Understanding the nucleon structure: basic formalism, modern tools and open questions

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TES HEP Trans European School of High Energy Physics

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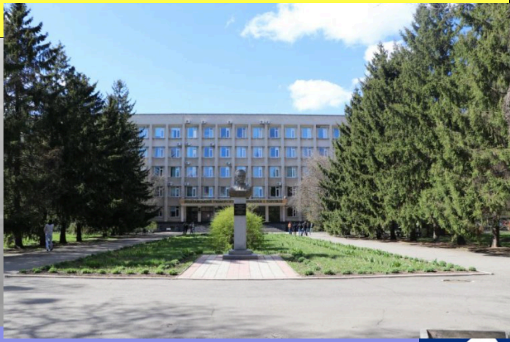

Outline

Part I

- Introduction
  - Motivation and scales
- Phenomenology
  - Elementary reactions
    - kinematics, crossing symmetry
    - Elastic scattering
    - Jlab and the GEp experiment
- Applications
    - Polarization
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Part II

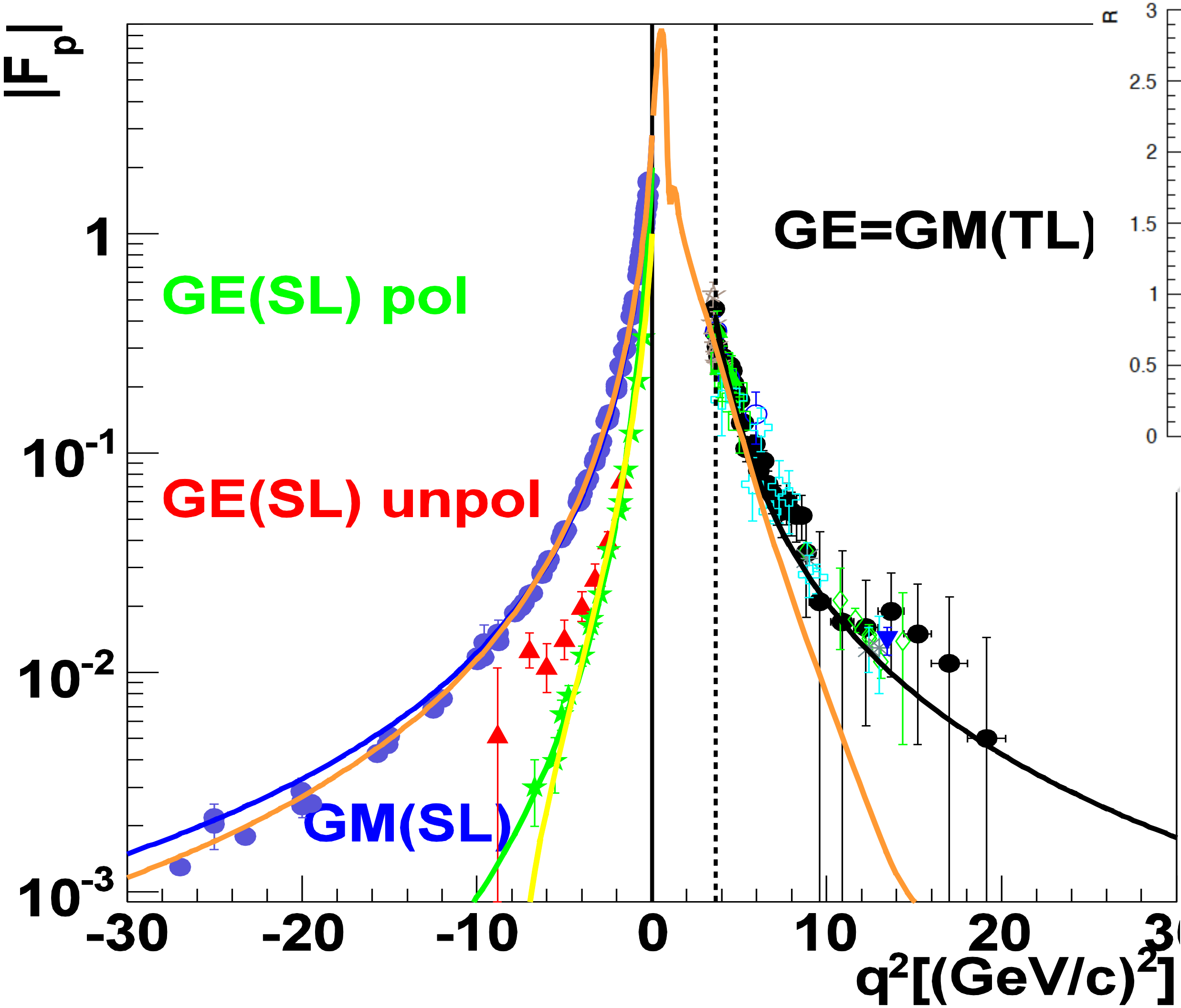
- Phenomenology
  - Elementary reactions
    - Annihilation reactions
    - The PANDA experiment
- Form factors in annihilation and scattering: *understanding how matter is formed*

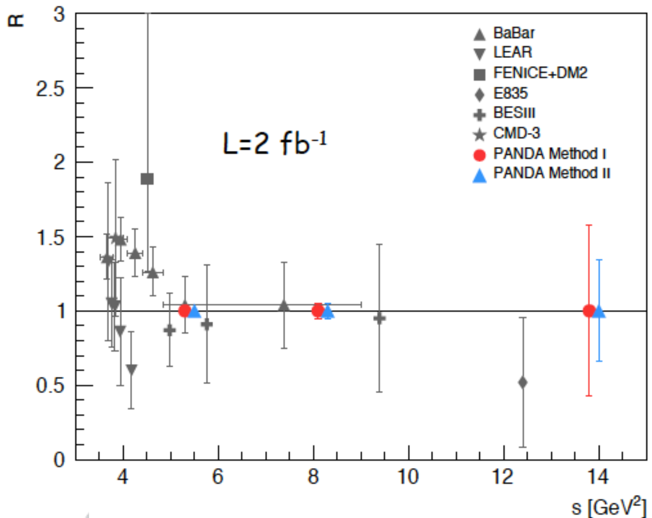
Outline

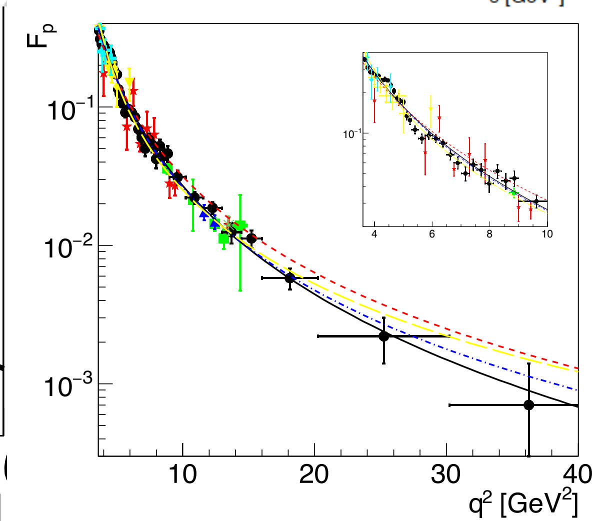
Part II

- Phenomenology
  - Elementary reactions
    - Annihilation reactions
    - The PANDA experiment
- Form factors in annihilation and scattering:
  understanding how matter is formed

SL & TL Form Factors



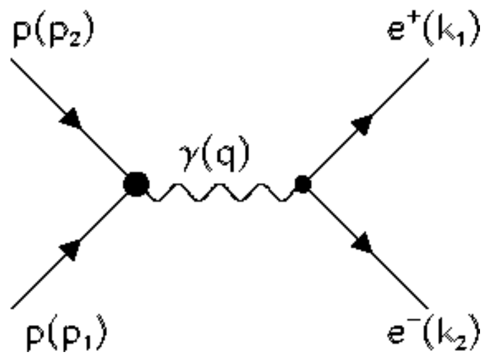




The time-like region

$$p(p_1) + \bar{p}(-p_2) \rightarrow e^-(k_2) + e^+(-k_1)$$

$$e^-(k_1) + e^+(-k_2) \rightarrow \bar{p}(-p_1) + p(p_2)$$



The measurement of the differential cross section

- At a fixed value of s
- For two different angles

allows the separation of GE and GM.

$$cos^2\tilde{\theta} = 1 + \frac{st + (s - M^2)^2}{t(\frac{t}{4} - M^2)} \rightarrow 1 + \frac{ctg^2\frac{\theta}{2}}{1+\tau}$$

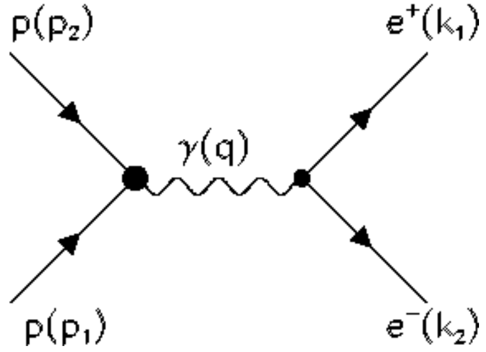
TL equivalent of the Rosenbluth separation in SL region

- It is simpler in TL region, because a collider works at constant *s* and 4π detectors allow to cover all angular range
- No individual determination of GE and GM has been done up to now
- Present and next future

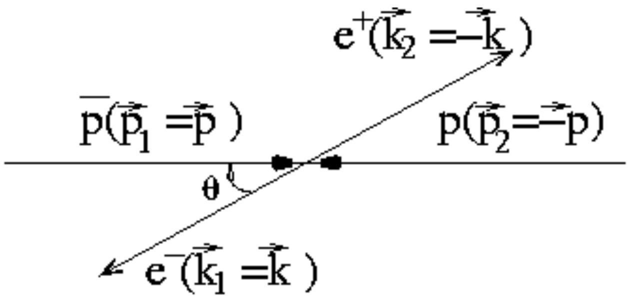
VEPP-3
Novosibirsk

Annihilation channel

$$\bar{p}(p_1) + p(-p_2) \longrightarrow e^-(k_2) + e^+(-k_1)$$



CMS system



Kinematics

$E_1=E_2=\varepsilon_1=\varepsilon_2=E,$

$s=t=(p_1+p_2)^2 = (k_1+k_2)^2 = 4E^2$

$\vec{p}_1=\vec{p}=-\vec{p}_2 \qquad \vec{k}_1=\vec{k}=-\vec{k}_2$

Current conservation

$L \cdot q = 0, \quad L_0 q_0 - \vec{L}\cdot\vec{q} = 0,$

$\vec{q} = \vec{k}_1 + \vec{k}_2 = 0 \qquad L_0 q_0 = 0$

$\forall\ q_0 \rightarrow L_0 = 0.$

The Matrix element:

$$\mathcal{M} = \frac{e^2}{q^2}\bar{v}(k_2)\gamma_\mu u(k_1)\bar{u}(p_2)J_\mu v(p_1),$$

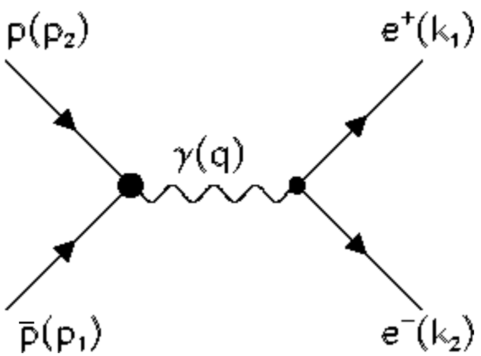
$$\mathcal{M} = \frac{e^2}{q^2}L_\mu J_\mu = \frac{e^2}{q^2}(L_0 J_0 - \vec{L}\cdot\vec{J}) = -\frac{e^2}{q^2}\vec{L}\cdot\vec{J},$$

$$J_\mu = \left[F_1(q^2)\gamma_\mu - \frac{\sigma_{\mu\nu}q_\nu}{2M_p}F_2(q^2)\right]$$

$$= \left[F_1(q^2) + F_2(q^2)\right]\gamma_\mu - \frac{(-p_1+p_2)_\mu}{2M_p}F_2(q^2),$$

The matrix element

$p(p_1) + \bar{p}(-p_2) \longrightarrow e^-(k_2) + e^+(-k_1)$



The Matrix element:

$$\mathcal{M} = \frac{e^2}{q^2}\overline{v}(k_2)\gamma_\mu u(k_1)\overline{u}(p_2)J_\mu v(p_1),$$

$$J_\mu = \left[F_1(q^2)\gamma_\mu - \frac{\sigma_{\mu\nu}q_\nu}{2M_p}F_2(q^2)\right]$$
$$= \left[F_1(q^2) + F_2(q^2)\right]\gamma_\mu - \frac{(-p_1+p_2)_\mu}{2M_p}F_2(q^2),$$

In terms of Pauli σ matrices:

$$\vec{J} = \sqrt{q^2}\varphi_2^\dagger\left[G_M(q^2)(\vec{\sigma} - \hat{\mathbf{p}}\vec{\sigma}\cdot\hat{\mathbf{p}}) + \frac{1}{\sqrt{\tau}}G_E(q^2)\hat{\mathbf{p}}\vec{\sigma}\cdot\hat{\mathbf{p}}\right]\varphi_1,$$

$$\vec{L} = \sqrt{q^2}\varphi_2^\dagger(\vec{\sigma} - \hat{\mathbf{k}}\vec{\sigma}\cdot\hat{\mathbf{k}})\varphi_1,$$

- Unpolarized leptons
- Threshold: $G_E(q^2=4M^2)=G_M(q^2=4M_p^2)$
- $\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}}$ annihilation from *D-state*

Annihilation Cross Section (1)

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{|\overline{\mathcal{M}}|^2}{64\pi^2 q^2}\frac{k}{p},\ k = \frac{\sqrt{q^2}}{2},\ p = \sqrt{\frac{q^2}{4} - m^2}$$

$$|\overline{\mathcal{M}}|^2 = \frac{1}{4}\frac{e^4}{q^4} L_{ab} J_{ab},\ L_{ab} = L_a L_b^*,\ J_{ab} = J_a J_b^*.$$

$$\overline{L_{ab}} = \overline{L_a L_b^*} \sim Tr(\sigma_a - \hat{k}_a \vec{\sigma}\cdot\vec{k})(\sigma_b - \hat{k}_b \vec{\sigma}\cdot\vec{k}) = 2(\delta_{ab} - k_a k_b)$$

as $\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{p} = \vec{p}\cdot\vec{p} = p^2 = 1$ (unit vectors)
$p_a \vec{\sigma}\cdot\vec{p}\sigma_b = p_a(\vec{p}\cdot\hat{b} + i\vec{\sigma}\cdot\vec{p}\times\hat{b}\ )$and Tr of one σ vanish.
$Tr\vec{\sigma}\cdot\vec{a}\vec{\sigma}\cdot\vec{b}\vec{\sigma}\cdot\vec{c} = i\vec{a}\cdot\vec{b}\times\vec{c}.$

Hadron tensor $J_{ab:}$: the product gives four terms. Let us classify along FFs.

$$\vec{J} = \sqrt{q^2}\varphi_2^\dagger\left[G_M(q^2)(\vec{\sigma} - \mathbf{\hat{p}}\vec{\sigma}\cdot\mathbf{\hat{p}}) + \frac{1}{\sqrt{\tau}}G_E(q^2)\mathbf{\hat{p}}\vec{\sigma}\cdot\mathbf{\hat{p}}\right]\varphi_1,$$

