HIM HELMHOLTZ Helmholtz-Institut Mainz

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence PRiSMA Precision Physics, Fundamental Interactions and Structure of Matter

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Proton Time-Like Electromagnetic Form Factor Measurements at BESIII

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668. WE-Heraeus Seminar on "Baryon Form Factors: where do we stand?"

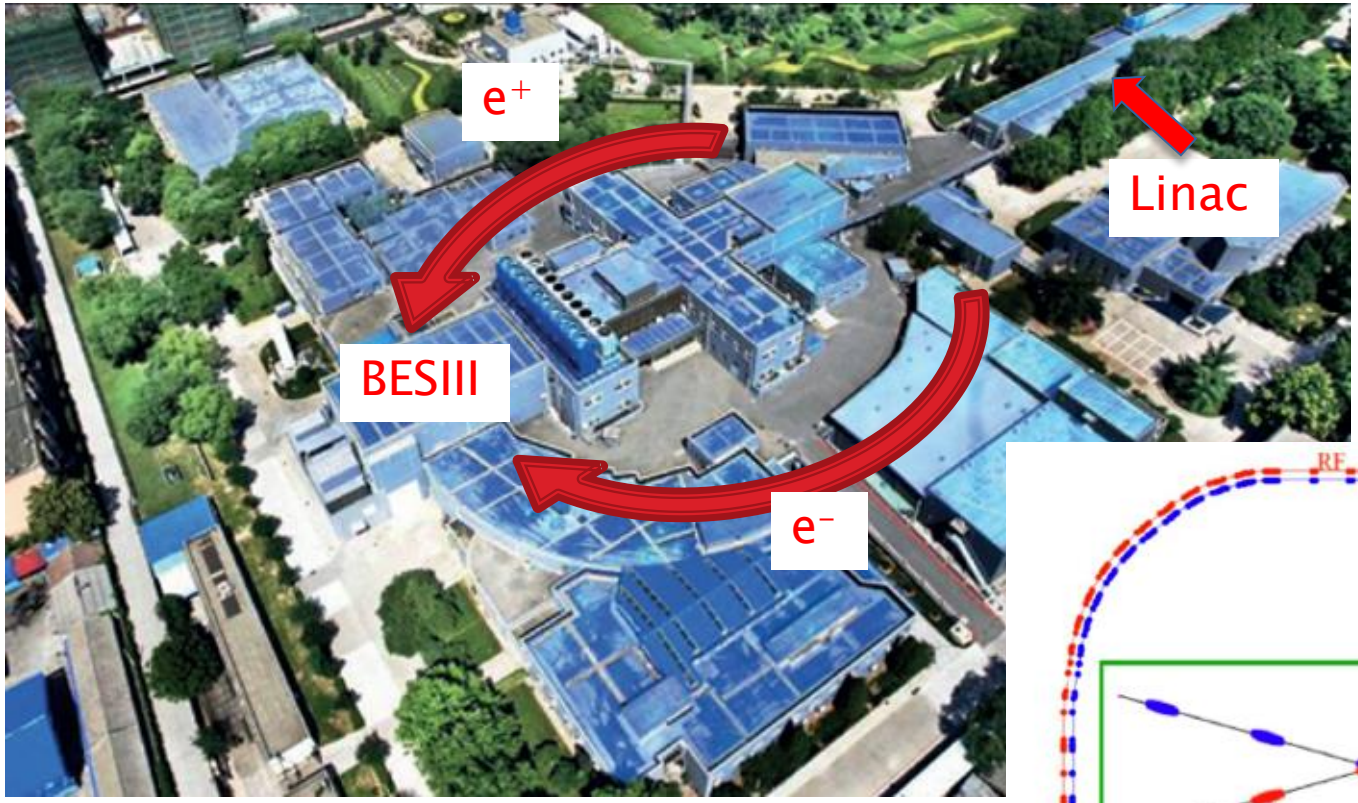
Physikzentrum Bad Honnef, Germany, 24. 4. 2018

BESIII

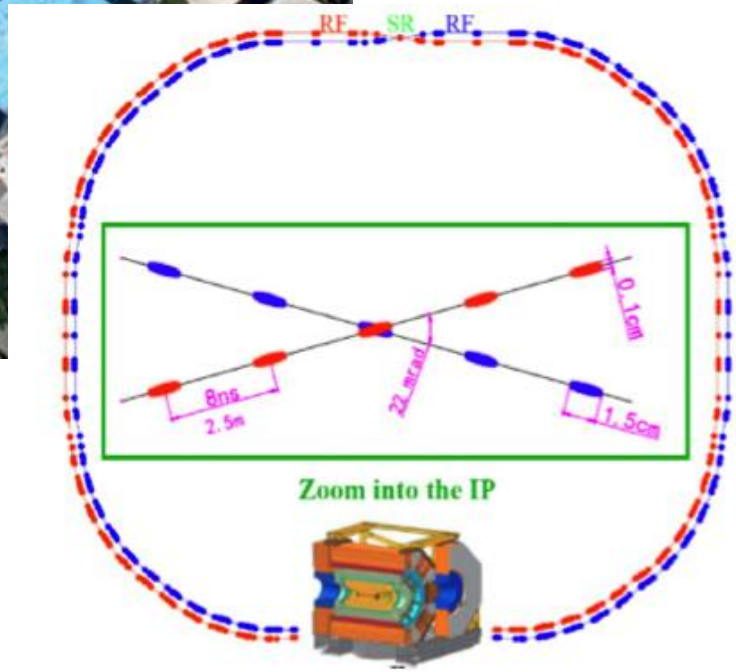
Outline

- Introduction:
  - BESIII detector
  - How to measure Form Factors (FFs)
- Proton Form Factors at BESIII
  - Scan method
  - Tagged initial state radiation (ISR) method
  - Untagged ISR method
- Summary

Beijing Electron Positron Collider



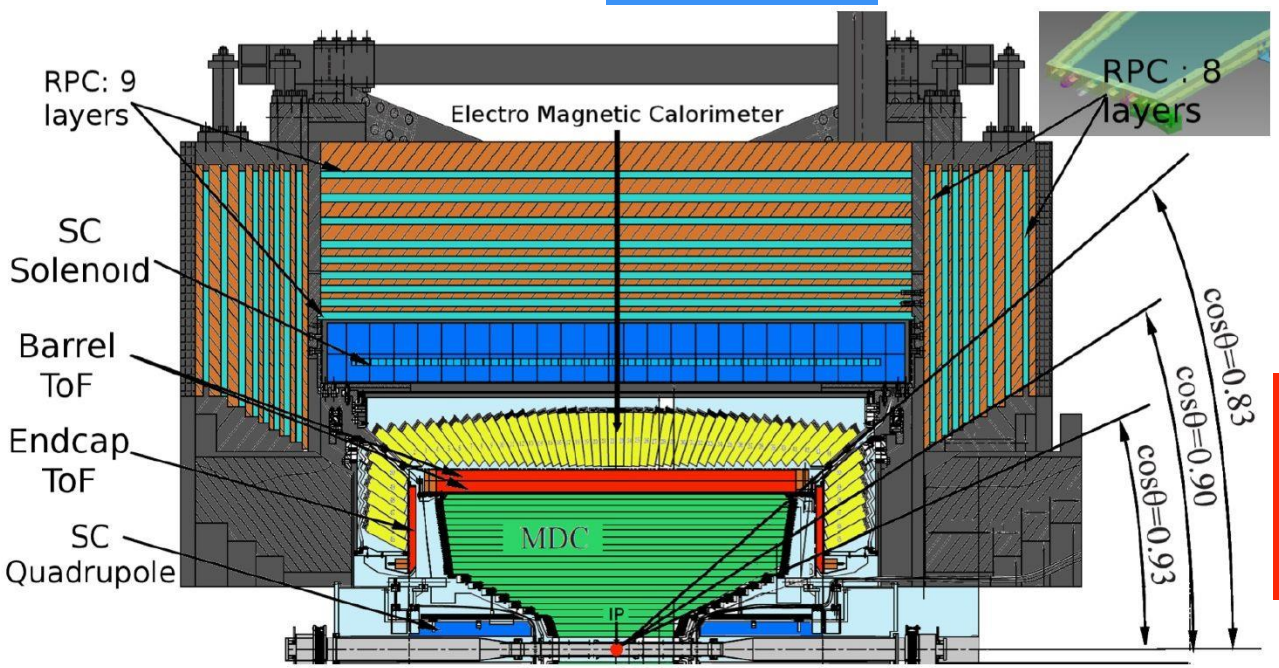
- start of construction 2004
- Data taking since 2009



