KPH institute seminar
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Monte Carlo event generators for PANDA

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OUTLINE

- **Introduction**

  $\rightarrow$ **the PANDA experiment**
  $\rightarrow$ **the electromagnetic proton form factors**
  $\rightarrow$ **goals**

- **Generating distributions**

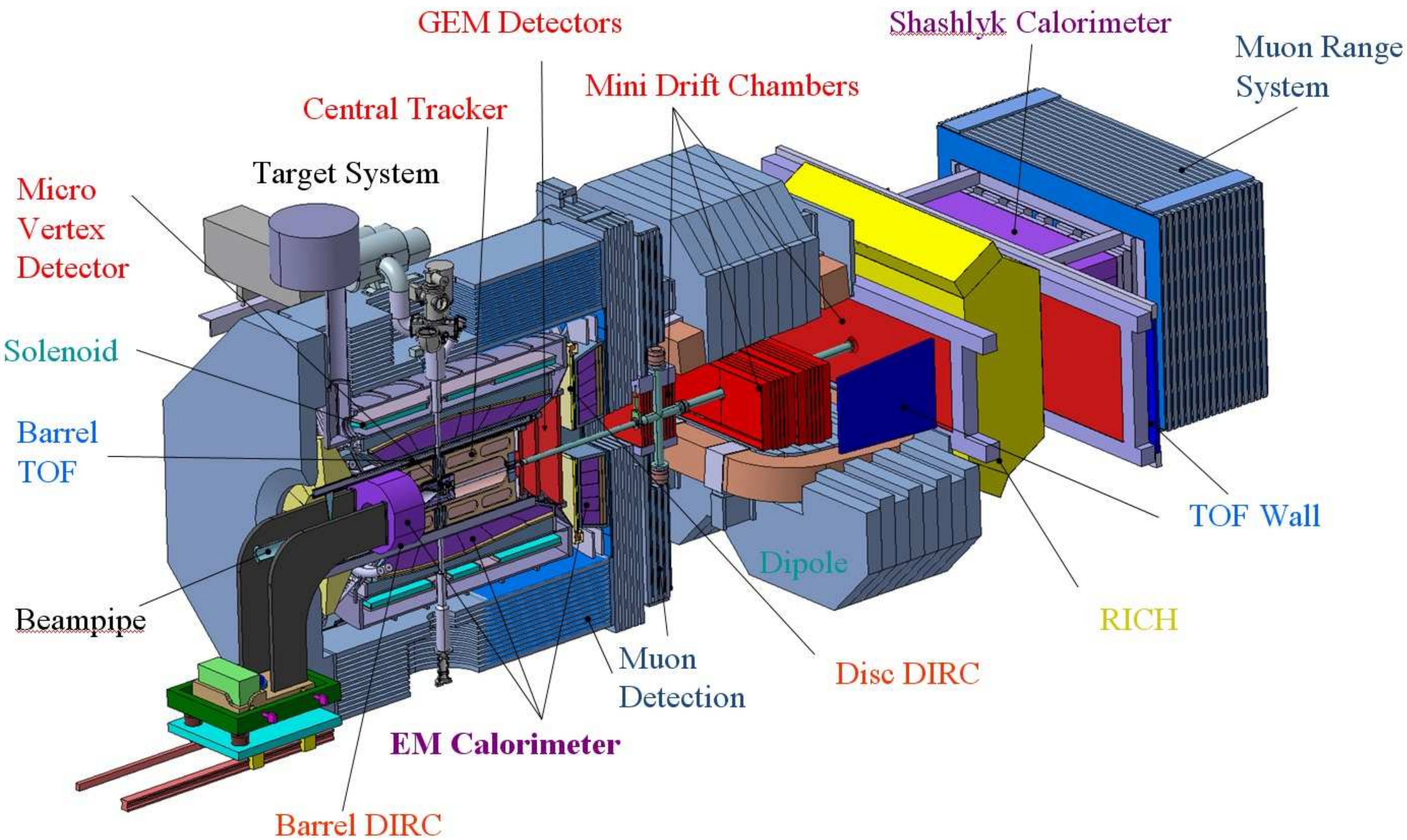
- $\bar{p}p \rightarrow e^+e^-$

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

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

- **Summary and Conclusions**

Introduction : The PANDA Experiment



- $\bar{p}p$ **fixed target experiment at the FAIR facility (GSI, Darmstadt)**
  $1.5 < \mathrm{p}(\bar{\mathrm{p}}) < 15$ GeV, **data taking programmed for 2018**
- **high performance: high luminosity** $\mathrm{L} = 2 \cdot 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, **good tracking/PID**
- **wide physics program: hadron spectroscopy (up to c-sector, exotics), hadron structure (time-like form factors, TPD), non-perturbative dynamics (TDA, spin), hypernuclei, etc.**

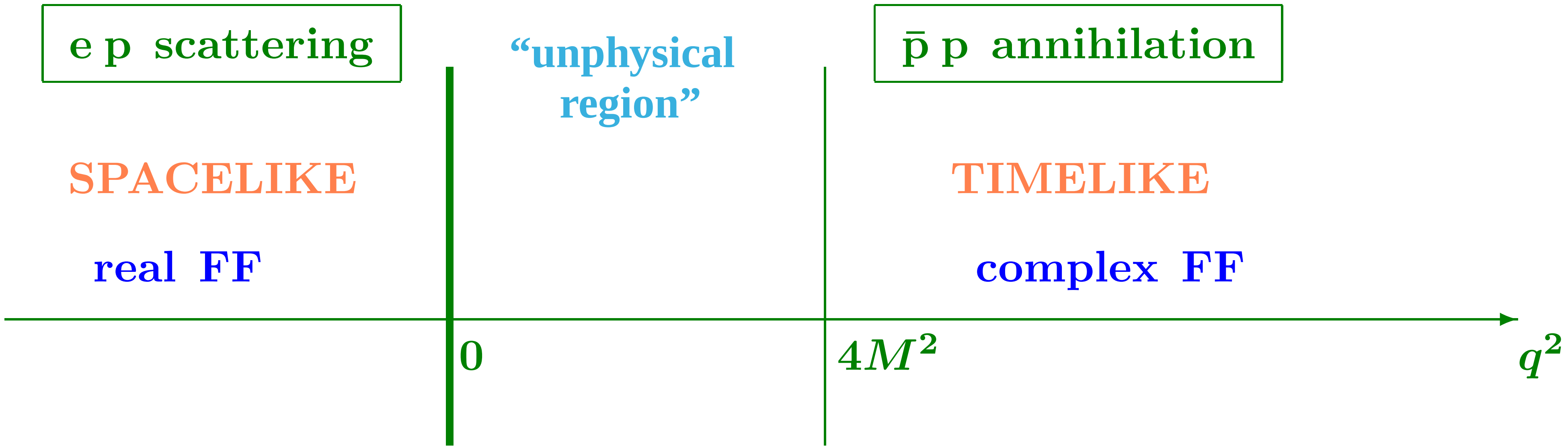
Introduction : The Electromagnetic Proton Form Factors

- **parametrisation of the nucleon structure:** G_E, G_M, (Sachs) / F_1, F_2 (Pauli-Dirac)

$$\rightarrow \langle p'|\Gamma_\mu(q)|p\rangle = \bar{u}(p')\left\{F_1(q^2)\gamma_\mu + \frac{F_2(q^2)}{4M}[\hat{q},\gamma_\mu]\right\}u(p), \quad \hat{q} \equiv q_\nu\gamma_\nu$$

→ **functions of the four-momentum transfer squared** q^2

→ **related by** $G_M = F_1 + F_2$ **and** $G_E = F_1 + \tau F_2$, **with** $\tau = \frac{q^2}{4M}$



$\bar{p}p \rightarrow e^+e^-\pi^0$:
$[\bar{p}p \rightarrow \pi^+\pi^-\pi^0]$
FF modulus/ relative phase

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

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

Introduction : goals

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**

$\Rightarrow$ implementation of realistic models needed

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

$i) + ii)$ $\Rightarrow$ **study background suppression, efficiency in signal reconstruction, etc.**

physics simulation is the topic of this talk

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 $R \times [0, C]$:
  - $\to$ if $h < f(X)$, accept event (and fill histogram)
  - $\to$ if $h > f(X)$, reject event
- iterate previous step until the desired statistics is reached

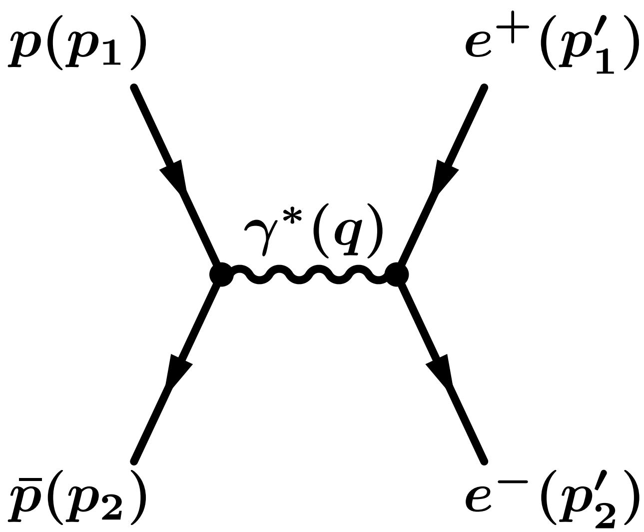
$\Rightarrow$ always work, but cumbersome in high dimension
improvements: importance sampling, etc.

In our case:

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

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

$\bar{\mathrm{p}}\mathrm{p} \rightarrow \mathrm{e}^+\mathrm{e}^-$: Physics



- **LO calculation (one-photon exchange approximation)**
  A.Zichichi et al., Nuovo Cimento XXIV, 170 (1962)
- **in $\bar{p}p$ CM frame, cross section given by**

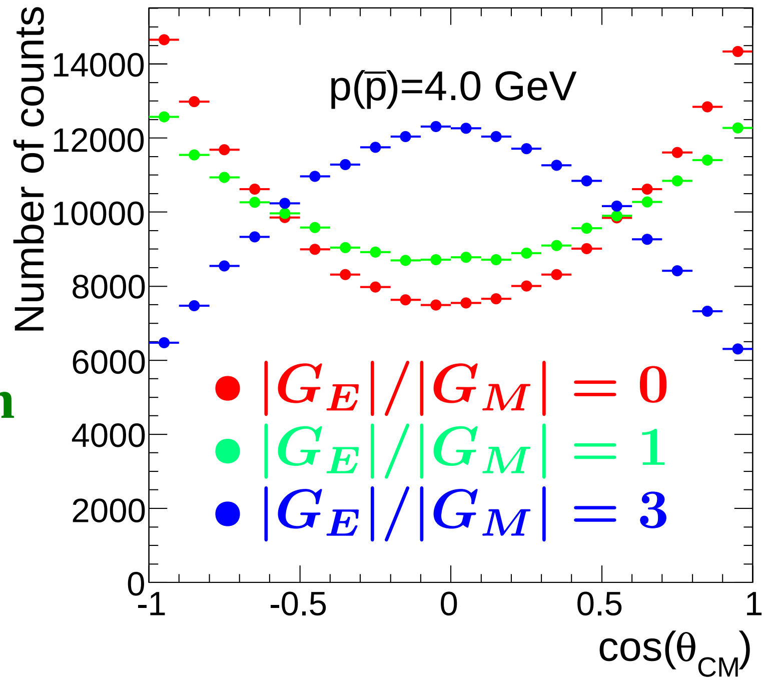
$$\frac{d\sigma}{d\cos\theta^*} \sim (1 + A\cos^2\theta^*)$$

$$\theta^* = \mathrm{angle}(\mathrm{e}^+, \bar{\mathrm{p}}) \quad \mathrm{A} = \frac{1-\mathrm{R}}{1+\mathrm{R}} \quad \mathrm{R} = \frac{|\mathrm{G_E}|}{|\mathrm{G_M}|}$$

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

Kinematics :

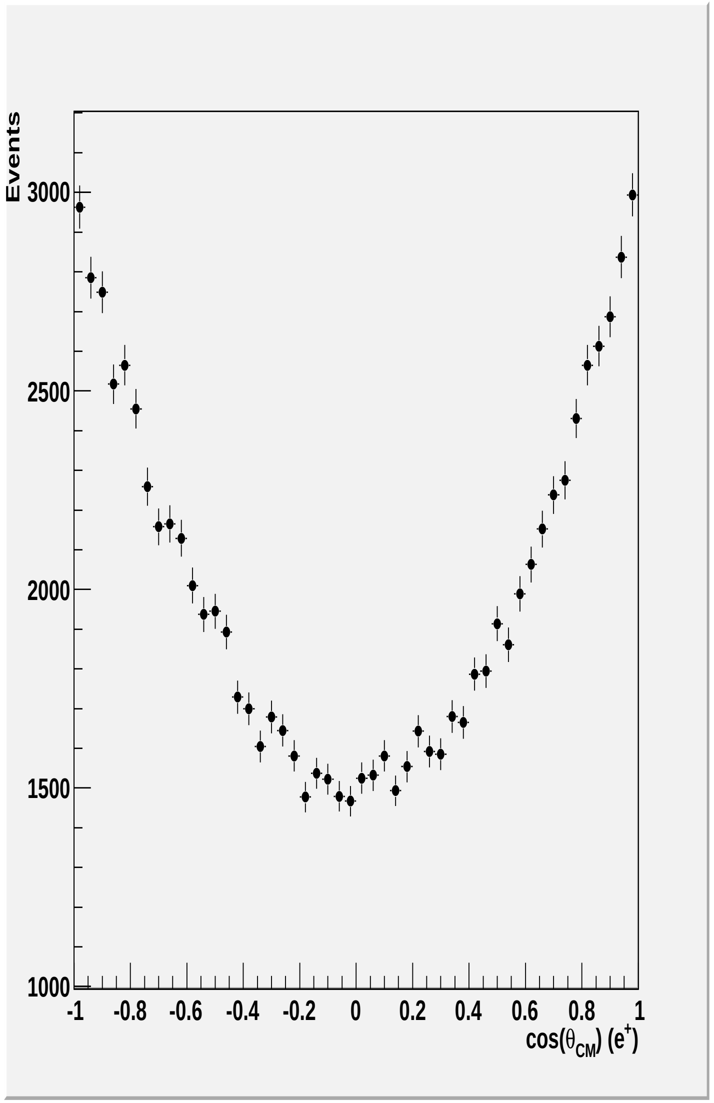
- **in CM frame:**
  - $\rightarrow E(e^+) = E(e^-) = \sqrt{s}/2$
  - $\rightarrow$ **e^+ and e^- in "back to back" configuration**
  - $\rightarrow$ **$\cos\theta^*$ distributed according to cross section (naive accept/reject algorithm)**
  - $\rightarrow$ **azymuthal symmetry, i.e. ϕ^* uniform**
- **boost event to LAB frame**



