Université Paris-Sud 11
Institut de Physique Nuclaire d'Orsay

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Event generators for $\bar{p}p$ electromagnetic interactions
Status Report

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OUTLINE

- **introduction**

  $\rightarrow$ **goals, overview, the Monte Carlo method**

- **simulation of** $\bar{\mathrm{p}}\mathrm{p} \rightarrow \mathrm{e}^+\mathrm{e}^-$
- **simulation of** $\bar{\mathrm{p}}\mathrm{p} \rightarrow \pi^+\pi^-$
- **simulation of** $\bar{\mathrm{p}}\mathrm{p} \rightarrow \mathrm{e}^+\mathrm{e}^-\pi^0$

- **summary and conclusions**

Introduction : goals

- **Form Factors (FF) parametrize structure of the nucleon:**
  G_E, G_M, (Sachs FF) or F_1, F_2 (Pauli-Dirac FF)
  - $\rightarrow$ **functions of the four-momentum transfer q^2**
  - $\rightarrow$ **related by $G_M = F_1 + F_2$ and $G_E = F_1 + \tau F_2$, with $\tau = \dfrac{q^2}{4M}$**

our goal:

> **make feasibility studies of proton form factors measurements**
>
> **via electromagnetic processes with the PANDA detector**

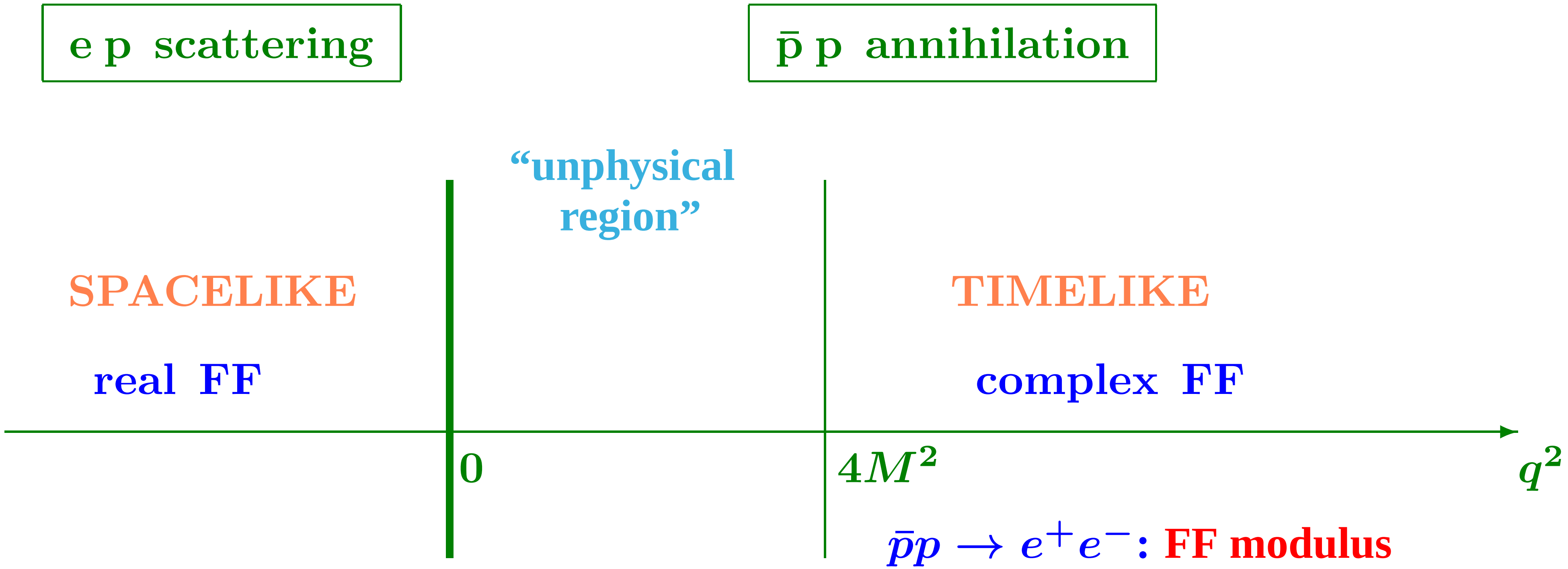
$\Rightarrow$ **need FULL Monte Carlo (MC) simulation:**

$i)$ **physics simulation:** **model "true-level" physics**

$ii)$ **detector simulation:** **model detector response to all particles in the final state**

physics simulation is the topic of this talk

Introduction : overview



$\bar{p}p \to e^+e^-$: **FF modulus**
$[\bar{p}p \to \pi^+\pi^-]$

$\bar{p}p \to e^+e^-$: **FF relative phase**
polarized target

$\bar{p}p \to e^+e^-\pi^0$: **FF modulus (below threshold)**
$[\bar{p}p \to \pi^+\pi^-\pi^0]$

$\Rightarrow$ **need MC for all these processes**

Generating distributions

The problem: generate distribution following $f(X)$, $X \in R \subset \mathbb{R}^n$

The simplest algorithm:

- find upper bound C to f in R, i.e. $f(X) < C \quad \forall X \in R$
- uniform sampling (X, h) in $R \times [0, C]$:
  - $\rightarrow$ if $h < f(X)$, accept event (and fill histogram)
  - $\rightarrow$ if $h > f(X)$, reject event
- iterate previous step until the desired statistics is reached

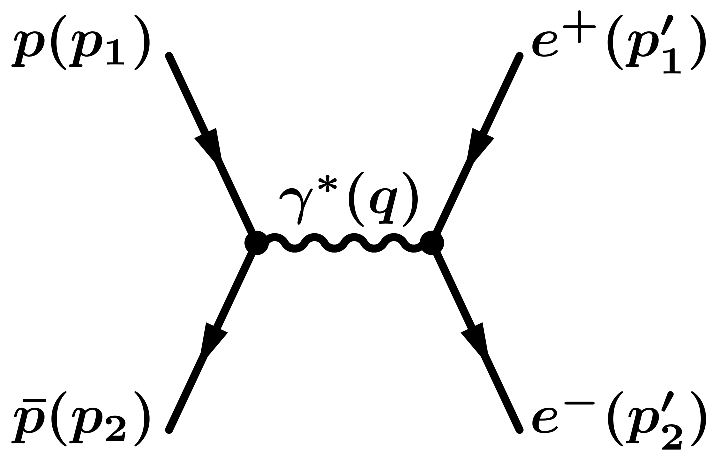
$\Rightarrow$ always work, but cumbersome in high dimension
improvements: importance sampling, etc.

In our case:

- worked well for $n = 1$ and $n = 2$, with reasonable rejection rates
- random number generator: $\mathrm{RANLUX}^{(*)}$
  - $\rightarrow$ widely used in lattice QCD monte carlo simulations
  - $\rightarrow$ huge periods $\sim 10^{171}$, even at the lowest “luxury level”

(*) M. Luescher, Comp. Phys. Comm. 79 (1994) 100

$\bar{\mathrm{p}}\mathrm{p} \to \mathrm{e}^+\mathrm{e}^-$: basics



Physics:

- one-photon exchange approximation

  A.Zichichi et al., Nuovo Cimento XXIV, 170 (1962)

- in γ^* rest frame [$\equiv \bar{p}p$ CM frame], cross section given by

$$\frac{d\sigma}{d\cos(\theta)} =\sim (1 + A\cos^2\theta); \qquad \text{with} \quad A = \frac{1-R}{1+R}, \qquad R = \frac{|G_E|}{|G_M|}$$

$\to$ sensitive to $|G_E|$ and $|G_M|$ (with absolute normalization)
$\to q = p_1 + p_2 \Rightarrow$ kinematic threshold $q^2 > 4M^2$

Kinematics:

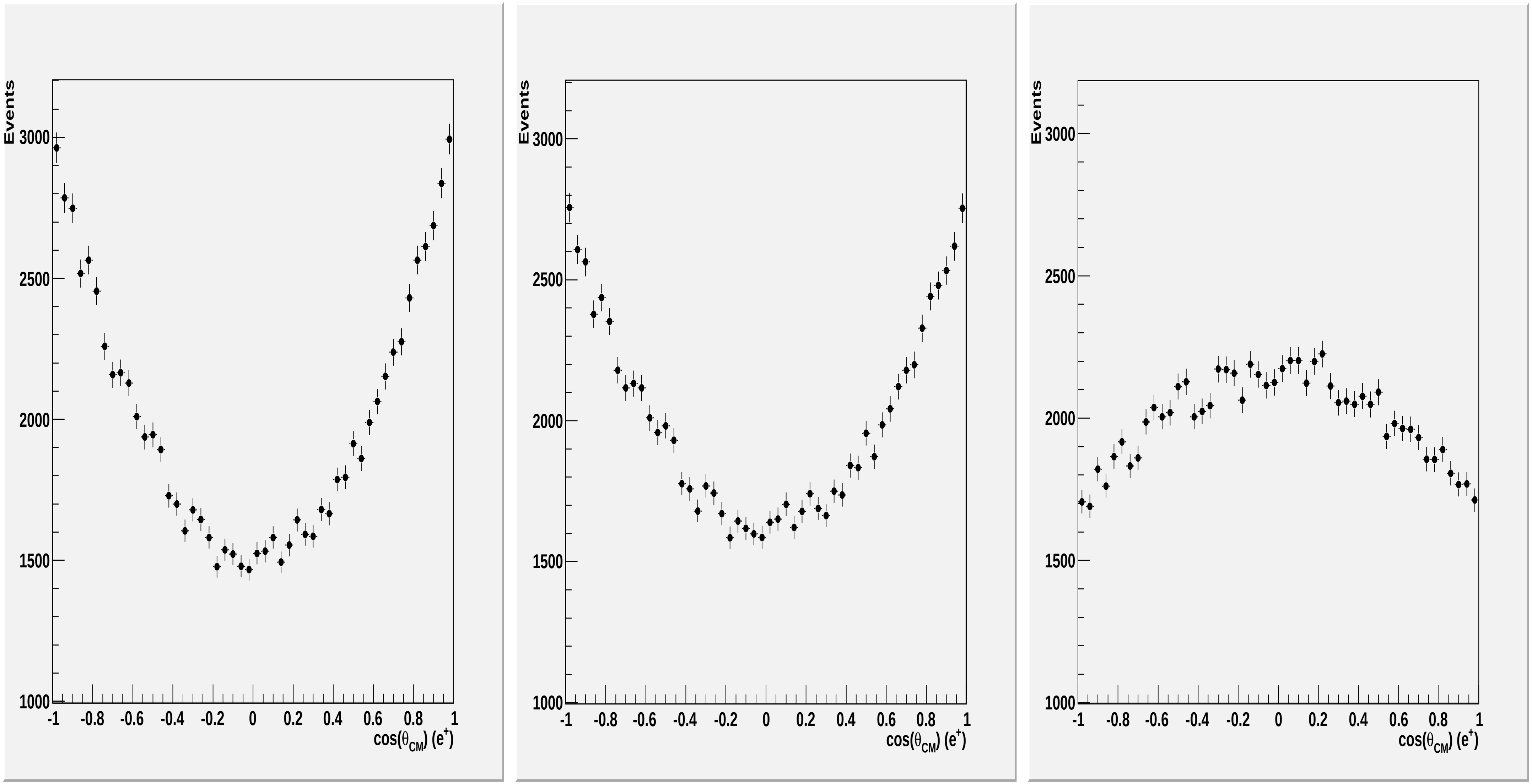
- in CM frame:

