Single spin asymmetry for forward neutron production

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Forward neutron production in pp collisions

Collaboration with Boris Kopeliovich, Irina Potashnikova and Ivan Schmidt

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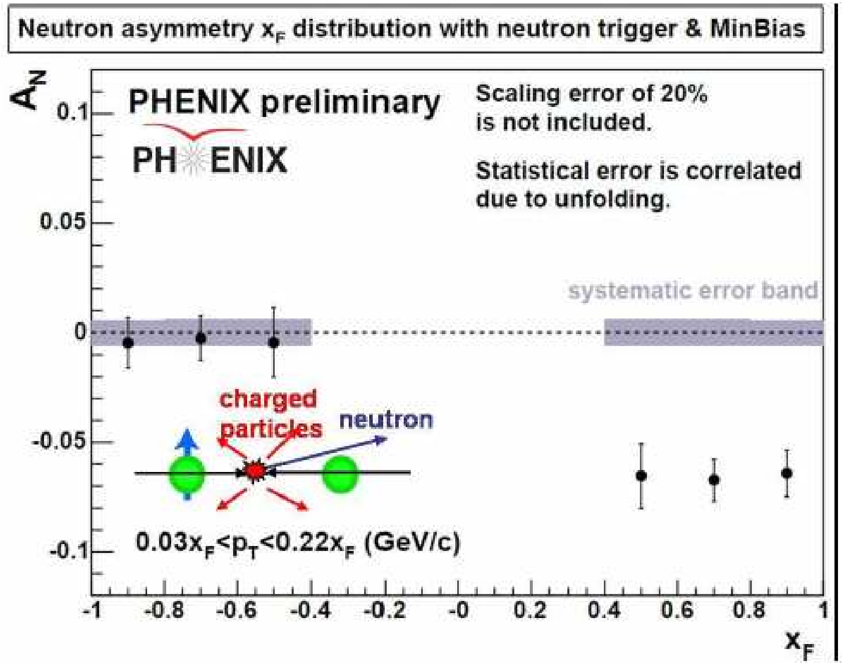
Single spin asymmetry A_N for neutron production at RHIC

K. Tanida (PHENIX Coll.) J. Phys. Conf. Ser. 295, 012097 (2011)

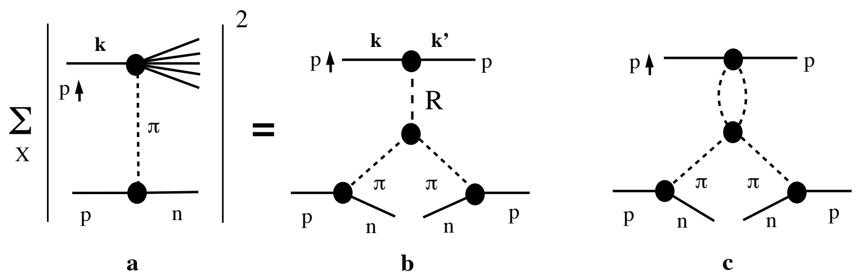
$A_N(x_F < 0) = 0$, a universal behavior, whereas $A_N(x_F > 0)$ is non-zero, at variance with the symmetry property of the cross section $\sigma(x_F) = \sigma(-x_F)$



