Study of Baryon Form factor and Collins effect at BESIII

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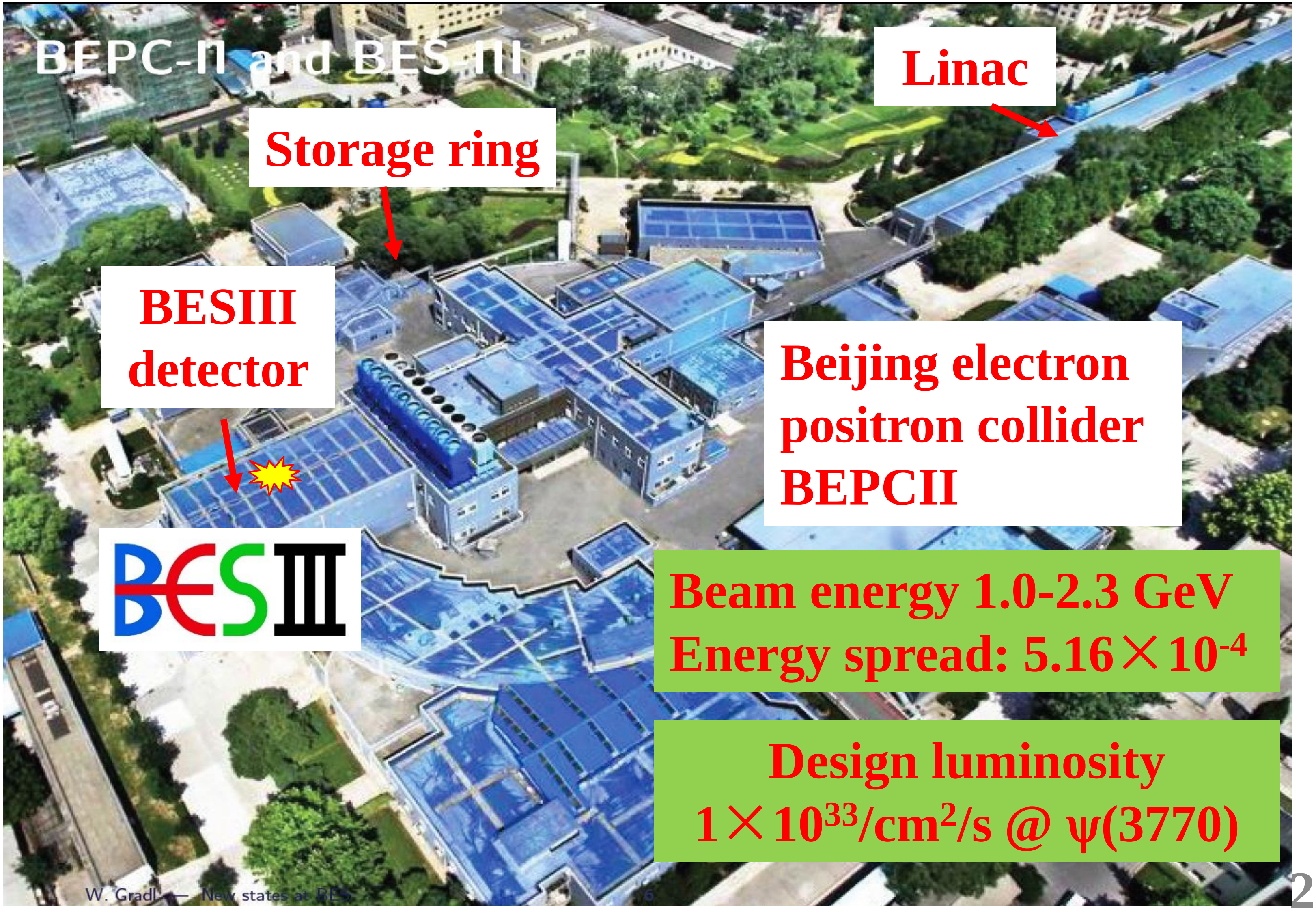
On behalf of BESIII Collaboration

INT Program INT-17-3
Hadron imaging at Jefferson Lab
and at a future EIC

Bird's View of BEPCII & BESIII



Linac

Storage ring

BESIII detector

Beijing electron positron collider BEPCII

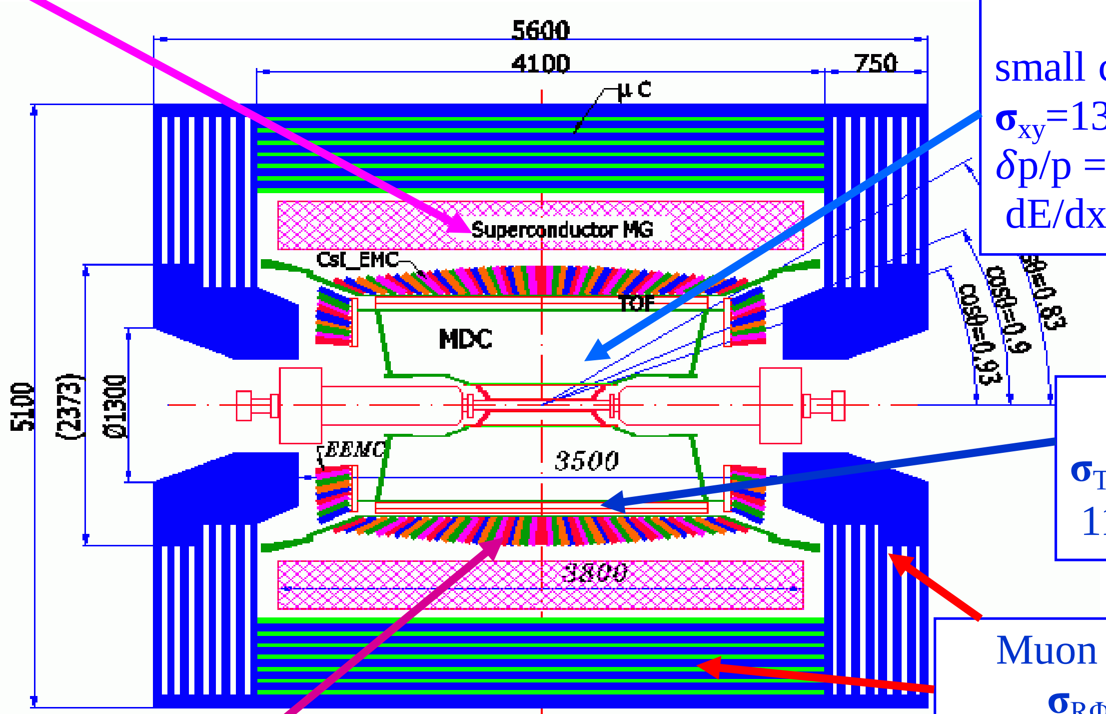
Beam energy 1.0-2.3 GeV

Energy spread: 5.16×10^{-4}

Design luminosity

$1\times10^{33}/\mathrm{cm}^2/\mathrm{s}$ @ $\psi(3770)$

BESIII detector



Solenoid Magnet: 1 T Super conducting

MDC
small cell & He gas
$\boldsymbol{\sigma}_{xy}$=130 **μ**m
$\delta p/p$ = 0.5%@1GeV
dE/dx=6%

NIM A614 345 (2010)

TOF
$\boldsymbol{\sigma}_T$ = 90 ps Barrel
110->80ps Endcap

Muon ID: 8~9 layer RPC
$\boldsymbol{\sigma}_{R\Phi}$=1.4 cm~1.7 cm

EMCAL: CsI crystal
ΔE/E = 2.5% @1 GeV
$\boldsymbol{\sigma}_{\varphi,z}$ = 0.5~0.7 cm/√E

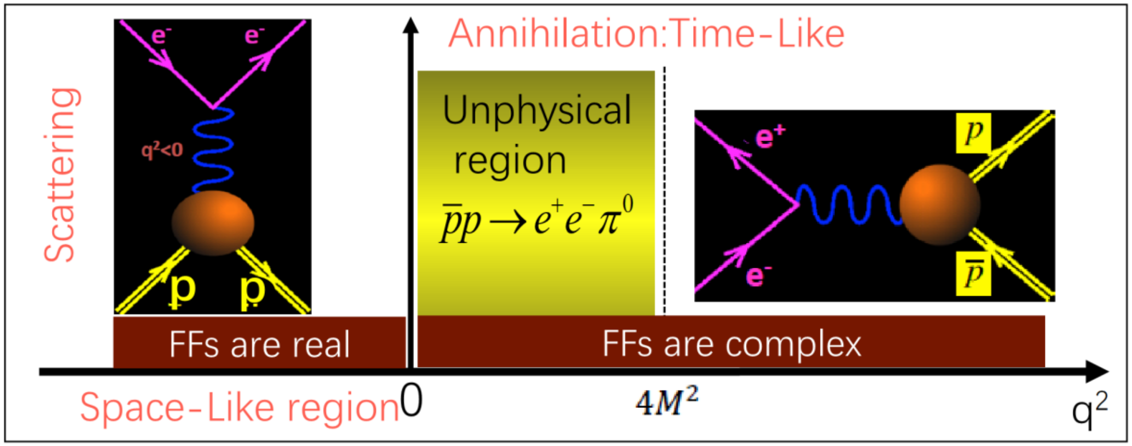
Data Acquisition:
Event rate = 3 kHz
Throughput ~ 50 MB/s

