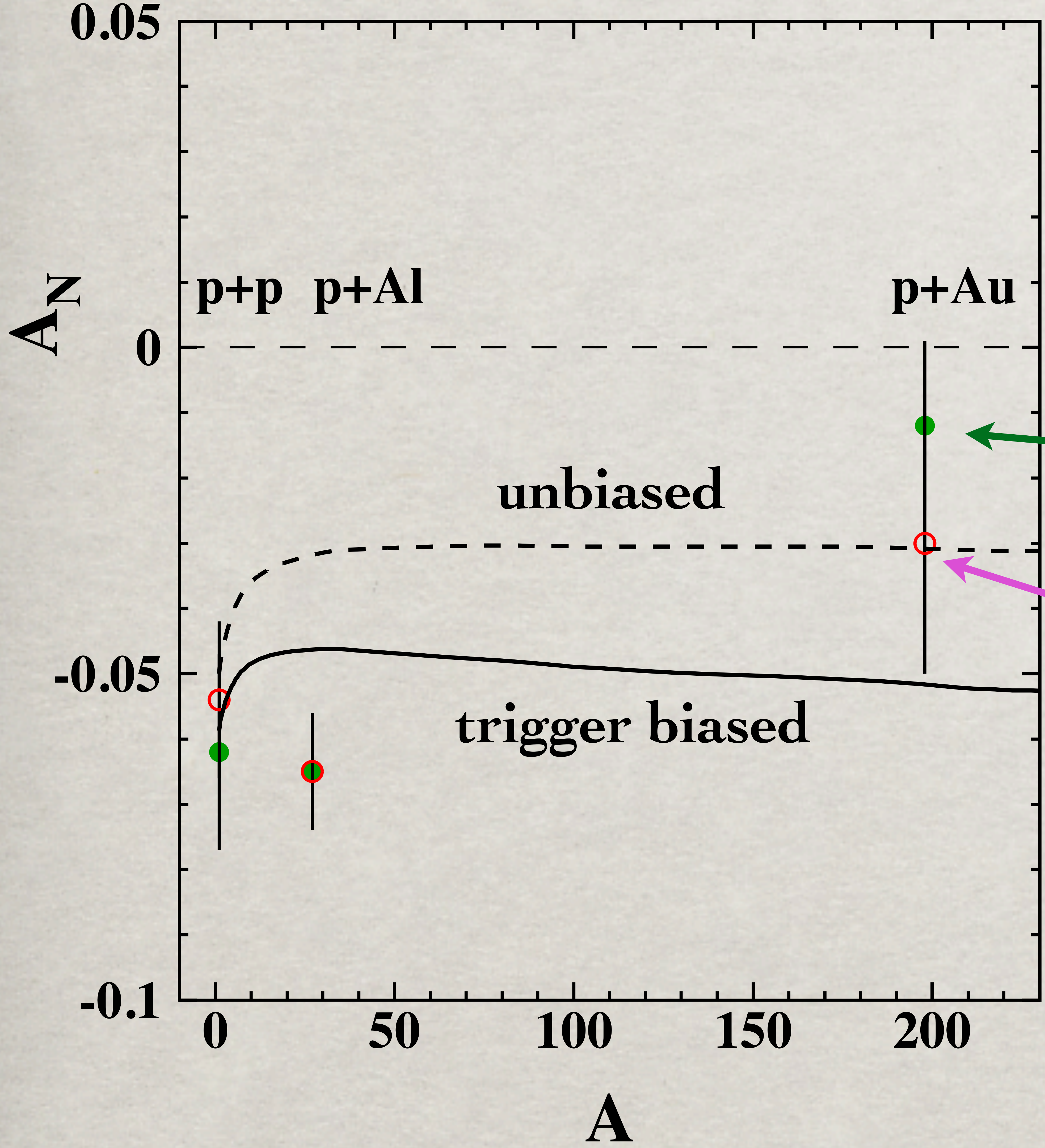
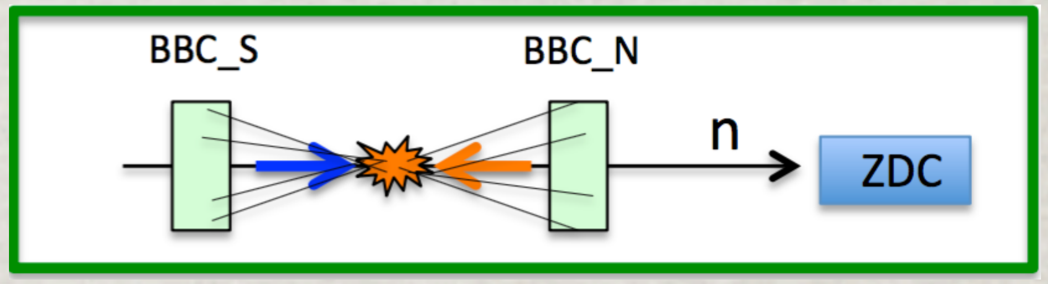
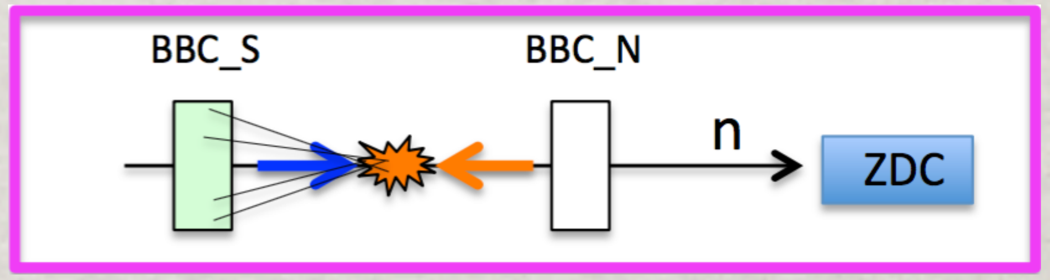
A_N in $pA \to nX$



