Study the pbar-p → $e^+e^-\pi^0$ process at low e^+e^- - invariant masses at PANDA

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Outline

- Model description of the process $\bar{p}p \rightarrow \gamma^{*}\pi^{0} -> e^{+}e^{-}\pi^{0}$ within the framework of
  - Transition Distribution Amplitudes (TDAs)
  - Regge pole description (baryon exchange and form factors)

- Feasibility measurements at PANDA

  I. P_{lab}= 1.7 GeV/c (s=5 GeV^2); q^2 = 0.605 ± 0.01 (GeV/c^2)^2

  II. P_{lab}= 1.7 GeV/c (s=5 GeV^2); q^2 = 2.0 ± 0.125 (GeV/c^2)^2

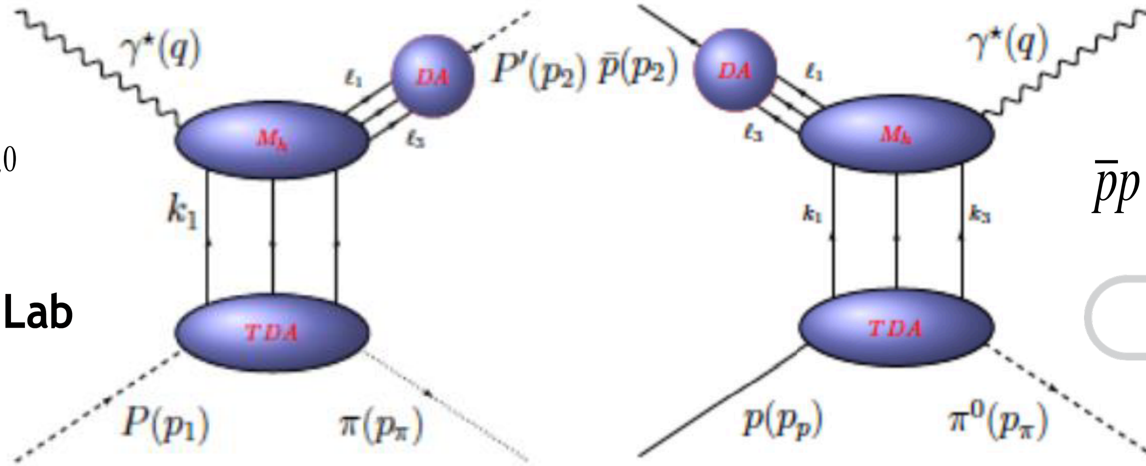
  - Determination of the signal efficiency (PANDAROOT)

  - Study of the reaction mechanism at PANDA – determination of the statistical precisions on the differential cross sections

  - Proton form factors in the unphysical region

Nucleon to meson TDAs

$ep \rightarrow e' p' \pi^0$



$\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+ e^- \pi^0$

J.P. Lansberg et al. (2012), B. Pire, L. Szymanowski, K. Semenov-Tian-Shansky (2013)

- **New class of non-perturbative structure functions**
- **Occur in collinear factorization description of various hard exclusive processes**
- **Are independent of reaction type, s and q^2**

Experimental checks of the collinear factorization regime in hard exclusive reactions:

$\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+ e^- \pi^0$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\ \mathrm{d}q^2\ \mathrm{d}\cos\theta_\ell^*}\Big|_{\text{Leading twist}} = \frac{K}{s - 4M^2} \boxed{\frac{1}{(q^2)^5}} \boxed{(1 + \cos^2\theta_\ell^*)}$$

Nucleon to meson TDAs at PANDA

Collinear factorization-TDAs
Large $q^2 \sim s$ (hard scale)
$|t| \ll q^2, s$, $|u| \ll q^2, s$

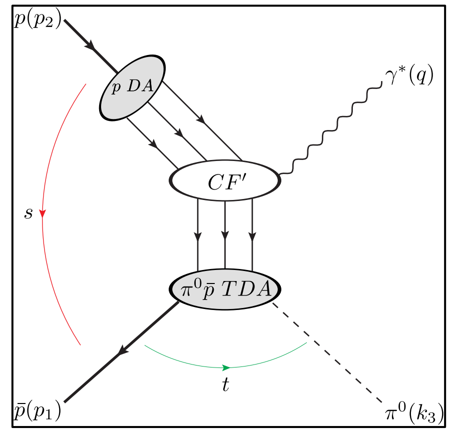
- Feasibility studies performed for q^2 above 3 $(\mathrm{GeV}/c^2)^2$
- Simplified model for TDAs – based on soft pion theorem: independent of t and u

➢ **Test QCD factorization**

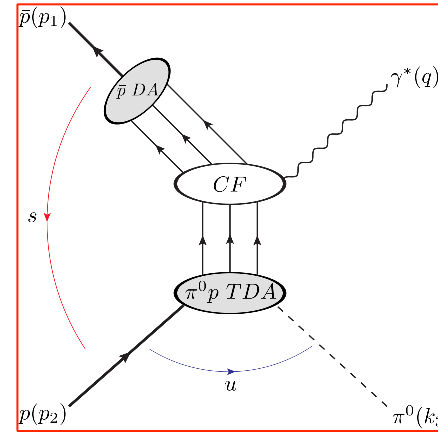
$$d\sigma / dq^2 = 1/(q^2)^5$$

$$d\sigma / \cos\theta_e^* \sim D \times (1 + C\cos^2\theta_e^*), C = 1$$

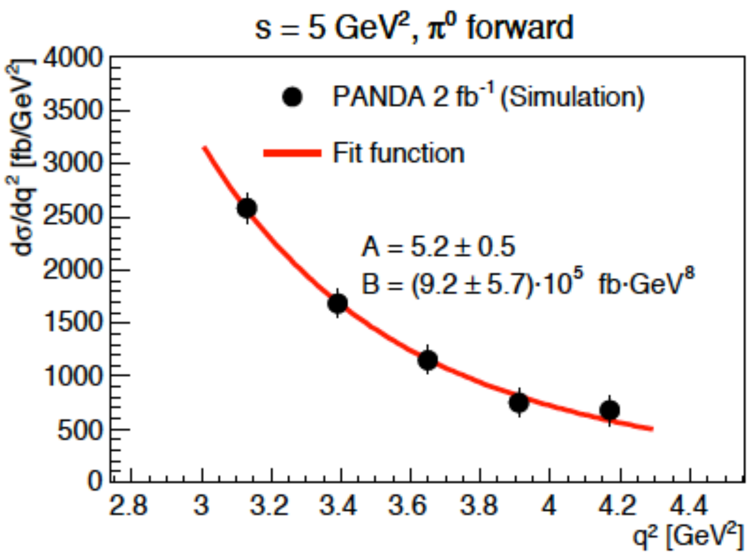
t is small
(near forward regime)

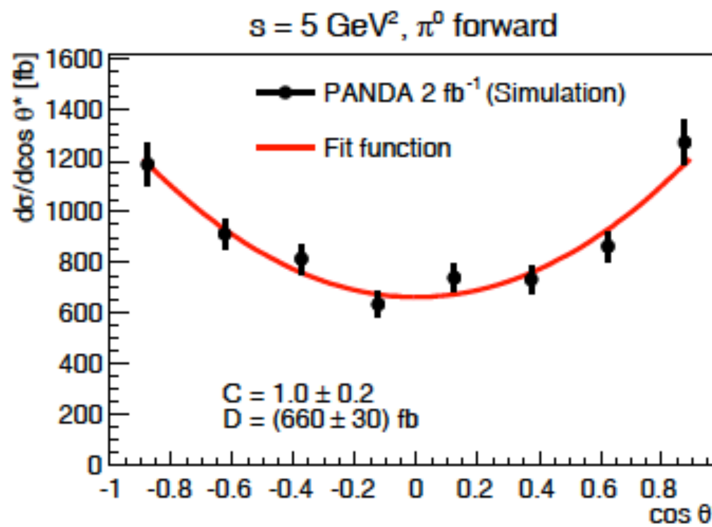


u is small
(near backward regime)



PANDA Collaboration
EPJA 51 (2015) 8, 107





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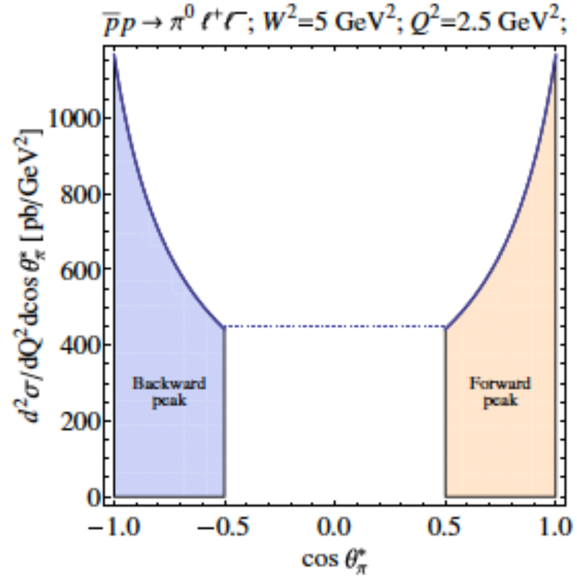
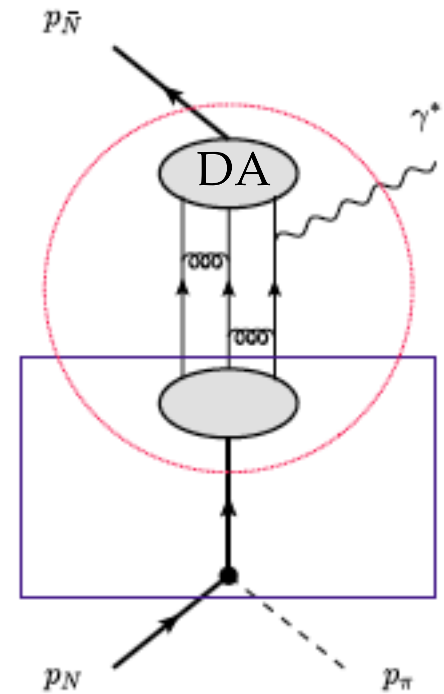
Nucleon to meson TDAs

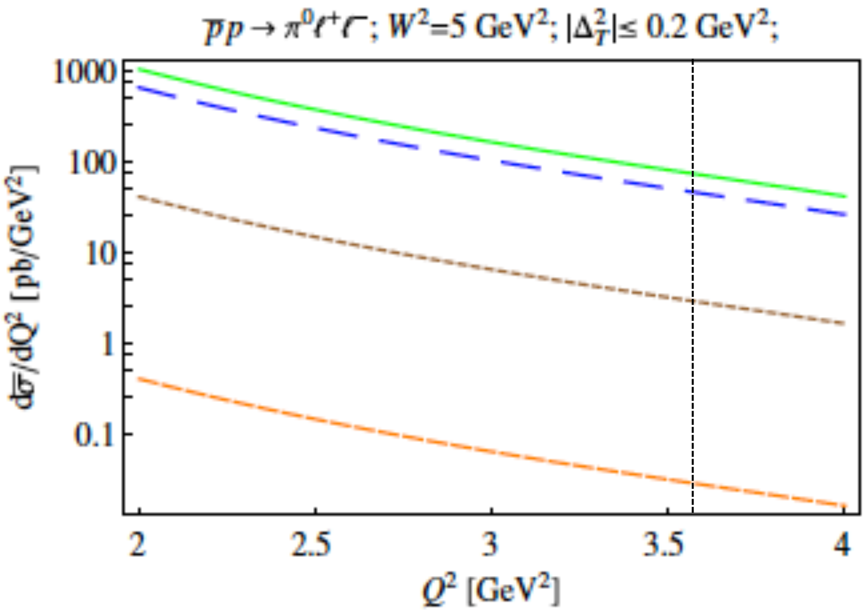
PRD 86, 114033 (2012)
B. Pire et al. [arXiv:2103.01079 [hep-ph]] (2020).

- More general model was proposed taking into account the dependence on t and u

- Contribution due to nucleon pole exchange was added





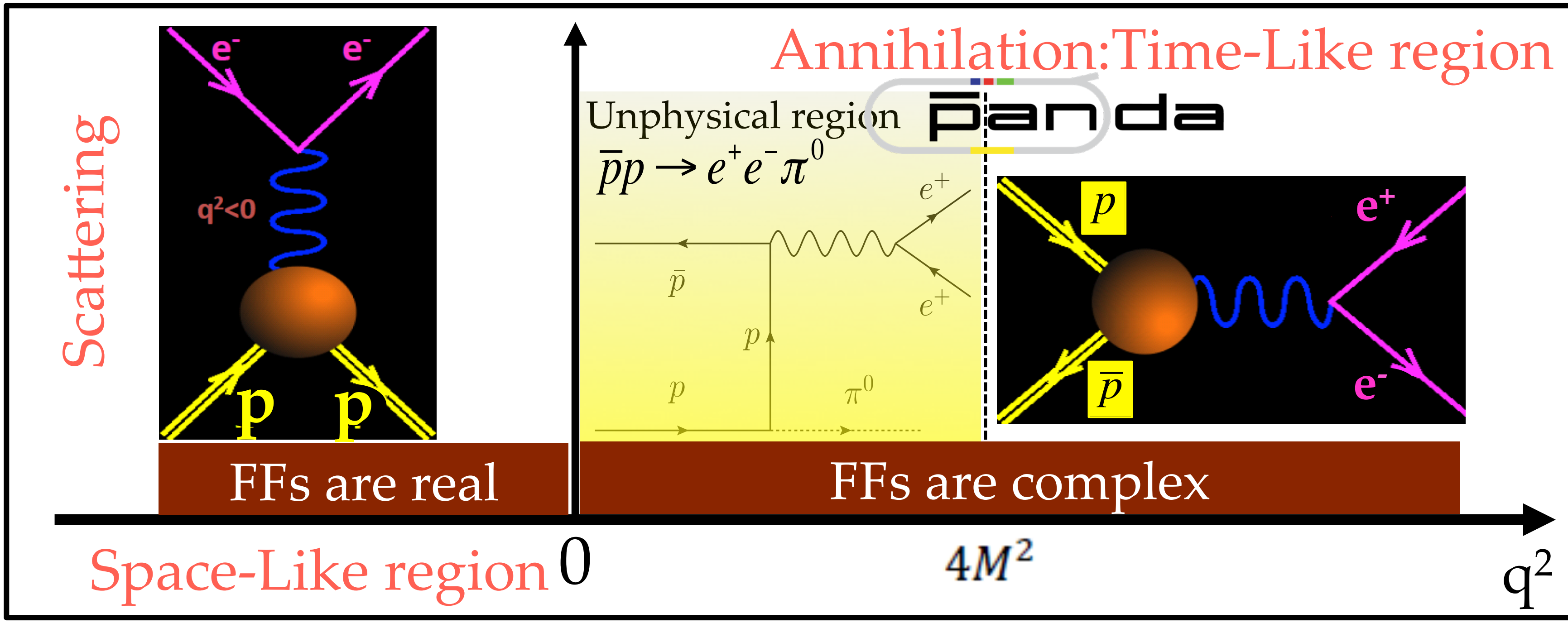


- Strong dependence of the cross section on proton distribution amplitude (DA) models

