Timelike form factor measurements at BESIII

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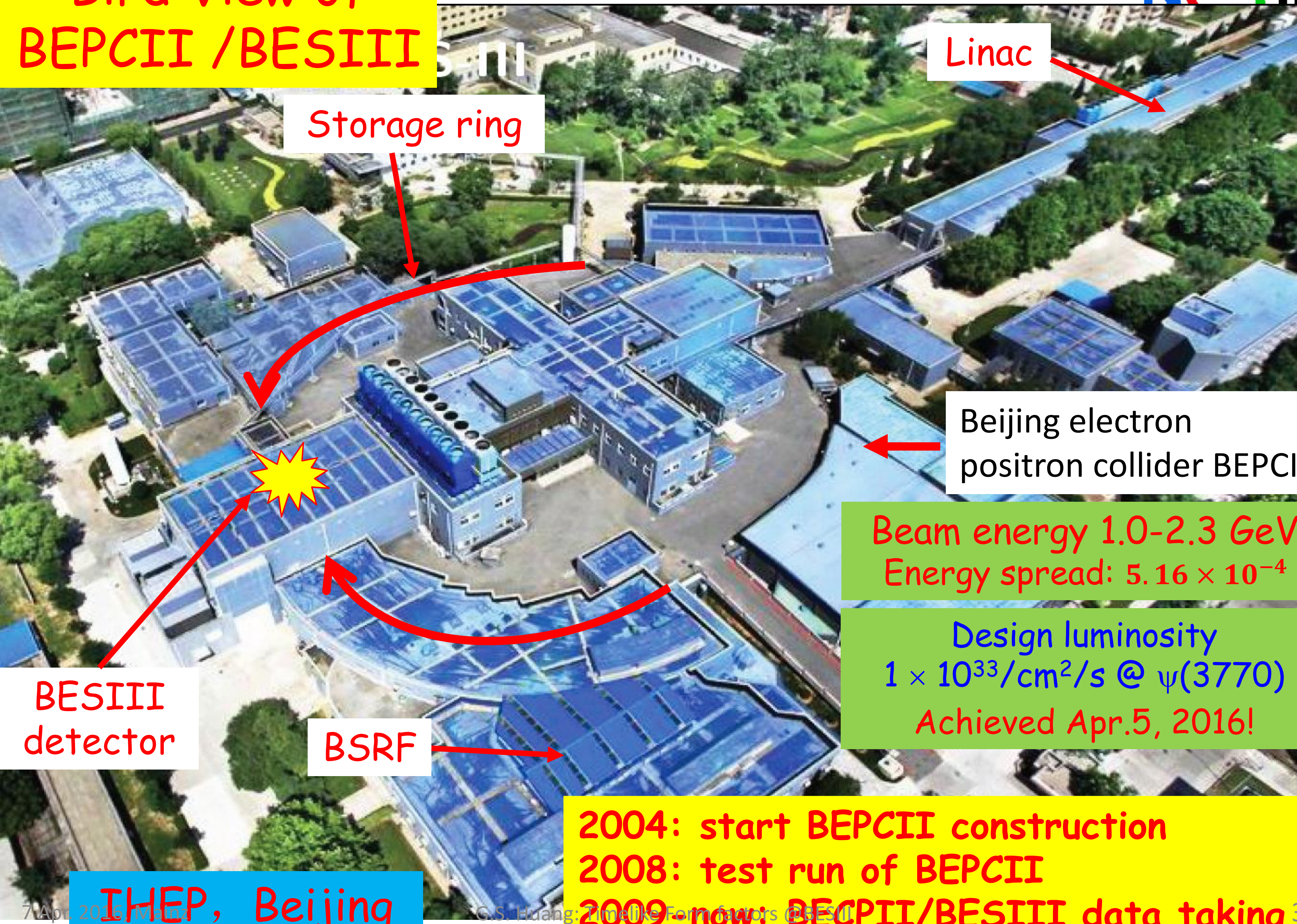
New Vistas in Low-Energy Precision Physics
4-7 April 2015, Mainz, Germany

Outline

- BEPCII/BESIII
- Energy scan and ISR
- Baryon form factor measurements
- Meson form factor measurements
- Summary

Bird View of BEPCII /BESIII



Beam energy 1.0-2.3 GeV
Energy spread: 5.16×10^{-4}

Design luminosity
$1 \times 10^{33}/cm^2/s$ @ $\psi(3770)$
Achieved Apr.5, 2016!

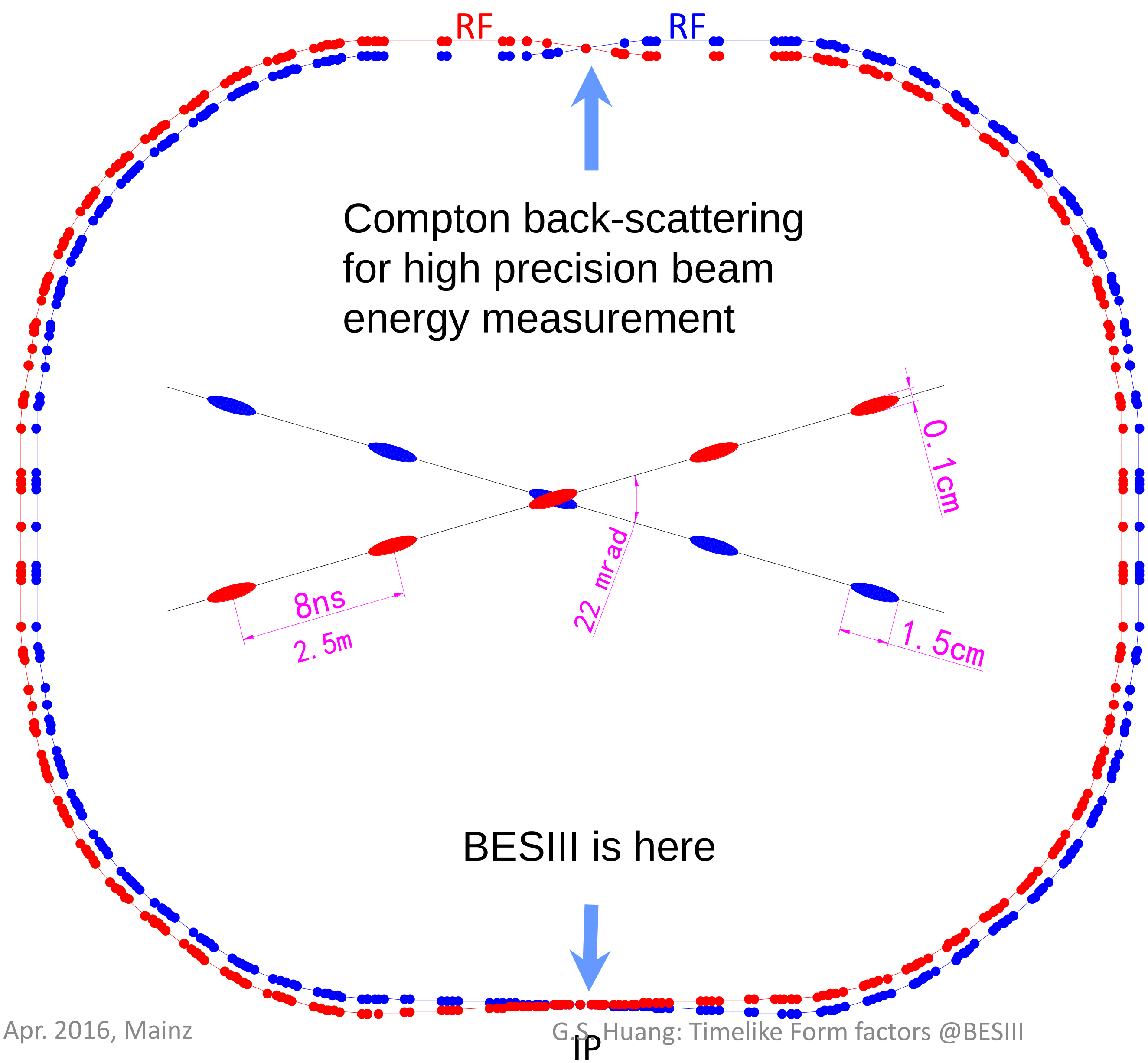
2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BECPII/BESIII data taking

Luminosity!

- After 8-year struggling, BEPCII reached its goal.

2 days ago

BEPC II: Large Crossing Angle, Double-ring



Beam energy:
1-2.3 GeV

Luminosity:
1×10^{33} $cm^{-2}s^{-1}$

Optimum energy:
1.89 GeV

Energy spread:
5.16×10^{-4}

No. of bunches:
93

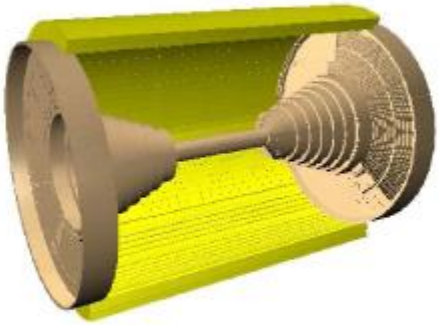
Bunch length:
1.5 cm

Total current:
0.91 A

SR mode:
0.25A@2.5GeV

BESIII Detector

MDC

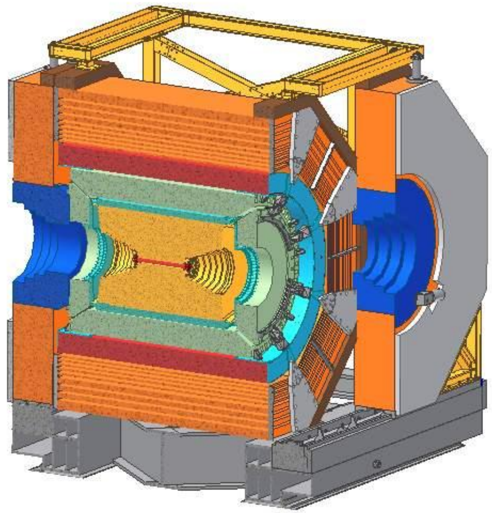


R inner: 63mm ;

R outer: 810mm

Length: 2582 mm

Layers: 43

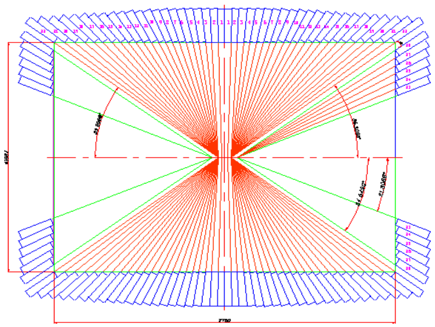


TOF

BTOF: two layers

ETOF: 48 for each

CsI(Tl) EMC



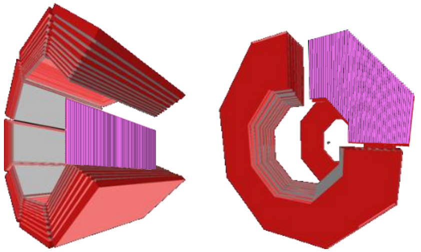
Crystals: 28 cm(15 X_0)

Barrel: $|\cos\theta|<0.83$

Endcap:

$0.85 < |\cos\theta| < 0.93$

RPC MUC

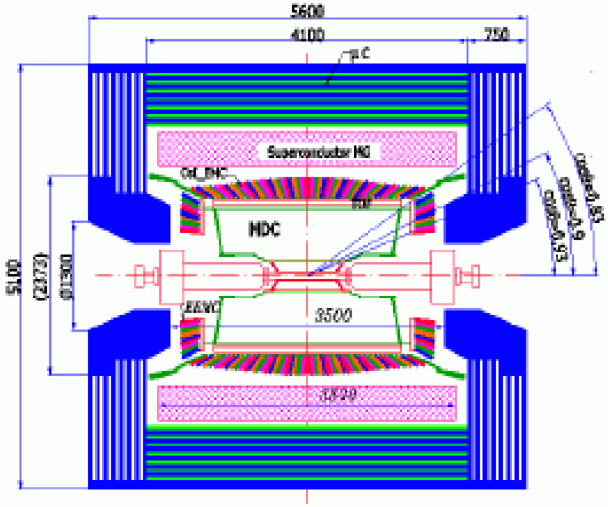


BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

BESIII Detector

Exps.	MDC Wire resolution	MDC dE/dx resolution	EMC Energy resolution
CLEO	110 μm	5%	2.2-2.4 %
Babar	125 μm	7%	2.67 %
Belle	130 μm	5.6%	2.2 %
BESIII（XYZ data）	115 μm	<5% (Bhabha)	2.3%



Exps.	TOF time resolution
CDFII	100 ps
Belle	90 ps
BESIII (XYZ data)	68 ps (BTOF) 100 ps (ETOF)

- New ETOF (MRPC), just installed
- New Inner MDC, built at IHEP

The BESIII Collaboration

http://bes3.ihep.ac.cn

US (5)
Univ. of Hawaii
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (13)
Germany: Univ. of Bochum, Univ. of Giessen, GSI
Univ. ofJohannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino， Frascati Lab
Netherland: KVI/Univ. of Groningen
Turkey: Turkey Accelerator Center

Mongolia (1)
Institute of phys. & Tech.

