Recent Results of Nucleon Time-like Form Factors at BESIII

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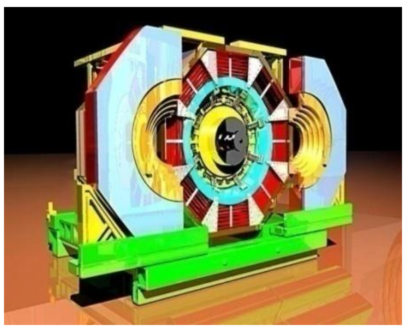
on behalf of the BESIII Collaboration



Overview

- Introduction

Electromagnetic Form Factors of nucleons

Motivation

BESIII spectrometer and data set

- Physics highlights

Proton Form Factors

Neutron Form Factors

Oscillating structure of effective FFs

- Summary

Electromagnetic Form Factors of Nucleons

- Hadrons are not pointlike particles
- EM FFs → internal structure and dynamics of nucleons

Electromagnetic vertex of nucleon:

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

$F_1^N(q^2)$: Dirac FF

$F_2^N(q^2)$: Pauli FF

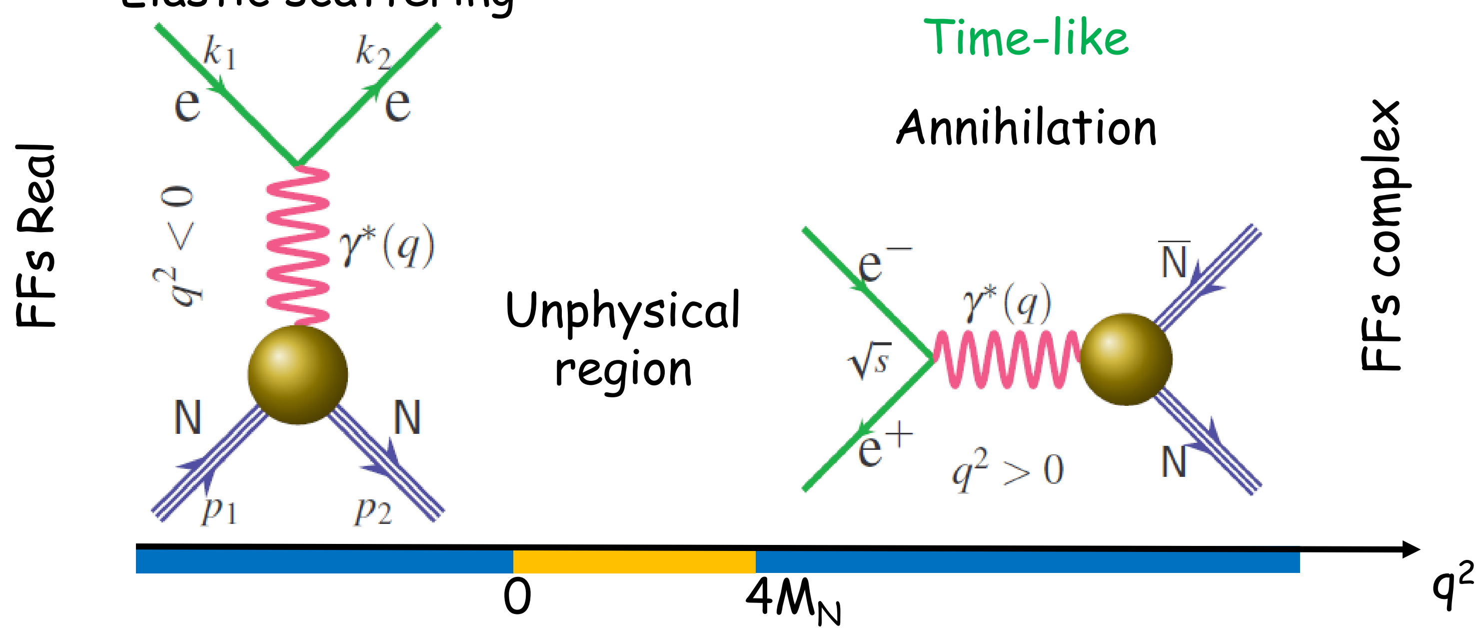
Sachs FFs: combination of Dirac and Pauli FFs

$$G_E = F_1(q^2) + (q^2/4M^2)F_2(q^2)$$

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

Space-like

Elastic scattering



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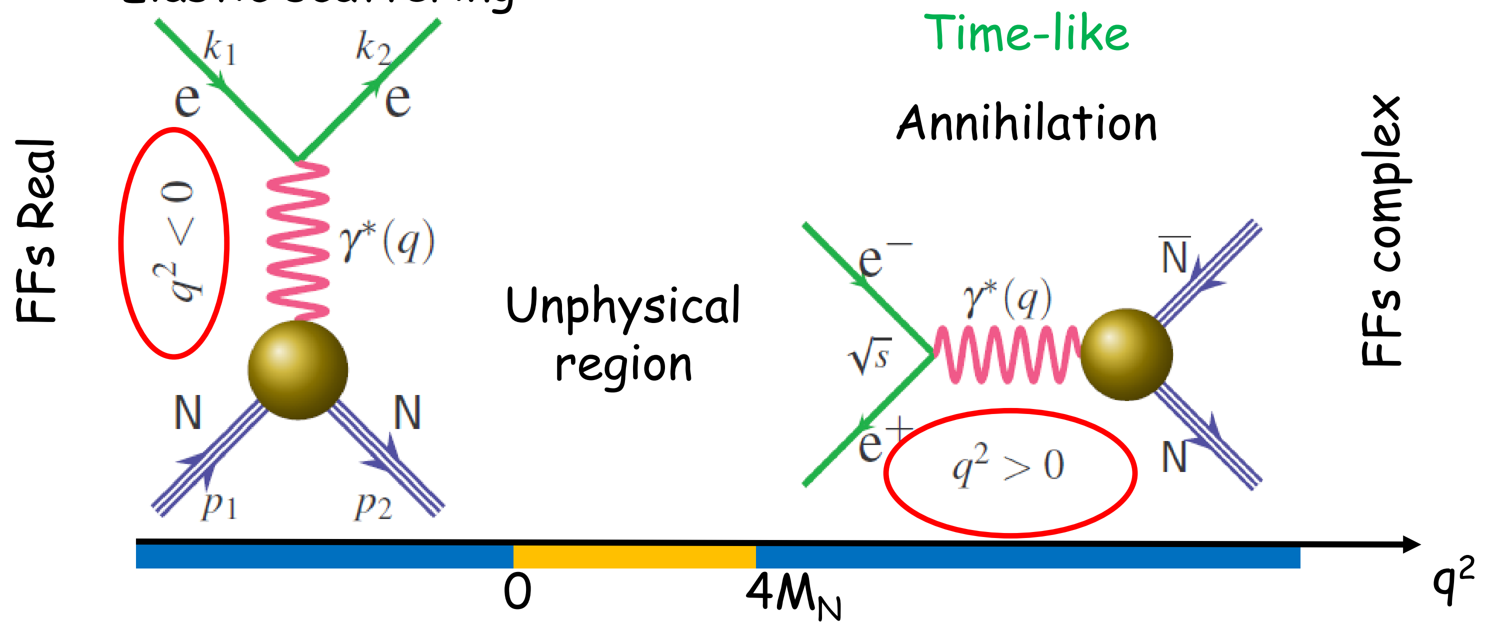