- For the same model used in previous feasibility studies, cross section is 2 order of magnitude larger

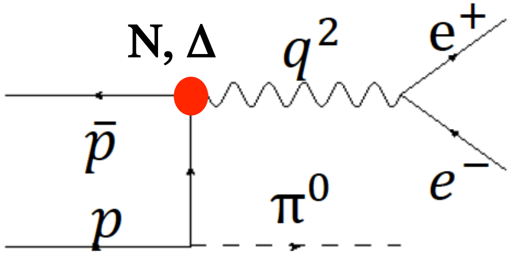
- Predictions down to 2 $(GeV/c^2)^2$ were given

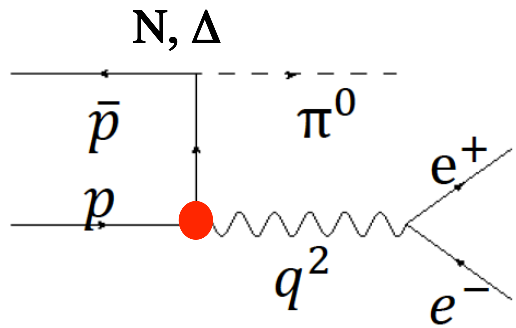
Proton electromagnetic form factors



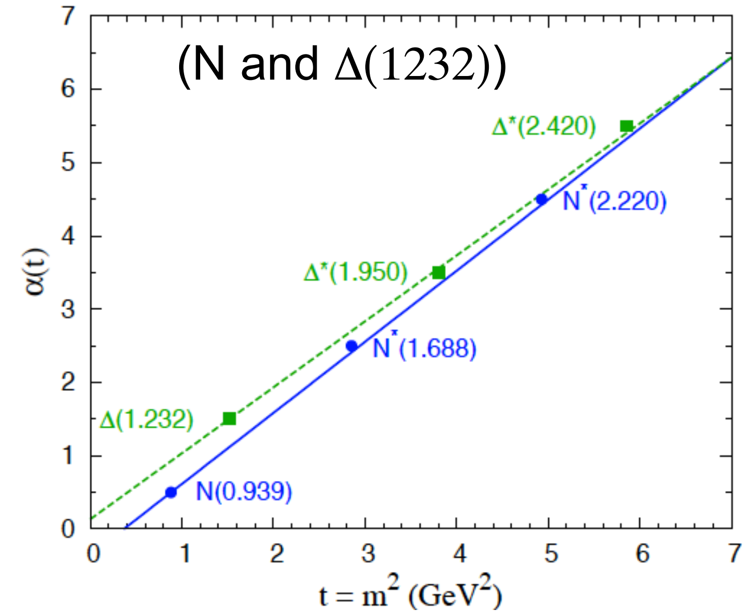
- M. P. Rekalo, Sov. J. Nucl. Phys. 1 (1965) 760
- C. Adamuscin et al., Phys. Rev. C 75, 045205 (2007)
- A.Z. Dubnickova , S. Dubnicka , M.P. Rekalo, Z. Phys. C 70, 473—481 (1996)
- G. I. Gakh et al. PHYSICAL REVIEW C 83, 025202 (2011)
- Feasibility studies by J. Boucher; PhD thesis (BaBar Framework)
- J. Guttmann, M. Vanderhaeghen, PLB B 719 (2013) 136–142

Differential cross section and hadronic tensors





PLB 719 (2013) 136–142



$$\frac{d\sigma}{dq^2 d\cos\theta_{\pi^0} d\Omega_e^*} \propto L^{\mu\nu} H_{\mu\nu}$$

Regge pole description at forward (|t|<<s) and backward (|u|<<s) regions (Regge limit)

Exchange of dominant baryon Regge trajectories

$$\frac{d\sigma}{dq^2 d\cos\theta_{\pi^0} d\Omega_e^*} = 4\pi e^2 q^2 (H_{11}+H_{22}+H_{33}) - 8e^2 p_e^{*2}\left(\frac{H_{11}+H_{22}}{2} + \frac{H_{11}-H_{22}}{2}\sin^2\theta_e^*\cos 2\varphi_e^* + 2H_{13}\sin\theta_e^*\cos\theta_e^*\cos\varphi_e^* + \frac{1}{2}(2H_{33}-H_{11}-H_{22})\cos^2\theta_e^*\right)$$

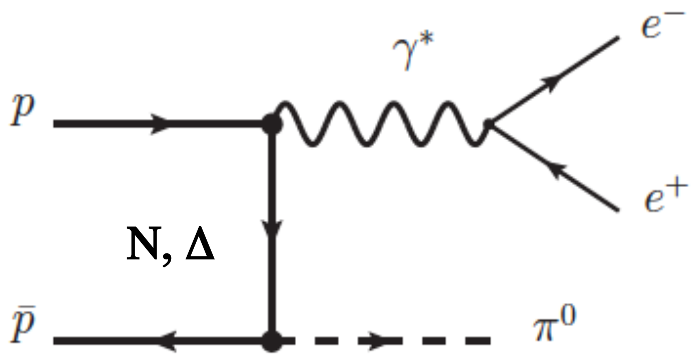
$\theta_{\pi 0}$ in the laboratory frame

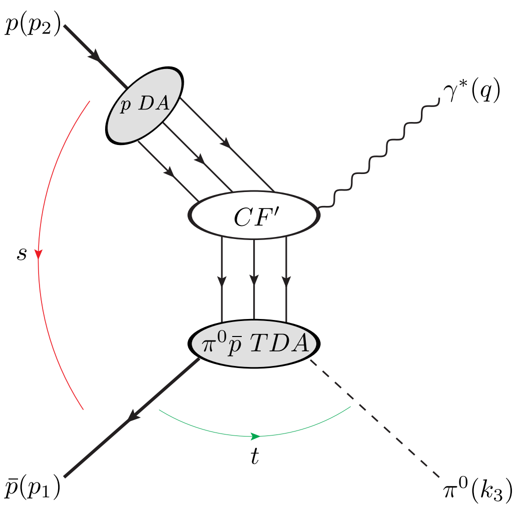
θ_e^*, φ_e^* in the γ^* rest frame

- $d\sigma/dq^2$ is predicted by the time-like form factors (~$1/q^5$ for TDAs)
- $d\sigma/dt$, $d\sigma/du$ by the **N and Δ** propagators (given by TDA model in collinear factorization)
- $d\sigma/d\cos\theta_e^*$ is a function of the process kinematical variables and the form factors (for TDAs ~ $1+\cos\theta_e^*$)

A. Study of the production mechanism

Measurements of the differential cross sections dσ/dt, dσ/du dσ/dcosθ_e* at PANDA





Description of the Monte Carlo simulations

- Signal $\bar{p}p \to e^+e^-\pi^0$; Main background $\bar{p}p \to \pi^+\pi^-\pi^0$

- PANDARoot version **oct19**, FairSoft **jun19p1**, FairRoot **v18.2**

- **Event generation**
  - Antiproton momentum (lab) p_{pbar}=1.7 GeV/c
    - $q^2 = 0.605 \pm 0.015$ (GeV/c^2)^2; $q^2 = 2.0 \pm 0.375$ (GeV/c^2)^2
  - PHSP angular distributions, PHOTOS switched on
  - 5.10^7 (10^8) events for the signal (background) in each q^2 interval

- **Event selection**
  - PID probability for e+/e- larger than 99% or 99.8% (EMC+STT+MVD+DRC)
  - $E_{EMC}/p > 0.8$ and dE/dx(STT) > 5.8
  - 4C kinematic fit ($\chi 2 < 50$ or $\chi 2 < 30$)

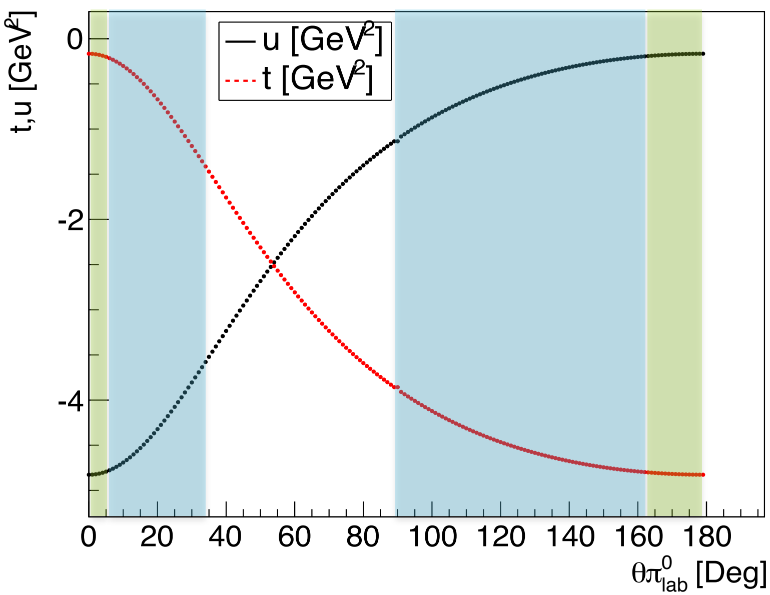
- **Signal efficiency in bins of q^2, $\theta_{\pi 0}$ $\cos\theta_e^*$, and φ_e^***
  - Integrated signal efficiency between 13% and 15%
  - Signal contamination from the main background at the order or below 1%

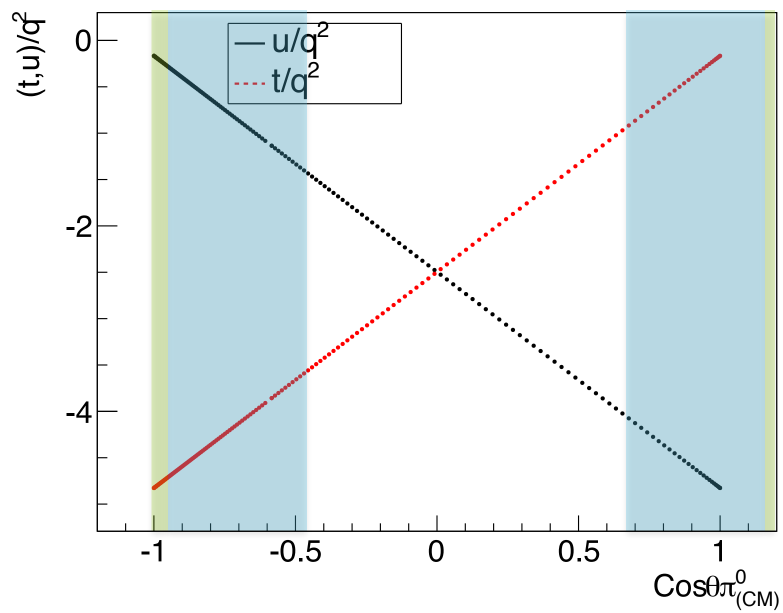
Feasibility studies – Case I

- P_{lab}= 1.7 GeV/c (s=5.4 GeV^2); q^2 = 0.605 ± 0.01 $(GeV/c^2)^2$

- Regge description expected for **$|cos\theta_{\pi 0}|_{CM}$ > 0.5 && $|t,u|/q^2$ > 20%**
  $\theta_{\pi 0}$(Lab)=[5°-32°], [83°-160°]

- TDAs description expected for **$|cos\theta_{\pi 0}|_{CM}$ > 0.5 && $|t,u|/q^2$ < 20%**
  $\theta_{\pi 0}$(Lab)=[0°-5°] , [160°-180°]



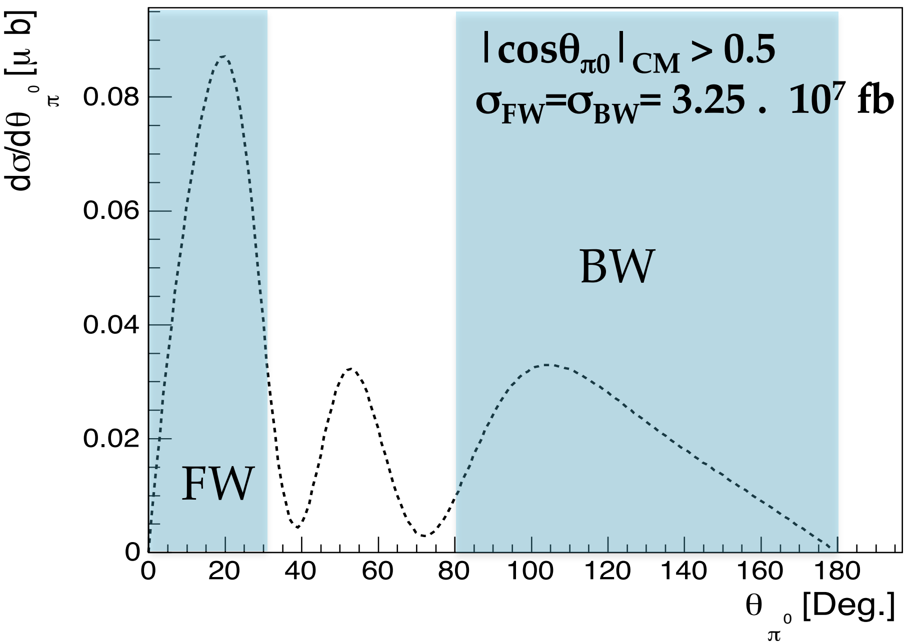


- At small s and q^2 below 1 $(GeV/c^2)^2$ the process is expected to occur through the exchange of dominant baryons
  - **Region for Time-like form factor measurements**