Annihilation Cross Section (2)

$$\vec{J} = \sqrt{q^2}\varphi_2^\dagger \left[G_M(q^2)(\vec{\sigma} - \hat{\mathbf{p}}\vec{\sigma}\cdot\hat{\mathbf{p}}) + \frac{1}{\sqrt{\tau}} G_E(q^2)\hat{\mathbf{p}}\vec{\sigma}\cdot\hat{\mathbf{p}} \right] \varphi_1,$$

$$1)|G_M|^2 \quad : \quad \frac{1}{2} Tr(\sigma_a - p_a\vec{\sigma}\cdot\vec{p})(\sigma_b - p_b\sigma\cdot p) \quad \rightarrow$$

$$\rightarrow \quad \sigma_a\sigma_b - p_a\vec{\sigma}\cdot\vec{p}\sigma_b - \sigma_a p_b\vec{\sigma}\cdot\vec{p} + p_a p_b\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{p}$$

$$= \quad \delta_{ab} - p_a p_b - p_b p_a + p_a p_b = \delta_{ab} - p_a p_b$$

2) $|G_E|^2 : \frac{1}{\tau} p_a\vec{\sigma}\cdot\vec{p}p_b\vec{\sigma}\cdot\vec{p} = \frac{1}{\tau}p_a p_b$

3) No interference terms :

$$G_E G_M^* \quad : \quad \frac{1}{2} Tr[p_a\vec{\sigma}\cdot\vec{p}(\sigma_b - p_b\vec{\sigma}\cdot\vec{p})]$$

$$\rightarrow \quad \frac{1}{\sqrt{\tau}}[p_a\vec{\sigma}\cdot\vec{p}\sigma\cdot\hat{b} - p_a p_b\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{p}]$$

$$= \quad (p_a p_b - p_a p_b) = 0$$

4) Similarly $G_M G_E^* : \frac{1}{2} Tr \frac{1}{\tau}(\sigma_a - p_a\sigma\cdot p)p_b\vec{\sigma}\cdot\vec{p} = 0.$

Annihilation Cross Section (3)

- 1) $|G_M|^2$:

$$\begin{aligned} & (\delta_{ab} - p_a p_b)(\delta_{ab} - k_a k_b) \\ = & \delta_{ab}\delta_{ab} - p^2 - k^2 + (\vec{p}\cdot\vec{k}) \\ = & 3 - 1 - 1 + \cos^2\theta = \boxed{1 + \cos^2\theta} \end{aligned}$$

- 2) $|G_E|^2$:

$$\begin{aligned} & \frac{1}{\sqrt{\tau}} p_a p_b(\delta_{ab} - k_a k_b) = \frac{1}{\sqrt{\tau}}[1 - (\vec{p}\cdot\vec{k})^2] \\ = & \frac{1}{\tau}(1 - \cos^2\theta) = \boxed{\frac{1}{\tau}\sin^2\theta.} \end{aligned}$$

We took into account the properties of σ matrices :
$\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{p} = p^2 = 1, \quad Tr\vec{\sigma}\cdot\vec{a}\vec{\sigma}\cdot\vec{b}\vec{\sigma}\cdot\vec{c} = i\vec{a}\cdot\vec{b}\times\vec{c}.$

Annihilation Cross Section (4)

$$\bar{p}(p_1) + p(-p_2) \rightarrow e^-(k_2) + e^+(-k_1)$$

The differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \mathcal{N}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right]$$

Magnetic — Electric

$$\mathcal{N} = \frac{\alpha^2}{4\sqrt{q^2(q^2-4m^2)}}.$$

$$\alpha = e^2/(4\pi) \simeq 1/137.$$

The angular Asymmetry

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \sigma_0\left[1+\mathcal{A}\cos^2\theta\right],$$

$$\mathcal{A} = \frac{\tau|G_M|^2-|G_E|^2}{\tau|G_M|^2+|G_E|^2} = \frac{\tau-\mathcal{R}^2}{\tau+\mathcal{R}^2}.$$

$$\mathcal{R} = |G_E|/|G_M|$$

$$\sigma_0 = \frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}\left(|G_M|^2+\frac{1}{\tau}|G_E|^2\right)$$

The total cross section

$$\sigma(q^2) = \mathcal{N}\frac{8}{3}\pi\left[2|G_M|^2+\frac{1}{\tau}|G_E|^2\right].$$

Polarized Antiprotons (1)

$\vec{P}_1$ and $\vec{P}_2$: polarizations of the colliding antiproton and proton :

$$\left(\frac{d\sigma}{d\Omega}\right)_0 (\vec{P}_1, \vec{P}_2) = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 + A_y(P_{1y} + P_{2y}) + A_{xx}P_{1x}P_{2x} + A_{yy}P_{1y}P_{2y} + A_{zz}P_{1z}P_{2z} + A_{xz}(P_{1x}P_{2z} + P_{1z}P_{2x})]$$

where A_i and A_{ij} $(i, j = x, y, z)$ are the analyzing powers and correlation coefficients, and depend on the nucleon FFs.
The polarized hadronic tensor :

$$W_{ab}(\vec{P}_1, \vec{P}_2) = \frac{1}{2} Tr J_a \vec{\sigma} \cdot \vec{P}_1 J_b^* \vec{\sigma} \cdot \vec{P}_2.$$

The cross section with unpolarized electrons is proportional to $L_{ab}\overline{W_{ab}}$.

Polarized antiproton beam (2)

$$\left(\frac{d\sigma}{d\Omega}\right)_0 \vec{A}_1 \sim -L_{ab}\frac{1}{4} Tr J_a \vec{\sigma} J_b^* =$$

$$[(\sigma_a - p_a \vec{\sigma}\cdot\vec{p})G_M + \frac{1}{\tau} G_E p_a \vec{\sigma}\cdot\vec{p}](-\vec{\sigma}\cdot\vec{P}_1)$$

$$[(\sigma_b - p_b \vec{\sigma}\cdot\vec{p})G_M^* + \frac{1}{\tau} G_E^* p_b \vec{\sigma}\cdot\vec{p}](\delta_{ab} - k_a K_b)$$

Note : $Tr\vec{\sigma}\cdot\vec{a}\vec{\sigma}\cdot\vec{b}\vec{\sigma}\cdot\vec{c} = i\vec{a}\cdot\vec{b}\times\vec{c} = ib\cdot\vec{c}\times\vec{a} = i\vec{c}\cdot\vec{a}\times\vec{b}$
For antiparticles we remember a global general sign :
$(-\vec{\sigma}\cdot\vec{P}_1)$

Polarized antiproton beam $|G_M|^2$(3)

$|G_M|^2$:

$$[1]:\ (\sigma_a - p_a\vec{\sigma}\cdot\vec{p})\vec{\sigma}\cdot\vec{P}_1(\sigma_b - p_b\vec{\sigma}\cdot\vec{p})\delta_{ab} -$$
$$[2]:\ (\sigma_a - p_a\vec{\sigma}\cdot\vec{p})\vec{\sigma}\cdot\vec{P}_1(\sigma_b - p_b\vec{\sigma}\cdot\vec{p})\hat{k}_a\hat{k}_b$$

$$[1]:\quad \sigma_a\vec{\sigma}\cdot\vec{P}_1\sigma_a - p_a\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1\sigma_a - \sigma_a\vec{\sigma}\cdot\vec{P}_1 p_a\vec{\sigma}\cdot\vec{p} +$$
$$p_a\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1 p_a\vec{\sigma}\cdot\vec{p}$$
$$= -p_a(a\cdot P_1\times\vec{p} + p\cdot P_1\times\vec{a}) + p_a^2\vec{\sigma}\cdot\vec{P}_1 = 0$$

$$[2]:\quad (\vec{\sigma}\cdot\vec{k} - \vec{p}\cdot{}^{\rightarrow}k\vec{\sigma}\cdot\vec{p})\vec{\sigma}\cdot\vec{P}_1(\vec{\sigma}\cdot\vec{k} - \vec{p}\cdot\vec{k}\vec{\sigma}\cdot\vec{p})$$
$$\vec{\sigma}\cdot\vec{k}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}\cdot\vec{k} - \vec{\sigma}\cdot\vec{k}\vec{\sigma}\cdot\vec{P}_1\vec{p}\cdot\vec{k}\vec{\sigma}\cdot\vec{p} -$$
$$\vec{p}\cdot\vec{k}\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}\cdot\vec{k} + (\vec{p}\cdot\vec{k})^2\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}\cdot\vec{p}$$
$$= -\cos\theta(\sigma\cdot\vec{k}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}\cdot\vec{p} + \sigma\cdot\vec{p}\sigma\cdot\vec{P}_1\sigma\cdot\vec{k}$$
$$= -\cos\theta[(\vec{k}\cdot\vec{P}_1\times\vec{p} + \vec{p}\cdot\vec{P}_1\times\vec{k}] = 0$$

$|G_E|^2$: $$\frac{1}{\tau}\left[p_a\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1 p_a\vec{\sigma}\cdot\vec{p} - (\vec{p}\cdot\vec{k})^2\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}\cdot\vec{p}\right] = 0$$

Polarized antiproton beam $G_E G_M^*$(4)

$G_M G^*_E$:

$$\frac{1}{\sqrt{\tau}}[(\vec{\sigma}_a - p_a \vec{\sigma}\cdot\vec{p})\vec{\sigma}\cdot\vec{P}_1 p_b \vec{\sigma}\cdot\vec{p}](\delta_{ab} - k_a k_b)$$

$$= \frac{1}{\sqrt{\tau}}[(\vec{\sigma}_a - p_a \vec{\sigma}\cdot\vec{p})\vec{\sigma}\cdot\vec{P}_1 p_a \vec{\sigma}\cdot\vec{p} -$$

$$(\vec{\sigma}\cdot\vec{k} - \vec{p}\cdot\vec{k}\vec{\sigma}\cdot\vec{p})\vec{\sigma}\cdot\vec{P}_1 \vec{p}\cdot\vec{k}\vec{\sigma}\cdot\vec{p}]$$

Explicitly each component:

$$\frac{1}{\tau}[(\sigma_x \vec{\sigma}\cdot\vec{P}_1 p_x \sigma_z + \sigma_y \vec{\sigma}\cdot\vec{P}_1 p_y \sigma_z)$$

$$-(\sigma_x \sin\theta + \sigma_z \cos\theta - \sigma_z \cos\theta)\vec{\sigma}\cdot\vec{P}_1 \cos\theta\sigma_z]$$

$$= -\sigma_x \sin\theta\cos\theta\vec{\sigma}\cdot\vec{P}_1\sigma_z = \boxed{-i\sin\theta\cos\theta P_{1y}}$$

Polarized antiproton beam $G_E G_M^*$ (5)

$G_E G^*_M$:

$$
\begin{aligned}
& [p_a\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1(\sigma_b - p_b\vec{\sigma}\cdot\vec{p})](\delta_{ab} - k_a k_b) \\
= & \; [p_a\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}_a - p_a\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1 p_a\vec{\sigma}\cdot\vec{p} - \\
& \; \vec{p}\cdot\vec{k}\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}\cdot\vec{k} - (\vec{p}\cdot\vec{k})^2\vec{\sigma}\cdot\vec{p}\vec{\sigma}\cdot\vec{P}_1\vec{\sigma}\cdot\vec{p} \\
= & \; i[p_a\vec{a}\cdot\vec{p}\times\vec{P}_1 - \cos\theta\,\vec{p}\cdot\vec{P}_1\times\vec{k}]
\end{aligned}
$$

$$\vec{a}\cdot\vec{p}\times\vec{P}_1 \longrightarrow p_x = p_y = 0; z\cdot p_z\times P_1 = 0$$

$$\left(\begin{array}{c|ccc|} p & 0 & 0 & 1 \\ P & P_{1x} & P_{1y} & P_{1z} \\ k & \sin\theta & 0 & \cos\theta \end{array}\right)$$

$$G_E G_M^* \longrightarrow \frac{i}{\sqrt{\tau}}\cos\theta\sin\theta P_{1y}$$

Single spin observables

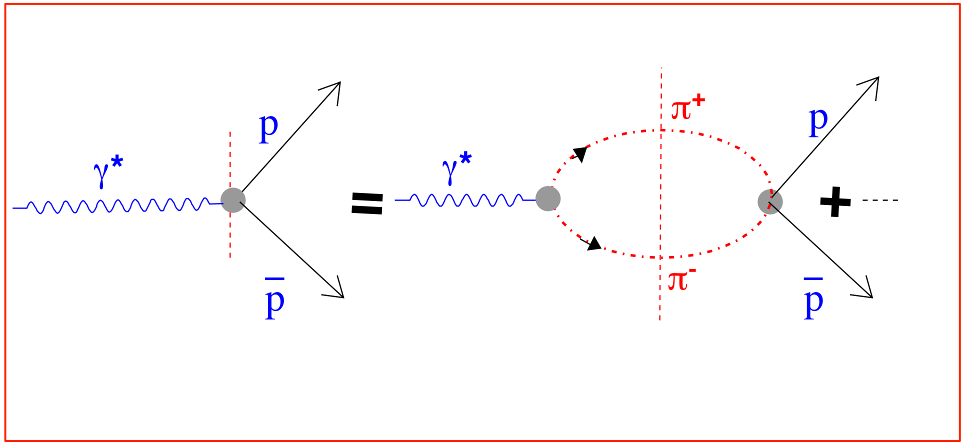
When the beam is polarized

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{1,y} = -\frac{i\mathcal{N}}{\sqrt{\tau}} \sin\theta\cos\theta[G_M G_E^* - G_E G_M^*] = \frac{\mathcal{N}}{\sqrt{\tau}} \sin 2\theta Im(G_M G_E^*).$$

When the target is polarized

$$\left(\frac{d\sigma}{d\Omega}\right)_0 \vec{A}_2 = L_{ab}\frac{1}{4} Tr J_a J_b^* \vec{\sigma}.$$

$$\vec{A}_2 = \vec{A}_1 = \vec{A}.$$



Unitarity
In TL region single spin observables do not vanish: FFs are complex (q^2>0).
Final state interaction

Double spin polarization observables

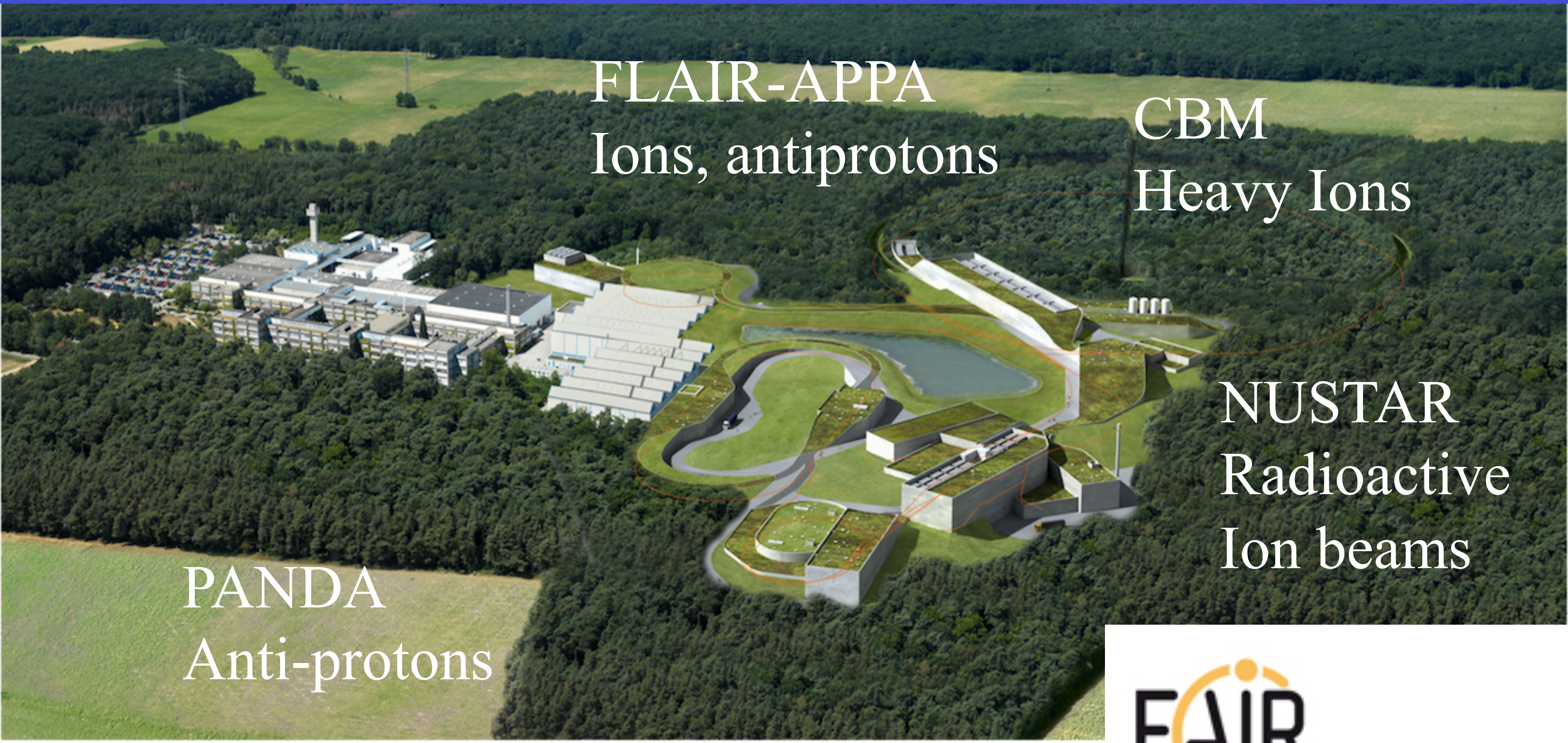
$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{ab} = -\frac{1}{4} L_{mn} Tr J_m \sigma_a J_n^\dagger \sigma_b,$$