- Beam energy: 1.0 – 2.3 GeV
- Optimised for 1.89 GeV
- Crossing angle: 11 mrad
- Design luminosity: 10^{33} cm^{-2} s^{-1} (Achieved in 2016)

BESIII Detector

1 Tesla solenoid magnet



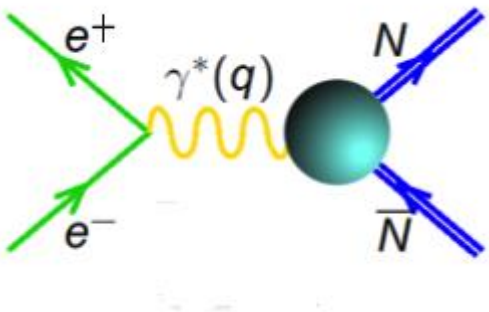
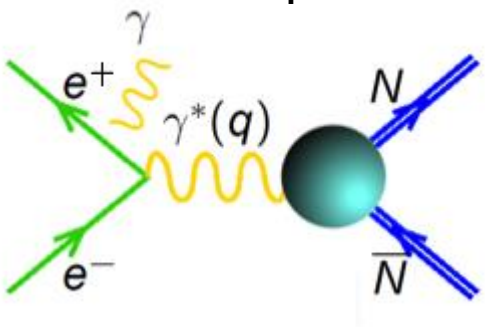
Muon Counter:
- Resistive plate chamber
- 9 layers (Barrel), 8 layers (Endcap)
- $\sigma_{xy} = 1.48$ cm

Time of Flight:
- Plastic scintillator
- $\sigma_T = 80\,ps$ (Barrel)
- $\sigma_T = 110\,ps$ (Endcap)

Main Drift Chamber:
- Small cell, 43 layers
- $\sigma_{xy} = 130\,\mu m, \frac{\sigma_{dE/dx}}{dE/dx} \approx 6\%$
- $\frac{\sigma_p}{p} < 0.5\%$ at 1 GeV/c²

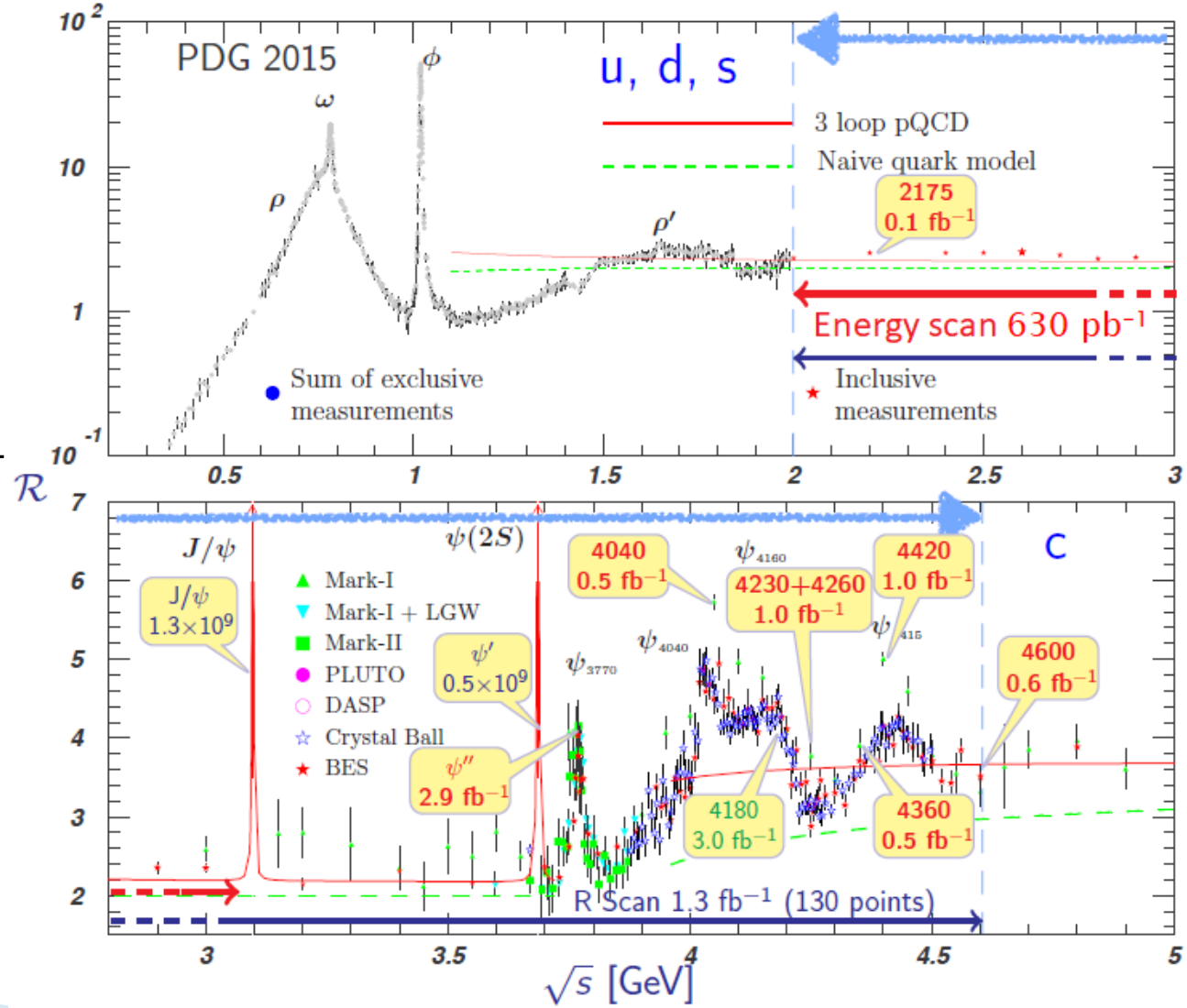
Electromagnetic Calorimeter:
- CsI(Tl), Barrel + Endcap
- $\frac{\sigma_E}{E} < 2.5\%$ at 1 GeV/c²
- $\sigma_x < 6$ mm at 1GeV/c²