Motivation

- Complete understanding of nucleon structure
- Electromagnetic Form Factors (FFs) of proton and neutron must be measured in the time-like region with high precision
- The only available results for neutron are **the effective form factor** but with **poor precision**
- The results from FENICE Experiment show an unexpected behavior (neutrons FFs twice as large as for the proton)
- Define the best and most precise model to describe nucleon structure
- The pQCD predicts asymptotic behavior for the Space-Like (SL) and Time-Like (TL) results
- Test of the predictions

Time-like Electromagnetic FFs

- Differential cross section

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

$$\beta = \sqrt{\frac{1}{1-\tau}}; \quad \tau = \frac{q^2}{4M^2}$$

$$C = \frac{y}{1-e^{-y}}; \quad y = \frac{\alpha\pi}{\beta}$$

- Born cross section

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

- $|G_E|/|G_M|$ ratio extracted from differential cross section at fixed energy

- Effective form factor

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

= $|G_M|$ if we assume $|G_E| = |G_M|$

- Investigation methods

Direct scan

- Fixed q^2
- Low integrated luminosity

Initial State Radiation (ISR)

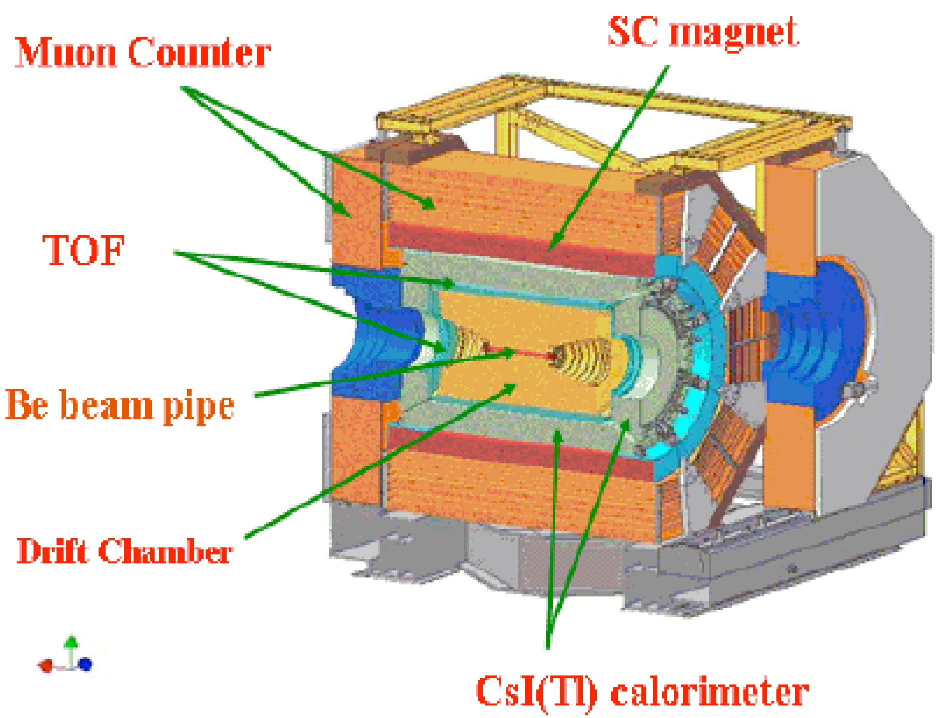
- Continuous q^2 (from threshold to s)
- High integrated luminosity

The BESIII Spectrometer @ IHEP

BEijing Spectrometer III

e^+e^- collisions

$\sqrt{S}$ tuned depending on energy



Physics program

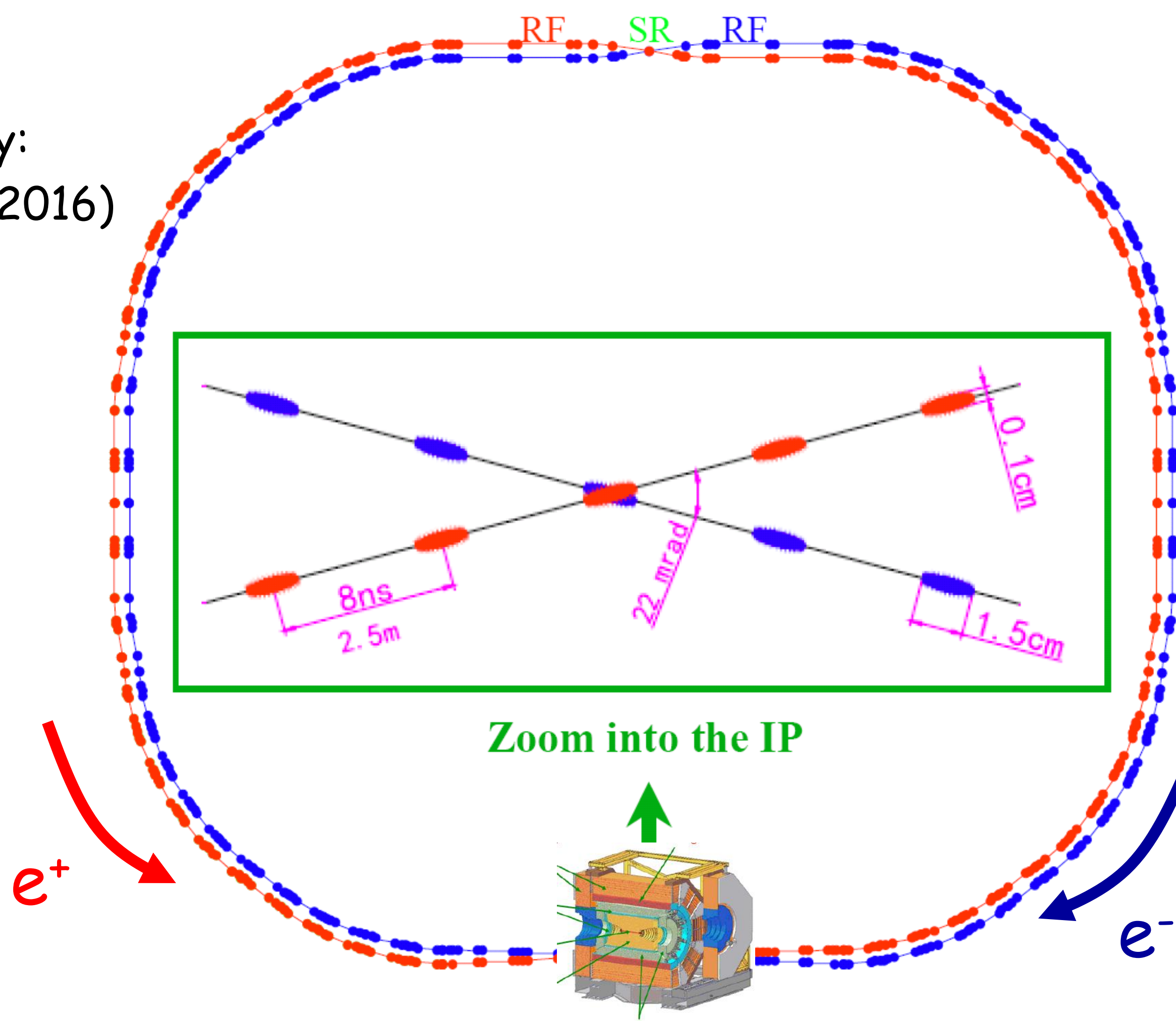
- Charmonium Physics
- D-Physics
- Light Hadron Spectroscopy
- τ-Physics
- ...