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

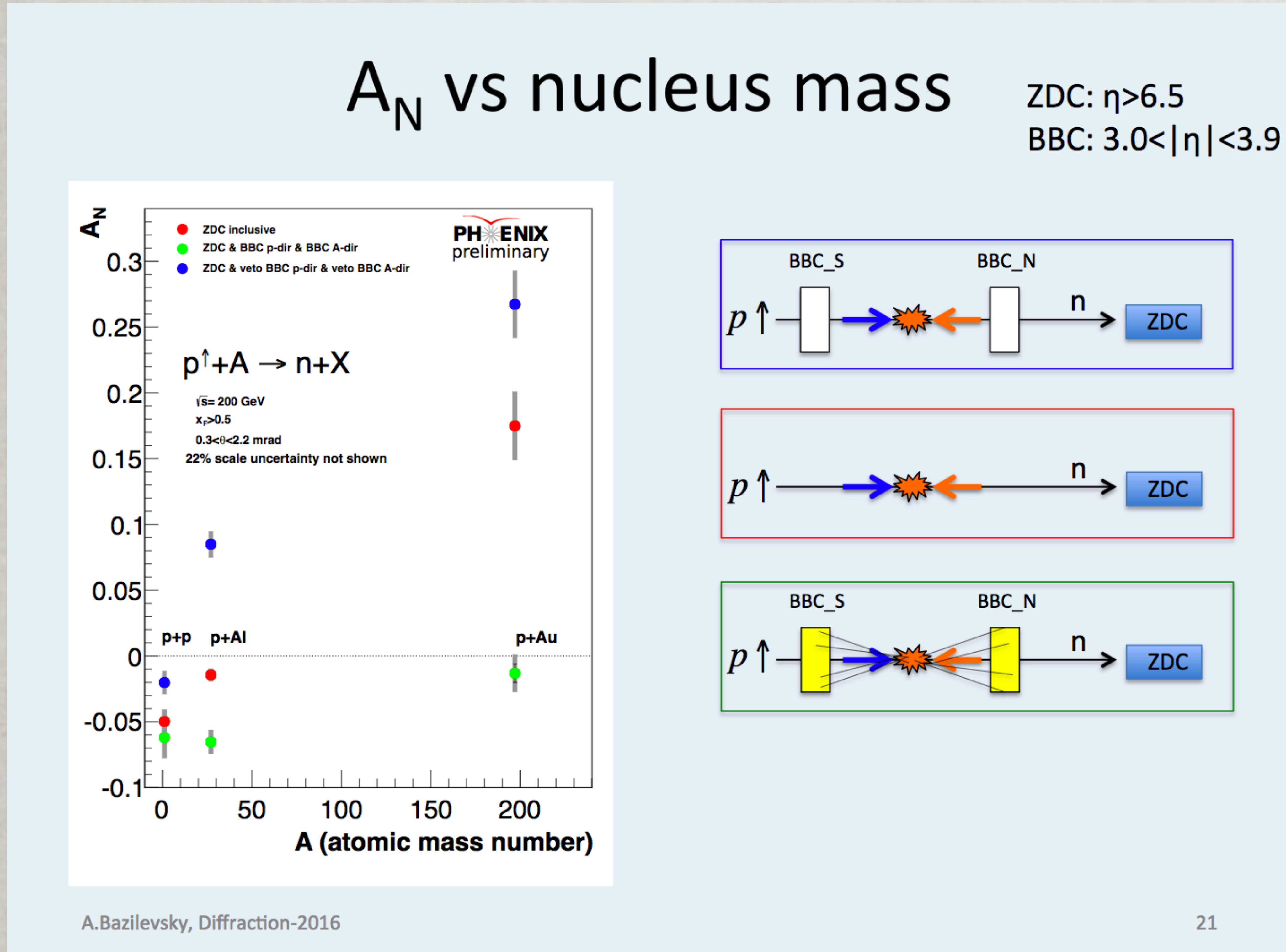




This sample of events with nuclear break-up is reasonably well explained.

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

Rapidity gap vs inclusive channels



$$\frac{\sigma_{\rm diff}(\mathbf{pA}\to\mathbf{nX})}{\sigma_{\rm incl}(\mathbf{pA}\to\mathbf{nX})} = \begin{matrix} 0.25 & \mathbf{pp} \\ 0.34 & \mathbf{pAl} \\ 0.66 & \mathbf{pAu} \end{matrix}$$

The fraction of rapidity-gap events rises with A, while hadronic mechanisms lead to a nearly A-independent fraction of 0.25.

★ This might indicate at an UPC Coulomb excitation mechanism, which has factor $\mathbf{Z^2}$

★ Another peculiar feature of the rapidity gap events is the extremely small invariant mass M of the diffractive excitation p->nπ.

The overall momentum transfer in coherent production $\mathbf{p_T^2 \sim 1/R_A^2 = 0.0008\,GeV^2}$ is small compared with the measured neutron $\langle \mathbf{q_T^2}\rangle = \mathbf{0.013\,GeV^2}$, and is even much less in Coulomb excitation. Neglecting qT, and fixing z=0.75, the invariant mass is very small,

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

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. $\pi - \tilde{\mathbf{a}}_1$ 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 $\mathbf{A_N}$ of leading neutrons due to $\pi - \tilde{\mathbf{a}}_1$ interference are calculated in good agreement with data for incoherent neutron production, associated with a nuclear break-up.

- Large values of $\mathbf{A_N}$ in diffractive/Coulomb dissociation p->nπ remain unexplained so far.