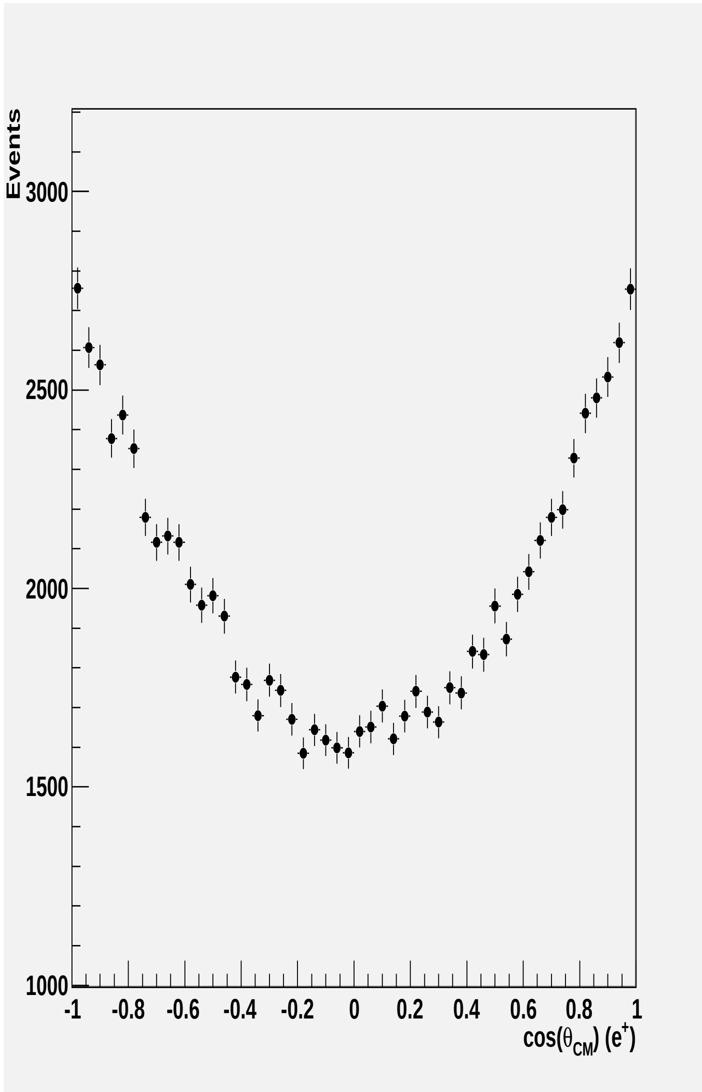
$\bar{p}p \to e^+e^-$: Simulations

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

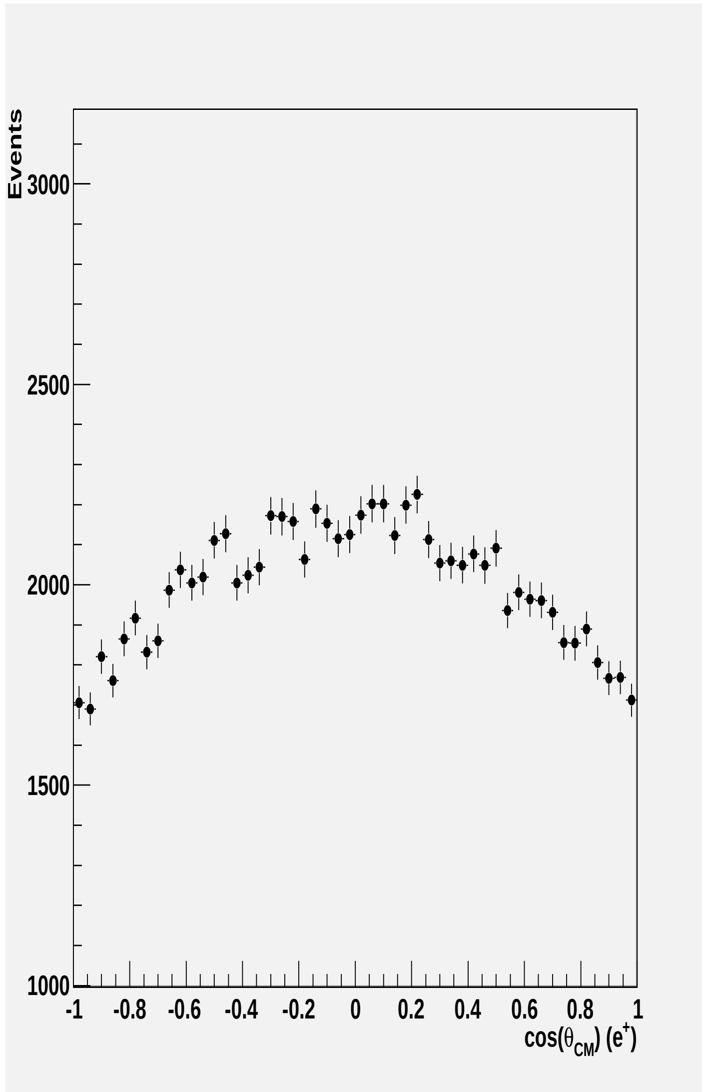
$|G_E|/|G_M| = 0$



$|G_E|/|G_M| = 1$

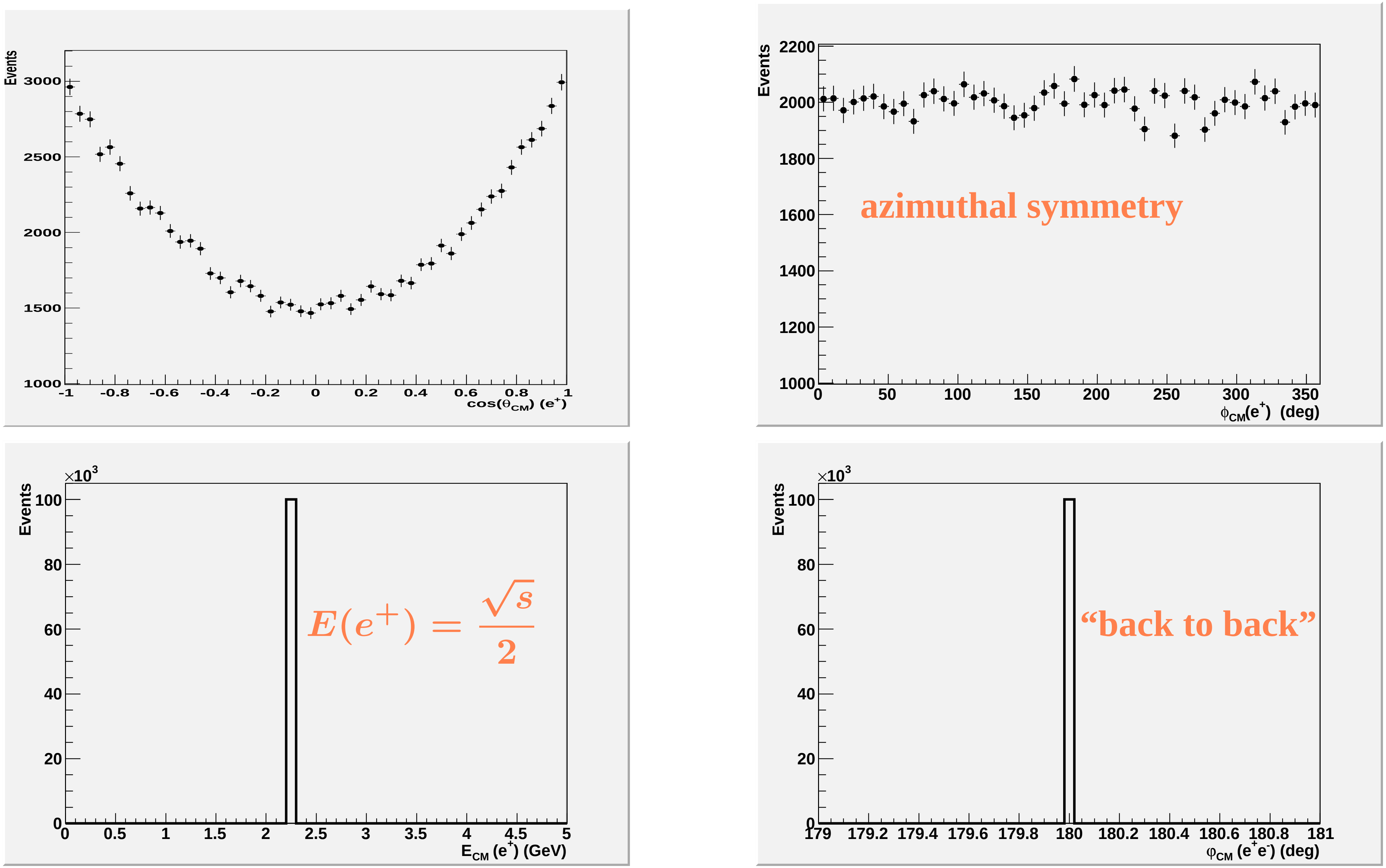


$|G_E|/|G_M| = 3$



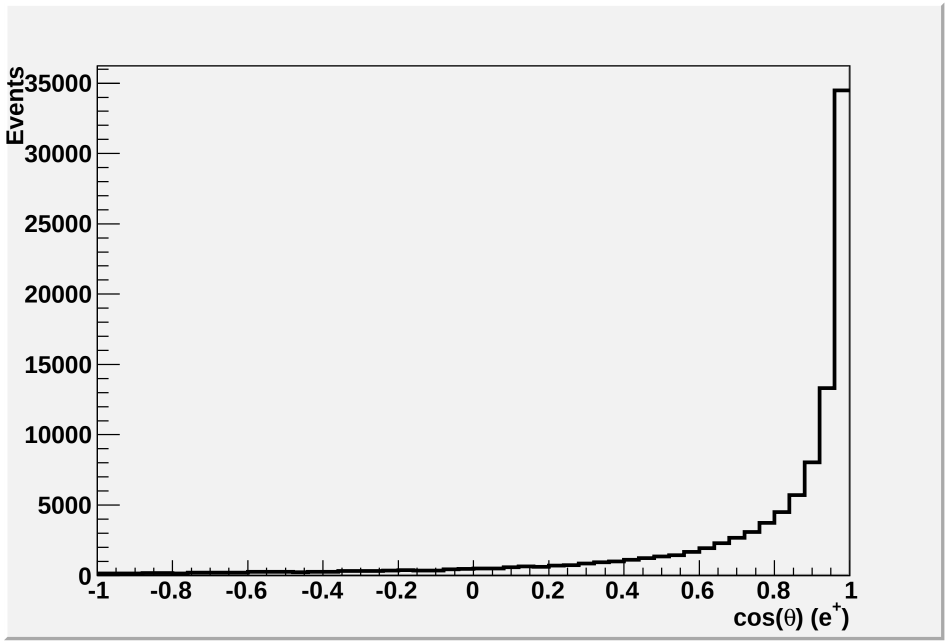
$\bar{p}p \rightarrow e^+e^-$: distributions in CM frame

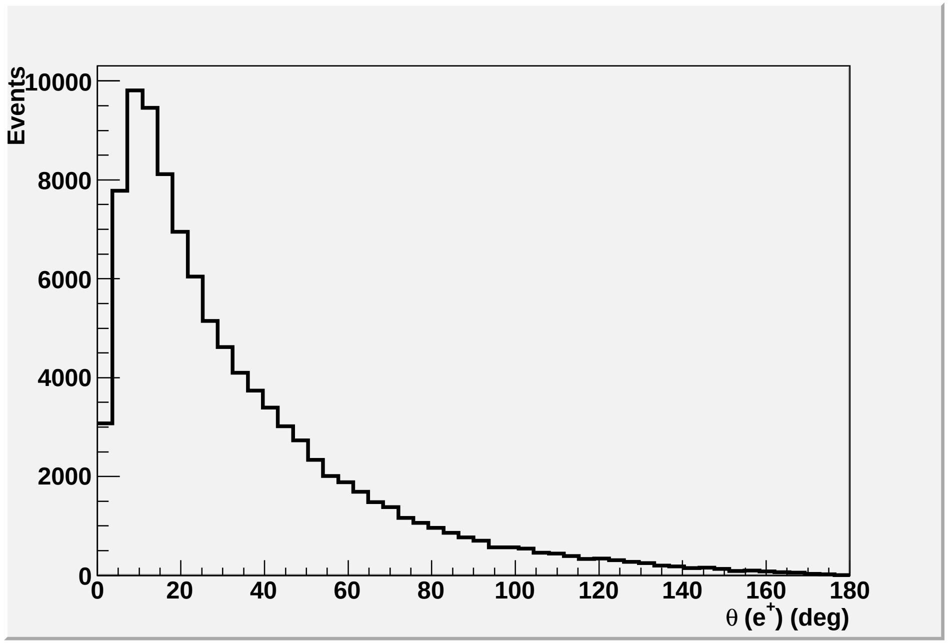
$$|G_E|/|G_M| = 0$$

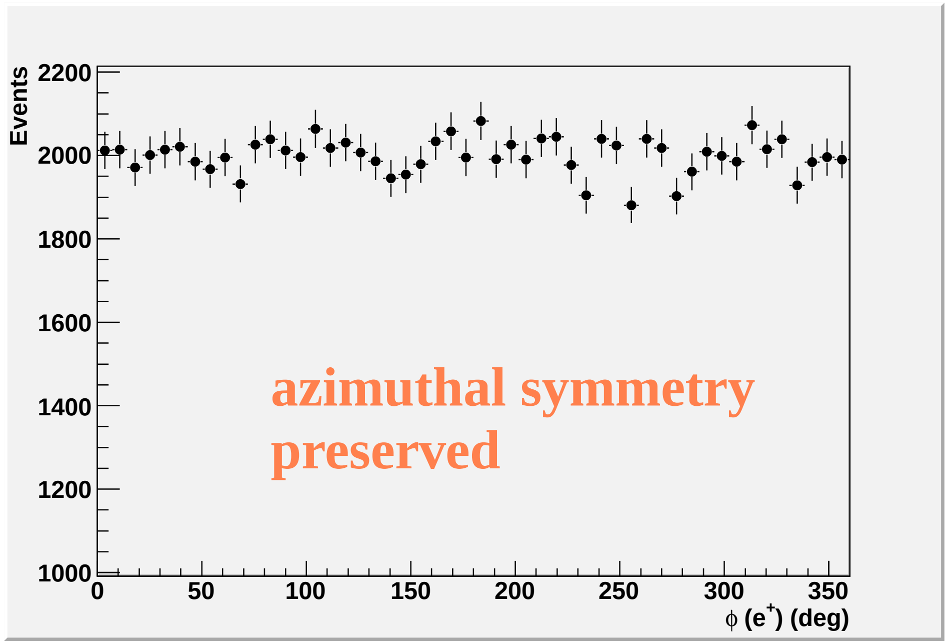


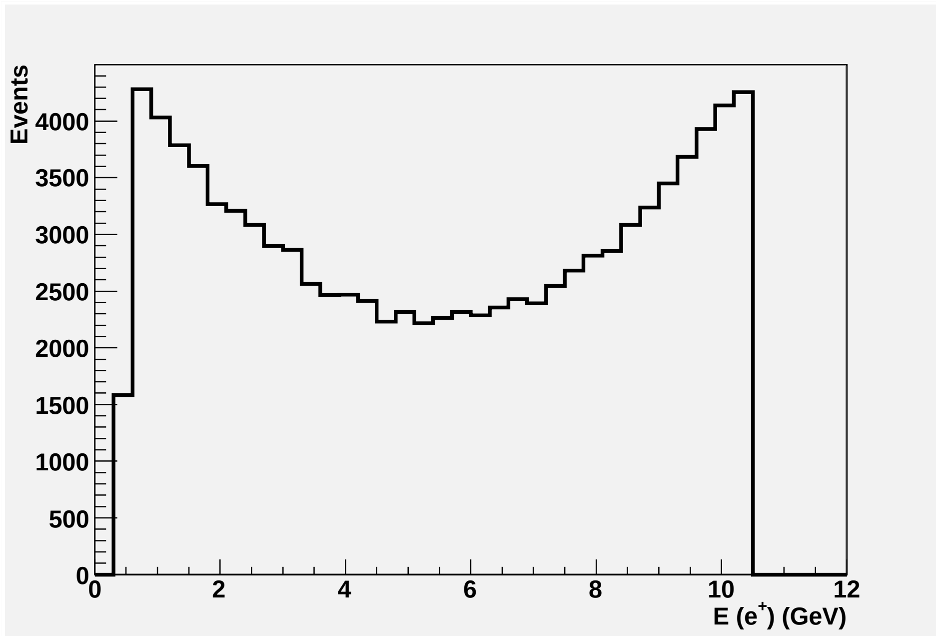
$\bar{p}p \to e^+e^-$: distributions in LAB frame

event boosted in the forward direction



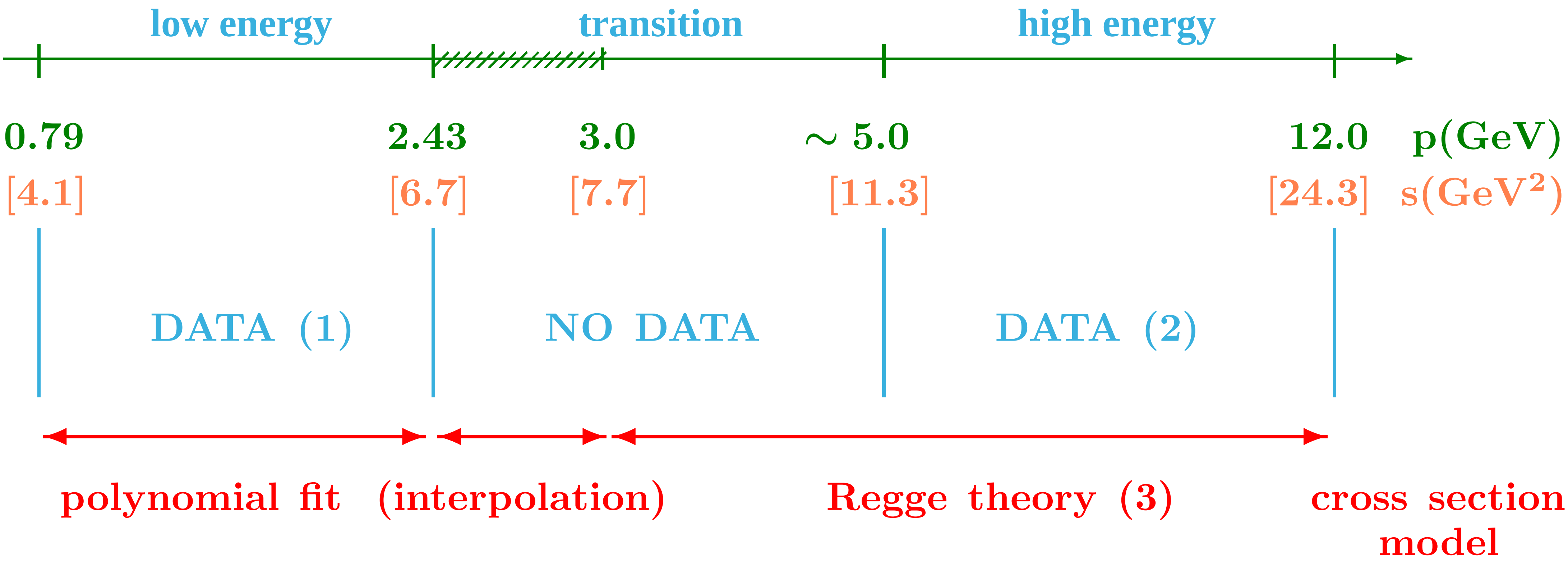






$\bar{p}p \to \pi^+\pi^-$: Kinematic regimes

- $\pi^+\pi^-$ **production is the main background channel to the** e^+e^- **signal,** $\frac{\sigma(\pi^+\pi^-)}{\sigma(e^+e^-)} \sim 10^6$