  $\to$ give to e^+ and e^- in the final state $E = \sqrt{s}/2$
  $\to e^+$ and e^- in "back to back" configuration
  $\to \cos\theta$ distributed according to cross section
  $\to$ azimuthal symmetry

$\bar{p}p \to e^+e^-$

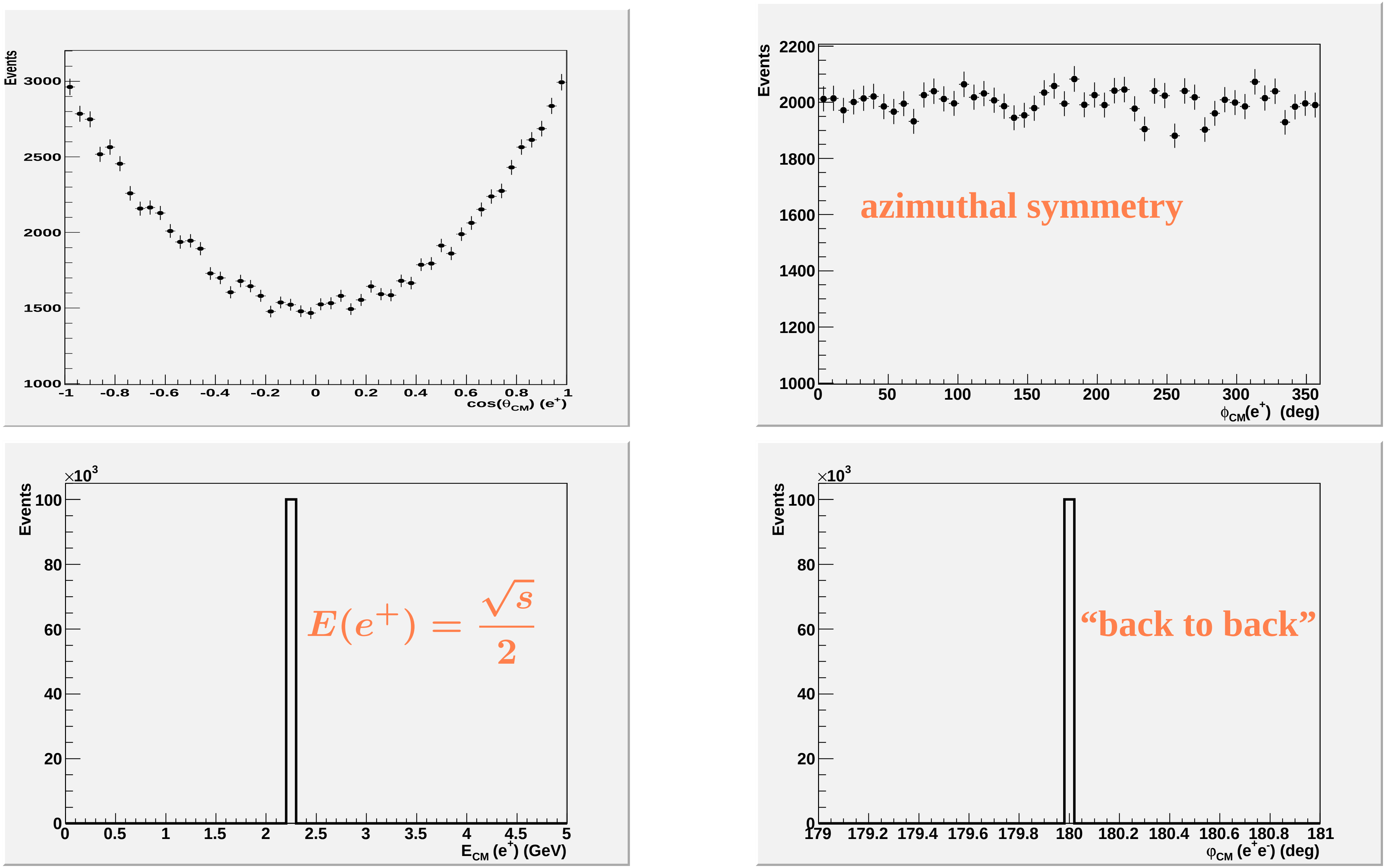
$N = 10^5$ events $\qquad p_z(\bar{p}) = 10.0$ GeV $\to q^2 = 20.6$ GeV^2

$|G_E|/|G_M| = 0 \qquad |G_E|/|G_M| = 1 \qquad |G_E|/|G_M| = 3$



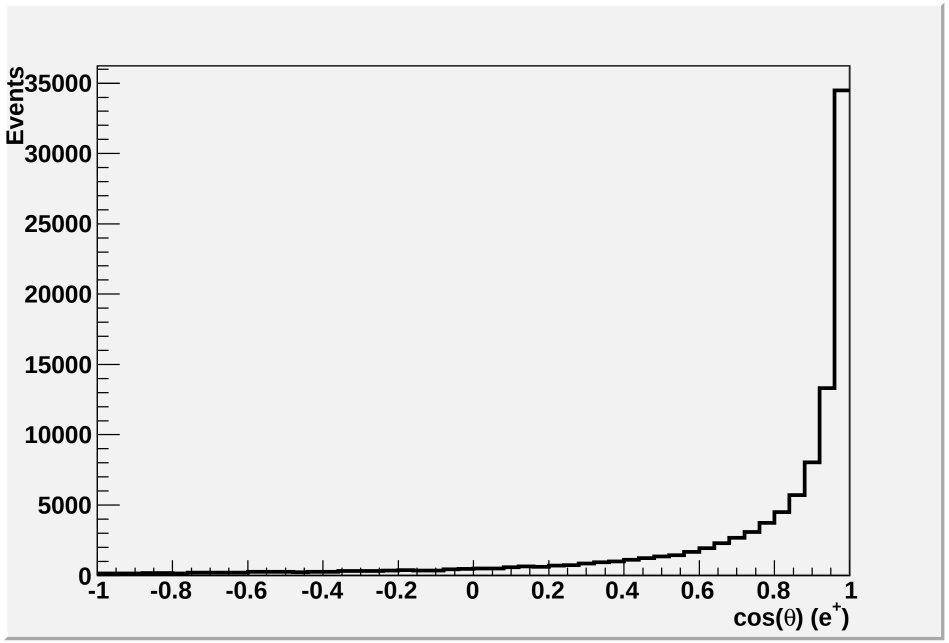
$\bar{p}p \to e^+e^-$: distributions in CM frame

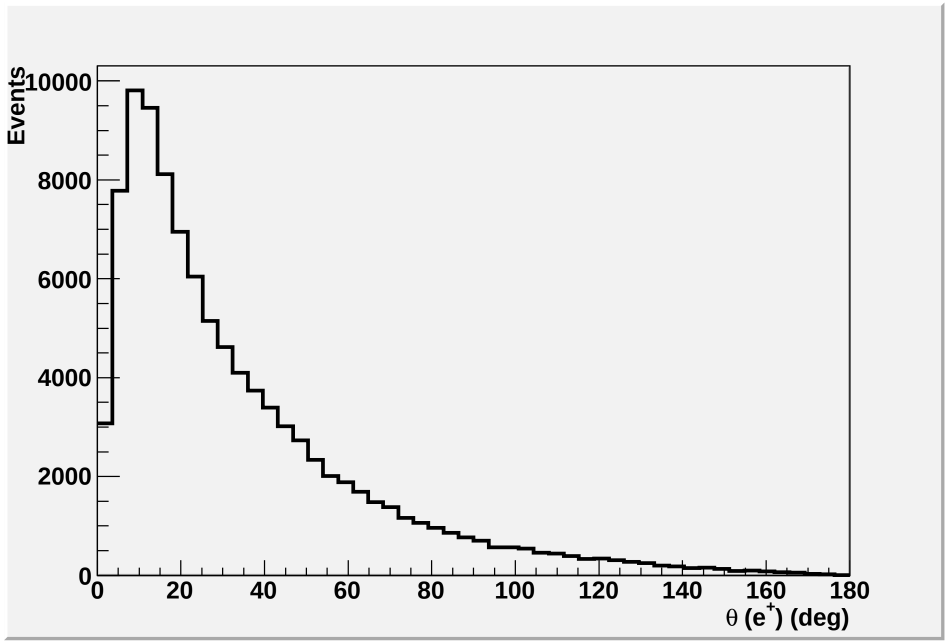
$$|G_E|/|G_M| = 0$$

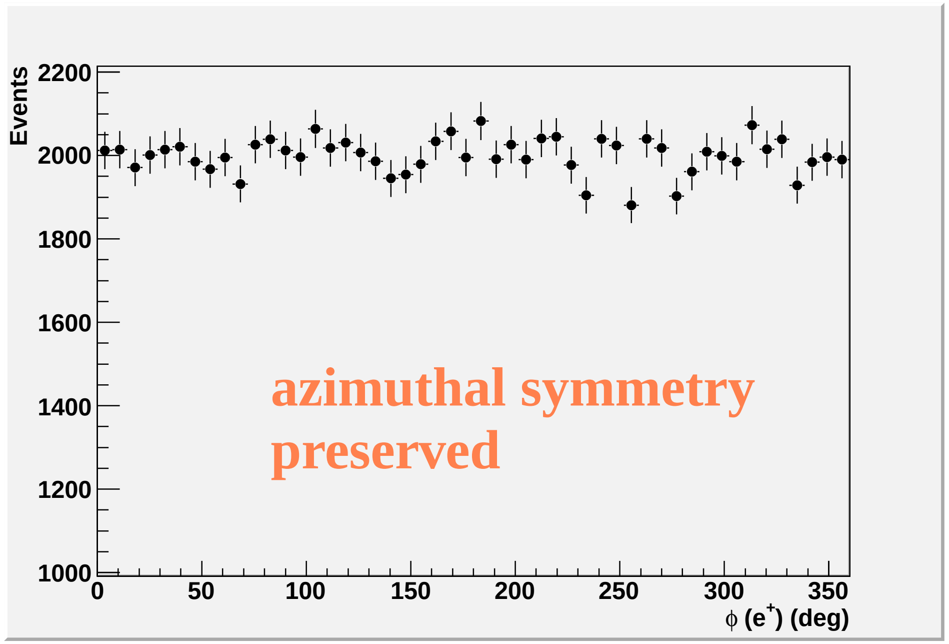


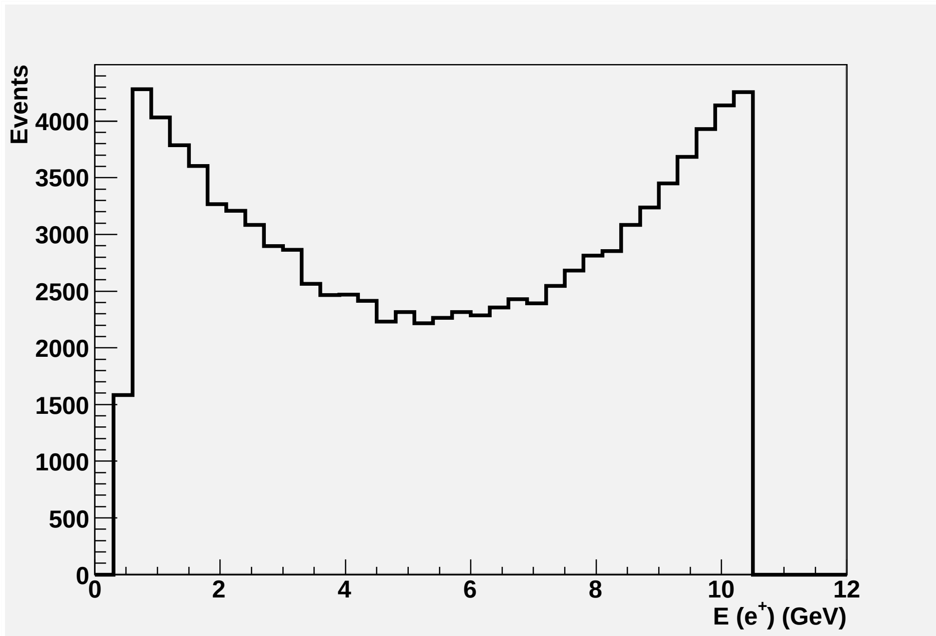
$\bar{p}p \rightarrow e^+e^-$: distributions in LAB frame