D.M. Asner et al, Physics at BES-III, arXiv:0809.1869v1 [hep-ex] (2008)

BEPCII Storage Rings

Beijing Electron-Positron Collider II

- Beam energy:
  1.0-2.473 GeV (2021)
- Design Luminosity:
  $1 \times 10^{33}\ cm^{-2}s^{-1}$
- Achieved Luminosity:
  $1 \times 10^{33}\ cm^{-2}s^{-1}$ (2016)
- Optimum energy:
  1.89 GeV
- Energy spread:
  5.16×10^{-4}
- No. of bunches:
  93
- Bunch length:
  1.5 cm
- Total current:
  0.91 A
- Circumference:
  237m



BESIII Detector

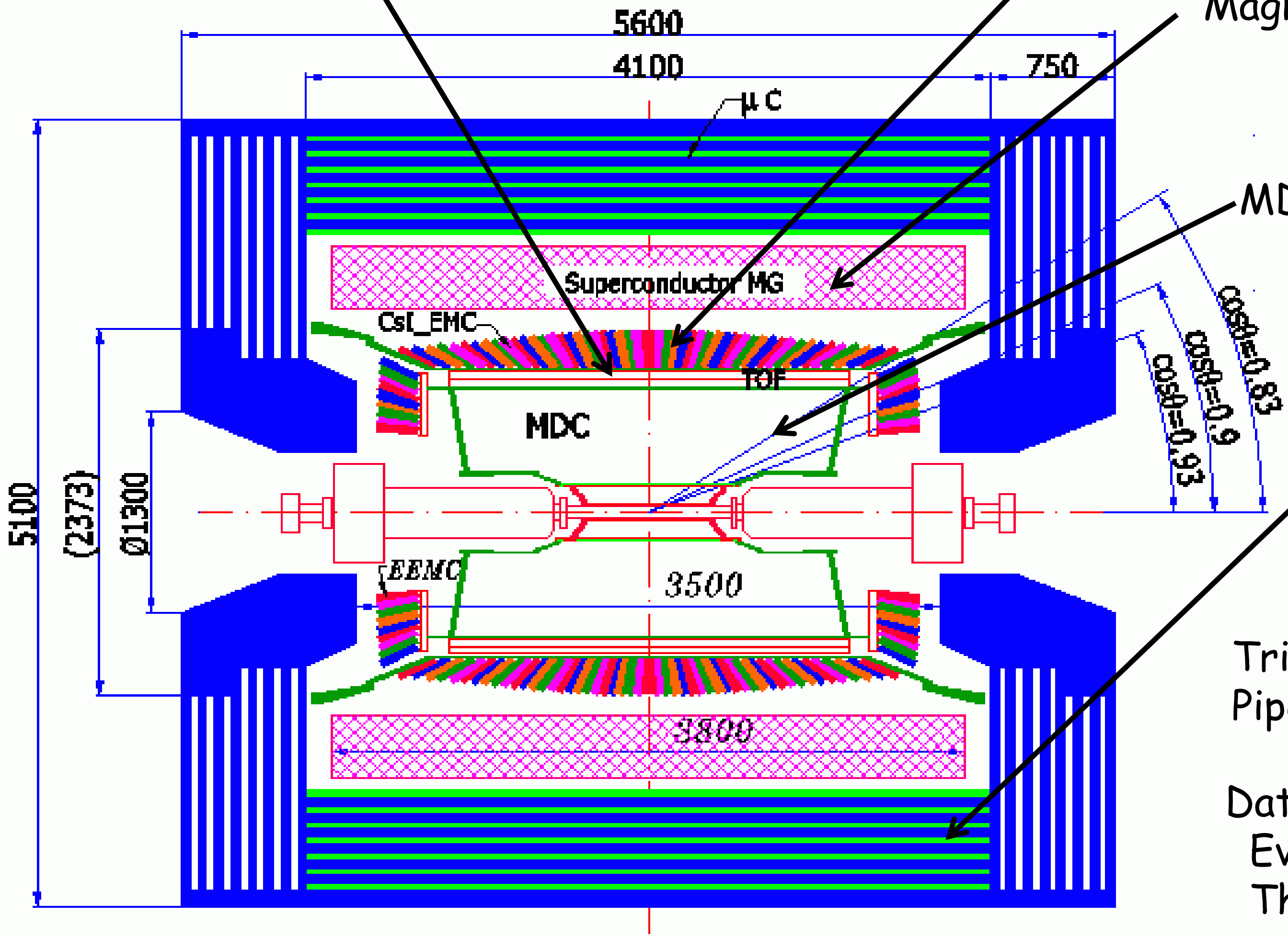
TOF:
σ_T = 80 ps Barrel
110 ps Endcap

EMC: CsI crystals, 28 cm
$\Delta E/E$ = 2.5% @1 GeV
σ_z = 0.6 cm/$\sqrt{E}$

Magnet: 1T Superconducting

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

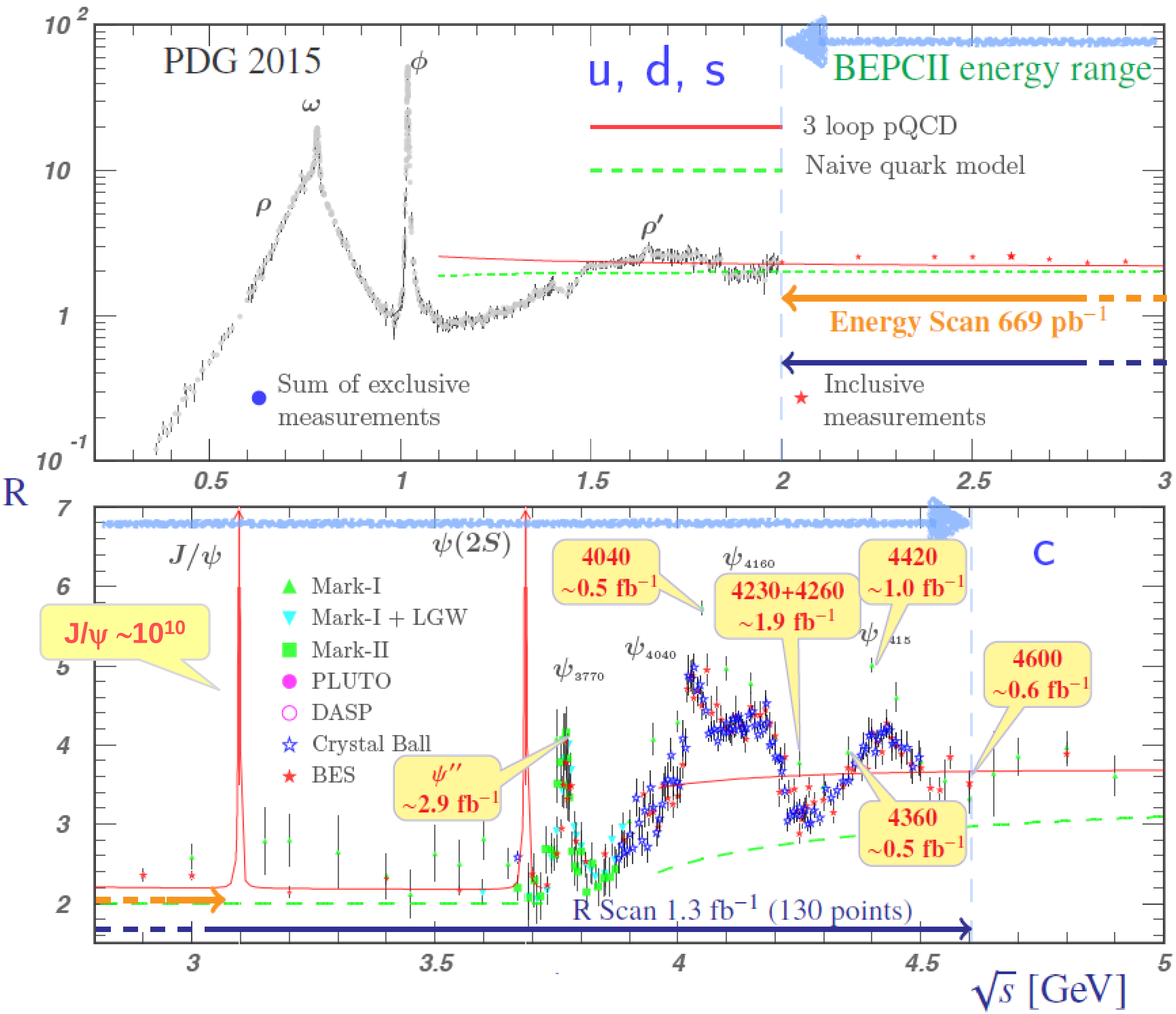
Muon: 9 layer RPC



Trigger: Tracks & Showers
Pipelined; Latency = 2.4 ms

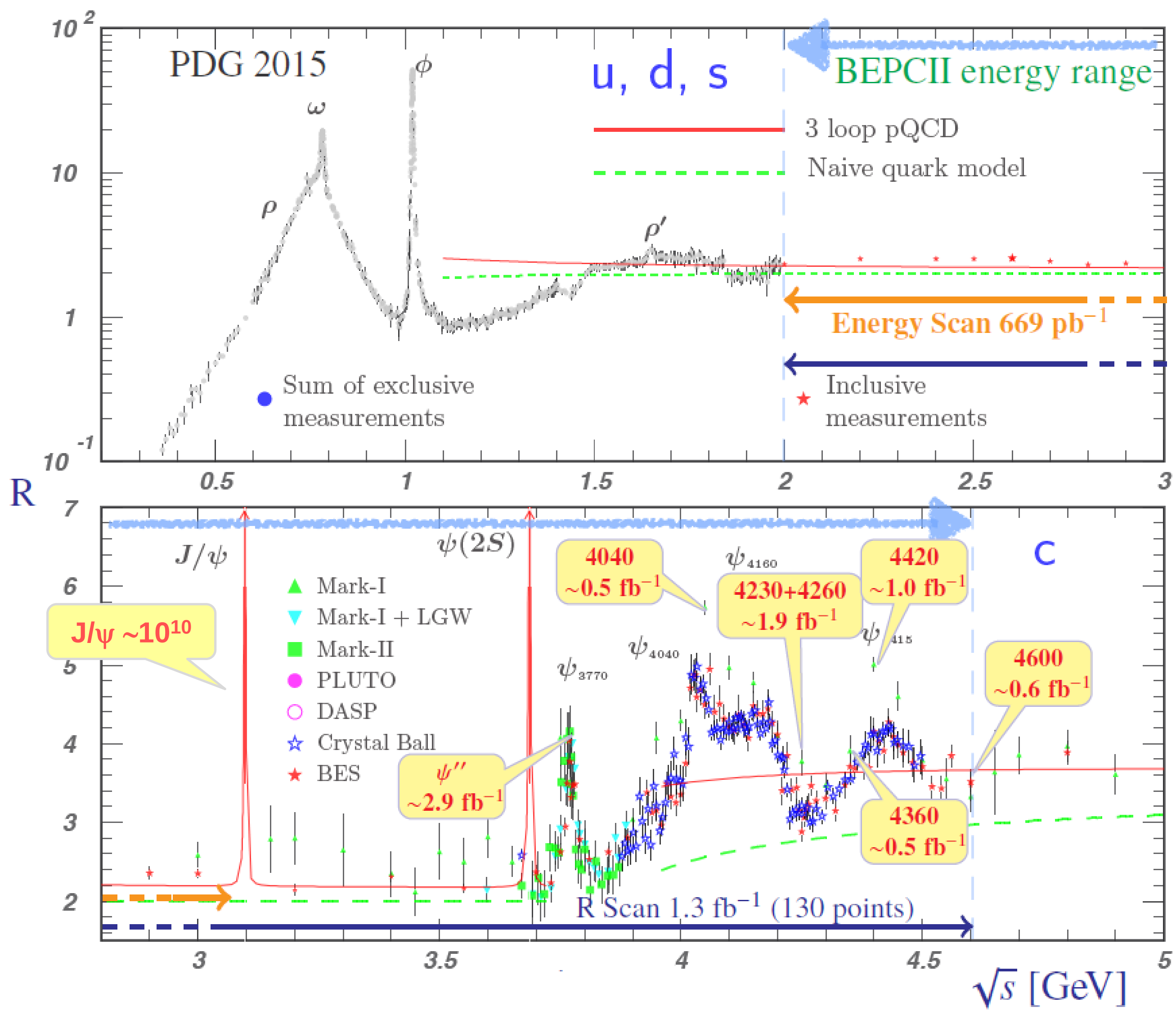
Data Acquisition:
Event rate = 3 kHz
Thruput ~ 50 MB/s

