Study of the ppbar->$e^+e^-\pi^0$ process in the unphysical region with PANDARoot

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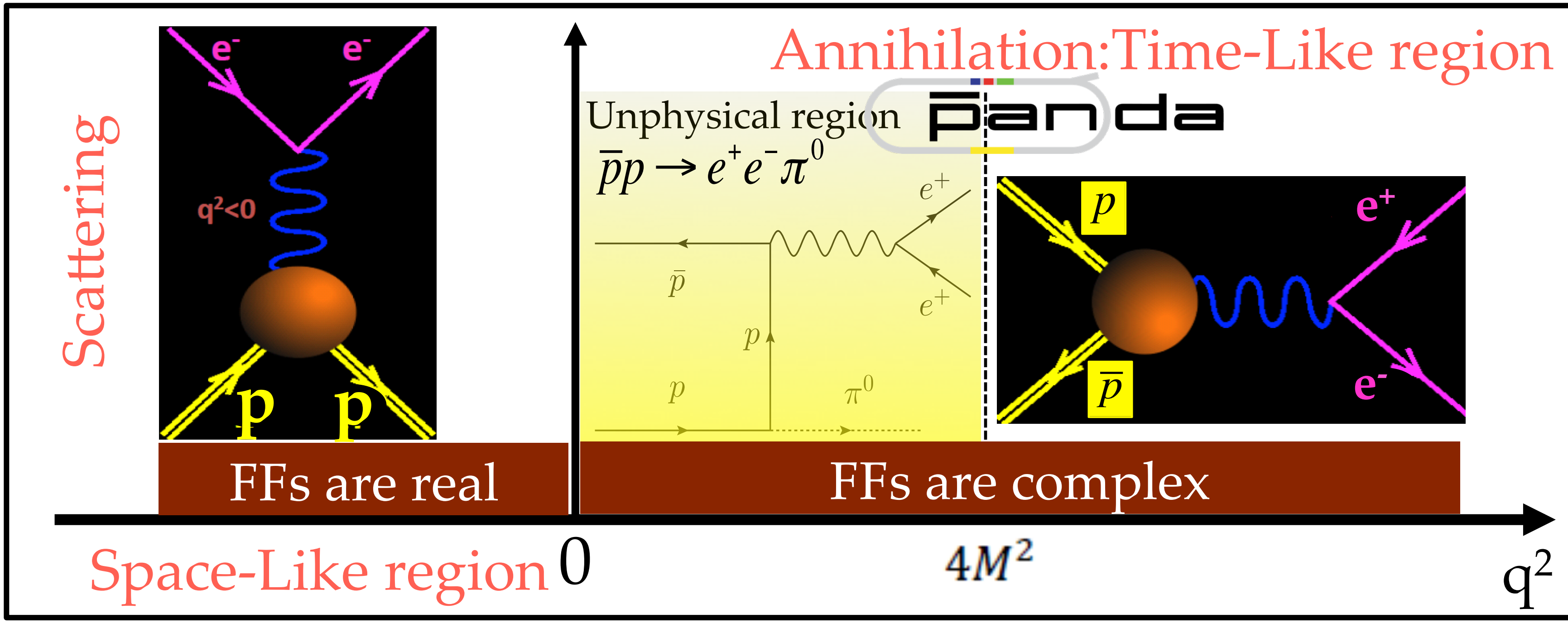
Outline

- Theoretical description of the signal differential cross section within the one nucleon exchange model
- Determination of statistical errors on the proton form factors in the unphysical region assuming **100% signal efficiency and acceptance**
- Results within PANDARoot

Electromagnetic Form Factors of the Proton



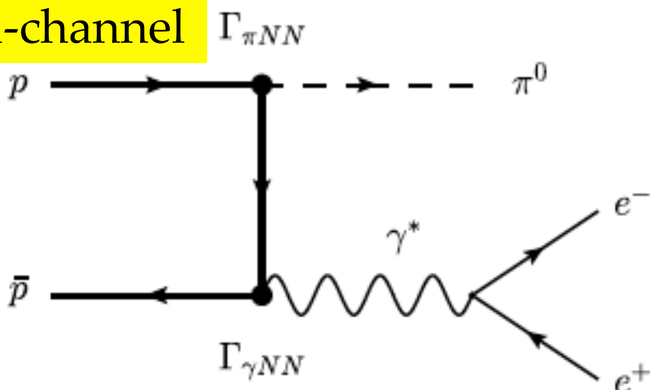
- **Electric G_E and magnetic G_M** proton FFs are analytical functions of the momentum transfer squared q^2

- Dispersion relations connect space-like and time-like form factors

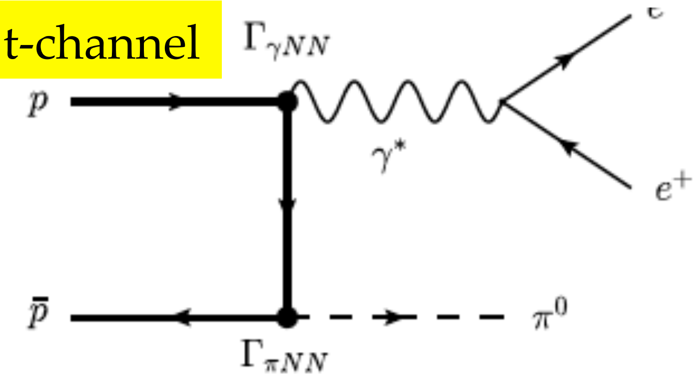
- No experimental data in the unphysical region

Feynman diagrams for the process pbar+p -> $e^+e^-\pi^0$

u-channel



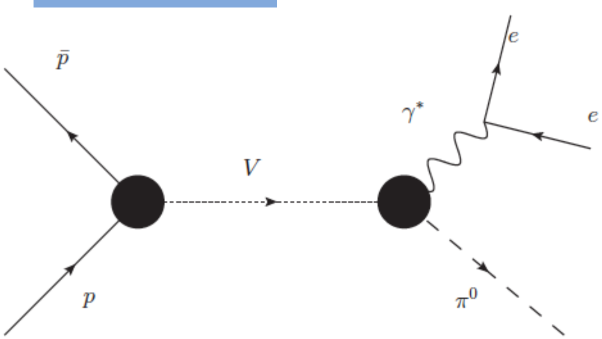
t-channel



Give access to the proton form factors in the unphysical region
Dominates at backward pion angles |u|, |t| <<s

- 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

s-channel

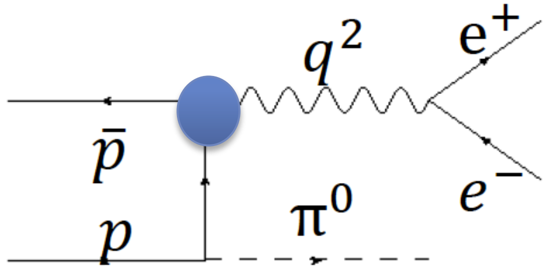


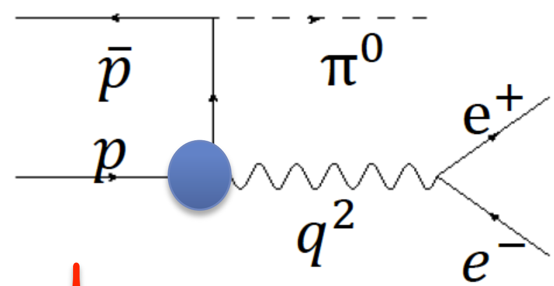
- Expected to play a role at moderate values of √s, when the pion is emitted around 90◦ in the center of mass.
- Forward and backward region: suppressed by the phase volume factor |t|/s or |u|/s.

E. A. Kuraev et al., J.Exp.Theor.Phys. 115 (2012) 93-104

Differential cross section in one nucleon exchange model

u-channel





t-channel

Hadronic current H^{μ}

$$M_t = \frac{1}{q^2} L_{\mu} \bar{v}(p_{\bar{p}}) \Gamma_{\pi NN} \left(\frac{\gamma.(p_{\pi} - p_{\bar{p}}) + M}{t - M^2} \right) \Gamma^{\mu}_{\gamma NN}(q) u(p_p)$$

Nucleon propagator

Proton-photon vertex:

$$\Gamma^{\mu}_{\gamma NN}(q) = e\left[F_1(q^2)\gamma^{\mu} - \frac{i}{2M} F_2(q^2)\sigma^{\mu\nu} q_{\nu} \right]$$

Pion-nucleon (Pseudoscalar, pseudovector) coupling:

$$\Gamma_{\pi NN}(q_{\pi}) = g_{\pi NN}\left[\gamma_5, \gamma_5 p^{\pi}_{\alpha} \gamma^{\alpha} \right]$$

C. Adamuscin, E.A. Kuraev, E. Tomasi-Gustafsson, F.E. Maas, Phys. Rev. C 75 (2007) 045205.

Differential cross section in one nucleon exchange model

J. Van de Wiele (PhD thesis of J. Boucher, Paris-Sud and JGU mainz, Orsay, 2011)

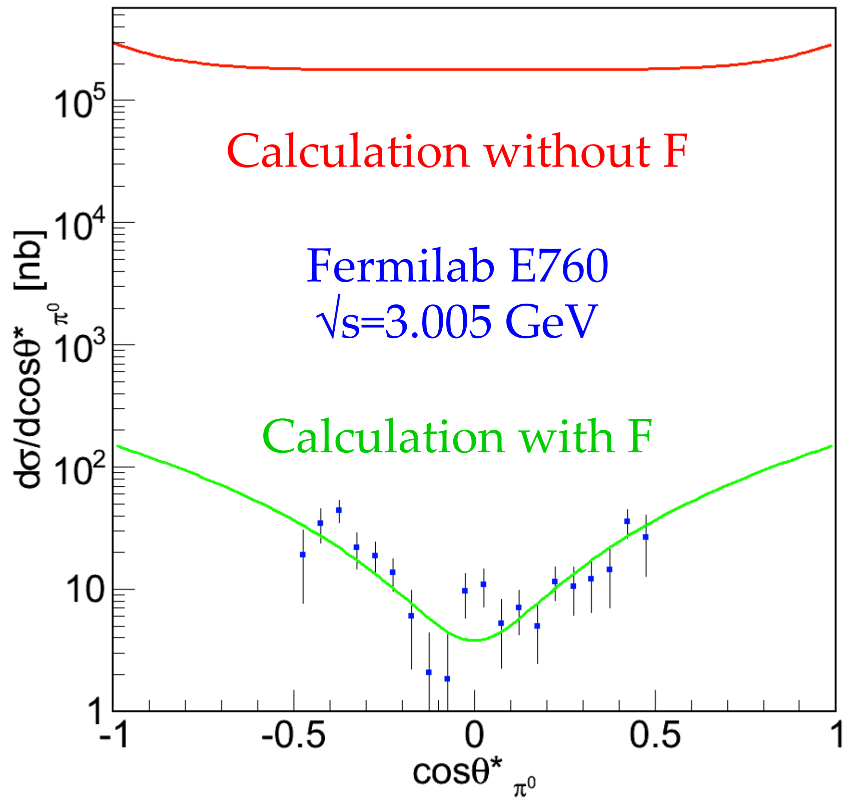
$$\bar{p}p \rightarrow \pi^0\gamma$$

Modified nucleon propagator:

$$t-channel: \frac{1}{t-M^2} \rightarrow \frac{1}{t-M^2}.F$$

$$u-channel: \frac{1}{u-M^2} \rightarrow \frac{1}{u-M^2}.F$$

$$F = \left[\frac{\lambda^2 - M^2}{\lambda^2 - t}\right]\left[\frac{\lambda^2 - M^2}{\lambda^2 - u}\right]$$



Differential cross section in one nucleon exchange model

J. Van de Wiele (PhD thesis of J. Boucher, Paris-Sud and JGU mainz, Orsay, 2011)

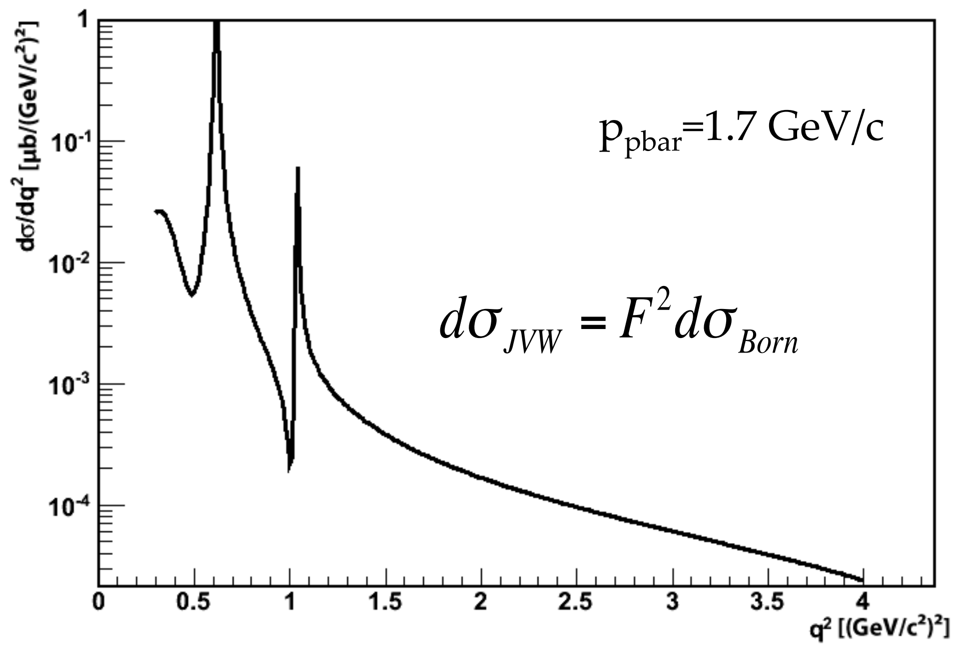
$$\bar{p}p \rightarrow \pi^0 e^+ e^-$$

Modified nucleon propagator:

$$t-channel: \frac{1}{t-M^2} \rightarrow \frac{1}{t-M^2}.F$$

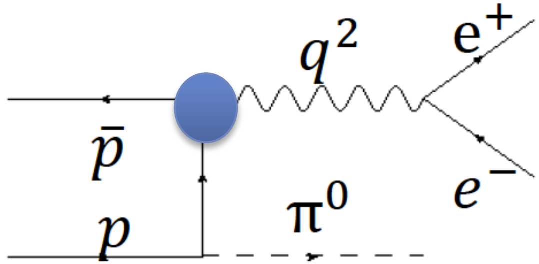
$$u-channel: \frac{1}{u-M^2} \rightarrow \frac{1}{u-M^2}.F$$