The region $x_F < 0$ in Regge Theory

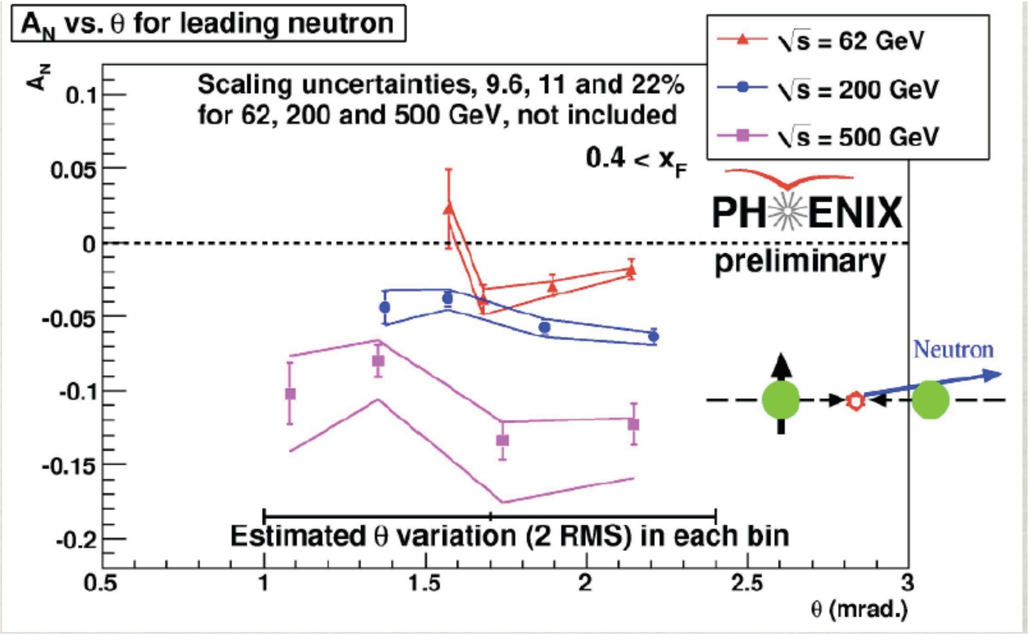
The Abarbanel-Gross theorem (PRL 26,732 (1971)), based on Regge factorization, predicts $A_N = 0$, for particle produced in the fragmentation region of an unpolarized beam.

Regge cuts in c) breakdown this statement, but one gets a tiny magnitude effect compatible with zero



Single spin asymmetry for neutron production at RHIC

This way of presenting data, suggests a strong energy dependence

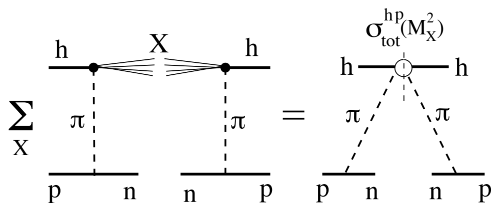


Spin structure of the pion pole

The Born approximation pion exchange contribution to the amplitude of neutron production $pp \to nX$, depicted below, in the leading order in small parameter $m_N/\sqrt{s}$ has the form

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

$z = p_n^+/p_p^+ \to 1$, $M_X^2 = (1-z)s$, $\vec{\sigma}$ are Pauli matrices, $\xi_{p,n}$ are the p, n spinors, $\vec{q}_T$ is the transverse component of the momentum transfer and $\tilde{q}_L = (1-z)\, m_N$.
It includes both non-flip and spin-flip terms, but no phase difference so $A_N = 0$.
In the region of small $1 - z \ll 1$ the pseudoscalar amplitude $\phi^B(q_T, z)$ has the triple-Regge form, $\phi^B(q_T, z) = \frac{\alpha'_\pi}{8}\, G_{\pi^+ pn}(t)\, \eta_\pi(t)\, (1-z)^{-\alpha_\pi(t)} \times A_{\pi^+ p\to X}(M_X^2)$
where the 4-momentum transfer squared t has the form, $t = -\frac{1}{z}\, \left(\tilde{q}_L^2 + q_T^2\right)$
and $\eta_\pi(t)$ is the phase (signature) factor which can be expanded near the pion pole as, $\eta_\pi(t) = i - ctg\left[\frac{\pi\alpha_\pi(t)}{2}\right] \approx i + \frac{2}{\pi\alpha'_\pi}\, \frac{1}{m_\pi^2 - t}$ We assume a linear pion Regge trajectory $\alpha_\pi(t) = \alpha'_\pi(t - m_\pi^2)$, where $\alpha'_\pi \approx 0.9^{-2}$.