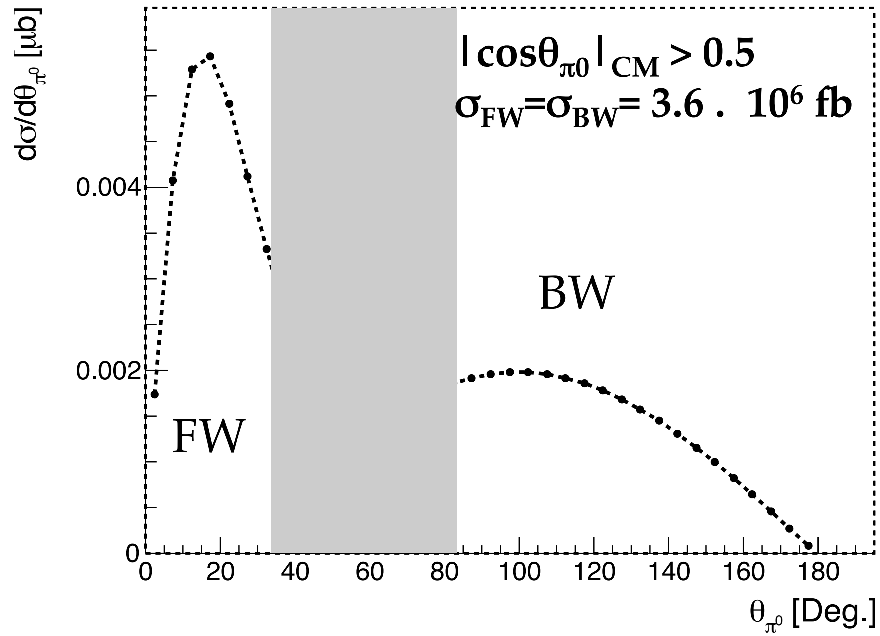
Theoretical cross sections- Case I

- P_{lab}= 1.7 GeV/c (s=5.4 GeV^2); $q^2 = 0.605 \pm 0.01\ (GeV/c^2)^2$

Regge description



TDA-model



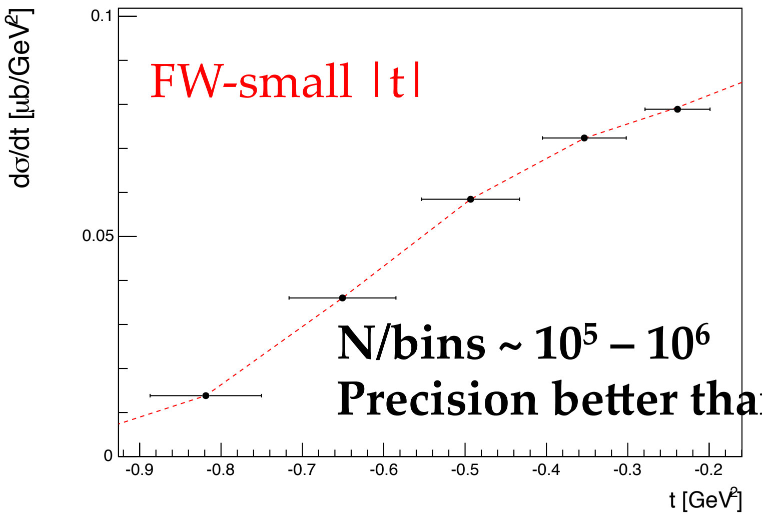
- Large cross section
- Form factors Vector Meson Dominance; F. Iachello, PRC 69, 055204 (2004)

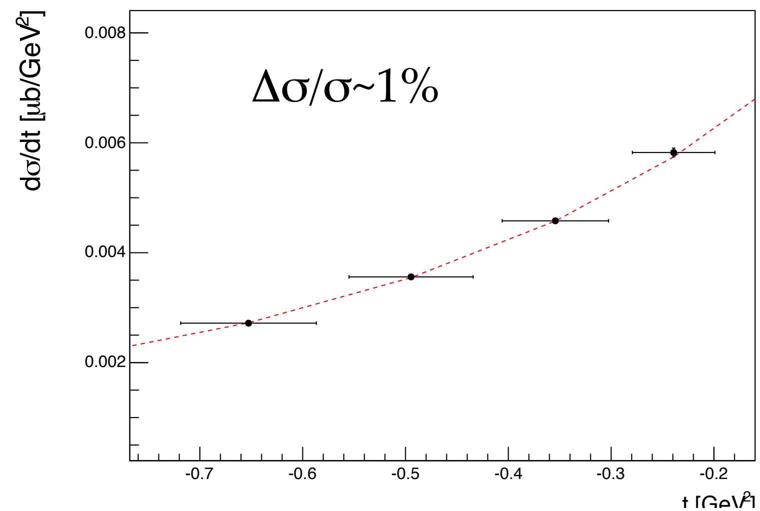
- TDA model shown only to compare the distributions with Regge description;
- non physical counting rate ($|t,u| \sim q^2$)

Feasibility studies – Case I - dσ/dt, dσ/du

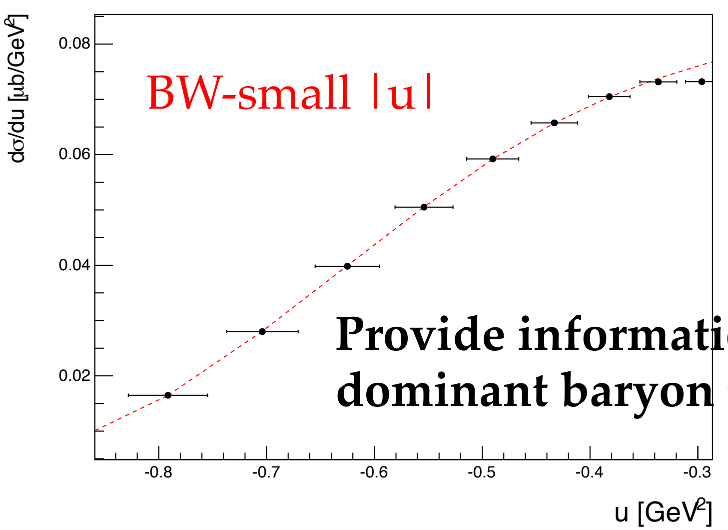
Regge description

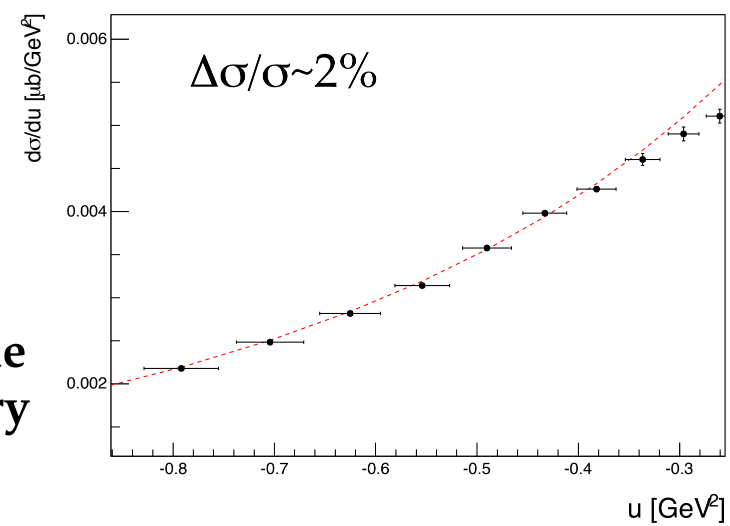
TDA-model





N/bins ~ 10^5 – 10^6
Precision better than 1 %





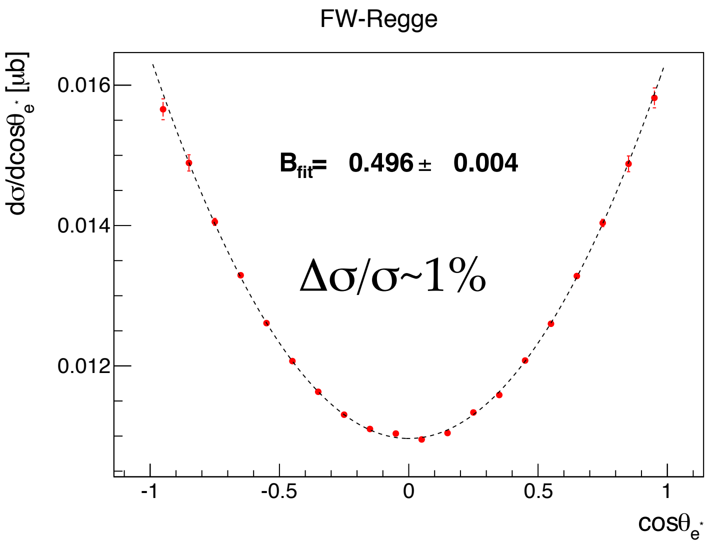
Provide information on the dominant baryon trajectory

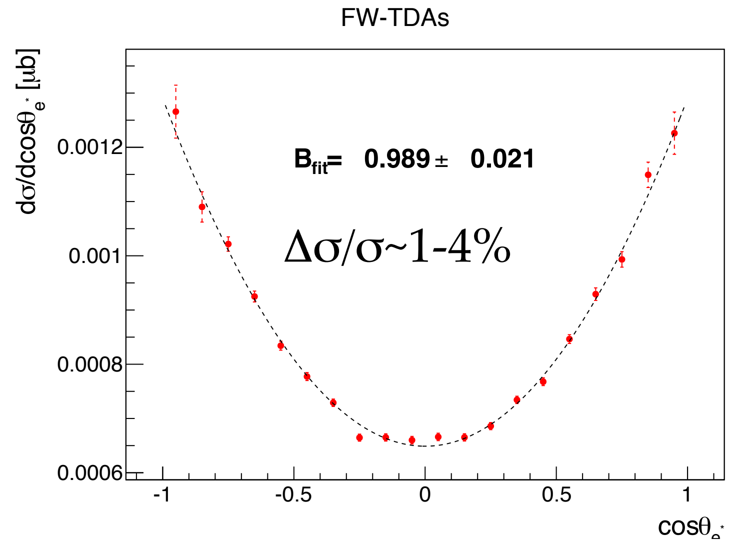
Feasibility studies – Case I - $d\sigma/d\cos\theta_e^*$

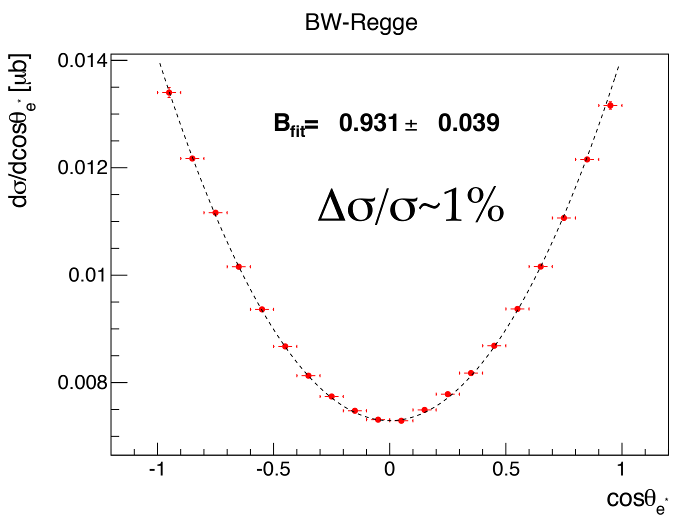
$$d\sigma / \cos\theta_e^* \sim A \times (1 + B\cos^2\theta_e^*)$$

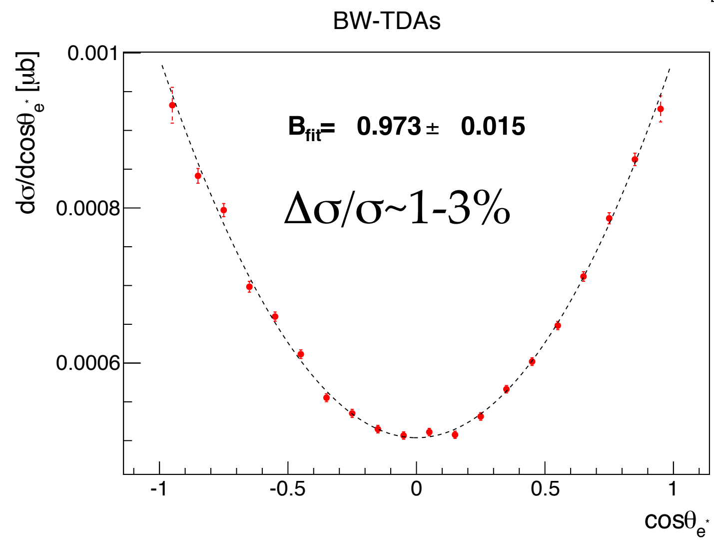
Regge description

TDA-model (B=1)