BESIII Datasets



- World largest data sample on J/ψ, ψ(2S), ψ(3770), Y(4260)… in e^+e^- collisions
- From light meson spectroscopy to $\Lambda_c\overline{\Lambda}_c$
- Fine and coarse scan of the accessible energy region

BESIII Datasets



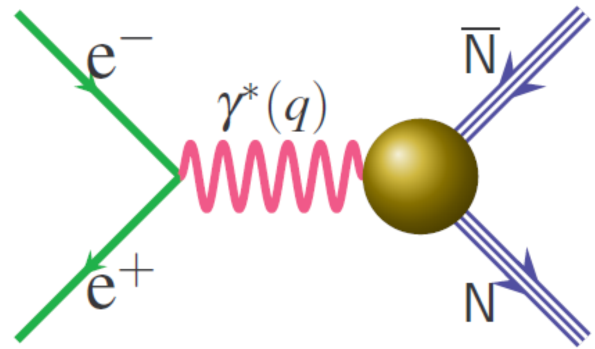
Data taken until 2016

Nucleon FFs

from energy scan data

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

2.0 – 3.8 GeV (669 pb^{-1})

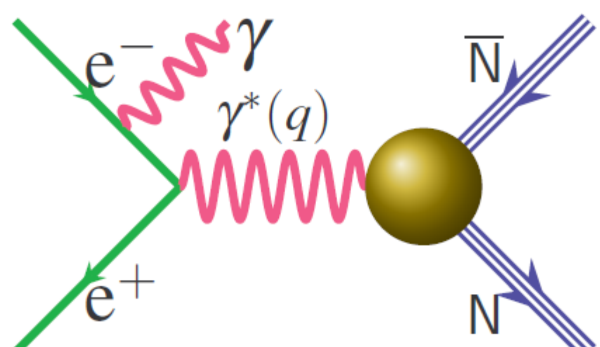


Proton FFs

from resonance data

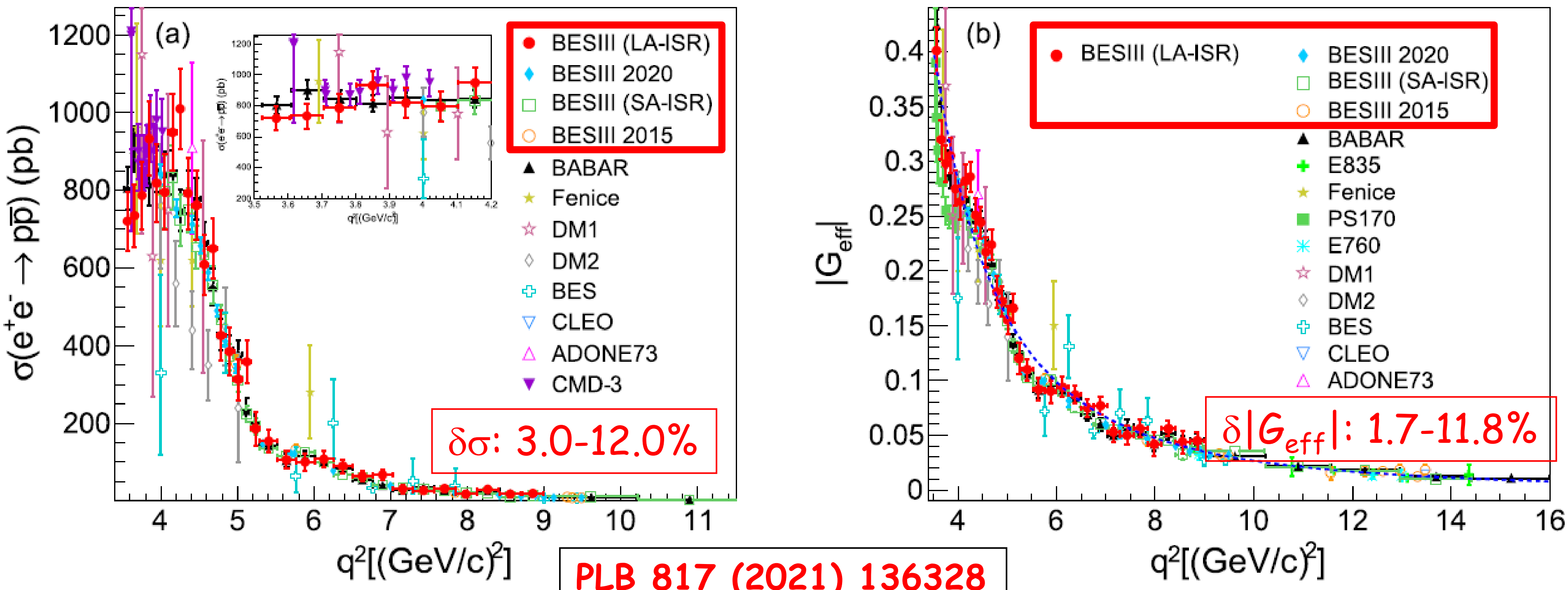
$e^+e^- \to p\bar{p}\gamma$

above ψ″ (7.5 fb^{-1})