events boosted in the forward direction









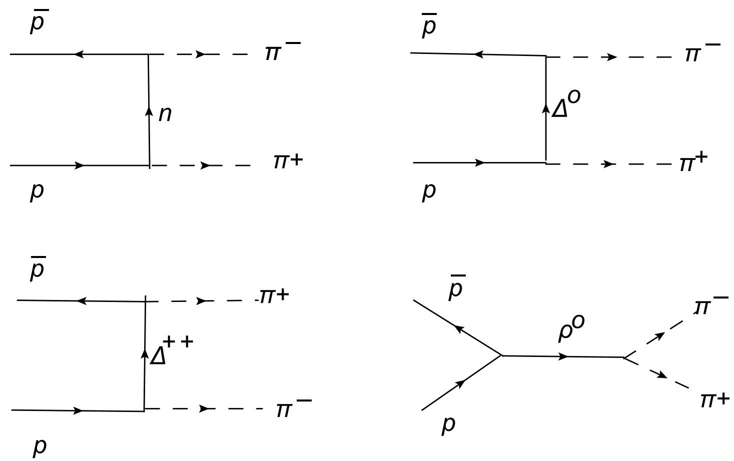
$\bar{p}p \to \pi^+\pi^-$

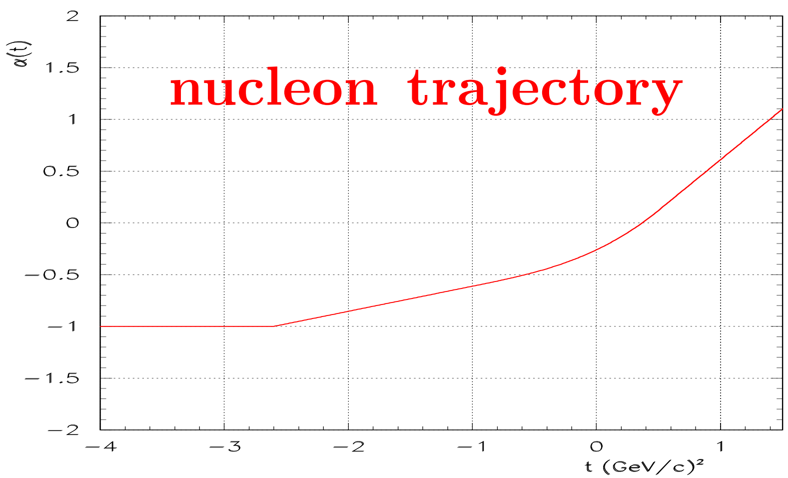
data :	yes	no	yes
model :	**polynomial fit**		**Regge description**
	Eisenhandler et al. Nucl. Phys. B96 (1975) 109		J. Van de Wiele and S. Ong Eur. Phys. J. A46, 291 (2010)

we use: Regge approach, extended to "transition region" (low energy: work in progress...)

$\Rightarrow$ cross section at a grid of (19×201) points $(s, \cos\theta_{CM}(\pi))$ (+ linear extrapolation)

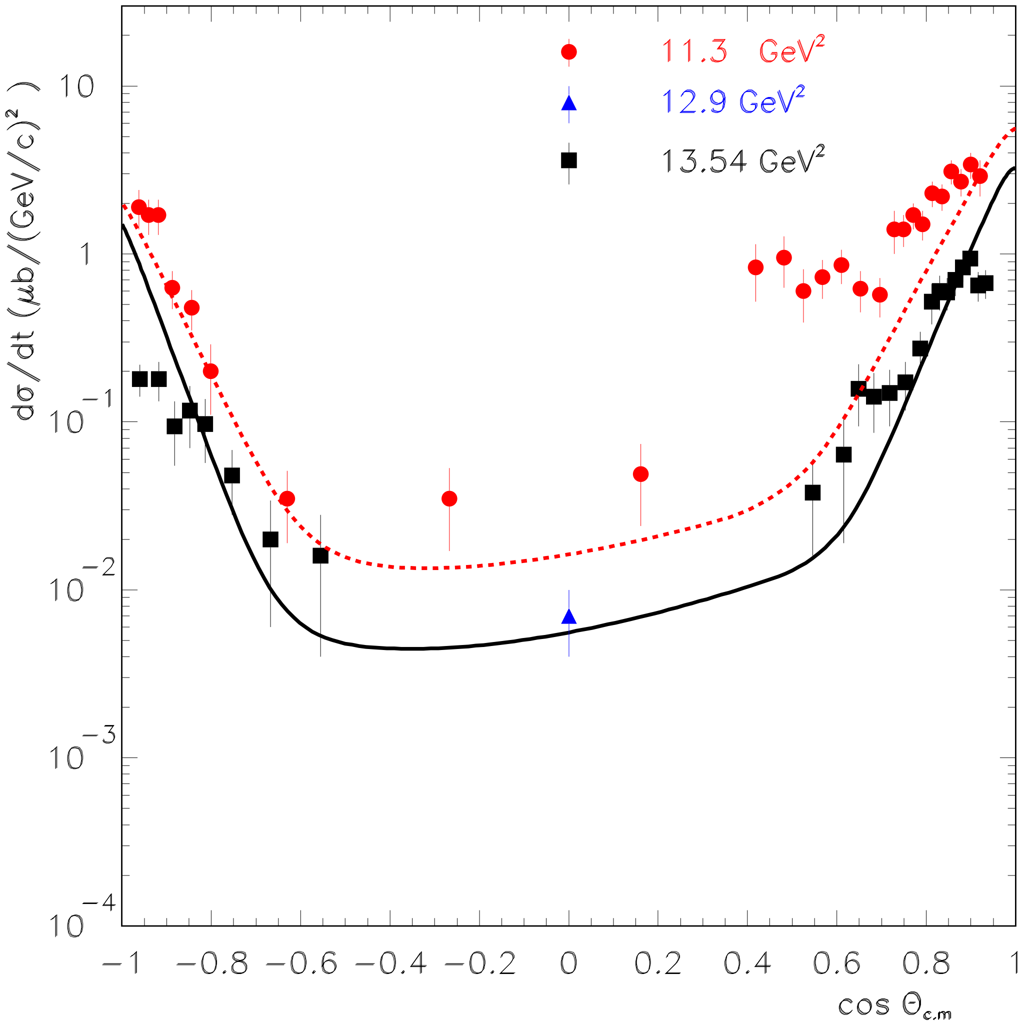
- **parametrization of scattering amplitudes in terms of "Regge trajectories" exchanged in the t and u channels**





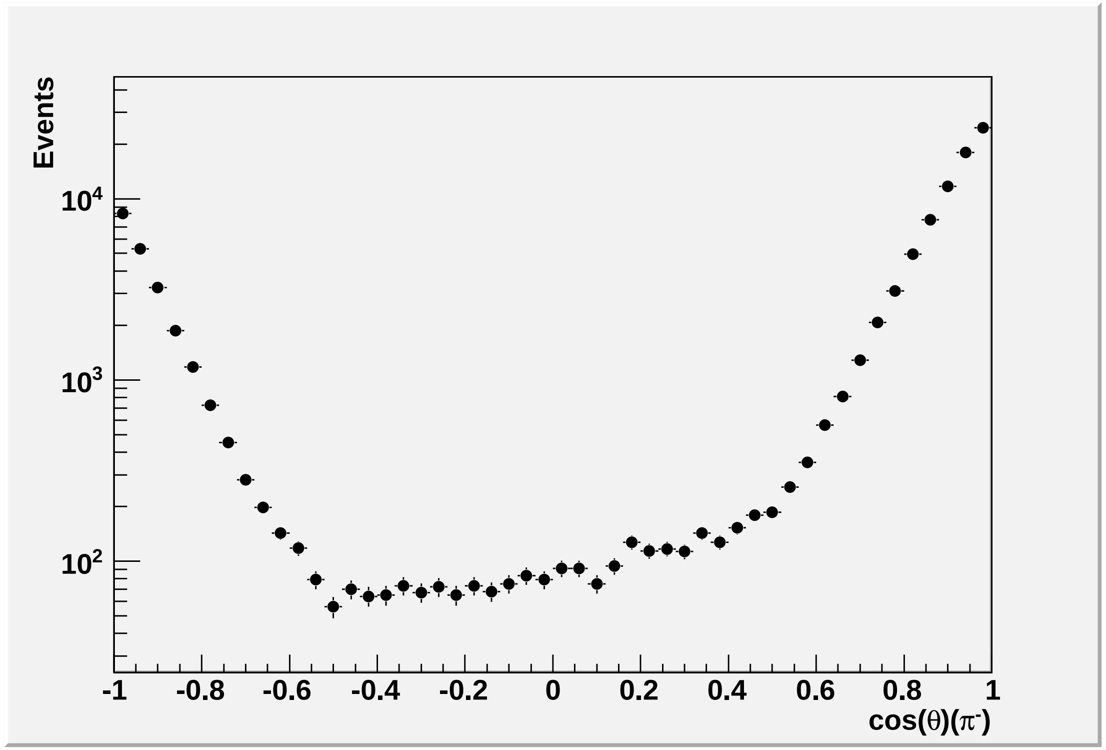
$\bar{p}p \to \pi^+\pi^-$

cross section



J. Van de Wiele and S. Ong

$s = 11.3\,\mathrm{GeV}^2, \qquad \mathrm{N} = 10^5$ events



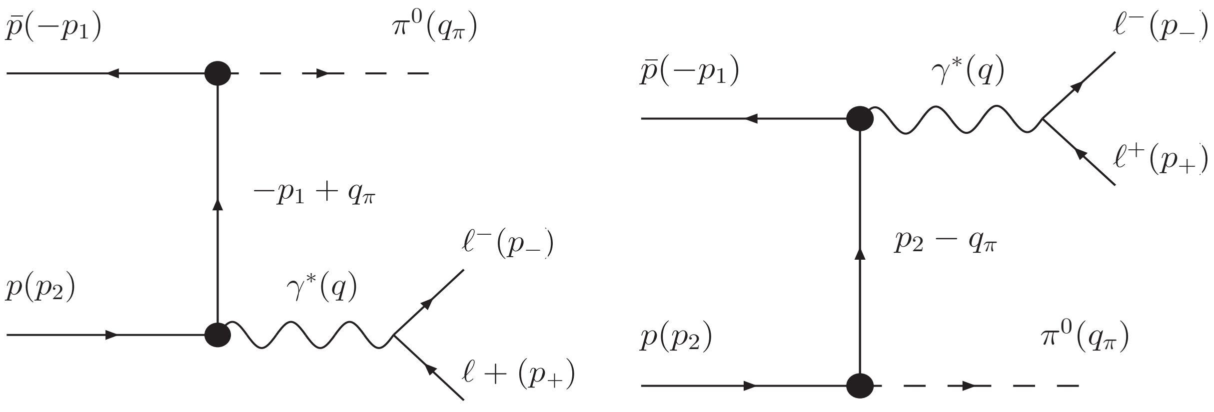
our simulation

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

Physis:

- **phenomenological approach based on Compton-like Feynman amplitudes**

  C. Adamuscin et al., Physical Review C 75, 04205 (2007)



(a) (b)

sequence of two 2-body decays:

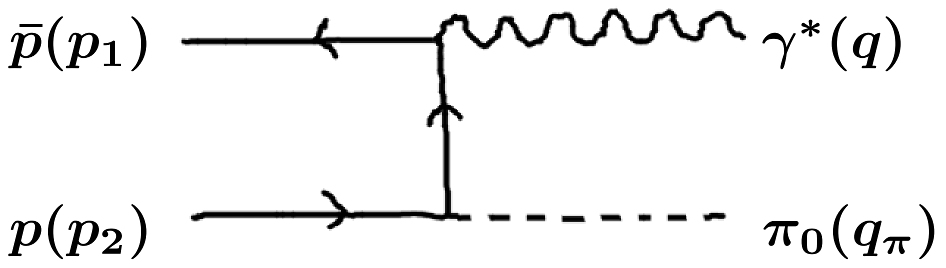
(1) $\bar{p}p \rightarrow \gamma^*\pi^0$: **cross section calculated in paper, 2 different models for FF**

(2) $\gamma^* \rightarrow e^+e^-$: **cross section NOT in paper $\rightarrow$ need to make assumption**

remark:

no FF modification due to virtuality of off-mass shell nucleons:
use electromagnetic current expression involving on-mass shell hadrons

$\bar{\mathrm{p}}\mathrm{p} \to \mathrm{e}^+\mathrm{e}^-\pi^0$: subprocess $\bar{\mathrm{p}}\mathrm{p} \to \gamma^*\pi^0$ (kinematics)



$$p_1 = (E, 0, 0, P)$$
$$p_2 = (M, 0, 0, 0)$$

4-momentum conservation: $p_1 + p_2 = q + q_\pi \quad \Rightarrow$

$$\boxed{\mathrm{q}^2 = \mathrm{s} + \mathrm{m}_\pi^2 - 2(\mathrm{E} + \mathrm{M})\mathrm{E}_\pi + 2\mathrm{P}\sqrt{\mathrm{E}_\pi^2 - \mathrm{m}_\pi^2}\cos(\theta_\pi)}$$

- $0 \le q^2 \le q^2_{\mathrm{max}}$, $\qquad q^2_{\mathrm{max}} = (\sqrt{s} - m_\pi)^2$

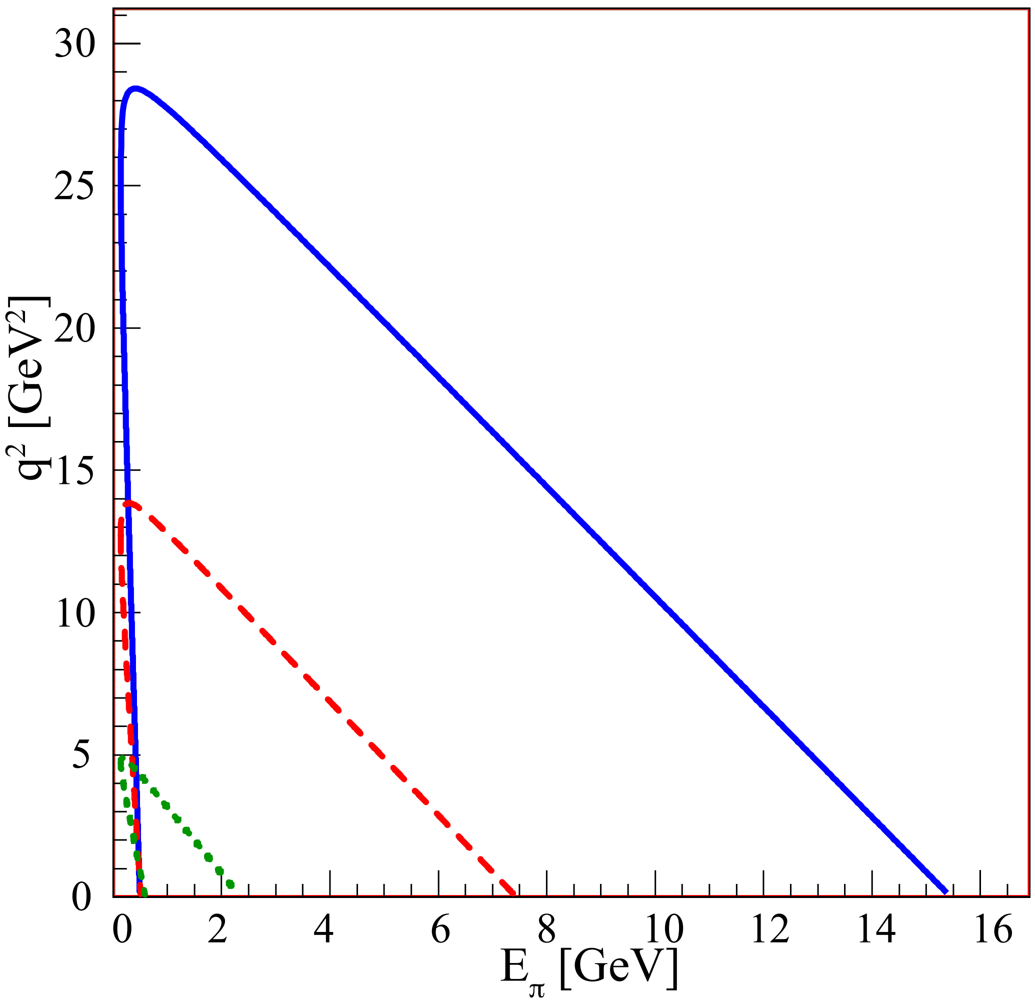
$\Rightarrow$ **take** (q^2, E_π) **as the independent variables**

$\rightarrow$ **sample** (q^2, E_π) **uniformly in** $[0, q^2_{\mathrm{max}}] \times [0, E + M]$

$\rightarrow$ **calculate** $\cos(\theta_\pi)$**, and accept if** $\quad -1 \le \cos(\theta_\pi) \le 1$

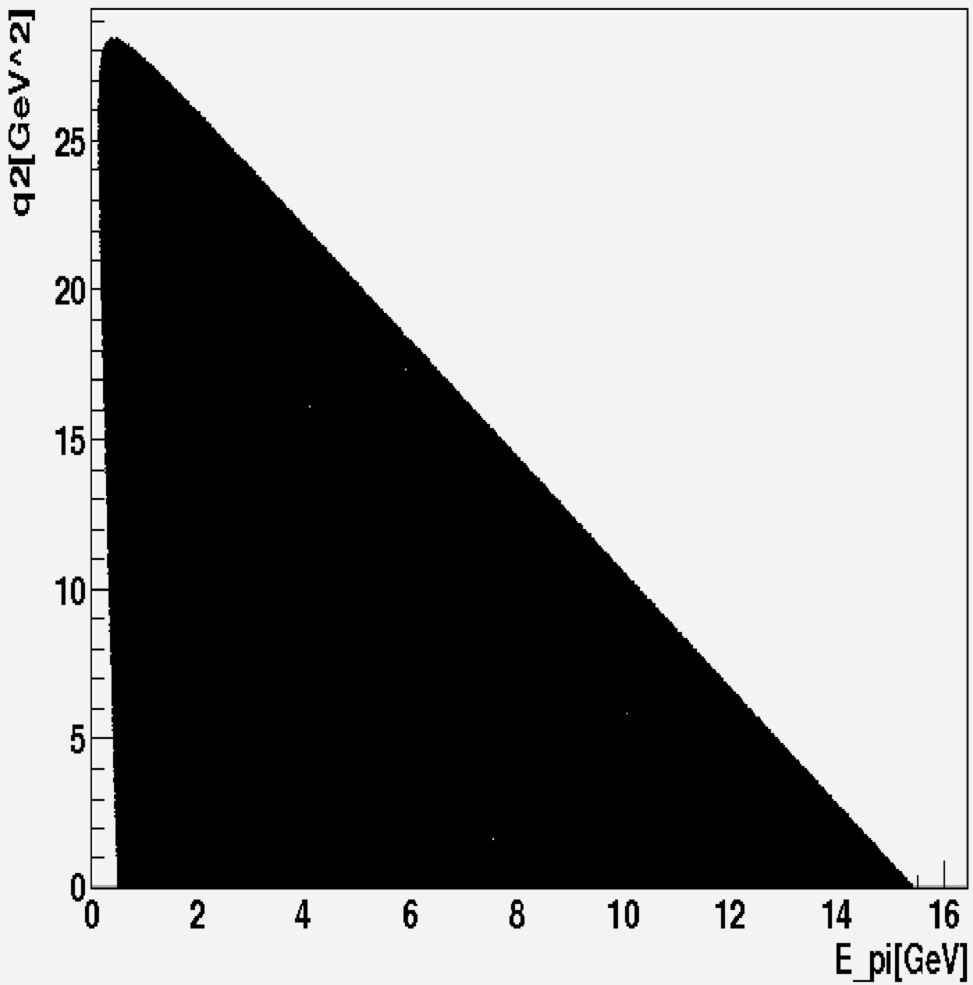
$\bar{p}p \to e^+e^-\pi^0$: subprocess $\bar{p}p \to \gamma^*\pi^0$ (kinematics)

kinematic region



Adamuscin et al.