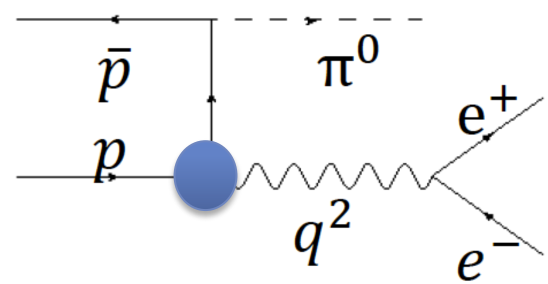
$$F = \left[\frac{\lambda^2 - M^2}{\lambda^2 - t}\right]\left[\frac{\lambda^2 - M^2}{\lambda^2 - u}\right]$$



Differential cross section in one nucleon exchange model

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





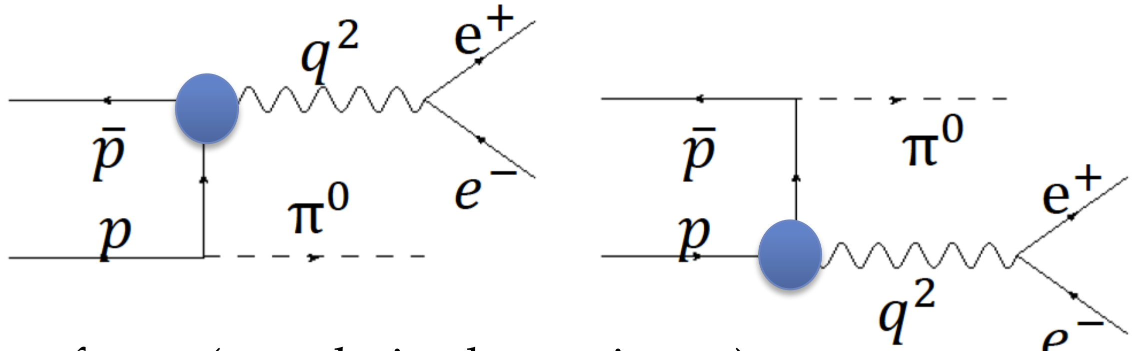
- 3 body final state: differential cross section is described by 5 independent kinematic variables (one choice: s, q^2, $\theta_{\pi 0}$, θ_e*, φ_e*)
  - $\theta_{\pi 0}$ in the laboratory frame
  - θ_e*, φ_e* in the virtual photon rest frame (*)

$L_{\mu\upsilon}$: leptonic tensors describing the γ*->e+e- process

$H_{\mu\upsilon}$: hadronic tensors describes pion-nucleon coupling, nucleon propagator (corrected to fit the $\pi^0\gamma$ data from Fermilab) and contains the information on G_E and G_M

J. Van de Wiele (PhD thesis of J. Boucher, Paris-Sud and JGU mainz, Orsay, 2011)

Differential cross section in one nucleon exchange model



- In the γ* rest frame (unpolarized experiment):

$$\frac{d\sigma}{dq^2 d\cos\theta_{\pi^0} d\Omega_e^*} = 4\pi e^2 q^2 (H_{11}+H_{22}+H_{33}) - 8e^2 p_e^{*2}\Bigg(\frac{H_{11}+H_{22}}{2}$$

$$+\frac{H_{11}-H_{22}}{2}\sin^2\theta_e^* \cos 2\varphi_e^* + 2H_{13}\sin\theta_e^*\cos\theta_e^* \cos\varphi_e^* + \frac{1}{2}(2H_{33}-H_{11}-H_{22})\cos^2\theta_e^*\Bigg)$$

- The polar and azimuthal angular distributions of e^+/e^- (θ_e^*, φ_e^*) gives access to 4 $H_{\mu\nu}$ (H_{11}, H_{22}, H_{33}, H_{13})

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

  - $\alpha_{\mu\upsilon}$, $\beta_{\mu\upsilon}$, $\gamma_{\mu\upsilon}$ depend on s, q^2 and $\theta_{\pi 0}$

J. Van de Wiele (PhD thesis of J. Boucher, Paris-Sud and JGU mainz, Orsay, 2011)

Determination of the proton form factors

- For one value of s, and fixing the q^2 and $\theta_{\pi 0}$ intervals:
  - Extract the proton form factors directly from the 2D distribution:
$$\frac{d^2\sigma}{d\Omega_e^*} = \int_{\Delta q^2}\int_{\Delta\theta_{\pi^0}} \frac{d\sigma}{dq^2\, d\cos\theta_{\pi^0}\, d\Omega_e^*}\, dq^2\, d\cos\theta_{\pi^0}$$
  - Integration over one variable (to avoid low statistics bins):

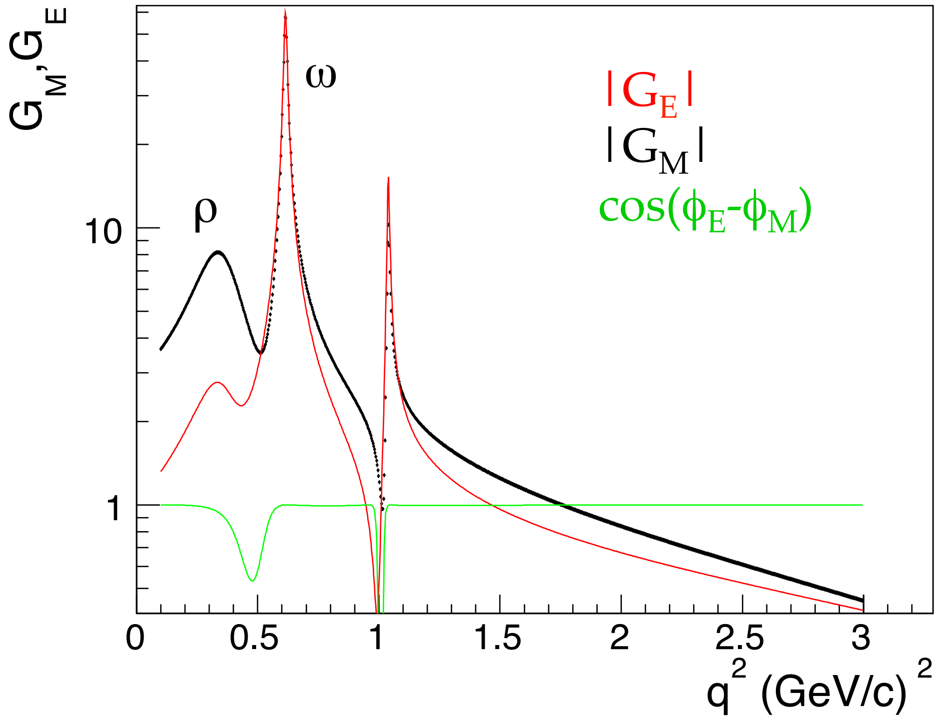
$$\frac{dN_1}{d\cos\theta_e^*} = L\int_{\Delta q^2}\int_{\Delta\theta_{\pi^0}}\int_0^{2\pi} \frac{d\sigma}{dq^2\, d\cos\theta_{\pi^0}\, d\Omega_e^*}\, dq^2\, d\cos\theta_{\pi^0}\, d\varphi_e^* = A(1 + B\cos^2\theta_e^*)$$

$$\frac{dN_2}{d\varphi_e^*} = L\int_{\Delta q^2}\int_{\Delta\theta_{\pi^0}}\int_{-1}^{1} \frac{d\sigma}{dq^2\, d\cos\theta_{\pi^0}\, d\Omega_e^*}\, dq^2\, d\cos\theta_{\pi^0}\, d\cos\theta_e^* = C(1 + D\cos 2\varphi_e^*)$$

$$\frac{dN_3}{d\varphi_e^*} = L\int_{\Delta q^2}\int_{\Delta\theta_{\pi^0}}\int_0^{1} \frac{d\sigma}{dq^2\, d\cos\theta_{\pi^0}\, d\Omega_e^*}\, dq^2\, d\cos\theta_{\pi^0}\, d\cos\theta_e^* = E(1 + F\cos 2\varphi_e^* + G\cos\varphi_e^*)$$

J. Van de Wiele (PhD thesis of J. Boucher, Paris-Sud and JGU mainz, Orsay, 2011)

Time-like proton form factors (VMD model)



Vector Meson Dominance (VMD)
F. Iachello, PRC 69, 055204 (2004)

$q^2=0.605\pm0.005$ (GeV/c^2)^2
R=1.066, $\cos(\phi_E-\phi_M)=0.998$ (4°)

$q^2=2\pm0.125$ (GeV/c^2)^2
R=0.802, $\cos(\phi_E-\phi_M)=0.999$ (3°)

2 fb^{-1}

s=5.4 GeV^2	$q^2=0.605\pm0.005$ (GeV/c^2)^2	$q^2 = 2\pm0.125$ (GeV/c^2)^2
$10° < \theta_{\pi 0} < 30°$	2.91271 . 10^6	18441
$30° < \theta_{\pi 0} < 50°$	2.47392 . 10^6	17379
$90° < \theta_{\pi 0} < 100°$	1.40351 . 10^6	9362
$120° < \theta_{\pi 0} < 140°$	840234	4989
$140° < \theta_{\pi 0} < 160°$	517112	2954

Determination of the proton form factors

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

1. Calculate the theoretical number of counts $N^{th}[i,j]$ in each bin of the 2D-distribution (θ^*_e, φ^*_e)

2. Calculate the number of reconstructed events $N^{rec}[i,j]$ taking into account signal efficiency

3. Calculate the number of 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 $N^{rec}[i,j]$)

4. Correct the observed events by the signal efficiency: $N^{cor}[i,j]$

5. Projections to obtain the three 1D-distrbutions:

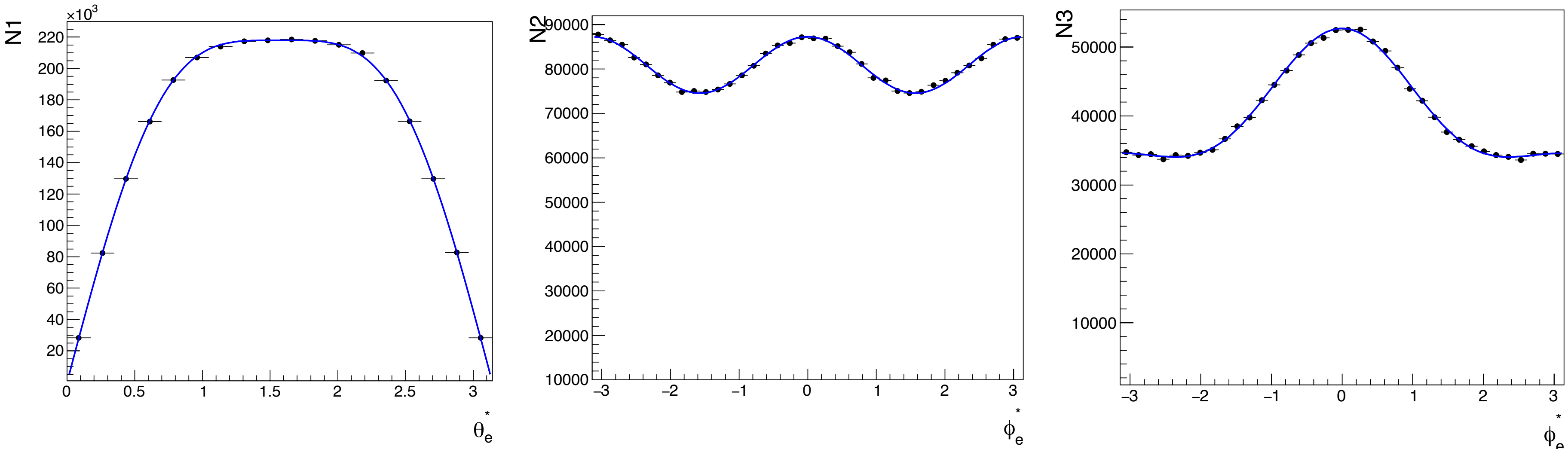
$$N_1 = \sum_{j=0}^{j<Nj} N^{cor}[i,j], N_2 = \sum_{i=0}^{i<Ni} N^{cor}[i,j], N_3 = \sum_{i=0}^{i<Ni/2} N^{cor}[i,j]$$

6. Extract the proton form factors by fitting the three 1D-distrubtions

7. Error estimation of the proton FFs by generating ~100 histograms using $N^{obs}[i,j]$ as input for random generation

Determination of the proton form factors

- $q^2 = 0.605 \pm 0.015$ $(GeV/c^2)^2$, $\theta_{\pi 0} = [10^o - 30^o]$, **100% signal efficiency** ($N^{th} = 2.9 \cdot 10^6$)



$$\frac{dN_1}{d\cos\theta_e^*} = A(1 + B\cos^2\theta_e^*)$$

$$\frac{dN_2}{d\varphi_e^*} = C(1 + D\cos 2\varphi_e^*)$$

$$\frac{dN_3}{d\varphi_e^*} = E(1 + F\cos 2\varphi_e^* + G\cos\varphi_e^*)$$

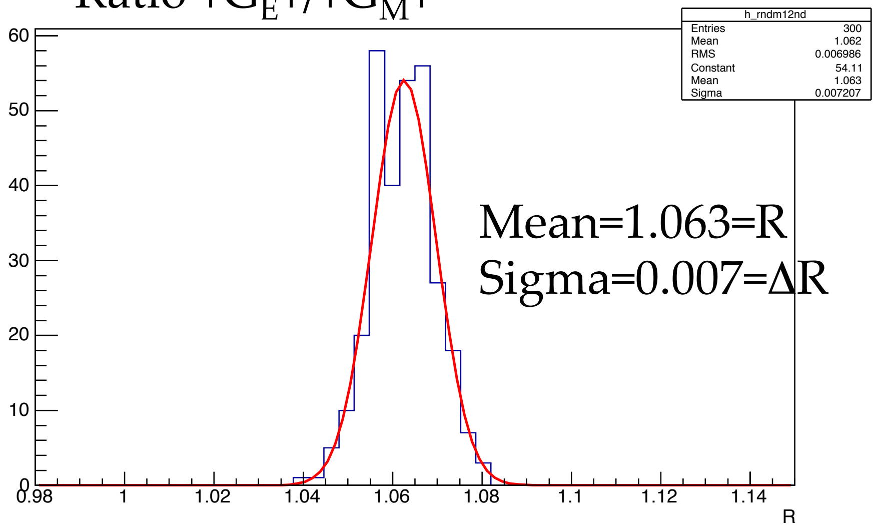
A, B, C, D, E, F, G are functions of the proton form factors

	R	$\cos(\phi_E - \phi_M)$
Theoretical values	1.066	0.998
Fit results (one simulation)	1.067± 0.006	1.040± 0.085

