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Hadron structure observables

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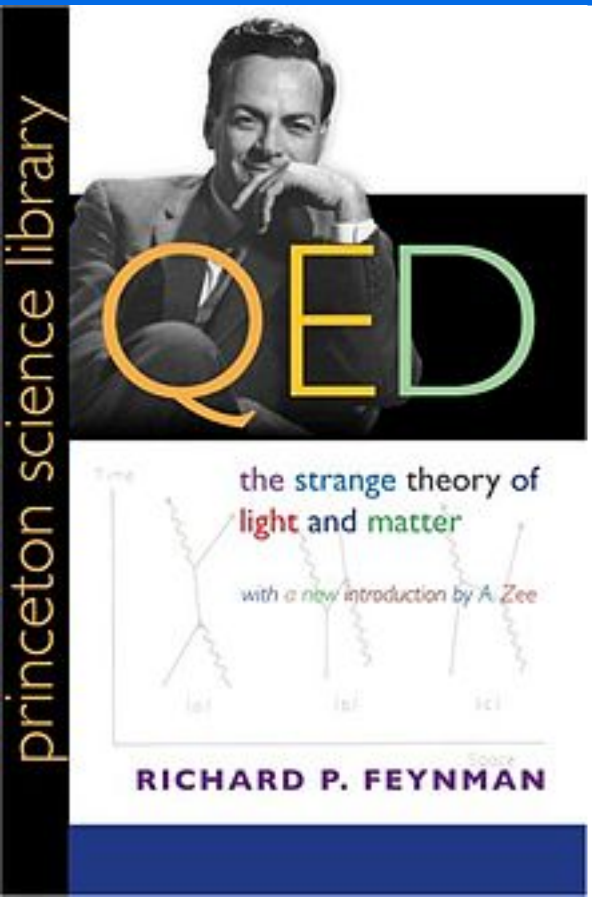
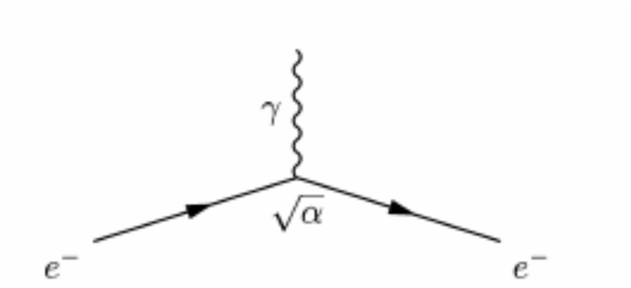
Helmholtz-Institut Mainz

EMMI Hadron Physics Seminar – GSI/Darmstadt 12.04.2017

QED: the strange theory of light and matter



Electromagnetic interaction via the exchange of virtual photons



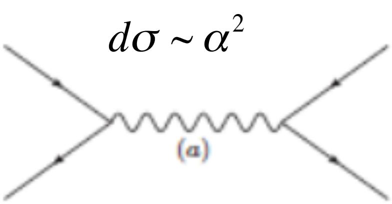
$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \cong \frac{1}{137}$$

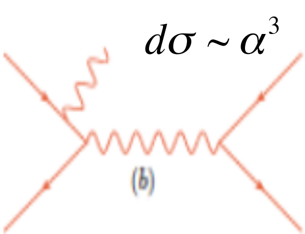
QED is a time dependent perturbation theory

One photon interaction: $\alpha = 1/137$

Perurbative corrections: $\alpha^n = (1/137)^n$

QED converges rapidly: accurate predictions





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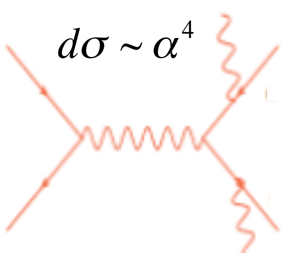
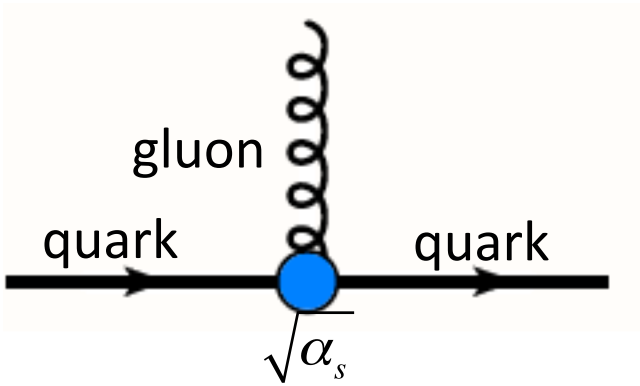


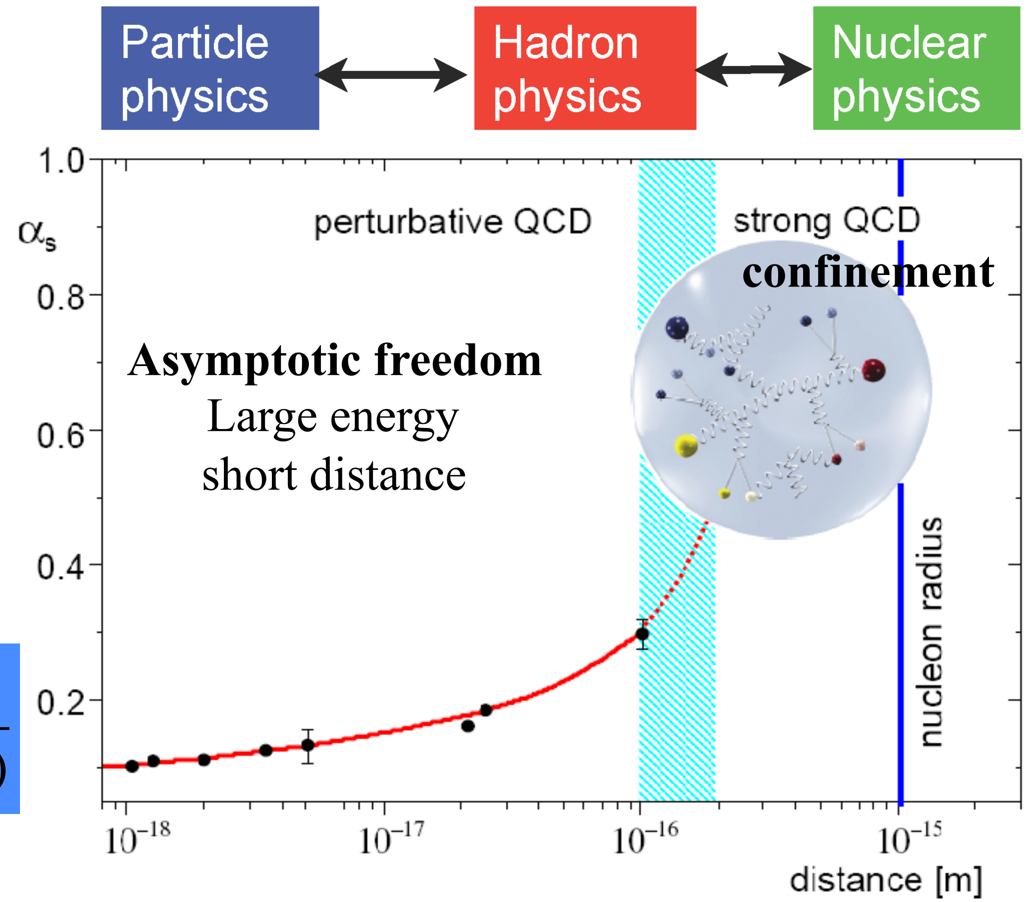
+...

From QED to the theory of the strong interaction QCD

Quark model (Gell-Mann 1964) :
hadrons are made of quarks which are held together by the strong interaction



$$\alpha_s(q^2) = \frac{\alpha_s(\Lambda_{QCD}^2)}{(1+\beta\alpha_s(\Lambda_{QCD}^2)\ln(q^2/\Lambda_{QCD}^2))}$$



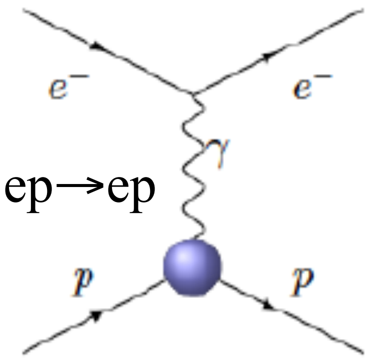
Hadronic scale ~ 1/fm (=1/139 MeV^{-1}) ~ Λ_{QCD} is non-perturbative

Studying the nucleon structure is an investigation of the non perturbative QCD

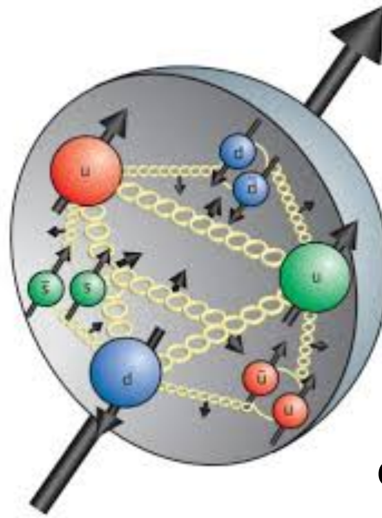
Electromagnetic structure of hadrons

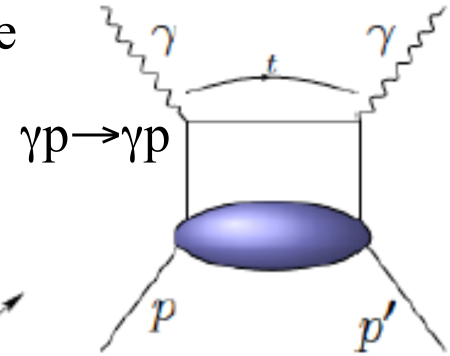
QED interactions to probe the non perturbative QCD

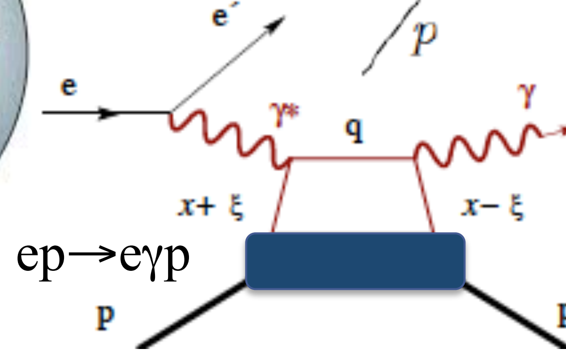
- Connect quarks and gluons to hadrons via non-perturbative but **universal distribution functions** (QCD factorization)
- Provide unified view of the nucleon structure



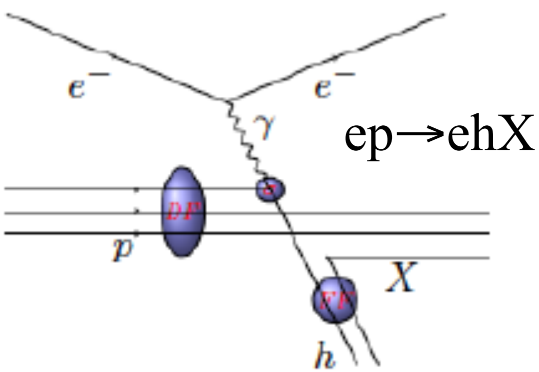
Elastic Electron Proton Scattering- FFs
- transverse spatial distributions







Deep Virtual Compton Scattering- Wide Angle Compton Scattering- GPDs – 1D momentum – 2D space distributions



Semi Inclusive Deep Inelastic Scattering- TMDs – 3D momentum distributions + Spin structure

and many other electromagnetic processes

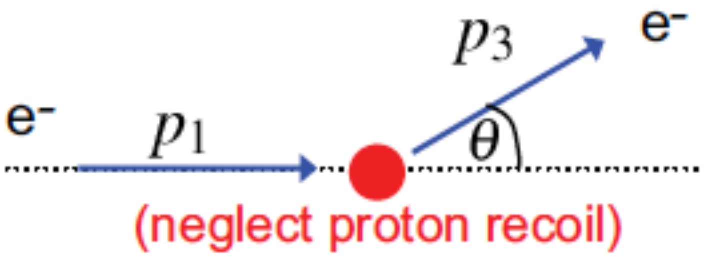
Outline

- Electromagnetic form factors of the proton
  - Space-like region
  - Time-like region
- Parton Distribution functions (PDF) in SIDIS and Drell-Yan
- Generalized Parton Distributions (GPD) and Generalized Distribution Amplitudes (GDA)

In connection to the opportunities offered by the future **antiproton beams** of FAIR

(1911) Rutherford scattering cross section

- Non relativistic electron ($E_k << m_e$)
- No recoil of the proton (neglected)
- Point-like proton



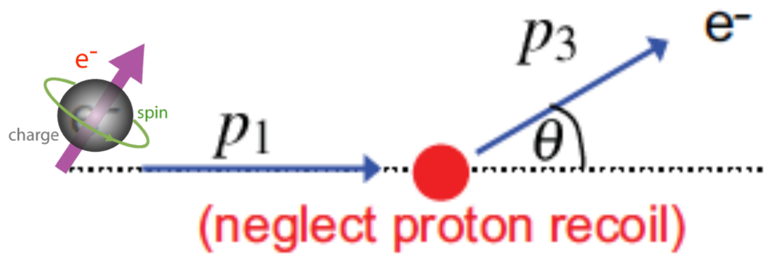
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} = \frac{\alpha^2}{16E_K^2 \sin^4 \theta/2}$$

Interaction between the electric charges of the particles matters.

