Hadron form factor and Collins effect at BESIII

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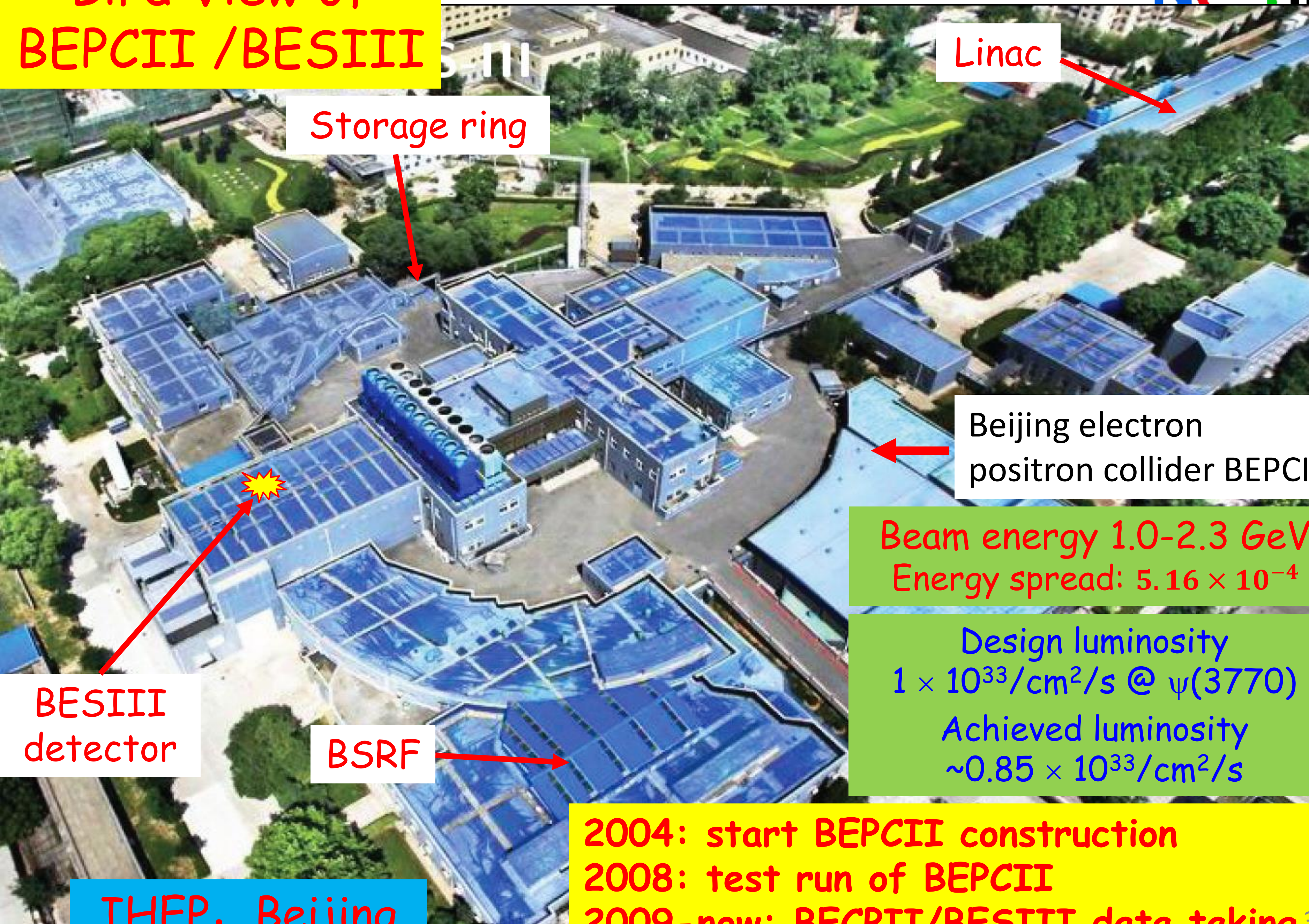
Duke Kunshan University

Outline

- BEPCII/BESIII
- Hadron form factor measurements
  - Proton
  - ISR $\pi^+\pi^-$
  - Other baryons/mesons
- Collins effect
- 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 luminosity

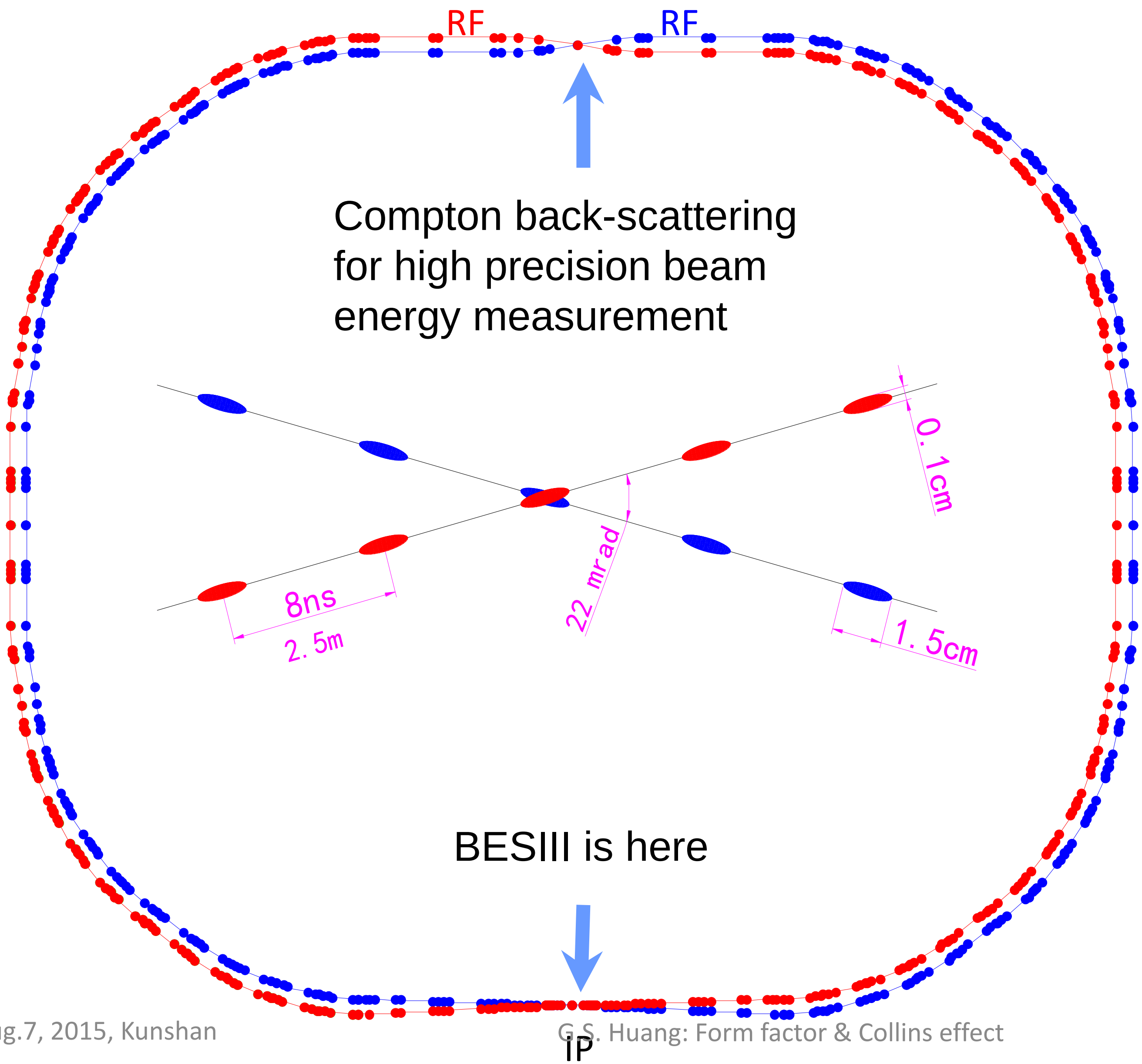
~$0.85 \times 10^{33}/cm^2/s$

2004: start BEPCII construction

2008: test run of BEPCII

2009-now: BECPII/BESIII data taking

BEPC II: Large Crossing Angle, Double-ring



Beam energy:
1-2.3 GeV
Luminosity:
$1\times10^{33}\ cm^{-2}s^{-1}$
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

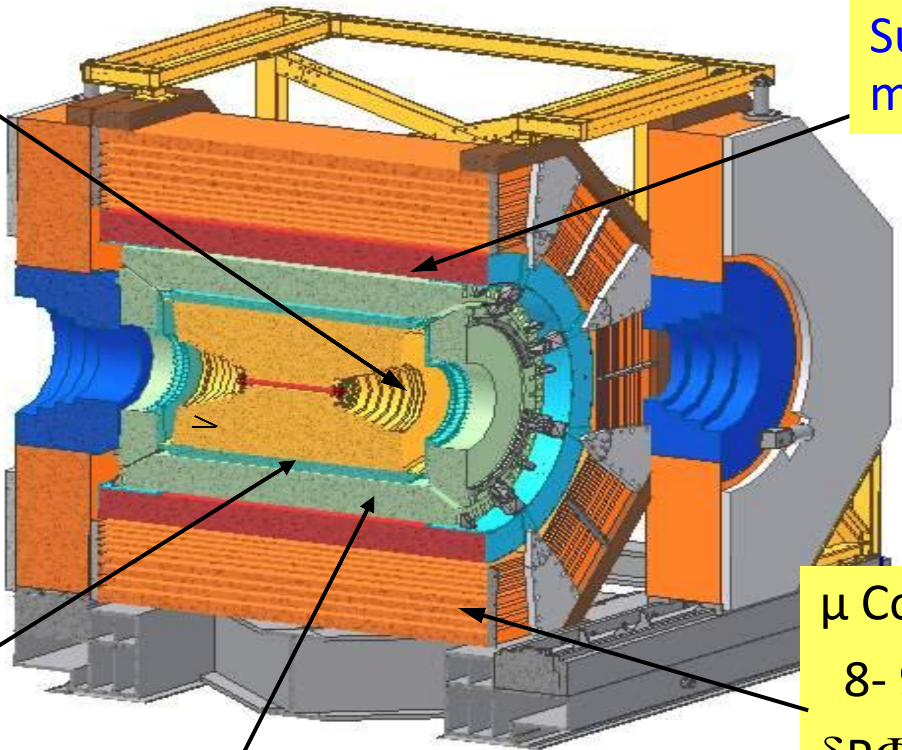
The BESIII Detector

Drift Chamber (MDC)

$\sigma p/p$ ($^0/_0$) = 0.5%(1GeV)

$\sigma_{dE/dx}$ ($^0/_0$) = 6%

Super-conducting magnet (1.0 Tesla)



Time Of Flight (TOF)

σ_T : 90 ps Barrel

110 ps endcap

μ Counter

8- 9 layers RPC

$\delta R\Phi$=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}$($^0/_0$) = 2.5 % (1 GeV)

(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

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} $\psi(3770)$
  ~0.5 fb^{-1} @ 4.01 GeV

} 3.5×CLEO-c

- 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).

