Complementary views on nucleon structure from JLab and BESIII to PANDA

Scattering and annihilation electromagnetic processes
ECT*, Trento, 18 - 22 February

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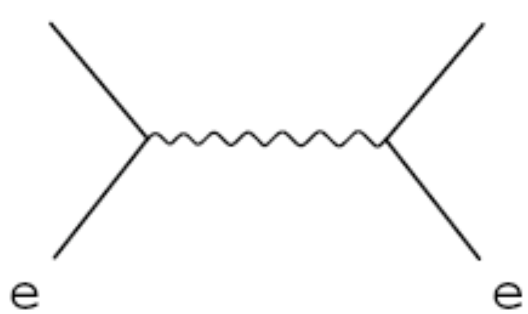
Outline

- EM Form Factor in the time like region
- Data (pp -> e^+e^-, e^+e^- -> pp, e^+e^- -> γpp)
- Electromagnetic probe opportunities

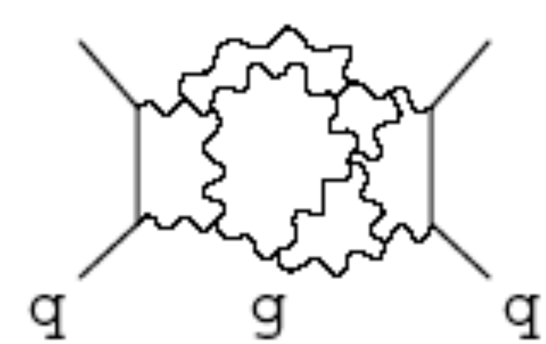
How do Hadrons arise from QCD?

- Fundamental differences relative to QED
  - Self-interacting: highly nonlinear
  - Interaction increases at large distance: Confinement
  - Interaction decreases at small distance: Asymptotic freedom

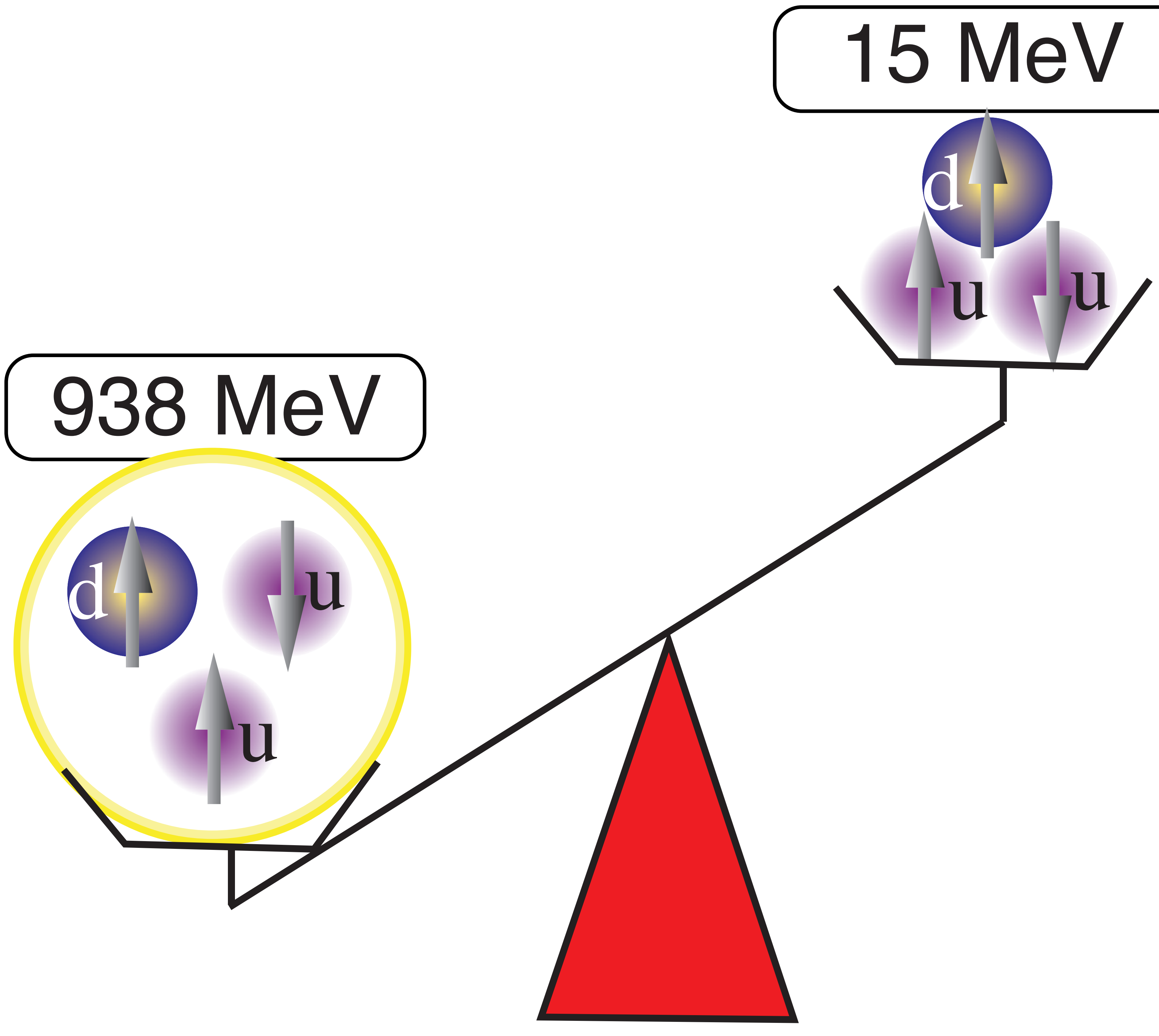
QED



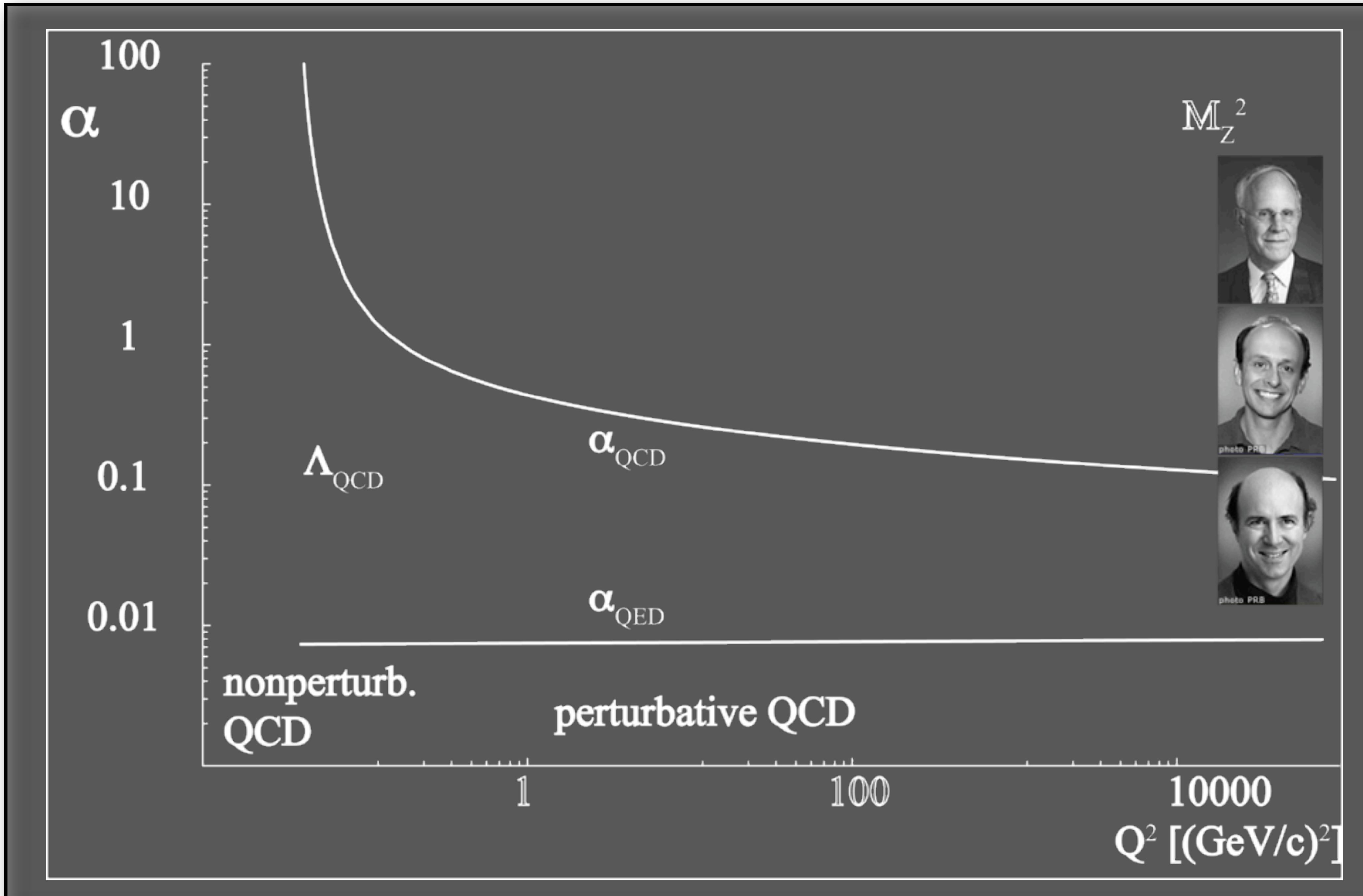
QCD



How do Hadrons arise from QCD?



QCD-Renormalisation à la QED



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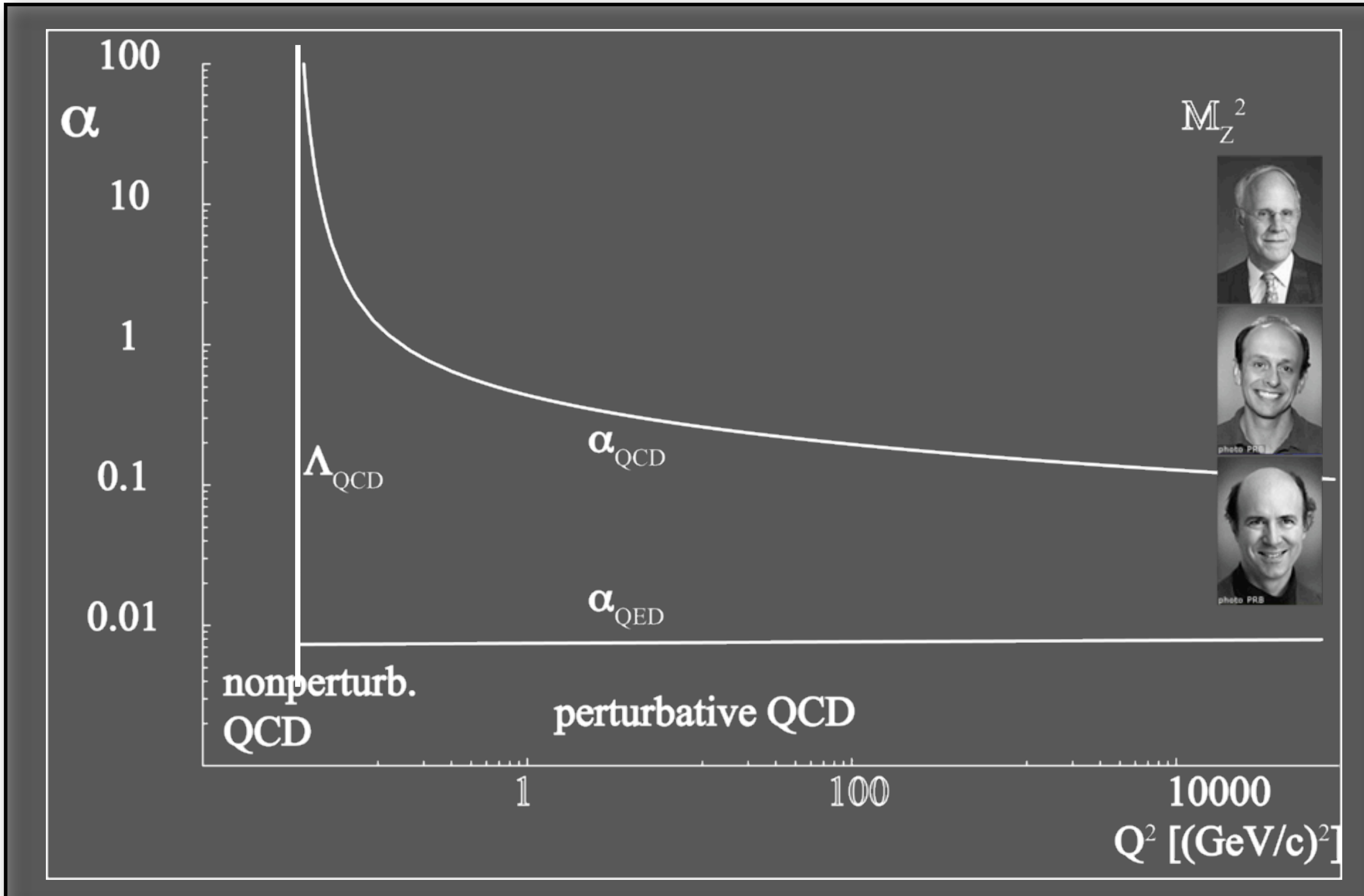

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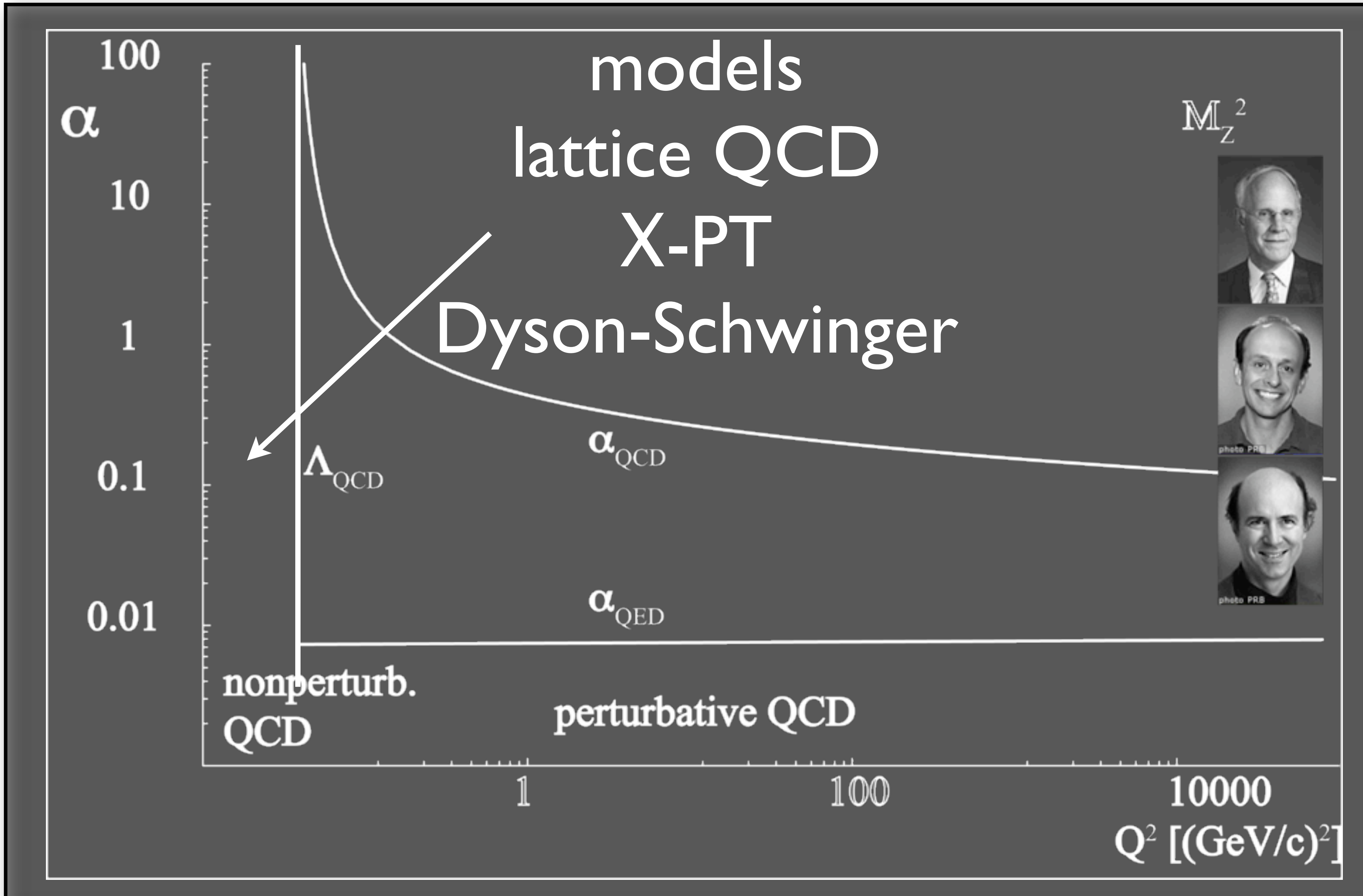

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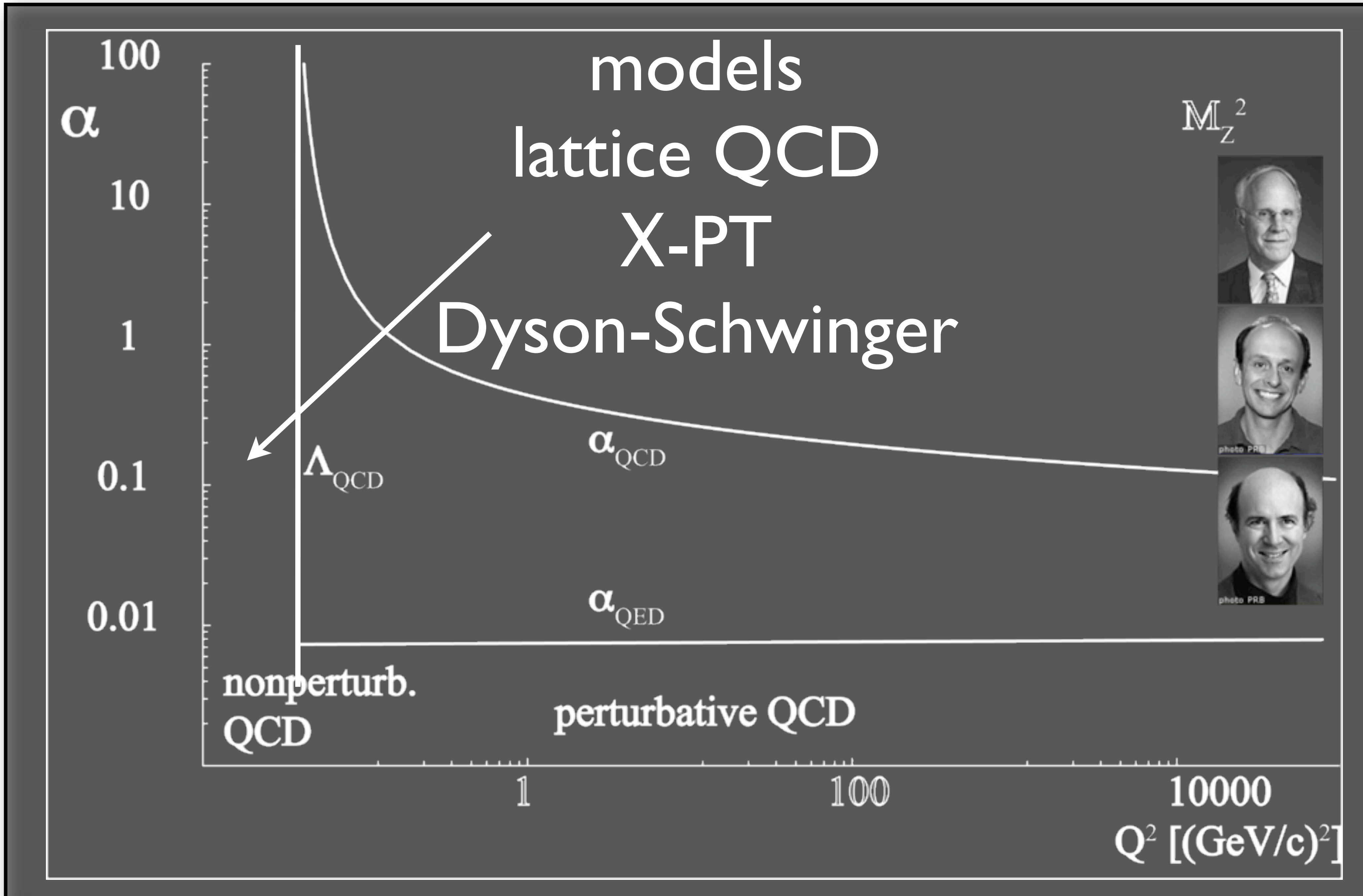
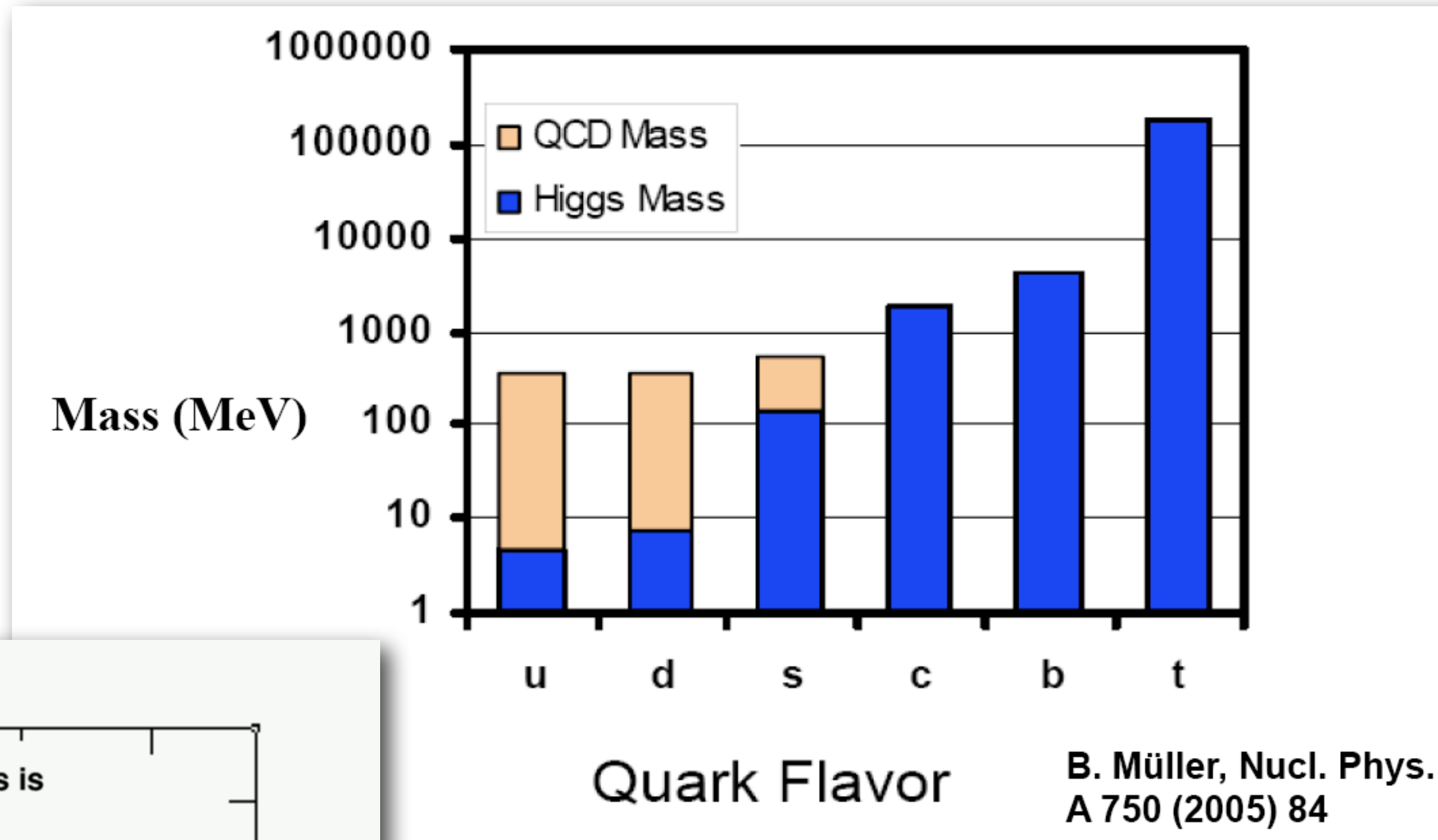
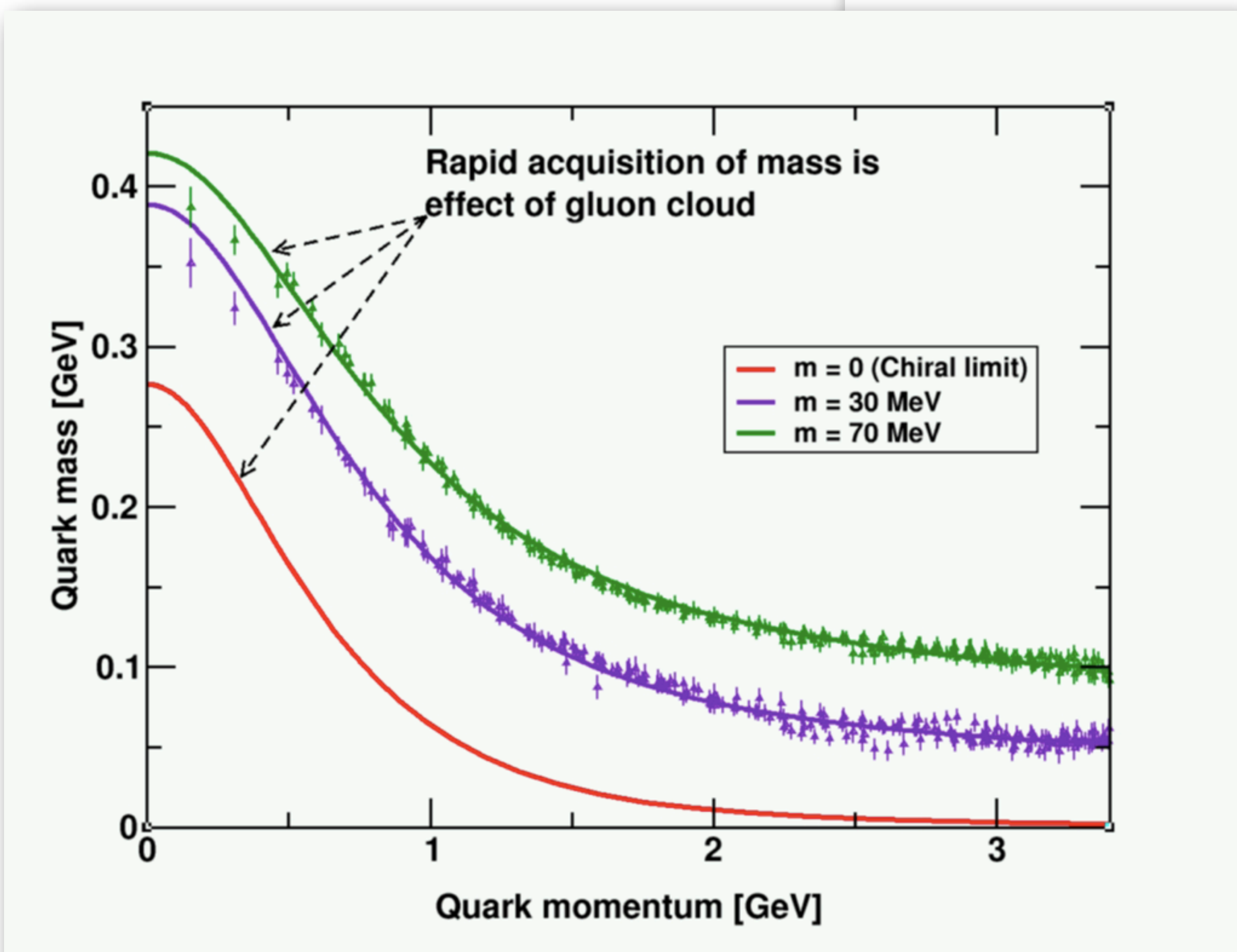


- origin of nucleon mass
- quark and gluon condensates
- structure of the nucleon -> Form Factor

Visible Baryonic Mass Dominated by QCD





R. Hofstadter (1956), Proton Electromagnetic Form Factor

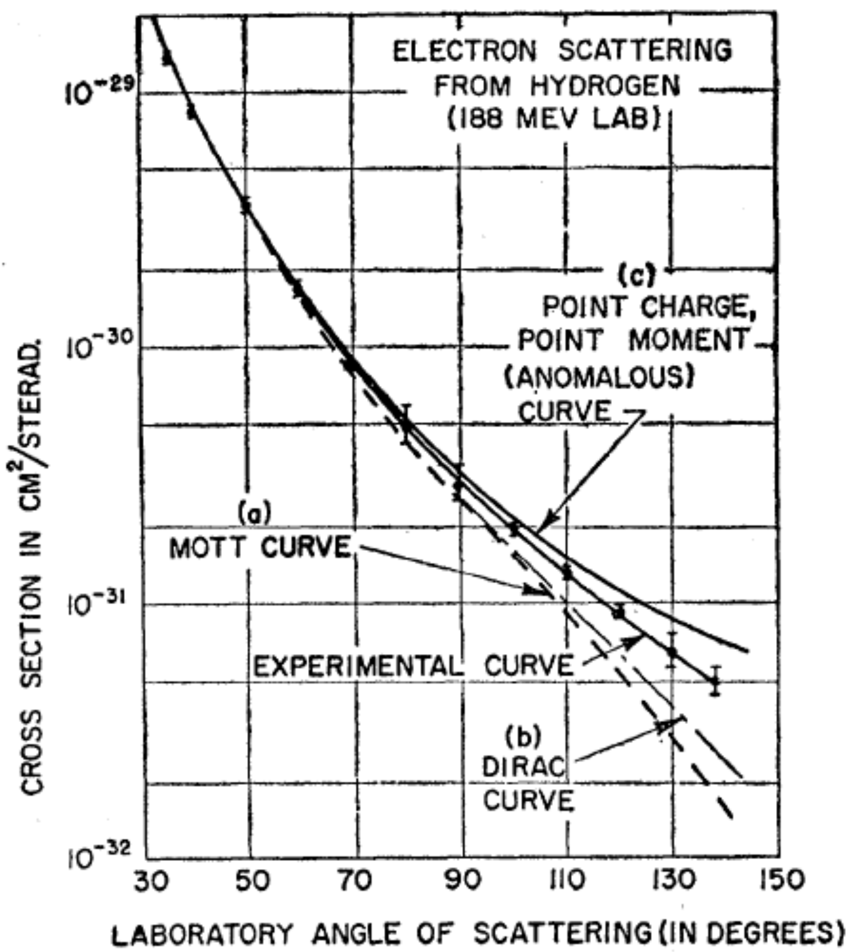


FIG. 24. Electron scattering from the proton at an incident energy of 188 Mev. The experimental points lie below the point-charge point-moment curve of Rosenbluth, indicating finite size effects.

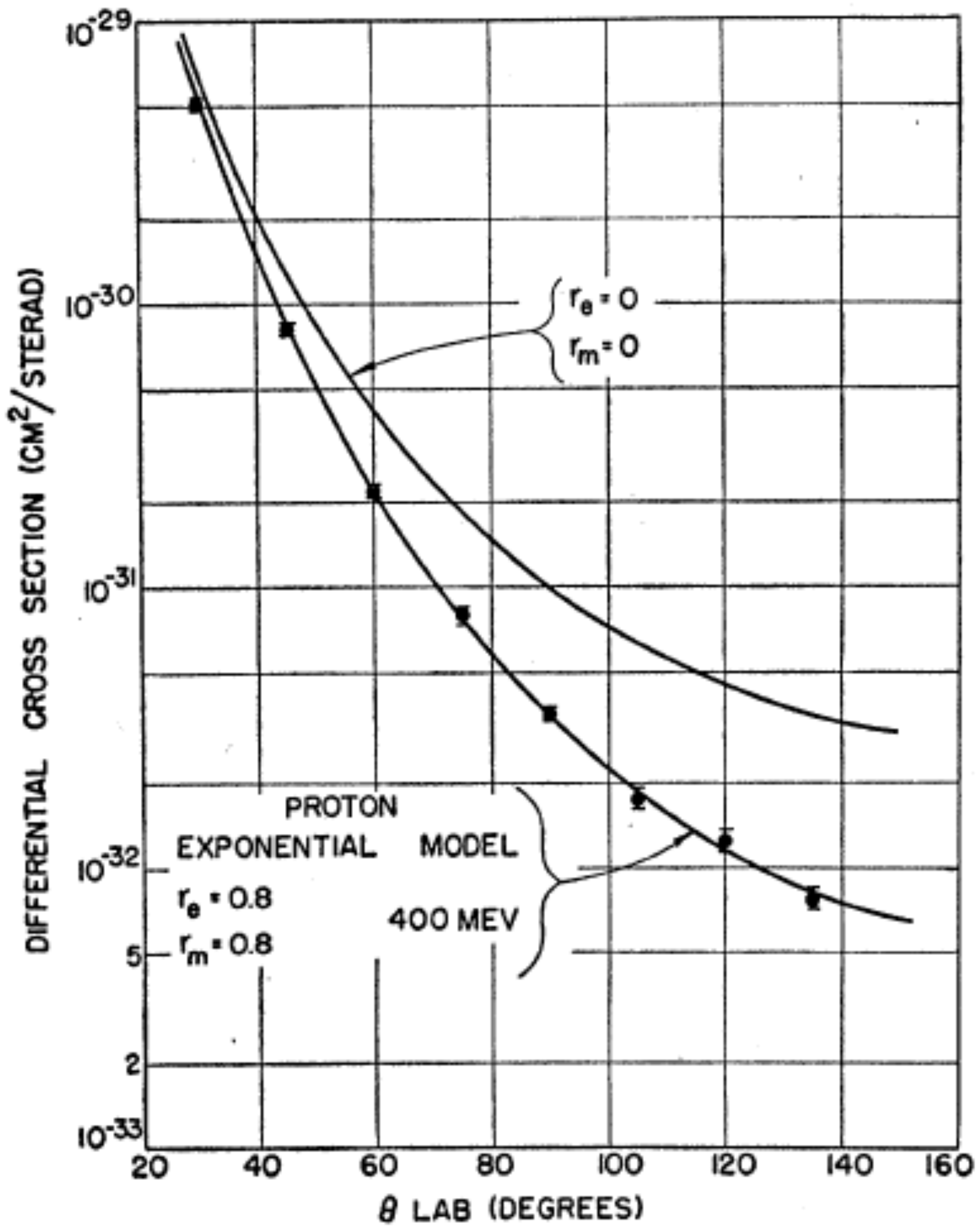
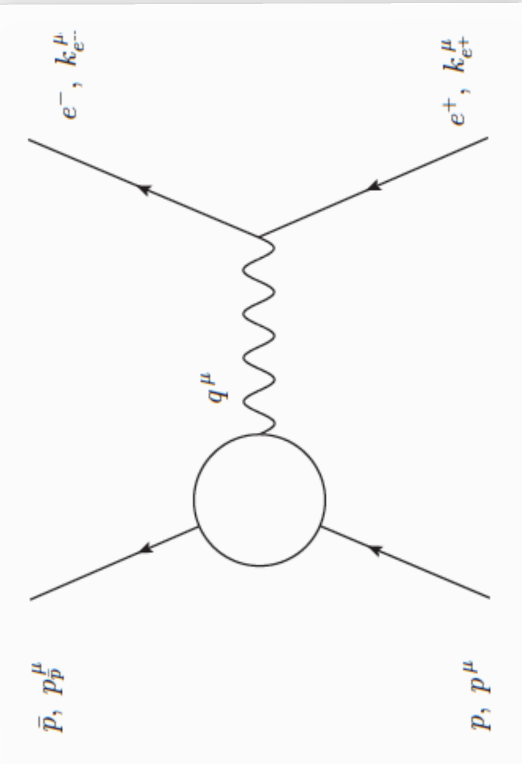


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $=0.80\times10^{-13}$ cm.