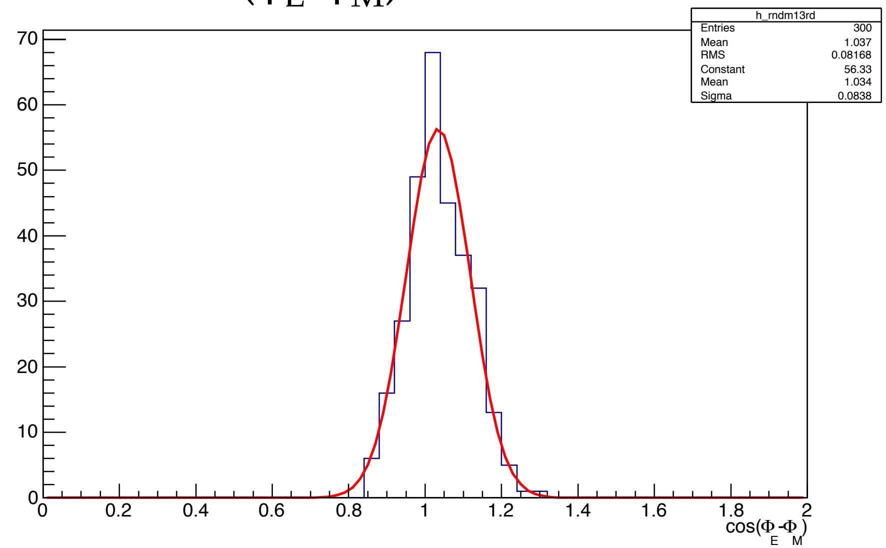
Determination of the proton form factors

- $q^2 = 0.605 \pm 0.015\ (\mathrm{GeV}/c^2)^2$, $\theta_{\pi 0} = [10^o - 30^o]$, **100% signal efficiency** ($N^{th} = 2.9 \,.\, 10^6$)

Ratio $|G_E|/|G_M|$



$\cos(\phi_E - \phi_M)$



	R	$\cos(\phi_E - \phi_M)$
Theoretical values	1.066	0.998
Fit results (500 simulations)	1.063±0.007	1.034±0.084

Determination of the proton form factors

- q^2=0.605 ± 0.015 $(GeV/c^2)^2$, **100% signal efficiency**

R	10°<$\theta_{\pi 0}$<30°	30°<$\theta_{\pi 0}$<50°	80°<$\theta_{\pi 0}$<100°	120°<$\theta_{\pi 0}$<140°	140°<$\theta_{\pi 0}$<160°
Events N^{th}	2.9 . 10^6	2.5 . 10^6	1.4 . 10^6	840234	517112
Theoretical values	1.066	1.066	1.066	1.066	1.066
Fit results (this work)	1.063±0.007 (0.7%)	1.065±0.004 (0.4%)	1.052±0.007 (0.6%)	1.024±0.022 (2.1%)	1.068±0.070 (6.4%)

$\cos(\phi_E-\phi_M)$	10°<$\theta_{\pi 0}$<30°	30°<$\theta_{\pi 0}$<50°	80°<$\theta_{\pi 0}$<100°	120°<$\theta_{\pi 0}$<140°	140°<$\theta_{\pi 0}$<160°
Theoretical values	0.998	0.998	0.998	0.998	0.998
Fit results (this work)	1.034±0.084 (8%)	1.086±0.063 (6%)	0.956±0.058 (6%)	0.665±0.129 (19%)	X

Determination of the proton form factors

- $q^2 = 2 \pm 0.125\ (GeV/c^2)^2$, **100% signal efficiency**

R	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Events N^{th}	18441	17379	9362	4989	2954
Theoretical values	0.802	0.802	0.802	0.802	0.802
Fit results (this work)	0.802±0.026 (3%)	0.809±0.017 (2%)	0.785±0.028 (3.5%)	0.761±0.075 (10%)	X

$\cos(\phi_E - \phi_M)$	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Theoretical values	0.999	0.999	0.999	0.999	0.999
Fit results (this work)	1.006±0.082 (8%)	0.905±0.076 (8.5%)	0.904±0.090 (10%)	0.929±0.244 (28%)	X

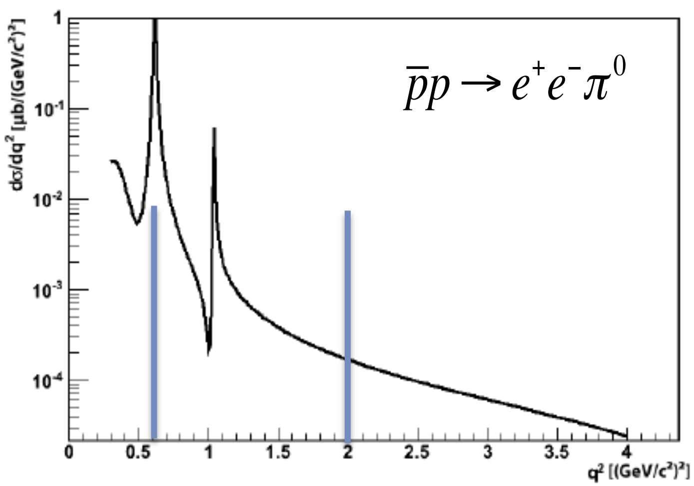
Feasibility studies with PANDARoot

Description of the Monte Carlo simulations

Monte Carlo Simulation Studies:
Background suppression versus signal efficiency

Signal $\bar{p}p \rightarrow e^+e^-\pi^0$ Background $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$

- PANDARoot version **oct19**, FairSoft **jun19p1**, FairRoot **v18.2**
- Simulation macros from master directory
- **Event generation**
  - Antiproton momentum (lab) p_{pbar}=1.7 GeV/c
    - $q^2 = 0.605 \pm 0.015$ $(GeV/c^2)^2$: M_{inv}=[0.77-0.79] GeV/c
    - $q^2 = 2.0 \pm 0.375$ $(GeV/c^2)^2$: M_{inv}=[1.27-1.54] GeV/c
  - PHSP angular distributions, PHOTOS switched on
  - 5.10^7 events for the signal in each q2 interval
  - 10^8 events for the background in each q2 interval
  - **Reconstruction and particle identification**
    - Kalman Filter with muon hypothesis
    - PID Correlator with pion hypothesis



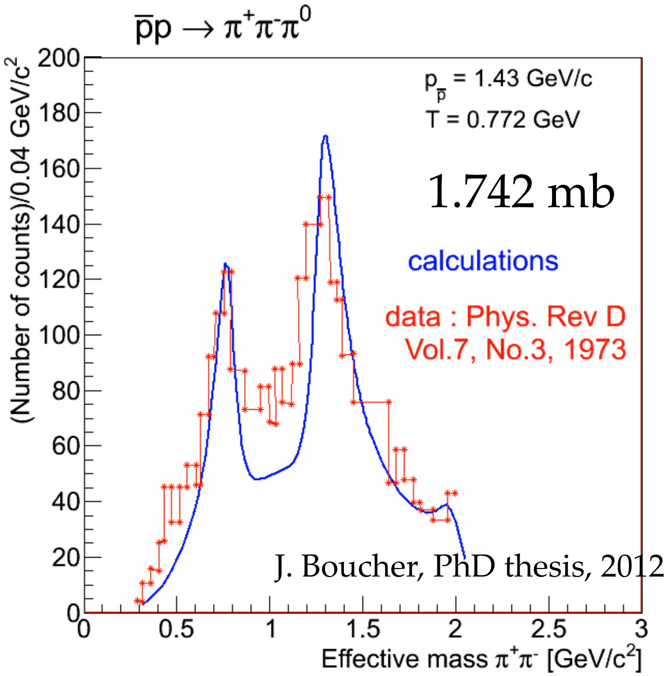
Signal and background cross sections

- P=1.7 GeV/c

- q^2=0.6 (GeV^2/c^2), M_{inv}=0.78 GeV/c

$$\frac{\sigma(\bar{p}p \to \pi^+\pi^-\pi^0)}{\sigma(\bar{p}p \to e^+e^-\pi^0)} \sim 10^3 - 10^4$$

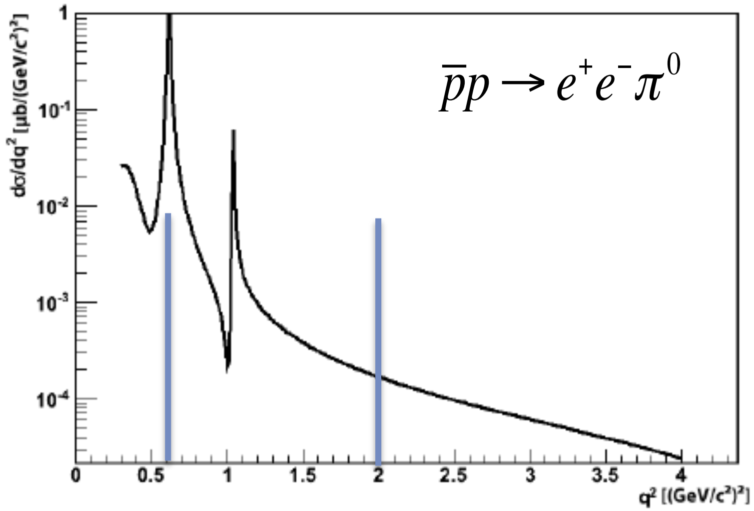
➢ **Background rejection ~ 10^{-6}-10^{-7} is needed for a signal pollution < 1%**



- q^2=2 (GeV^2/c^2), M_{inv}=1.4 GeV/c

$$\frac{\sigma(\bar{p}p \to \pi^+\pi^-\pi^0)}{\sigma(\bar{p}p \to e^+e^-\pi^0)} \sim 10^6 - 10^7$$

➢ **Background rejection < 10^{-8} is needed for a signal pollution at few percent level**



Event Selection

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

I. Charged track selection (related to the background suppression)

a) Events with only two charged tracks are selected
b) PID probability for the detected particle to be identified as e+/e- larger than 99% or 99.8% (EMC+STT+MVD+DRC)
c) EMC deposit energy over the tracking momentum $E_{EMC}/p>0.8$
d) Energy loss in the STT $dE/dx(STT) > 5.8$

II. Pion reconstruction (RN-QCD-2018-002)

- At least two photons/event with EMC raw energy > 15 MeV
- Pion mass cut: $M_{\pi 0} - 0.05 < M_{\gamma\gamma} < M_{\pi 0} - 0.05$ (GeV/c^2)
- Mass constraint fit to the nominal π0 mass : Prob. > 10^{-3}. In case of more than one reconstructed pion/event, the pair (γγ) of higher fit probability is selected.

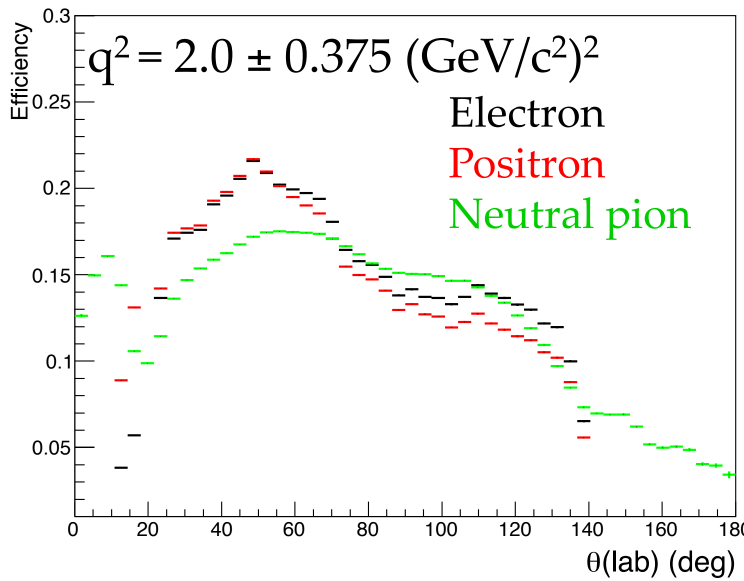
III. Events selection

- 4C fit is applied to the reconstructed three particles ($\chi 2 < 50$ or $\chi 2 < 30$)

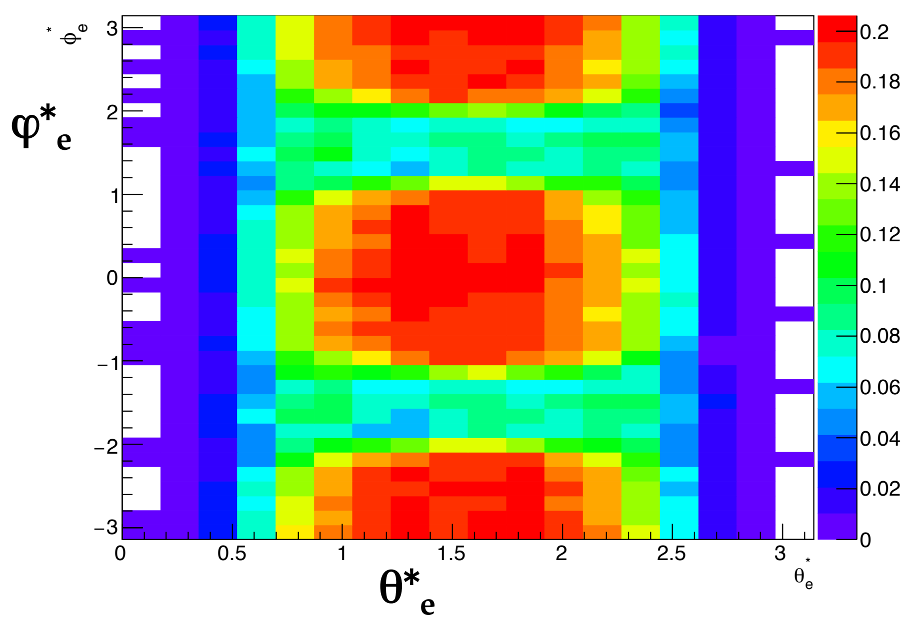
Signal and background Efficiencies

$q^2=0.605 \pm 0.015\ (GeV/c^2)^2$			$q^2=2.0 \pm 0.375\ (GeV/c^2)^2$		
Sequential eff.	Signal	background		Signal	Background
Reconstruction	65%	63 %	Reconstruction	69 %	68%
PID (Prob.>99%, E_{EMC}/p, dE/dx)	22%	$4 . 10^{-5}$	PID (Prob.>99.8%, E_{EMC}/p, dE/dx)	30%	$2 . 10^{-5}$
pi0 Rec.	16%	$7 . 10^{-6}$	pi0 Rec.	19%	$9 . 10^{-6}$
4C-fit (χ2_4C<50)	13%	$2 . 10^{-7}$	4C-fit (χ2_4C<30)	15%	$<10^{-8}$