(1929) – Mott scattering cross section

- Relativistic electron ($E_k >> m_e$)
- Electron is carrying a spin
- No recoil of the proton (neglected)
- Point-like proton

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \cos^2 \frac{\theta}{2}$$

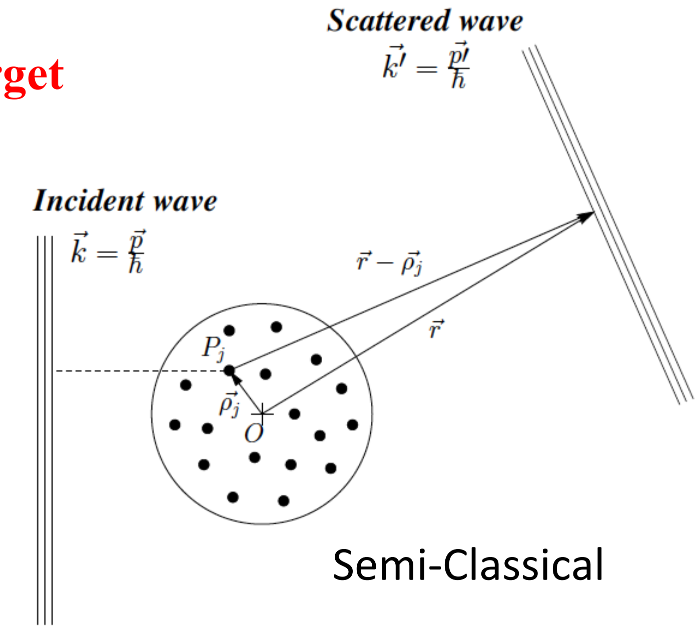


Electron-Proton Elastic Scattering: the form factor

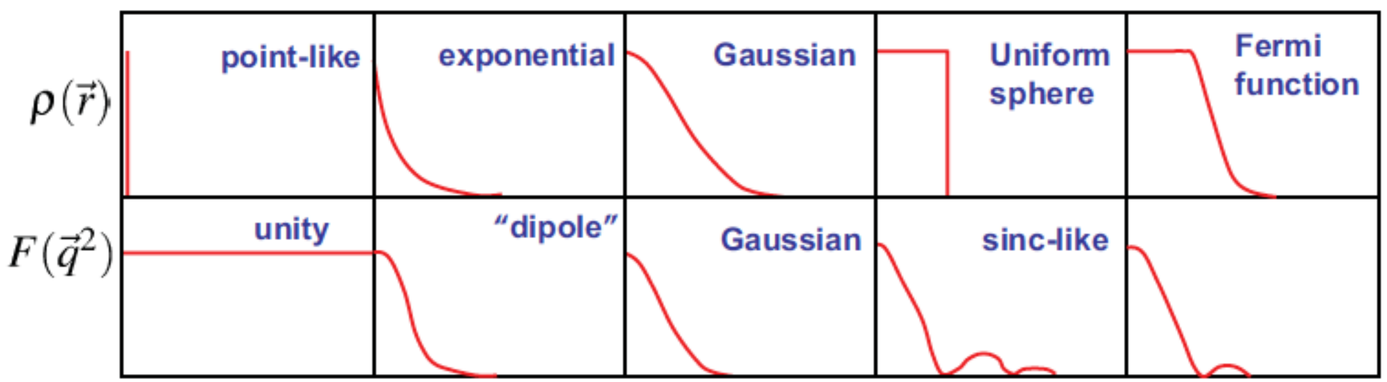
(1943-1951) – Scattering cross section off finite size target

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{Mott}}{d\Omega} \left| \int \rho(\vec{x}) e^{\vec{q}\cdot\vec{x}} d\vec{x} \right|^2$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{Mott}}{d\Omega} \, | F(\vec{q}^{\,2}) |^2$$

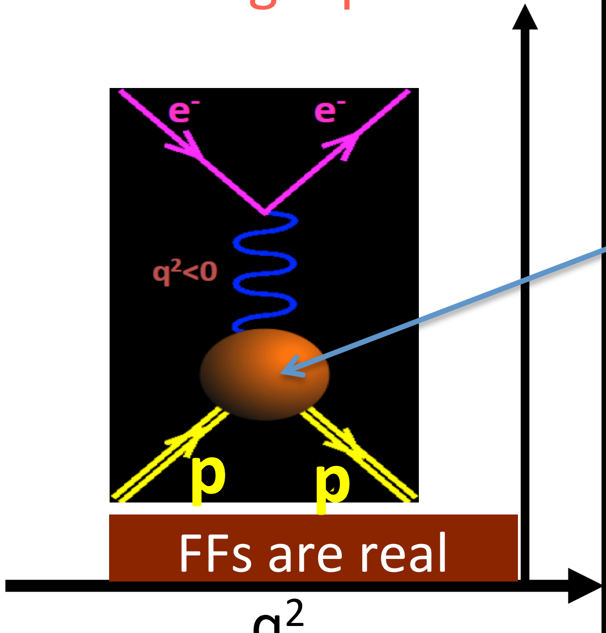


The resulting cross section is the cross section for scattering from a point source multiplied by the **form factor**



Proton electromagnetic form factor

Scattering: Space-Like



$$q^2 = (k_1 - k_2)^2 < 0$$

$$q^2 = E_\gamma^2 - \vec{q}_\gamma^2$$

0

Dirac and Pauli form factors:

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\gamma}{2M} F_2(q^2)$$

Sachs form factors:

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4M^2} F_2(q^2), \quad G_E(0) = 1$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2) \quad , \quad G_M(0) = \mu_p$$

(1951-1965) Rusenbluth formula

- **Non point like proton**
- **Proton recoil is not neglected**
- **Magnetic moment of the proton is taking into account**

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4\theta/2} \frac{E_3}{E_1} \left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)} \cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2} \right)$$

- In the Breit frame (q=(0,**q**)) and in non relativistic approach, Sachs form factors are the Fourier transforms of charge and magnetic spatial distributions of the nucleon

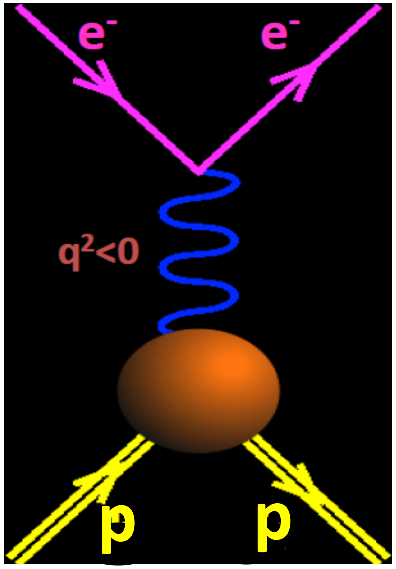
Rosenbluth separation method

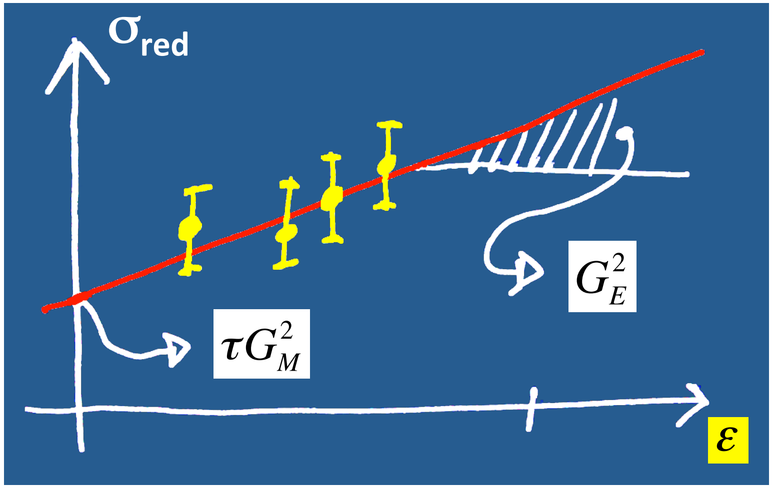
Unpolarized elastic ep scattering (Born approximation)

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega} \frac{1}{\varepsilon(1+\tau)} [\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)], \tau = Q^2 / 4M_p^2$$

$$\varepsilon = [1 + 2(1+\tau)\tan^2(\theta_e / 2)]^{-1}$$

$$\sigma_{red} = \frac{d\sigma}{d\sigma_{Mott}} \varepsilon(1+\tau) = \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$





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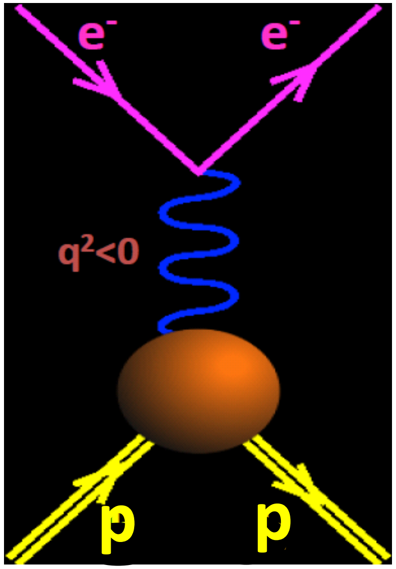
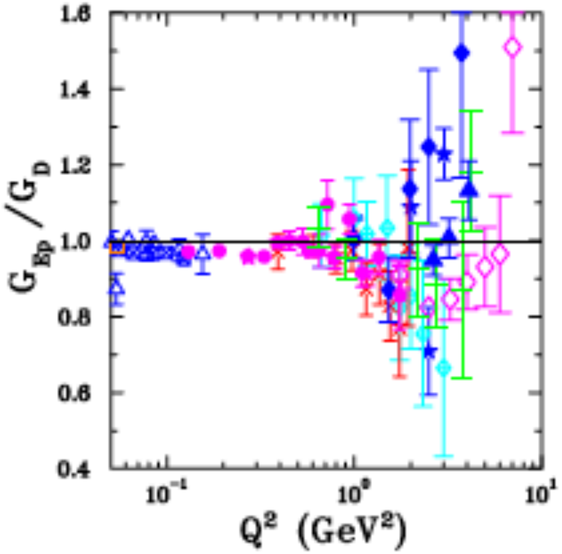
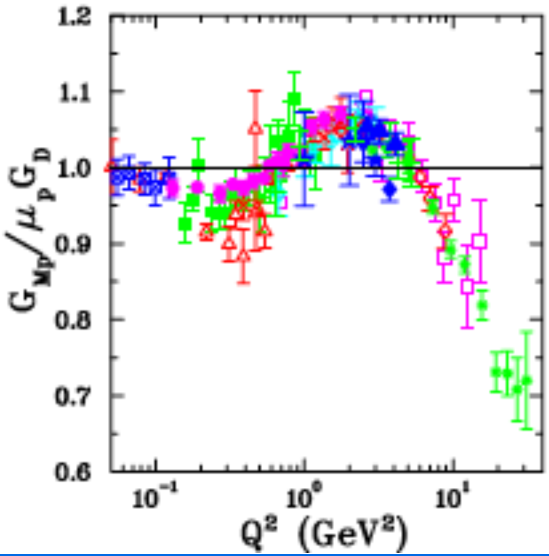
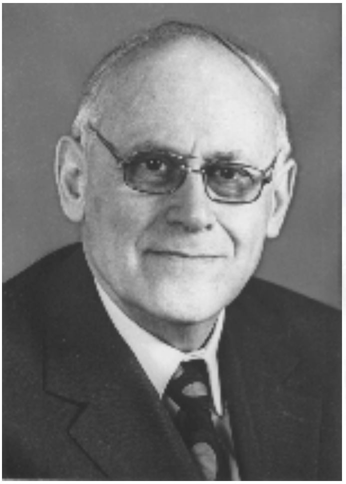






C. F. Perdrisat at al.
Prog. Part. Nucl. Phys. 59 (2007) 694

Polarization method (1967)



SOVIET PHYSICS – DOKLADY VOL. 13, NO. 6 DECEMBER, 1968

PHYSICS

POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

Academician A. I. Akhiezer* and M. P. Rekalo

Physicotechnical Institute, Academy of Sciences of the Ukrainian SSR
Translated from Doklady Akademii Nauk SSSR, Vol. 180, No. 5, pp. 1081–1083, June, 1968
Original article submitted February 26, 1967