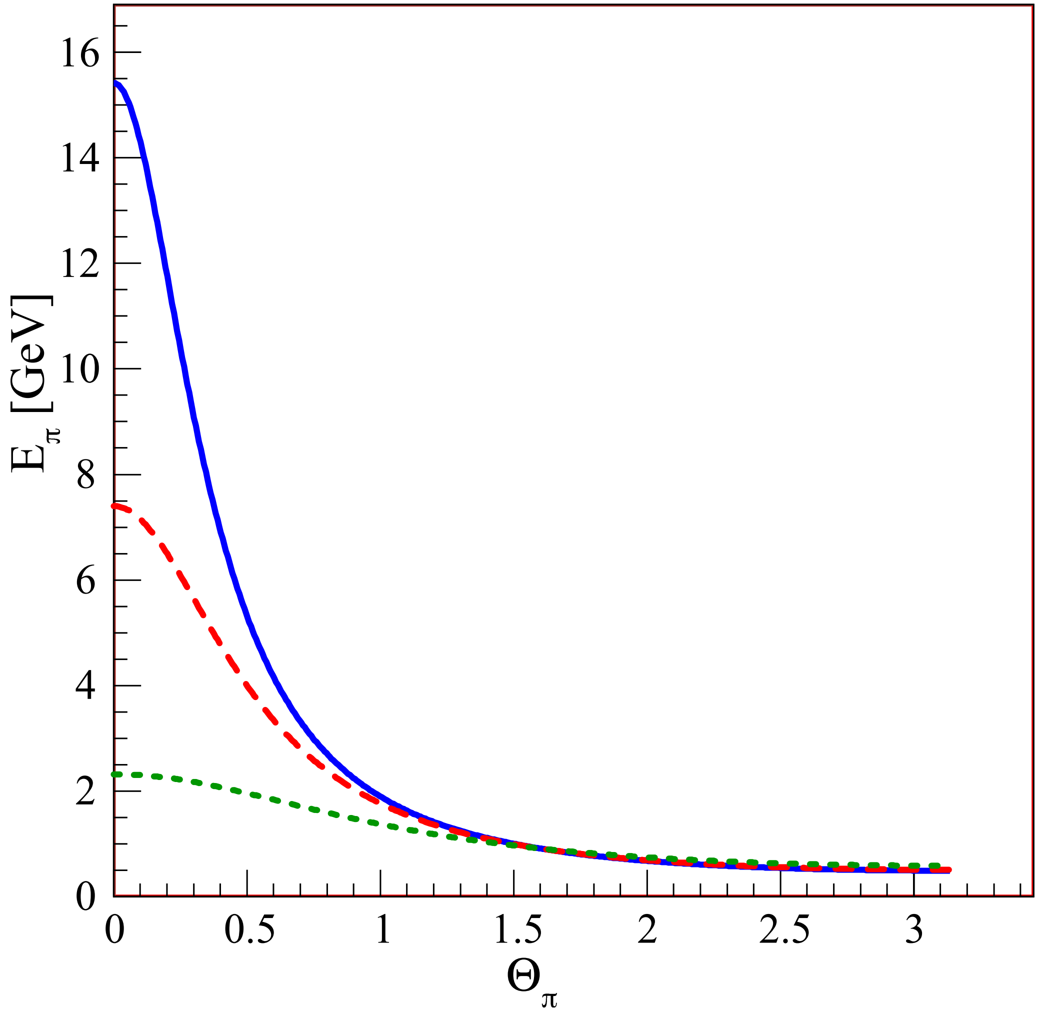
$E = 15$ GeV, $N = 10^6$ events



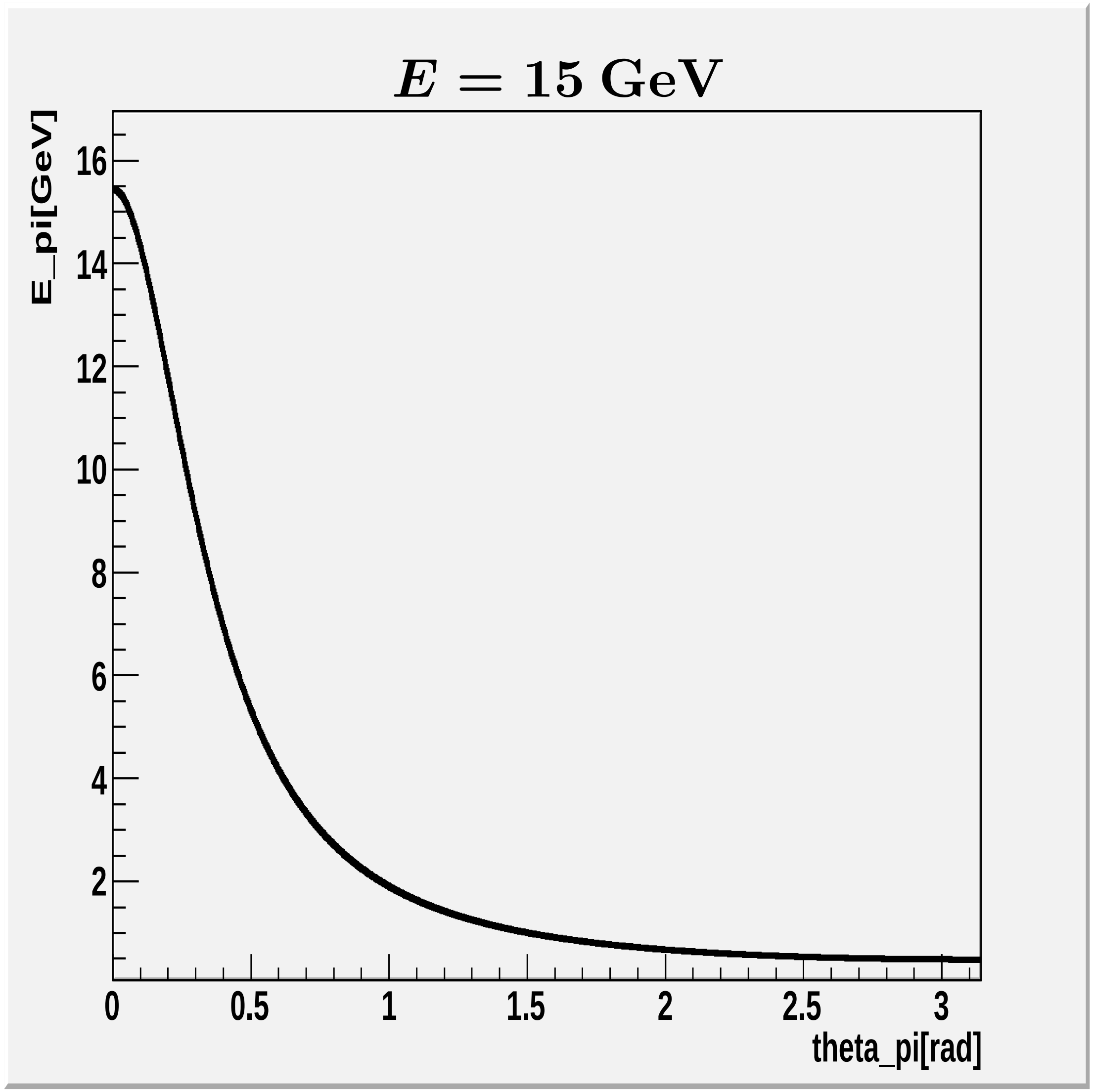
our calculation

$\bar{p}p \to e^+e^-\pi^0$: subprocess $\bar{p}p \to \gamma^*\pi^0$ (kinematics)

pion energy dependence



Adamuscin et al.



our calculation

$\bar{\mathrm{p}}\mathrm{p} \to \mathrm{e}^+\mathrm{e}^-\pi^0$: subprocess $\bar{\mathrm{p}}\mathrm{p} \to \gamma^*\pi^0$ (dynamics)

cross section:

$$\mathrm{d}\sigma^0 = [\text{kinematics}] \times \underbrace{[\text{dynamics}]}_{} \times \mathrm{d}(\text{phase space volume})$$

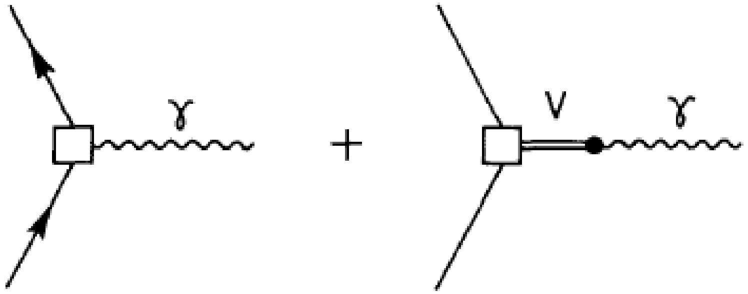
$\equiv \mathrm{D}^0$: **coupling $g_{\pi NN}$, FF $F_1(q^2)$ and $F_2(q^2)$**

two parametrizations for FF:

(1) **"perturbative QCD inspired" (pQCD)**

$$|G_E| = |G_M| \sim \frac{1}{q^4\left(\ln\left(\frac{q^2}{\Lambda^2}\right) + \pi^2\right)}, \quad q^2 > \Lambda^2 \qquad \textbf{(smooth)}$$

(2) **"vector meson dominance" (vmd)** **F. Iachello et al., Phys. Rev. C69, 055204 (2004)**



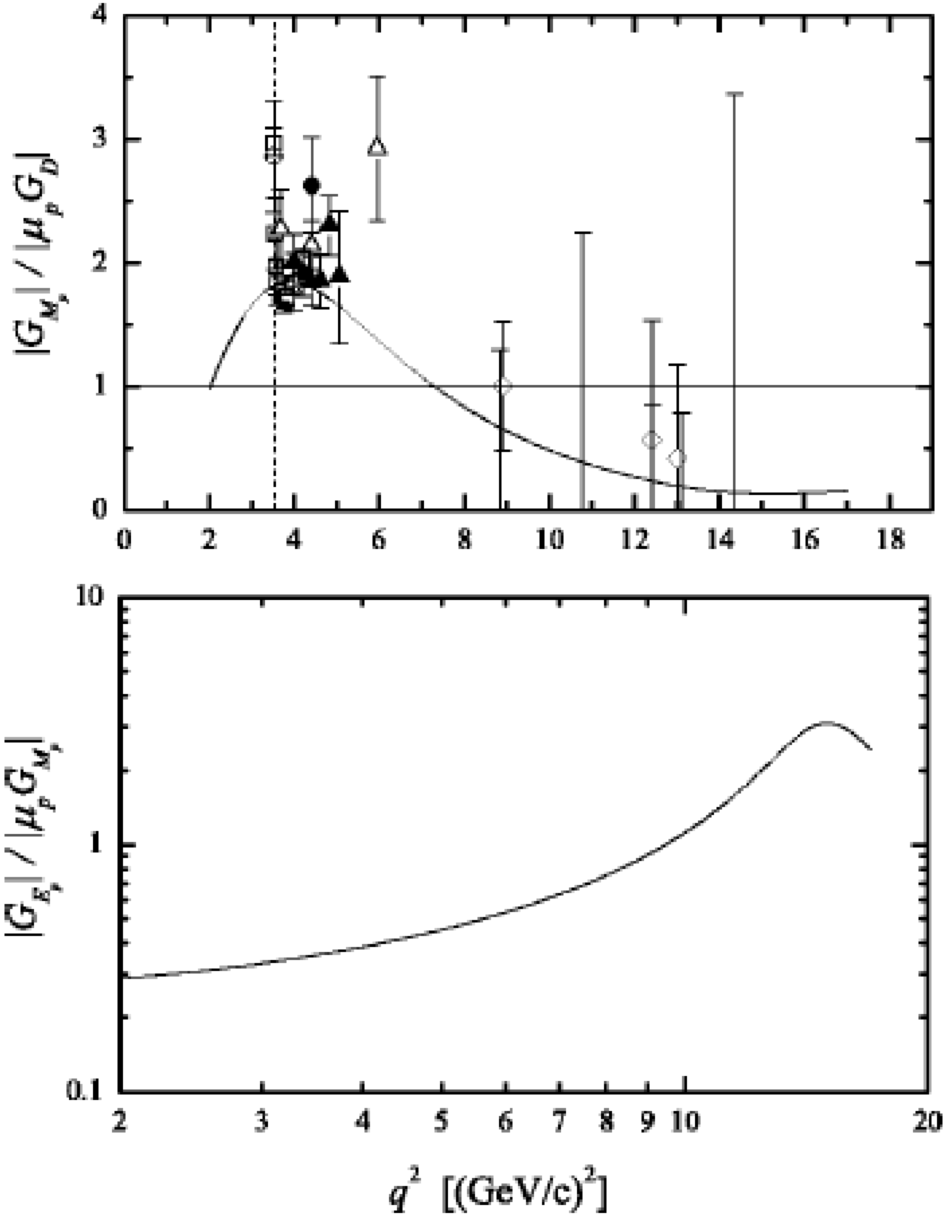
photon couples to both intrinsic structure $g(q^2)$
+meson cloud (ρ, ω, ϕ)