Korea (1)
Seoul Nat. Univ.

Japan (1)
Tokyo Univ.

Pakistan (2)
Univ. of Punjab
COMSAT CIIT

China(32)
IHEP, CCAST, UCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ., Beihang Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Univ. of Sci. & Tech. Liaoning

~400 physicists
55 institutions from 12 countries

BESIII Data Sets

- July 19, 2008: first e^+e^- collision event in BESIII
- Nov. 2008: ~14M $\psi(2S)$ events for detector calibration
- 2009: 106M $\psi(2S)$, 42pb^{-1}@3.65GeV
  225M J/ψ

World's largest samples

- 2010: ~0.9 fb^{-1} $\psi(3770)$
- 2011: ~2.0 fb^{-1} $\psi(3770)$
  } 3.5×CLEO-c
  ~0.5 fb^{-1} @ 4.01 GeV
- 2012: tau scan: ~24 pb^{-1} ; $\psi(2S)$: 0.4B; J/ψ: 1B; J/ψ scan; R scan (2.23, 2.4, 2.8, 3.4 GeV): ~12 pb^{-1};
- 2013-2014: ~5.0 fb^{-1} @ 4.26, 4.36 GeV, …, 19 points for XYZ studies; ~0.8 fb^{-1} R scan in 3.8-4.6 GeV, 104 points;
- 2015: ~0.5 fb^{-1} in 2-3.1 GeV, 20 points; 0.1 fb^{-1} Y(2175);
- 2016: → 3 fb^{-1} @4.18 GeV for Ds.

R-QCD scan in 2 – 3.1 GeV

- 2014.12.30-2015.5.1;
- From high to low;
- Added 2.05 GeV;
- 20(21) energy points, with a total online luminosity 525 pb^{-1};
- Allows for form factor measurements, threshold studies, …

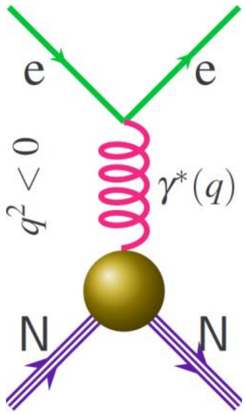
E_{cm} (GeV)	E_{th} (GeV)	L_{Needed} (pb^{-1})	t_{beam} ($days$)	Purpose
2.0		≥8.95	14.6	Nucleon FFs
2.1		10.8	14.8	Nucleon FFs
2.15		2.7	2.29	Y(2175)
2.175		10(+)	8.5	Y(2175)
2.2		13	11	Nucleon FFs, Y(2175)
2.2324	2.2314	11	4	Hyp threshold ($\Lambda\bar{\Lambda}$)
2.3094	2.3084	20	16	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Lambda}$)
2.3864	2.3853	20	8.7	Hyp Threshold ($\Sigma^0\bar{\Sigma}^0$) Hyp FFs
2.3960	2.3949	≥64	27.8	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^-\bar{\Sigma}^+$)
2.5		0.4895	8h	R scan
2.6444	2.6434	65	18	Nucleon & Hyp FFs Hyp Threshold ($\Xi^-\bar{\Xi}^+$)
2.7		0.5542	4.2h	R scan
2.8		0.6136	4h	R scan
2.9		100	18.5	Nucleon & Hyp FFs
2.95		15	2.8	$m_{p\bar{p}}$ step
2.981		15	2.8	η_c , $m_{p\bar{p}}$ step
3.0		15	2.8	$m_{p\bar{p}}$ step
3.02		15	2.8	$m_{p\bar{p}}$ step
3.08		120	13.2	Nucleon FFs (+30 pb^{-1})

6-month plan, finished in ~4 months.

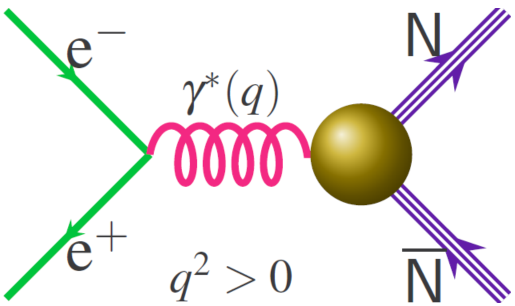
Electromagnetic Form Factors

Space-like:
FF real

$eN \rightarrow eN$



$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \ldots$



Time-like:
FF complex

Vector current, **two form factors** (F_1 and F_2)

$$\Gamma_\mu = e\bar{u}(p')[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M_N}F_2(q^2)i\sigma_{\mu\nu}q^\nu]u(p)e^{iqx}$$

Dirac	**Pauli**
$F_1^p(q^2=0)=1$	$F_2^p(q^2)=1$
$F_1^n(q^2=0)=0$	$F_2^n(q^2)=1$

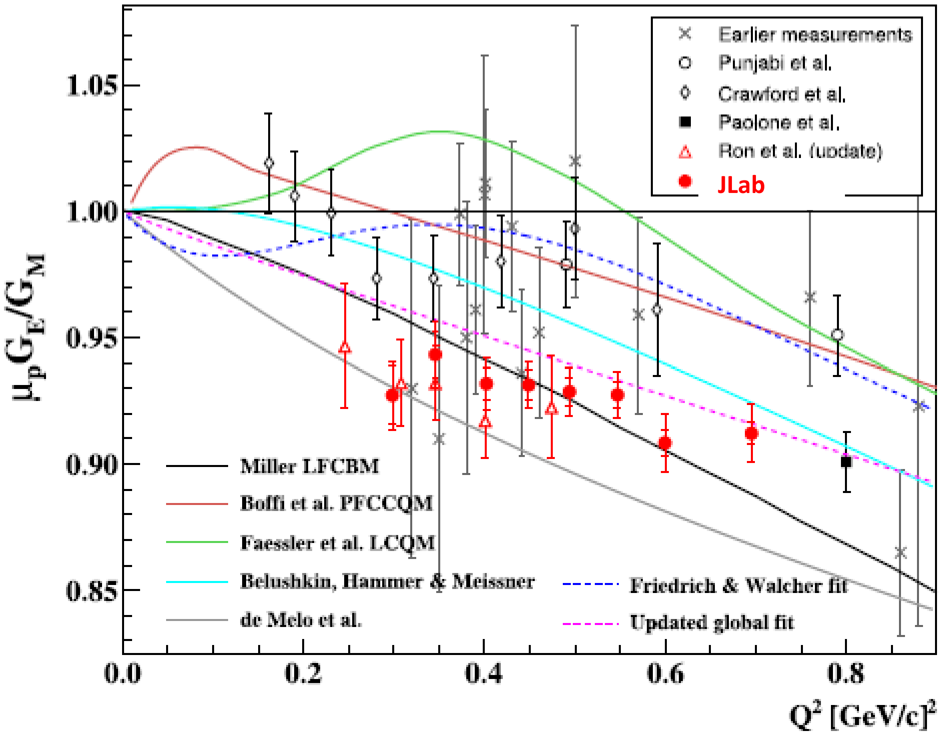
Sachs

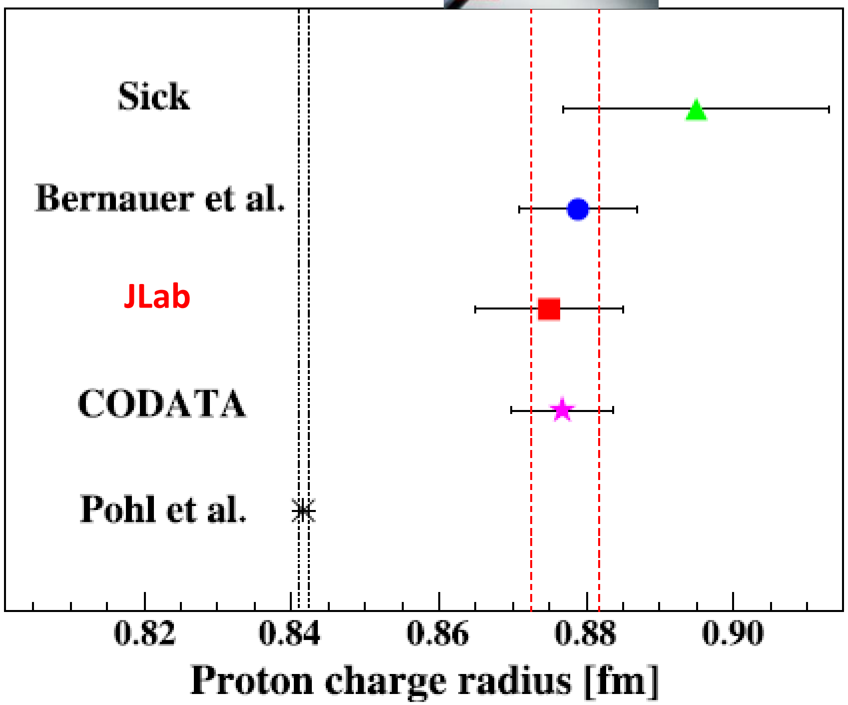
$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

$$G_E(4M_p^2) = G_M(4M_p^2)$$

Space-Like(SL) FF: e.g. proton

There have been many measurements of the proton form factors in the space-like region. At JLab, the proton factor ratio was measured precisely with an uncertainty of ~1%, based on which the proton electronic and magnetic radii could be extracted.