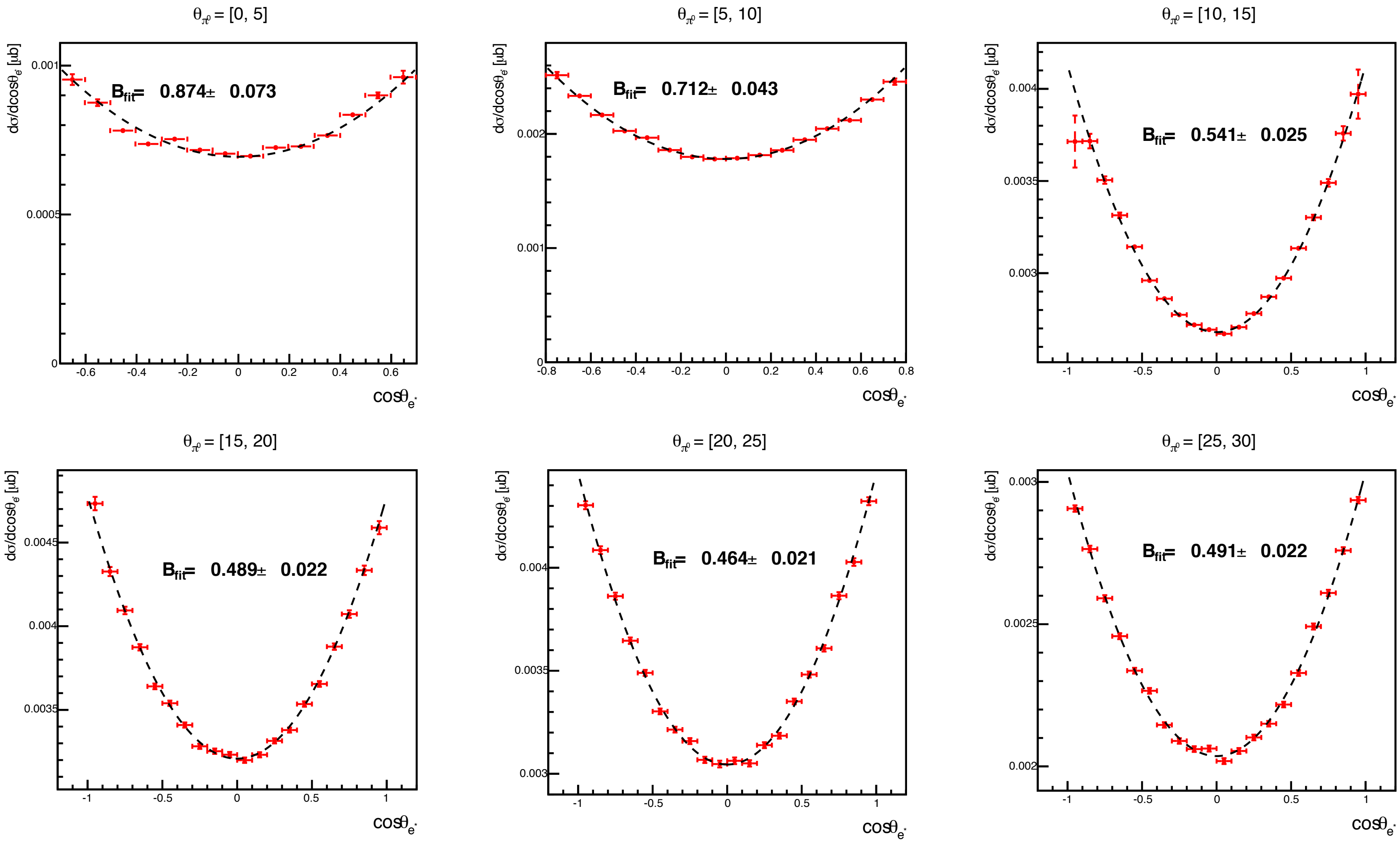






Feasibility studies – Case I - $d\sigma/d\cos\theta_e^*$

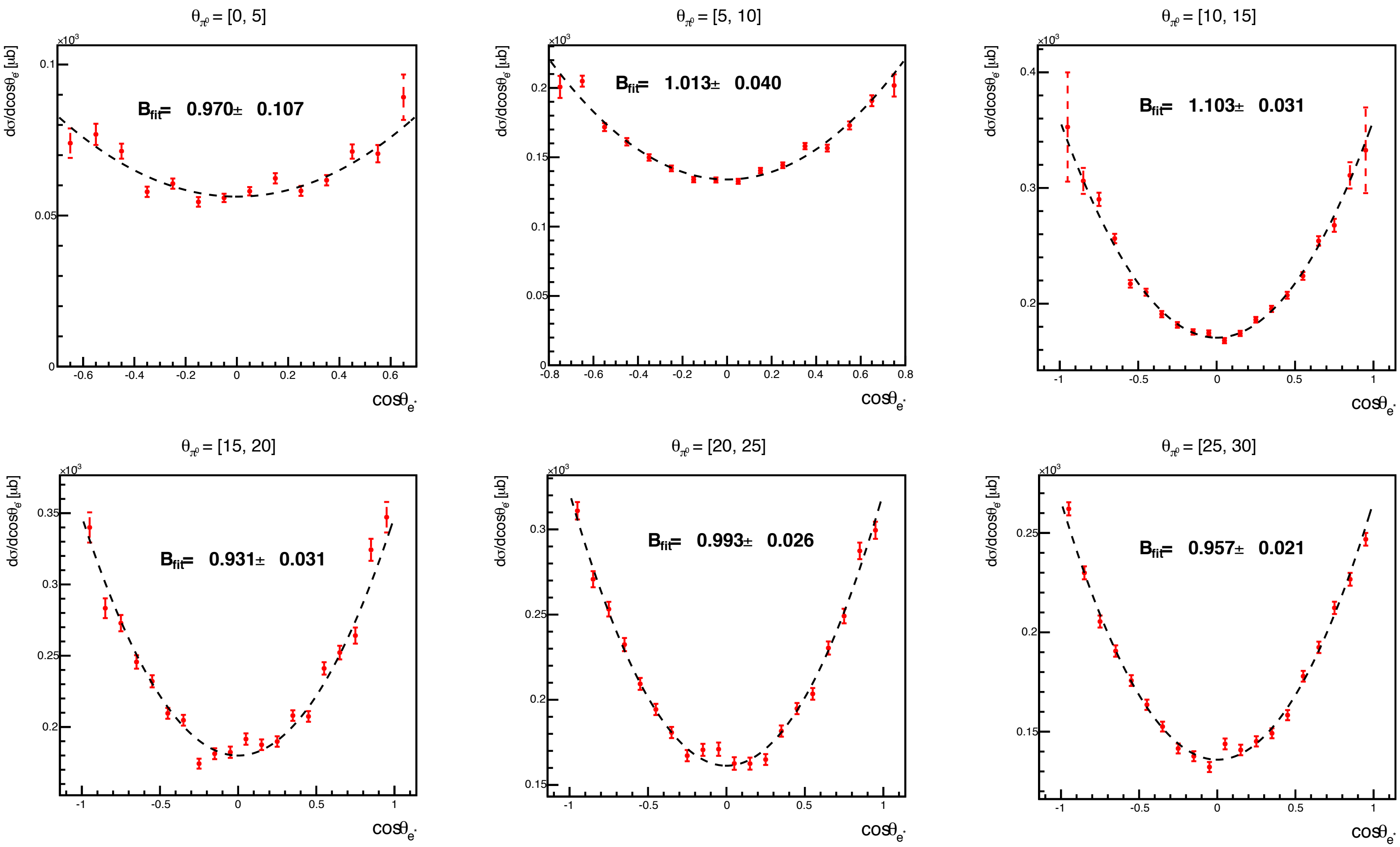
Regge description



- The evolution of "B" as a function of t and u ($\theta_{\pi 0}$) is independent of the form factors: test of the model

Feasibility studies – Case I - $d\sigma/d\cos\theta_e^*$

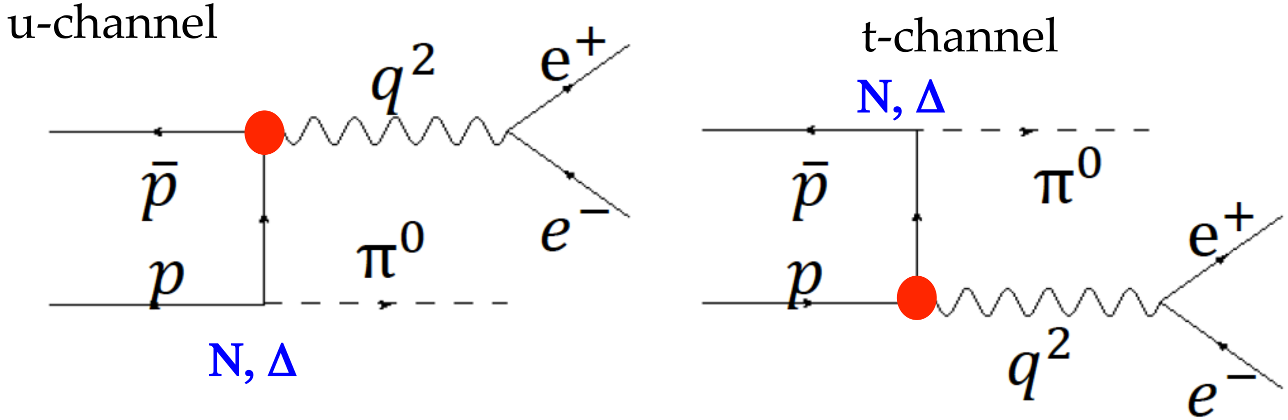
TDA description



Possibility to scan t and u bins ($\theta_{\pi 0}$) and detect any transition of production mechanism

B. Studies within the Regge-pole frame work

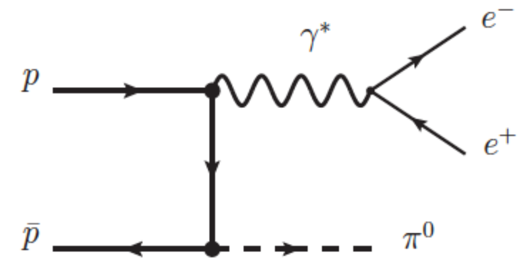
Measurements of the hadronic tensors and the proton form factors in the unphysical region



Differential cross section and hadronic tensors

Model independent form (assuming no factorization of the process):

$$\frac{d\sigma}{dq^2\, d\cos\theta_{\pi^0}\, d\Omega_e^*} = 4\pi e^2 q^2 (H_{11}+H_{22}+H_{33}) - 8e^2 p_e^{*2}\left(\frac{H_{11}+H_{22}}{2} + \frac{H_{11}-H_{22}}{2}\sin^2\theta_e^*\cos 2\varphi_e^* + 2H_{13}\sin\theta_e^*\cos\theta_e^*\cos\varphi_e^* + \frac{1}{2}(2H_{33}-H_{11}-H_{22})\cos^2\theta_e^*\right)$$

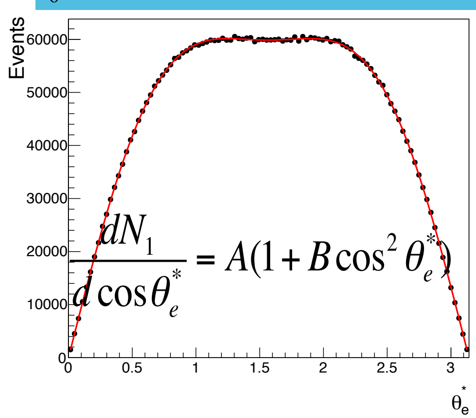


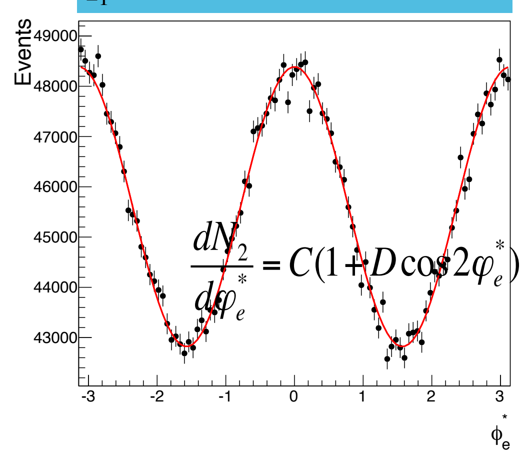
- In each interval of $\theta_{\pi 0}$, projections to obtain three 1D-distrbutions:

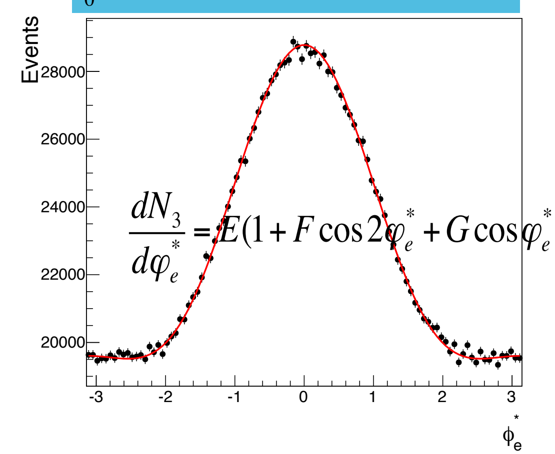
$$\int_0^{2\pi} N(\Omega_e^*)\, d\varphi_e^* \to H_{11}+H_{22}-2H_{33}$$

$$\int_{-1}^{1} N(\Omega_e^*)\, d\cos_e^* \to H_{11}-H_{22}$$

$$\int_0^{1} N(\Omega_e^*)\, d\cos_e^* \to H_{11}+H_{22}, H_{13}$$





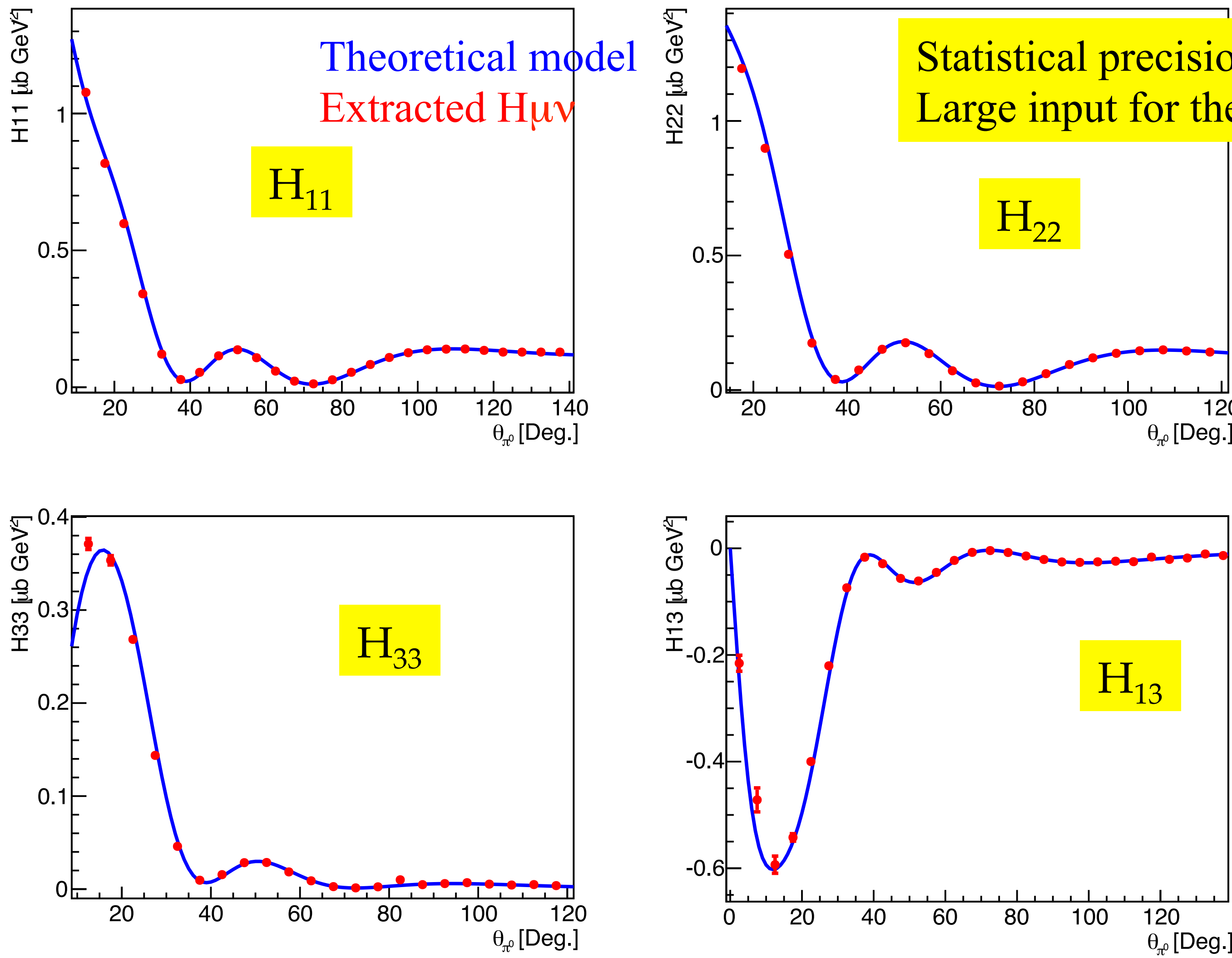


- Extract the hadronic tensors $H_{\mu\nu}$ by fitting the three 1D-distrubtions simultaneously

