Electromagnetic Form Factors in the Time Like Domain

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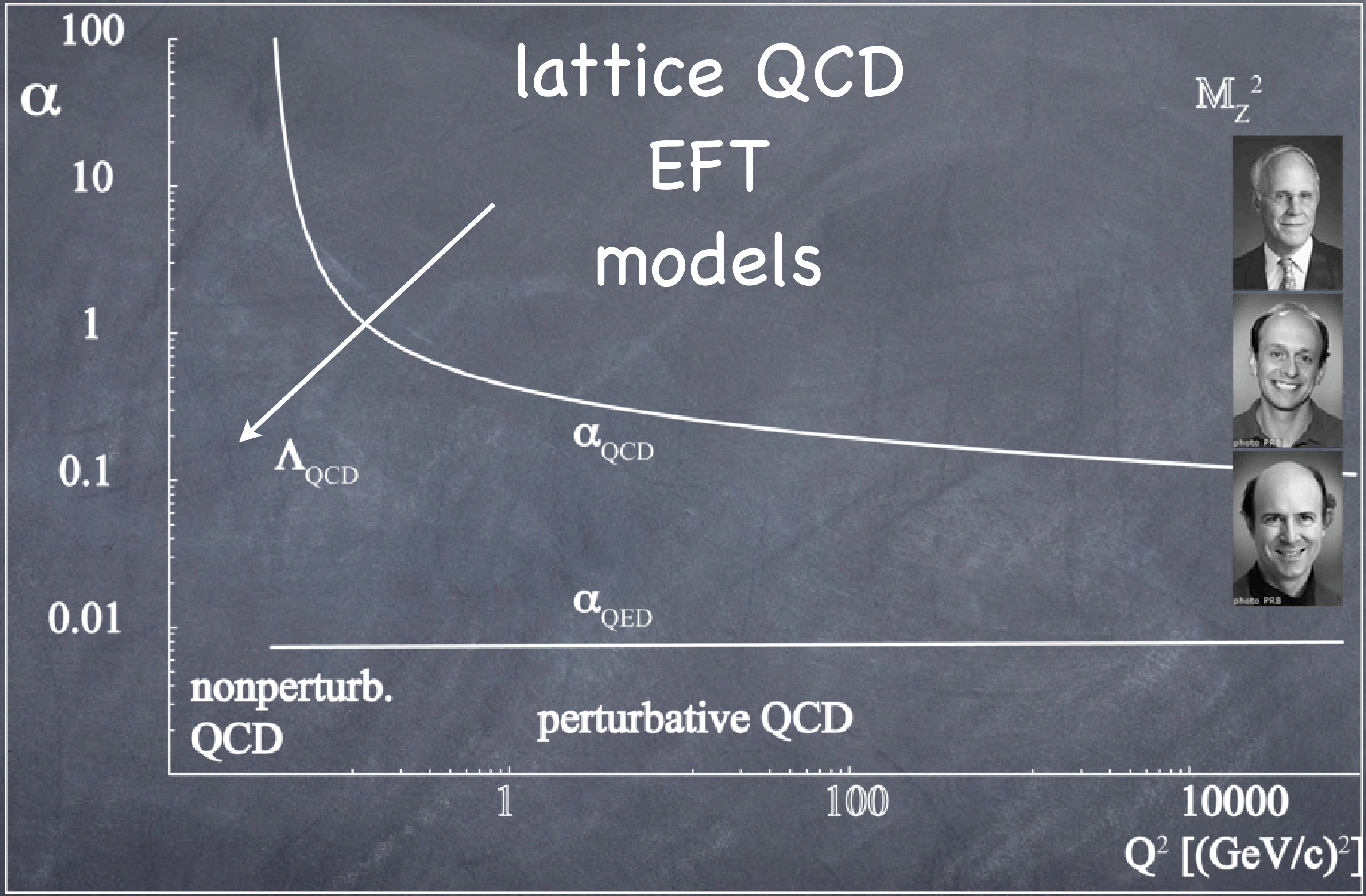
PhiPsi08 Frascati, April 7, 2008

Outline

- EM Form Factor in the time like region
- Existing Data ($\bar{p}p$ -> e^+e^-, e^+e^- -> $\bar{p}p$, e^+e^- -> γpp) most recent data from BaBar
- Possibilities in PANDA

QCD-Renormalisation à la QED



- origin of nucleon mass, effective degrees?
- quark and gluon condensates?
- structure of the nucleon -> Form Factor

Electromagnetic Form Factor

vector current of quarks $Q_f \bar{q}\gamma_\mu q$

Dirac Pauli

$$< N(p')| Q_u \bar{u}\gamma_\mu u + Q_d \bar{d}\gamma_\mu d + \ldots |N(p)> =$$

$$<\bar{p}| F_1(q^2) \gamma_\mu + i(\kappa_p/2M_p) F_2(q^2) \sigma_{\mu\upsilon} q^\mu |p>$$

$$G_E = F_1 + F_2$$

$$G_M = F_1 + \tau F_2$$

vector current: two form factors

internal structure of hadron ground state

Dirac

$F_1^p(q^2=0) = 1$

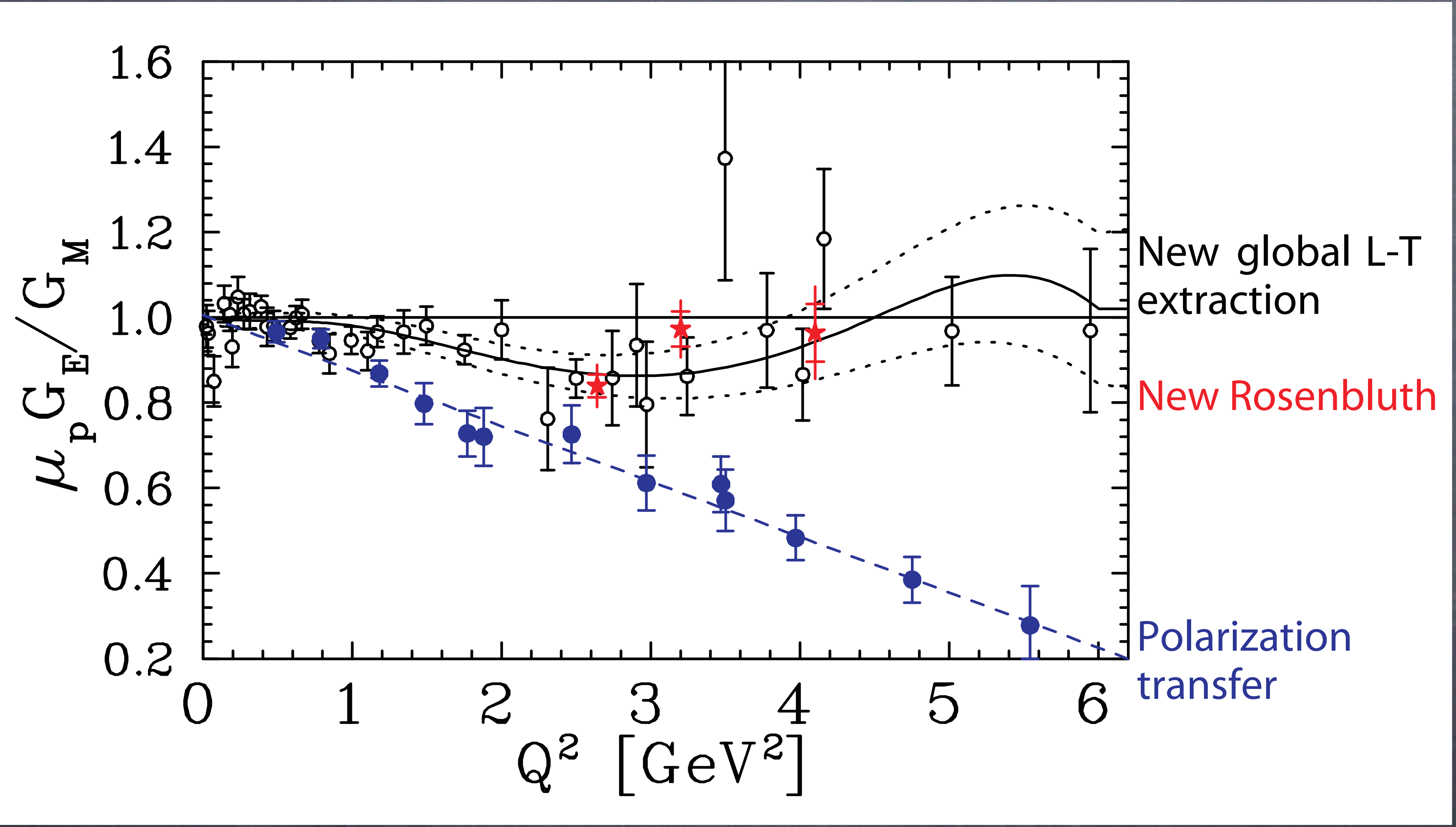
$F_1^n(q^2=0) = 0$

Pauli

$F_2^p(q^2) = 1$

$F_2^n(q^2) = 1$

EM form factor ($q^2 < 0$) recent data



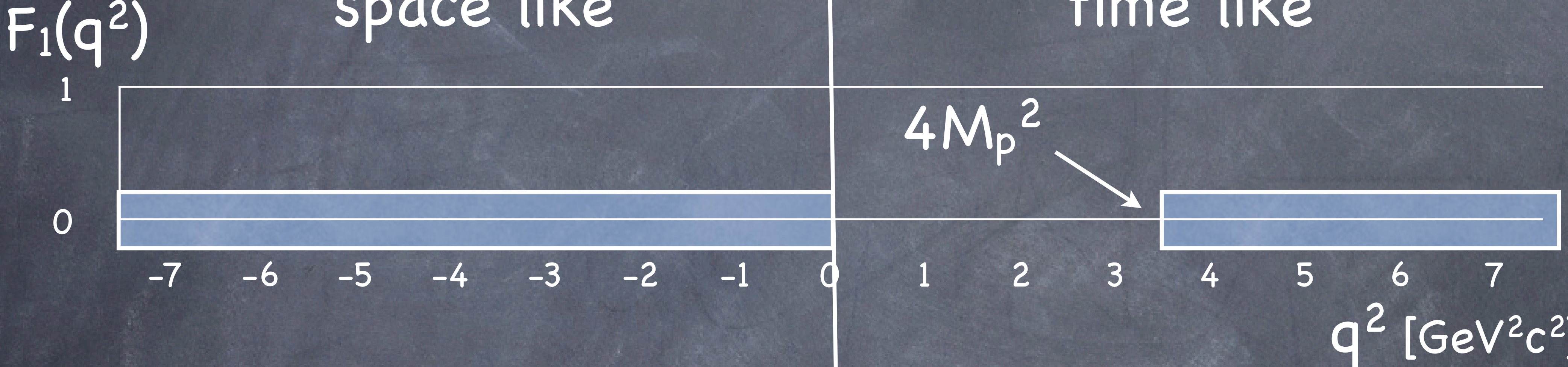
"Polarisation transfer"-technique:

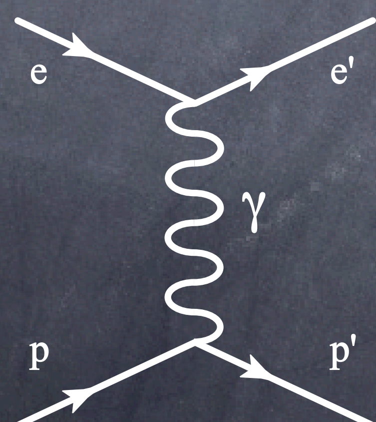
$\mu_P G_E \neq G_M$

Definitions

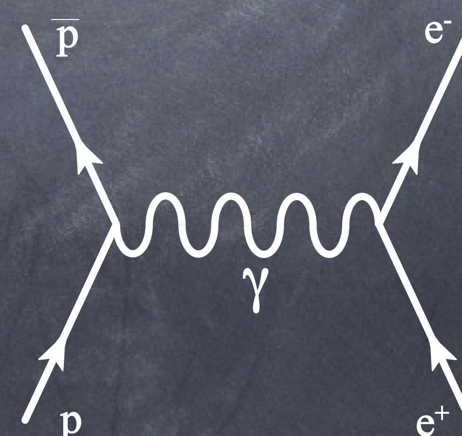
$q^2 < 0$
space like

$q^2 > 0$
time like





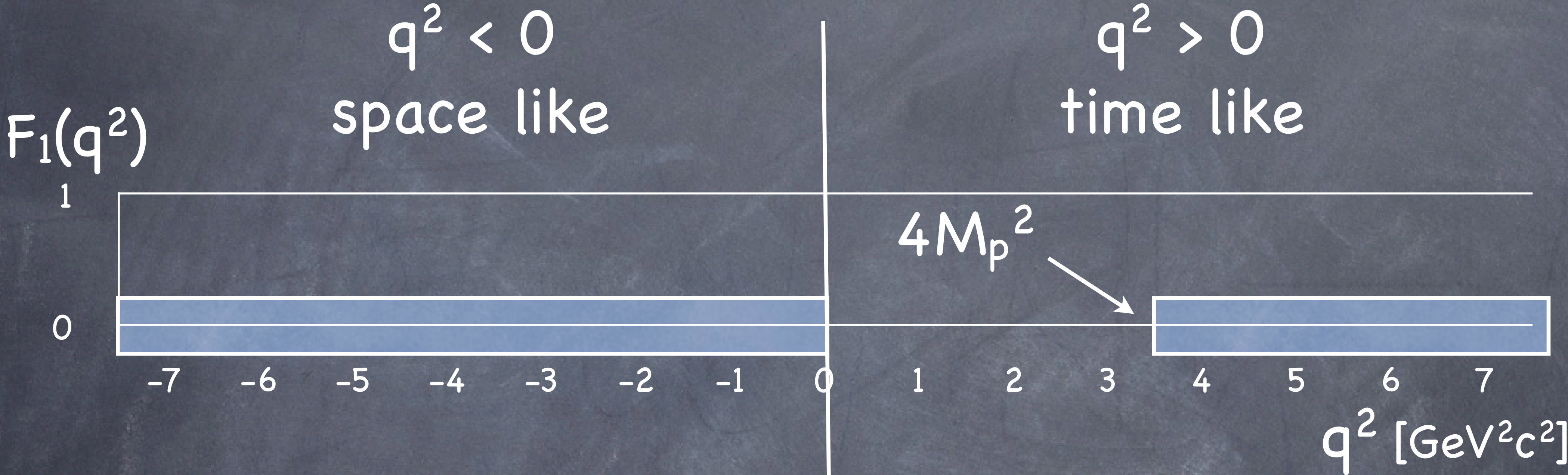
electron scattering



$m_e << m_p$

annihilation

Definitions



Form Factor real

Form Factor complex

connected by Dispersion relations

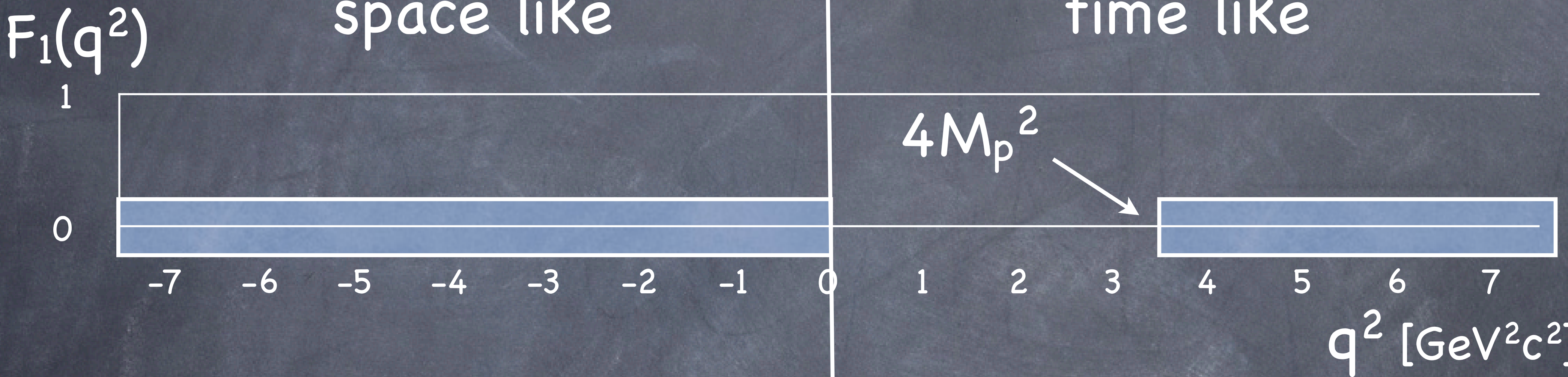
no interference in cross section

$|F_1|$, $|F_2|$

Definitions

$q^2 < 0$ space like

$q^2 > 0$ time like



Form Factor real

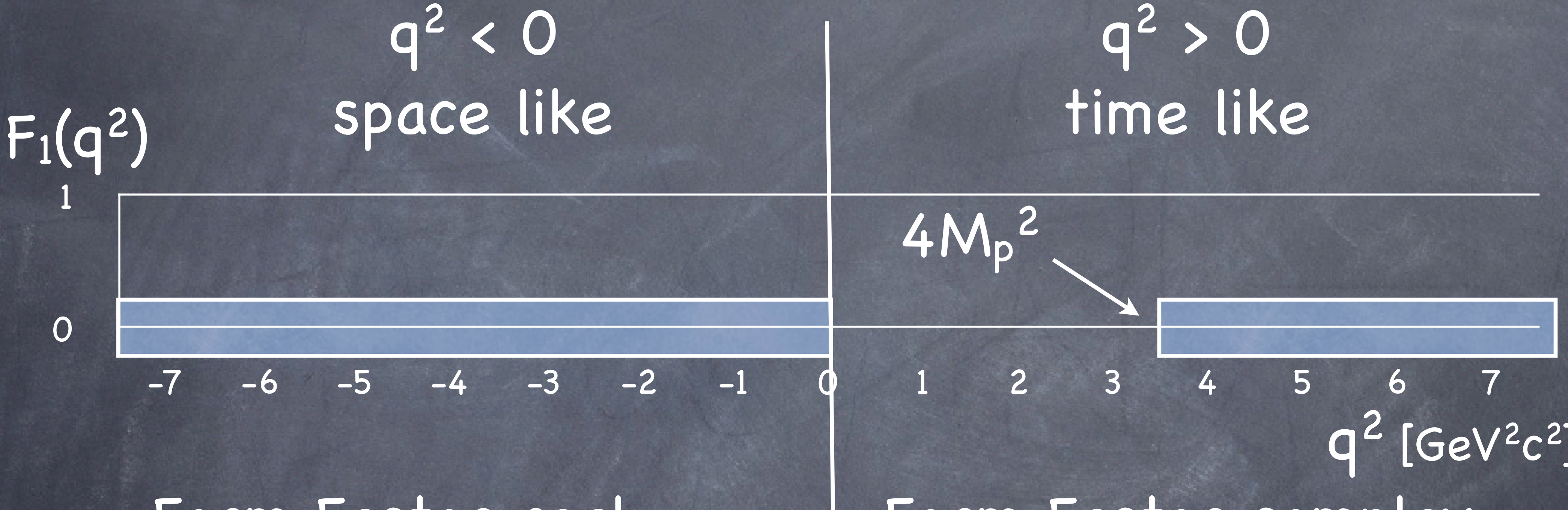
Form Factor complex

connected by Dispersion relations

no interference in cross section $|F_1|$, $|F_2|$

imaginary Part: Polarisation

Observables



Form Factor real

Form Factor complex

cross section (Rosenbluth)
no single spin observables
double spin observables

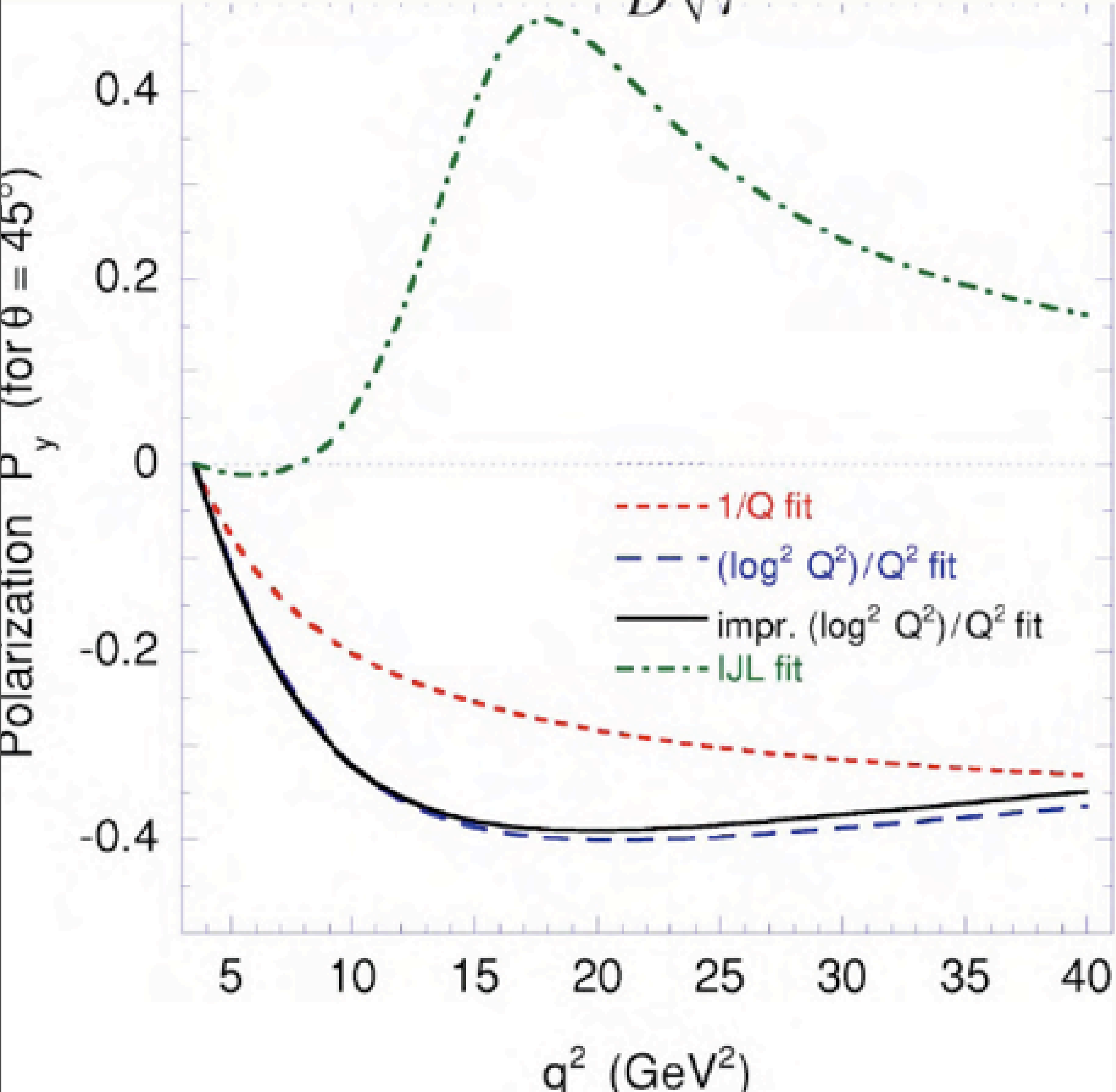
cross section (Rosenbluth)
single spin observables
double spin observables

Imaginary Part of Time Like FF

Single-spin polarization effects and the determination of timelike proton form factors

$$\mathcal{P}_y = \frac{\sin 2\theta \, \mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta \, \mathrm{Im}\, F_2^* F_1}{D\sqrt{\tau}}$$

Carlson, Hiller, Hwang, sjb



$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

$$\tau \equiv q^2/4m_B^2$$

Measure relative phase of form factors

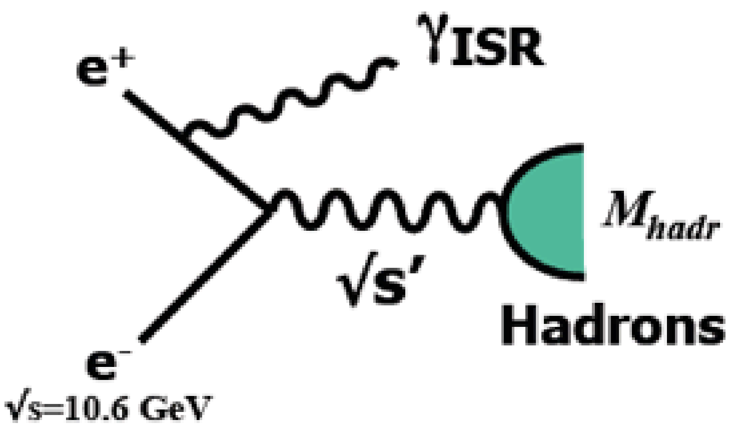
Initial State Radiation
(BaBar)

Radiative Return

Modern particle factories such as **DAΦNE or PEP-II are designed for a fixed center-of-mass-energy**: e.g. $\sqrt{s} = m_{\Upsilon(4S)} = 10.6$ GeV in case of PEP-II

Energy-Scan impossible!

Complementary approach :
Consider events with Initial State Radiation (***ISR***)



Master-Formula:

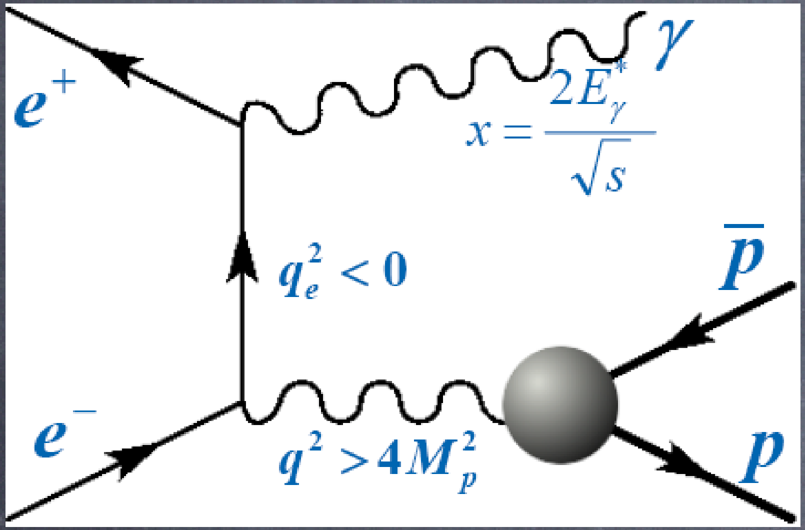
$$M_{hadr} \frac{d\sigma_{Hadr+\gamma}}{dM_{hadr}} = \sigma_{hadr}(s) \times H(s)$$

Radiator-Function (NLO)
MC-Generators EVA, Phokhara, AfkQed
J. Kühn, H. Czyz, G. Rodrigo

Data comes as a by-product to the main physics goals of the particle factories

EM form factor ($q^2 > 0$)

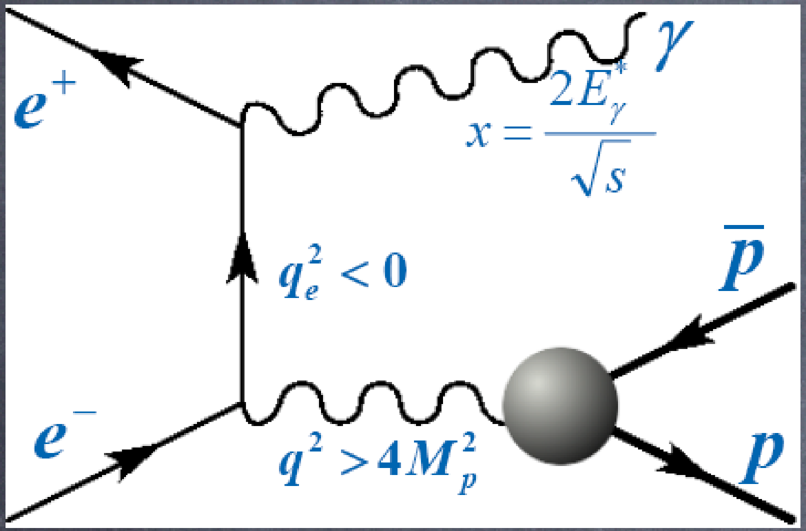
Babar: Initial state radiation (ISR), radiative return