Still today a hot topic of hadron physics. Electromagnetic form factors a testing ground for our understanding of QCD

R. Hofstadter, Rev. Mod. Phys. , 28 (1956), 243



Electromagnetic Form Factor (QED)

vector current of quarks

$$< \bar{N}(p')|q_u \bar{u}\gamma_\mu u + q_d \bar{d}\gamma_\mu d + \ldots |N(p) >$$

matrix element

$$\frac{e^2}{q^2}\ \bar{u}(k_2)\gamma_\mu u(k_1)\ \ \bar{u}(p_2)[F_1(q^2)\gamma_m u + i\kappa\frac{\sigma_{\mu\nu}q^\nu}{2m_p}F_2(q^2)]u(p_1)$$

Dirac

$G_E = F_1 + F_2$

$G_M = F_1 + \tau\, F_2$

Pauli

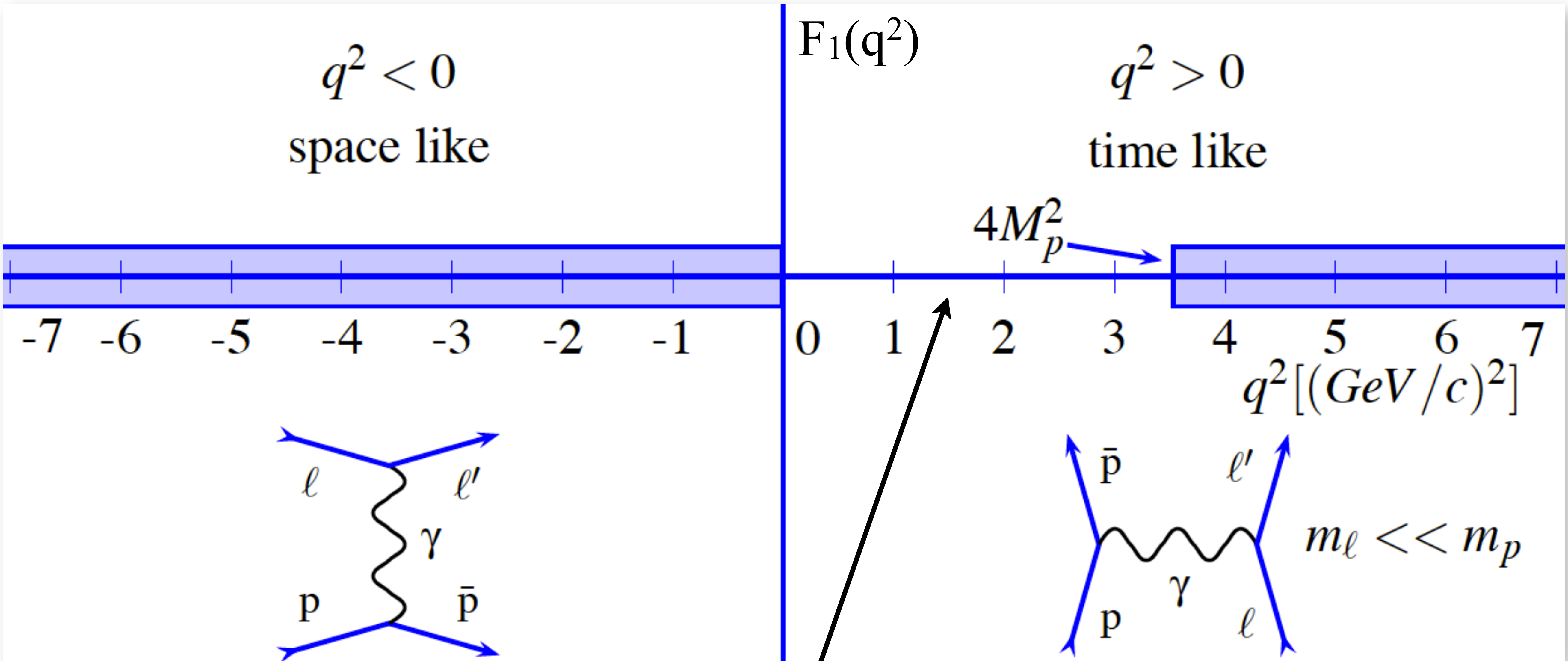
all hadronic structure and strong interaction in form factors, but subject to electromagnetic (QED) radiative corrections

hadronic vector current: two form factors (2 s + 1)

internal structure of hadron ground state

Dirac	Pauli
$F_1^p(q^2=0) = 1$	$F_2^p(q^2=0) = 1$
$F_1^n(q^2=0) = 0$	$F_2^n(q^2=0) = 1$

Electromagnetic Form factors of the Nucleon



unphysical region

Form Factor real

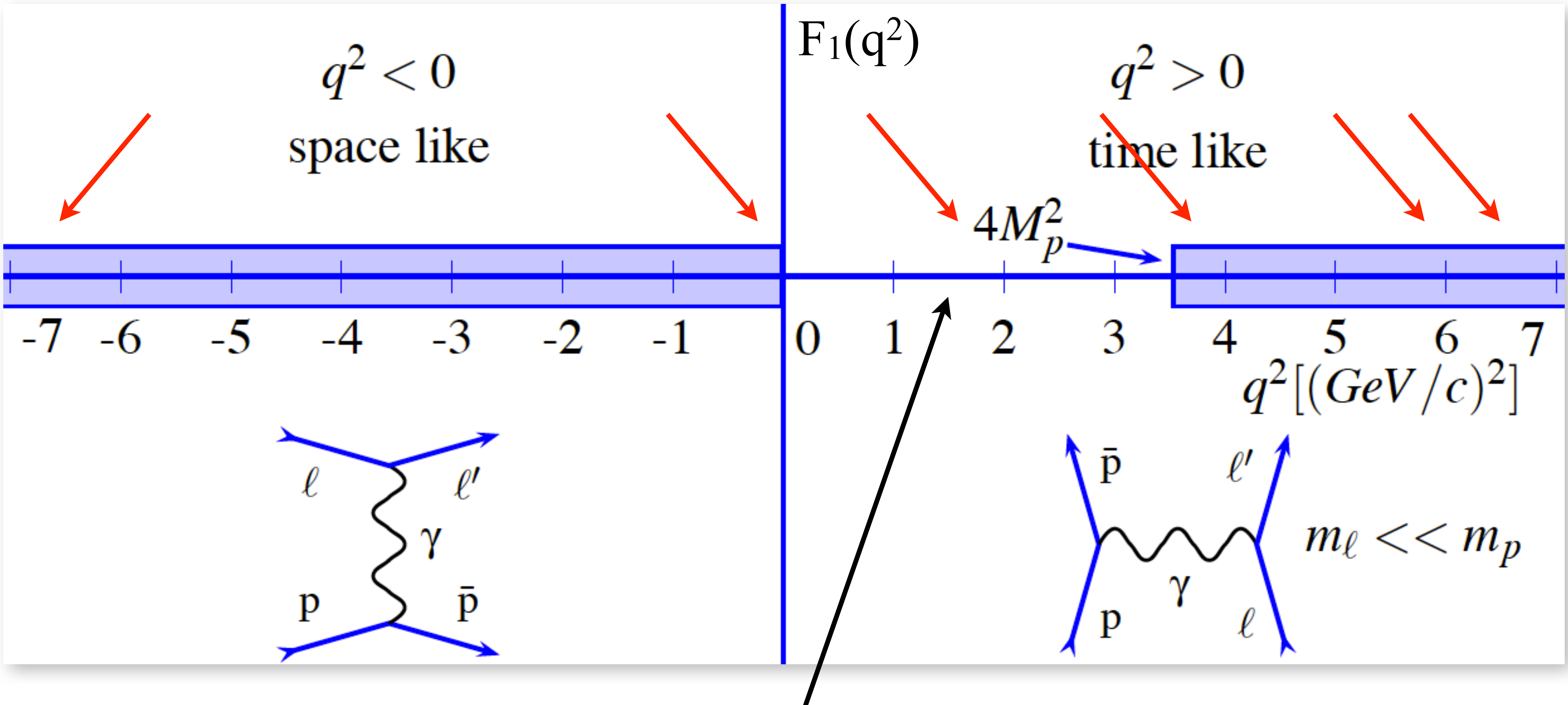
cross section (Rosenbluth)
no single spin observables
double spin observables

Form Factor complex

cross section (angular Distr.)
single spin observables (P_y)
double spin observables

connected by dispersion relations

Electromagnetic Form factors of the Nucleon



Form Factor real

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

Form Factor complex

cross section (angular Distr.)
single spin observables (P_y)
double spin observables

connected by dispersion relations

Timelike Form Factors

QCD counting rules constrain asymptotic behavior

$$\begin{aligned} q^2 &\rightarrow -\infty \\ F_i(q^2) &\rightarrow (-q^2)^{-(i+1)} \\ i = 1\ \mathrm{Dirac\,FF} & \qquad i = 2\ \mathrm{Pauli\,FF} \\ G_{E,M} &\rightarrow (-q^2)^{-2} \end{aligned}$$

Analyticity

$$\begin{aligned} q^2 &\rightarrow \pm\infty\ \ \mathrm{Phragmen\,Lindeloef} \\ G_{E,M}(-\infty) &= G_{E,M}(+\infty) \end{aligned}$$

(imaginary part must vanish for large q^2)

Observables

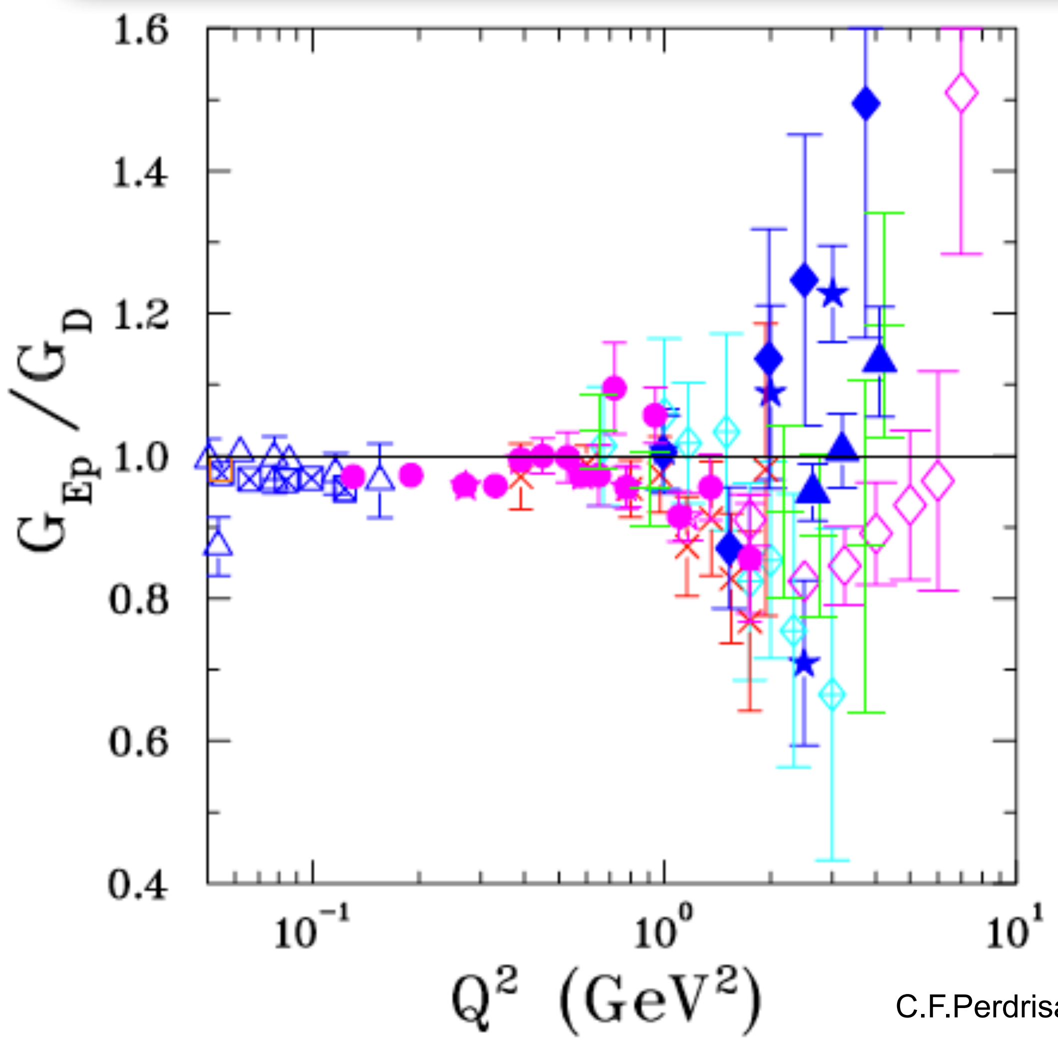
Cross Section (scattering)
(Rosenbluth Separation)

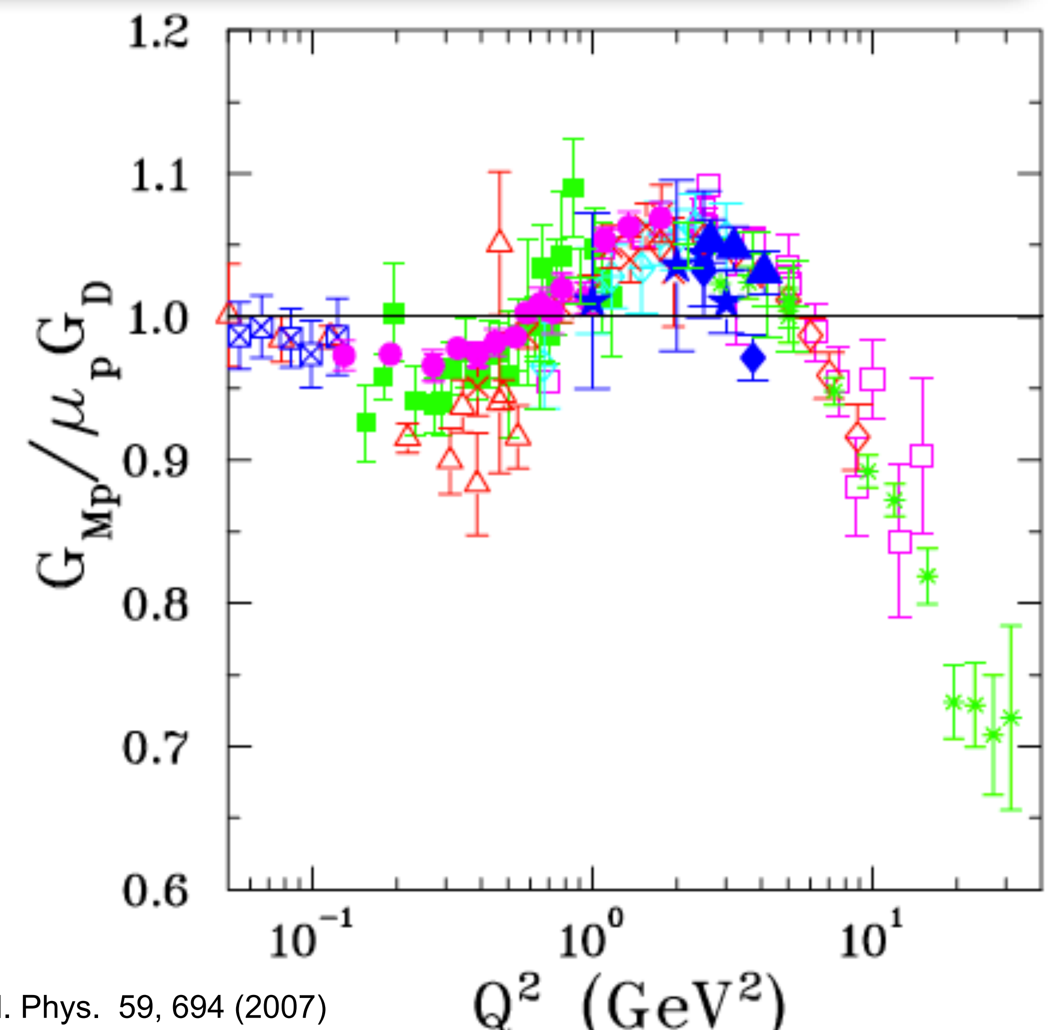
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \left(G_E^2 + \tau \boxed{\left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]} G_M^2\right)/(1+\tau)$$

$$\tau = Q^2/4M^2$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \left[G_E^2 + \frac{\tau}{\epsilon} G_M^2\right]/(1+\tau)$$

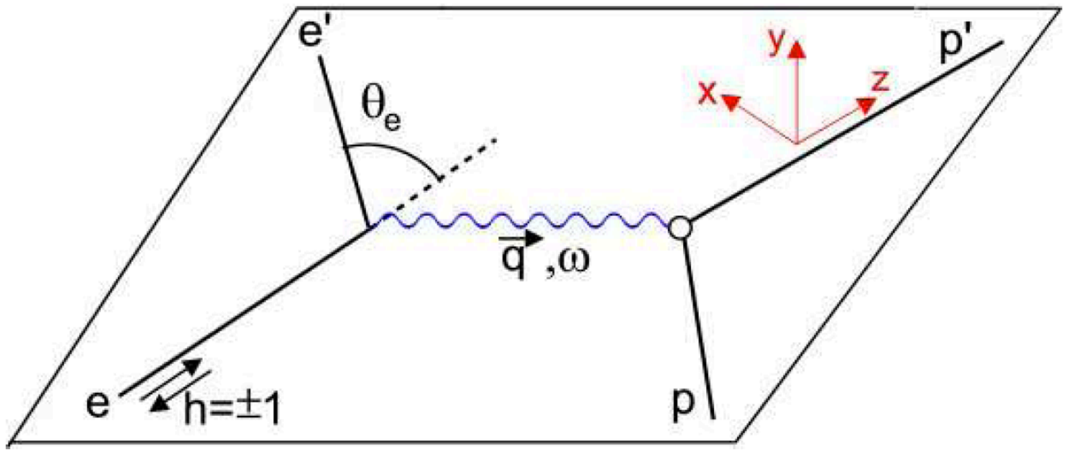
$$\boxed{\left(\frac{d\sigma}{d\Omega}\right)_{reduced} = \frac{\epsilon(1+\tau)}{\tau}\left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = G_M^2 + \frac{\epsilon}{\tau} G_E^2}$$





C.F.Perdrisat et al., Prog. Part. Nucl. Phys. 59, 694 (2007)

Polarisation Transfer (scattering)

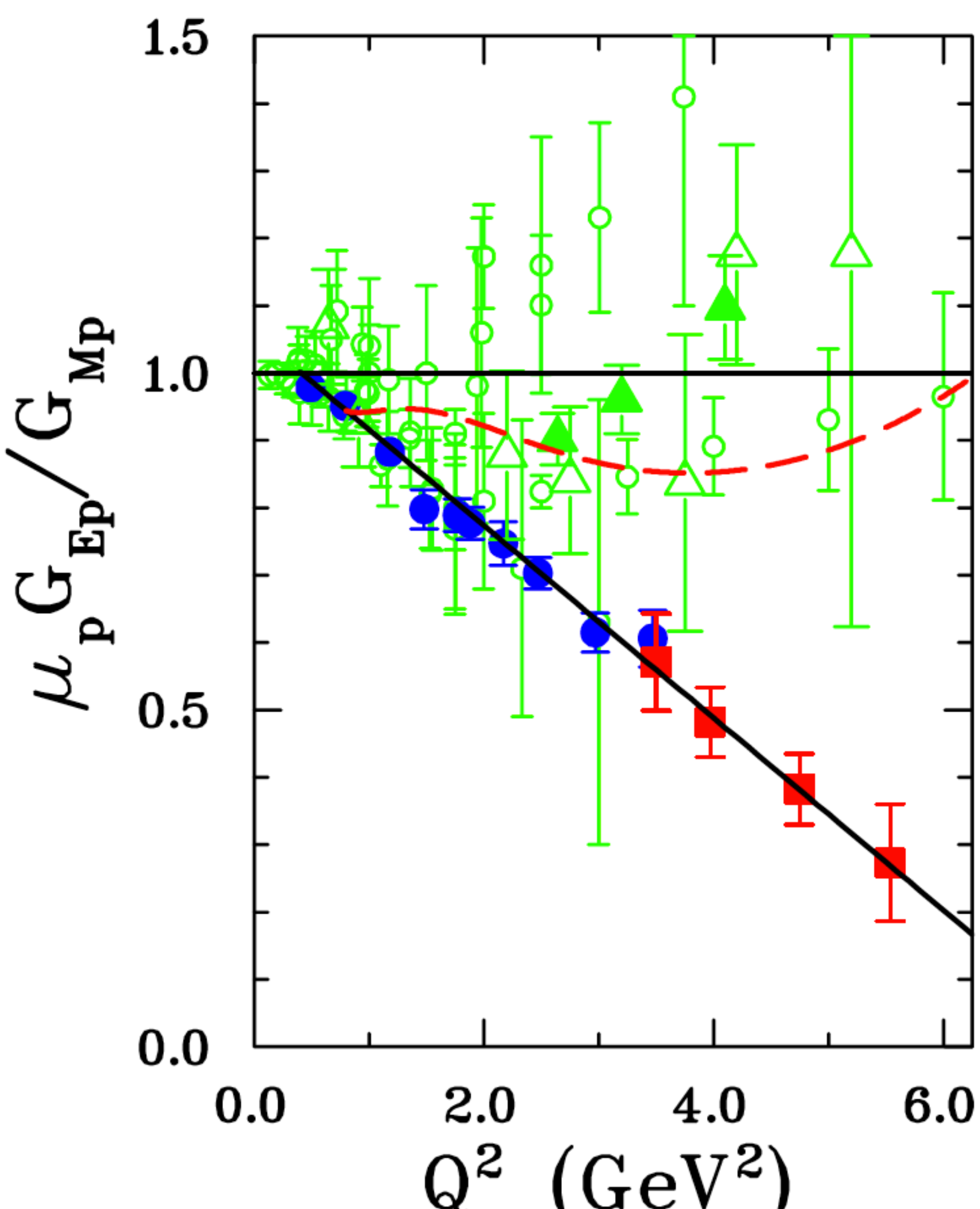


$$I_0 P_x = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_z = \frac{1}{M}(E_{beam}+E_e)\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta_e}{2}$$

$$I_0 = G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)$$

$$\boxed{\frac{G_E}{G_M} = -\frac{P_x}{P_z}\frac{(E_{beam}+E_e)}{2M}\tan(\frac{\theta_e}{2})}$$



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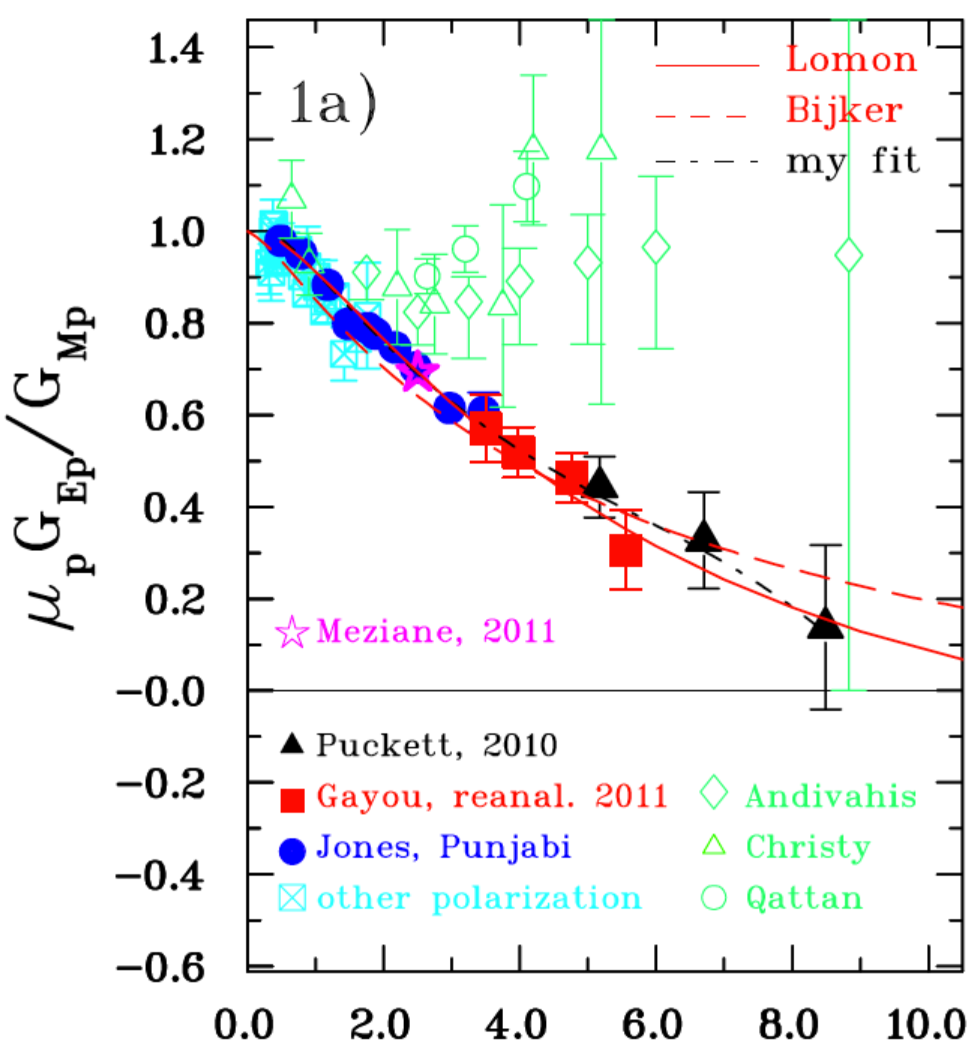
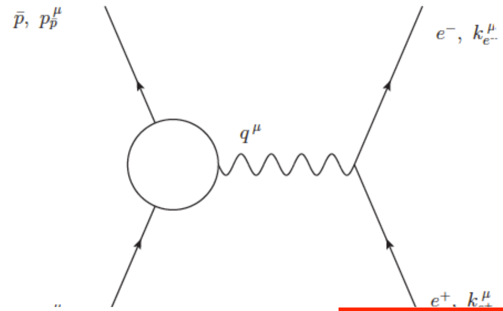
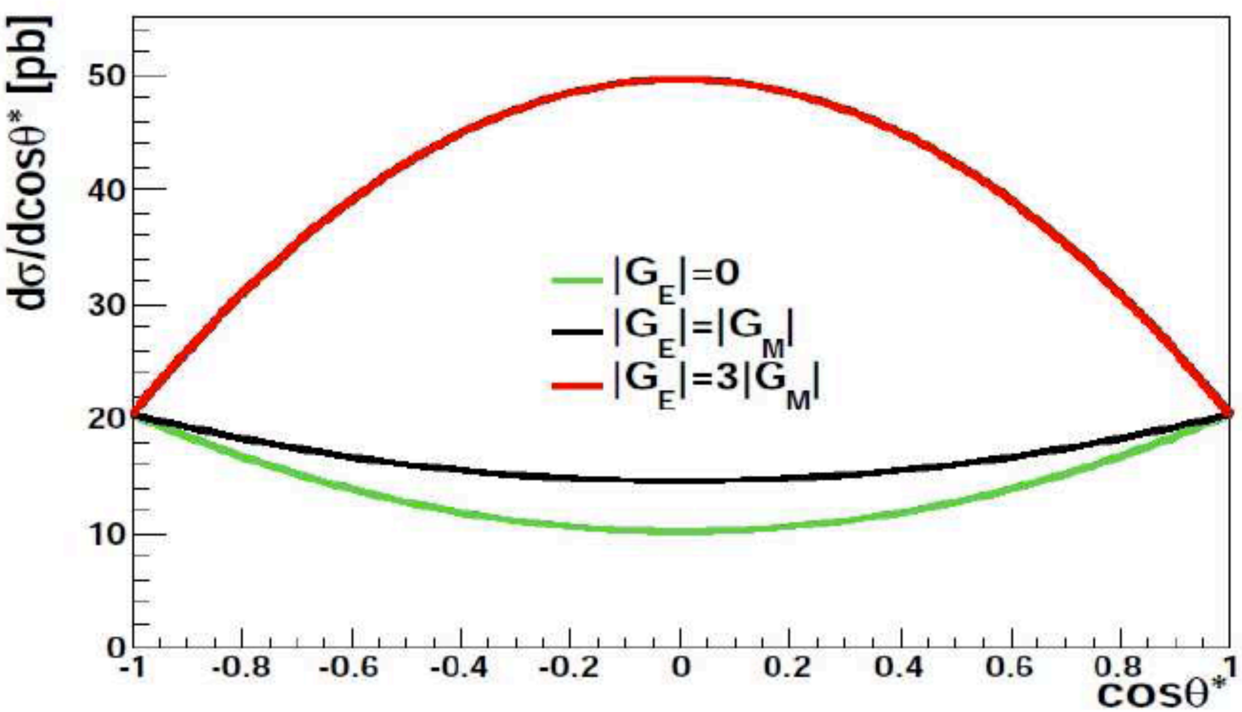




Cross Section (pbar annihilation) (Angular Distribution)

$$\frac{d\sigma}{d\cos\theta_{CM}} = \boxed{\frac{\pi\alpha^2}{8M_p\tau\sqrt{\tau(\tau-1)}}|G_M|^2}\left[\tau\left(1+\cos^2\theta_{CM}\right)+\frac{|G_E|^2}{|G_M|^2}\left(1-\cos^2\theta_{CM}\right)\right]$$