Time-Like(TL) FF: e.g. proton

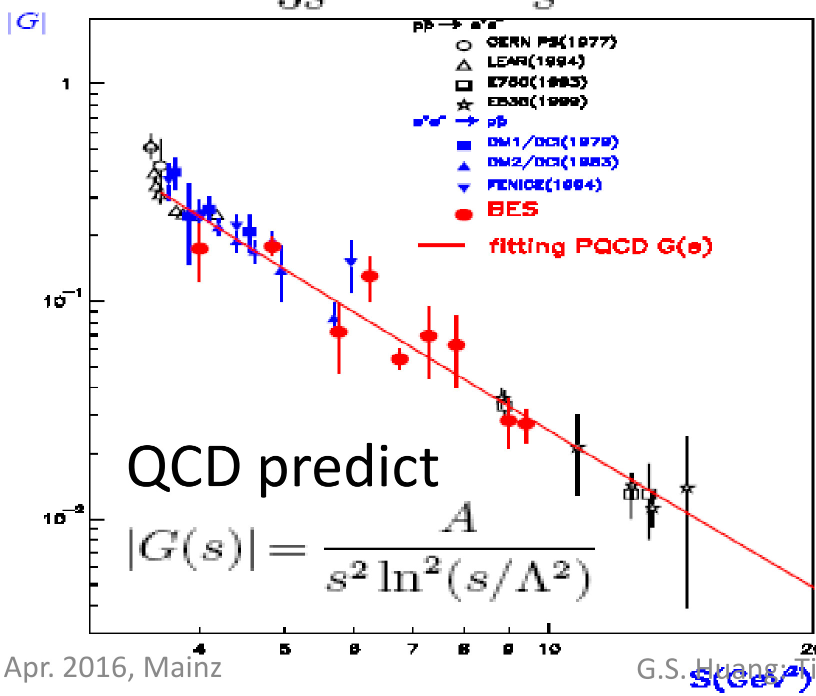
$$e^+e^-\to p\bar{p}: \frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}C[|G_M(s)|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E(s)|^2\sin^2\theta]$$

$$|G_M(q^2)| = [1 + (q^2 - 4M_p^2)/q_2^2]^{-2}$$

$$|G_E(q^2)| = |G_M(q^2)|[1 + (q^2 - 4M_p^2)/q_1^2]^{-1}$$

Most experiments assumed $G_E=G_M$:

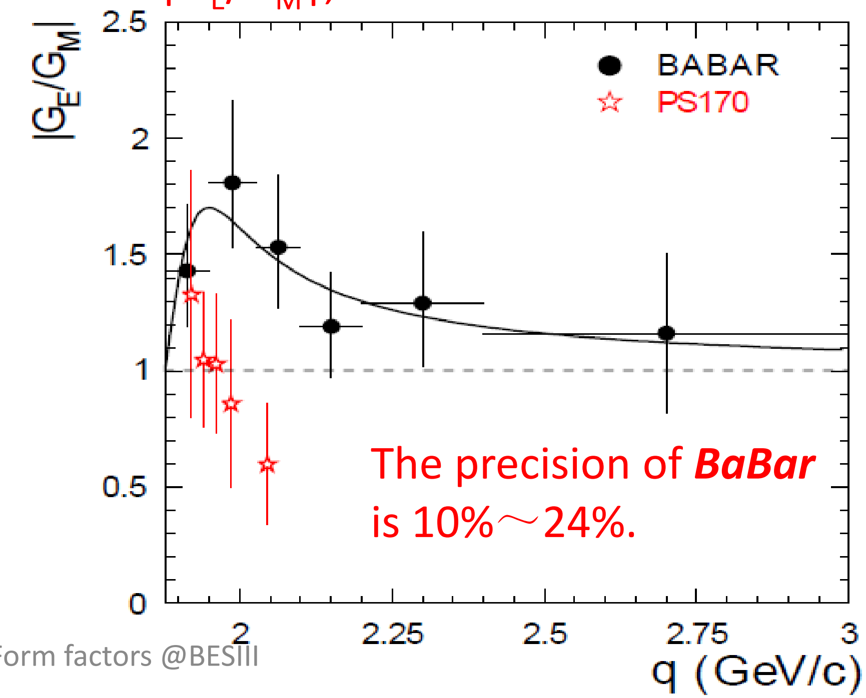
$$\sigma_0 = \frac{4\pi\alpha^2\beta}{3s}(1+\frac{2M^2}{s})|G(s)|^2$$



QCD predict

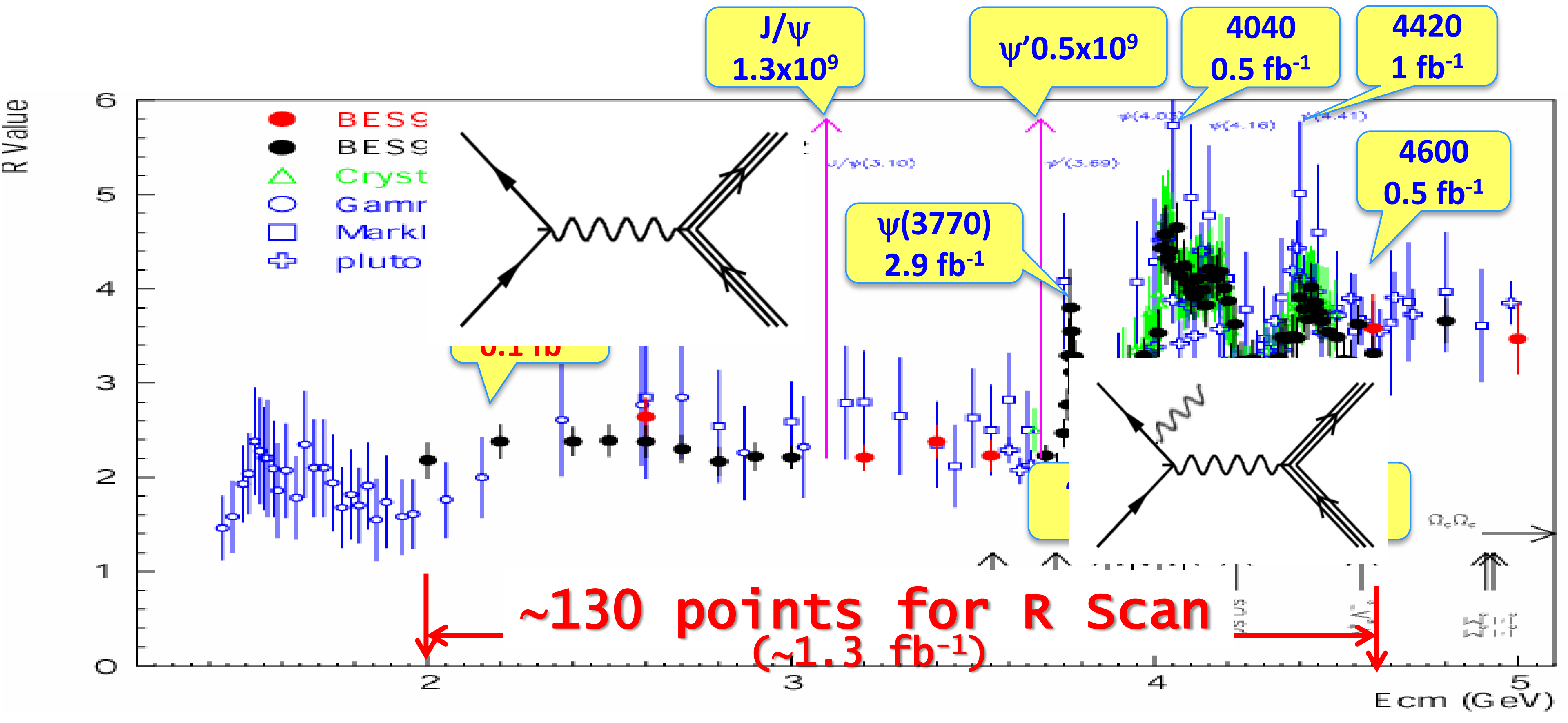
$$|G(s)| = \frac{A}{s^2\ln^2(s/\Lambda^2)}$$

Only two experiments measured $|G_E/G_M|$, with inconsistent results:



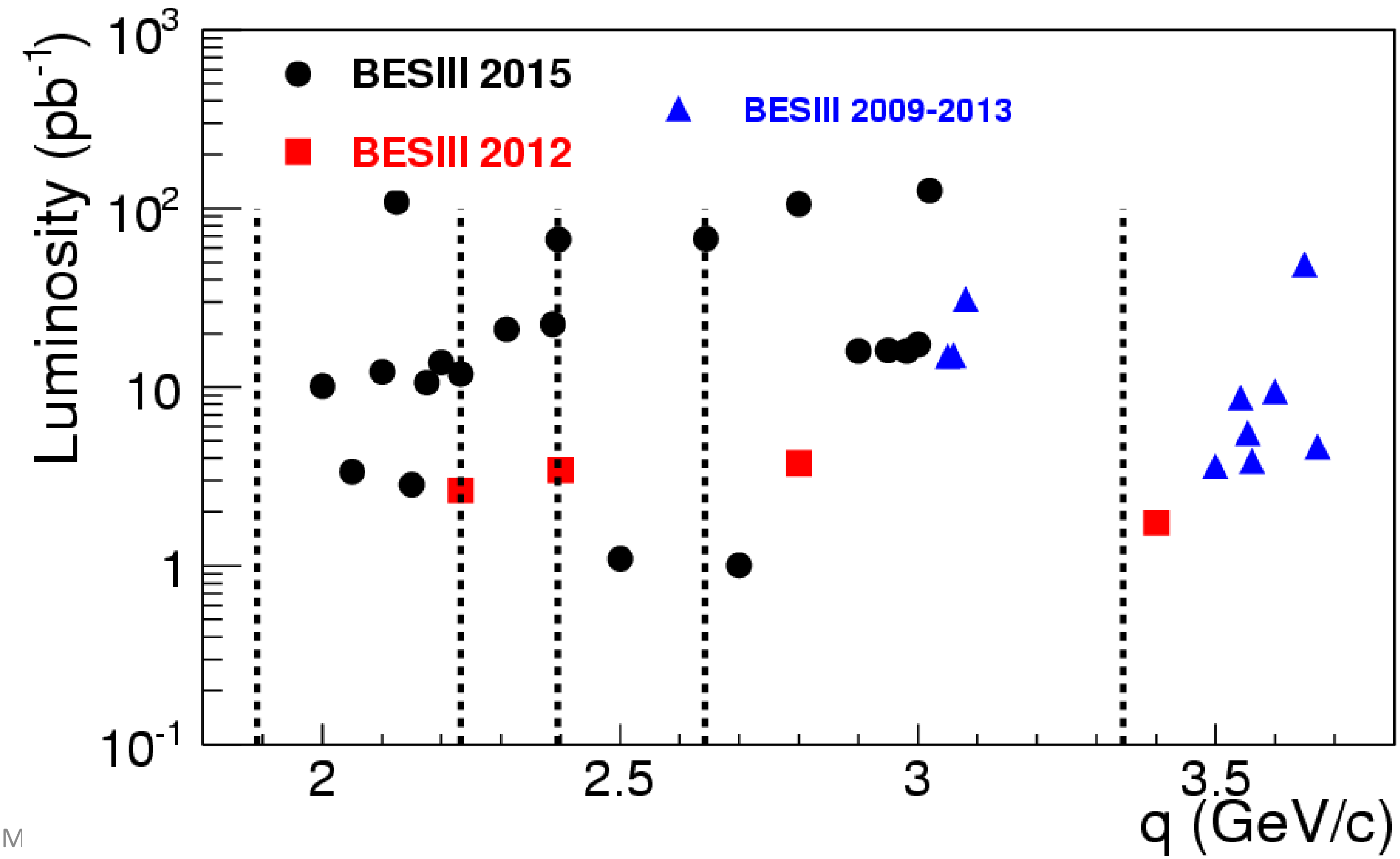
The precision of ***BaBar*** is 10%～24%.