How to measure FFs at BESIII

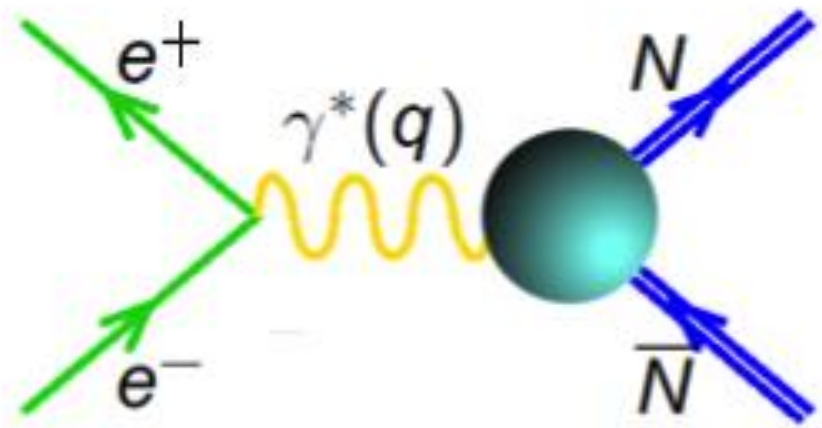
Energy scan		ISR technique
		
$\frac{d\sigma_{p\bar{p}}(s)}{d\cos\theta_p} = \frac{2\pi\alpha^2\beta C}{4s}\left[\lvert G_M(s)\rvert^2(1+\cos^2\theta_p)+\frac{4m_p^2}{s}\lvert G_E(s)\rvert^2\sin^2\theta_p\right]$	<u>Cross section</u>	$\frac{d^2\sigma_{p\bar{p}\gamma}}{dx\,d\theta_\gamma} = W(s,x,\theta_\gamma)\sigma_{e^+e^-\to p\bar{p}}(s),$ $W^{LO}(x,\theta_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma}-\frac{x^2}{2}\right)$
Discrete energy scan points	<u>Beam energy</u>	Fixed energy (resonance)
Low for each point	<u>Luminosity</u>	High at that point, but lowered by factor $\alpha/\pi \approx 1/400$

BESIII data samples

$$R_{had} = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

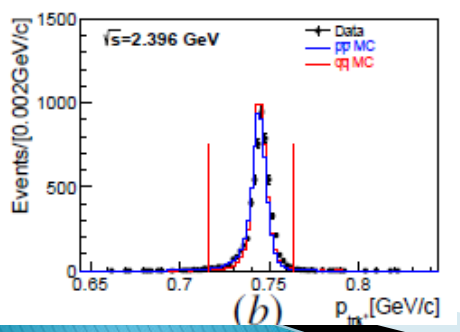


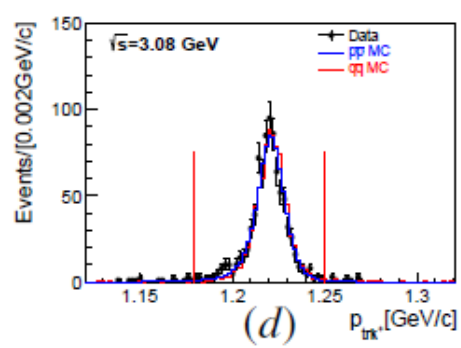
Scan method



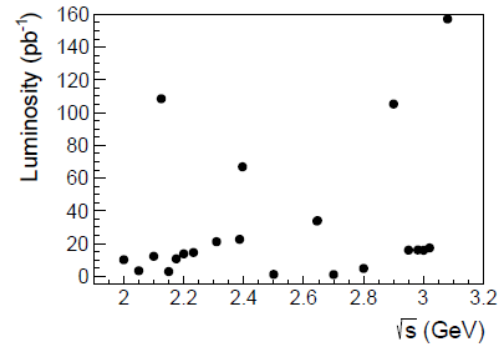
Scan: event selection

- Two scan data sets taken at BESIII in 2012 and 2015
- 2012 data: 12 energy points between 2.2324 and 3.671 GeV, total luminosity: 156.9 pb^{-1}
- 2015 data: 22 energy points between 2.0 and 3.08 GeV, total luminosity: 630 pb^{-1}
- Event selection:
  - 2 opositely charged tracks in MDC from vertex, identified as proton by PID system (ToF , dedx)
  - Back to back signature
  - Tof difference cut (veto cosmics)
  - EMC Information (E/P) to veto bhabha
  - Momentum window cut
- Negligible background





2015 scan data:



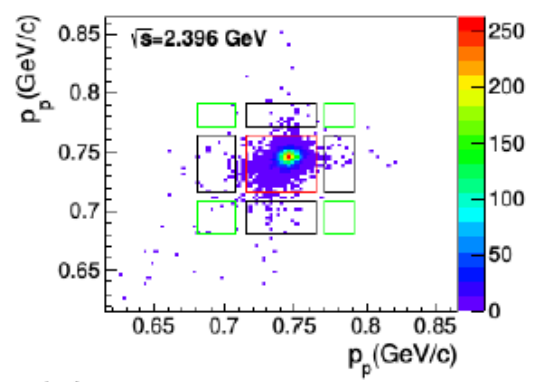
$\sqrt{s}$[GeV]	Lumi[pb^{-1}]
2	$10.074 \pm 0.005 \pm 0.067$
2.05	$3.343 \pm 0.003 \pm 0.027$
2.1	$12.167 \pm 0.006 \pm 0.085$
2.12655	$108.49 \pm 0.02 \pm 0.94$
2.15	$2.841 \pm 0.003 \pm 0.024$
2.175	$10.625 \pm 0.006 \pm 0.091$
2.2	$13.699 \pm 0.007 \pm 0.092$
2.2324	$11.856 \pm 0.007 \pm 0.087$
2.3094	$21.089 \pm 0.009 \pm 0.143$
2.3864	$22.549 \pm 0.010 \pm 0.176$
2.396	$66.869 \pm 0.017 \pm 0.475$
2.5	$1.098 \pm 0.002 \pm 0.009$
2.6444	$33.722 \pm 0.013 \pm 0.216$
2.6464	$34.003 \pm 0.013 \pm 0.282$
2.7	$1.034 \pm 0.002 \pm 0.007$
2.8	$1.008 \pm 0.002 \pm 0.007$
2.9	$105.253 \pm 0.025 \pm 0.905$
2.95	$15.942 \pm 0.010 \pm 0.143$
2.981	$16.071 \pm 0.010 \pm 0.095$
3	$15.881 \pm 0.010 \pm 0.110$
3.02	$17.290 \pm 0.011 \pm 0.123$
3.08	$126.185 \pm 0.029 \pm 0.921$