$G_E = F_1 + F_2$

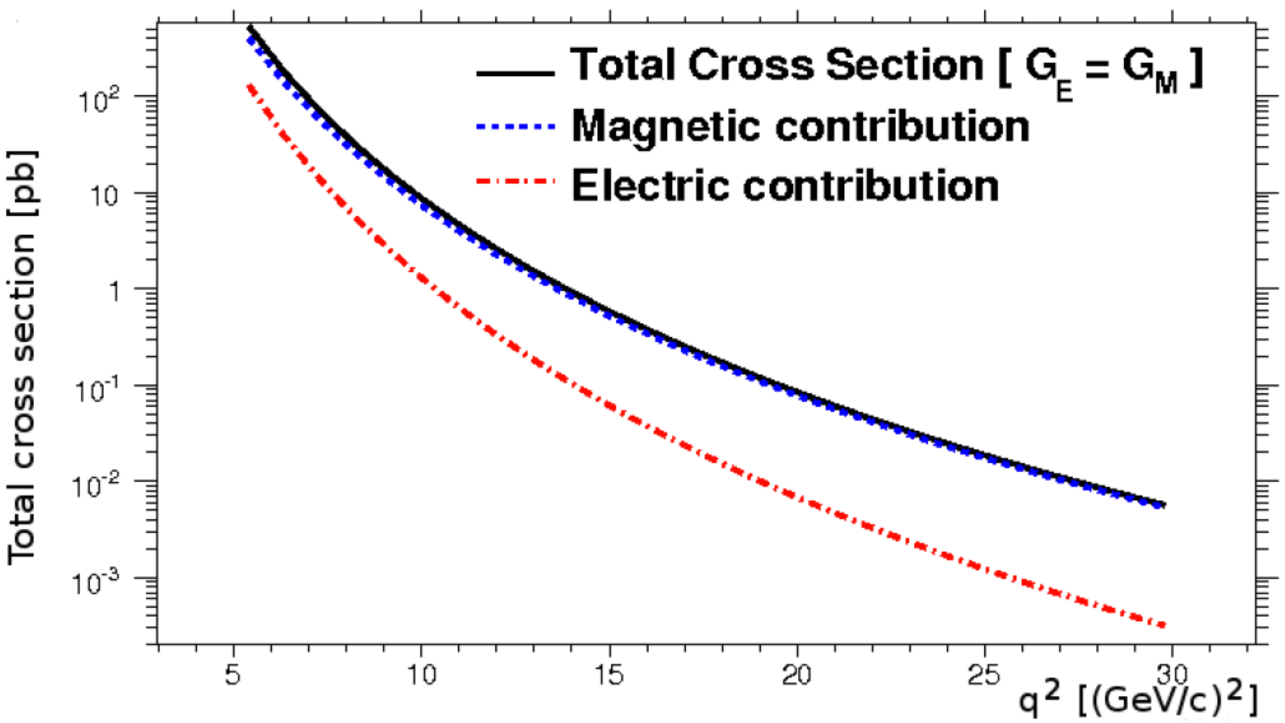
$G_M = F_1 + \tau F_2$

at threshold: $G_E = G_M$

two approaches:

assume G_E/G_M

extract G_E and G_M



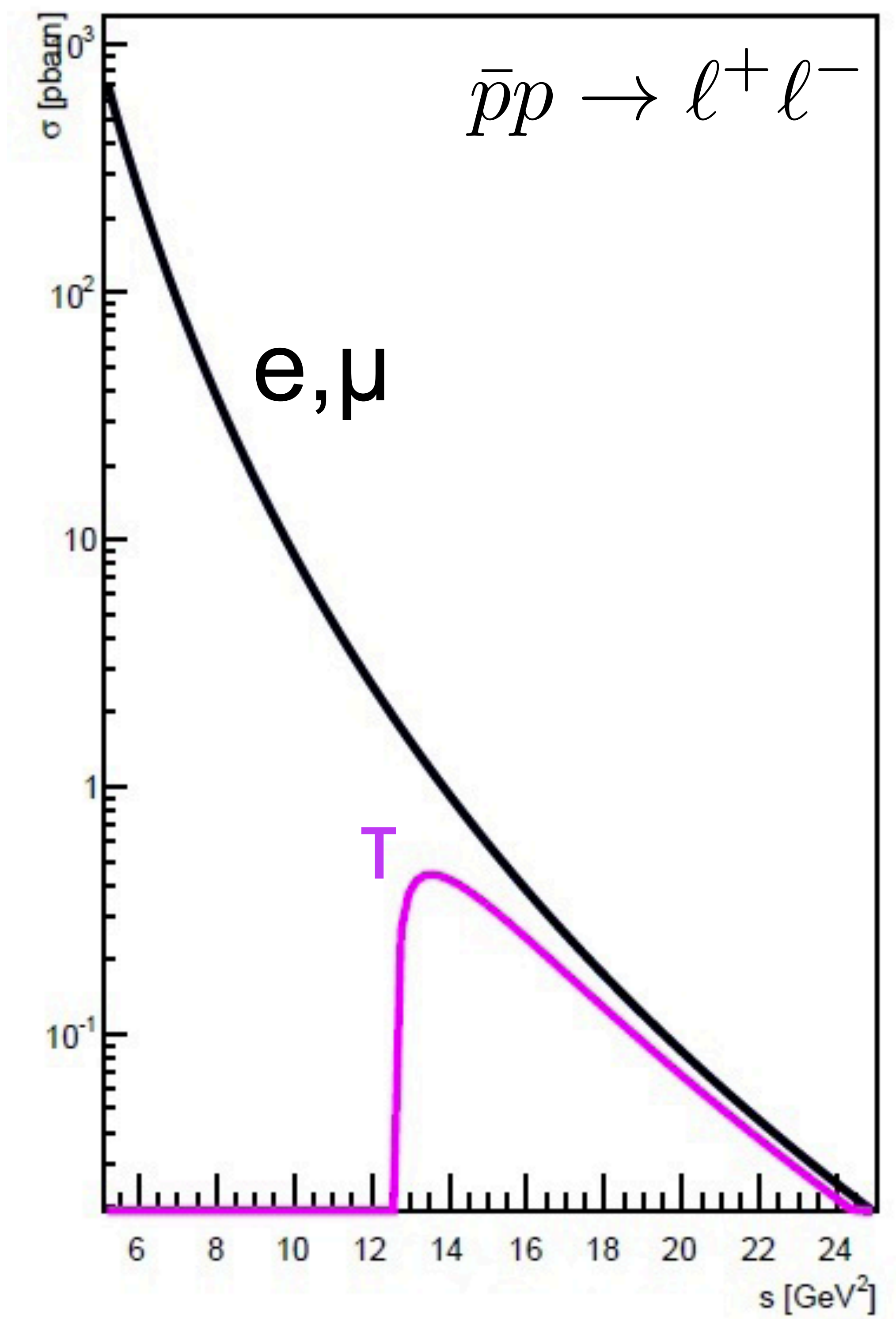
Integrated (Total) Cross Section:

$$\sigma = \frac{4\pi\alpha^2\beta C}{3q^2}\boxed{\left[|G_M|^2+\frac{1}{2\tau}|G_E|^2\right]}$$

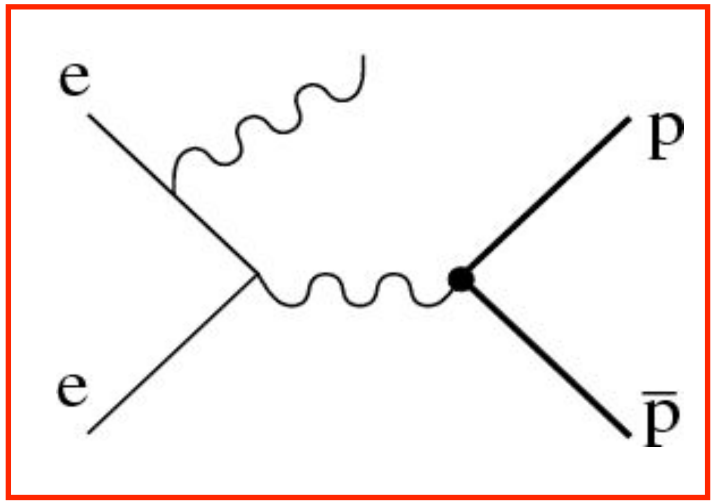
Effective FF

- Need Luminosity Measurement
- not on Resonance

Cross Section (pbar annihilation)
(total cross section)



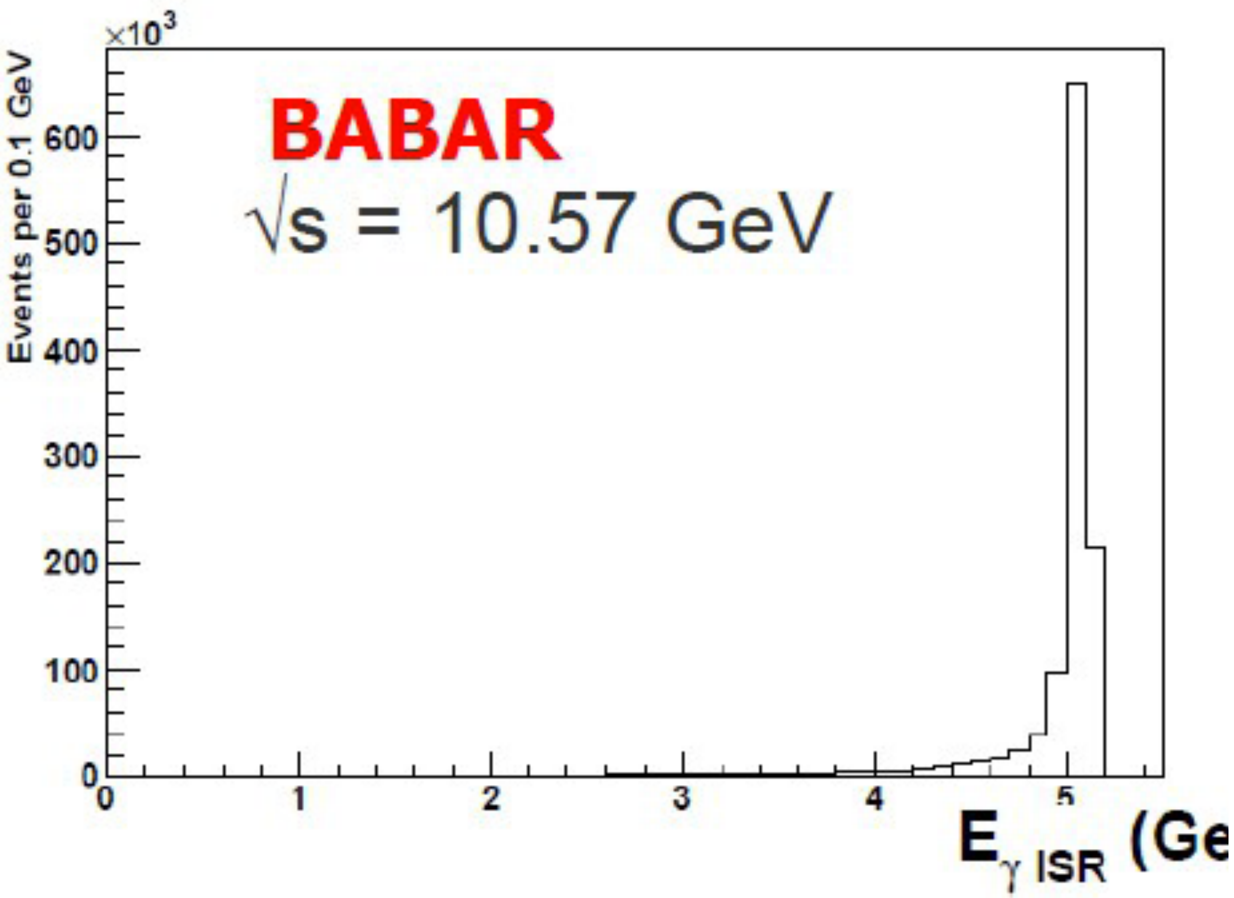
Cross Section (Initial State Radiation)

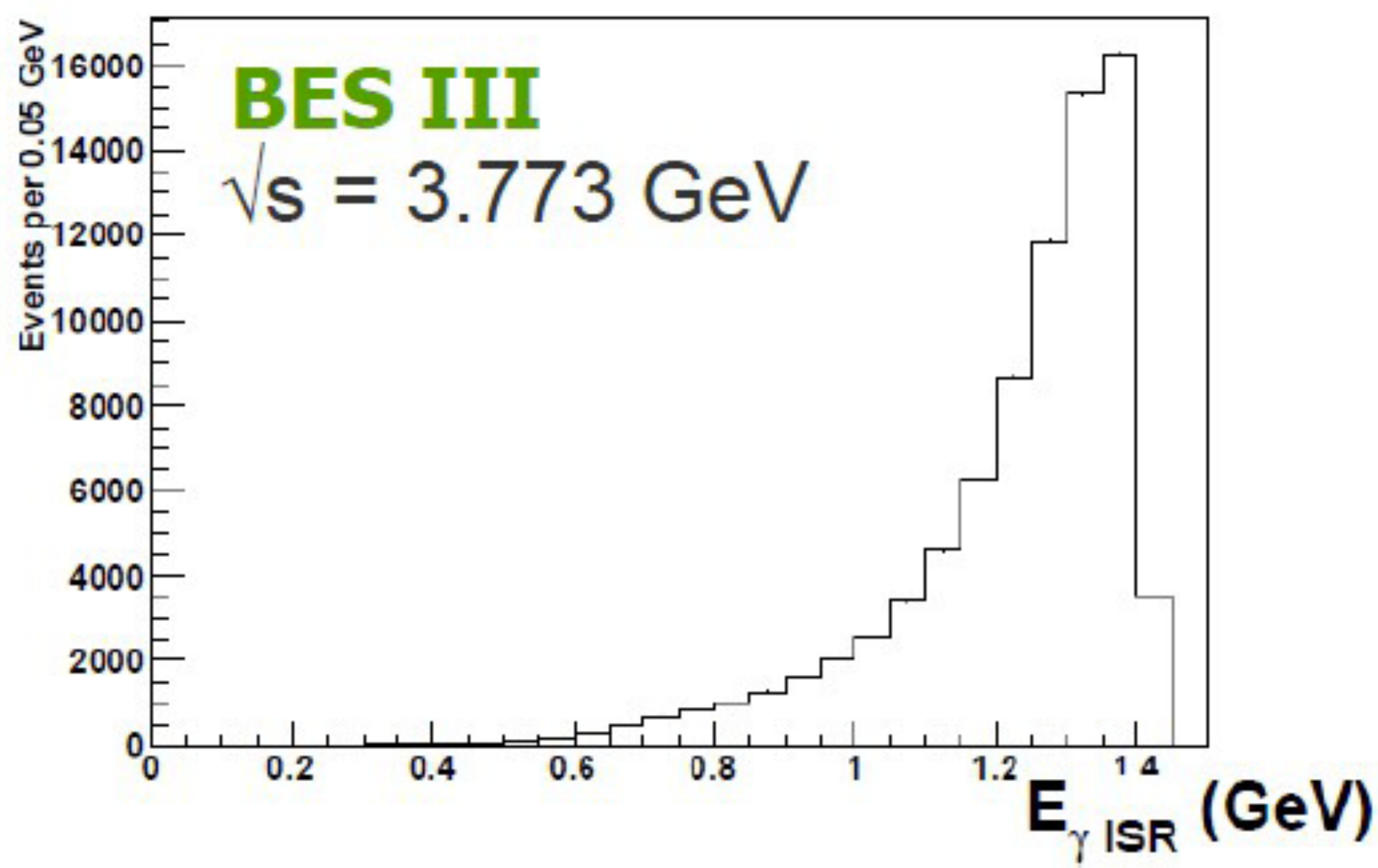


Mass spectrum of pp system in the $e^+e^- \to pp\gamma$ reaction is related to cross section of $e^+e^- \to pp$ reaction at E=m.

$$\frac{d\sigma(e^+e^- \to p\bar{p}\gamma)}{dm\, d\cos\theta} = \frac{2m}{s} W(s,x,\theta)\sigma(e^+e^- \to p\bar{p})(m), \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s},$$

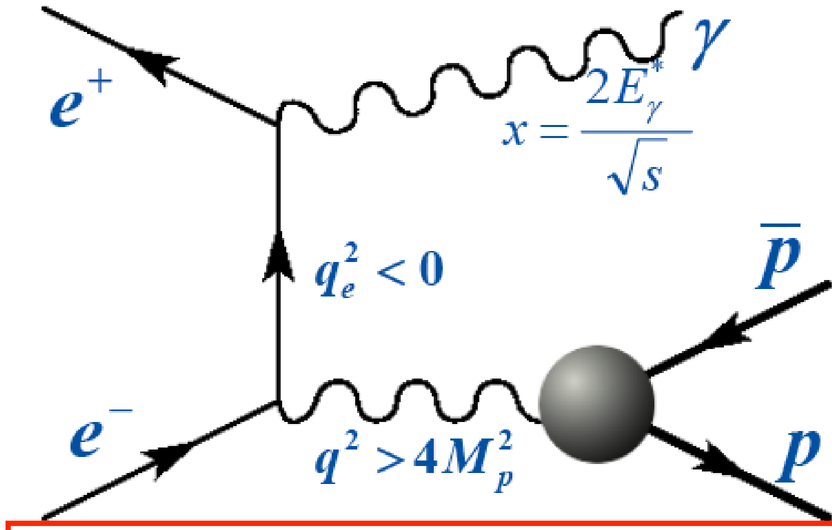
$$W(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right), \quad \theta >> \frac{m_e}{\sqrt{s}}.$$



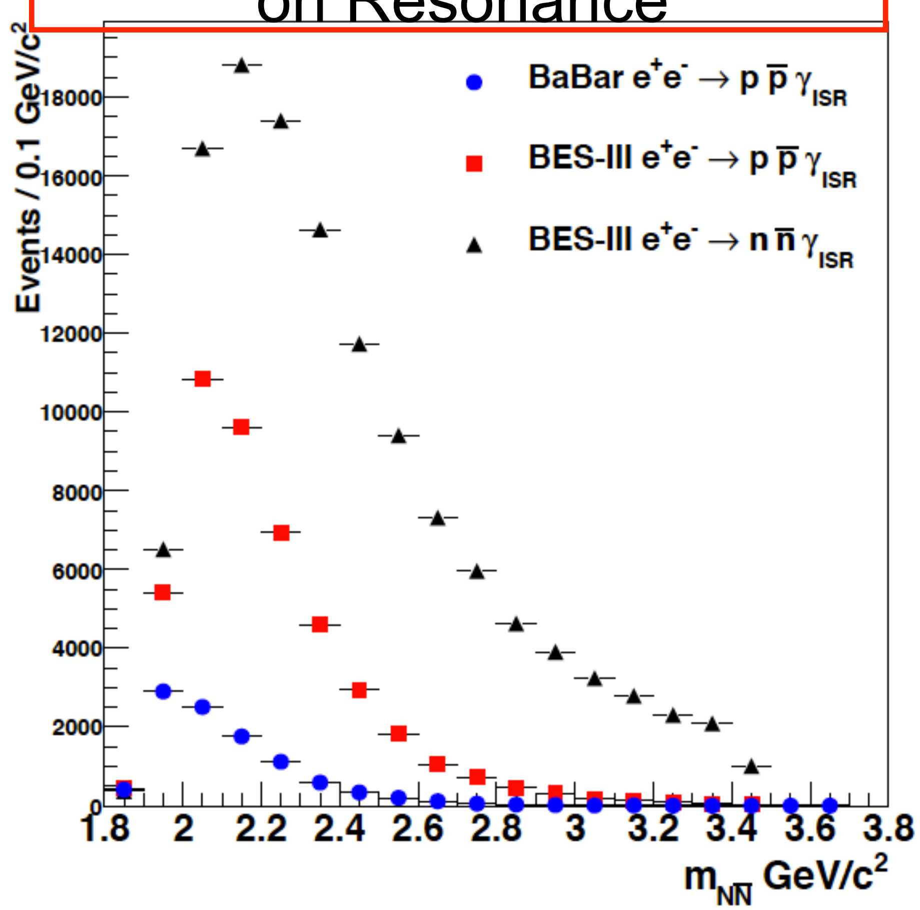


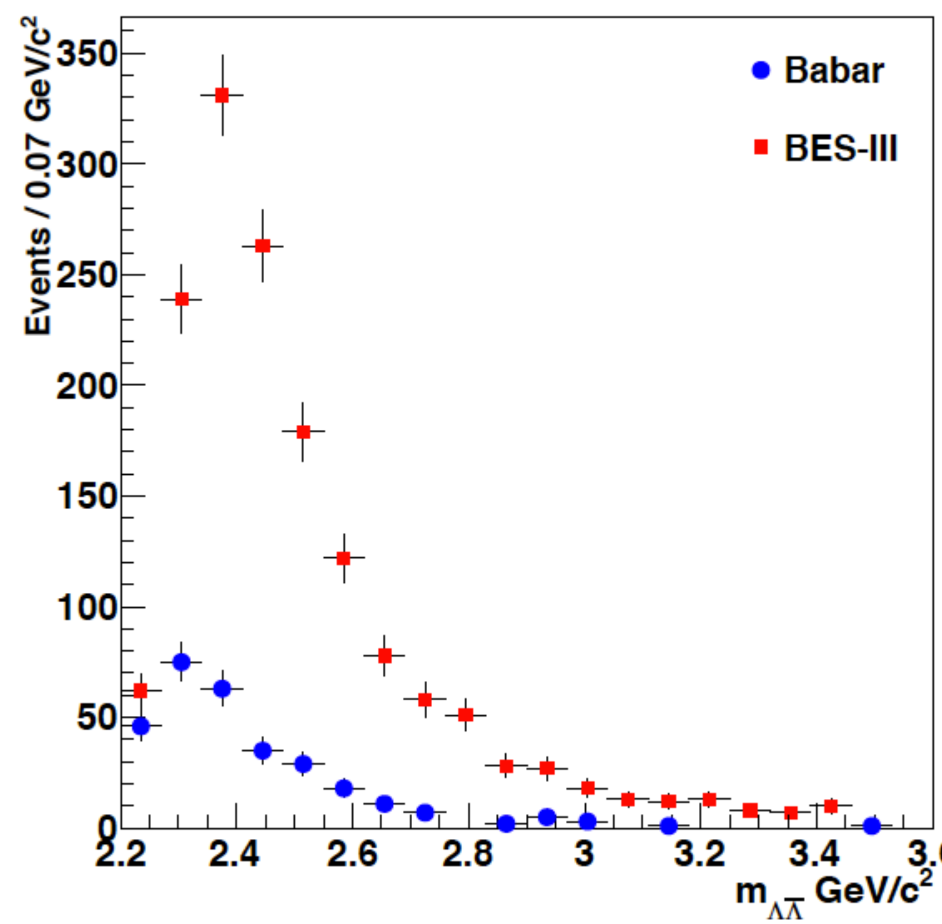
EM form factor ($q^2 > 0$)

Babar, BESIII: Initial state radiation (ISR), radiative return

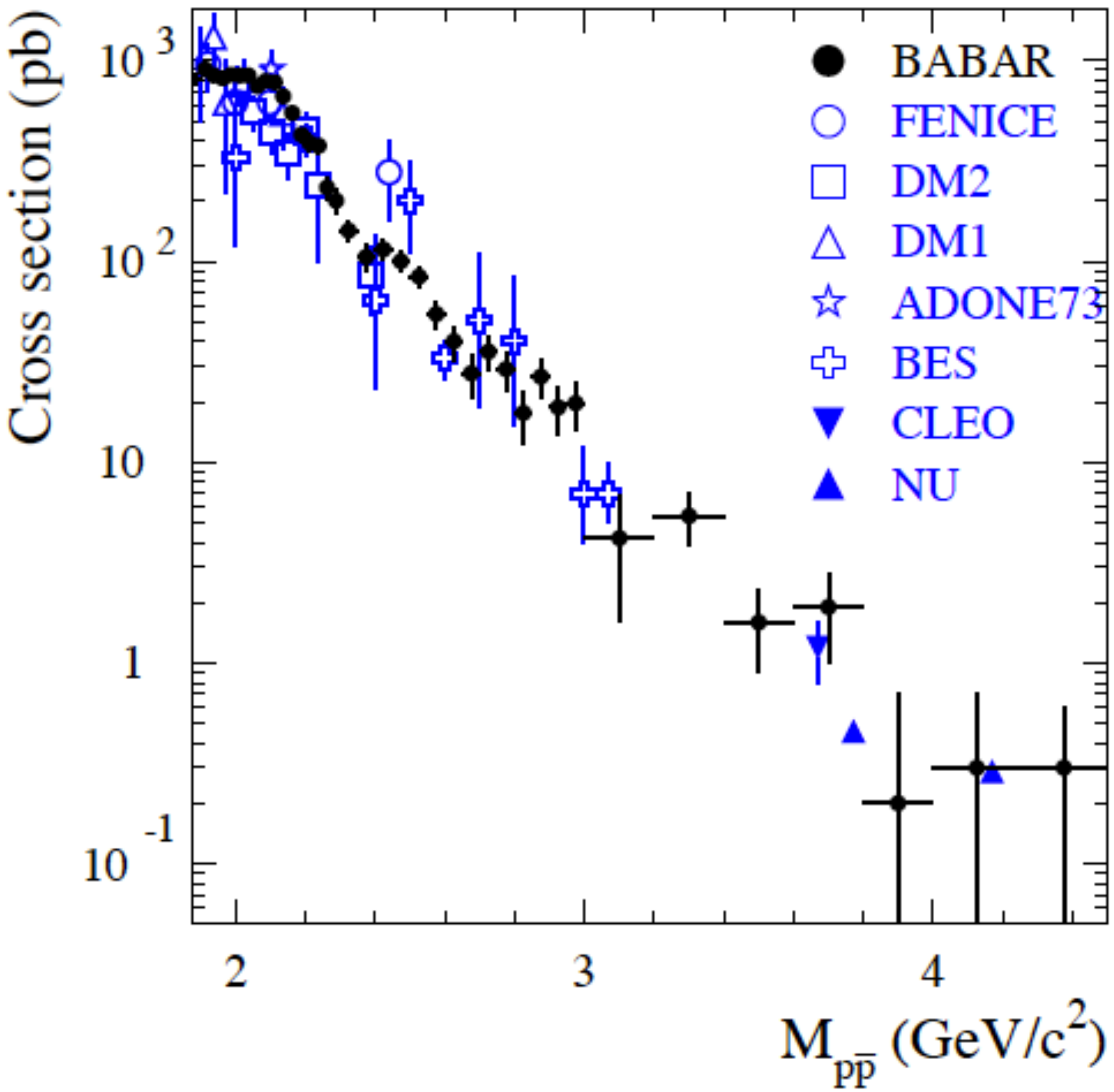


BaBar, BESIII: Measurement on Resonance





Cross section (q^2 > 0)

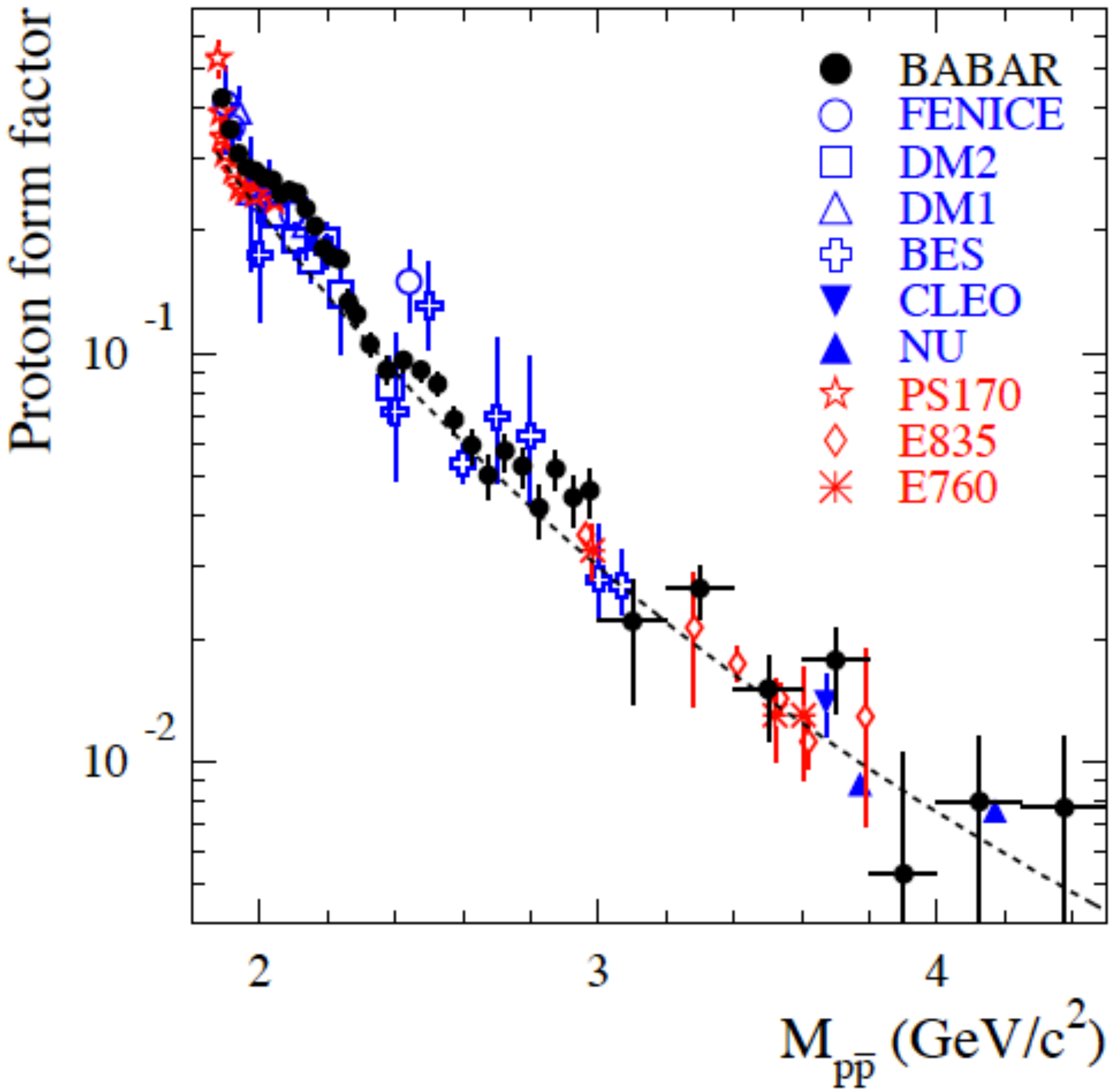


Adone e^+e^-: 25, 69 ev.
ELPAR $\bar{p}p$: 34 ev.
DM1,2 e^+e^-: 63, 172 ev.
$|G_E|/|G_M| = 0.34$
PS170 $\bar{p}p$: 3667 ev.
$|G_E|/|G_M| \approx 1$
E760 $\bar{p}p$: 29 ev.
E835 $\bar{p}p$: 206 ev.

CLEO e^+e^-: 14 ev.
BES e^+e^-: higher stat
BaBar e^+e^-: high stat

All data: Measure integrated cross section

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



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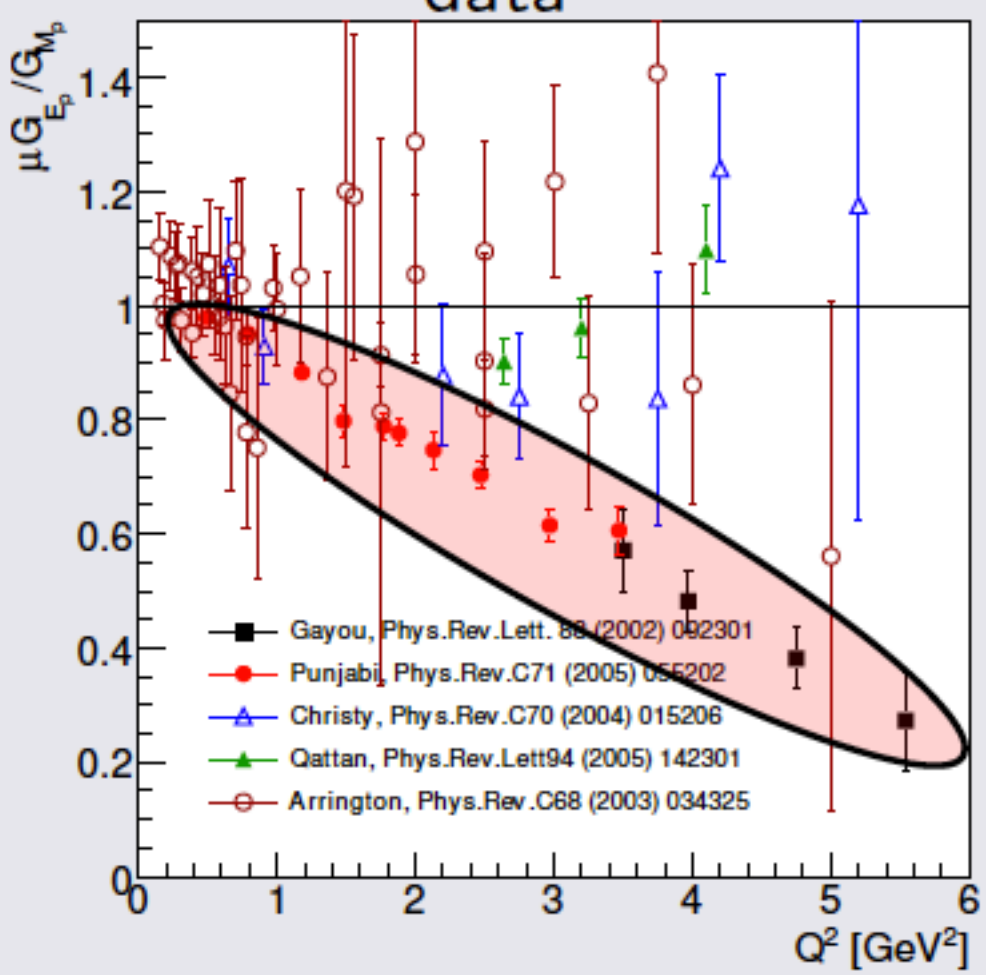
All data: Measure integrated cross section

assume: $G_E = G_M$, or $F = (\sigma)^{0.5}$

EM form factor

Rossenbluth separation Space-like data

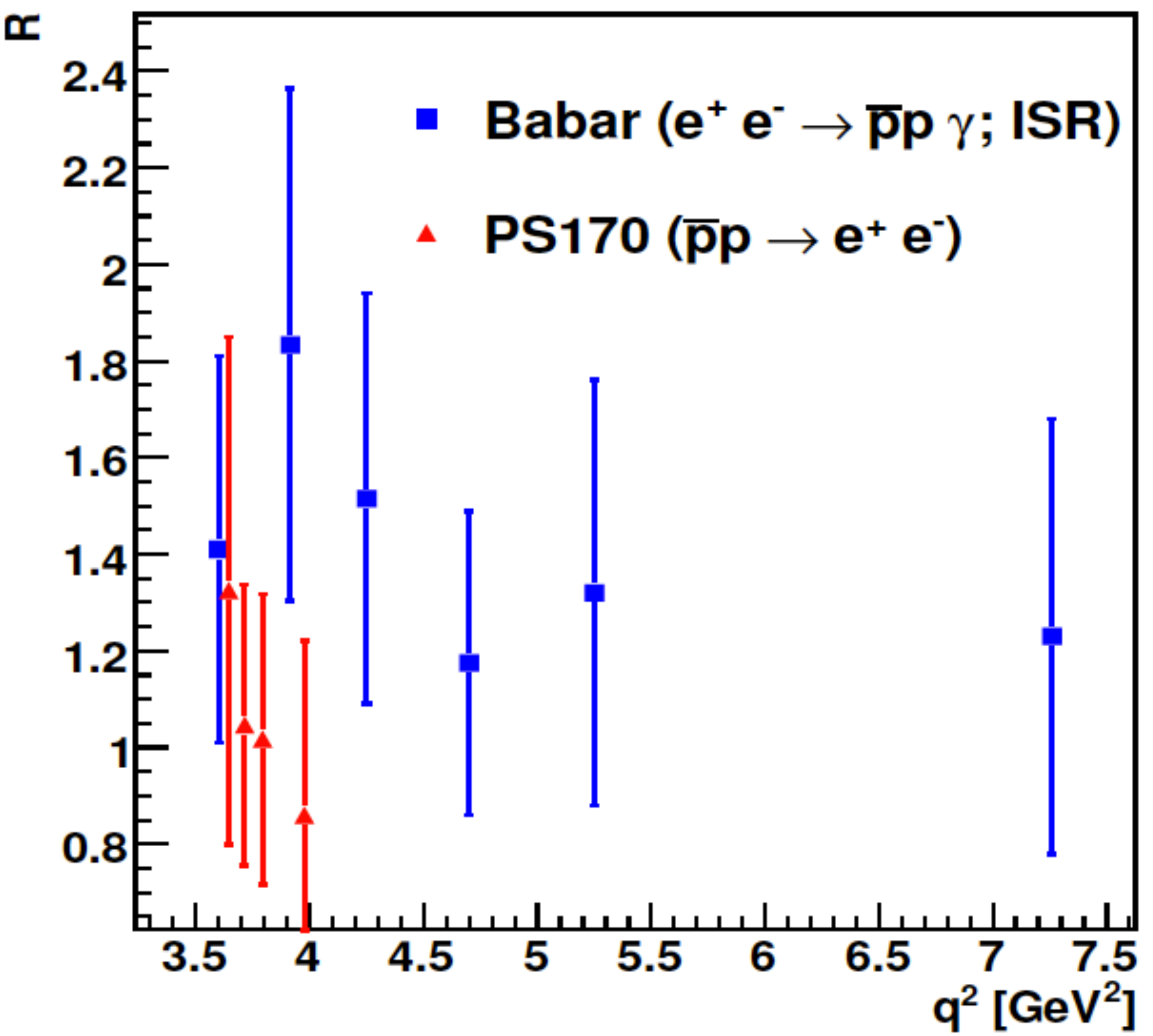


Polarization transfer experiments

$\rightarrow \boxed{G_E \neq G_M}$

$(q^2 < 0)$

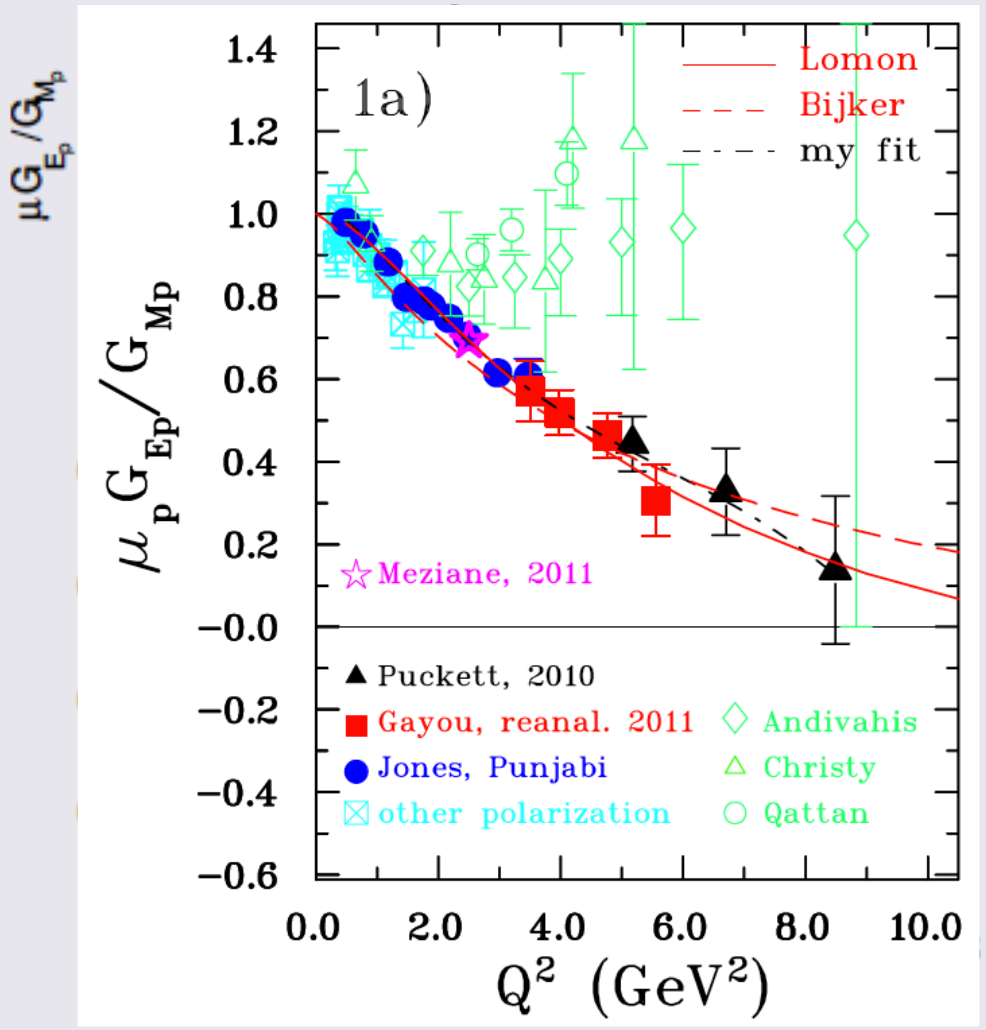
From Angular Distribution:



