Recent results on Nucleon ElectroMagnetic Form Factors @ BESIII

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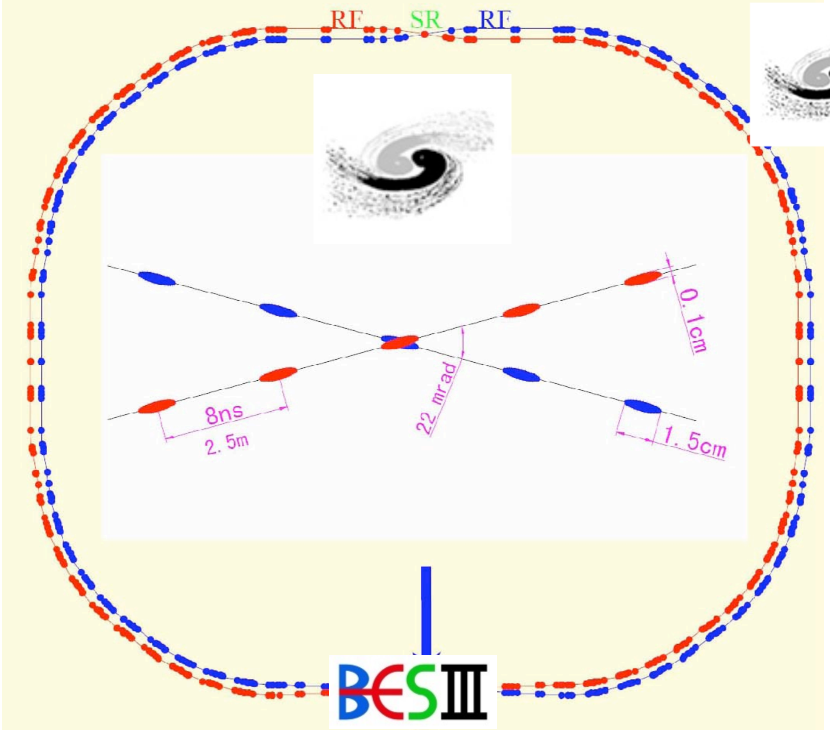
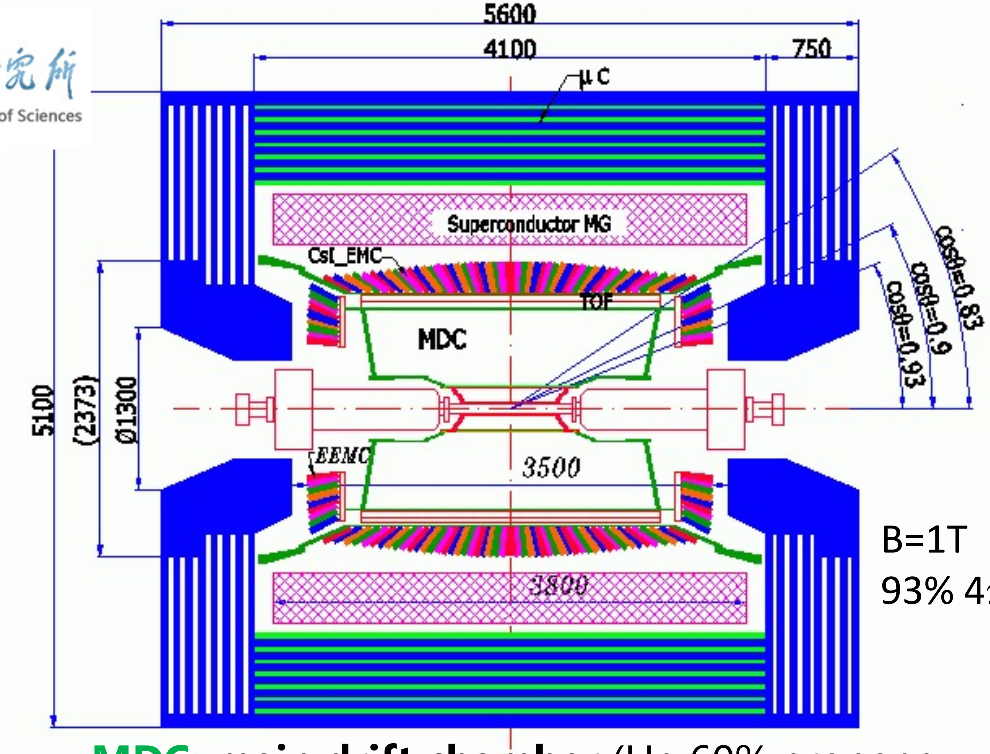
Outline

- The BESIII Experiment & Data Set
- Brief introduction to Electromagnetic Form Factors of the Nucleon
- Status: Form Factors of the Proton @BESIII
- Status: Form Factors of the Neutron @BESIII
- Summary

BEPCII & BESIII



Institute of High Energy Physics Chinese Academy of Sciences



B=1T
93% 4π acceptance

Double ring electron-positron collider
Beam energy tunable (RECORD ECM 4.946 GeV in feb 2021)
Single beam current 0.91 A
Crossing angle: ±11 mrad
Reached design luminosity @$\Psi(3770)=10^{33}$ cm^{-2} s^{-1}
BEMS by Laser compton back
Scattering $\Delta E/E \approx 5 * 10^{-5}$
Energy spread : $5.16 \cdot 10^{-4}$

About 500 members , 78 institution, 16 countries

MDC: main drift chamber (He 60%,propane 40%)) σ(p)/p < 0.5 % @1 GeV, σ(xy) =130 μm, 6% dE/dx

TOF: time of flight (2 layers plastic scintillator): σ~ 68 ps (barrel)): (MRPC) σ~ 65ps @0.8 GeV(end-caps)

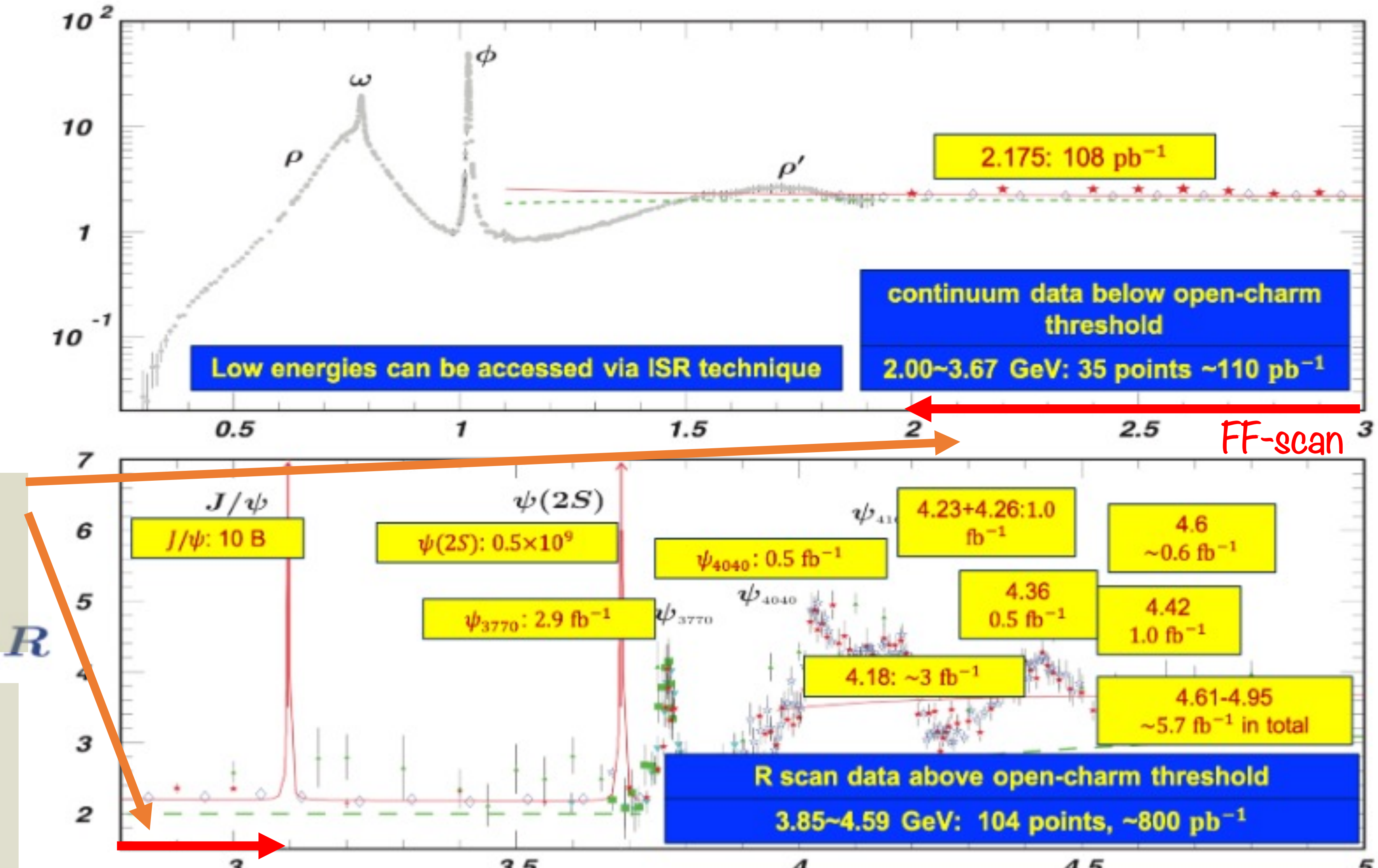
EMC(neutral &charged): Cs I(Tl), barrel+2 end caps: σ(E)/E < 2.5 %, σ(x) < 6mm for 1 GeV e-, Position resolution: δz ~ 0.6/ E