(1) Eisenhandler et al., Nucl. Phys. B96 (1975) 109

(2) ref [6], [8] and [26] in (3)

(3) J. Van de Wiele and S. Ong, Eur. Phys. J. A46 (2010) 291

The cross section in the low energy regime

- **data:** $\frac{d\sigma}{d\Omega}$ at a $(\mathrm{p}, \cos\theta^*)$ grid with (20×48) lattice sites

  [Eisenhandler et al., Nucl. Phys. B96 (1975) 109]

  p = antiproton momentum in lab frame, $\mathrm{p} = 0.79, \ldots, 2.43$ GeV
  θ^* = angle $(\pi^-, \bar{\mathrm{p}})$ in $\bar{\mathrm{p}}\mathrm{p}$ CMS frame, $\cos\theta^* = -0.94, \ldots, 0.94$

- **at each momentum value, cross section fitted using a Legendre polynomial series:**

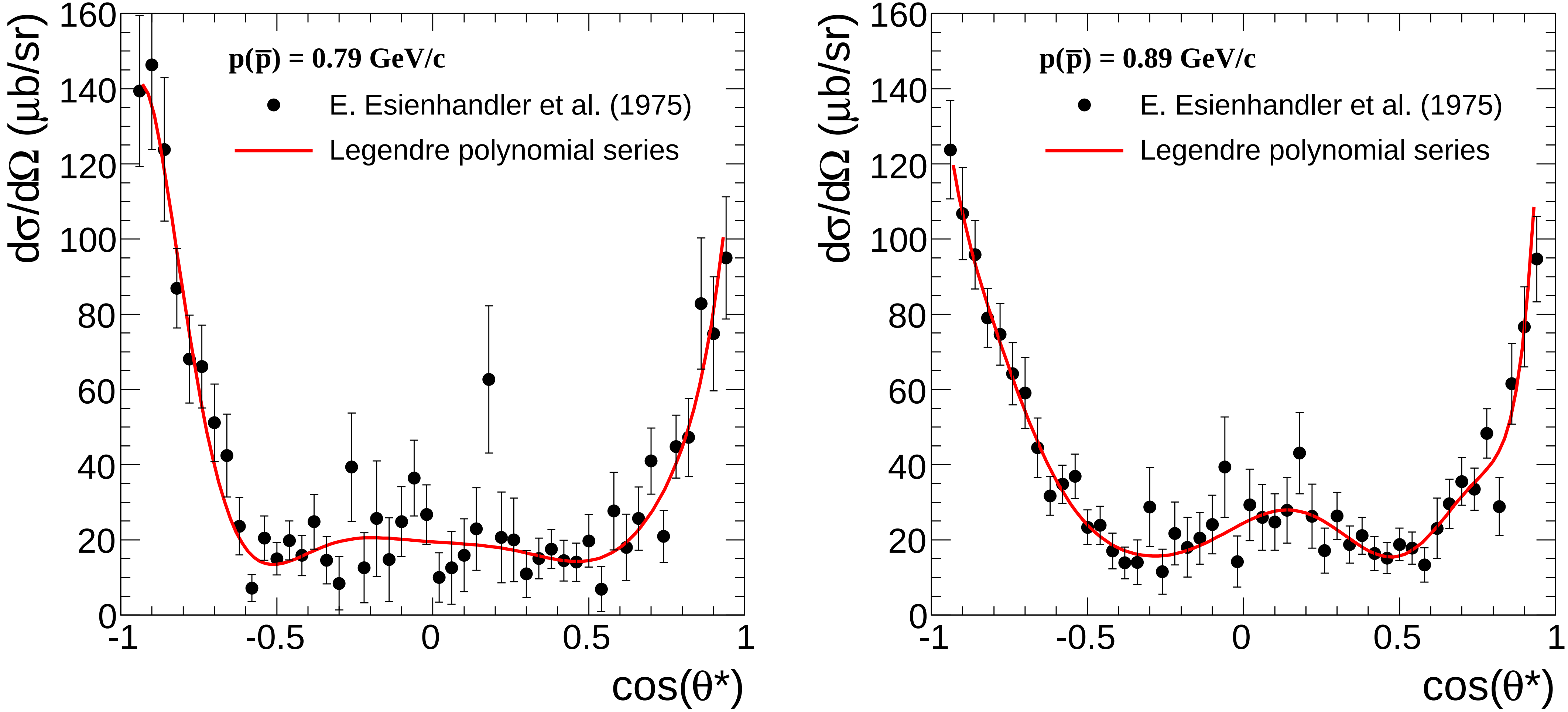
$$\frac{d\sigma}{d\Omega} = \sum_{i=0}^{10} a_i P_i(\cos\theta^*)$$

$\rightarrow$ fit function follows data

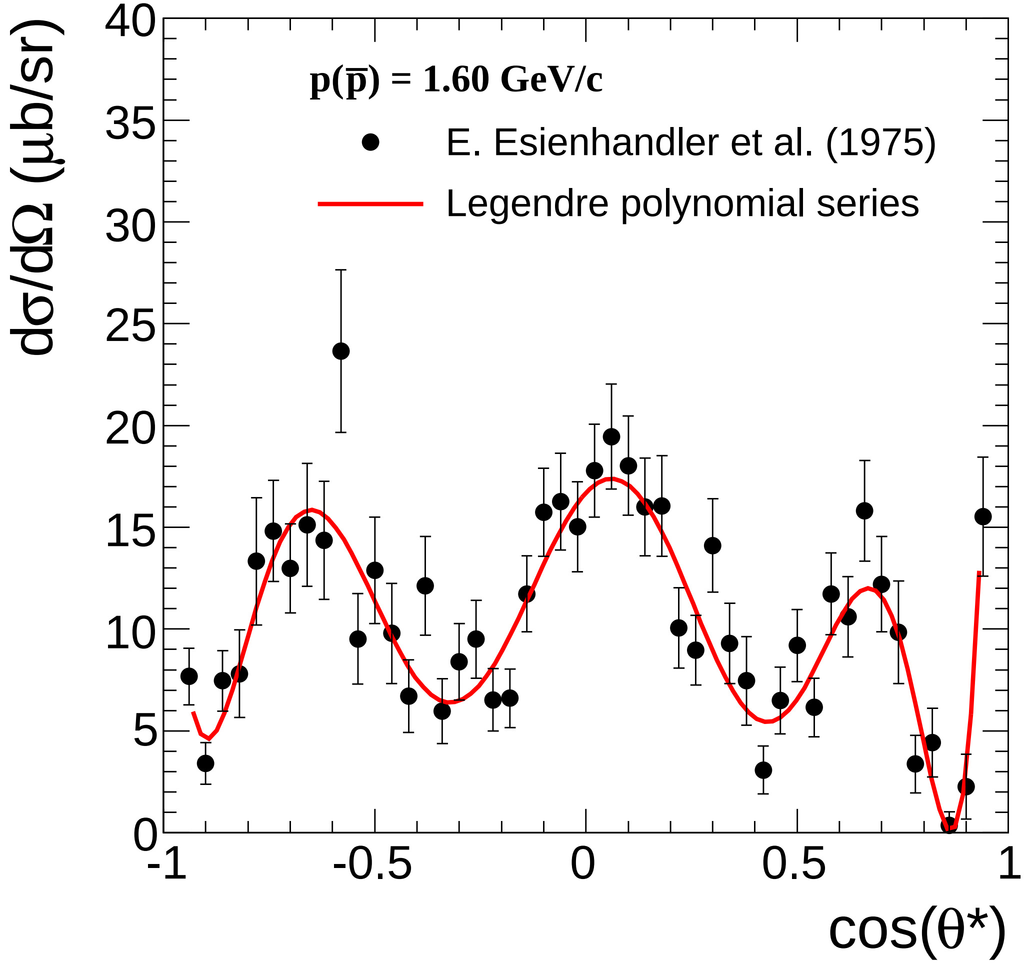
$\rightarrow \chi^2/\mathrm{dof} \sim 1$

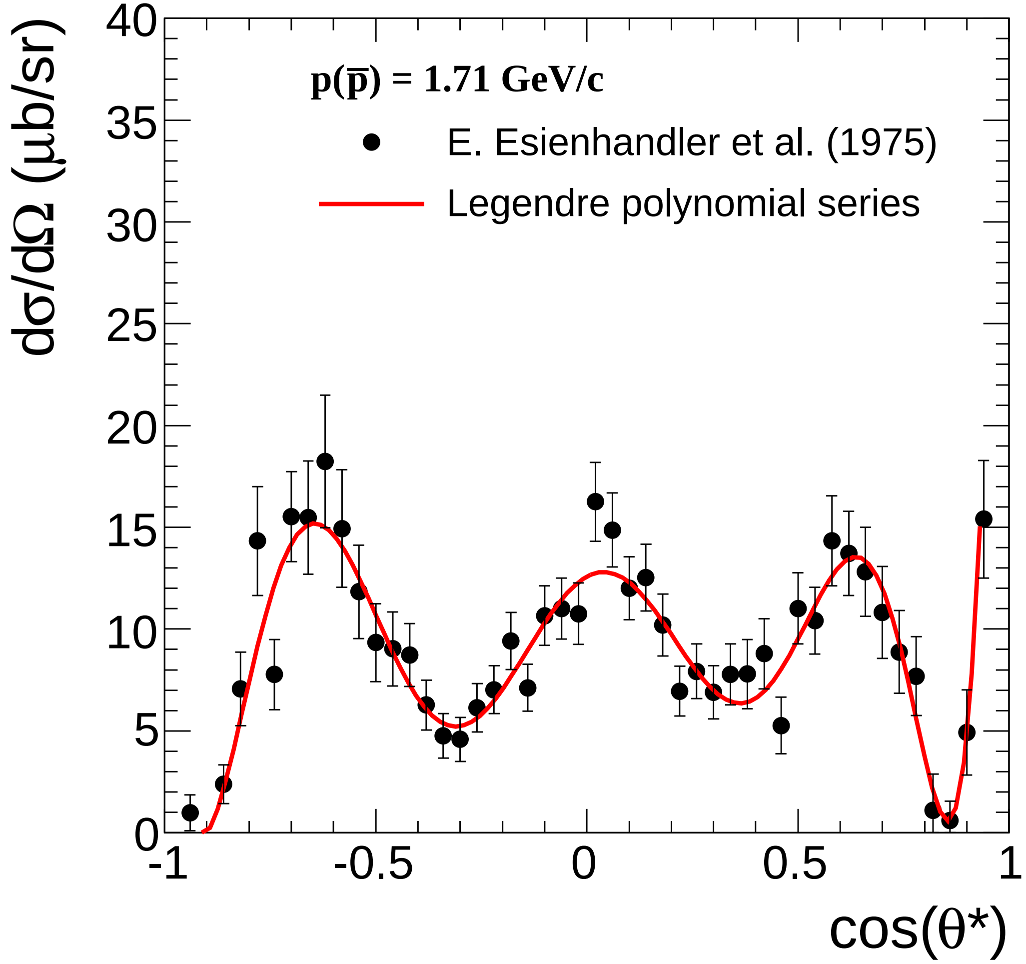
$\rightarrow$ MINUIT output : status = "CONVERGED"
error matrix = "ACCURATE"

The cross section in the low energy regime

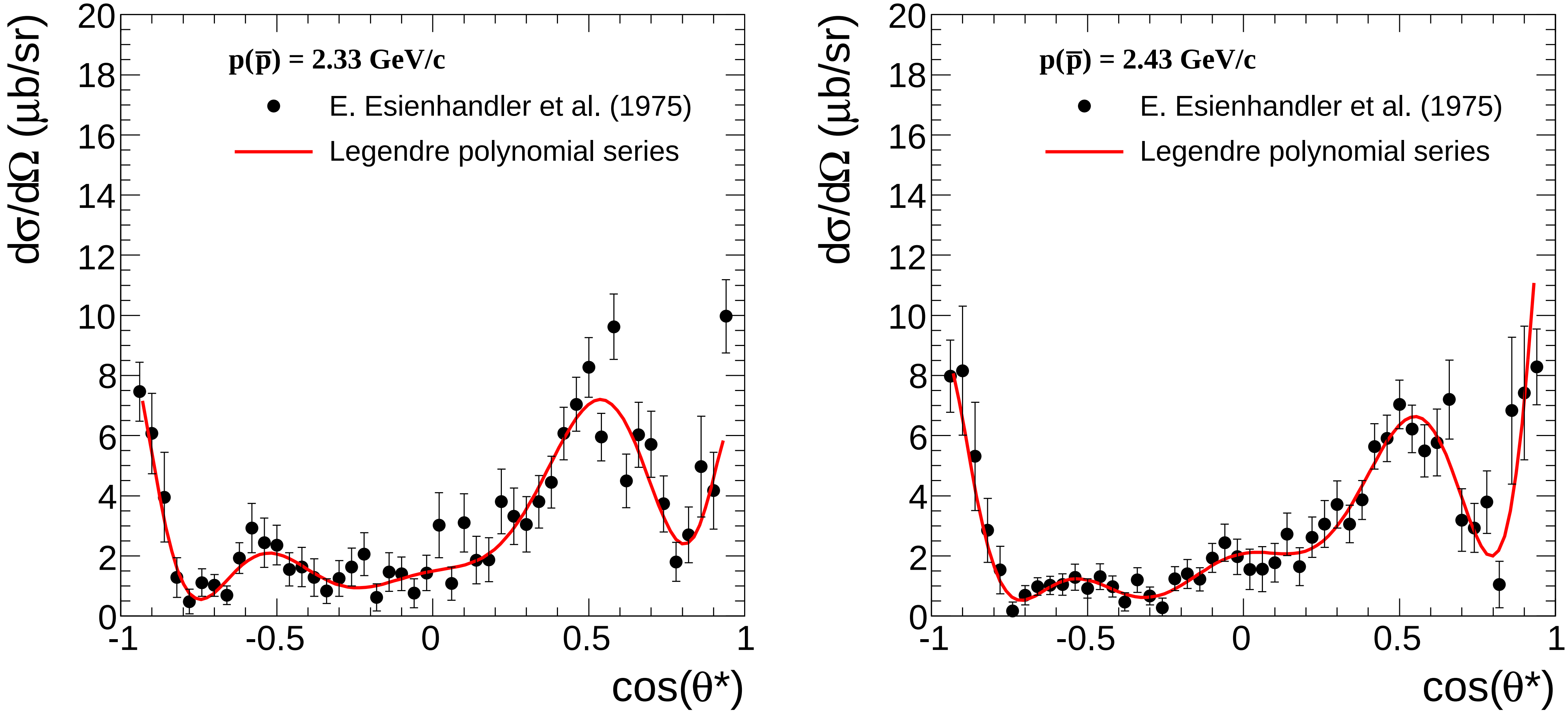


The cross section in the low energy regime





The cross section in the low energy regime



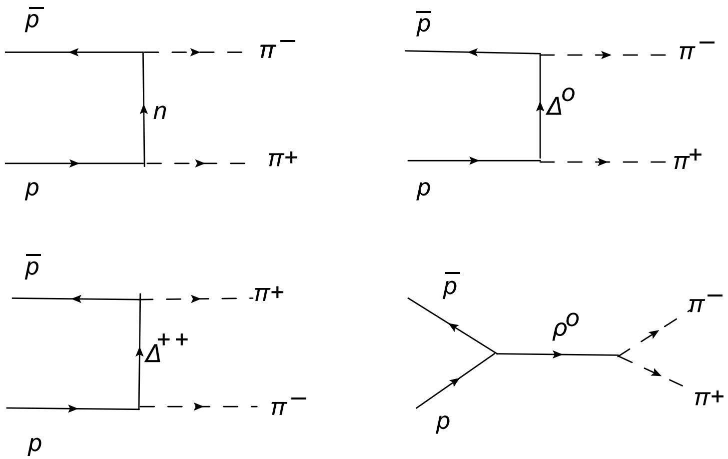
$\Rightarrow$ cross section oscillates in $\cos\theta^*$

