$\bar{\mathrm{P}}$ANDA Collaboration Meeting - EMP Session

Measurement of the Neutron Form Factors via $e^+e^- \to \bar{n}n$ at BESIII

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on behalf of the BESIII Collaboration

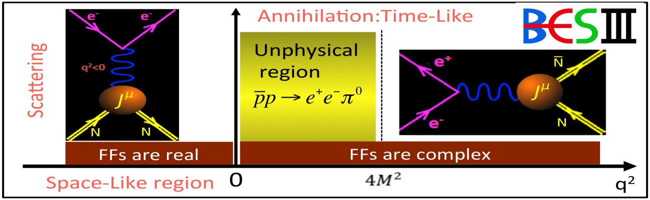
11. November 2019

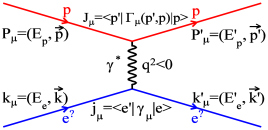
Outline

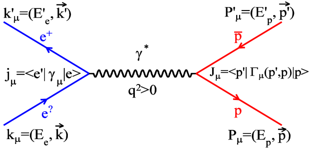
- Electromagnetic Form Factors of the Nucleon at BESIII
- Data Analysis: $e^+e^- \to \bar{n}n$ at $\sqrt{s} = 2.0 - 3.08$ GeV
- Results from the BESIII Experiment and Discussion

Electromagnetic Form Factors of the Nucleon

Nucleon Electromagnetic Form Factors (EMFFs)







- EMFFs parametrize the **internal structure** and **dynamics** of the nucleon
- Can be measured in space-like (**SL**) or time-like (**TL**) region
- The hadronic vector current J^μ for spin-$\frac{1}{2}$ particles contains **2 form factors**:

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

Properties of the TL EMFF of the Nucleon

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

- $\boldsymbol{F_1(q^2)}$ and $\boldsymbol{F_2(q^2)}$ are the **Dirac- and Pauli FF**, functions of q^2.
- EMFFs are analytical functions: For high q^2 pQCD and asymptotic behavior:

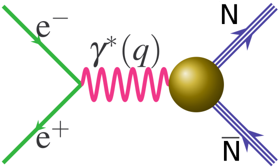
$$\boldsymbol{F_1(q^2)} \propto \frac{1}{q^4} \qquad \boldsymbol{F_2(q^2)} \propto \frac{1}{q^6}$$

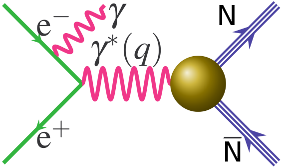
- Experimental access: Sachs FFs $\rightarrow$ linear combination of $F_1(q^2)$ and $F_2(q^2)$:

$$G_E(q^2) = \boldsymbol{F_1(q^2)} + \tau \boldsymbol{F_2(q^2)}, \qquad G_M(q^2) = \boldsymbol{F_1(q^2)} + \boldsymbol{F_2(q^2)}, \qquad \tau = \frac{q^2}{4m_N^2}$$

- Properties of EMFF of the nucleon with respect to q^2:
  - At threshold ($q^2 = 4m_N^2$): by definition $G_E = G_M$
  - At $q^2 = 0$ for Proton: $\boldsymbol{F_1} = \boldsymbol{F_2} = 1$, $G_E = 1$, $G_M = \mu_p$
  - At $q^2 = 0$ for Neutron: $\boldsymbol{F_1} = 0$, $\boldsymbol{F_2} = 1$, $G_E = 0$, $G_M = \mu_n$

Measurement of Nucleon EMFFs in the TL Region





- Two methods: Direct Scan and Radiative Return

$$s = q^2$$

- Beam energy is discrete.
- Luminosity is relatively small.

$$\left(\frac{d\sigma_{N\bar{N}}}{d\Omega}\right) = \frac{\alpha^2 C\beta}{4q^2}\left[|G_M^N|^2(1+cos^2\theta) + \frac{1}{\tau}|G_E^N|^2(1-cos^2\theta)\right]$$

- q^2 is single at each beam energy.

$$s' = q^2$$

$$s' = x \cong 2E_\gamma/\sqrt{s}$$

- Beam energy is fixed.
- Luminosity is relatively high.

$$\left(\frac{d^2\sigma_{N\bar{N}\gamma}}{dq^2 d\theta}\right) = \frac{1}{q^2} W(q^2, x, \theta_\gamma)\sigma_{N\bar{N}}(q^2)$$

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

- q^2 is continuous from threshold to s.

Observables of the EMFF in the TL Region

Integrated measurement (if statistics are low):

- Born cross section (one photon approximation):

$$\sigma_B^{e^+e^-\to\bar{N}N} = \frac{4\pi\alpha^2\beta\mathcal{C}}{3q^2}\left[|G_M^N|^2 + \frac{1}{2\tau}|G_E^N|\right] = \frac{N_{data}}{\mathcal{E}_{MC}\times\mathcal{E}_{corr}\times\mathcal{L}_{int}\times(1+\delta)}$$

$$\beta = \sqrt{1-1/\tau}, \qquad \mathcal{C} = \frac{\pi\alpha}{\beta(1-e^{\pi\alpha/\beta})} \text{ (if neutral} \to \mathcal{C}=1)$$

- Effective form factor: $|G_{eff}^N| = \sqrt{\frac{\sigma_B^{e^+e^-\to\bar{N}N}}{(1+\frac{1}{2\tau})\left(\frac{4\pi\alpha^2\beta\mathcal{C}}{3q^2}\right)}}$

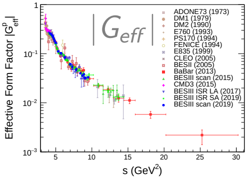
Disentangled measurement (if statistics are high enough for angular analysis):

