Measurement of Timelike Neutron Form Factors at BESIII

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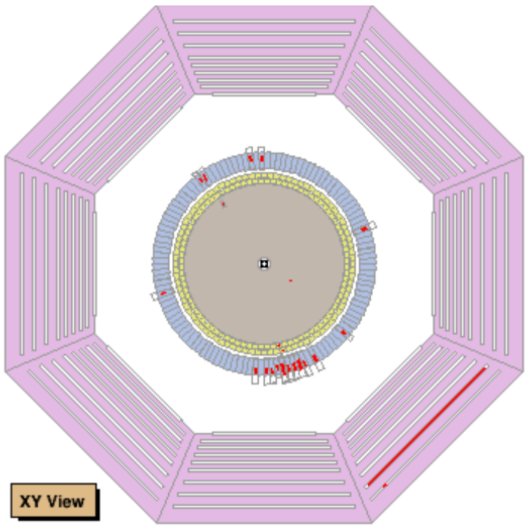
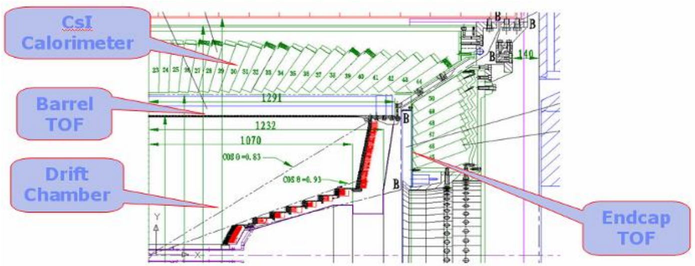
Outline

- Introduction
- Event selection
- Signal extraction
- Efficiency correction
- Angular distribution
- Cross section
- Conclusion

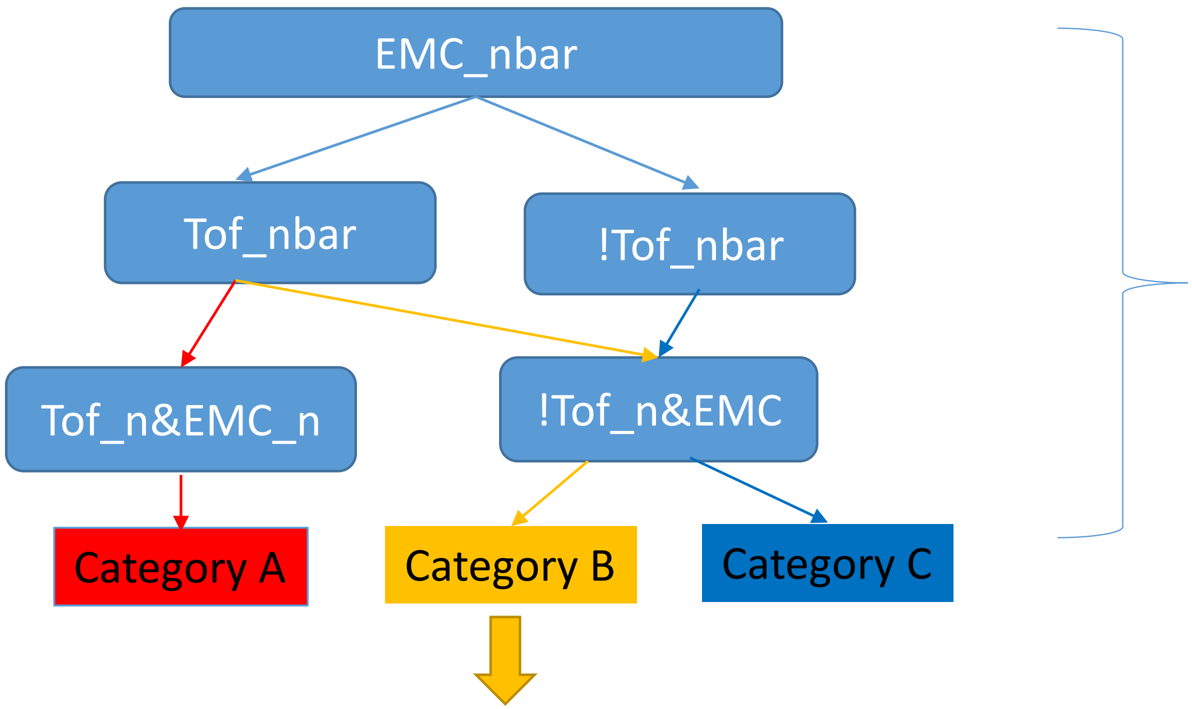
Basic idea of the event selection

- Number of charged tracks equals to 0, $N_{track}=0$
- Most energetic shower as $\bar{n}$ candidate
- Searching for neighbor TOF counters
  - 1. Locate X, Y in TOF
  - 2. Find out all the hit information in raw data within $\Delta\Phi < 25°$ ($\Delta\Phi = |\Phi_{tof} - \Phi_{EMC}|$
  - 3. Determine Z in TOF, select the hit in tof with minimum $\Delta\forall$
  - $t_{texp} = L/(\beta c), \beta = p/\sqrt{p^2c^2 + M^2c^4}$
  - t_0: determined under photon/neutron hypothesis $(t_{tof} - t_{texp})/N_{bcht}$
- Search for back-to-back TOF counter as neutron
- No neutron TOF? Search for second energetic shower as neutron



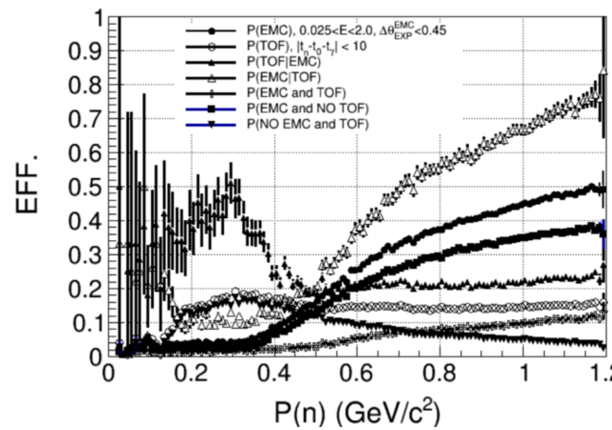


Analysis strategy

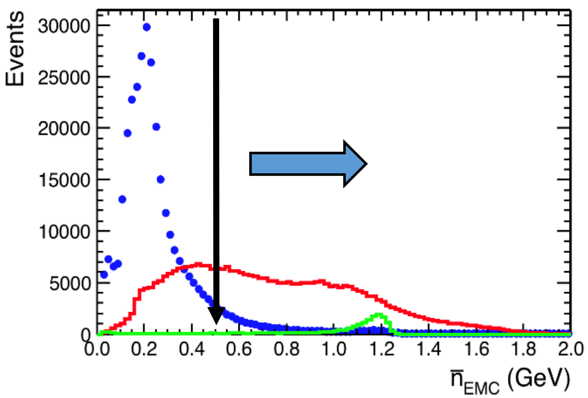


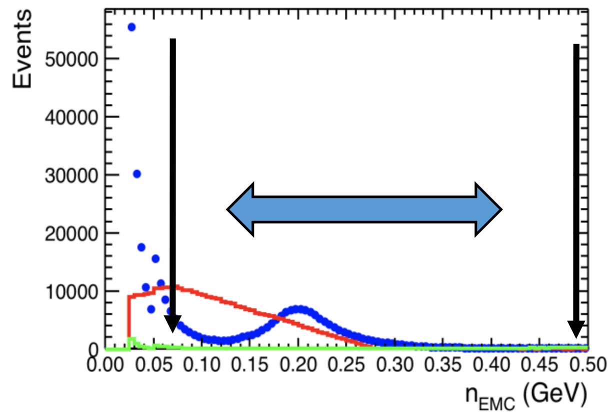
Event distribute

Expression	cut value	comments
$N_{charged}$	=0	number of charged track without constraint on vertex
$E_{\bar{n}}$	> 0.5 GeV	energy deposition of $\bar{n}$ candidate in EMC
$\|\Delta T_{\gamma 1}\|$	> 0.5 ns	time diifference for γ hypothesis
E_n	|0.06, 0.5| GeV	energy deposition of n candidate in EMC
$cos\theta$	> 0.75	polar angle of n candidate
BDT descriminator	> 0.1	MVA output with seven input variables



Distributions used in category B

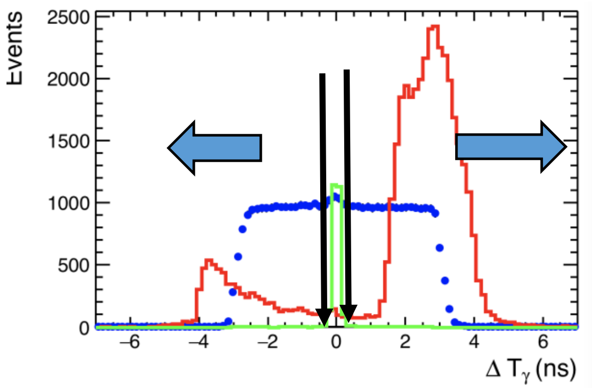


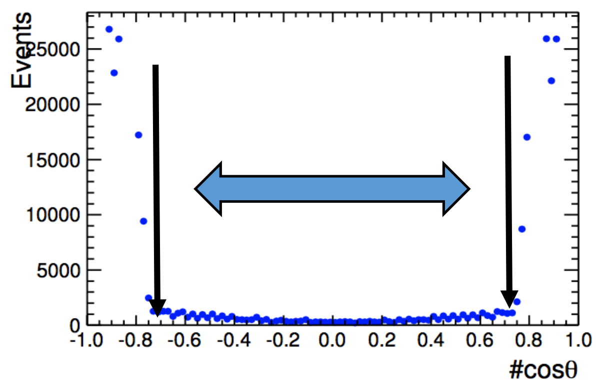


Ensure trigger efficiency &

Remove beam-associated bkg

- ➢ $\bar{n}_{EMC}$>0.5 GeV
- ➢ 0.06<n_{EMC}<0.5 GeV





Remove digam bkg

- ➢ $|\Delta T_{\gamma}|$>0.5 ns
- ➢ $|\cos\theta| < 0.75$

Application of BDT

- TMVA is applied for further selection, with the variables all from **track** level.
- In TMVA (BDT booked):
  - Signal:
    - ★ n and n̄ are selected from $J/\psi \to pn\pi$
    - ★ The β in control sample is suitable for different β in signal process
    - ★ Six momentum region selected for energy points between 2.1 to 3.08 GeV
  - Background:
    - ★ Treat survived data as background, since S/B is extremely low