Spin structure of the pion pole

The effective vertex function $G_{\pi^+pn}(t) = g_{\pi^+pn}\exp(R_1^2 t)$ includes the pion-nucleon coupling and the form factor which incorporates the t-dependence of the coupling and of the πN inelastic amplitude. We take, $g^2_{\pi^+pn}(t)/8\pi = 13.85$ and $R_1^2 = 0.3$GeV^{-2}.
Notice that the choice of R_1 does not bring much uncertainty, since we focus here at data for forward production, $q_T = 0$, so t is quite small.
The amplitudes are normalized as, $\sigma_{tot}^{\pi^+p}(s' = M_X^2) = \frac{1}{M_X^2}\sum\limits_X |A_{\pi^+p\to X}(M_X^2)|^2$,
where different hadronic final states X are summed at fixed invariant mass M_X.
Correspondingly, the differential cross section of inclusive neutron production reads,

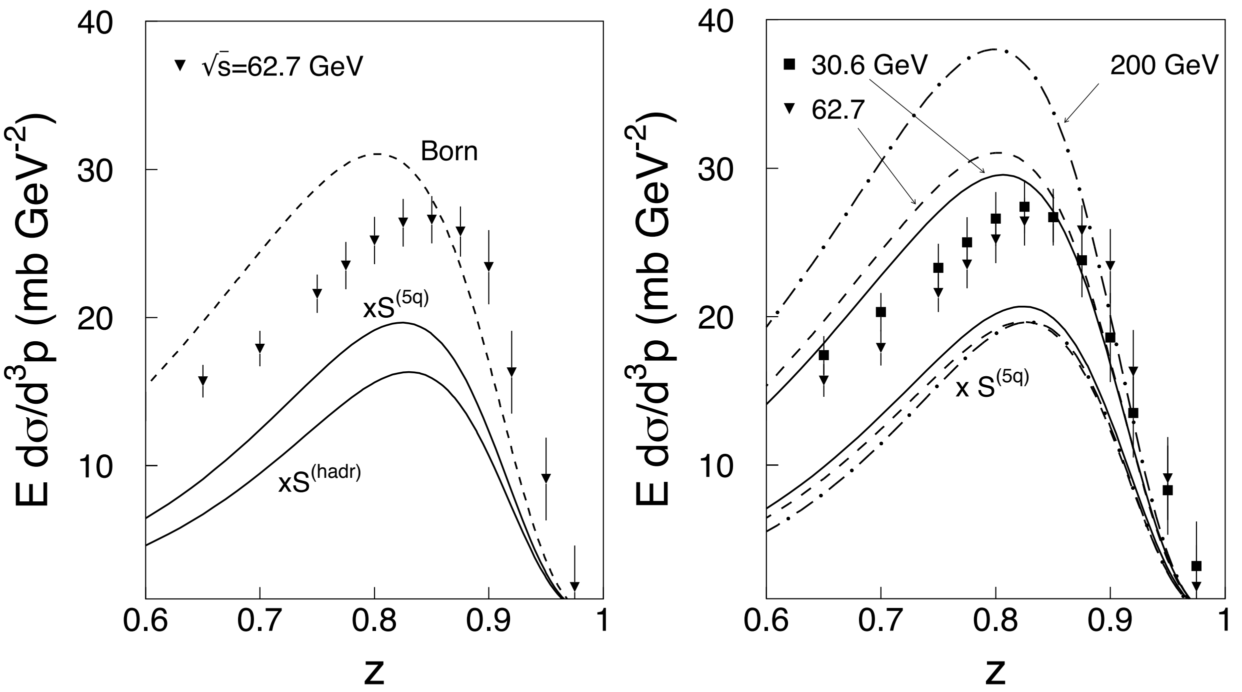
$$z\,\frac{d\sigma^B_{p\to n}}{dz\,dq_T^2} = \frac{1}{s}\left|A^B_{p\to n}(\vec{q}_T, z)\right|^2 =$$

$$\left(\frac{\alpha'_\pi}{8}\right)^2 |t| G^2_{\pi^+pn}(t)\,|\eta_\pi(t)|^2\,(1-z)^{1-2\alpha_\pi(t)} \times \sigma^{\pi^+p}_{tot}(s' = M_X^2)$$

Since at $z \to 1$ the value of M_X^2 decreases, we rely on a realistic fit to the experimental data for π^+p total cross section.
The results of the Born approximation calculation, at $\sqrt{s} = 200,\ 62.7$ and 30.6, are depicted together with the ISR data.