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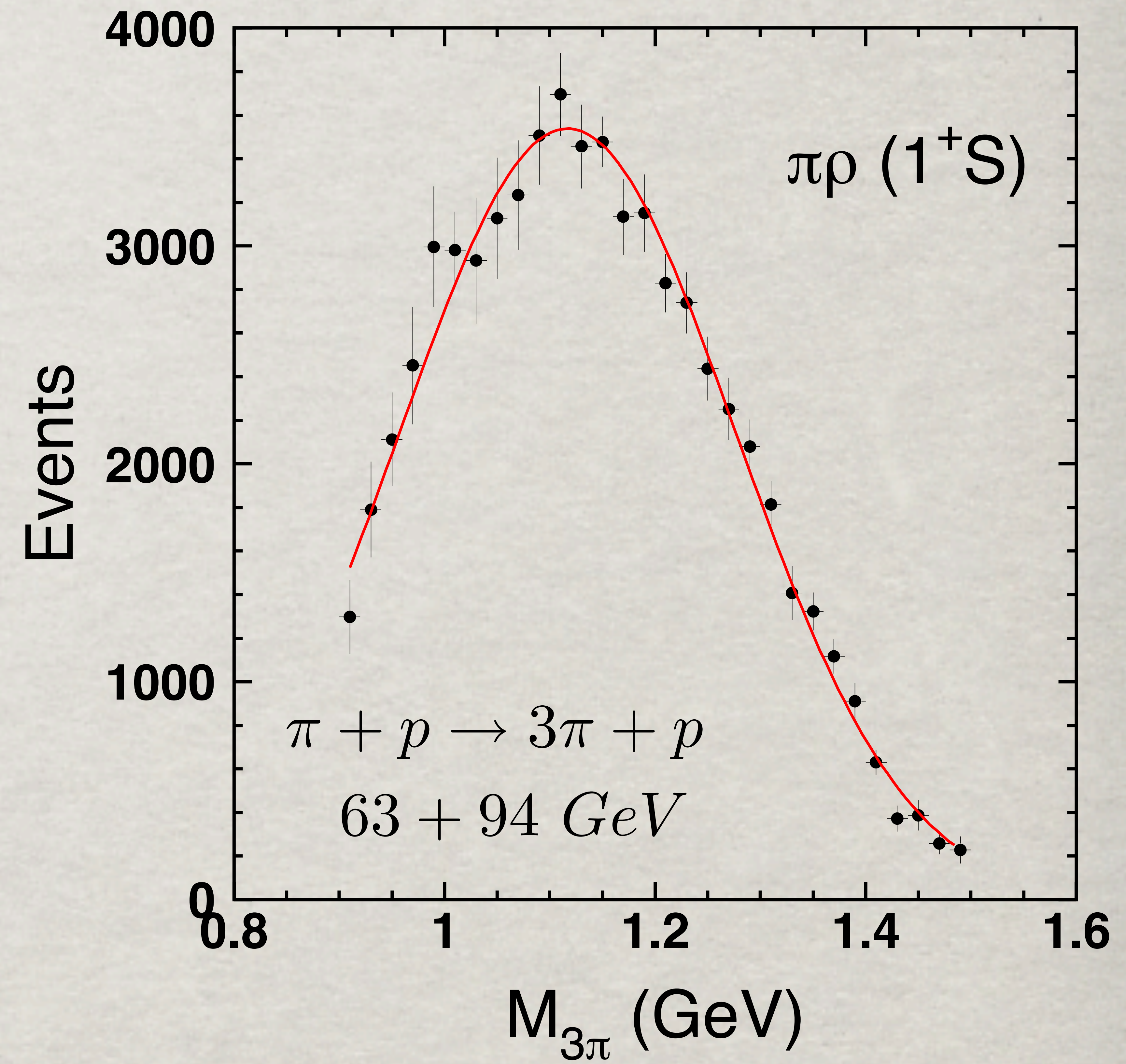
BACKUPS

a_1 production cross section

The $\mathbf{a_1}$ is a weak pole: no axial-vector dominance for the axial current.

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



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

$$\left.\frac{\mathbf{d}\sigma_{\pi\mathbf{p}\to\mathbf{ap}}(\mathbf{E_{lab}} = \mathbf{94}\,\mathrm{GeV})}{\mathbf{dq_T^2}}\right|_{\mathbf{q_T=0}} = \mathbf{0.8 \pm 0.08}\frac{\mathrm{mb}}{\mathrm{GeV}^{\mathbf{2}}}$$

Extrapolated to the RHIC energy range correcting for absorption.