$\sqrt{s}$ (GeV)	$\beta 1$	$\beta 2$
2.1	0.45	[0.42, 0.50]
2.125	0.47	
2.175	0.50	[0.5, 0.57]
2.2	0.52	
2.2324	0.54	
2.3094	0.58	[0.55, 0.60]
2.3864	0.62	[0.60, 0.65]
2.396	0.62	
2.6444	0.70	[0.68, 0.72]
2.90	0.76	>0.7
3.08	0.79	

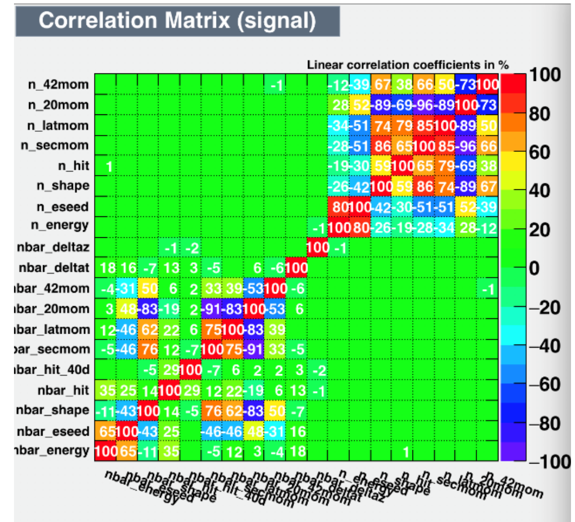
$\beta 1$: $\beta = \sqrt{1 - \frac{4m_p^2}{s}}$ in signial region

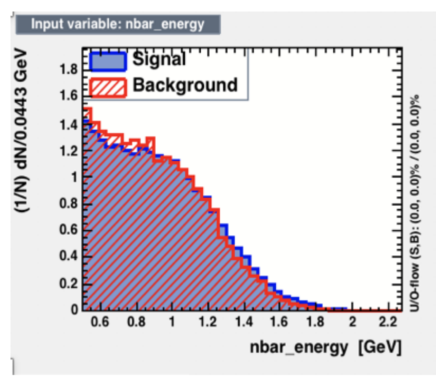
$\beta 2$: $\beta = p/E$ of recoiled $p\pi$ in control sample

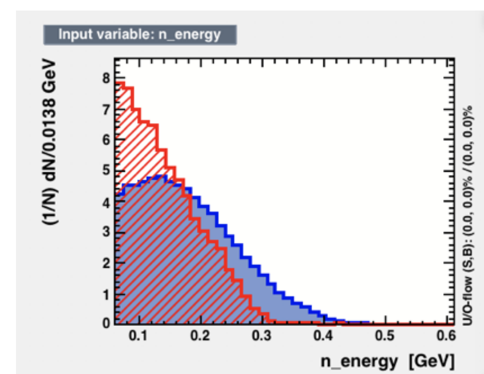
Application of BDT

- Selection of variables

Emc based		Tof based
nbar_energy	n_nergy	**nbar_ΔT_{nbar}**
nbar_eseed	n_eseed	**nbar_Δz**
nbar_shape	n_shape	
nbar_hit	**n_hit**	
nbar_hit_40d		
nbar_secmom	n_secmom	
nbar_latmom	n_latmom	
nbar_A20mom	n_A20mom	
nbar_A42mom	n_A42mom	







remove large correlated variables
remove variables varies a lot with momentum

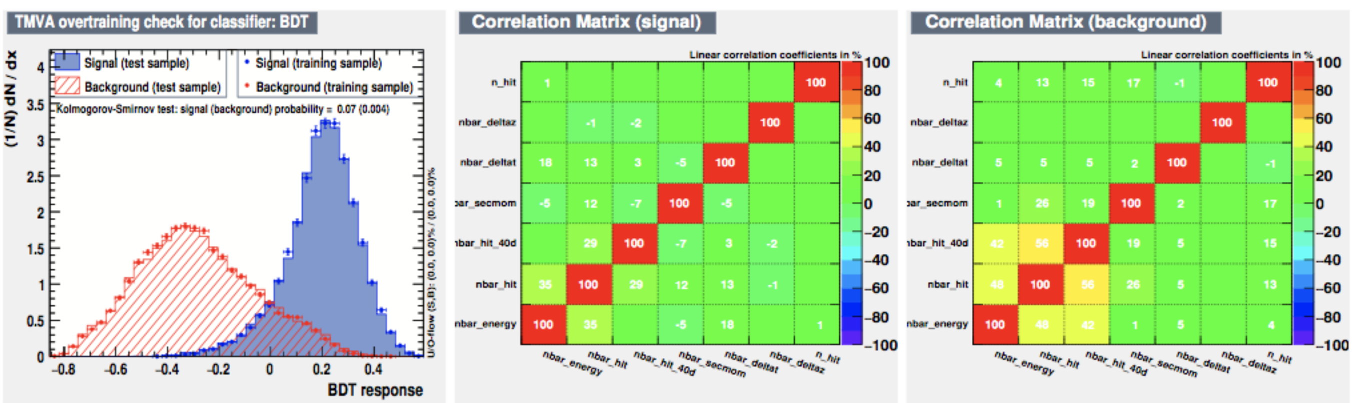
variables in β region [0.6, 0.65] & [0.55, 0.7]

Application of BDT

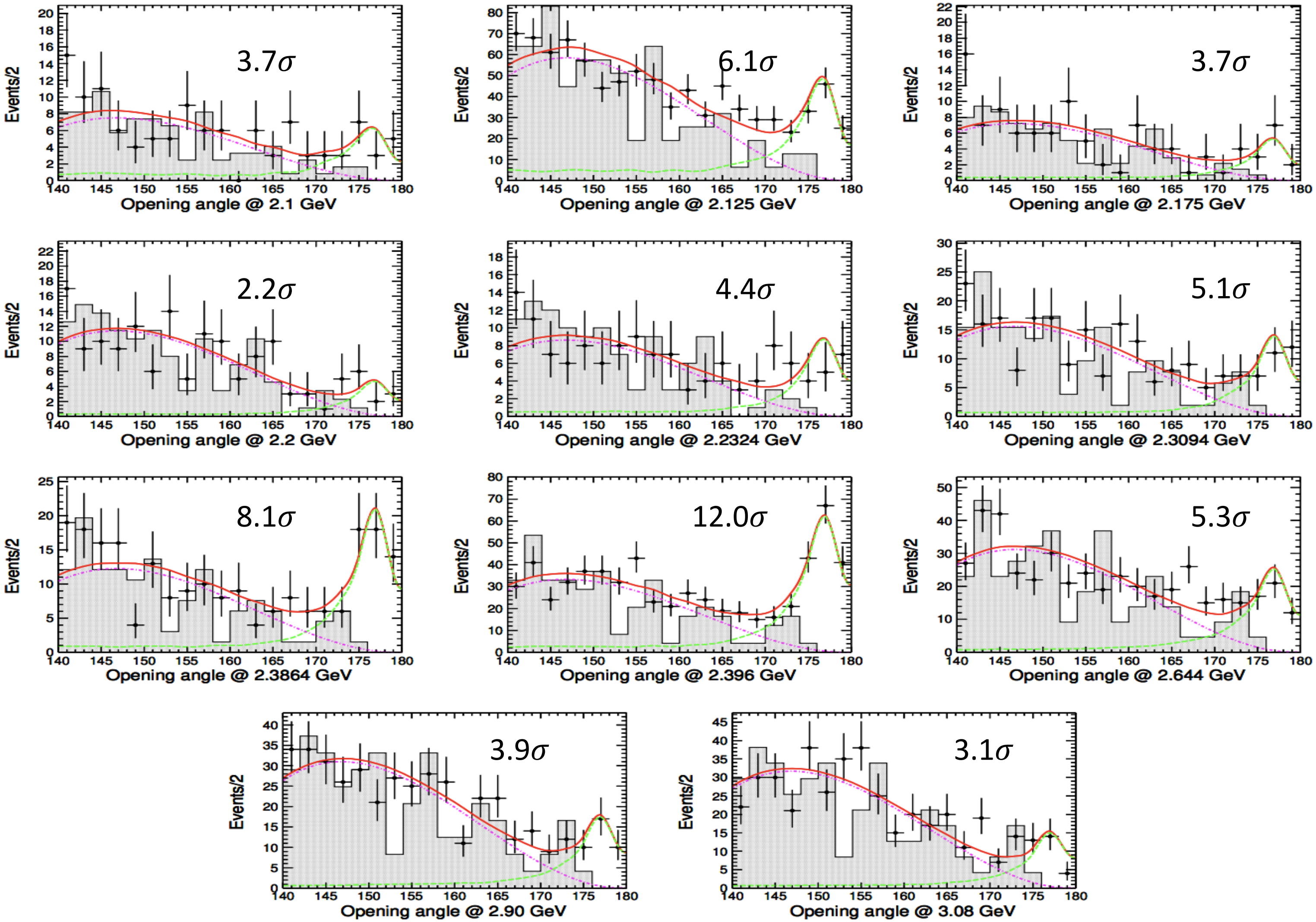
Table 6: The variables used in the BDT classifier, ranked by the importance at $\sqrt{s}$=2.396 GeV.

Rank	Variable	Importance	comment
1	*nbar_hit_40d*	2.400e-01	number of hit within 40° cone of $\bar{n}$ shower
2	*nbar_deltat*	1.936e-01	$T_{TOF1} - T_{\bar{n}} - T_0$
3	*nbar_energy*	1.459e-01	deposition energy of $\bar{n}$ in EMC
4	*n_hit*	1.257e-01	number of hit of n shower
5	*nbar_hit*	1.074e-01	number of hit of $\bar{n}$ shower
6	*nbar_deltaz*	9.700e-02	distance difference of $\bar{n}$ between tof and EMC in z direction
7	*nbar_secmom*	9.030e-02	second moment of $\bar{n}$

- The output descriminator of BDT training are shown in Fig. 3.



