

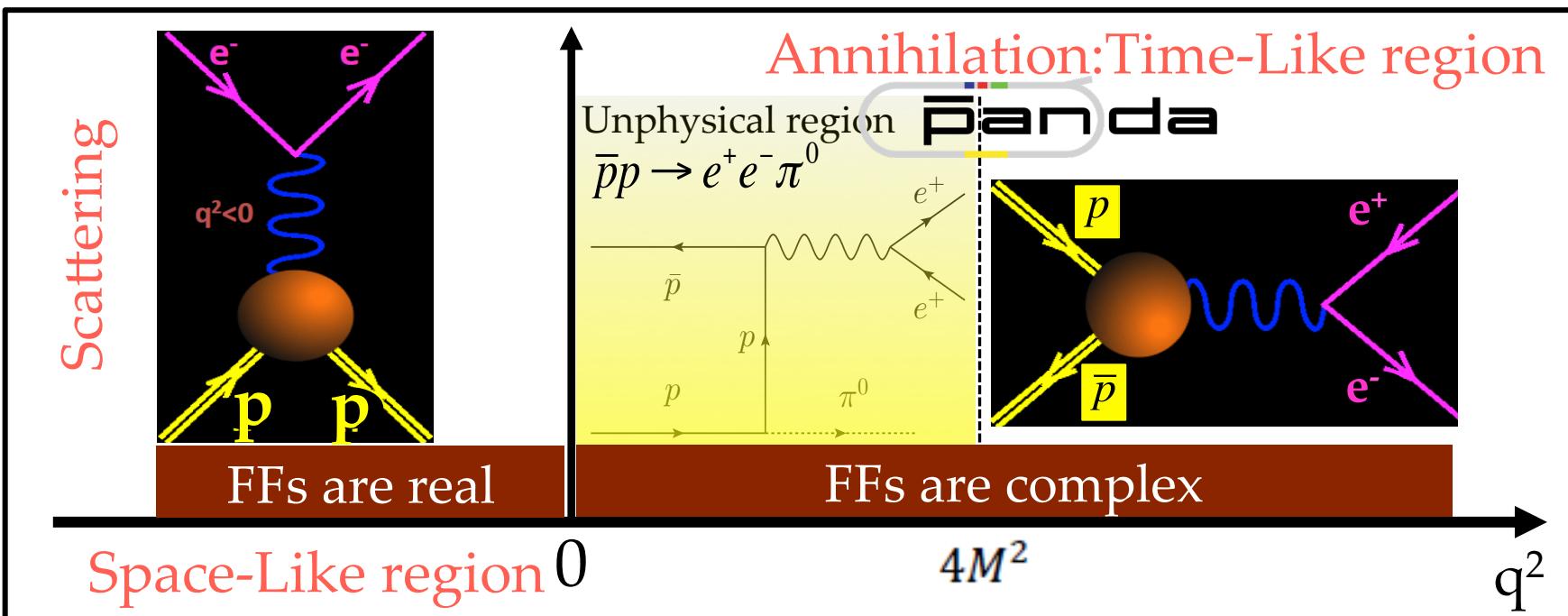
Study of the $p\bar{p} \rightarrow e^+e^-\pi^0$ process in the unphysical region with PANDARoot

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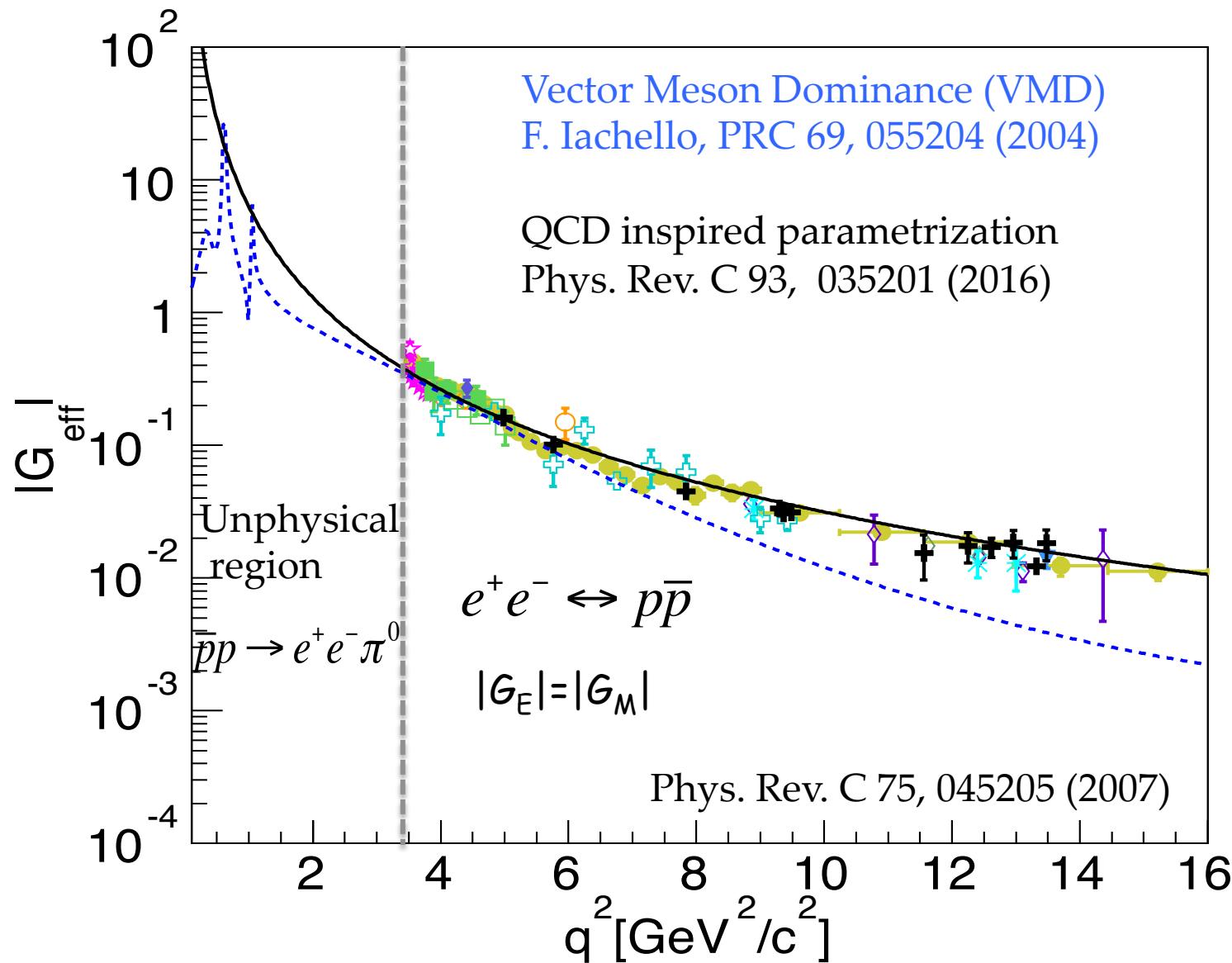
Electromagnetic Form Factors of the Proton



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

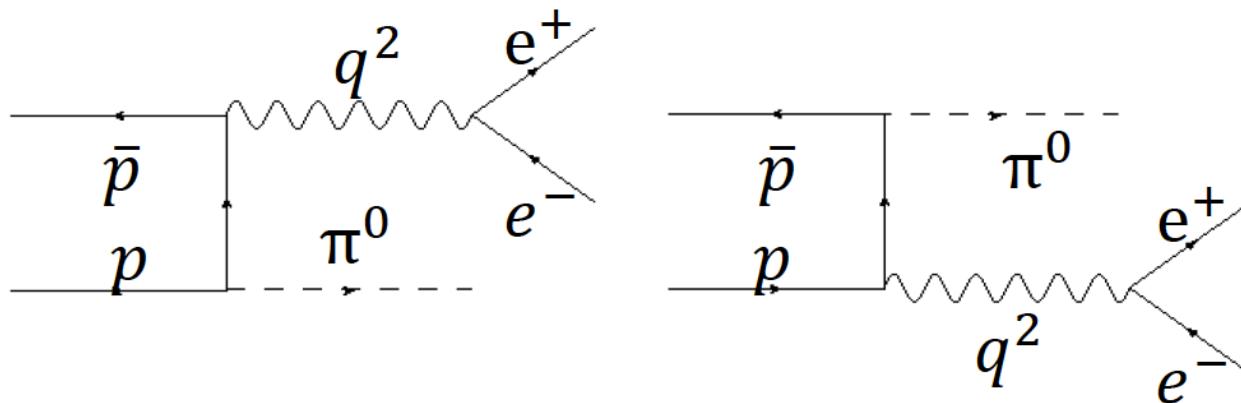
$$G(q^2)_{SL} = \frac{1}{\pi} \left[\int_{4m_\pi^2}^{4m_p^2} \frac{\text{Im } G(s)}{s - q^2} ds + \int_{4m_p^2}^{\infty} \frac{\text{Im } G(s)}{s - q^2} ds \right]$$