$(q^2 > 0)$

EM form factor

Rossenbluth separation Space-like



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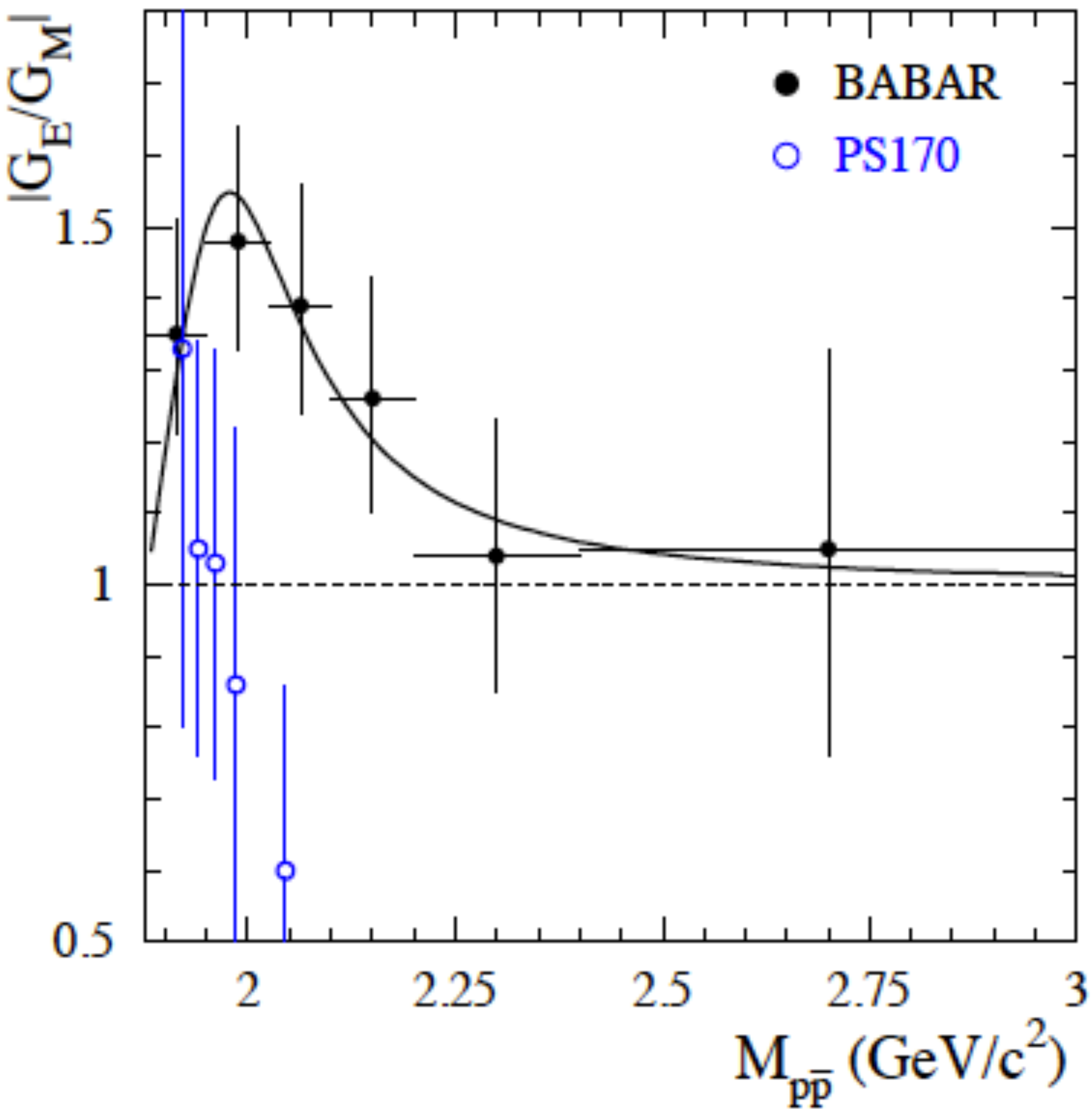


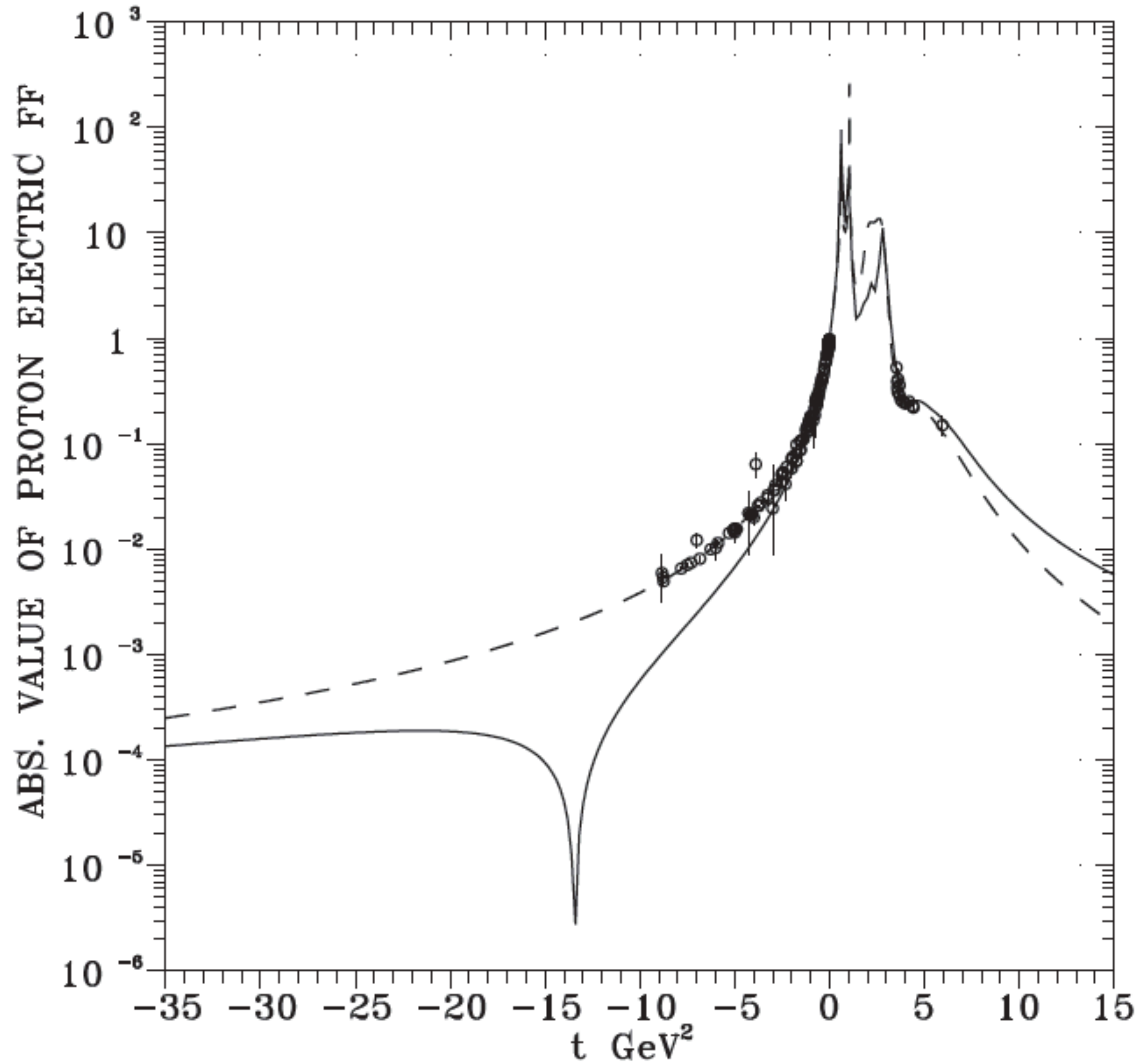
(q^2 < 0)

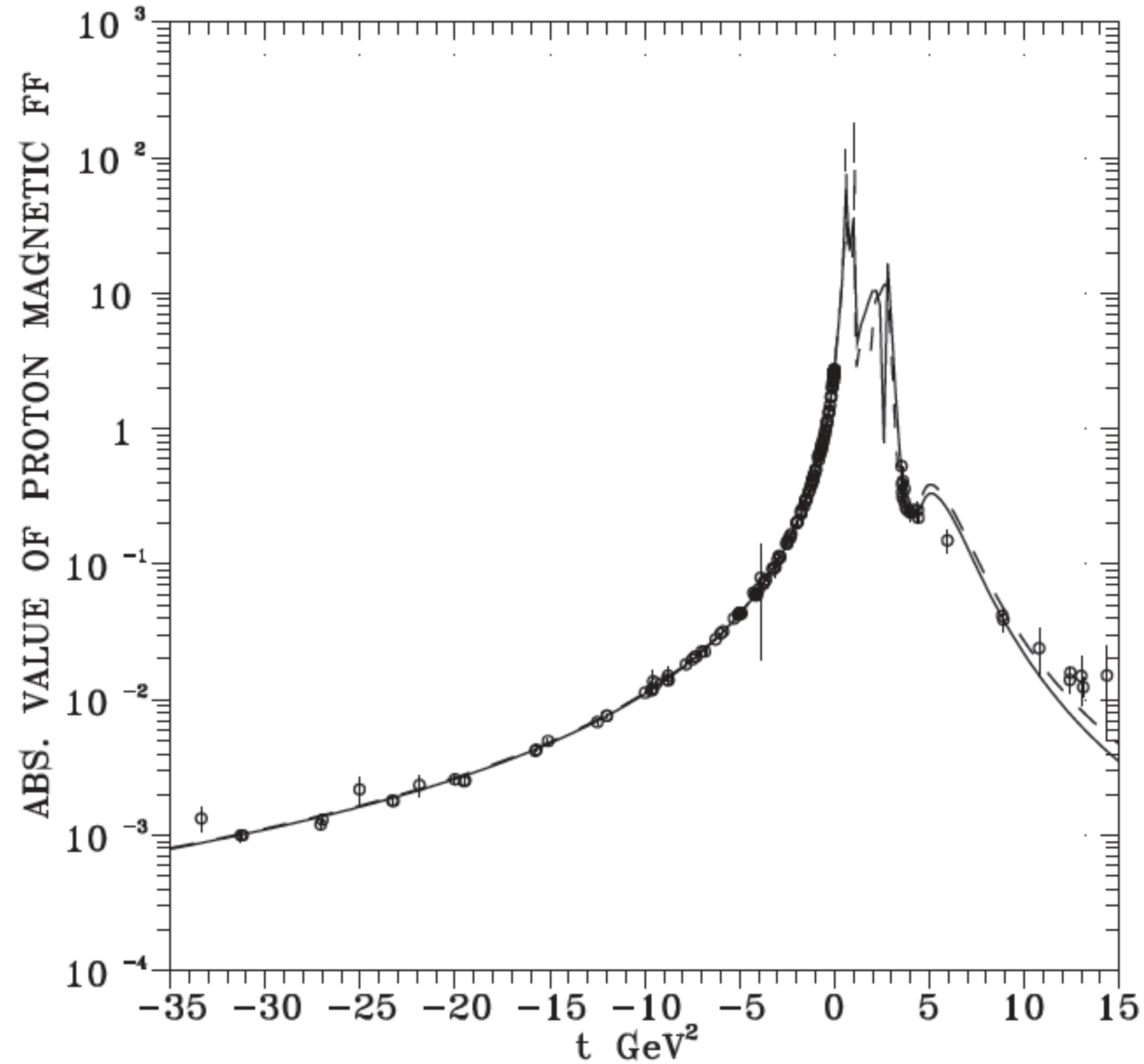
recent GEP-III results

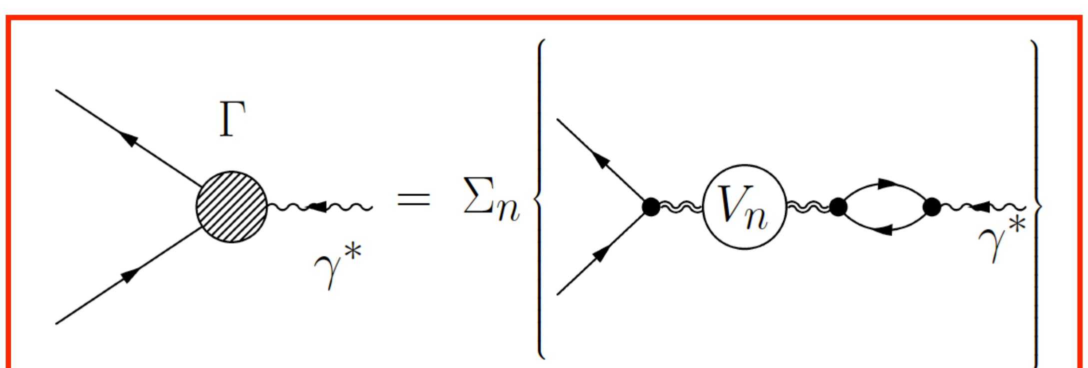
(q^2 > 0)

new BABAR-Analysis: arxiv:1302.0055v1

EM form factor ($q^2 > 0$) and Vector Meson Dominance

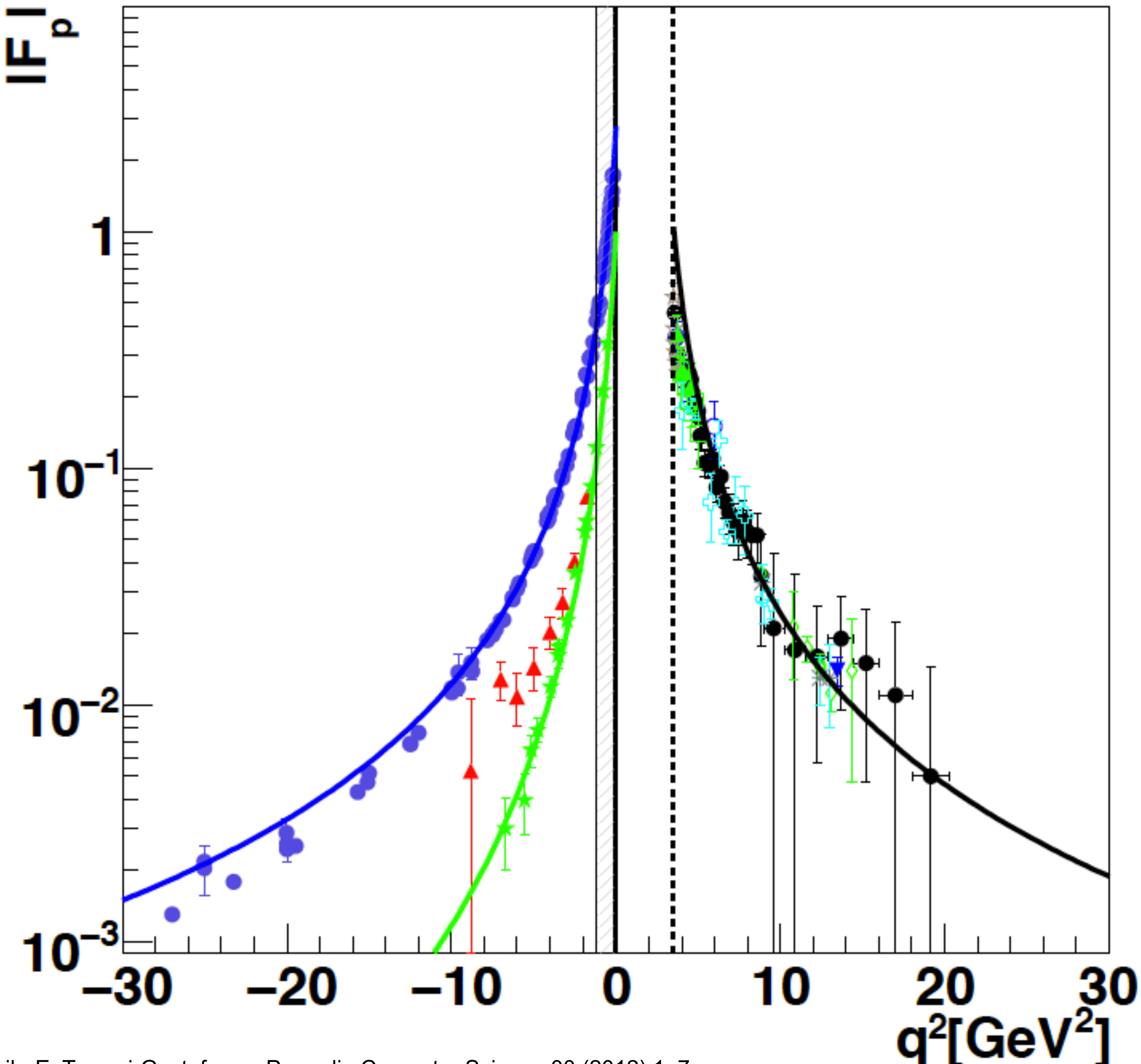






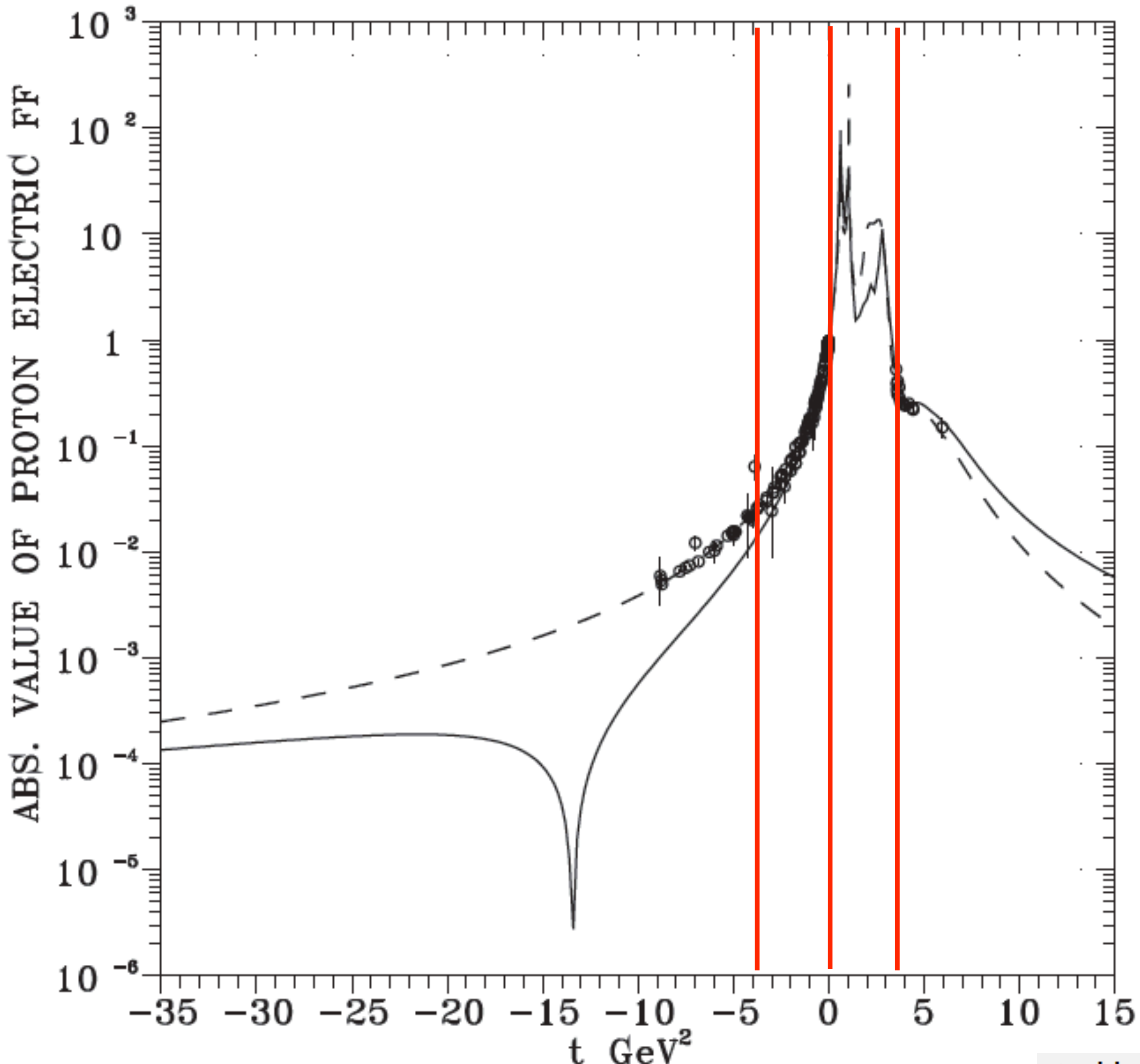
Vector Mesons

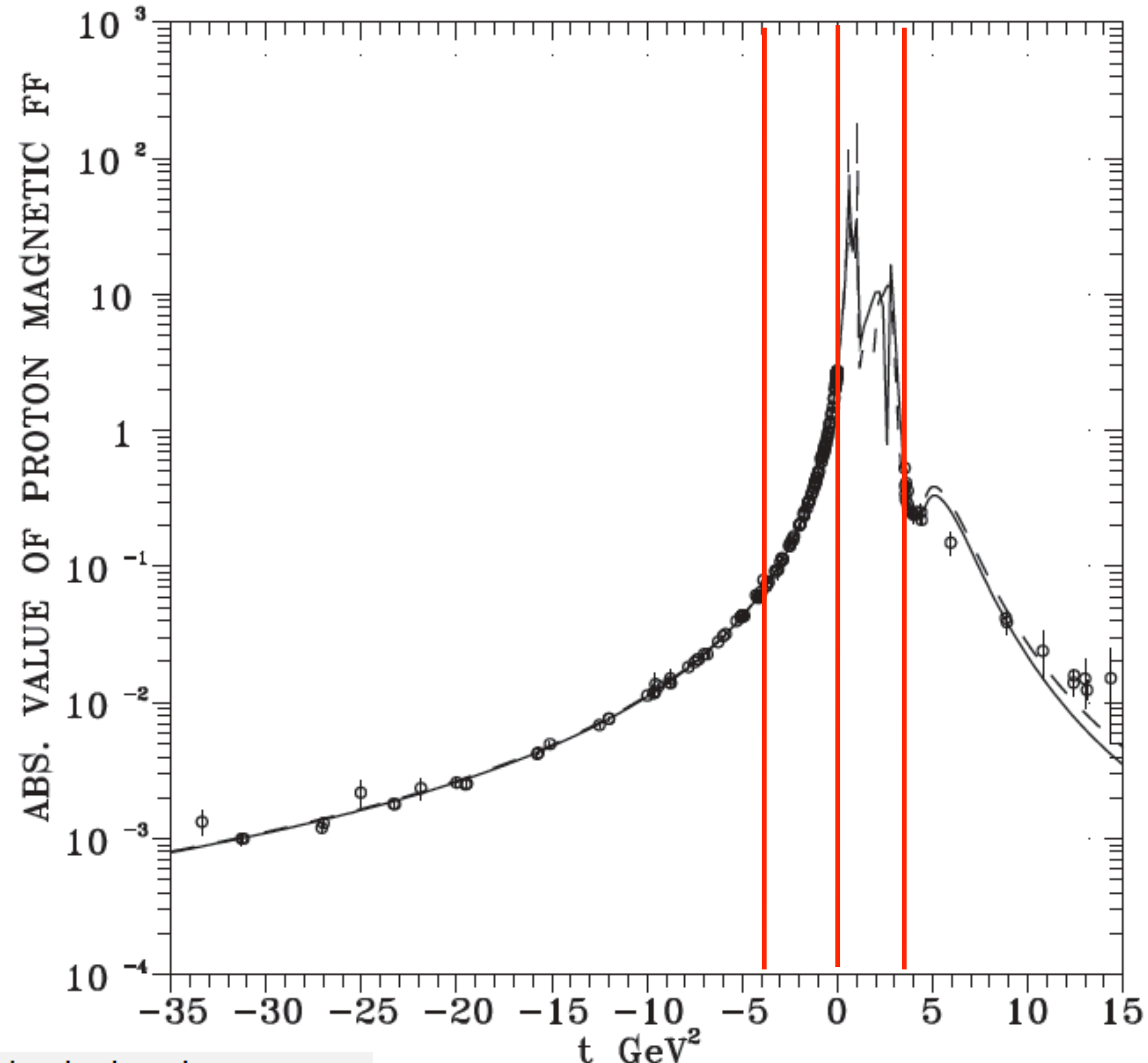
EM form factor ($q^2 > 0$)

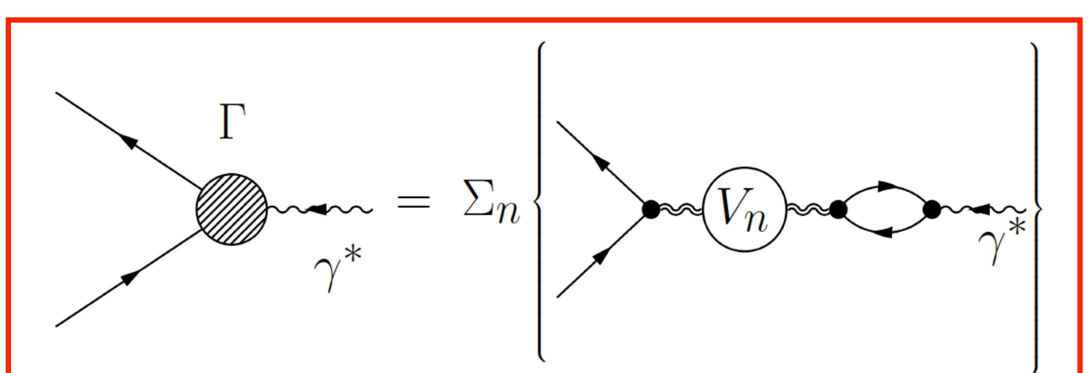


E.A.Kuraev, A.Dbeyssib, E. Tomasi-Gustafsson, Procedia Computer Science 00 (2012) 1–7

EM form factor ($q^2 > 0$) and Vector Meson Dominance (VMD) use pion-initial-state-radiation



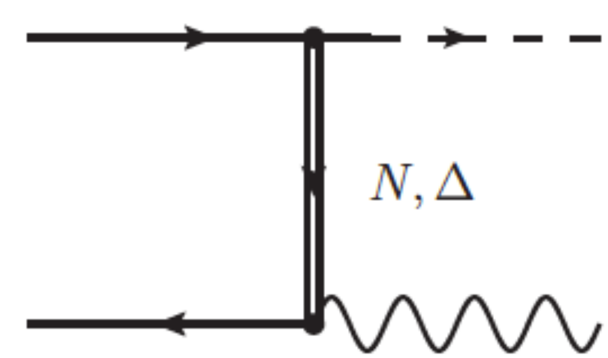




Vector Mesons

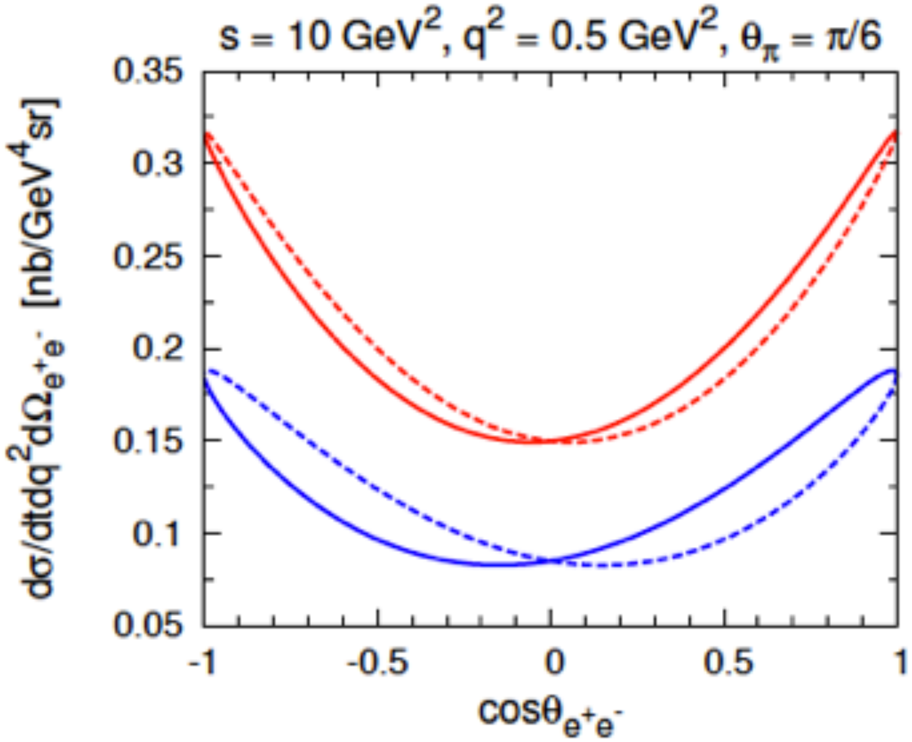
- Unphysical region: $0 < q^2 < 4m_N^2$
- Not accessible by process $p + \bar{p} \to e^+ + e^-$
- Idea: Consider process $p + \bar{p} \;\to\; \pi^0 + \gamma^*$ $\to\; \pi^0 + e^+ + e^-$