MUC: time of flight (RPC): σ(xy) < 2 cm

Important upgrades in the next future: CGEM

The BESIII Data set

BESIII physics program: Charm physics, light hadrons, charmonium spectroscopy, ..., form factors measurement



World largest data set in $\sqrt{s}$ = 2 - 3.08 GeV (L_{data} ~ 669 pb^{-1}) Nucleon FF-scan method

high statistics samples at and above the peak of the ψ(3770) resonance (L >=7.5fb^{-1}) for ISR measurements (proton FFs)

World largest data sample for J/ψ, ψ(2S) and ψ(3770)

ElectroMagnetic Form Factors

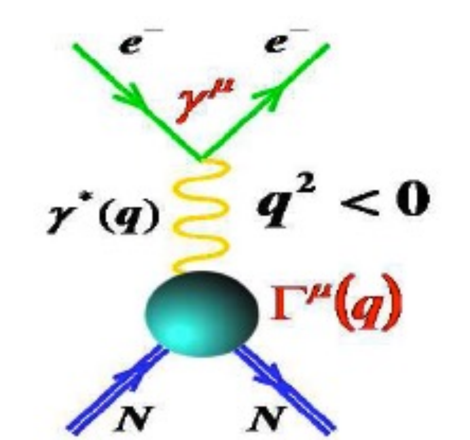
Hadrons are not point-like particles

- Internal structure
- Internal dynamics → $M_{hadron} \neq \sum m_{q\text{-valence}}$

EMFF simplest structure observables
Form Factors (FFs) used to parametrize the structure and internal dynamics:
2 FFs involved for nucleons

test ground for our understanding of the strong interactions

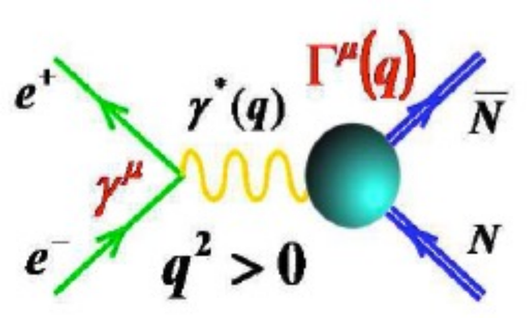
SPACE-LIKE FF
(Real functions)



Electron scattering
$q^2 < 0$

Unphysical region

TIME-LIKE FF
(Complex functions)



Annihilation processes
$q^2 > 0$

0 $4M_N^2$ q^2

Γ_μ Vertex contains the unknown structure, parametrized by F_1 and F_2 (Dirac and Pauli FFs):

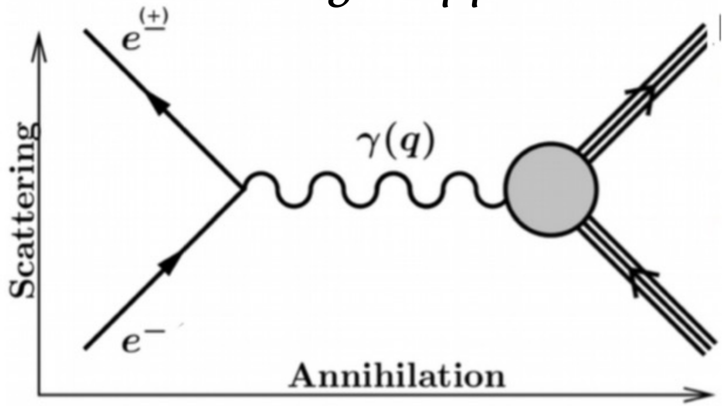
Dirac FF: related to the charge

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

Pauli FF: related to the Magnetization

TL ElectroMagnetic Form Factors

(One photon exchange approx.)



- Sachs parameterization:

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4M_B} F_2(q^2)$$

Electric FF

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$

Magnetic FF

- Differential cross section

$$\left[\frac{d\sigma}{d\Omega_{CM}}\right] = \frac{\alpha^2 \beta^2 C}{4q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta\, |G_E|^2\right]$$

in the CM frame

$$\beta = \sqrt{1-\frac{1}{\tau}},\ \tau = \frac{q^2}{4M^2},\ C = \frac{y}{(1-exp(-y))},\ y = \frac{\alpha\pi}{\beta}$$

C=1 for neutral baryons

From differential cross section → ratio $|G_E|/|G_M|$

- Total cross section:

$$\sigma(q^2) = \frac{2\pi\alpha^2\beta C}{3q^2\tau}\left(2\tau|G_M|^2 + |G_E|^2\right)$$

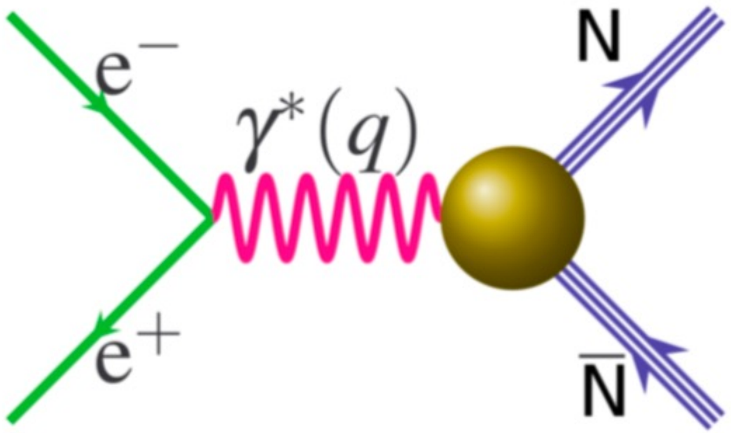
- From the total cross section the effective FF can be measured:

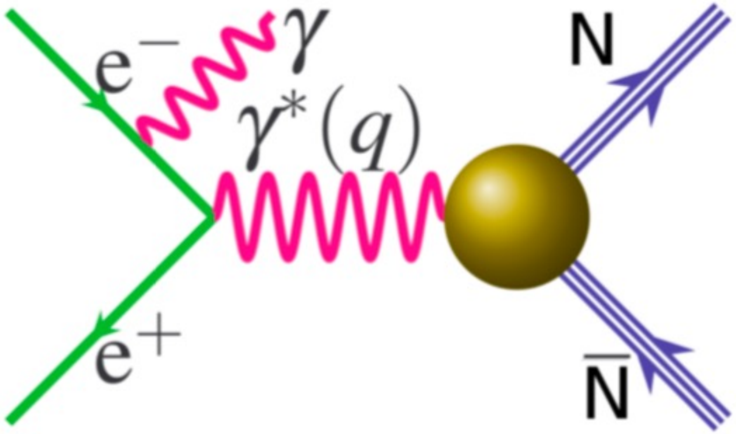
$$|G_{eff}| = \sqrt{\frac{2\tau|G_M|^2 + |G_E|^2}{2\tau + 1}}$$

$$|G_{\text{eff}}(s)| = \sqrt{\frac{\sigma}{\frac{4\pi\alpha^2\beta C}{3s}\left(1+\frac{2m_N^2}{s}\right)}},$$

⇒ equivalent to $|G_M|$ for $|G_E|=|G_M|$ (analyticity of FF implies it at threshold)