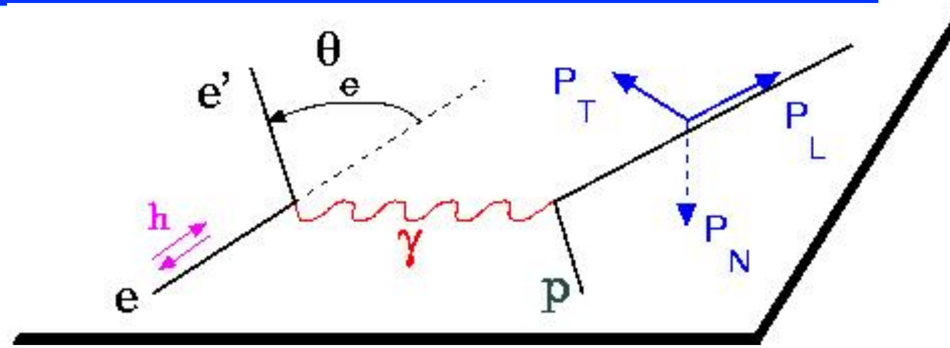
The polarization induces a term in the cross section proportional to $G_E\, G_M$

Polarized beam and target or

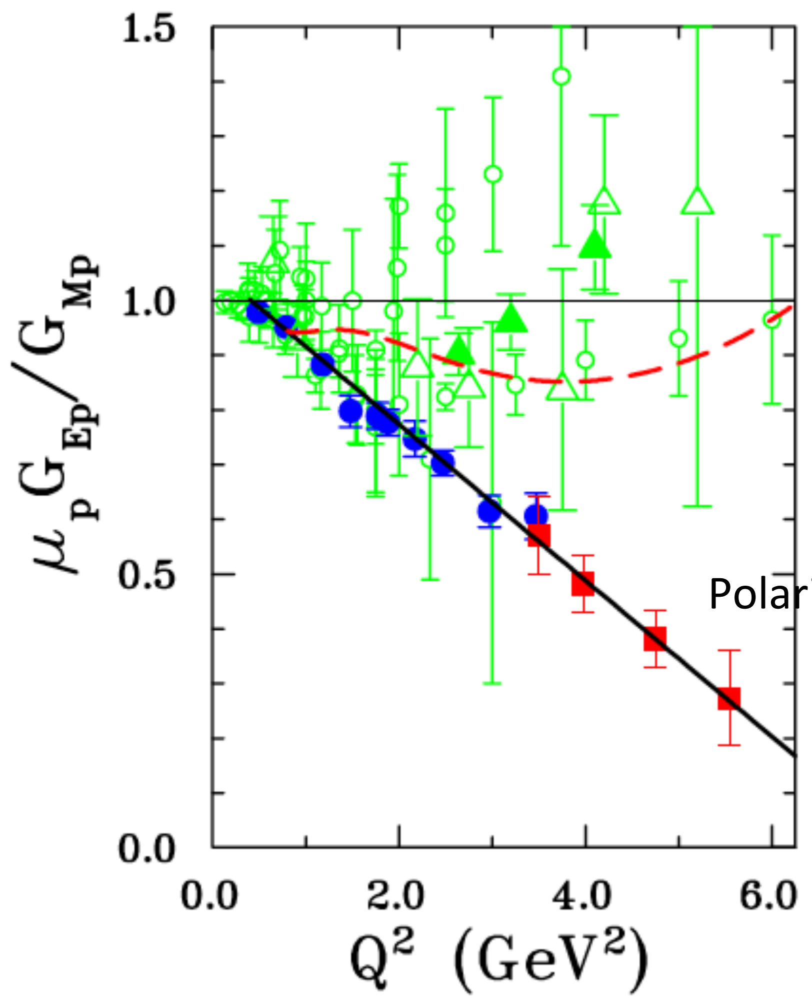
polarized beam and recoil proton polarization

GEp Collaboration at JLab

$$R = \frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{\epsilon_1 + \epsilon_2}{2M}\tan(\vartheta/2),$$



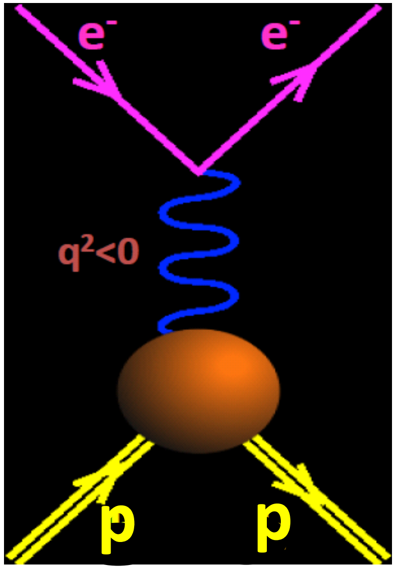
JLab Polarization and Rosenbluth separation data



Contradiction between polarized and unpolarized measurements

Rosenbluth separation data

Polarization data



C. F. Perdrisat at al.
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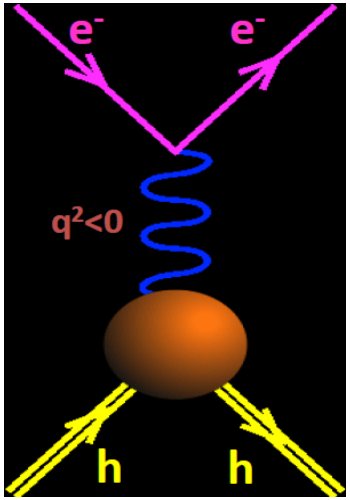
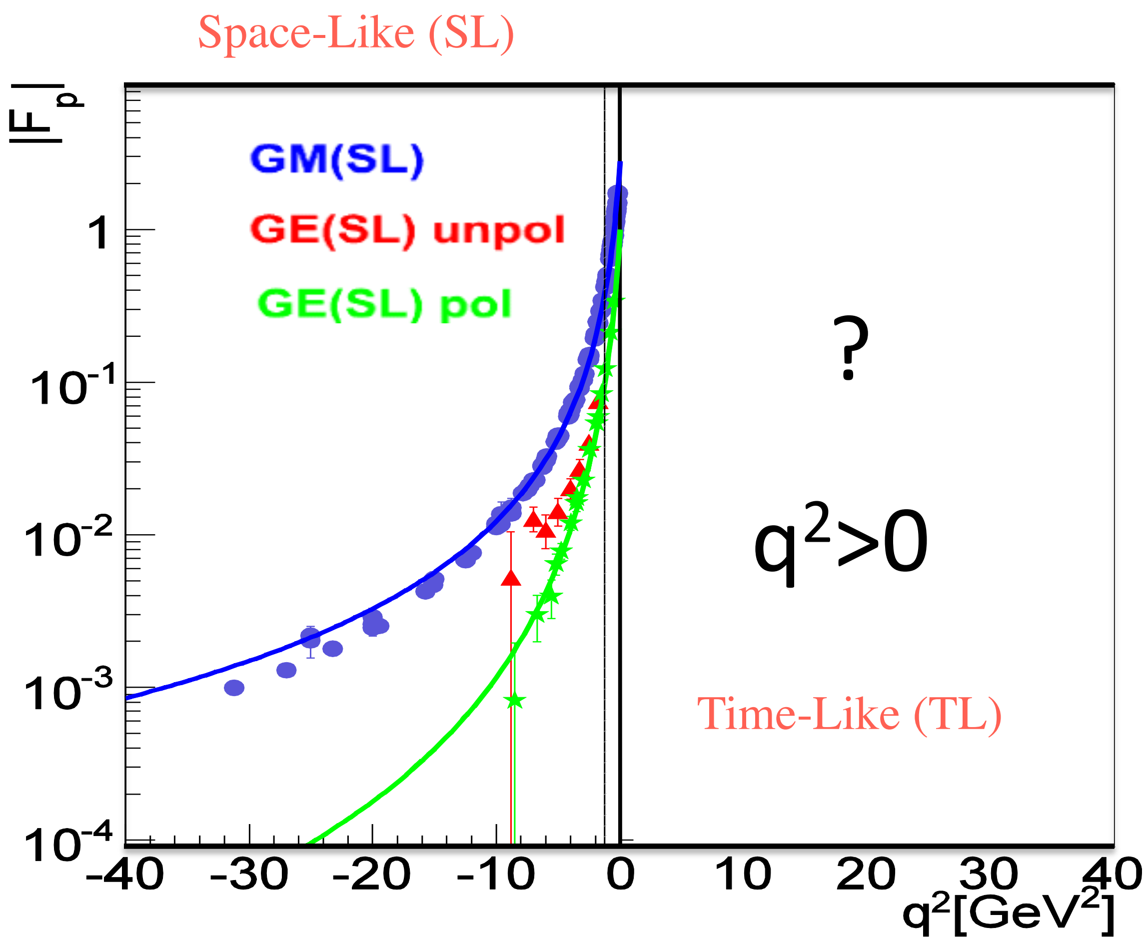
Data on the proton electromagnetic FFs (SL)

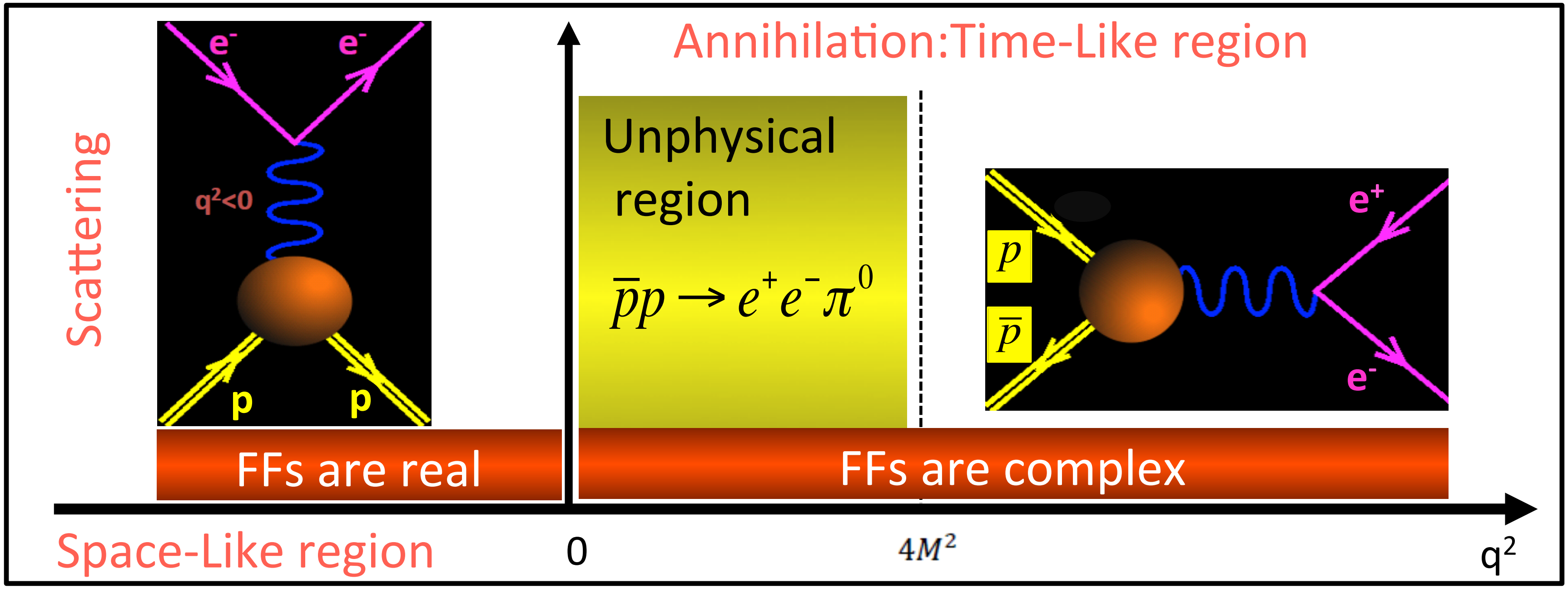
- **Electric G_E and magnetic G_M** proton form factors are analytical functions of the momentum transfer squared q^2



$$q^2 = (k_1 - k_2)^2 < 0$$



Electromagnetic Form Factors: the analyticity



At the threshold: $G_E(4M^2) = G_M(4M^2)$ (only s-wave)

Point-like proton: $G_E(4M^2) = G_M(4M^2) = 1$

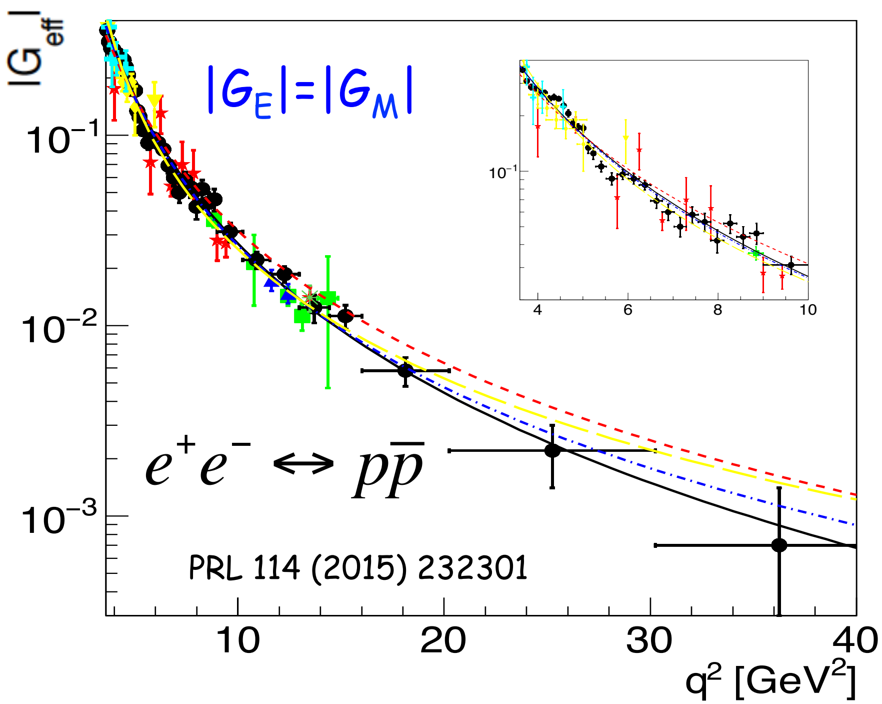
Unified frame for the description of FFs:

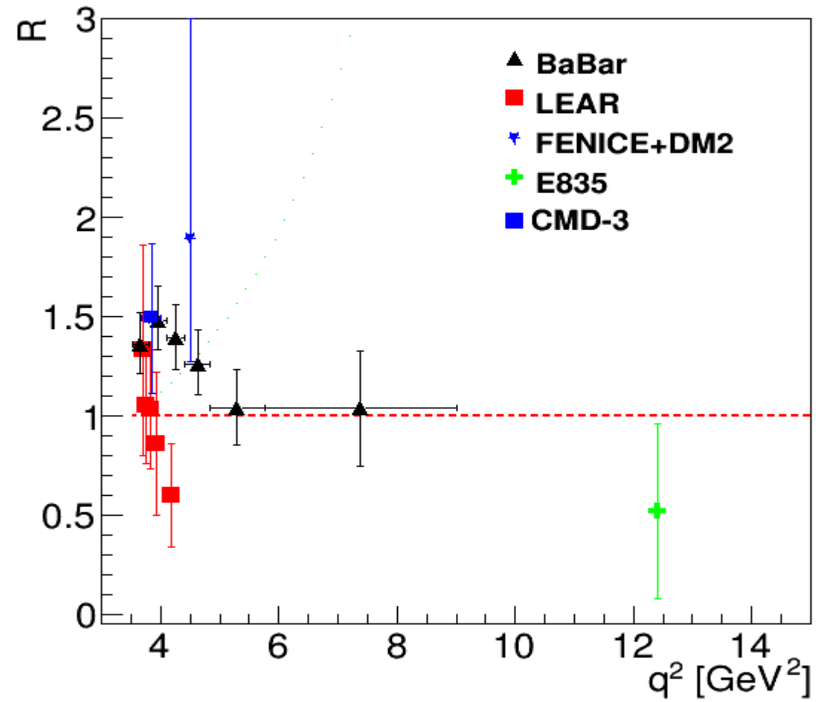
$$G(q^2) = \frac{1}{\pi}\left[\int_{4m_\pi^2}^{4m_p^2} \frac{\operatorname{Im} G(s)\,ds}{s-q^2} + \int_{4m_p^2}^{\infty} \frac{\operatorname{Im} G(s)\,ds}{s-q^2}\right]$$

$$\lim_{q^2\to-\infty} G_{E,M}^{SL}(q^2) = \lim_{q^2\to+\infty} G_{E,M}^{TL}(q^2)$$

The measurement of the From Factors at large q^2 and in all the kinematical region: test of the analytical nature of the FFs

Time-Like proton electromagnetic FFs



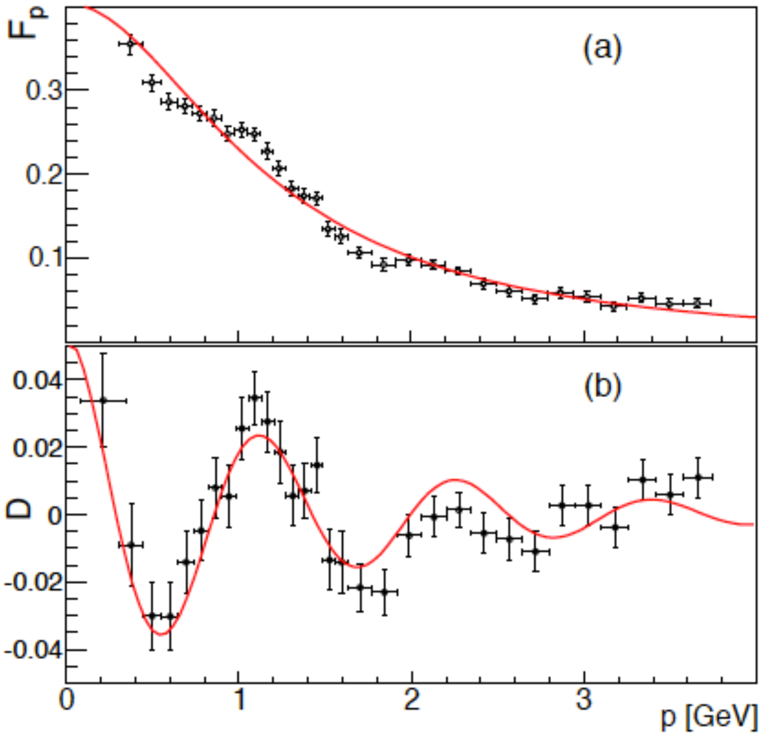


- No individual determination of G_E and G_M
- Steep behaviour of the **effective FF (G_{eff})** at threshold
- Structures appeared in BaBar data (PRD 87 (2013) 092005)?
  - Resonances (PRD 92 (2015) 034018)
  - Rescattering processes between few coherent sources (PRL 114 (2015) 232301)
- **Form factor ratio (R)**: discrepancy between LEAR (NPB 411 (1994) 3) and BaBar data

Periodic structures in TL proton FFs

Andrea Bianconi, Egle Tomasi-Gustafsson

Phys. Rev. Lett. 114,232301 (2015), arXiv:1510.06338[nucl-th]

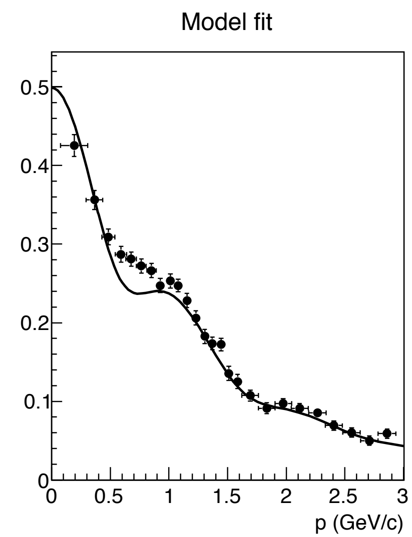


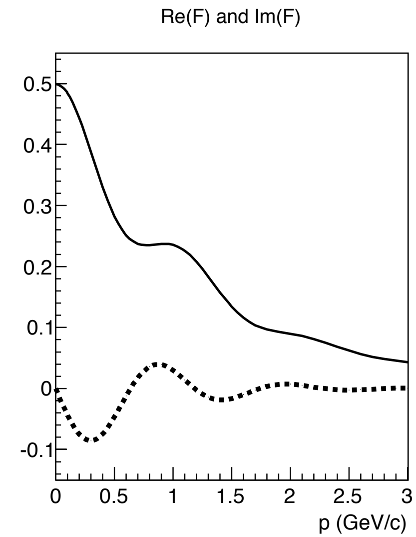
P_{Lab}

$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D).$$

Optical potential analysis: double layer rescattering densities :

- feeding at small r (by decay of higher mass states into pbar-p)
- depletion at large r (from annihilation into mesons)



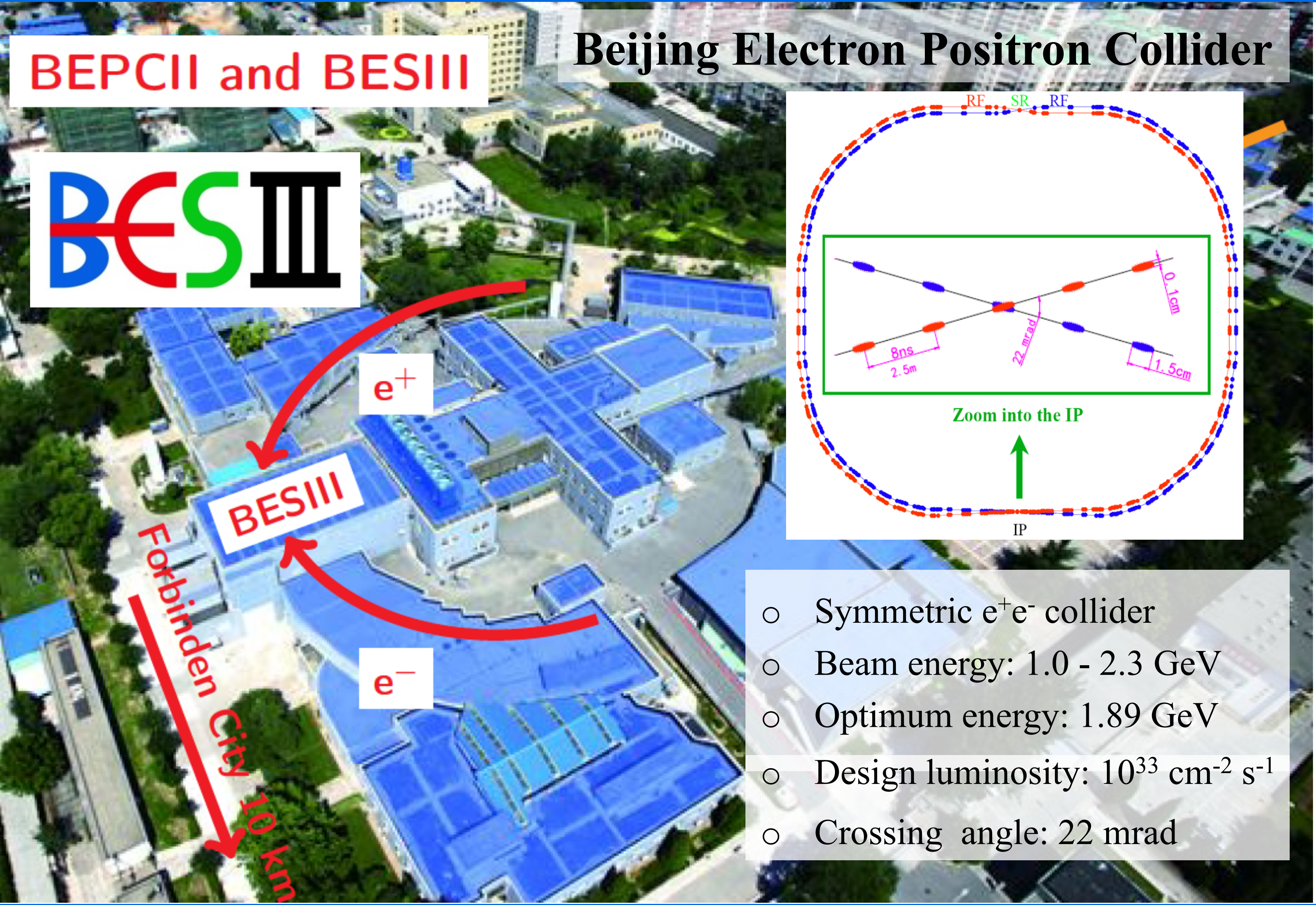


Looking for the current and future experiments

- Separate measurement of $|G_E|$ and $|G_M|$
- Information on the relative phase G_E/G_M
- Steep behavior at threshold
- Babar: Structures? Resonances?
  - Confirmation by other experiments? for other baryons and mesons?
  - Are time reversal related reactions equivalent?
- Analyticity:
  - FF measurement over large energy range
  - Asymptotic behavior (TL proton FFs twice larger than in SL at the same Q^2)
  - Access the unphysical region
- Difference between proton/neutron TL FFs