Scan: background evaluation

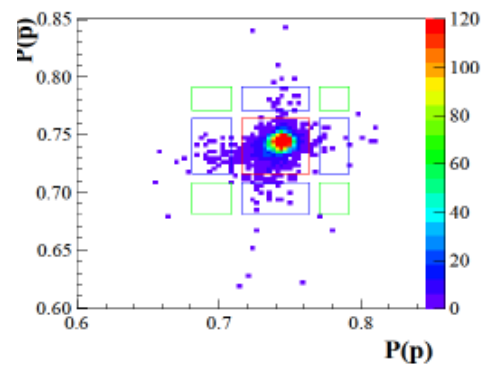
- Main background: radiative Bhabha scattering due to high cross section
- No Background surviving from generated MC channels

Process	Size	Generator
$p\bar{p}$	2.5M	ConExc and PHOKHARA
$p\bar{p}\pi^+\pi^-$	1.5M	ConExc
$q\bar{q}$	3.5∼11M	ConExc
e^+e^-	2∼193M	Babayaga
$\mu^+\mu^-$	0.8∼89.6M	Babayaga
$\gamma\gamma$	1∼4.3M	Babayaga
$p\bar{p}\pi^0$	0.65M	ConExc
K^+K^-	0.5M	ConExc
$p\bar{p}\pi^0\pi^0$	0.5M	ConExc
$\pi^+\pi^-$	0.5M	PHOKHARA

- 2 dimensional sideband method shows ~1% background
- Same level for signal MC sample



(f) Data Momentum window.



(c) MC Momentum window.

Scan: cross section

- Extraction of cross section and effective form factor:

$$\sigma_{born} = \frac{N_{sel}}{L \cdot \varepsilon \cdot (1+\delta)},$$

with ε: efficiency and $(1+\delta)$: radiative correction factor obtained from MC simulations, L: Luminosity

$$G_{eff} = \sqrt{\frac{3q^2}{4\pi\alpha^2\beta C} \cdot \frac{\sigma_{born}}{1+1/2\tau}},$$

with $\tau = \frac{E_{cm}^2}{4M_p^2}$

2012 Scan: cross section

- From 2012 scan data:

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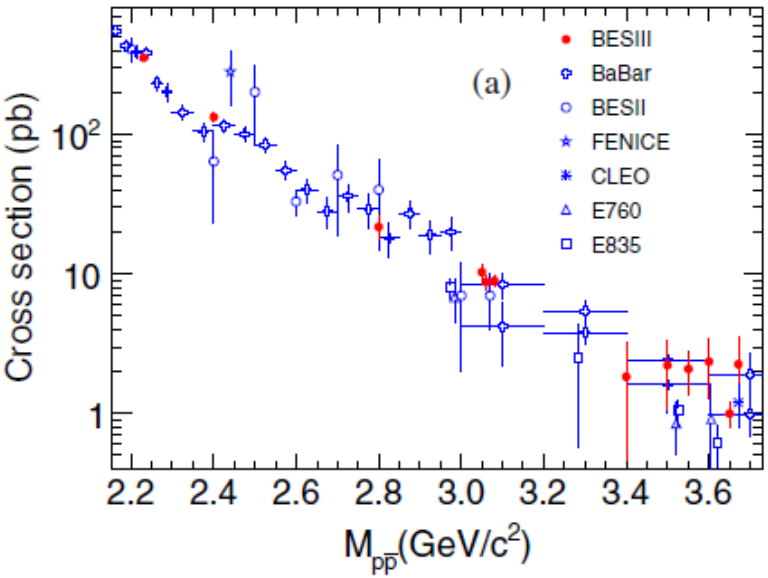
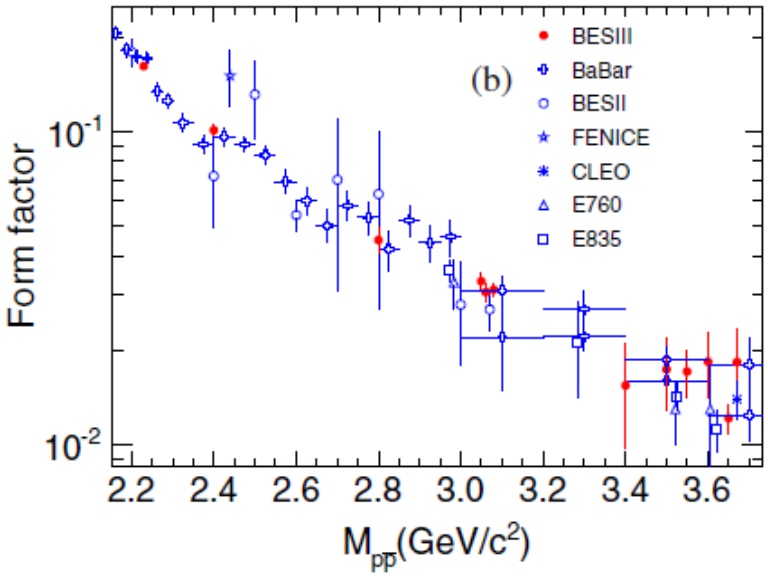
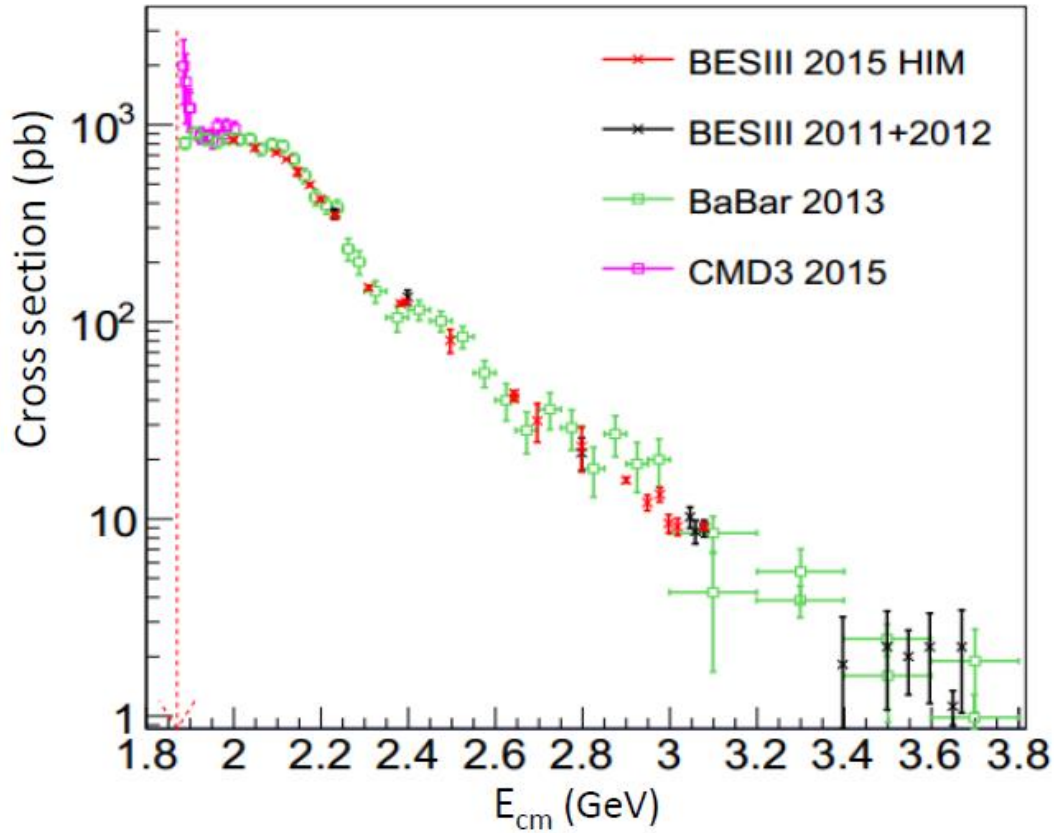