Experimental access to EMFF's of the Nucleon in the Time-Like Region





Direct Scan:

Fixed q^2, single data point @ each beam energy
Relatively low integrated luminosity @ each data point

$$\frac{d\sigma^{Born,1\gamma}}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{4M^2}{q^2}\sin^2\theta |G_E|^2\right]$$

ISR:

continuous q^2, from threshold to s
Relatively high integrated luminosity @one beam energy

$$\frac{d^2\sigma^{ISR}}{dx\,d\theta_\gamma} = W(s,x,\theta_\gamma)\sigma^{Born}(q^2)$$

~ 1/400 suppression

$$W^{LO}(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2}\right)$$

$$x = 1 - q^2/s = 2E_\gamma/\sqrt{s}$$

Status of the proton form factors @BESIII

Proton form factors: energy scan method

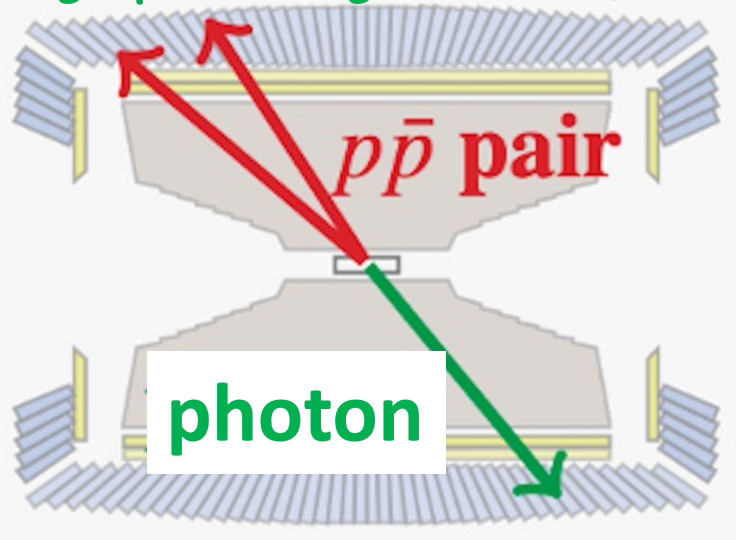
VIA DIRECT SCAN:

FIRST:Phys.Rev.D 91 (2015) 11, 112004
~157 pb^{-1}, $\sqrt{s}$ = 2.232 – 3.671 GeV (12 center-of-mass energies)

LAST:Phys.Rev.Lett. 124 (2020) 4, 042001
~669 pb^{-1}, $\sqrt{s}$ = 2.0 – 3.08 GeV (22 energy points)

ISR METHOD

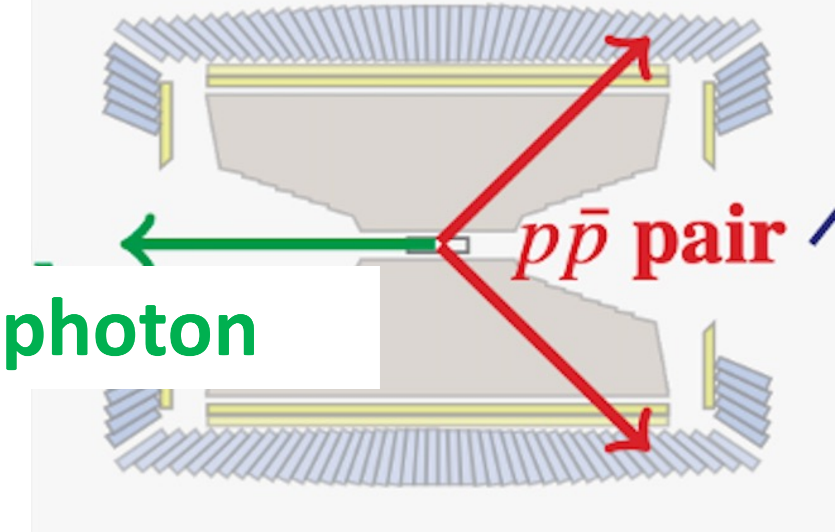
(Large polar Angle LA-ISR)



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

Data sets:
3.773 - 4.600 GeV,
7.5 fb^{-1}

(Small polar Angle SA-ISR)



Only way to access production threshold region
Wide range measurements
Measurement of proton helicity angle θ_p in the full $M_{p\bar{p}}$ range

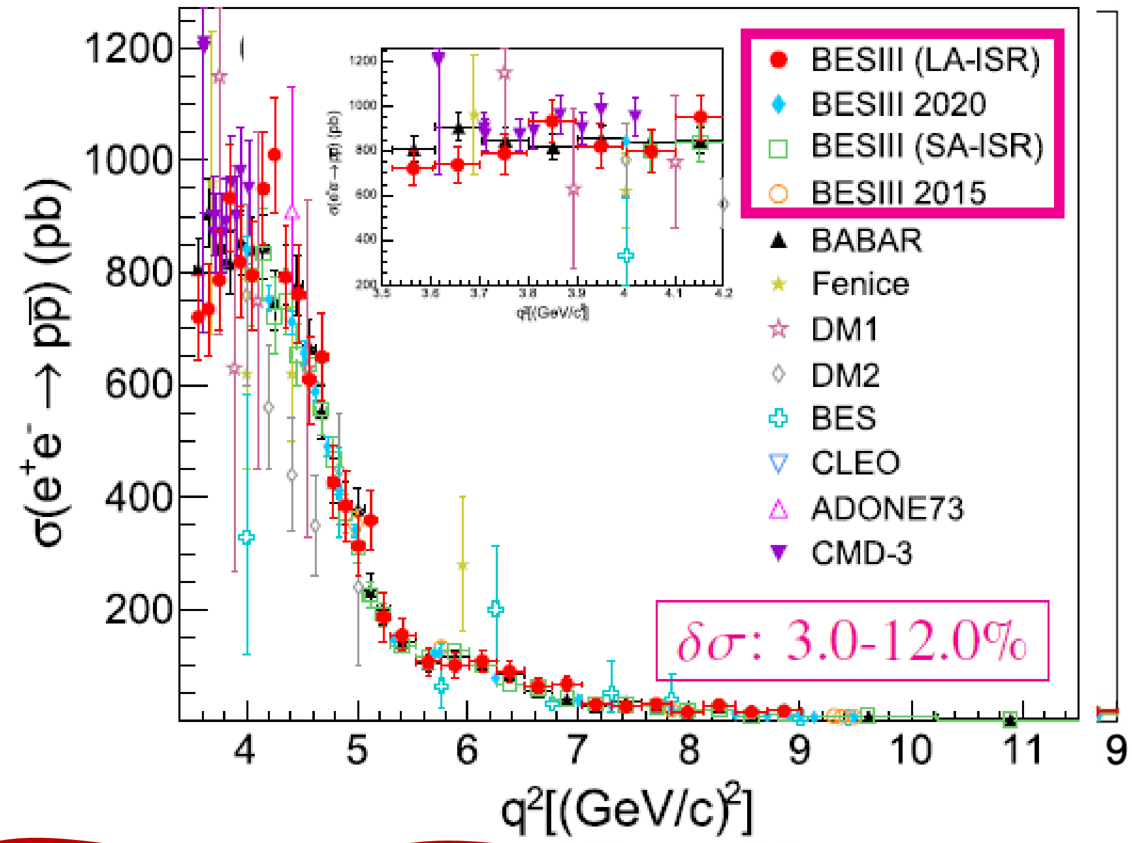
Production threshold region not accessible (limited detector acceptance), but larger statistics