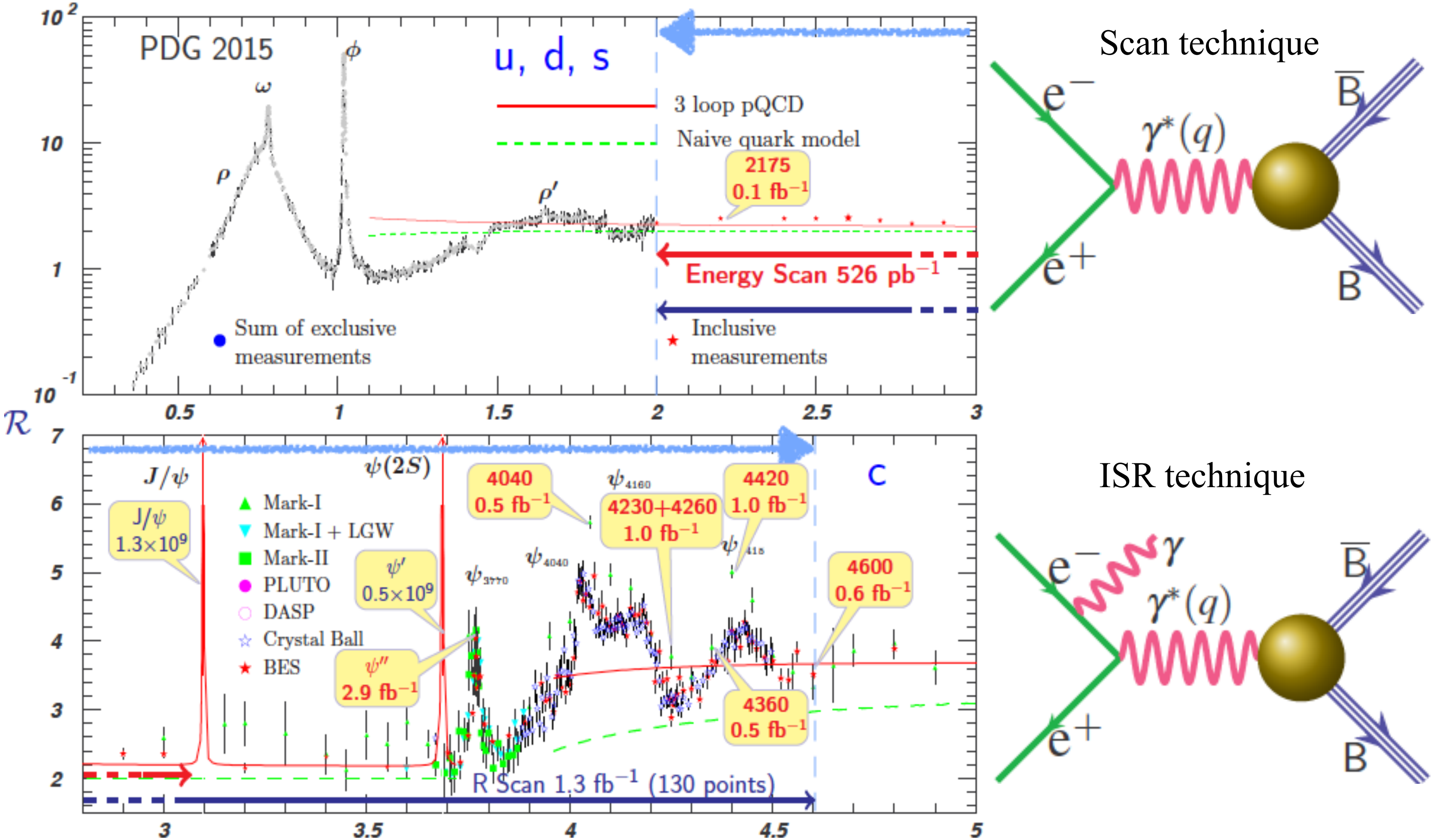
BESIII experiment at BEPCII

BESIII experiment at BEPCII



- Symmetric e^+e^- collider
- Beam energy: 1.0 - 2.3 GeV
- Optimum energy: 1.89 GeV
- Design luminosity: 10^{33} cm^{-2} s^{-1}
- Crossing angle: 22 mrad

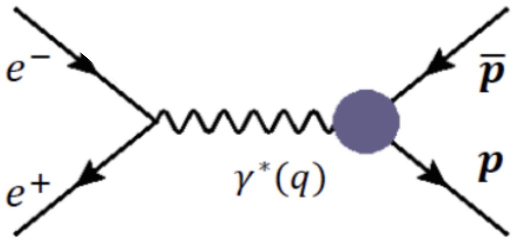
BESIII data samples



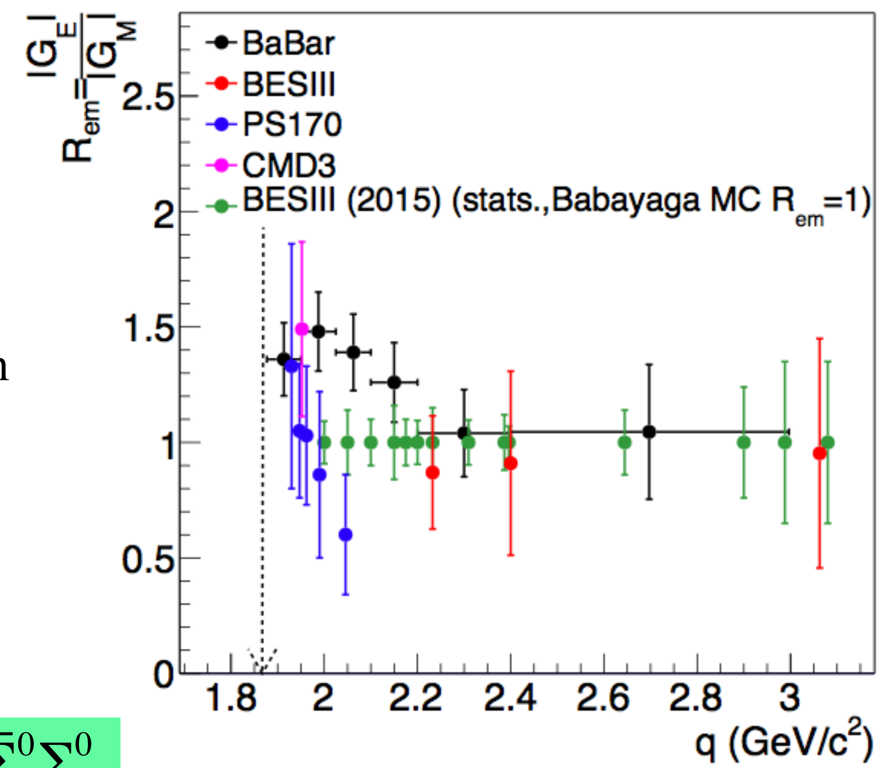
From D. Lin (talk at SPIN2016)

Proton FFs at BESIII

Scan data 2015 between 2 and 3.08 GeV (552 pb^{-1})
21 energy points



- Precise measurement of proton FFs in narrow q^2-bins
- Expected (MC) statistical accuracies on proton $R=|G_E|/|G_M|=1$, between 9 % and 35%
- First time measurement of proton $|G_M|$ and $|G_E|$ separately

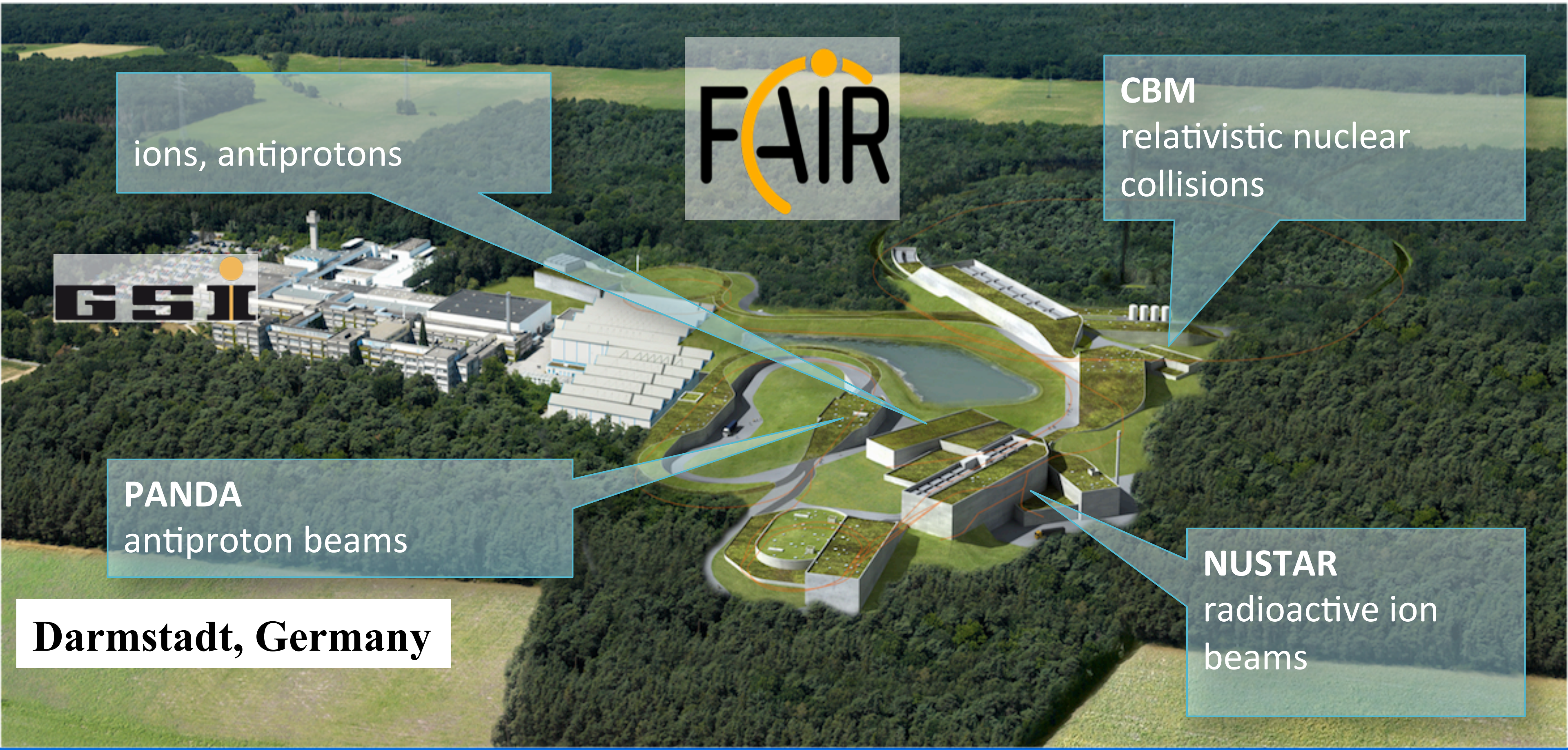


From Yadi Wang (PANDA CM 2016)

$$e^+e^- \to \bar{p}p, \bar{n}n, \bar{\Lambda}\Lambda, \bar{\Lambda}_{c-}\Lambda_{c+}, \Lambda\bar{\Sigma}^0, \bar{\Sigma}^0\Sigma^0,$$
$$\bar{\Sigma}^-\Sigma^+, \bar{\Sigma}^+\Sigma^-, \bar{\Xi}^0\Xi^0, \bar{\Xi}^+\Xi^-, \bar{\Omega}^+\Omega^-$$

Facility for **A**ntiproton and **I**on **R**esearch - FAIR

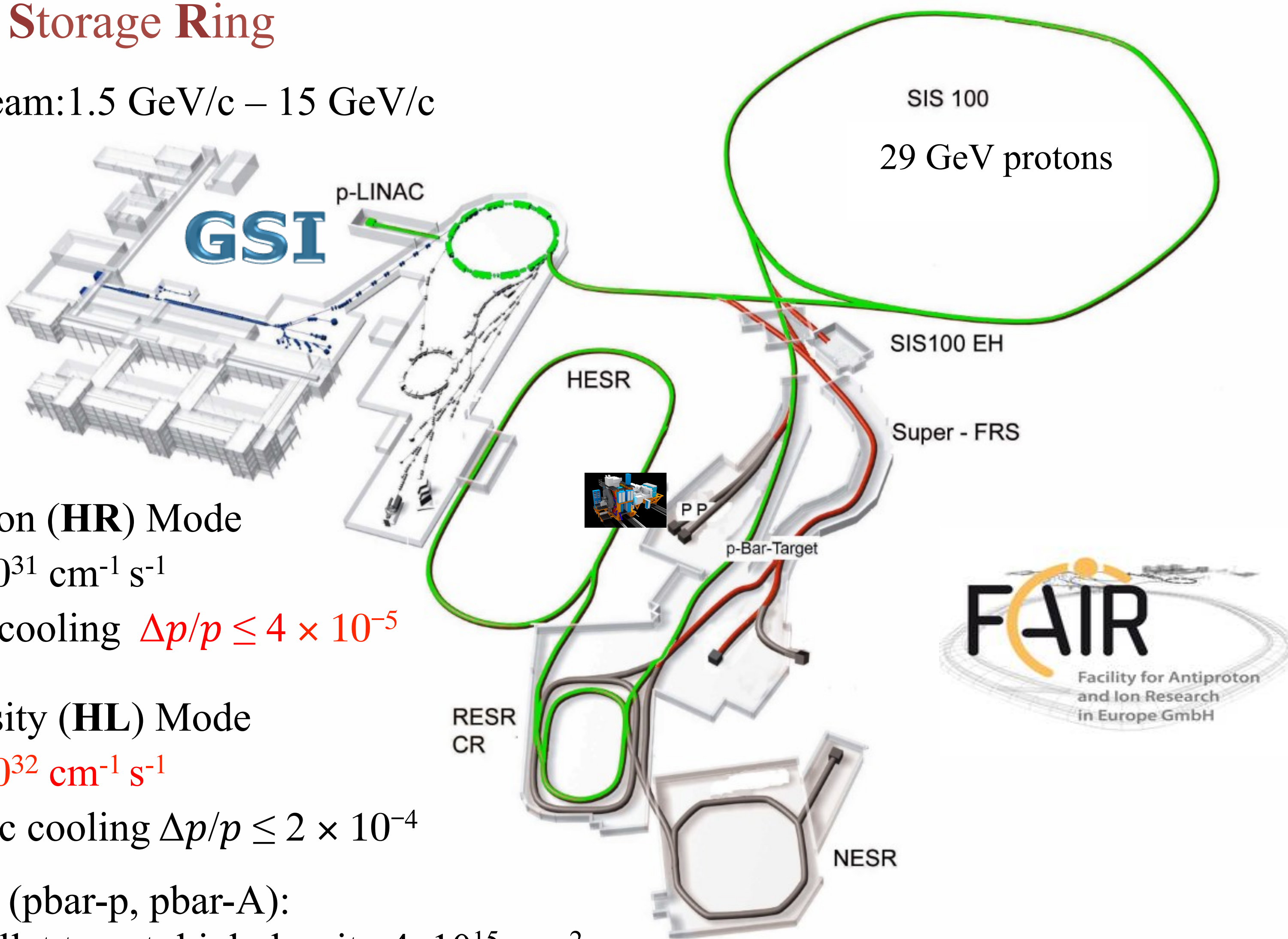
A high quality and energy antiproton beam will be an excellent tool for a **complementary** study of the nucleon structure with lepton or photon experiments