Energy scan and ISR at BESIII



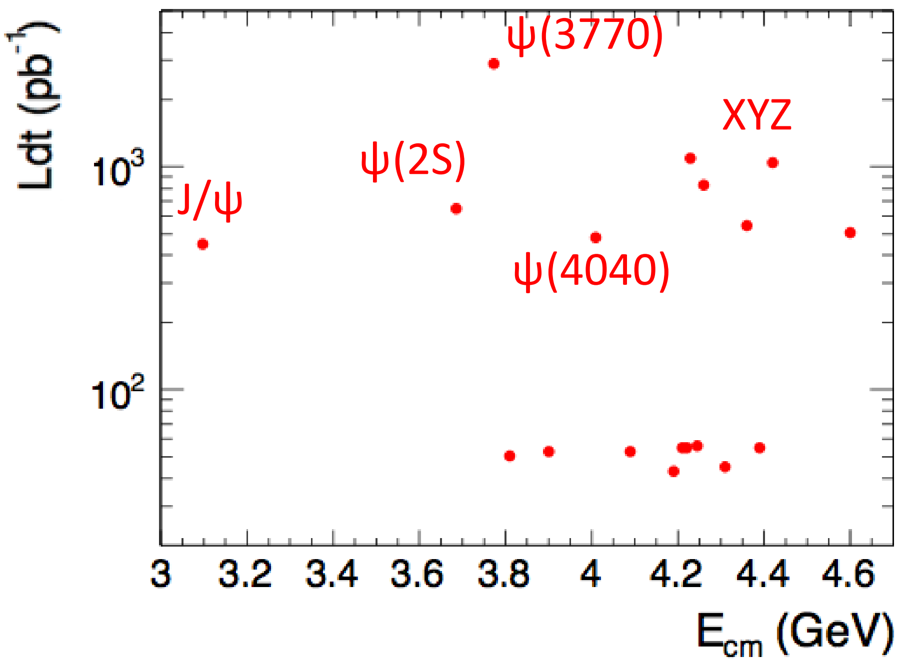
Scan data for form factors

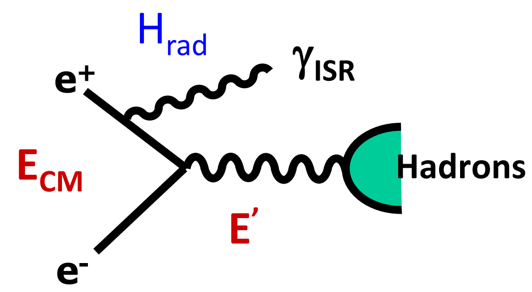
- ~800 pb^{-1} in 2.0 – 3.671 GeV;
- For proton, neutron, hyperons, and mesons.



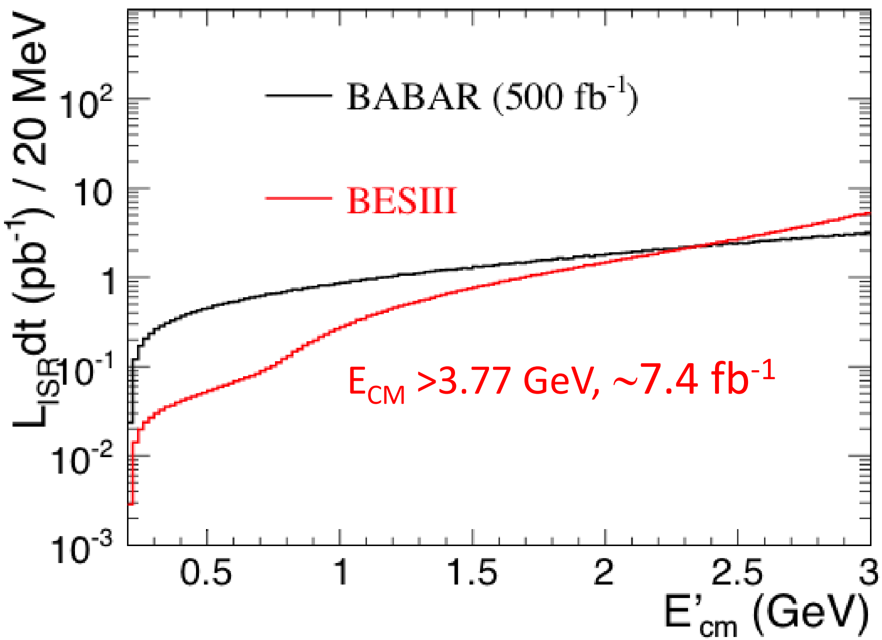
Data Samples for ISR Physics

Integrated luminosities at BESIII





ISR luminosity = Ldt x H_{rad}



- $\pi^+\pi^-\gamma_{ISR}$
- $\pi^+\pi^-\pi^0\gamma_{ISR}$
- $p\bar{p}\gamma_{ISR}$
- …

To measure timelike nucleon em FFs:

- Extraction of $R_{em} = |G_E/G_M|$ independent from normalisation through angular analysis

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

$R_{em} = |G_E(q^2) / G_M(q^2)|$ $\qquad \tau = 4m^2/q^2$

q^2 : 4-momentum transferred by the virtual photon

θ : polar angle of nucleon at the CM

We need to collect data at different √s of the collider and fit with:

$$f(\cos\theta) = \text{Norm} \cdot [\text{tau}\,(1+\cos^2\theta) + R_{em} \cdot (1-\cos^2\theta)]$$

- Extraction of $|G_E|$ and $|G_M|$ with the knowledge of the absolute normalisation (Luminosity, rad. corr., systematics, etc.)

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

$|G_E|$ is supressed at high s by 1/s !!

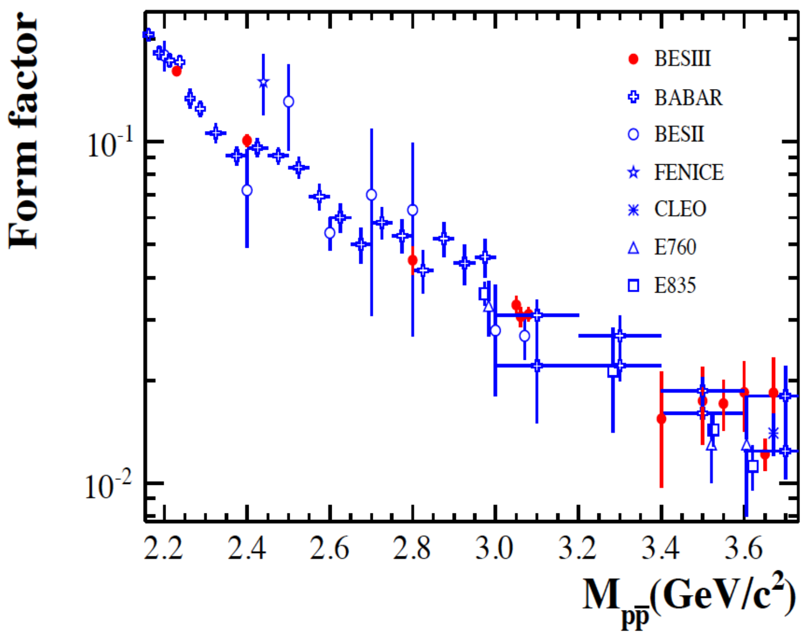
Proton Form Factors from 2012 test run

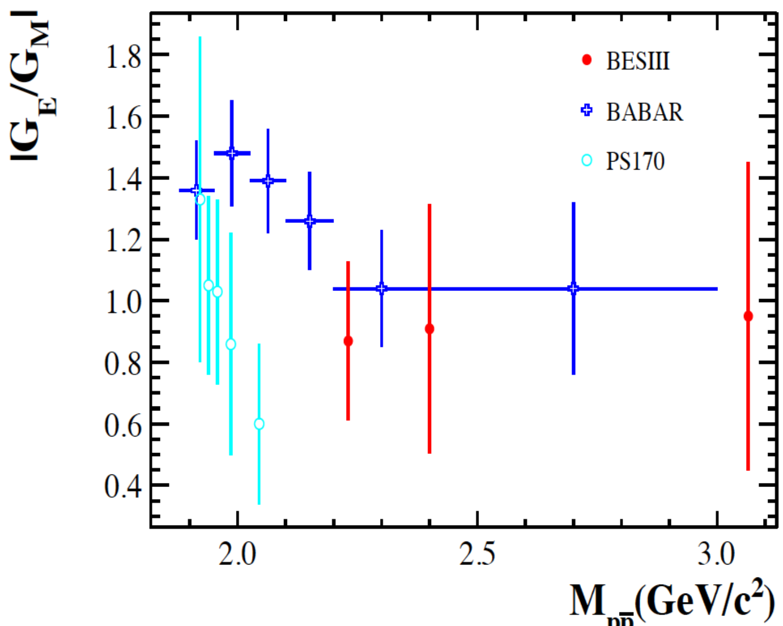
Phys. Rev. D 91, 112004 (2015)

Analysis Features:

- Radiative corrections from Phokhara8.0 (scan)
- Normalization to $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$ (BABAYAGA 3.5)
- Efficiencies 60% (2.23 GeV) .... 3% (~4 GeV)
- $|G_E/G_M|$ ratio obtained for 3 c.m. energies

E_{cm}/GeV	L_{int} / pb^{-1}
2.23	2.6
2.40	3.4
2.80	3.8
3.05, 3.06, 3.08	60.7
3.40, 3.50, 3.54, 3.56	23.3
3.60, 3.65, 3.67	63.0



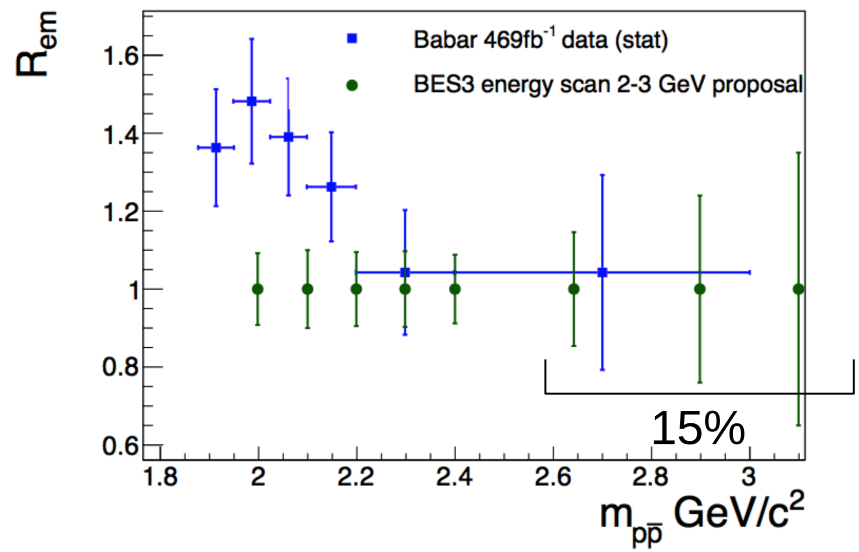


Proton FF: expectation from 2015 data

Based on the 2015 scan data in 2-3.1 GeV:

E_{cm} (GeV)	Luminosity (pb^{-1})	$\delta R_{em}/R_{em}$	$\delta G_M/G_M$	$\delta G_E/G_E$
2.0	8.95	9.2%	3%	9%
2.1	10.8	10%	3%	10%
2.2	13	9.5%	3%	11%
2.3084	20	9.7%	3%	10%
2.3950	35	8.8%	3%	9%
2.644	65	14.6%	5%	16%
2.9	100	24%	6%	25%
3.1	150	~ 35%	8.5%	35%