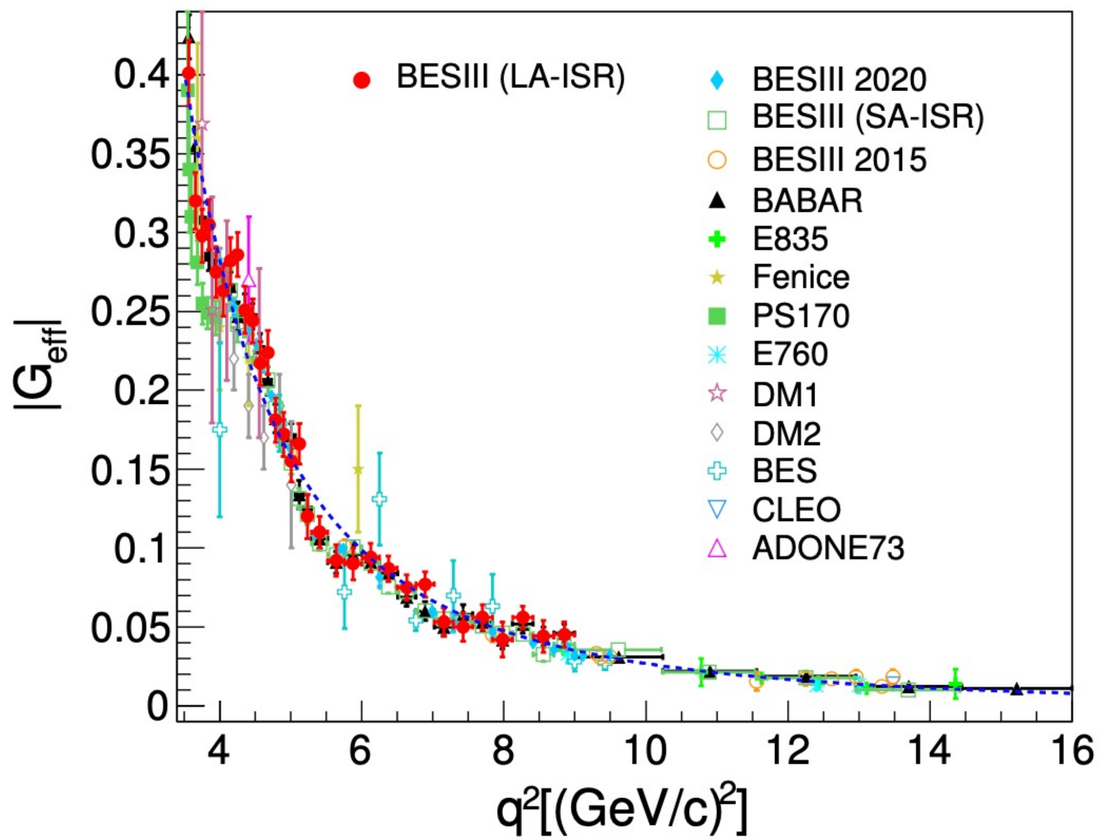
Phys.Lett.B 817 (2021) 136328
two oppositely charged tracks identified as (anti-)protons and one high energetic photon (TAGGED photon)candidate are selected(-> 4C kinematic fit to suppress bkg
Additional veto to successful 5C kinematic fit with one additional photon to suppress dominant $e^+e^- \to p\bar{p}\pi^0$

Phys. Rev. D 99 (9) (2019) 092002
two oppositely charged tracks, which have been identified as (anti)protons
→missing momentum with small polar angle (undetected photon).
Large invariant mass range from 2 to 3.8 GeV/c². Angular analysis in 3 bins.

Total cross section and Effective form factor (ALL)

[Phys.Lett.B 817 (2021) 136328](#)





Fair agreement with the previous ones in wide energy range from 2.0 – 3.08 GeV in scan (to 3.8 GeV for SA-ISR). . In scan Method most accurate measurement of cross section.

Effective form factor (G_{EFF}) is extracted with uncertainty ~ 1.7-11.8%

Modified dipole function well describes the data Phys. Lett. B 504, 291 (2001)

Oscillating behaviour

- Periodic behavior in F_p observed by BaBar experiment, confirmed by BESIII experiment
- Oscillating behaviour observed in reduced form factor F(p), as function of relative momentum of p and antiproton

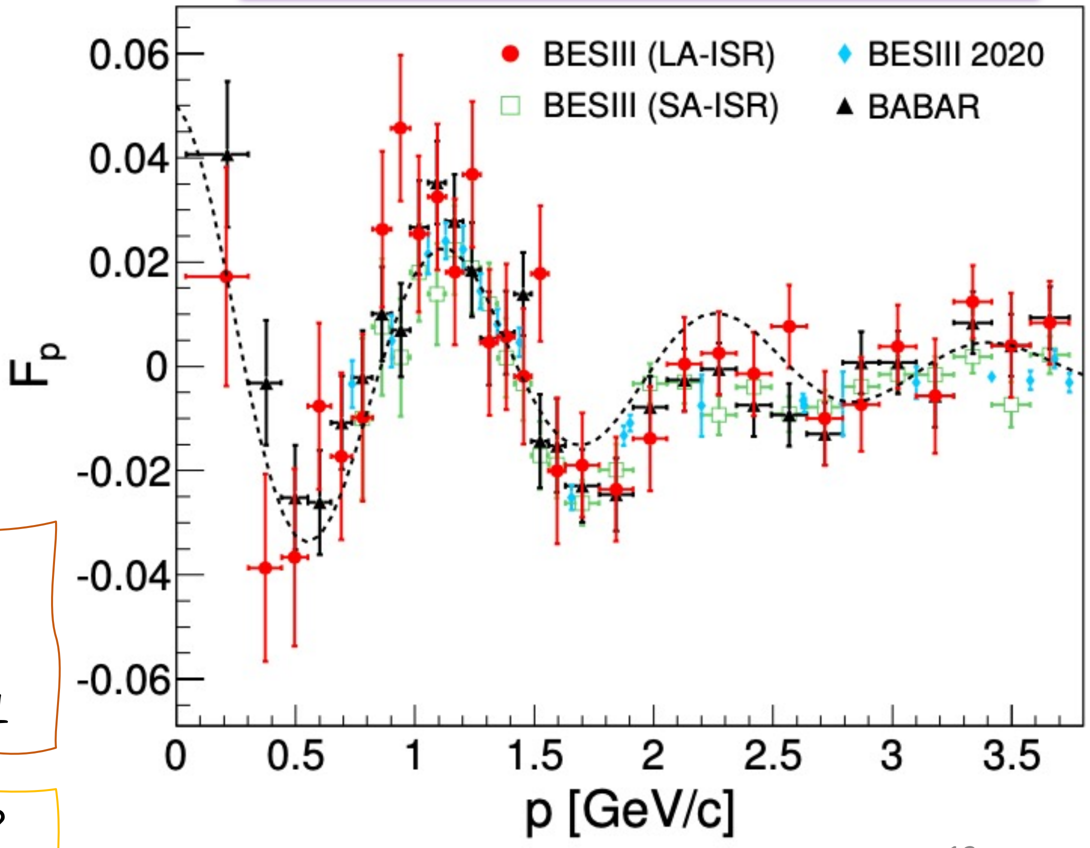
$$F_p = |G| - G_D;$$

Modified dopole function, that reproduce eff FF behaviour

$$G_D(s) = \frac{\mathcal{A}}{(1+\frac{s}{m_a^2})[1-\frac{s}{0.71(\mathrm{GeV}/c)^2}]^2},$$

Phys. Lett. B 504, 291 (2001)