New scan in 2 – 3.1 GeV

- 2014.12.30-2015.5.1;
- From high to low;
- Added 2.05 GeV;
- 20 energy points, 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		$\geq$8.95	14.6	Nucleon FFs
2.1		10.8	14.8	Nucleon FFs
2.15		2.7	2.29	Y(2175)
2.175		10(+)	8.5	Y(2175)
2.2		13	11	Nucleon FFs, Y(2175)
2.2324	2.2314	11	4	Hyp threshold ($\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	$\geq$64	27.8	Nucleon & Hyp FFs Hyp Threshold ($\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.

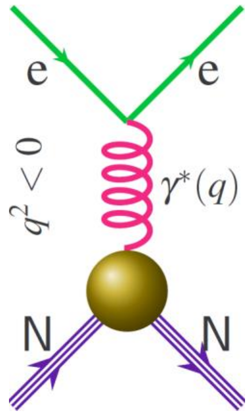
Nucleon Form Factors (FF)

- **Fundamental properties of the nucleon**
  - Connected to charge, magnetization distribution
  - Crucial testing ground for models of the nucleon internal structure
  - Necessary input for experiments probing nuclear structure, or trying to understand modification of nucleon structure in nuclear medium
- **Driving renewed activity on theory side**
  - Models trying to explain all four electromagnetic form factors
  - Trying to explain data at both low and high Q^2
  - Progress in QCD based calculations

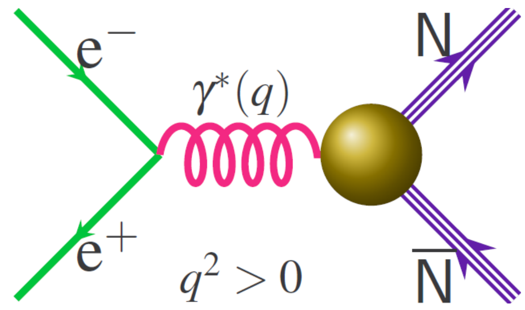
Electromagnetic Form Factors

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

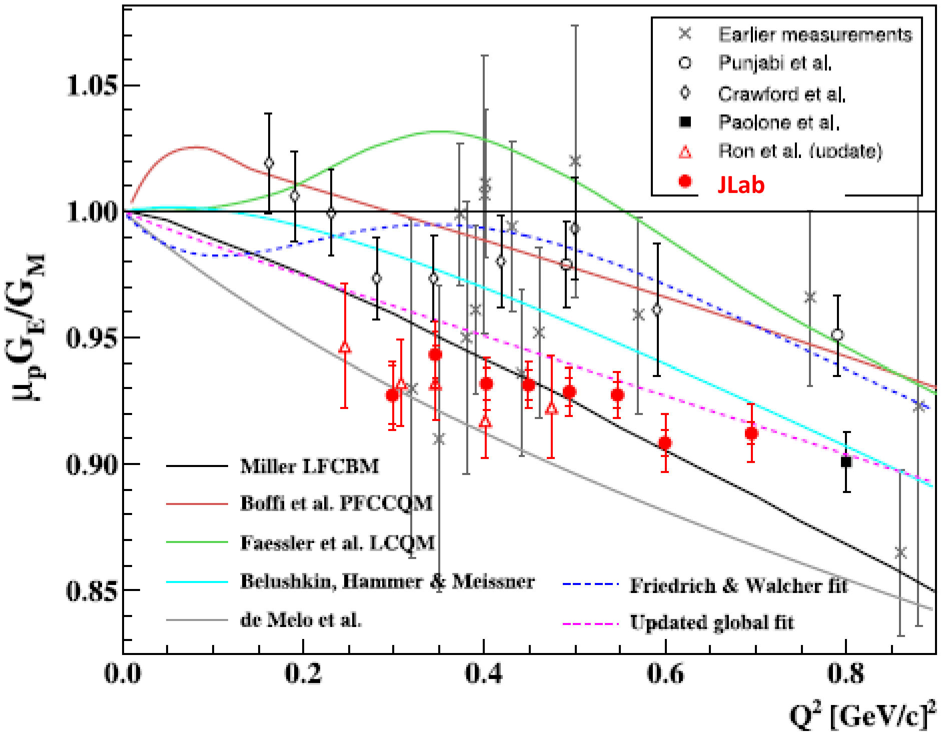
Sachs

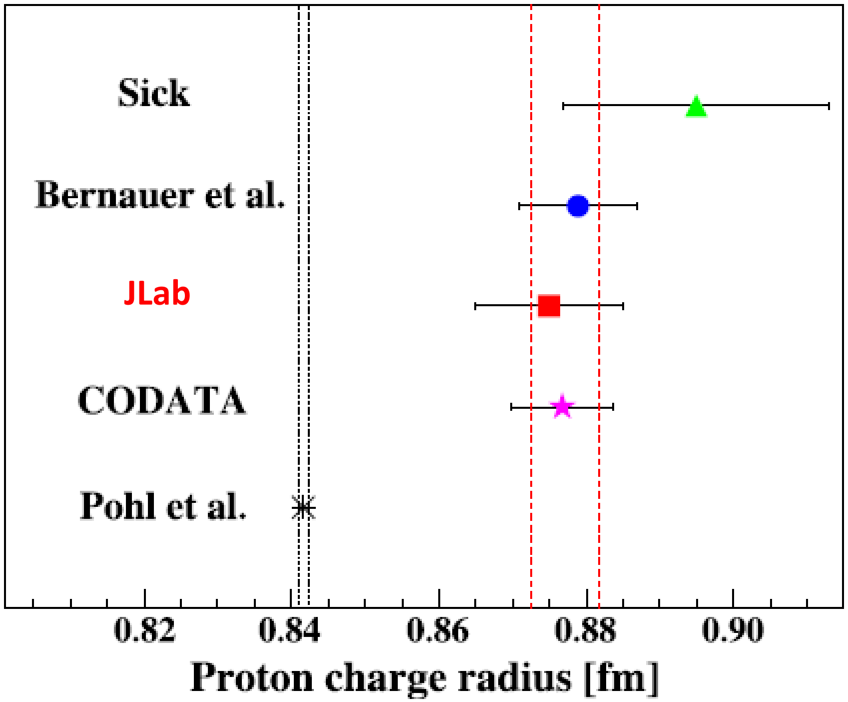
$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

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

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

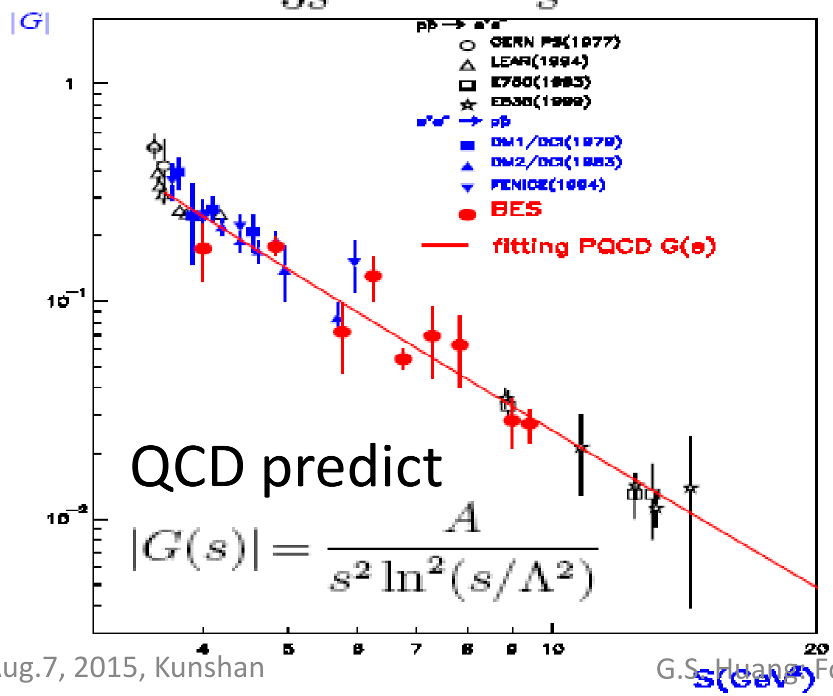
$$e^+e^-\to p\bar{p}:\ \frac{d\sigma}{d\Omega}=\frac{\alpha^2\beta}{4s}C[|G_M(s)|^2(1+\cos^2\theta)+\frac{1}{\tau}|G_E(s)|^2\sin^2\theta]$$

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

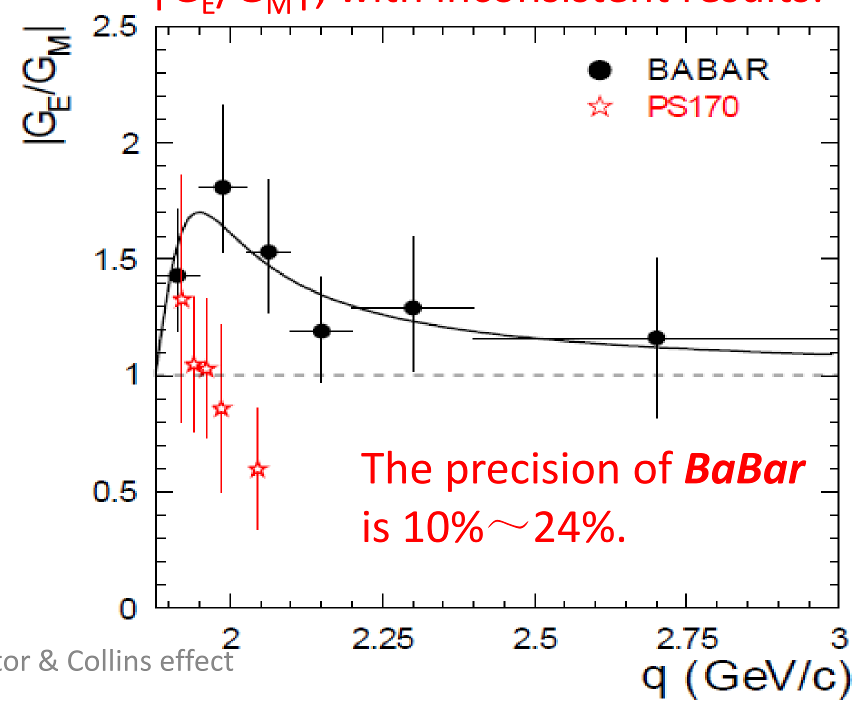
$$|G_E(q^2)| = |G_M(q^2)|[1+(q^2-4M_p^2)/q_1^2]^{-1}$$

Most experiments assumed $G_E=G_M$:

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



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



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

How to measure TL 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 !!