15%



$\delta|R_{EM}|/|R_{EM}|$ ~ 9% - 35%

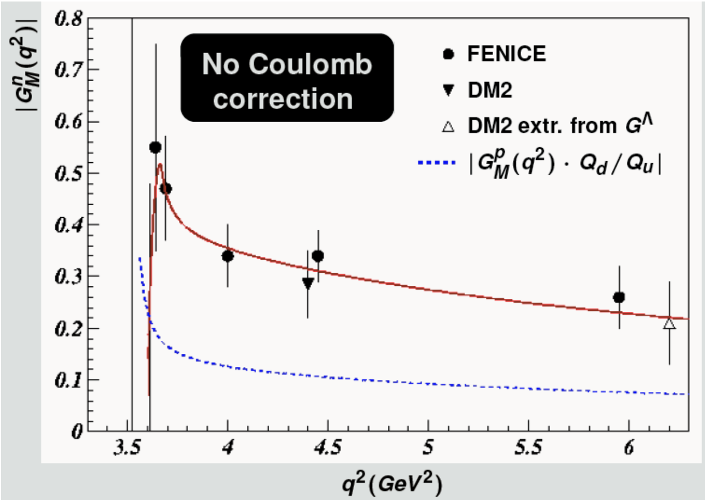
$\delta|G_M|/|G_M|$ ~ 3% - 9%

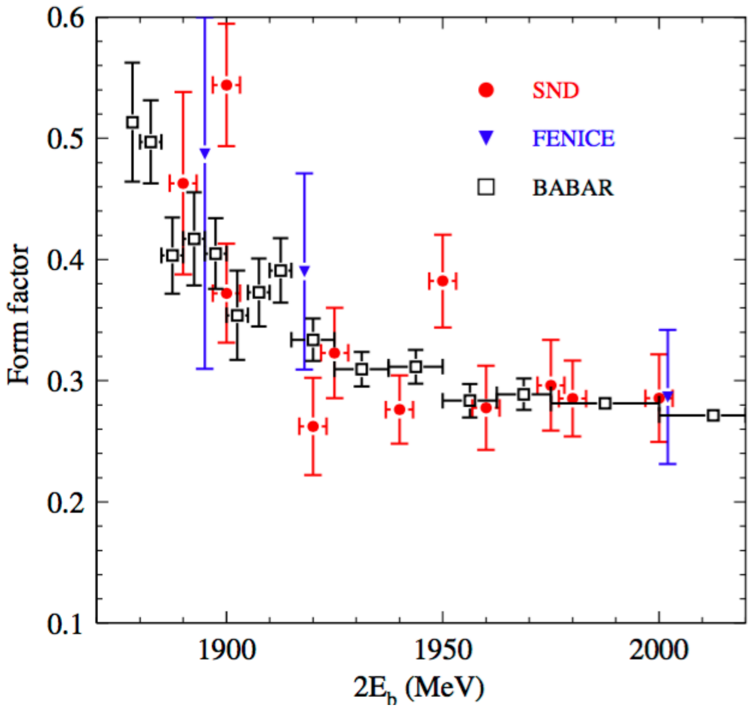
$\delta|G_E|/|G_E|$ ~ 9% - 35%

Will top BaBar result

First time extraction without any assumption!

TL neutron form factors





Two measurements:

- ➢ Old from Fenice with 74 $e^+e^- \to n\bar{n}$ events, assuming $G_E=0$, motivated by angular distribution of $n\bar{n}$ events, Nucl. Phys. B517, 3 (1998)
- ➢ Recent data from SND, which is consistent with the proton FFs result of BaBar

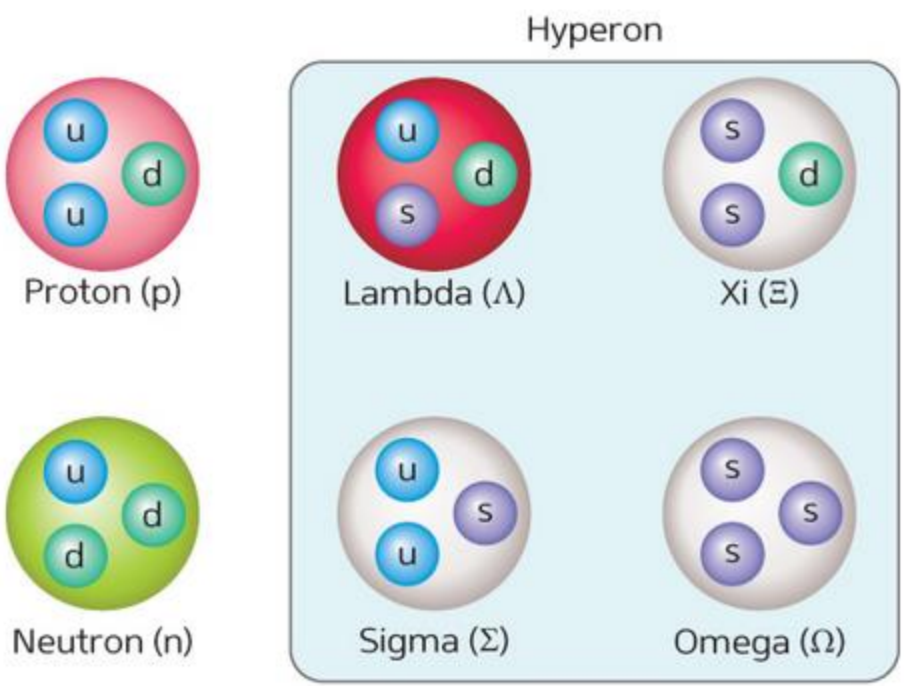
BESIII Goal

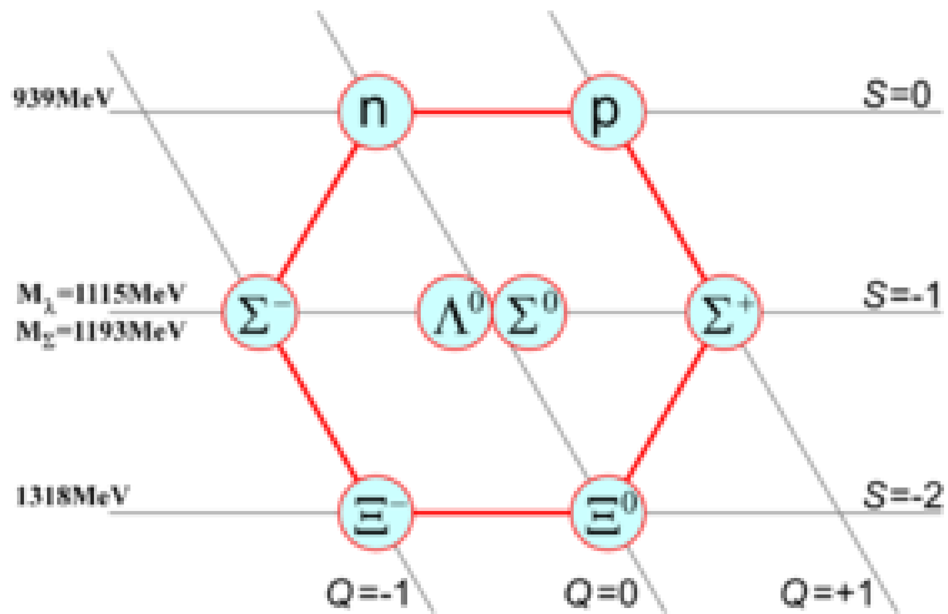
- ➢ **To extract EM FFs in wide region;**
- ➢ **To measure the ratio for the first time, with an uncertainty as similar as possible to the proton case.**

Hyperon TL Form Factors

Key question:

"What happens with the baryon structure when a light quark is replaced by a heavier one?"





Spin $\frac{1}{2}^{+}$ SU(3) octet

Baryon-pair production near threshold

- The Born cross section for $e^+e^- \rightarrow \gamma^* \rightarrow B\bar{B}$, can be expressed in terms of electromagnetic form factor G_E and G_M :

$$\sigma_{B\bar{B}}(m) = \frac{4\pi\alpha^2 C\beta}{3m^2}\left[|G_M(m)|^2 + \frac{1}{2\tau}|G_E(m)|^2\right]$$

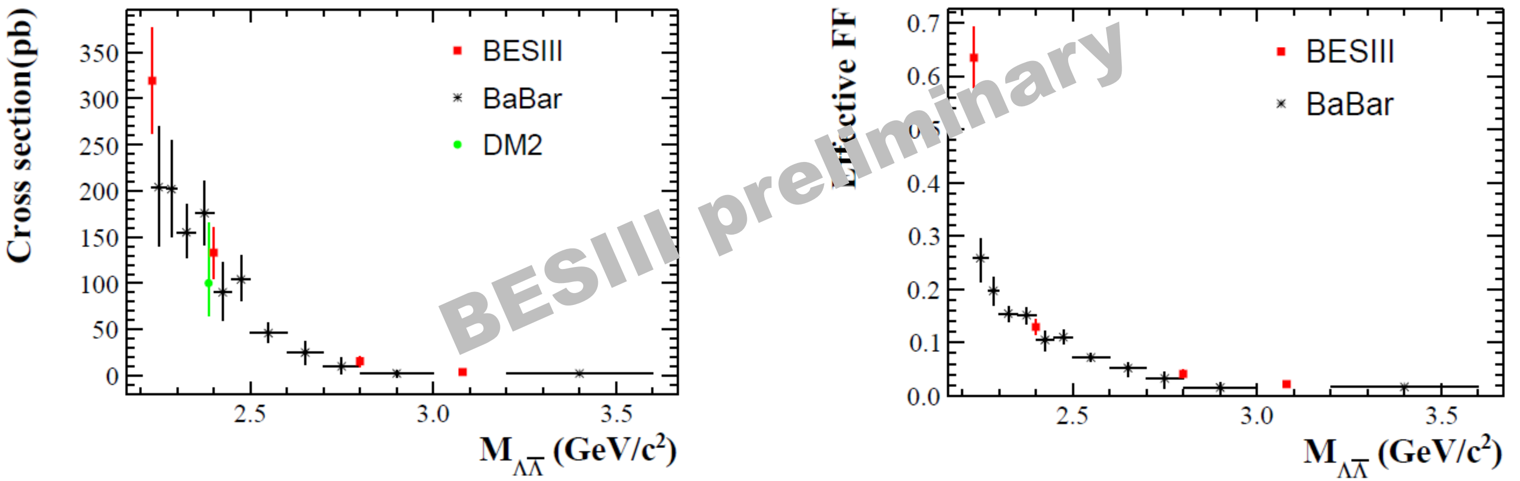
$\alpha = \frac{1}{137}$ is fine structure constant, $\beta = \sqrt{1 - 4m_B^2/m^2}$ is the velocity, $\tau = m^2/4m_B^2$

- The Coulomb factor C= $\begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})} & \text{for a charged } B\bar{B} \text{ pair} \\ 1 & \text{for a neutral } B\bar{B} \text{ pair} \end{cases}$

- For the neutral pair production, the cross section should be 0 at threshold, and is expected to increase with the velocity near the threshold.

Example: $e^+e^- \to \Lambda\bar{\Lambda}$

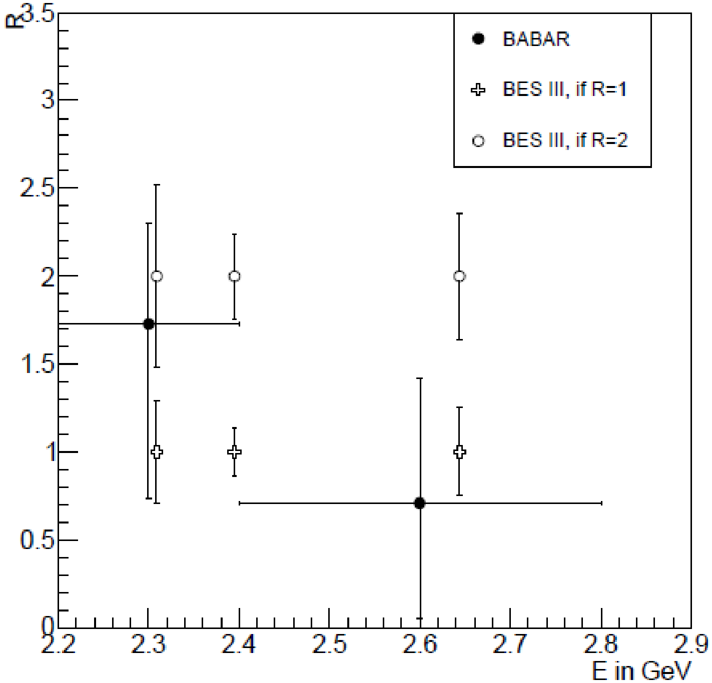
Cross section and effective form factor from 2012 test run



$\sqrt{s}$ (MeV)	Reconstruction	σ_{Born} (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2232.4	$\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$	$325 \pm 53 \pm 46$	
	$\bar{\Lambda} \to \bar{n}\pi^0$	$(3.0\pm1.0\pm0.4)\times10^2$	
	combined	320 ± 58	63.4 ± 5.7
2400.0		$133 \pm 20 \pm 19$	$12.93 \pm 0.97 \pm 0.92$
2800.0		$15.3 \pm 5.4 \pm 2.0$	$4.16 \pm 0.73 \pm 0.27$
3080.0		$3.9 \pm 1.1 \pm 0.5$	$2.21 \pm 0.31 \pm 0.14$

- The first point is just 1 MeV above threshold.
- Cross section does not vanish at threshold!
- Possible explanation: Coulomb interaction at quark level.