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



Theoretical studies of the pbarp->e⁺e⁻p⁰ process

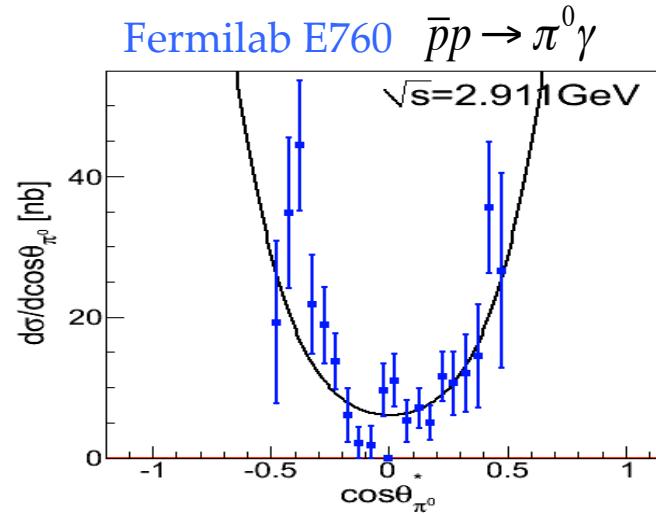
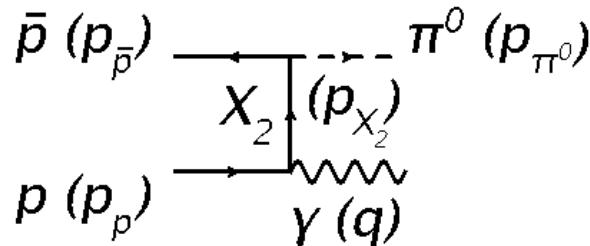
“Electromagnetic FFs in the unphysical region”



- M. P. Rekalo, Sov. J. Nucl. Phys. 1 (1965) 760. A.Z. Dubnickova , S. Dubnicka , M.P. Rekalo, Z. Phys. C 70, 473–481 (1996): **possibility to access the TL form factors in the unphysical region**
- C. Adamuscin, E.A. Kuraev, E. Tomasi-Gustafsson and F.E. Maas, Phys. Rev. C 75, 045205 (2007): **One nucleon exchange model ($d^2\sigma/dq^2 d\cos\theta_{\pi 0}$)**
- G. I. Gakh, A. P. Rekalo, E. Tomasi-Gustafsson, J. Boucher, A. G. Gakh PHYSICAL REVIEW C 83, 025202 (2011): **Polarization effects**

Theoretical and simulation studies of the pbarp->e⁺e⁻p⁰ process electromagnetic FFs in the unphysical region

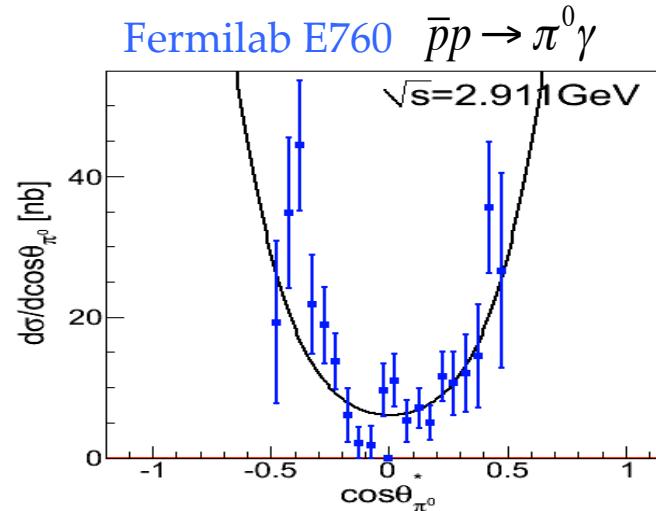
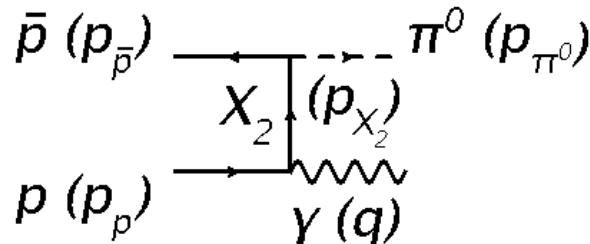
- J. Van de Wiele (PhD thesis of J. Boucher, Paris-Sud and JGU mainz, Orsay, 2011): **5 fold differential cross section, one nucleon exchange model fit to the experimental data on ppbar-> π⁰ γ**



- J. Boucher, PhD thesis, Paris-Sud Orsay and JGU Mainz Universities, 2011: **Feasibility studies of the pbarp → e⁺e⁻π⁰ electromagnetic channel at PANDA (BABAR framework)**
- J. Guttmann, M. Vanderhaeghen, Physics Letters B 719 (2013) 136–142: **theoretical analysis within a Regge framework (constraints on the TL FFs)**

Theoretical and simulation studies of the pbarp->e⁺e⁻p⁰ process electromagnetic FFs in the unphysical region

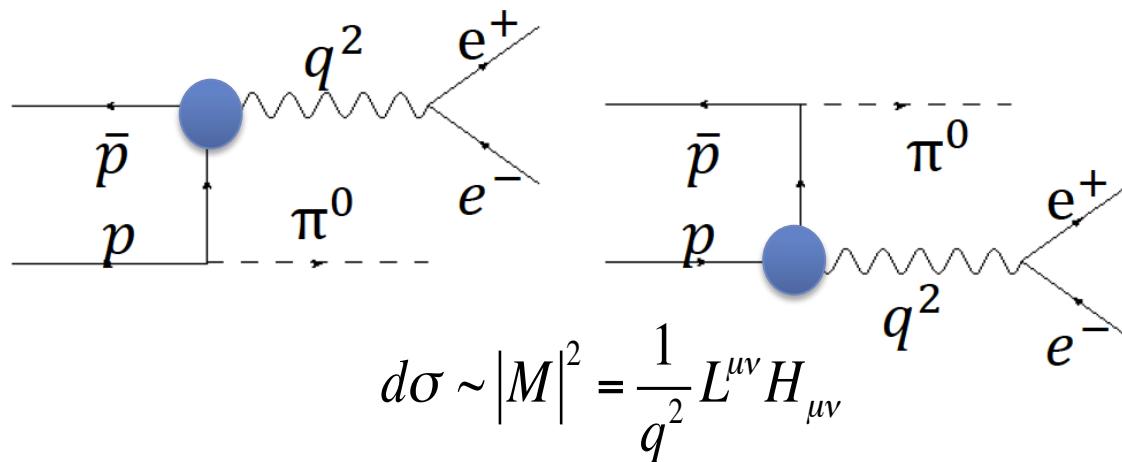
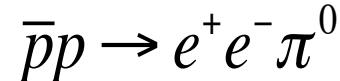
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Feasibility studies with PANDARoot are needed

Differential cross section in one nucleon exchange model

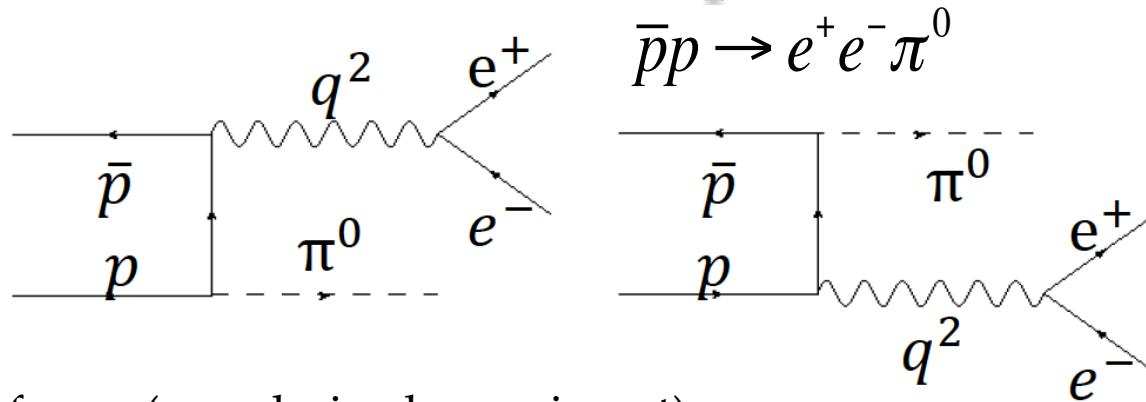


$L_{\mu\nu}$: leptonic tensor describing the $\gamma^* \rightarrow e^+e^-$ process