Extraction of the hadronic tensors- Case I

- $q^2=0.605 \pm 0.015\ (GeV/c^2)^2$, $\Delta\theta_{\pi 0}=5^o$,

→ **Direct access to Hμν whatever the model is**



Statistical precisions ~ few %
Large input for theoretical analyses

Extraction of the proton form factors

Model dependent calculations of the hadronic tensors

$$H_{\mu\nu} = |G_M|^2 \left[\alpha_{\mu\nu} R^2 + \beta_{\mu\nu} + \gamma_{\mu\nu} R \cos(\phi_E - \phi_M)\right]$$

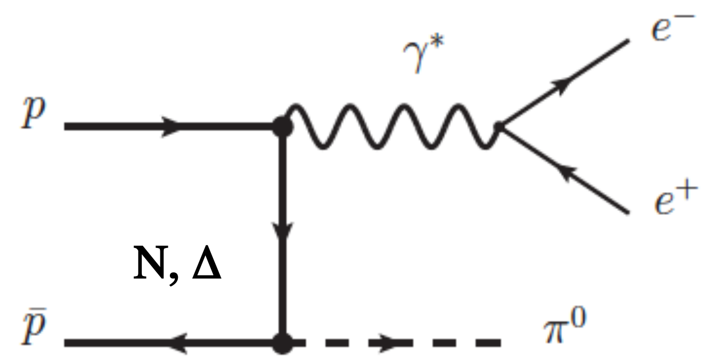
N-exchange

$$+\eta_{\mu\nu} |G_D|^2$$

Δ(1232)-exchange

$$+|G_D||G_E|\left[\tau_{\mu\nu} \cos(\phi_E - \phi_D) + \xi_{\mu\nu} \sin(\phi_E - \phi_D)\right]$$
$$+|G_D||G_M|\left[\kappa_{\mu\nu} \cos(\phi_M - \phi_D) + \rho_{\mu\nu} \sin(\phi_M - \phi_D)\right]$$

N−Δ(1232)- interference



- $\alpha_{\mu\upsilon}$, $\beta_{\mu\upsilon}$, $\gamma_{\mu\upsilon}$, $\tau_{\mu\upsilon}$, $\xi_{\mu\upsilon}$, $\kappa_{\mu\upsilon}$, $\rho_{\mu\upsilon}$, $\gamma_{\mu\upsilon}$ depend on s, q^2 and $\theta_{\pi 0}$ and pion coupling type (pseudo-scalar or pseudo-vector)

$$V_{\pi NN} = g_{\pi NN}\left[\gamma_5, \frac{\gamma_5 \gamma_\alpha p_\pi^\alpha}{2M}\right]$$

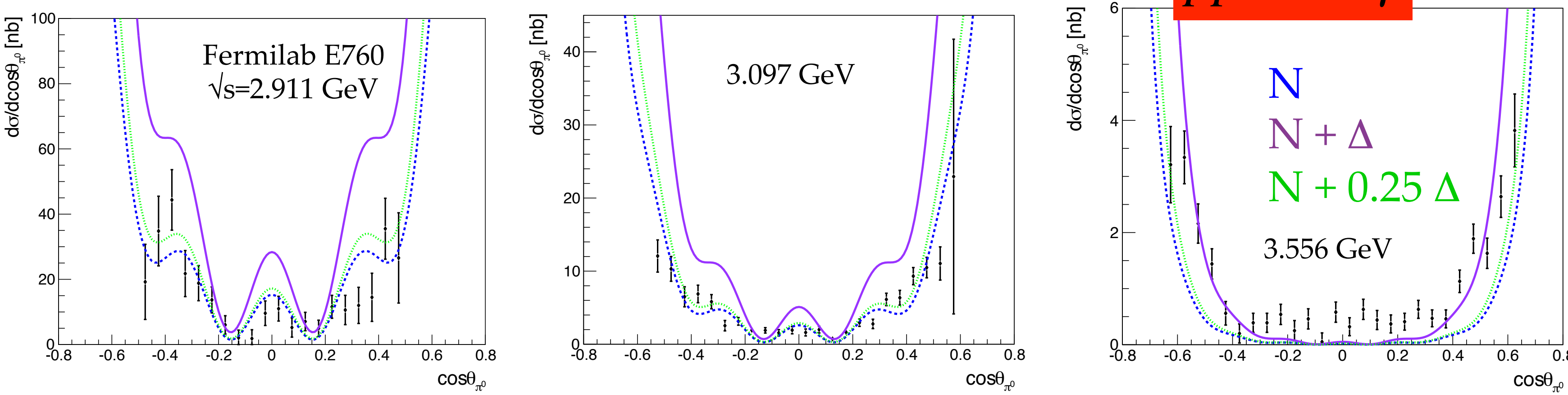
- Determination of the proton form factors requires precise knowledge of the pion coupling type and the effective contributions of the dominant baryon trajectories

  - ➢ Test of the model using pbarp → $\pi^0\gamma$ data (no form factors)

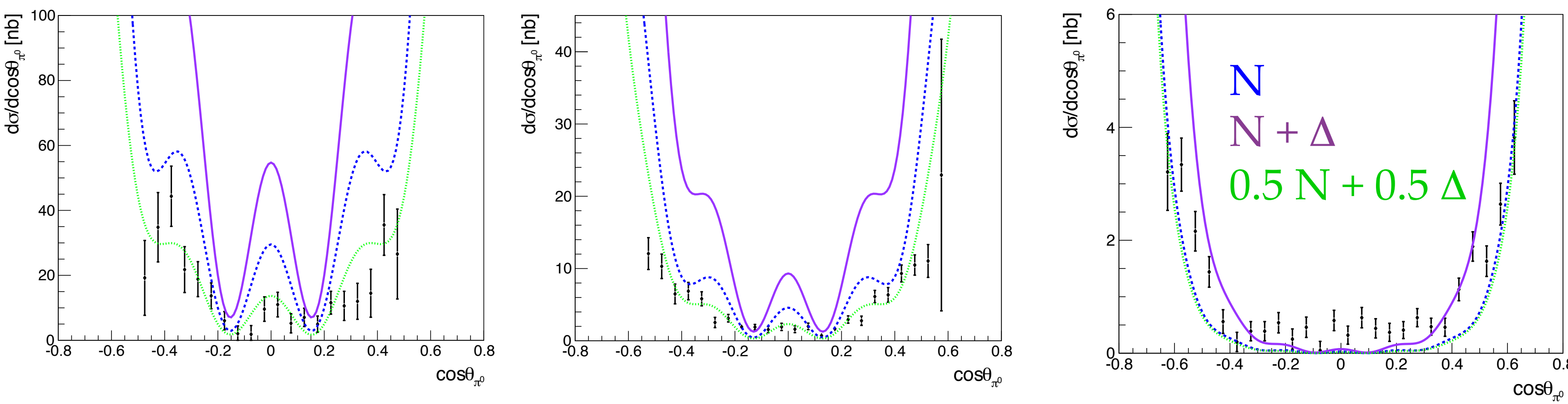
Differential cross section within Regge framework

$\bar{p}p \rightarrow \pi^0\gamma$

- Pseudo-vector pion coupling and Regge (N + 0.25 Δ):



- Pseudo-scalar pion coupling and Regge (0.5 N + 0.5 Δ):



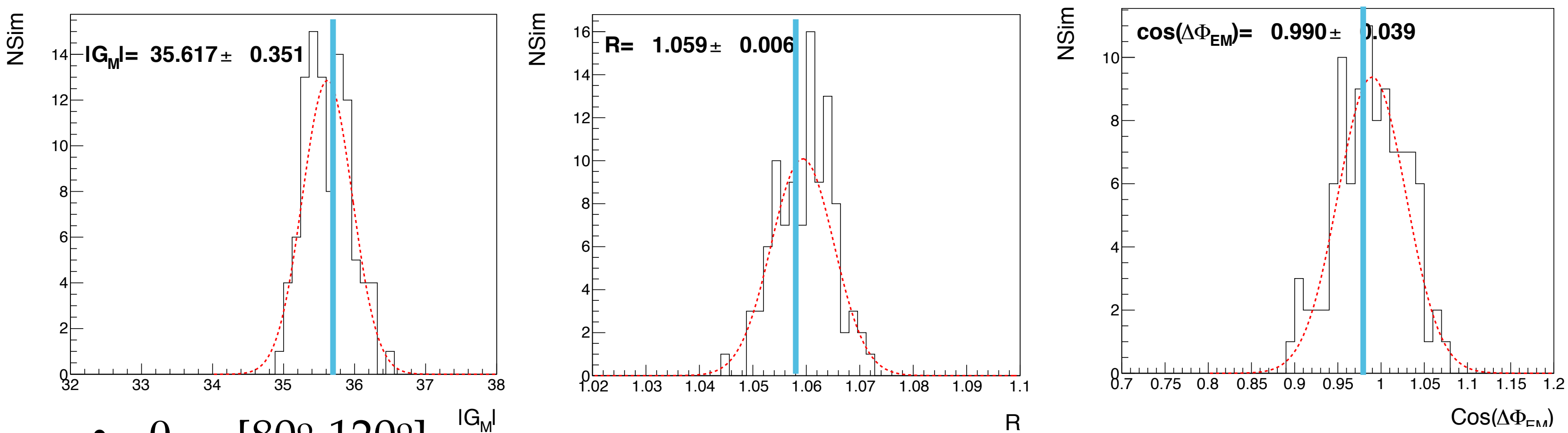
The Δ is further away from the pole position than in the nucleon case, the description of the residues of the Regge poles through their on-shell couplings can be expected to be modified: **Pseudo-vector case is more probable**

20

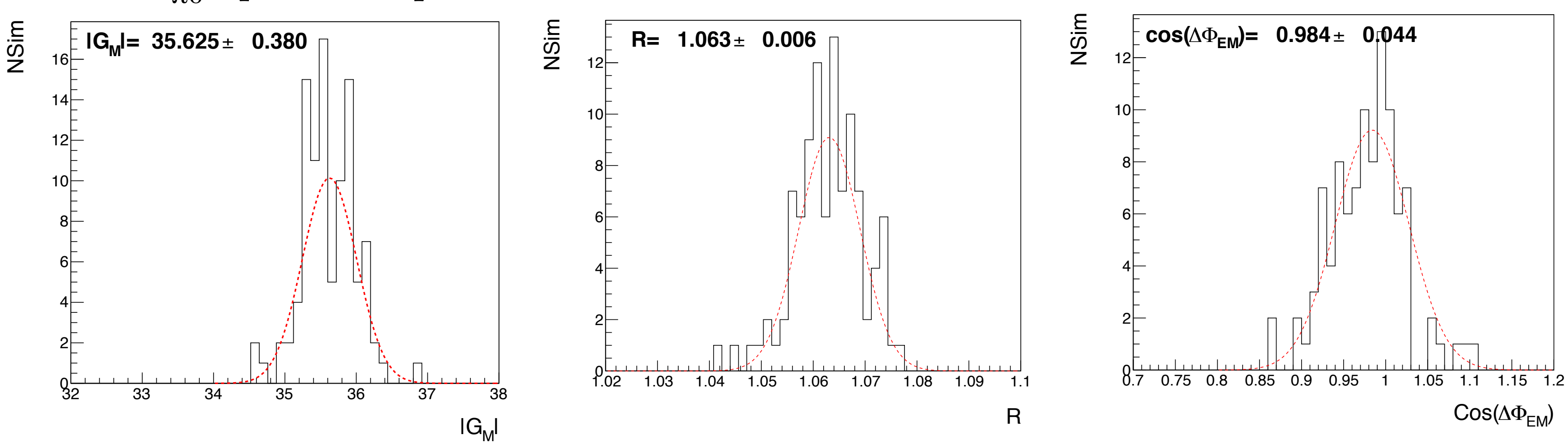
Determination of proton form factors – Case I

- Form factors are determined by minimizing the $H_{\mu\upsilon}$
- Data are generated using complete Regge model (N and Delta), PV pion coupling
- Fit model for $H_{\mu\upsilon}$ based only on N exchange
  - $\theta_{\pi 0}$ =[10°-30°]

Theoretical input

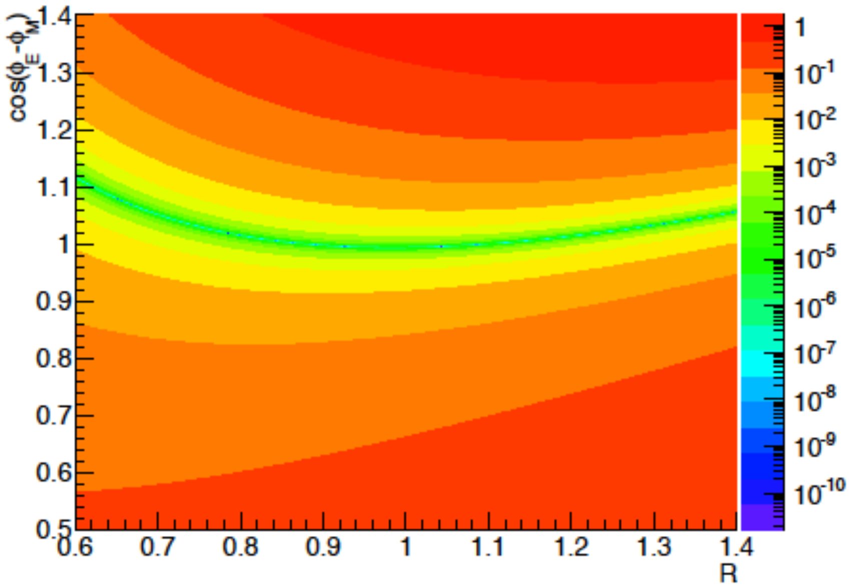


- $\theta_{\pi 0}$ =[80°-120°]