$$F_p = b_0^{osc} e^{-b_1^{osc} p} \cos(b_2^{osc} p + b_3^{osc}),$$



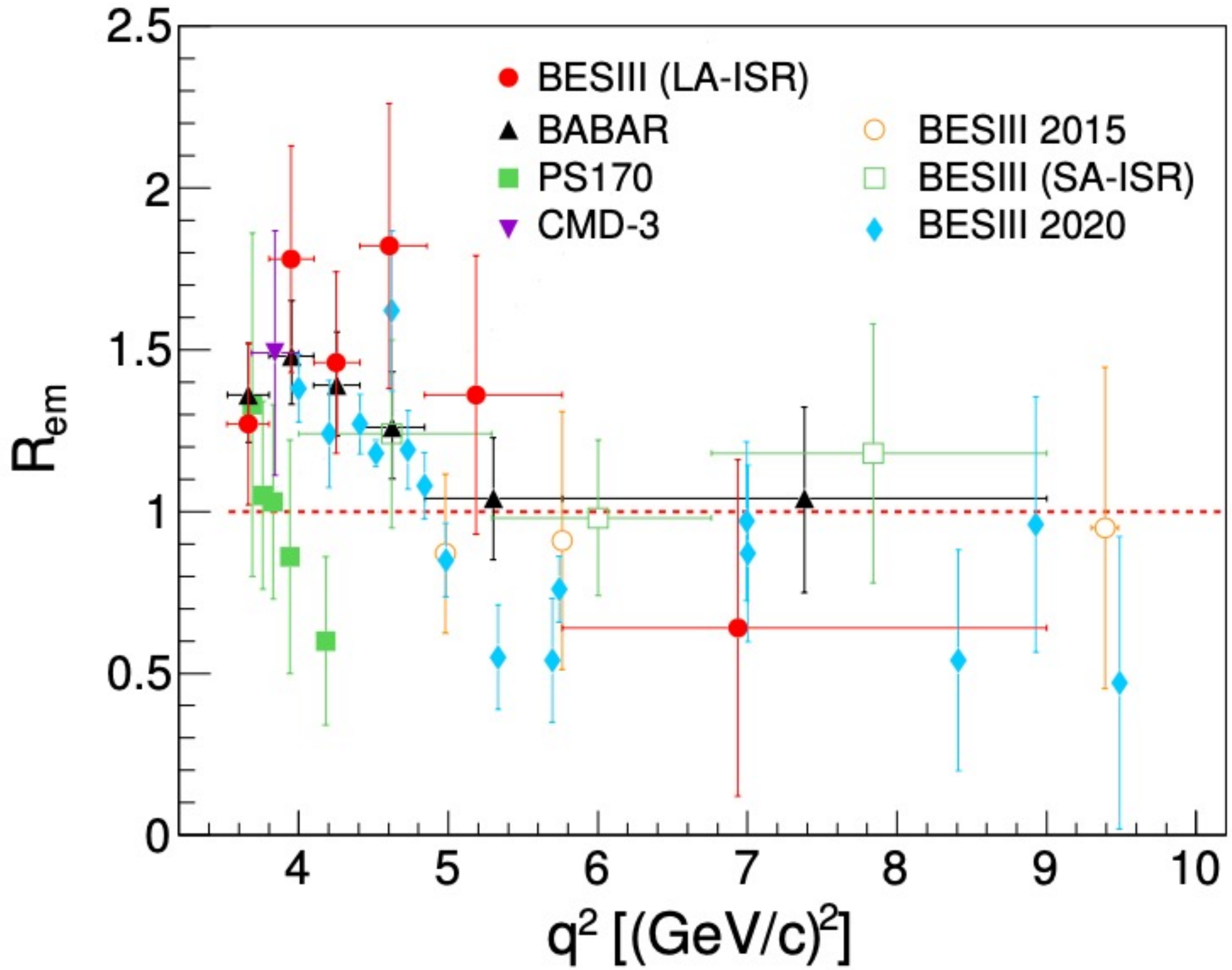
More complex dynamics. WHY?

Interference effects in final state re-scattering at moderate kinetic energies and separation around 1 fm?
Phys.Rev.C 103 (2021) 3, 035203, PRL 114 (2015) 232301

Resonant structures in data (i.e. ϕ(1020), Δ(1232), ...)?
Phys.Rev.D 92 (2015) 3, 034018

Summary for R_{em} measurements (ALL)

R_{em} helps to compare the TL and SL regions



In the TL region, we bring new information with comparable precision as in the scattering region towards unified view of the scattering and annihilation regions

$|G_E|/|G_M|$ ratio from the study of $\cos\theta_p$ distribution, with high accuracy

pQCD prediction (asymptotic)

Before:
$|R_{em}|$ inconsistentency between BaBar and PS170(<2.1 GeV)

Babar confirmed

Nucleons'FSI as explanation of the steep deviation from 1

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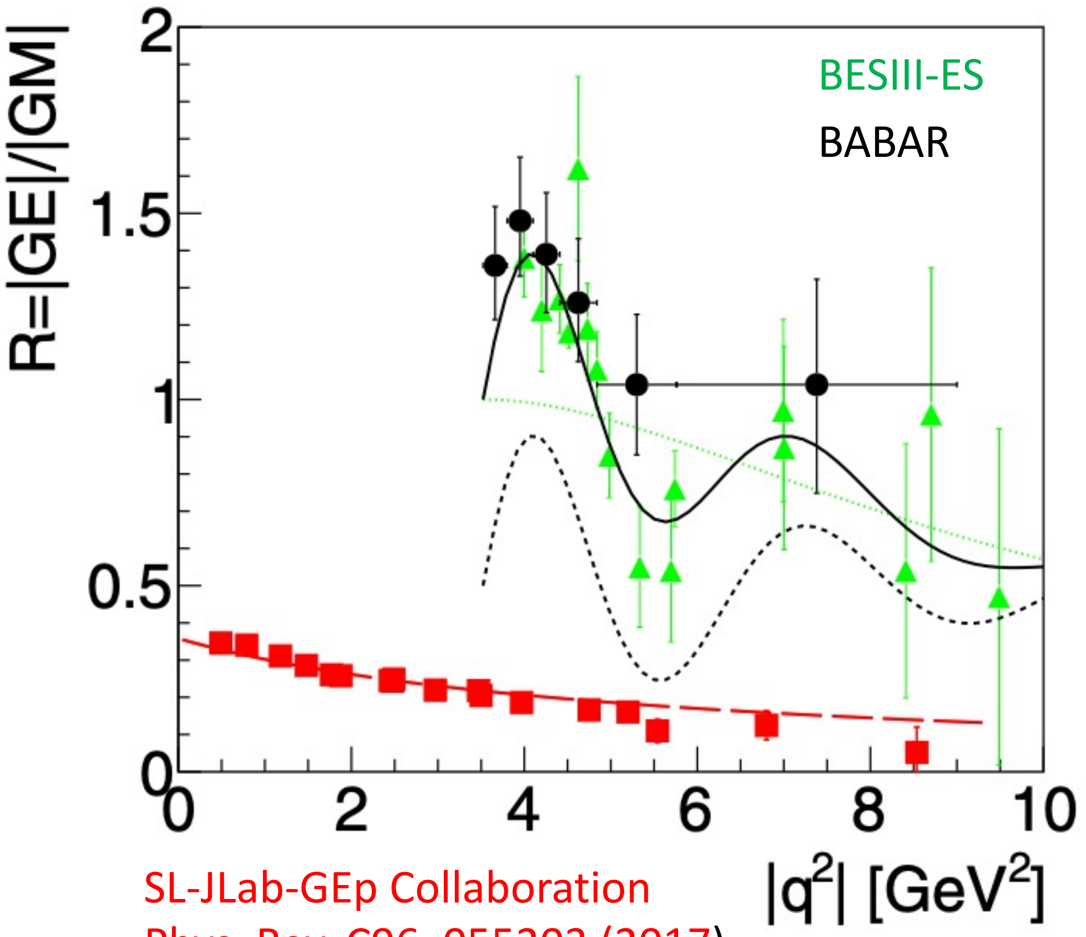

SL-JLab-GEp Collaboration
Phys. Rev. C96, 055203 (2017)

Tomasi-Gustafson, Bianconi, Pacetti
Phys.Rev.C 103 (2021) 3, 035203

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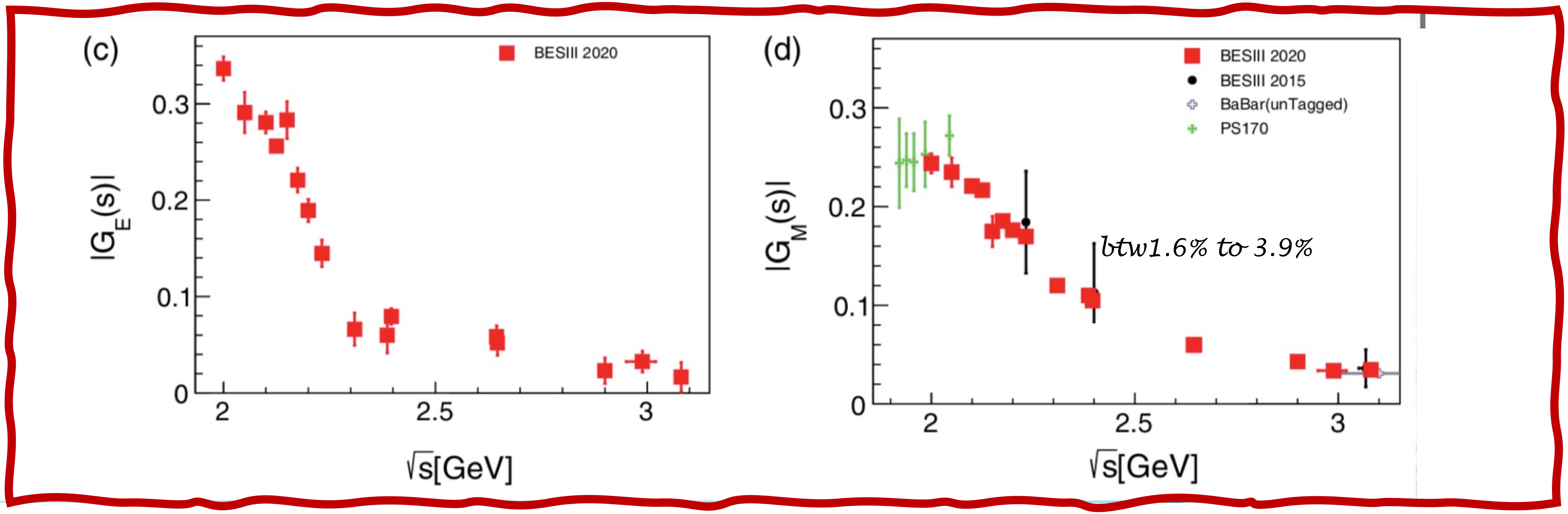
Proton form factors: scan method