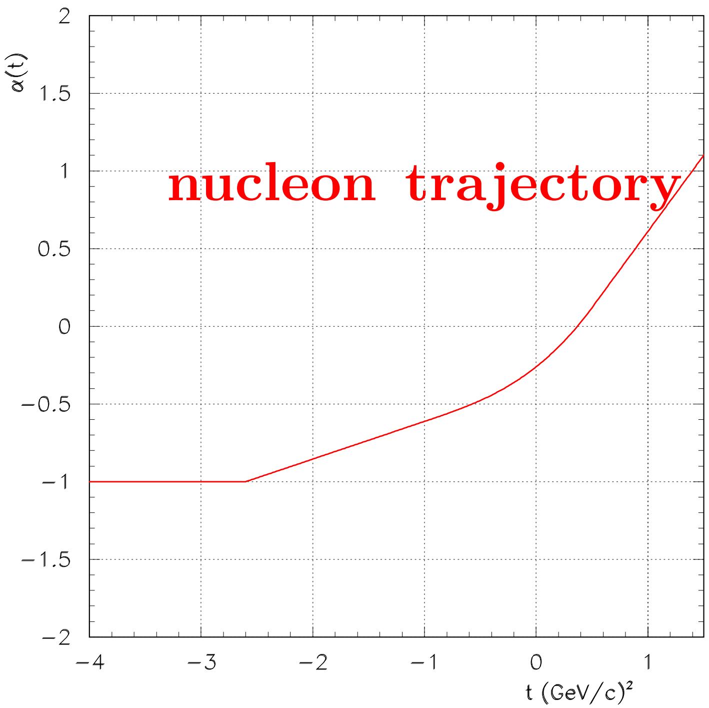
The cross section in the high energy regime

- **Regge Theory approach to cross section calculation**

  [J. Van de Wiele and S. Ong, Eur. Phys. J. A46 (2010) 291]

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





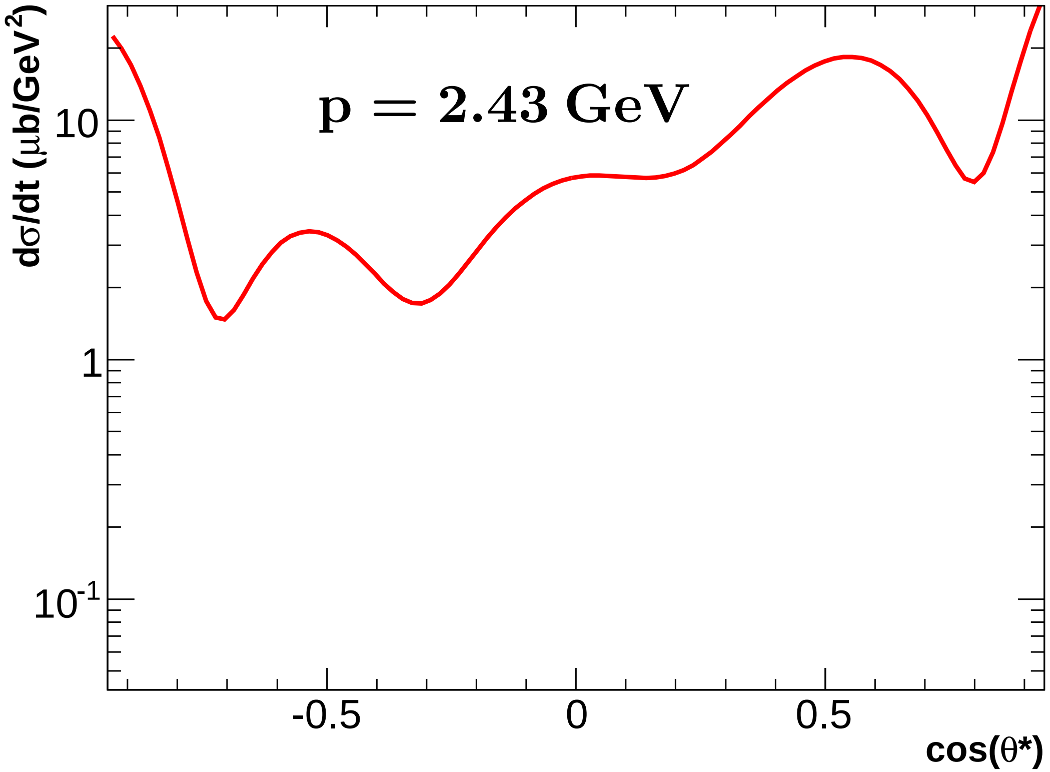
$\Rightarrow$ $\frac{d\sigma}{dt}$ **at a $(\mathrm{p}, \cos\theta^*)$ grid of (19×201) lattice sites**

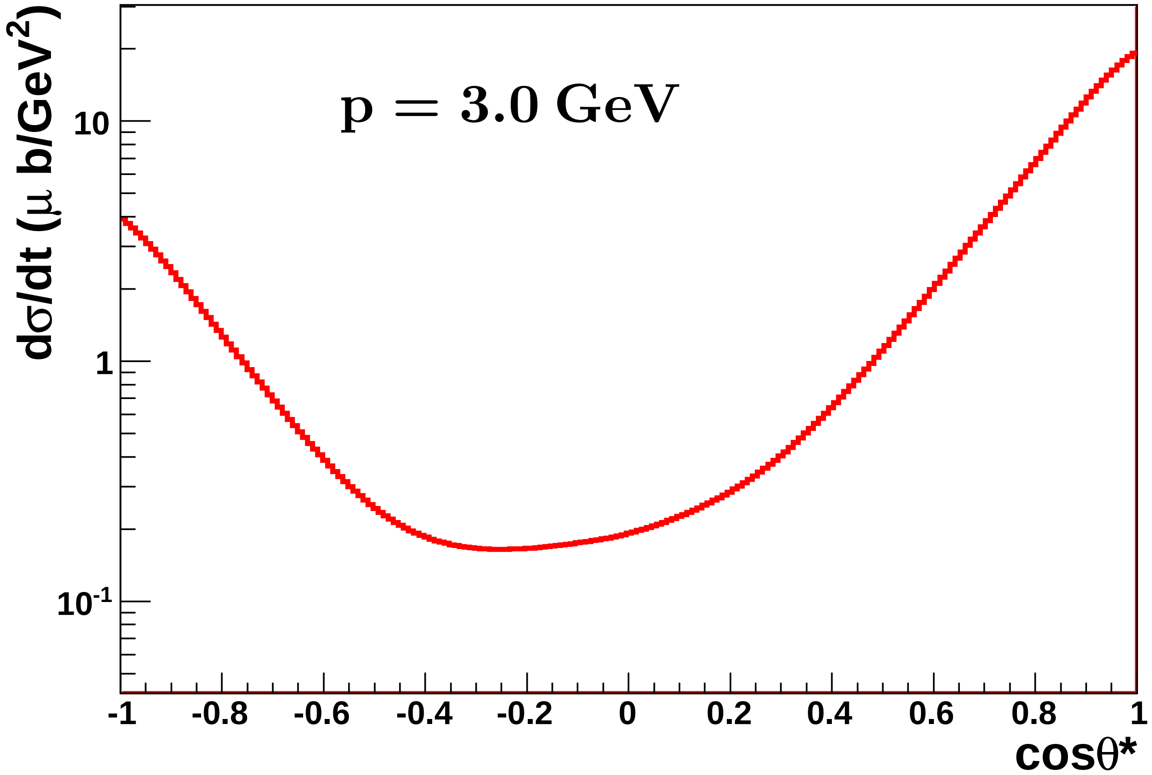
$\mathbf{p = 3.0, \ldots, 5.0, \ldots, 12.0\ \ GeV} \Rightarrow$ **high+transition-extrapolated energy regime**

$\mathbf{\cos\theta^* = -1.0, \ldots, 1.0}$

The cross section in the transition energy regime

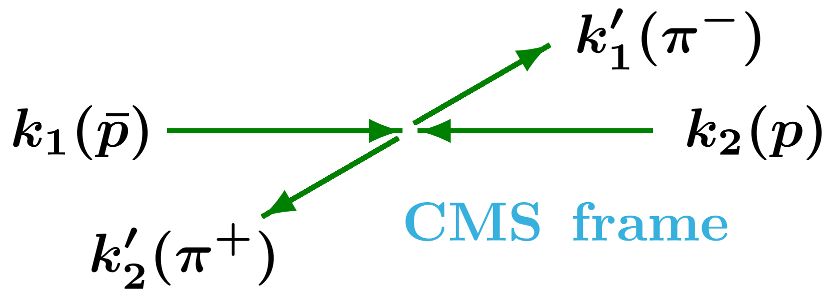
$$\frac{d\sigma}{d\Omega} \rightarrow \frac{d\sigma}{dt}$$



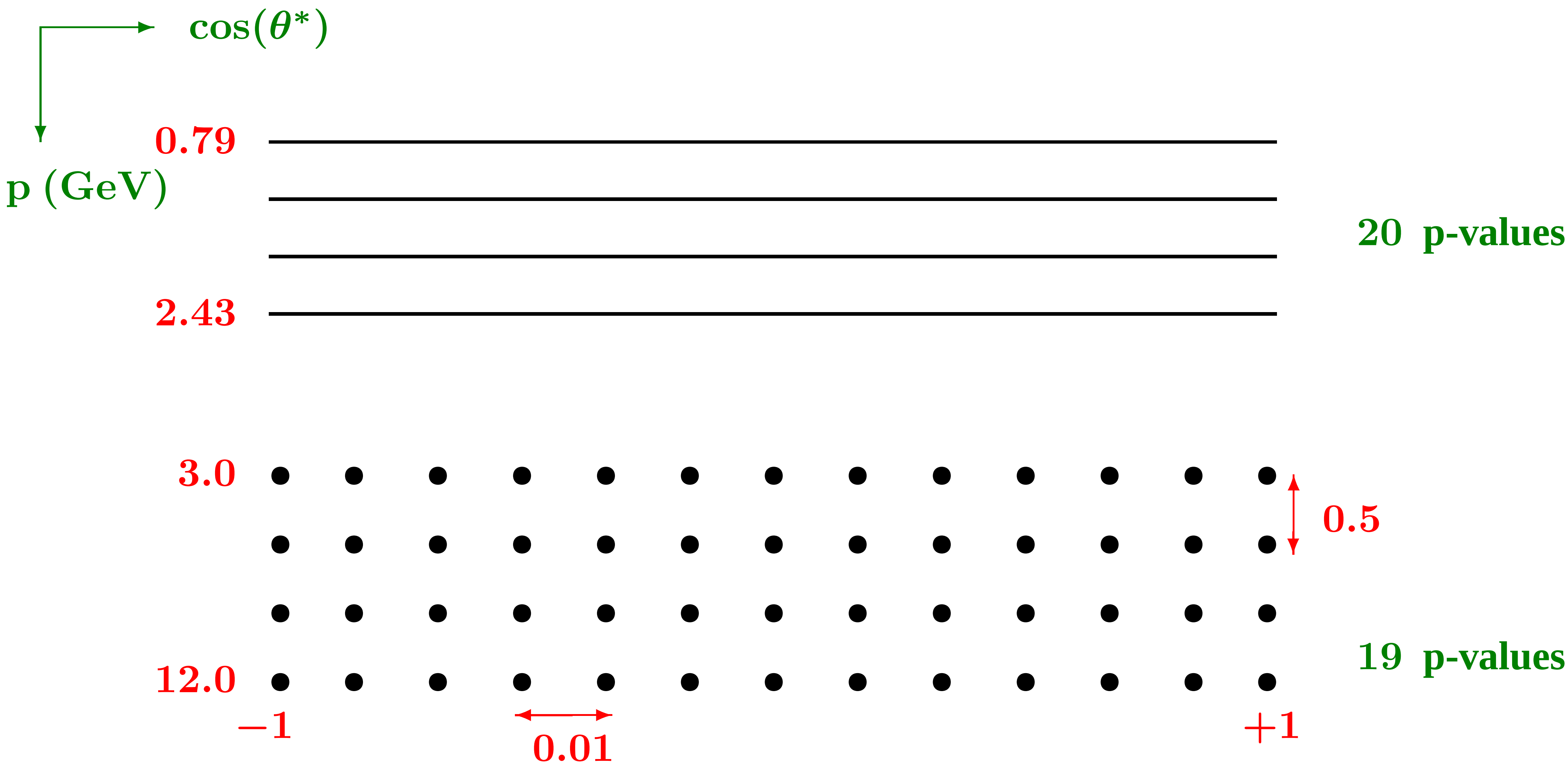


$$t = -(k_1' - k_1)^2$$

$$\Rightarrow dt = 2|k_1||k_1'|d(\cos\theta^*)$$



The cross section : general overview



σ at $(\mathrm{p}, \cos\theta^*)$ point NOT sitting at line or dot:

$\Rightarrow$ **linear interpolation from nearest neirboughs** $\longrightarrow$ 8 different cases

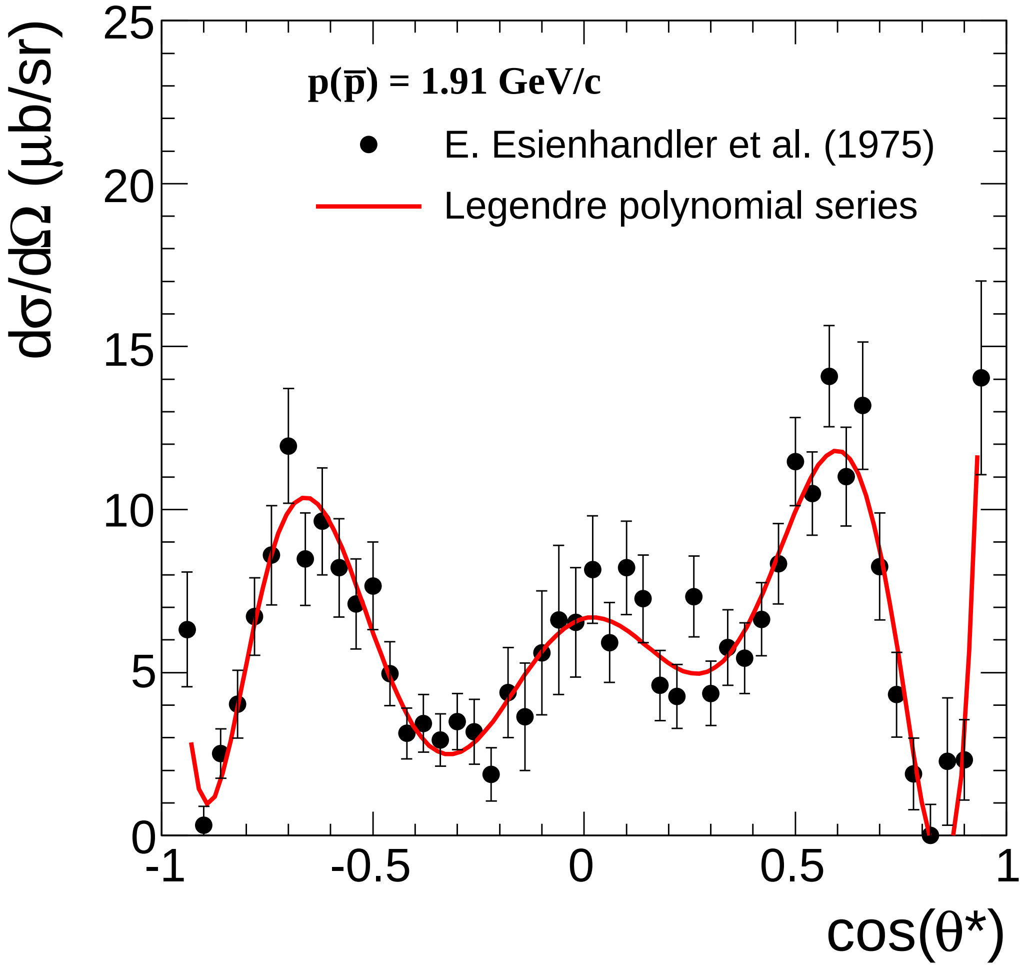
Event generation : example in the low energy regime