$H_{\mu\nu}$: hadronic tensor, contains the information on G_E and G_M

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

Differential cross section in one photon exchange model



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

$$L^{\mu\nu} H_{\mu\nu} = 4e^2(H_{11} + H_{22} + H_{33})$$

Calc. by J. Van de Wiele

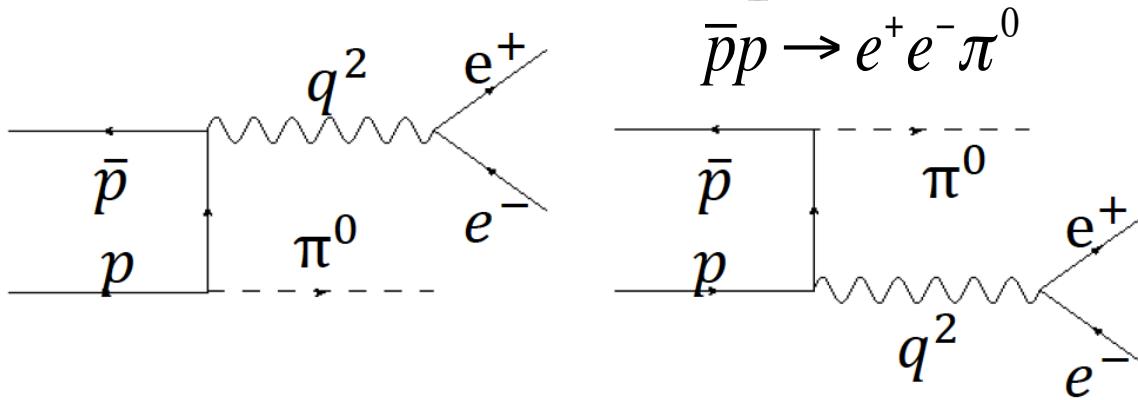
$$\begin{aligned} & -8e^2 p_e^{*2} (H_{11} \sin^2 \theta_e^* \cos^2 \varphi_e^* + 2H_{13} \sin \theta_e^* \cos \theta_e^* \cos \varphi_e^* \\ & + H_{22} \sin^2 \theta_e^* \sin^2 \varphi_e^* + H_{33} \cos^2 \theta_e^*) \end{aligned}$$

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

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

Relative phase between GE and GM

Differential cross section in one photon exchange model



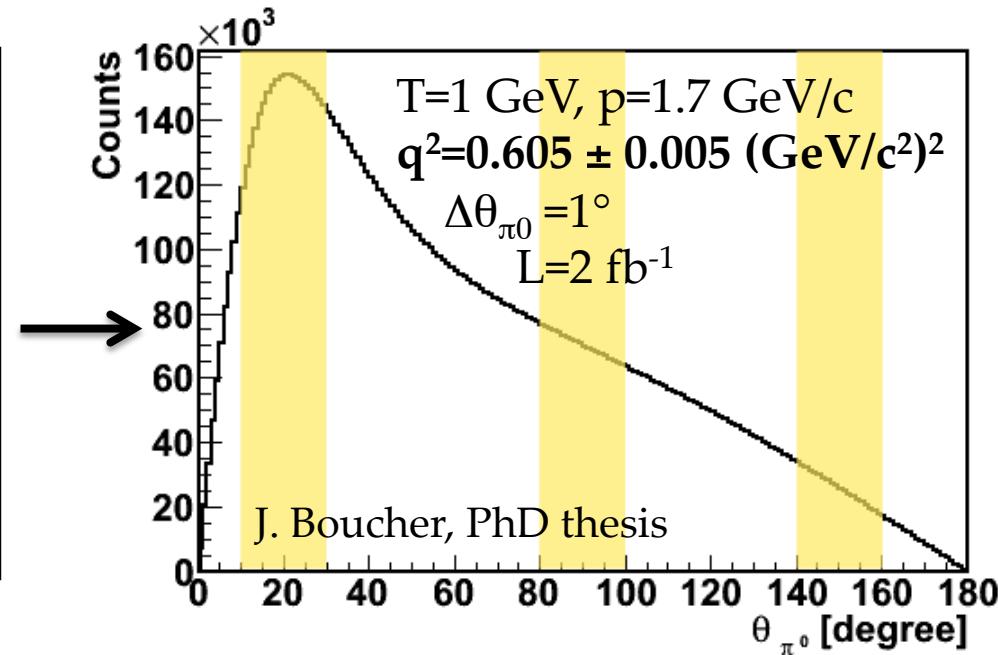
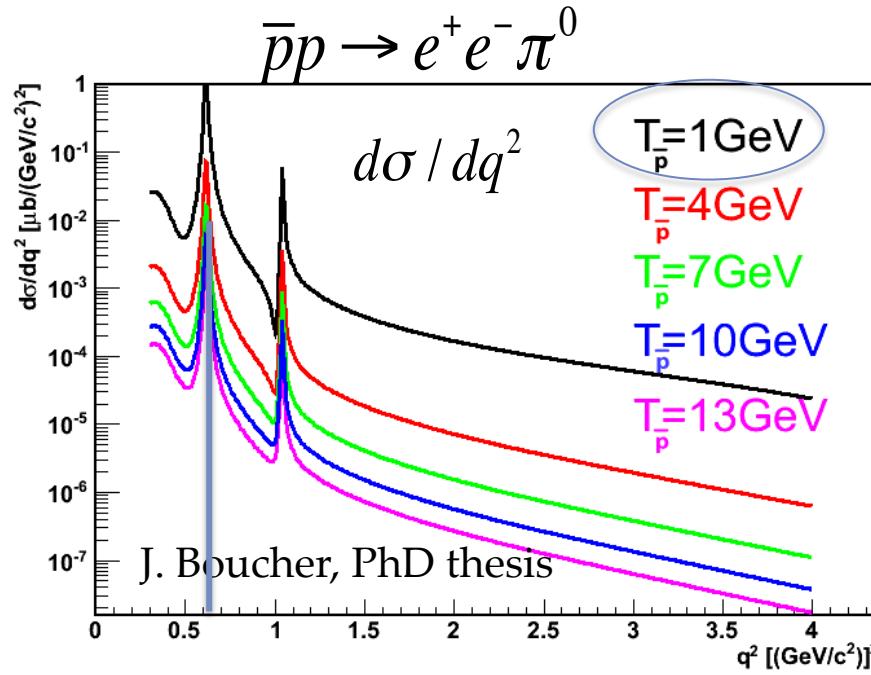
$$H_{\mu\nu} = |G_M|^2 \left[\alpha_{\mu\nu} R^2 + \beta_{\mu\nu} + \gamma_{\mu\nu} R \cos(\phi_E - \phi_M) \right]$$

Relative phase between G_E and G_M

- $\alpha_{\mu\nu}, \beta_{\mu\nu}, \gamma_{\mu\nu}$ depend on s, q^2 and θ_{π^0}
- At fixed s, q^2 and integrating over θ_{π^0} the angular distributions θ_e^* of φ_e^* of e^+/e^- are driven by G_E and G_M
- Without control on the absolute normalization (model), one uses ratios of $H_{\mu\nu}$ and access only two parameters: R and $\cos(\phi_E - \phi_M)$

Calc. by J. Van de Wiele

Differential cross section in one photon exchange model



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

- Form factors are functions of q^2
- At fixed s , q^2 , the measurements of the θ_e^* of φ_e^* distributions in intervals of θ_{π^0} (forward, backward and barrel) provide:
 - Control and test of the cross section parameterization in different kinematical regions
 - Monte Carlo studies : Efficiency determination of the signal is model independent