Trigger: Tracks & Showers
Pipelined; Latency = 6.4 **μ**s

Hermetic spectrometer for neutral and charged particle with excellent resolution, PID, and large coverage

Baryon form factors at BESIII

Proton form factor



- **Hadron vertex are described by Dirac FF (F_1) & Pauli FF (F_2)**

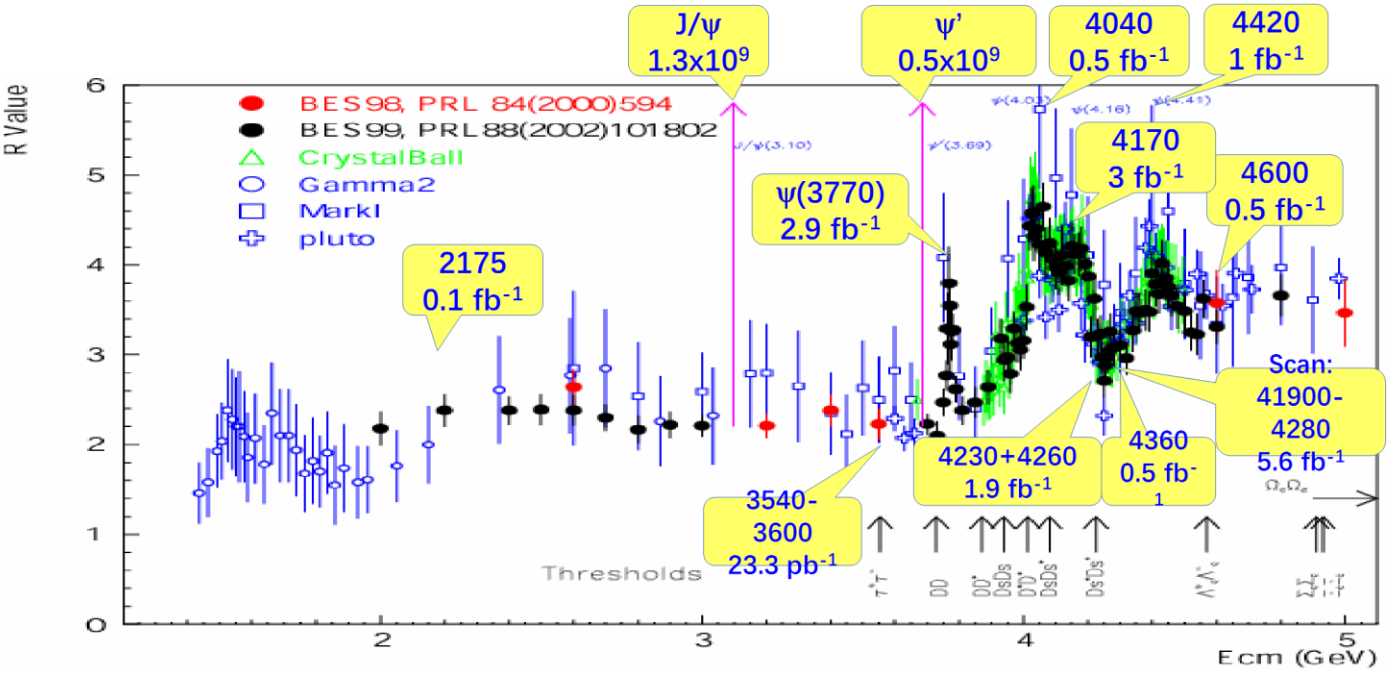
$$\Gamma_\mu(p',p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p}F_2(q^2)$$

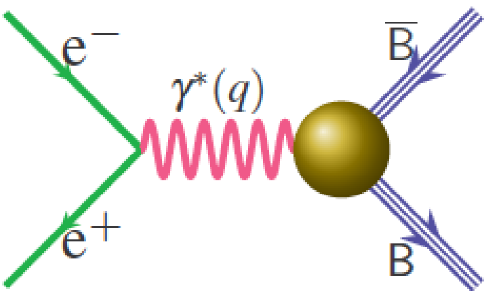
- **Sachs FFs: electric G_E and magnetic G_M**

$$G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2) \qquad \tau = \frac{q^2}{4m_p^2}, \quad \kappa_p = \frac{g_p - 2}{2} = \mu_p - 1$$
$$G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$$

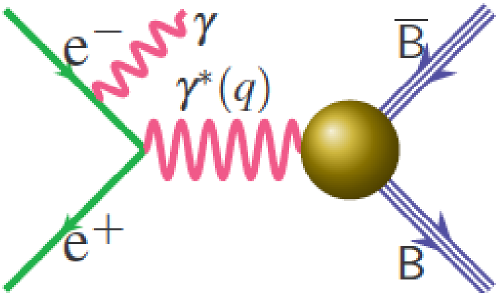
- **G_E & G_M : spatial distribution of charge and magnetization, charge density distribution** $\rho(\vec{r}) = \int \frac{d^3q}{2\pi^3} e^{-i\vec{q}\cdot\vec{r}} \frac{M}{E(\vec{q})} G_E(\vec{q}^2)$

Proton form factor





Energy scan method



Initial state radiation (ISR) method

$e^+e^- \rightarrow p\bar{p}$

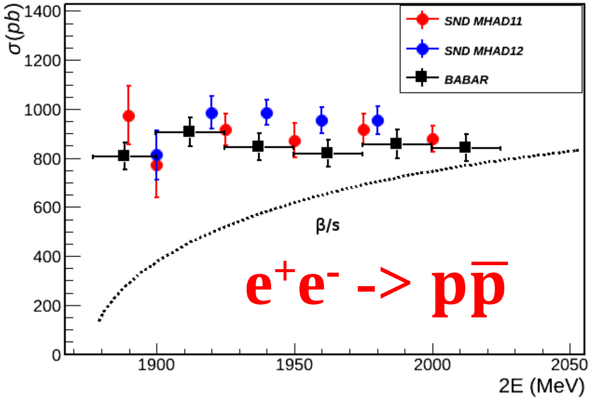
- **Differential cross section**

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

$$\beta = \sqrt{1-4M^2/s}$$
$$\tau = s/4M^2,$$
$$y = \pi\alpha M/\beta\sqrt{s}$$

- **Coulomb correction C: subtle and important near threshold**

$$C = \frac{y}{1-exp(-y)}$$



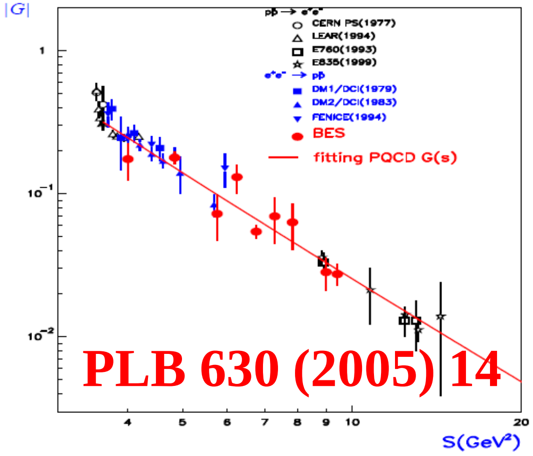
e^+e^- -> $p\bar{p}$

- **Born cross section**

$$\sigma = \frac{4\alpha^2\pi\beta}{3s} C[|G_M(s)|^2 + \frac{1}{2\tau}|G_E(s)|^2]$$

- **Effective FF, assume $|G_E| = |G_M|$**

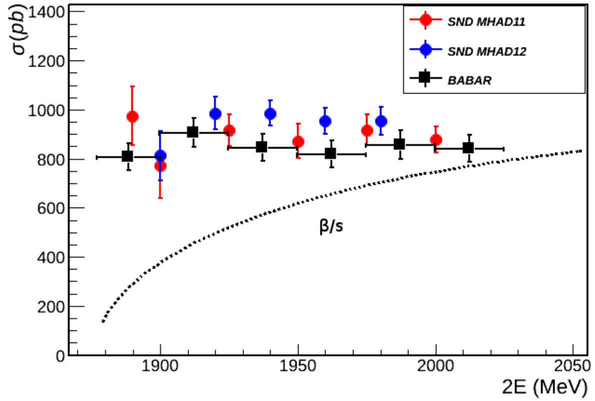
$$|G_{eff}| = \sqrt{\frac{3q^2\sigma_{Born}}{4\pi\alpha^2\beta C(1+1/2\tau)}}$$