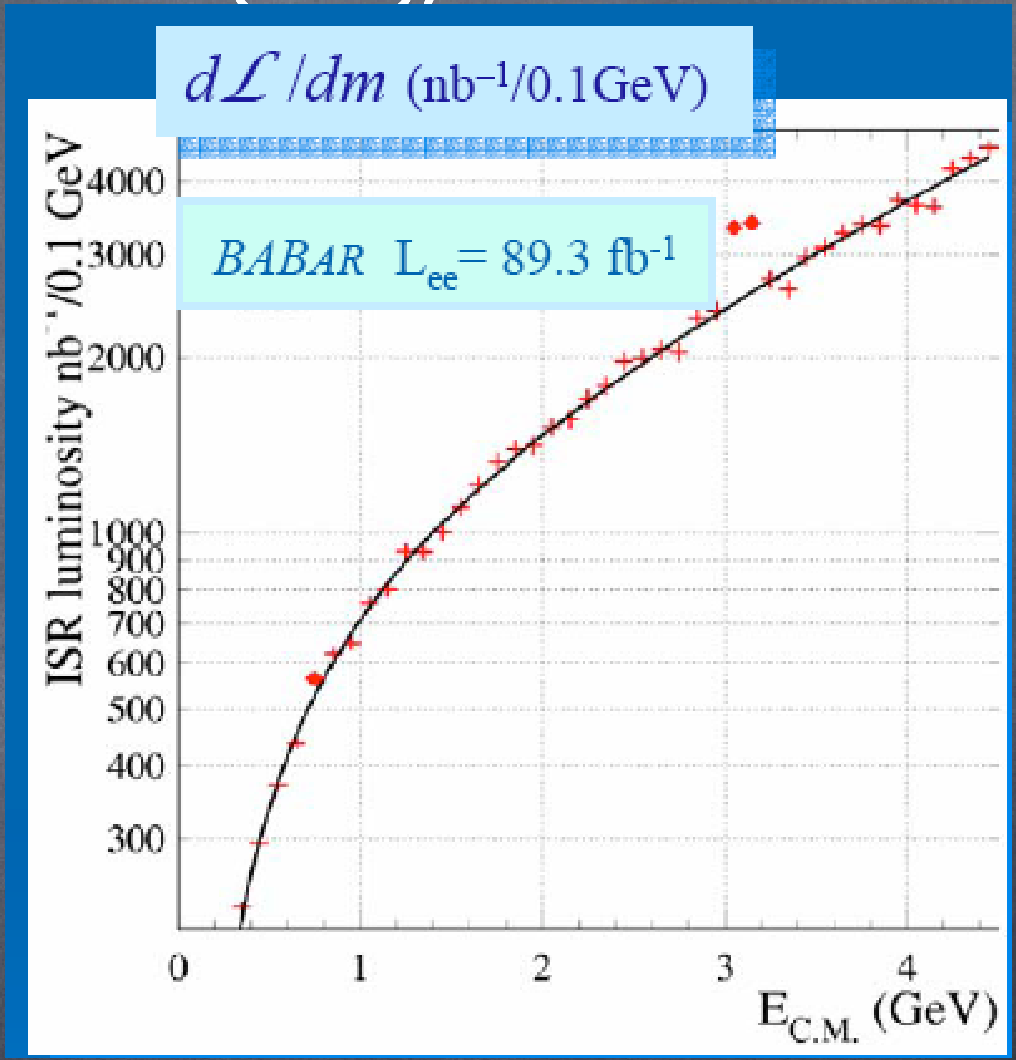


Thanks to V. Zallo and F. Annulli INFN Frascati

EM form factor ($q^2 > 0$)

Babar: Initial state radiation (ISR), radiative return





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Data

Rosenbluth Technique (time like)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \rho(s)}{4s} \left(|G_M^p(s)|^2 (1 + \cos^2(\theta)) + \frac{1}{\tau} |G_E^p(s)|^2 \sin^2(\theta) \right)$$

$$\tau = s/4M_p^2$$

$G_E = F_1 + F_2$

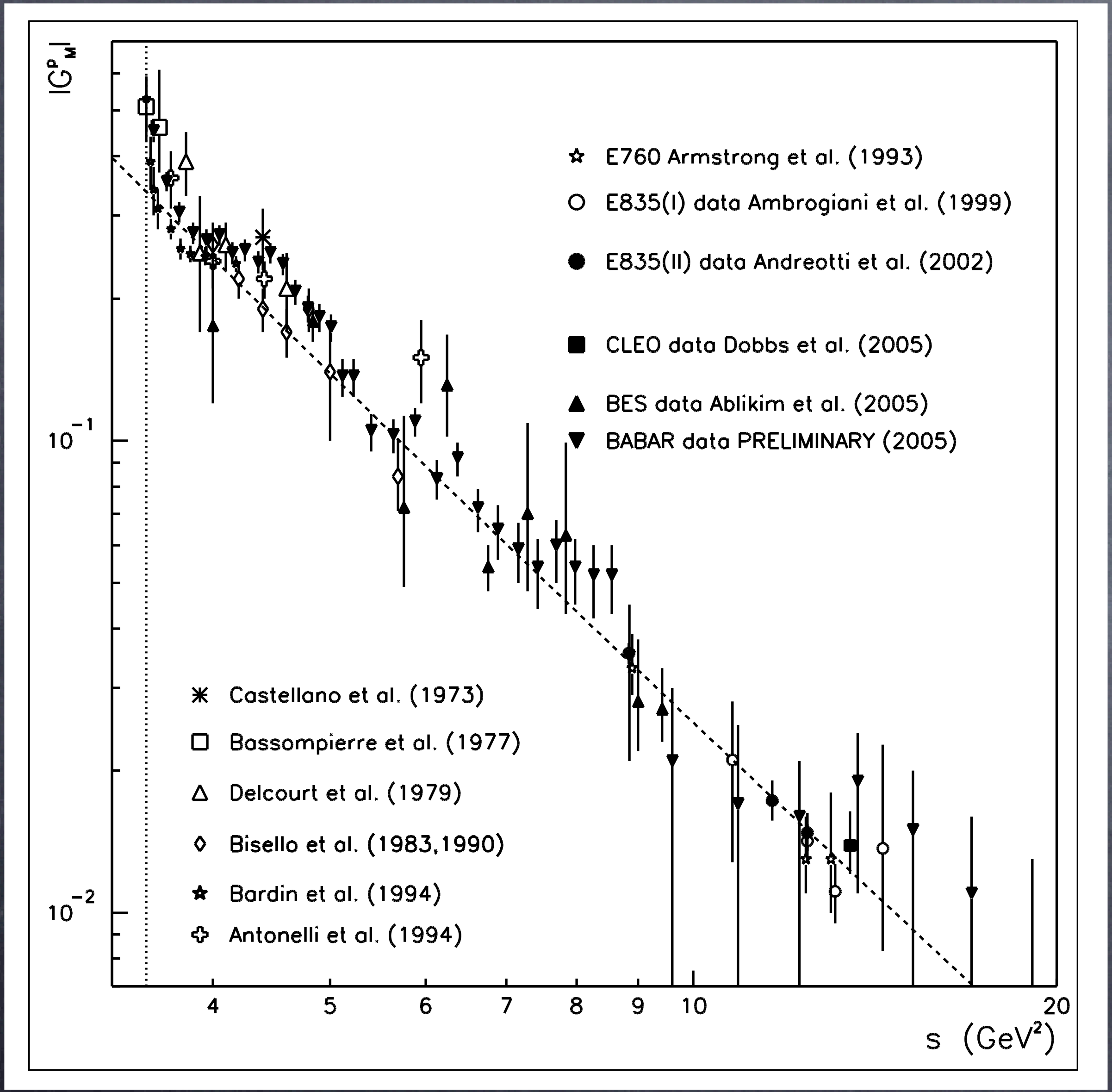
$G_M = F_1 + \tau F_2$

at threshold: $G_E = G_M$

two approaches:

assume G_E/G_M <-> extract G_E and G_M

EM form factor ($q^2 > 0$)



Adone e^+e^-: 25, 69 ev.

ELPAR $p\bar{p}$: 34 ev.

DM1,2 e^+e^-: 63, 172 ev.

$|G_E|/|G_M| = 0.34$

PS170 $p\bar{p}$: 3667 ev.

$|G_E|/|G_M| \approx 1$

E760 $p\bar{p}$: 29 ev.

E835 $p\bar{p}$: 206 ev.

CLEO e^+e^-: 14 ev.

BES e^+e^-: higher stat

BaBar e^+e^-: high stat

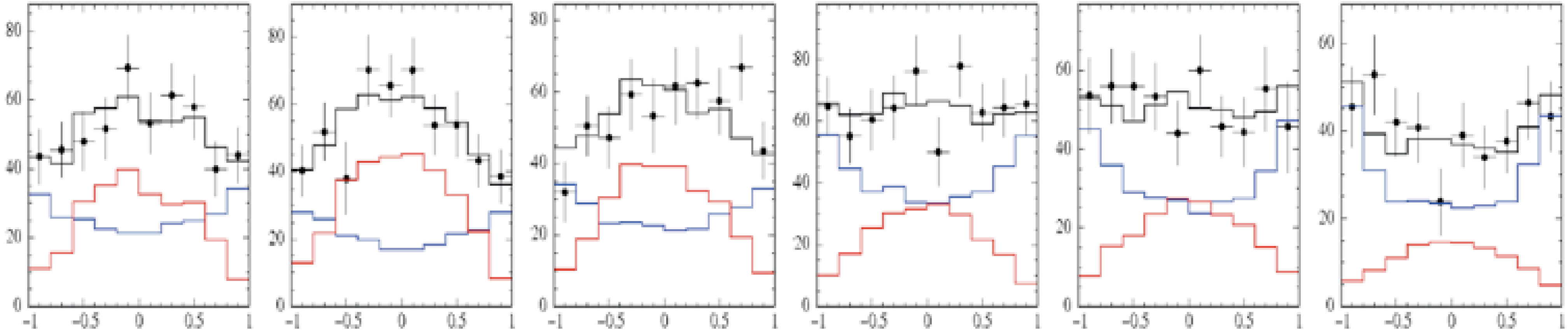
All data: Measure absolute cross section $G_E = G_M$

$e^+e^- \longrightarrow p\bar{p}$ angular distribution

PRD73, 012005

$\cos\theta_p$ distributions form threshold up to 3 GeV [intervals in $E_{CM} \equiv q$ (GeV)]

1.877 ÷ 1.950 | 1.950 ÷ 2.025 | 2.025 ÷ 2.100 | 2.100 ÷ 2.200 | 2.200 ÷ 2.400 | 2.400 ÷ 3.000

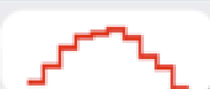


Events/0.2 vs. $\cos\theta_p$

$$\frac{d\sigma}{d\cos\theta_p} = A\left[H_E(\cos\theta_p, q^2)\left|\frac{G_E^p(q^2)}{G_M^p(q^2)}\right|^2 + H_M(\cos\theta_p, q^2)\right]$$

H_E and H_M from MC

Histograms show contributions from

- G_E 
- G_M 

At low q

$\sin^2\theta_p > 1 + \cos^2\theta_p$

$\Rightarrow$

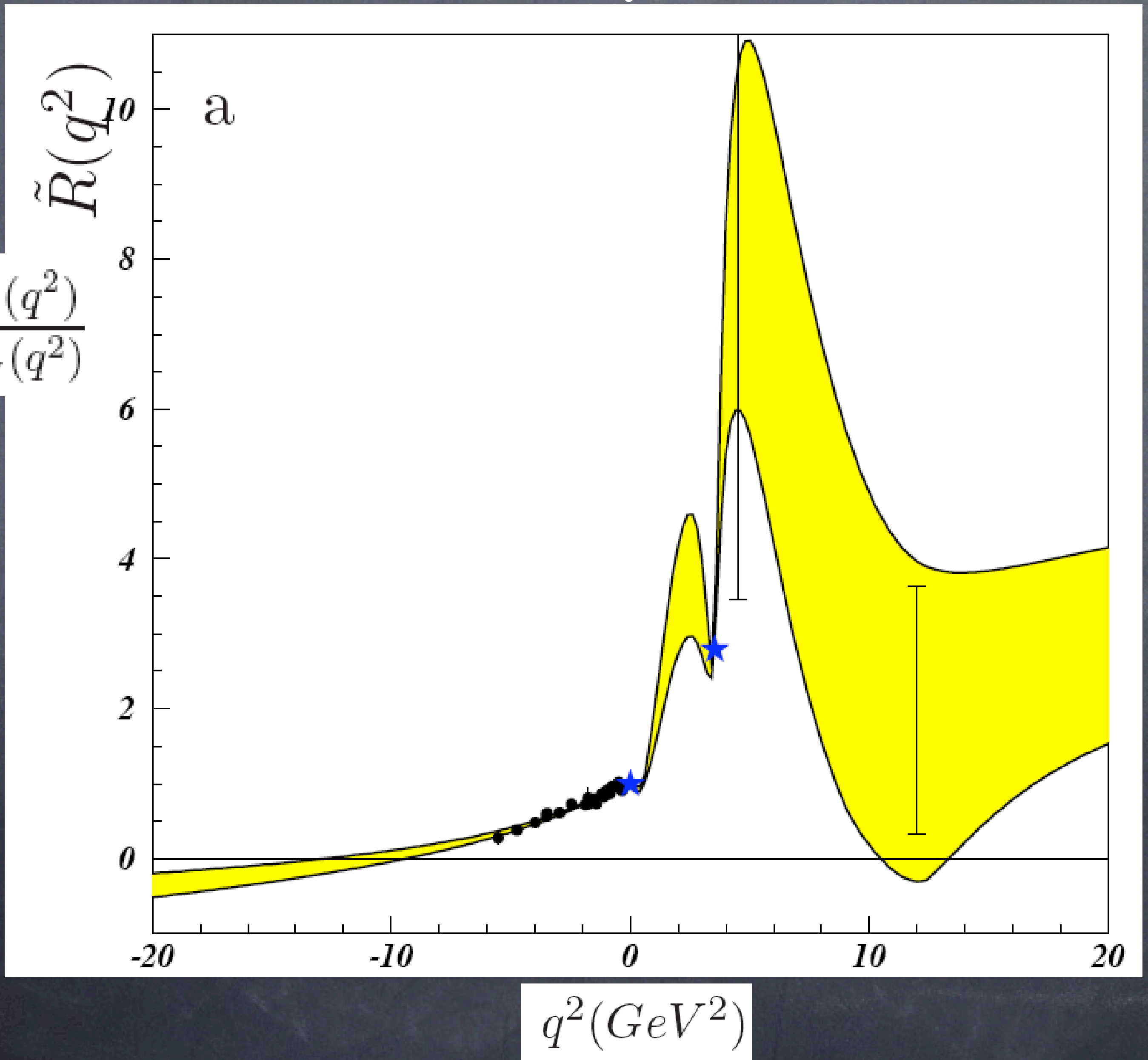
First observation!