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B. Kopeliovich, Diffraction 2016

BACKUPS

aNN coupling

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

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

Goldberger-Treiman relation

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

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

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

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

Thus,

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

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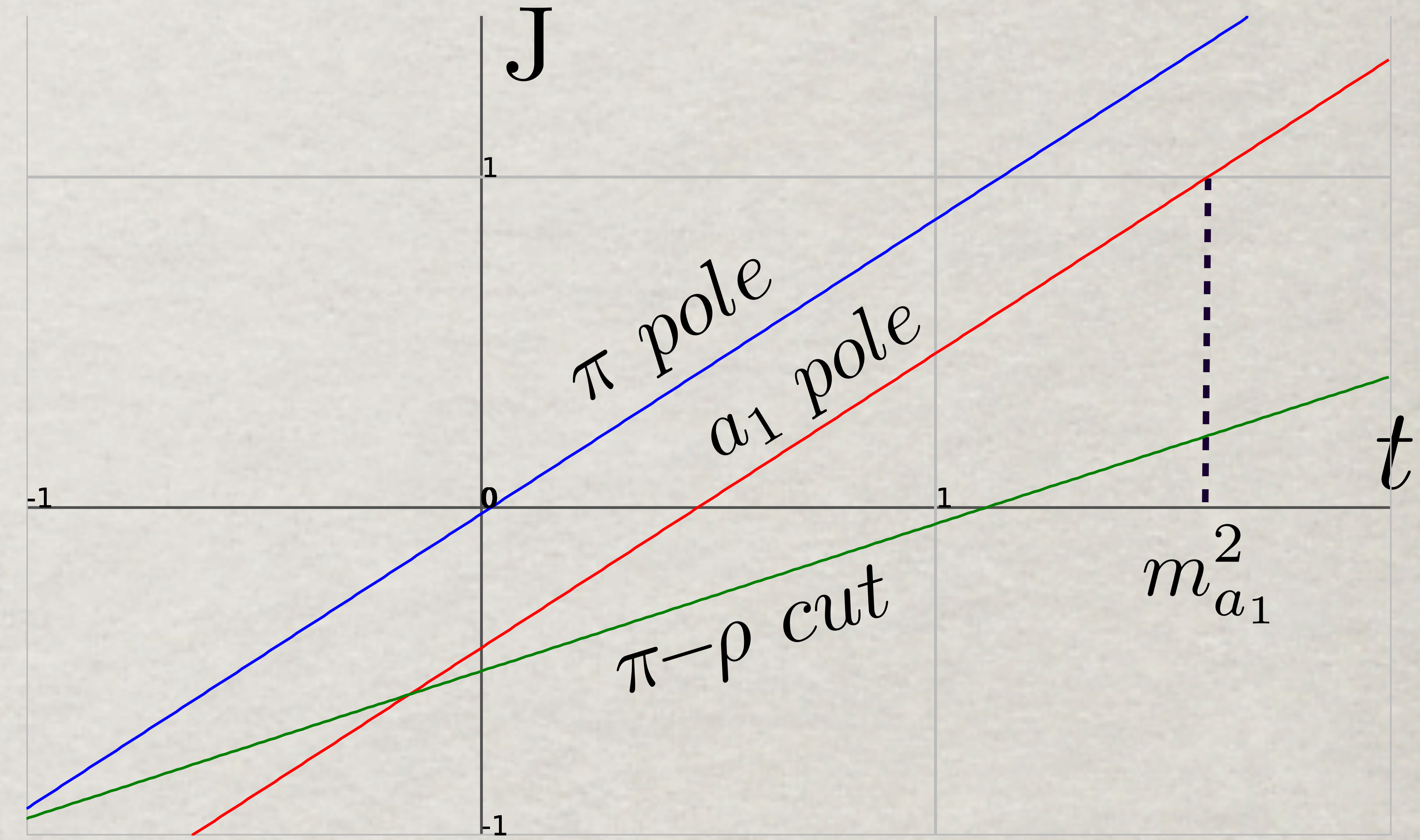
BACKUPS
Regge trajectories

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

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

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

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



The signature factor of the effective $\mathbf{1^+S}$ state

$$\eta_{\mathbf{a}}(\mathbf{t}) = -\mathbf{i} - \mathbf{tg}\left[\pi\alpha_{\mathbf{a}}(\mathbf{t})/\mathbf{2}\right]$$

The phase shift relative the pion pole is large

$$\phi_{\mathbf{a}}(\mathbf{t}) - \phi_\pi(\mathbf{t}) \approx \frac{\pi}{\mathbf{2}}\left[\mathbf{1.5 + 0.45\,t}\right]$$