Signal extraction



Efficiency correction

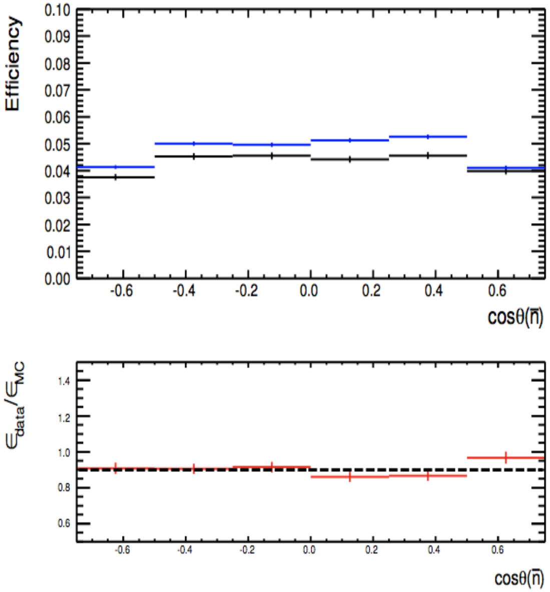
- Definition
  - $\varepsilon_{\bar{n}}(p, cos\theta)$, efficiency at the momentum, polar angle space for anti-neutron
  - $\varepsilon_{n}(p, cos\theta)$, efficiency at the momentum, polar angle space for neutron
- In signal case, anti-neutron and neutron emitted oppositely, negatively correlated
  - antineutron emitted at $(p, cos\theta)$, then neutron expected at $(p, -cos\theta)$
  - P=$\sum_{p}^{cos\theta} f_{\bar{n}}(p, cos\theta)\ \varepsilon_{\bar{n}}(p, cos\theta)\varepsilon_{n}(p, -cos\theta)$
  - $\varepsilon_{n}(p, -cos\theta)$=$\varepsilon_{n}(p, cos\theta)$ since angular distribution symmetry
- If there are some event level selections,
  - P=$\sum_{p}^{cos\theta} f_{evt}(n, \bar{n}) f_{\bar{n}}(p, cos\theta)\ \varepsilon_{\bar{n}}(p, cos\theta)\varepsilon_{n}(p, -cos\theta)$, the efficiency will affect since no control sample to determine $f_{evt}(n, \bar{n})$
  - In category B case, no event level selections, we use

$$P=\sum^{cos\theta} f_{\bar{n}}(cos\theta)\ \varepsilon_{\bar{n}}(cos\theta)\varepsilon_{n}(cos\theta)$$

(assuming p makes no difference on the efficiency in a narrow momentum region)

Efficiency correction

- Three data/MC correction curves
  - nbar-based selection
  - n-based selection
  - BDT discriminator
- Efficiency curve expressed versus cos-theta, the difference curve has weak dependence with cos-theta.
- The difference can fitted with a linear function under $|G_E/G_M|$ assumption.



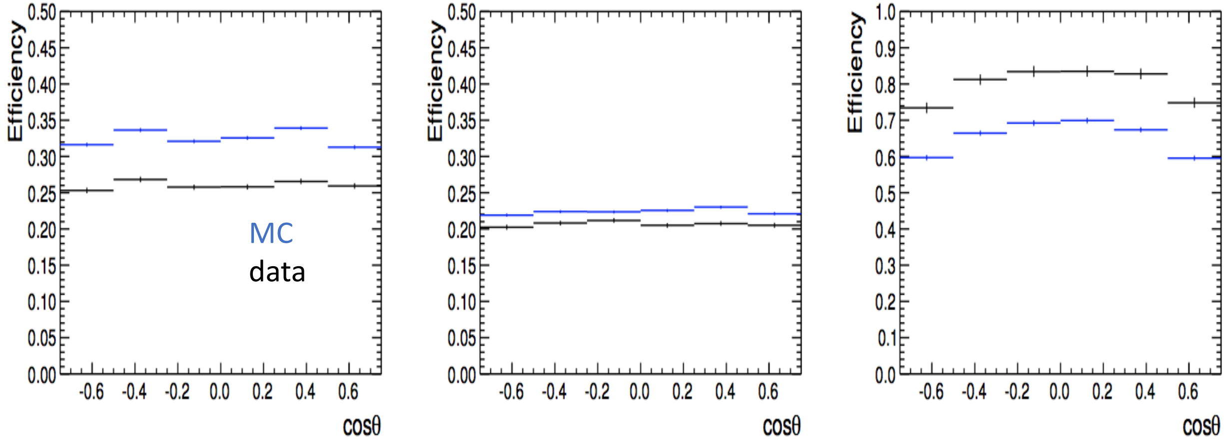


Table 12: Corrections of Detection Efficiency.

$\sqrt{s}$	ϵ_{cor}
2.1, 2.125	0.86 ± 0.02
2.175, 2.2, 2.2324	0.89 ± 0.02
2.3094	0.87 ± 0.02
2.3864, 2.396	0.90 ± 0.01
2.644	0.84 ± 0.01
2.90, 3.08	0.82 ± 0.01

Cross sections and FFs

Experimentally, the Born cross sections of $e^+e^- \to n\bar{n}$ can be calculated by

$$\sigma_{Born} = \frac{N^{\mathrm{obs}}}{\mathcal{L}_{\mathrm{int}}\,(1+\delta)\,\epsilon_{mc}\,\epsilon_{cor}}$$

The theoreitcal Born cross section of baryon pair from e^+e^- annihilation can be expressed as:

$$\sigma_{Born} = \frac{4\pi\alpha^2 C\beta}{3s}[|G_M|^2 + \frac{2m^2}{s}|G_E|^2]$$

The effective form factor defined by

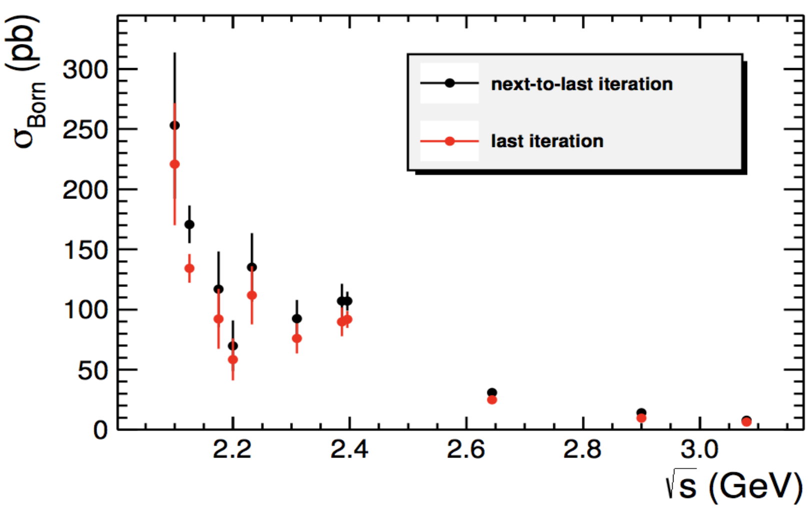
$$|G| = \sqrt{\frac{|G_M|^2 + (2m^2/s)|G_E|^2}{1 + 2m^2/s}}$$

is proportional to the square root of the baryon pair production cross section, which can be calculated accroding to

$$|G| = \sqrt{\frac{3s\sigma_{Born}}{4\pi\alpha^2\beta(1 + 2m^2/s)}}$$

Cross sections and FFs

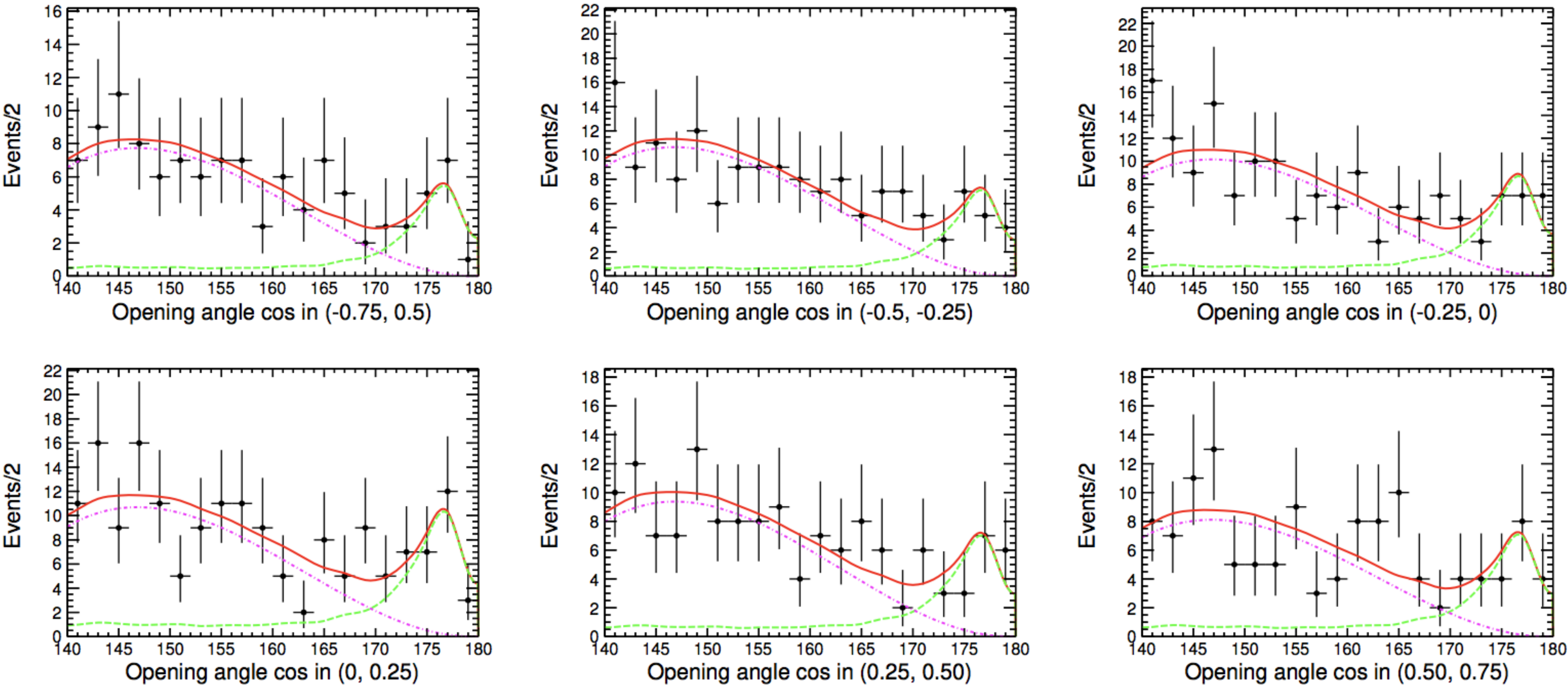
$\sqrt{s}$ (GeV)	N^{obs}	$\mathcal{L}_{int}$ (pb^{-1})	$(1+\delta)$	ϵ_{mc} (%)	ϵ_{cor}	σ_{Born} (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)	significance
2.1000	31.7 ± 7.6	12.2	0.99	1.39	0.86	220.8 ± 50.8	13.4 ± 1.5	3.7σ
2.1250	223 ± 20	108.5	1.08	1.64	0.86	134.3 ± 12.0	10.4 ± 0.5	6.1σ
2.1750	22.2 ± 5.9	10.6	1.12	2.27	0.89	92.2 ± 24.9	8.5 ± 1.2	3.7σ
2.2000	19.6 ± 5.9	13.7	1.09	2.54	0.89	58.4 ± 17.5	6.8 ± 1.0	2.2σ
2.2324	35.0 ± 7.5	11.9	1.05	2.83	0.89	111.7 ± 24.6	9.4 ± 1.0	4.4σ
2.3094	52.9 ± 8.9	21.1	1.10	3.48	0.87	75.9 ± 12.5	7.8 ± 0.6	5.1σ
2.3864	77 ± 10	22.5	1.04	4.05	0.90	89.7 ± 11.8	8.5 ± 0.6	8.1σ
2.3960	233 ± 17	66.9	1.03	4.06	0.90	91.7 ± 7.1	8.6 ± 0.3	12.0σ
2.6444(+2)	99 ± 12	67.7	1.45	4.83	0.84	24.8 ± 3.2	4.7 ± 0.3	5.3σ
2.9000	68 ± 10	105.3	1.68	4.89	0.82	9.7 ± 1.6	3.2 ± 0.3	3.9σ
3.0800	59 ± 10	126.2	1.87	4.77	0.82	6.4 ± 1.2	2.7 ± 0.2	3.1σ