Hyperon: expectation from 2015 data



- For $\Lambda\bar{\Lambda}$, larger data samples allow to extract angular distribution, no need model dependent efficiency;
- Form Factors G_E & G_M and ratio $R=|G_E/G_M|$ can be measured at several points with unprecedented precision.

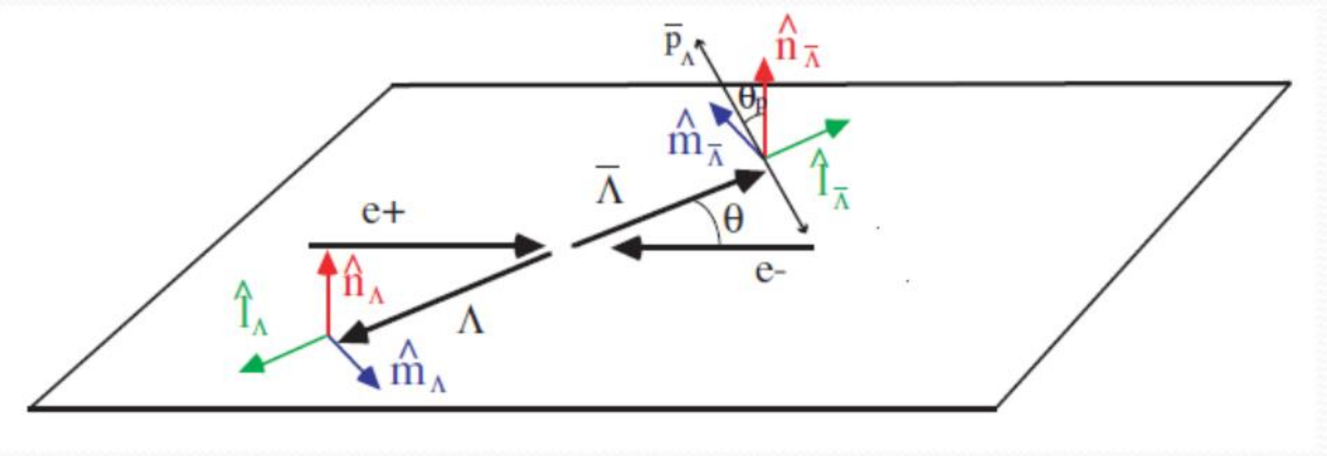
We shall also be able to measure $e^+e^- \to \Lambda\bar{\Sigma}^0$, $\Sigma^0\bar{\Sigma}^0$, $\Sigma^+\bar{\Sigma}^-$, $\Sigma^-\bar{\Sigma}^+$, etc.

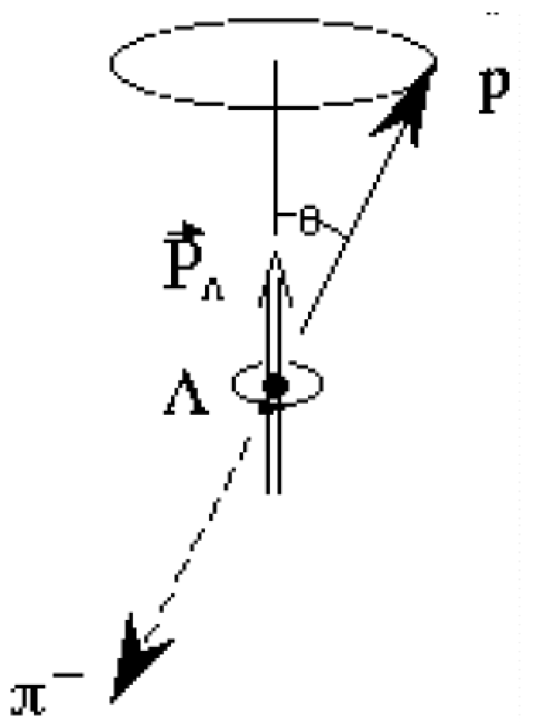
Λ polarization

- Relative phase in G_E & G_M: $\Delta\phi = \phi_M - \phi_E$;
- Nonzero phase → polarization of Λ (P_n), to be extracted from the decay proton angle:

$$\frac{d\sigma}{dcos\theta_p} = \frac{1}{2}(1 + \alpha_\Lambda P_n cos\theta_p)$$

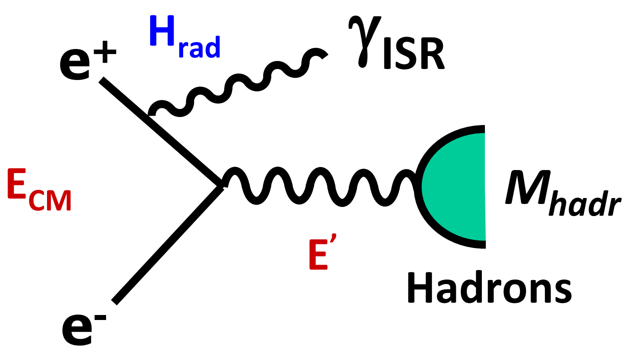
- ~600 events @2.396 GeV (65 pb^{-1})



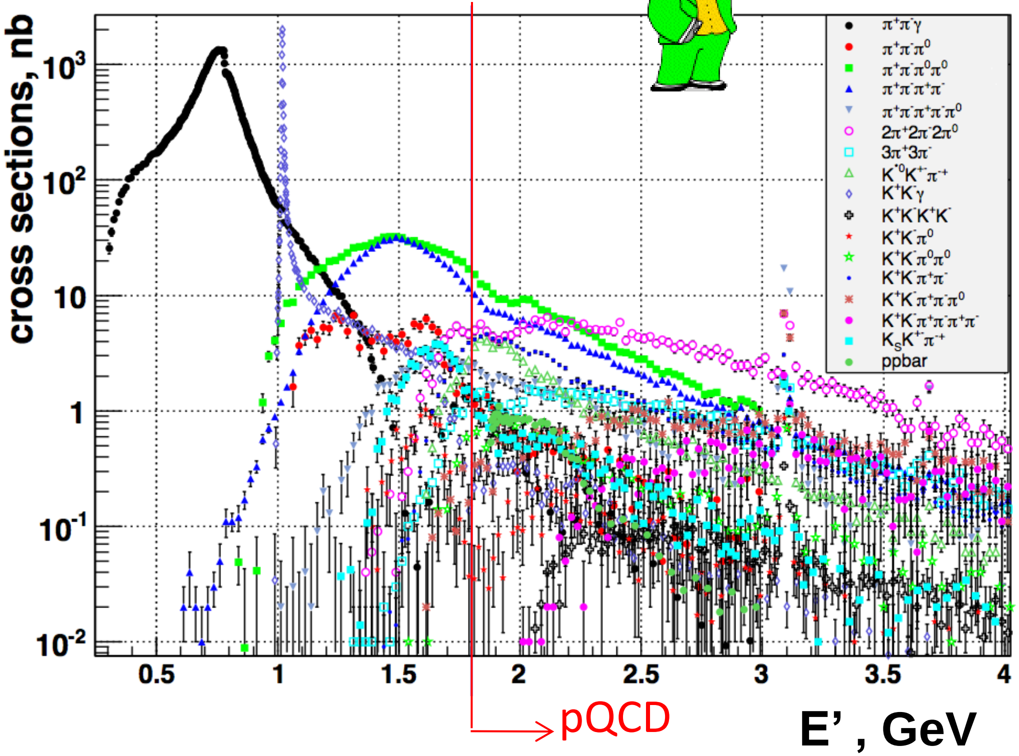


Initial State Radiation (ISR)

Rev. Mod. Phys. 83, 1545-1588 (2011)



ISR spectra measured by BABAR



- Needs **no** systematic variation of beam energy
- High statistics thanks to high integrated luminosities
- Precise knowledge of radiative corrections mandatory (H_{rad})

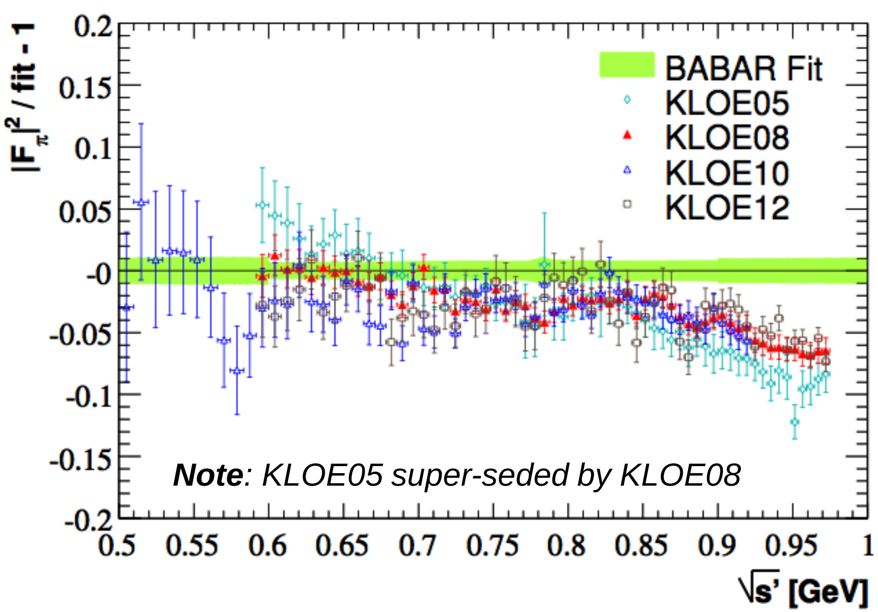
→ Entire E range <E_{CM} accessible

PHOKHARA event generator, Czyż, Kühn, et al.

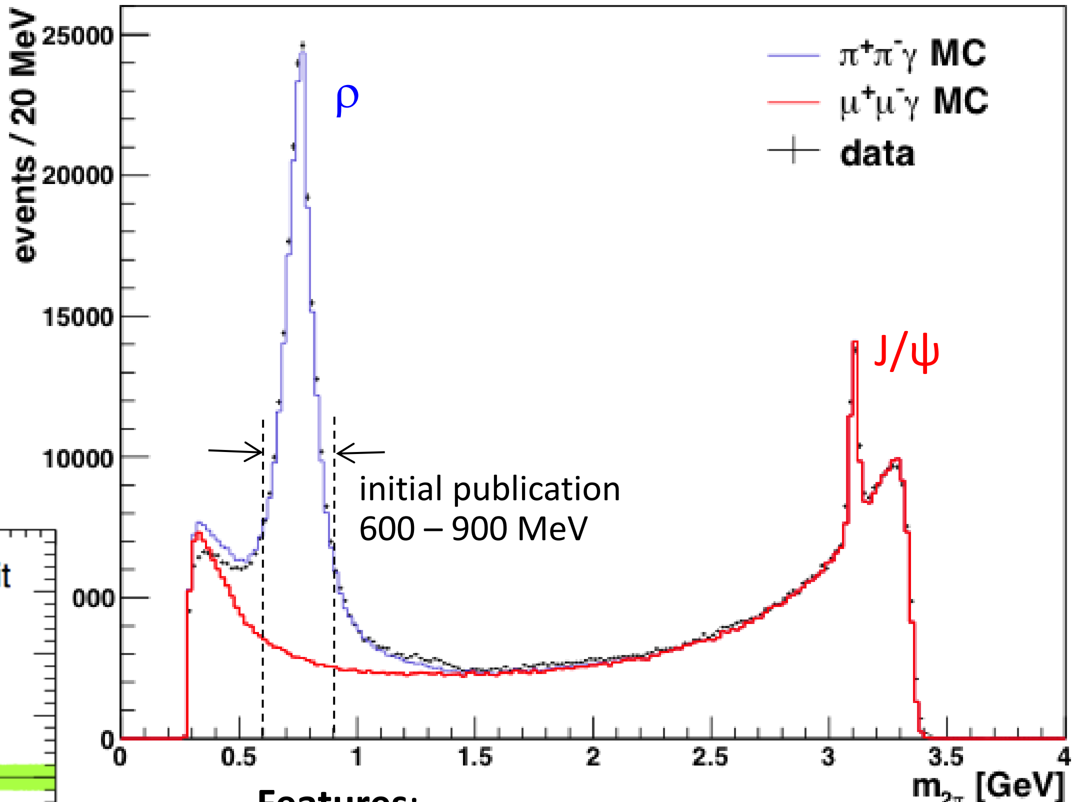
ISR Analysis: $e^+e^- \to \pi^+\pi^-\gamma_{ISR}$