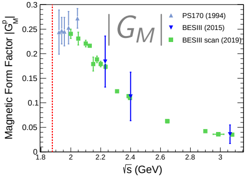
- Separation of $|G_E^N|$ and $|G_M^N|$ via angular analysis (of $e^+e^- \to \bar{N}N$):

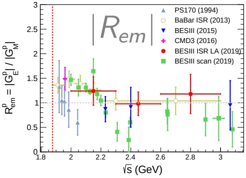
$$\frac{d\sigma_B^{e^+e^-\to\bar{N}N}}{d\Omega_{cm}} = \frac{\alpha^2\beta\mathcal{C}}{4q^2}\left[(1+\cos^2\theta_{N(\bar{N})}^{cm})|G_M^N|^2 + \frac{1}{\tau}|G_E^N|^2\sin^2\theta_{N(\bar{N})}^{cm}\right]$$

Status of the EMFF Measurement in the TL Region

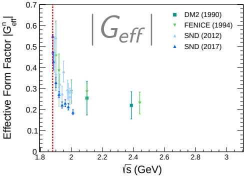
Proton: rich data

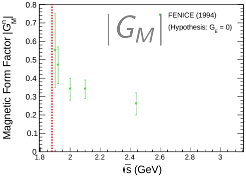


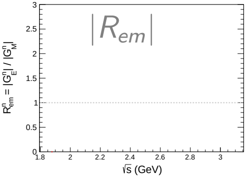




Neutron: poor data

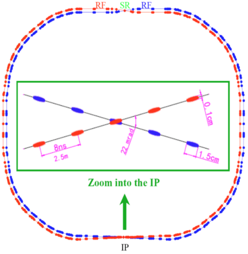






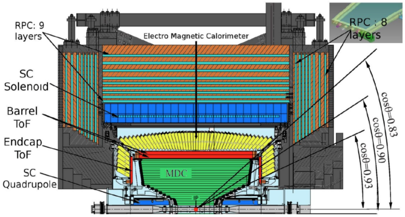
The BESIII Experiment at the BEPCII Collider

Beijing Electron Positron Collider



- 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 detector



Electromagnetic Calorimeter
$\sigma_E/\sqrt{E}(\%)$=2.5% (1 GeV),
(CsI) $\sigma_{z,\phi}$(cm)=0.5-0.7 cm/$\sqrt{E}$

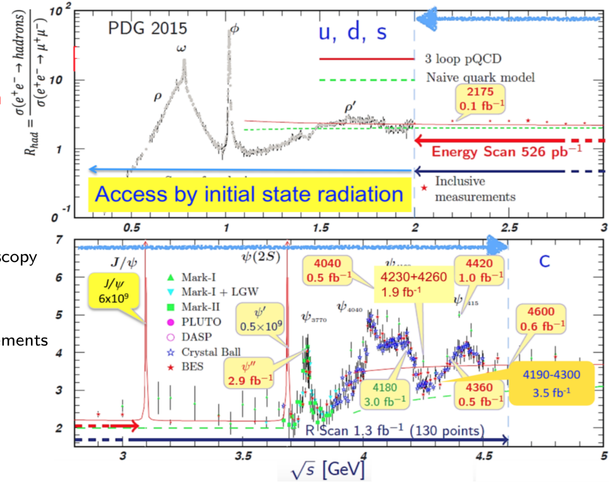
Muon Counter
σ_{xy}<2 cm

Time Of Flight
σ_T(barrel)=90 ps
σ_T(endcap)=110 ps

Main Drift Chamber
σ_{xy}=130 mm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

Physics and Data Sets at the BESIII Experiment

- World largest data samples for J/ψ, ψ' and ψ''



- Charm physics
- Charmonium spectroscopy
- Light hadrons
- New physics research
- Form factors measurements
- ....

Motivation

Why measuring the TL electromagnetic form factors of the neutron?

- TL EMFF required for the complete understanding of the nucleon structure
- The available results on the effective FF show a poor precision, limited range
- Published results from FENICE experiment show unexpected behavior:
  $\rightarrow$ photon-neutron coupling stronger than photon-proton coupling?
- Many theoretical predictions and parametrizations of EMFF of the nucleon:
  $\rightarrow$ which model describes the nucleon structure in a most precise way?
- pQCD predicts an asymptotic behavior between SL and TL FFs:
  $\rightarrow$ at which q^2 can we observe this behavior?
- Periodic structure observed by the BaBar experiment for proton EFF results:
  $\rightarrow$ is there a similar structure in the effective FF of the neutron?

Data Analysis

Available Data and Monte Carlo Samples

Collider data:

- Collision data sets at 18 center-of-mass energies (total luminosity $\sim$ 651 pb^{-1}):

$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})	$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})
2.0000	$10.074 \pm 0.005 \pm 0.067$	2.3864	$22.549 \pm 0.010 \pm 0.176$
2.0500	$3.344 \pm 0.003 \pm 0.027$	2.3960	$66.869 \pm 0.017 \pm 0.475$
2.1000	$12.167 \pm 0.006 \pm 0.085$	2.6454	$67.725 \pm 0.018 \pm 0.249$
2.1266	$108.49 \pm 0.02 \pm 0.94$	2.9000	$105.253 \pm 0.025 \pm 0.905$
2.1500	$2.841 \pm 0.003 \pm 0.024$	2.9500	$15.942 \pm 0.010 \pm 0.142$
2.1750	$10.625 \pm 0.006 \pm 0.091$	2.9810	$16.071 \pm 0.010 \pm 0.095$
2.2000	$13.699 \pm 0.007 \pm 0.092$	3.0000	$15.881 \pm 0.010 \pm 0.110$
2.2324	$11.856 \pm 0.007 \pm 0.087$	3.0200	$17.290 \pm 0.011 \pm 0.123$
2.3094	$21.089 \pm 0.009 \pm 0.143$	3.0800	$126.185 \pm 0.029 \pm 0.921$