Possible background channels

$$\bar{p}p \rightarrow n\pi^+ n\pi^- m\pi^0 \quad (n > 1, m \geq 0)$$

$$\bar{p}p \rightarrow \pi^+ \pi^- \omega$$

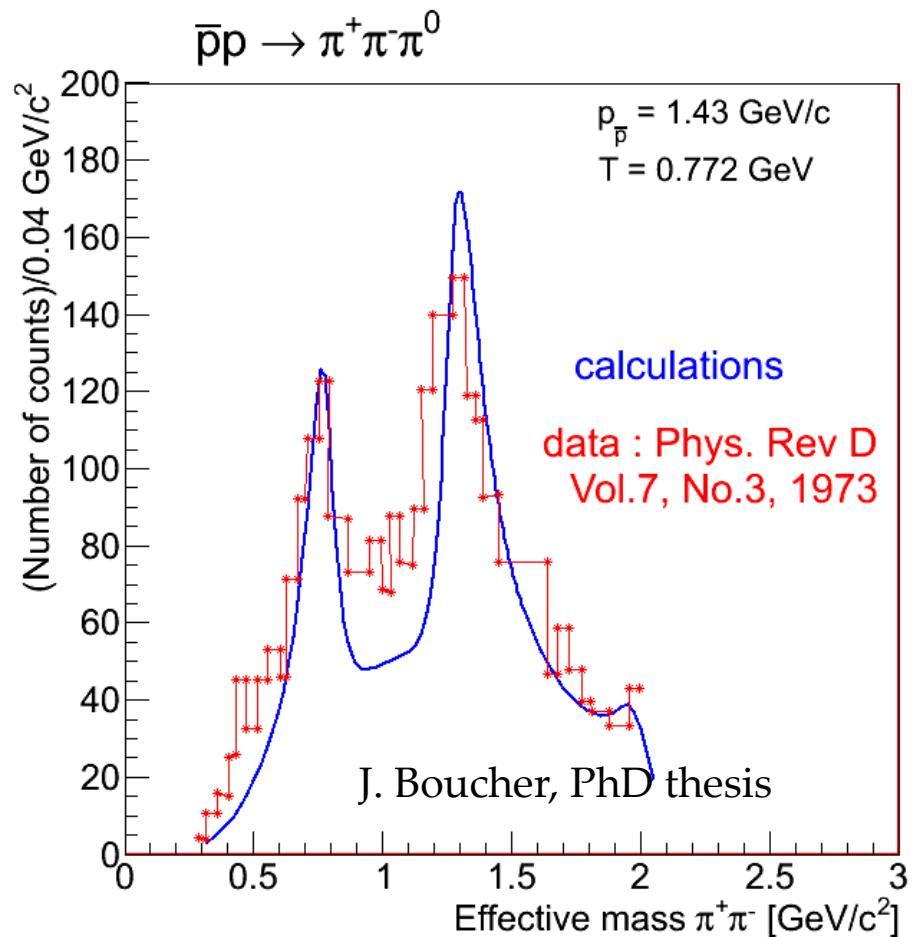
$$\bar{p}p \rightarrow \pi^+ \pi^- \rho^0$$

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

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

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

$$\boxed{\frac{\sigma(\bar{p}p \rightarrow \pi^+ \pi^- \pi^0)}{\sigma(\bar{p}p \rightarrow e^+ e^- \pi^0)} \sim 10^4, q^2 = 0.6 \text{ GeV}^2}$$



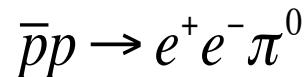
- Background rejection $\sim 10^{-6}\text{-}10^{-7}$ is needed for a signal pollution $< 1\%$

Description of the Monte Carlo simulations

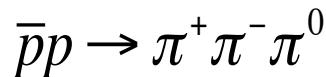
Monte Carlo Simulation Studies:

Background suppression versus signal efficiency

Signal:



Background:



- $p_{p\bar{p}} = 1.7 \text{ GeV}/c$
- $q^2 = 0.605 \pm 0.005 (\text{GeV}/c^2)^2$

10^7 events are generated for the signal with PHSP model:

$\sim 10^6$ event in each θ_{π^0} interval: $[0^\circ - 180^\circ]$, $[80^\circ - 100^\circ]$, $[140^\circ - 160^\circ]$

10^8 events are generated for the background with PHSP model:

$\sim 10^7$ event in each θ_{π^0} interval: $[0^\circ - 180^\circ]$, $[80^\circ - 100^\circ]$, $[140^\circ - 160^\circ]$

**Standard chain
Simulation & Analysis
with PANDARoot:**

Event generation

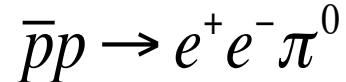
Digitization

Reconstruction

Particle Identification

Event Analysis

Event Selection



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% (EMC+STT+MVD+DRC)**
- c) EMC deposit energy over the tracking momentum $E_{\text{EMC}}/p > 0.8$
- d) Energy loss in the STT $dE/dx(\text{STT}) > 5.8$

II. Pion reconstruction (following RN-QCD-2018-002 (A.Gillitzer et al.))

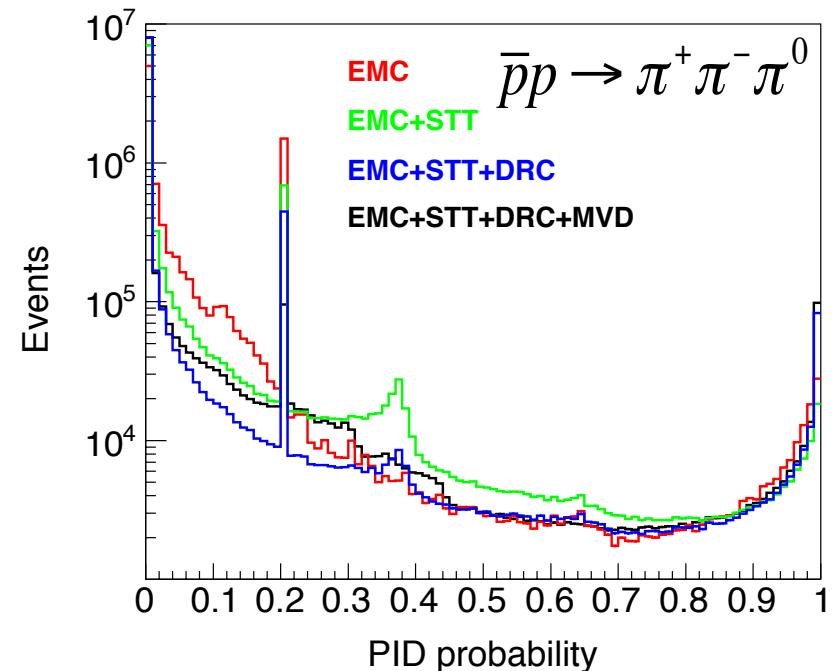
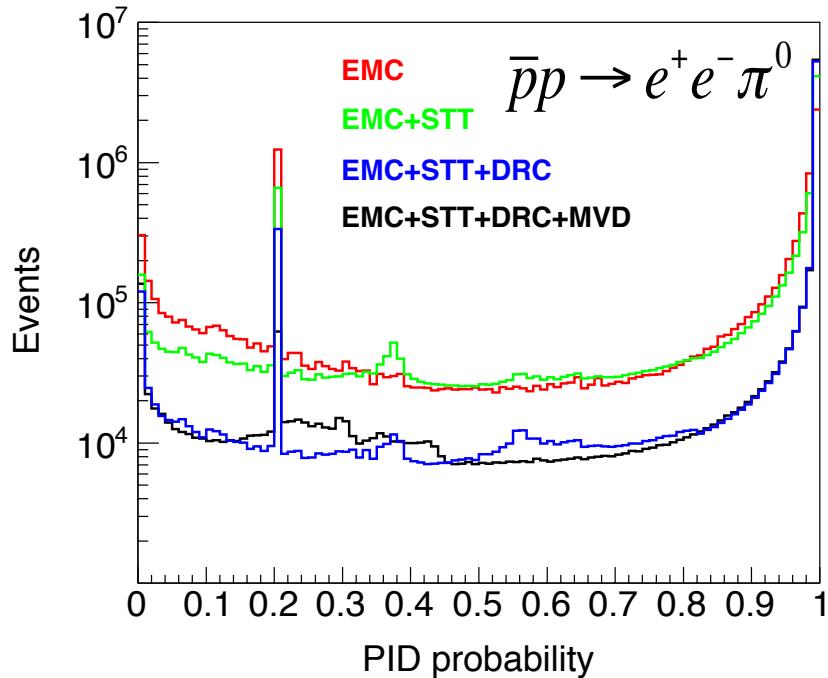
- Neutral candidates (photons) with **EMC raw energy > 15 MeV**
- At least two neutral candidates/event
- Pion mass cut: $M_{\pi^0} - 0.05 < M_{\gamma\gamma} < M_{\pi^0} + 0.05$ (GeV/c²)
- Mass constraint fit to the nominal π^0 mass : Prob. > 10⁻³
- In case of more than one candidate/event, the pair ($\gamma\gamma$) of higher fit probability is selected.