kinematics : as in $\bar{p}p \to e^+e^-$, $m_e \to m_\pi$

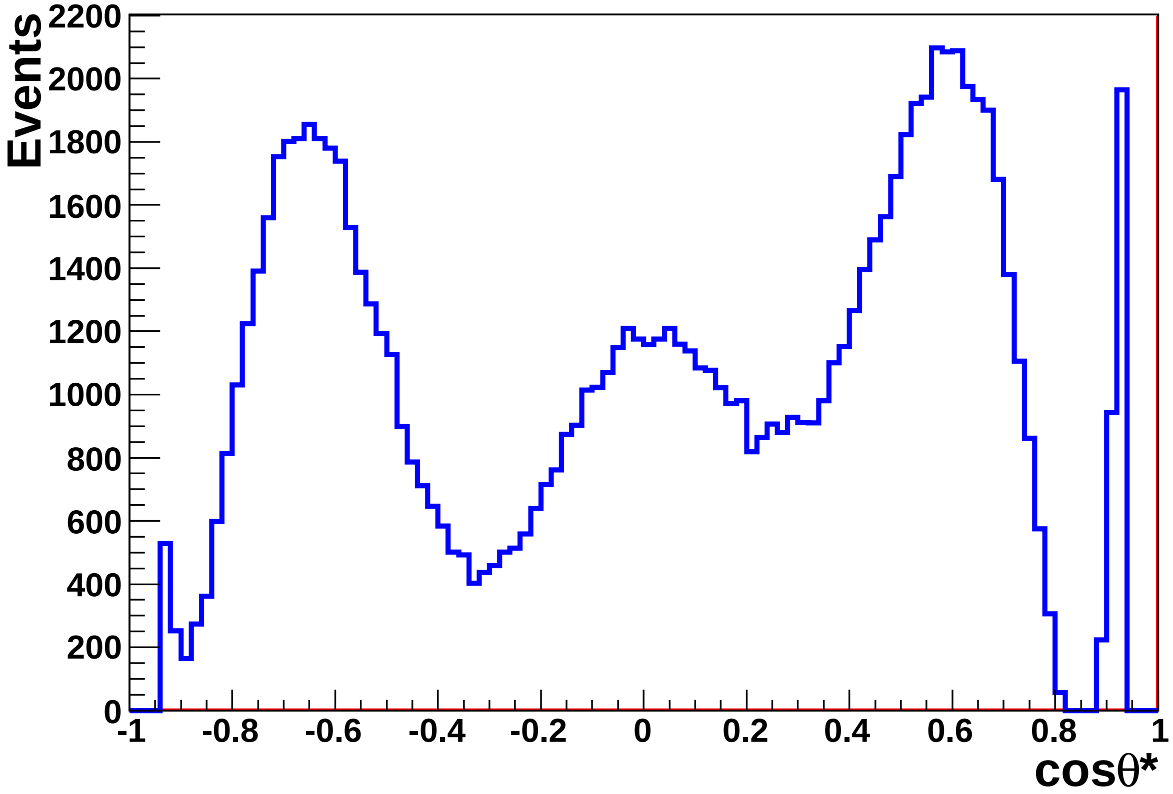
$E_{\pi^+} = E_{\pi^-} = \sqrt{s}/2$, $\varphi_{\pi^+\pi^-} = 180$ deg in $\bar{p}p$ CM frame

$\mathrm{prob}(\cos\theta^*) \sim \frac{d\sigma}{d\cos\theta^*}$, ϕ^* flat distribution

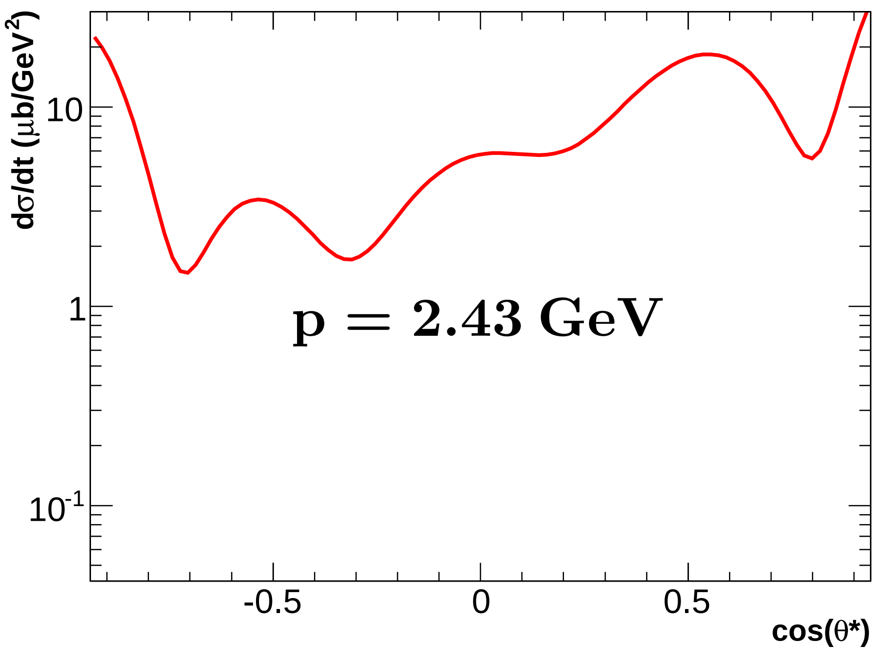
naive accept/reject algorithm $\Rightarrow$ $T \sim 30\,\mu$ sec/event

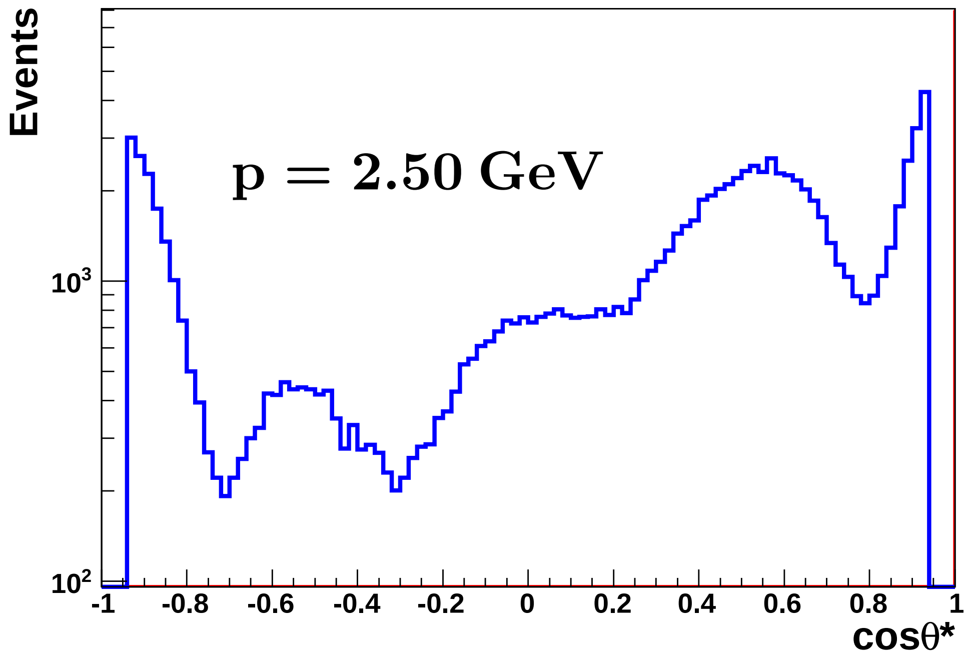


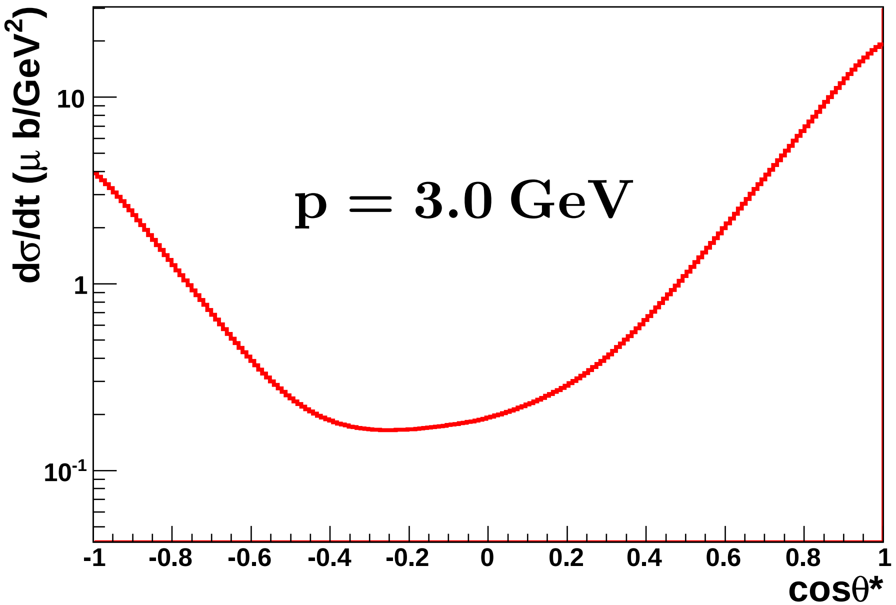
$N = 10^5$ events

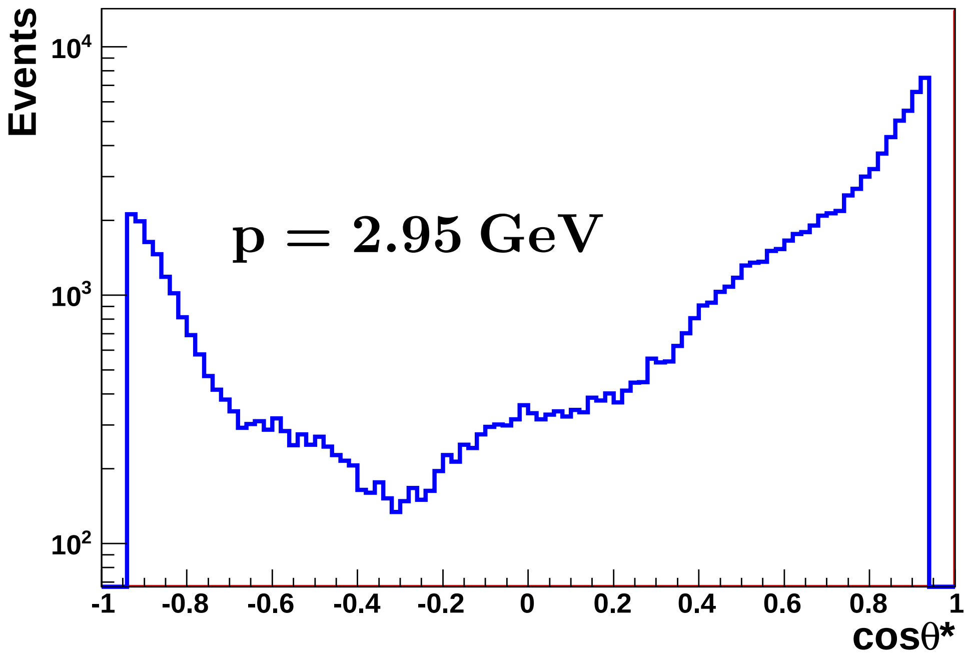


Event generation : example in the transition energy regime

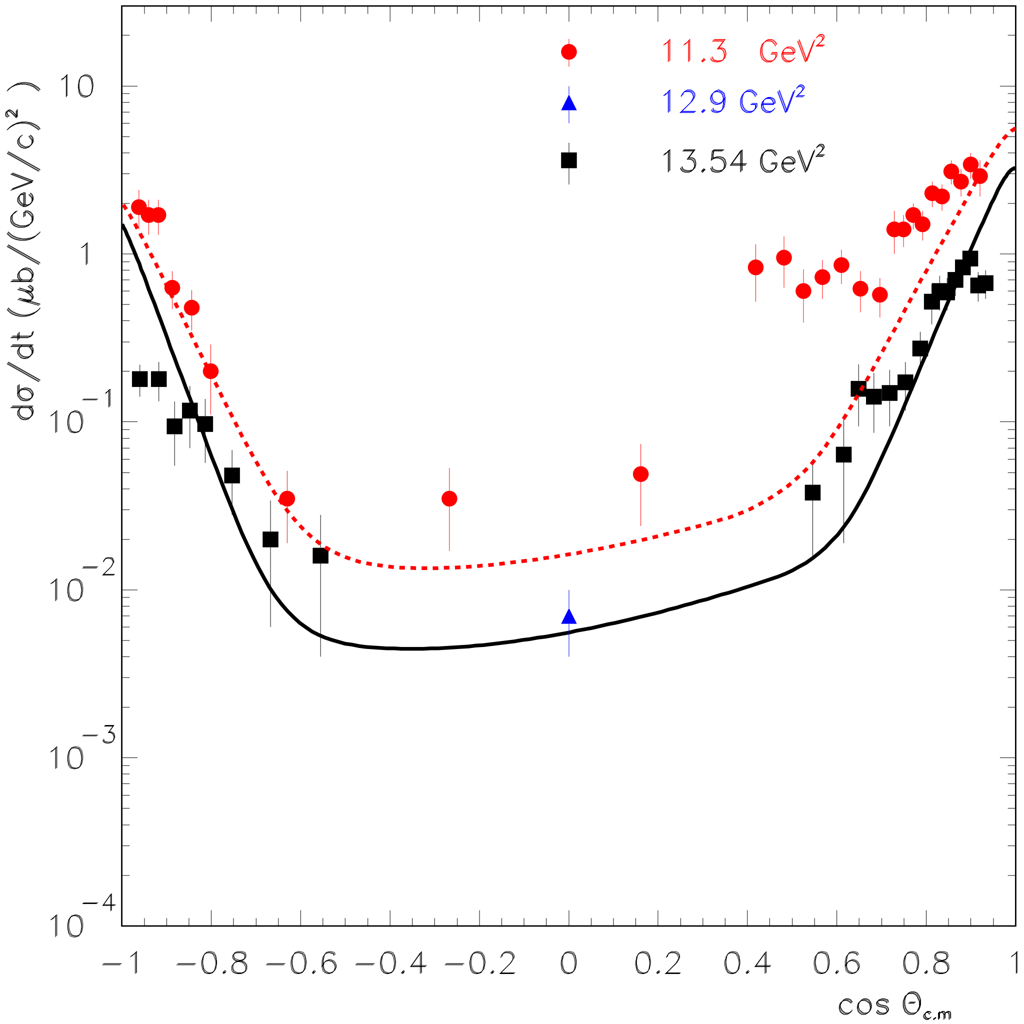






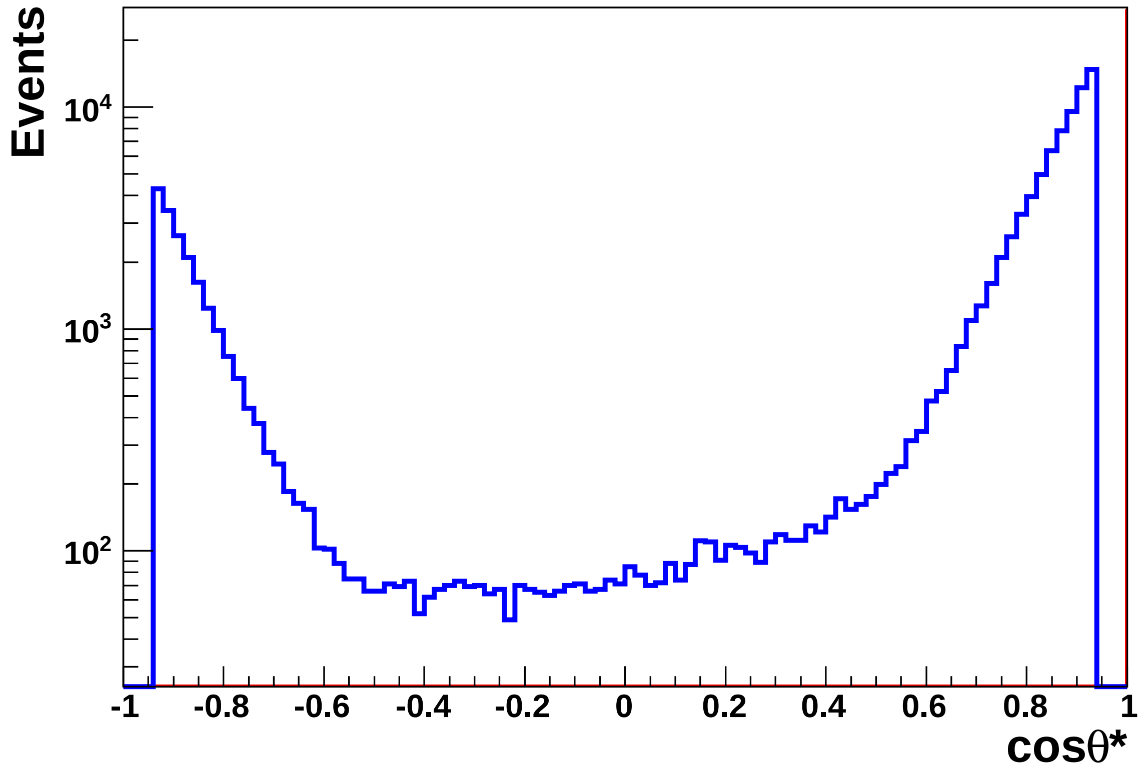


Event generation : example in the high energy regime



J. Van de Wiele and S. Ong

$\mathbf{p = 5.0\ GeV \Rightarrow s = 11.3\ GeV^2}$



Interface to PandaRoot

- **generator successfully interfaced to PandaRoot (simulation framework)**

  → output (i.e. particle momenta) directly streamed to simulation framework during execution time (no ASCII files or trees needed)