- Non-collision data sets: at 2.2324 and 2.6444 GeV for background studies
- Control channels: 1.3B J/ψ events for n, $\bar{n}$ and γ efficiency studies

Monte Carlo simulation samples:

- Signal MC simulation with ConExc and Phokhara: 500k for each energy point
- Bhabha, di-gamma, di-muon with Babayaga 3.5 (NNLO) according to $\mathcal{L}_{data}$
- Multi-hadronic final states with LundAreaLaw (NLO) according to $\mathcal{L}_{data}$
- MC simulation samples for the control channels according to $\mathcal{L}_{data}$

Idea of Analysis Strategy

- No charged tracks in event
- Most energetic shower in EMC as $\bar{n}$ candidate

1. Search for TOF1 signal with:

   $\Delta\Phi^1 = |\phi^1_{TOF} - \phi_{EMC}| < 3$ TOF's ($\sim 12°$)

   → Search for TOF2 signal as n with

   $\Delta\Phi^2 = |\phi^2_{TOF} - \phi^{recoil}_{EMC}| < 6$ TOF's ($\sim 25°$)

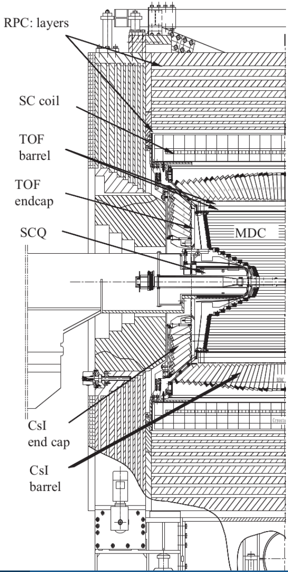
   → further selection criteria: Category A

2. No TOF2? Search for second energetic shower as n with $\sphericalangle_n^{\bar{n}} > 90°$

   → further selection criteria: Category B

3. No TOF1? Search for second energetic shower as n with $\sphericalangle_n^{\bar{n}} > 90°$

   → further selection criteria: Category C



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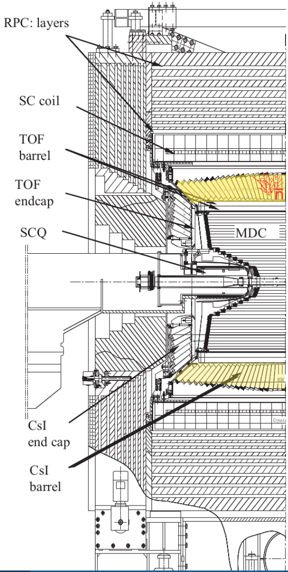

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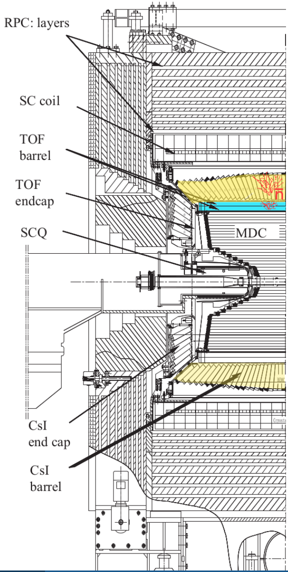

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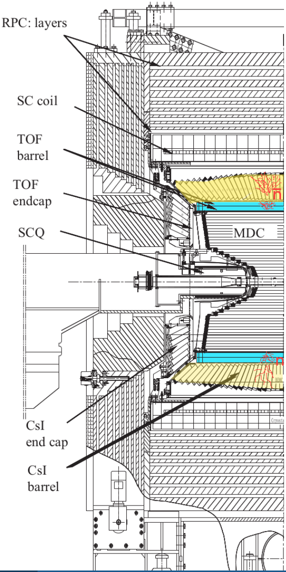

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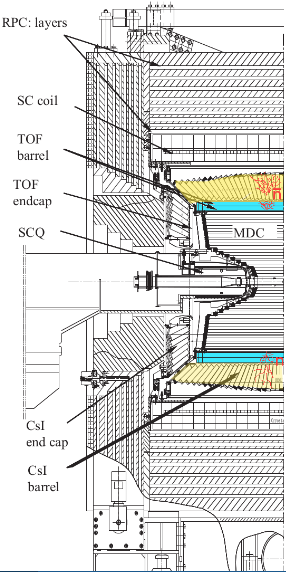

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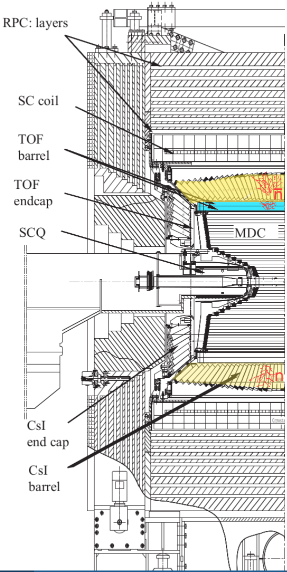

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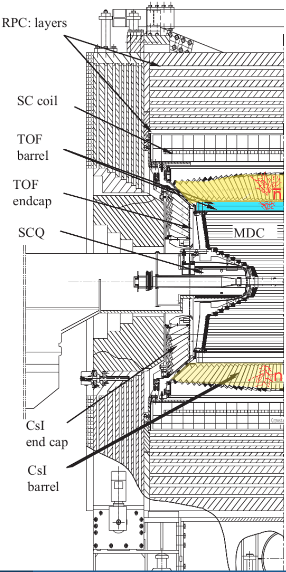