Facility for Antiproton and Ion Research - FAIR

High Energy Storage Ring

- Antiproton beam: 1.5 GeV/c – 15 GeV/c

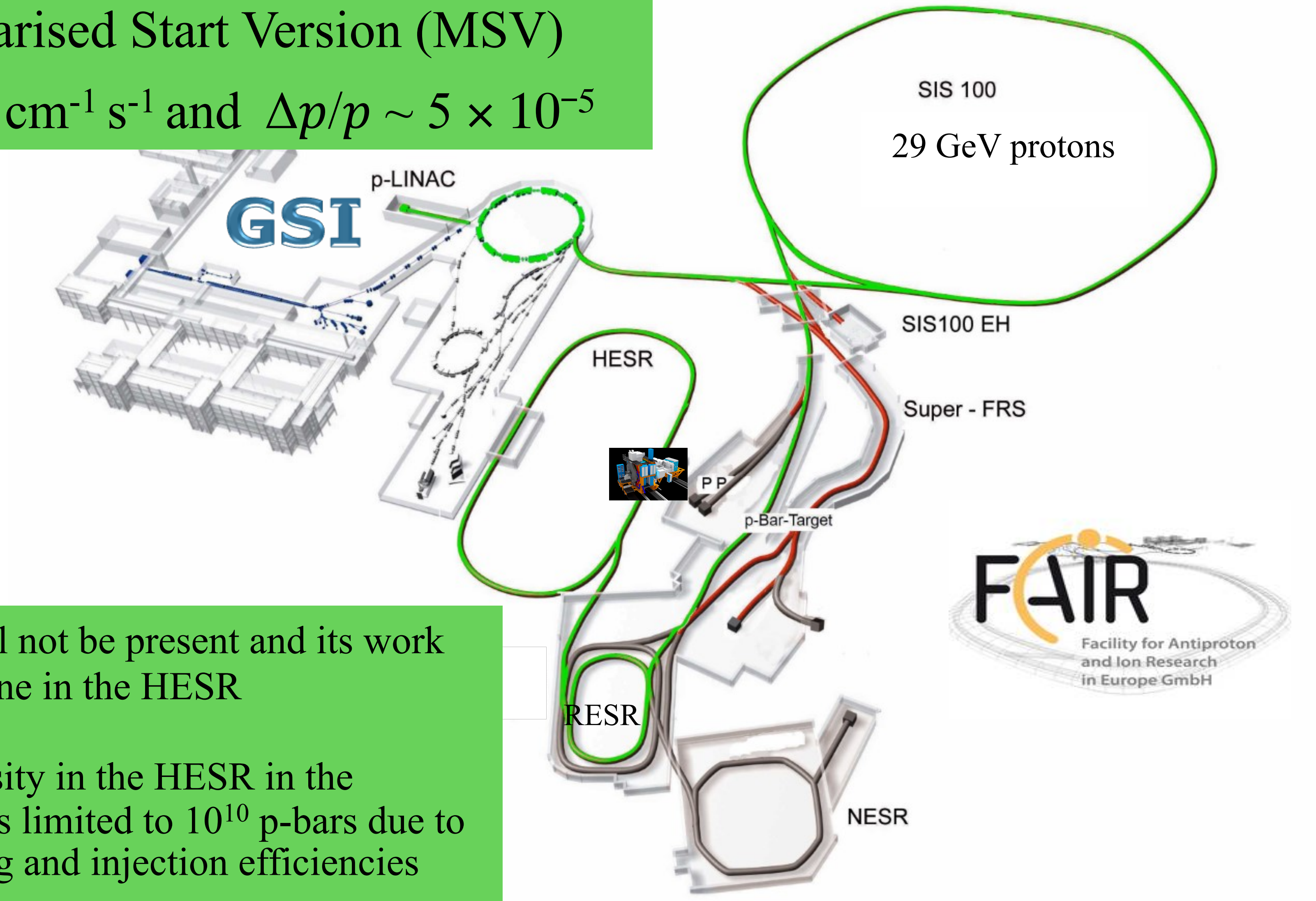


- High Resolution (**HR**) Mode
  - $L = 2 \times 10^{31}\ cm^{-1}\ s^{-1}$
  - Electron cooling $\Delta p/p \leq 4 \times 10^{-5}$
- High Luminosity (**HL**) Mode
  - $L = 2 \times 10^{32}\ cm^{-1}\ s^{-1}$
  - Stochastic cooling $\Delta p/p \leq 2 \times 10^{-4}$
- Internal target (pbar-p, pbar-A):
  cluster jet / pellet target; high density $4 \times 10^{15}\ cm^{-2}$

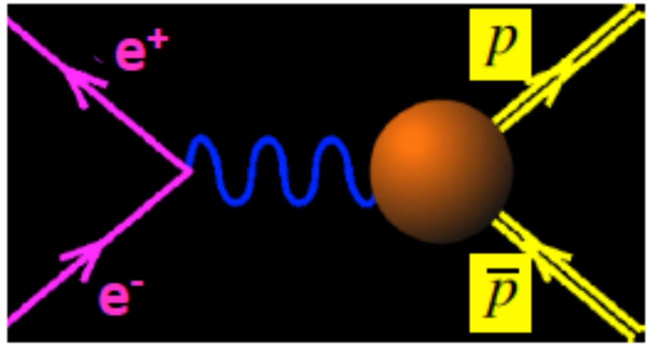
FAIR-HESR (start version)

Modularised Start Version (MSV)

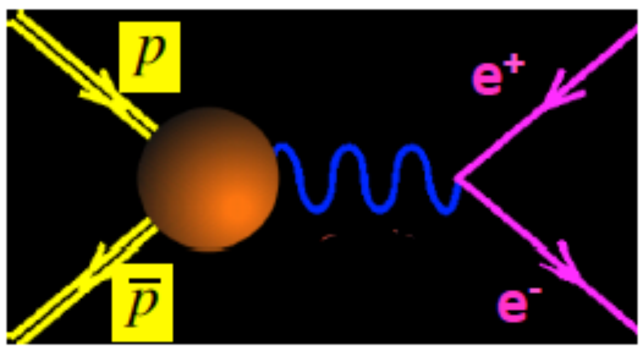
$L \sim 10^{31}\ cm^{-1}\ s^{-1}$ and $\Delta p/p \sim 5 \times 10^{-5}$



- RESR will not be present and its work will be done in the HESR
- The intensity in the HESR in the MSV0-3 is limited to 10^{10} p-bars due to the cooling and injection efficiencies

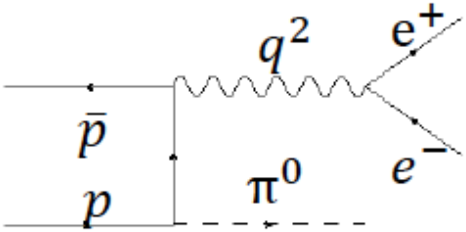


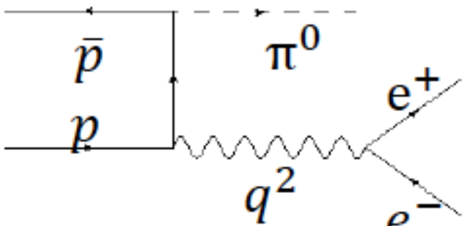
Same proton vertex in both channels



Measurement of TL proton FFs at PANDA: Goals

- Measurements of the proton effective form factor in the TL region over a large kinematical region through: $\bar{p}p \to e^+e^-$ $\bar{p}p \to \mu^+\mu^-$
- Individual measurement of $|G_E|$ and $|G_M|$ and their ratio
- Possibility to access the relative phase of proton TL FFs
  - Polarization observables (**Born approximation**) give access to $G_E G_M^*$
  - Development of a transverse polarized proton target for PANDA in Mainz
- Measurement of proton FFs in the unphysical region: $\bar{p}p \to e^+e^-\pi^0$

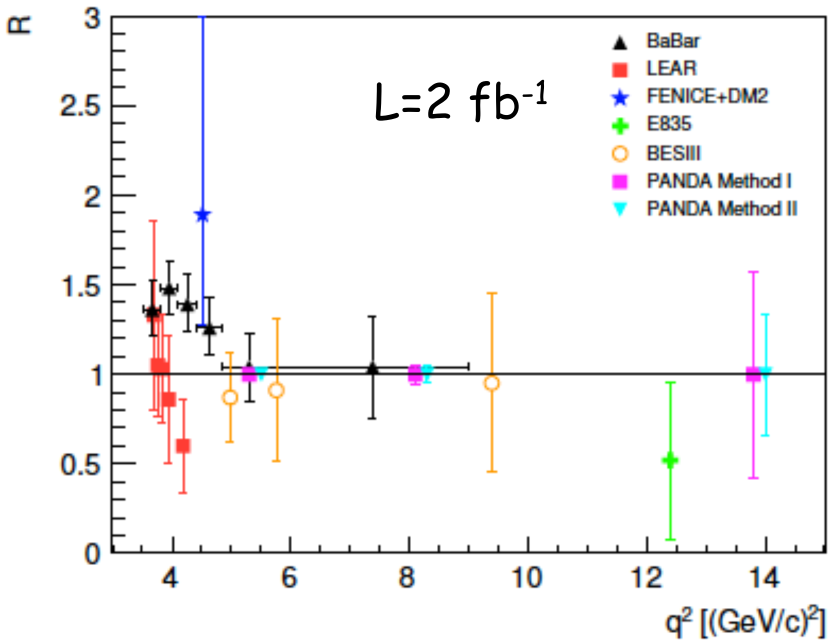




- M.P. Rekalo. Sov. J. Nucl. Phys., 1:760, 1965
- Adamuscin, Kuraev, Tomasi-Gustafsson and F. Maas, Phys. Rev. C 75, 045205 (2007)
- C. Adamuscin, E.A. Kuraev, G. I. Gakh, …
- Feasibility studies (J. Boucher, M. C. Mora-Espi PhD)

Current/future experiments: PANDA

➢ Feasibility studies (PANDARoot) for measuring $\bar{p}p \to e^+e^-$ at PANDA:



	q^2 $[(\mathrm{GeV}/c)^2]$	Stat	Systematic Bg	Lumi	Total
$\Delta\|G_E\|/\|G_E\|$	5.40	0.9%	0.3%	2.0%	2.2%
	8.21	4.1%	2.9%	2.0%	5.4%
	13.9	48%	3.1%	2.0%	48%
$\Delta\|G_M\|/\|G_M\|$	5.40	0.4%	2.8%	2.0%	3.5%
	8.21	1.2%	1.1%	2.0%	2.6%
	13.9	9.4%	1.0%	2.0%	9.7%
Δ R/R	5.40	1.3%	2.9%	n/a	3.3%
	8.21	5.3%	4.0%	n/a	6.6%
	13.9	56%	4.1%	n/a	57%

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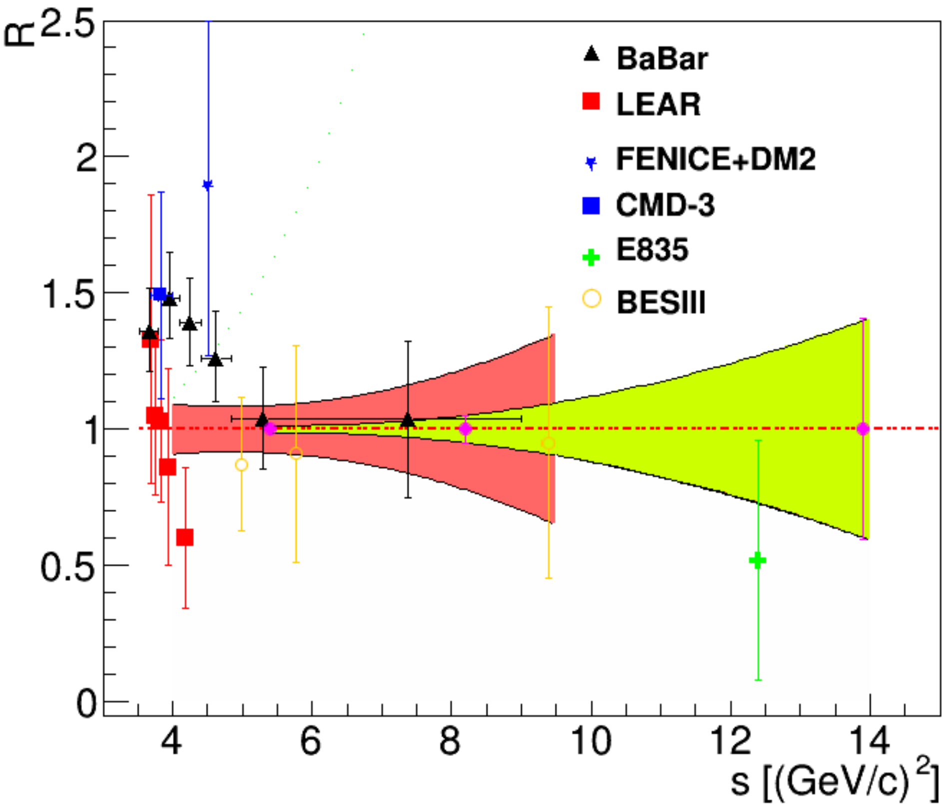
Measurement of proton FFs with unprecedented accuracy in e^+e^- final state