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

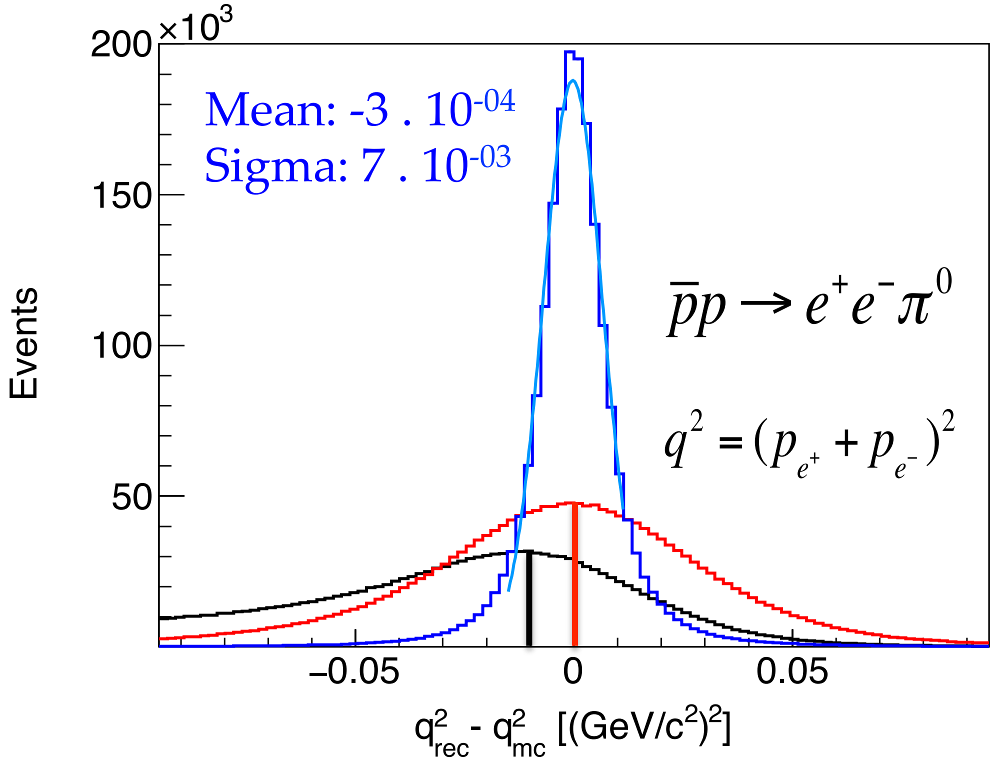


$\bar{p}p \rightarrow e^+e^-\pi^0$



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

- $q^2 = 0.605 \pm 0.015\ (GeV/c^2)^2$



"Before Bremsstrahlung correction, without 4C kinematic fit"

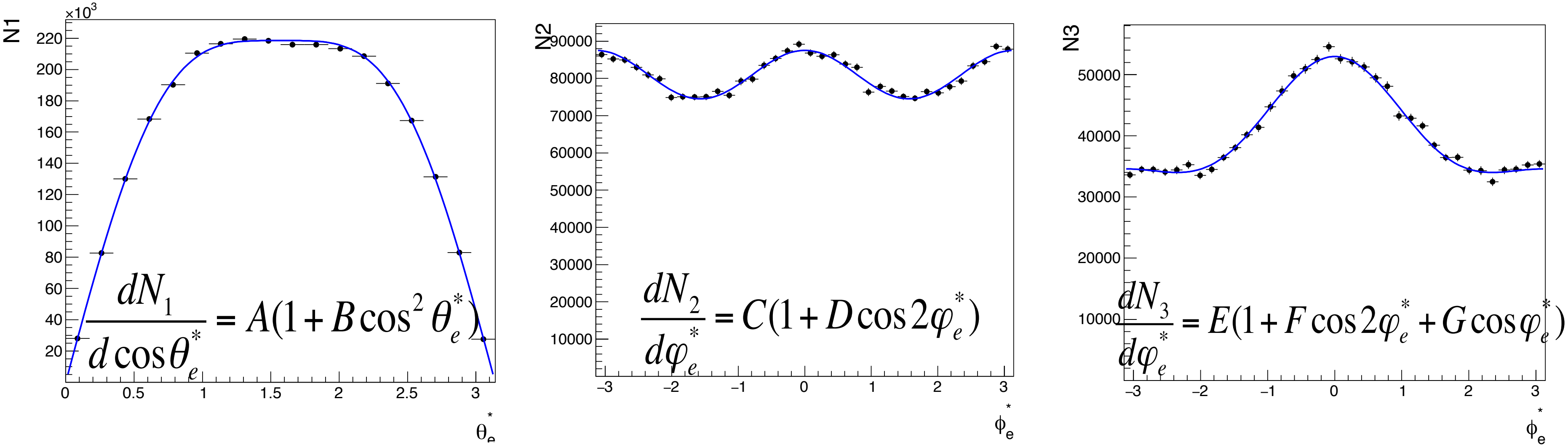
"After Bremsstrahlung correction without 4C kinematic fit" (Methode described in: E. ATOMSSA TN-STT-2015-001)

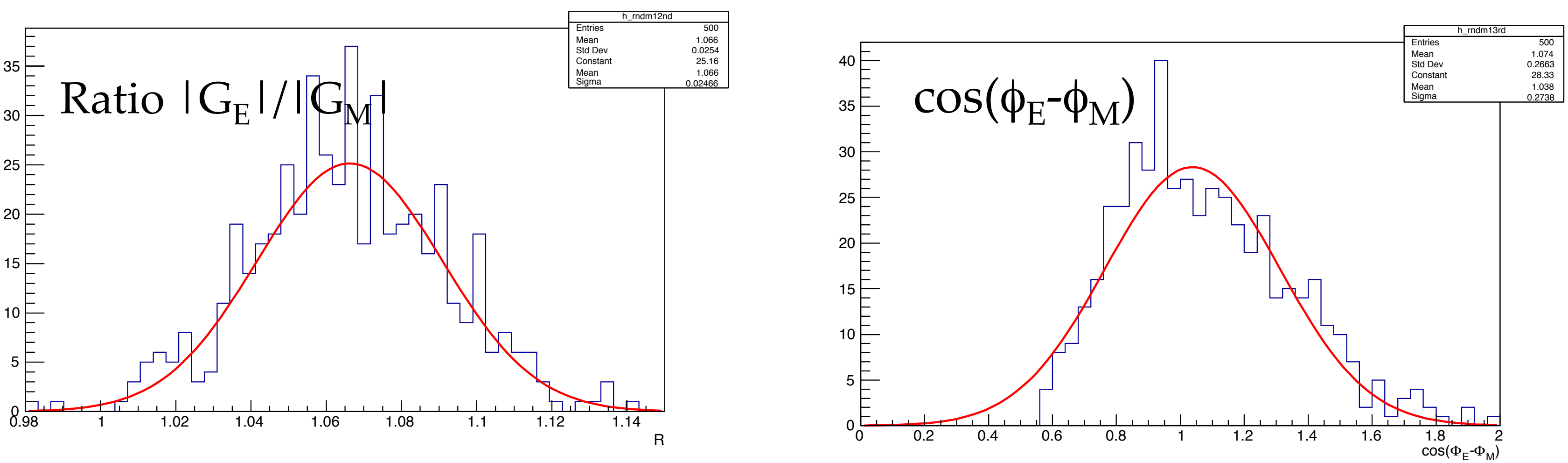
"After Bremsstrahlung correction with 4C kinematic fit"

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

Determination of the proton form factors

- $q^2 = 0.605 \pm 0.015$ $(GeV/c^2)^2$, $\theta_{\pi 0} = [10^o - 30^o]$,





Determination of the proton form factors (Results)

- $q^2 = 0.605 \pm 0.015\ (GeV/c^2)^2$

R	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Theoretical values	1.066	1.066	1.066	1.066	1.066
Fit results (100% signal efficiency)	1.063±0.007 (0.7%)	1.065±0.004 (0.4%)	1.052±0.007 (0.6%)	1.024±0.022 (2.1%)	1.068±0.070 (6.4%)
Fit results (PANDARoot)	**1.061±0.029 (2.7%)**	**1.059±0.009 (0.8%)**	**1.072±0.018 (1.6%)**	**1.171±0.672 (57%)**	**X**

$\cos(\phi_E-\phi_M)$	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Theoretical values	0.998	0.998	0.998	0.998	0.998
Fit results (100% signal efficiency)	1.034±0.084 (8%)	1.086±0.063 (6%)	0.956±0.058 (6%)	0.665±0.129 (19%)	X
Fit results (PANDARoot)	**1.302±0.334 (26%)**	**1.156±0.131 (11%)**	**0.785±0.138 (18%)**	**X**	**X**

Determination of the proton form factors (Results)

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

R	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Theoretical values	0.802	0.802	0.802	0.802	0.802
Fit results (100% signal efficiency)	0.802±0.026 (3%)	0.809±0.017 (2%)	0.785±0.028 (3.5%)	0.761±0.075 (10%)	X
Fit results (PANDARoot)	**0.638±0.099 (16%)**	**0.745±0.041 (5%)**	**0.628±0.068 (11%)**	**0.656±0.165 (25%)**	**X**

$\cos(\phi_E-\phi_M)$	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Theoretical values	0.999	0.999	0.999	0.999	0.999
Fit results (100% signal efficiency)	1.006±0.082 (8%)	0.905±0.076 (8.5%)	0.904±0.090 (10%)	0.929±0.244 (28%)	X
Fit results (PANDARoot)	**1.179±0.343 (29%)**	**1.576±0.210 (13%)**	**0.556±0.302 (54%)**	**X**	**X**

Summary

- The process **ppbar->$e^+e^-\pi^0$** is considered within the one nucleon exchange model in t-and u-channels
  - to access the proton form factors in the unphysical region

- Monte Carlo simulations for signal and background processes are performed with PANDARoot. The results show that

  - Background can be sufficiently suppressed
  - The proton form factor ratio and the relative phase term $\cos(\phi_E - \phi_M)$ can be determined in different intervals of q2 and thetepi0 with good precisions

➢ Next step: investigation of the **ppbar->$e^+e^-\pi^0$** process beyond the one nucleon exchange model:
  - Theoretical analysis of the **ppbar->$e^+e^-\pi^0$** process within a Regge framework (J. Guttmann, M. Vanderhaeghen, PLB 719 (2013) 136–142)-> exchange of dominant baryon Regge trajectories

Backup slides

Differential cross section within Regge framework

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

Regge trajectory for the nucleon

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

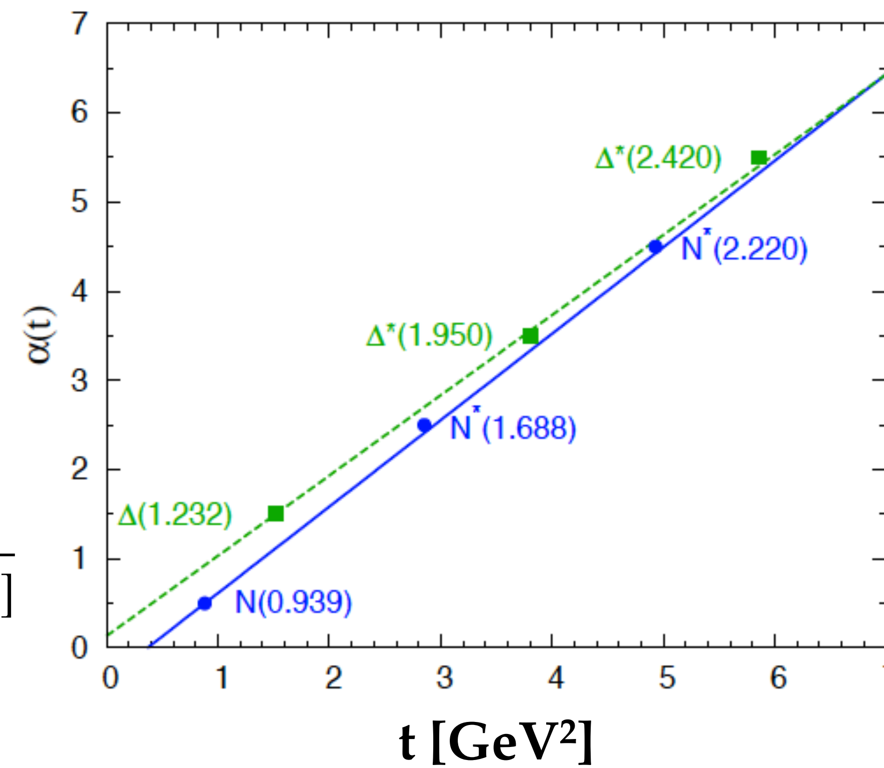
Modified nucleon propagator:

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

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

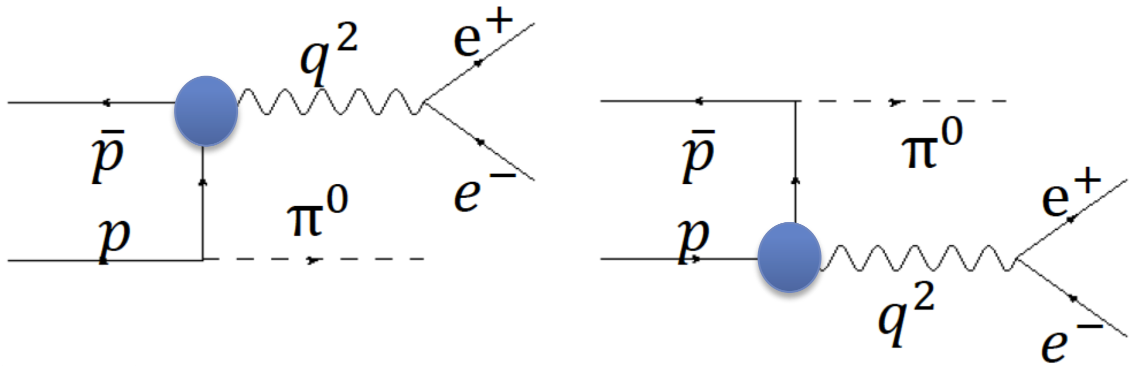
$$u-channel: \frac{1}{u - M^2} \rightarrow$$

$$D_N^{Regge}(u,s) = \frac{s^{\alpha_N(u)-0.5}}{\Gamma[\alpha_N(u)+0.5]} \pi\alpha_N^{'} \frac{e^{-i\pi(\alpha_N(u)+0.5)}}{\sin[\pi(\alpha_N(u)+0.5)]}$$



Differential cross section in one nucleon exchange model

$$\frac{d^5\sigma}{dq^2 d\Omega_{\pi^0} d\Omega_e^*} \propto L^{\mu\nu} H_{\mu\nu}$$