Determination of proton form factors – Case I

- Form factors are determined by minimizing the $H_{\mu\upsilon}$
- Data are generated using complete Regge model (N and Delta), PS pion coupling
- Fit model for $H_{\mu\upsilon}$ based only on N exchange



- Many solutions for the minimization function
- Ratio and relative phase can not be separated

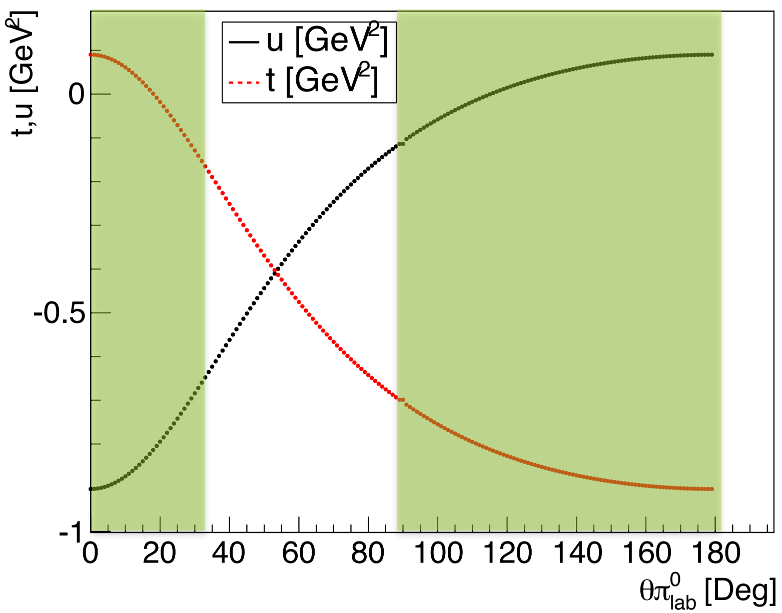
- $|G_M|$ can be precisely measured (~1%)
- Ratio can be measured based on a assumption of the relative phase
- Upper and lower limits of the ratio and the relative phase can be determined; in the present case: $0.98<\cos(\Phi_{EM})<1$ and $0.8<R<1.3$

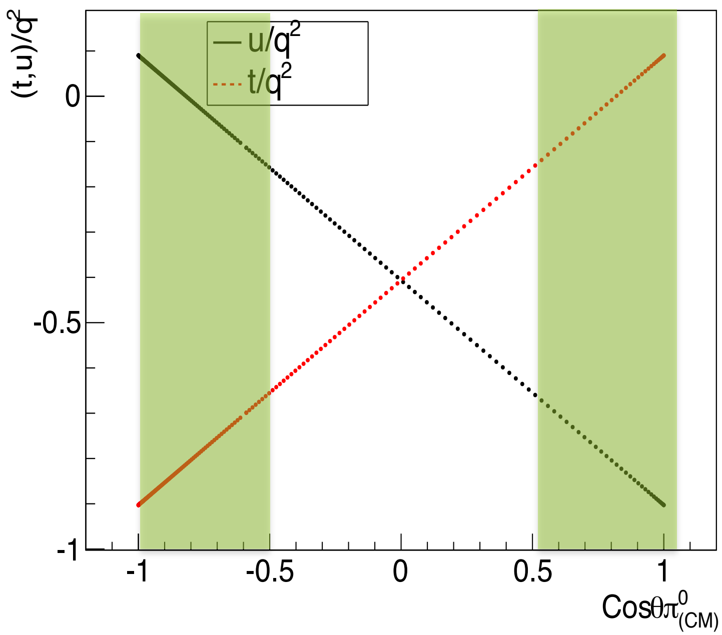
Feasibility studies – Case II

- P_{lab}= 1.7 GeV/c (s=5.4 GeV^2); q^2 = 2 ± 0.125 (GeV/c^2)^2

- Regge description expected for **$|\cos\theta_{\pi 0}|_{CM}$ > 0.5 && $|t,u|/q^2$ > 20%**

- TDAs description expected for **$|\cos\theta_{\pi 0}|_{CM}$ > 0.5 && $|t,u|/q^2$ < 20%**
  $\theta_{\pi 0}$(Lab)=[0°-32°] , [83°-180°]



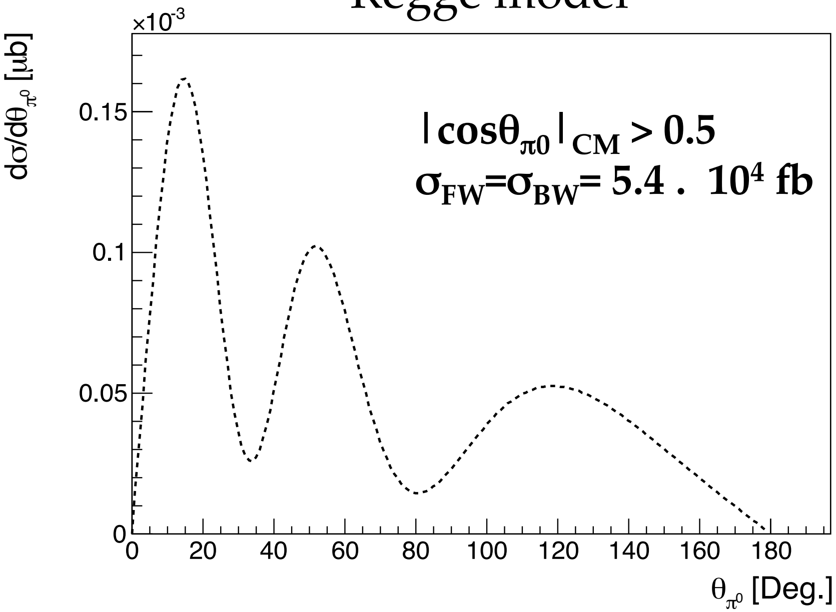


- At small s and q^2 ~2 (GeV/c^2)^2 the process is expected to occur through the collinear factorization description
  - **Region for TDA studies**

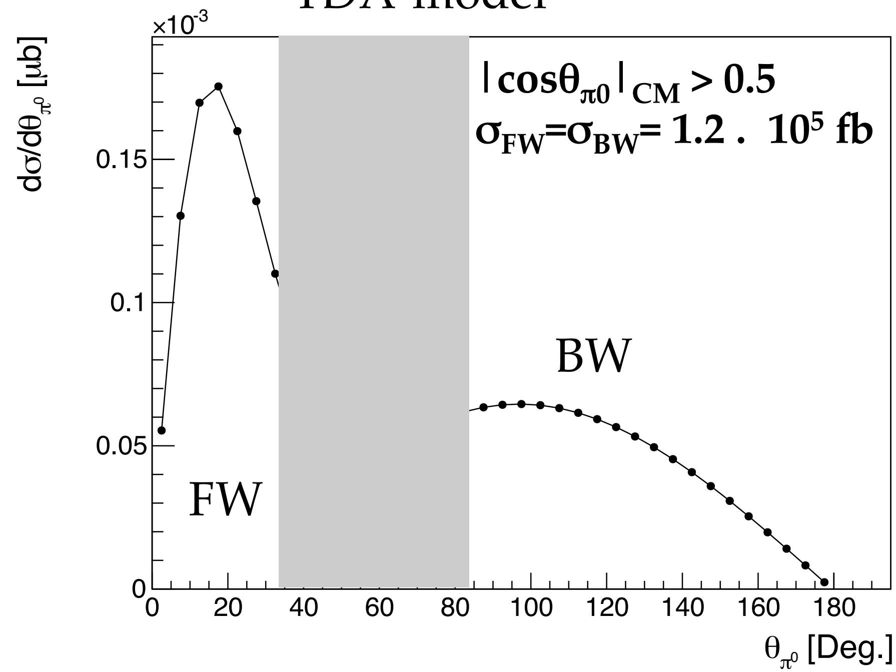
Theoretical cross sections – Case II

- P_{lab}= 1.7 GeV/c (s=5.4 GeV^2); $q^2 = 2 \pm 0.125\ (GeV/c^2)^2$

Regge model



TDA-model



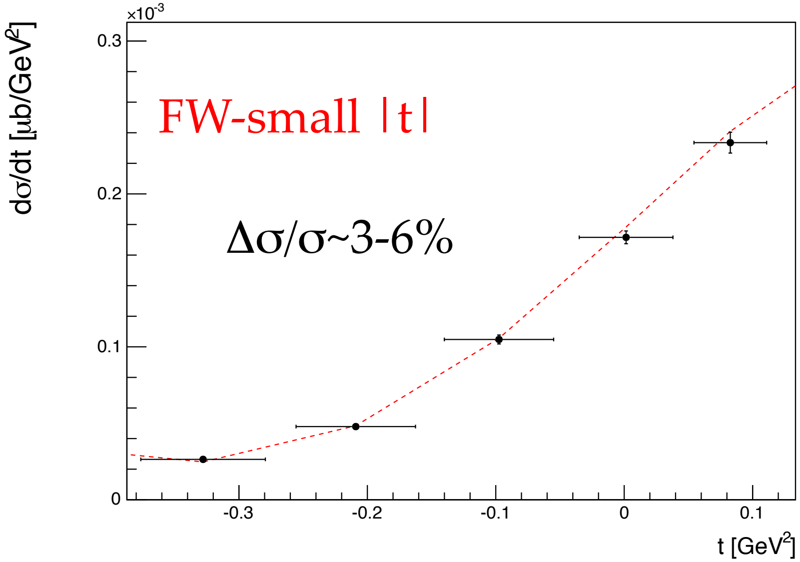
- Smaller cross section than **case I** due to the form factors

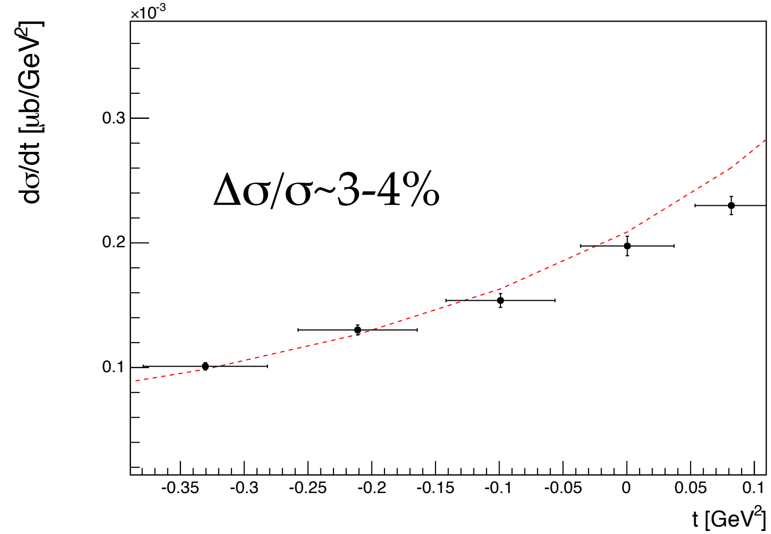
- Smaller cross section than **case I** due to the scaling characteristic of the cross section in q^2

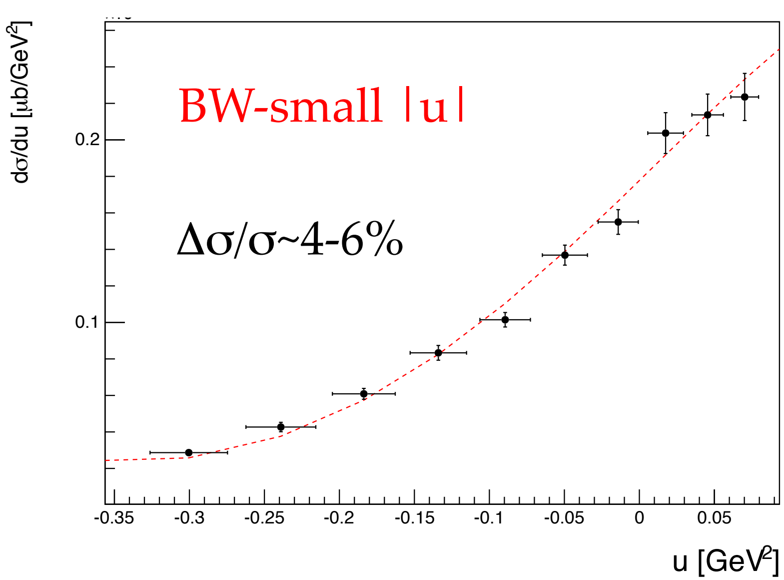
Feasibility studies – Case II - dσ/dt, dσ/du