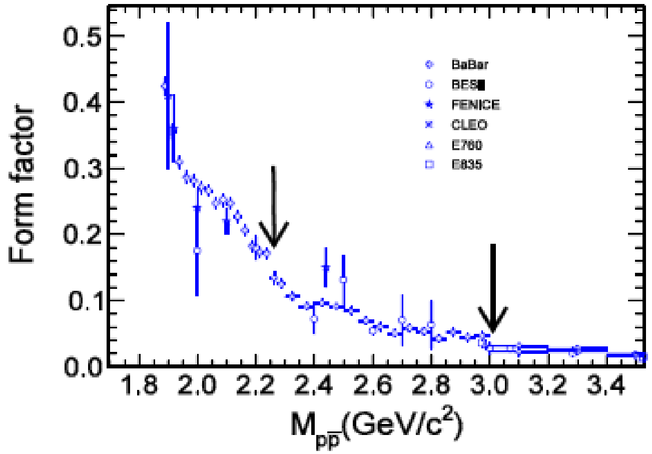
PLB 630 (2005) 14

$e^+e^- \rightarrow p\bar{p}$

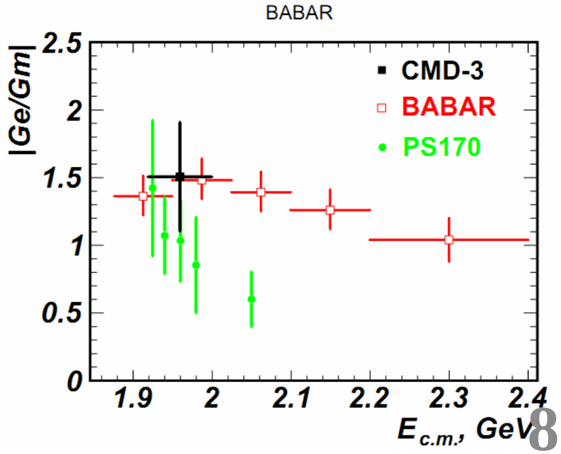
- Steep rise toward threshold



- Rapid decrease

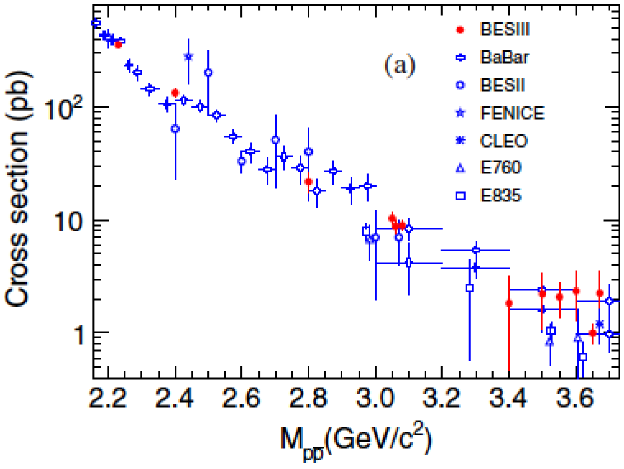


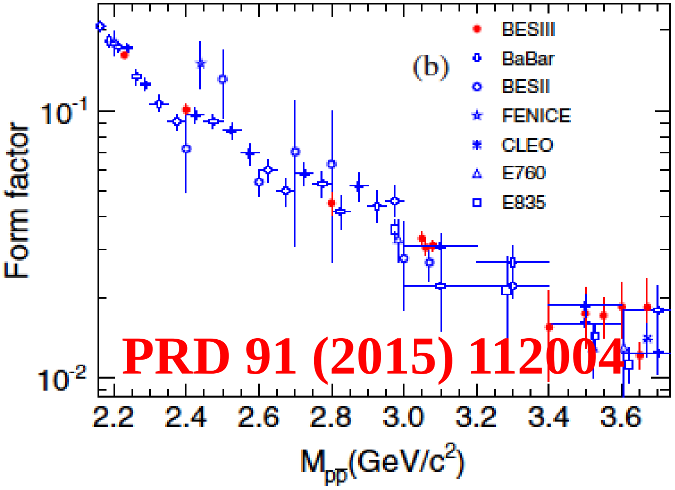
- Ratio R=$|G_E/G_M|$: disagreement between PS170 & Babar/CMD-3
  - ✓ Poor precision
  - ✓ Limited energy points



Proton G_E & G_M @ energy scan

- **Proton G_E & G_M with 12 scan points between 2.22 and 3.71GeV**





PRD 91 (2015) 112004

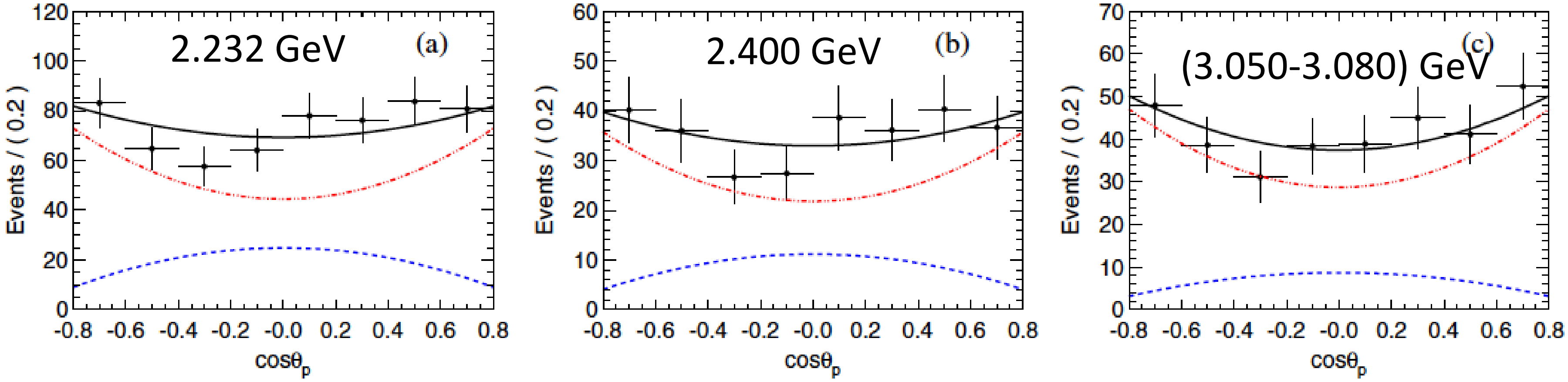
$$\sigma_{Born} = \frac{N_{obs} - N_{bkg}}{L\varepsilon(1+\delta)}$$

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

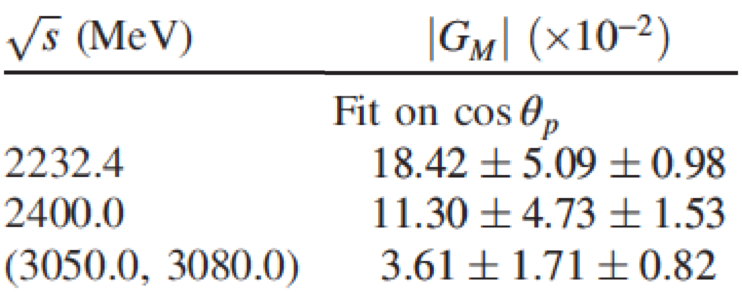
N_{obs}: observed e^+e^- -> $p\bar{p}$ event number
N_{bkg}: background event number
L: luminosity; ε: detection efficiency;
(1+δ): radiative correction

- **Consistent with previous results**
- **Compared with Babar results, uncertainty improved by ~30%**

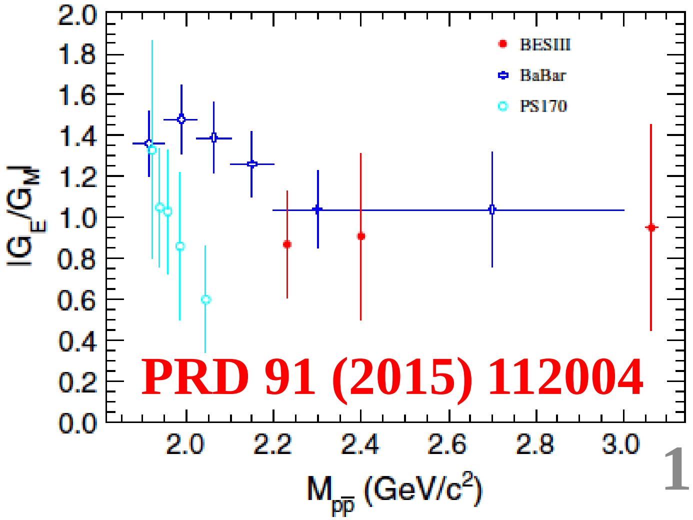
Proton $R=|G_E/G_M|$@ energy scan



$$\frac{dN}{d\cos\theta_p} = N_{norm}\left[\left(1+\cos^2\theta_p\right) + R^2 \ \frac{1}{\tau}\sin^2\theta_p\right]$$