III. Events selection

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

Charged Track Selection (PID Probabilities)

$$q^2 = 0.605 \pm 0.005 \text{ (GeV/c}^2)^2, \quad 0^\circ < \theta_{\pi^0} < 180^\circ$$



PID info from EMC, STT, DRC
and MVD

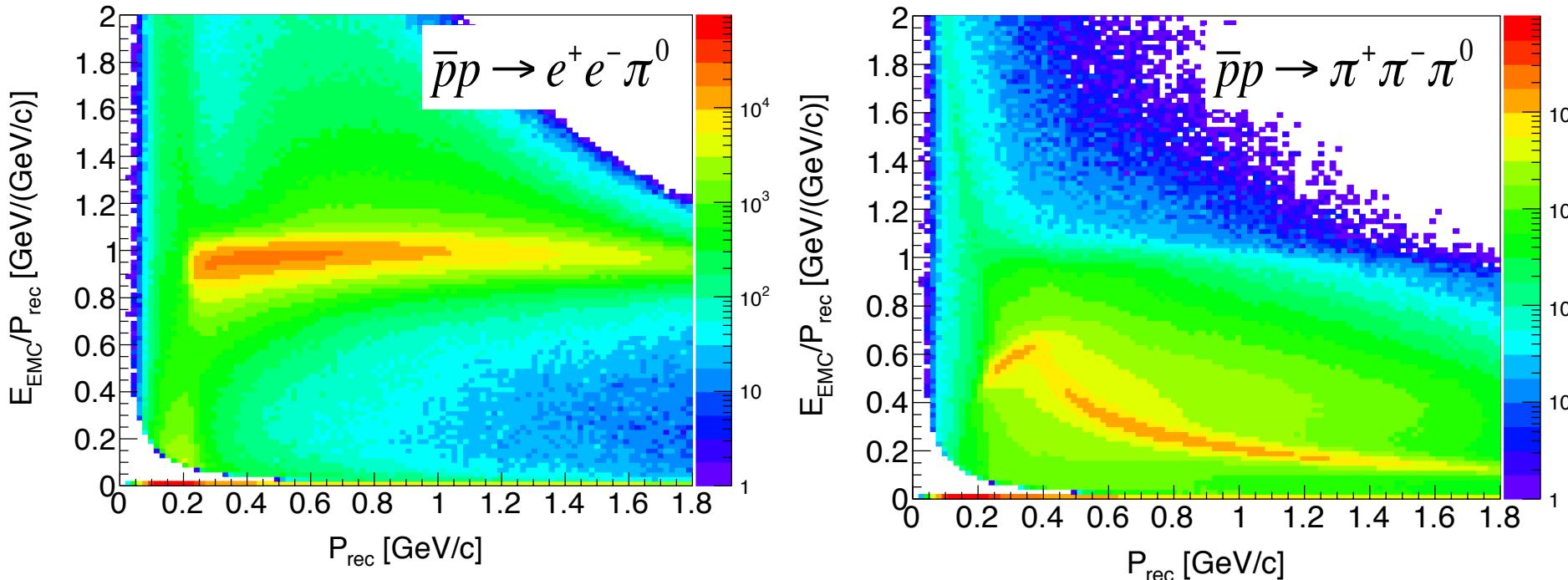
PID > 0.99	Signal	Background
Cut Eff.	68 %	0.07 %
Eff.	42 %	0.04 %

Cut Eff. = $N(\text{after cut})/N(\text{before cut})$

Eff. = $N(\text{after cuts})/N(\text{generated})$

Charged Track Selection (E/P)

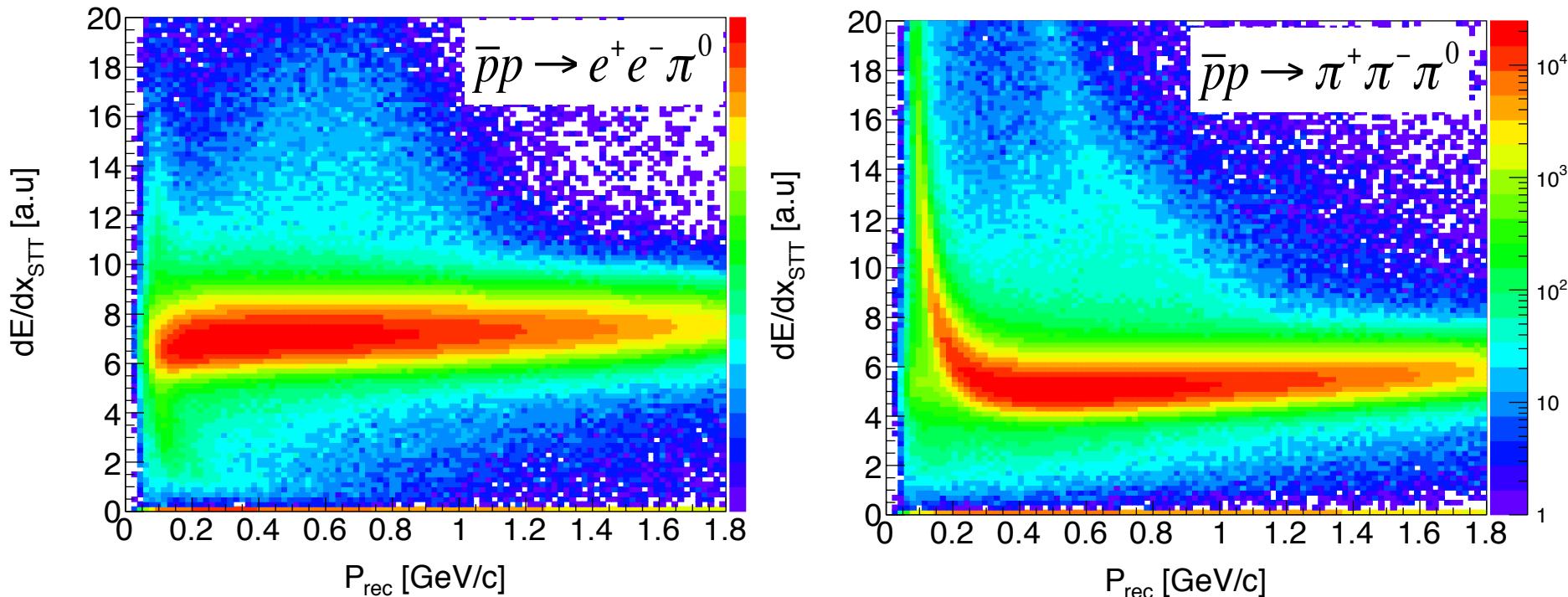
$$q^2 = 0.605 \pm 0.005 \text{ (GeV/c}^2)^2, \quad 0^\circ < \theta_{\pi^0} < 180^\circ$$



$E_{\text{EMC}}/P > 0.8$	Signal	Background
Cut Eff.	73 %	19 %
Eff.	31 %	0.008 %

Charged Track Selection (dE/dx STT)