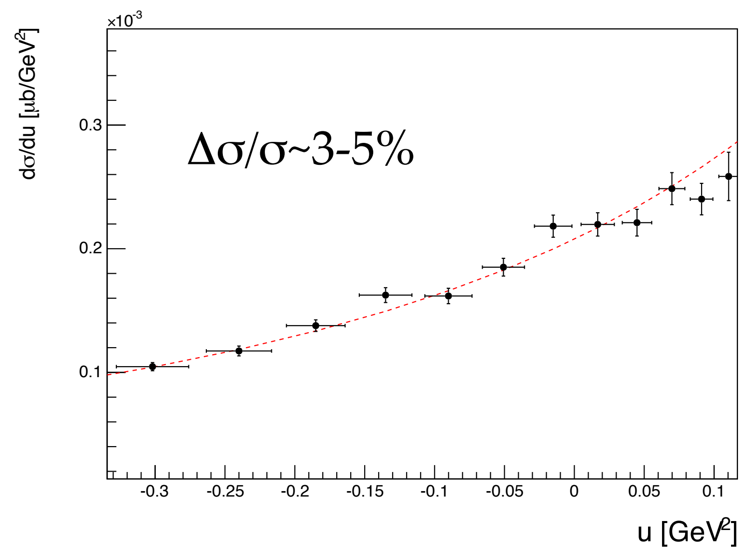
Regge description

TDA-model

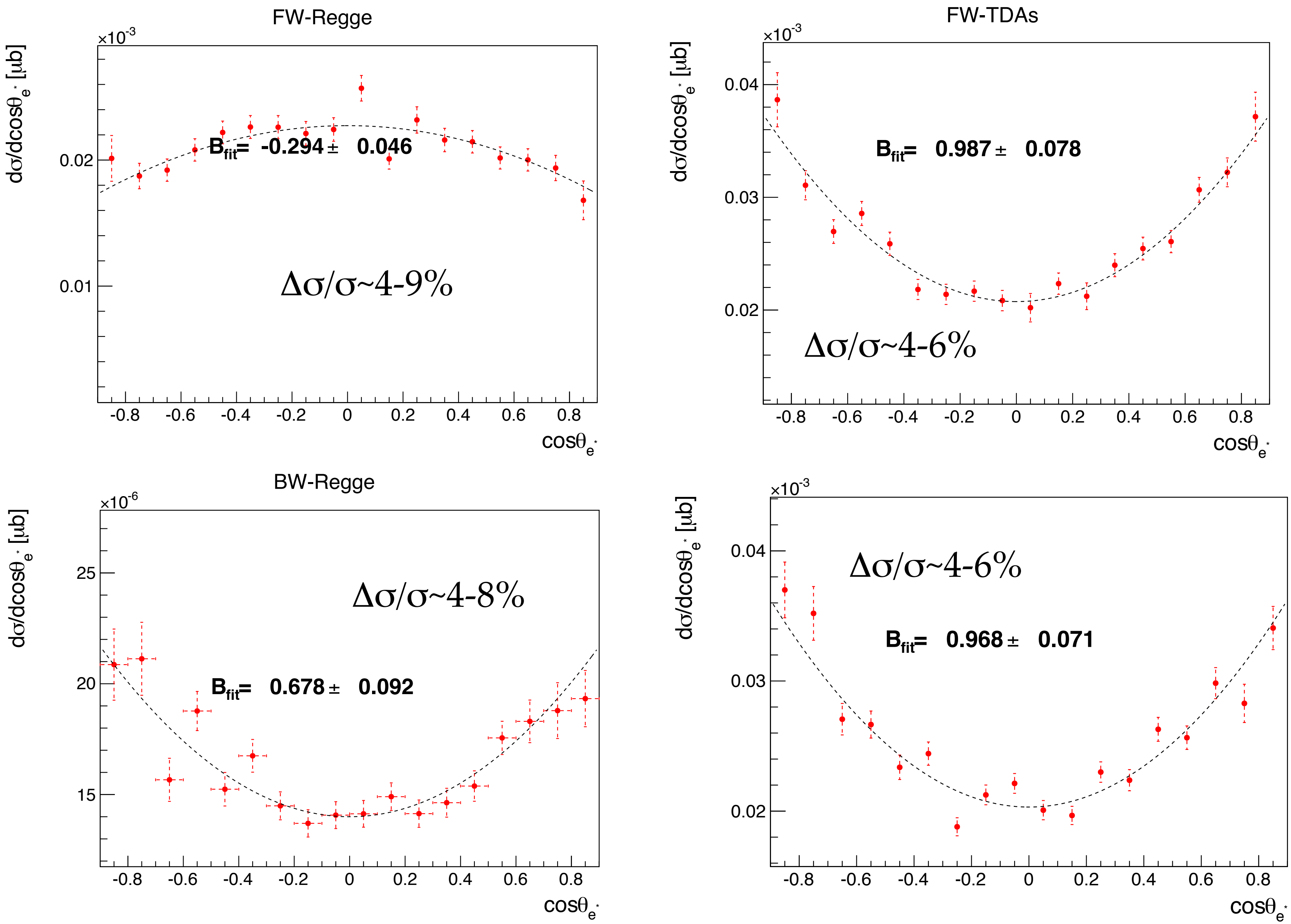






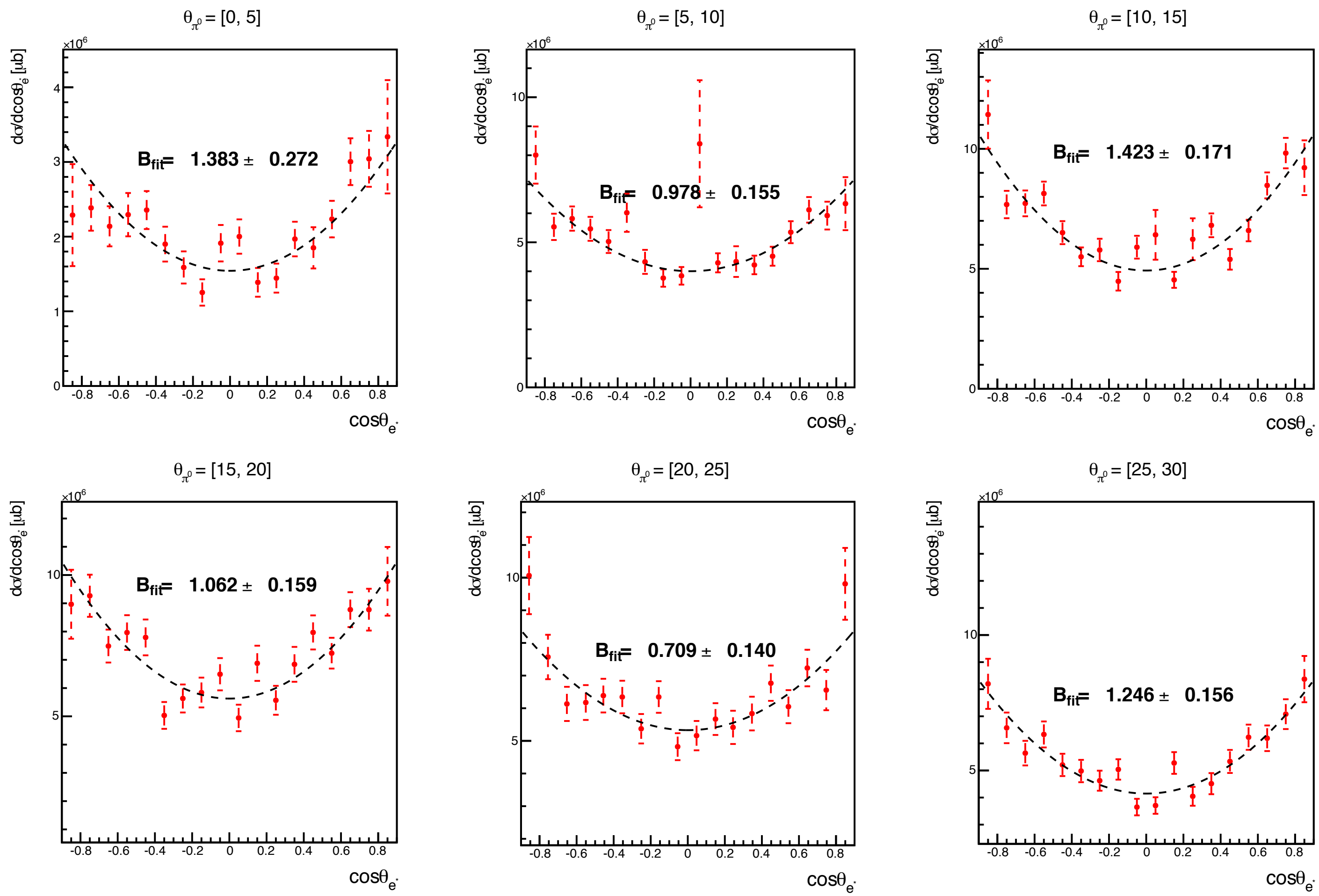


Feasibility studies – Case II - $d\sigma/d\cos\theta_e^*$



Feasibility studies – Case II - $d\sigma/d\cos\theta_e^*$

TDA description



- Possibility to scan t and u bins ($\theta_{\pi 0}$) and detect any transition of the production mechanism

Summary

- First experimental indications of the TDA factorization was recently observed in backward p-and backward ω- electroproduction at Jlab: more statistics are needed for confirmation

- TDA model can be studied at PANDA in proton-anitproton annihilation into e+e- pi0 final state (in collinear factorization regime): test of the TDA universality

- The same process can be used to perform first measurements of the proton time-like form factors in the unphysical region (outside the collinear factorization regime).

- Feasibility measurements of this process have been performed using two models: Regge pole description and TDA-factorization at low q^2 values (0.605 and 2 $(GeV/c^2)^2$)

- Precise measurements of the differential cross sections are feasible at PANDA

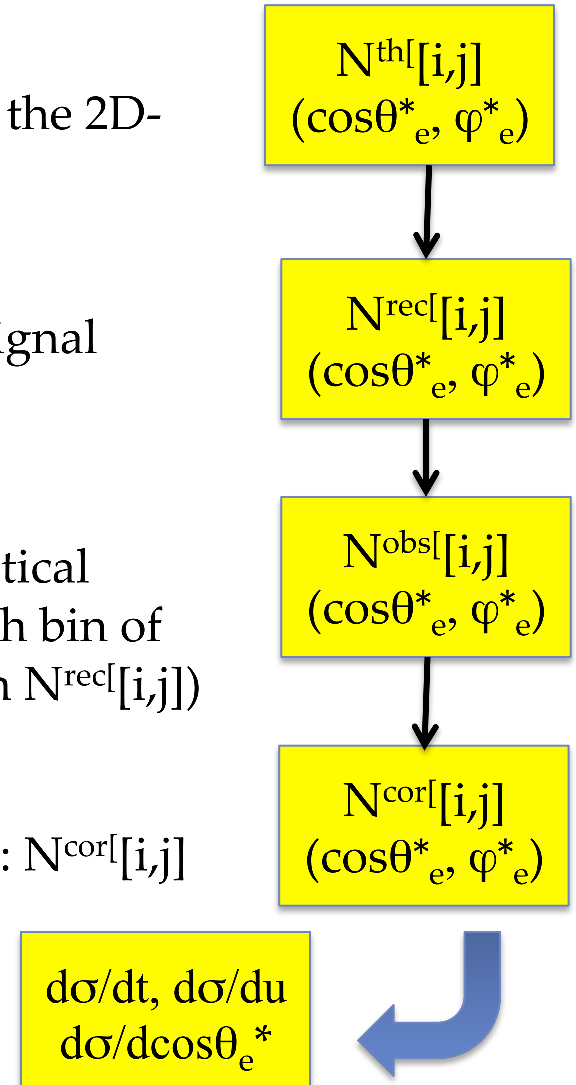
- Valuable information on the proton form factors can be extracted

➢ Simulations using dedicated event generators (for low statistics and non full acceptance regions)
➢ Simulations with new PANDAROOT version and also at higher center of mass energies

Measurements of the differential cross sections

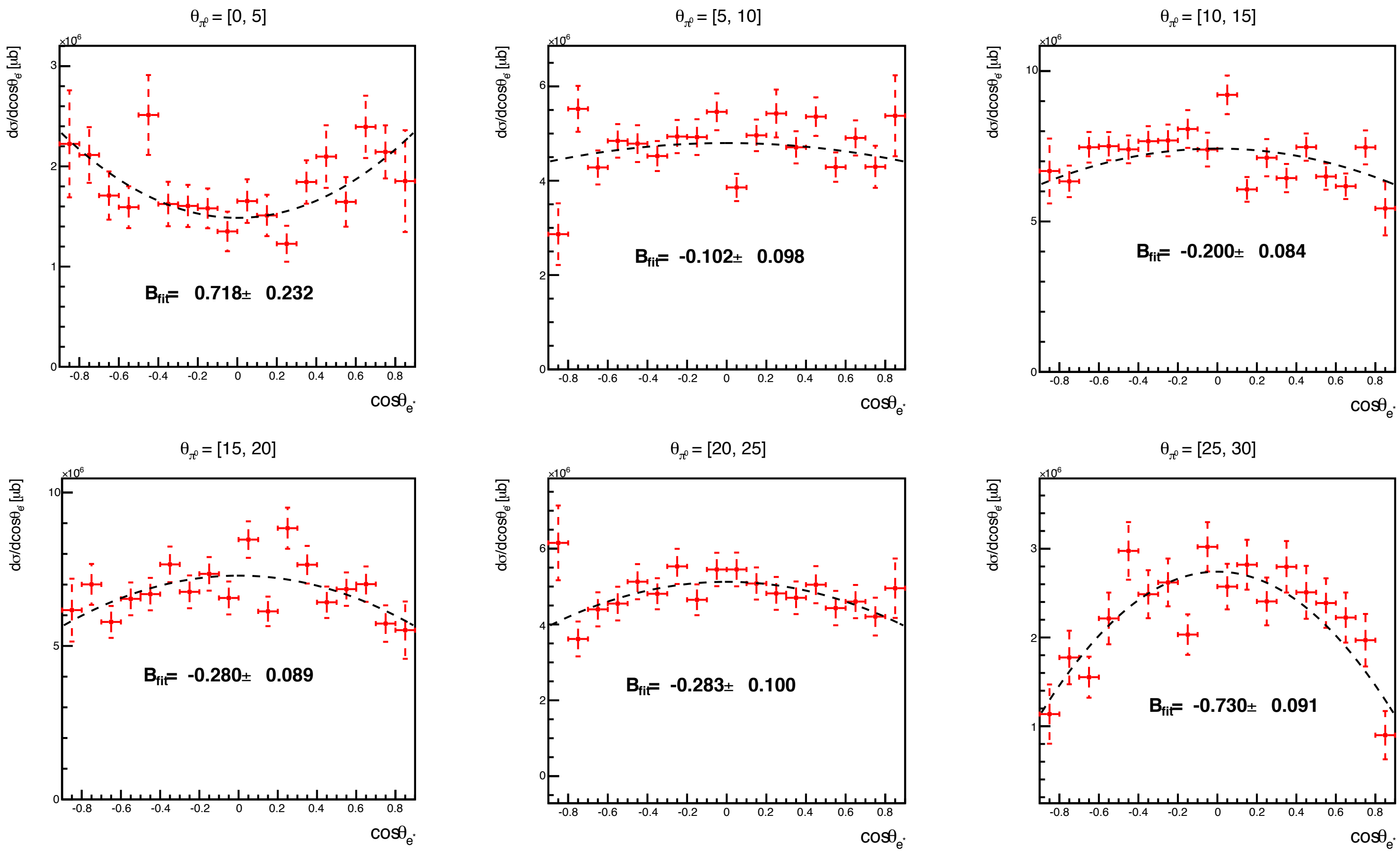
For each interval of q^2 and $\theta_{\pi 0}$:

- Theoretical number of counts $N^{th[}[i,j]$ in each bin of the 2D-distribution $(\cos\theta^*_e, \varphi^*_e)$
- Reconstructed events $N^{rec[}[i,j]$ taking into account signal efficiency
- Observed events $N^{obs[}[i,j]$ taking into account statistical fluctuations by generating a random number in each bin of the 2D-distribution (Poisson distribution with mean $N^{rec[}[i,j]$)
- Correct the observed events by the signal efficiency: $N^{cor[}[i,j]$
- Projections to obtain 1D-distrbutions