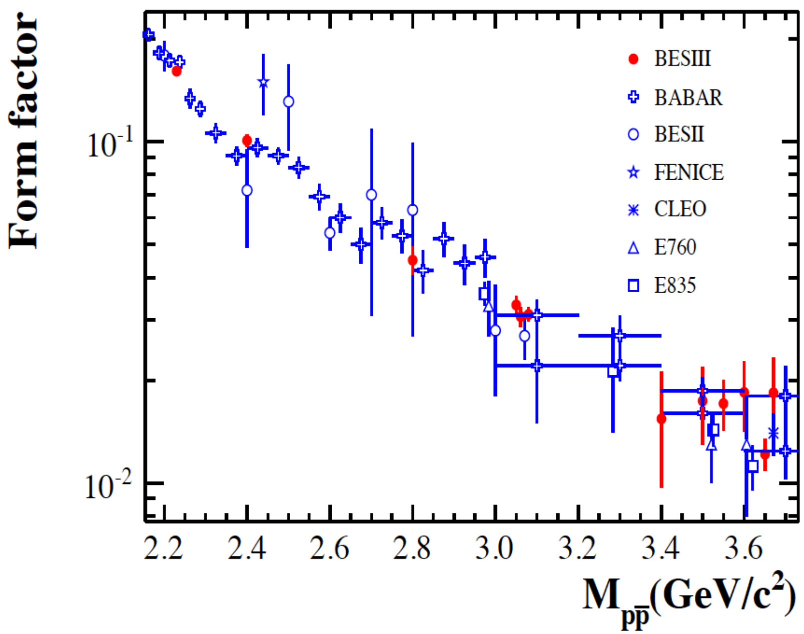
Proton Form Factors from 2012 test run

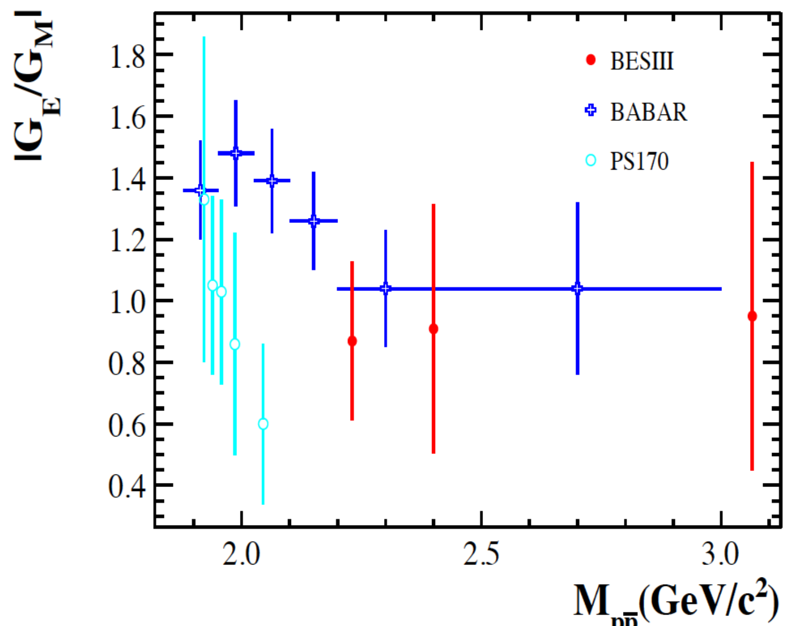
Phys. Rev. D 91, 112004 (2015)

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



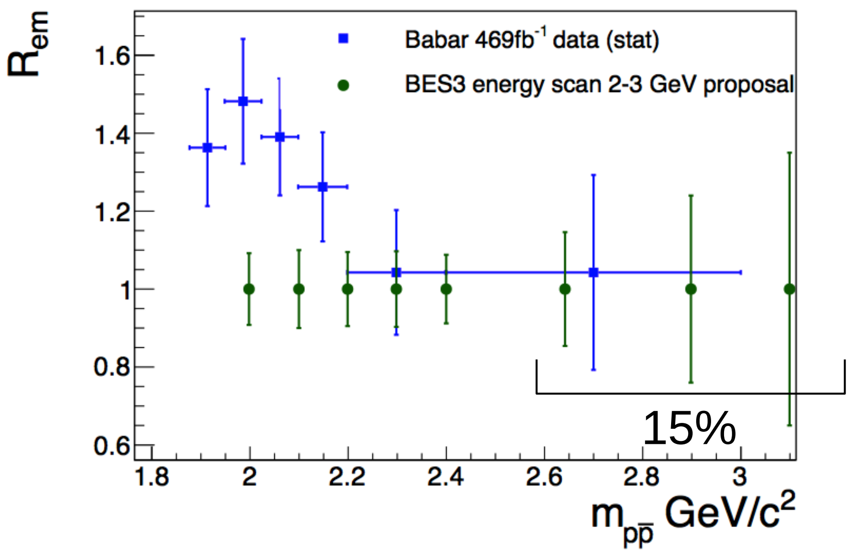


Proton FF: expectation from 2015 data

Based on the new 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	$\sim$ 35%	8.5%	35%

15%



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

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

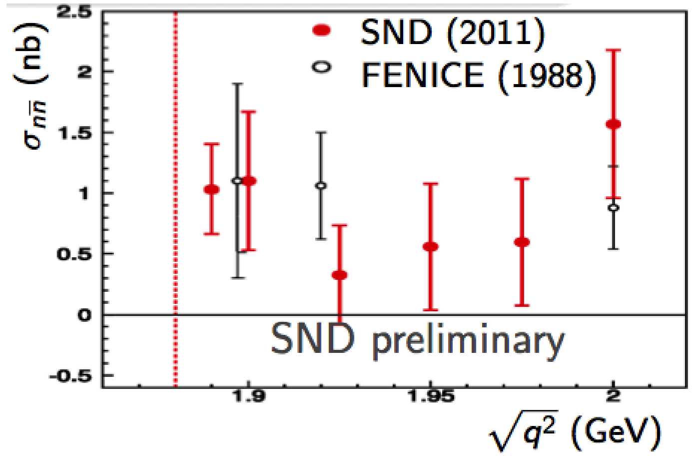
$\delta|G_E|/|G_E|$ ~ 9% - 35%

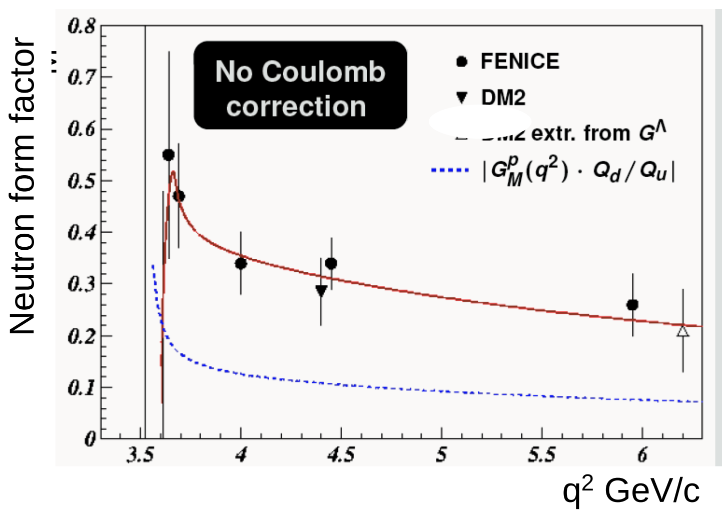
Will top BaBar result

First time extraction without any assumption!