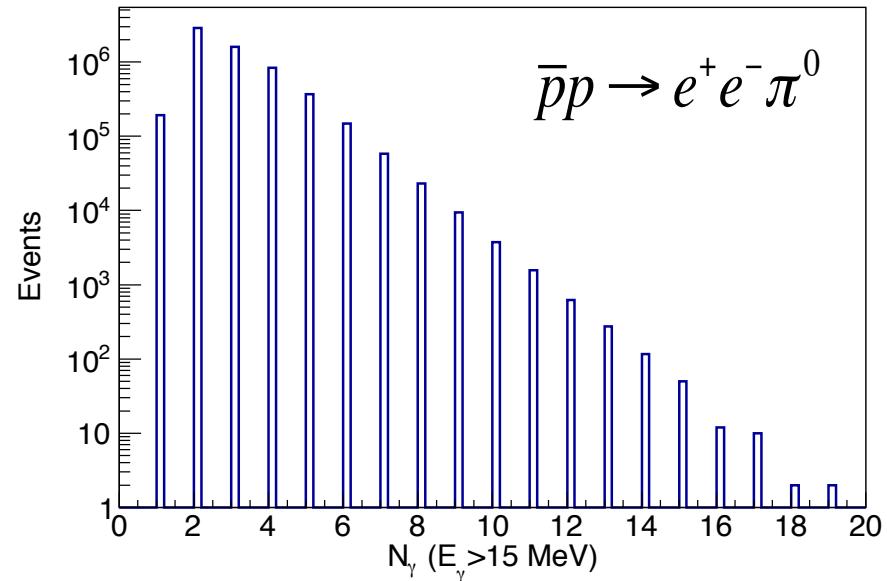
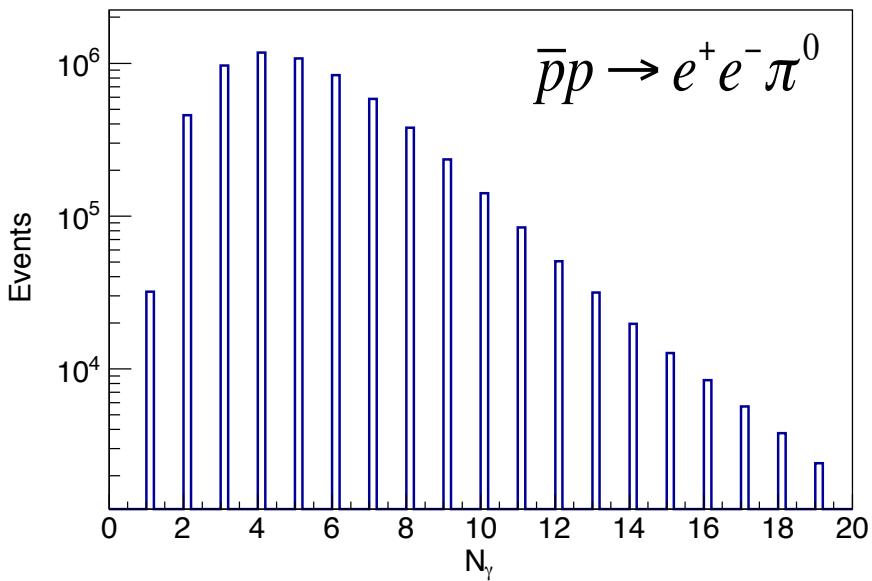
$q^2 = 0.605 \pm 0.005 \text{ (GeV/c}^2)^2$, $0^\circ < \theta_{\pi^0} < 180^\circ$



dE/dx (STT) > 5.8	Signal	Background
Cut Eff.	95 %	56 %
Eff.	29 %	0.004 %

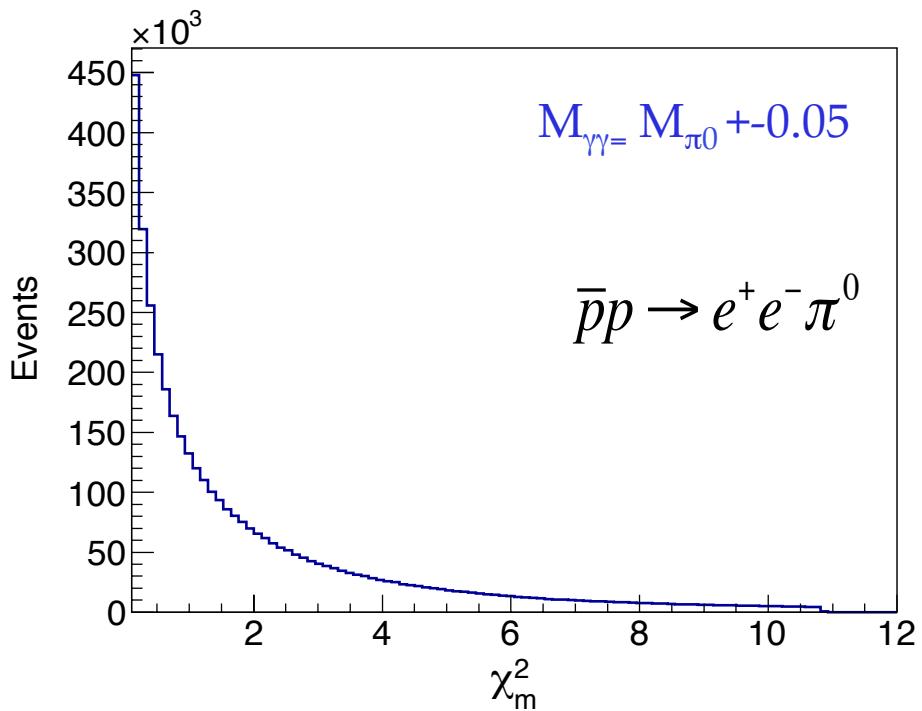
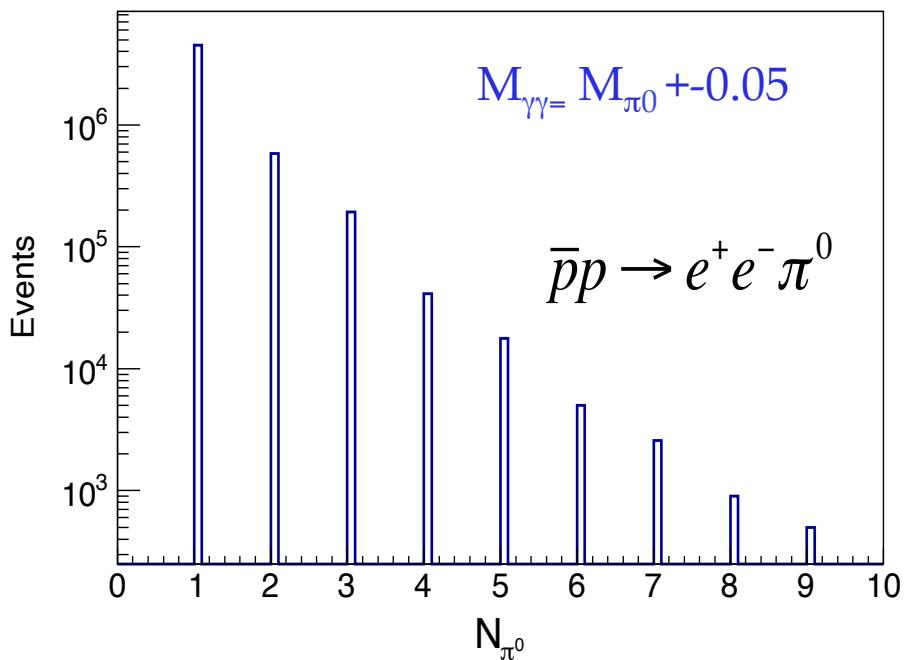
Neutral pion reconstruction (photon candidates)

- Neutral candidates (photons) with EMC raw energy > 15 MeV
- At least two neutral candidates /event
- Pion mass cut: $M_{\pi^0} - 0.05 < M_{\gamma\gamma} < M_{\pi^0} + 0.05$ (GeV/c²)
- Mass constraint fit to the nominal π^0 mass : Prob. $> 10^{-3}$
- In case of more than one candidate/event, the pair ($\gamma\gamma$) of higher fit probability is selected.



Neutral pion reconstruction (pion multiplicity)