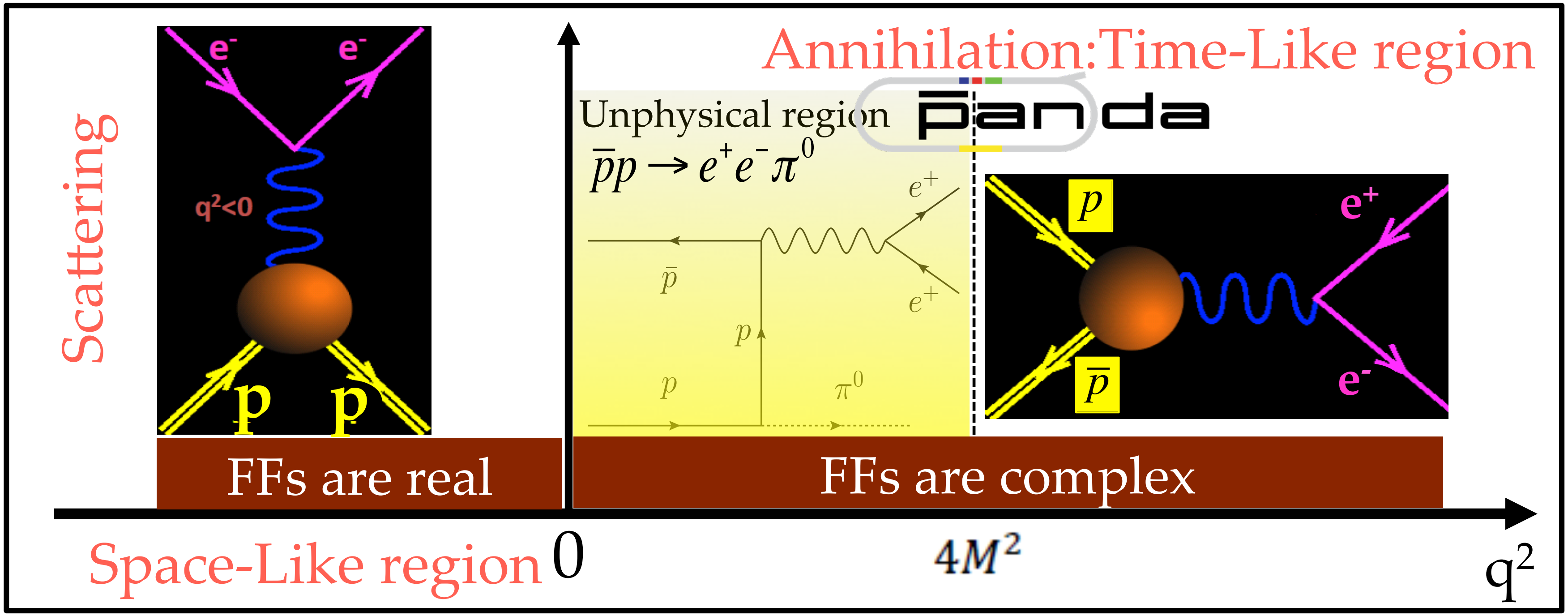
- In the γ* rest frame (unpolarized experiment):

$$L^{\mu\nu} H_{\mu\nu} = 2e^2 q^2 (H_{11} + H_{22} + H_{33})$$
$$-8e^2 p_e^{*2} (H_{11} \sin^2\theta_e^* \cos^2\varphi_e^* + 2H_{13} \sin\theta_e^* \cos\theta_e^* \cos\varphi_e^*$$
$$+H_{22} \sin^2\theta_e^* \sin^2\varphi_e^* + H_{33} \cos^2\theta_e^*)$$

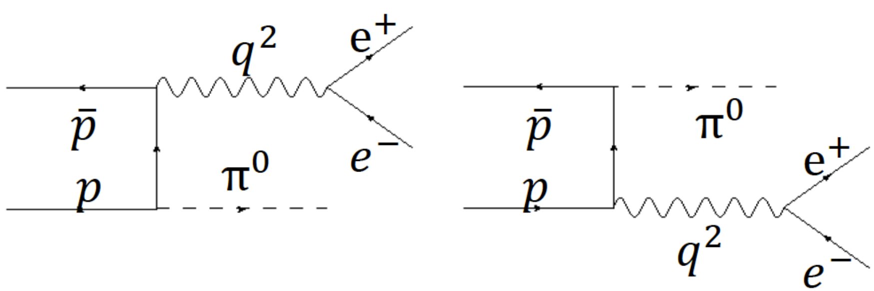
- Non zero hadronic tensors H_{11}, H_{22}, H_{33}, H_{13}
- $H_{0\nu}=0$ by gauge invariance (in this frame $q_\mu H^{\mu\nu}=q_0 H^{0\nu}+q_i H^{i\nu}=0$)
- H_{12}, H_{23} numerically zero

J. Van de Wiele (PhD thesis of J. Boucher, Paris-Sud and JGU mainz, Orsay, 2011)

Electromagnetic Form Factors of the Proton

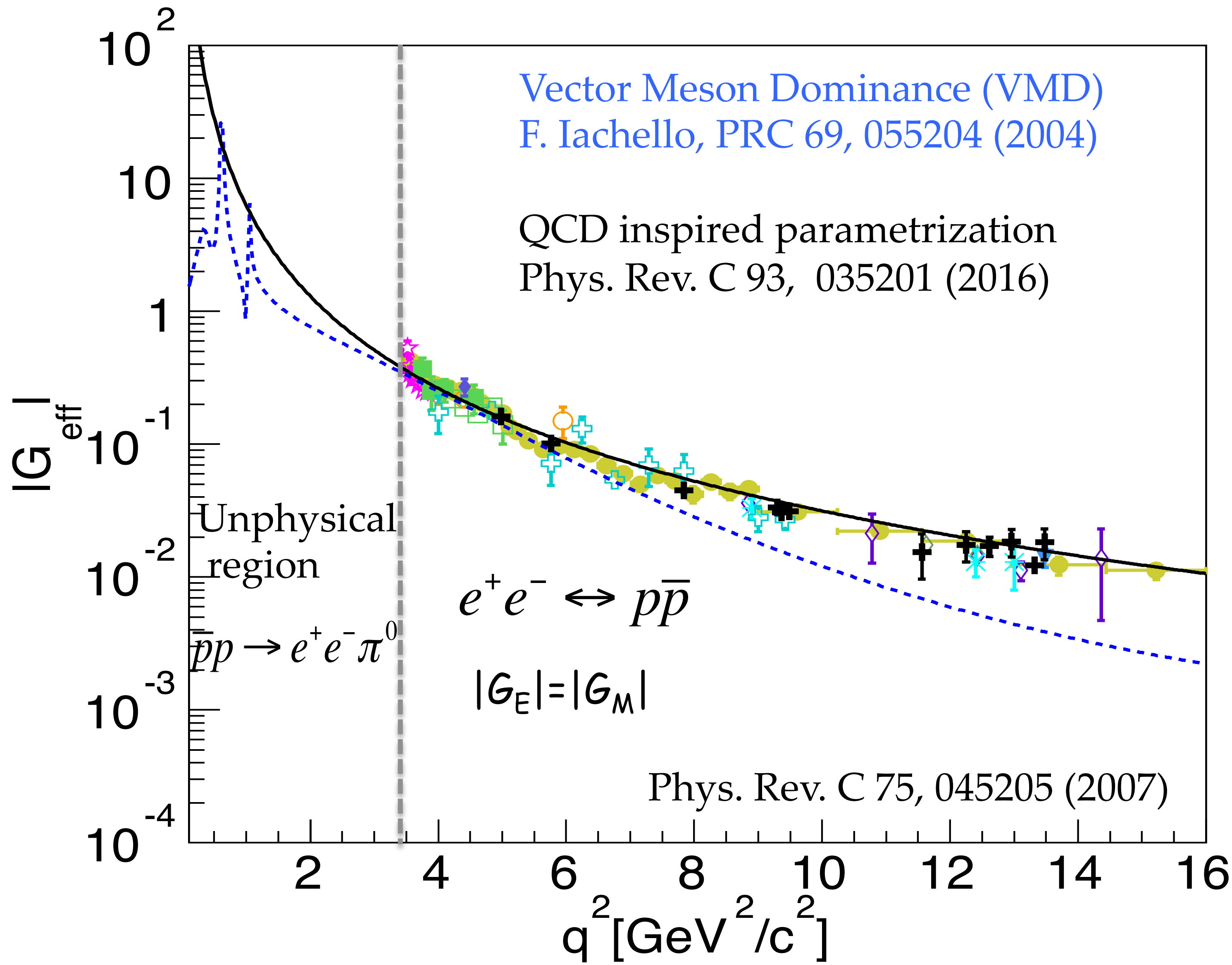


- Electric G_E and magnetic G_M proton FFs are functions of q^2
- Unphysical region can be accessed by:



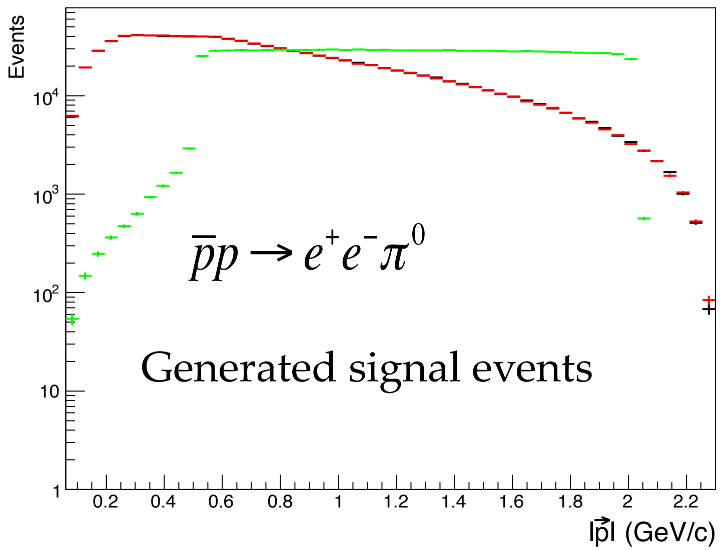
Phys. C 70, 473—481 (1996)
Phys. Rev. C 75, 045205 (2007)

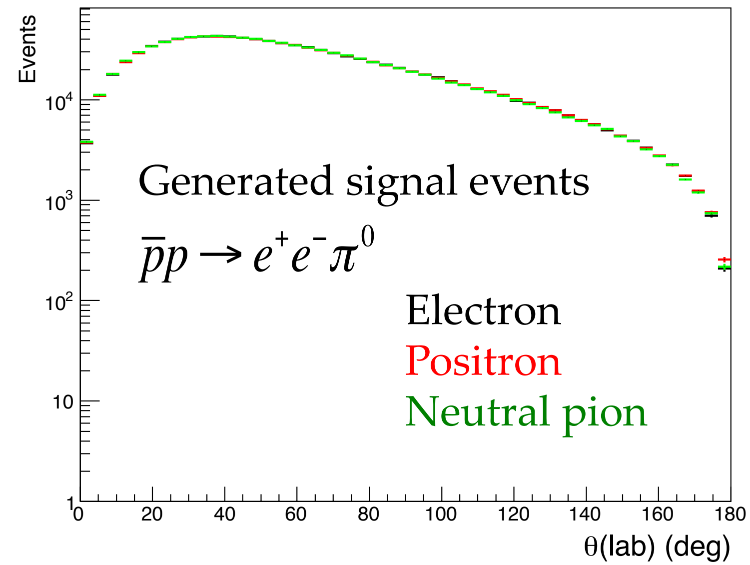
Electromagnetic form factors of the proton (Time-Like region)



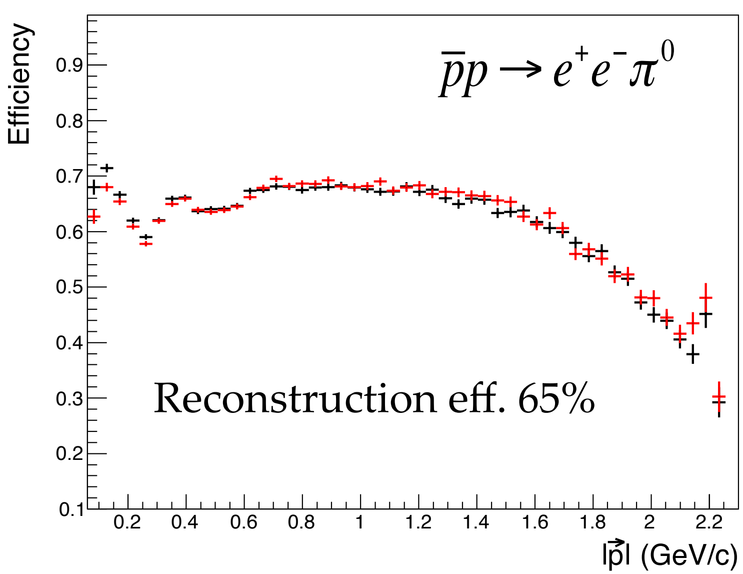
Charged Track Reconstruction

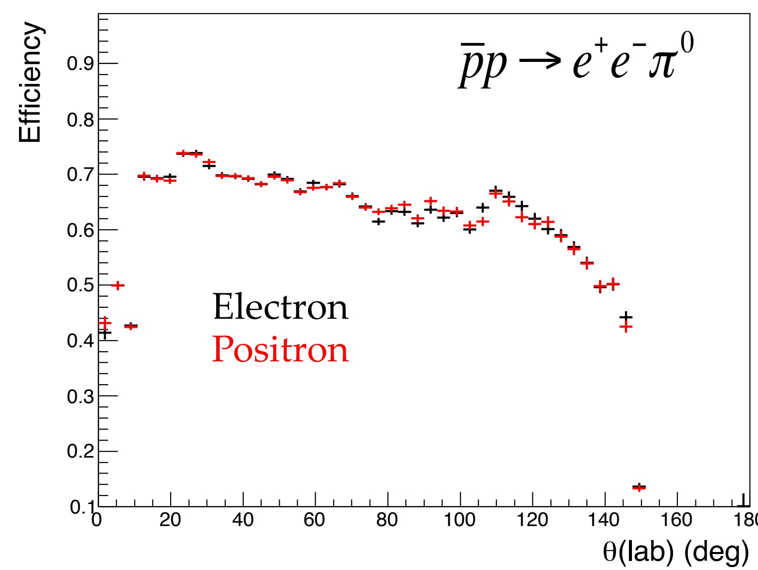
$q^2 = 0.605 \pm 0.015\ (\mathrm{GeV}/c^2)^2$