TL neutron form factors

Two measurements: Fenice with 74 $e^+e^- \to n\bar{n}$ events and recently SND





FENICE: Assumption $G_E = 0$, motivated by angular distributions of $n\bar{n}$ events;

Result from FENICE Nucl.Phys.B517,3(1998);

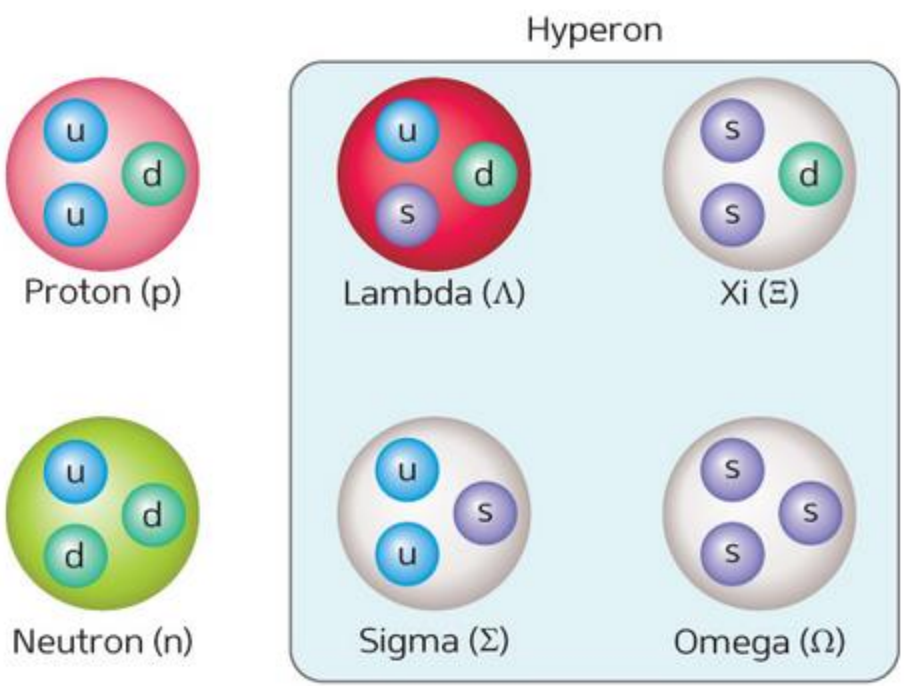
Confirmed by SND (two years a eCONF110613(11);

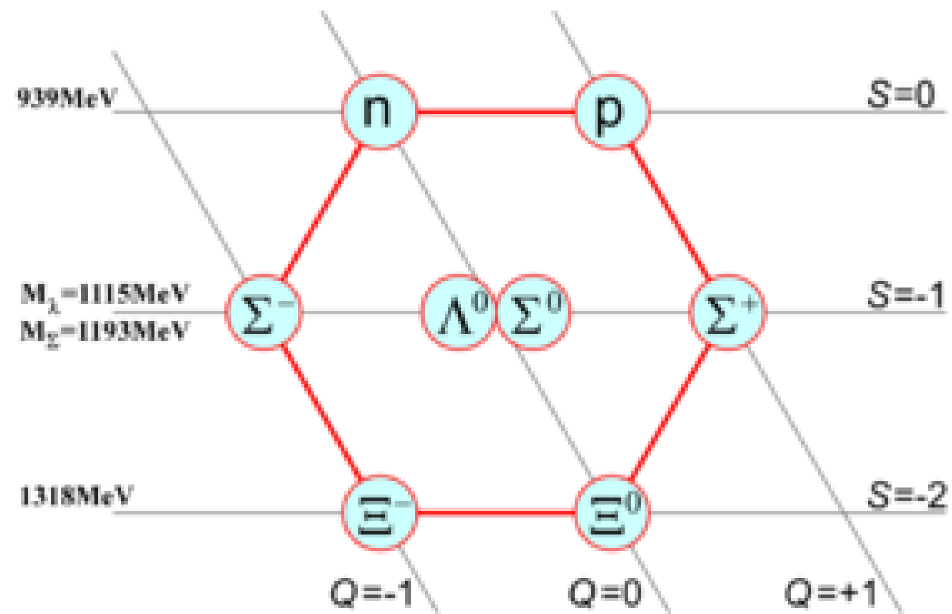
Goal: extract em form factors and ratio for the first time with an uncertainty as similar as possible to the proton case

Hyperon TL Form Factors

Key question:

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

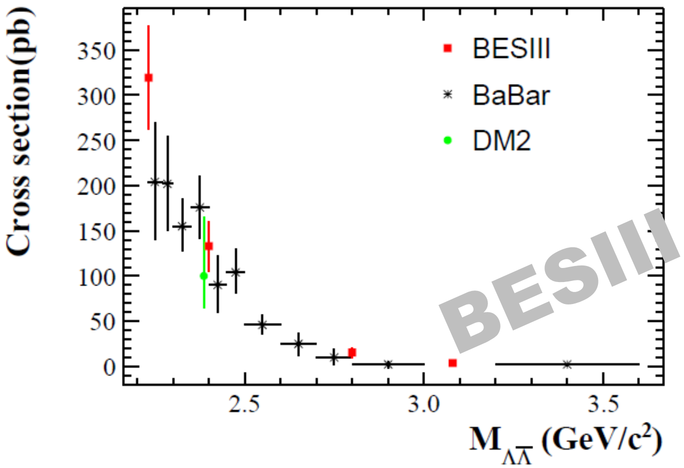


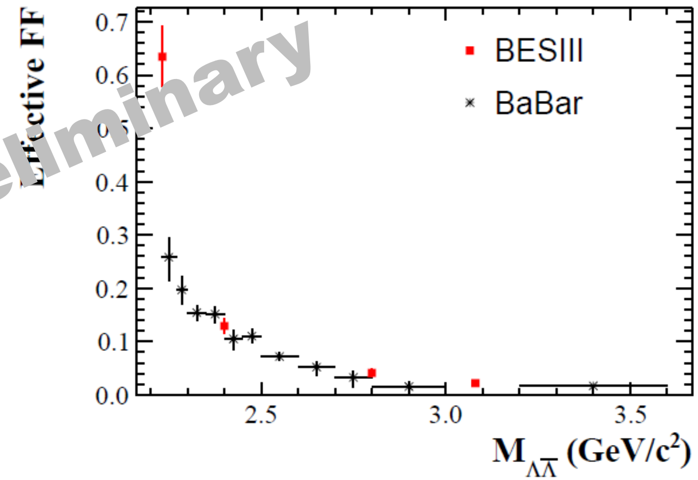


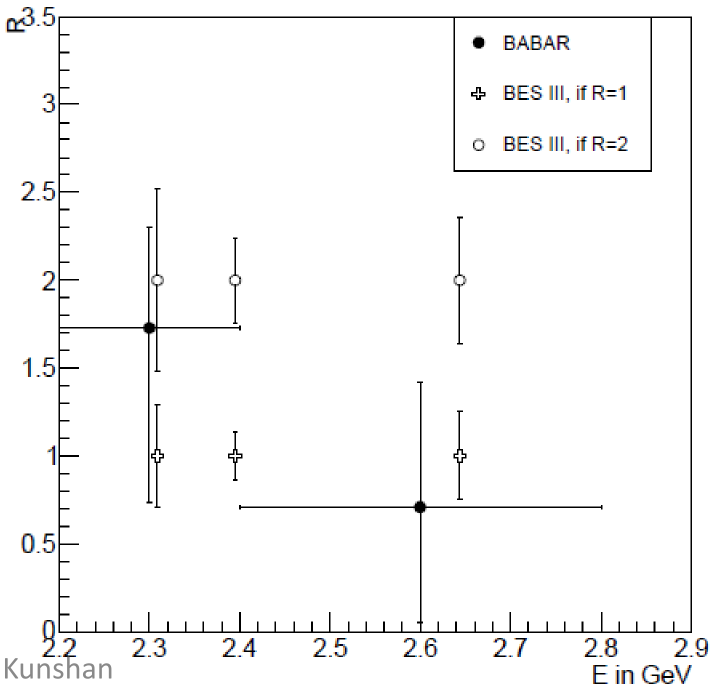
Spin $\frac{1}{2}^{+}$ SU(3) octet

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

Cross section and effective form factor from 2012 test run



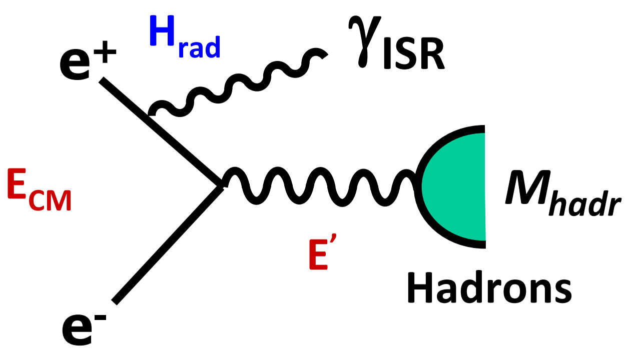




Expectation from the new scan data in 2 - 3.1 GeV, $R=|G_E/G_M|$ can be measured at several points and with unprecedented precision.

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.

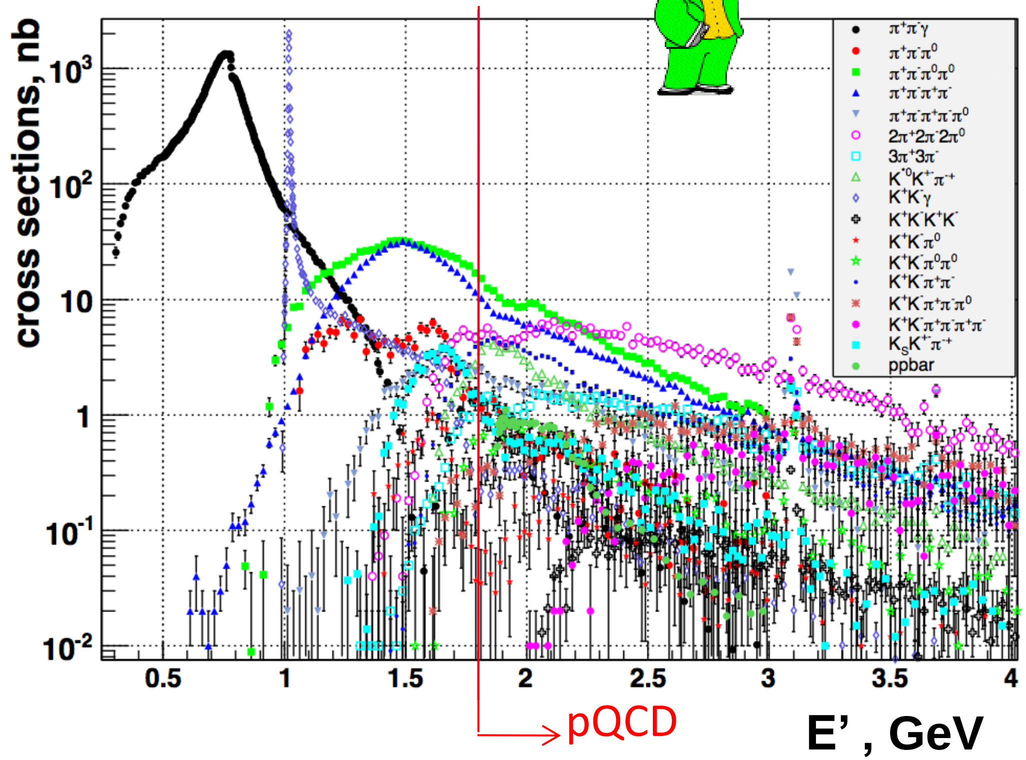
Initial State Radiation (ISR)