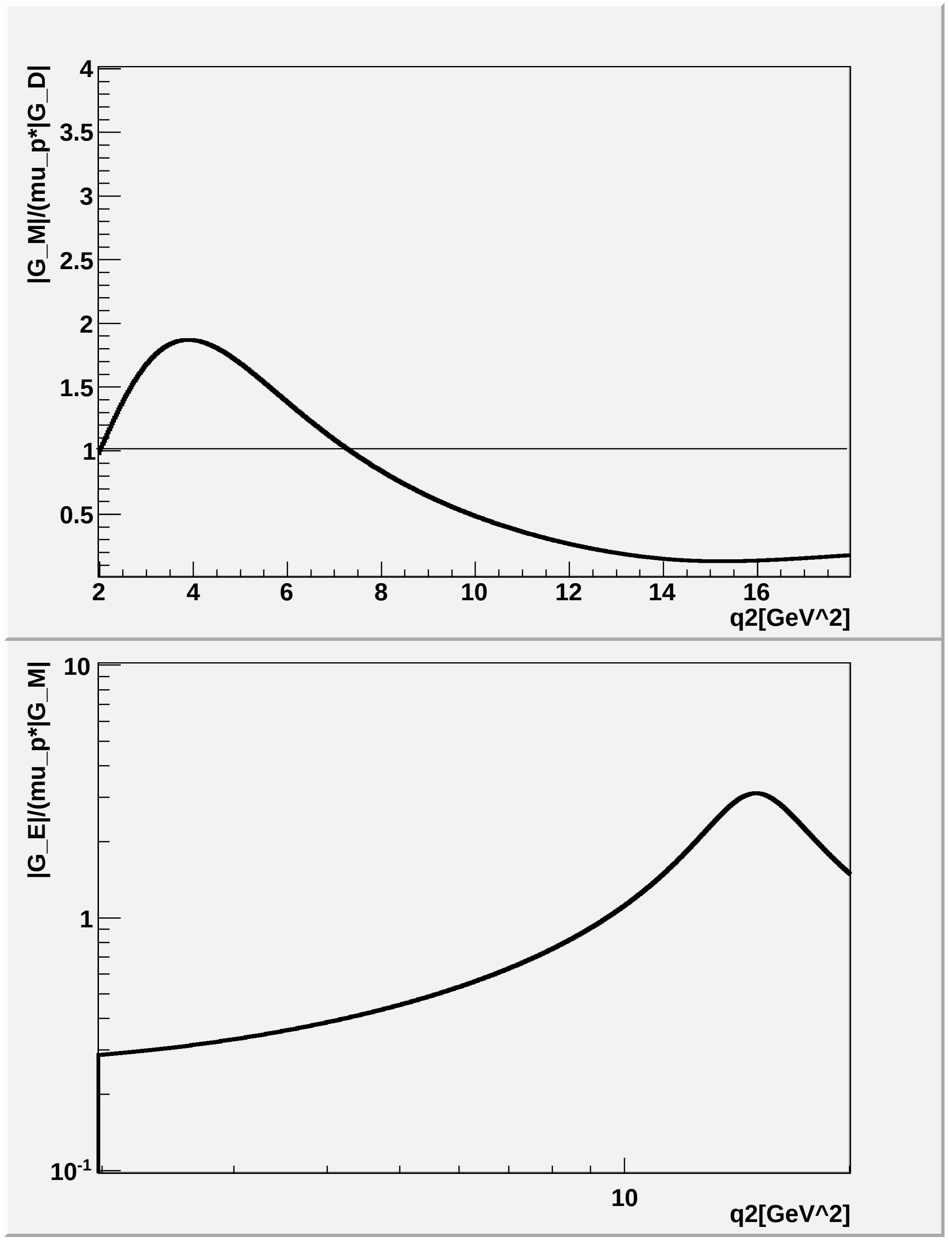
$\to$ **parametrization in spacelike domain, analytically continued to timelike**

$\to$ **singularities at $q^2 = m_\omega^2$ and $q^2 = m_\phi^2$**

$\bar{p}p \to e^+e^-\pi^0$: form factors

$$G_D(q^2) = (1 - q^2/0.71)^{-2}$$



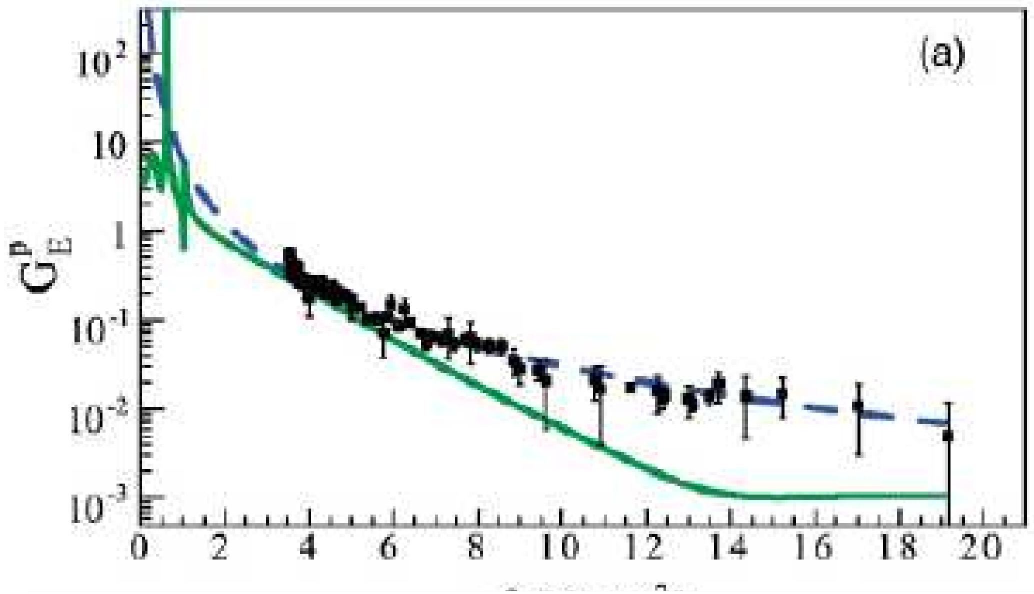


Iachello et al.

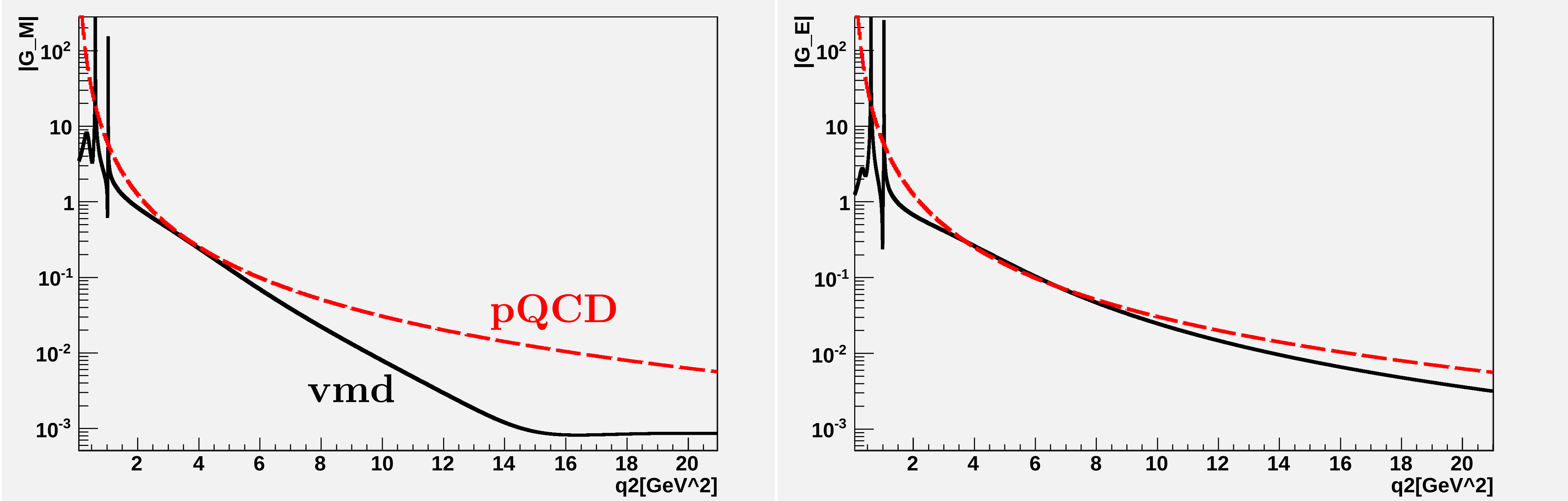
our calculation

$\bar{p}p \to e^+e^-\pi^0$: form factors

Adamuscin et al.