The nonzero components are:

$$\begin{aligned}
\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xx} &= \sin^2\theta\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right)\mathcal{N},\\
\left(\frac{d\sigma}{d\Omega}\right)_0 A_{yy} &= -\sin^2\theta\left(|G_M|^2 - \frac{1}{\tau}|G_E|^2\right)\mathcal{N},\\
\left(\frac{d\sigma}{d\Omega}\right)_0 A_{zz} &= \left[(1+\cos^2\theta)|G_M|^2 - \frac{1}{\tau}\sin^2\theta|G_E|^2\right]\mathcal{N},\\
\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xz} &= \left(\frac{d\sigma}{d\Omega}\right)_0 A_{zx} = \frac{1}{\sqrt{\tau}}\sin 2\theta Re G_E G_M^* \mathcal{N}.
\end{aligned}$$

Relative phase: *Ay, Axz*

Facility for Antiproton and Ion Research (Darmstadt/Germany)



FAIR
Facility for Antiproton and Ion Research in Europe GmbH

All physics communities are represented

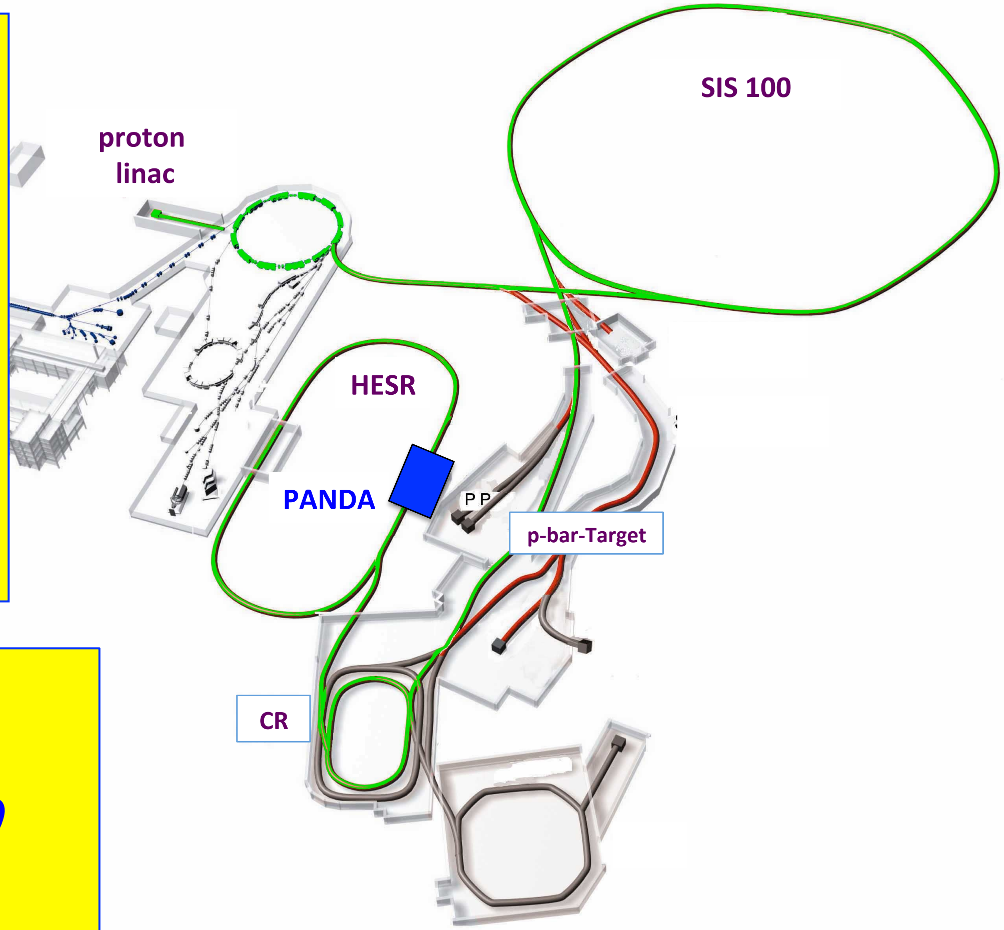
Antiprotons at FAIR

http://www.fair-center.eu/

https://panda.gsi.de

Parameters of HESR

- *Injection of pbar at 3.7 GeV*
- *Slow synchrotron*
- *Momentum 1.5-15 GeV/c*
- *Luminosity 10^{31} $cm^{-2}s^{-1}$*
  (up to L_{peak}~ $2x10^{32}$ $cm^{-2}s^{-1}$)
- *Beam cooling*



Pbar production

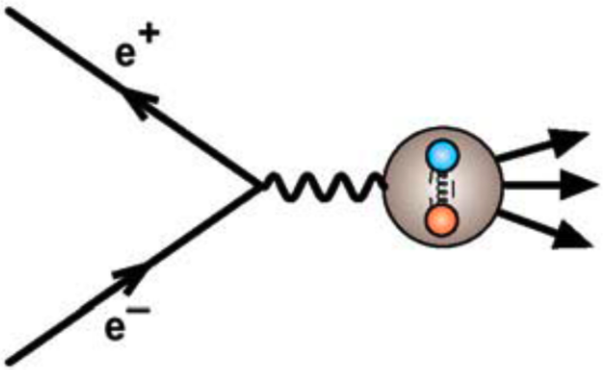
- *Proton Linac 70 MeV*
- *Accelerate p in SIS18/SIS100*
- *Produce pbar on NI/Cu target*
- *Collect pbar in CR*
- *Storage in HESR*

Antiproton facilities

Experiment	Years	Intensity $\bar{p}/s$	Momentum range [GeV/c]	$\Delta p/p$
CERN -LEAR	1983-1996	$2 \cdot 10^6$	0.06-1.94	10^{-3}
FermiLab 45% polarized $\bar{p}$	1985-2011	$2 \cdot 10^6$ 10^4	<8.9 (Low energy beams)	10^{-4}
PANDA		$2 \cdot 10^7$	1.5-15	10^{-5}

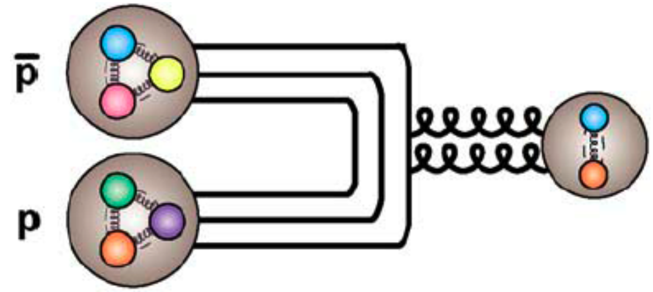
Panda will have:
- Better luminosity
- Better beam momentum resolution
- Better detector (coverage, PID,magnetic field..)

Proton-Antiproton Annihilation

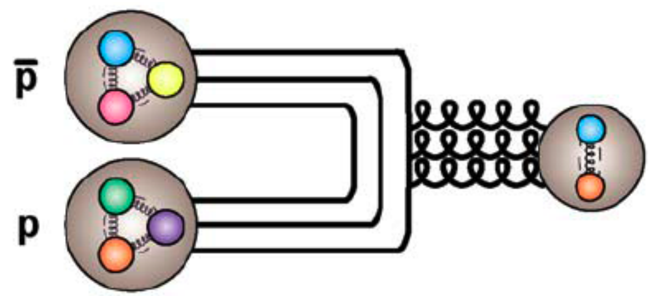


$J^{PC} = 1^{--}$

- *Formation:*
  -> (precision physics)



$J = 0,2,..\quad C = +$

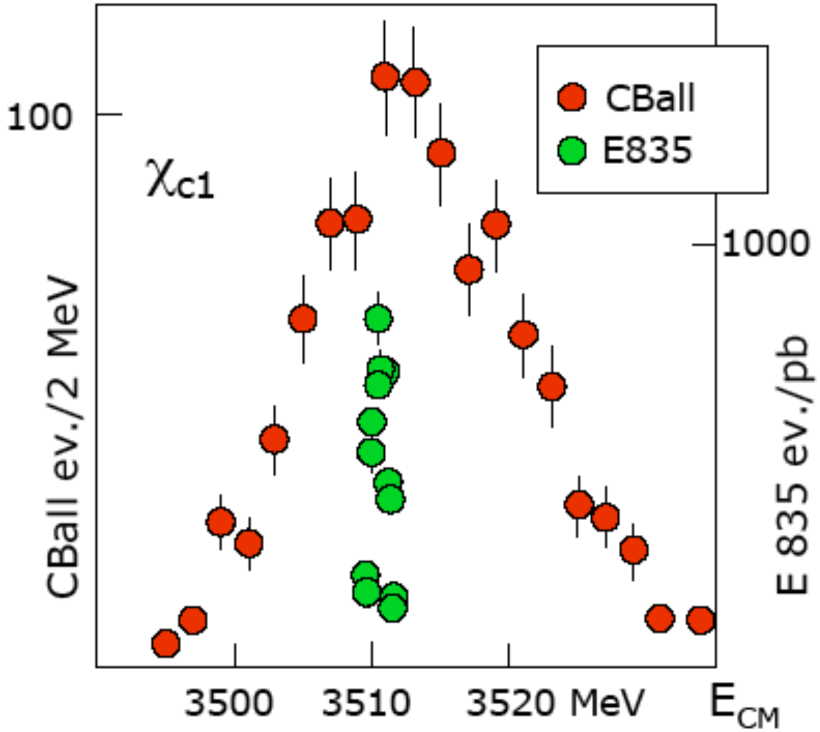


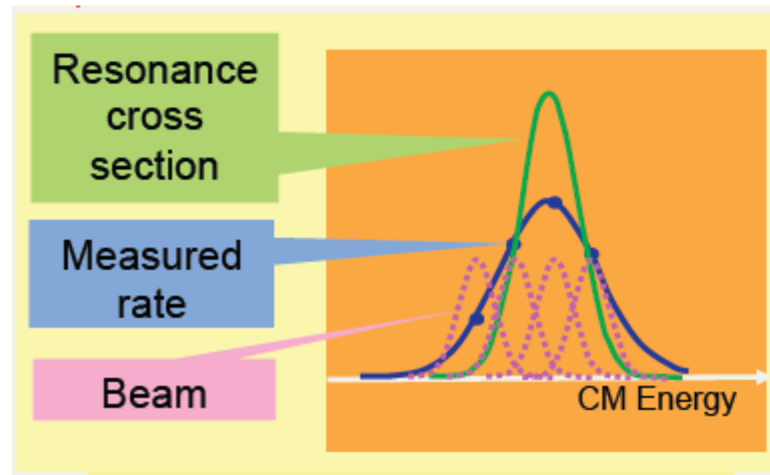
$J = 1,..\quad C = -$

- *q-qbar annihilate into gluons*
- *gluon-rich environment*
- *all quantum numbers allowed by qqbar*

Search for glueballs, hybrids

Very precise scan of a resonance in formation mode:
depends on HESR beam momentum resolution Dp/p~2x10^{-5}



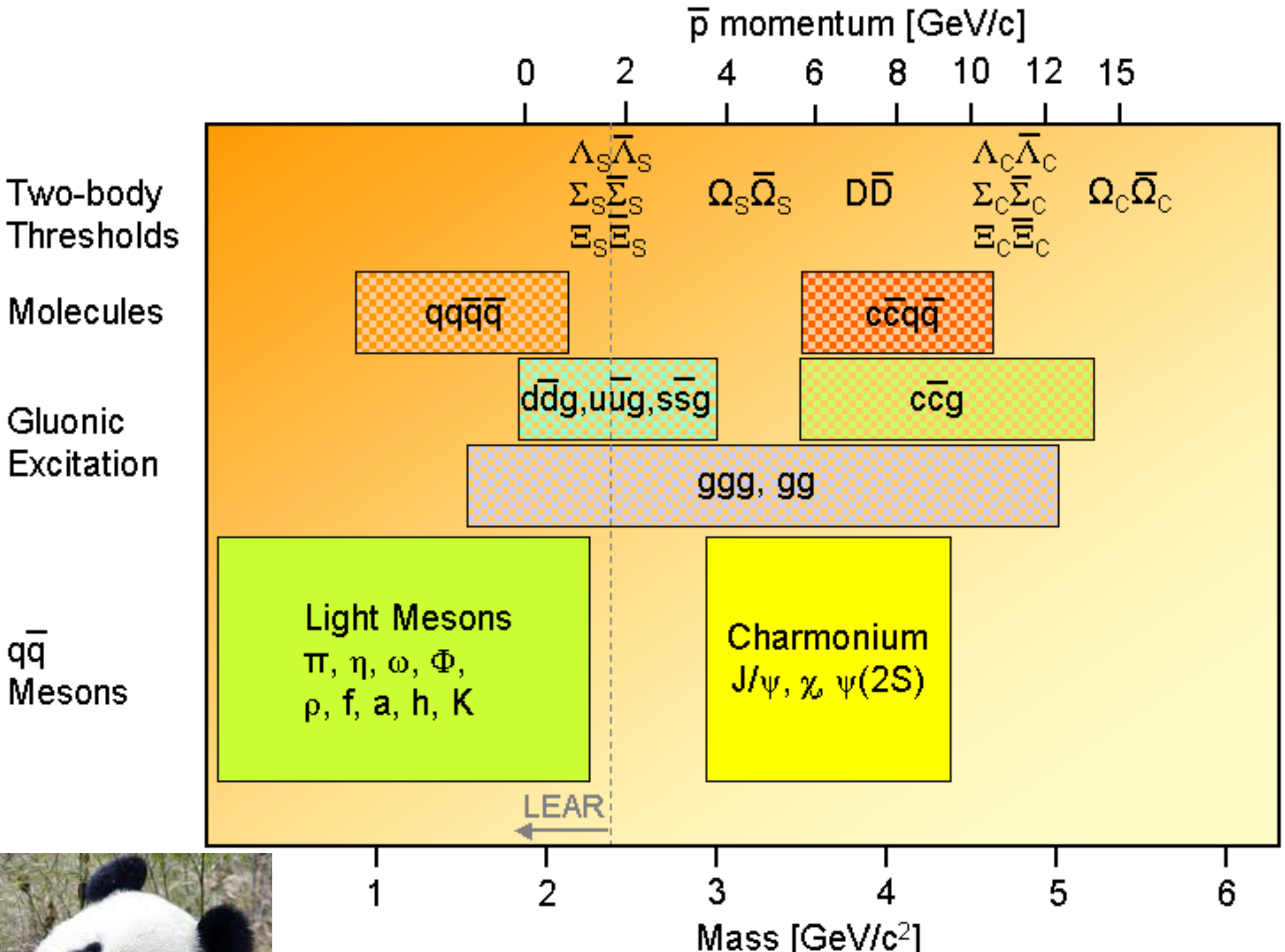


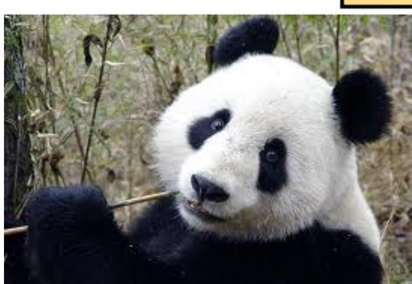
Mass resolution

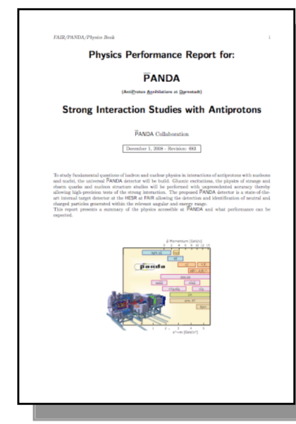
e+e- :	*2 MeV*
FermiLab	*240 keV*
HESR	*50 keV*