$\sqrt{s}$ (MeV)	$\lvert G_M\rvert$ ($\times 10^{-2}$)
	Fit on $\cos\theta_p$
2232.4	$18.42 \pm 5.09 \pm 0.98$
2400.0	$11.30 \pm 4.73 \pm 1.53$
(3050.0, 3080.0)	$3.61 \pm 1.71 \pm 0.82$

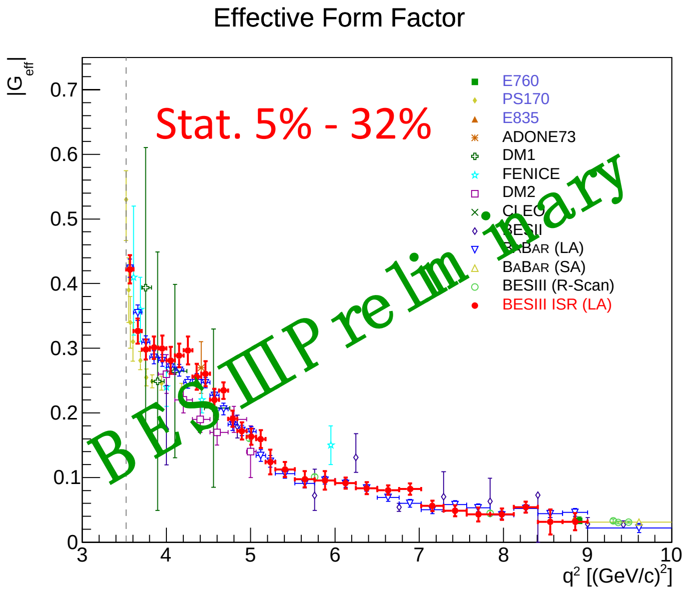


PRD 91 (2015) 112004

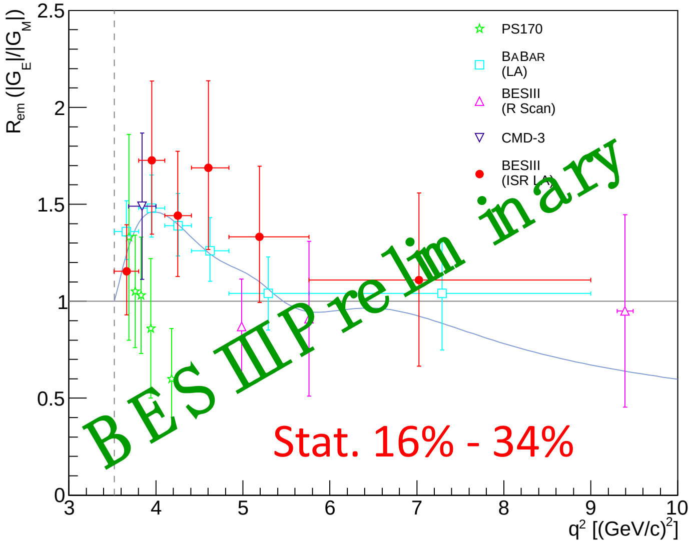
Proton G_E & G_M @ ISR method

- use $e^+e^- \to \gamma_{ISR} p\bar{p}$ with tagged photon

E_{cm} (GeV)	3.773	4.009	4.230	4.260	4.360	4.420	4.600
Taking time	2010-2011	2011	2013	2013	2013	2014	2014
Lumi. (pb^{-1})	2917.00	481.96	1047.34	825.67	539.84	1028.89	566.93

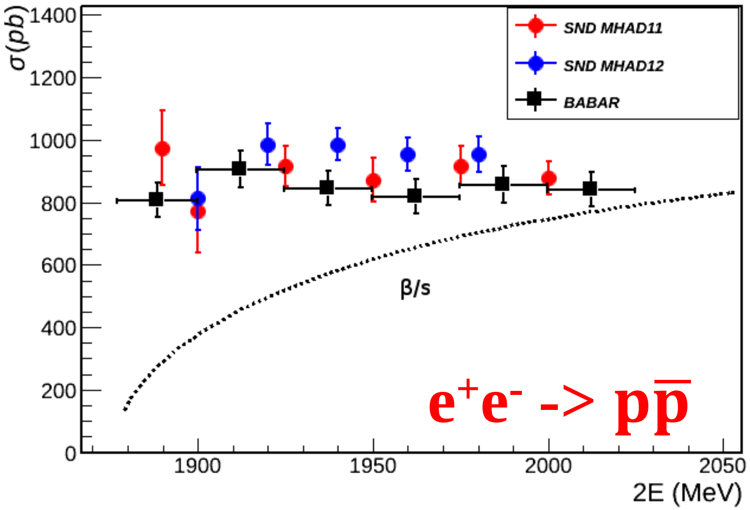


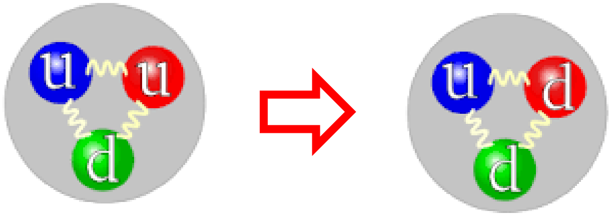
Stat. 5% - 32%

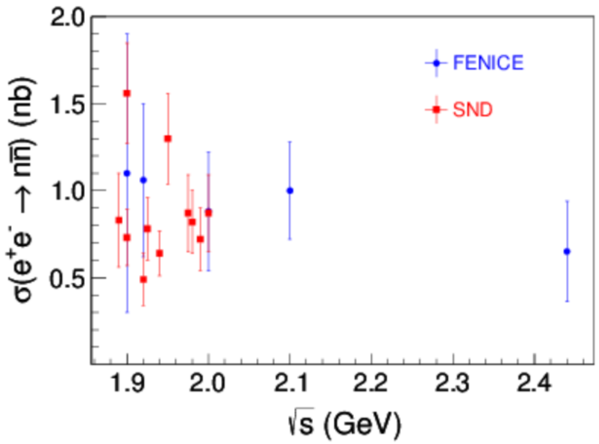


Stat. 16% - 34%

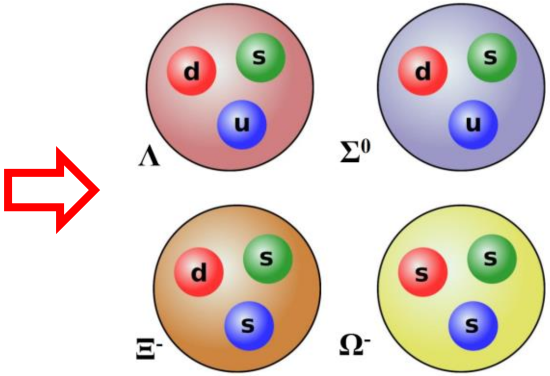
Baryon pair production



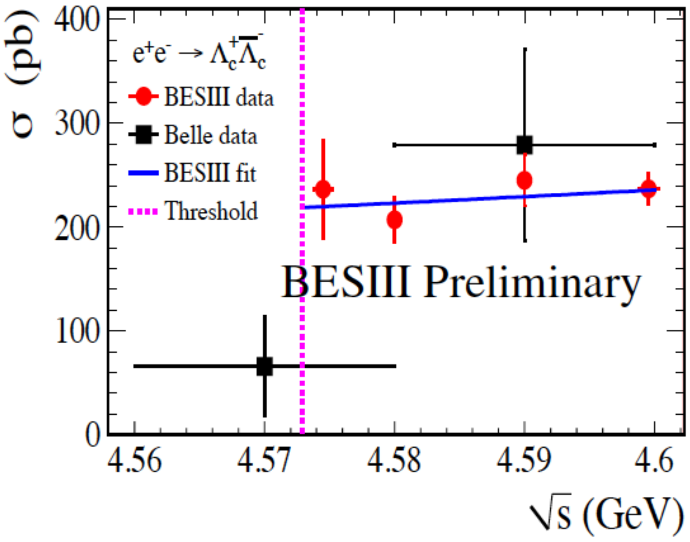


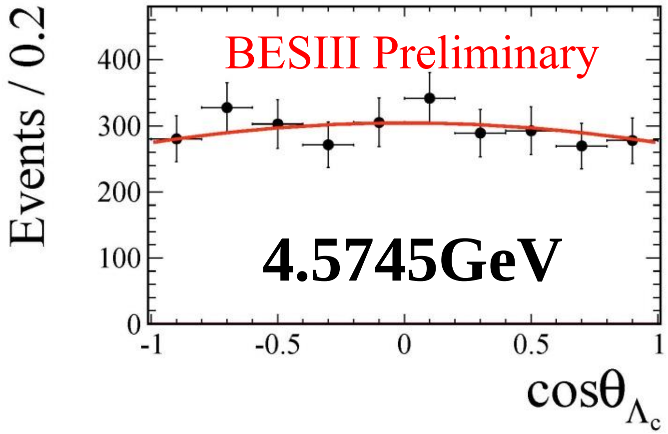


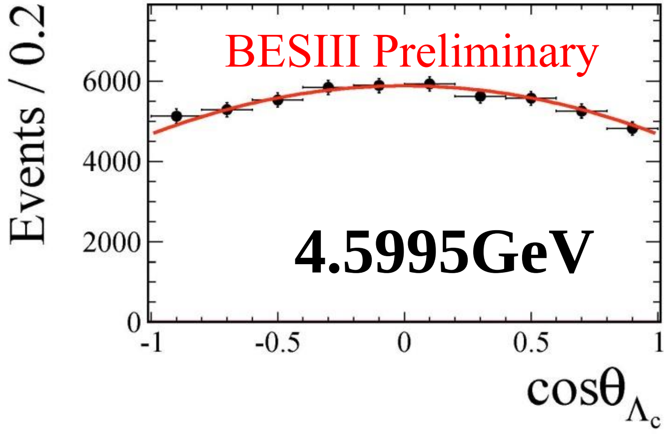
- **Cross section around threshold**
  - ✓ **Charged baryon**
  - ✓ **Neutral baryon**
- **G_E & G_M form factor**