The most relevant Channel

- KLOE and BABAR dominate the world average
- Relatively large systematic differences, esp. above ρ peak
- Knowledge of a_μ^{had} dramatically limited due to this difference



Event yield after acceptance cuts **only**



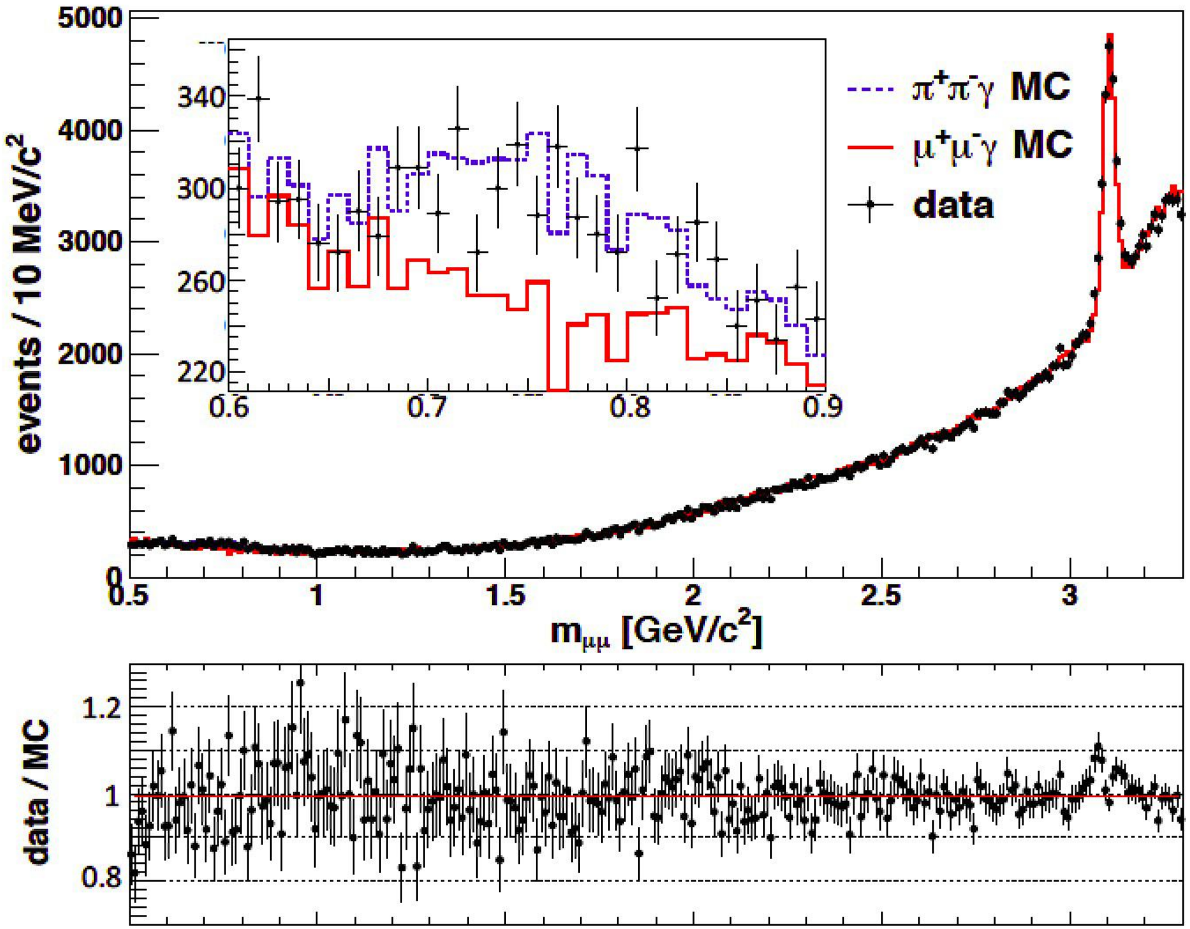
Features:

- ψ(3770) data only (2.9 fb^{-1})
- no dedicated background subtraction
- tagged ISR photon

→ large statistics of $e^+e^- \to \pi\pi\gamma$ events
→ background dominated by $e^+e^- \to \mu\mu\gamma$
→ data – MC differences visible

Measurement of $\mu^+\mu^-\gamma$: Data vs. QED

Event yield $\mu\mu\gamma$ after π-μ separation and all efficiency corrections



Features:

- background from $\pi\pi\gamma$ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha events, 0.5% accuracy

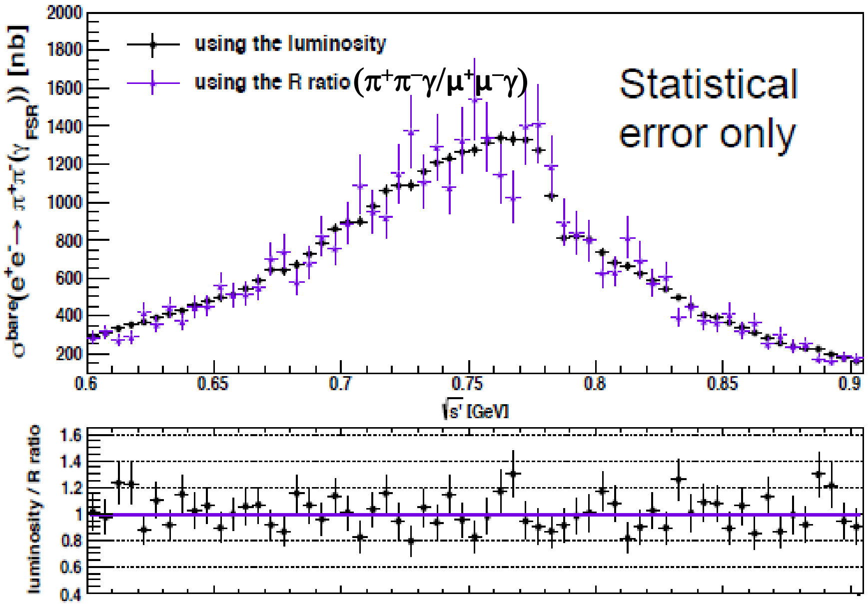
→ excellent agreement with QED

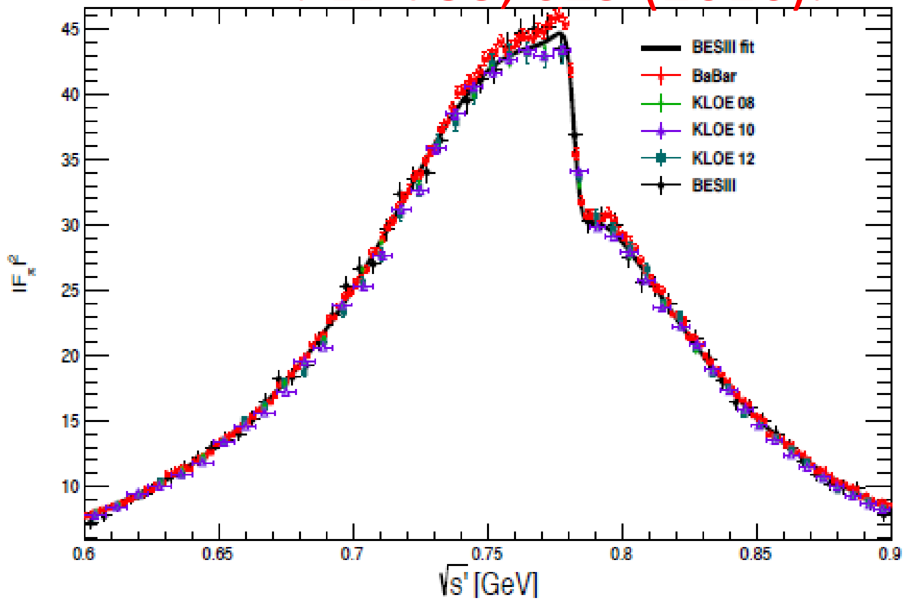
Δ(MC/QED-data) -1 = (1.0 ± 0.3 ± 0.9) %

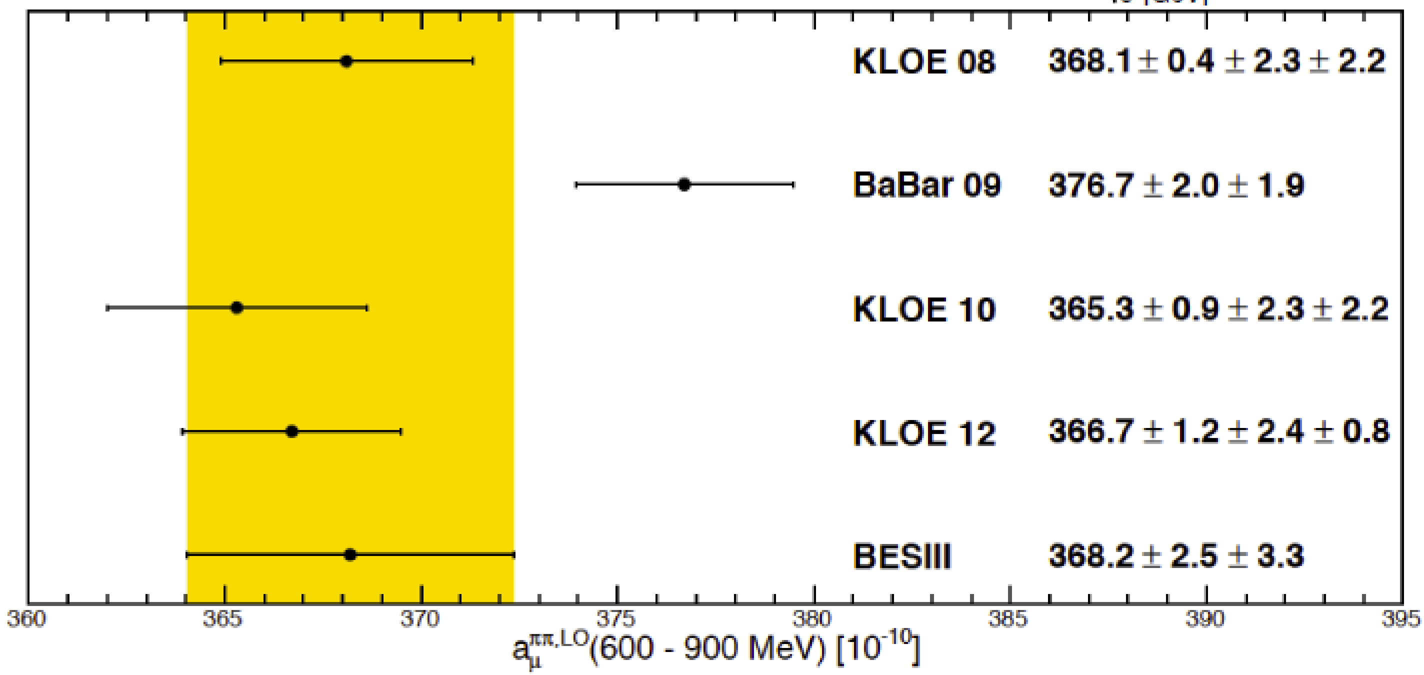
→ accuracy on 1% level as needed to be competitive !