- $\varepsilon \cdot (1+\delta) \sim 60\%$
- Uncertainty improved compared to previous experiments below 3.08 GeV: 6% – 18.9%

2015 Scan: cross section

- 2015 scan data: MC study with luminosity according to data
- Expected accuracy: between 0.5% (2.125 GeV) and 26% (2.8 GeV)
- BaBar: 9.4% – 26.9%



Scan: extraction of R and G_M

- Differential cross section is given by:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4E_{cm}^2}\left(\left(1+\cos^2\theta_p\right)|G_M|^2 + \frac{1}{\tau}\left(\sin^2\theta_p\right)|G_E|^2\right)$$

with $\tau = \frac{E_{cm}^2}{4M_p^2}$, $\beta = \sqrt{1-1/\tau}$, $C = y/(1-e^{-y})$ and $y = \frac{\pi\alpha}{\beta}$

- Leads to two parameter fit function to extract R and G_m:

$$\frac{dN}{\varepsilon(1+\delta)d\cos\theta_p} = \underbrace{\frac{L\hbar c\pi\alpha^2\beta C}{2E_{cm}^2}}_{\text{normalisation}}\underbrace{|G_M|^2}_{P_1}\left(\left(1+\cos^2\theta_p\right)\tau + \left(1-\cos^2\theta_p\right)\frac{1}{\tau}\underbrace{\frac{|G_E|^2}{|G_M|^2}}_{P_2 = R}\right)$$

Method of moments

- Cross check of fit method: R and G_M from expectation value of $\cos(\theta_p)$:

$$< \cos^2\theta >= \frac{N_1}{N_{norm}} \int_{x_{min}}^{x_{max}} \cos^2\theta \left\{ [(1+\cos^2\theta)]|G_M|^2 + \frac{4m_p^2}{s}\sin^2\theta|G_E|^2 \right\} d\cos\theta$$

$$\boxed{R = |\frac{G_E}{G_M}| = \sqrt{\tau \frac{y_4 - y_2 < \cos^2\theta >}{< \cos^2\theta > y_1 - y_3}} \qquad G_M = \sqrt{\frac{N_{norm}}{N_1(y_2 + \frac{1}{\tau}R^2 y_1)}}}$$

with

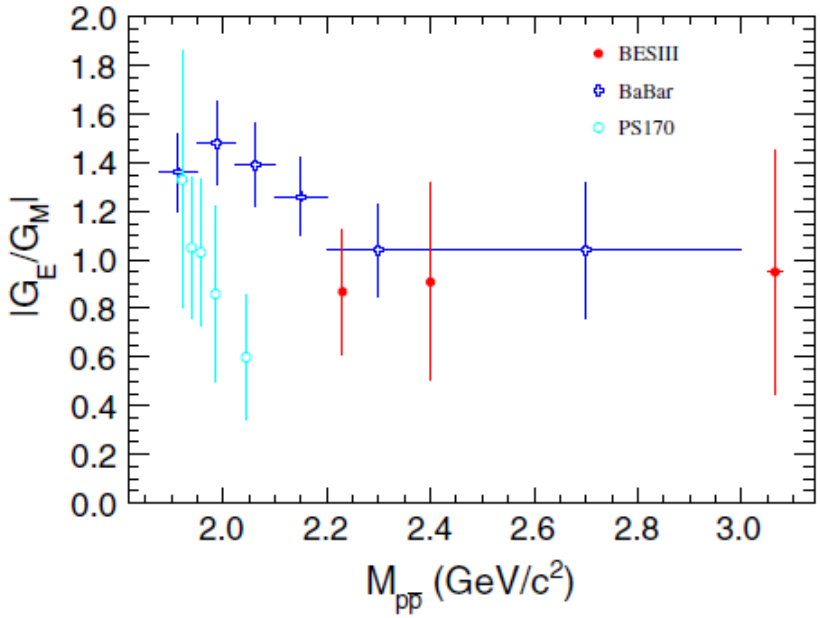
$$N_{norm} = \int_{x_{min}}^{x_{max}} \left\{ [(1+\cos^2\theta)]|G_M|^2 + \frac{4m_p^2}{s}\sin^2\theta|G_E|^2 \right\} d\cos\theta$$

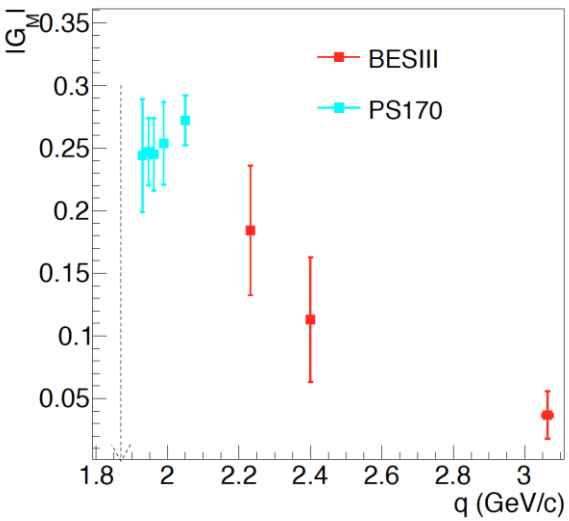
$$y_1 = \int_{x_{min}}^{x_{max}} (1-x^2)dx, \quad y_2 = \int_{x_{min}}^{x_{max}} (1+x^2)dx,$$

$$y_3 = \int_{x_{min}}^{x_{max}} (x^2-x^4)dx, \quad y_4 = \int_{x_{min}}^{x_{max}} (x^2+x^4)dx$$

2012 Scan: Form Factors

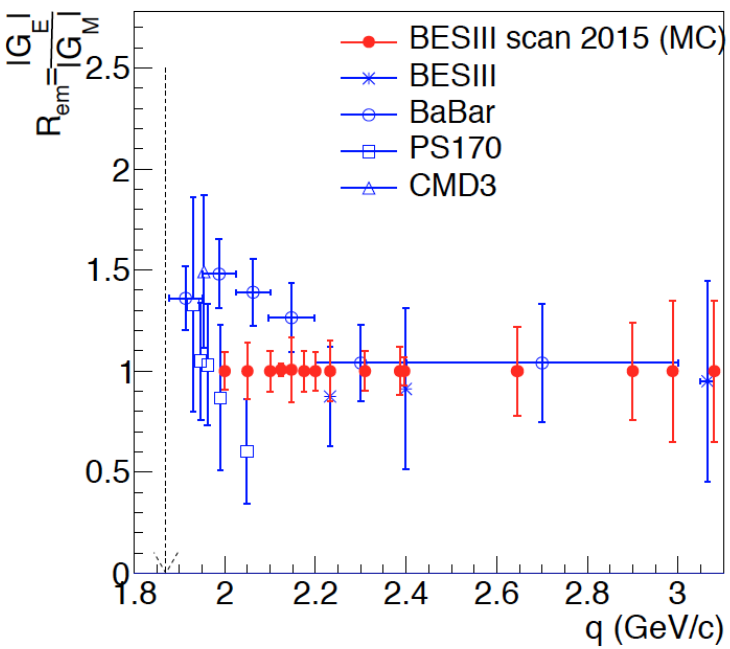
- 2012 data: ratio and G_M extracted at 2.232, 2.4 GeV and combined sample of 3.05, 3.06 and 3.08 GeV
- R consistent with Babar and R = 1
- $\frac{\delta R}{R} = 25\% - 50\%$, comparable to BaBar
- Extraction of G_M in a wider q^2 range