Proton Form Factors

Scan method



PLB 817 (2021) 136328

LA-ISR: γ tagged analysis

SA-ISR: γ untagged analysis

Direct process with scan data

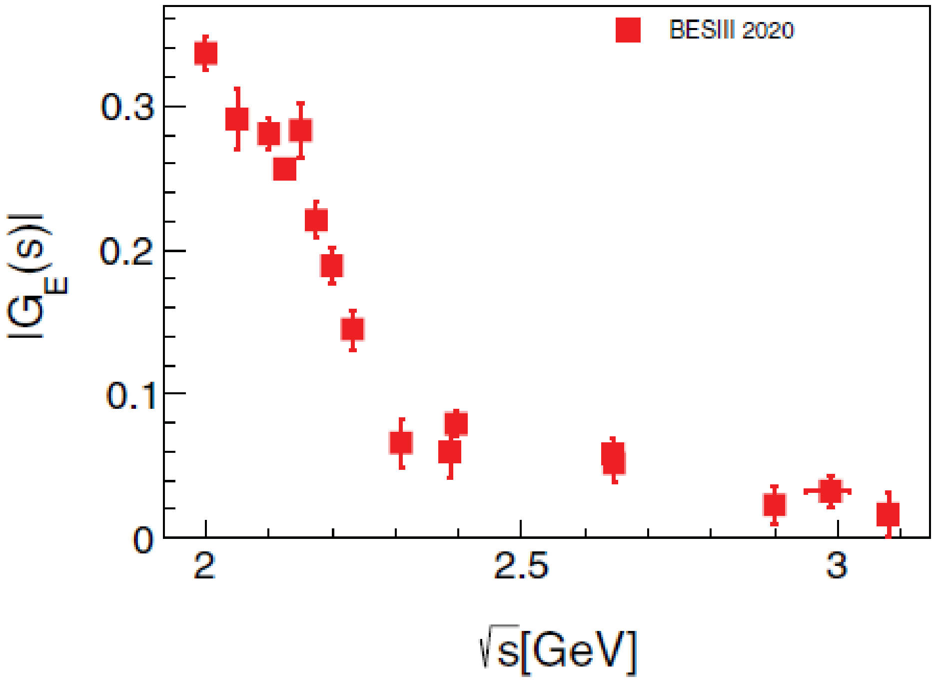
- $\sqrt{s}$ = 2.232 – 3.671 GeV, 157 pb^{-1}, PRD 91 (2015) 112004
- $\sqrt{s}$ = 2.000 – 3.080 GeV, 667 pb^{-1}, PRL 124 (2020) 042001
- most precise measurement at $\sqrt{s}$ = 2.125 GeV

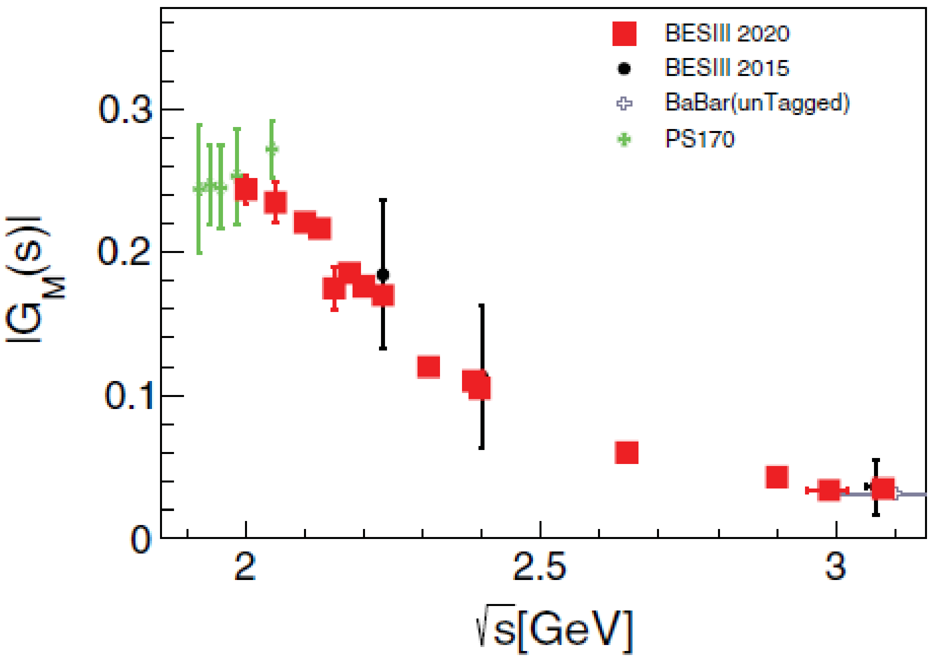
ISR process with scan data

- LA-ISR: $\sqrt{q^2}$ = 1.876-3.000 GeV/c, PLB 817 (2021) 136328
- SA-ISR: $\sqrt{q^2}$ = 2.000-3.800 GeV/c, PRD 99 (2019) 092002
- data set at $\sqrt{s}$ = 3.773-4.600 GeV, L_{int} = 7.5 fb^{-1}