- Different angular distribution
  - First iteration : $1 + cos^2\theta$
  - Second iteration: 1
- Different line-shape

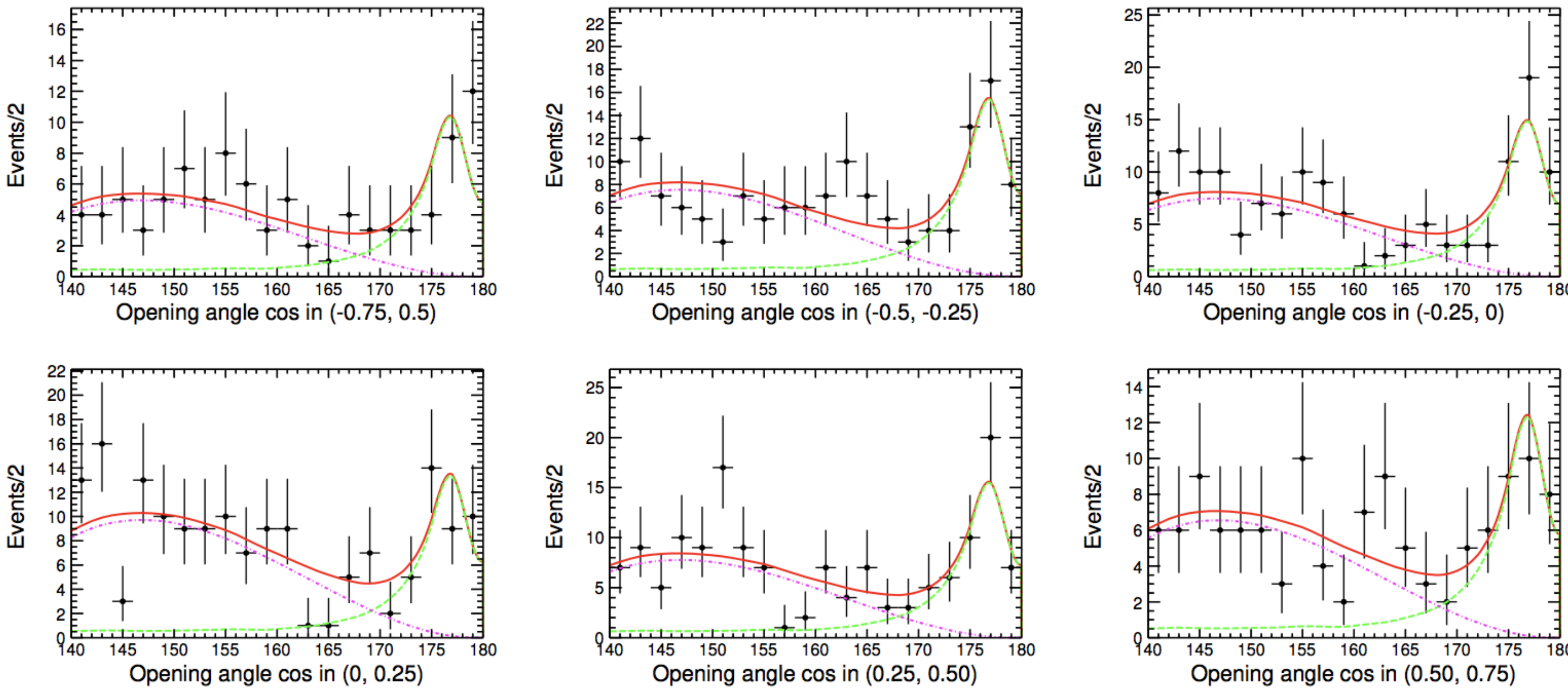
Angular analysis at $\sqrt{s} = 2.125$ GeV

- Divide cos-theta into 6 bins
- Fit opening angle in each bin



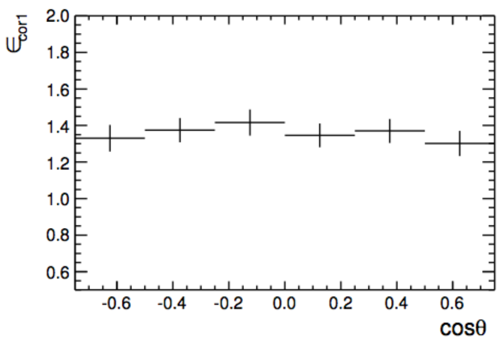
Angular analysis at $\sqrt{s} = 2.3864, 2.396$ GeV

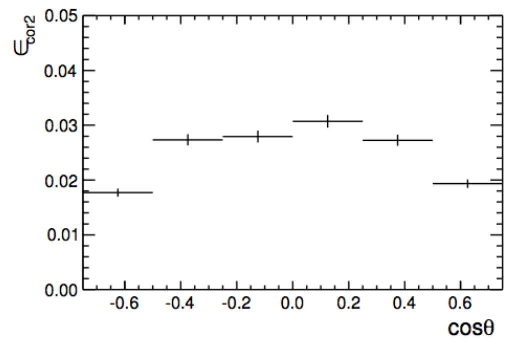
- Combined energy points $\sqrt{s} = 2.3864, 2.396$ GeV

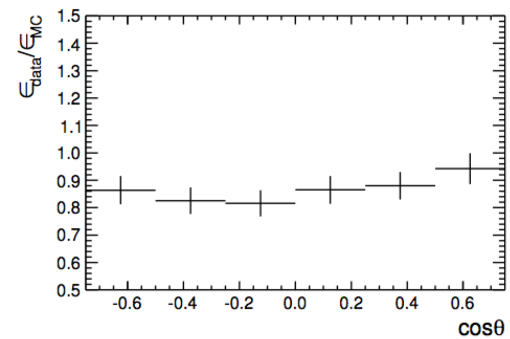


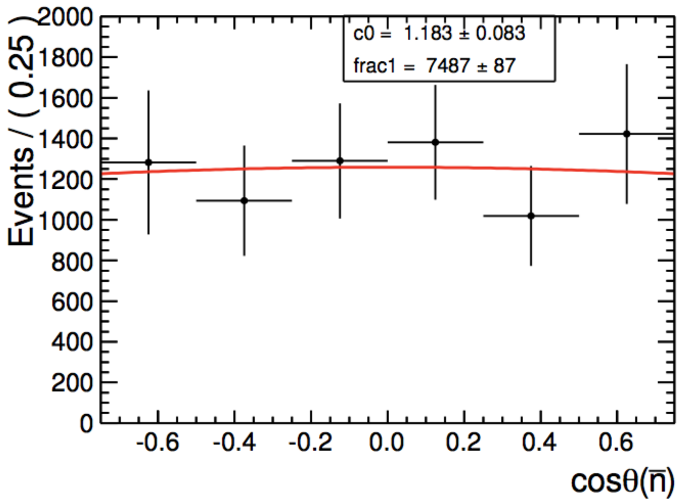
Efficiency correction for Angular distribution

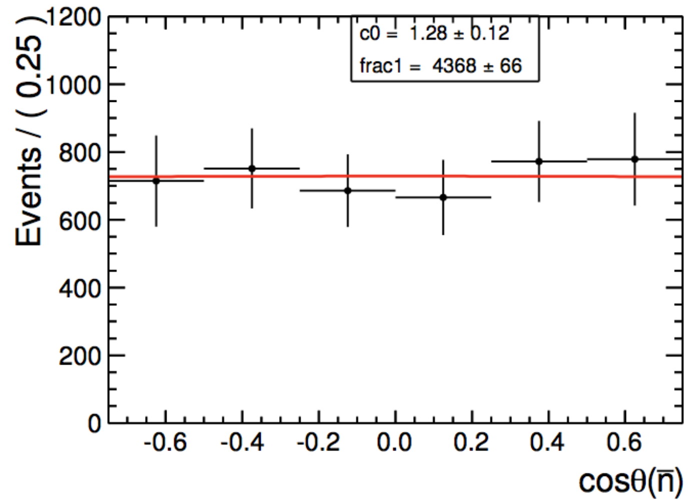
1. Correction1: ratio of the observed events to its Born level
2. correction2:ratio of reconstructed level to its generated level
3. correction 3: efficiency difference between data and MC











Extraction of GE/GM ratio

The total efficiency correction is the multiply of the three corrections described above. The distribution of neutron polar angle $\theta_{\bar{n}}$ in data dividing the correction curve is shown in Fig. 12. The angular dsitribution depends on the electric and magnetic FFs, expressed as:

$$F(\cos\theta(\bar{n})) = N_{\text{norm}}[1 + \cos^2\theta + \frac{4m^2}{s}R^2(1 - \cos^2\theta)] \quad (12)$$

where $R = |G_E/G_M|$ is the ratio of electric to magnetic FFs, and N_{norm} is the overall normalization factor. Both R and N_{norm} can be extracted directly by fitting the $\cos\theta$ distriutions with Eq. 12.

$$N_{norm} = \int_{-0.75}^{0.75} \frac{\pi\alpha^2\beta\mathcal{L}}{2s}[G_M^2(1 + \cos\theta^2) + \frac{4m^2}{s}G_E^2(1 - \cos\theta^2)] = \frac{\pi\alpha^2\beta\mathcal{L}}{2s}[1.78 + 4.87\frac{m^2}{s}R^2]G_M^2 \quad (13)$$

The corresponding ratios $R = |G_E/G_M|$ and $|G_M|$ are shown in Table 9.