a) Reconstructed events with only two charged tracks are selected

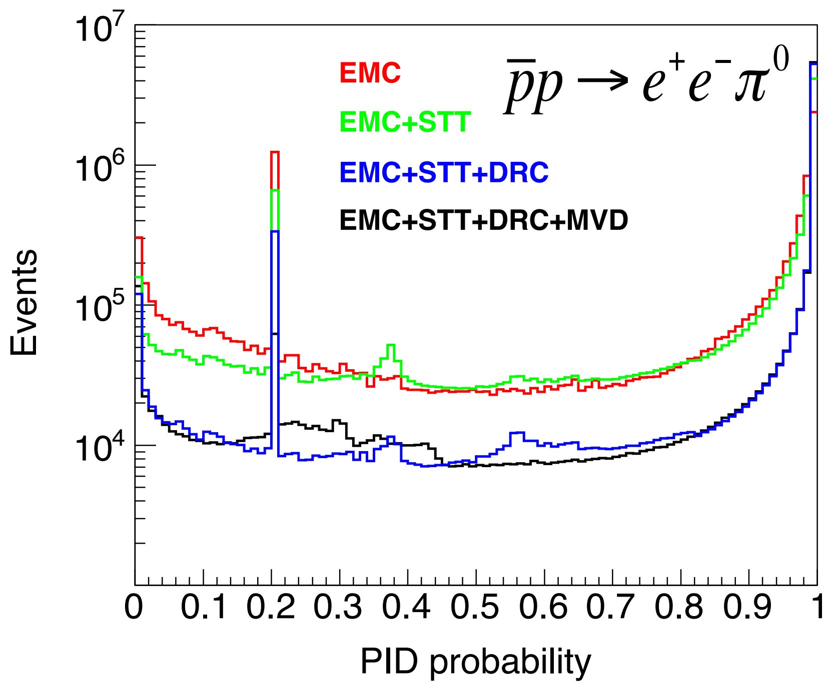


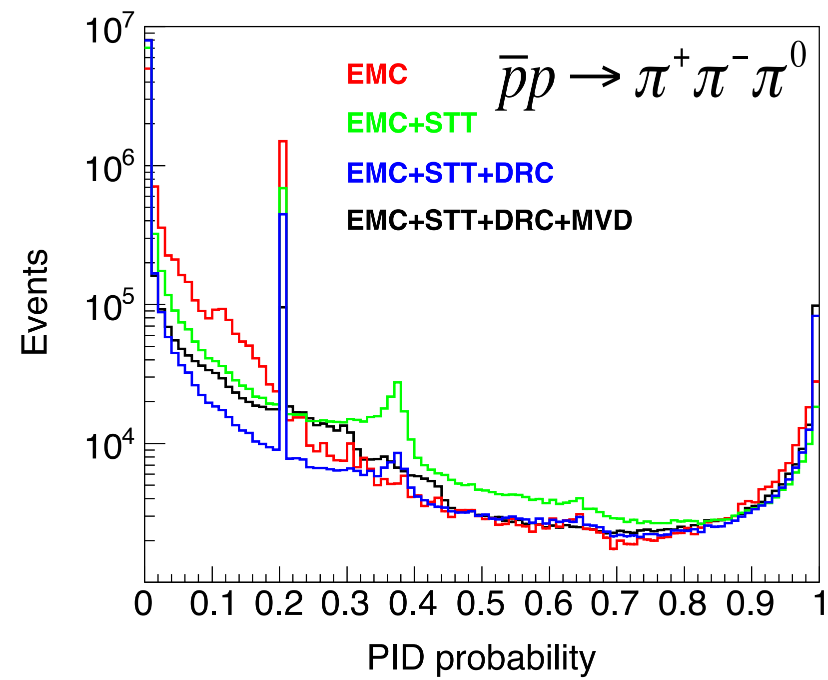


Charged Track Selection (PID Probabilities)

q^2=0.605 ± 0.015 $(GeV/c^2)^2$

PID probability for the negative track to be identified as electron:

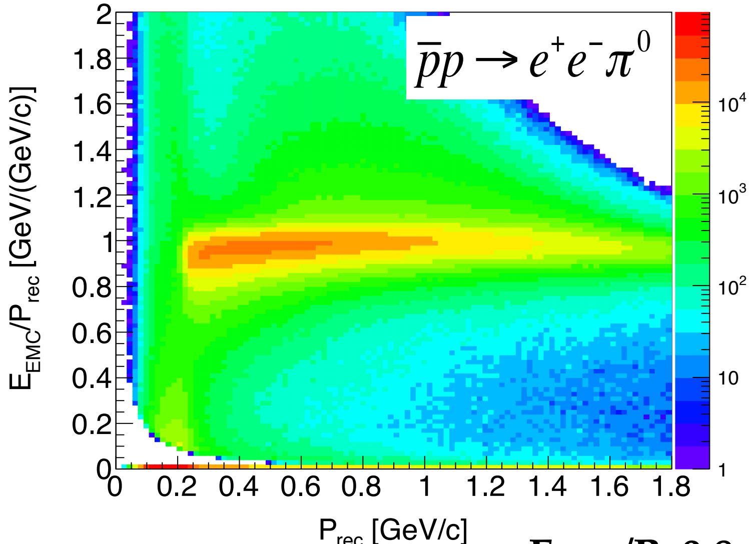


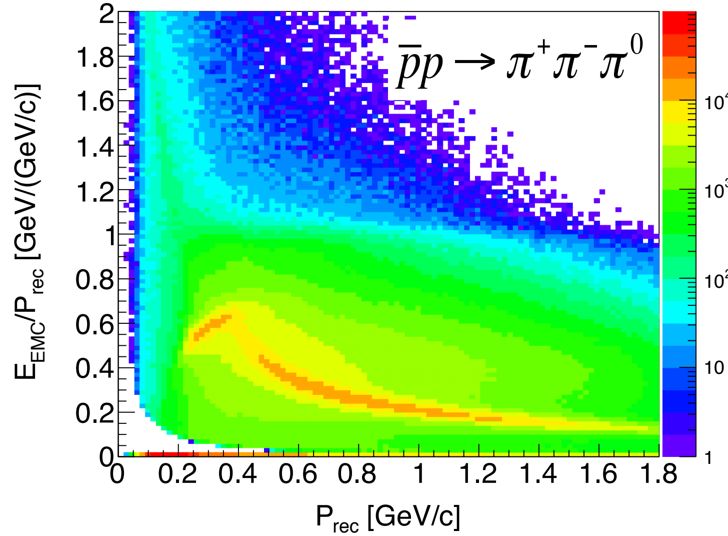


PID probability for the detected particle to be identified as e+/e- larger than 99% (**EMC+STT+MVD+DRC**)

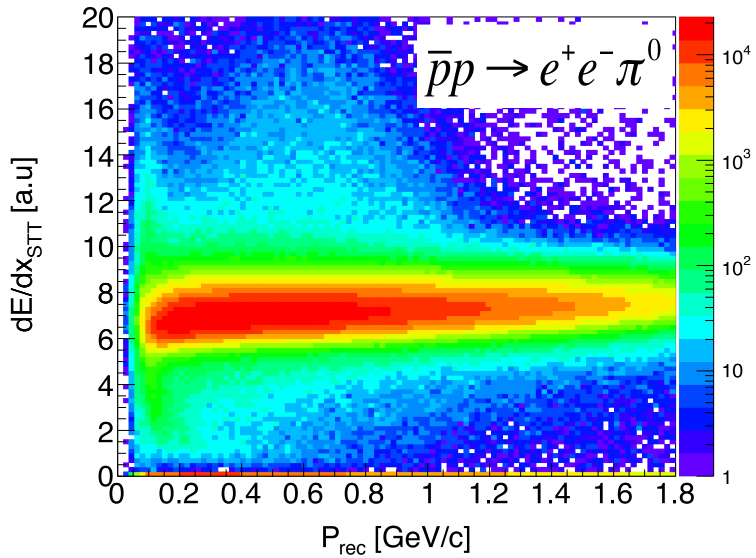
Charged Track Selection (E_{EMC}/P and dE/dx STT)

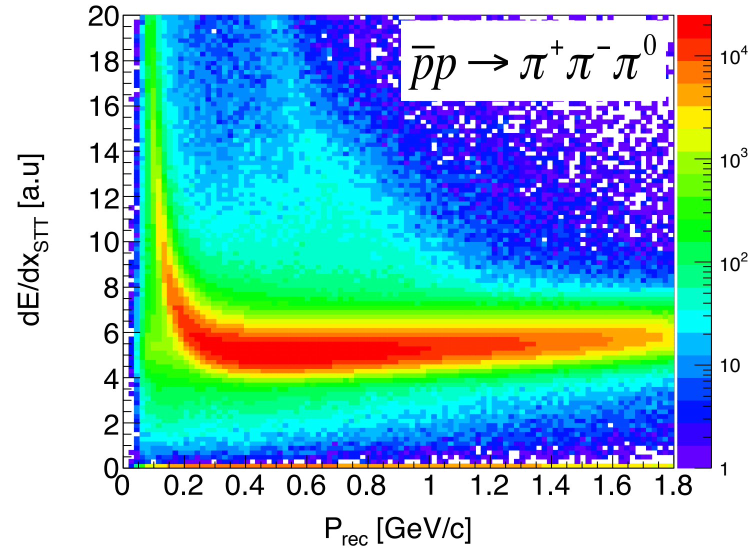
q^2=0.605 ± 0.015 $(GeV/c^2)^2$,





E_{EMC}/P>0.8 and dE/dx (STT)>5.6



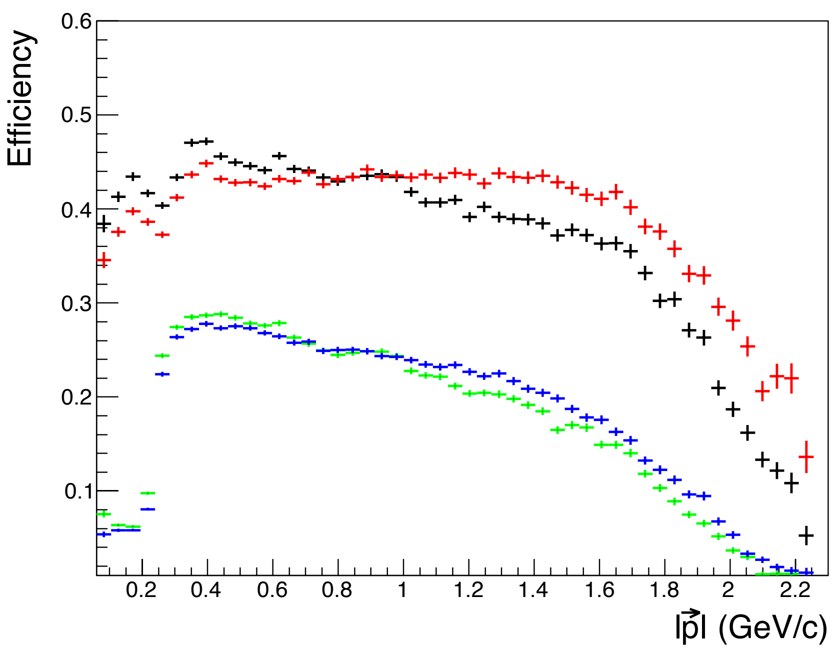


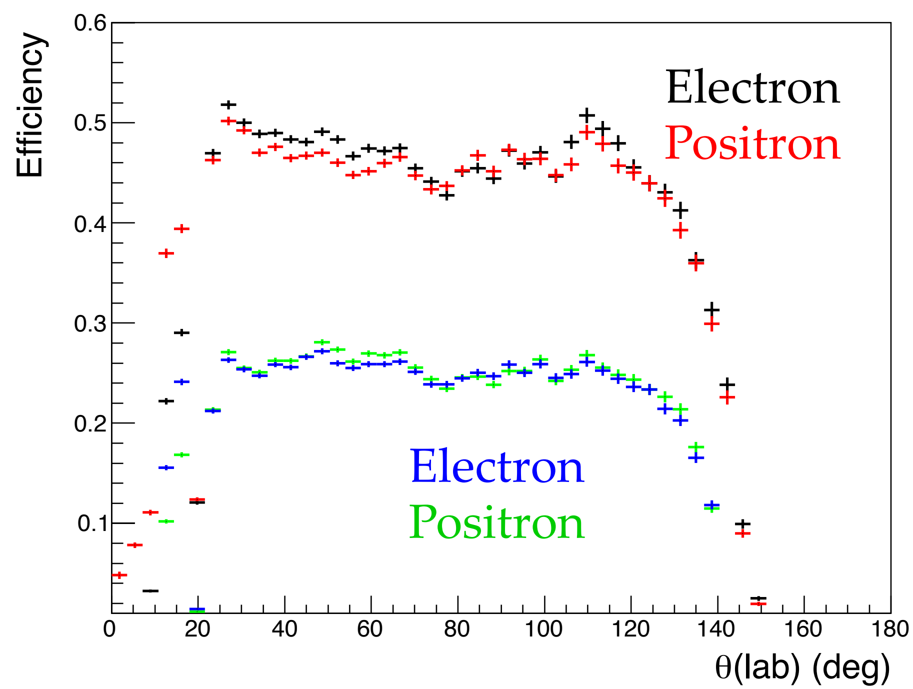
Charged Track Reconstruction (PID)

$q^2 = 0.605 \pm 0.015\ (GeV/c^2)^2$

- PID probability for the detected particle to be identified as e+/e- larger than 99% (EMC+STT+MVD+DRC)
- $E_{EMC}/p > 0.8$ and $dE/dx(STT) > 5.8$

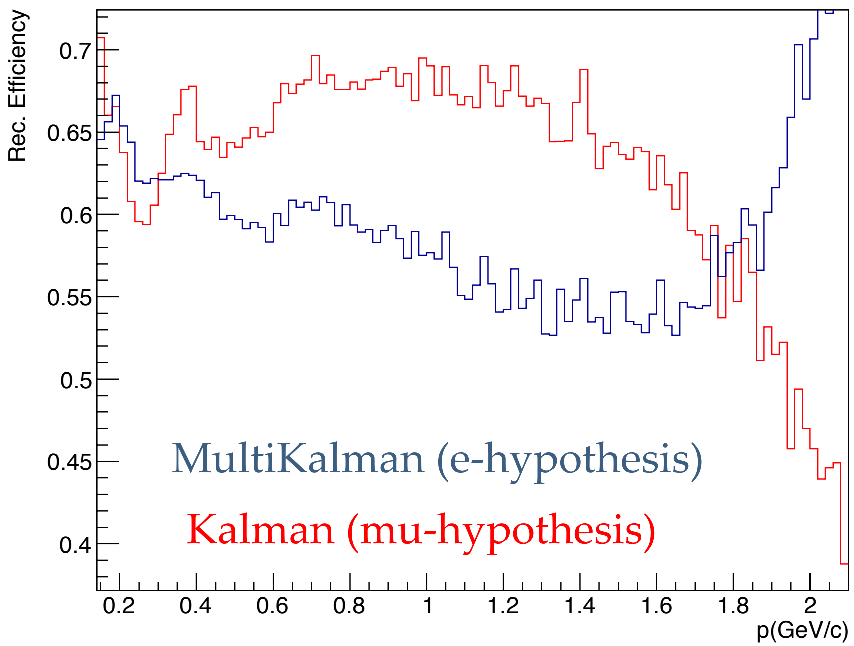
Signal eff. after PID prob.: 42%
Signal efficiency after PID prob., E_{EMC}/p and $dE/dx(STT)$ cut: 22%