$$\frac{dN}{\epsilon(1+\delta)\times d\cos\theta_p} = \frac{\mathcal{L}\hbar c\pi\alpha^2\beta C}{2s}|G_M|^2\left[\left(1+\cos^2\theta_p\right) + \frac{4m_p^2}{s}\left|\frac{G_E}{G_M}\right|^2\left(1-\cos^2\theta_p\right)\right]$$



- first EVER measurement of independent values of $|G_E|$ and $|G_M|$ in TL region

Status of the neutron form factors @BESIII

Why is so important to study the process $e^+e^- \rightarrow n\bar{n}$?

1) Only little data available (inconsistencies/R_{np}>1 for FENICE)

2) Comparison with proton FF

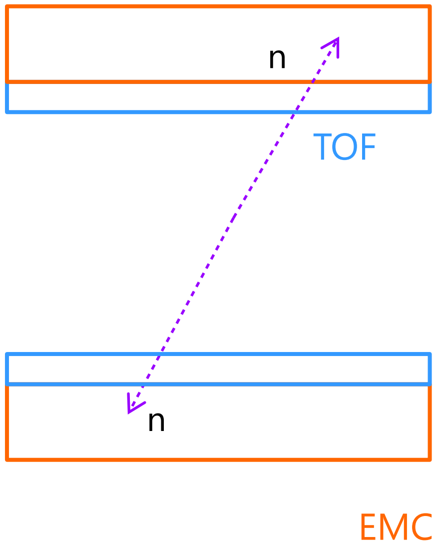
3) Comparison time-like region ↔ space-like region

Neutrons reconstruction(event classification)

AIM:maximize the reconstruction efficiency and produce statistically independent samples

No charged tracks and one or two EMC showers

anti-neutron signal in EMC (most energetic)



TOF signal correponding To EMC shower?

- NO → Type "C": EMC for n e nbar
- YES → TOF signal opposite To nbar EMC one?
  - NO → Type "B": TOF and EMC for nbar, EMC for n
  - YES → Type "A": TOF and EMC for nbar, TOF for n

FIRST HIGH LUMINOSITY OFF-RESONANCE ENERGY SCAN

18 data sets at center-of-mass energies between 2.0 and 3.08 GeV, 647.9 pb^{-1}

VERY challenging recon. of two neutral particles w/o Hadronic calorimeter

Accepted by Nature Physics

https://arxiv.org/abs/2103.12486

Cross Section and Effective Form Factor

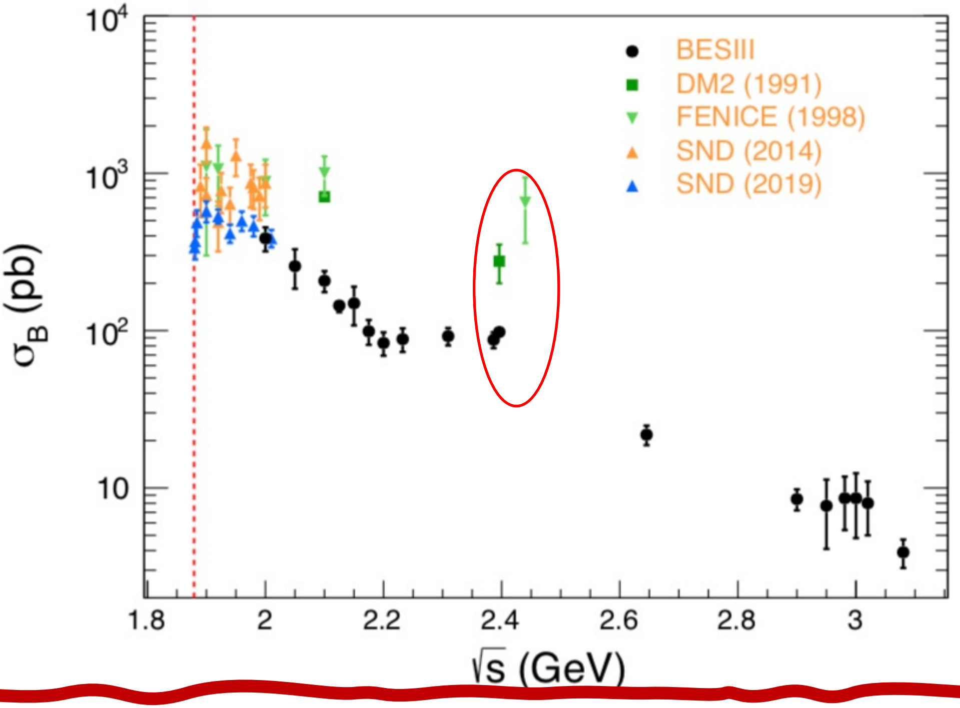
https://arxiv.org/abs/2103.12486

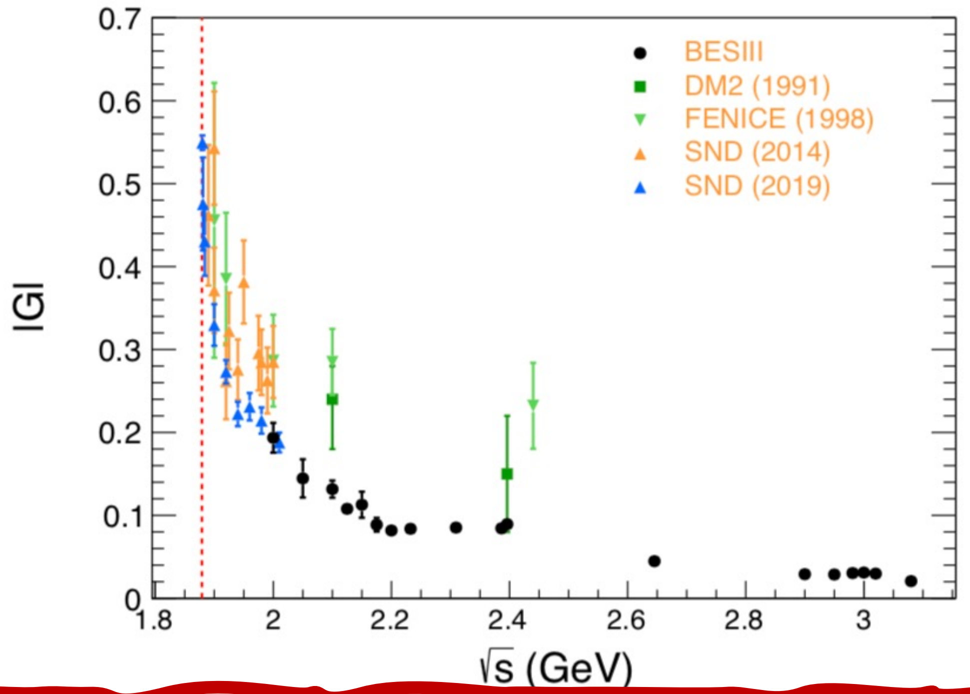
$$\sigma_{Born} = \frac{N_{data}}{\epsilon^{MC}_{n\bar{n}} \times \mathcal{C}_{dm} \times \mathcal{C}_{trg} \times (1+\delta) \times \mathcal{L}_{Int}}$$

Data/MC

Radiative corrections

$$|G_{eff}| = \left(\frac{3q^2}{4\pi\alpha^2\beta(1+\frac{2m_n^2}{q^2})}\right)^{\frac{1}{2}}\sqrt{\sigma_{Born}}$$