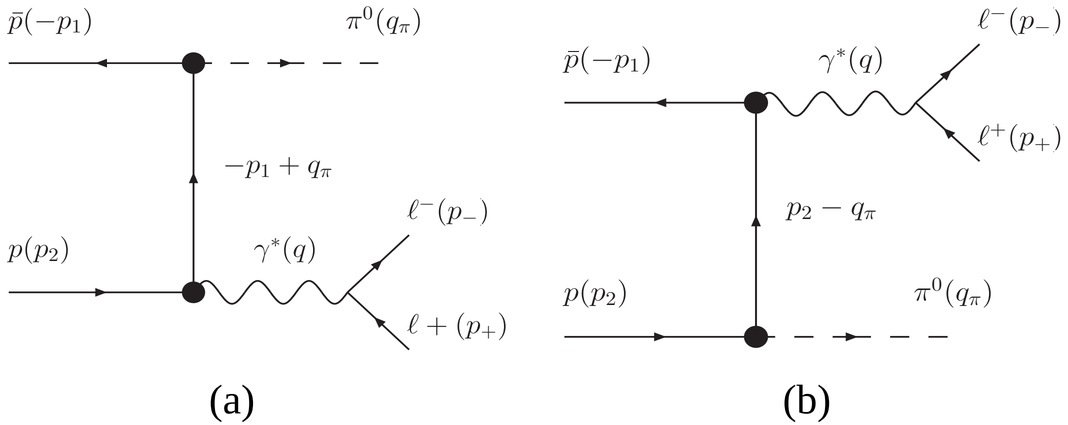
- **generator made public to the PANDA Collaboration and available for simulations in current "trunk" PandaRoot version**
- **complete documentation already available:**

```
http://panda-wiki.gsi.de/
cgi-bin/view/PANDAMainz/EventGenerators
```

$\bar{p}p \to e^+e^-\pi^0$: Form Factors below Threshold

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

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



- **sequence of two 2-body decays: $\bar{p}p \to \gamma^*\pi^0, \gamma^* \to e^+e^-$**
  $\to$ cross section integrated over the dilepton phase space

kinematics :

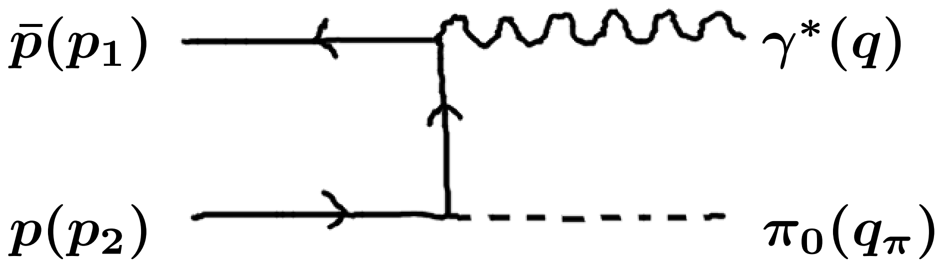
part of the total initial four-momentum transferred to π^0

$$\Rightarrow 4m_e^2 < q^2 < q^2_{max}; \;\; q^2_{max} = (\sqrt{s} - m_\pi)^2$$

$$\Rightarrow \;\; \text{region } 4m_e^2 < q^2 < 4M^2 \text{ becomes accesible}$$

remark: off-shell effects neglected
$\to$ no FF modification due to virtuality of off-mass shell nucleons

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



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

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

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

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

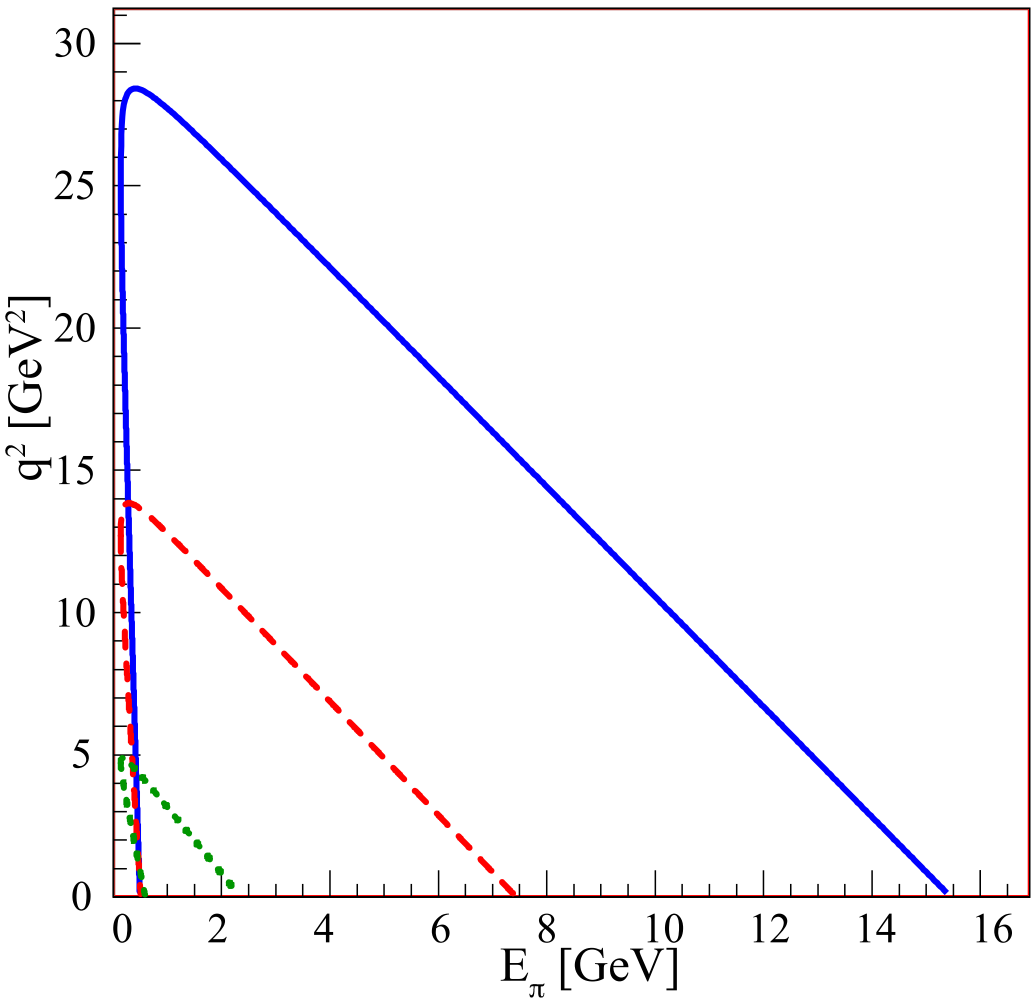
$\Rightarrow$ **take** (q^2, E_π) **as the independent variables**

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

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

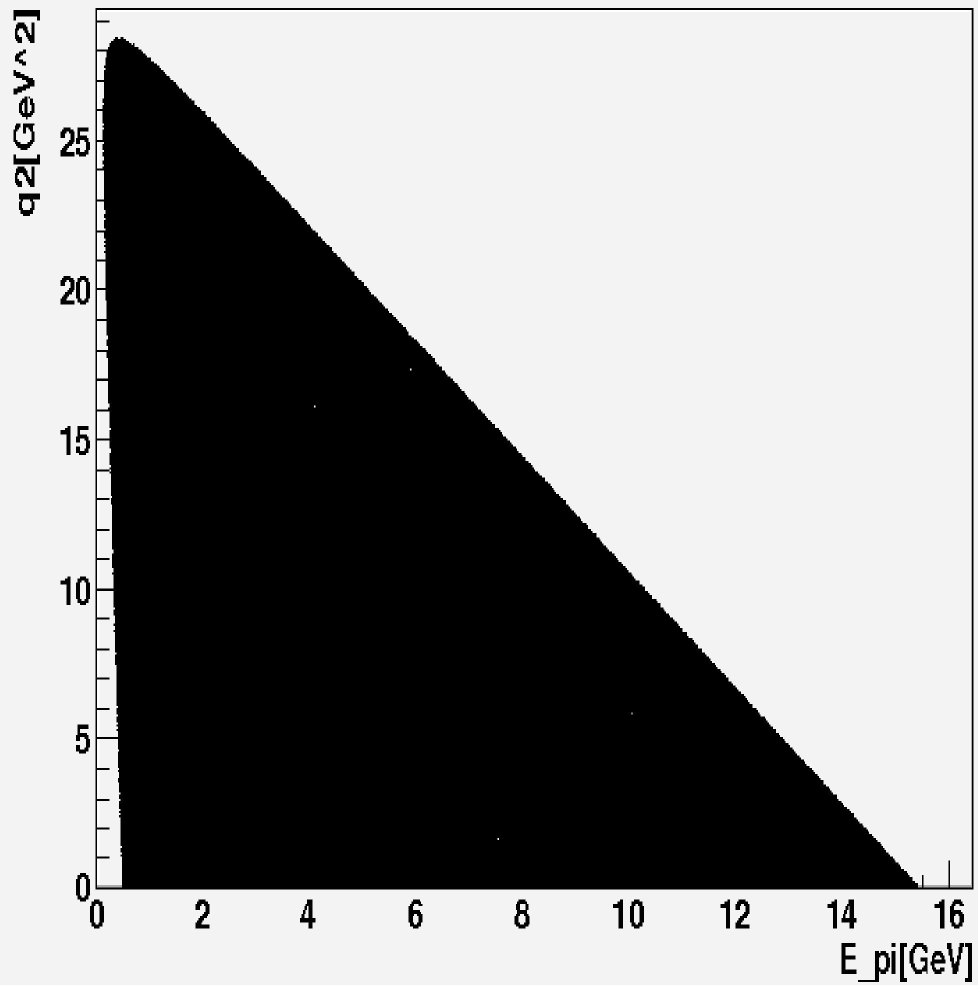
$\bar{p}p \to e^+e^-\pi^0$: subprocess $\bar{p}p \to \gamma^*\pi^0$ (kinematics)

kinematic region



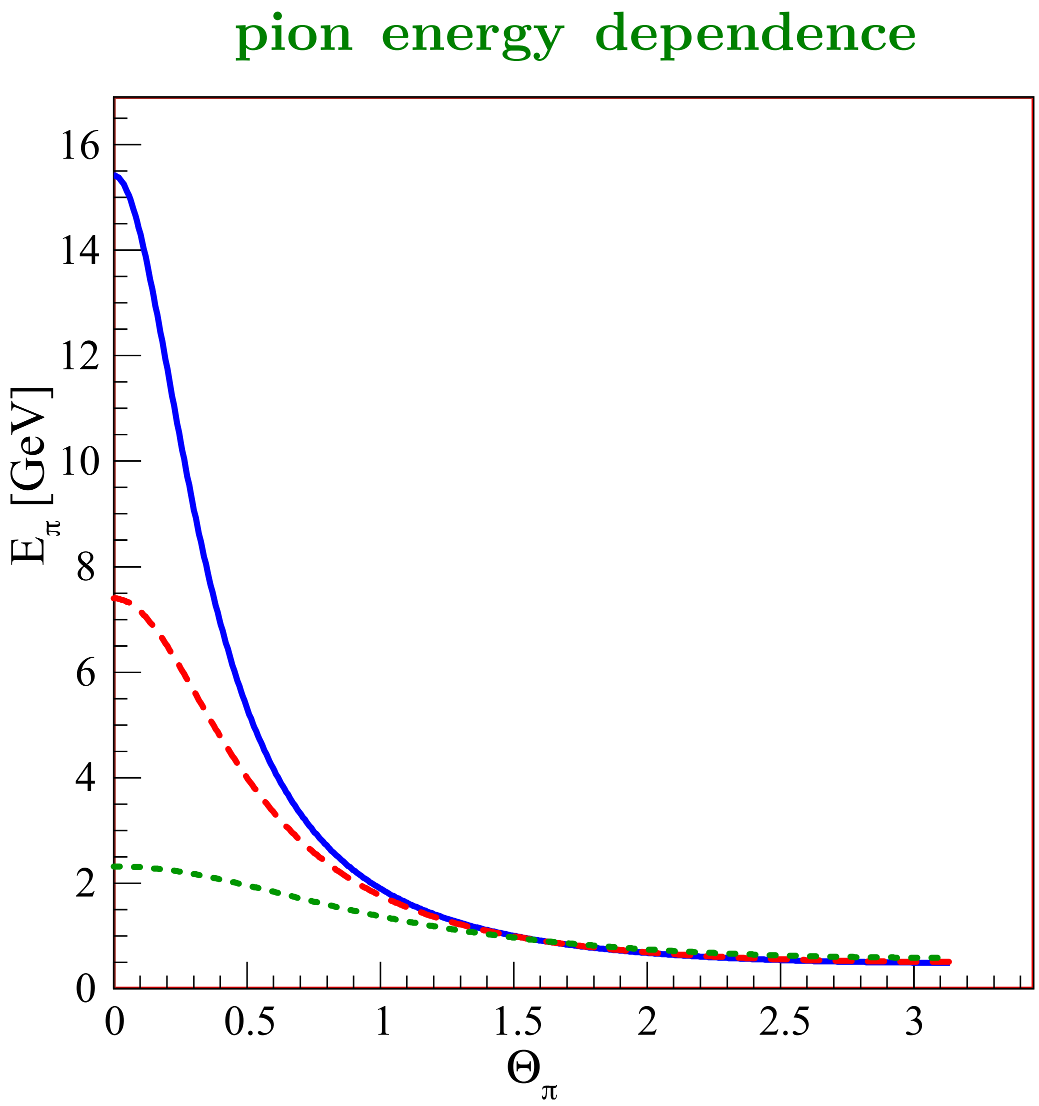
Adamuscin et al.