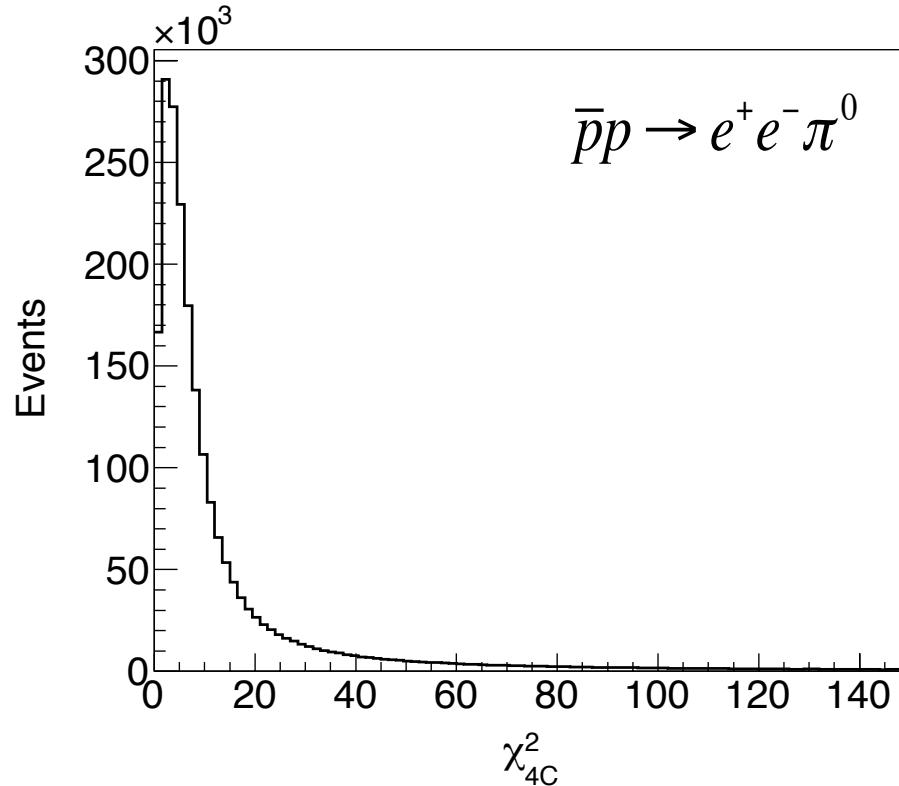
- Pion mass cut: $M_{\pi^0} - 0.05 < M_{\gamma\gamma} < M_{\pi^0} + 0.05$ (GeV/c²)
- Mass constraint fit to the nominal π^0 mass : Prob. > 10⁻³
- In case of more than one candidate/event, the pair ($\gamma\gamma$) of higher fit probability is selected.



	Signal	Background
Pion reconstruction Eff.	80 %	42 %
Eff.	23 %	0.002%

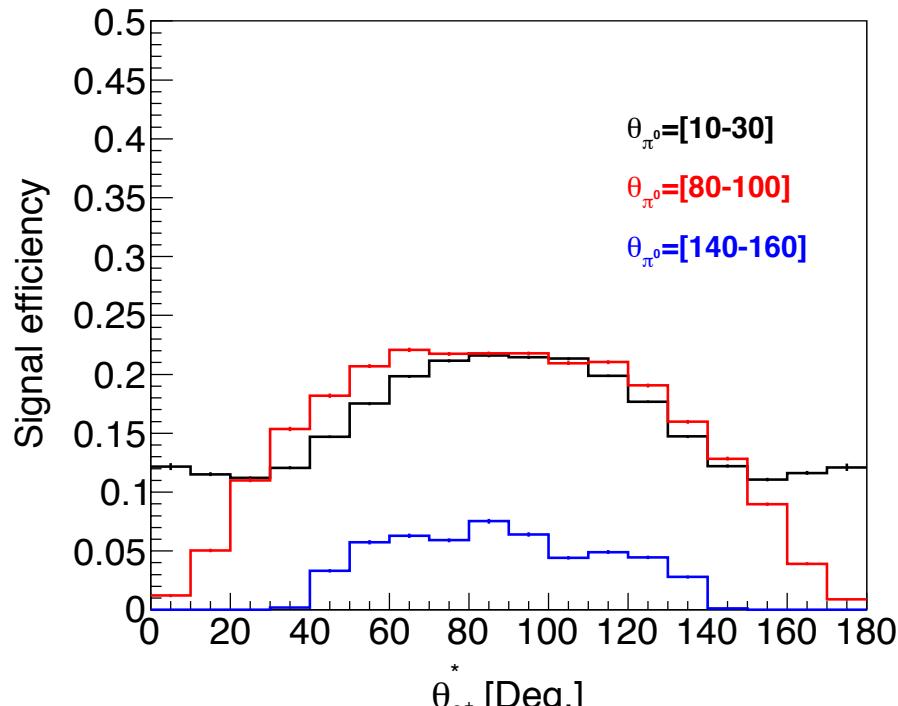
Event selection (4C kinematic fit)

Charged tracks and neutral pion selections are applied

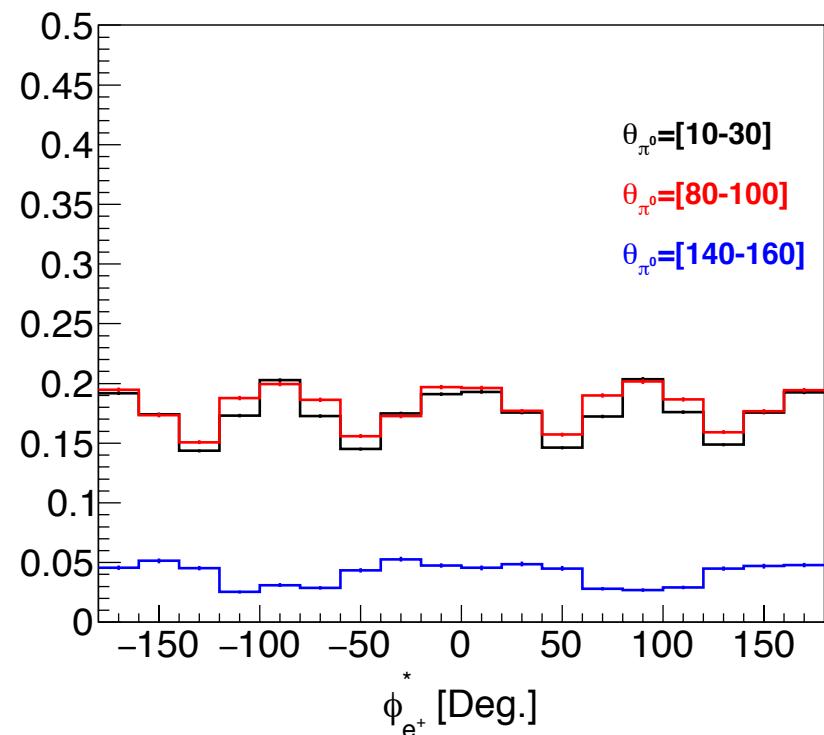


Chi2_4C < 50	$10^\circ < \theta_{\pi 0} < 30^\circ$	$80^\circ < \theta_{\pi 0} < 100^\circ$	$140^\circ < \theta_{\pi 0} < 160^\circ$
Cut Eff. (Signal)	84 %	82 %	75 %
Cut Eff. (Background)	0.3 %	1.1 %	2.6 %

Signal and background Efficiencies



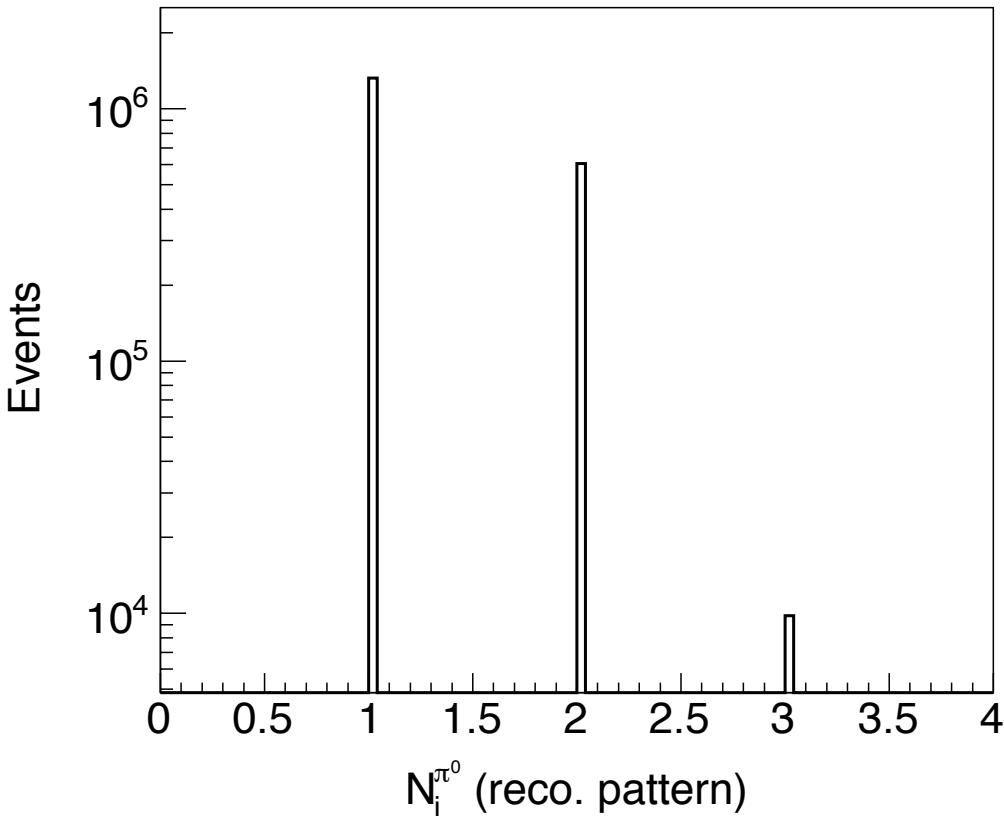
$$q^2 = 0.605 \pm 0.005 \text{ (GeV/c}^2)^2$$