<u>Appearance of a resonance</u> in production mode and <u>disappearance</u> in formation mode <u>sign its exotic nature</u>

Hadron Physics

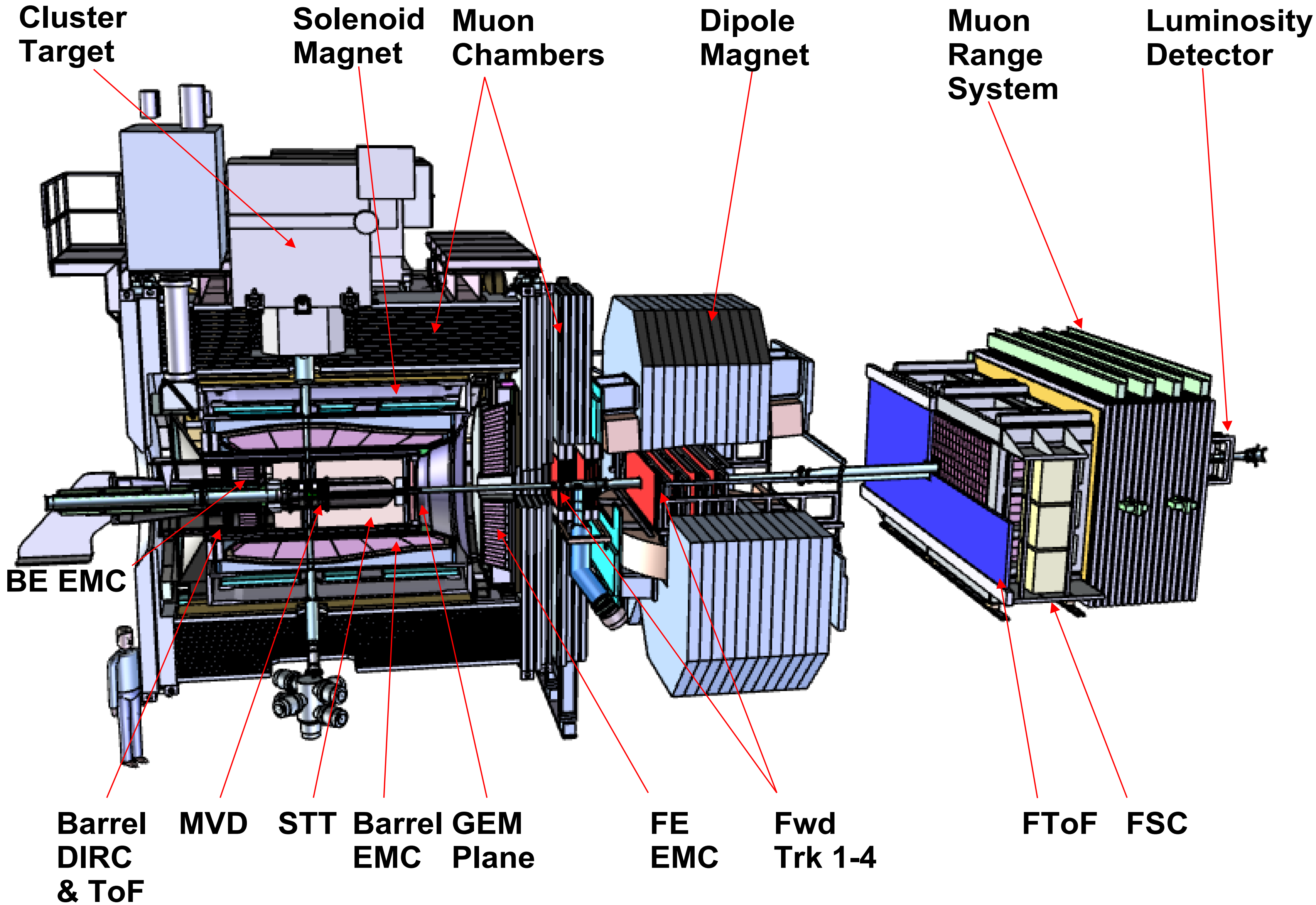






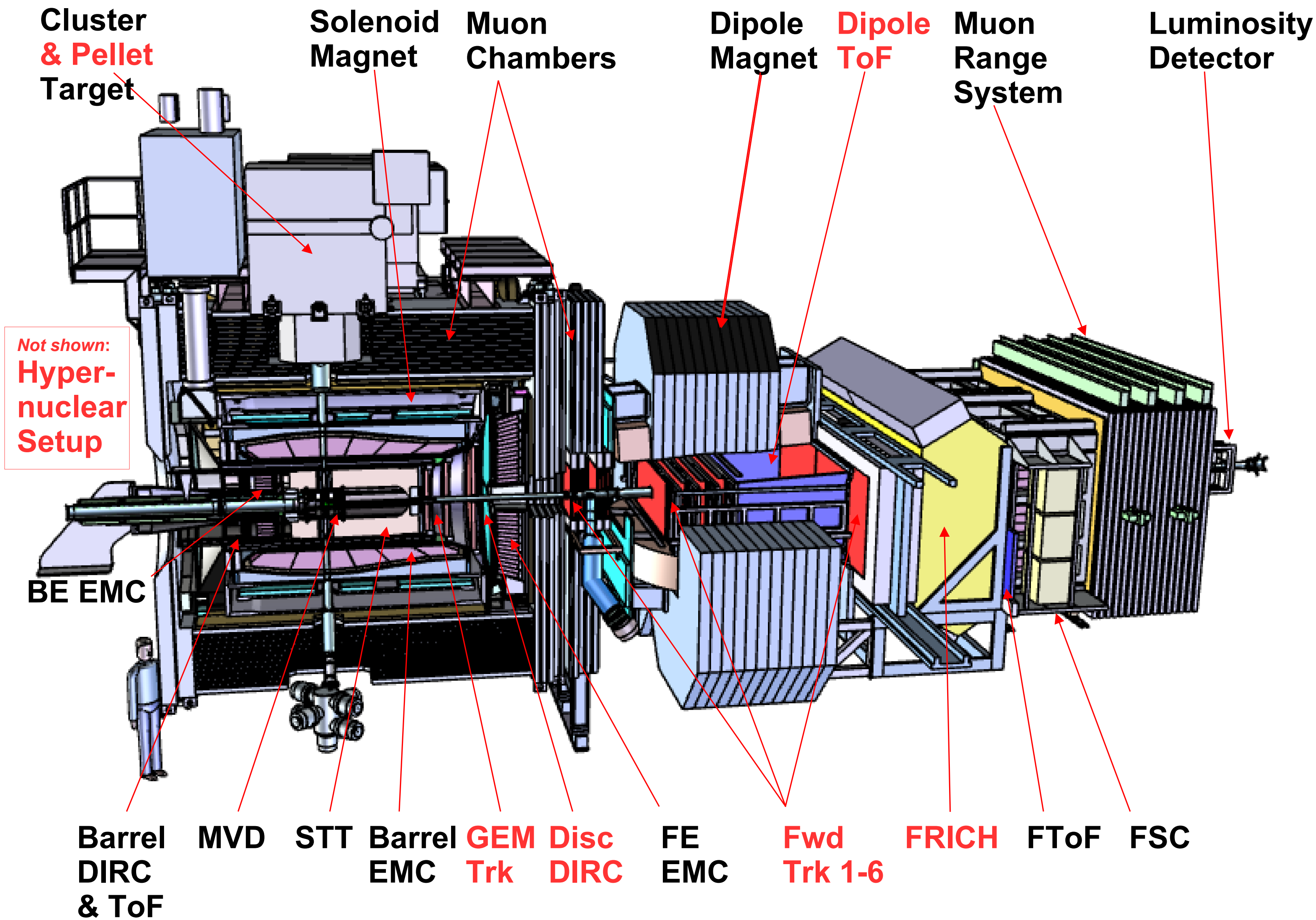
arXiv:0903.3905v1

START SETUP

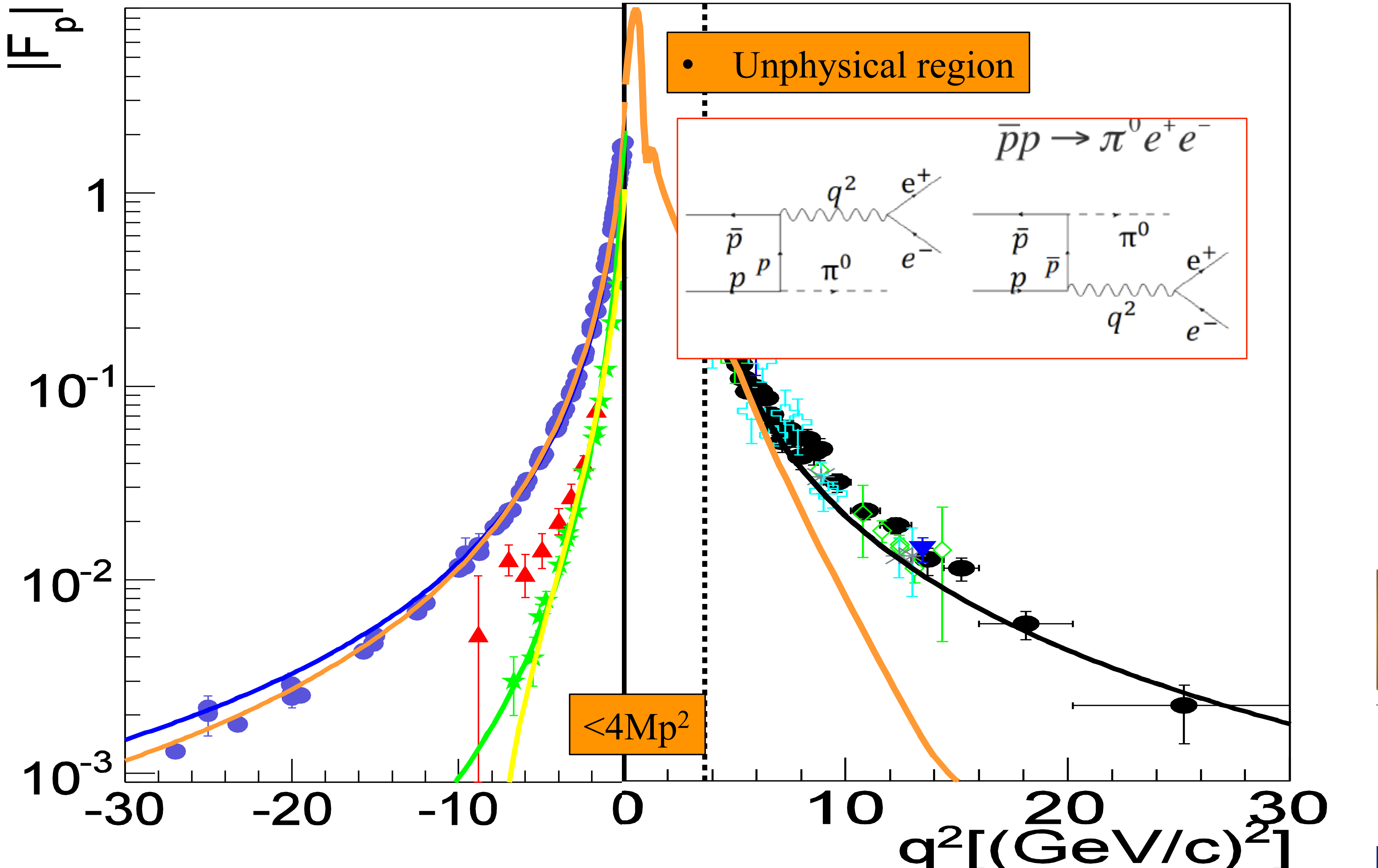


Cluster Target
Solenoid Magnet
Muon Chambers
Dipole Magnet
Muon Range System
Luminosity Detector
BE EMC
Barrel DIRC & ToF
MVD
STT
Barrel EMC
GEM Plane
FE EMC
Fwd Trk 1-4
FToF
FSC

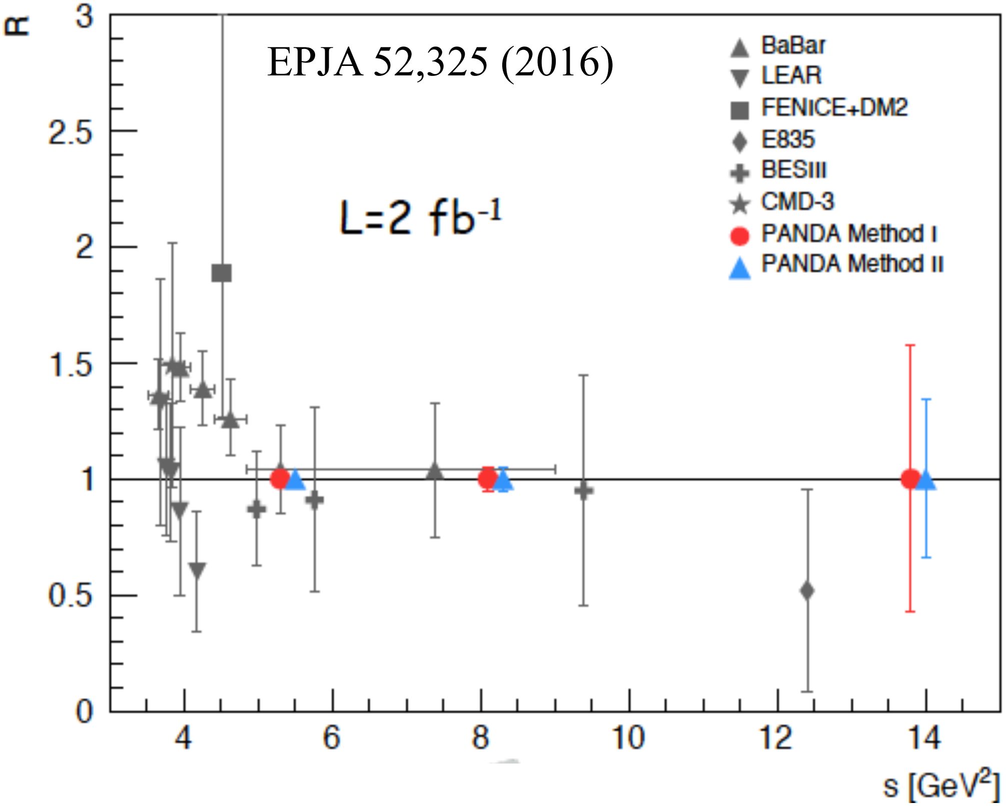
START/ FULL SETUP



Hadron Electromagnetic Form factors



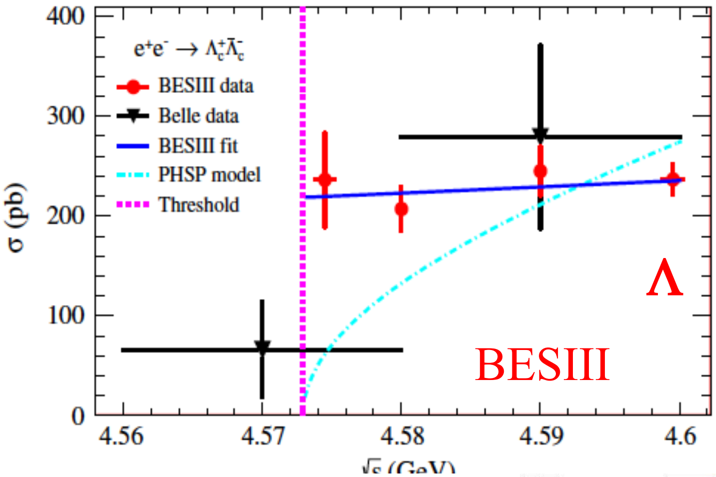
Antiprotons at FAIR



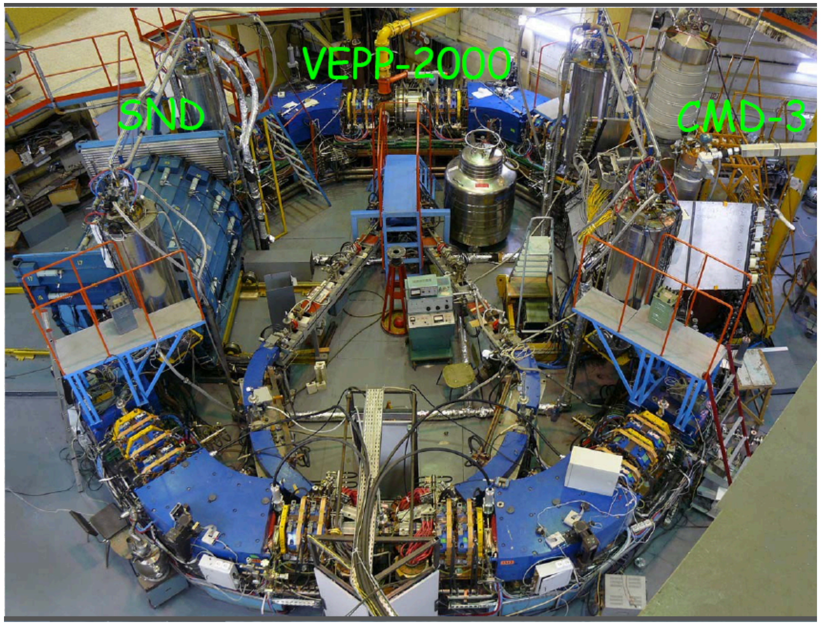
- Individual determination of G_E and G_M
- Large transferred momentum
- Unphysical region
- Oscillation pattern
- e^+e^- & $\mu^+\mu^-$