$|G_E^p| > |G_M^p|$

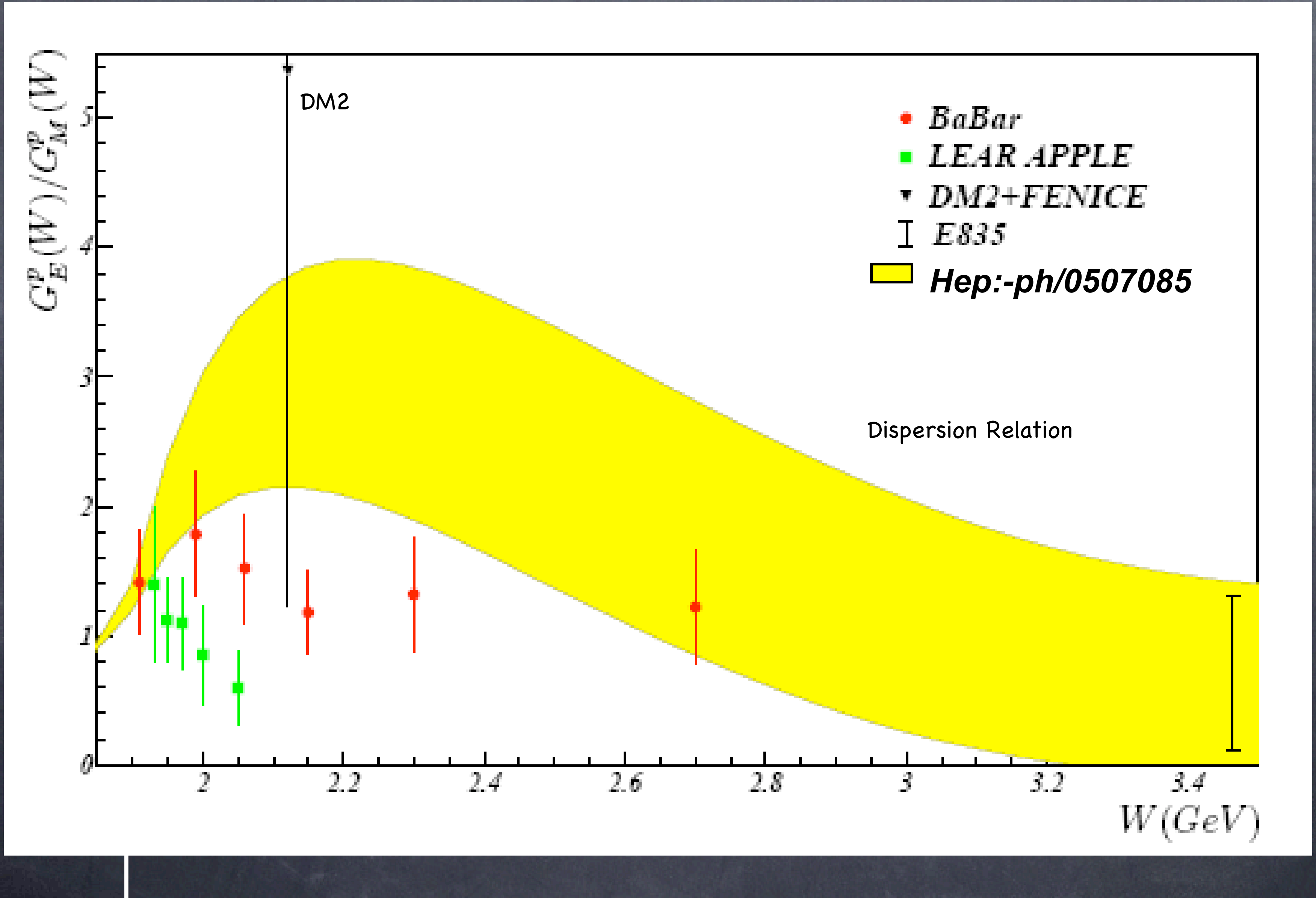
At higher q, $|G_E^p| \longrightarrow |G_M^p|$