$e^+e^- \to \Lambda_c^+ \overline{\Lambda}_c^-$



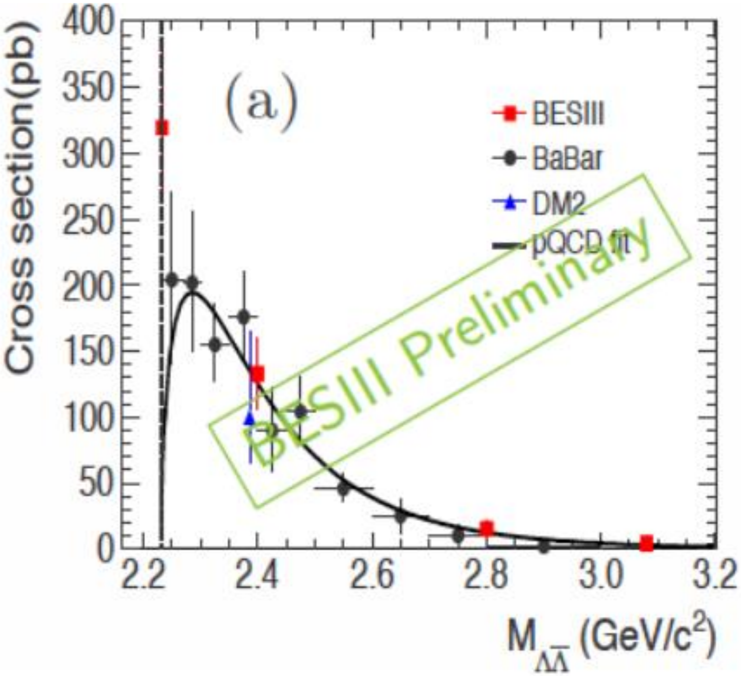




- **First measurement of Λ_c FFs**
- **Very close to threshold ~1.6MeV**
- **Coulomb correction C ?**

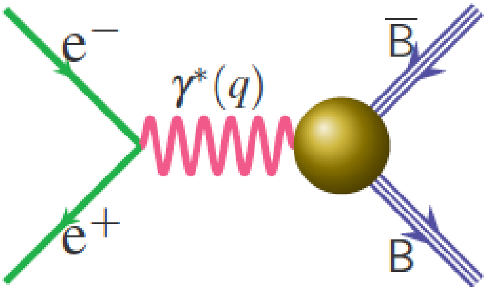
GeV	$\lvert G_E/G_M \rvert$
4.5745	$1.14 \pm 0.14 \pm 0.07$
4.5995	$1.23 \pm 0.05 \pm 0.03$

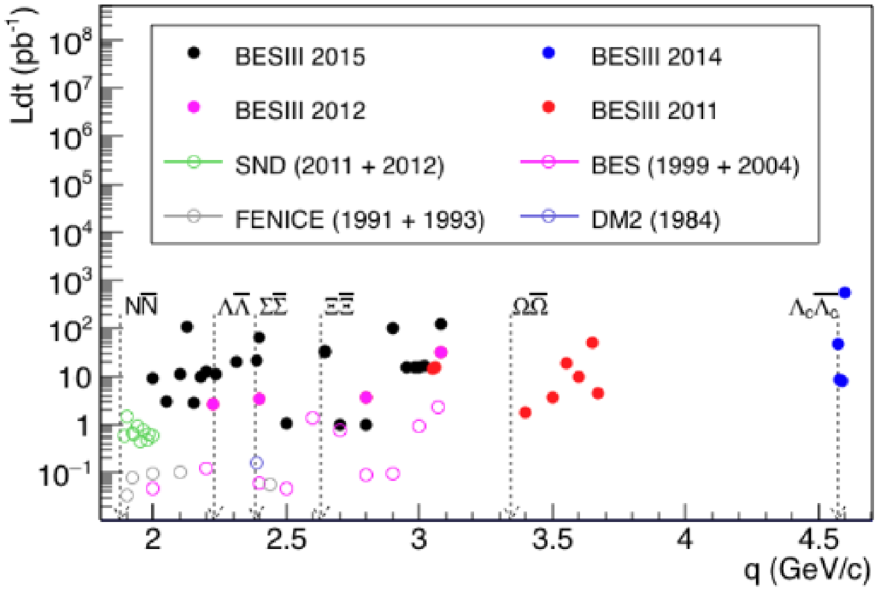
$e^+e^- \rightarrow \Lambda\bar{\Lambda}$



- **Non-zero behavior around threshold**
- **Consistent with previous results, improved by 10%**

Prospects: new energy scan 2015

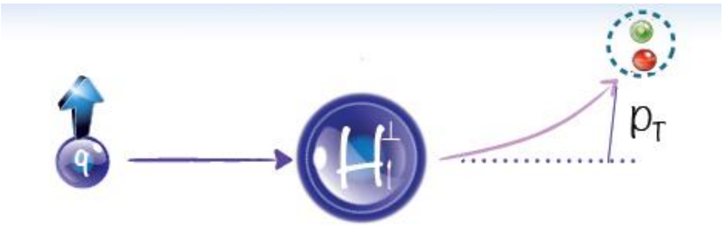




- Energy scan between 2 and 3.08GeV (552pb^{-1})

Collins effect at BESIII

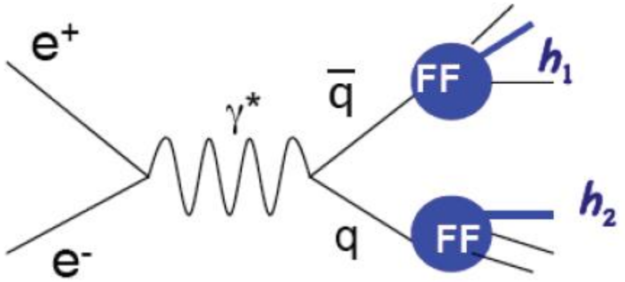
Spin-dependent Fragmentation



PLB396 (1993) 161

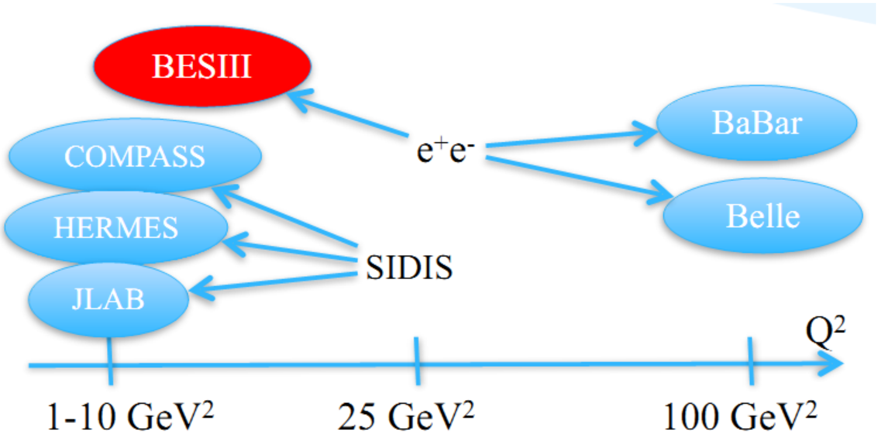
$$D_{hq^\uparrow}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2)\frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{zM_h}$$

- **D_1: unpolarized fragmentation function (FF)**
- **H_1: Collins FF**
  - **✓ Describes fragmentation of a transversely polarized quark into a spinless hadron h**
  - **✓ Depend on $z=2E_h/\sqrt{s}$, and $P_{h\perp}$**
  - **✓ Leads to an azimuthal modulation of hadrons around quark momentum**