First time measurement of proton FFs with muons

Current/future experiments: BESII-PANDA



BESIII

21 scan points 2015 (552 pb^{-1})

Monte Carlo Sim., R=1 (C. Morales)

PANDA

L=2 fb^{-1}

2.10^{32} cm^{-1} s^{-1}

	BESIII	PANDA
s [(GeV/c)^2]	4 - 9.5	5 - 14
$R=\|G_E\|/\|G_M\|$	9 % - 35 %	1.4 % - 41 %

Proton form factors with a polarized proton target @ PANDA

Access the relative phase between the proton form factors:

- Time-Like form factors are complex: $G_E=|G_E|e^{i\phi E}$ $G_M=|G_M|e^{i\phi M}$

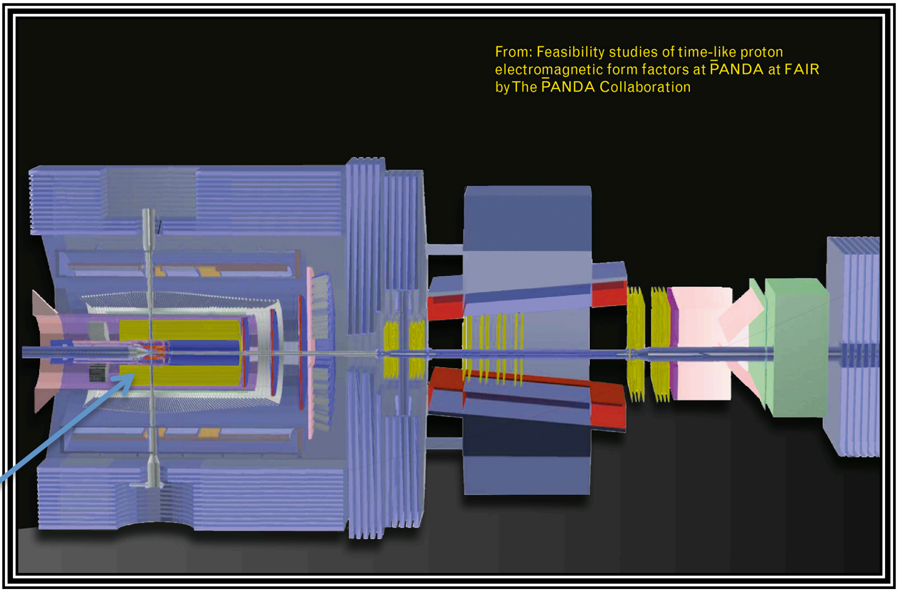
- Differential cross section of unpolarized **signal reaction** $\bar{p}p \rightarrow e^+e^-$

$$\frac{d\sigma}{d\cos\theta_{CM}} \propto Norm \times \left[(1+\cos^2\theta_{CM})|G_M|^2 + \frac{|G_E|^2}{\tau}(1-\cos^2\theta_{CM}) \right]$$

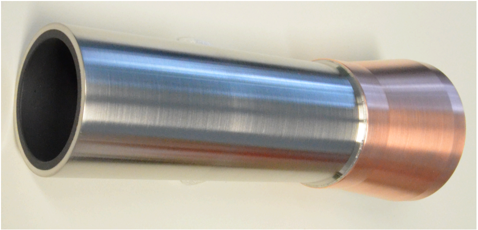
- with transverse polarized target: $\left(\frac{d\sigma}{d\Omega}\right)_0 A_{1,y} \propto \sin 2\Theta \, \mathrm{Im}\left(G_M G_E^*\right)$

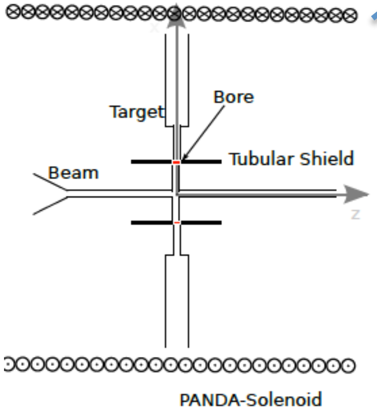
Transverse Polarized target at PANDA

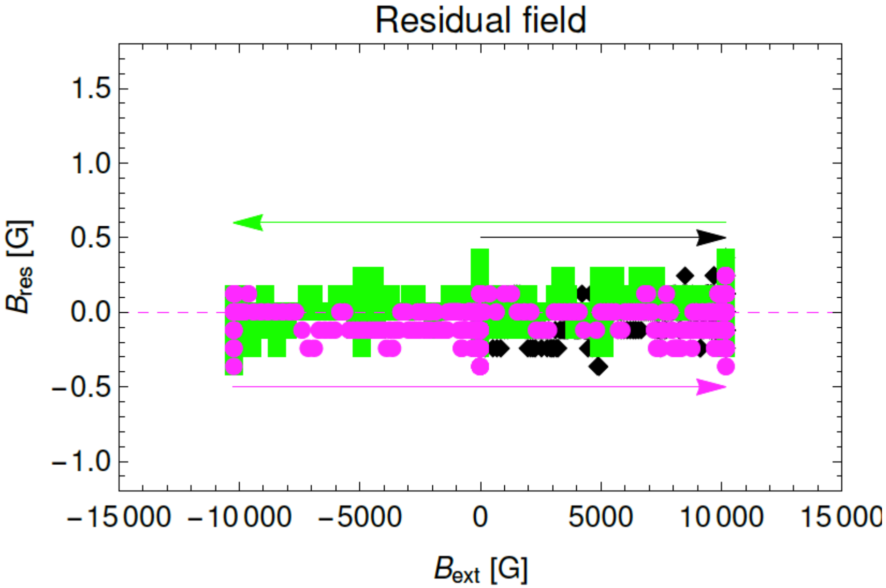
- To shield the target region from the longitudinal 2 T magnetic field induced by the PANDA solenoid one can use a superconducting tube
- The superconducting tube could induce a magnetic field opposite to the PANDA solenoid magnetic field



BSCCO-2212







Current status (**Bertold Froehlich et al. (HIM)**): B_{ext}=1.0 T and **Residual field <1 Gauss (shielding factor >10^4)**

Proton structure functions

Form Factors
$F_1(t)$, $F_2(t)$

$\int dx d^2 k_\perp$

2D Fourier Transform
$(t \leftrightarrow \vec{b}_\perp)$

Parton Distribution Functions
PDF f(x)

$\int d^2 k_\perp, t \to 0$

Wigner distributions

$(x, \vec{k}_\perp, \vec{b}_\perp)$

(x) Longitudinal momentum
$(\vec{k}_\perp)$ Transverse momentum
$(\vec{b}_\perp)$ Transverse spatial variable

$\int d^2 k_\perp$

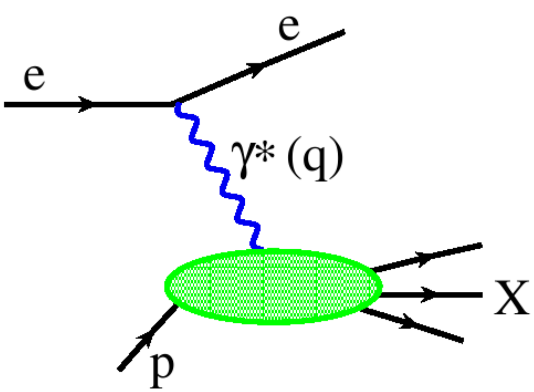
Generalized Parton Distributions
GPDs, GDAs ($t \leftrightarrow s$)
F(x,t)

$t \to 0$

Transverse Momentum
Dependance (TMD) PDF

$f(x, \vec{k}_\perp)$

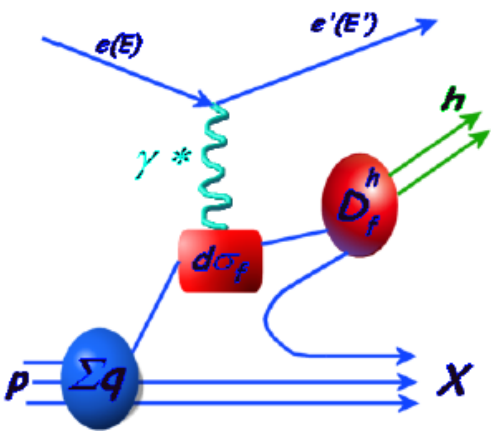
(Semi) Inclusive Deep Inelastic Scattering



- When we are scattering from individual point-like quarks within the target, we are in the regime of deep-inelastic scattering
  - Scattering at high q^2 and $W^2=(p+q)^2$ (Bjorken limit)…. α_s is small → QCD factorization (perturbative and non perurbative parts)

$$\frac{d\sigma}{dx\,dQ^2} = \left(\frac{d\sigma}{dx\,dQ^2}\right)_{\text{point(eq}\rightarrow\text{eq)}} \cdot \sum_{q=u,d,s,\bar{u},\bar{d},\bar{s}} e_q^2\, q(x,Q^2)$$

PDFs: functions of the Bjorken x = fraction of nucleon momentum carried by struck quark



- In **SIDIS**, a hadron h is detected in coincidence with the scattered lepton:

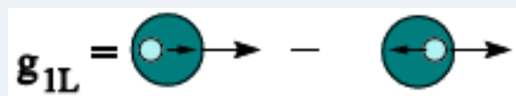
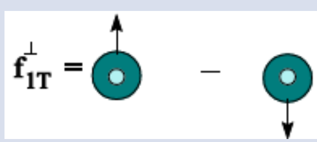
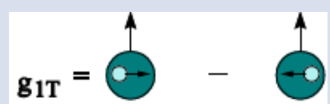
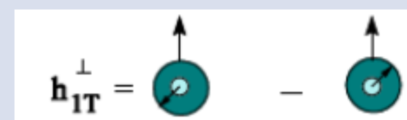
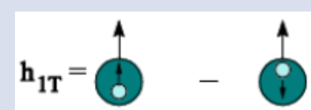
- Scattering at high Q^2 and W^2 ... but create only one particle in final-state!

$$d\sigma^h \sim \sum_q e_q^2\, q(x) \cdot \hat{\sigma} \cdot D^{q\rightarrow h}(z)$$

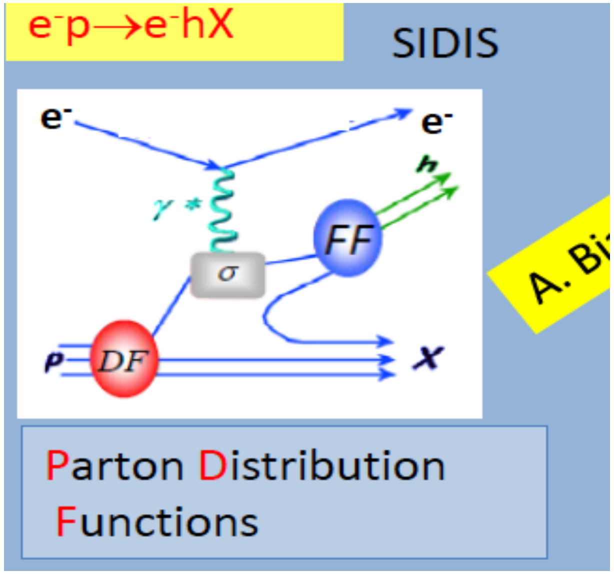
Transverse Momentum Dependence PDFs

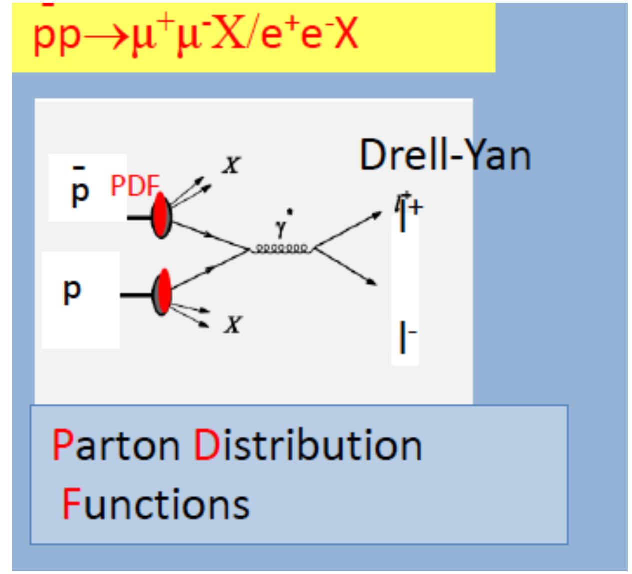
Quark polarization

Nucleon polarization

	U	L	T
U	 Unpolarized TMD		 Boer-Mulders
L		 Helicity	 Worm-gear
T	 Sivers	 Worm-gear	 pretzelosity  Transversity