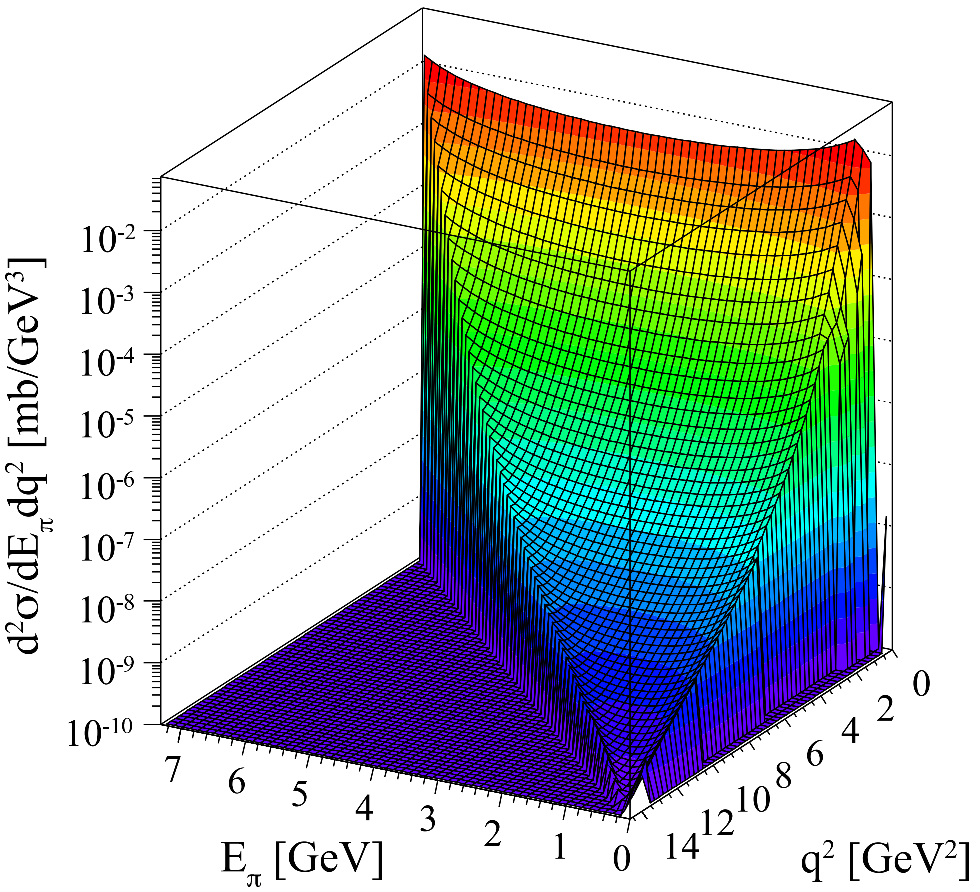
our calculation



$\bar{p}p \to e^+e^-\pi^0$: cross section and event generation

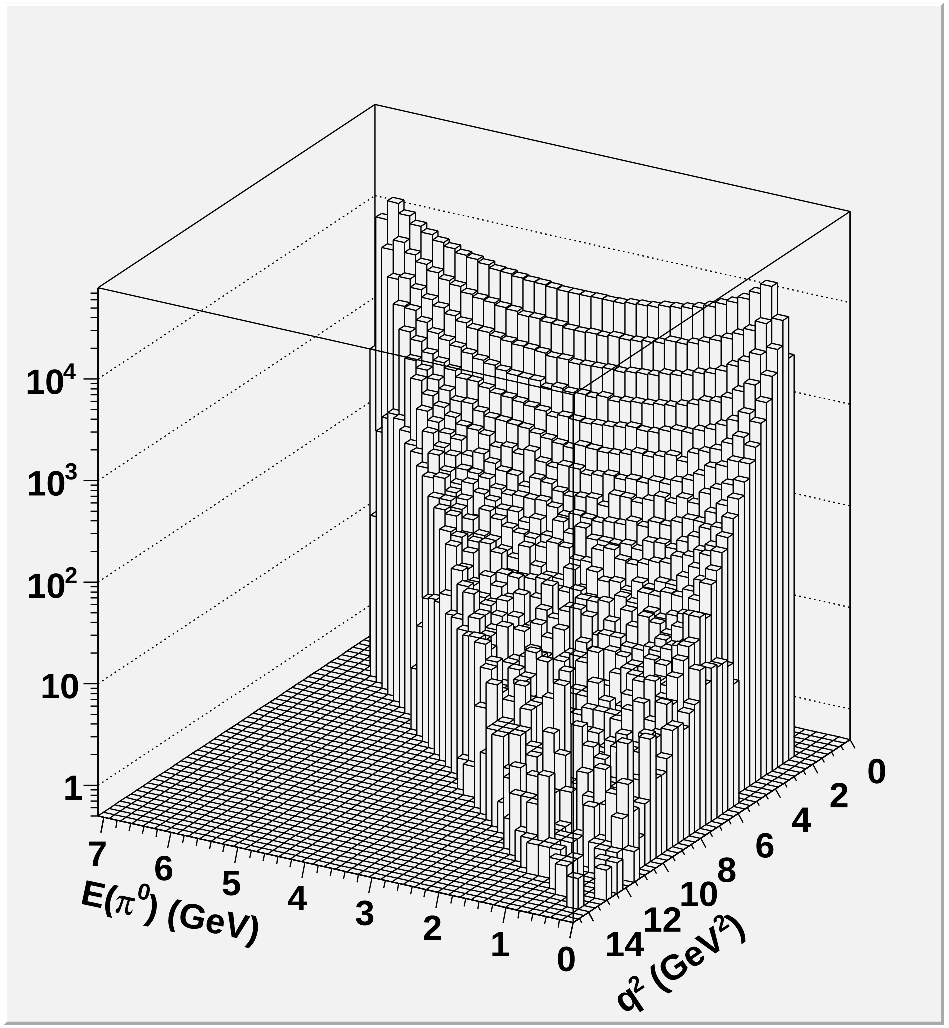
cross section

$E = 7$ GeV **(pQCD FF)**



Adamuscin et al.

$N = 10^6$ events $q^2 > 2\,\mathrm{GeV}^2$



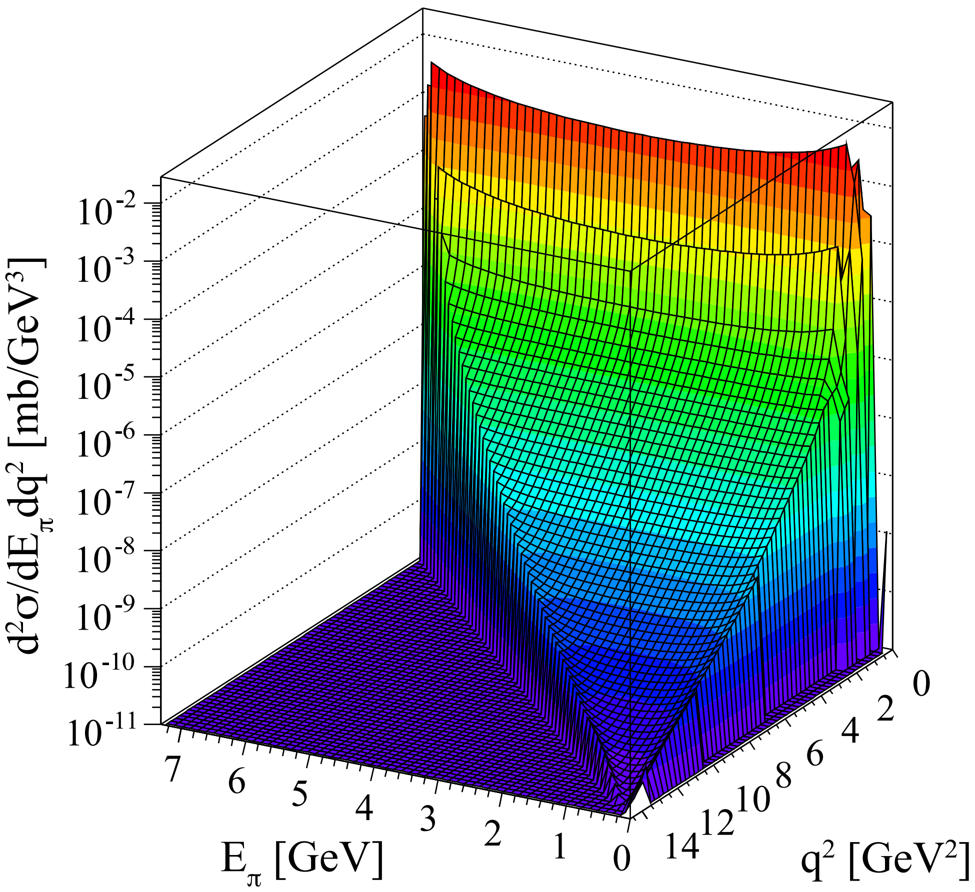
our simulation

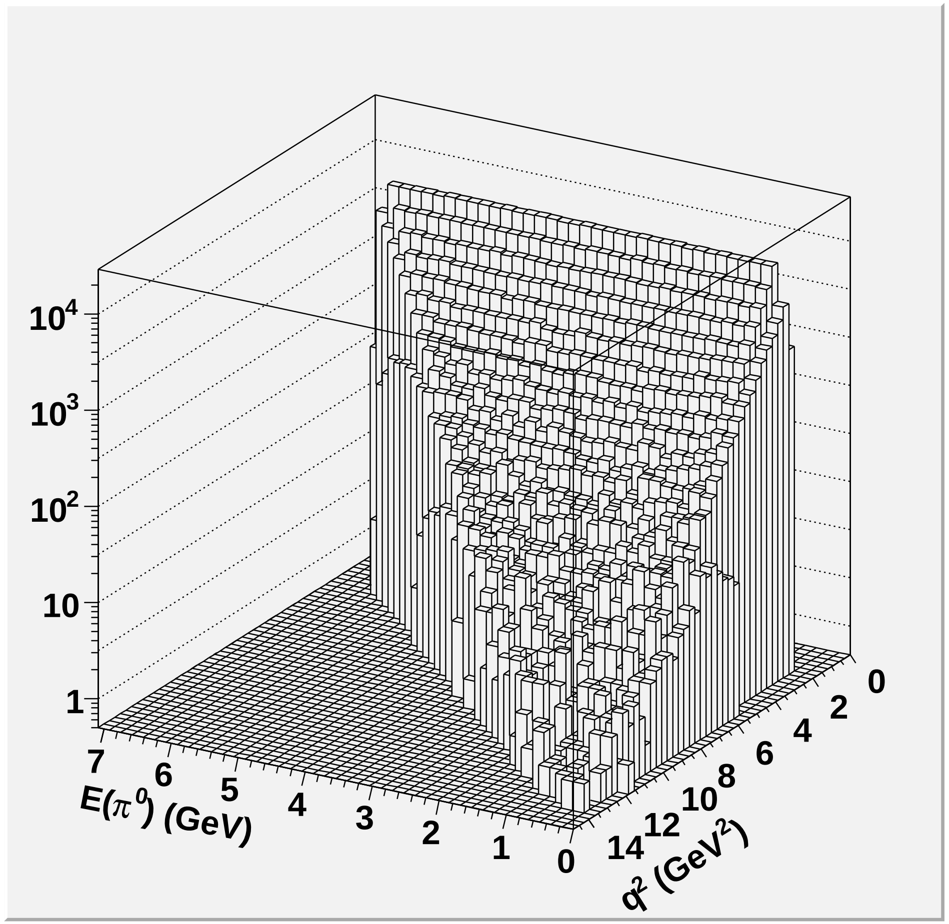
$\bar{p}p \to e^+e^-\pi^0$: cross section and event generation

cross section

$E = 7$ GeV (vmd FF)