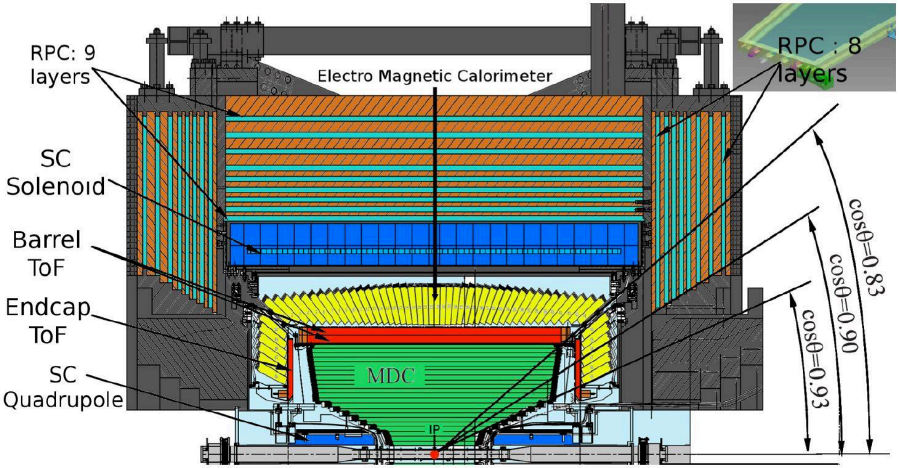
Threshold physics

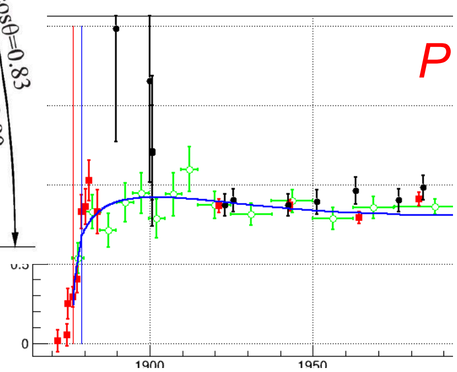
Beijing, BEPC2, BES3

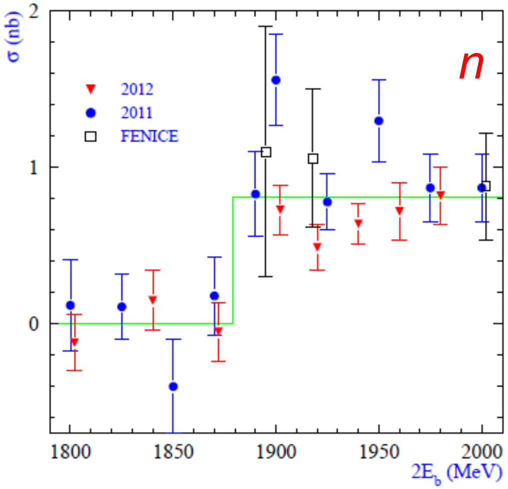


VEPPII, Novosibirsk

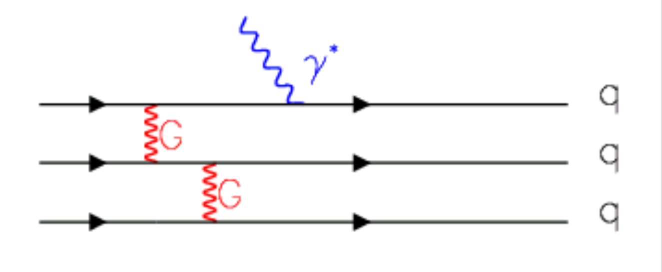








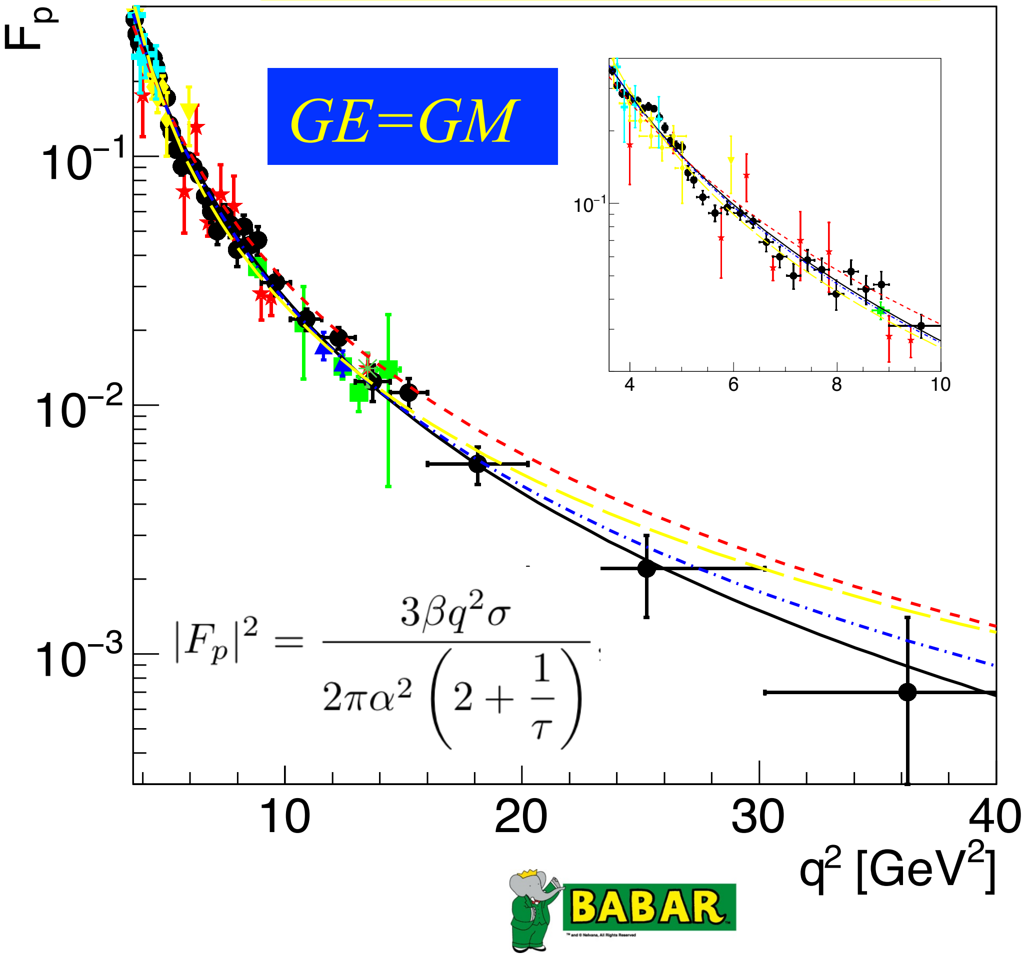
The Time-like Region



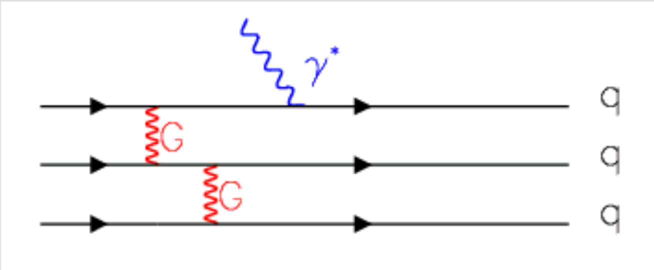
Expected QCD scaling $(q^2)^2$

$$|F_{scaling}(q^2)| = \frac{\mathcal{A}}{(q^2)^2 \log^2(q^2/\Lambda^2)}$$

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



The Time-like Region



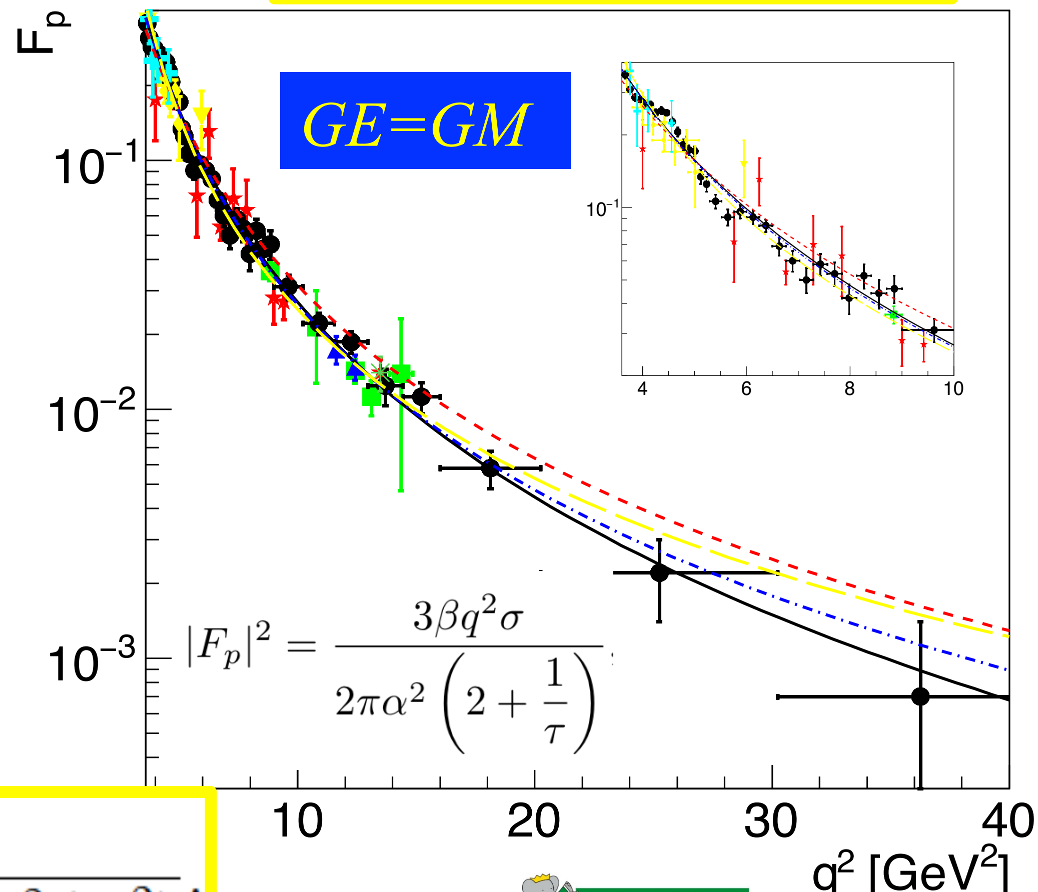
Expected QCD scaling $(q^2)^2$

$$\frac{\mathcal{A}}{(q^2)^2\left[\log^2(q^2/\Lambda^2)+\pi^2\right]}.$$

$$\frac{\mathcal{A}}{(1+q^2/m_a^2)\left[1-q^2/0.71\right]^2},$$

$$|F_{T3}(q^2)| \;=\; \frac{\mathcal{A}}{(1-q^2/m_1^2)(2-q^2/m_2^2)}.$$

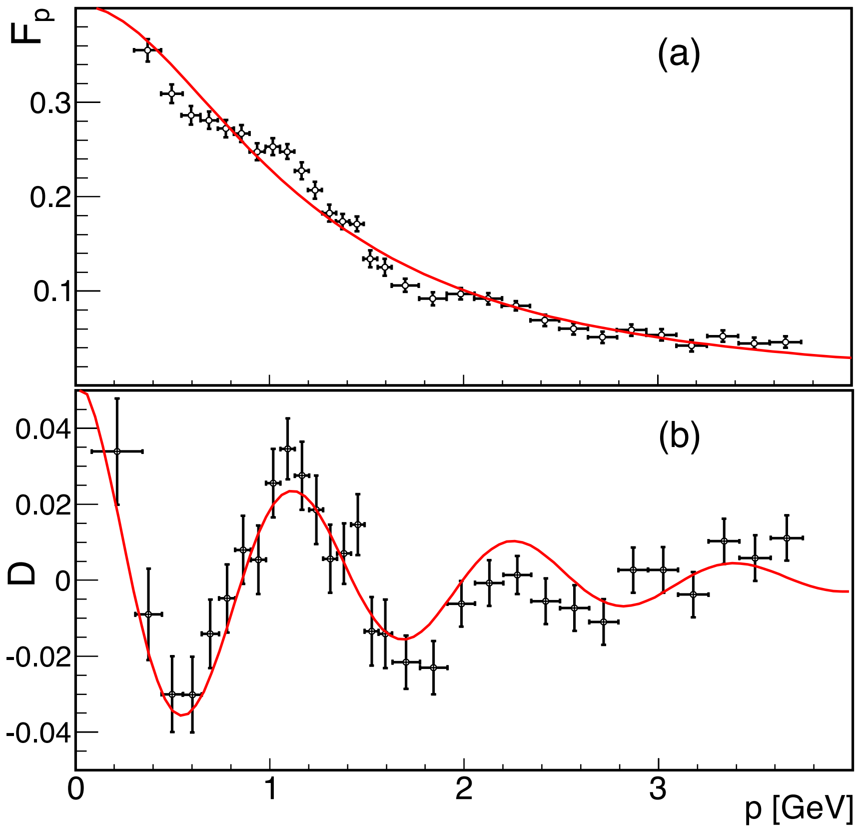
$$e^+ + e^- \to \bar{p} + p\,,$$
$$\bar{p} + p \to e^+ + e^-$$



BABAR

Oscillations : regular pattern in P_{Lab}

The relevant variable is p_{Lab} associated to the relative motion of the final hadrons.