Factorization and universality





PDFs are convoluted with
the fragmentation functions

SIDIS@ hermes

SIDIS@ COMPASS

Jefferson Lab

Drell-Yan@ Fermilab

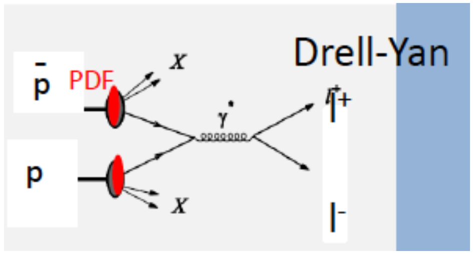
Test of Universality
and the QCD TMD factorization

$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$$

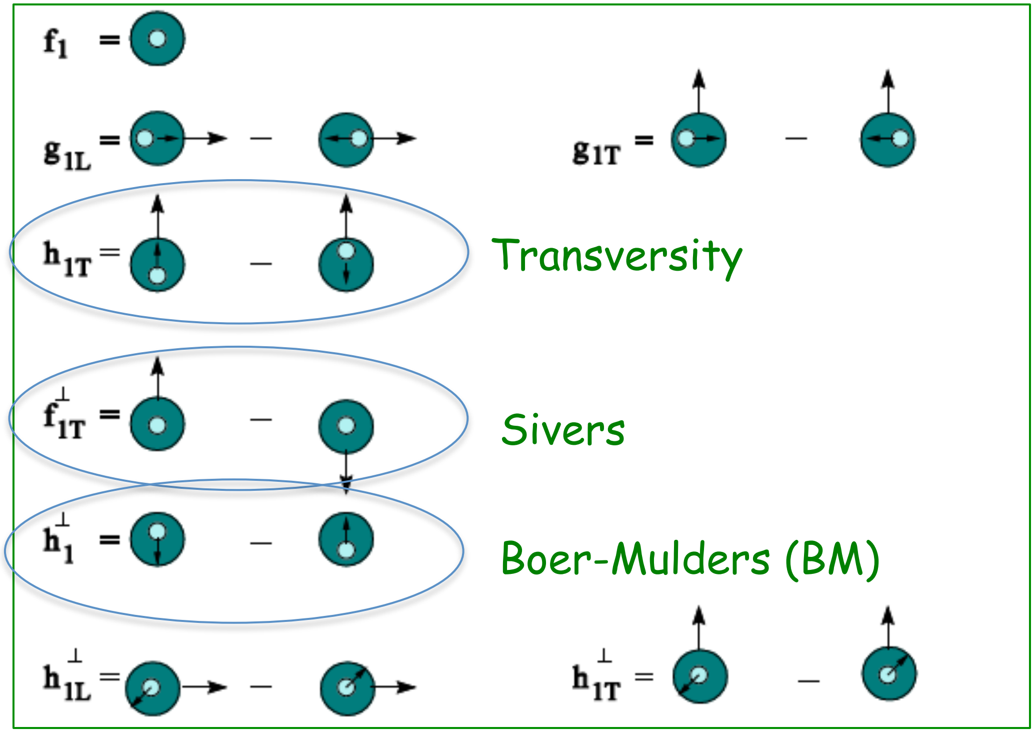
$$h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

Z production@ Fermilab

Transverse momentum dependence PDFs @ PANDA



@ PANDA unique energy range up to s~30 GeV^2



Asymmetry measurements:

Unpolarized DY

$$A^{\cos 2\varphi} \rightarrow h_1^{\perp}$$

Single-polarized DY

$$A^{\sin(\varphi \pm \varphi s2)} \rightarrow h_1^{\perp}, h_{1T}, f_{1T}^{\perp}$$

$$A = \frac{U - D}{U + D}$$

φ : angle between hadron and lepton planes

φ_{s2} : angle between hadron spin and lepton plane

$U = N(\cos 2\varphi > 0)$	$U = N(\sin(\varphi \pm \varphi_{s2}) > 0)$
$D = N(\cos 2\varphi < 0)$	$D = N(\sin(\varphi \pm \varphi_{s2}) > 0)$

Proton structure functions

Form Factors
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$(t \leftrightarrow \vec{b}_\perp)$

Parton Distribution Functions
PDF f(x)

$\int d^2 k_\perp, t \to 0$

Wigner distributions
$(x, \vec{k}_\perp, \vec{b}_\perp)$

(x) Longitudinal momentum
$(\vec{k}_\perp)$ Transverse momentum
$(\vec{b}_\perp)$ Transverse spatial variable

$\int d^2 k_\perp$

Generalized Parton Distributions
GPDs, GDAs (t<->s)
F(x,ζ,t)

$t \to 0$

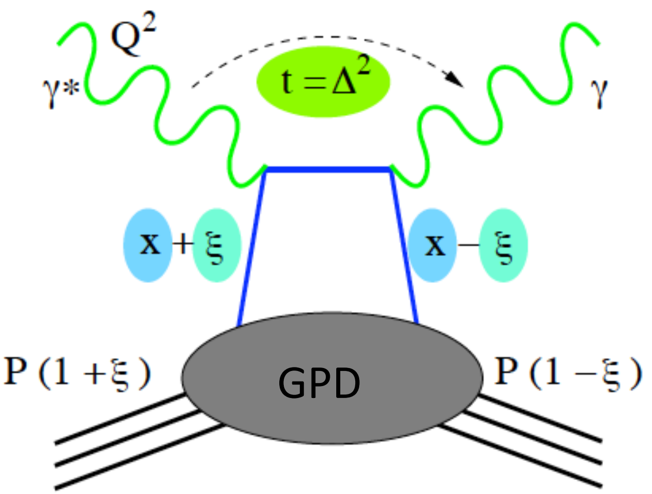
Transverse Momentum
Dependance (TMD) PDF
$f(x, \vec{k}_\perp)$

Generalized Parton Distributions

Hard exclusive processes leads to a new class of parton distributions

Deep Virtual Compton Scattering

ep→eγp



- At twist-2 approximation there are four chiral-even functions for each parton, related to QCD operators by Fourier transform:

$$H^{g,q}(x,\xi,t), E^{g,q}(x,\xi,t)$$

$$\tilde{H}^{g,q}(x,\xi,t), \tilde{E}^{g,q}(x,\xi,t)$$

- Contain PDFs probed in DIS experiments:

$$H^{q}(x,\xi=0,t=0) = q(x), -\bar{q}(-x)$$

$$\tilde{H}^{q}(x,\xi=0,t=0) = \Delta q(x), \Delta\bar{q}(-x)$$

- They are related to the elastic Form Factors:

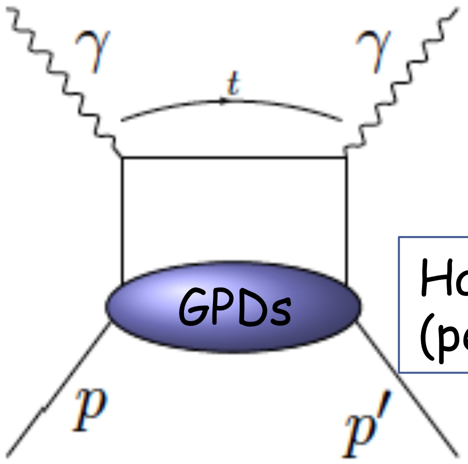
$$\int_{-1}^{+1} dx H^{q}(x,\xi,t) = F_1^{q}(t), \int_{-1}^{+1} dx E^{q}(x,\xi,t) = F_2^{q}(t)$$

- GPDs are 3D functions describing partonic structure of nucleons:

$$H^{q}(x,b_{\perp}) = \int \frac{d^2 b_{\perp}}{(2\pi)^2} e e^{-ib_{\perp}.b_{\perp}} H^{q}(x,\xi=0,t=-\Delta_{\perp}^2)$$

Hard exclusive processes at PANDA

(SL) γp→γp

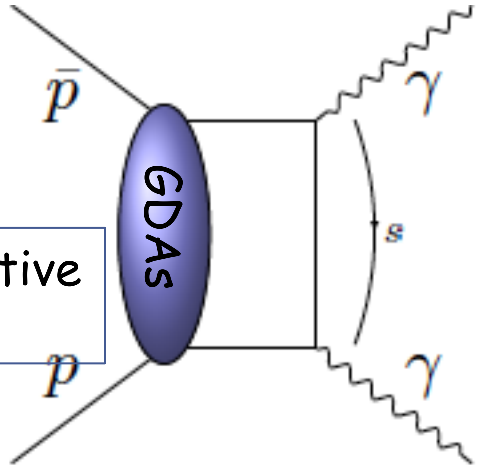


large transverse momentum
(hard scale)

QCD factorization

Hard scattering (perturbative)	Non perturbative (GPDs, GDAs)

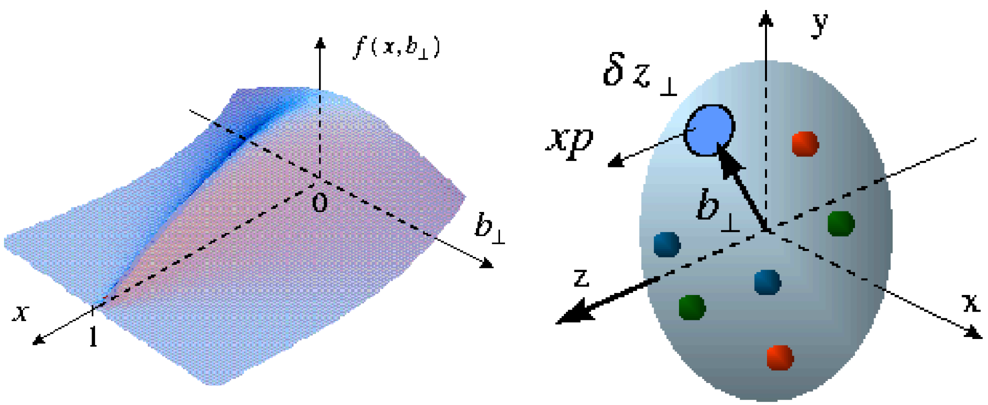
(TL) ppbar→γγ, $\pi^0\gamma$



Wide **A**ngle **C**ompton **S**cattering
Generalized Parton Distributions GPDs

Time-Like Wide **A**ngle **C**ompton **S**cattering
Generalized Distribution Amplitudes GPDs

Correlated quark momentum and helicity distributions in transverse space - GPDs



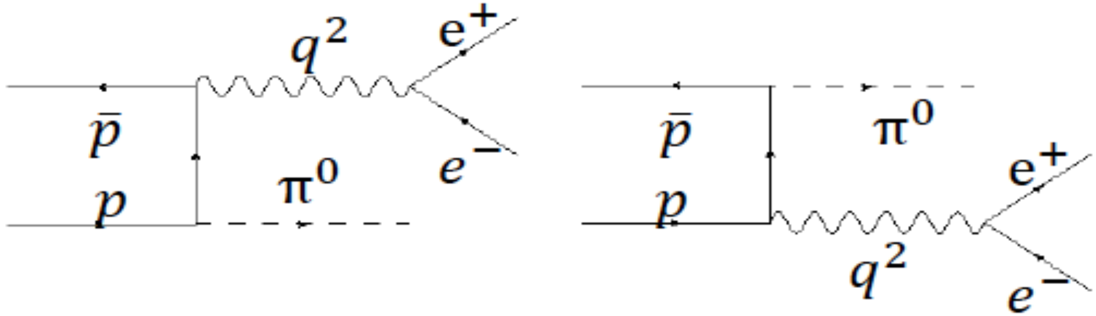
Summary

- Hadron structure functions are universal frame to study various types of electromagnetic processes
- Measurements of the hadron structure functions in different channels and in different kinematical regions is required to test their universality/analyticity.
- The high quality antiproton beams of FAIR between 1.5 and 15 GeV/c allows the PANDA experimental to provide a **complementary** study of the nucleon structure with lepton or photon experiments

Thank you for your attention

Back-up

Proton FFs in the unphysical region



J. Boucher,
PhD Thesis 2011, IPNO

One nucleon exchange model

Feasibility studies were performed @ **p=1.7 GeV/c** with:

- **q^2=0.605 ±0.005, 2.0±0.125 $(GeV/c^2)^2$, at each q^2:**
  - 10° < $\theta_{\pi 0}$< 30°, 80° < $\theta_{\pi 0}$ < 100° and 140° < $\theta_{\pi 0}$ < 160° (Lab. System)

π^0 decay into $\gamma\gamma$ has to be taken into account