EM form factor ($q^2 > 0$)
$|G_E|/|G_M|$ from dispersion relations

$$R(q^2) = \mu_p \frac{G_E^p(q^2)}{G_M^p(q^2)}$$

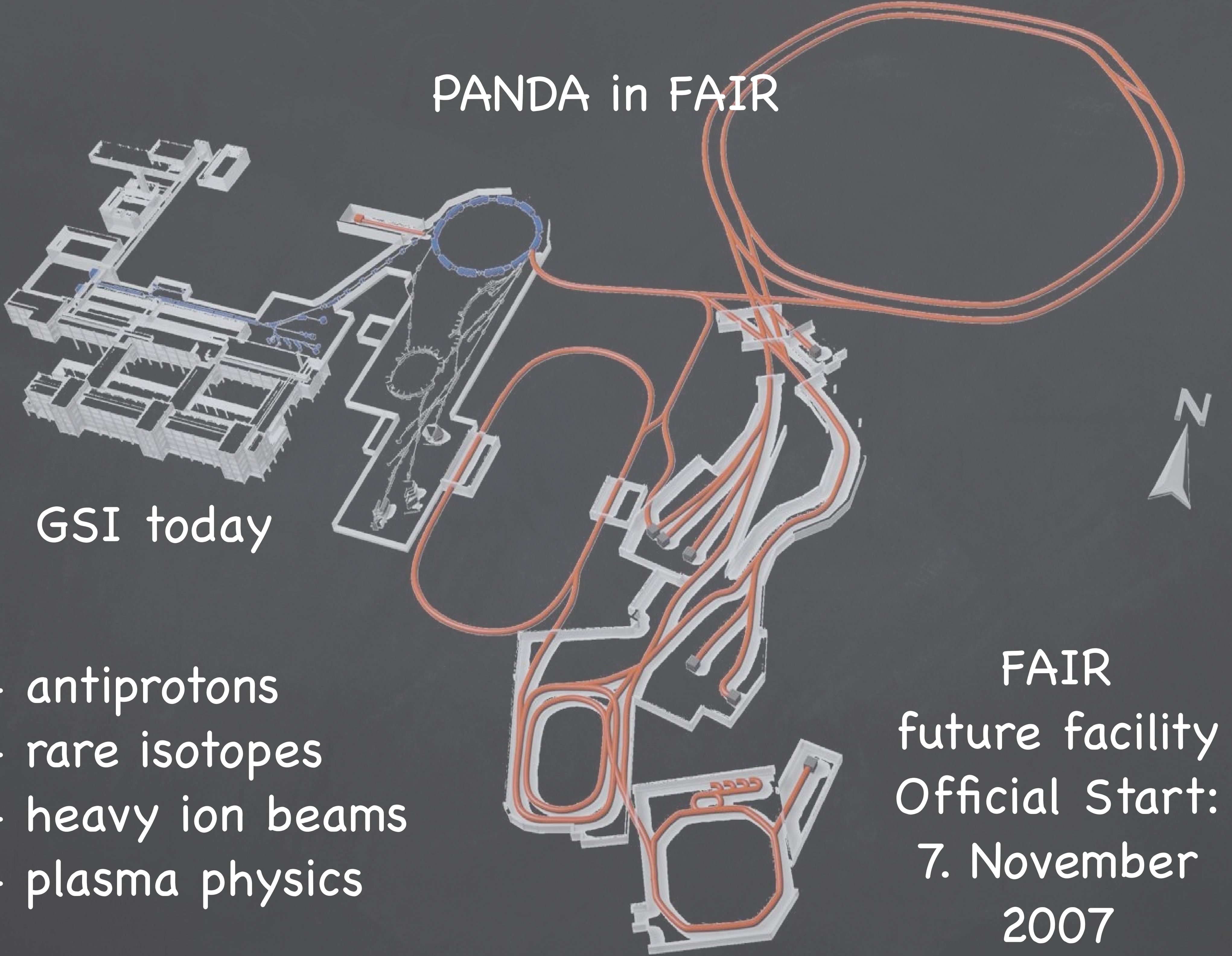


EM form factor ($q^2 > 0$)
$|G_E|/|G_M|$



$\sqrt{4M_p^2}$

PANDA in FAIR

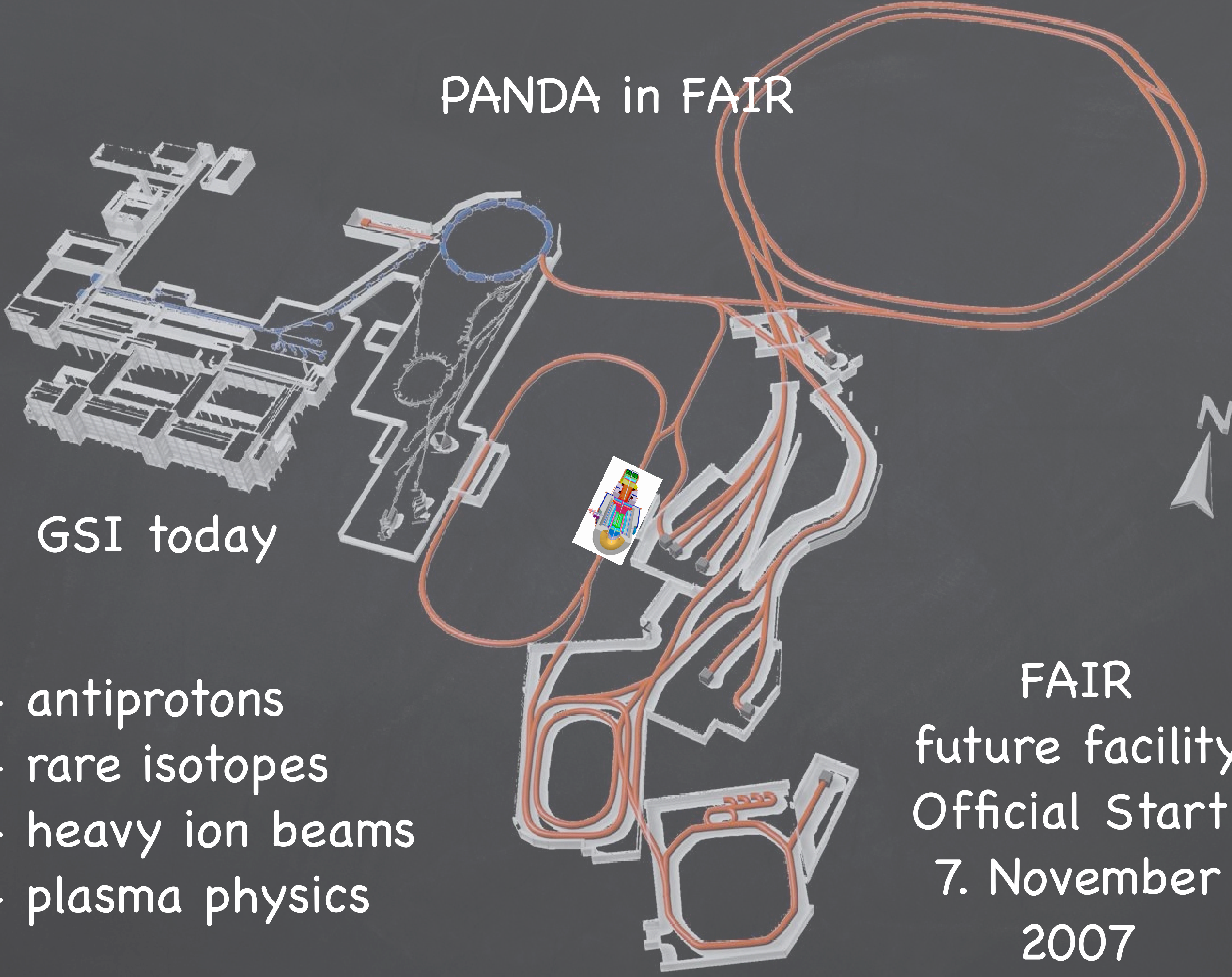


GSI today

- antiprotons
- rare isotopes
- heavy ion beams
- plasma physics

FAIR
future facility
Official Start:
7. November
2007

PANDA in FAIR



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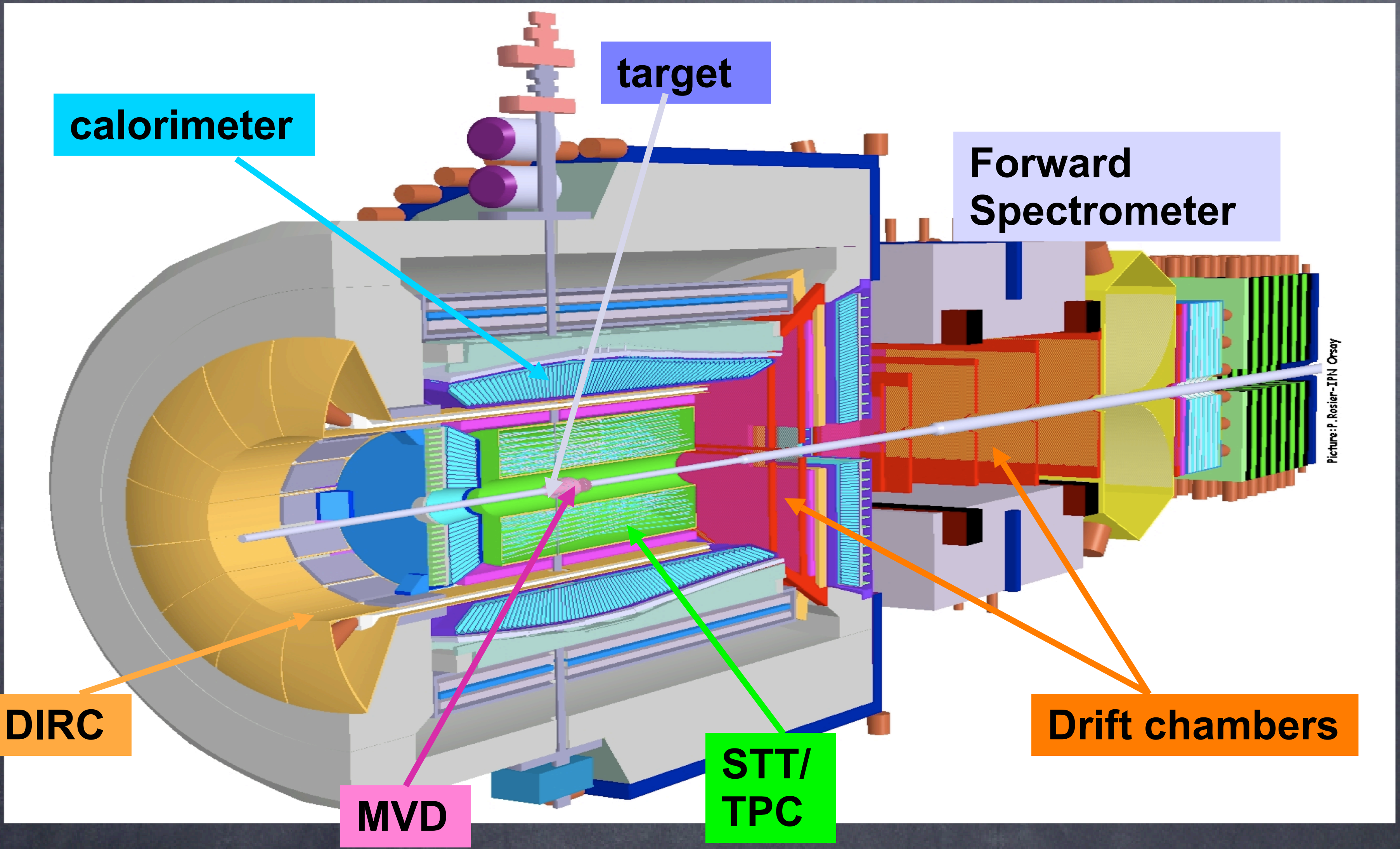
PANDA: the detector



use PID capability of each subdetector

Detection and idenfication in the different regions

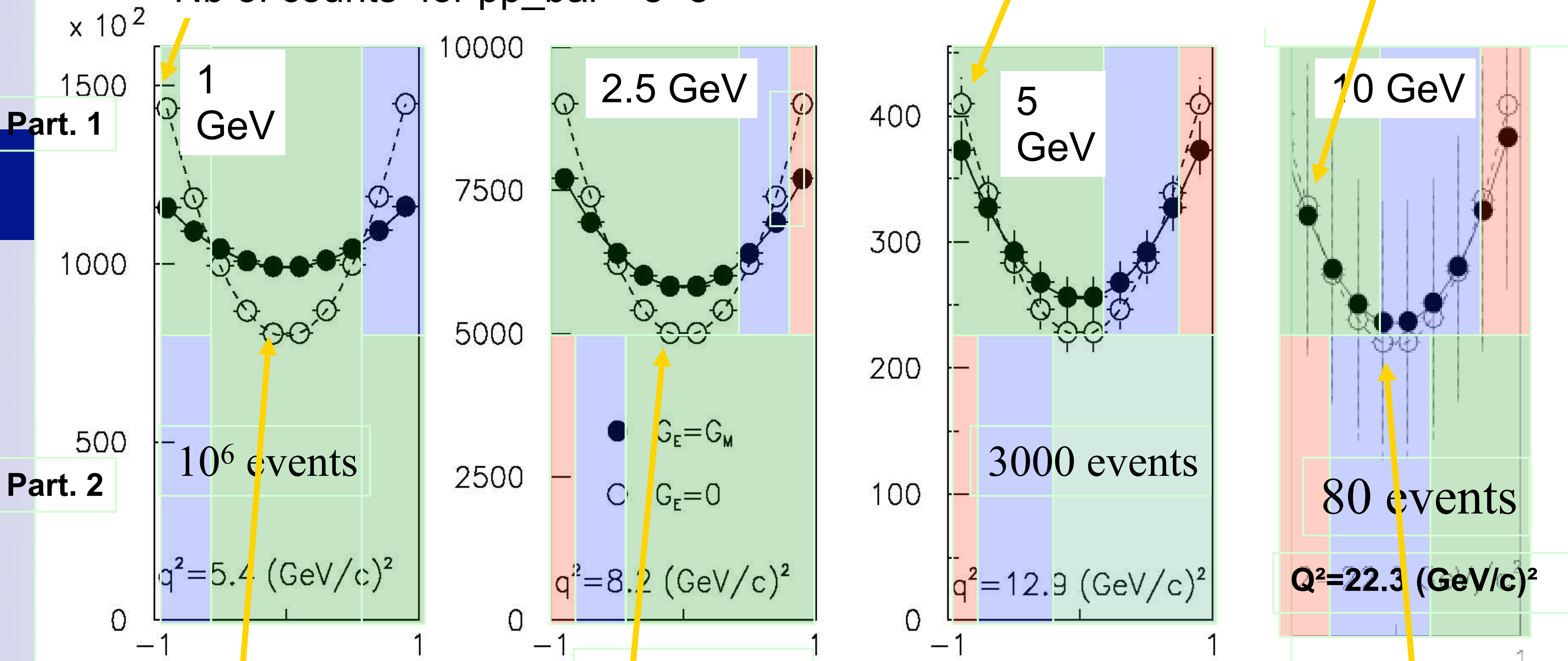
θ_1=13.°, p1=2.2 GeV
θ_2=132°, p_2=0.67 GeV

θ_1=7.4°, p1=6.1 GeV
θ_2=102°, p_2=0.8 GeV

θ_1=5.4 °, p1=10.9 GeV
θ_2=85°, p_2=1.0 GeV

Nb of counts for pp_bar→e+e-

•~100 days, $\mathcal{L}$ = 2. 10^{32} $cm^{-2}s^{-1}$ 2 fb^{-1}



θ_1= θ_2=54 ° p1=p2=1.43 GeV

$\cos(\theta_{cm})$

θ_1= θ_2= 41 °
p1=p2=2.2 GeV

θ_1= θ_2= 23.5 °
p1=p2=5.95 GeV

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

- ✓ **Reactions with at least 3 particles produced:**
  (e^+e^-X, $\pi^+\pi^-X$,...)
  Particle identification and kinematics constraints
  → no problem (still to be quantified)

- ✓ **Reactions with 2 charged particles ($\pi^+\pi^-$)**
  - **$\sigma(\pi^+\pi^-)/\sigma(e^+e^-) \approx 10^6$ ($2\mu b/8pb$ at $q^2=9.(GeV/c)^2$)**

    need rejection of $\bar{p}p \to \pi^+ \pi^-$ by 10^{-8}

    binary event, mean reject. of 10^{-4} per π^+ and per π^-
  - **very close kinematics**
  - **PID is crucial, EMC, DIRC, dE/dx**

can we separate $\pi^+\pi^-/e^+ e^-$

preliminary:efficieny for e^+e^- and misidentification

based on E/p, PID from DIRC and EMC, kinemat. fit

	$e^+ e^-$ no QED corr.	$e^+ e^-$ w/ QED corr.	$\pi^+ \pi^-$
charged	-	60,76%	$8,49 * 10^{-3}$
very loose	73,10%	57,69%	$5,0 * 10^{-6}$
loose	70,60%	55,81%	$6 * 10^{-7}$
tight	58,37%	46,15%	$1 * 10^{-7}$
very tight	48,91%	38,21%	$< 10^{-7}$