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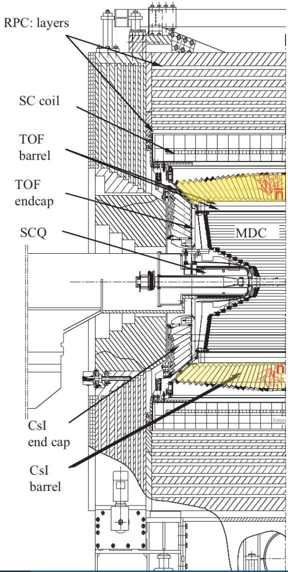

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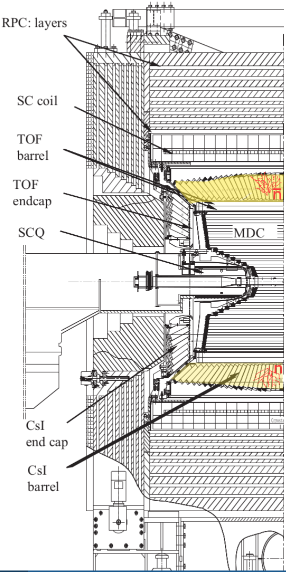
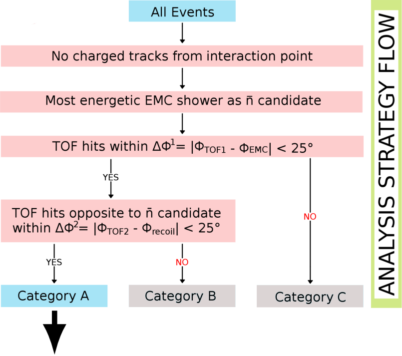
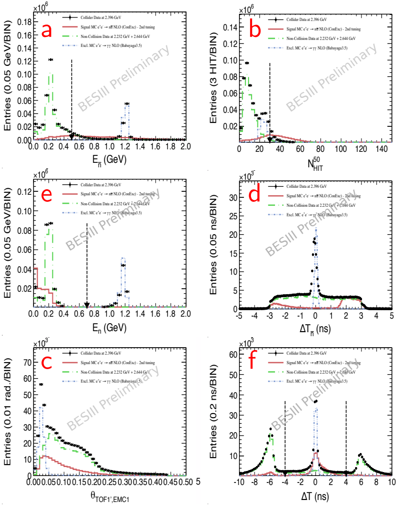


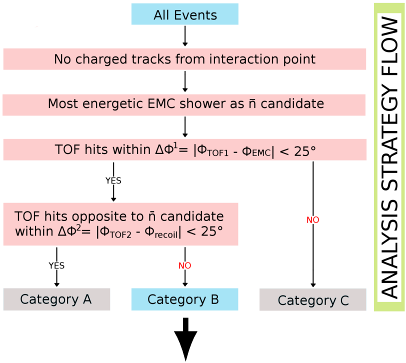
Analysis Strategy: Category A - $\bar{n}_{TOF} + n_{TOF}$

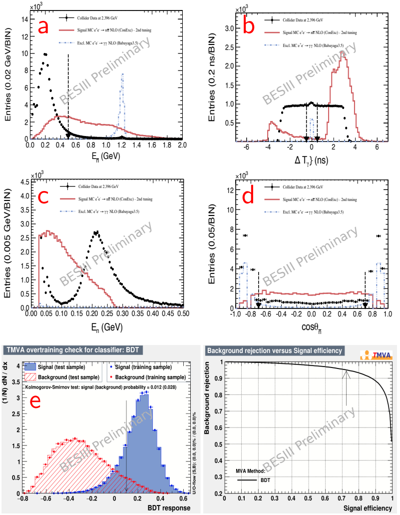




	Expression	Unit	Object	Notation
	$N_{charged} == 0$	-	$\bar{n}, n$	S_A0
a	$0.3 < E_{\bar{n}} < 2.0$	GeV	$\bar{n}$	S_A1
b	$35 < N^{50}_{HIT} < 140$	-	$\bar{n}$	S_A2
	$\lvert\cos\theta\rvert < 0.8$ ($\lvert\cos\theta\rvert < 0.7$)	radian	$\bar{n}$	S_A3 (S_A3')
	$\lvert\Delta\phi_{(TOF1,EMC1)}\rvert < 3\ \phi_c$	radian	$\bar{n}$	S_A4
c	$\theta_{(TOF1,EMC1)} < 0.5$	radian	$\bar{n}$	S_A5
d	$0.5 < \lvert\Delta T_{\bar{n}}\rvert < 10$ ($\lvert\Delta T_{\bar{n}}\rvert < 10$)	ns	$\bar{n}$	S_A6 (S_A6')
	$\lvert\Delta\phi_{(TOF2,EMC1')}\rvert < 6\ \phi_c$	radian	n	S_A7
	$\lvert\Delta T_n\rvert < 4$ ($\lvert\Delta T_n\rvert < 0.5$)	ns	n	S_A8 (S_A8')
e	$E_n < 0.7$ ($0.06 < E_n < 0.7$)	GeV	n	S_A9 (S_A9')
f	$\theta_{TOF2',EMC1} > 2.9$ ($\theta_{TOF2',EMC1} > 3.0$)	radian	$n, \bar{n}$	S_A10 (S_A10')
	$\lvert\Delta T\rvert < 4.0$	ns	$n, \bar{n}$	S_A11
	$\theta_{EMC2,EMC1} > 3.0$	radian	$n, \bar{n}$	S_A12