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

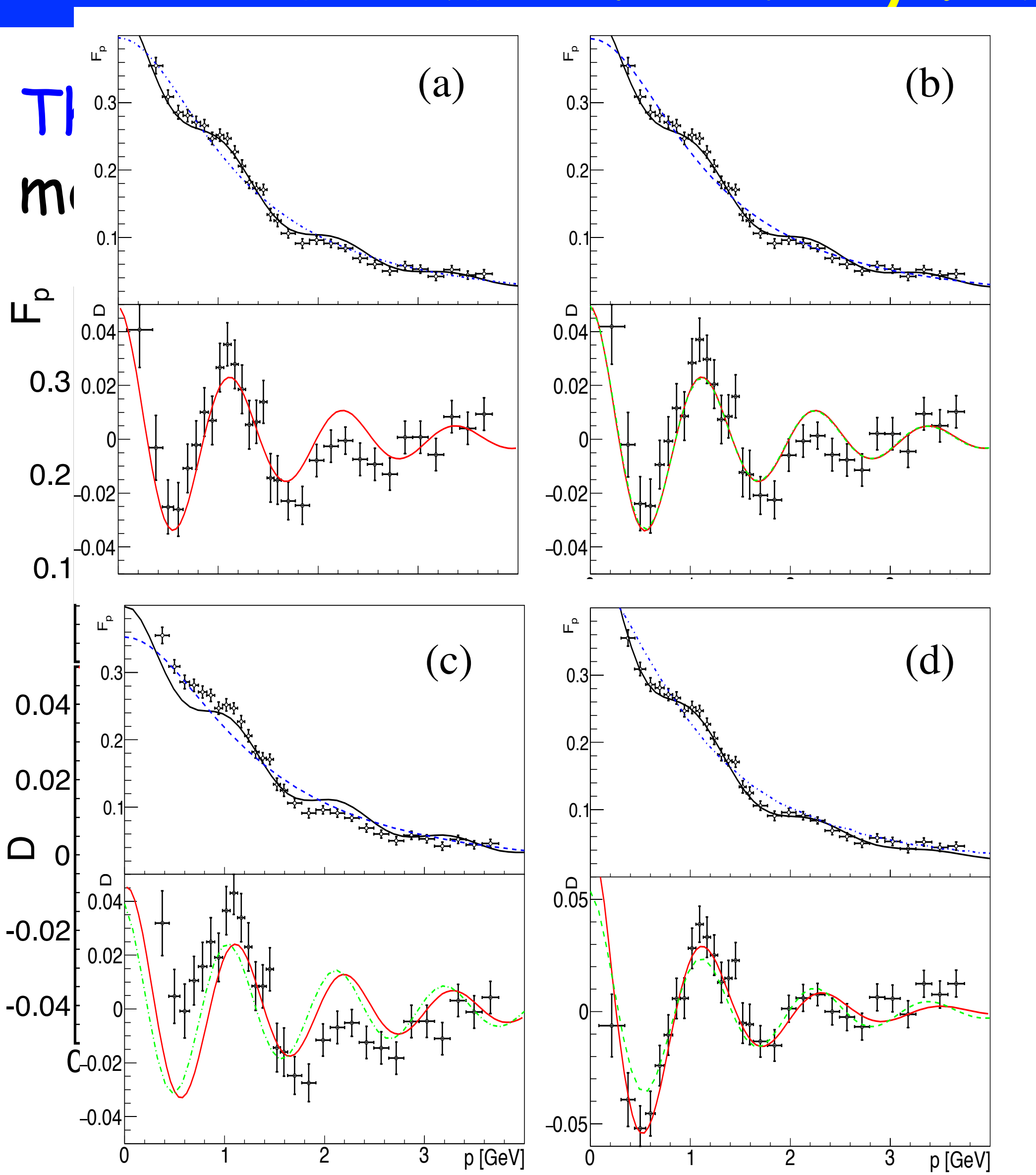
$A \pm \Delta A$	$B \pm \Delta B$ $[GeV]^{-1}$	$C \pm \Delta C$ $[GeV]^{-1}$	$D \pm \Delta D$	$\chi^2/n.d.f$
0.05 ± 0.01	0.7 ± 0.2	5.5 ± 0.2	0.03 ± 0.3	1.2

A: Small perturbation B: damping
C: r < 1fm D=0: maximum at p=0

Simple oscillatory behaviour
Small number of coherent sources

A. Bianconi, E. T-G. Phys. Rev. Lett. 114,232301 (2015)

Oscillations : regular pattern in P_{Lab}



Th... ciated to the relative

m...

$$... p) \equiv A \exp(-Bp) \cos(Cp + D).$$

.	$B \pm \Delta B$ $[GeV]^{-1}$	$C \pm \Delta C$ $[GeV]^{-1}$	$D \pm \Delta D$	$\chi^2/n.d.f$
)1	0.7 ± 0.2	5.5 ± 0.2	0.03 ± 0.3	1.2

ll perturbation B: damping
fm D=0: maximum at p=0

ple oscillatory behaviour
ll number of coherent sources

A.Bianconi, E. T-G. Phys. Rev. Lett. 114,232301 (2015), PRC 93, 035201 (2016)

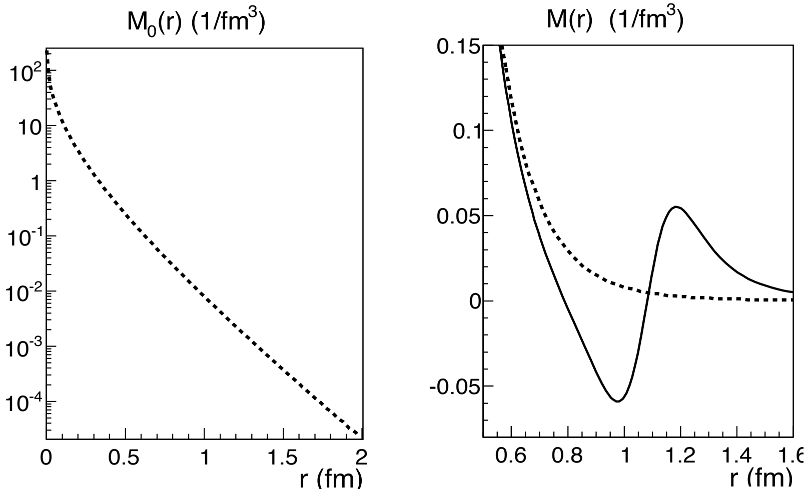
Fourier Transform

$$F_0(p) \equiv \int d^3\vec{r}\; exp(i\vec{p}\cdot\vec{r})\; M_0(r)$$

$$F(p) = F_0(p) + F_{osc}(p) \equiv \int d^3\vec{r}\; exp(i\vec{p}\cdot\vec{r}) M(r).$$

$$F_0 = \frac{\mathcal{A}}{(1 + q^2/m_a^2)\,[1 - q^2/0.71]^2},$$

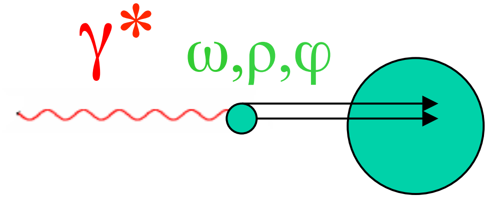
$$F_{osc}(p) \;\equiv\; A\; \exp(-Bp)\; \cos(Cp \;+\; D).$$



- *Rescattering processes*
- *Large imaginary part*
- *Related to the time evolution of the charge density?*
  (E.A. Kuraev, E. T.-G., A. Dbeyssi, PLB712 (2012) 240)
- *Consequences for the SL region?*
- *Data from BESIII confirm the structures*
- *Expected from PANDA*

VMD: Iachello, Jakson and Landé (1973)

Isoscalar and isovector FFs



$$F_1^s(Q^2) = \frac{g(Q^2)}{2}\left[(1-\beta_\omega-\beta_\phi)+\beta_\omega\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\beta_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],$$

$$F_1^v(Q^2) = \frac{g(Q^2)}{2}\left[(1-\beta_\rho)+\beta_\rho\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],$$

$$F_2^s(Q^2) = \frac{g(Q^2)}{2}\left[(\mu_p+\mu_n-1-\alpha_\phi)\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\alpha_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],$$

$$F_2^v(Q^2) = \frac{g(Q^2)}{2}\left[(\mu_p-\mu_n-1)\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],$$

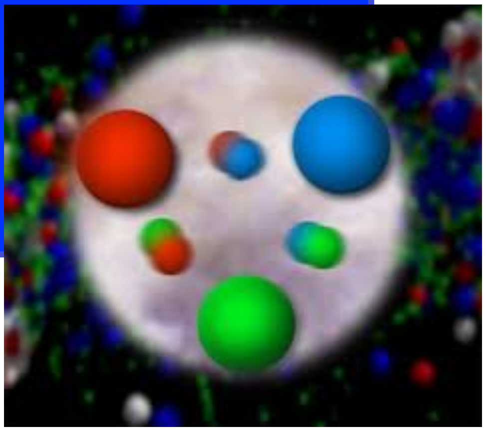
$$g(Q^2) = \frac{1}{(1+\gamma e^{i\theta}Q^2)^2}$$

$$\alpha(Q^2) = \frac{2}{\pi}\sqrt{\frac{Q^2+4\mu_\pi^2}{Q^2}}\,ln\left[\frac{\sqrt{(Q^2+4\mu_\pi^2)}+\sqrt{Q^2}}{2\mu_\pi}\right]$$

$$2F_i^p = F_i^s + F_i^v,$$

$$2F_i^n = F_i^s - F_i^v.$$

The nucleon



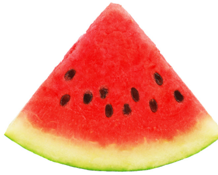
3 valence quarks and
a neutral sea of $q\bar{q}$ pairs

antisymmetric state of
colored quarks

$$|p> \sim \epsilon_{ijk}|u^i u^j d^k>$$
$$|n> \sim \epsilon_{ijk}|u^i d^j d^k>$$

New assumption :

..does not hold in the spatial center of the nucleon: the center of the nucleon *is electrically neutral,* due to strong gluonic field



E.A. Kuraev, E. T-G, A. Dbeyssi, Phys.Lett. B712 (2012) 240

Definition of TL-SL Form Factors

$$F(q) = \int d^4x e^{iqx} F(x).$$

$$F_{SL,Breit}(q) = \int d^3\vec{x}\, e^{-i\vec{q}\cdot\vec{x}} \int dt F(t,\vec{x}) \equiv \int d^3\vec{x}\, e^{-i\vec{q}\cdot\vec{x}} \rho(|\vec{x}|),$$
$$\rho(|\vec{x}|) = \int dt F(t,\vec{x}).$$

$$F_{TL,CM}(q) = \int dt\, e^{iqt} \int d^3\vec{x} F(t,\vec{x}) \equiv \int dt\, e^{iqt} R(t),$$
$$R(t) = \int d^3\vec{x} F(t,\vec{x}).$$

$\rho(\vec{x})$ and $R(t)$, represent projections of the same distribution in orthogonal subspaces

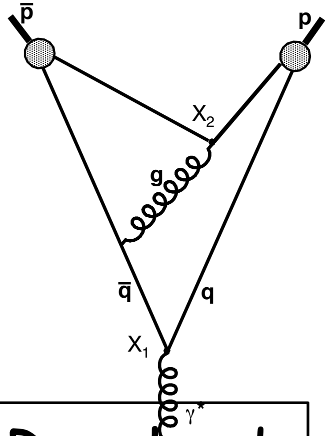
Charge: photon-charge coupling

$\rho(\vec{x})$ Fourier transform of a stationary charge and current distribution

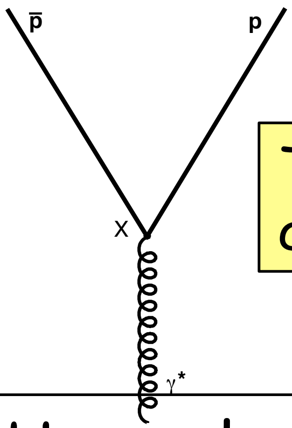
$R(t)$ Amplitude for creating charge-antICharge pairs at time *t.*

Charge distribution => distribution in time of

$$\gamma^* \to charge - anticharge \text{ vertexes}$$



Resolved



Unresolved

The simplest picture:
qq pair + compact di-quark

representation

Conclusion - Discussion

- Deep understanding of polarization phenomena born in Kharkov

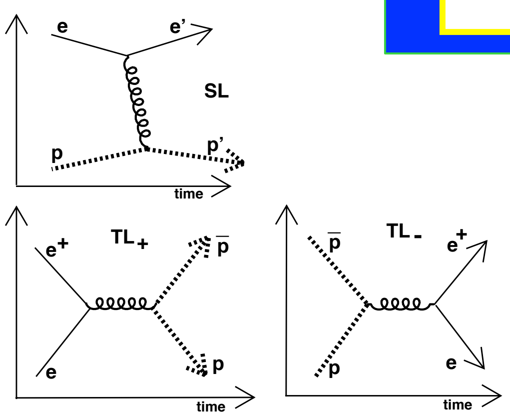
Jefferson Lab

In the 70's the theory was well advanced on experiment

VEPP-3 Novosibirsk

- Unified models in SL and TL: new understanding of the nucleon structure?

$$F(q^2) = \int_{\mathcal{D}} d^4x e^{iq_\mu x^\mu} \rho(x), \; q_\mu x^\mu = q_0 t - \vec{q} \cdot \vec{x}$$



$\rho(x) = \rho(\vec{x}, t)$ space-time distribution of the electric charge in the space-time volume

SL photon 'sees' a charge density

TL photon 'sees' the particle creation from vacuum

(1) Equivalent forms J_μ

$$J_\mu = \left[F_1(q^2) + F_2(q^2)\right]\gamma_\mu - \frac{(-p_1+p_2)_\mu}{2M_p}F_2(q^2),$$

$$J_\mu \to \varphi_2 \tilde{J}_\mu \varphi_1$$

$$\begin{aligned}
J_\mu &= (F_1+F_2)\left(\chi_2,\ -\frac{\vec\sigma\cdot(-\vec p)}{E+m}\chi_2\right)\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}0 & \vec\sigma\\ -\vec\sigma & 0\end{pmatrix}\begin{pmatrix}\frac{\vec\sigma\cdot\vec p}{E+m}\chi_1\\ \chi_1\end{pmatrix}\\
&+\left(\chi_2,\ \frac{\vec\sigma\cdot(-\vec p)}{E_1+m}\chi_2\right)\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\frac{2\vec p}{2m}F_2\begin{pmatrix}\frac{\vec\sigma\cdot\vec p}{E_1+m}\chi_1\\ \chi_1\end{pmatrix}\\
&= (F_1+F_2)\left(\chi_2,\ \frac{\vec\sigma\cdot\vec p}{E+m}\chi_2\right)\begin{pmatrix}\vec\sigma\chi_1\\ -\vec\sigma\frac{\vec\sigma\cdot\vec p}{E+m}\chi_1\end{pmatrix} + \frac{\vec p}{m}F_2\chi_2\left(\frac{\vec\sigma\cdot\vec p}{E+m}+\frac{\vec\sigma\cdot\vec p}{E+m}\right)\chi_1\\
&= (F_1+F_2)\left[\vec\sigma - \frac{1}{(E+m)^2}\vec\sigma\cdot\vec p\,\vec\sigma\,\vec\sigma\cdot\vec p\right] + \frac{2\vec p}{m}F_2\chi_2\frac{\vec\sigma\cdot\vec p}{E+m}\chi_1
\end{aligned}$$

$(E+M_p)$ Global factor

(2) Equivalent forms J_μ

Properties of Pauli σ matrices:

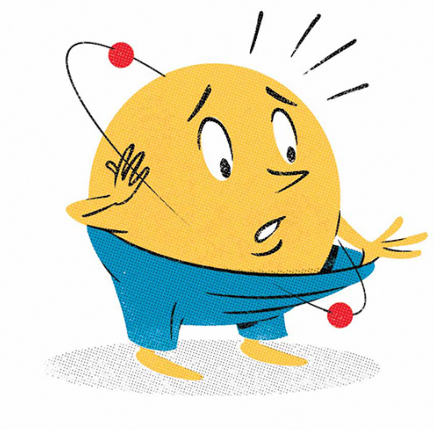
$$(2\hat{\vec{p}} - \vec{\sigma}\vec{\sigma}\cdot\hat{\vec{p}})\vec{\sigma}\cdot\hat{\vec{p}} = 2\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}} - \vec{\sigma}$$

$$\begin{aligned}
J_\mu &= (F_1+F_2)\left(\vec{\sigma} - 2\frac{E-m}{E+m}\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}} + \frac{E-m}{E+m}\vec{\sigma}\right) + \frac{2(E-m)}{m}F_2\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}} \\
&= (F_1+F_2)\left(\vec{\sigma} + \frac{E-m}{E+m}\vec{\sigma}\right) - 2\left[(F_1+F_2)\frac{E-m}{E+m} - \frac{E-m}{m}F_2\right]\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}} \\
&= \frac{2E}{E+m}(F_1+F_2)\vec{\sigma} - \frac{2(E-m)}{m(E+m)}[mF_1+mF_2-EF_2-mF_2]\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}} \\
&= \frac{2E}{E+m}(F_1+F_2)\vec{\sigma} - 2E(F_1+F_2)\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}} + 2m\left(F_1+\frac{E^2}{m^2}F_2\right) \\
&= \frac{2E}{E+m}\left[G_M(\vec{\sigma}-\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}})\right] + 2mG_E\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}}
\end{aligned}$$

Finally (reminding the global factor $(E+m)$) :

$$J = 2E\left[G_M\left(\vec{\sigma}-\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}}\right) + \frac{1}{\sqrt{\tau}}G_E\hat{\vec{p}}\vec{\sigma}\cdot\hat{\vec{p}}\right]$$

The proton radius



Root mean square radius

$$F(q) = \frac{\int_\Omega d^3\vec{x} e^{i\vec{q}\cdot\vec{x}} \rho(\vec{x})}{\int_\Omega d^3\vec{x} \rho(\vec{x})}.$$

$$< r_c^2 >= \frac{\int_0^\infty x^4 \rho(x) dx}{\int_0^\infty x^2 \rho(x) dx}.$$

Expanding in Taylor series:

$$F(q) \sim 1 - \frac{1}{6} q^2 < r_c^2 > + O(q^2),$$

$$\langle r_{E/M}^2 \rangle = - \frac{6\hbar^2}{G_{E/M}(0)} \frac{dG_{E/M}(Q^2)}{dQ^2} \Big|_{Q^2=0}.$$

RMS is *the limit of the* ***form factor derivative*** *for* $Q^2 \to 0$

PRL 105, 242001 (2010) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2010

High-Precision Determination of the Electric and Magnetic Form Factors of the Proton

J. C. Bernauer,[1,*] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1] M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[6,3] Th. Walcher,[1] and M. Weinriefer[1]

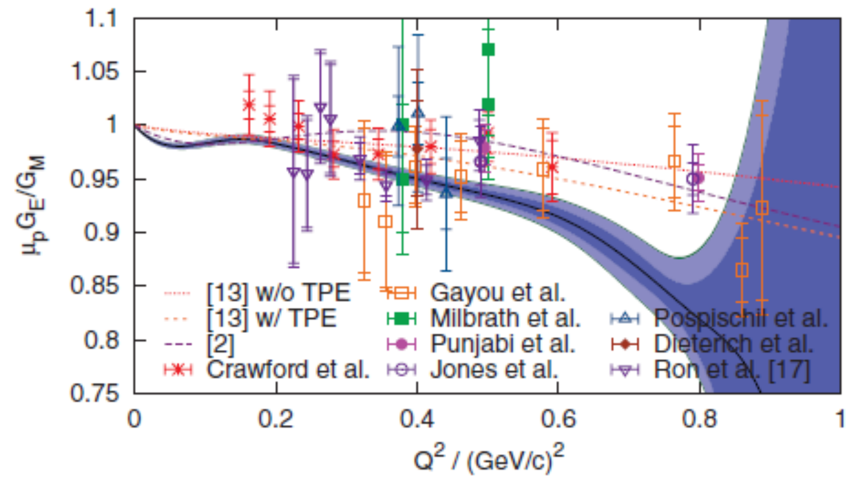
Mainz, A1 collaboration (1400 points)

$Q^2 > 0.004$ GeV^2

- Radiative corrections
- Two photon exchange
- Coulomb corrections

$$\langle r_E^2 \rangle^{1/2} = 0.879(5)_{\rm stat}(4)_{\rm syst}(2)_{\rm model}(4)_{\rm group}\ \text{fm},$$

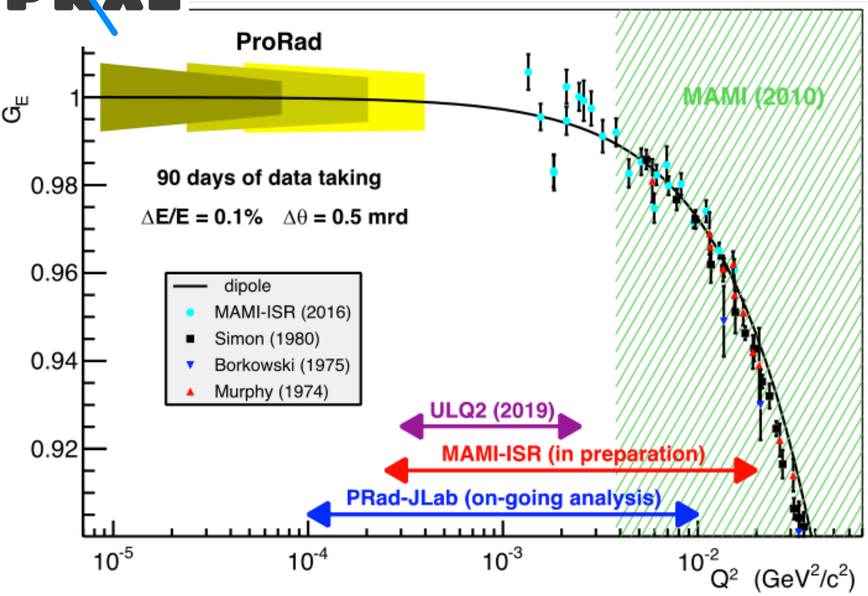
$$\langle r_M^2 \rangle^{1/2} = 0.777(13)_{\rm stat}(9)_{\rm syst}(5)_{\rm model}(2)_{\rm group}\ \text{fm}.$$

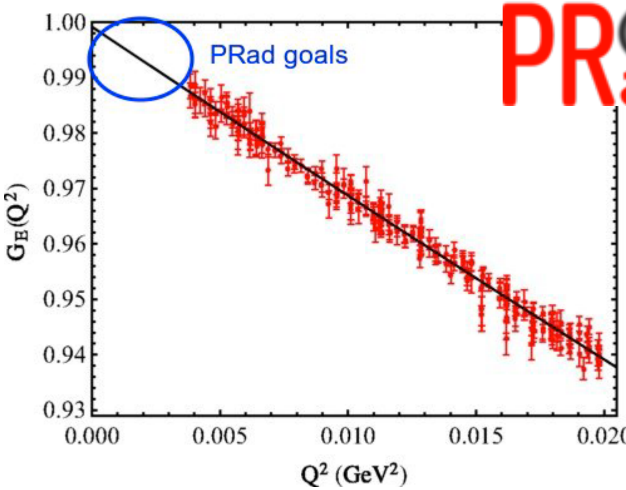


What about extrapolation to $Q^2 \rightarrow 0$?

G.I. Gakh, A. Dbeyssi, E.T-G, D. Marchand, V.V. Bytev, Phys.Part.Nucl.Lett. 10 (2013) 393, Phys.Rev. C84 (2011) 015212

Planned ep experiments



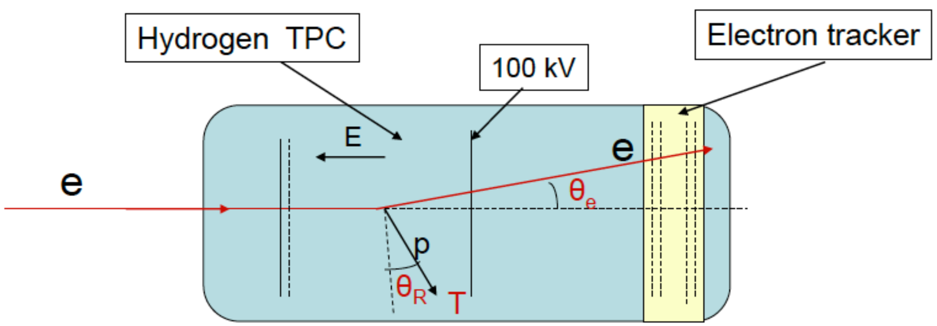


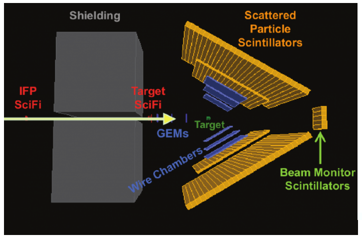
Systematics at sub%
Abs Norm by Moller

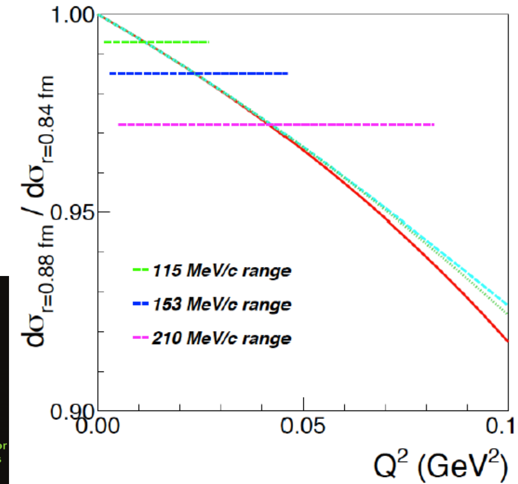
MUSE@PSI: muon beam

PNPI@MAMI: e and p detection

Combined recoiled proton@forward tracker detector





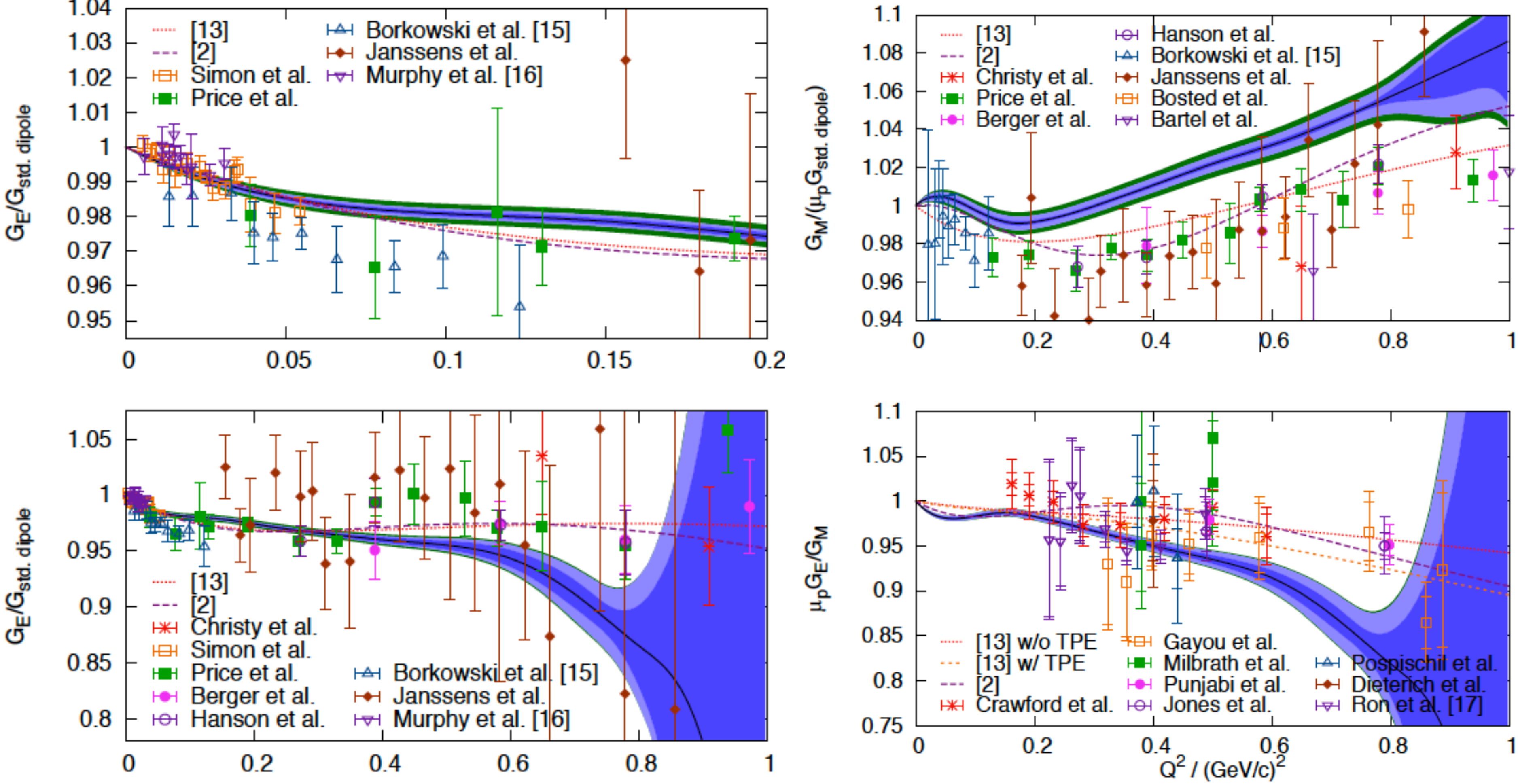


Mainz ep elastic scattering

GEp

$$\left\langle r^2_{E/M} \right\rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \frac{\mathrm{d}G_{E/M}(Q^2)}{\mathrm{d}Q^2}\Bigg|_{Q^2=0}$$

GMp



Mainz ep elastic scattering

$$\left\langle r^2_{E/M} \right\rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \frac{\mathrm{d}G_{E/M}(Q^2)}{\mathrm{d}Q^2}\Bigg|_{Q^2=0}$$

1) Rosenbluth extraction

2) Direct extraction
(assuming a function for FFs)

Spline

$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.875(5)_{\mathrm{stat.}}(4)_{\mathrm{syst.}}(2)_{\mathrm{model}}\,\mathrm{fm},$$
$$\langle r_M^2 \rangle^{\frac{1}{2}} = 0.775(12)_{\mathrm{stat.}}(9)_{\mathrm{syst.}}(4)_{\mathrm{model}}\,\mathrm{fm}$$

Polynomial

$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.883(5)_{\mathrm{stat.}}(5)_{\mathrm{syst.}}(3)_{\mathrm{model}}\,\mathrm{fm},$$
$$\langle r_M^2 \rangle^{\frac{1}{2}} = 0.778(^{+14}_{-15})_{\mathrm{stat.}}(10)_{\mathrm{syst.}}(6)_{\mathrm{model}}\,\mathrm{fm}.$$

ATOMIC PHYSICS

International Nuclear Physics Conference 2010 (INPC2010) IOP Publishing
Journal of Physics: Conference Series **312** (2011) 032002 doi:10.1088/1742-6596/312/3/032002