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

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

ISR spectra measured by BABAR

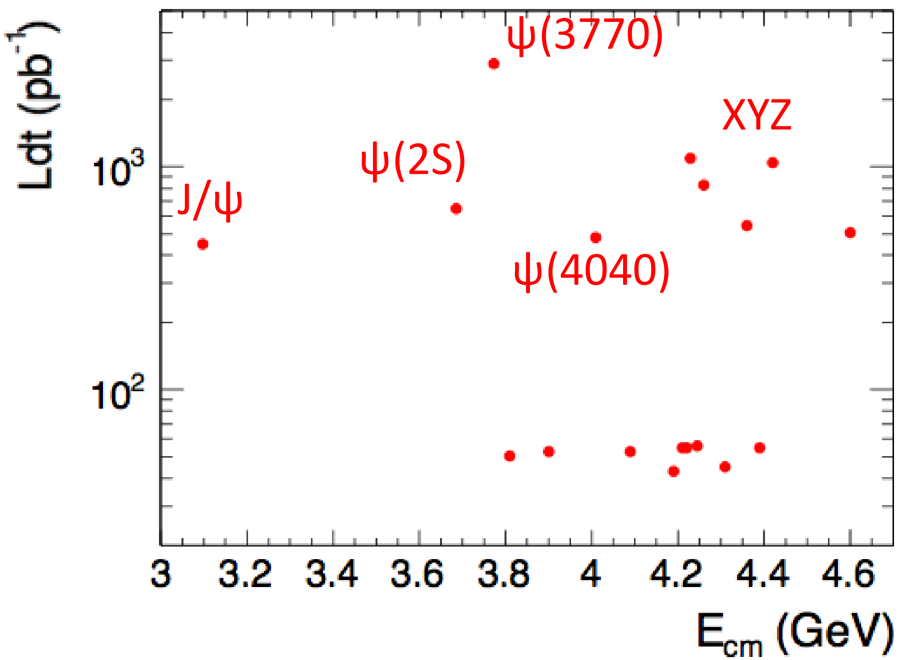


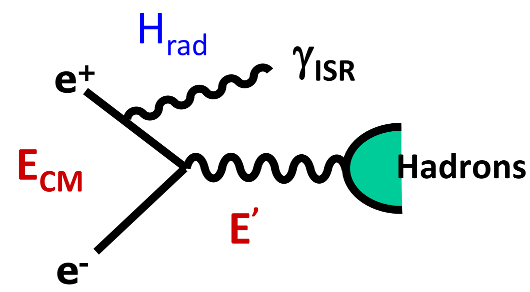
→ **Entire E range <E_{CM} accessible**

PHOKHARA event generator, Czyż, Kühn, et al.

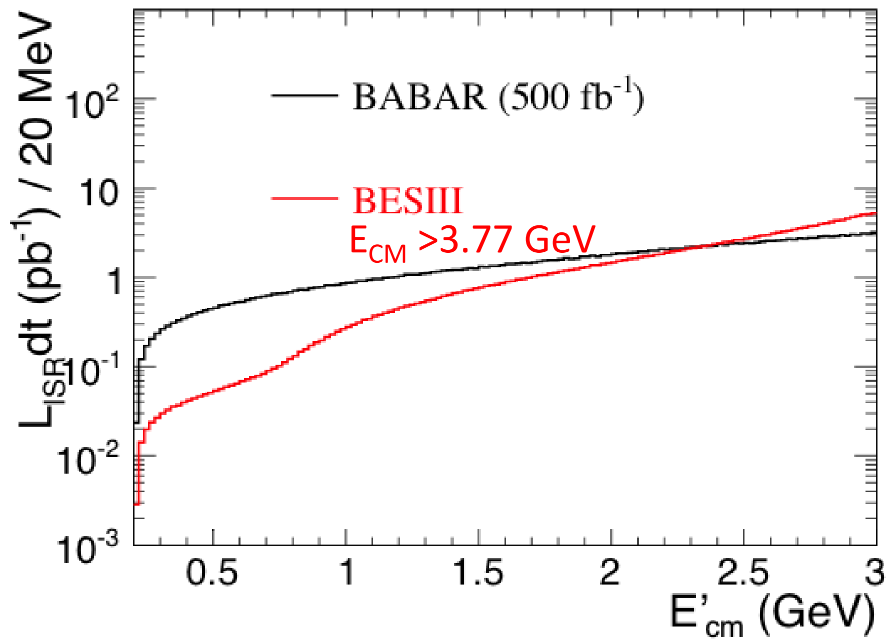
Data Samples for ISR Physics

Integrated luminosities at BESIII





ISR luminosity = Ldt x H_{rad}

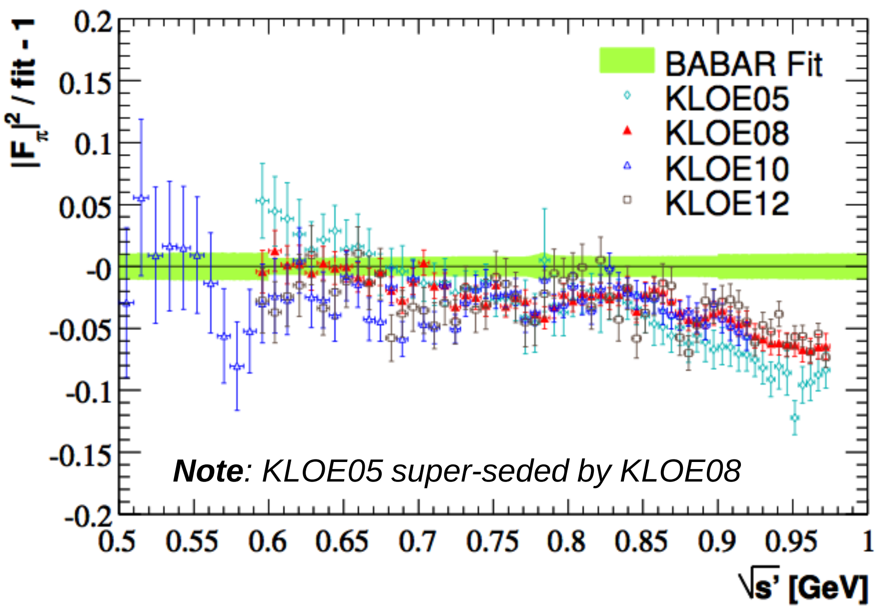


- $\pi^+\pi^-\gamma_{ISR}$
- $\pi^+\pi^-\pi^0\gamma_{ISR}$
- $p\bar{p}\gamma_{ISR}$
- …

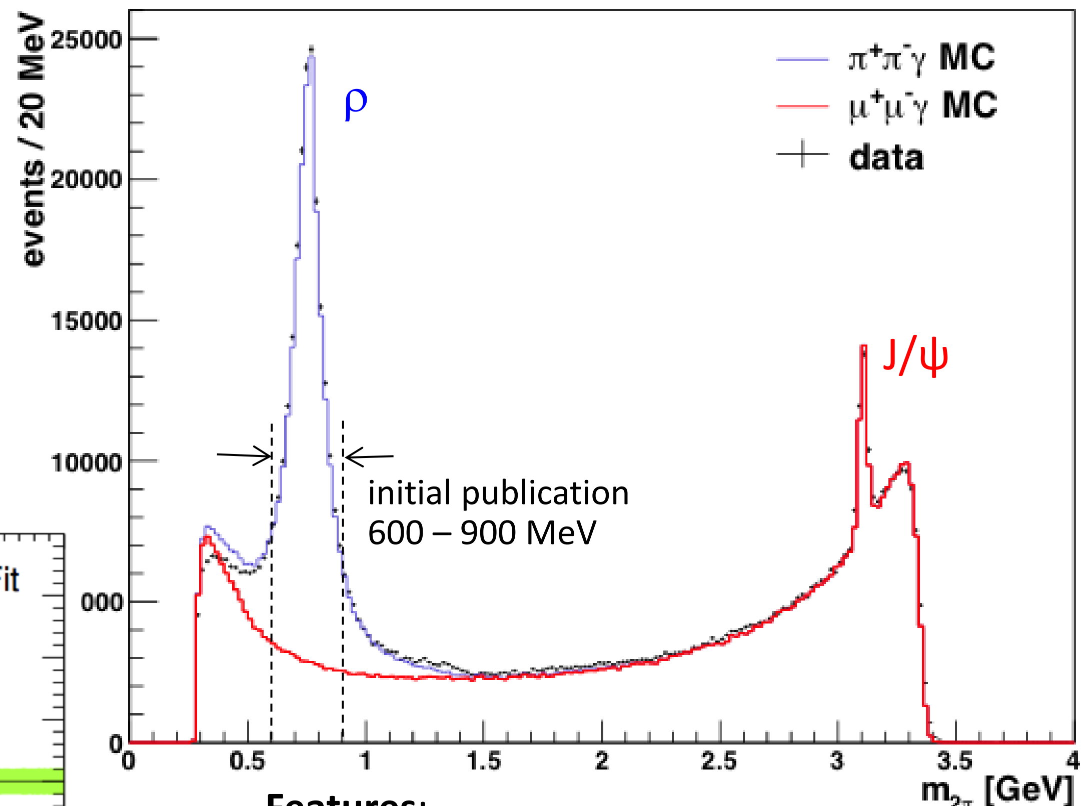
ISR Analysis: $e^+e^- \to \pi^+\pi^-\gamma_{ISR}$