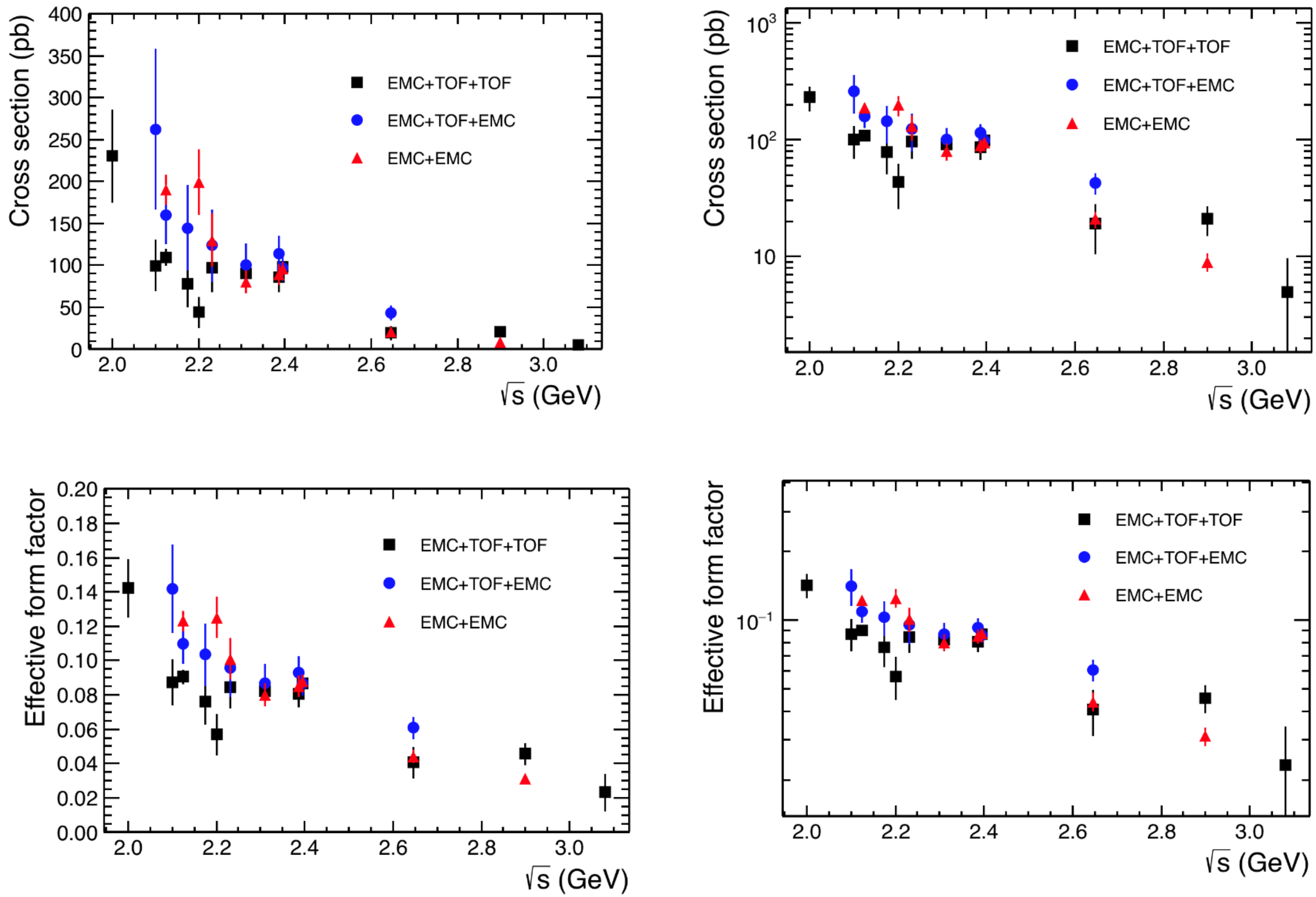
Table 9: Summary of the ratio of electric to magnetic FFs $|G_E/G_M|$ and magnetic FF $|G_M|$ by means of fitting on the distribution of $\cos\theta$.

$\sqrt{s}$ GeV	$\|G_E/G_M\|$	$\|G_M\|$ ($\times10^{-2}$)
2.125	1.18 ± 0.08	8.1 ± 0.3
2.3864+2.396	1.28 ± 0.12	6.8 ± 0.3

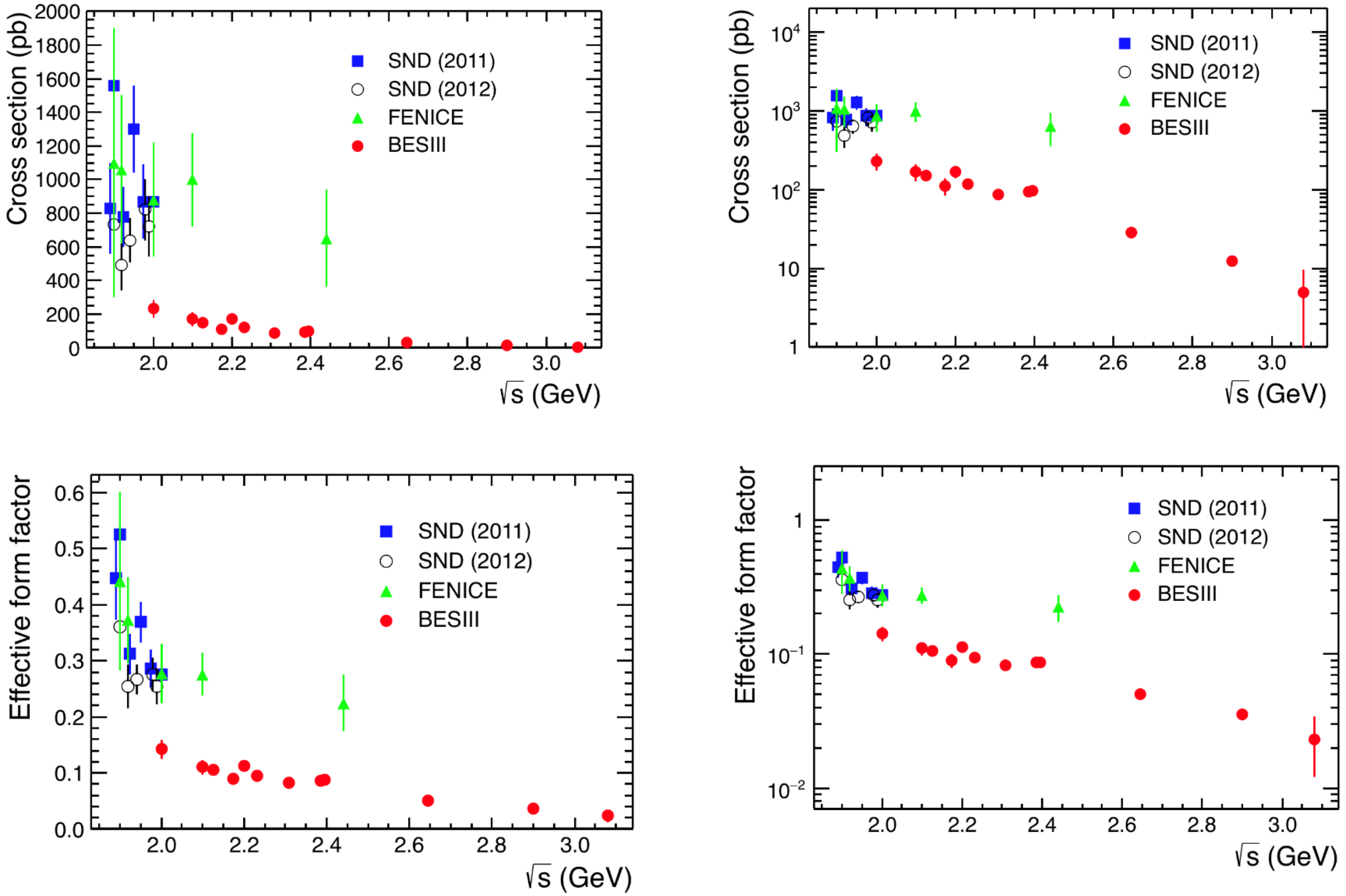
Systematic uncertainty

Sources	Uncertainty	Comments
nbar enegy	2.9%	varying energy threshold of nbar in EMC
n energy	8.5%	varying energy threshold of n in EMC
cut-based	6.7%	using pure cut-based selection
MLP	~4.0%	using MLP method to train
BDT input	~4.8%	different BDT input variables
BDT>0.15	~4.0%	different BDT>0.1 to BDT>0.15
correction factor	2.3%	1σ data/MC correction factor
line-shape	<1%	last two iterations
Angular distribution	<10% for 2.125, 2.3864, 2.396 GeV ~20% for other energy points	Varying G_E/G_M ratio within 1σ Difference $\|G_E\|=0$, $\|G_M\|=0$
Luminosity	1%	
In total	<16.9% for 2.125, 2.3864, 2.396 GeV ~24.2% for other energy points	