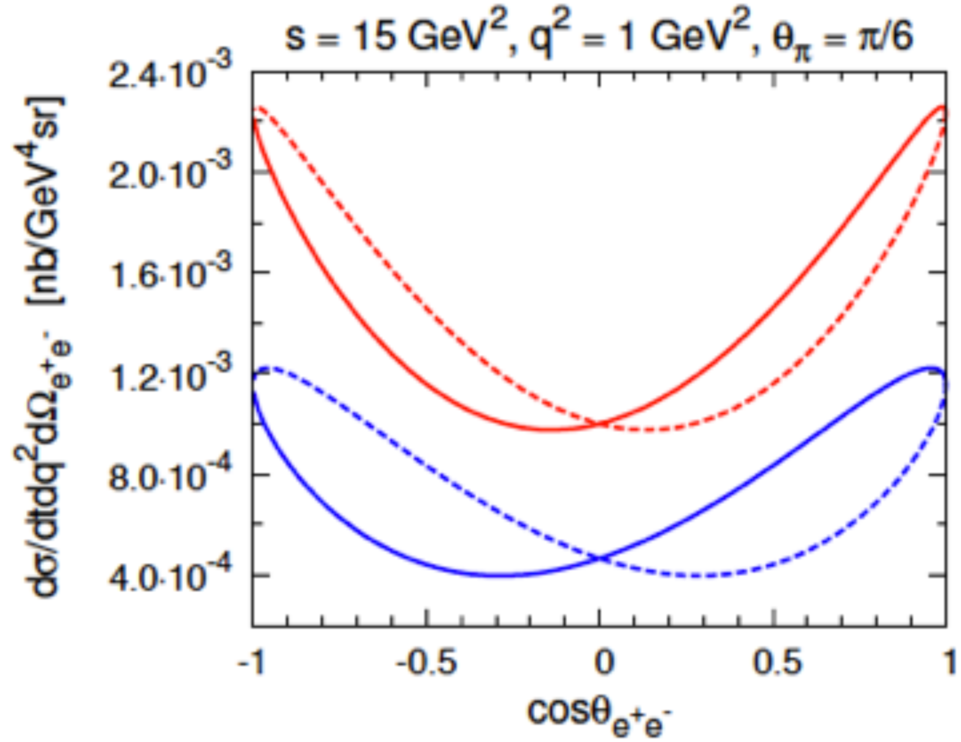
(Dubničková et al., ZPhys. (1996), Adamuščín et al., PRC (2007))



$p\bar{p} \to \pi^0 e^+ e^-$: Results in the Regge framework

Cross Section: $d\sigma/(dt dq^2 d\Omega_{e^+e^-})$ $\left[nb/GeV^4 sr\right]$





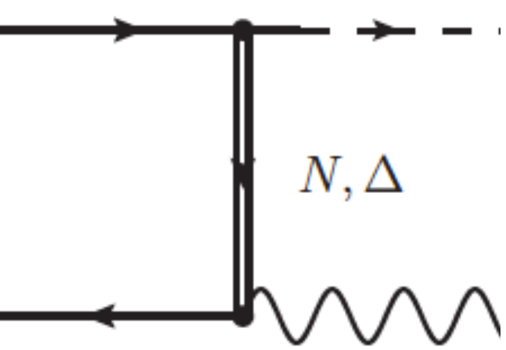
N-trajectory exchange: $\Phi_{e^+e^-} = 0$ (solid) and $\Phi_{e^+e^-} = \pi$ (dashed)

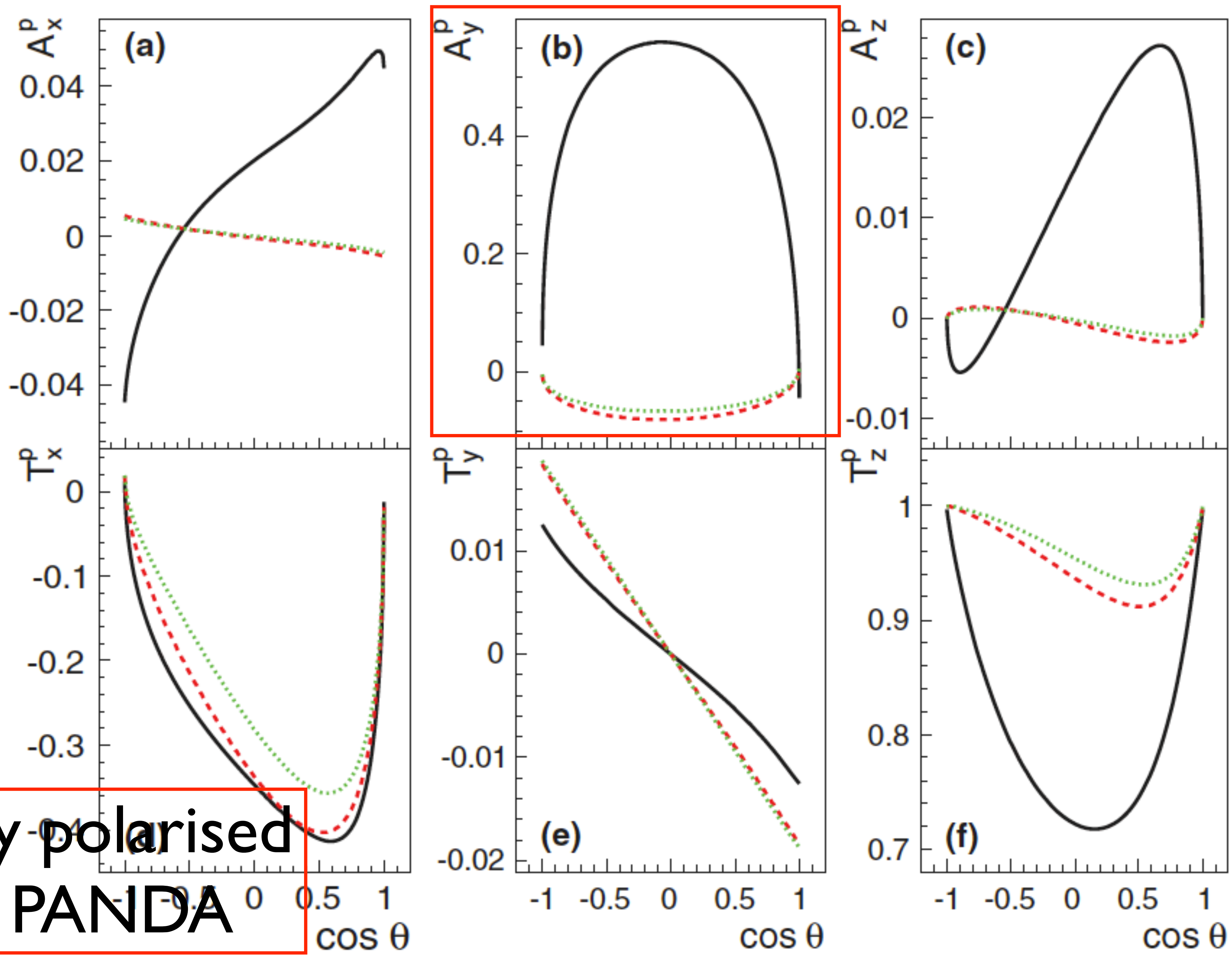
(N+Δ)-trajectory exchange: $\Phi_{e^+e^-} = 0$ (solid) and $\Phi_{e^+e^-} = \pi$ (dashed)

complementary approach to ff at and below threshold

Target Asymmetry and Polarisation Transfer

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

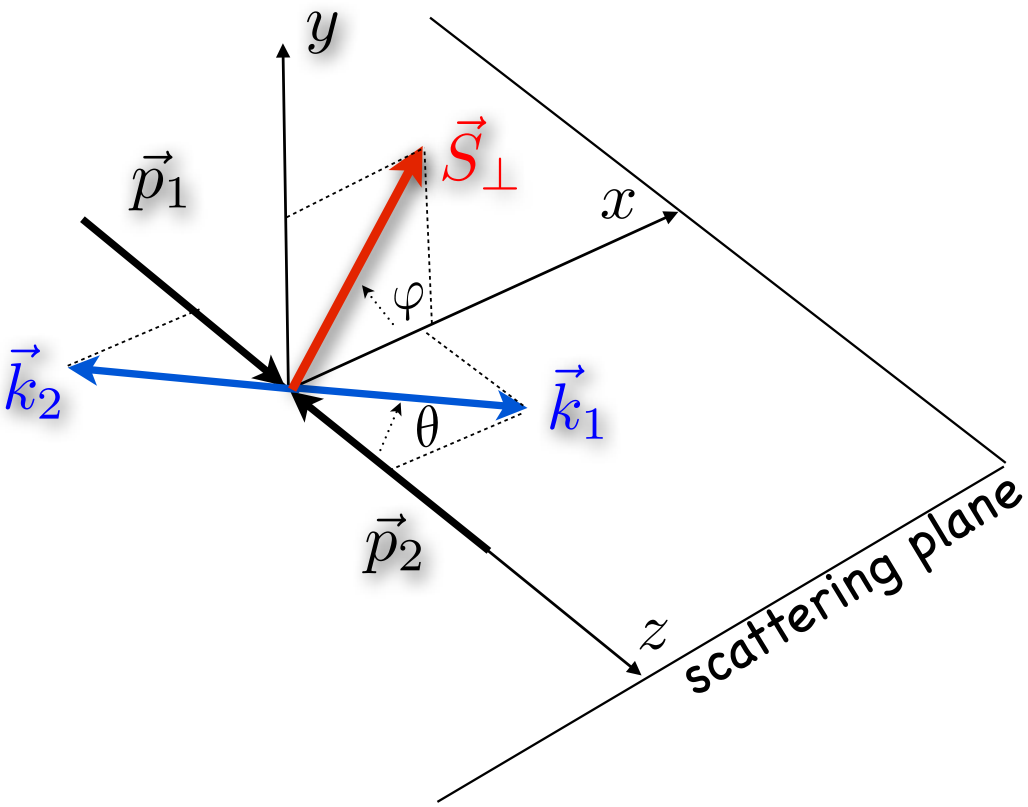




transversely polarised
Target in PANDA

G. I. Gakh, E. Tomasi-Gustafsson, A. Dbeyssi, A. G. Gakh, Phys. Rev. C 86, 025204 (2012)

Imaginary Part of Time Like FF single spin target asymmetry

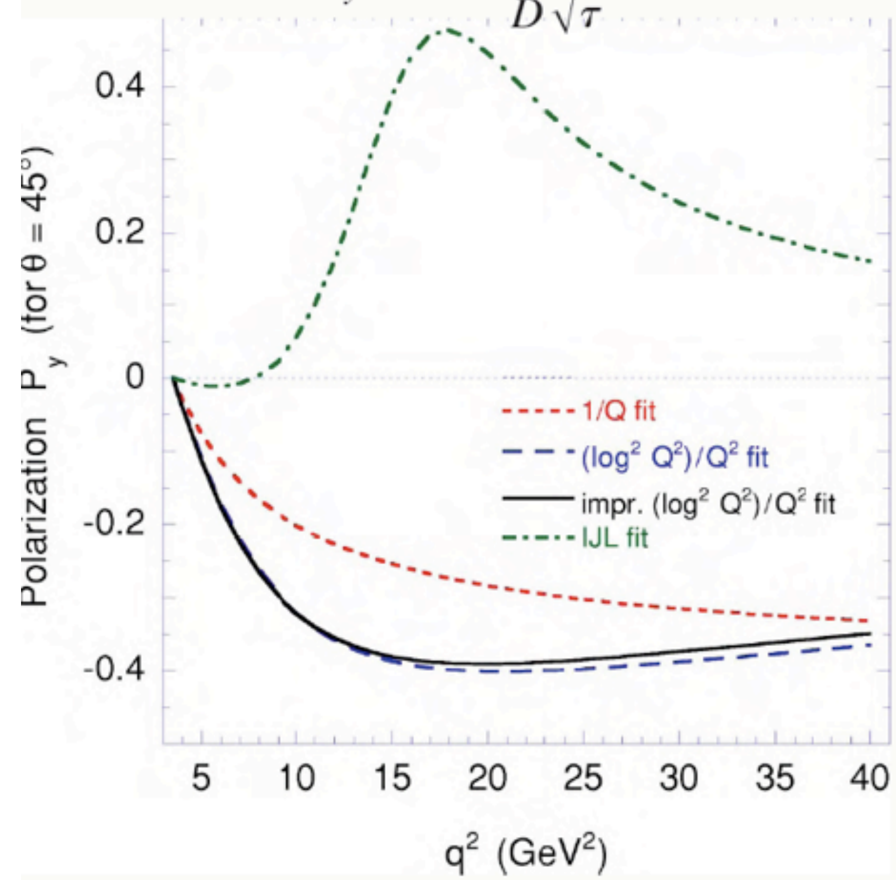


$$\bar{p}p \to e^+e^-$$

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



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

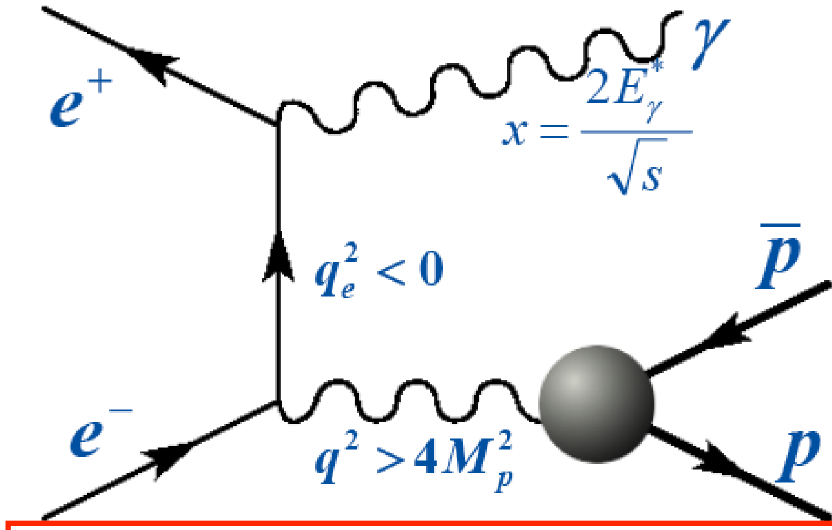
$$\tau \equiv q^2/4m_B^2$$

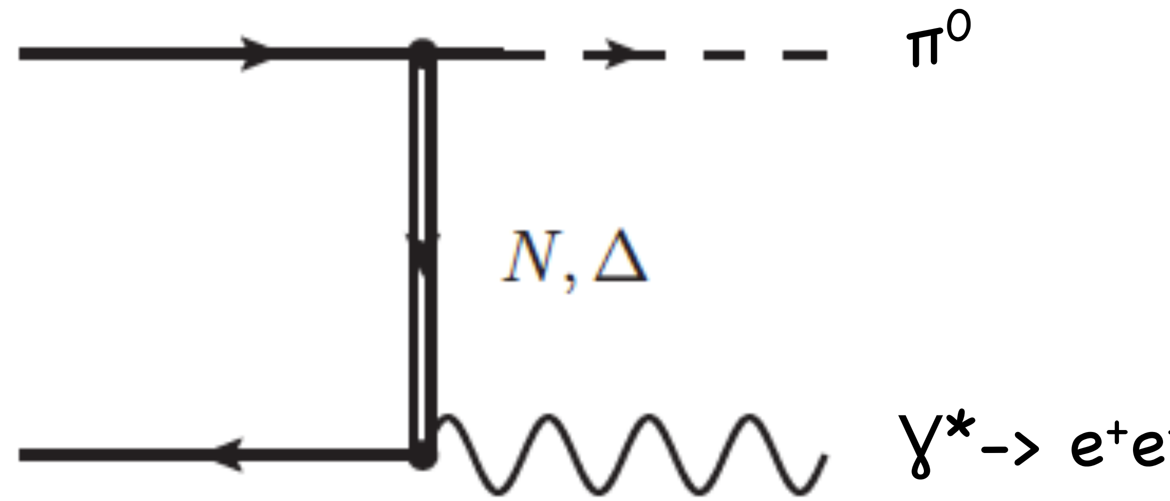
Measure relative phase of form factors

transversely polarised Target in PANDA

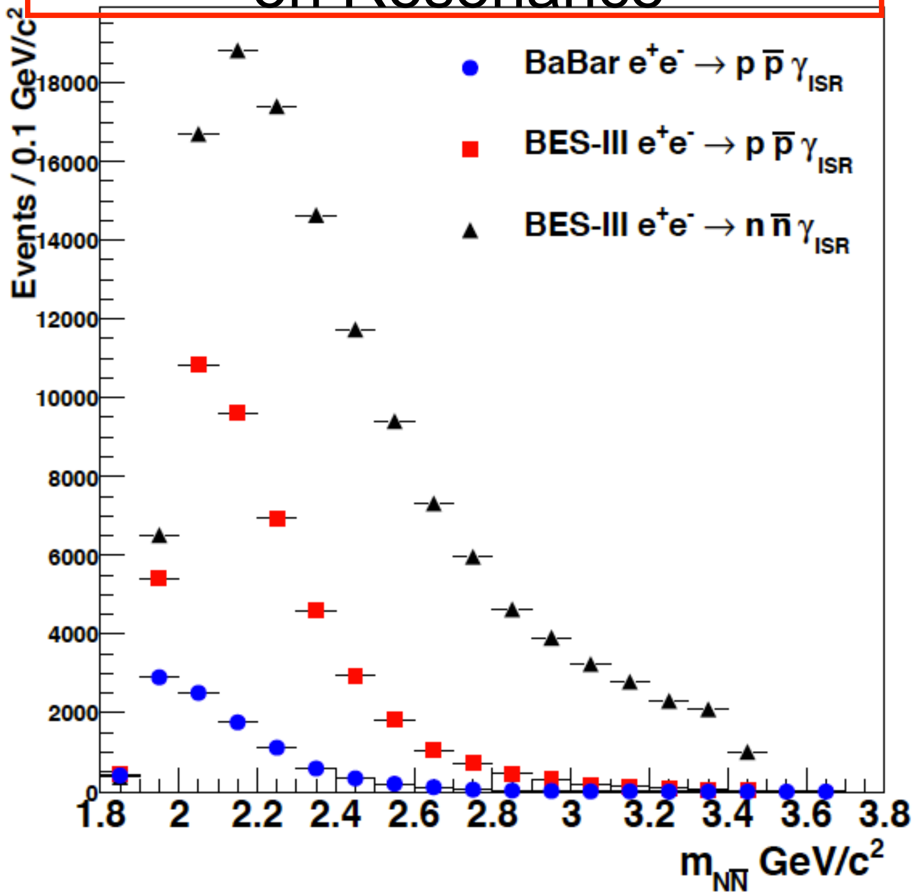
EM form factor ($q^2 > 0$)

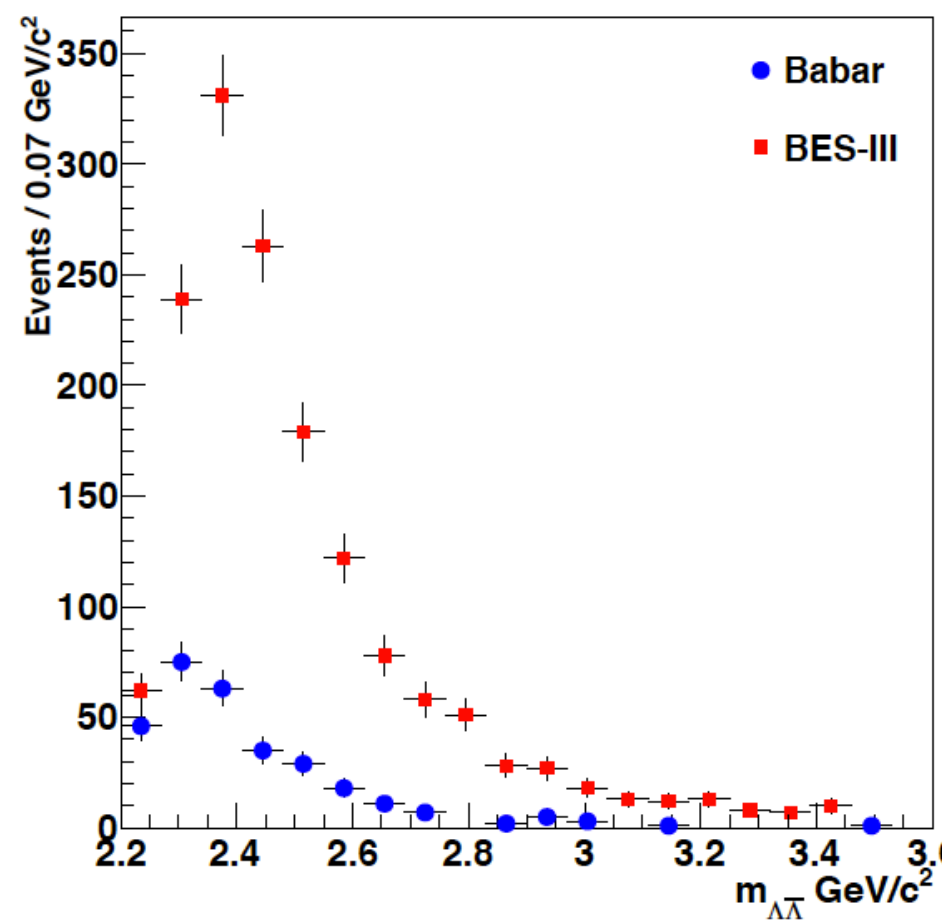
Babar, BESIII: Initial state radiation (ISR), radiative return



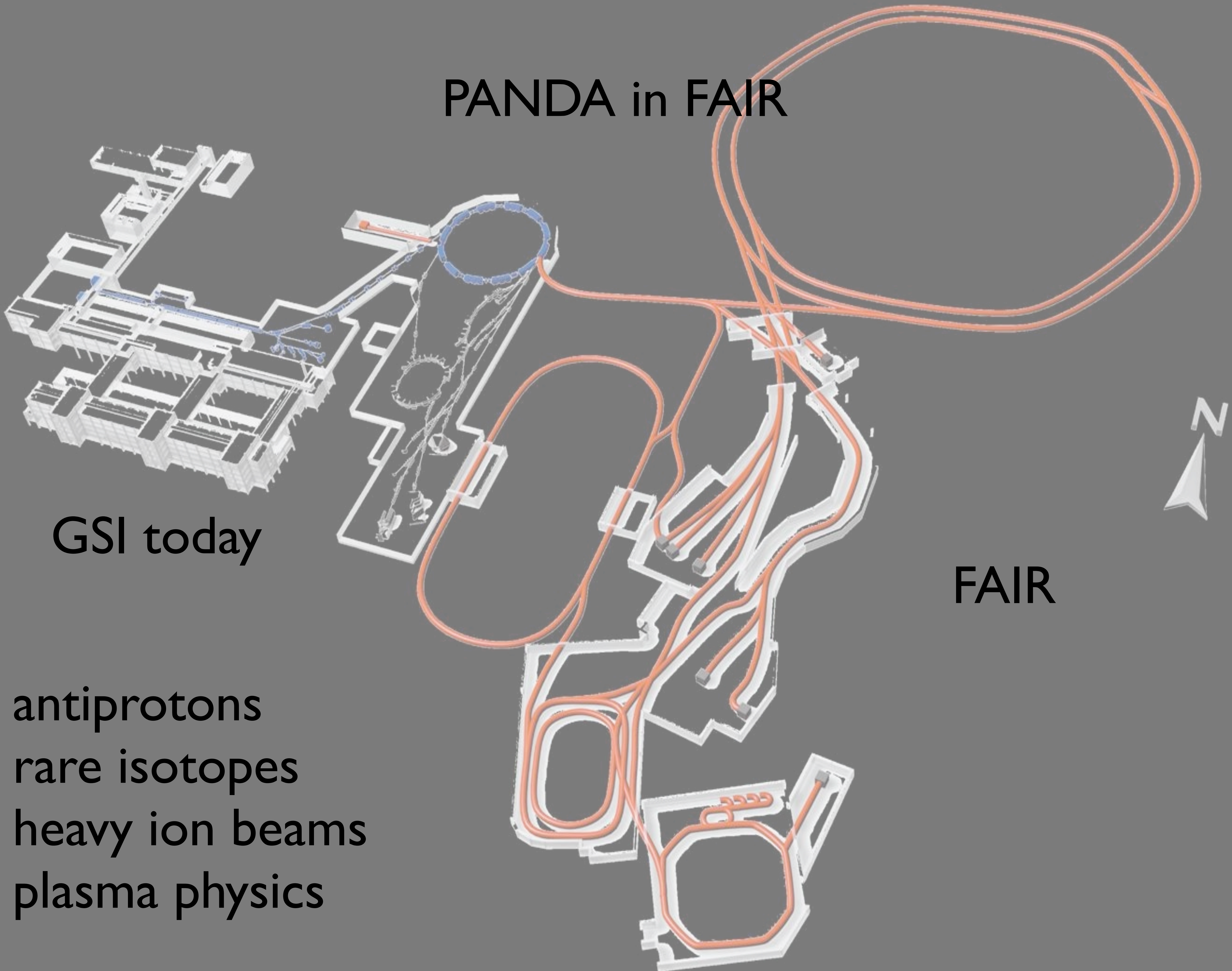


BaBar, BESIII: Measurement on Resonance





PANDA in FAIR

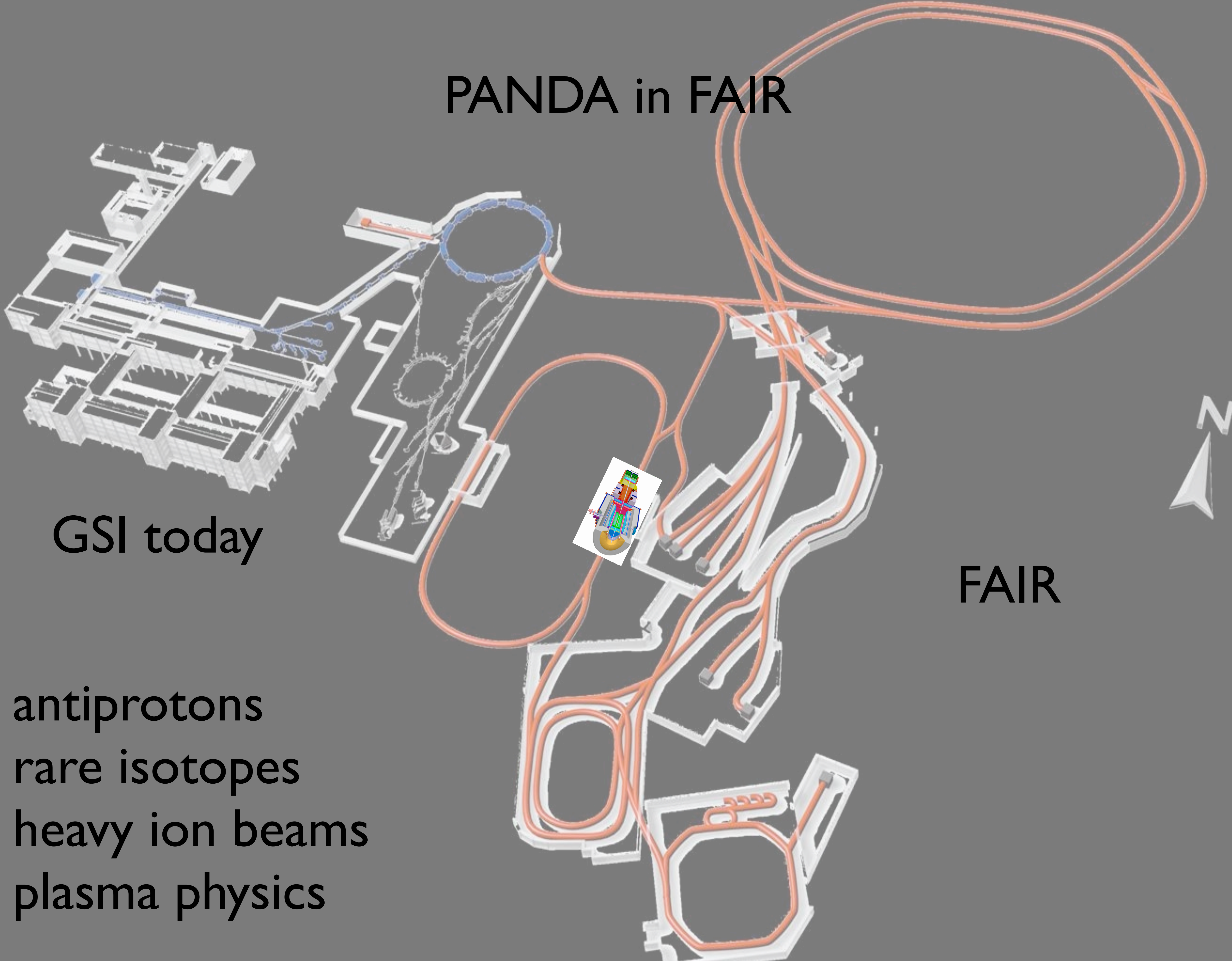


GSI today

FAIR

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

PANDA in FAIR



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

Timelines FAIR Modularised Start Version

- 6 Submission building permits
- 7 Site preparation
- 8 Civil construction contracts
- 9 Building of accelerator & detector components
- 10 Completion of civil construction work
- 11 Installation & commissioning of accelerators and detectors
- 12 Data taking

PANDA Collaboration

- At present a group of **500 physicists** from 62 institutions and 16 countries

Austria – Belaruz – China – France – Germany – India – Italy – The Netherlands – Poland – Romania – Russia – Spain – Sweden – Switzerland – U.K. – U.S.A.

AMU Aligarh, Basel, Beijing, BITS Pillani, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, IIT Chicago, AGH-UST Cracow, JGU Cracow, IFJ PAN Cracow, Cracow UT, Edinburgh, Erlangen, Ferrara, Frankfurt, Gauhati, Genova, Giessen, Glasgow, GSI, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, Legnaro, LNF, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow, TU München, Münster, BARC Mumbai, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, IHEP Protvino, PNPI St.Petersburg, South Gujarat University, SVNIT Surat, Sadar Patel University, KTH Stockholm, Stockholm, FH Südwestfalen, Suranaree University of Technology, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, NCBJ Warsaw, TU Warsaw, AAS Wien

http://www.gsi.de/panda

PANDA physics program

Hadron Spectroscopy

Experimental Goals: *mass, width & quantum numbers J^{PC} of resonances*

Charm Hadrons*: charmonia, D-mesons, charm baryons*

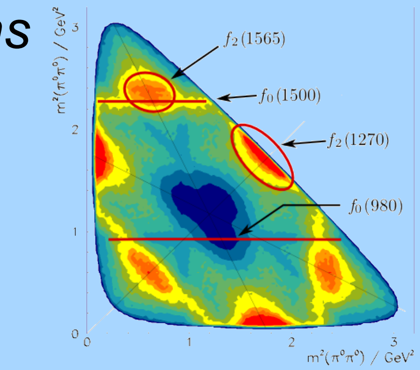
➔ Understand new XYZ states, $D_s(2317)$ and others

Exotic QCD States*: glueballs, hybrids, multi-quarks*

Spectroscopy with Antiprotons:

Production of states of all quantum numbers

Resonance scanning with high resolution



Hadron Structure

Generalized Parton Distributions

➔ Formfactors and structure functions, L_q

Timelike Nucleon Formfactors

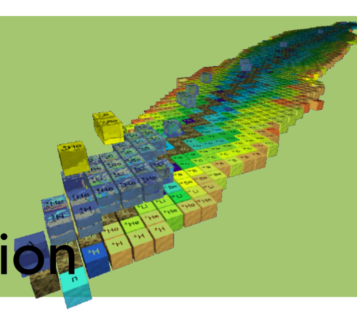
Drell-Yan Process Transition Distribution Amplitudes

Nuclear Physics

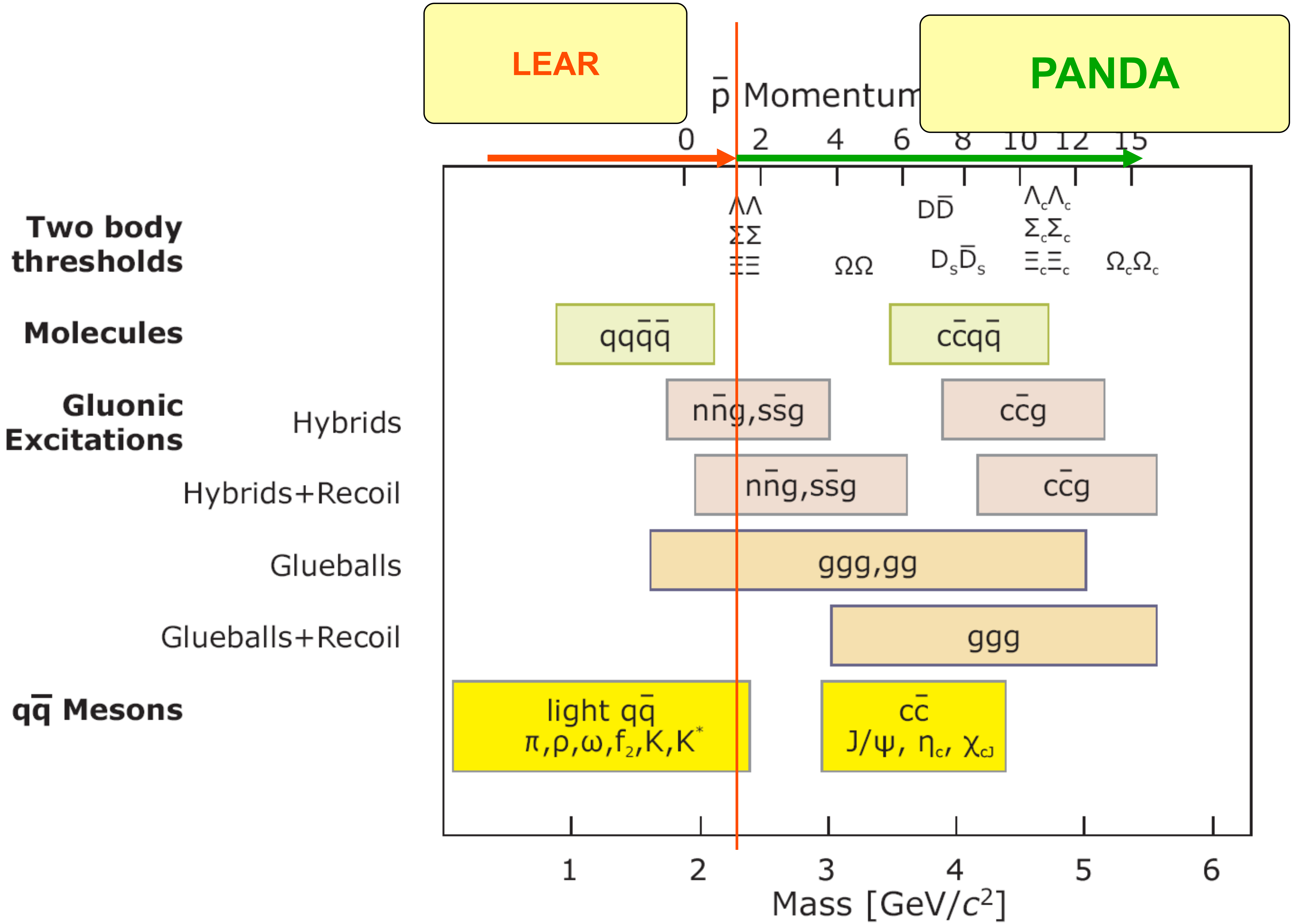
Hypernuclei*:* Production of double Λ-hypernuclei