Proton Form Factors

PRL 124 (2020) 042001

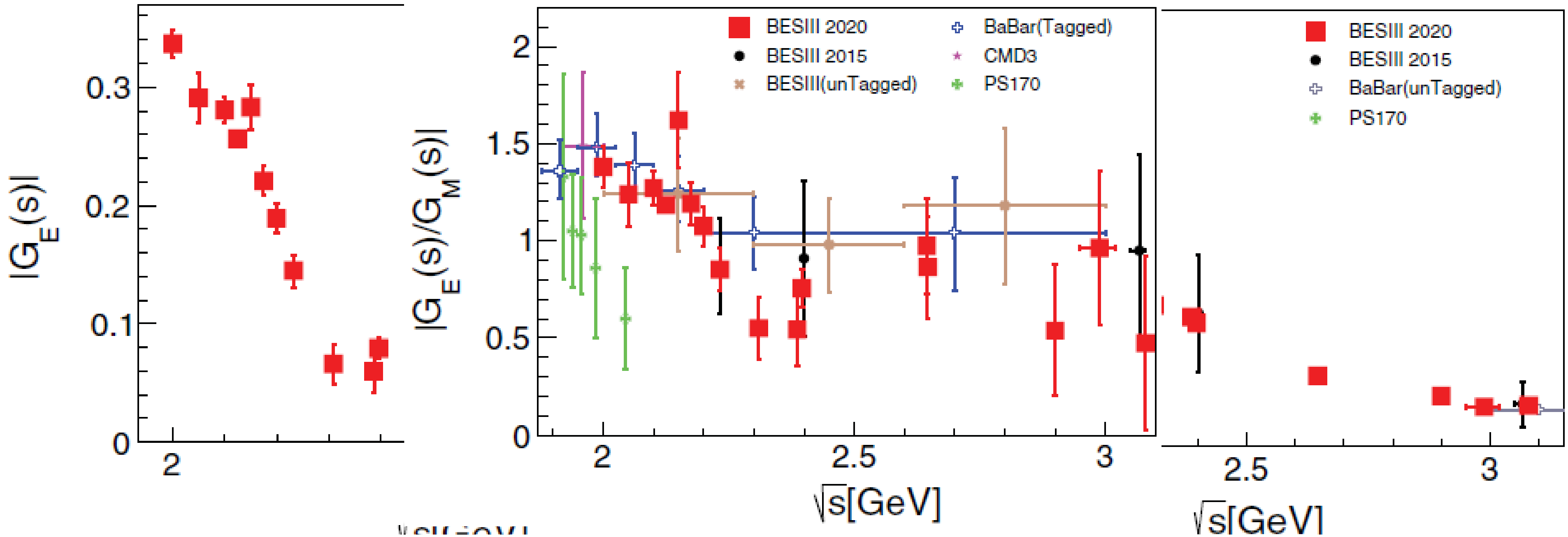




- $|G_E|$ measured for the first time in the time-like region
- Precision of the measurement of $|G_M|$ improved significantly
- $|G_M|$ measured for the first time over a wide range of energies

Proton Form Factors

PRL 124 (2020) 042001



ISR process:

$$\frac{dN}{d\cos\theta_p} \propto [\mathcal{F}_M(\cos\theta_p, M_{p\bar{p}}) + \frac{|R_{em}|^2}{2\tau}\mathcal{F}_E(\cos\theta_p, M_{p\bar{p}})]$$

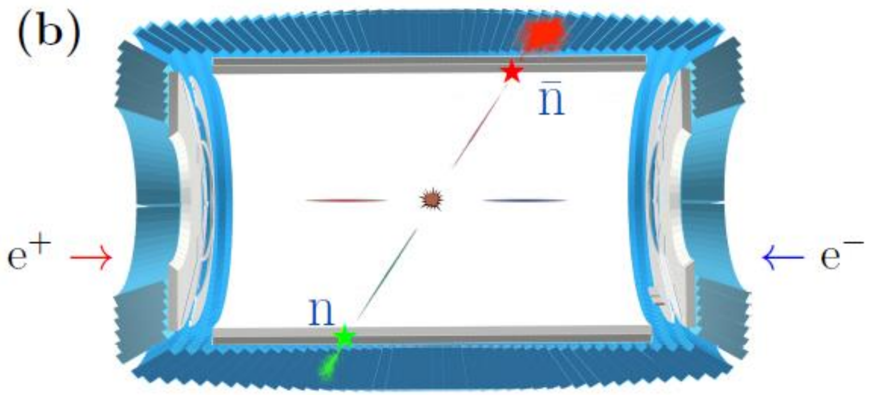
direct process:

$$\frac{d\sigma}{d\cos\theta_p} = \frac{\pi\alpha^2\beta C}{2s}|G_M|[(1+\cos^2\theta_p) + \frac{|R_{em}|^2}{\tau}\sin^2\theta_p]$$

- $|G_E|$ measured for the first time in the time-like region
- Precision of the measurement of $|G_M|$ improved significantly
- $|G_M|$ measured for the first time over a wide range of energies
- High accuracy determination of $|G_E|/|G_M|$ ($|R_{em}|$) from $\cos\vartheta_p$ distribution
- BESIII results support BABAR data

Measurement of Neutron Form Factors

- $e^+e^- \rightarrow n\bar{n}$
- Data set collected between 2.000 and 3.080 GeV at 18 different center of mass energies
- Pure neutral channel
- Only EMC and/or TOF information
- Sophisticated background suppression



arXiv:2103.12486

Accepted by Nature Physics

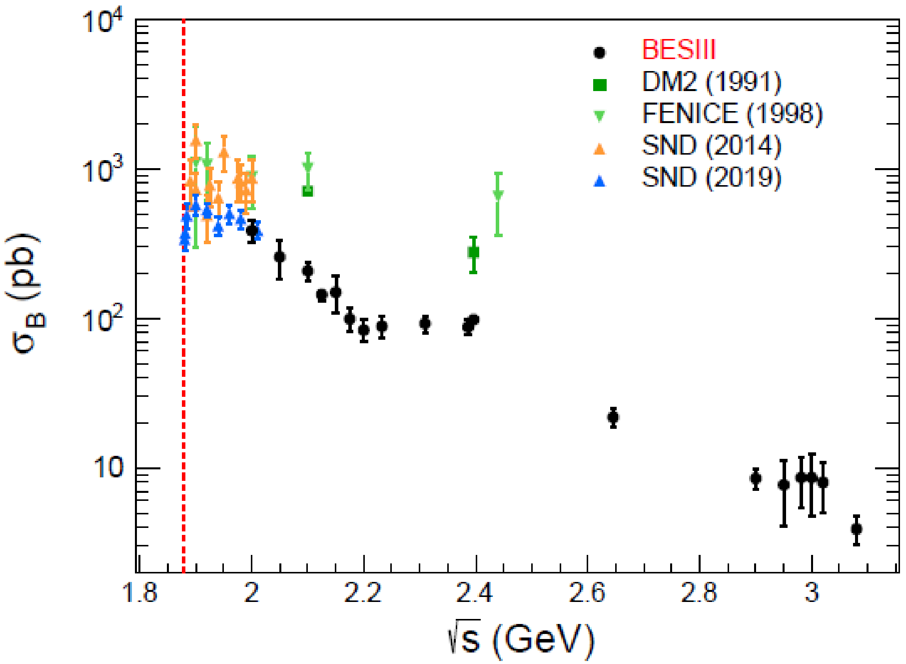
Spectrometer signals:

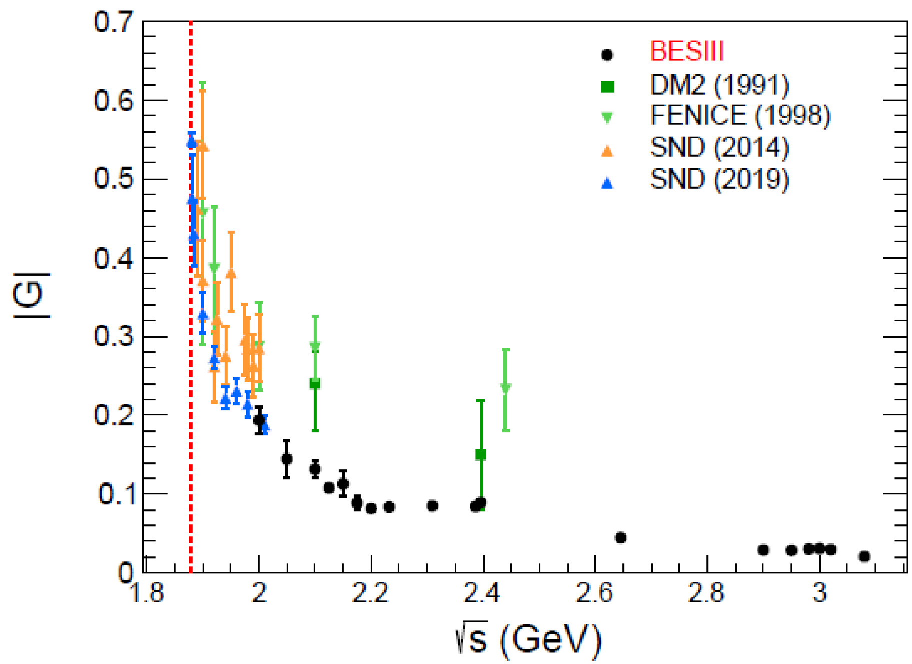
- Category A: $(EMC + TOF)_{nbar} + (TOF)_n$
- Category B: $(EMC + TOF)_{nbar} + (EMC)_n$
- Category C: $(EMC)_{nbar} + (EMC)_n$

Most energetic signal in EMC associated with anti-neutron

Neutron Effective Form Factors

Scan method

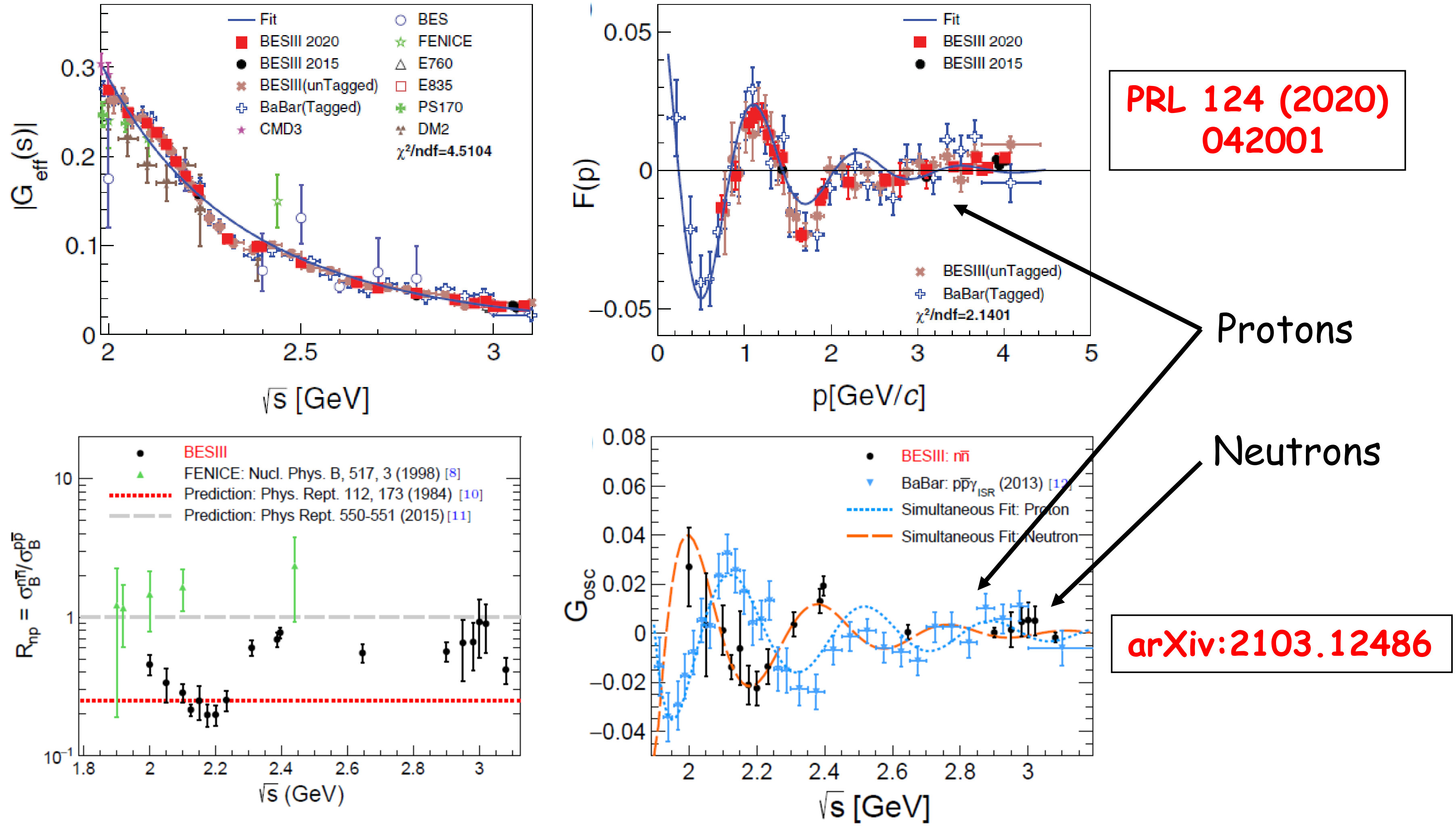




arXiv:2103.12486

- Direct measurement of $e^+e^- \to n\bar{n}$
- $\sqrt{s} = 2.000\text{-}3.080$ GeV, 669 pb^{-1}
- Very high precision at $\sqrt{s} = 2.125$ GeV (679 events, $\Delta\sigma_{stat}/\sigma \sim 4.15\%$)
- Consistent with SND data at $\sqrt{s} = 2.0$ GeV
- 2σ difference from FENICE data at $\sqrt{s} = 2.4$ GeV

Oscillation Structure of Effective FFs



- The oscillations can be extracted from the effective form factor as $F^{osc} = |G_{eff}| - F^0$ (F^0 describes the regular behavior of the form factor over the long range of the ppbar invariant mass)

Summary

- High precision measurements of FFs in the Time-like region

  Both direct and ISR processes accessible at BESIII

  Very high precision in the $\sqrt{s} = 2.0$ - 3.0 GeV region

  Threshold region ($\sqrt{s} < 2.0$ GeV) needs more precise data

  ISR process offers a unique key to access threshold region

  Larger data sample collected by BESIII (20 fb^{-1})

  investigation of nucleon EMFFs

  investigation of other baryons EMFFs

- Stay tuned for new results!!