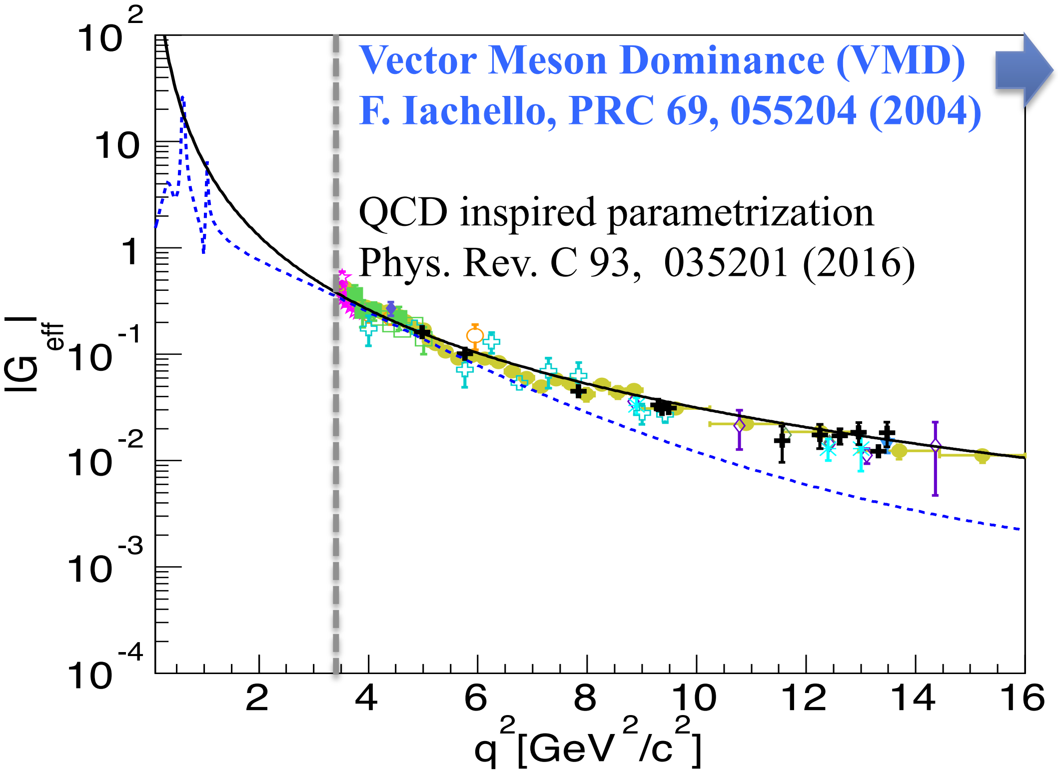
Feasibility studies – Case II - $d\sigma/d\cos\theta_e^*$

Regge description



- Possibility to scan t and u bins ($\theta_{\pi 0}$) and detect any transition of production mechanism

Proton and Delta(1232) form factor model



Photon couples to the nucleon through the exchange of intermediate vector mesons $(\omega, \varphi, \rho, \ldots)$:

$$F(q^2) \sim g(q^2)\left[\sum_\nu A_\nu \frac{M_\nu^2}{q^2 - M_\nu^2}\right]$$

The magnetic dipole form factor of the N->Δ transition

$$G_D(q^2) = \frac{G_D(0)}{\kappa_V}\left(F_2^p(q^2) - F_2^n(q^2)\right)$$

$q^2 = 0.605 \pm 0.005$ (GeV/c^2)^2

$|G_E| = 35.72$, $|G_M| = 35.56$

R=1.066, cos(ϕ_E-ϕ_M)=0.998 (4°)

$|G_D| = 3.8$

$q^2 = 2 \pm 0.125$ (GeV/c^2)^2

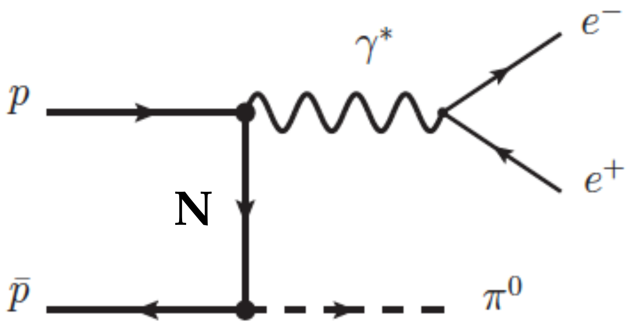
$|G_E| = 0.67$, $|G_M| = 0.84$

R=0.802, cos(ϕ_E-ϕ_M)=0.999 (3°)

$|G_D| = 0.74$

Differential cross section within Regge framework

J. Guttmann, M. Vanderhaeghen / PLB 719 (2013) 136–142



- Modification of the exchanged nucleon propagator:

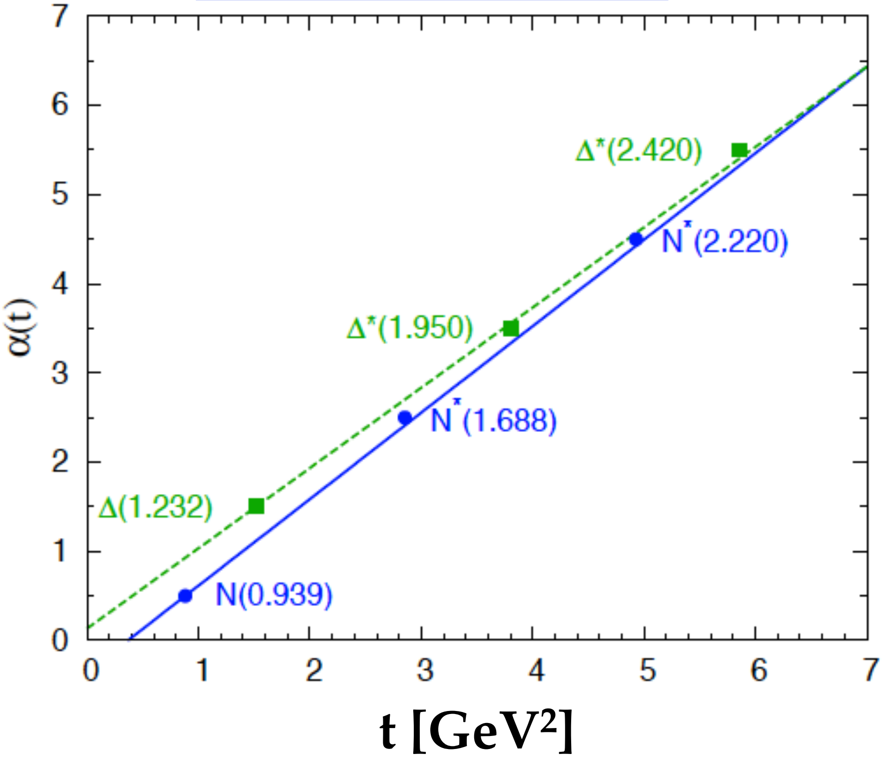
$$t-channel: \frac{1}{t-m_N^2} \rightarrow$$

$$D_N^{Regge}(t,s) = \frac{s^{\alpha_N(t)-0.5}}{\Gamma[\alpha_N(t)+0.5]} \pi\alpha_N^{'} \frac{e^{-i\pi(\alpha_N(t)+0.5)}}{\sin[\pi(\alpha_N(t)+0.5)]}$$

- Γ_μ remain unchanged - no additional unknown parameters are introduced

Regge trajectory for the nucleon

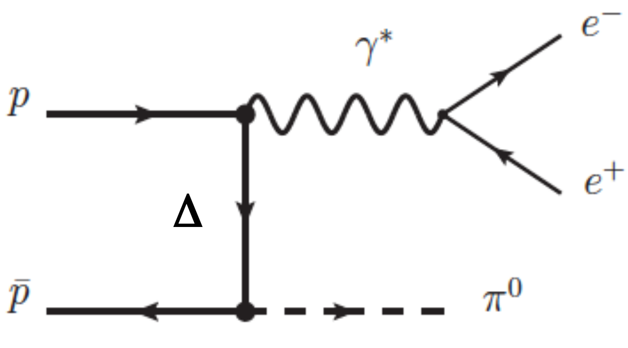
$$\alpha_N(t) = 0.5 + 0.97(t - m_N^2)$$



$$\Gamma_\mu(q) = e\left[F_1(q^2)\gamma_\mu - \frac{i}{2M} F_2(q^2)\sigma_{\mu\nu}q^\nu\right]$$

Differential cross section within Regge framework

J. Guttmann, M. Vanderhaeghen / PLB 719 (2013) 136–142



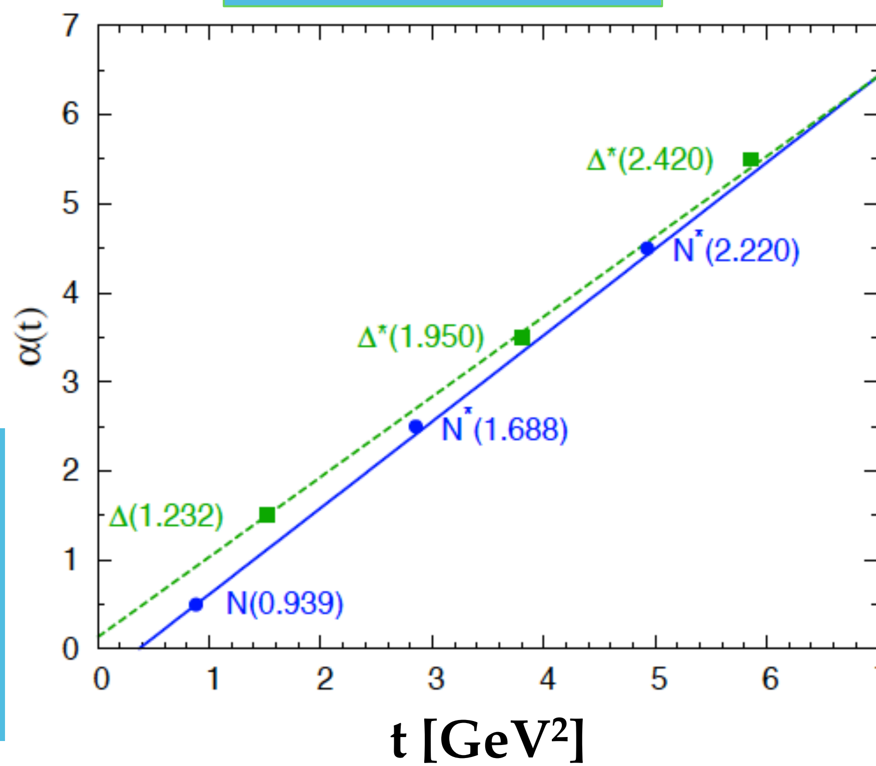
- Modification of the exchanged $\Delta(1232)$ propagator:

$$t-channel: \frac{1}{t-m_\Delta^2} \rightarrow$$

$$D_\Delta^{Regge}(t,s) = \frac{s^{\alpha_\Delta(t)-1.5}}{\Gamma[\alpha_\Delta(t)+0.5]} \pi\alpha_\Delta' \frac{e^{-i\pi(\alpha_\Delta(t)-0.5)}}{\sin[\pi(\alpha_\Delta(t)-0.5)]}$$

Regge trajectory for the nucleon

$$\alpha_\Delta(t) = 1.5 + 0.9(t - m_\Delta^2)$$

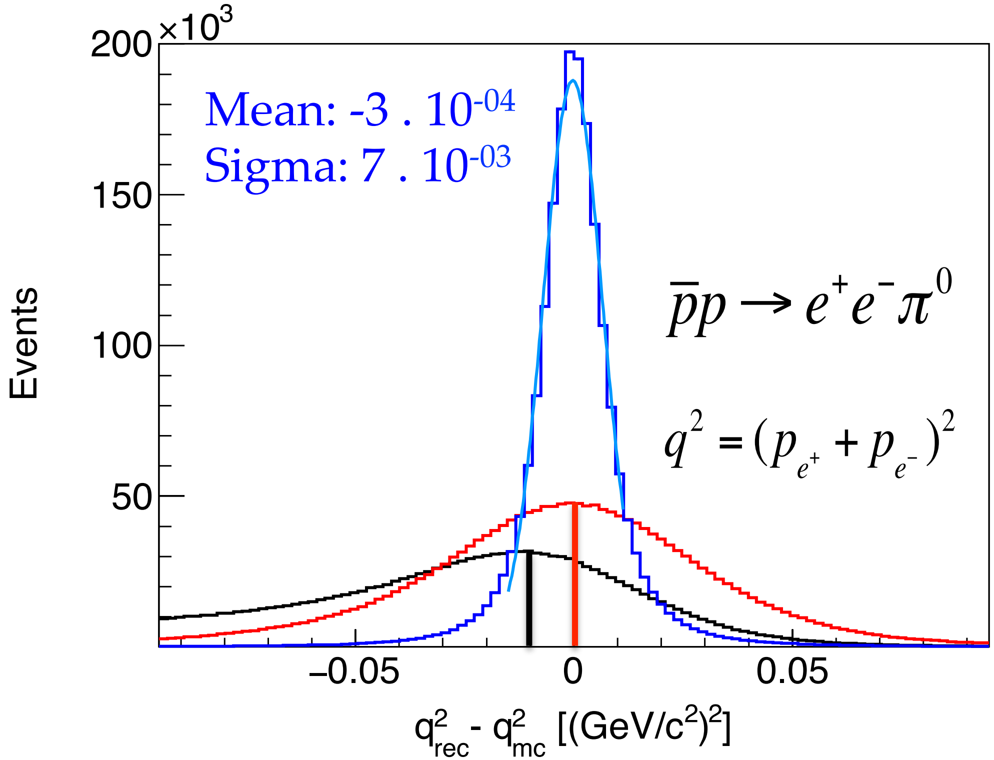


- $\Gamma_{\gamma N\Delta}$ introduces the magnetic dipole form factor G_D

$$\Gamma^\alpha_{\gamma N\Delta} = i\sqrt{\frac{2}{3}} \frac{3e(m_\Delta + m_N)}{2m_N((m_\Delta + m_N)^2 - q^2)} G_D(q^2)\varepsilon^{\alpha\mu\rho\sigma} p_\Delta q_\sigma$$

Invariant mass squared of the selected e^+e^-

- q^2=0.605 ± 0.015 $(GeV/c^2)^2$



"Before Bremsstrahlung correction, without 4C kinematic fit"

"After Bremsstrahlung correction without 4C kinematic fit" (Methode described in: E. ATOMSSA TN-STT-2015-001)

"After Bremsstrahlung correction with 4C kinematic fit"

Measurement of the proton FFs in small intervals of q^2 (in the unphysical region) is possible at PANDA