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

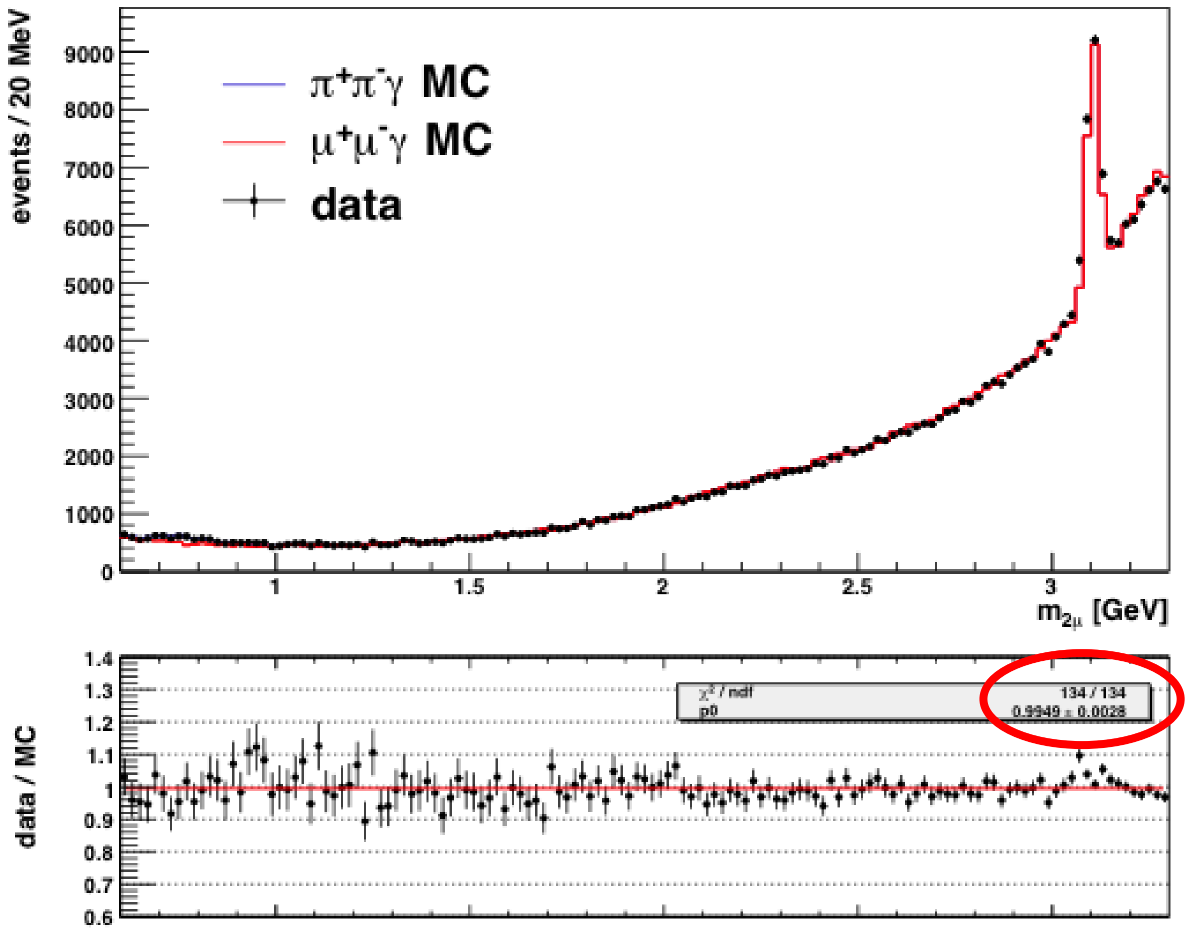
→ large statistics of $e^+e^- \to \pi\pi\gamma$ events

→ background dominated by $e^+e^- \to \mu\mu\gamma$

→ data – MC differences visible

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

Event yield μμγ after π-μ separation and all efficiency corrections



Features:

- background from ππγ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha events, 1.0% accuracy

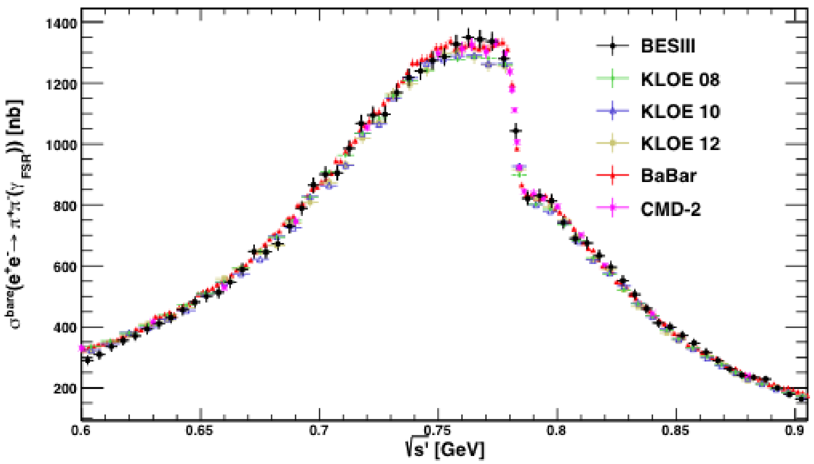
→ excellent agreement with QED

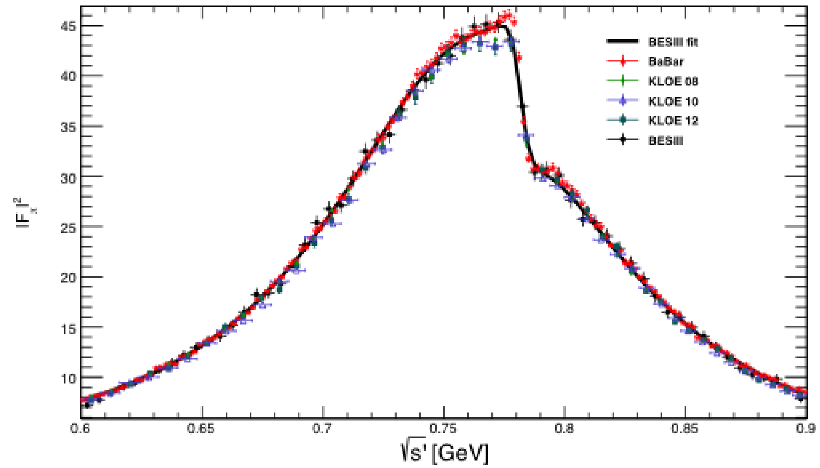
Δ(MC/QED-data) = (0.51 ± 0.28) %

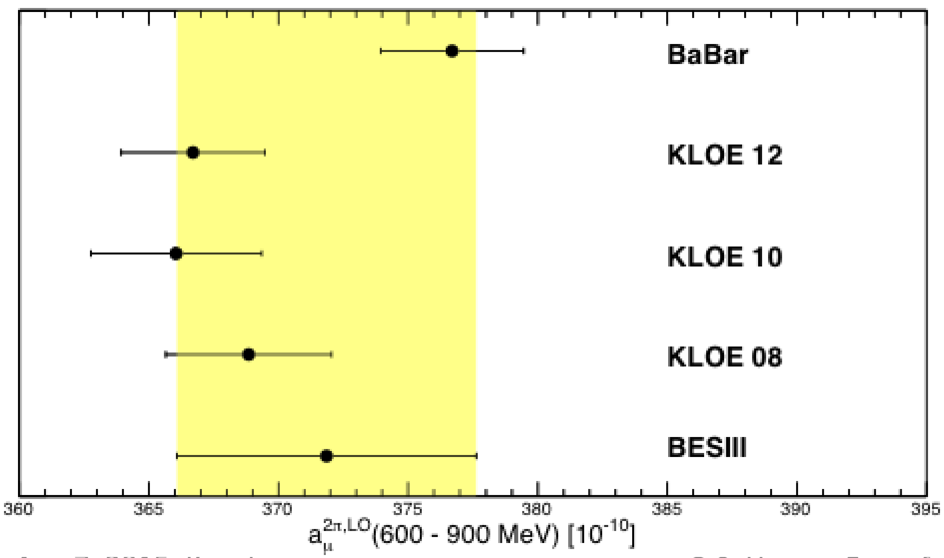
→ accuracy on 1% level as needed to be competitive !

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

arXiv:1507.08188, submitted to PLB a few days ago.





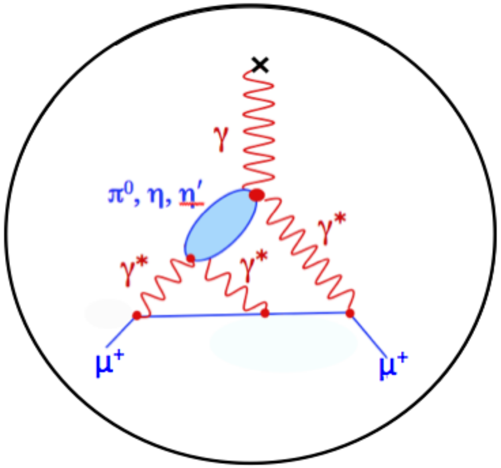


Exp.	$a_\mu^{2\pi,LO}$ (600 – 900 MeV) [10^{-10}]
BaBar	$376.7 \pm 2.0_{stat} \pm 1.9_{sys}$
KLOE08	$368.9 \pm 0.4_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE10	$366.1 \pm 0.9_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE12	$366.7 \pm 1.2_{stat} \pm 2.4_{sys,exp} \pm 0.8_{sys,theo}$
BESIII	$371.9 \pm 2.6_{stat} \pm 5.2_{sys}$

Meson Transition Form Factors

$F(Q_1^2,Q_2^2)$

Important to $(g\text{-}2)_\mu$ HLbL.