very promising

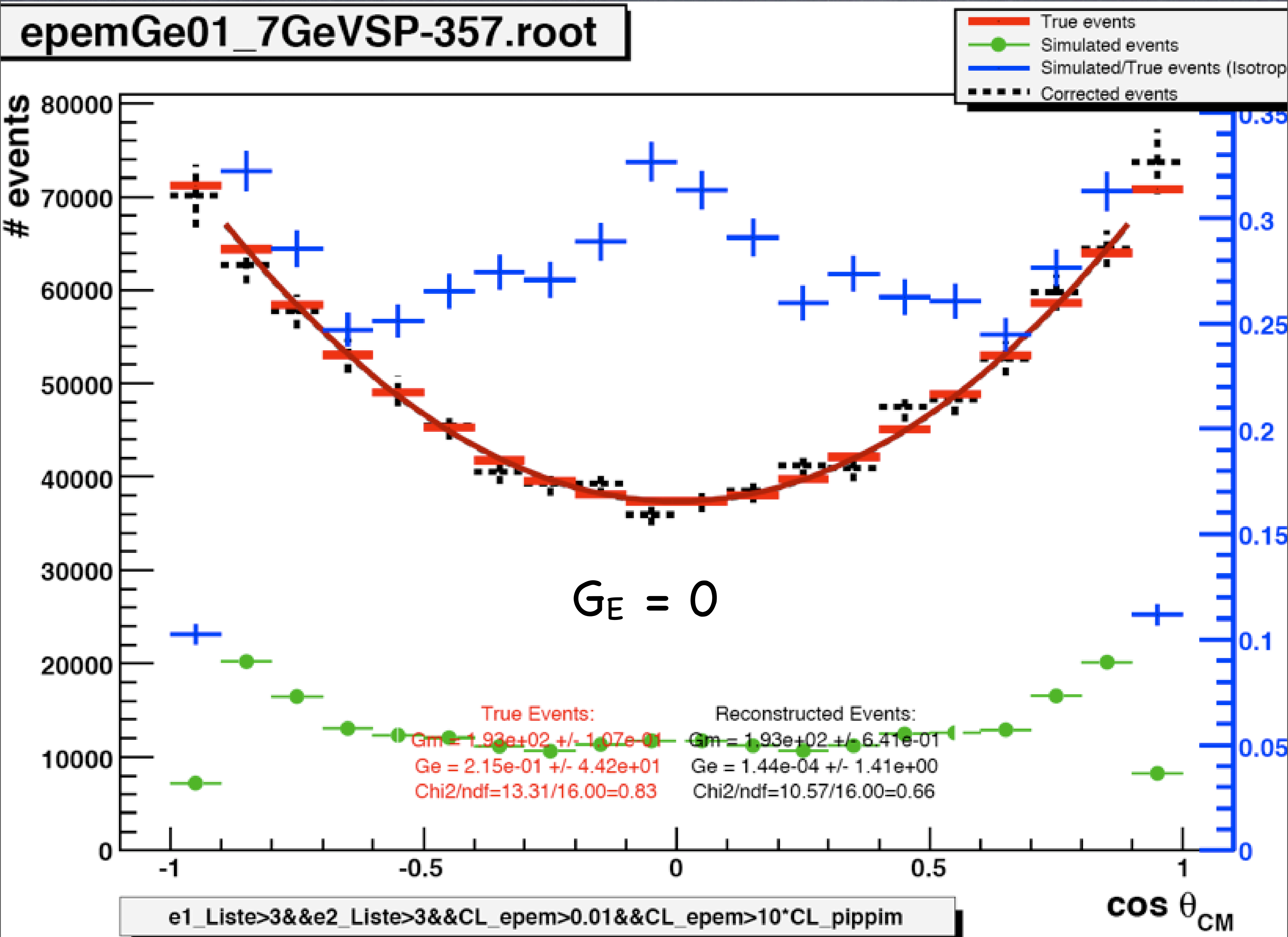
from B.Kopf, Bochum

can we separate G_E and G_M

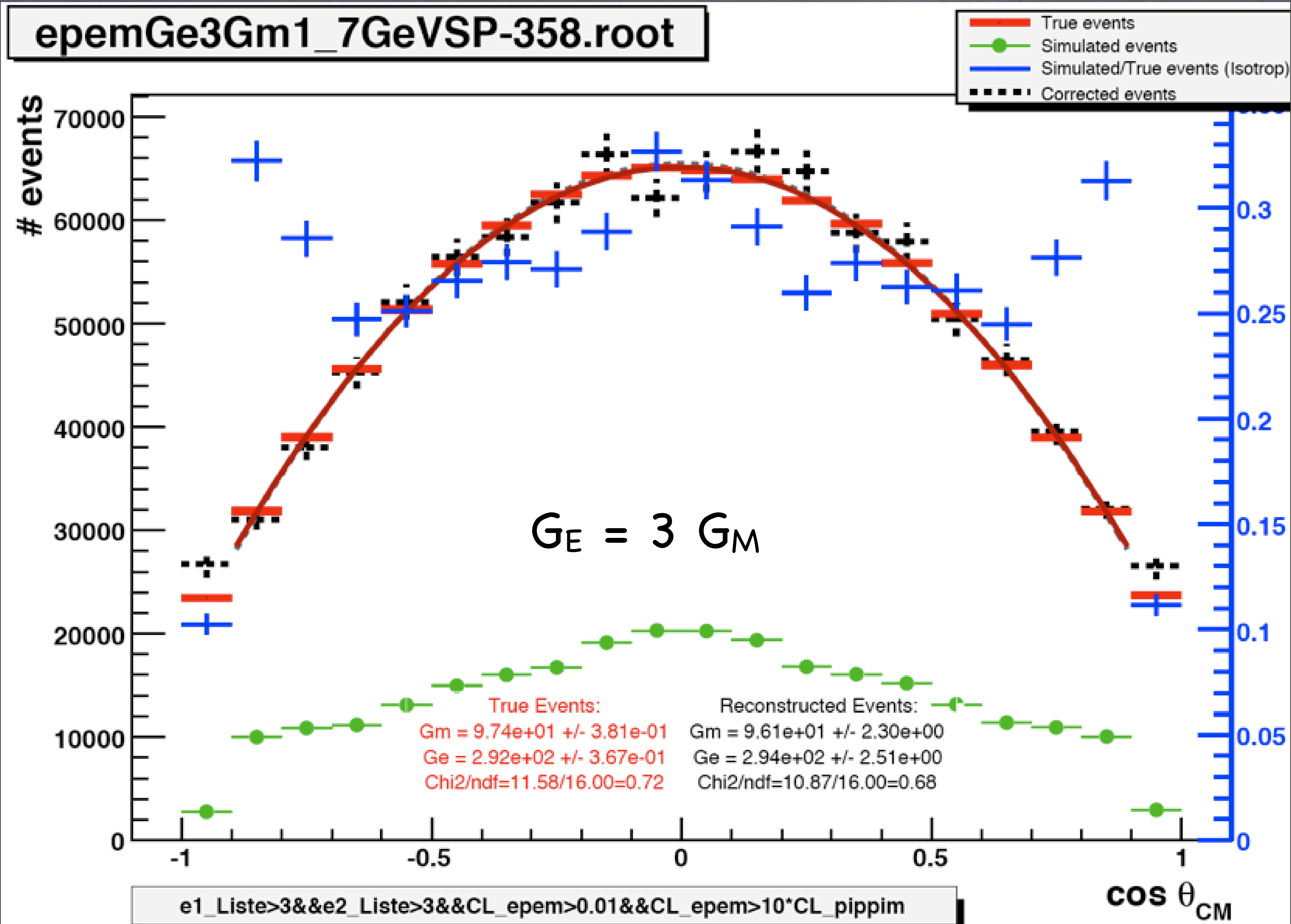
Rosenbluth Technique (time like)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \rho(s)}{4s} \left(|G_M^p(s)|^2 (1 + \cos^2(\theta)) + \frac{1}{\tau} |G_E^p(s)|^2 \sin^2(\theta) \right)$$

$$\tau = s/4M_p^2$$



epemGe01_7GeVSP-357.root
True events
Simulated events
Simulated/True events (Isotrop
Corrected events
events
80000
70000
60000
50000
40000
30000
20000
10000
0
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.5
0
0.5
1
G_E = 0
True Events:
Gm = 1.93e+02 +/- 1.07e-01
Ge = 2.15e-01 +/- 4.42e+01
Chi2/ndf=13.31/16.00=0.83
Reconstructed Events:
Gm = 1.93e+02 +/- 6.41e-01
Ge = 1.44e-04 +/- 1.41e+00
Chi2/ndf=10.57/16.00=0.66
e1_Liste>3&&e2_Liste>3&&CL_epem>0.01&&CL_epem>10*CL_pippim
cos θ_CM

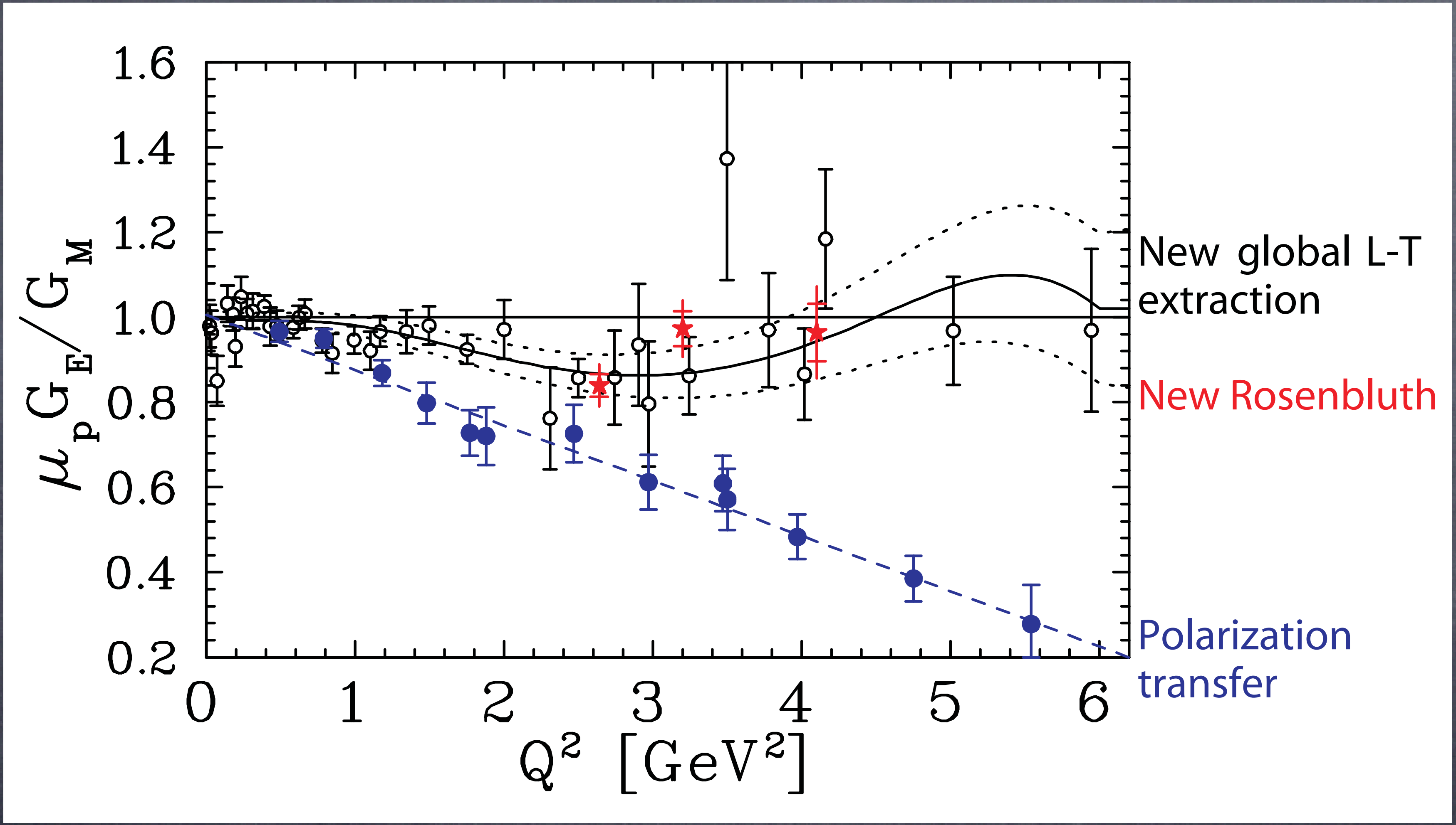


epemGe3Gm1_7GeVSP-358.root
True events
Simulated events
Simulated/True events (Isotrop)
Corrected events
events
70000
60000
50000
40000
30000
20000
10000
0
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.5
0
0.5
1
cos θ_CM
G_E = 3 G_M
True Events:
Gm = 9.74e+01 +/- 3.81e-01
Ge = 2.92e+02 +/- 3.67e-01
Chi2/ndf=11.58/16.00=0.72
Reconstructed Events:
Gm = 9.61e+01 +/- 2.30e+00
Ge = 2.94e+02 +/- 2.51e+00
Chi2/ndf=10.87/16.00=0.68
e1_Liste>3&&e2_Liste>3&&CL_epem>0.01&&CL_epem>10*CL_pippim

Summary

- electromagnetic form factors:
  fundamental property of Nucleon
- space like -> impact on time like
- what is G_E in time like domain?
- possibilities to measure in timelike domain
  new data from BaBar, not yet from Belle
  proposals DAPHNE, BESIII, VEPP-2000, PANDA
- PANDA opens door to new EM nucleon structure
  EM form factors below threshold
  Axial form factor in time like domain
  space like GPDs -> time like GDA

EM form factor ($q^2 < 0$) recent data



"Polarisation transfer"-technique:

$$\mu_P \, G_E \neq G_M$$

Unpolarized cross section

dapnia
cea
saclay

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}D,$$

$$D = (1+\cos^2\theta)(|G_M|^2 + 2ReG_M\Delta G_M^*) + \frac{1}{\tau}\sin^2\theta(|G_E|^2 + 2ReG_E\Delta G_E^*) + 2\sqrt{\tau(\tau-1)}\cos\theta\sin^2\theta Re(\frac{1}{\tau}G_E - G_M)F_3^*.$$

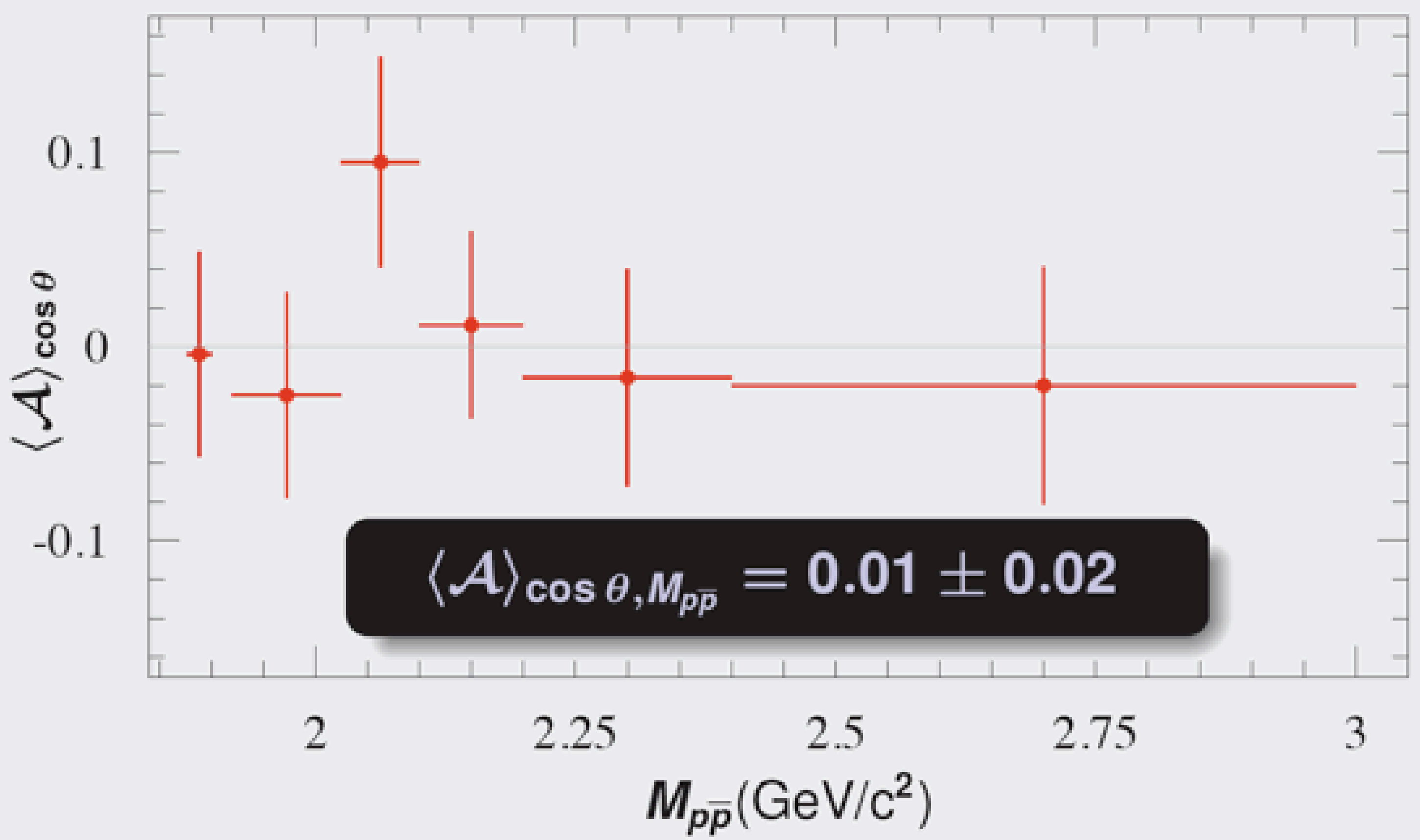
2γ–contribution:

- **Induces four new terms**
- **Odd function of *θ*:**
- **Does not contribute at *θ* =90°**