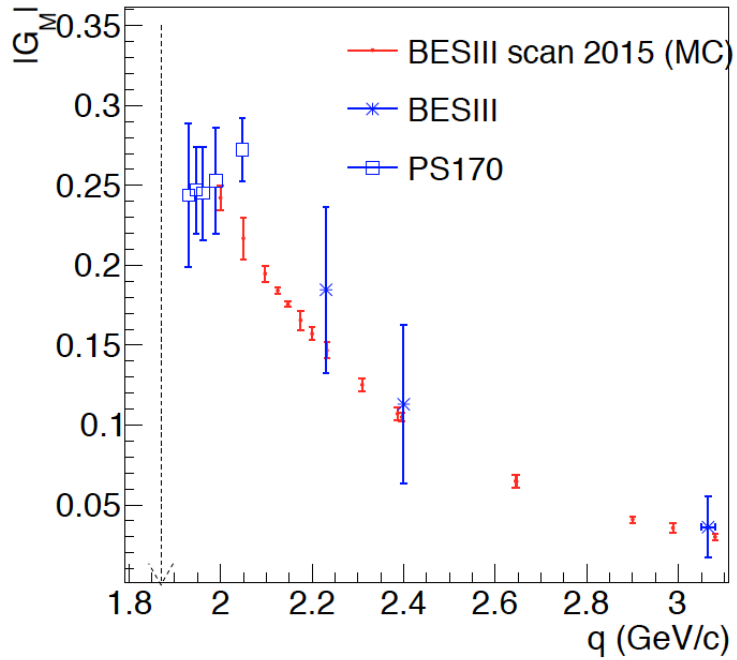




2015 Scan: Form Factors

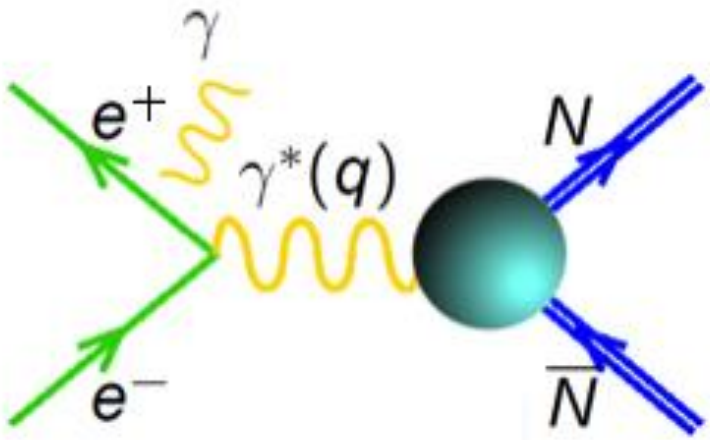
- Prospects for 2015 scan data
- Assuming R = 1 and the luminosity of the 2015 data:



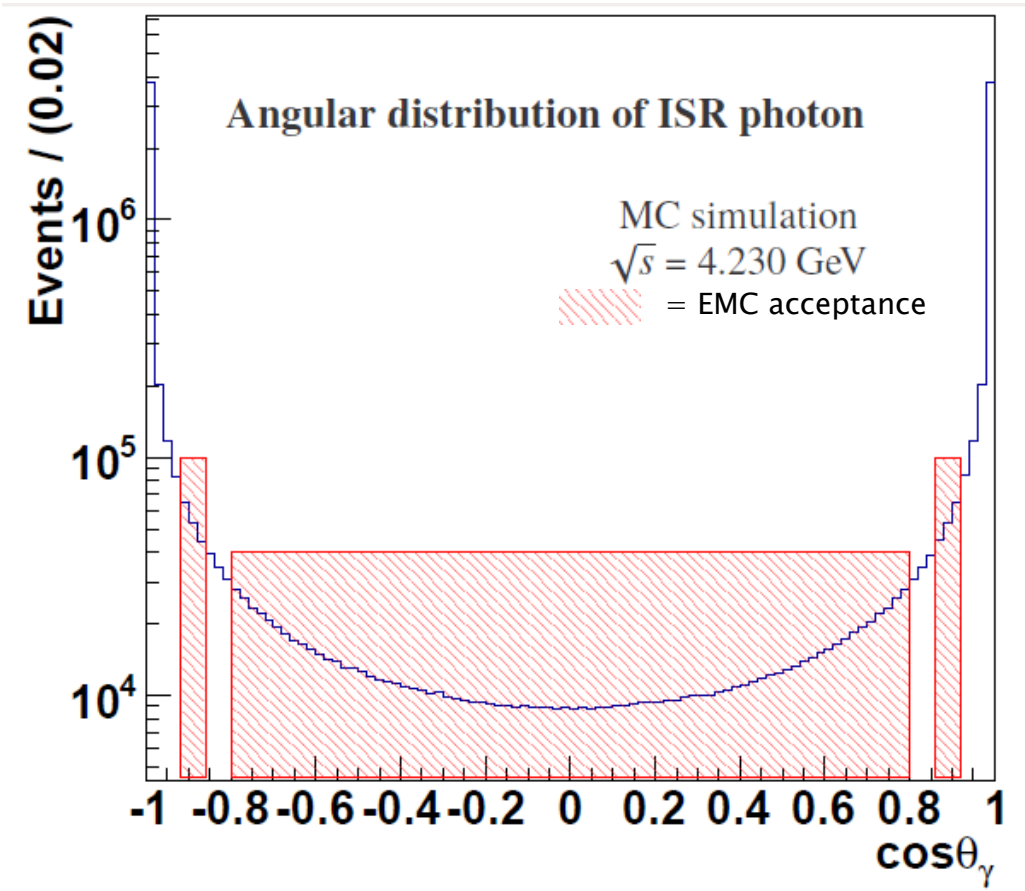


- Predicted uncertainties: 3% – 35% for R, 1% – 9% for G_m
- Uncertainty of ratio ~10% for most energy points, comparable to space like region for the first time