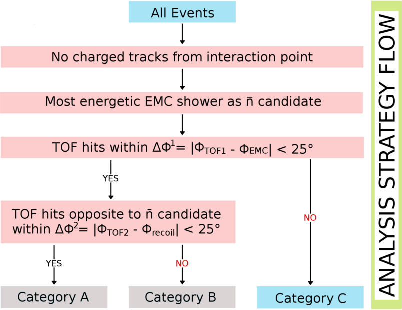
Analysis Strategy: Category B - $\bar{n}_{TOF} + n_{EMC}$



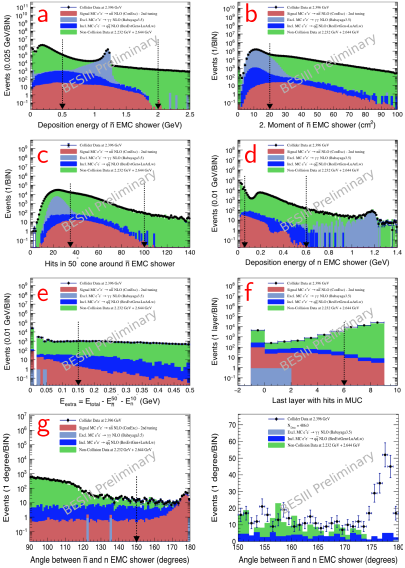


	Expression	Unit	Object	Notation
	$N_{charged} == 0$	-	$\bar{n}, n$	S_B0
a	$E_{\bar{n}} > 0.5$	GeV	$\bar{n}$	S_B1
	$T_{\bar{n}}$ valid	ns	$\bar{n}$	S_B2
b	$\lvert\Delta T_{\bar{n}}\rvert > 0.5$	ns	$\bar{n}$	S_B3
c	$0.04 < E_n < 0.5$ $(0.06 < E_n < 0.5)$	GeV	n	S_B4
	T_n not valid	ns	n	S_B5
d	$\lvert cos\theta\rvert_n < 0.75$	-	n	S_B6
e	BDT descriminator > 0.1	-	$n, \bar{n}$	S_B7

Analysis Strategy: Category C - $\bar{n}_{EMC} + n_{EMC}$



	Expression	Unit	Object	Notation
	$N_{charged} == 0$	-	$\bar{n}, n$	S_C0
	$\lvert cos\theta\rvert_{\bar{n}} < 0.75$	-	$\bar{n}$	S_C1
a	$0.5 < E_{\bar{n}} < 2.0$	GeV	$\bar{n}$	S_C2
b	$2M_{\bar{n}} > 20$	cm^2	$\bar{n}$	S_C3
c	$35 < N_{hits}^{50^\circ cone} < 100$	-	$\bar{n}$	S_C4
d	$0.04 < E_n < 0.6$ $(0.06 < E_n < 0.6)$	GeV	n	S_C5
e	$E_{extra} < 0.15$	GeV	$n, \bar{n}$	S_C6
f	$ll_{muc} < 6$	-	$n, \bar{n}$	S_C7
g	$\angle_{\bar{n}}^{n} > 150^\circ$	degree	$n, \bar{n}$	S_C8



Determination of the Signal Yield via Fit

- We use a composite fit to determine the signal event yield from data
- The signal shape is modeled with the signal MC simulation
- The background shapes are modeled with MC simulation and non-collision data samples, the normalizations are set to the luminosity of the collider data

$$\mathcal{F}(q^2) = \sum_i \mathcal{N}_i^{s,b}(q^2)\cdot PDF_i(q^2), \qquad (i = signal,\ beam,\ hadronic,\ digamma)$$

Category A: $(\text{EMC}+\text{TOF})_{\bar{n}}+(\text{TOF})_n$

Category B: $(\text{EMC}+\text{TOF})_{\bar{n}}+(\text{EMC})_n$

Category C: $(\text{EMC})_{\bar{n}}+(\text{EMC})_n$

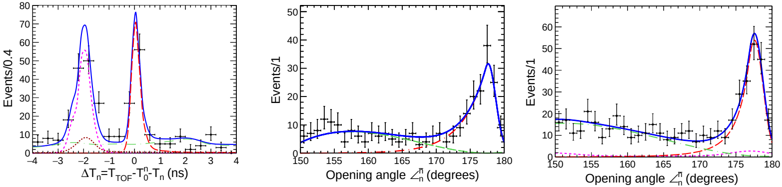
Category A:

$$\Delta T_n \equiv T_{TOF2} - T_0^n - T_n$$

$$T_n = \frac{L}{\beta C}, \beta = \frac{\sqrt{E_{cm}^2 - m^2}}{E_{cm}}$$

Categories B and C:

$$\theta_{n,\bar{n}} \equiv \arccos\left(\frac{V_{EMC1}\cdot V_{EMC2}}{|V_{EMC1}||V_{EMC2}|}\right)$$

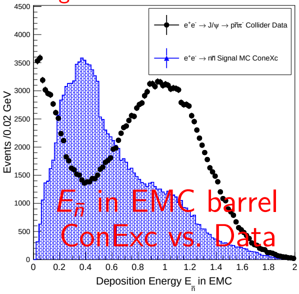


Efficiency Corrections for Born Cross Section

Reminder: Reconstruction efficiency crucial for the Born cross section determination!

$$\sigma_B^{e^+e^-\to\bar{n}n} = \frac{N_{data}}{\mathcal{E}_{MC}\times\mathcal{E}_{cor}\times\mathcal{L}_{int}\times(1+\delta)} \qquad \mathcal{E}_{cor} = \mathcal{C}_{n(\bar{n})}\times\mathcal{C}_{trg}(\times\mathcal{C}_{muc}\times\mathcal{C}_{ee}\times\mathcal{C}_{BDT}\ldots)$$