Cross section: Theory versus Data

Born term overestimates rather inaccurate ISR data. What next?

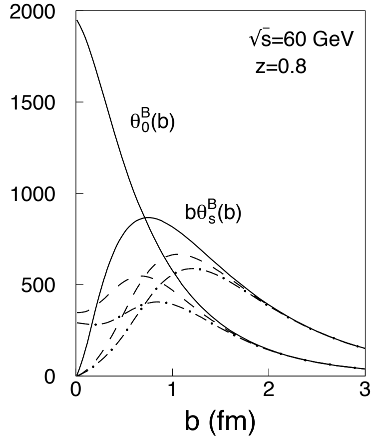


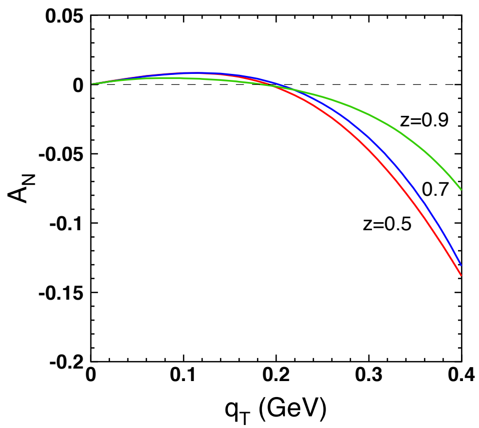
Initial/Final state interactions

These absorptive corrections factorize in impact parameter and become much simpler than in momentum representation. So we perform a Fourier transform of the amplitude to get

$$f^B_{p\to n}(\vec{b},z) = \frac{1}{\sqrt{z}}\,\bar{\xi}_n\left[\sigma_3\,\tilde{q}_L\,\theta^B_0(b,z) - i\,\frac{\vec{\sigma}\cdot\vec{b}}{b}\,\theta^B_s(b,z)\right]\xi_p$$

reduced after multiplication by the survival probability $f_{p\to n}(b,z) = f^B_{p\to n}(b,z)\,S(b,z)$. It leads to a too strong reduction of the cross section. Although non-flip and spin-flip amplitudes have different phases, it is too small to explain the PHENIX data for A_N.





Interference with other Reggeons

In addition to pion exchange, other Regge poles $R = \rho,\ a_2,\ \omega,\ \ a_1$, etc. and Regge cuts can contribute to the $pp \to nX$ reaction

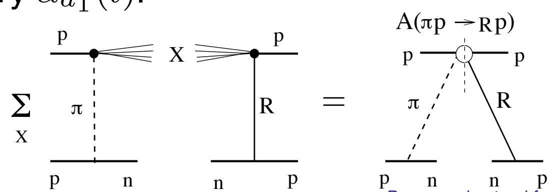
The c.m. collision energy squared M_X^2 of $\pi p \to Rp$ is large and the forward amplitude $A(\pi p \to Rp)$ for natural parity states $R = \rho, a_2, \omega, ..$is suppressed at RHIC energies. Only unatural parity states can be produced diffractively, so $A(\pi p \to a_1 p) \sim const.$.
The $a_1 NN$ vertex is known to be pure non spin-flip and gives
$A^{a_1}_{p\to n}(q_T, z) = e^L_\mu \,\bar{n}\, \gamma_5 \gamma_\mu \, p = \frac{2 m_N q_L}{\sqrt{|t|}}\ \phi^a_0(q_T, z)\, \bar{\xi}_n \sigma_3 \xi_p$. In the Born approximation,

$$\phi^a_0(q_T, z) = \frac{\alpha'_{a_1}}{8}\, G_{a_1^+ pn}(t)\, \eta_{a_1}(t) \times (1-z)^{-\alpha_{a_1}(t)} \times A_{a_1^+ p \to X}(M_X^2),$$ and