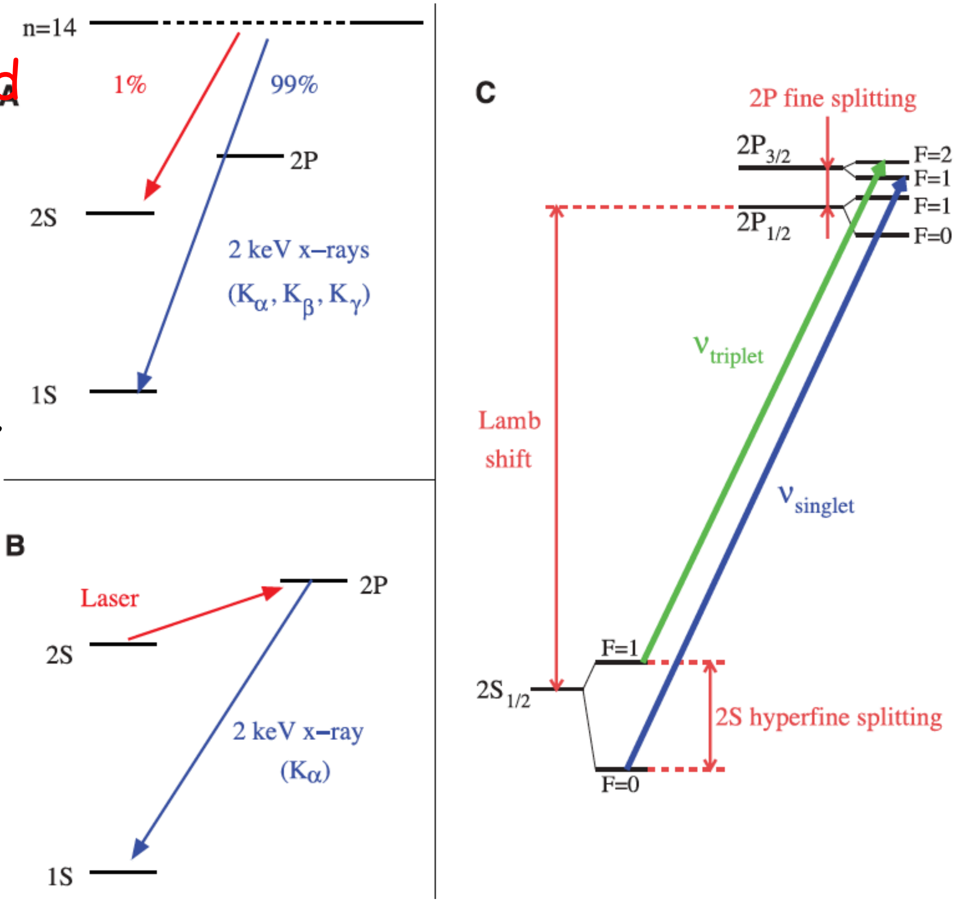
The proton radius puzzle

A Antognini[1,2], F D Amaro[3], F Biraben[4], J M R Cardoso[3], D S Covita[5], A Dax[6], S Dhawan[6], L M P Fernandes[3], A Giesen[7], T Graf[8], T W Hänsch[1,9], P Indelicato[4], L Julien[4], C-Y Kao[10], P Knowles[11], F Kottmann[2], E-O Le Bigot[4], Y-W Liu[10], J A M Lopes[3], L Ludhova[11], C M B Monteiro[3], F Mulhauser[11], T Nebel[1], F Nez[4], P Rabinowitz[12], J M F dos Santos[3], L A Schaller[11], K Schuhmann[7], C Schwob[4], D Taqqu[13], J F C A Veloso[5] and R Pohl[1]

Abstract. By means of pulsed laser spectroscopy applied to muonic hydrogen ($\mu^- p$) we have measured the $2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$ transition frequency to be 49881.88(76) GHz [1]. By comparing this measurement with its theoretical prediction [2, 3, 4, 5, 6, 7] based on bound-state QED we have determined a proton radius value of $r_p = 0.84184(67)$ fm. This new value differs by 5.0 standard deviations from the CODATA value of 0.8768(69) fm [8], and 3 standard deviation from the e-p scattering results of 0.897(18) fm [9]. The observed discrepancy may arise from a computational mistake of the energy levels in μp or H, or a fundamental problem in bound-state QED, an unknown effect related to the proton or the muon, or an experimental error.

Lamb shift and hyperfine splitting (1)

Negative μ beams at PSI are stopped in H_2 gas target at 1 hPa and 20°C



A) Formation of *μp* atoms in highly excited states. 1% populates the 2S state (τ=1 μs).

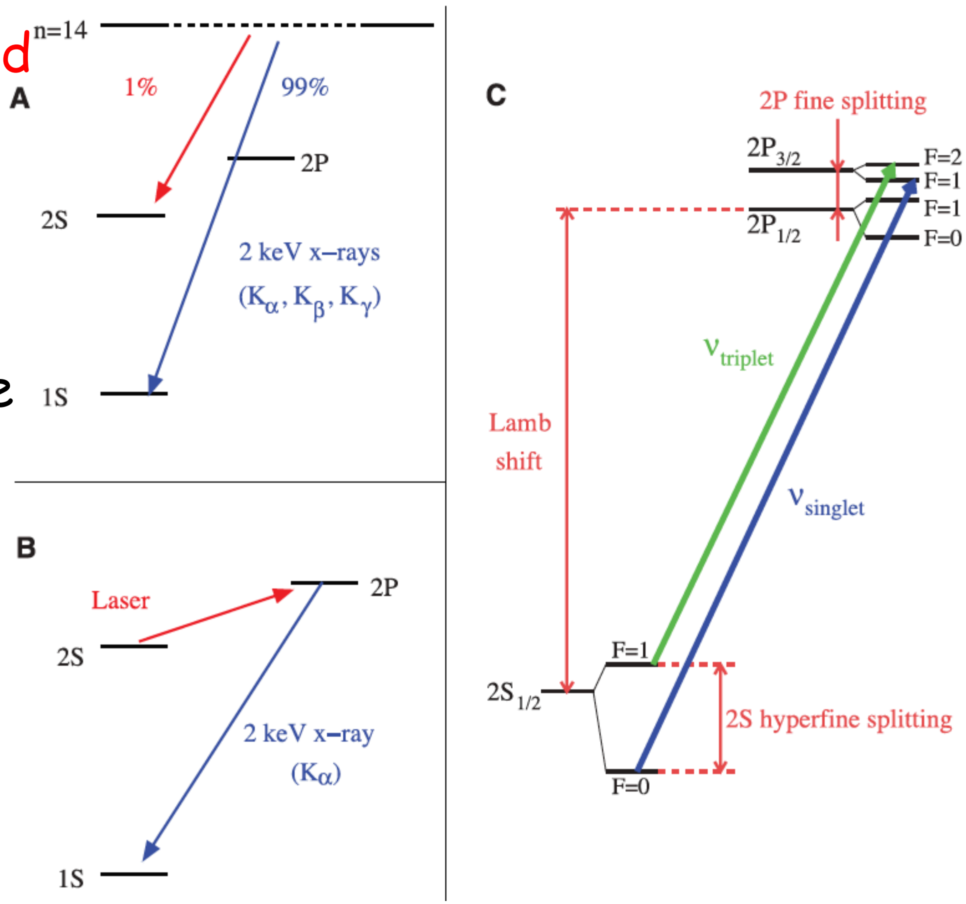
B) Laser excitation of 2S-2P transition

C) 2S and 2P energy levels.
ν_s and ν_p: measured transitions

Proton radius
Rydberg constant

Lamb shift and hyperfine splitting (1)

Negative μ beams at PSI are stopped in H_2 gas target at 1 hPa and 20°C



A) Formation of *μp* atoms in highly excited states. 1% populates the 2S state (τ=1 μs).

B) Laser excitation of 2S-2P transition

C) 2S and 2P energy levels.

ν_s and ν_p: measured transitions

An *e* or μ in S state has some probability to be inside the proton.
The electric field (charge distribution) is modified by the proton size.
The ν_s and ν_p transitions are affected by the proton size (few %)

Lamb shift and hyperfine splitting

$$\Delta E_{\text{finite size}} = \frac{2\pi Z\alpha}{3} r_E^2 |\Psi(0)|^2$$

Atomic wave function at the origin

$| \Psi(0)|^2 \approx m_r^3$, $m_r(\mu p \text{ system}) \cong 186\ m_e$

H radius : 60000 x p radius
μH Bohr radius is ≈ 200 times smaller: larger sensitivity!

$$\frac{1}{4} h\nu_s + \frac{3}{4} h\nu_t = \Delta E_L + 8.8123(2)\text{meV}$$

$$h\nu_s - h\nu_t = \Delta E_{HFS} - 3.2480(2)\text{meV}$$

$$\Delta E_L^{exp} = 202.3706(23)\ \text{meV}$$

$$\Delta E_{HFS}^{exp} = 22.8089(51)\ \text{meV}$$

$$\Delta E_L^{th} = 206.0336(15) - 5.2275(10) r_E^2 + \Delta E_{TPE}$$

$$\Delta E_{TPE} = 0.0332(20)\ \text{meV}$$

$$r_E = 0.84087(26)^{exp}(29)^{th}\ \text{fm} = 0.84087(39)\ \text{fm}$$

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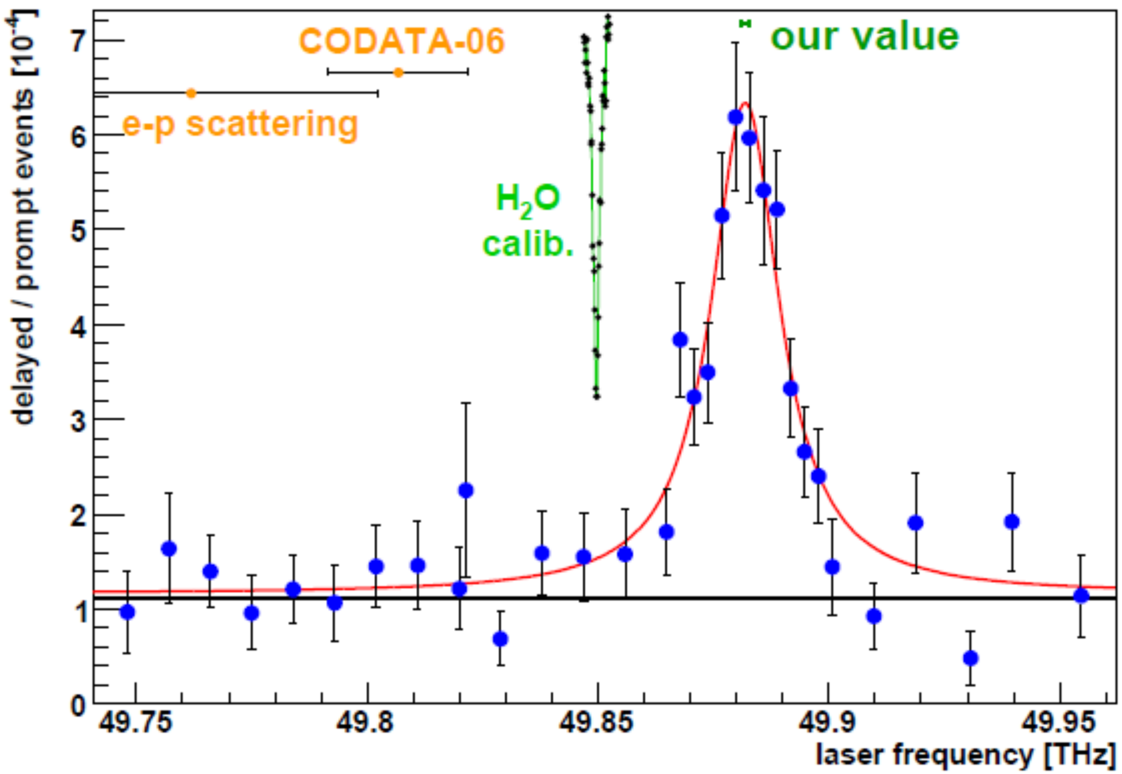


Abstract. B … rogen ($\mu^- p$) we have
measured the … Hz [1]. By comparing
this measurem… on bound-state QED
we have detern… w value differs by 5.0
standard devia… 3 standard deviation
from the e-p sc… ncy may arise from a
computational … oblem in bound-state
QED, an unkn… nental error.

PHYSICS

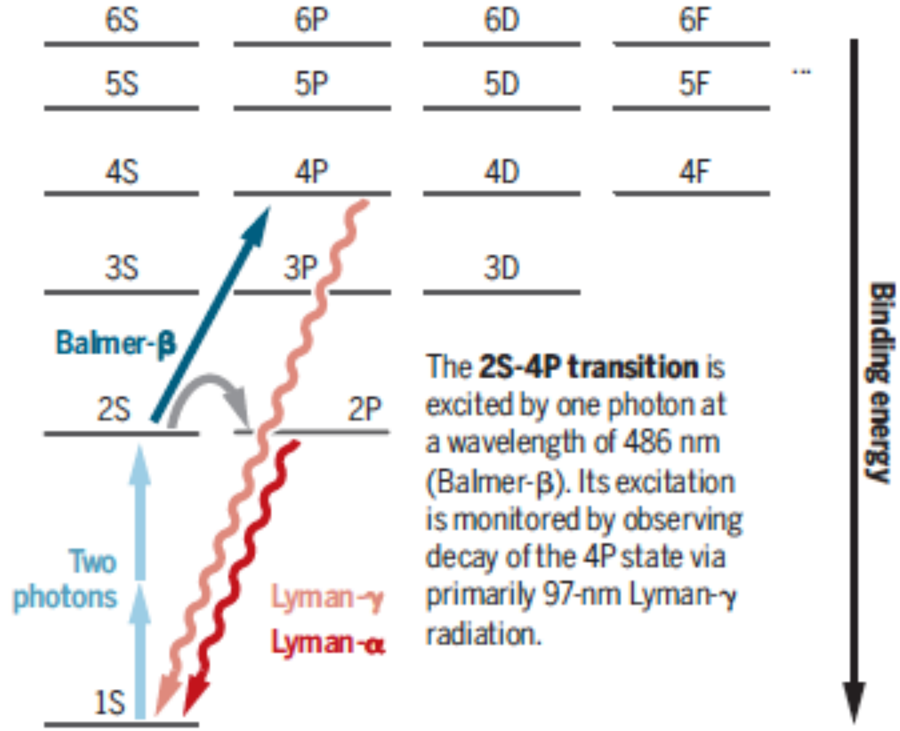
The proton radius revisited

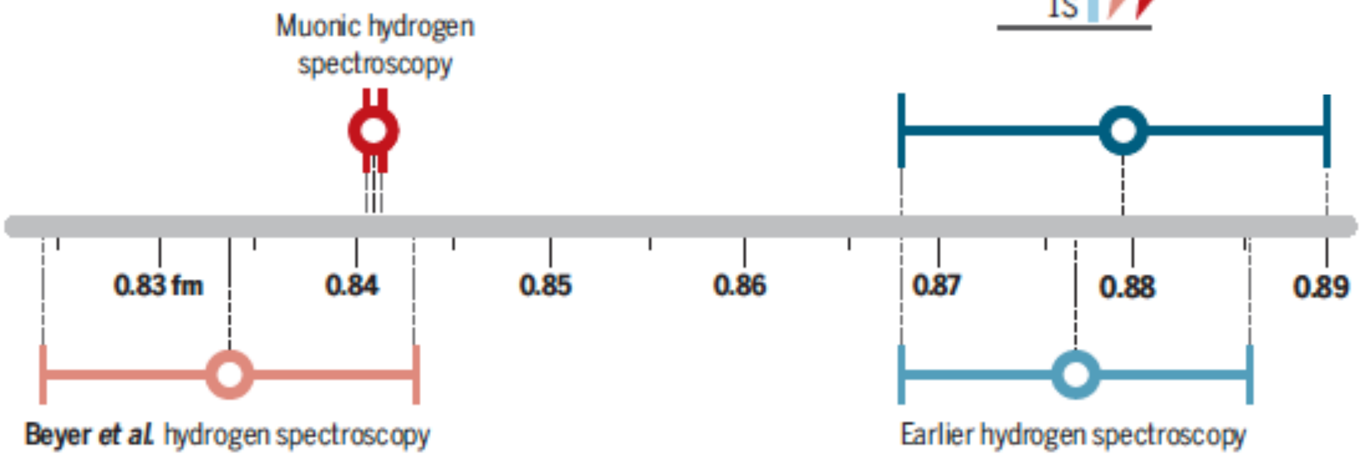
Hydrogen spectroscopy brings a surprise in the search for a solution to a long-standing puzzle

Science 06 Oct 2017: Vol. 358, 6359, pp. 39
DOI: 10.1126/science.aao3969

New !

R_p=0.8335(95) fm





new Rydberg constant, deuterium…

The Proton Size (Radius)