Signal MC at 2.396 GeV



Corrections for the signal MC simulation reconstruction efficiency:

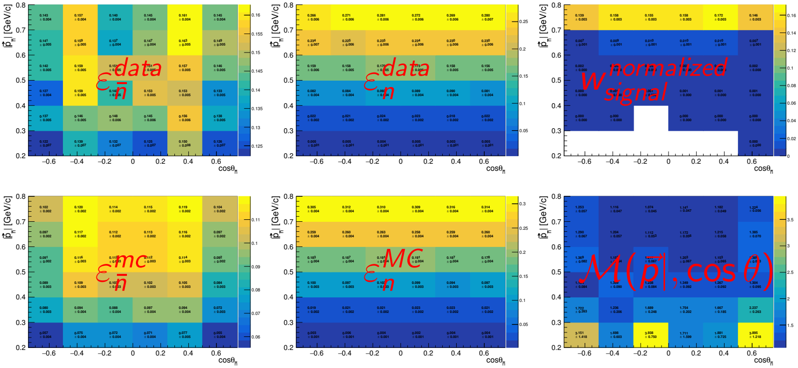
- $\mathcal{C}_{n(\bar{n})}$, $\mathcal{C}_{muc}$, $\mathcal{C}_{ee}$, $\mathcal{C}_{BDT}$: corrections due to data/MC differences
- $\mathcal{C}_{trg}$: trigger efficiency correction (data/MC differences in deposition energy)

Application of Data/MC Efficiency Correction

Data/MC efficiency correction for the selection criteria of n and $\bar{n}$ $\mathcal{C}_{n(\bar{n})}$:

$$\mathcal{M}_{j,k} = \frac{\varepsilon_{\bar{n}}^{data}(|\vec{p}|, \cos\theta)\varepsilon_{n}^{data}(|\vec{p}|, -\cos\theta)}{\varepsilon_{\bar{n}}^{MC}(|\vec{p}|, \cos\theta)\varepsilon_{n}^{MC}(|\vec{p}|, -\cos\theta)}$$

$$\mathcal{C}_{n(\bar{n})} = \sum_{j,k} \mathcal{M}_{j,k} \cdot w_{j,k}, \qquad \Delta\mathcal{C}_{n(\bar{n})} = \sqrt{\sum_{j,k} (\Delta\mathcal{M}_{j,k})^2 \cdot w_{j,k}^2,}$$



Trigger Efficiency Correction $\mathcal{C}_{trg}$

- **Category individual** trigger efficiency dependant on energy deposition in event i: based on the method from *N. Berger et al. Chin. Phys. C 34 1779 (2010).*

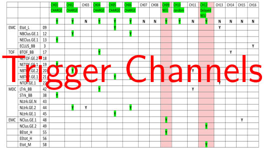
$$\mathcal{C}_{trg} = \frac{\sum_{i=1}^{N} f(E^i_{total})}{N} \quad \text{with} \quad f(E^i_{total}) = 0.5 + 0.5 Erf\left(\frac{E^i_{total} - a}{b}\right)$$

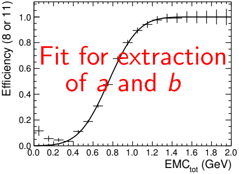
- Calculating trigger efficiency via $e^+e^- \to p\bar{p}$ (based on BESIII $e^+e^- \to \bar{p}p$): (is pre-requested trigger for charged tracks based on MDC signal)

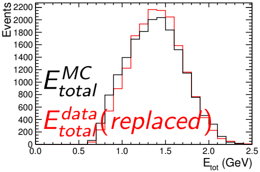
$$\mathcal{E}_{trigger}(8,11) = \frac{N_{(sel,nshower \geq 2, trigger[8]=1 || trigger[11]=1)}}{N_{(sel,nshower \geq 2)}}$$

- $a = 0.758 \pm 0.005$ and $b = 0.334 \pm 0.009$ are extracted from $e^+e^- \to p\bar{p}$ in scan data 2015 and validated with $e^+e^- \to$ hadronic inclusive and from RAW data

- **Remider**: can't rely on MC $\to$ replace E^i_{total} in signal MC with $E^i_{total}(data)$ from control samples under the requirement $|\vec{p}^{\,i}_{MC} - \vec{p}^{\,k}_{data}| < 0.1$ (GeV/c)







Estimation of the Systematic Uncertainties

- The systematic uncertainty on the Born cross section σ_B and effective form factor $|G_{eff}|$ is studied independently for each category (A, B, C)
- The systematic uncertainty on the magnetic form factor $|G_M|$ and the form factor ratio $R_{em} = |G_E|/|G_M|$ is studied from the combined analysis

σ_B and $|G_{eff}|$

- Luminosity
- Individual selection
- Fit for the signal yield extraction (fit range, signal and background model)
- Trigger efficiency
- Radiative corrections
- Iterative MC tuning

$|G_M|$

- Differential selections
- Differential signal yield extraction (range, signal and background model)
- Luminosity
- Trigger efficiency
- Radiative corrections
- Iterative MC tuning

$|R_{em}| = |G_E|/|G_M|$

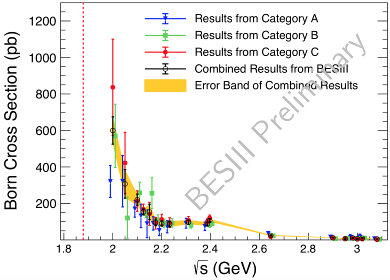
- Differential selection
- Differential signal yield extraction (range, signal and background model)
- Bin width
- Angular fit range
- Radiative corrections