$\gamma\gamma$ exchange from $e^+e^- \to p\bar{p}\gamma$ BABAR data

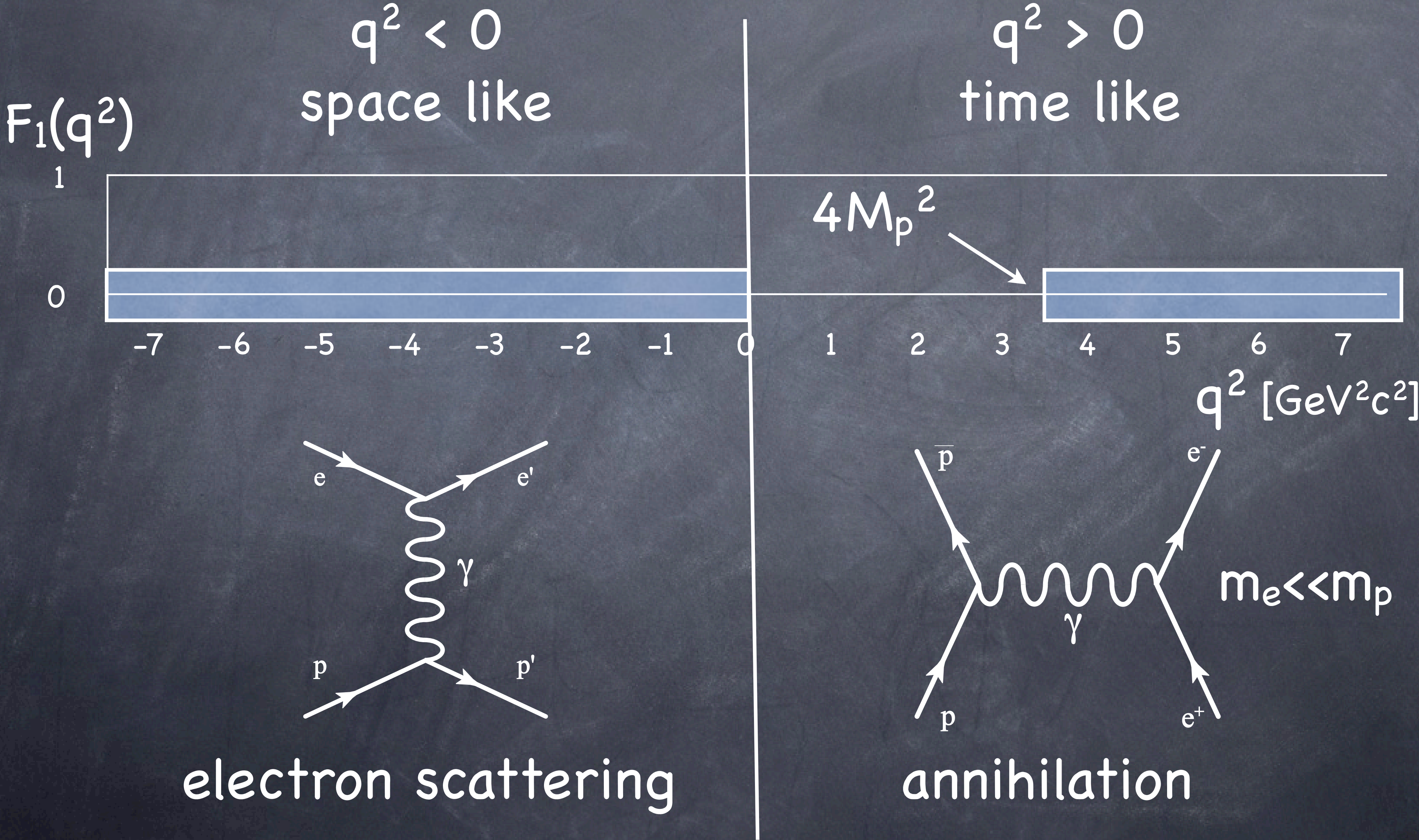
PLB659, 197

$$\mathcal{A}(\cos\theta, M_{p\bar{p}}) = \frac{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) - \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) + \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}$$



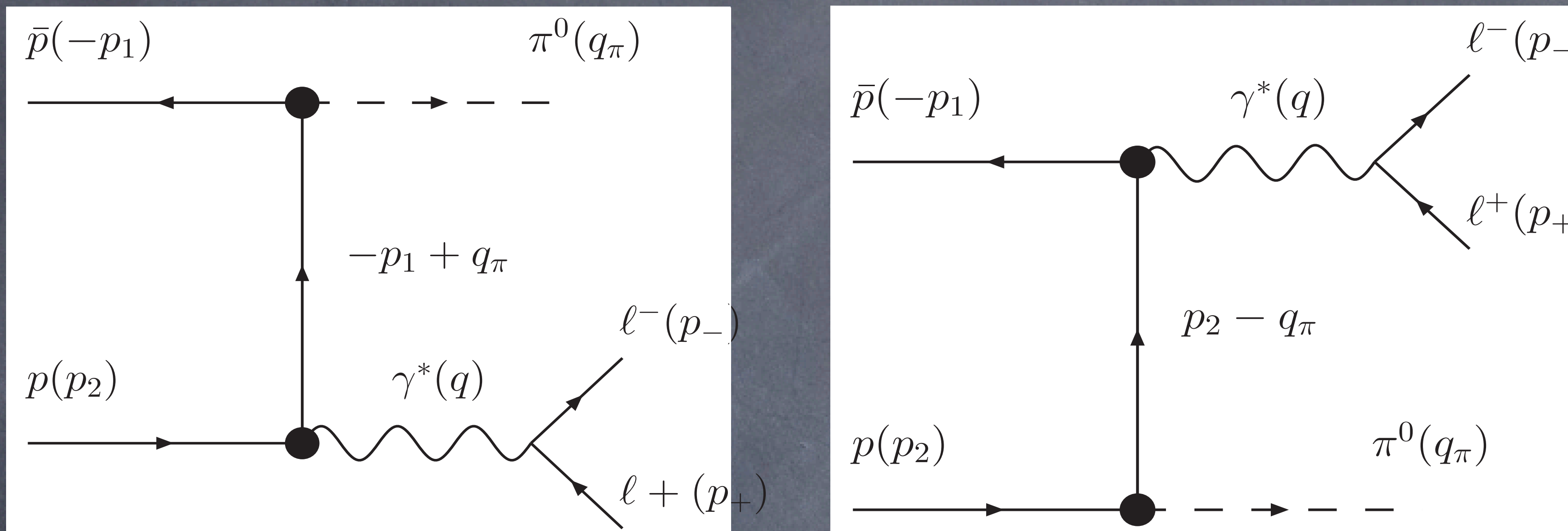
Other EM structure Physics

Definitions

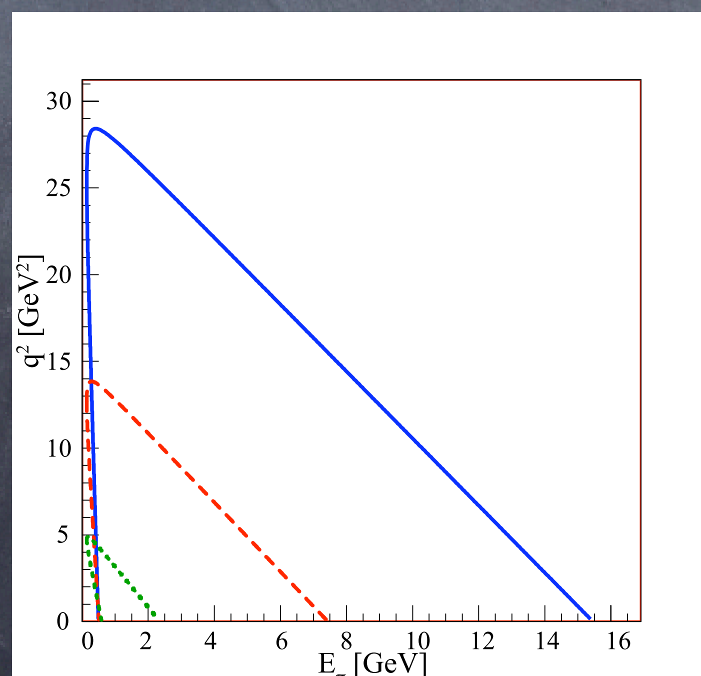


EM form factor below threshold

Process: $\bar{p}p \to \pi^0 e^+e^-$ analogue to ISR



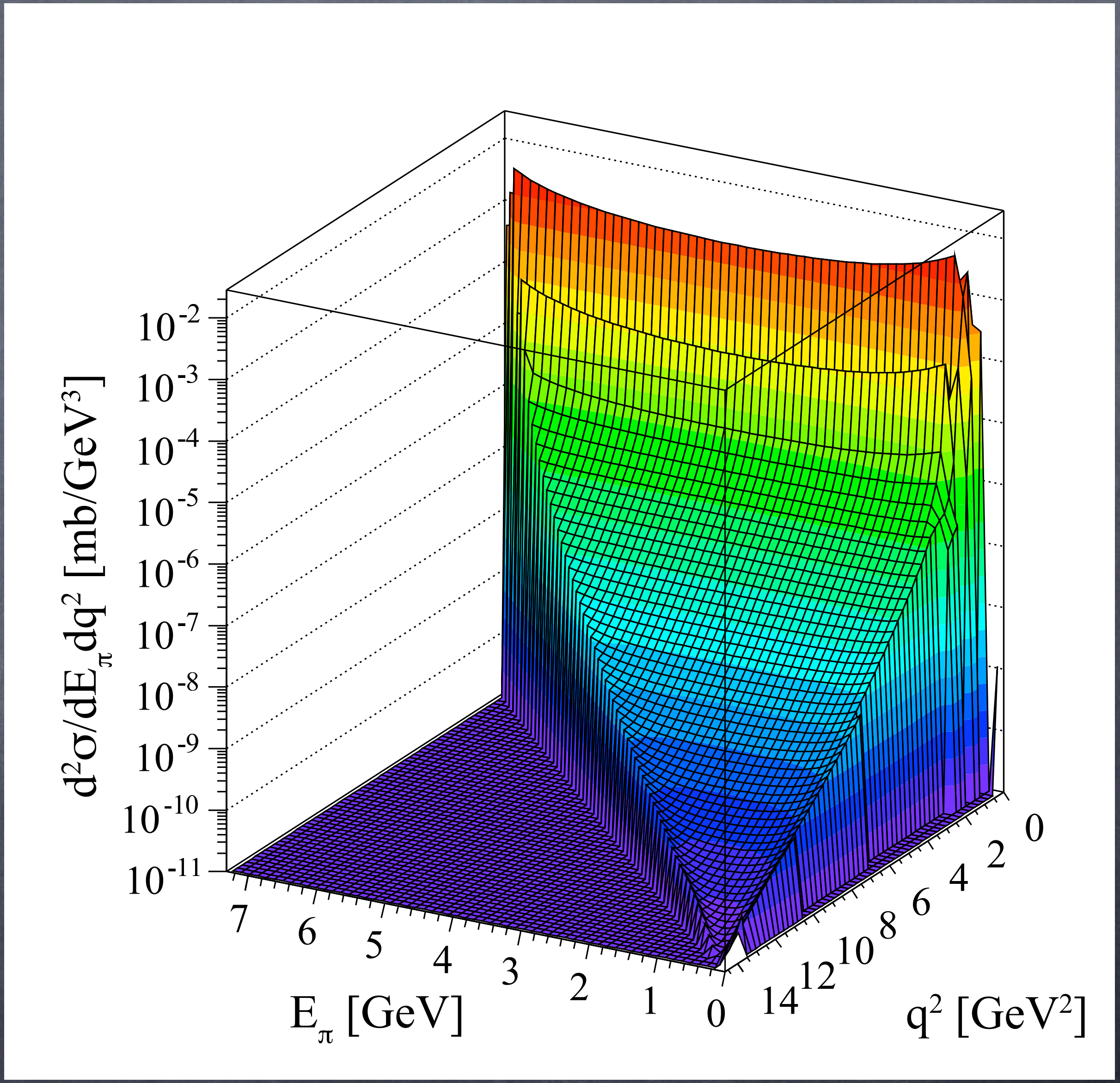
(a) (b)



EM form factor below threshold

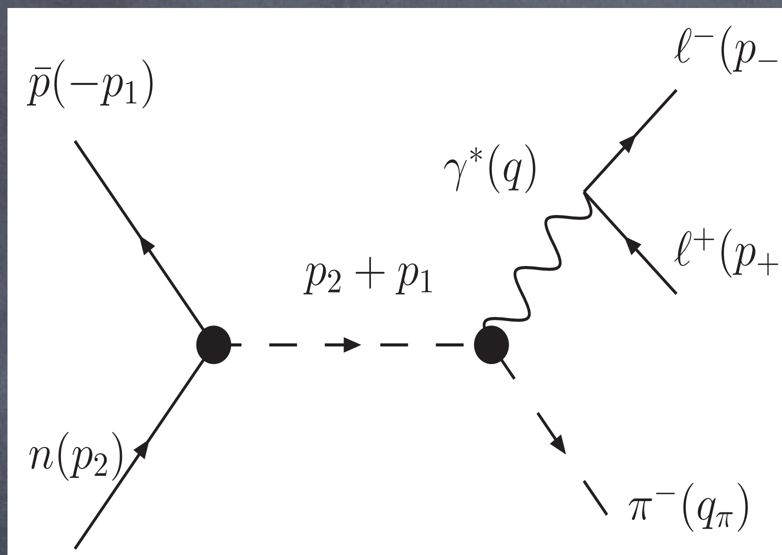
Process:

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

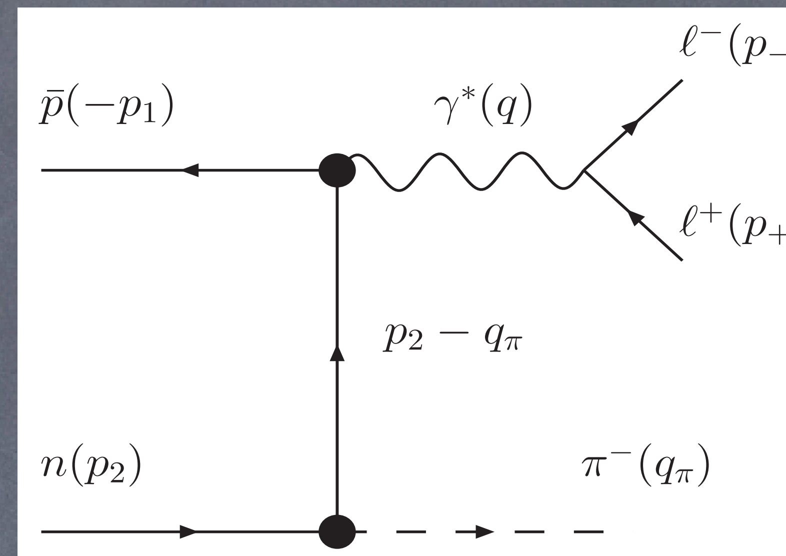


Axial form factor $Q_{wf}\ \bar{q}\gamma_\mu\gamma^5 q$

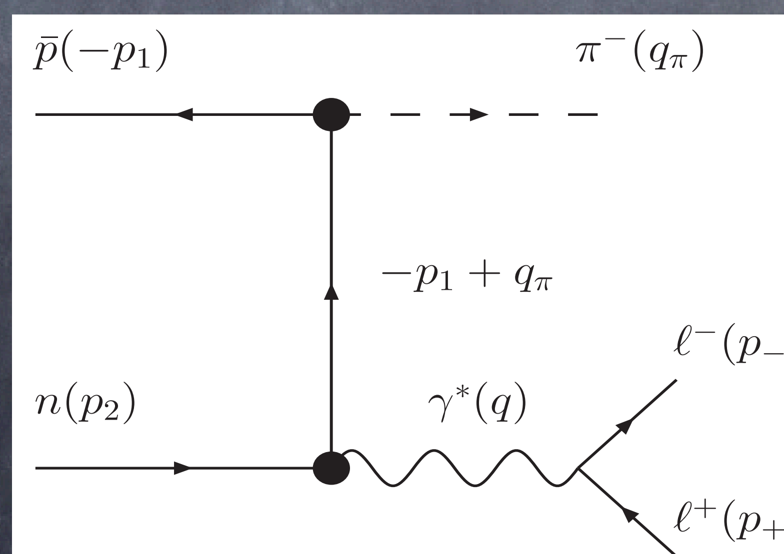
Process: $\bar{p}n \to \pi^- e^+e^-$



(a)



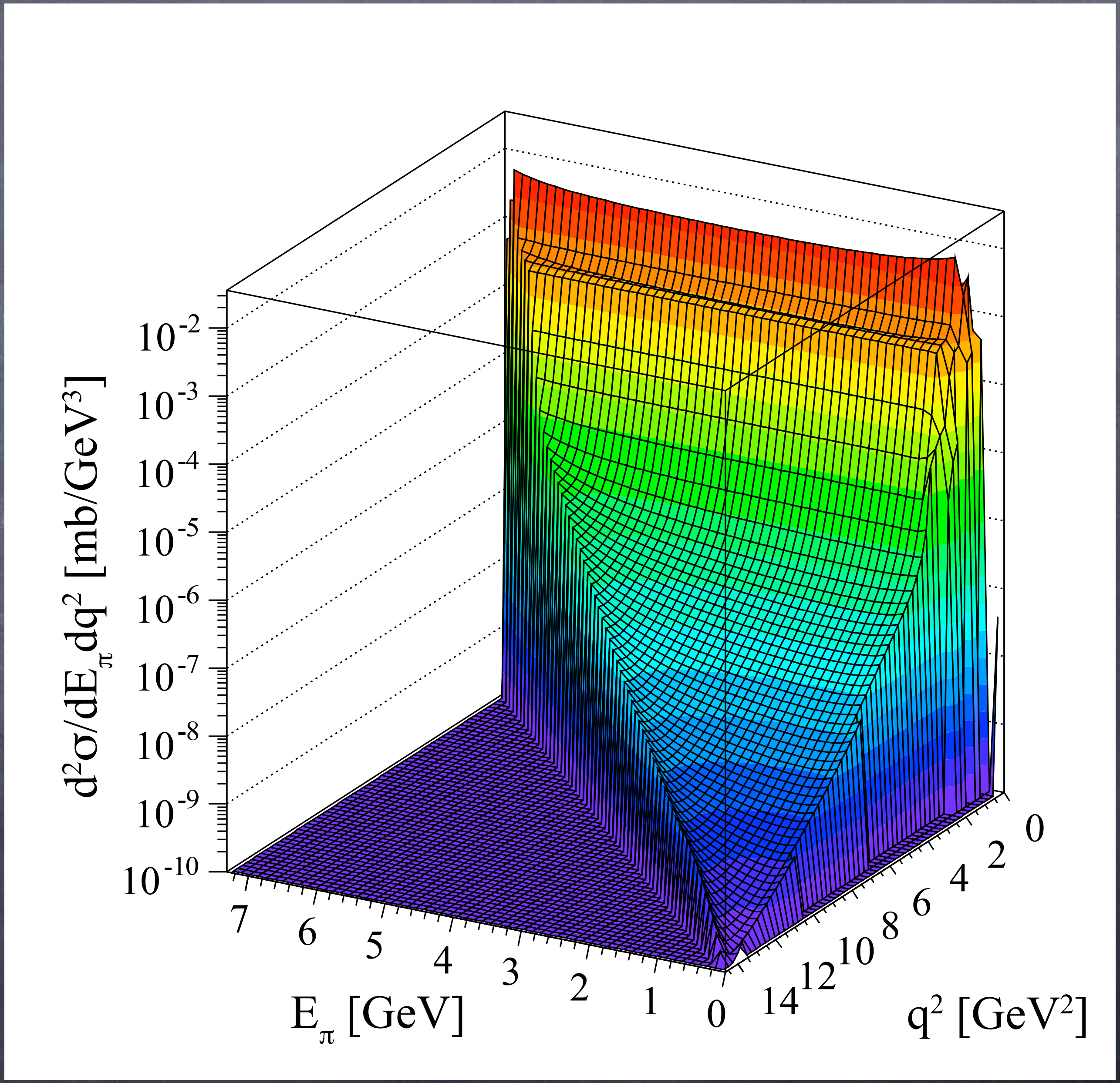
(b)



Axial form factor

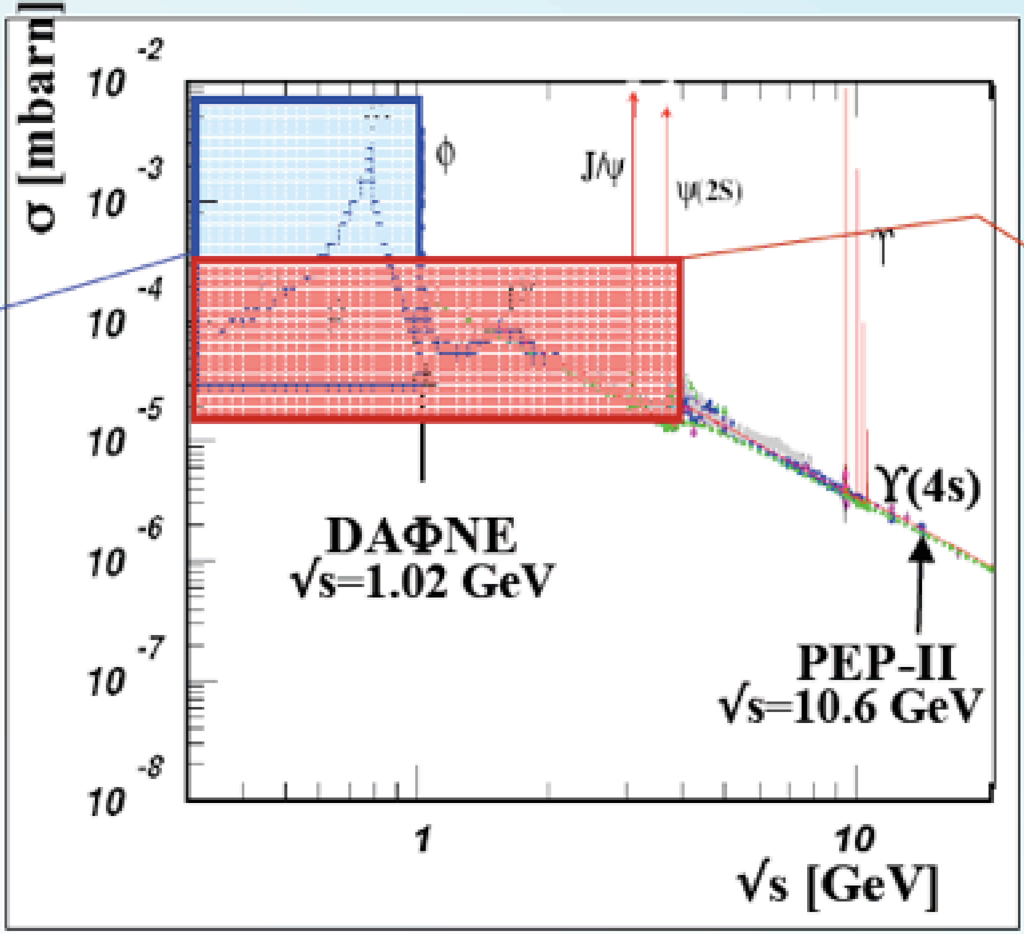
Process:

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



Radiative Return at Particle Factories

Experiment KLOE:
Energy region < 1 GeV, dominated by 2π-channel (ρ-resonance)



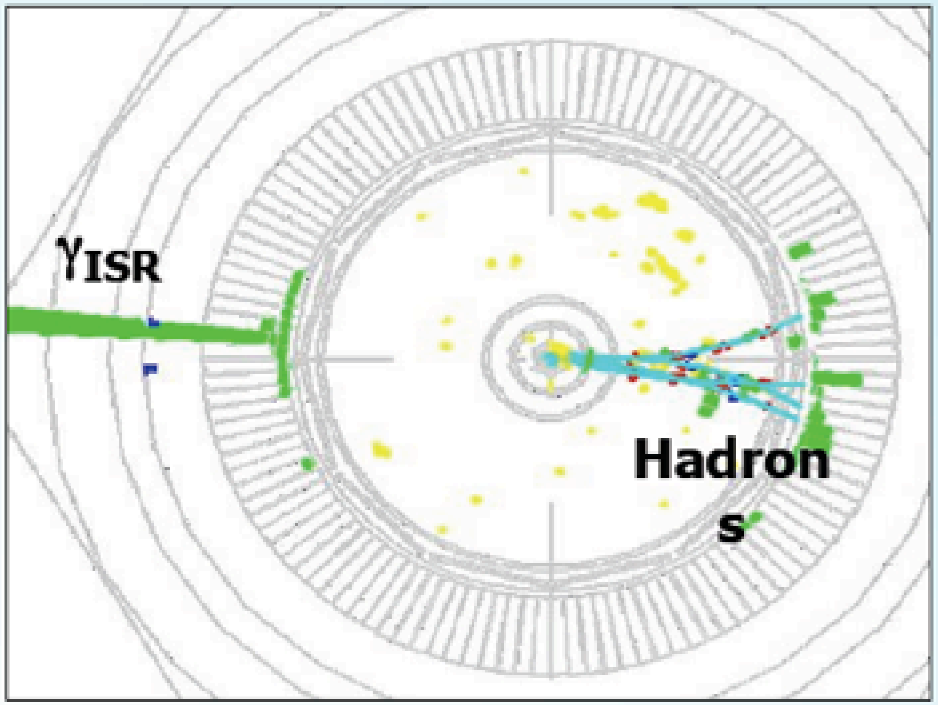
Experiment BaBar:
Energy region 1 ... 3 GeV, dominated by higher multiplicities (esp. 4π), up to recently data with 20 ... 50% systematic errors!

Using the method of the **Radiative Return** one can study the entire **energy region below ca. 4...5 GeV**!

ISR at Υ(4S) Energies

Features:

- Rely on **tagged photon** for identifying ISR-events , **$E_\gamma > 3$ GeV ↔ $M_{hadr} < 5$ GeV**
- High **fiducial efficiency** :
  wide-angle ISR-γ forces hadronic system into detector fiducial region at large polar angles; untagged measurement (as done with at DAΦNE) not possible at PEP-II, since hadronic system cannot be measured with high geometrical acceptance in such a case



- Harder momentum spectrum
  - **fewer problems with soft particles;**
  - **allows to go down to threshold**
- Excellent momentum resolution by means of **kinematic fit**
- Typically **systematic uncertainties ~5%** up to ~20% depending on mass and channel

T_{p_bar} (GeV)	Q^2 $(GeV/c)^2$	θ_{CM}	θ_{lab}	p_{lab} (GeV/c)	one π Misident. Probability ECAL×DIRC×dE/dx	$\pi^+ \pi^-$ Misident. Probability
1.	5.4	20°	13°	2.2	0.001 × 0.5 ×0.05 = 2.5 10^{-5}	0.1 10^{-9}
		160°	132°	0.57	0.033 × 0.003 ×0.03 = 3.0 10^{-6}	
		90°	54°	1.43	0.001 × 0.3 ×0.03 = 9. 10^{-6}	0.1 10^{-9}
		90°	54°	1.43	0.001 × 0.3 × 0.03 = 9. 10^{-6}	
2.5	8.2	20°	10°	3.7	0.001 × 1. ×0.05 = 5. 10^{-5}	0.3 10^{-9}
		160°	117°	0.7	0.014 × 0.014 × 0.03 = 6. 10^{-6}	
		90°	41°	2.2	0.001 × 1. × 0.03 = 3. 10^{-5}	0.9 10^{-9}
		90°	41°	2.2	0.001 × 1. × 0.03 = 3. 10^{-5}	
5.	12.9	20°	7.4°	6.1	0.001 × 1. × 0.1 = 10^{-4}	0.6 10^{-9}
		160°	102°	0.8	0.014 × 0.014 × 0.03 = 6. 10^{-6}	
		90°	32°	3.4	0.001 × 1. × 0.05 = 5. 10^{-5}	2.5 10^{-9}
		90°	32°	3.4	0.001 × 1. × 0.05 = 5. 10^{-5}	
10.	22.3	20°	5.4°	10.9	0.001 × 1. × 0.3 = 3. 10^{-4}	5.4 10^{-9}
		160°	85°	1.0	0.005 × 0.12 × 0.03 = 1.8 10^{-5}	
		90°	24°	5.95	0.001 × 1. × 0.1 = 1. 10^{-4}	10. 10^{-9}
		90°	24°	5.95	0.001 × 1. × 0.1 = 1. 10^{-4}	