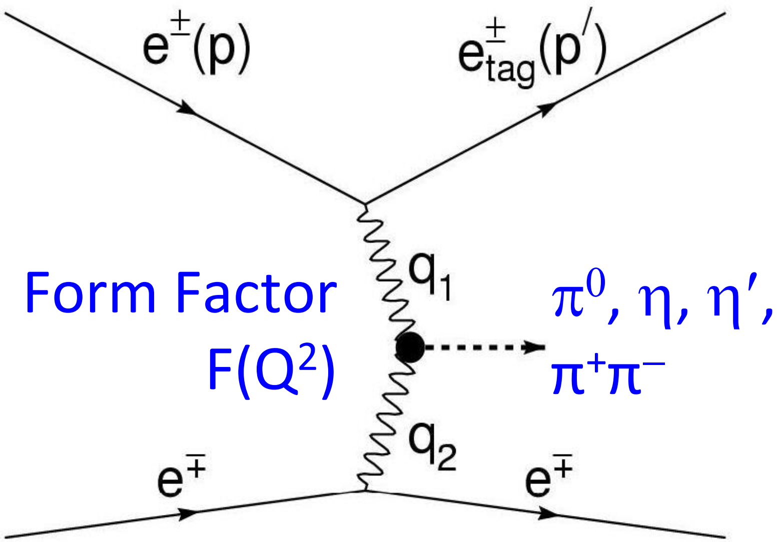


Extract Space-Like FFs using $\gamma\gamma^* \to P$

Selection criteria

- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed
- → cut on angle of missing momentum

Single Tag Method



Momentum transfer

- tagged: $Q^2 = -q_1^2 = -(p - p')^2$

  $\rightarrow$ Highly virtual photon

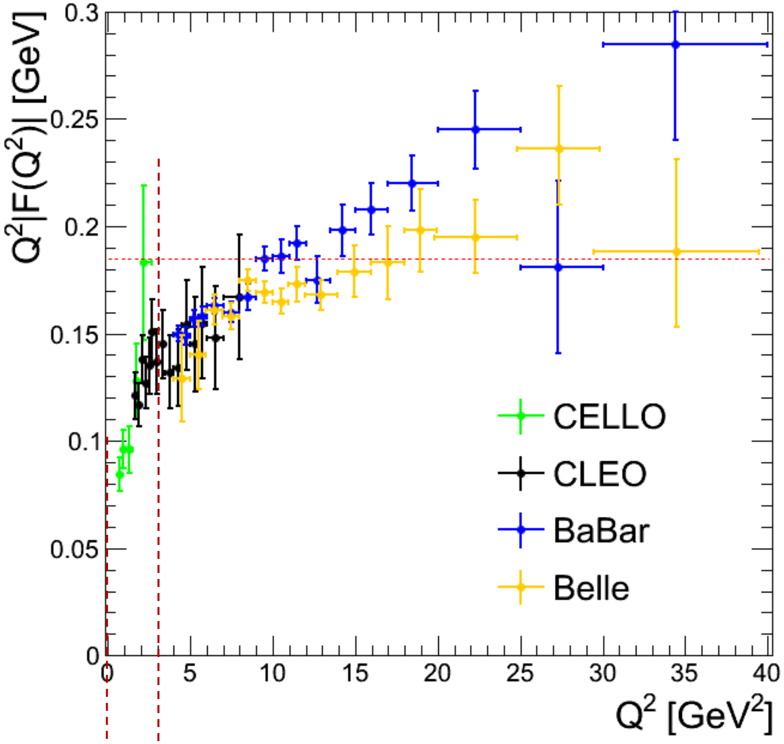
- untagged: $q^2 = -q_2^2 \sim 0$ GeV^2

  $\rightarrow$ Quasi-real photon

EKHARA event generator
Czyż, Ivashyn

Existing Data on SL Transition FFs

$e^+e^- \to e^+e^- \pi^0$



initial BESIII publication
< 3.1 GeV²

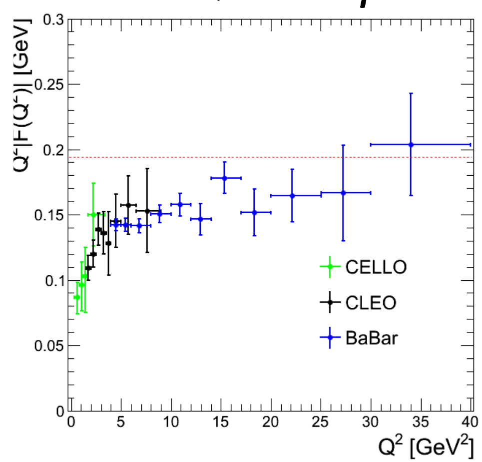
Features:

- recent high-Q^2 data from BABAR and BELLE $Q^2 > 4$ GeV^2
- above 1.5 GeV^2 data from CLEO
- below 1.5 GeV^2 data from CELLO, very poor accuracy

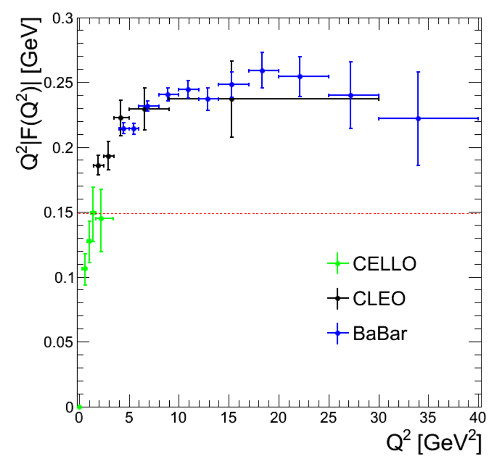
→ low Q^2 range not covered
most relevant for HLbL contribution to $(g\text{-}2)_\mu$

→ most relevant channels: π^0, η, η', $\pi\pi$

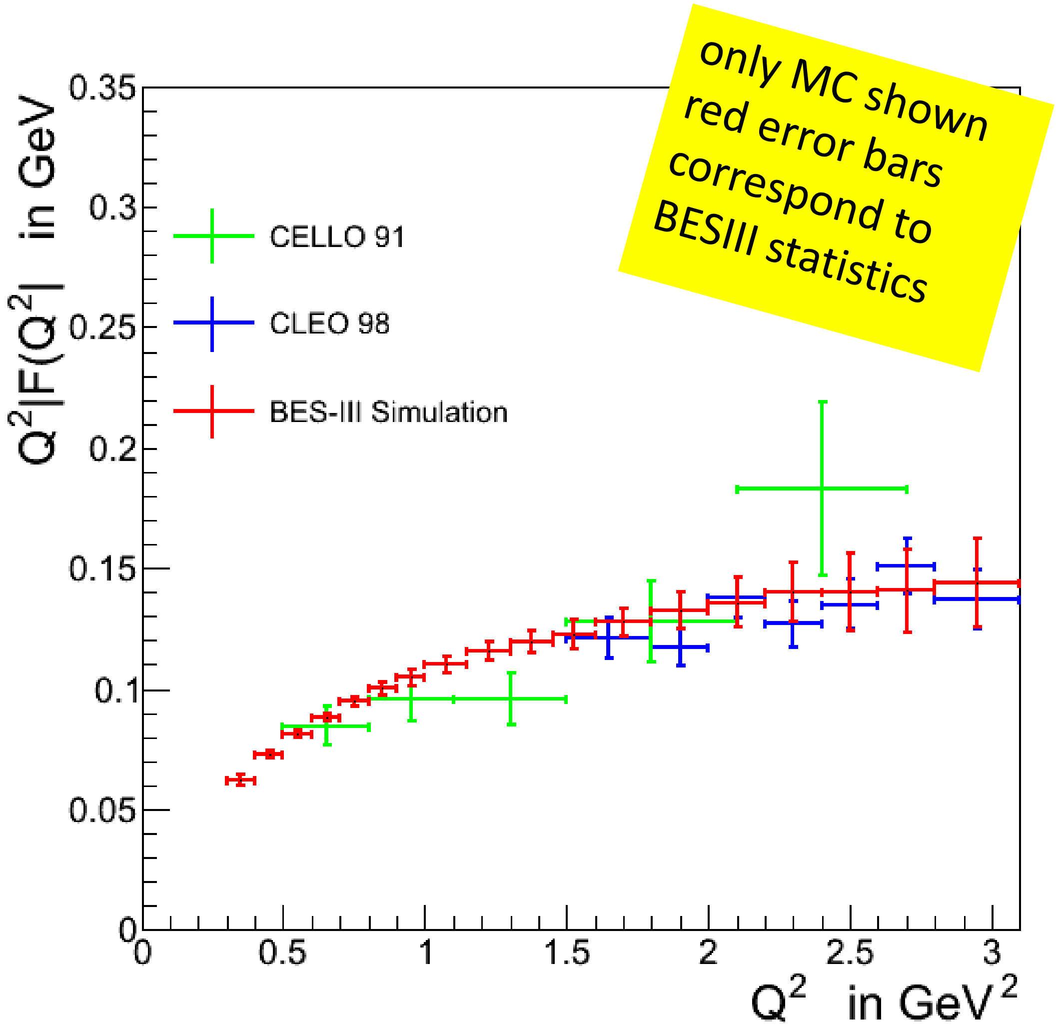
$e^+e^- \to e^+e^- \eta$



$e^+e^- \to e^+e^- \eta'$



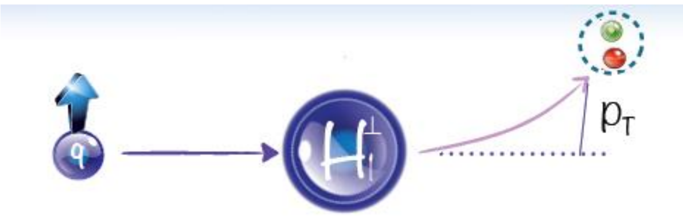
BES III Analysis: $e^+e^- \to e^+e^- \pi^0$



- Full Simulation
  - L_{int}: 2.92 fb^{-1}
  - Single Tag with both, $e^{\pm}$
- Extract TFF for $0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

→ Unprecedented $Q^2 < 1.5$ GeV^2 Input for $(g\text{-}2)_\mu$

Collins Fragmentation Function(FF)



J. C. Collins, Nucl.Phys. B396, 161 (1993)

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

D_1: unpolarized FF

H_1: Collins FF

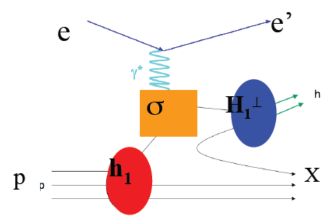
→ describes the fragmentation of a transversely polarized quark into a spinless hadron *h*.

→ depends on $z = 2E_h/\sqrt{s}$, $\mathbf{P}_{h\perp}$

→leads to an azimuthal modulation of hadrons around the quark momentum.