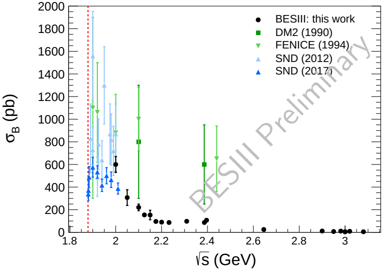
Discussion of the Results

Results for the Born Cross Section: $\sigma_B(e^+e^- \to \bar{n}n)$

Results from three categories A, B, C consistent within 1 standard deviation:
$\to$ **error weighted combination**

$$\sigma_B^{av} = \sum_i w_i \sigma_i, \quad \Delta\sigma_B^{av} = \sqrt{\frac{1}{\sum V_j}}, \quad w_i = \frac{V_i}{\sum V_j}, \quad V_j = \frac{1}{(\Delta\sigma_j)^2}, \quad i,j = A, B, C$$

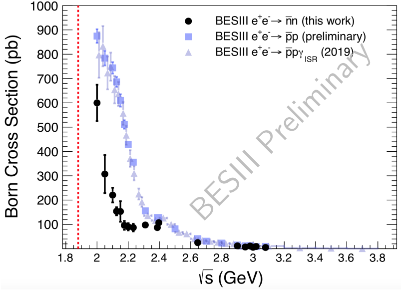


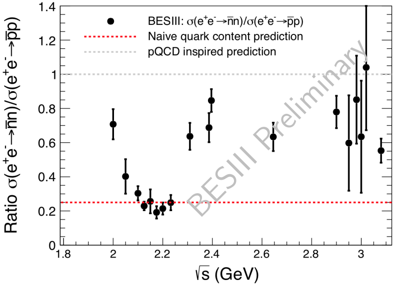


- **Unrivaled precision**: best is achieved at $\sqrt{s} = 2.396$ GeV with 7.3%
- σ_B^{av} in **agreement** at $\sqrt{s} = 2.0$ GeV with FENICE and SND results
- σ_B^{av} in **disagreement** at $\sqrt{s} = 2.396$ GeV with FENICE results ($\sim 2\sigma$)

Born Cross Section for $e^+e^- \to \bar{n}n$ and $e^+e^- \to \bar{p}p$

Reminder: Surprising results from FENICE experiment: $R_{np} = \sigma_B^{n\bar{n}} / \sigma_B^{p\bar{p}} \sim 2$





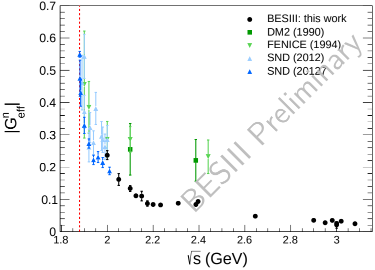
- Born cross section **different** below $\sqrt{s} = 2.4$ GeV, **similar** above
- Ratio of Born cross sections R_{np} shows a **structure** around $\sqrt{s} = 2.2$ GeV
- **Predictions**: pQCD[1]: $R_{np} < 1$, quark counting[2]: $R_{np} \sim |q_d/q_u|^2 \sim 0.25$
- Our results **do not support** the results from FENICE ($R_{np} \sim 2$)

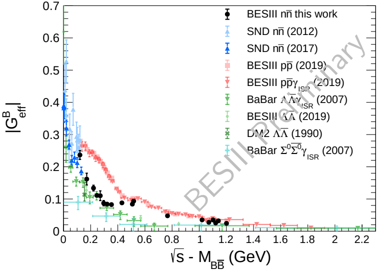
1 J. Ellis, and M. Karliner, New J. Phys. 4, (2002) 18.

2 V.L.Chernyak,I.R.Zhitnitsky, Nucl.Phys. B246 (1984) 52.

Results for the Effective Form Factor $|G^n_{eff}|$

Reminder: Effective Form Factor: $|G^n_{eff}| = \sqrt{\frac{\sigma_B}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta\mathcal{C}}{3q^2})}} \propto \sigma_B$





- $|G^n_{eff}|$ similar to results for $\mathbf{\Lambda}$ and $\mathbf{\Sigma}$ below $\sqrt{s} - M_{B\bar{B}} = 0.3$ GeV
- Similar to results for **proton** above $\sqrt{s} - M_{B\bar{B}} = 0.3$ GeV
- Shows a plateau between $\sqrt{s} - M_{B\bar{B}} = 0.3 - 0.6$ GeV

Periodic Structure[1] in the Effective FF $|G_{eff}|$

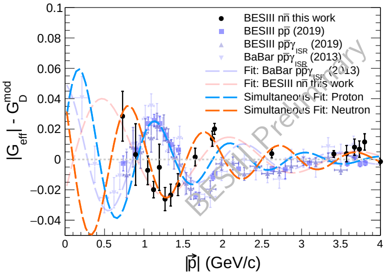
$$|G_D^{mod}| = \frac{1}{\left(1 - \frac{q^2}{(0.71\ GeV)^2}\right)^2} \cdot \frac{\mathcal{A}}{1+\frac{q^2}{m_a^2}}$$