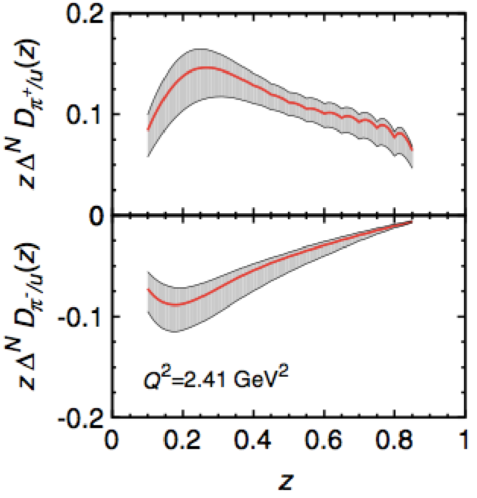


Collins FF: Global analysis

- University of Collins FF

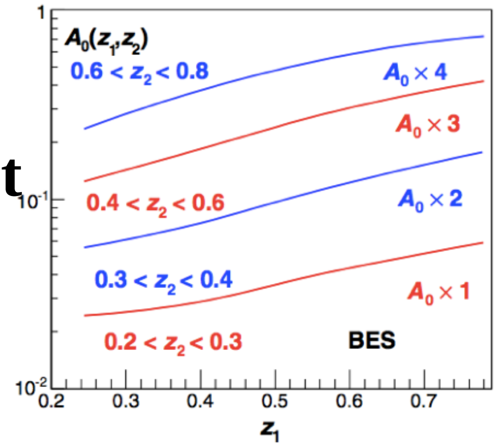


PRD 87 (2013) 074019

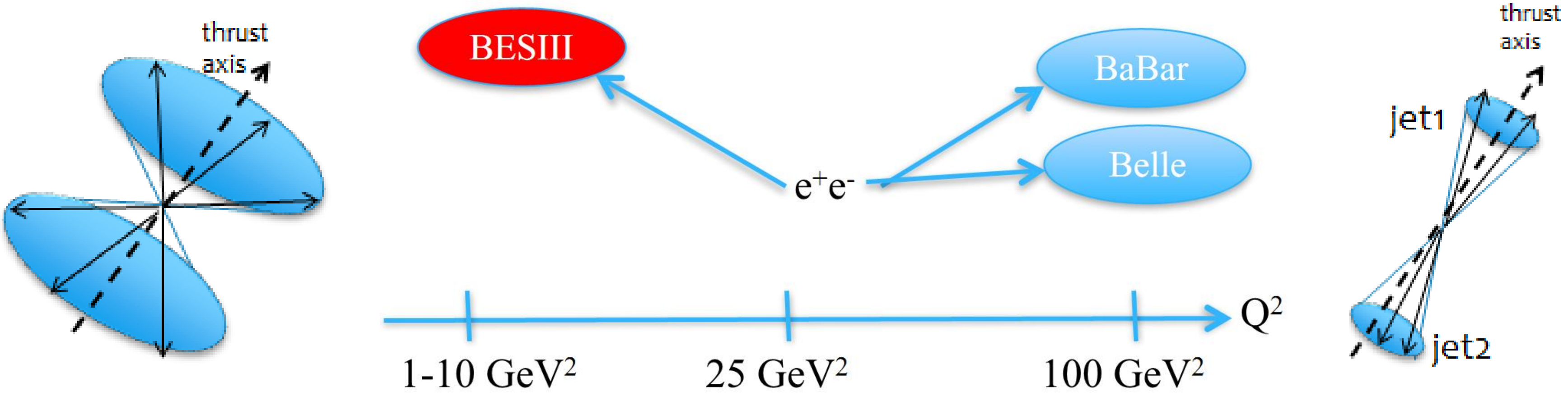


- Q^2 evolution of TMD FFs
  - ✓ BEPCII: Q^2 similar of SIDIS
  - ✓ e$^+$e$^-$ annihilation process at different energy with respect to B factories

PRD 88 (2013) 034016



Collins FF at BESIII



- **Jet structure at BESIII is not clear, can not reconstruct thrust axis correctly.**
  - ✓ **$e^+e^- \rightarrow \pi\pi + X$: $\theta_{\pi\pi}>120^O$, back-to-back pion**
- **Difficult to suppress backgrounds with on-resonance datasets, prefer off-resonance data in continuum region**
  - ✓ **62 pb^{-1} @ 3.65GeV, below open charm threshold**

PRL 116 (2016) 042001

$e^+e^- \to \pi\,\pi + X$

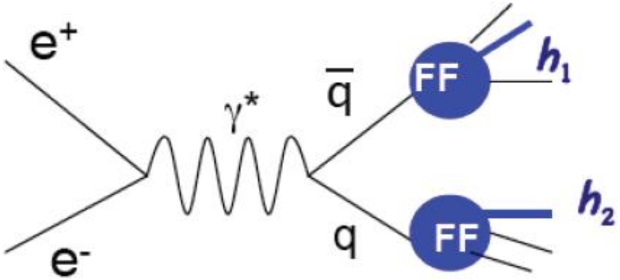
Two Collins FFs

$$\frac{d\sigma(e^+e^-\to\pi_1\pi_2X)}{dz_1\,dz_2\,d\Omega\,d^2\mathbf{q}_T} \sim \frac{3\alpha^2}{Q^2}z_1^2z_2^2\,\Big\{(1+\cos^2\theta_2)\mathcal{F}[D_1\bar{D}_1]$$

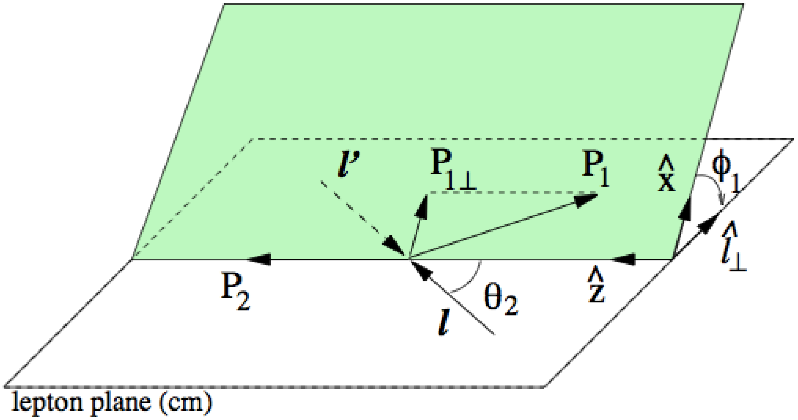
$$\sin^2\theta_2\,\boxed{\cos(2\phi)}\,\mathcal{F}\left[(2\hat{\mathbf{h}}\cdot\mathbf{k_T}\hat{\mathbf{h}}\cdot\mathbf{p_T}-\mathbf{k_T}\cdot\mathbf{p_T})\frac{\boxed{H_1^\perp\bar{H}_1^\perp}}{M_1M_2}\right]$$

$$\mathcal{F}[D\bar{D}] \equiv \sum_a e_a^2\int d^2\mathbf{k}_T d^2\mathbf{p}_T\,\delta^2(\mathbf{k}_T+\mathbf{p}_T-\mathbf{q}_T)$$

$$D^a(z_1,z_1^2\mathbf{k}_T^2)\bar{D}^a(z_2,z_2^2\mathbf{p}_T^2)$$



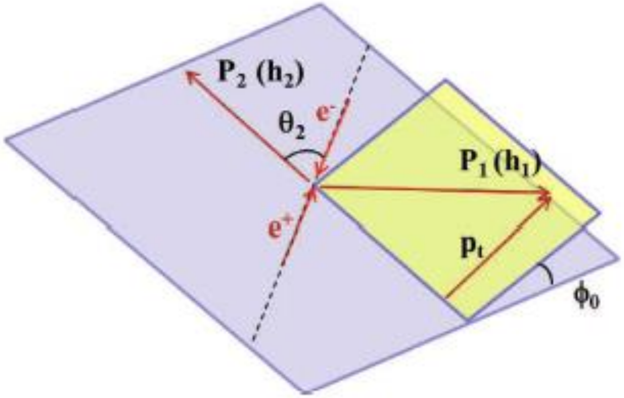
Collins FF ⊗ Collins FF



NP B806 (2009) 23

$e^+e^- \longrightarrow \pi\, \pi + X$

- **Normalized ratio R=$\frac{N(2\phi_0)}{<N_0>}$**
  - ✓ **$N(2\phi_0)$: di-pion yield in each $2\phi_0$ subdivision**
  - ✓ **$< N_0 >$: averaged bin content**
  - ✓ **R^U: unlike sign ($\pi^{\pm}\pi^{\mp}$)**
  - ✓ **R^L: like sign ($\pi^{\pm}\pi^{\pm}$)**
  - ✓ **R^C: all pion pair**