➔ γ-spectroscopy of hypernuclei, YY interaction

Hadrons in Nuclear Medium antiproton annihilation

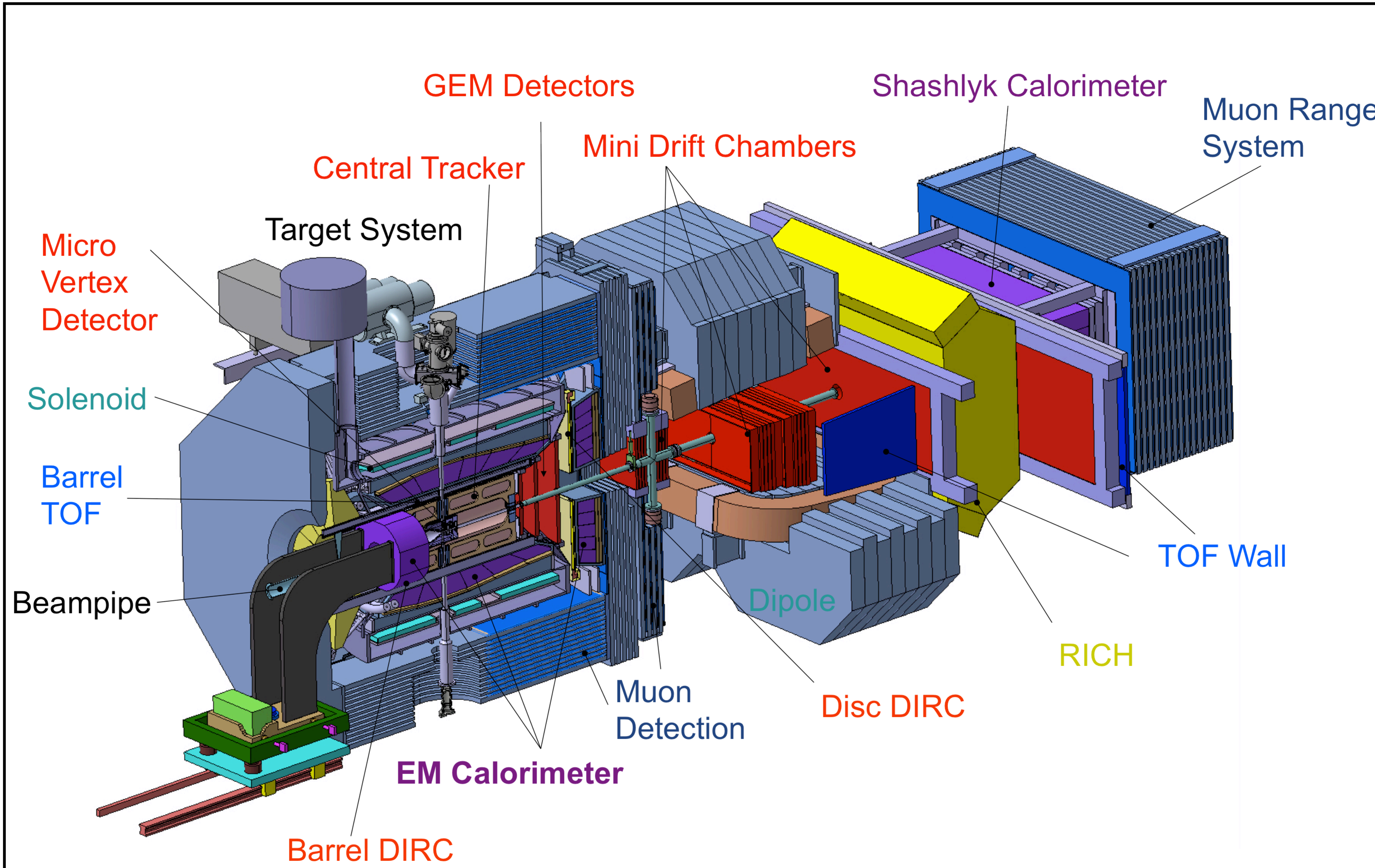


Physics performance report: arXiv:0903.3905v1

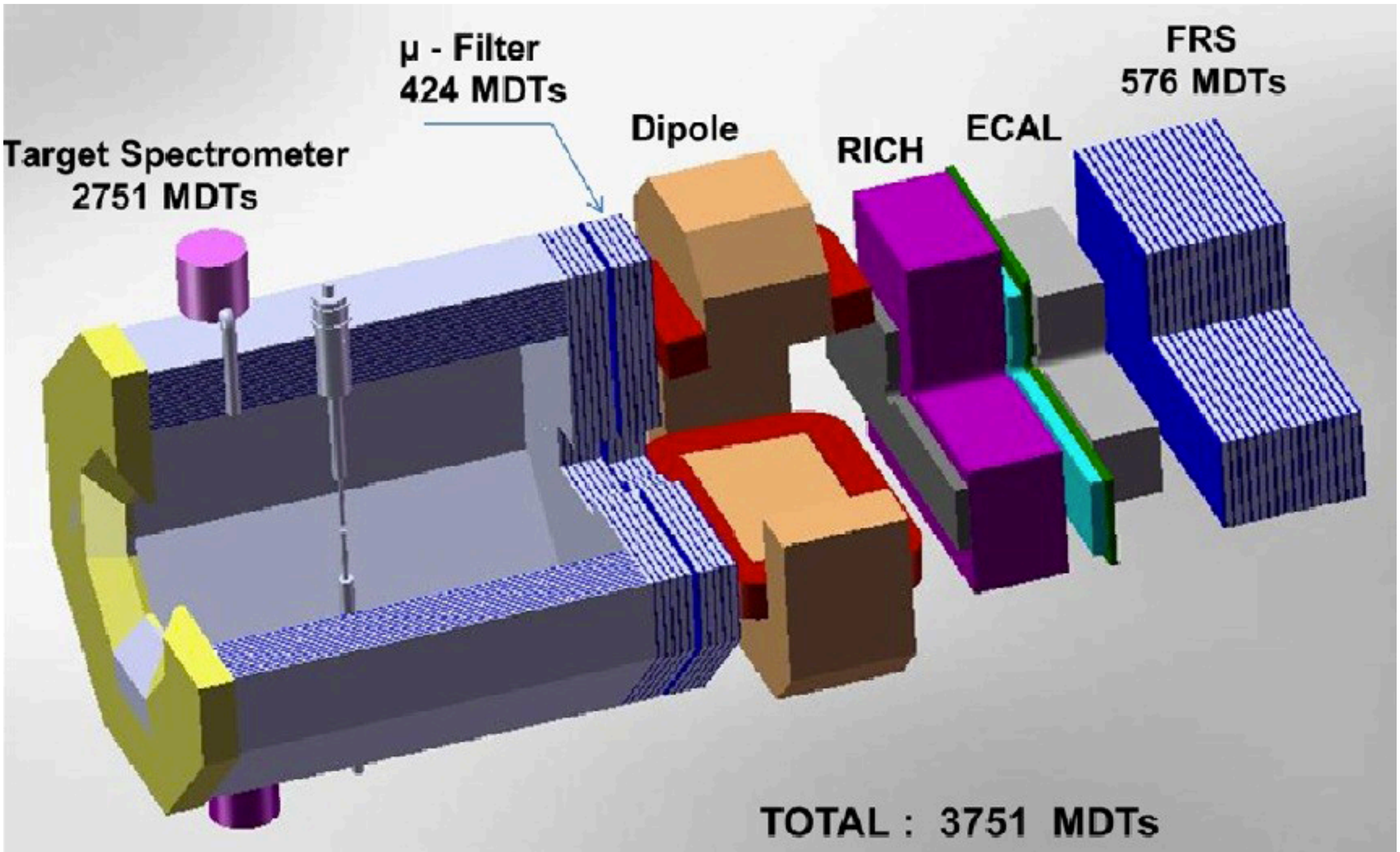


Physics performance report: arXiv:0903.3905v1

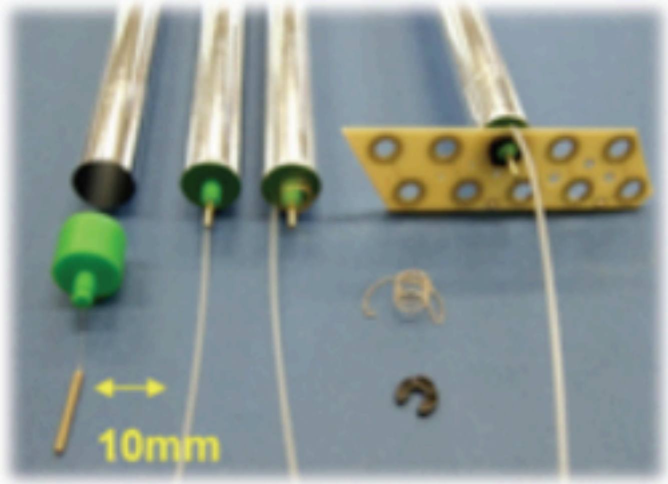
PANDA: the detector

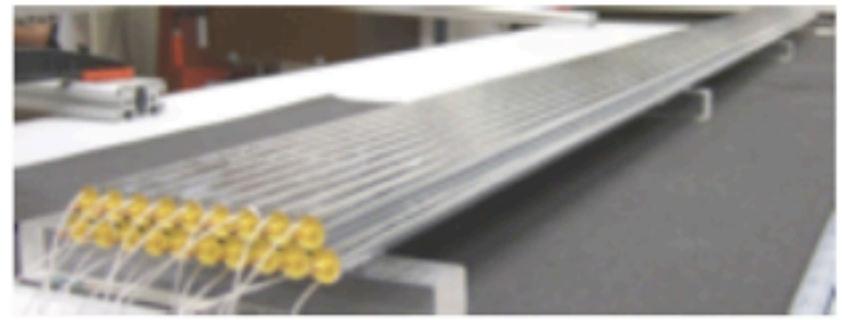


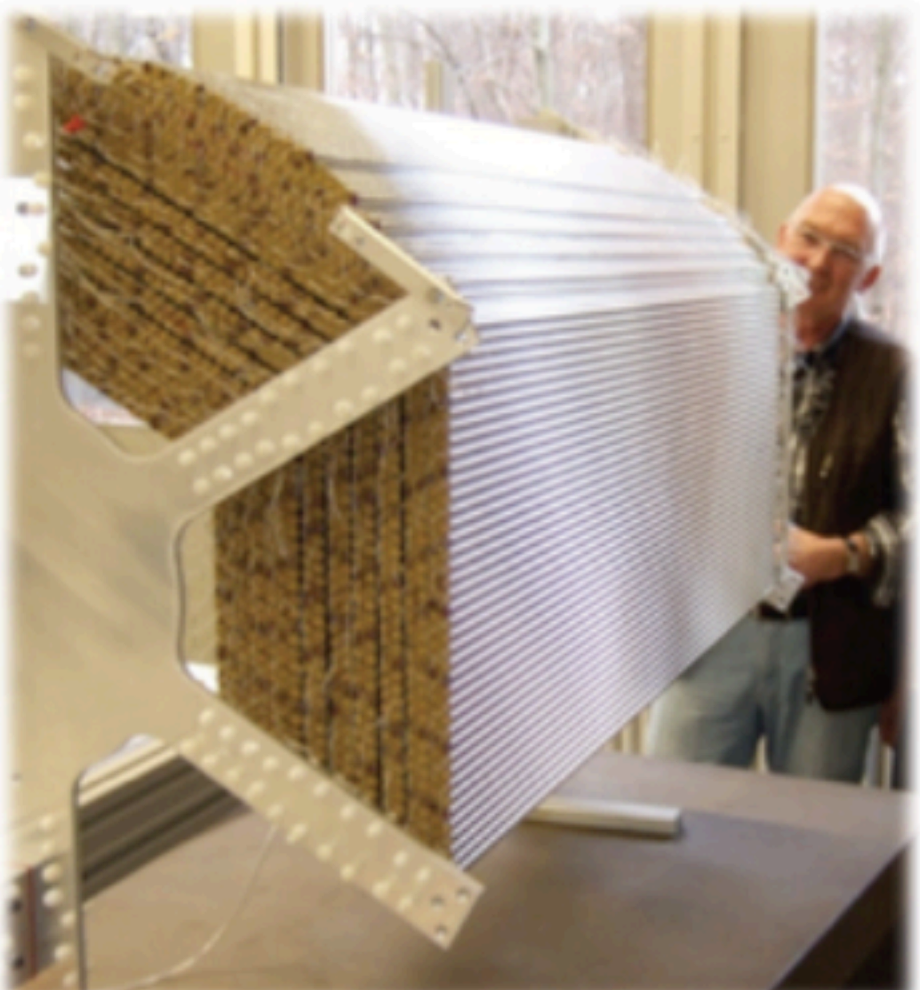
PANDA: the detector (muon counter system)

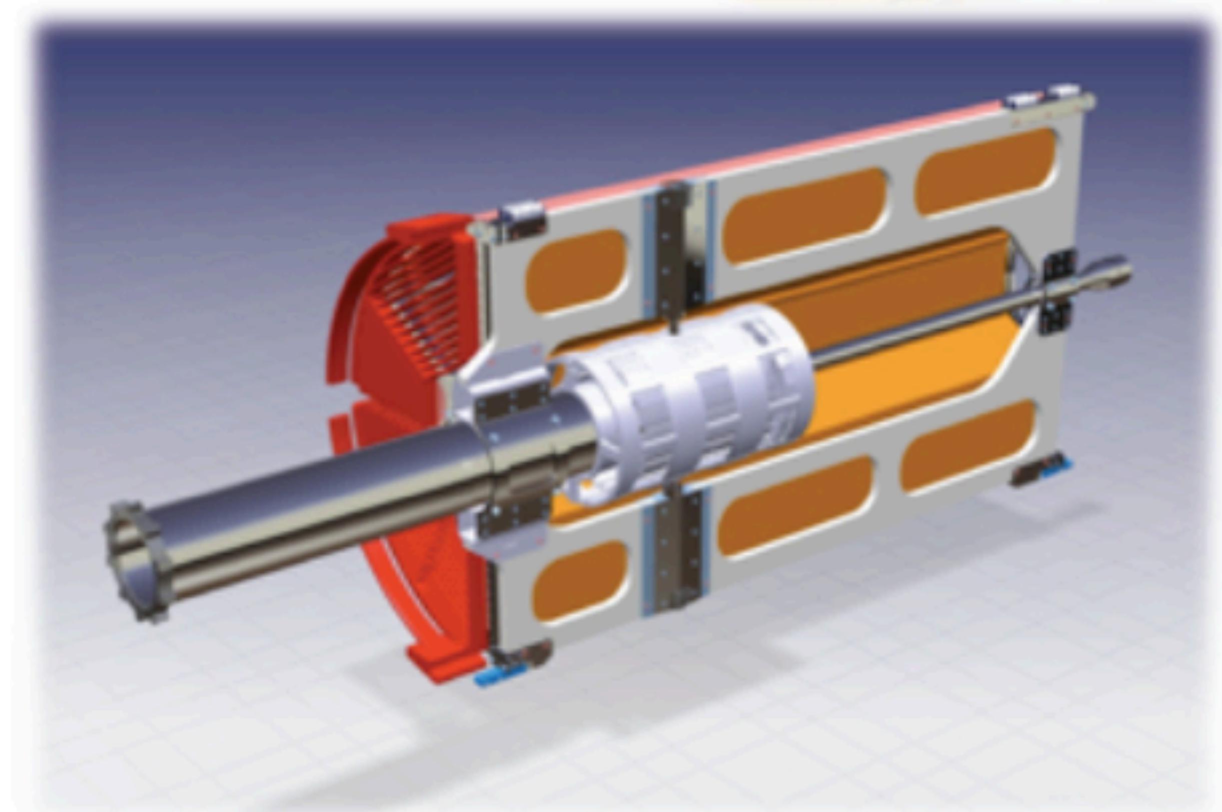


The PANDA Central Tracker

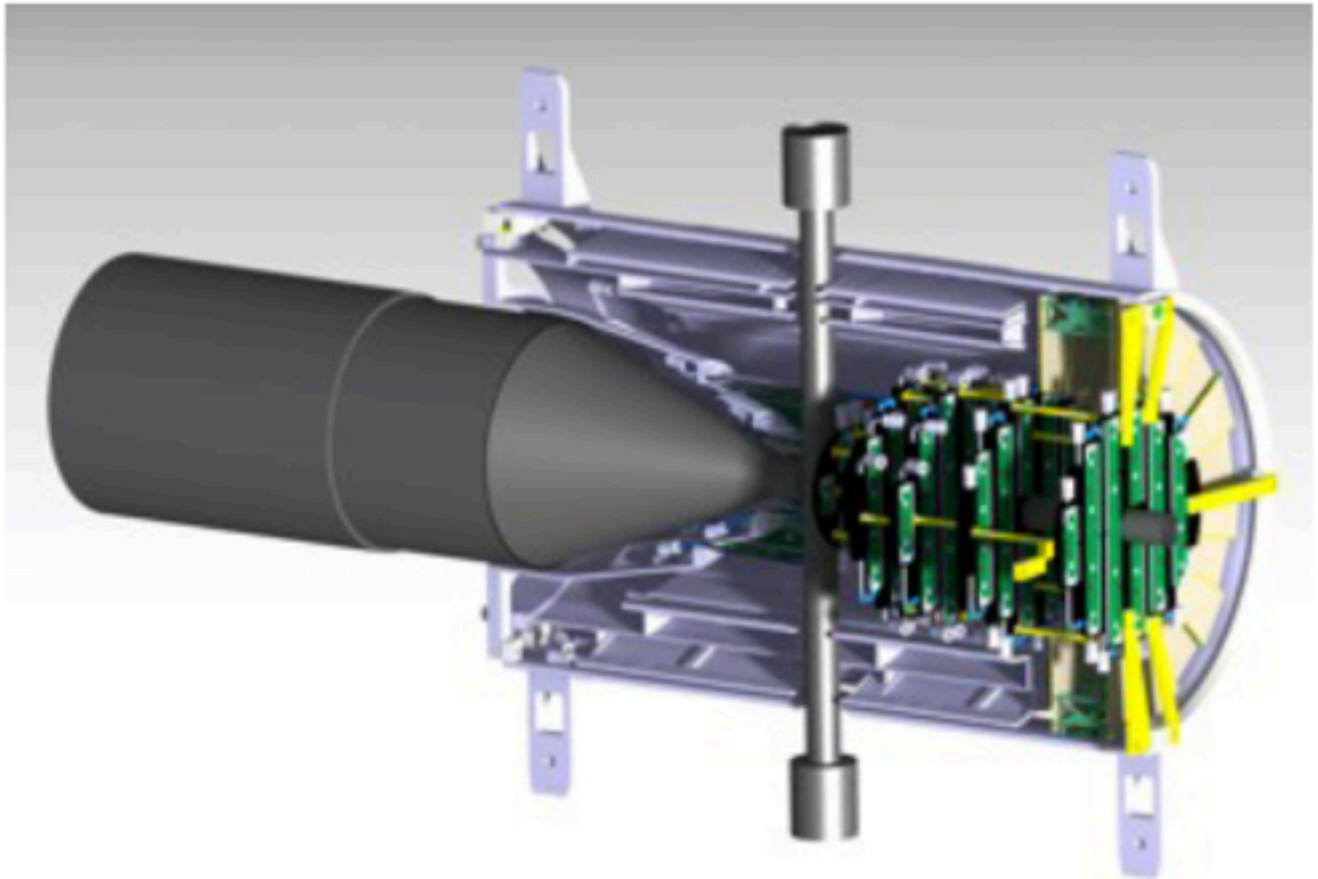




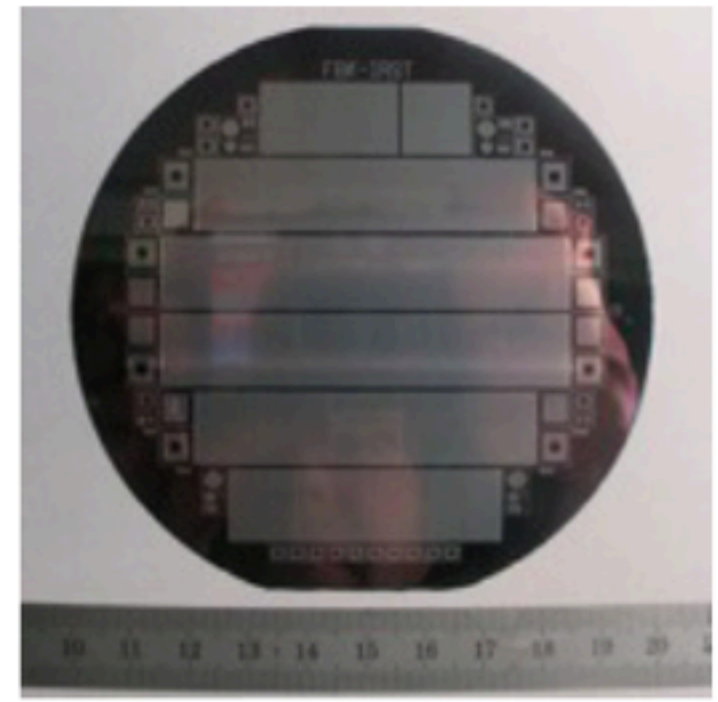




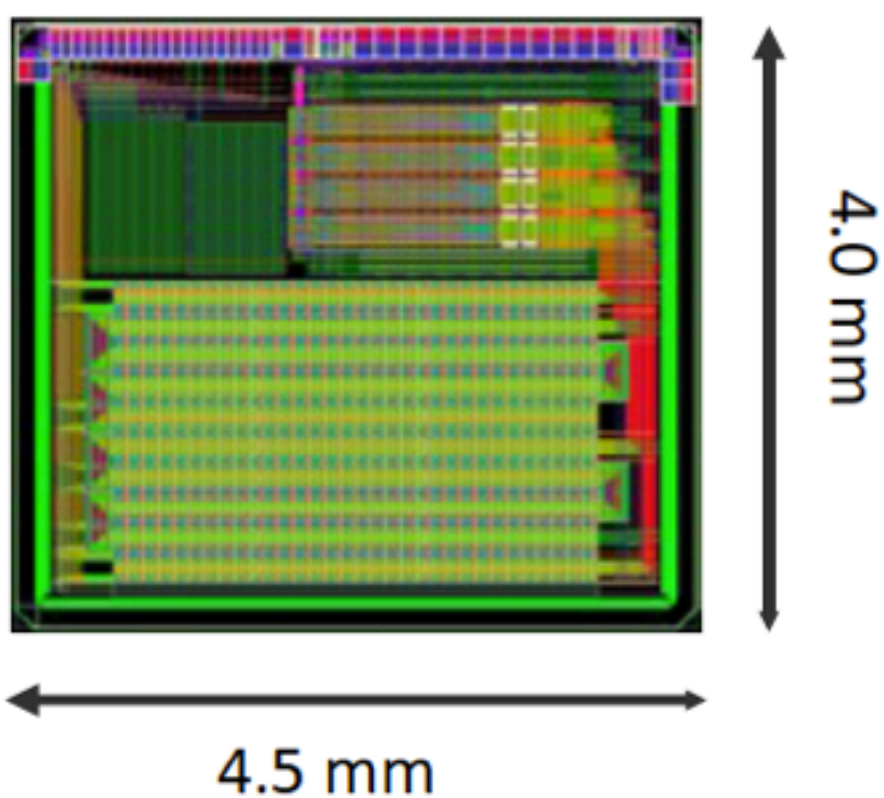
The PANDA MVD



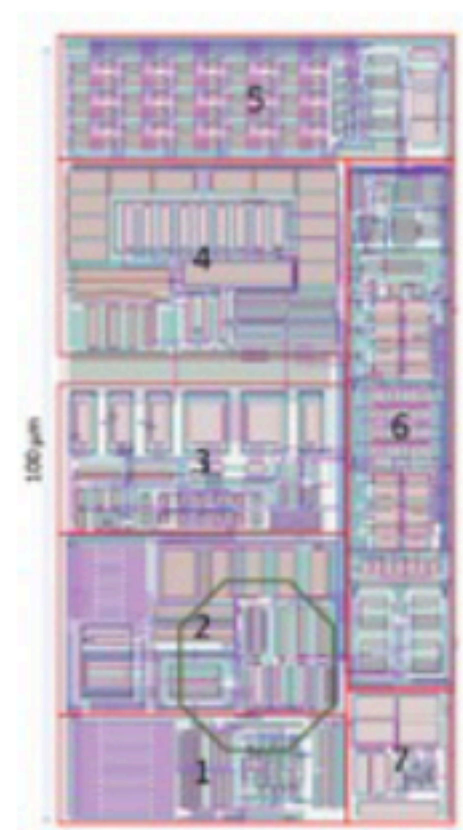
Full-Size Prototypes

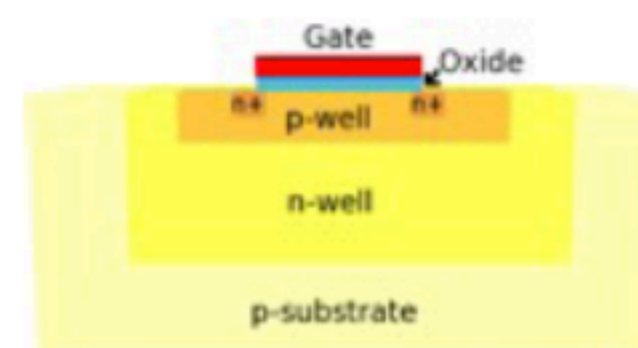


ASIC Prototypes

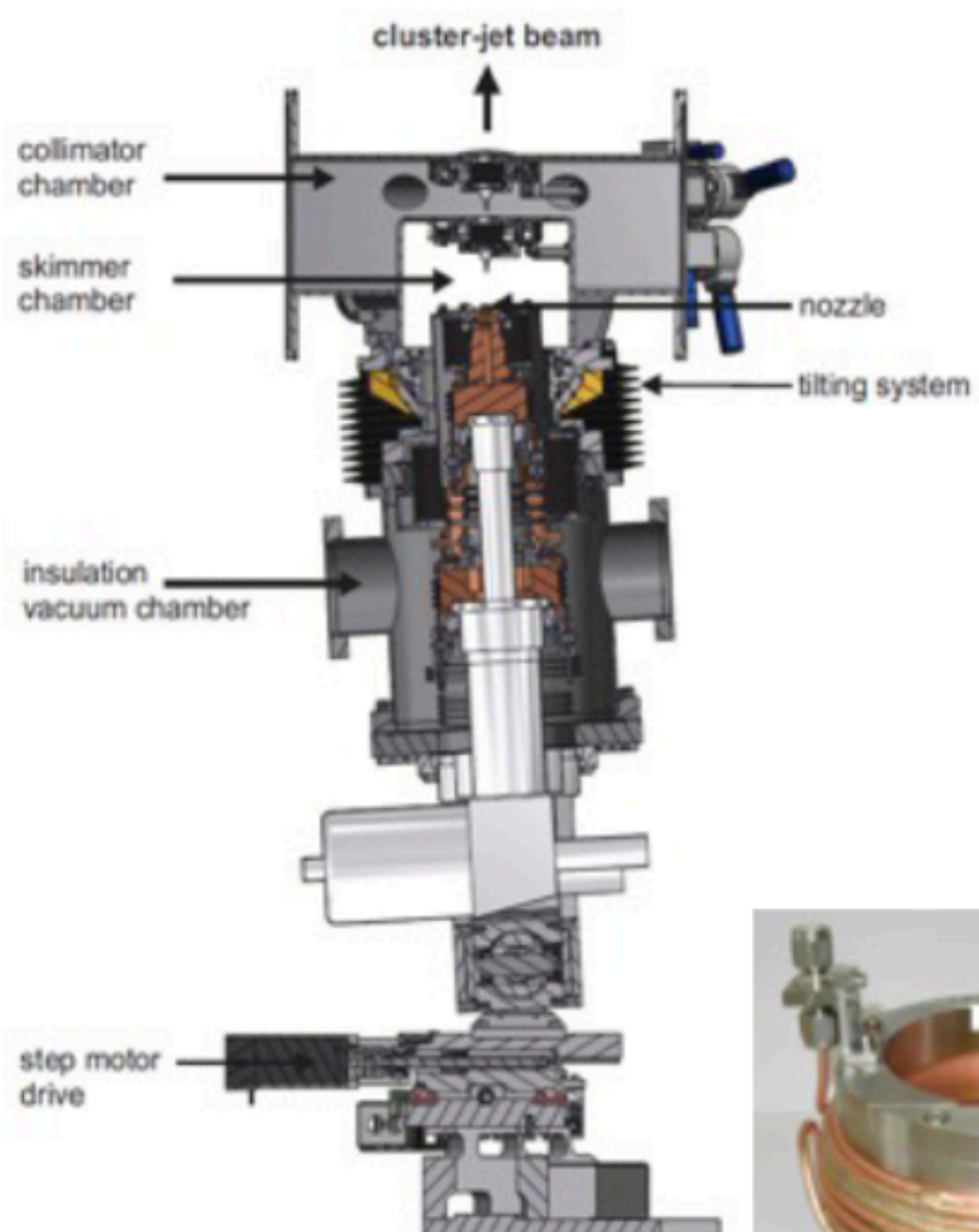


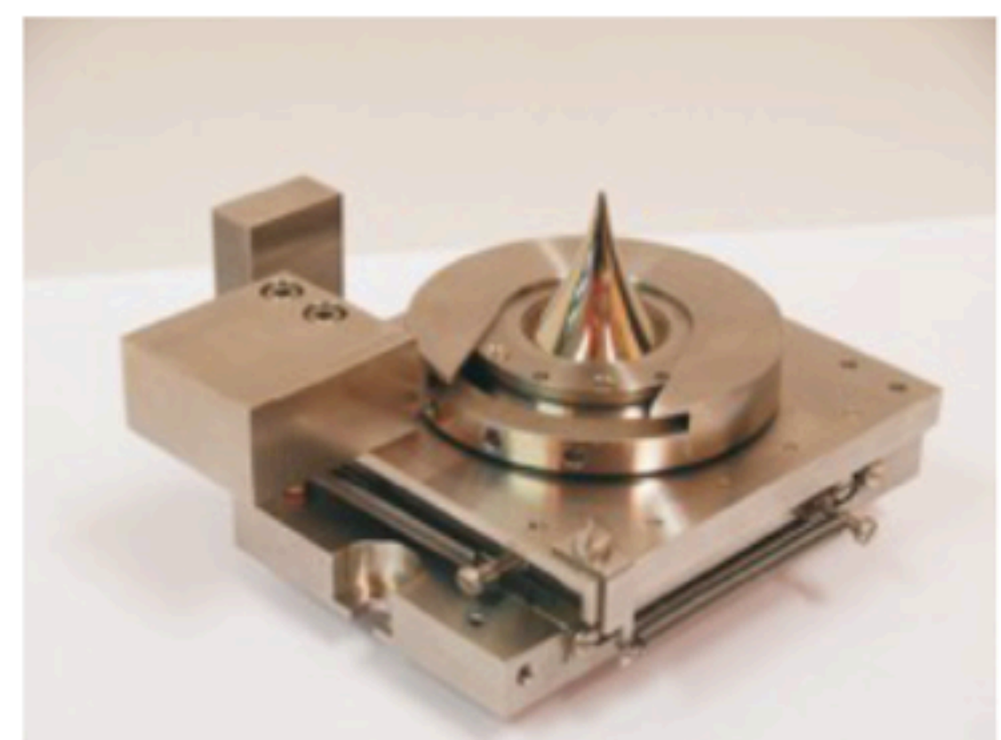
ToPix v3 Full-Feature Prototype





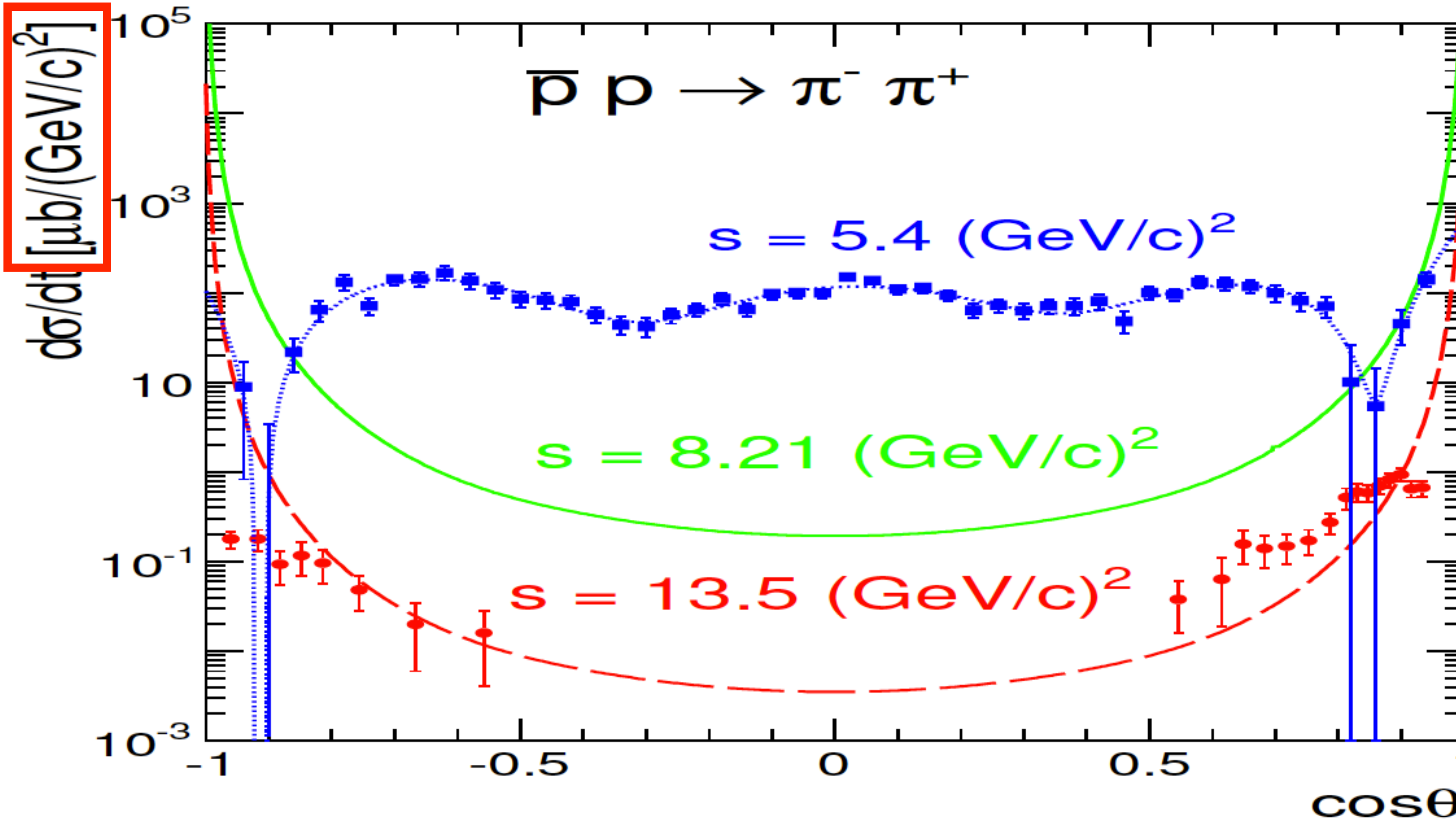
The PANDA Cluster Target





Background

- Input for event generator:

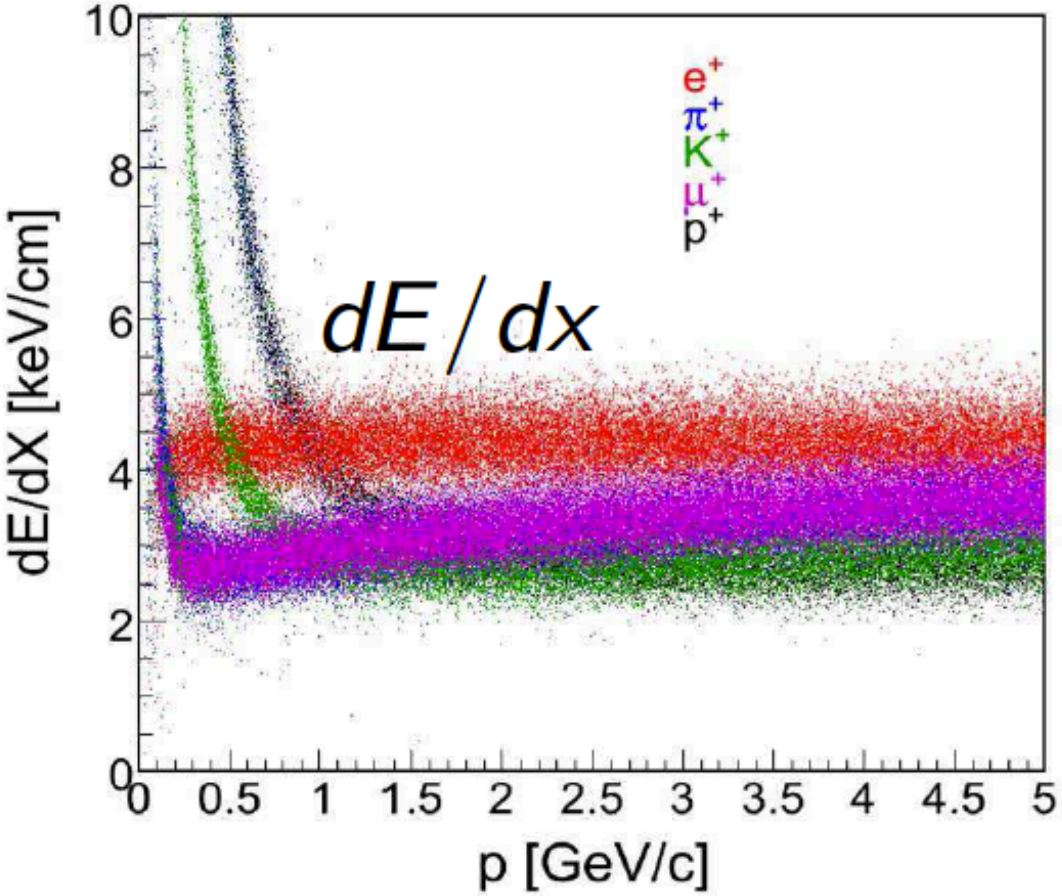


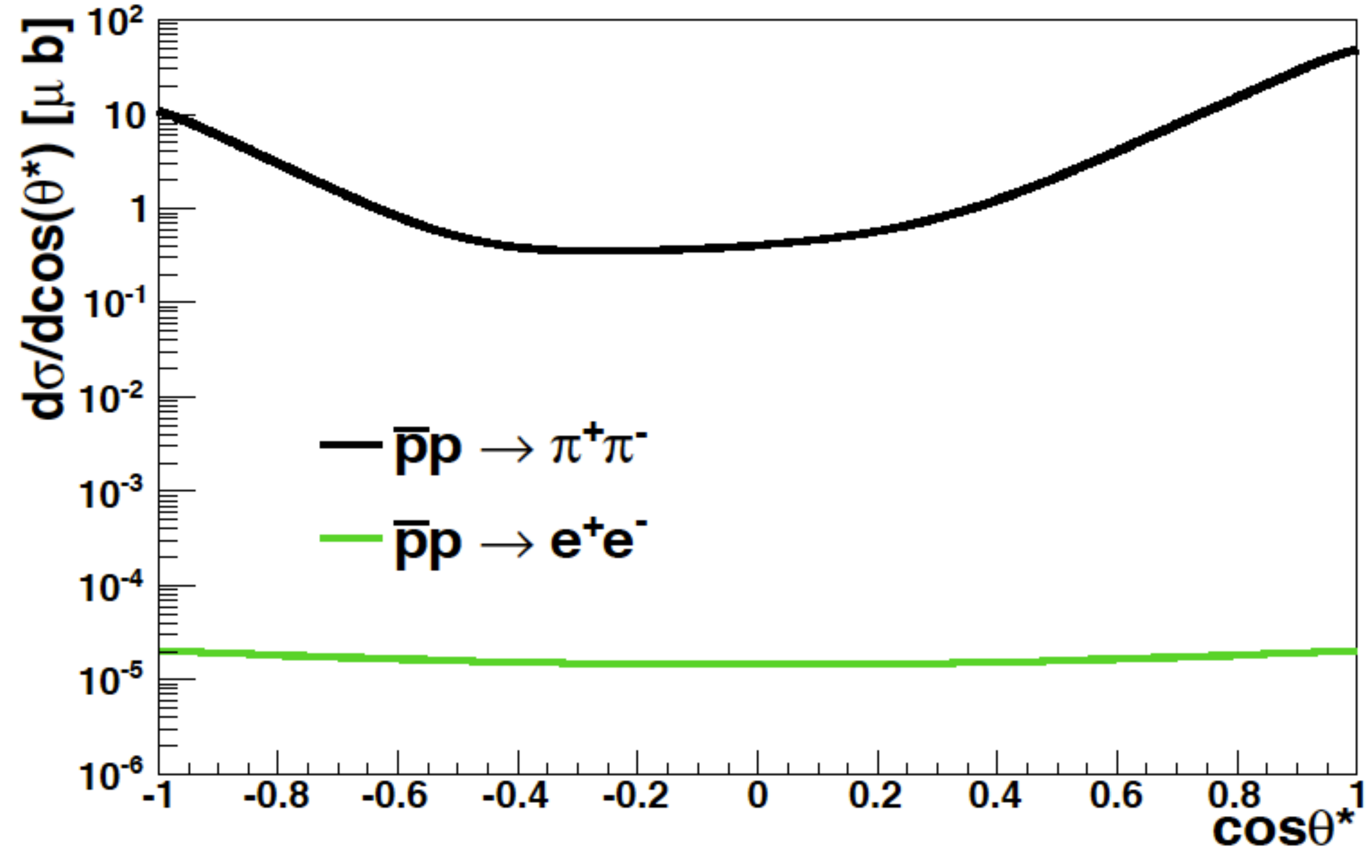
$\sigma(\pi^+\pi^-)/\sigma(e^+e^-) \approx 10^6$ **(2μb/8pb at q^2=9.(GeV/c)²)**

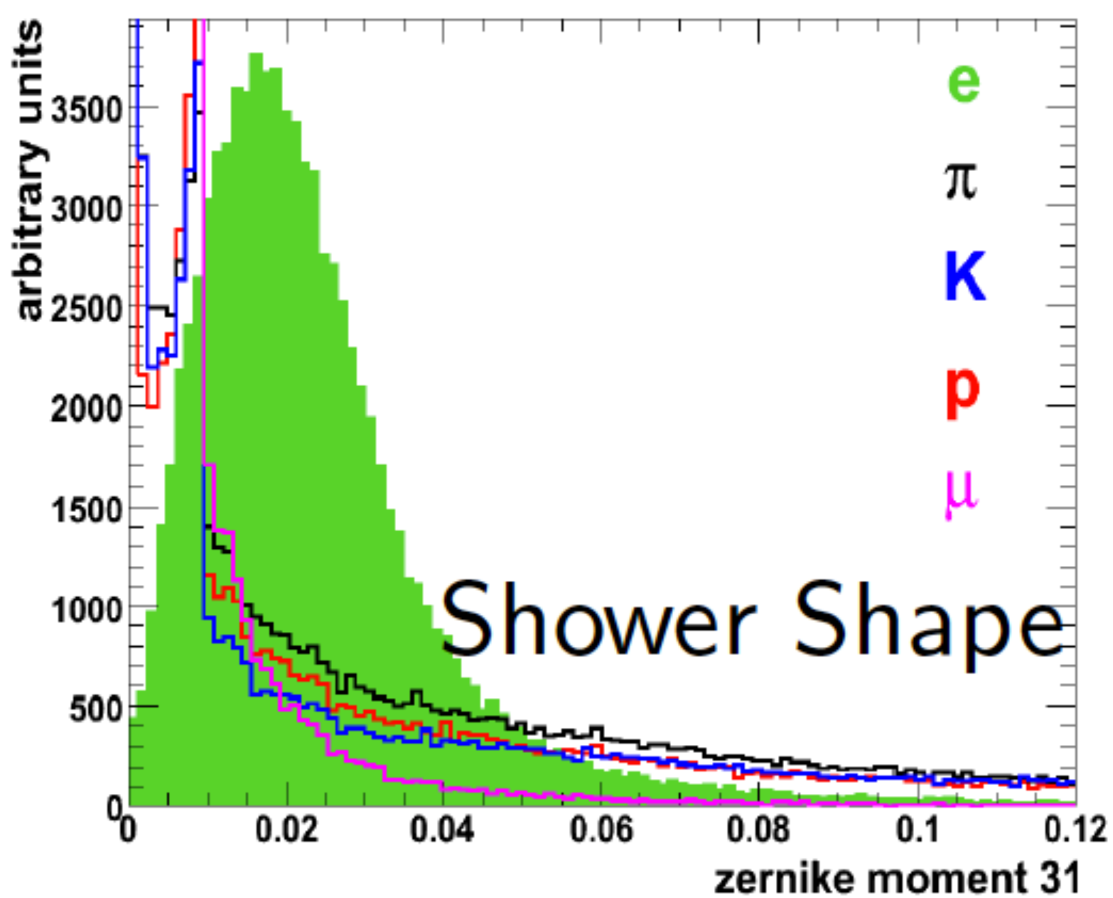
need rejection of **pp** → $\pi^+ \pi^-$ by 10^{-8}, 1% Pollution

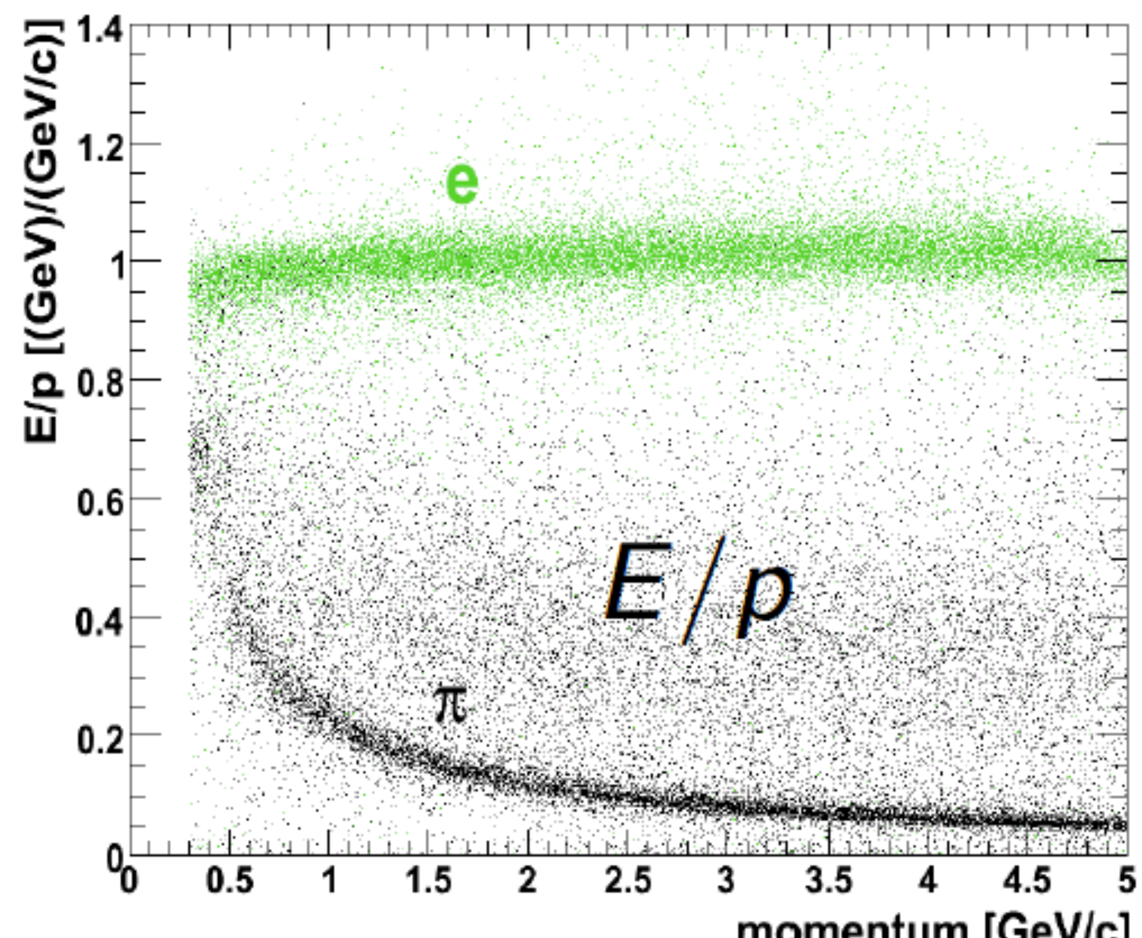
binary event, mean reject. of 10^{-4} per π^+ and per π^- **PID is crucial**

Particle Identification Capability of PANDA

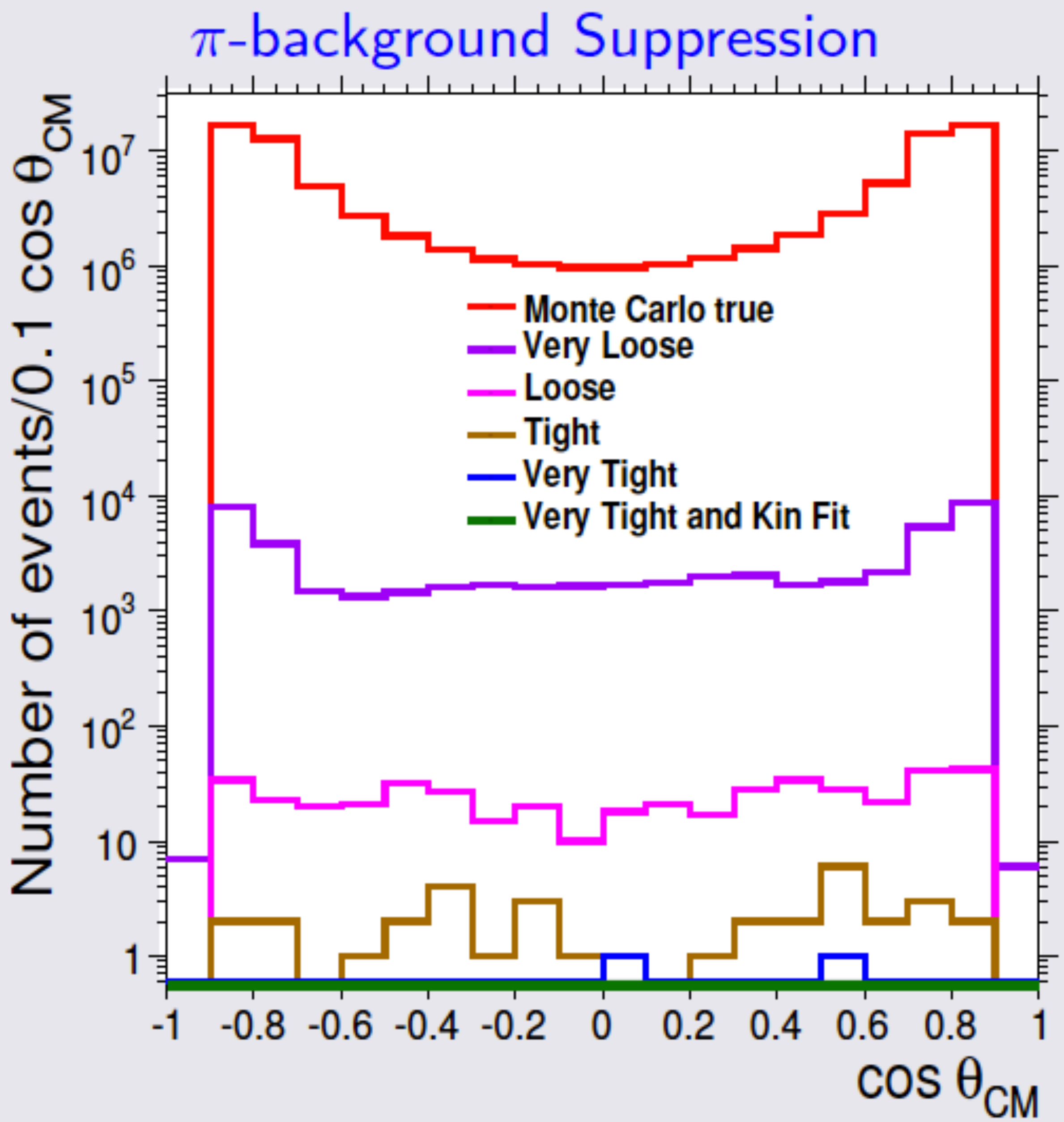




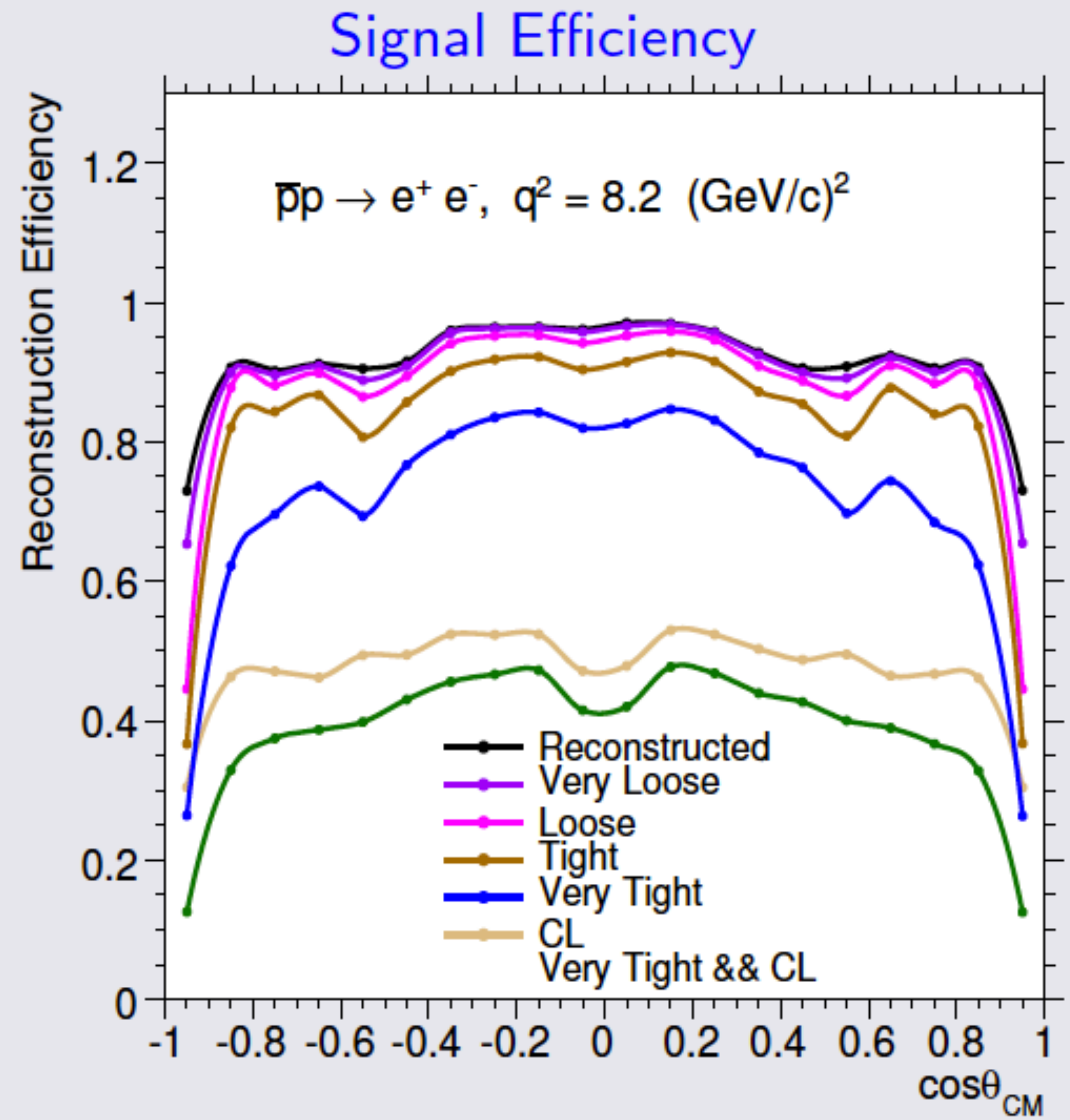




Simulation of pion background versus signal in PANDA



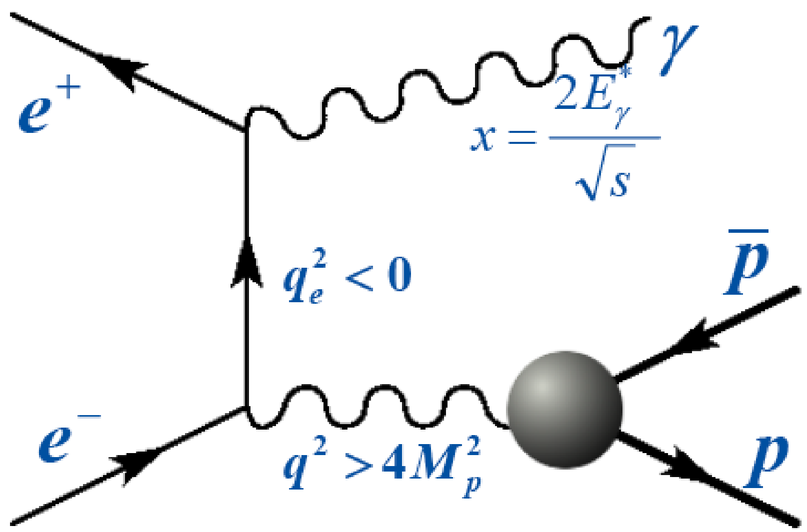
A suppression factor 10^9 is achieved



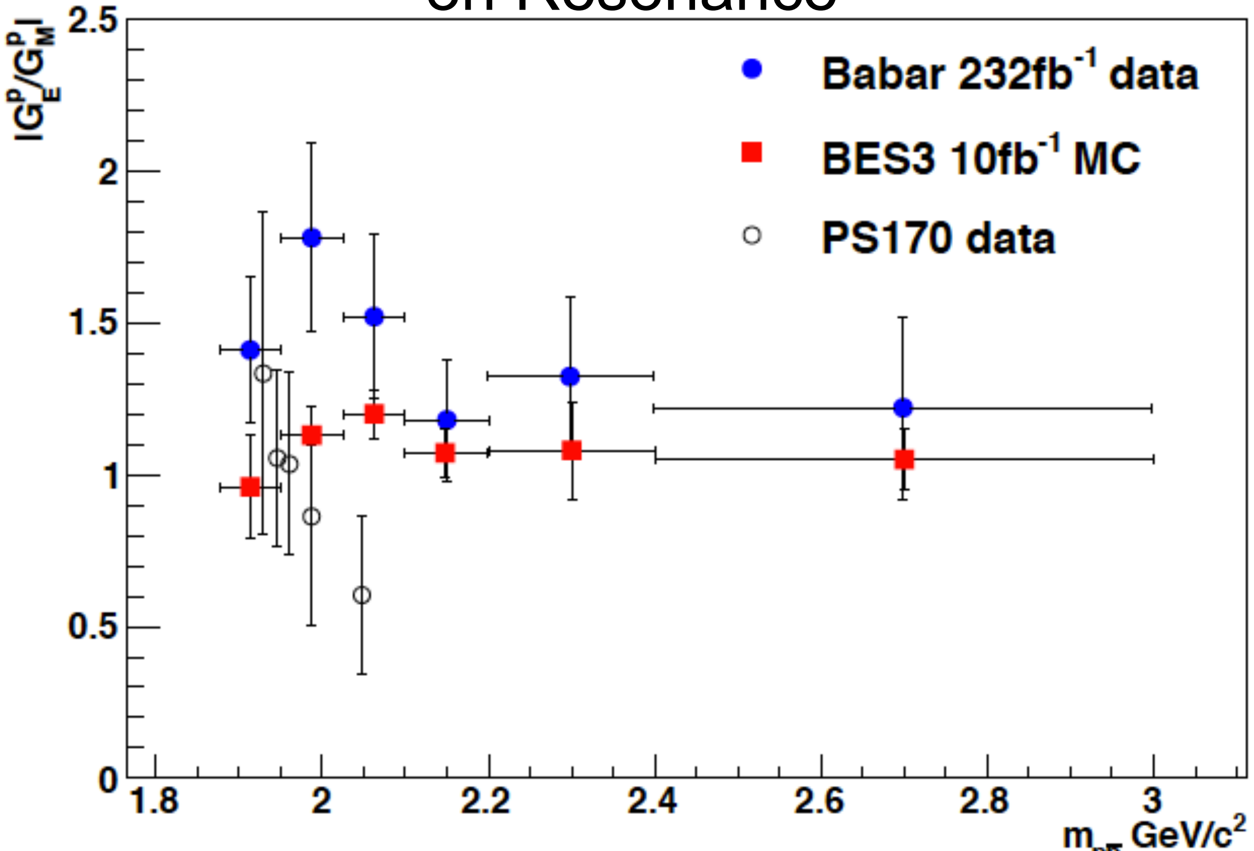
The signal efficiency is about 40%

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

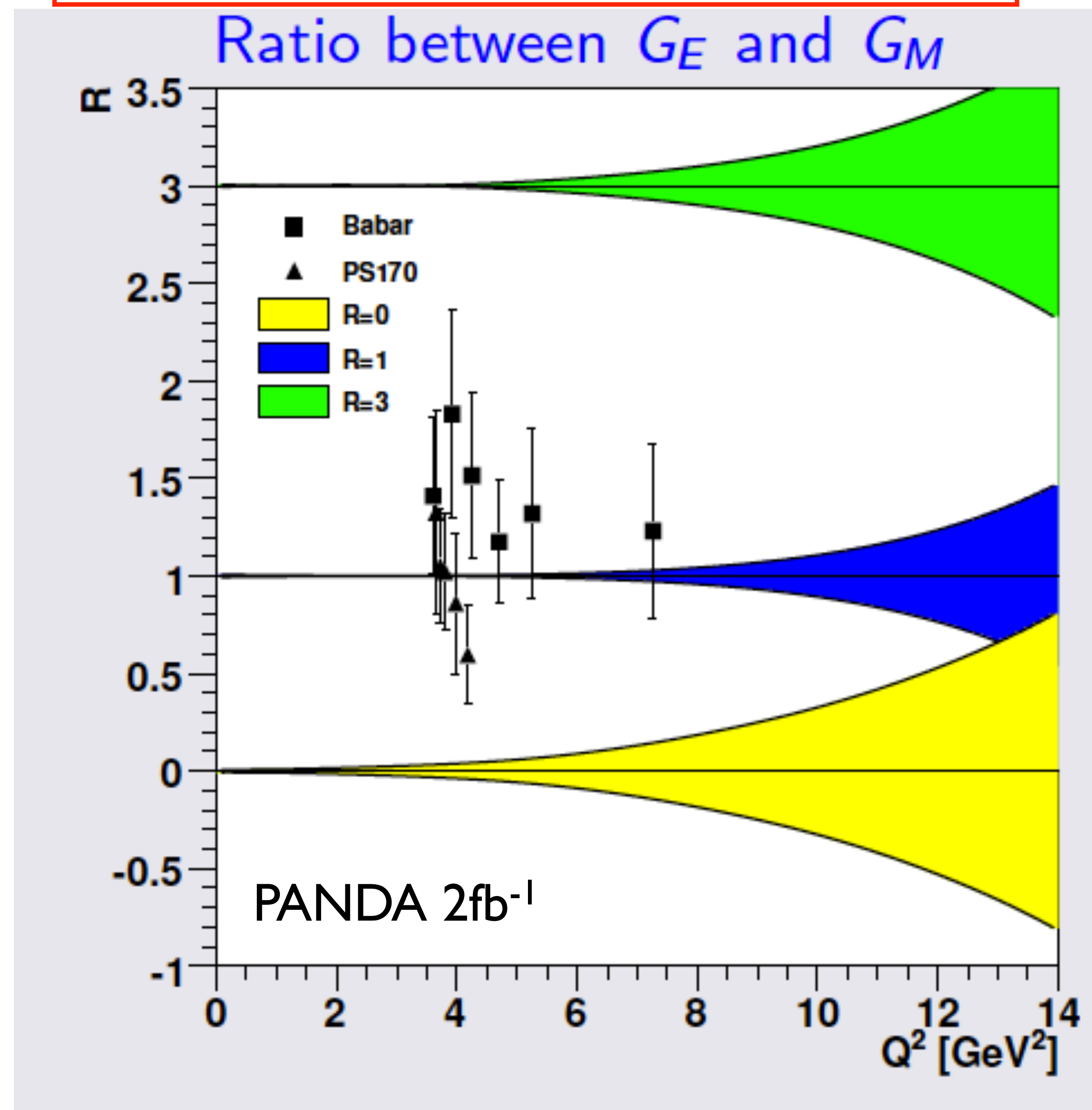
Babar, BESIII: Initial state radiation (ISR), radiative return



BaBar, BESIII: Measurement on Resonance



PANDA: Measurement off Resonance



Extension to other Observables

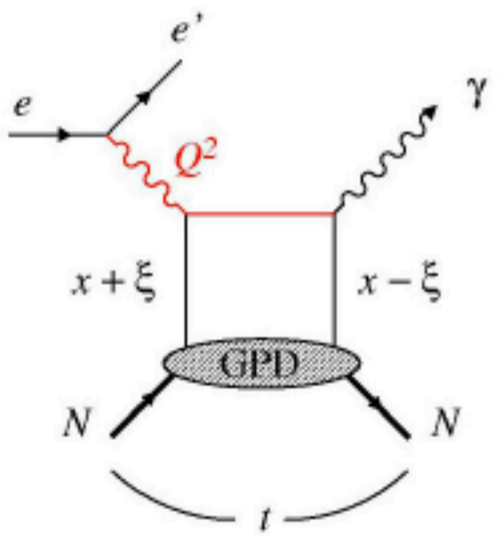
$$\bar{p}p \rightarrow e^+e^-\pi^0$$

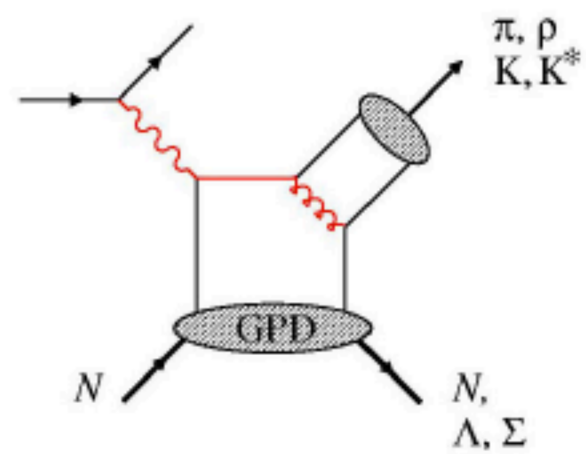
Generalized Parton Distributions and Transition Distribution Amplitudes (scattering)

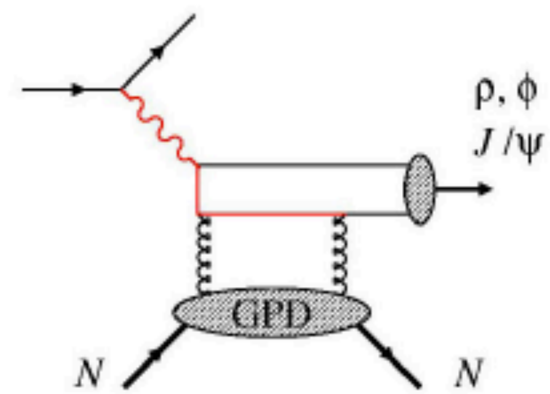
- Factorization theorems for DVCS and HMP: amplitude can be presented as convolution of parton level amplitudes and GPDs

Generalized Bjorken limit:

Q^2, W^2 – large x_B – fixed ;
$-t \equiv -(p' - p)^2$ – small
(compared to Q^2 and W^2)