BaBar: $\mathcal{A} = 7.7\ \text{GeV}^{-4}$, $m_a^2 = 14.8\ \text{GeV}^2$

BESIII: $\mathcal{A} = 4.9\ \text{GeV}^{-4}$, $m_a^2 = 14.8\ \text{GeV}^2$

$$F_{osc}(|\vec{p}|) = A\exp(-B)\cos(C + D)$$

A: normalization, B^{-1}: damping, C: frequency, D: phase

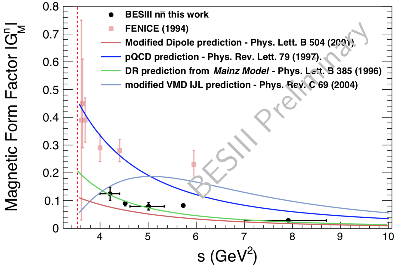


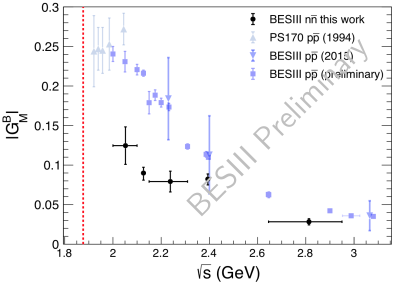
- **Oscillation:** Interference in final state rescattering[1]? Resonant structure[2]?
- **Similar oscillation** of $|G_{eff}^n|$ observed, comparable to the proton results
- F_{osc} **describes** the neutron results **well** $(\chi^2/dof = 23.1/14)$
- **Simultaneous fit**: shared $C = 6.6 \pm 0.1\ \text{GeV}^{-1}$, $\Delta D = (235.5 \pm 10.8)^\circ$

1 A. Bianconi and E. Tomasi-Gustafsson, Phys. Rev. C 93, 035201, (2016).

2 I. T. Lorentz, H.-W. Hammer, and U.-G. Meiner, Phys. Rev. D 92, 034018 (2015).

Results for the Magnetic Form Factor $|G_M^n|$

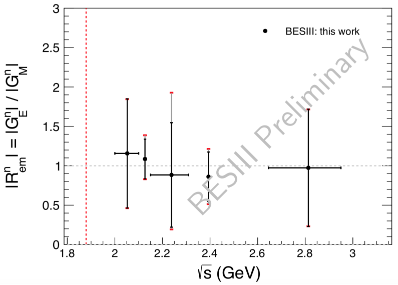


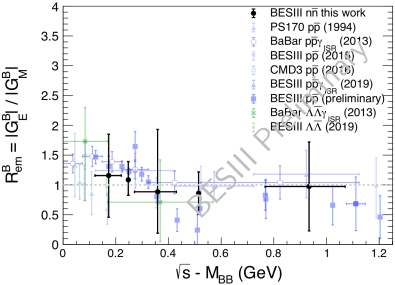


- First measurement of $|G_M^n|$ in the TL region above $\sqrt{s} = 2.0$ GeV
- Statistical precision: **9.5%** and **7.1%** at $\sqrt{s} = 2.127$ and 2.394 GeV
- Our results are in **agreement** with the **DR Mainz model**
- Results are in **disagreement** with other models[1,2,3] (normalization?)

1 Modified Dipole prediction: Phys. Lett. B 504 (2001)
2 pQCD prediction: Phys. Rev. Lett. 79 (1997)
3 Modified Vector Meson Dominance model: Phys Rev. C 69 (2004)

Results for the Form Factor Ratio $R_{em}^n = |G_E^n| / |G_M^n|$

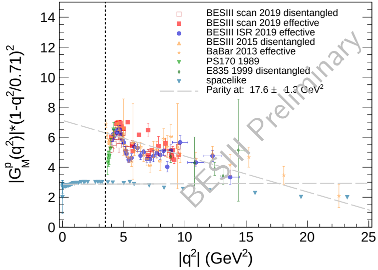


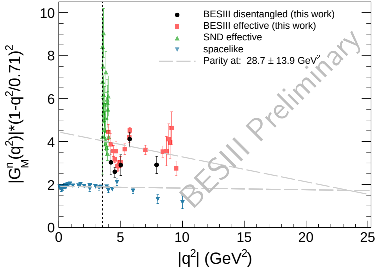


- First measurement of R_{em}^n in the TL region above $\sqrt{s} = 2.0$ GeV
- Statistical precision: **35.7%** and **52.2%** at $\sqrt{s} = 2.127$ and 2.394 GeV
- Our results are in **agreement** with $\boldsymbol{R_{em} = 1}$
- The uncertainty is **dominated by the statistical precision**

Nucleon Form Factors in the SL and TL Region

Reminder: pQCD predicts asymptotic behavior for SL and TL form factors[1]





- Linear fit: Proton FFs SL = TL at $\mathbf{17.6 \pm 1.2}$ **GeV²**
- Neutron FFs SL = TL at $\mathbf{28.7 \pm 13.9}$ **GeV²** (w/o data at $\sim$ 7 GeV)
- The **TL results** for proton and neutron are **larger** than the SL results
- In future: Take the periodic structure into account?

1 S. D. Drell and F. Zachariasen, "Electromagnetic Structure of nucleons", Oxford University Press, (1961).

Summary

- BESIII provides excellent conditions to measure the nucleon FFs
- The SL electromagnetic structure of the nucleon (G_{eff}, G_E, G_M, R_{em}) has been measured in a wide energy range for $-10 > q^2 > 30$ GeV

  → BESIII performed high precision measurements for proton and neutron in the TL region
- σ_B for $e^+e^- \to \bar{n}n$ has been measured for $\sqrt{s} = 2.0 - 3.08$ GeV
- The results on $\boldsymbol{\sigma_B}$ from BESIII show an **unprecedented precision**
- The Born cross section ratio $\boldsymbol{R_{np} < 1}$ **contradicts the FENICE results**
- A **periodic structure** has been observed in the effective form factor $|\boldsymbol{G^n_{eff}}|$
- The magnetic form factor $|G_M|$ and the electromagnetic form factor ratio $|R_{em}| = |G_E|/|G_M|$ of the neutron have been measured for the first time!
- A **test for the asymptotic behavior** of the FFs has been performed

THANK YOU!