$$\eta_{a_1}(t) = -i - tg\left[\frac{\pi \alpha_{a_1}(t)}{2}\right].$$

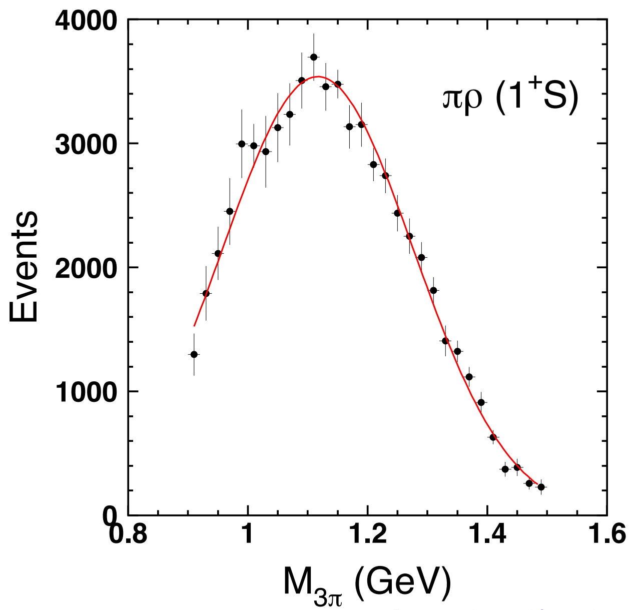
The amplitude contains three unknowns, to be fixed before numerical evaluation:

- The amplitude $A_{a_1^+ p \to X}(M_X^2)$;
- The a_1-nucleon vertex $G_{a_1^+ pn}(t)$;
- The Regge trajectory $\alpha_{a_1}(t)$.



a_1 production cross section

The a_1 is a very weak pole. Nevertheless, the invariant mass distribution of diffractively produced $\pi\rho$ pair in 1^+S state forms a strong and narrow peak, with a similar position and width as a_1. This can be treated as an effective pole "'a"' with mass m_a =1.1GeV. The cross section of $\pi + p \to \pi\rho(1^+S) + p$ was measured up to 94GeV $d\sigma/dp_T^2|_{p_T=0} = 0.8 \pm 0.08 mbGeV^{-2}$. Must extrapolated to RHIC energy range



aNN coupling and Regge trajectories

PCAC relates the pion-nucleon coupling with the axial constant
$g_{\pi NN} = \sqrt{2} m_N G_A / f_\pi$ (Goldberger Treiman relation)
G_A represents the contribution to the dispersion relation of all axial-vector states heavier than the pion. Assuming dominance of the $1^+ S$ a-peak, we get
$G_A = \sqrt{2} f_a g_{aNN} / m_a^2$
According to the second Weinberg sum rule which relates vector and axial currents one has
$f_a = f_\rho = \sqrt{2} m_\rho^2 / \gamma_\rho$, where γ_ρ is the universal coupling ($\rho NN, \rho\pi\pi$,..) $\gamma_\rho^2 / 4\pi = 2.4$
Thus we get $g_{aNN} / g_{\pi NN} = m_a^2 f_\pi / 2 m_N f_\rho \simeq 0.5$

Concerning the Regge trajectories
$\alpha_{\pi\rho}(t) = \alpha_\pi(0) + \alpha_\rho(0) - 1 + \alpha' t/2$ with $\alpha' = 0.9$GeV^{-2}
The phase shift relative to the pion pole is large
$\phi_a(t) - \phi_\pi(t) \simeq \pi/2 [1.5 + 0.45 t]$