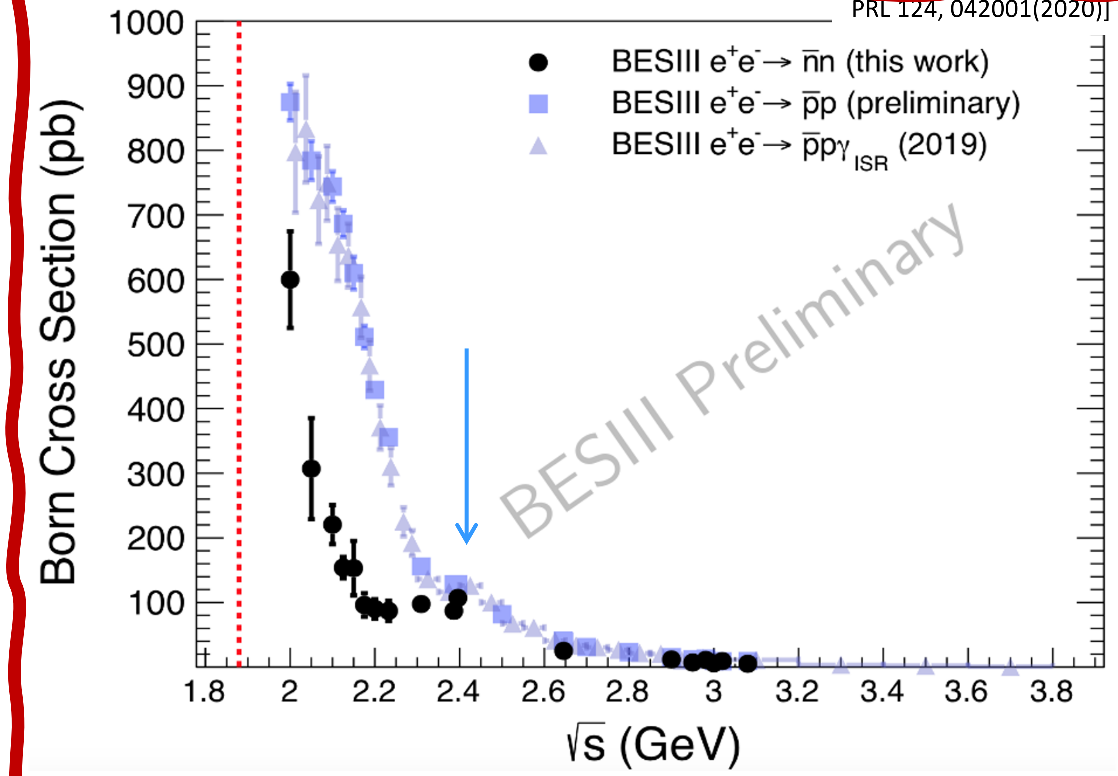
Agree with FENICE and SND at 2.0 GeV
Systematically lower above 2.0 GeV,
differ by 2σ with FENICE around 2.4 GeV.

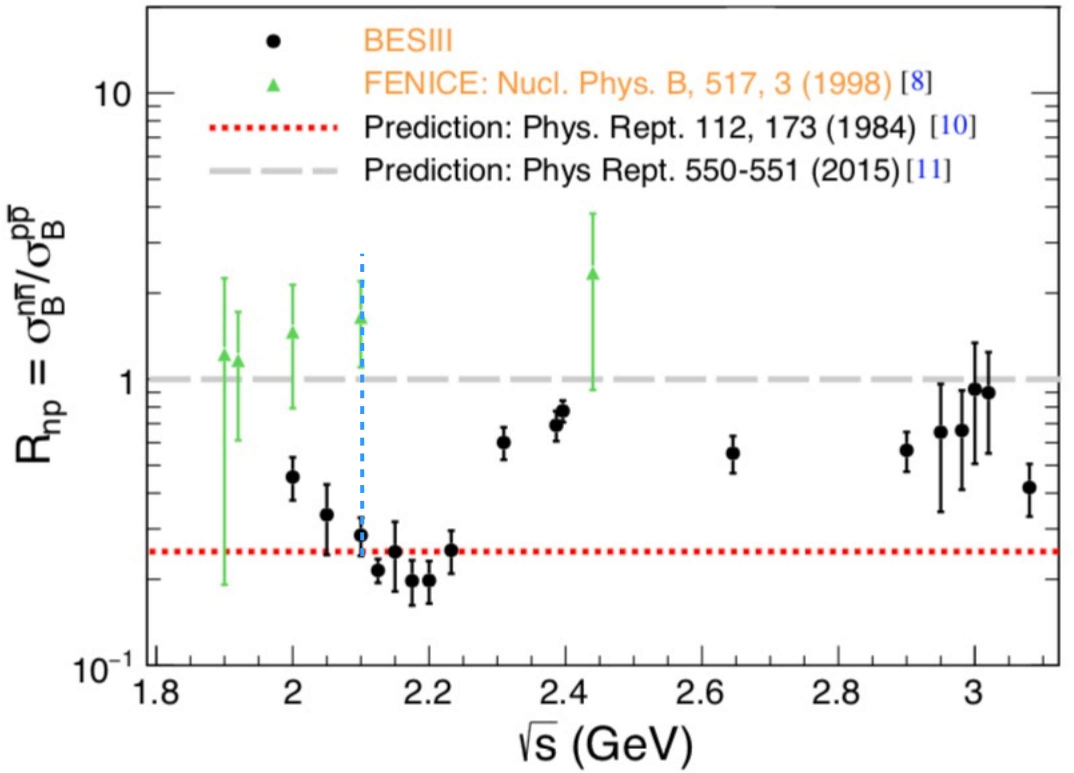
$|G_{eff}|$ precision lower than 10% @ 2.396 GeV
competitive with scattering results

PROTON and NEUTRON-comparison

• Long standing puzzle from FENICE results $R_{np} > 1$?

PRL 124, 042001(2020)]





Similar above 2.4 GeV

https://arxiv.org/abs/2103.12486

E > 2.4 GeV (R$_{np}$ ~ 1 as isospin symmetry prediction)

E < 2.4 GeV ($R_{np} \sim |q_d/q_u|^2 \sim 0.25$ as quark charges model)

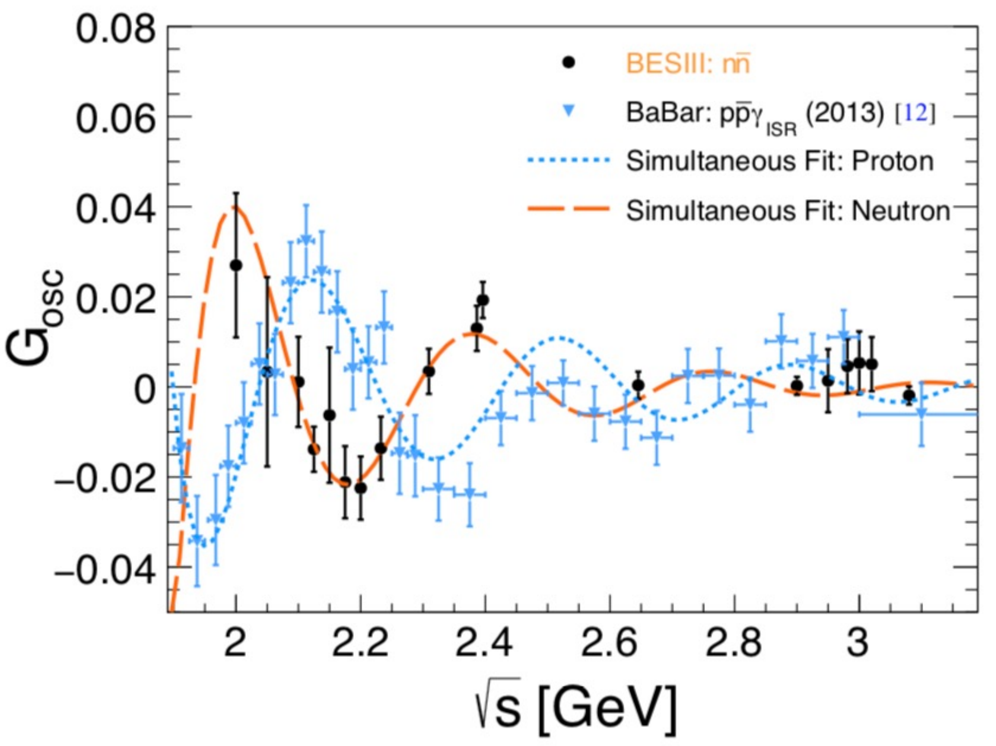
EM interaction?