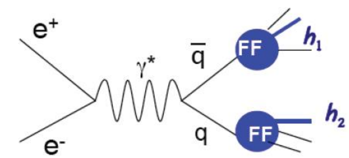
SIDIS

Transversity ⊗ Collins FF



e+ e-

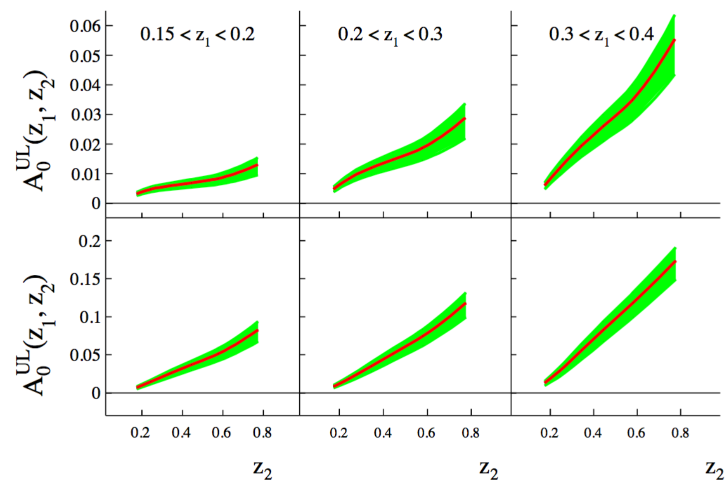
Collins FF ⊗ Collins FF



P. Sun, F. Yuan, PRD 88. 034016 (2013)

arXiv1505.05589

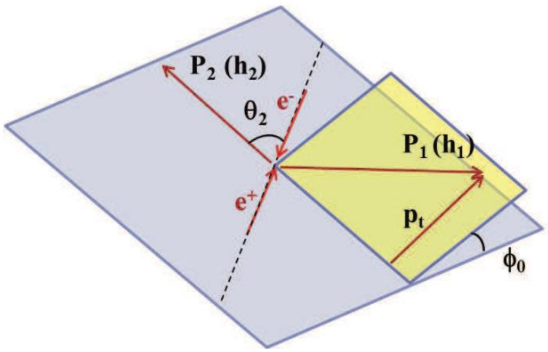
Predicted Collins asymmetries for BESIII:



Method && Technique

D. Boer Nucl.Phys.B806:23(2009)

$$e^+ e^- \to q\bar{q} \to \pi_1^{\pm}\pi_2^{\mp}X$$

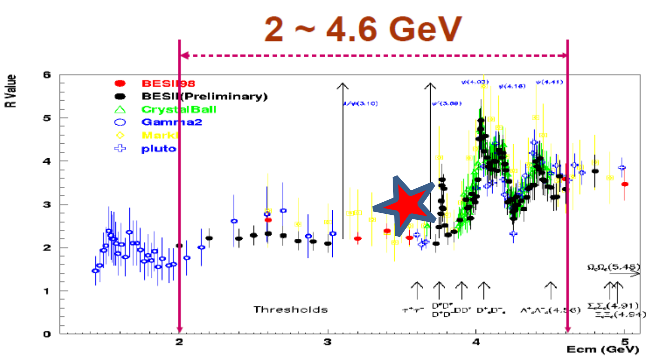


- **Collins effect: cosine modulation**

$$\sigma \sim 1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_0)\mathcal{F}\left[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$

- **Double Ratio to cancel detection effects**
- **Unlike-sign** $(\pi^{\pm}\pi^{\mp})$ **; Like-sign:** $(\pi^{\pm}\pi^{\pm})$
- **Charged:** $(\pi\pi)$

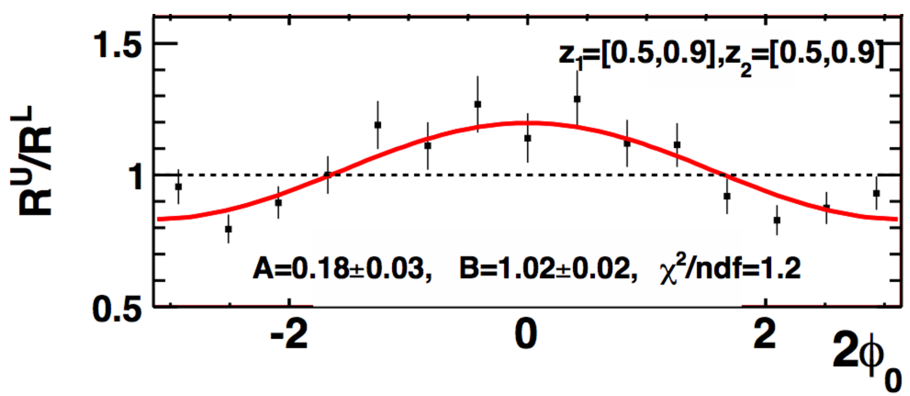
$$A_{UL(C)} = \frac{R^U}{R^{L(C)}} = A\cos(2\phi) + B$$



- A_{UL}, A_{UC} **denote asymmetries for UL and UC ratios, respectively**

~62 pb $^{-1}$ @3.65GeV

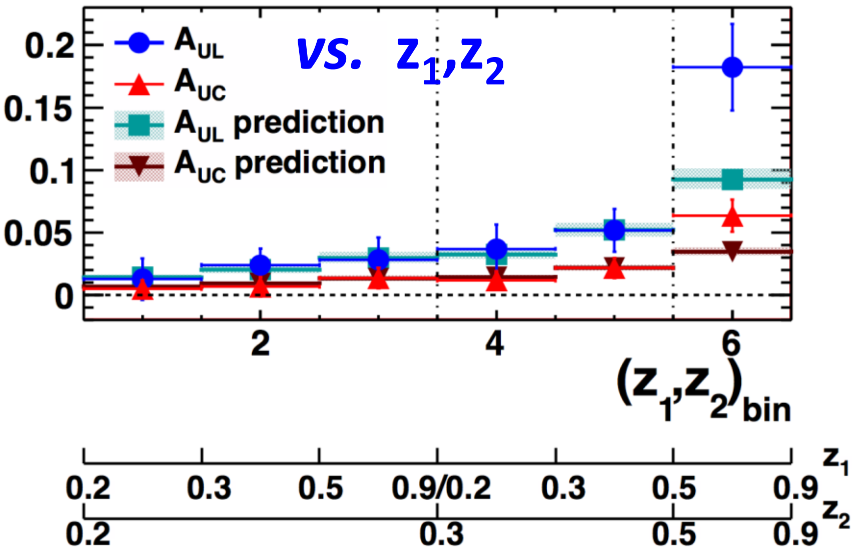
- **Continuum region**



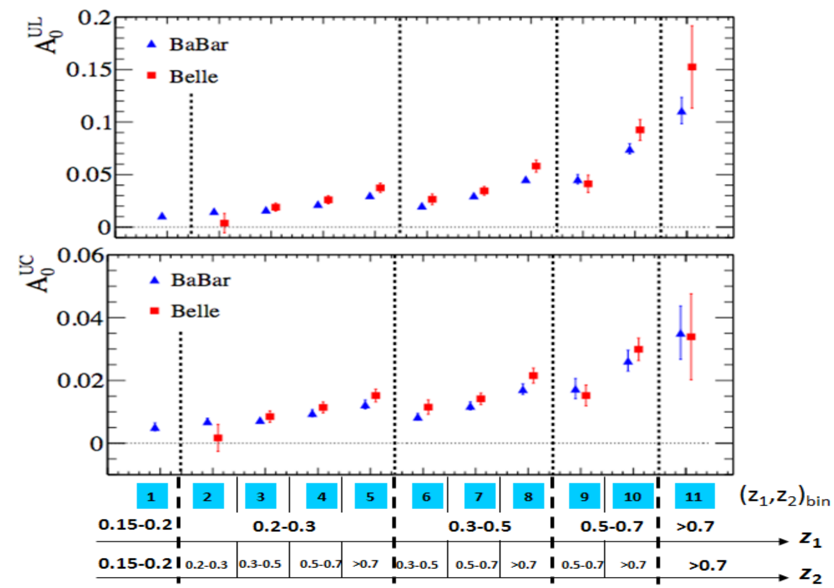
arXiv1507.06824
Submitted to PRL

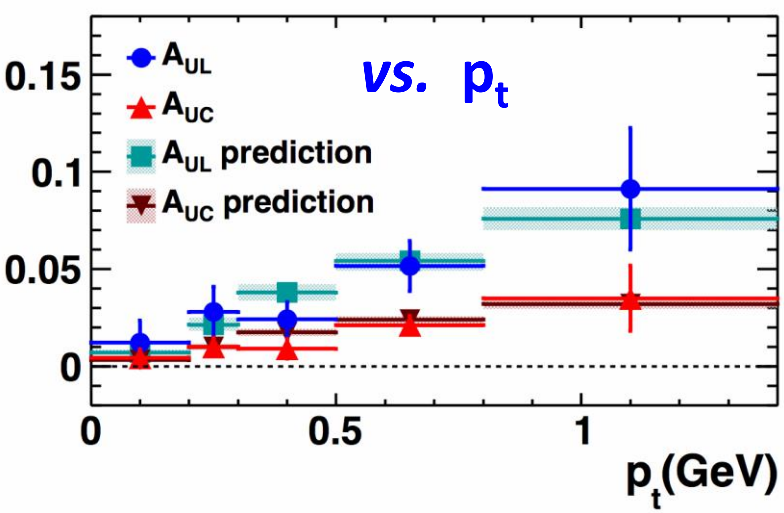
Collins effect at BESIII

Q^2~13GeV^2



Q^2~110GeV^2





Nonzero Collins effect at BESIII

Basically consistent with predictions from **arXiv1505.05589.**

important inputs for understanding the spin structure of the nucleon combining SIDIS

valuable to explore the energy evolution of the spin-dependent fragmentation function.

Summary

- Excellent data at BESIII offer opportunities for QCD studies;
- The proton form factors and their ratio have been measured using a small amount of data;
- Preliminary results of Λ were just released;
- The new high statistics data in 2 – 3.1 GeV will significantly improve FF measurements, not only for proton, but also for neutron and other baryons;
- ISR technique allows access to energy below 2 GeV: the first result is charged pion FF, more to come;
- Nonzero Collins effect was observed.