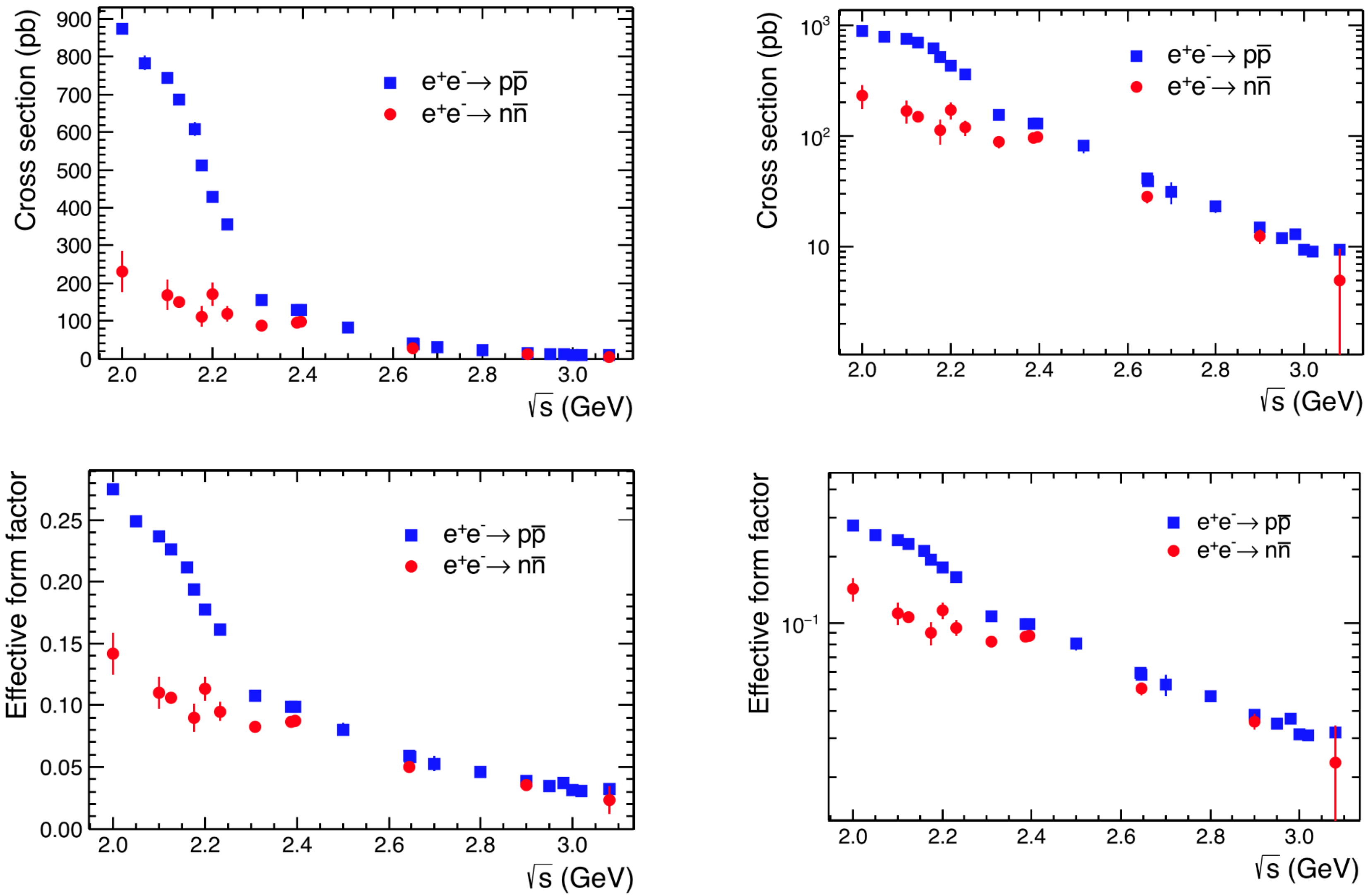
Compare of Cross section and Effective form factor (not updated)



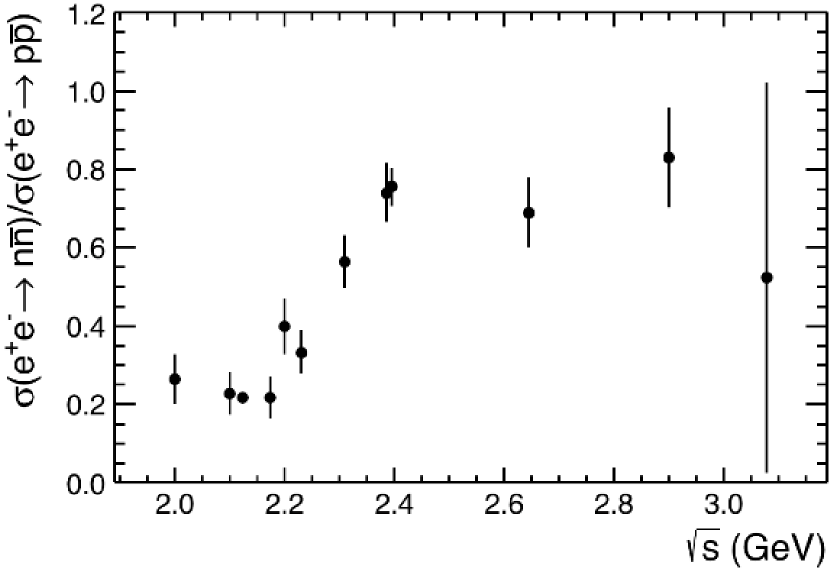
Comparison with other experimental results (not updated)



Comparison with $e^+e^- \to p\bar{p}$ (not updated)



Comparison with $e^+e^- \to p\bar{p}$ (not updated)



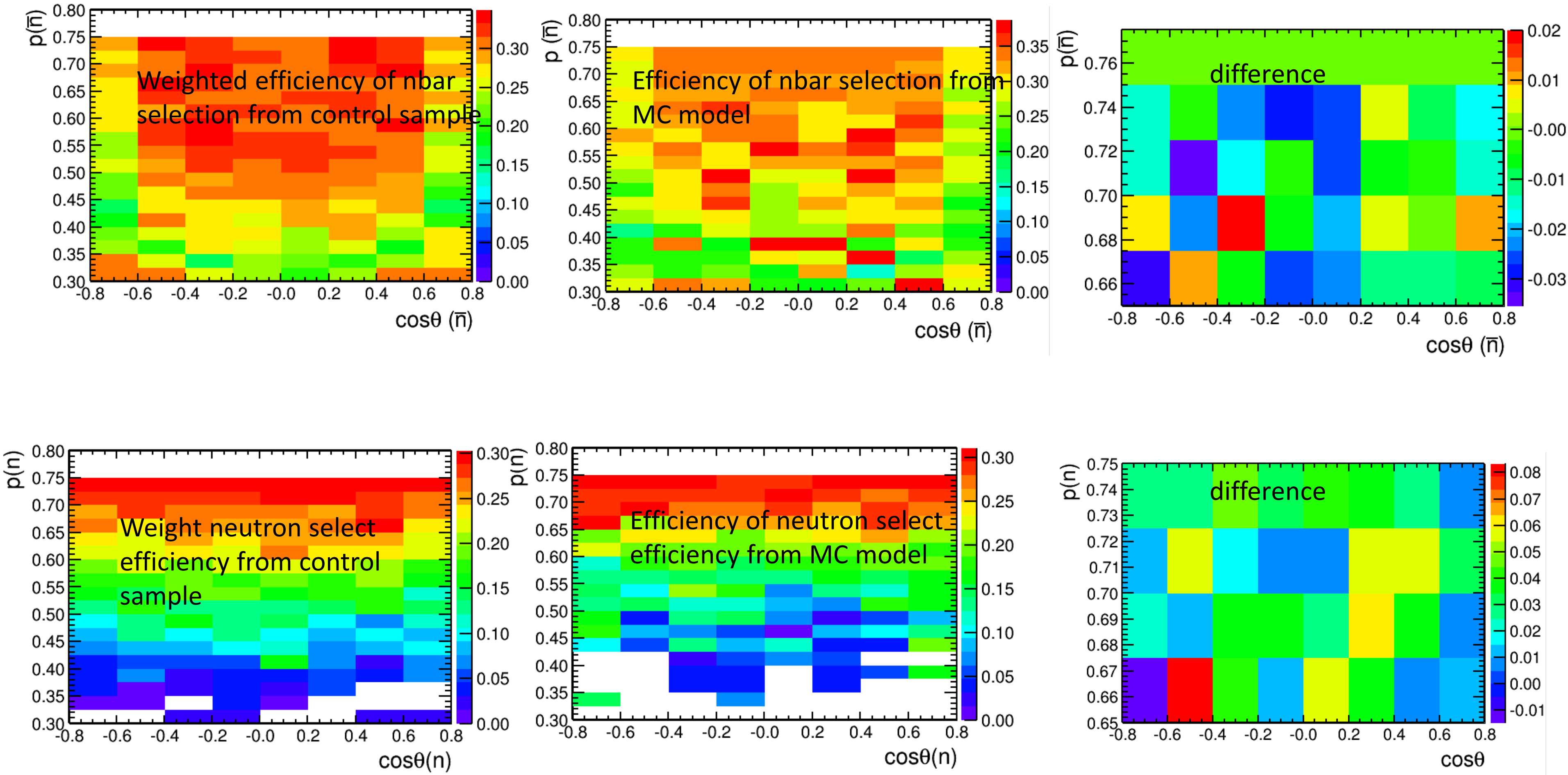
$$G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$$
$$G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$$

At high q^2 pQCD predicts: $F_1(q^2) \propto \frac{\alpha_s^2(q^2)}{q^4}$ $\quad F_2(q^2) \propto \frac{\alpha_s^2(q^2)}{q^6}$

Naïve prediction for the neutron: $|\frac{G_M^n}{G_M^p}|^2 \approx (\frac{q_d}{q_u})^2 = 0.25$