photon-proton stronger than the corresponding photon-neutron interaction

Oscillating behaviour of effective FF

https://arxiv.org/abs/2103.12486

counterpart to that observed for protons



Fit to the deviation of the effective form factor |G| of the nucleon from the dipole law.

$$G_{osc}(q^2) = |G| - G_D,$$

$$G_D(q^2) = \frac{\mathscr{A}_n}{(1 - \frac{q^2}{0.71(\mathrm{GeV}^2)})^2},$$

dipole law

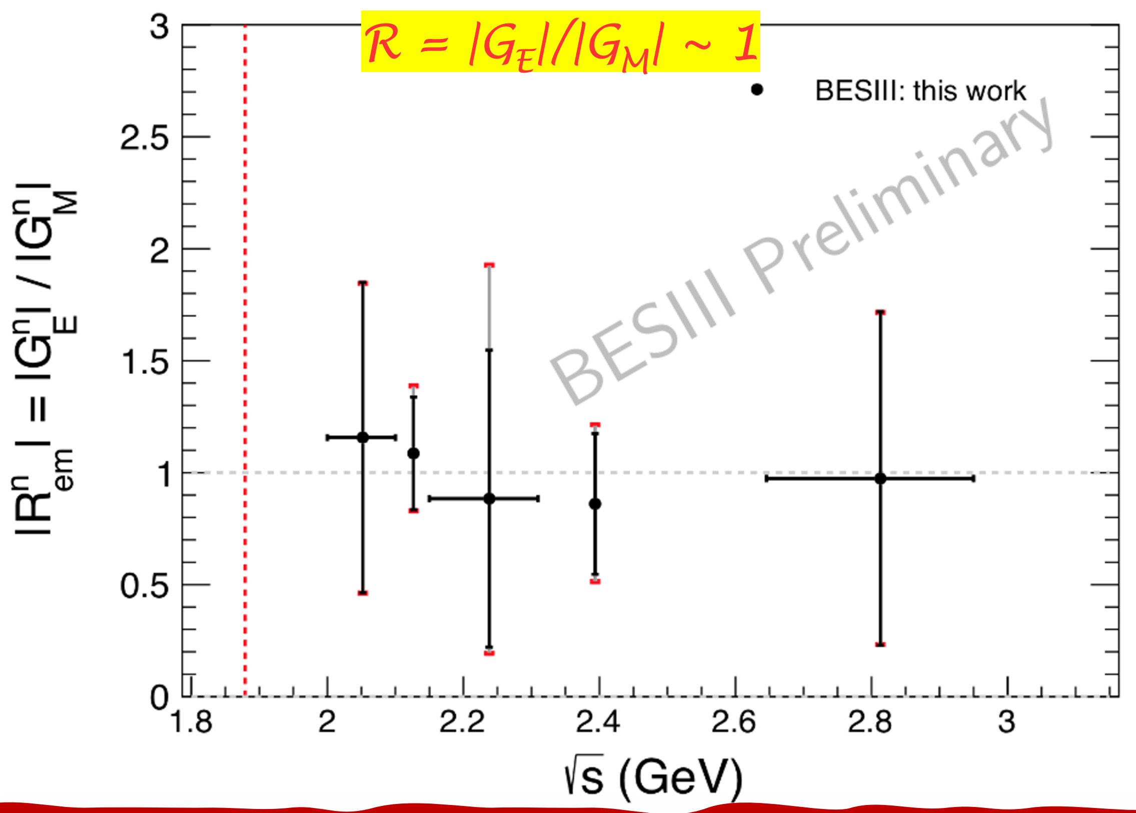
$$G^{osc}_{sim} = \mathbf{A} \cdot \exp(-\mathbf{B}|\mathbf{p}|) \cdot \cos(\mathbf{C}_{shared}|\mathbf{p}| + \mathbf{D})$$

The oscillation is observed → Simultaneous fit of proton and neutron data, shared frequency with a relative phase shift of ~125° ±12° to that for the proton.

R_{em} & Magnetic form factor extraction

$$\frac{d\sigma^{Born}_{n\bar{n}}}{dcos\theta_{\bar{n}}} = \frac{d\mathcal{N}/dcos\theta_{\bar{n}}}{\epsilon^{MC}_{n\bar{n}} \times \mathcal{C}_{dm} \times \mathcal{C}_{trg} \times (1+\delta) \times \mathcal{L}_{Int}} = A \times |G_M|^2 \left[(1+cos^2\theta_{\bar{n}}) + R^2_{em}\frac{4M^2_n}{s}(1-cos^2\theta_{\bar{n}})\right]$$

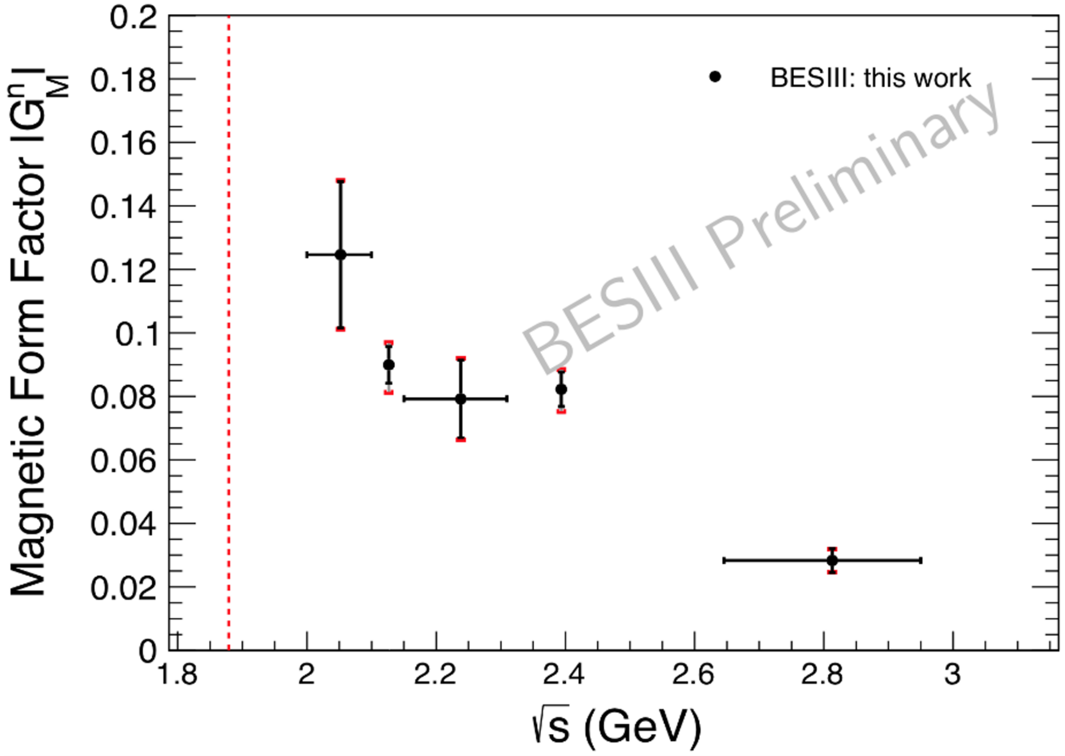
FIRST meas. from angular distribution in TL region!!!



best precision at s = 2.125 GeV and 2.396 GeV with 28.1% and 41.5%

dominated by statistical uncertainties

FIRST direct measurement



The statistical precision of the $|G^n_M|$ is around 10% (9.5% and 7.1% @$\sqrt{s}$= 2.125 and $\sqrt{s}$= 2.394 GeV)

Allows comparison space↔time

Summary

- The BESIII experiment provides an ideal environment to measure the nucleon FFs.
- The cross section of the $e^+e^- \rightarrow$ ppbar and $e^+e^- \rightarrow$nn bar processes measured in a wide range of q^2 (with both SCAN and ISR methods (thr.accessible) for the first)
- The effective form factor of the proton measured in wider range and improved precision and for neutron is determined at 18 c.m. energies.
- The proton form factors (G_M and R_{em}) measured with unprecedented precision, Independent G_M and G_E measurements with uncertainties comparable with SL.
- First measurement of R_{em} and first direct one of G_M *for nnbar process*
- An oscillating behaviour in the effective form factor of both the proton and of the neutron is observed.
- A step further towards unified view of the scattering and annihilation regions (phenomenological VDM and dispersion relations)
- STAY TUNED for further results with larger luminosity!