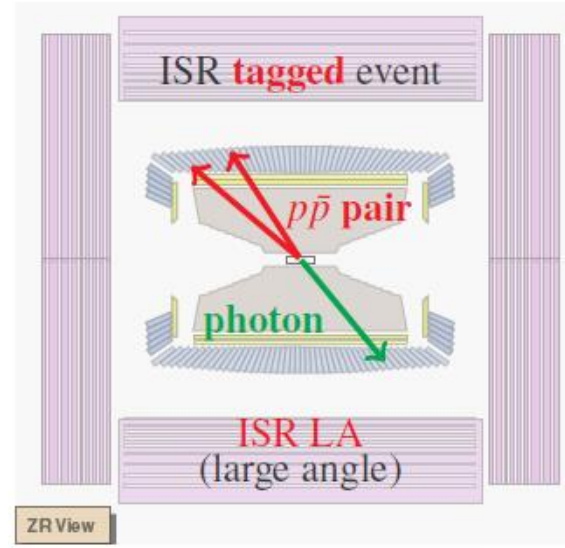
ISR Method

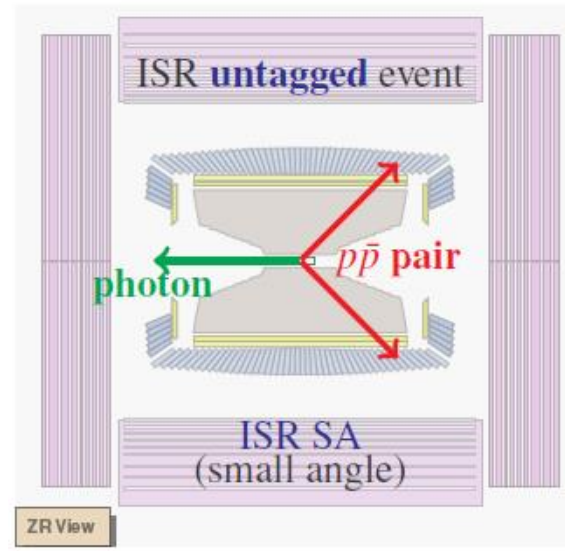


ISR analysis: tagged and untagged



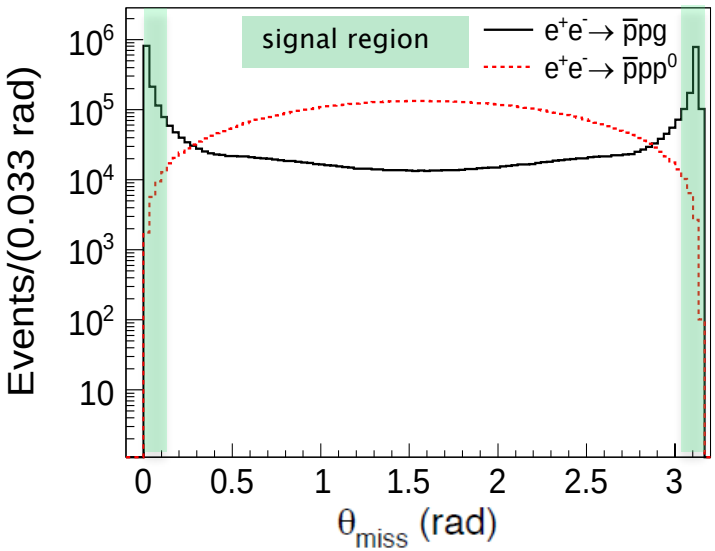
$p\bar{p}$ pair	42-58%	
ISR γ	tagged	untagged
	11-12%	31-46%

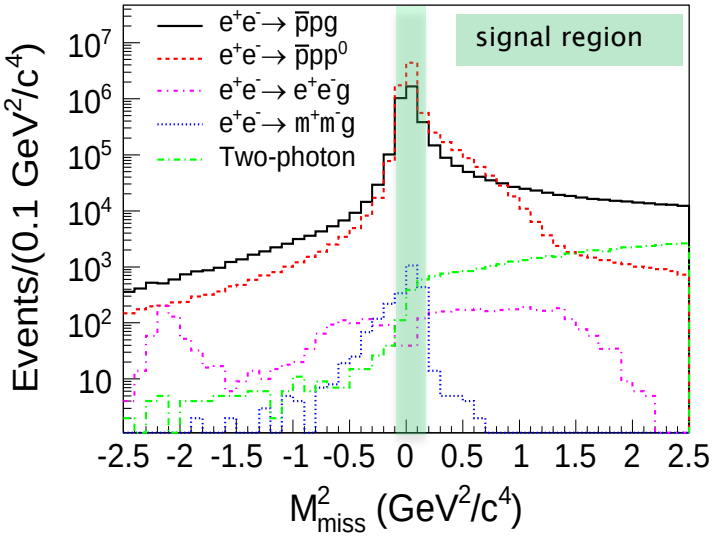




ISR untagged: event selection

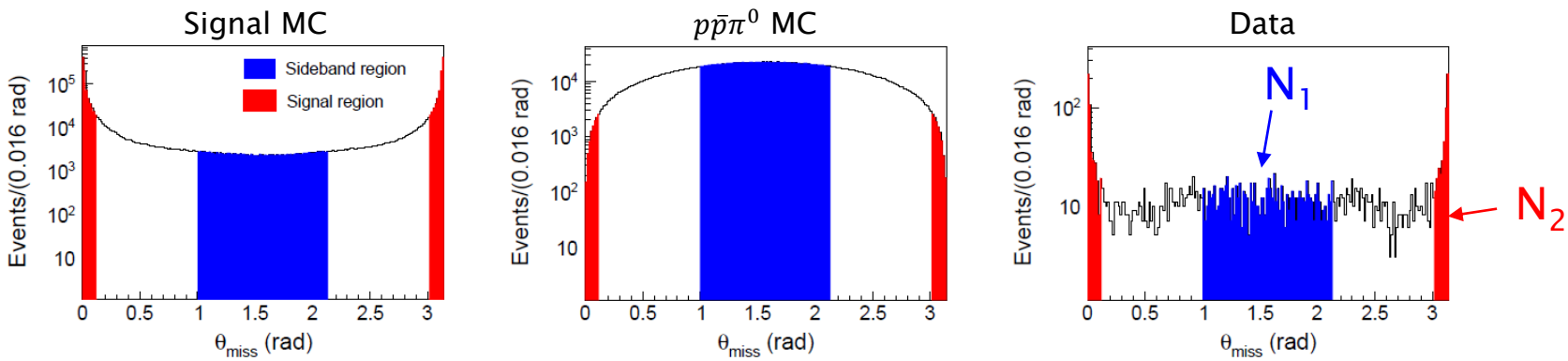
- 7 data sets between 3.773 and 4.6 GeV, total luminosity 7.41 fb^{-1}
- Selection of $p\bar{p}$ system:
  - MDC: two charged tracks from vertex
  - Identified as proton by PID (dedx and ToF)
  - E/p cut
- Identification of the undetected ISR photon based on distributions of:
  - Polar angle of missing momentum
  - Missing mass squared recoiling against the $p\bar{p}$ system





ISR untagged: background

- Estimated from MC samples: Most channels ($e^+e^- \to e^+e^-\gamma, \mu^+\mu^-\gamma, \pi^+\pi^-\gamma,\ K\bar{K}\gamma$ and $e^+e^- \to \Lambda\bar{\Lambda} \to \pi^+\pi^-p\bar{p}$) are suppressed
- Background from $e^+e^- \to \mathcal{R}$ ($\mathcal{R} \to p\bar{p}\gamma$) suppressed to below 1%