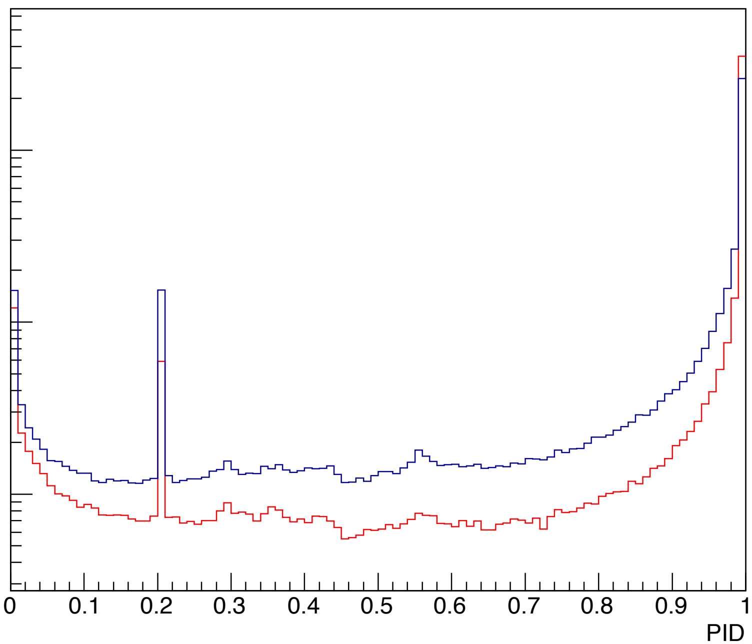




Charged Track Reconstruction and PID

$q^2 = 0.605 \pm 0.015\ (GeV/c^2)^2$





Rec. efficiency 65%
Rec. efficiency 61%

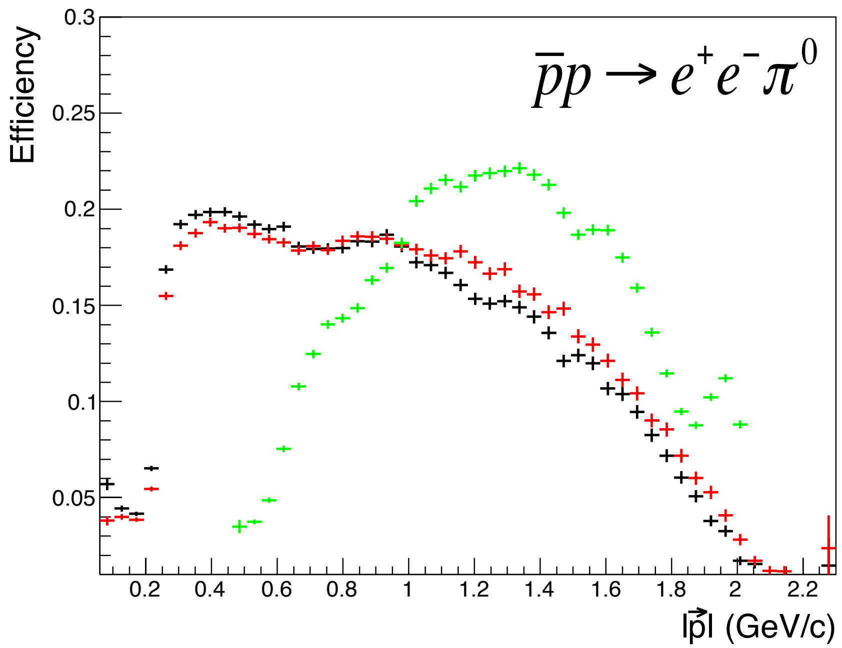
Efficiency after PID (>0.99) 42%
Efficiency after PID (>0.99) 19%

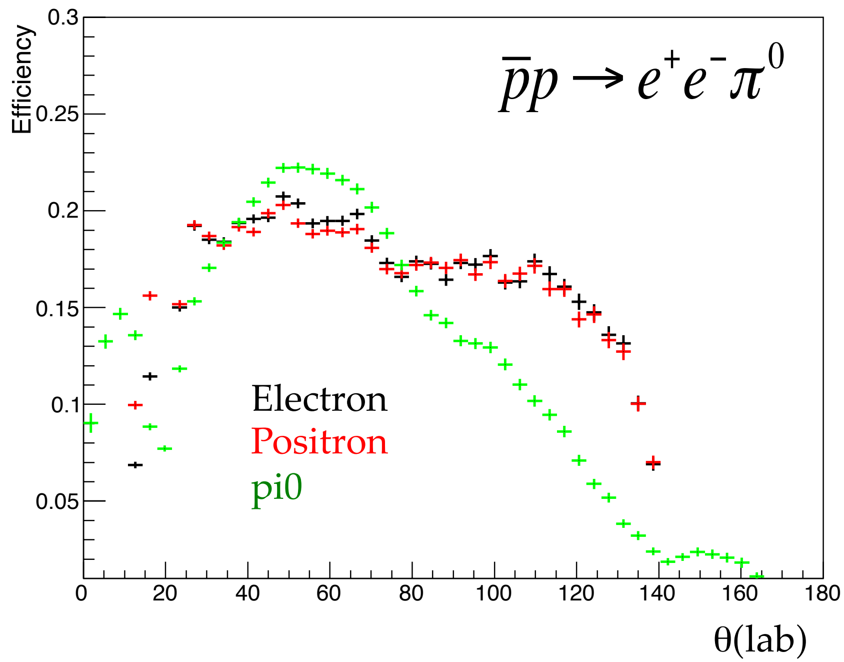
Neutral pion reconstruction (photon candidates)

q^2=0.605 ± 0.015 $(GeV/c^2)^2$

- At least two photons/event with EMC raw energy > 15 MeV
- Pion mass cut: $M_{\pi 0}$ - 0.05 < $M_{\gamma\gamma}$ <$M_{\pi 0}$ - 0.05 (GeV/c^2)
- Mass constraint fit to the nominal π0 mass : Prob. > 10^{-3}. In case of more than one reconstructed pion/event, the pair (γγ) of higher fit probability is selected.

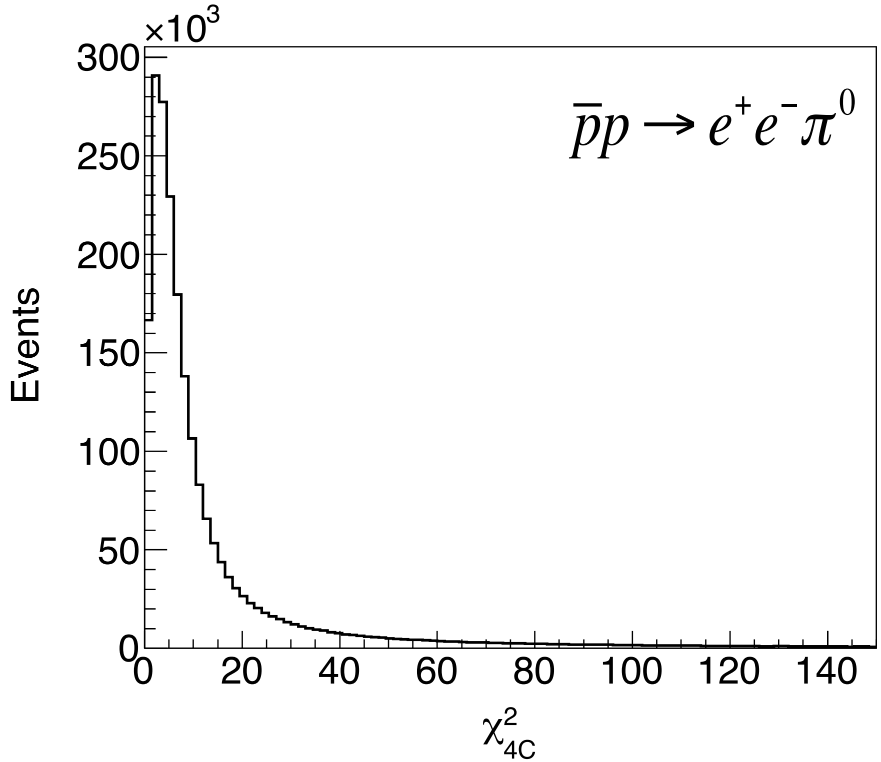
Signal eff. after pi0 selection 16%

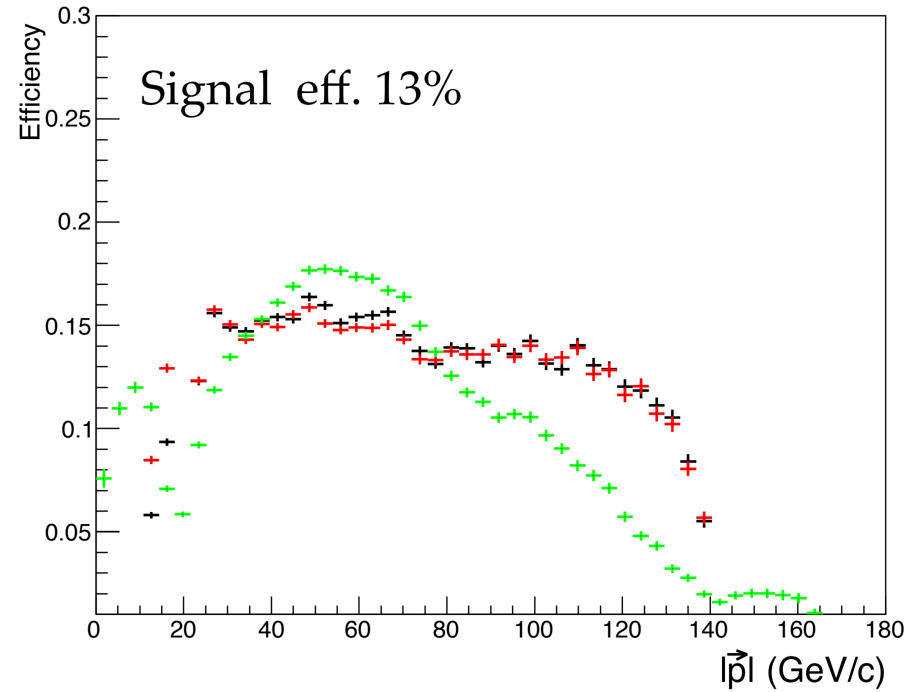




Event selection (4C kinematic fit)

Charged tracks and neutral pion selection conditions are applied





Determination of the proton form factors

- $q^2 = 0.605 \pm 0.015\ (GeV/c^2)^2$, **100% signal efficiency**

R	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Events N^{th}	$2.9 \cdot 10^6$	$2.5 \cdot 10^6$	$1.4 \cdot 10^6$	840234	517112
Theoretical values	1.066	1.066	1.066	1.066	1.066
Fit results (this work)	1.063±0.007 (0.7%)	1.065±0.004 (0.4%)	1.052±0.007 (0.6%)	1.024±0.022 (2.1%)	1.068±0.070 (6.4%)
Fit results (J. Boucher PhD)	1.066±0.008		1.063±0.007		1.067±0.074

$\cos(\phi_E-\phi_M)$	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Theoretical values	0.998	0.998	0.998	0.998	0.998
Fit results (this work)	1.034±0.084 (8%)	1.086±0.063 (6%)	0.956±0.058 (6%)	0.665±0.129 (19%)	X
Fit results (J. Boucher PhD)	1.049±0.103		0.997±0.063		X

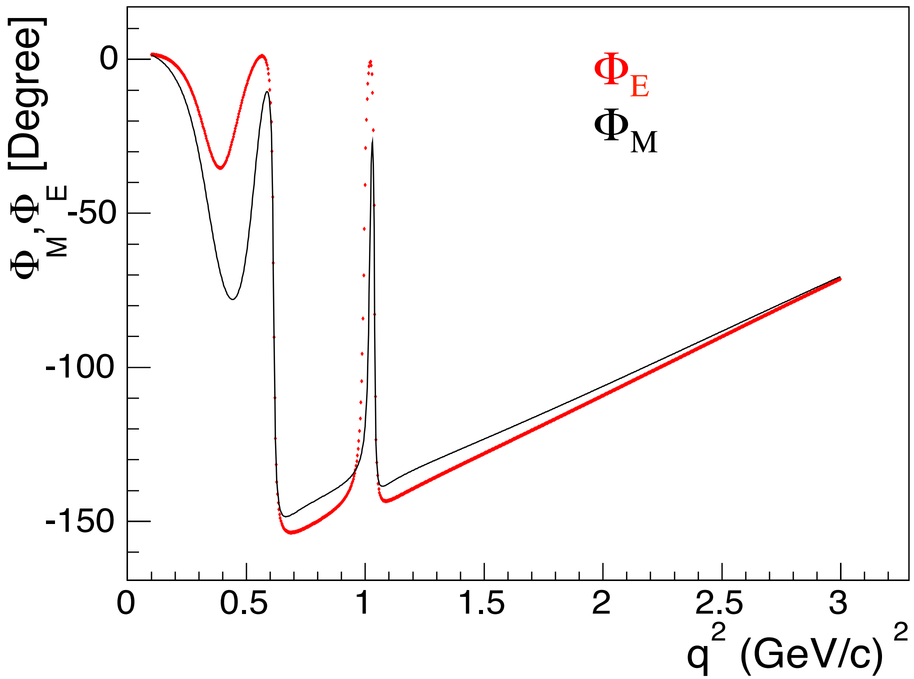
Determination of the proton form factors

- $q^2 = 2 \pm 0.125\ (GeV/c^2)^2$, **100% signal efficiency**

R	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Events N^{th}	18441	17379	9362	4989	2954
Theoretical values	0.802	0.802	0.802	0.802	0.802
Fit results (this work)	0.802±0.026 (3%)	0.809±0.017 (2%)	0.785±0.028 (3.5%)	0.761±0.075 (10%)	X
Fit results (J. Boucher PhD)	0.8±0.028		0.802±0.031		X

$\cos(\phi_E-\phi_M)$	$10^o<\theta_{\pi 0}<30^o$	$30^o<\theta_{\pi 0}<50^o$	$80^o<\theta_{\pi 0}<100^o$	$120^o<\theta_{\pi 0}<140^o$	$140^o<\theta_{\pi 0}<160^o$
Theoretical values	0.999	0.999	0.999	0.999	0.999
Fit results (this work)	1.006±0.082 (8%)	0.905±0.076 (8.5%)	0.904±0.090 (10%)	0.929±0.244 (28%)	X
Fit results (J. Boucher PhD)	1.001±0.076		0.999±0.084		X

Time-like proton form factors (VMD model)