All cuts	$10^\circ < \theta_{\pi^0} < 30^\circ$	$80^\circ < \theta_{\pi^0} < 100^\circ$	$140^\circ < \theta_{\pi^0} < 160^\circ$
Signal Eff.	18%	18 %	4 %
Background Eff.	$0.5 \cdot 10^{-7}$	$1.8 \cdot 10^{-7}$	$< 4 \cdot 10^{-7}$

Signal pollution at the order or below 1% and good signal efficiency

Monte Carlo truth matching (π^0)



$$q^2 = 0.605 \pm 0.005 \text{ (GeV/c}^2)^2, \\ 0^\circ < \theta_{\pi^0} < 180^\circ$$

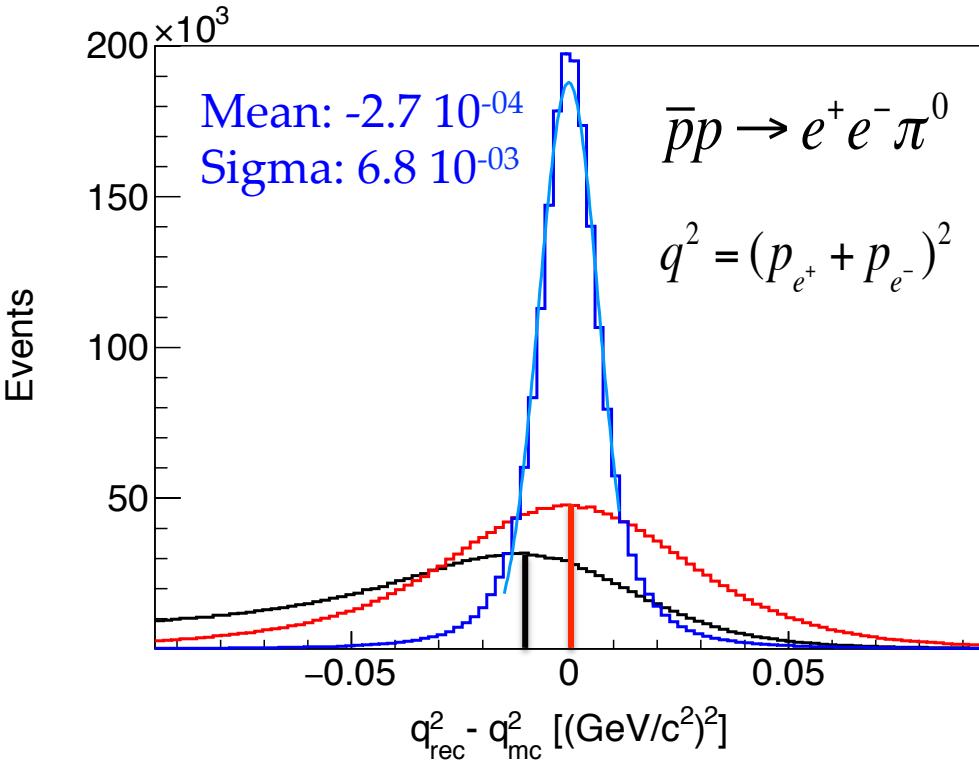
The cuts applied on $E\gamma > 15 \text{ MeV}$ and $\text{Prob.} > 10^{-3}$ (from the π^0 mass constrain fit) decrease the number of non good reconstructed π^0 ($N_i^{\pi^0} = 3$)

The Number of good rec. π^0 from the total number of rec. π^0 is larger than 99%

- ✓ $N_i^{\pi^0} = 1$ (68 %): pi0 reco. candidate is MC truth matched primary $\pi^0 \rightarrow \gamma\gamma$
- ✓ $N_i^{\pi^0} = 2$ (31 %): pi0 reco. candidate is true π^0 with g conversion ($\gamma \rightarrow e^+e^-$)
- $N_i^{\pi^0} = 3$ (0.5 %): pi0 reco. candidate is not matching true π^0 (background)

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

- $q^2 = 0.605 \pm 0.005 \text{ (GeV/c}^2)^2$, $0^\circ < \theta_{\pi 0} < 180^\circ$



“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”

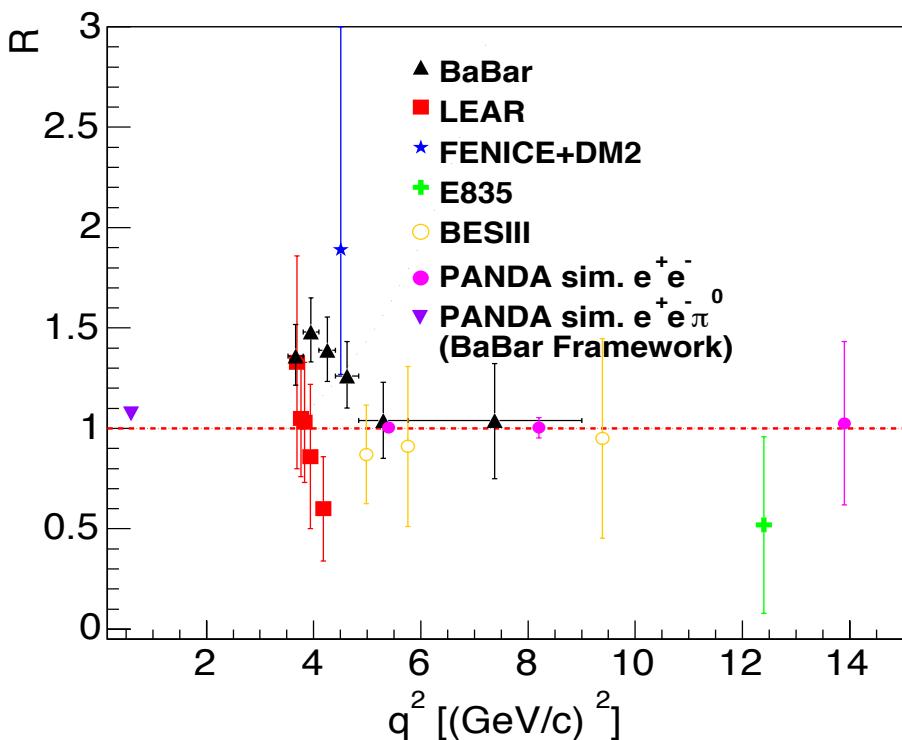
Measurement of the proton FFs in small intervals of q^2 (in the unphysical region) is possible at PANDA

Signal and background Efficiencies

PANDARoot vs. BABAR framework results

- $q^2 = 0.605 \pm 0.005 \text{ (GeV/c}^2)^2$, $10^\circ < \theta_{\pi_0} < 30^\circ$, $80^\circ < \theta_e^* < 90^\circ$

All cuts	Signal Eff.	Background Eff.
BaBar framework results	30 %	$6.1 \cdot 10^{-7}$
PANDARoot results	22 %	$3.5 \cdot 10^{-7}$



Preliminary results: performance of the PID probability cuts need to be studied more in details

Expected precision on the measurement of the form factor ratio at $q^2 = 0.605 \text{ (GeV/c}^2)^2$ (PANDARoot)
 $\sim 2\% (2 \text{ fb}^{-1})$

Summary and outlook

- Feasibility studies for the $\bar{p}p \rightarrow e^+e^-\pi^0$ reaction to access the unphysical region at PANDA have been first performed by J. Boucher et al. (PhD thesis, 2011) using the **BABAR framework**.
 - Possibility to access the form factor ratio and get information on the relative phase between G_E and G_M with good precisions.
- **PANDARoot** simulations at low q^2 (unphysical region) show the possibility to:
 - measure the signal process with a good efficiency.
 - suppress the main background channel to a sufficient value (signal pollution <1%).
- Next steps:
 - Development of an event generator for the signal process.
 - Extend the feasibility studies within **PANDARoot** to different values of q^2 and extract the statistical errors on the the form factor ratio and the Cosine of the relative phase between G_E and G_M