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

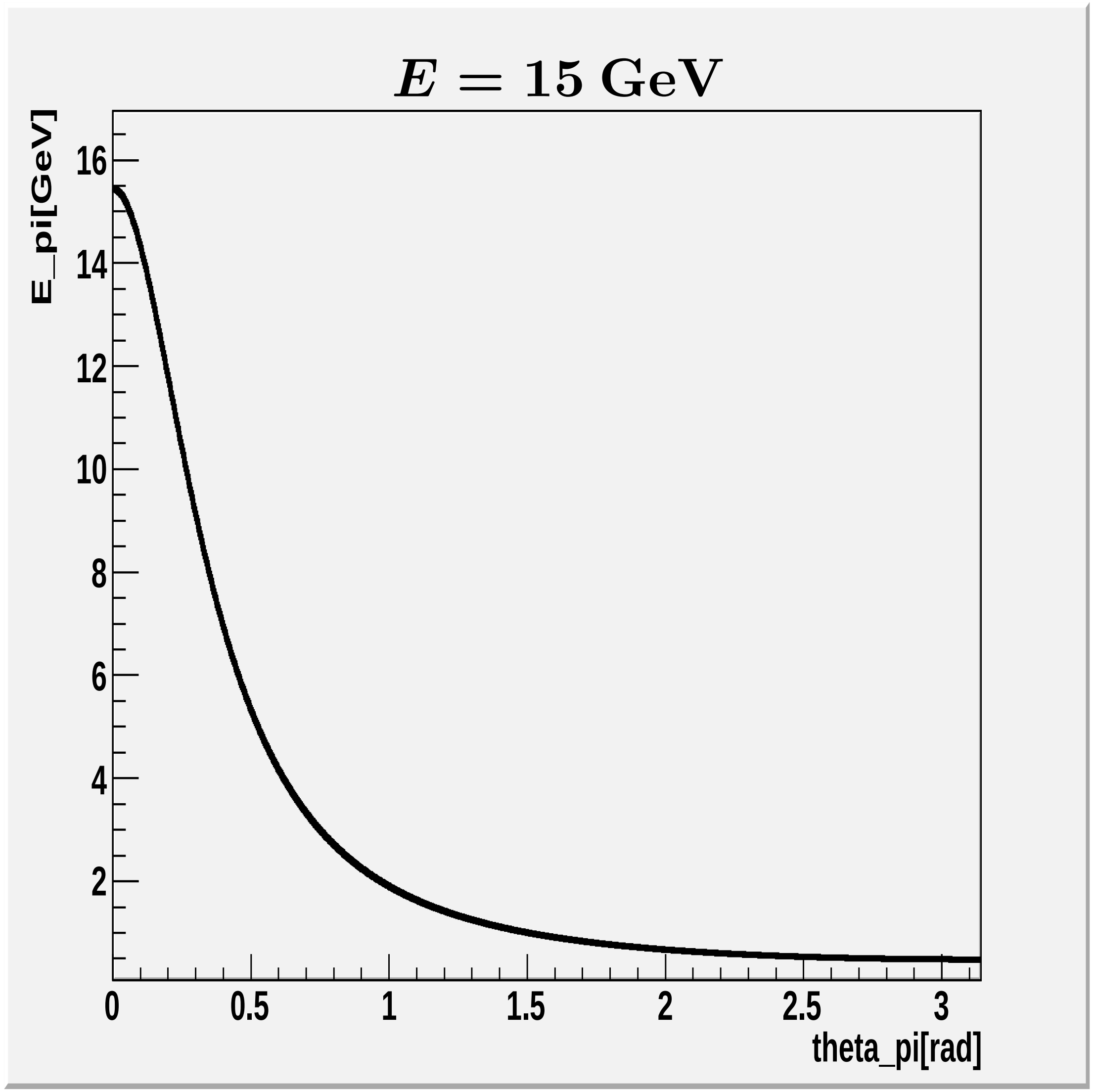


our calculation

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



Adamuscin et al.



our calculation

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

cross section: (integrated over the lepton phase space)

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

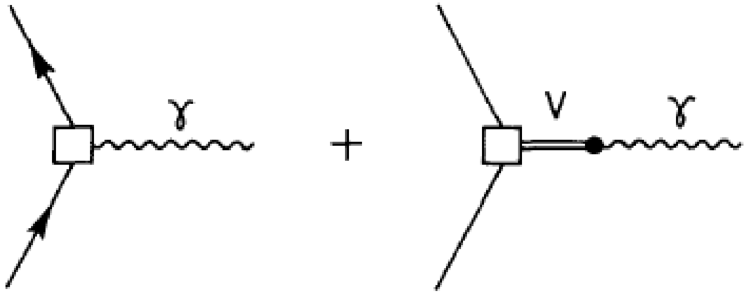
$\equiv$ D: coupling $g_{\pi NN}$, FF $F_1(q^2)$ and $F_2(q^2)$

two parametrizations for FF:

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

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

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



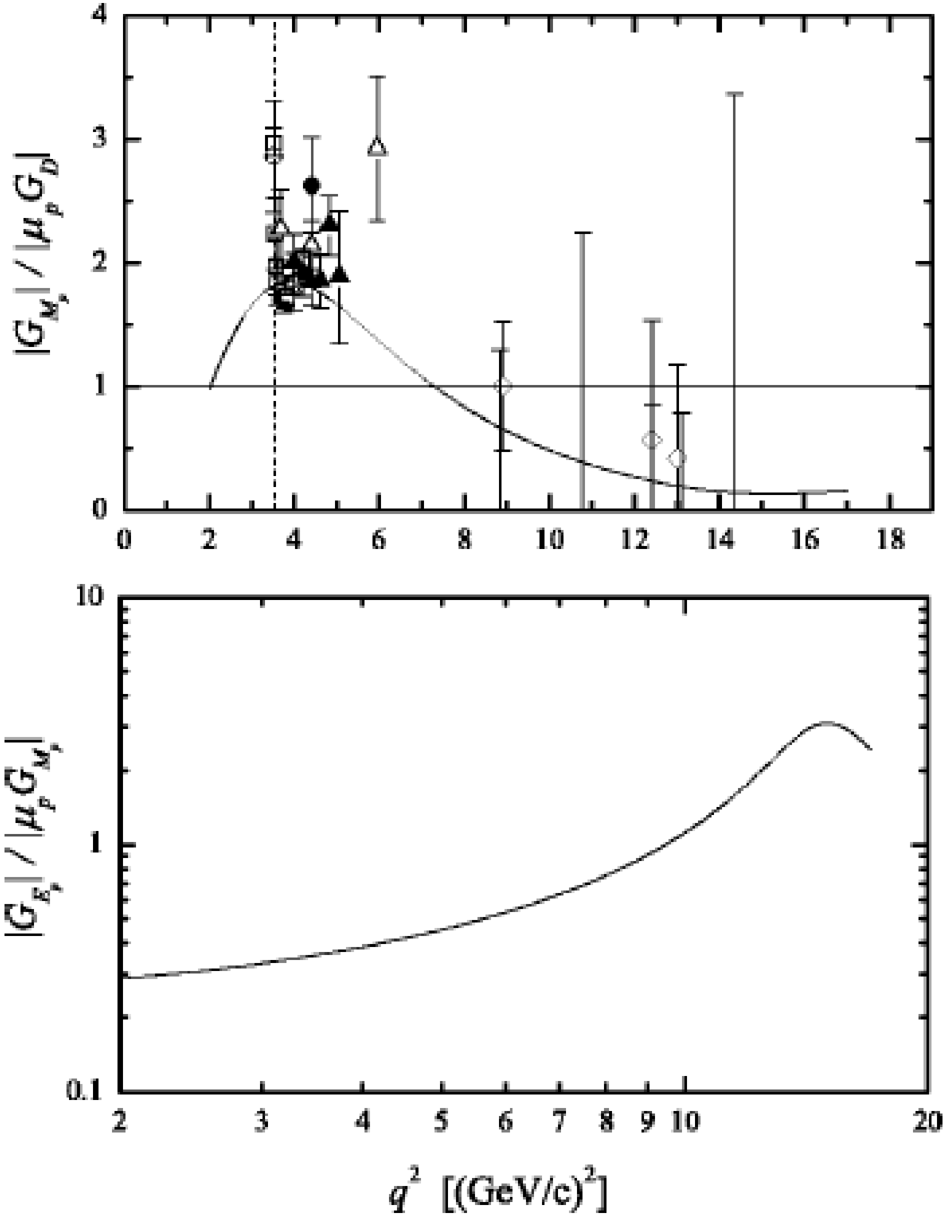
photon couples to both intrinsic structure $g(q^2)$
+meson cloud (ρ, ω, ϕ)

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

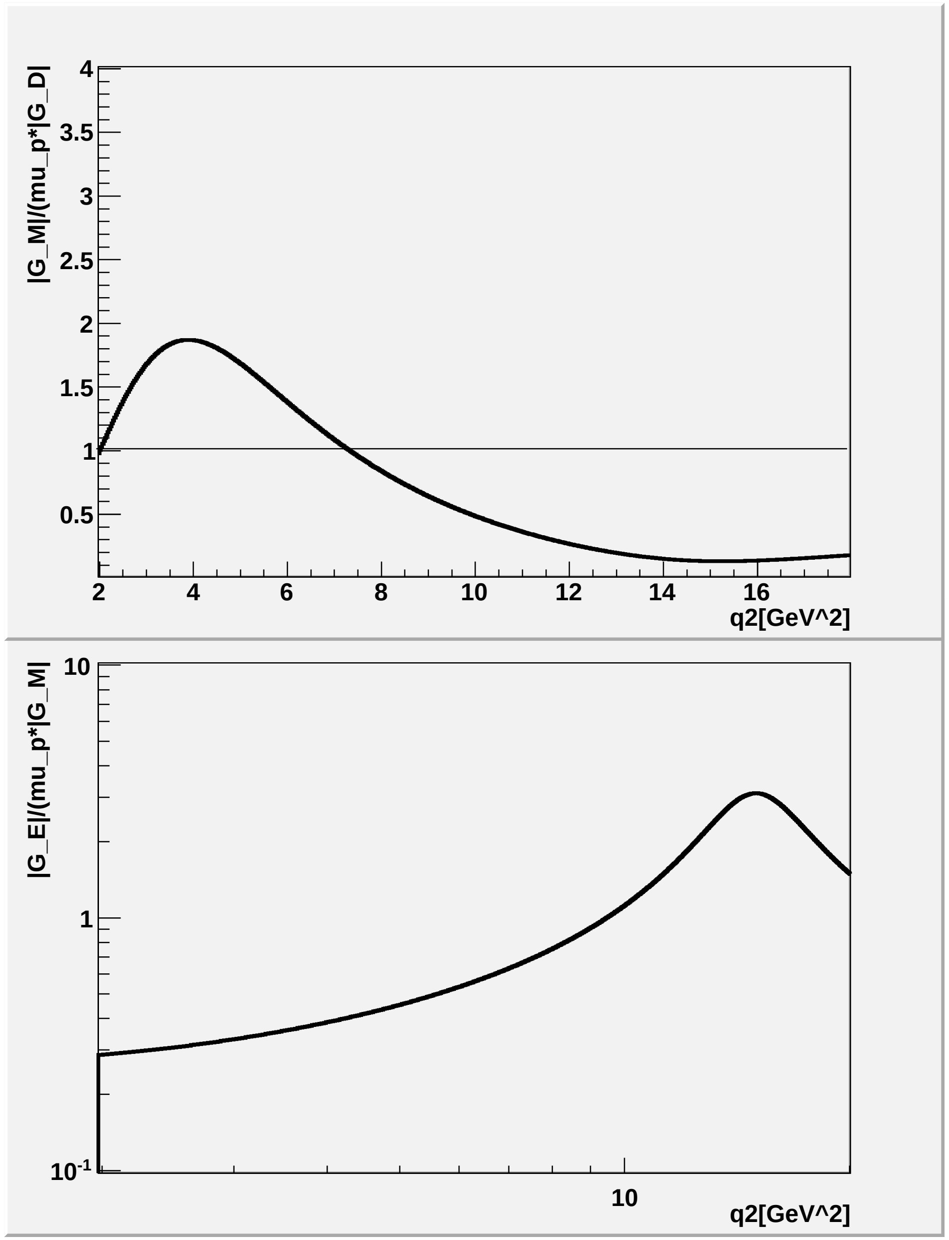
$\to$ **singularities at $q^2 = m_\omega^2$ and $q^2 = m_\phi^2$** $\Rightarrow$ **regularization**

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

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



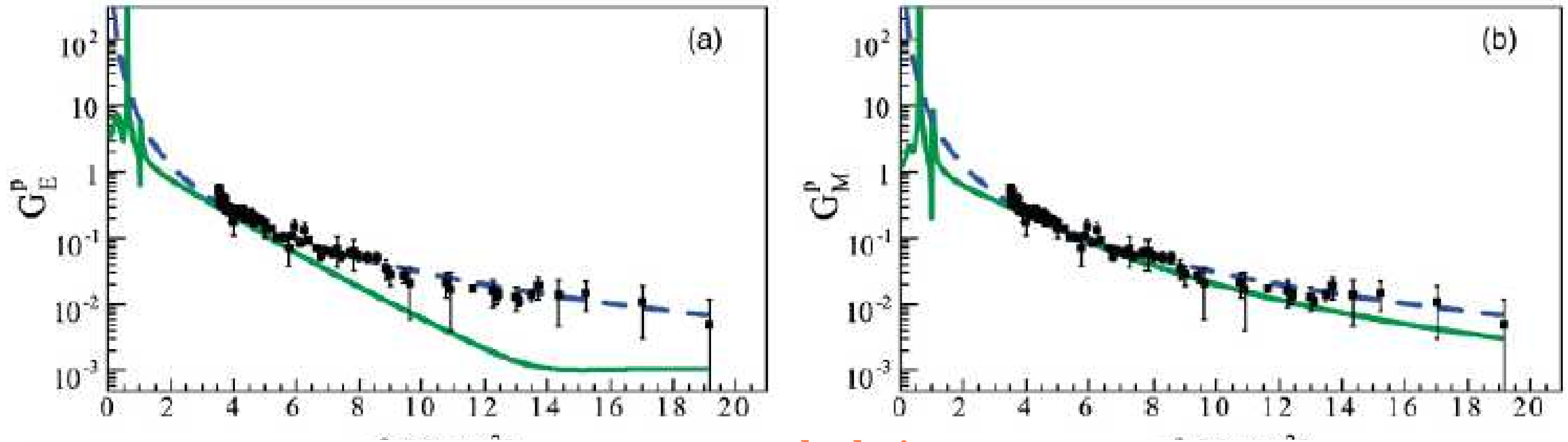
Iachello et al.



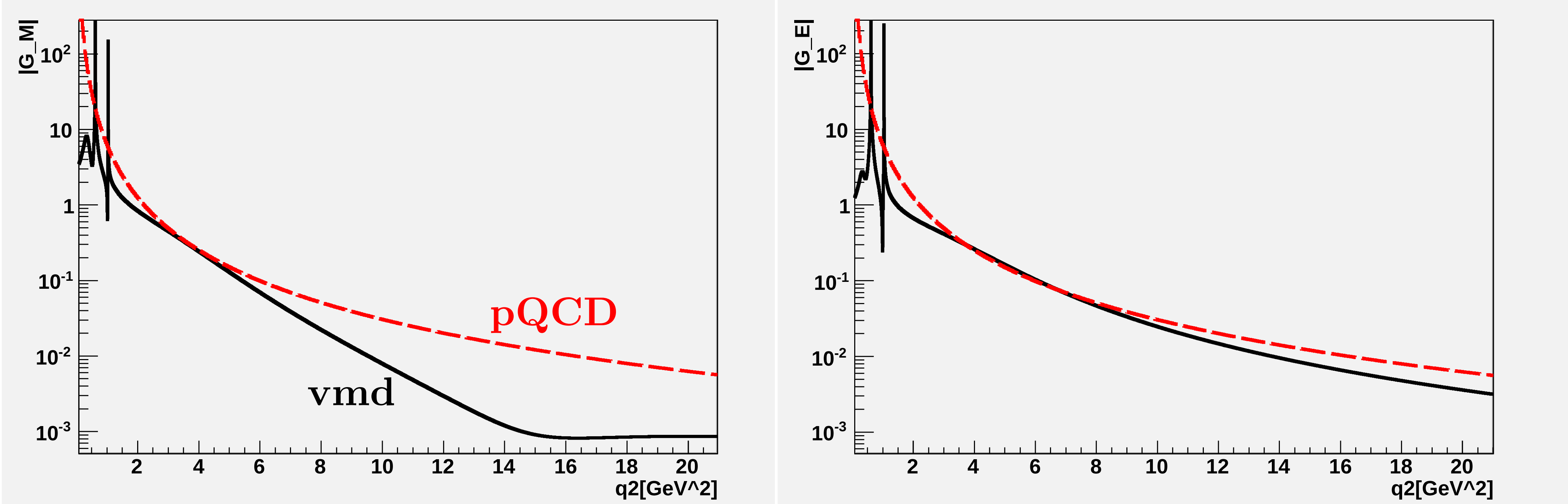
our calculation

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

Adamuscin et al.