$N = 10^6$ events $q^2 > 2\,\mathrm{GeV}^2$



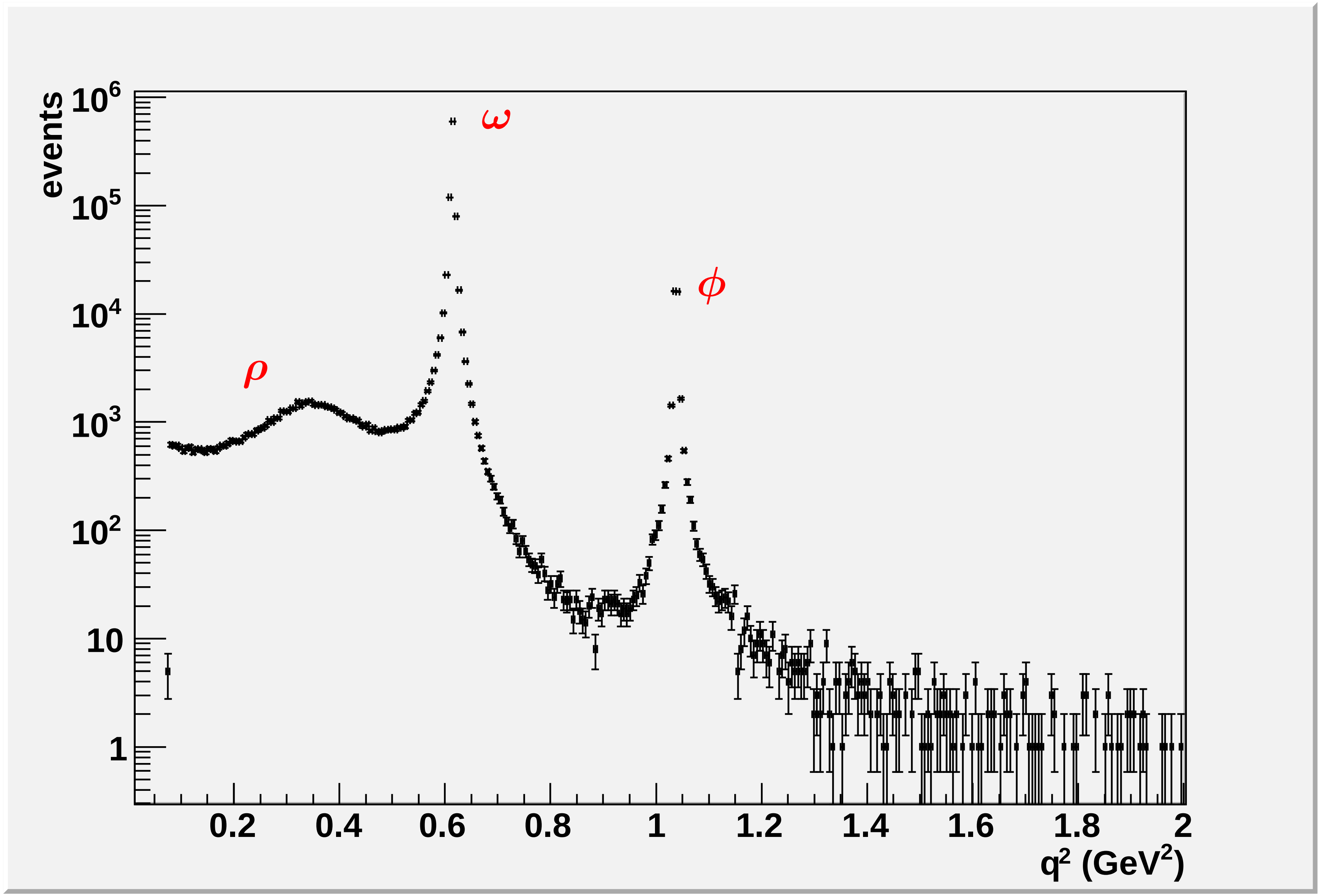


Adamuscin et al.

our simulation

$\bar{p}p \to e^+e^-\pi^0$: cross section and event generation

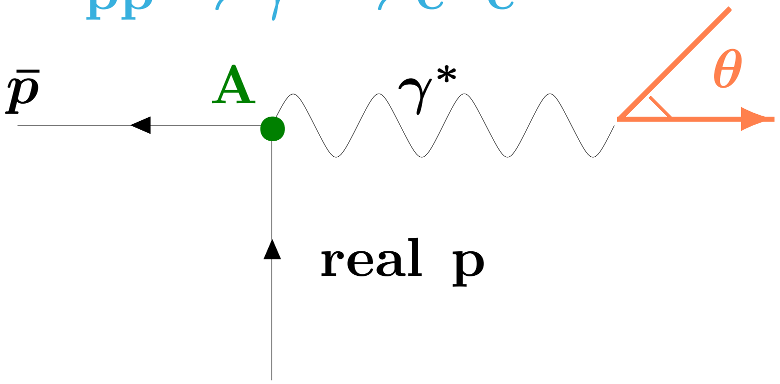
vmd FF $\quad N = 10^6$ events $\quad E = 7\ \mathrm{GeV}^2 \quad q^2 > 4m_\pi^2$



our simulation

$\bar{p}p \to e^+e^-\pi^0$: subprocess $\gamma^* \to e^+e^-$

$\bar{p}p \to \gamma^* \to e^+e^-$

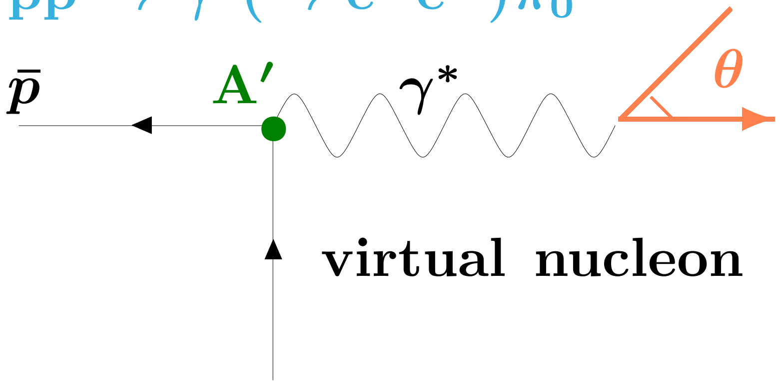


$$\mathrm{prob}(\cos\theta) \sim 1 + A\cos^2\theta$$

θ: γ^* rest frame, z axe: γ^* LAB

$$A = \frac{1-R}{1+R}, \quad R = \frac{|G_E|}{|G_M|}$$

$\bar{p}p \to \gamma^*(\to e^+e^-)\pi_0$



$$\mathrm{prob}(\cos\theta) \sim 1 + A'\cos^2\theta$$

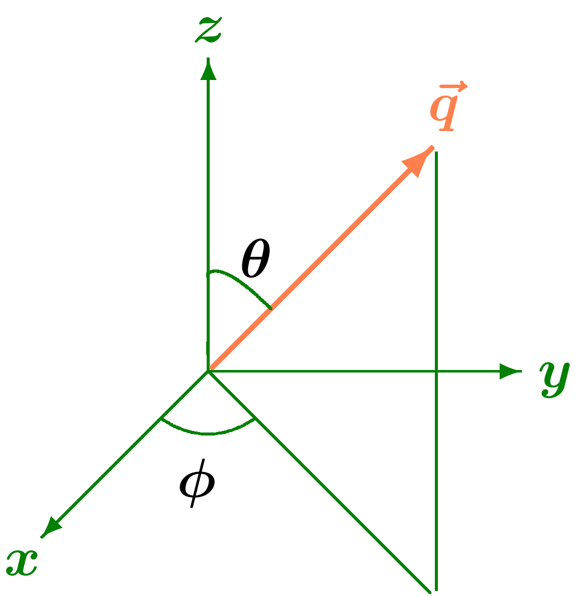
θ: γ^* rest frame, z axe: γ^* LAB

assumption:

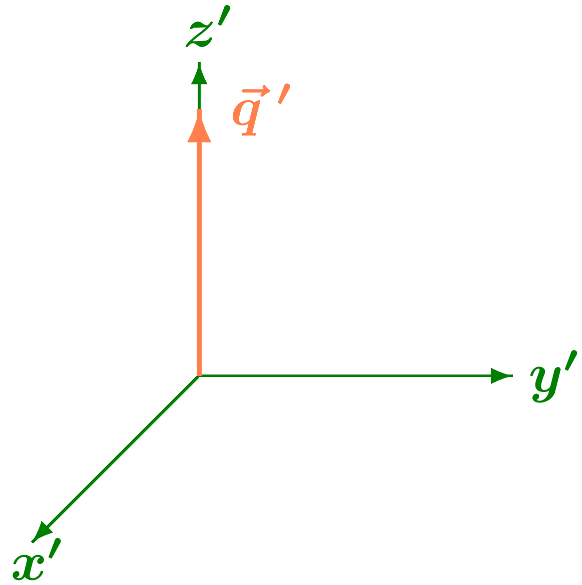
$$\boxed{A' = A}$$

$\bar{\mathrm{p}}\mathrm{p} \to \mathrm{e}^+\mathrm{e}^-\pi^0$: subprocess $\gamma^* \to \mathrm{e}^+\mathrm{e}^-$

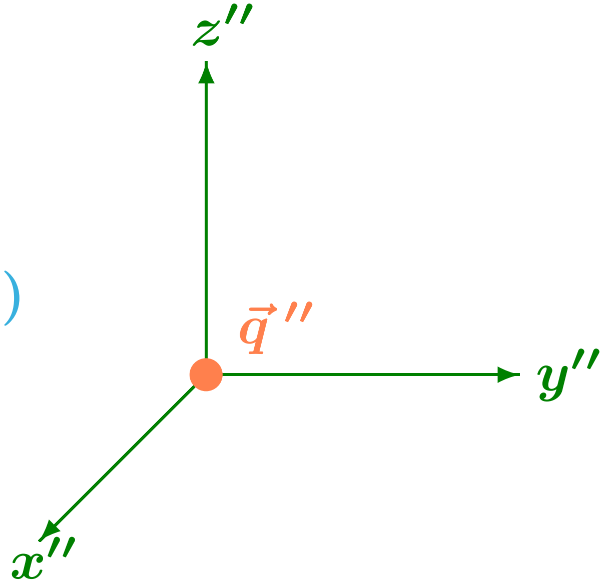
prescription :



$\mathrm{R_y}(-\theta)\mathrm{R_z}(-\phi)$
$\Rightarrow$



$\Lambda_{\mathrm{z}'}(\mathrm{q}^2)$
$\Rightarrow$



- z'' **defines** $\cos(\theta'')$**: event dependent**
- **decay** $\gamma^* \to e^+e^-$ **with** $\cos^2\theta''$ **distrib.**
- **bring** e^+e^- **back to lab:**

$$[\Lambda_{\mathrm{z}'}(\mathrm{q}^2)\mathrm{R_y}(-\theta)\mathrm{R_z}(-\phi)]^{-1} =$$

$$\mathrm{R_z}(\phi)\mathrm{R_y}(\theta)\Lambda_{\mathrm{z}'}^{-1}(\mathrm{q}^2)$$

work in progress . . .

Summary and conclusions

MC generators ready for :

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

work in progress . . .

$\to$ **full integration in PANDA ROOT + analysis**
$\to$ **MC development for other models (TDA, etc.)**
$\to$ **MC development for other processes (polarization, etc.)**