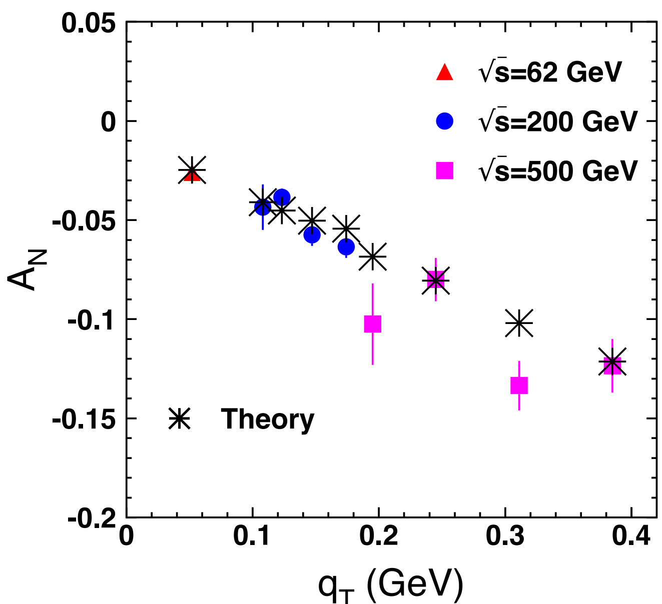
Pion-a_1 interference

$A_N(q_T, z) =$

$$q_T \frac{4 m_N\, q_L}{|t|^{3/2}} (1 - z)^{\Delta\alpha(t)} \frac{\mathrm{Im}\,\eta_\pi^*(t)\, \eta_{a_1}(t)}{|\eta_\pi(t)|^2} \times \frac{g_{a_1^+ pn}}{g_{\pi^+ pn}} \left(\frac{d\sigma_{\pi p \to a_1 p}(M_X^2)/dp_T^2|_{p_T=0}}{d\sigma_{\pi p \to \pi p}(M_X^2)/dp_T^2|_{p_T=0}} \right)^{1/2}$$

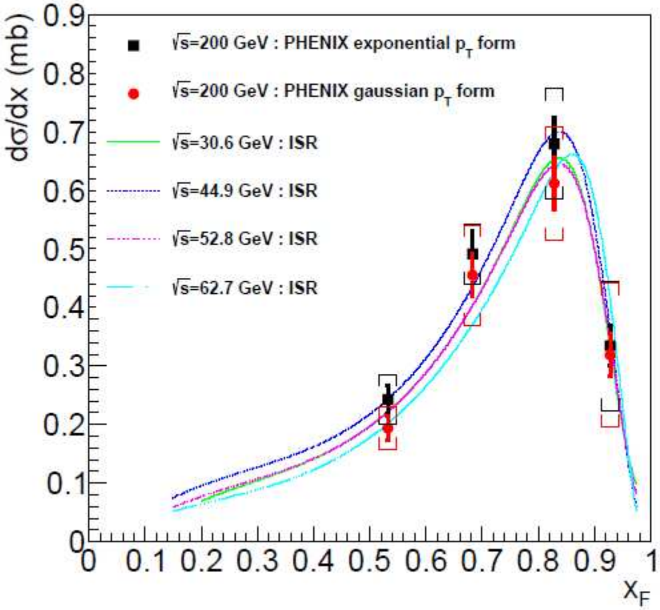
where $\Delta\alpha(t) = \alpha_\pi(t) - \alpha_{a_1}(t)$.

The data agree well with energy independence.



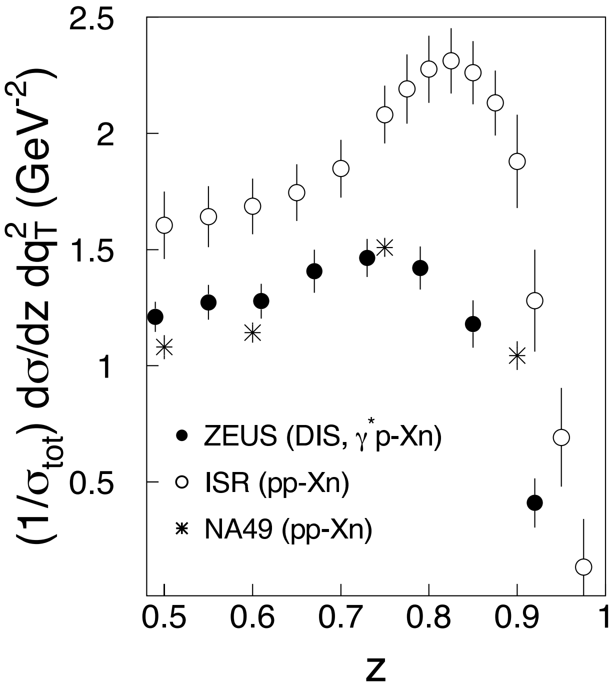
Cross section from PHENIX arXiv:1209.3283

This integrated cross section, with huge errors, was obtained using data from two different ISR experiments, with 20% normalization error each and assuming a constant slope $B = 4.8\text{GeV}^{-1}$, which is obviously incorrect. Need urgently some clarification. May be from LHCf.