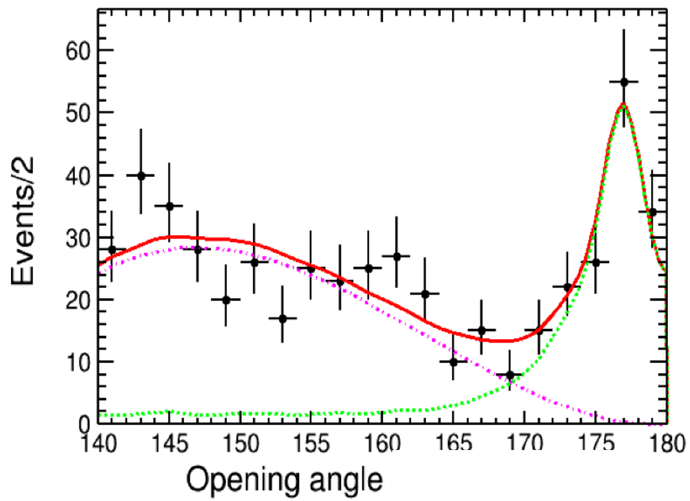
Backup

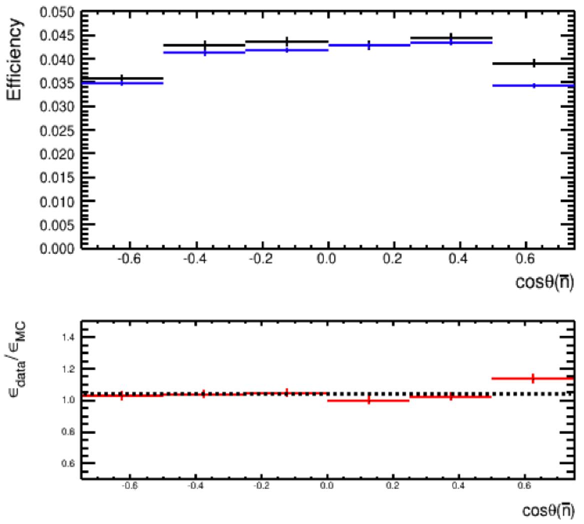
2D efficiency between MC model & MC control sample



Category 2: cut-based

1. $E_{\bar{n}} > 0.5$ GeV
2. $Hit_{\bar{n}40^\circ} > 40$
3. $Tof_{\bar{n}}$ valid
4. $|Tof_{\bar{n}}\text{-}T_{\gamma}^{exp}| > 0.5$ ns
5. $0.06 < E_n < 0.5$ GeV
6. Tof_n not valid
7. $E_{extra} < 0.1$ GeV
8. $|\cos\theta|$<0.75





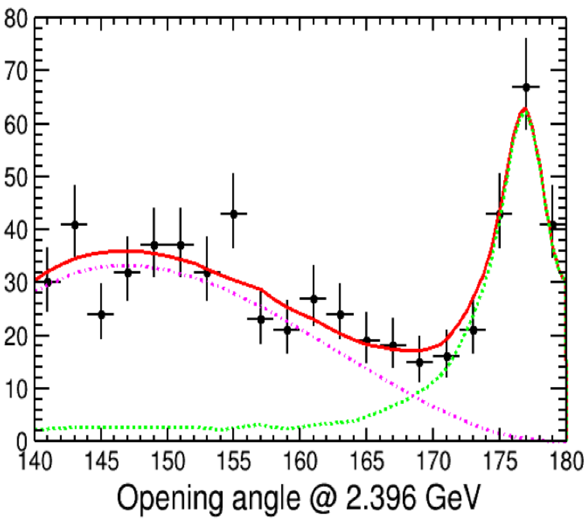
Yielding: $N_{sig} = 177 \pm 15$, $\varepsilon_{MC} = 2.8\%$

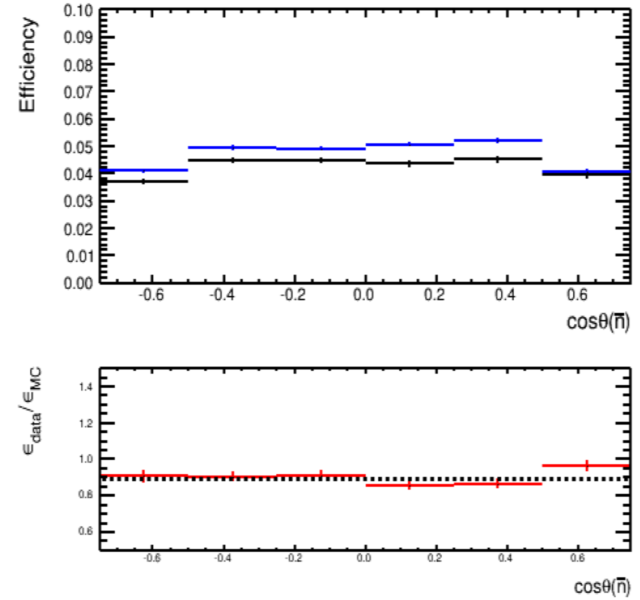
Data/MC correction: ε_{cor} =1.04

Cross section: $\sigma^B = \frac{177 \pm 15}{2.8\% \times 1.04 \times 66.87 \times 1.04} = 85.5 \pm 7.3$ pb

Category 2: BDT

1. $E_{\bar{n}} > 0.5$ GeV
2. $Tof_{\bar{n}}$ valid
3. $|Tof_{\bar{n}}\text{-}T_{\gamma}^{exp}| > 0.5$ ns
4. $0.06 < E_n < 0.5$ GeV
5. Tof_n not valid
6. $|\cos\theta|$<0.75
7. BDT>0.1





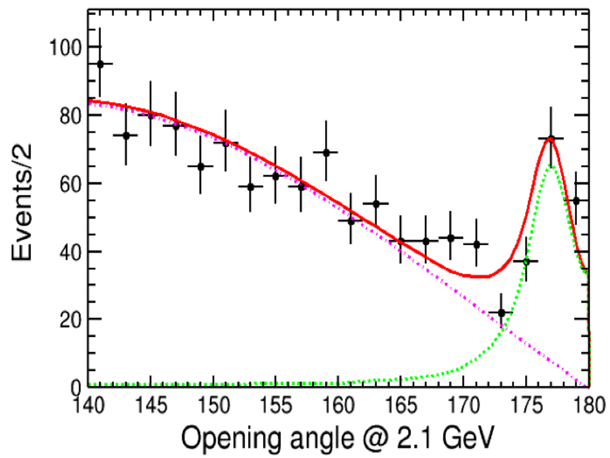
Yielding: $N_{sig} = 233 \pm 17$, $\varepsilon_{MC} = 4.0\%$

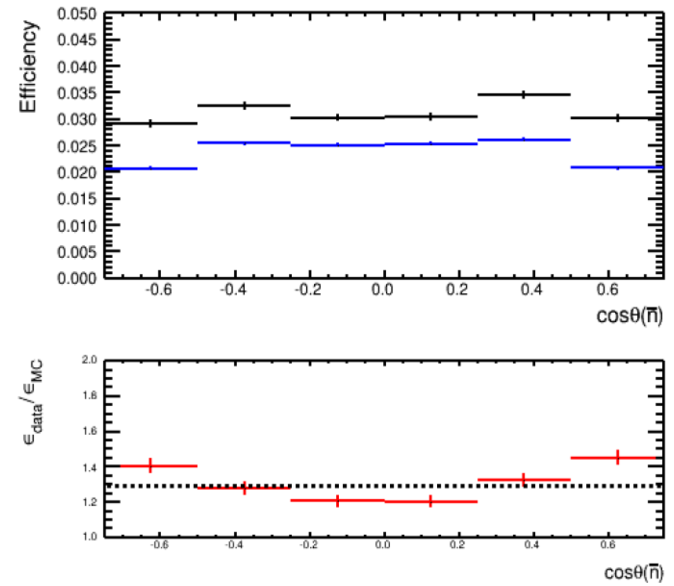
Data/MC correction: $\varepsilon_{cor} = 0.90$

Cross section: $\sigma^B = \frac{233\pm17}{4.0\%\times0.90\times66.87\times1.04} = 91.7 \pm 6.7$ pb

Category 3: cut-based

1. $E_{\bar{n}} > 0.5$ GeV
2. $Hit_{\bar{n}40^{\circ}} > 40$
3. $Secmom_{\bar{n}} > 20$
4. $Tof_{\bar{n}}$ not valid
5. $0.06 < E_n < 0.5$ GeV
6. Tof_n not valid
7. $E_{extra} < 0.1$ GeV
8. $|\cos\theta|$<0.75





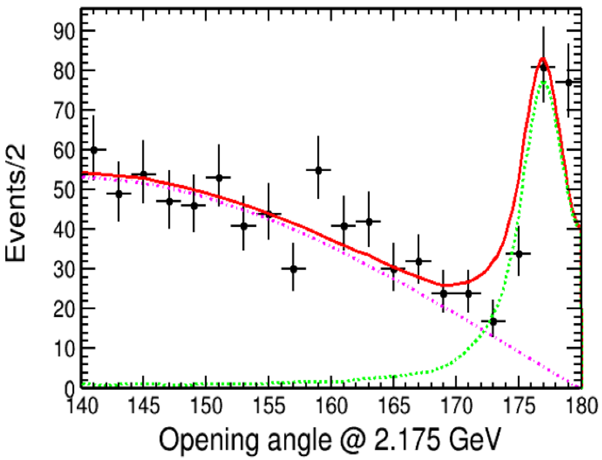
Yielding: $N_{sig} = 193 \pm 17$, $\varepsilon_{MC} = 2.4\%$

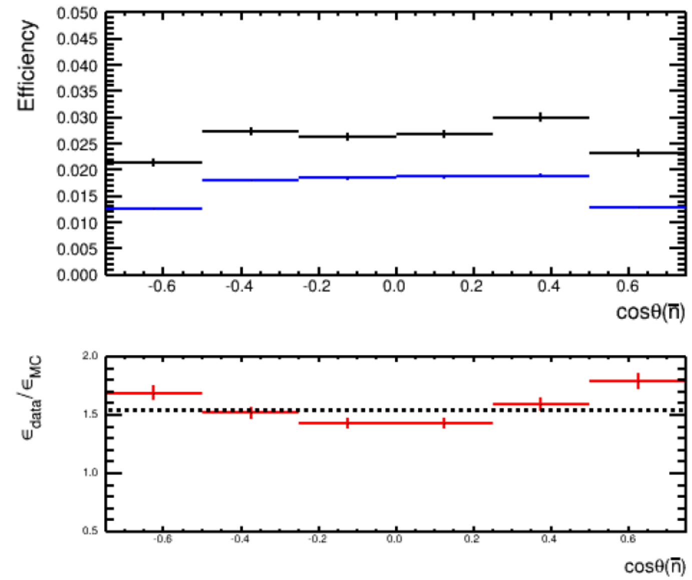
Data/MC correction: ε_{cor} =1.3

Cross section: $\sigma^B = \frac{193 \pm 17}{2.4\% \times 1.3 \times 66.87 \times 1.04} = 88.9 \pm 7.8$ pb