Vector Meson Dominance (VMD)
F. Iachello, PRC 69, 055204 (2004)

q^2=0.605±0.005 (GeV/c^2)^2
R=1.066, $\cos(\phi_E-\phi_M)$=0.998 (4°)

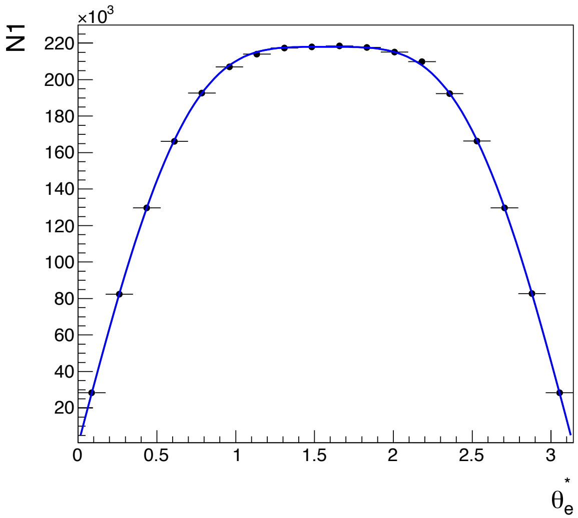
q^2=2±0.125 (GeV/c^2)^2
R=0.802, $\cos(\phi_E-\phi_M)$=0.999 (3°)

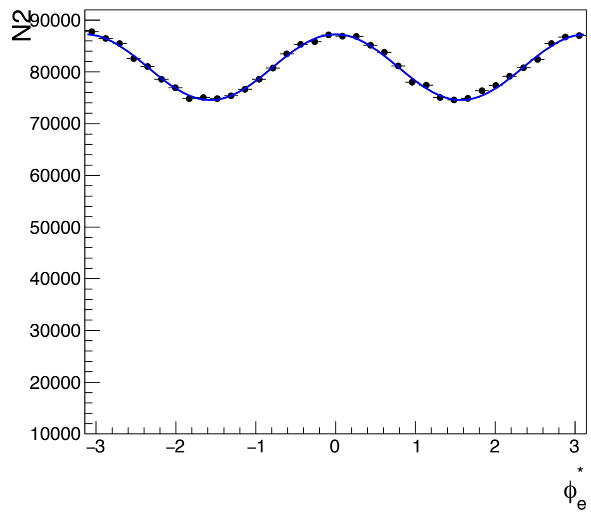
2 fb^{-1}

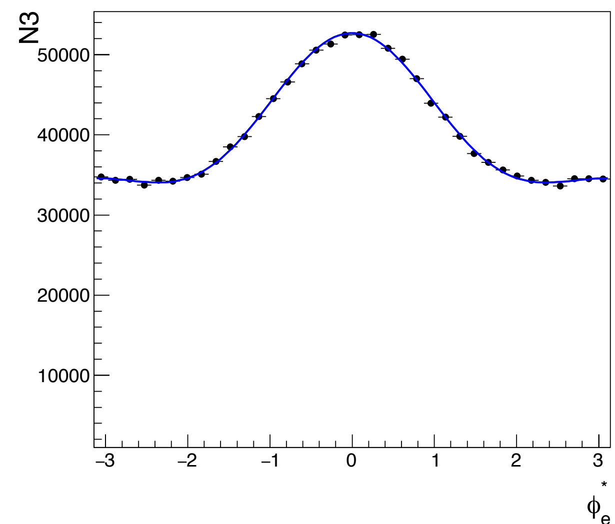
s=5.4 GeV^2	q^2=0.605±0.005 (GeV/c^2)^2	q^2 = 2±0.125 (GeV/c^2)^2
$10° < \theta_{\pi 0} < 30°$	2.91271 . 10^6	18441
$30° < \theta_{\pi 0} < 50°$	2.47392 . 10^6	17379
$90° < \theta_{\pi 0} < 100°$	1.40351 . 10^6	9362
$120° < \theta_{\pi 0} < 140°$	840234	4989
$140° < \theta_{\pi 0} < 160°$	517112	2954

Determination of the proton form factors

- $q^2 = 0.605 \pm 0.015\ (\mathrm{GeV}/c^2)^2$, $\theta_{\pi 0} = [10^o - 30^o]$, **100% signal efficiency** ($N^{th} = 2.9\ .\ 10^6$)







$$\frac{dN_1}{d\cos\theta_e^*} = A(1 + B\cos^2\theta_e^*)$$

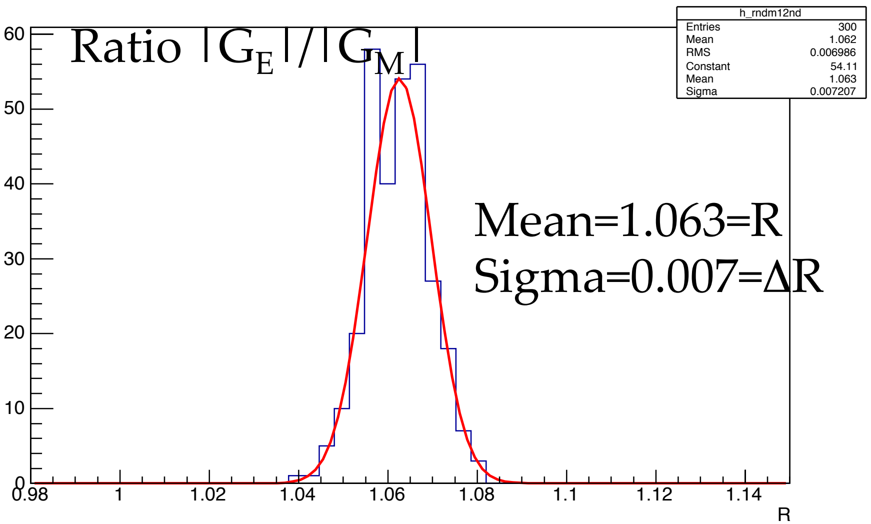
$$\frac{dN_2}{d\varphi_e^*} = C(1 + D\cos 2\varphi_e^*)$$

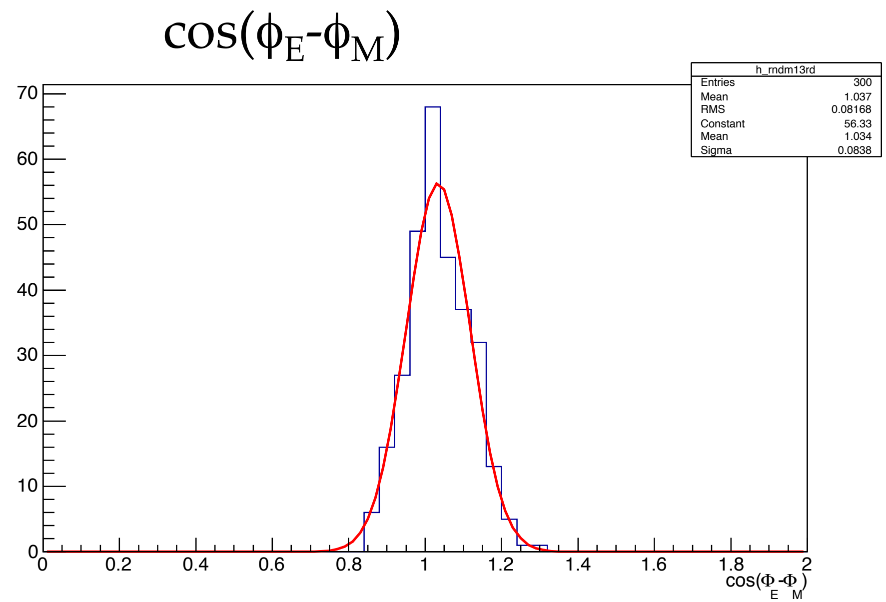
$$\frac{dN_3}{d\varphi_e^*} = E(1 + F\cos 2\varphi_e^* + G\cos\varphi_e^*)$$

	R	$\cos(\phi_E - \phi_M)$
Theoretical values	1.066	0.998
Fit results (one simulation)	1.067± 0.006	1.040± 0.085

Determination of the proton form factors

- q^2=0.605 ± 0.015 $(GeV/c^2)^2$, $\theta_{\pi 0}$=[10^o−30^o], **100% signal efficiency** (N^{th}=2.9 . 10^6)

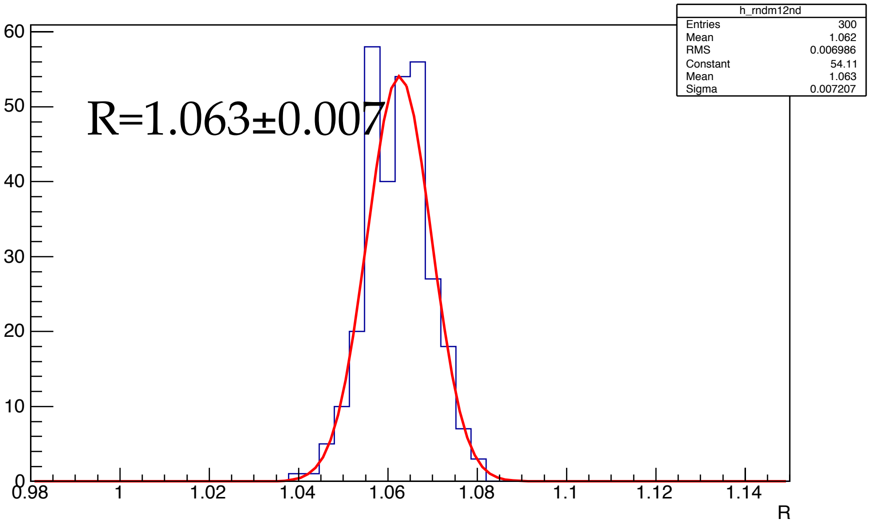




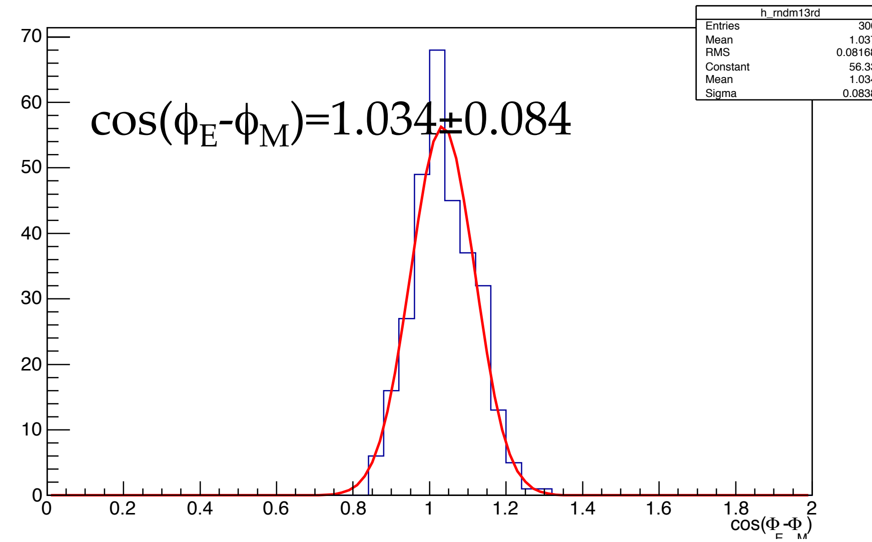
	R	$\cos(\phi_E-\phi_M)$
Theoretical values	1.066	0.998
Fit results (one simulation)	1.067± 0.006	1.040± 0.085
Fit results (500 simulations)	1.063±0.007	1.034±0.084

Determination of the proton form factors

- $q^2=0.605 \pm 0.015$ $(GeV/c^2)^2$, $\theta_{\pi 0}=[10^o-30^o]$, **100% signal efficiency** ($N^{th}=2.9 \cdot 10^6$)

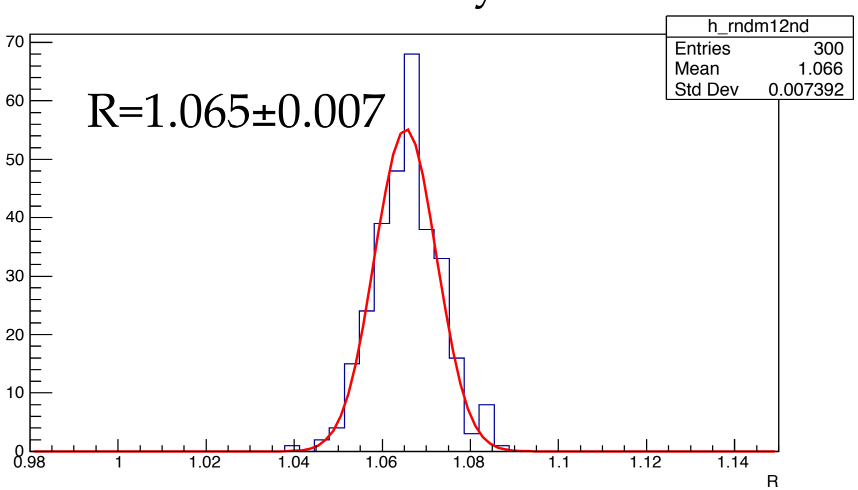


$R=1.063\pm0.007$

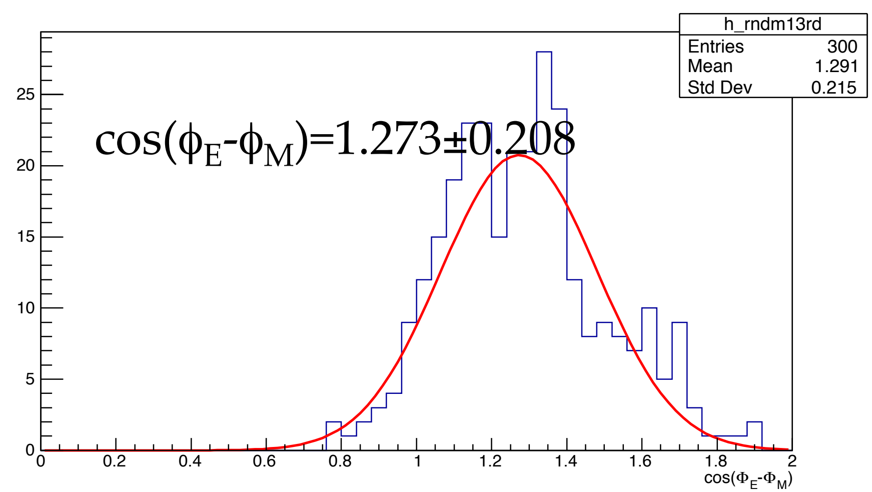


$\cos(\phi_E-\phi_M)=1.034\pm0.084$

Fit to N1 and N2 only:



$R=1.065\pm0.007$



$\cos(\phi_E-\phi_M)=1.273\pm0.208$