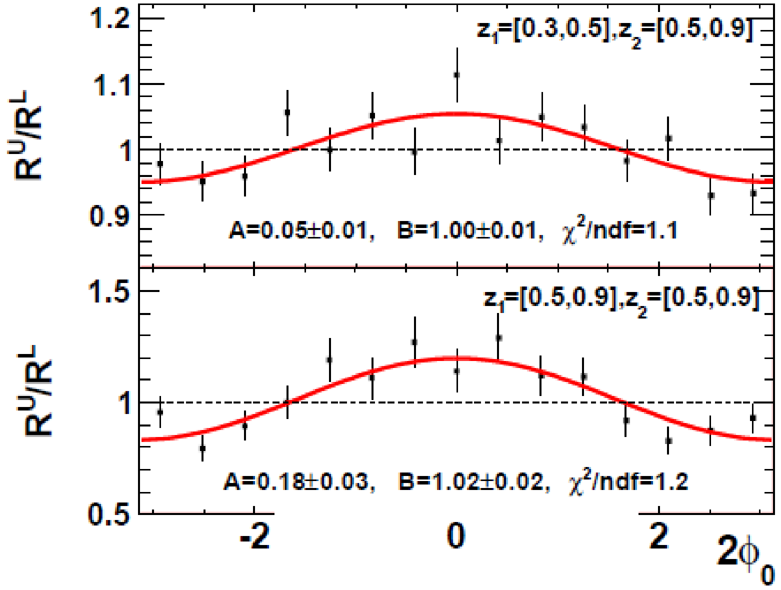
- **Double ratio: reduce acceptance and radiation effect**

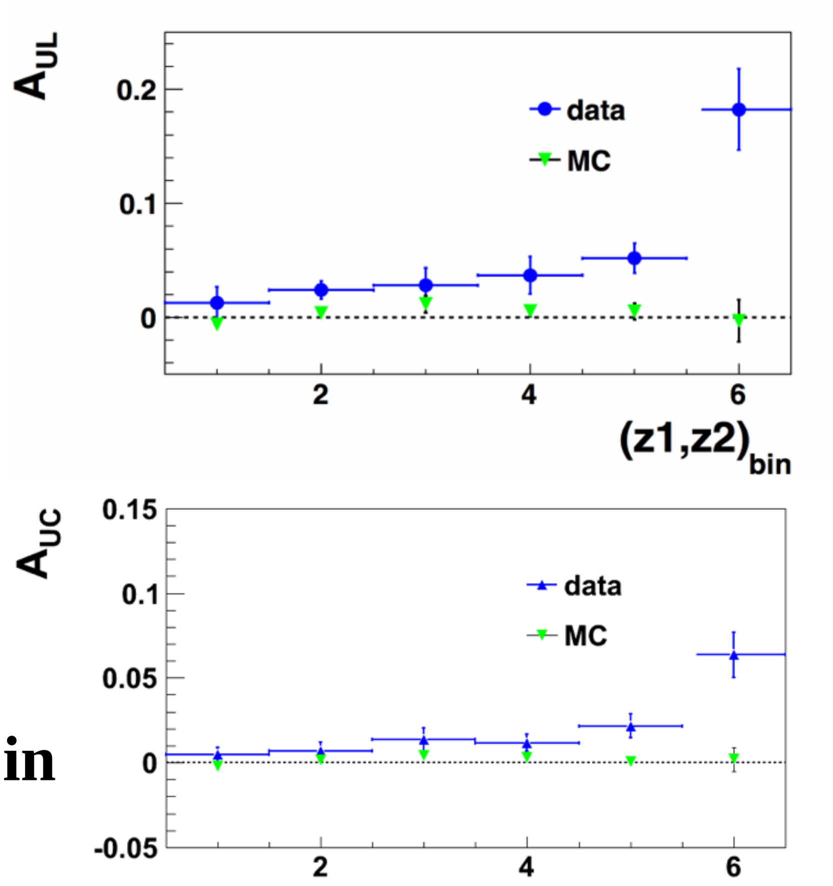
$$\frac{R^U}{R^{L(C)}} = 1 + \cos(2\phi_0) \cdot \frac{\sin^2\theta_2}{1+\cos^2\theta_2} \frac{\mathcal{F}(H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)/M_1M_2)}{D_1(z_1)\bar{D}_1(z_2)} = 1 + \cos(2\phi_0) \cdot A^{UL(UC)}$$

Fit function $$\frac{R^U}{R^{L(C)}} = A\cos(2\phi_0) + B$$

$A^{UL/UC}$ mainly contains Collins effect
B should be consistent with unity

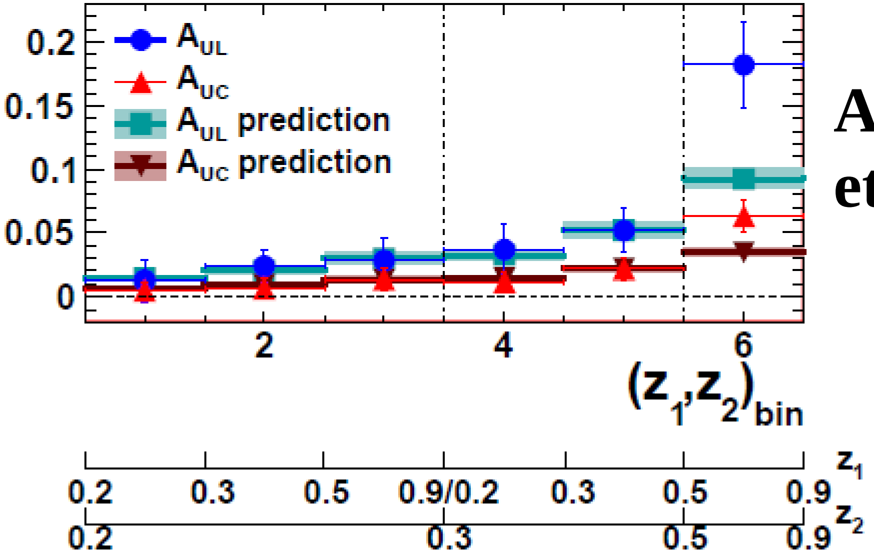
$e^+e^- \rightarrow \pi\, \pi + X$



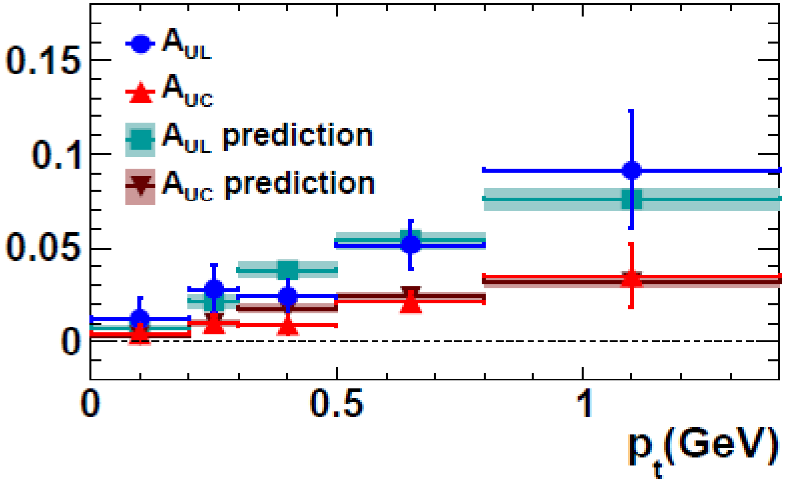


- Non-zero $A^{UL/UC}$ asymmetries in data
- MC data (without Collins FF): $A^{UL/UC}$ are consistent with zero