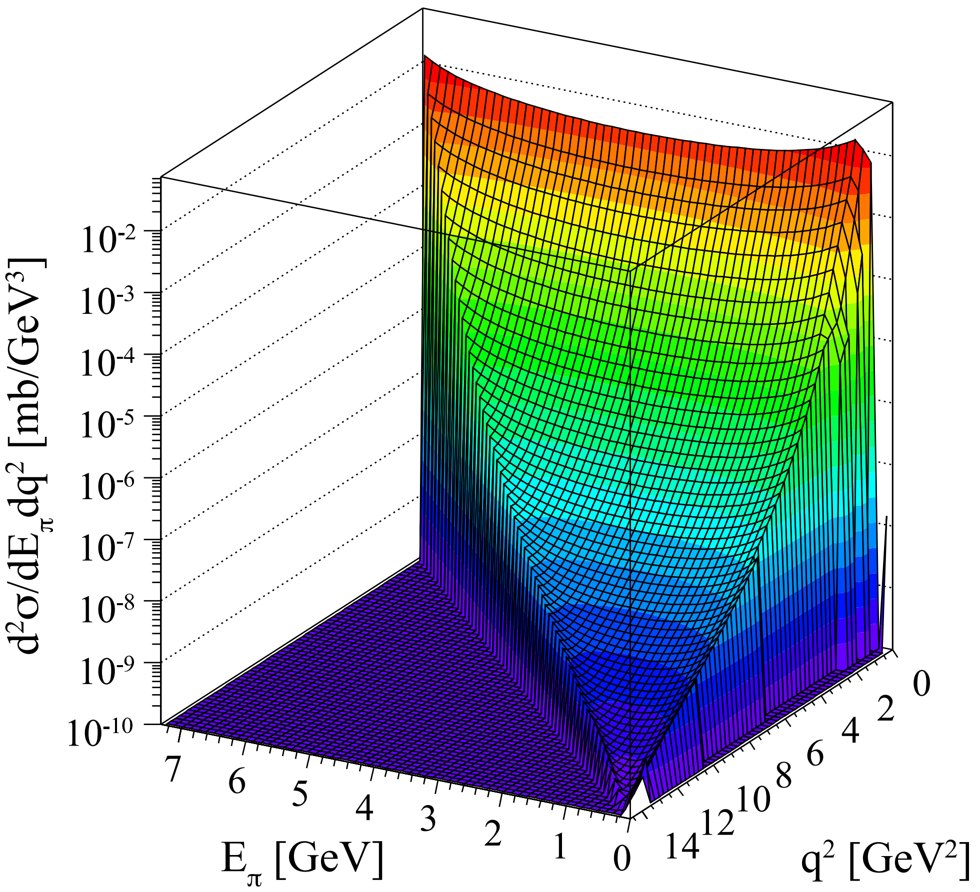
our calculation



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

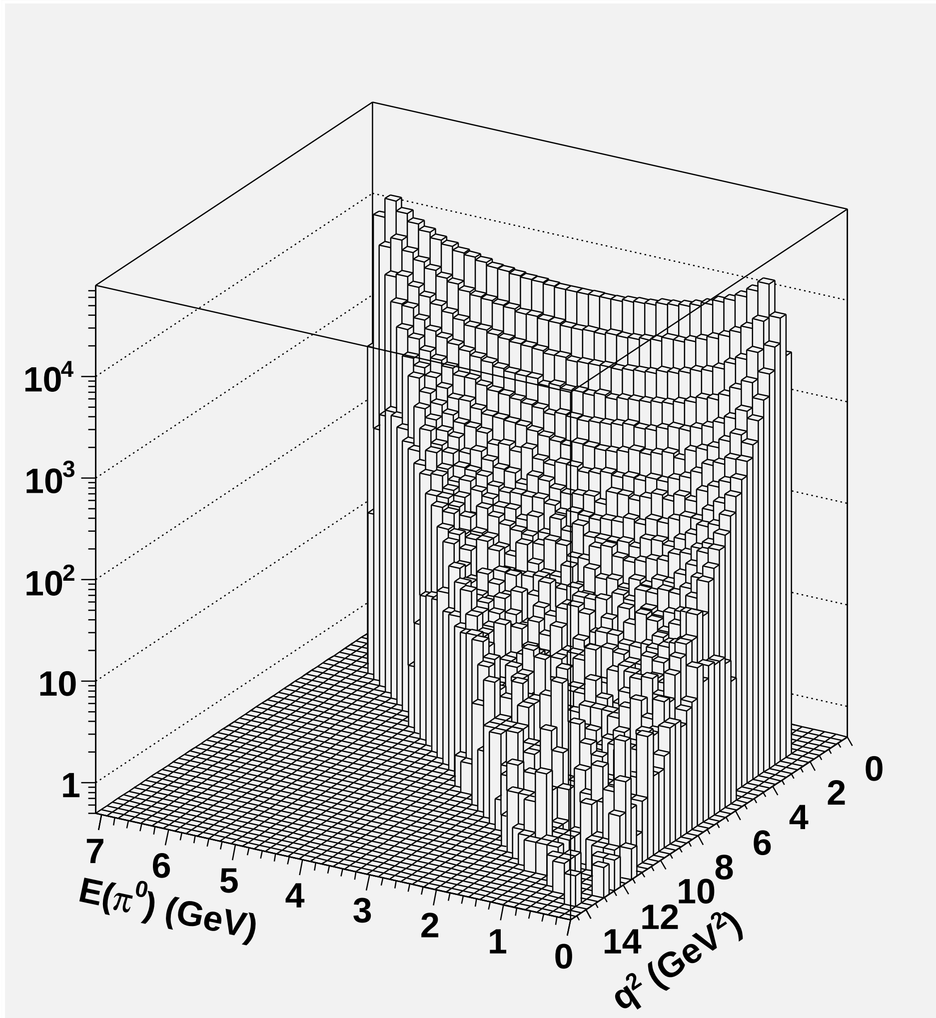
cross section

E = 7 GeV (pQCD FF)



Adamuscin et al.

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



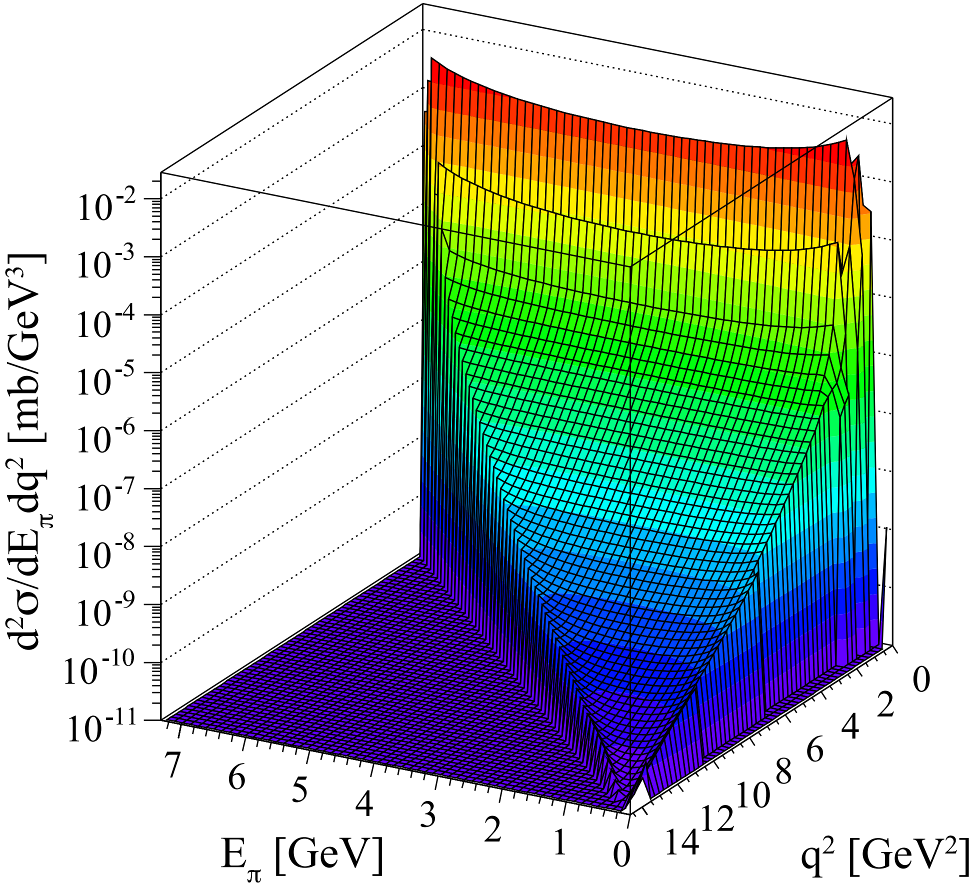
our simulation

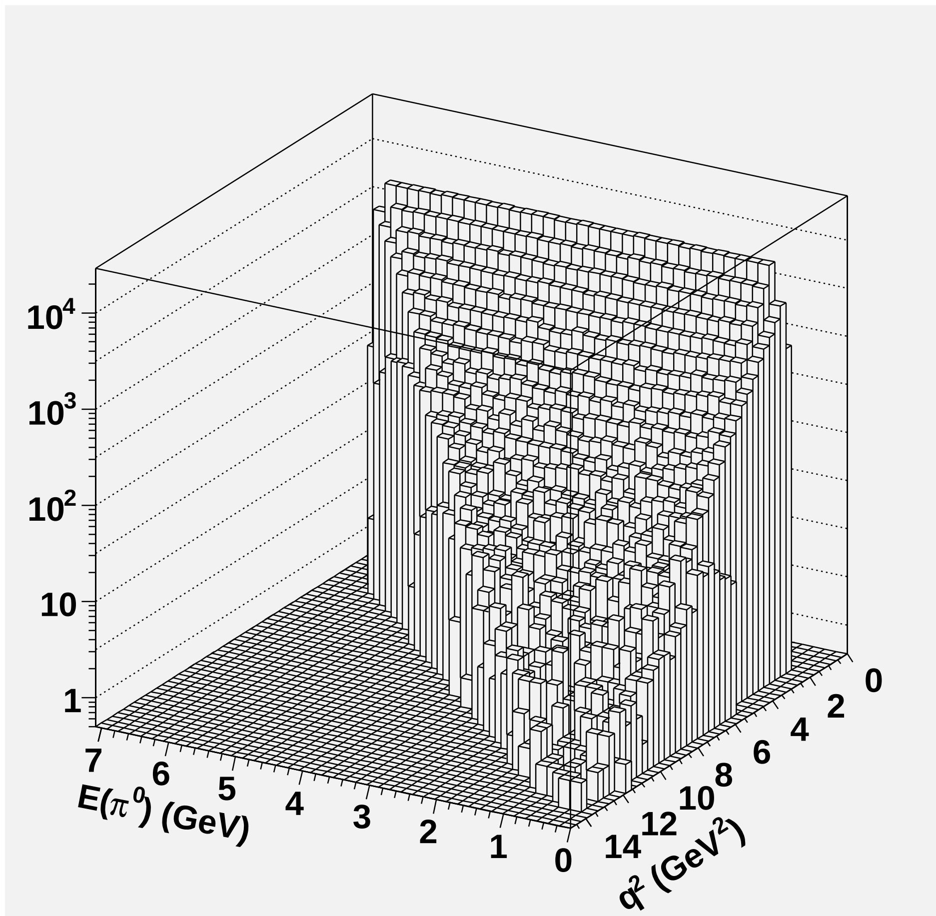
$\bar{p}p \to e^+e^-\pi^0$: cross section and event generation

cross section

$E = 7$ GeV (vmd FF)

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



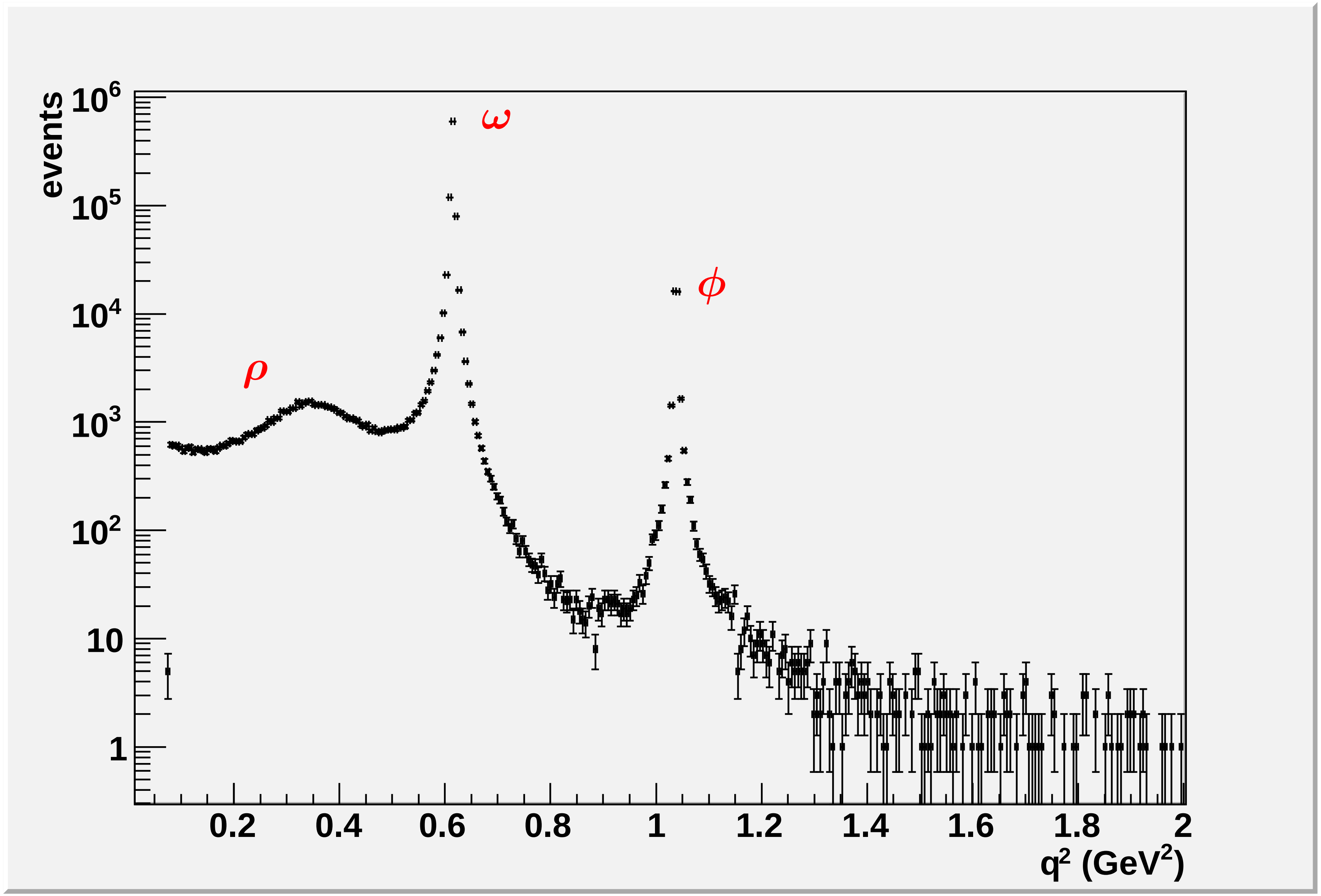


Adamuscin et al.

our simulation

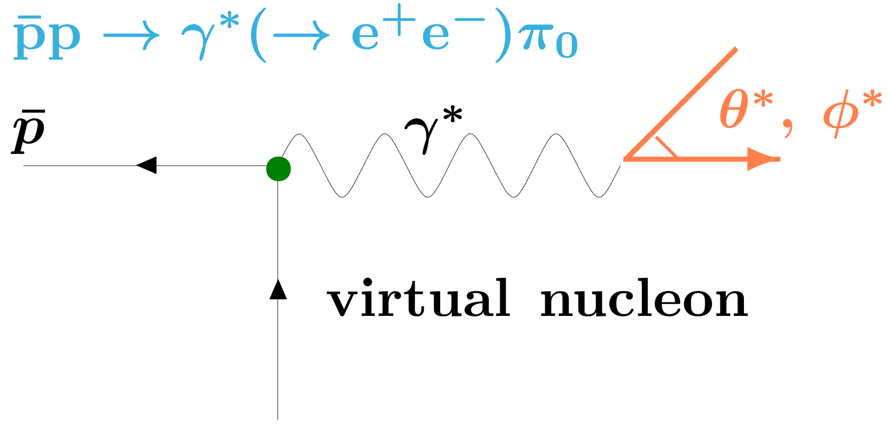
$\bar{p}p \to e^+e^-\pi^0$: cross section and event generation

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



our simulation

$\bar{p}p \to e^+e^-\pi^0$: cross section in the full phase space



- **integrated cross sections in lepton phase space looses the angular distribution of dilepton pair**

  → not enough for full event generator

- **full phase space is 5-dimensional:**

$$\frac{d\sigma}{dq^2\ \underbrace{d\cos\theta_{\pi^0}\ d\phi_{\pi^0}}_{\bar{p}p\ \text{CM frame}}\ \underbrace{d\cos\theta^*\ d\phi^*}_{\gamma^*\ \text{rest frame}}}$$

θ^* = **polar angle of one of the leptons measured with respect γ^* direction**
ϕ^* = **angle between hadronic ($\bar{p}\pi^0$) and leptonic (e^+e^-) plane**

⇒ **calculation in progress** (Julia Guttmann and Cyril Adamuscin)

Summary and Conclusions

- **event generators developed for**

  $i)$ $\bar{p}p \to e^+e^-$
  $ii)$ $\bar{p}p \to \pi^+\pi^-$
  $iii)$ $\bar{p}p \to e^+e^-\pi^0$ **(preliminary)**

- **interfaced to PandaRoot**

  $\to$ **code public and ready for simulations, documentation available**

ongoing work . . .

$\to$ simulation and data analysis (Dmitry Khaneft)

$\to$ calculation full differential cross section for $\bar{\mathrm{p}}\mathrm{p} \to \mathrm{e}^+\mathrm{e}^-\pi^0$ (J. Guttmann, C. Adamuscin)

$\to$ more channels : $\bar{\mathrm{p}}\mathrm{p} \to \mathrm{e}^+\mathrm{e}^-\pi^0$ (TDA), $\bar{\mathrm{p}}\mathrm{p} \to \pi^+\pi^-\pi^0$, etc.