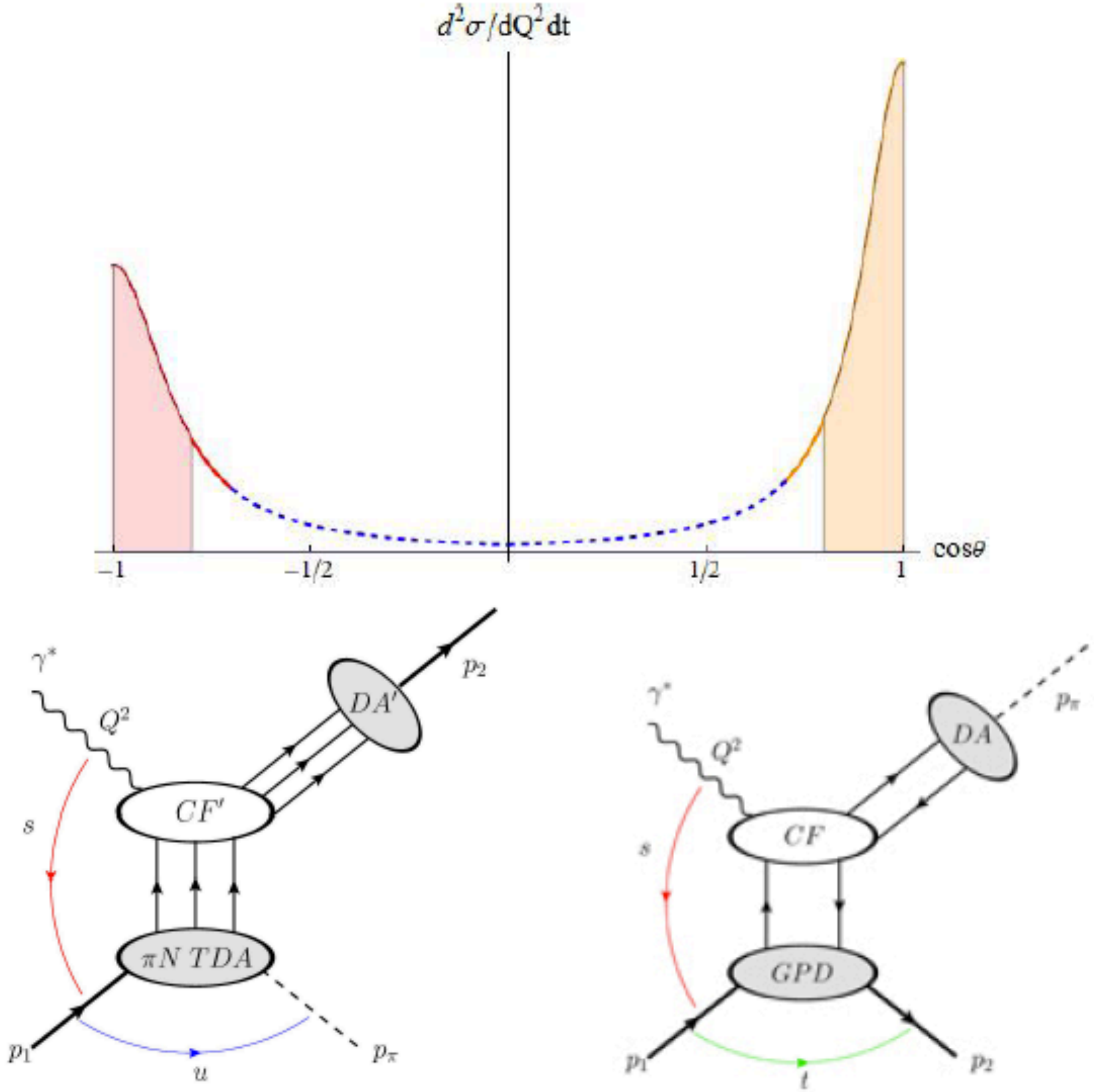




Generalized Bjorken limit ($-q^2 = Q^2$, W^2 – large; $x_B = \frac{Q^2}{2p\cdot q}$ – fixed)

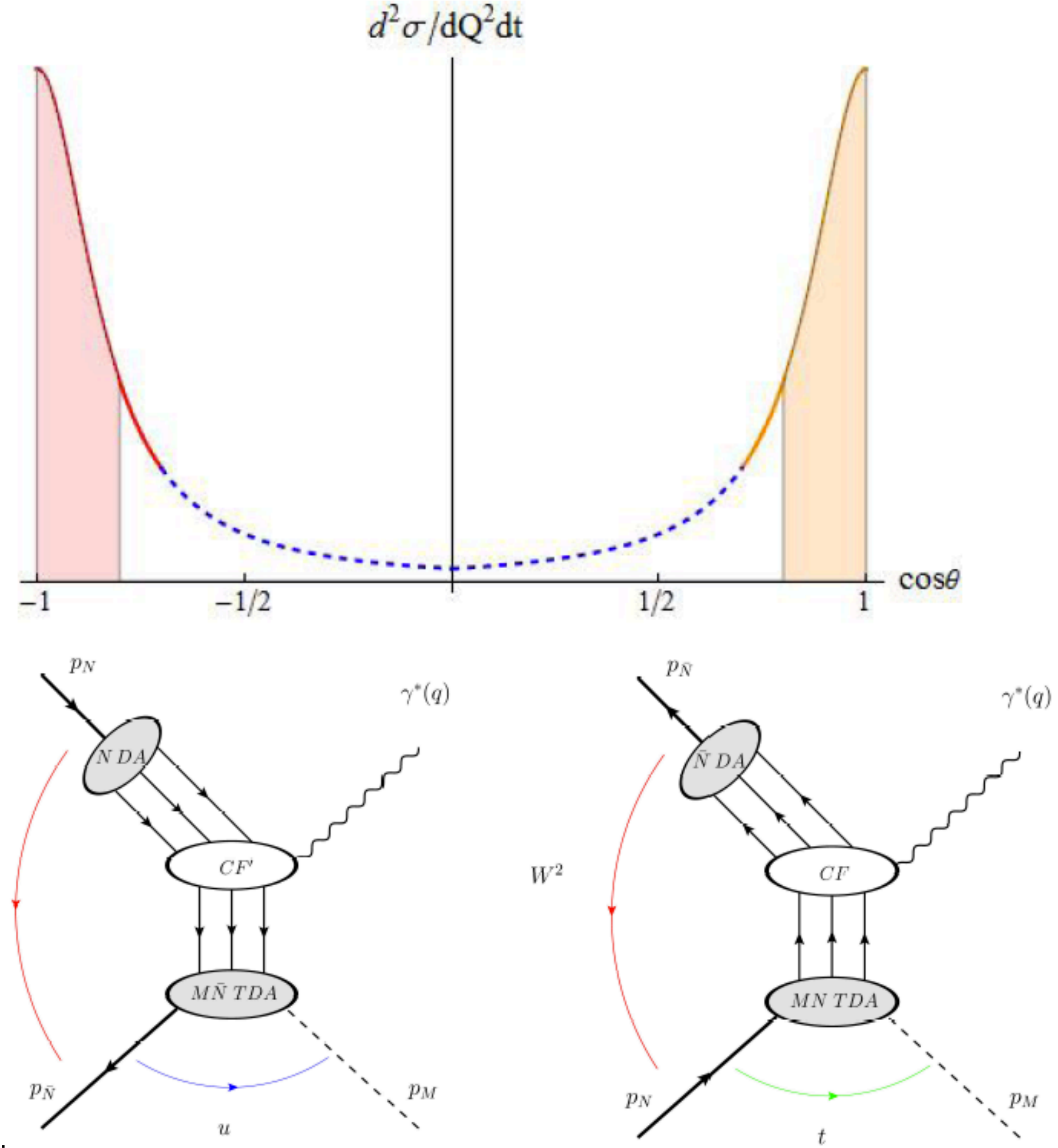
- $t \sim 0$ (forward peak) factorized description in terms of GPDs
- $u \sim 0$ (backward peak) factorized description in terms of TDAs (L. Frankfurt, M. V. Polyakov, M. Strikman et al.'02; B. Pire, L. Szymanowski'05)

Generalized Parton Distributions and Transition Distribution Amplitudes (scattering)



Generalized Parton Distributions and Transition Distribution Amplitudes (annihilation)

- Factorized description of $\bar{N}N \to \ell^+\ell^- M$ in terms of MN TDAs for near forward ($q^2 = Q^2$, W^2 – large, $\frac{q^2}{2p_N \cdot q}$ – fixed, $t \sim 0$) and near backward ($q^2 = Q^2$, W^2 – large, $\frac{q^2}{2p_{\bar{N}} \cdot q}$ – fixed, $u \sim 0$) regimes (Lansberg et al.'07)

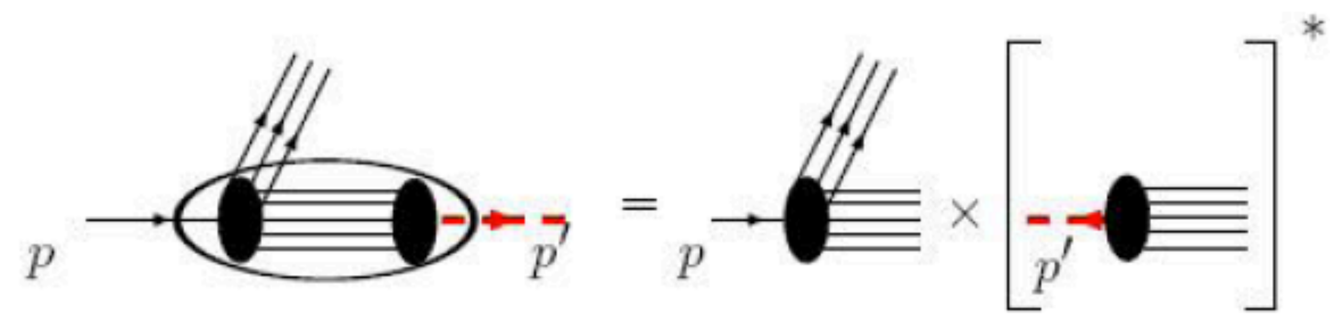


Generalized Parton Distributions and Transition Distribution Amplitudes (annihilation)

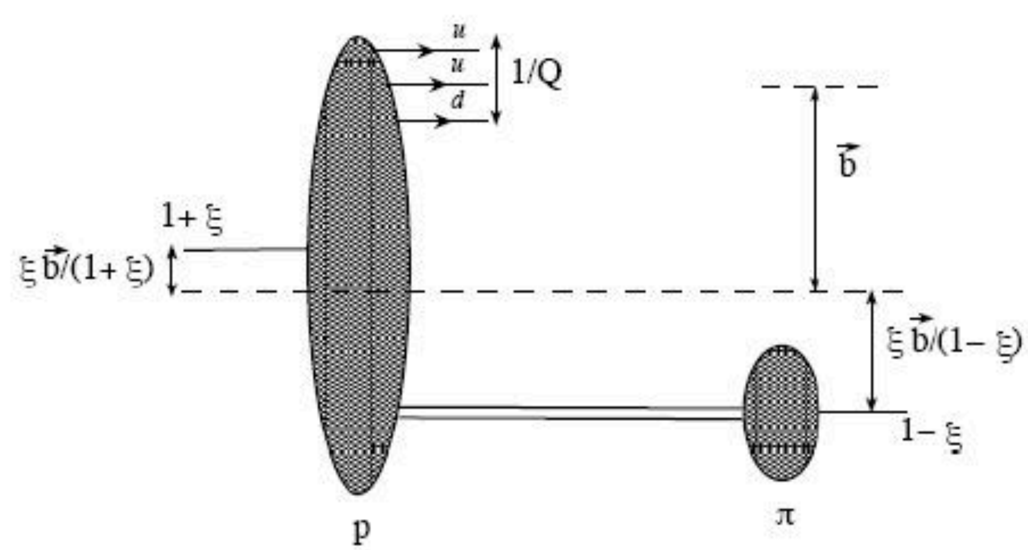
- develop the proton wave function as:

$$\underbrace{|qqq\rangle}_{\text{Described by nucleon DA}} \quad +|qqq\,\pi\rangle + \ldots$$

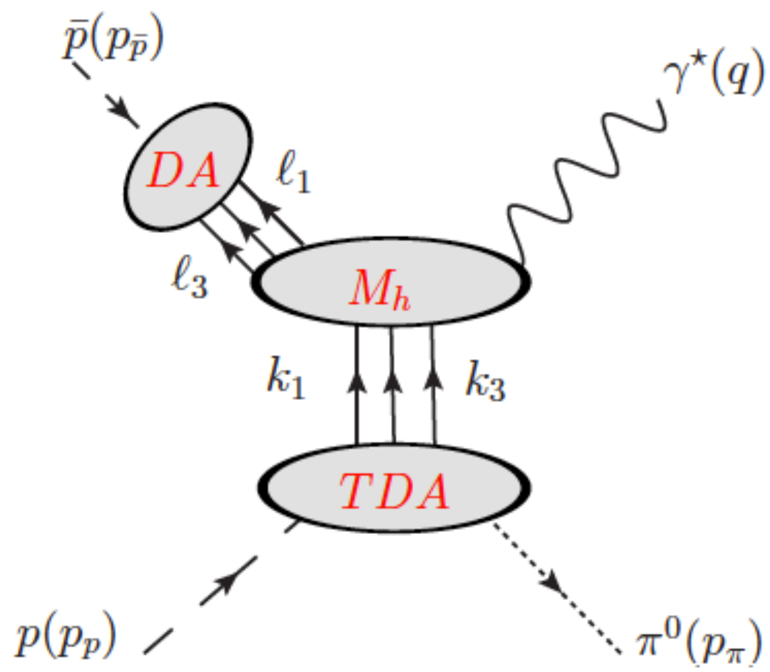
- πN TDAs provides information on the next to minimal Fock state in the baryon;



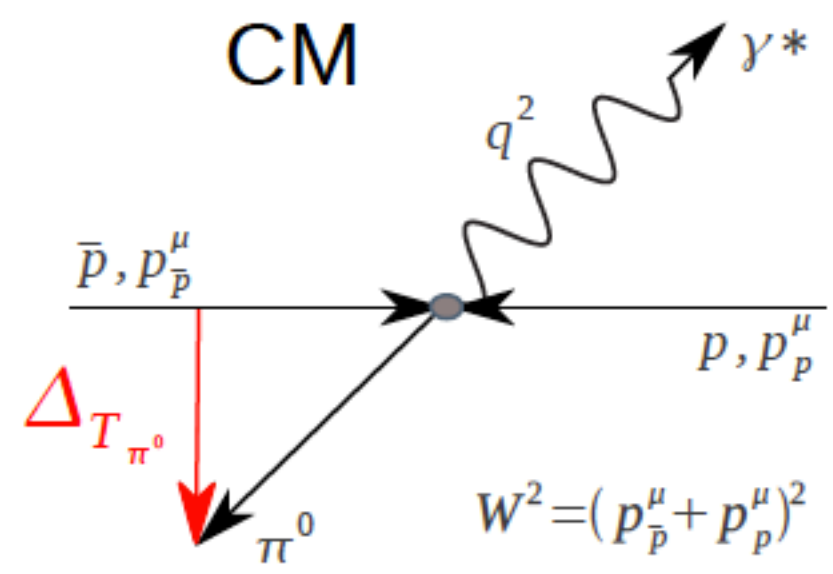
- Impact parameter space interpretation: the Fourier transform $\Delta_T \to b_T \Rightarrow$ transverse picture of pion cloud in the proton



Transition Distribution Amplitudes

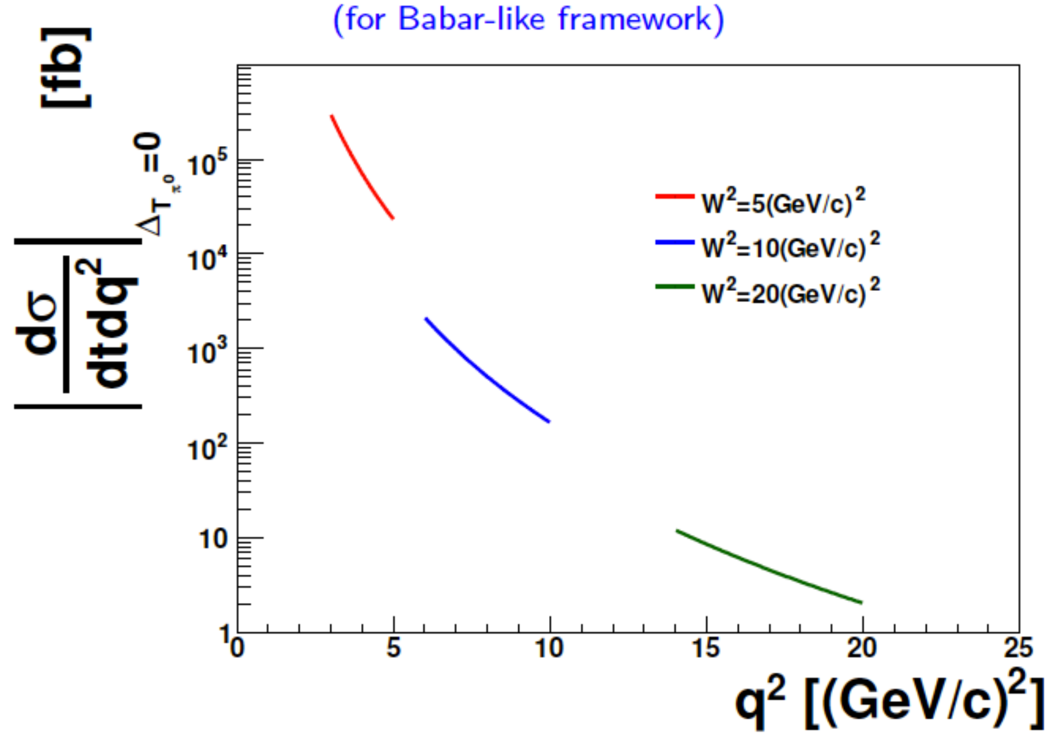


$\bar{p}p \to e^+e^-\pi^0$



Input for the Event Generator

(for Babar-like framework)

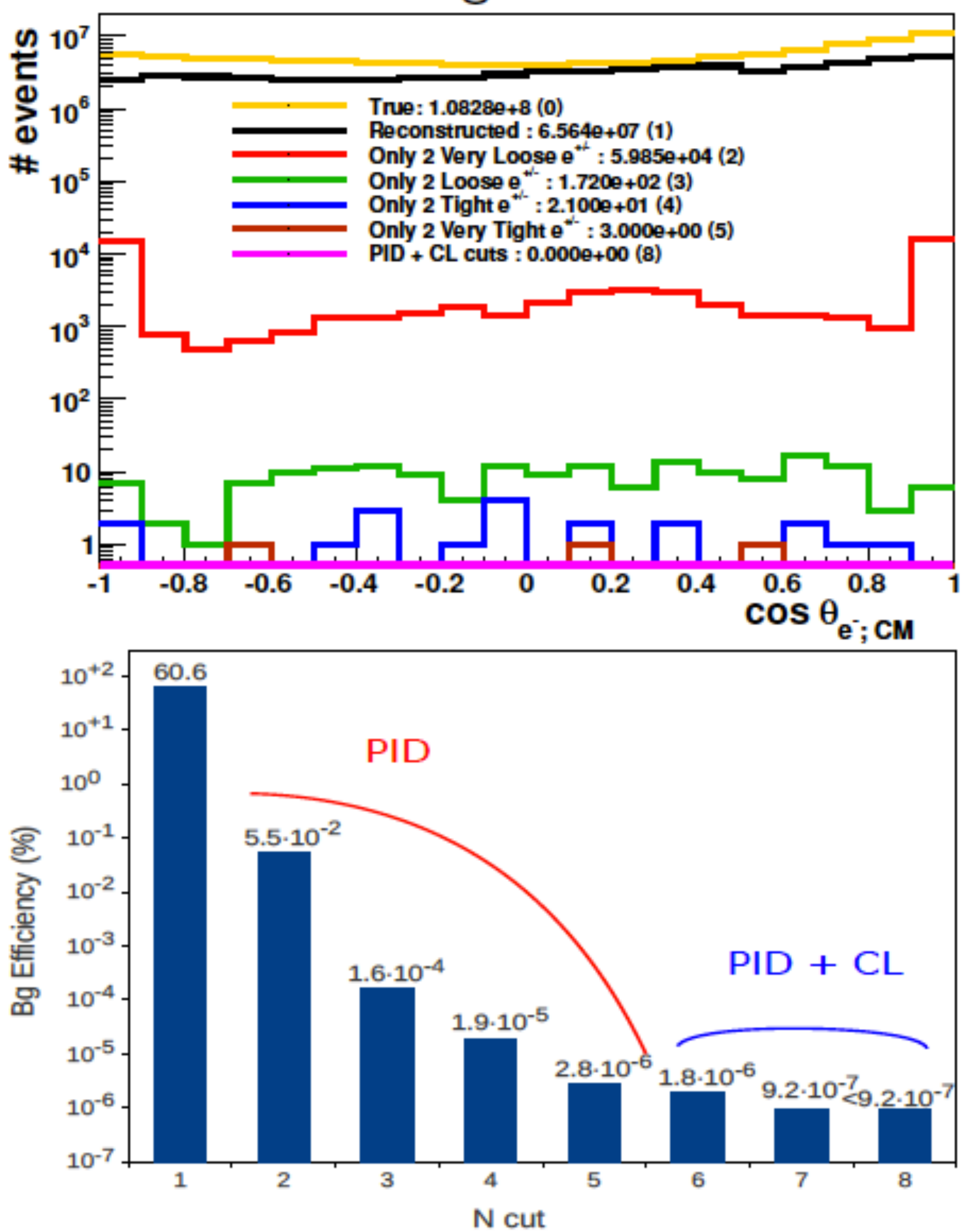


Background: $\bar{p}p \to \pi^+\pi^-\pi^0$

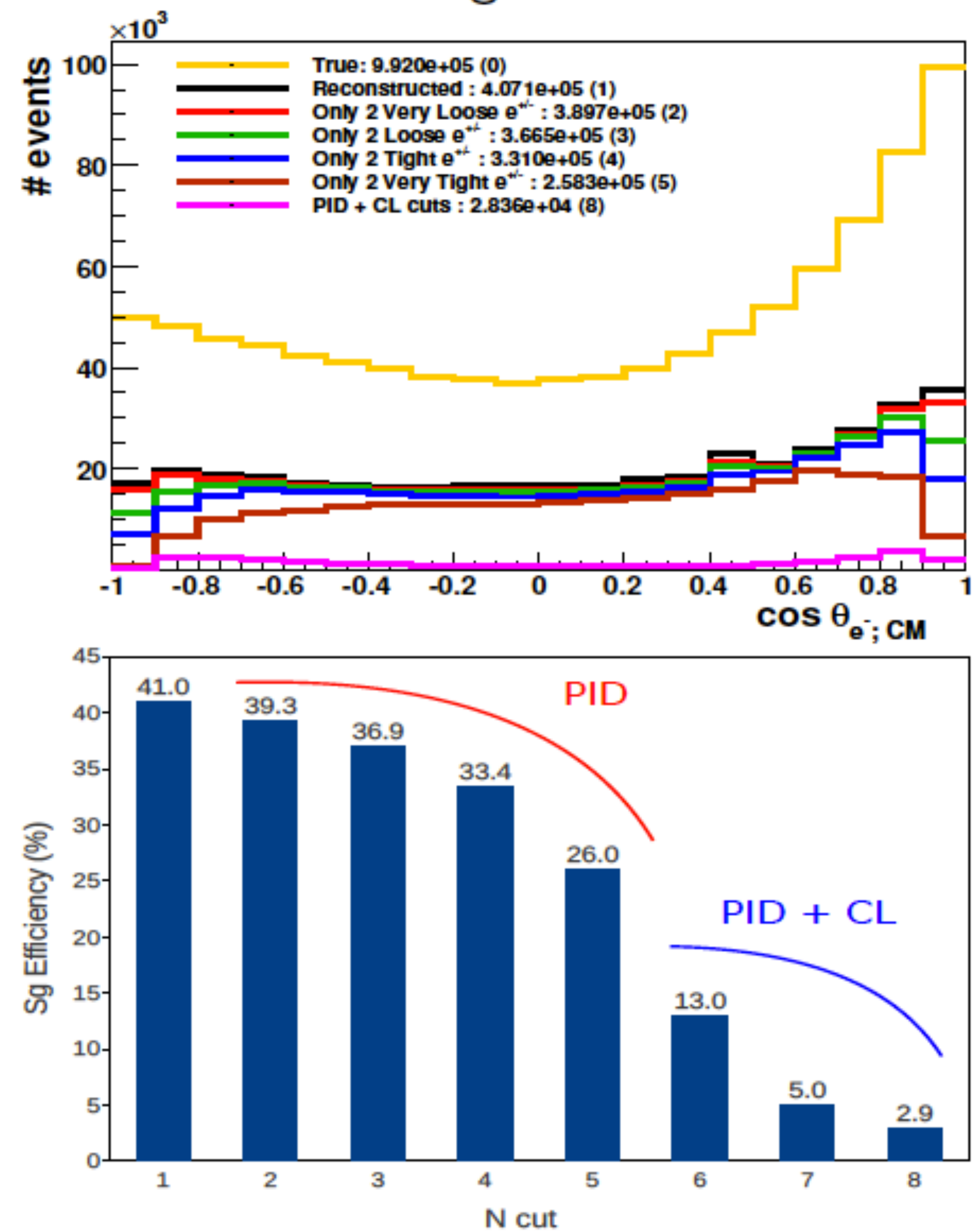
- No data
- The same angular distribution as the signal
- 10^6 times higher

Transition Distribution Amplitudes

Background

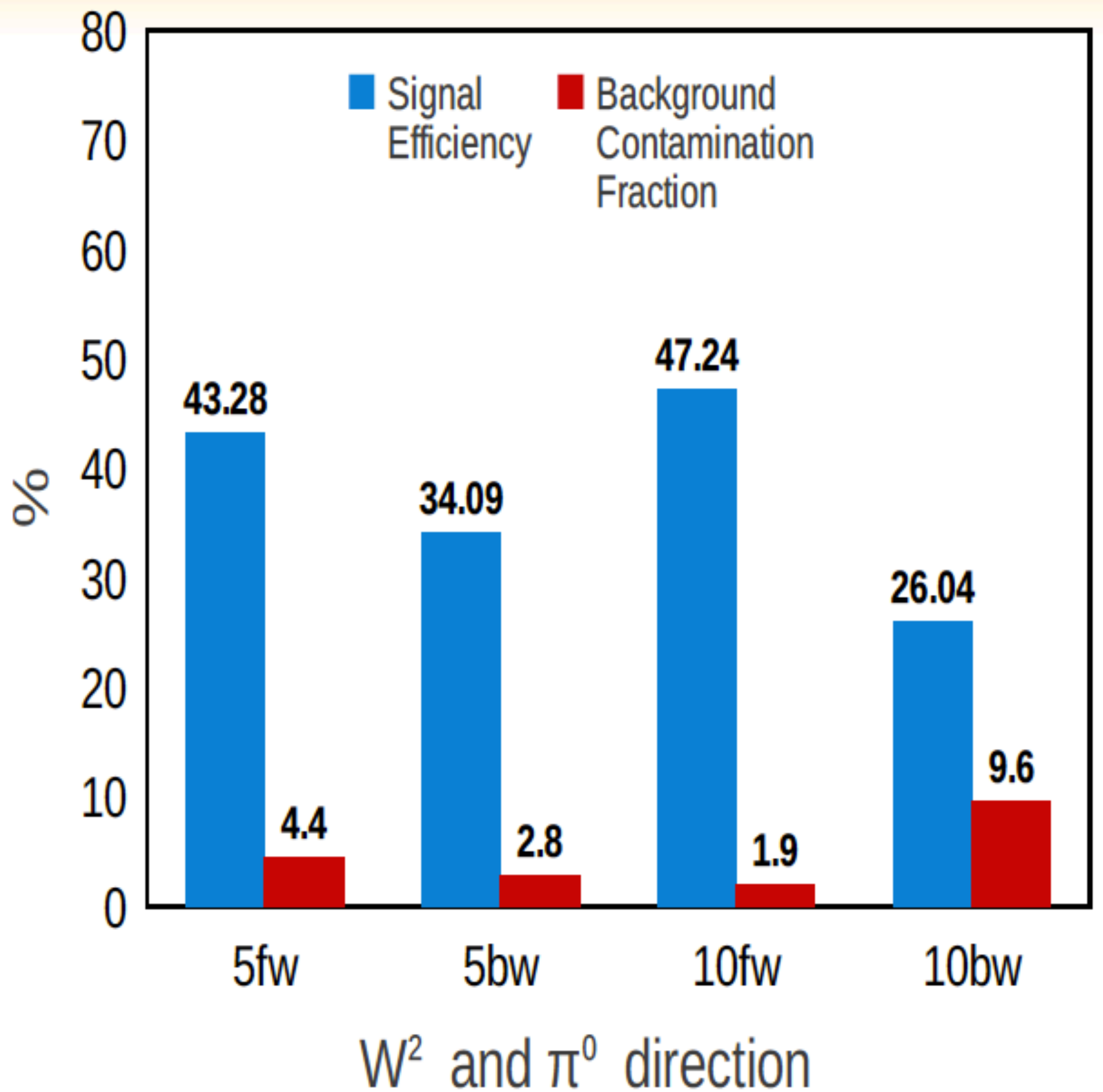


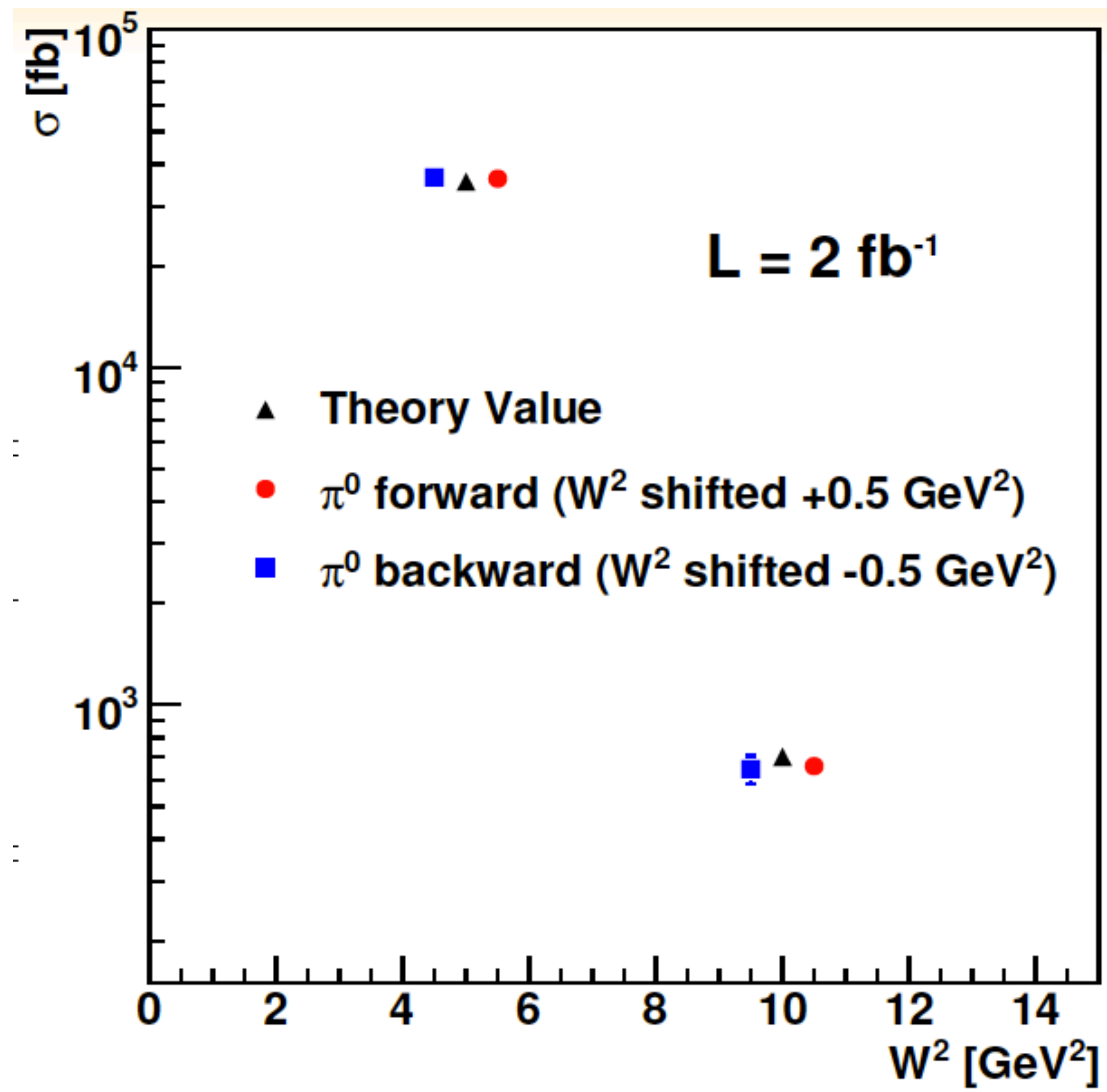
Signal



PID+CL: Only 2 Very Loose $e^{+/-}$ + $CL(e) > 10^{-3}$ + $CL(e) > 3 \cdot CL(\pi)$

Transition Distribution Amplitudes





Exciting times for Nucleon Electromagnetic Form Factors

- New BaBar-results on electromagnetic form factors from ISR
- BES-III data from ISR under analysis
- JLab 11 GeV upgrade brings new data, new experiments for proton radius (JLab, MAMI, PSI)
- Electromagnetic Form Factors of the Nucleon with PANDA: Unprecedented Accuracy (from 50% to 3-5%) $pp \rightarrow e^+e^-$
- Supression of hadronic background better than 10^{-8} due to PANDA particle identification capabilities and kinematical constraints
- Theory activity: Models for time like FF, Radiative Corrections (ISR, FSR, Polarisation, Two-Photon-Exchange)
- Extented to Transition Distribution Amplitudes: $pp \rightarrow e^+e^-\pi^0$
- Extension to Muons, Drell-Yan with Muons, Electrons: $pp \rightarrow e^+e^- X$, Time like GDAs, ... rich nucleon structure program in PANDA
- Transversely Polarized Target in PANDA