Compare with theory

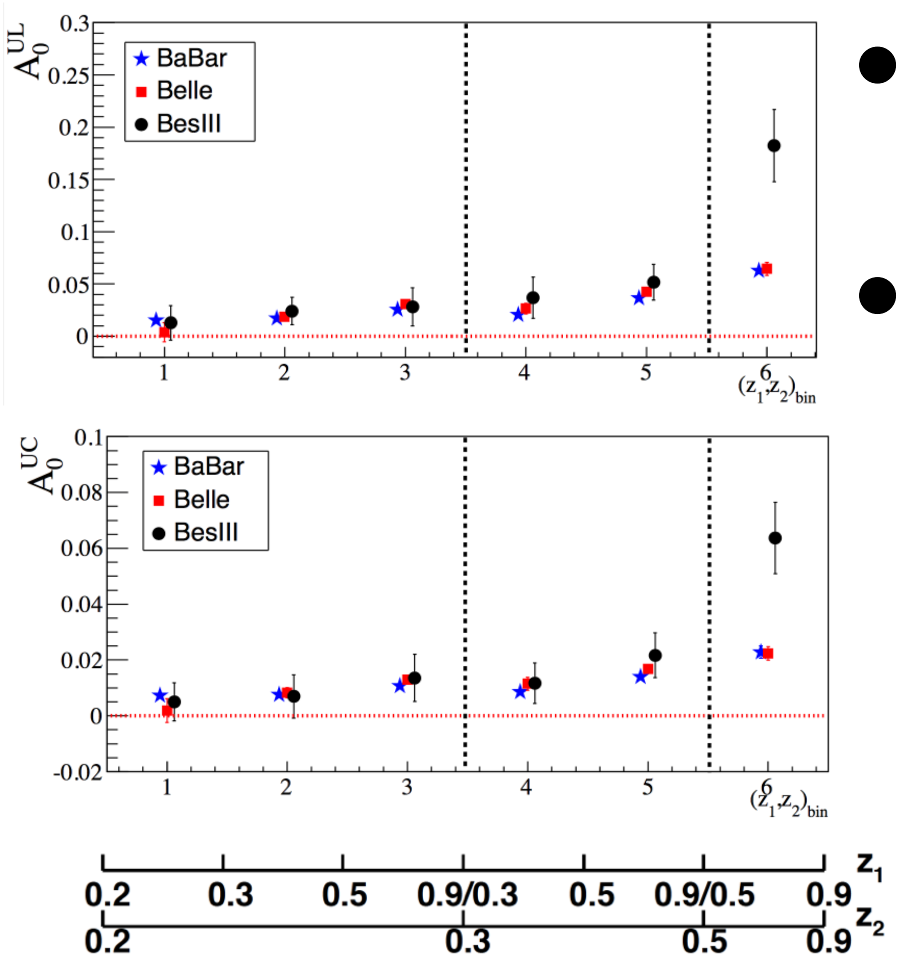


$A^{UL/UC}$ prediction is from Z. B. Kang et al., PRD93 (2016) 014009

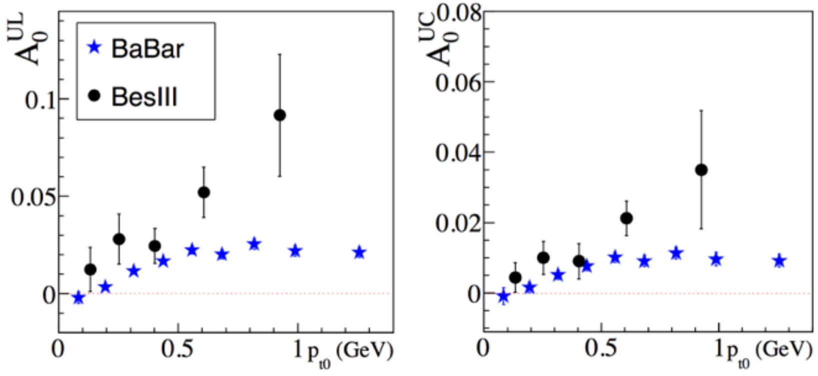


Asymmetry dependence transverse momentum

Compare with other experiments



- **Results at e+e- collision**
  - ✓ **Babar & Belle @ Q^2 ~110GeV^2**
  - ✓ **BESII @ Q^2 ~13GeV^2**
- **Prediction in Collins paper**
  - ✓ **Larger asymmetry at lower Q^2**
  - ✓ **Asymmetry increase as z grows**



Summary

- **Rich program on baryon form factor at BESIII**
  - ✓ **Proton FFs are studied by energy scan and ISR methods**
  - ✓ **First measurement of Λ_c FFs, very close to threshold**
  - ✓ **Non-zero behavior around threshold for $\Lambda\bar{\Lambda}$**
- **Collins asymmetry @ 3.65GeV**
  - ✓ **Clear non-zero asymmetry**
  - ✓ **Larger that that of Babar and Belle**
  - ✓ **Comparable to theoretical predictions**
  - ✓ **$e^+e^- \rightarrow K\,\pi + X$; $e^+e^- \rightarrow \pi\,\pi^0/\eta + X$; $e^+e^- \rightarrow K\,K_s + X$: plan**

Collins FF at BESIII

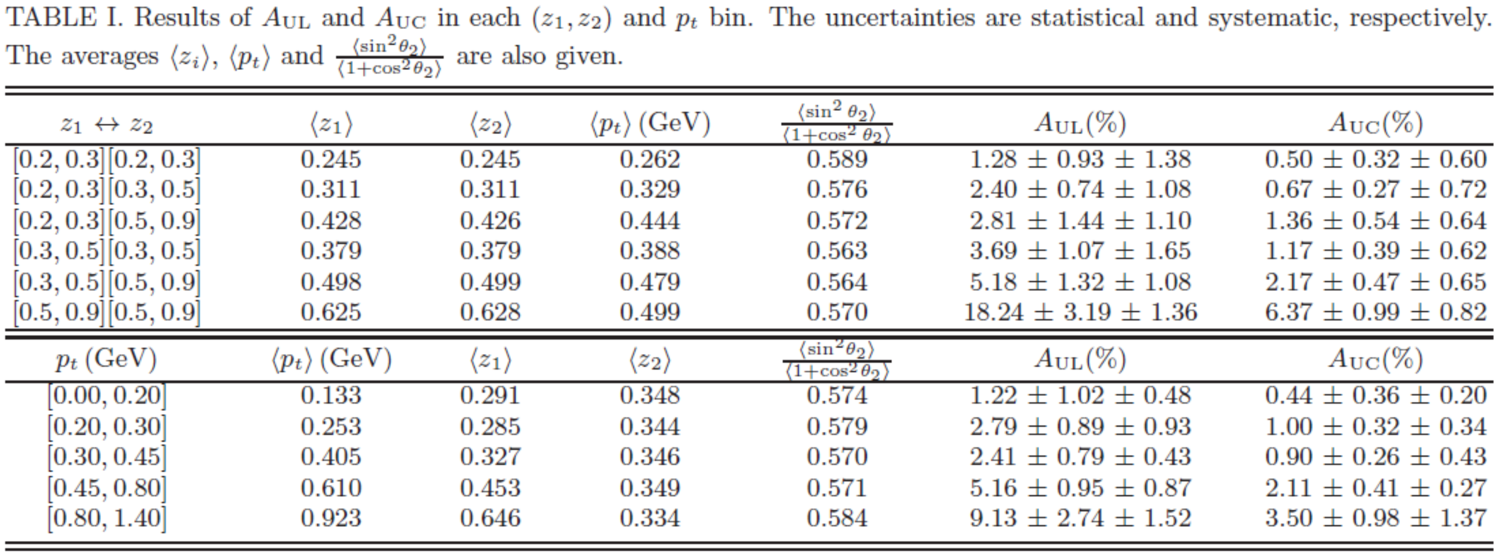


TABLE I. Results of A_{UL} and A_{UC} in each (z_1, z_2) and p_t bin. The uncertainties are statistical and systematic, respectively. The averages $\langle z_i \rangle$, $\langle p_t \rangle$ and $\frac{\langle \sin^2\theta_2 \rangle}{\langle 1+\cos^2\theta_2 \rangle}$ are also given.

$z_1 \leftrightarrow z_2$	$\langle z_1 \rangle$	$\langle z_2 \rangle$	$\langle p_t \rangle$ (GeV)	$\frac{\langle \sin^2\theta_2 \rangle}{\langle 1+\cos^2\theta_2 \rangle}$	$A_{\mathrm{UL}}(\%)$	$A_{\mathrm{UC}}(\%)$
[0.2, 0.3][0.2, 0.3]	0.245	0.245	0.262	0.589	1.28 ± 0.93 ± 1.38	0.50 ± 0.32 ± 0.60
[0.2, 0.3][0.3, 0.5]	0.311	0.311	0.329	0.576	2.40 ± 0.74 ± 1.08	0.67 ± 0.27 ± 0.72
[0.2, 0.3][0.5, 0.9]	0.428	0.426	0.444	0.572	2.81 ± 1.44 ± 1.10	1.36 ± 0.54 ± 0.64
[0.3, 0.5][0.3, 0.5]	0.379	0.379	0.388	0.563	3.69 ± 1.07 ± 1.65	1.17 ± 0.39 ± 0.62
[0.3, 0.5][0.5, 0.9]	0.498	0.499	0.479	0.564	5.18 ± 1.32 ± 1.08	2.17 ± 0.47 ± 0.65
[0.5, 0.9][0.5, 0.9]	0.625	0.628	0.499	0.570	18.24 ± 3.19 ± 1.36	6.37 ± 0.99 ± 0.82

p_t (GeV)	$\langle p_t \rangle$ (GeV)	$\langle z_1 \rangle$	$\langle z_2 \rangle$	$\frac{\langle \sin^2\theta_2 \rangle}{\langle 1+\cos^2\theta_2 \rangle}$	$A_{\mathrm{UL}}(\%)$	$A_{\mathrm{UC}}(\%)$
[0.00, 0.20]	0.133	0.291	0.348	0.574	1.22 ± 1.02 ± 0.48	0.44 ± 0.36 ± 0.20
[0.20, 0.30]	0.253	0.285	0.344	0.579	2.79 ± 0.89 ± 0.93	1.00 ± 0.32 ± 0.34
[0.30, 0.45]	0.405	0.327	0.346	0.570	2.41 ± 0.79 ± 0.43	0.90 ± 0.26 ± 0.43
[0.45, 0.80]	0.610	0.453	0.349	0.571	5.16 ± 0.95 ± 0.87	2.11 ± 0.41 ± 0.27
[0.80, 1.40]	0.923	0.646	0.334	0.584	9.13 ± 2.74 ± 1.52	3.50 ± 0.98 ± 1.37