Category 3: BDT

1. $E_{\bar{n}} > 0.5$ GeV
2. $Hit_{\bar{n}40^{\circ}} > 40$
3. $Tof_{\bar{n}}$ not valid
4. $0.06 < E_n < 0.5$ GeV
5. Tof_n not valid
6. $E_{extra} < 0.1$ GeV
7. $|\cos\theta|$<0.75
8. BDT>0.1





Yielding: $N_{sig} = 228 \pm 30$, $\varepsilon_{MC} = 2.56\%$

Data/MC correction: $\varepsilon_{cor} = 1.5$

Cross section: $\sigma^B = \frac{228 \pm 30}{2.56\% \times 1.5 \times 66.87 \times 1.04} = 83.1 \pm 10.9$ pb

Combine of Cross section (not updated)

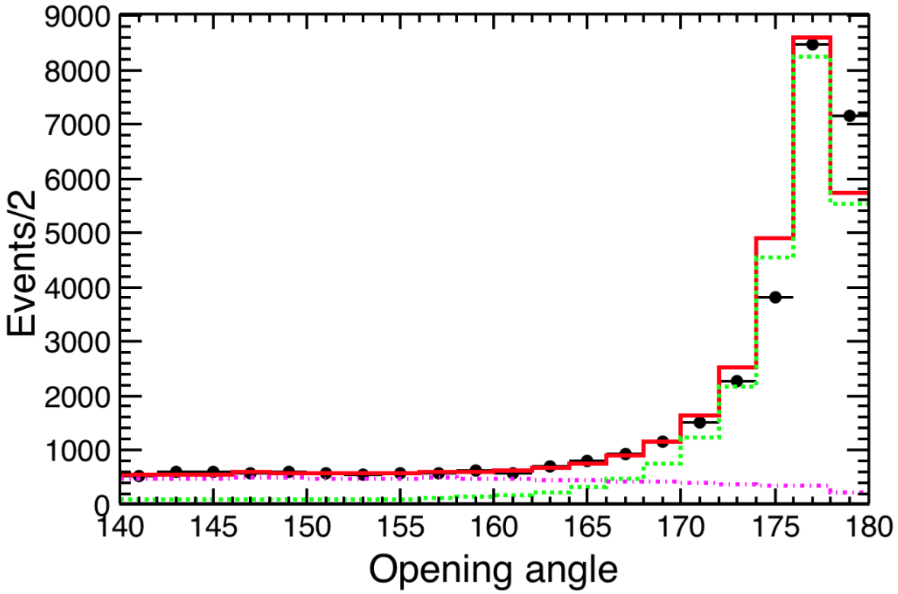
$$\sigma = \frac{\sum w_i \sigma_i}{\sum w_i}, \delta\sigma = \sqrt{\frac{\sum w_i^2 \delta_i^2}{\sum w_i^2}} \ (w_i = \frac{1}{\delta_i^2})$$

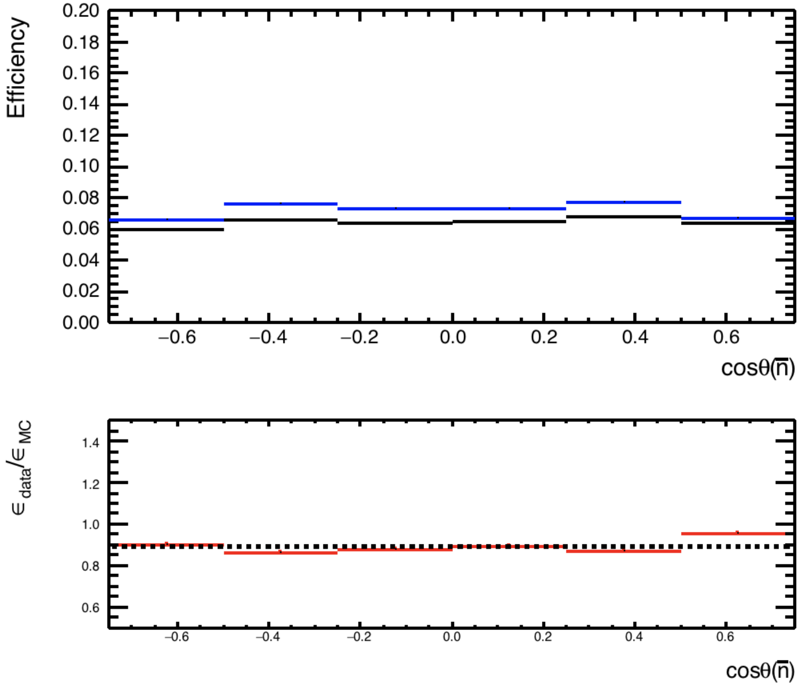
$\sqrt{s}$ (GeV)	σ_2 (pb)	σ_2 (pb)	σ_3 (pb)	σ_3 (pb)
2.0	230.4±55.4	-	-	230.4±55.4
2.1	99.6±31.1	262.7±95.5	-	168.7 ±39.9
2.125	109.3±10.1	159.5±33.9	190.1±18.1	149.3±9.5
2.175	77.8±27.6	144.4±50.9	-	111.2±27.8
2.2	43.8±18.6	-	198.9±39.5	171.0±30.7
2.2324	97.4±29.1	123.6±43.6	130.1±32.1	118.3±19.8
2.3094	90.8±19.1	100.7±26.0	80.0±13.6	87.7±10.3
2.3864	85.6±17.6	113.8±22.0	88.9±12.5	94.7±9.4
2.396	98.2±10.6	97.7±15.8	95.5±8.5	96.8±6.1
2.6444(+2MeV)	19.1±8.7	42.7±9.1	20.9±3.4	28.3±3.5
2.90	21.0±5.9	-	9.0±1.6	12.4±1.9
3.08	4.9±4.7	-	-	4.9±4.7

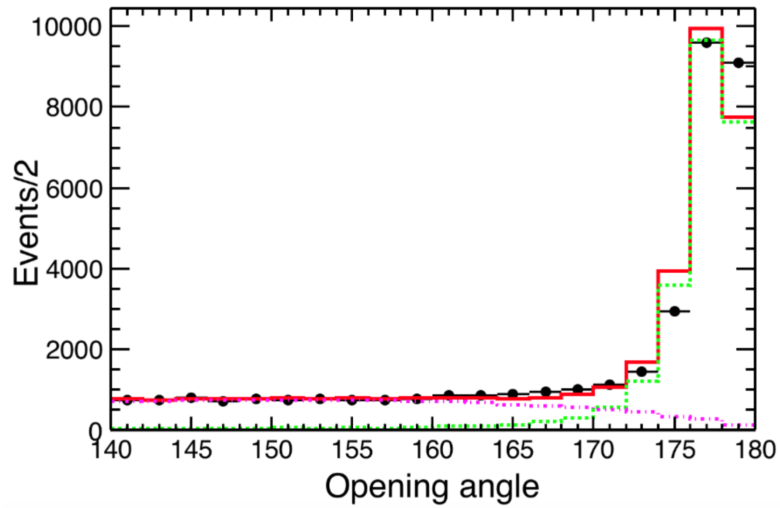
Combine of Effective form factor (not updated)

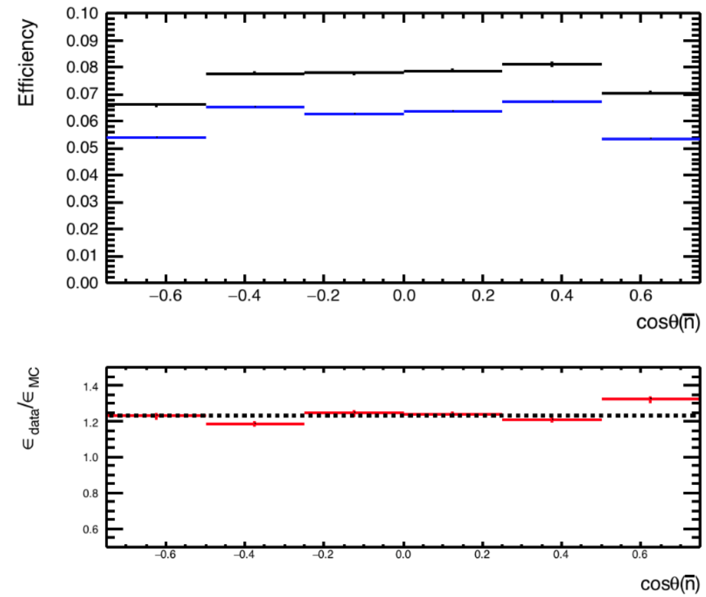
$\sqrt{s}$ (GeV)	$\lvert G_{eff}\rvert 1$ ($\times 10^{-2}$)	$\lvert G_{eff}\rvert 2$ ($\times 10^{-2}$)	$\lvert G_{eff}\rvert_3$ ($\times 10^{-2}$)	$\lvert G_{eff}\rvert$ ($\times 10^{-2}$)
2.0	14.2±1.7			14.2±1.7
2.1	8.7±1.3	14.2±2.6		11.0±1.3
2.125	9.1±0.4	11.0±1.1	12.3±0.6	10.6±0.3
2.175	7.6±1.3	10.3±1.9		8.9±1.1
2.2	5.7±1.3		12.5±1.2	11.3±0.9
2.2324	8.4±0.9	9.5±1.7	10.1±1.2	9.5±0.7
2.3094	8.2±0.8	8.7±1.1	8.0±0.7	8.2±0.5
2.3864	8.1±0.8	9.3±0.9	8.5±0.6	8.6±0.5
2.396	8.7±0.5	8.6±0.7	8.8±0.4	8.7±0.3
2.6444(+2MeV)	4.0±0.9	6.1±0.6	4.4±0.4	5.0±0.3
2.90	4.6±0.6		3.1±0.3	3.6±0.3
3.08	2.3±1.1			2.3±1.1

check (between BDT and Cut-based)






10000
8000
6000
4000
2000
0
Events/2
140
145
150
155
160
165
170
175
180
Opening angle


Efficiency
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
cosθ(n̄)
ε data/ε MC
1.4
1.2
1.0
0.8
0.6
cosθ(n̄)