$\sigma(e^+e^- \to \pi^+\pi^-)$ and form factor

PLB 753, 629 (2016).





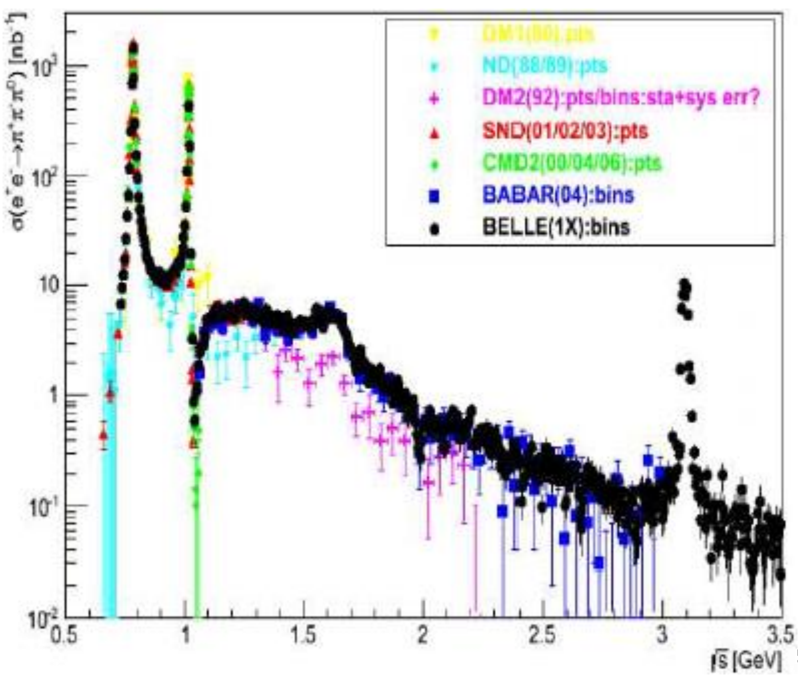


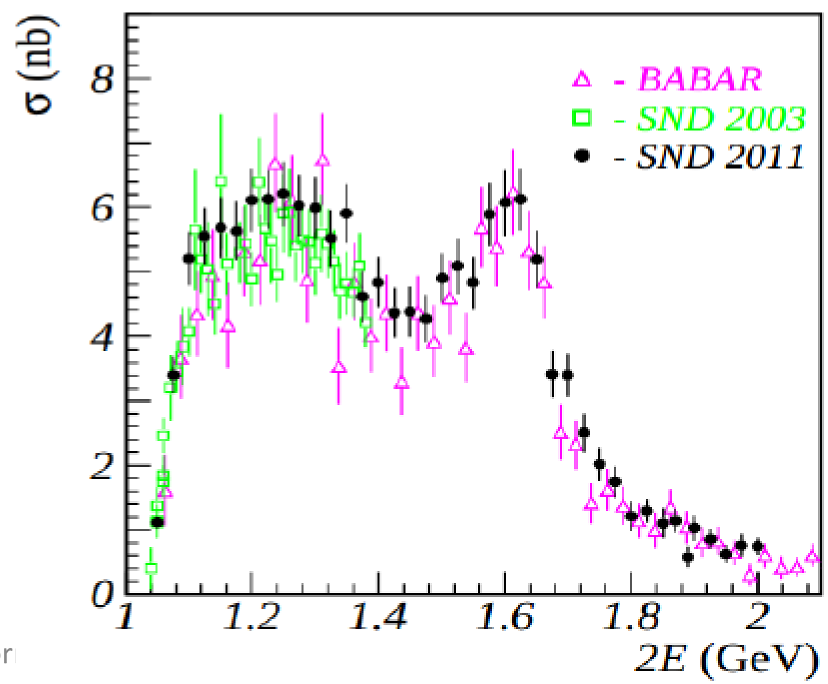
ISR Analysis: $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$

- Results from
  - SND: up to 2.0 GeV
  - DM2: 1.34 ~ 2.4 GeV
  - BaBar: 1.05 ~ 3.0 GeV
  - Belle: 0.7 ~3.5 GeV
- Apparent ω, ϕ, ω’, ω’’.

BESIII work ongoing

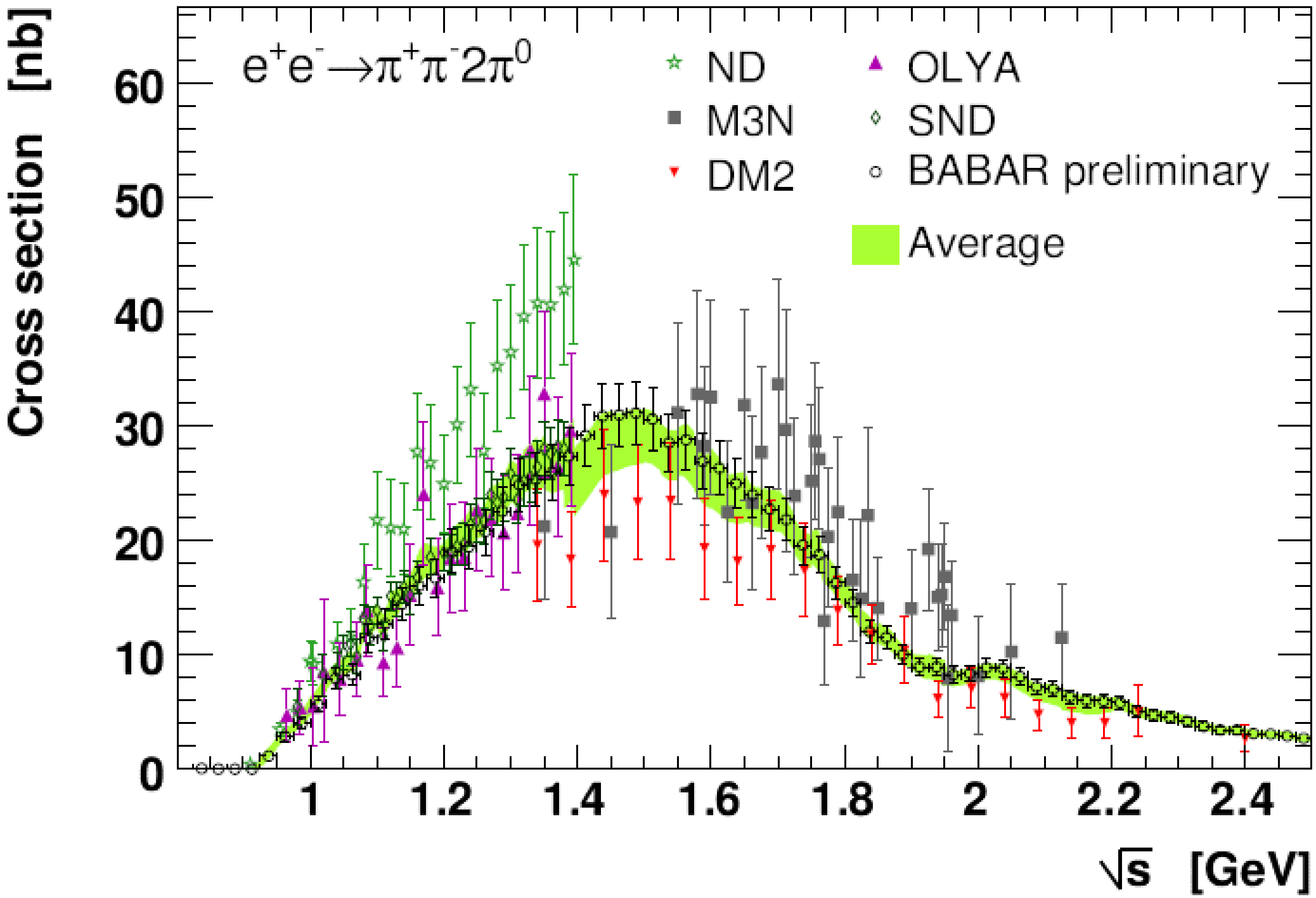
Uncertainty potential: <5%





ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma_{ISR}$

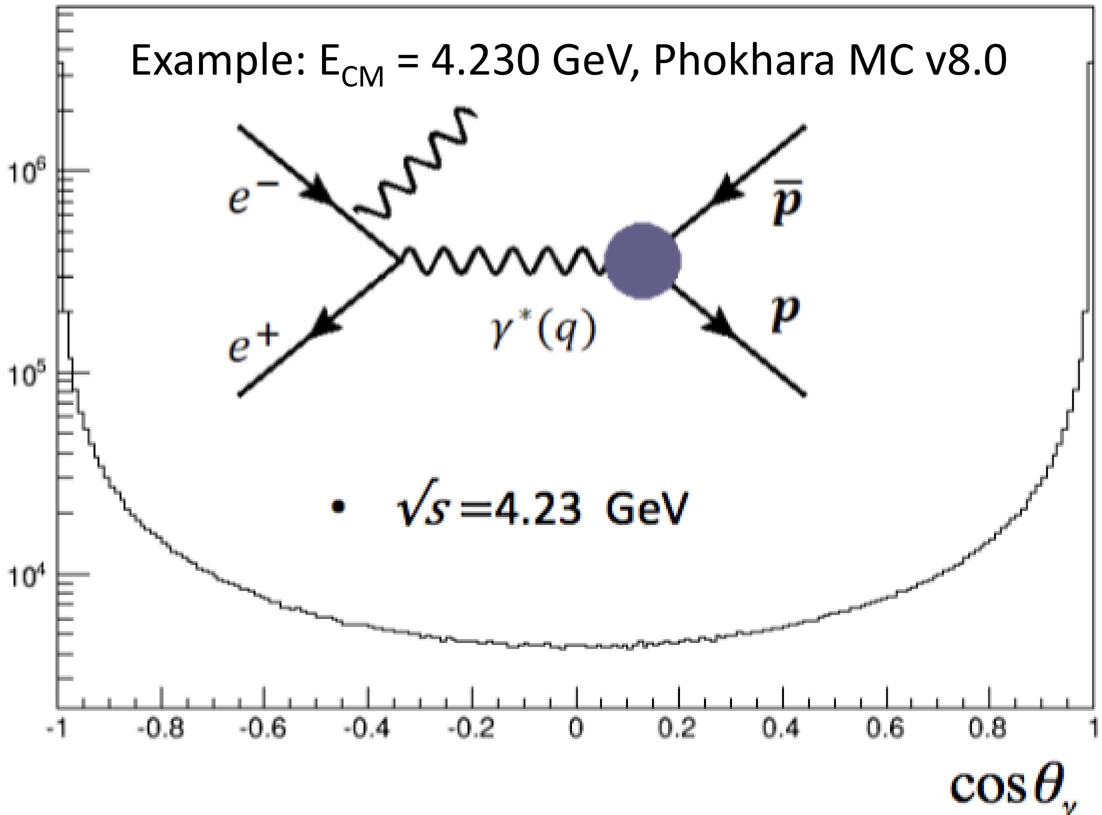
- BESIII work ongoing



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

BESIII internal review

- Efficiencies: untagged ~20%, tagged ~6%;
- Dominant bkgd: $e^+e^- \to p\bar{p}\pi^0$, subtracted from data;
- Final statistics competitive with BaBar.



Summary

- Excellent data @BESIII offer timelike FF studies;
- Energy scan:
  - First result of proton form factors published;
  - Preliminary result of Λ released;
  - High statistics data in 2 – 3.1 GeV for: proton & neutron FFs, Λ polarization, …
- ISR technique allows access to energy below 2 GeV:
  - $\pi^+\pi^-$ form factor in 600 ~ 900 MeV published;
  - More results to follow: $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $p\bar{p}$, …