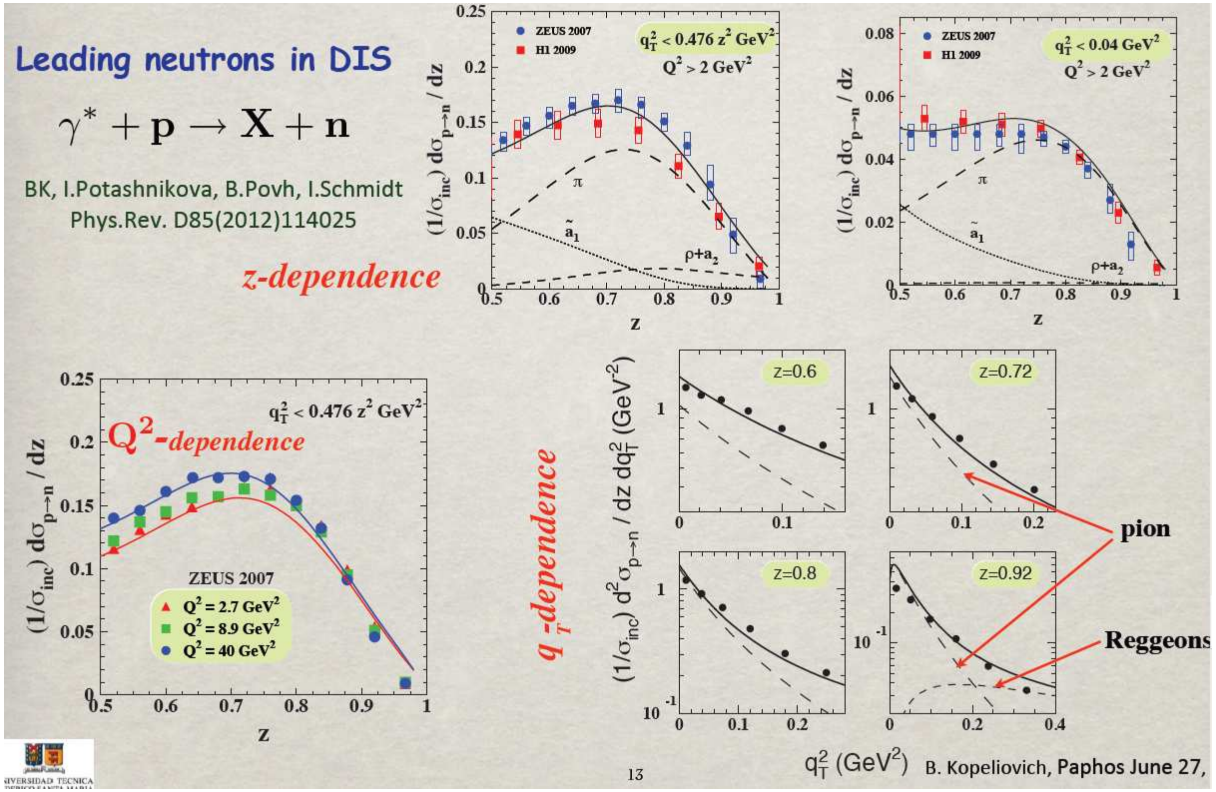
ISR data disagree with ZEUS

One may suspect that ISR data has an important normalization error ???



ZEUS and H1 data at HERA

Excellent description of DIS data



Concluding remarks

- We have a simple mechanism to describe the single spin asymmetry data
- It might be useful to investigate both experimentaly and theoreticaly at higher qT
- The cross section data remains a problem for
- The theory