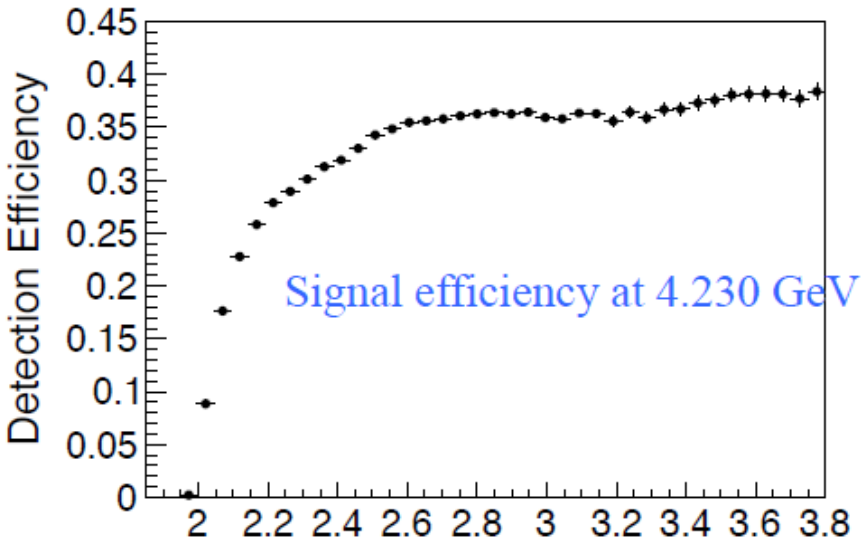


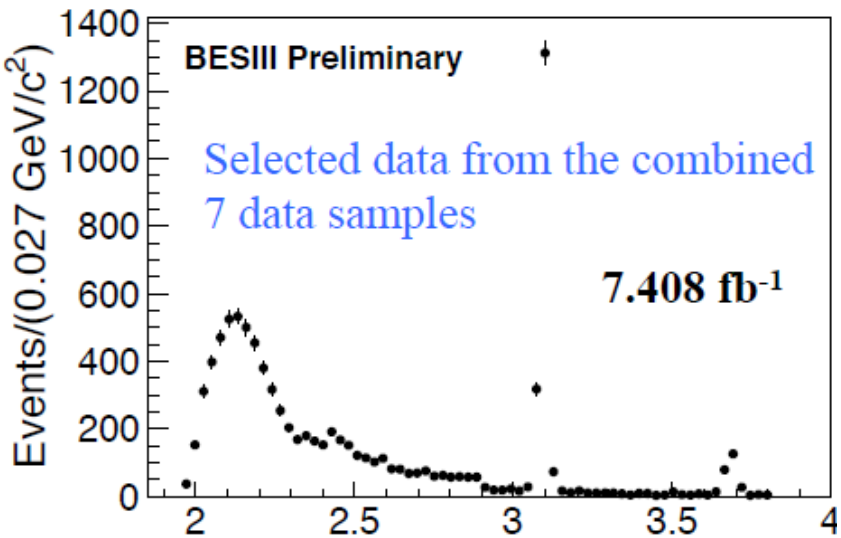
- $e^+e^- \to p\bar{p}\pi^0$ and two-photon channel are subtracted by sideband method:

$$N_{bkg} = \frac{N_2 - \beta_{sig} N_1}{\beta_{bkg} - \beta_{sig}}, \ \beta = \frac{N_2}{N_1} \text{ from MC}$$

ISR untagged: signal efficiency

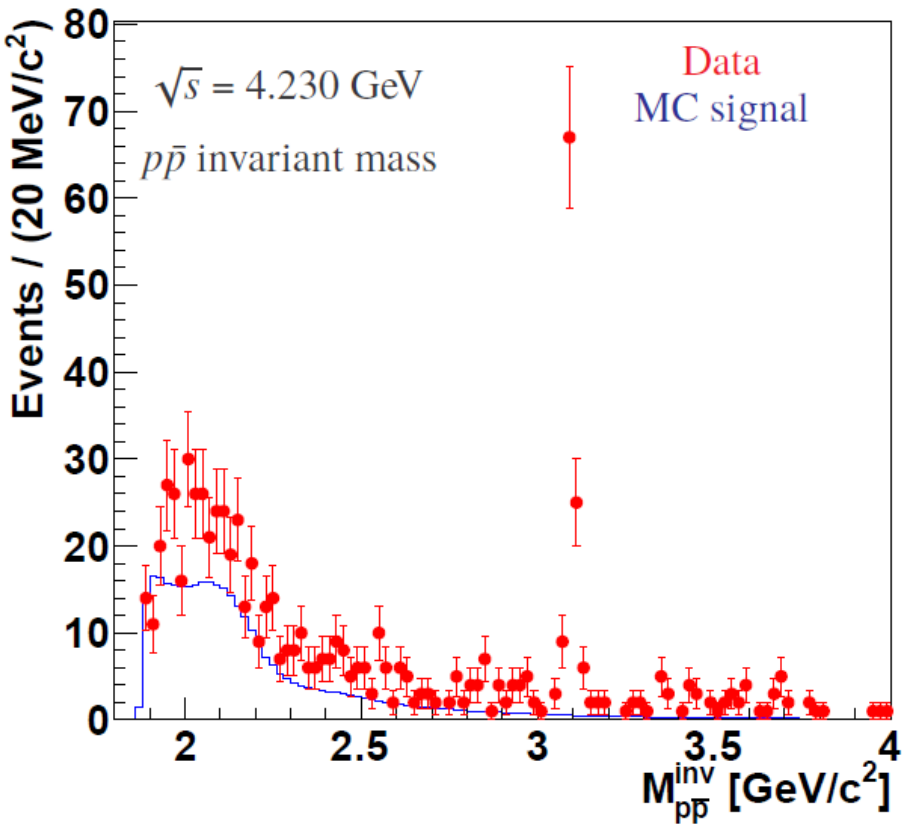
- Determined by MC, using phokhara event generator up to NNLO radiative corrections, for each interval of M_{ppbar}
- Integrated signal efficiency between 17.8% (3.773 GeV) and 12.6% (4.6 GeV)





ISR tagged: event selection

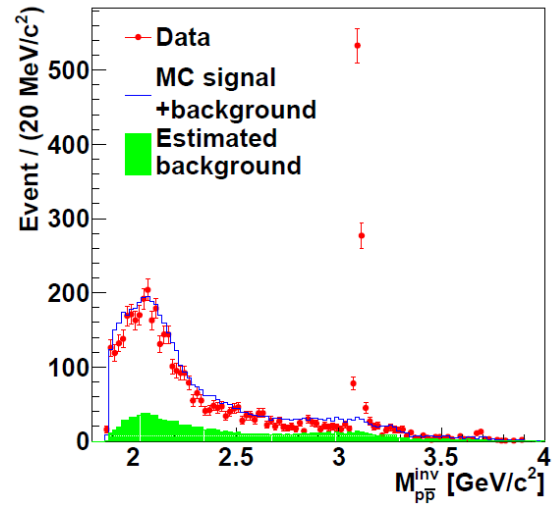
- Same selection for $p\bar{p}$ system as in untagged case
- Selection of ISR Photon: most energetic shower in EMC
- 4-constraints kinematic fit (4 momentum conservation) to select $p\bar{p}\gamma$ events
- Background suppression:
  - combine two showers to $\pi^0(\eta)$ candidate
  - 5C kinematic fit with $\pi^0(\eta)$ mass to remove $e^+e^- \to p\bar{p}\pi^0$
- Most background channels suppressed, remaining $p\bar{p}\pi^0$ needs to be subtracted

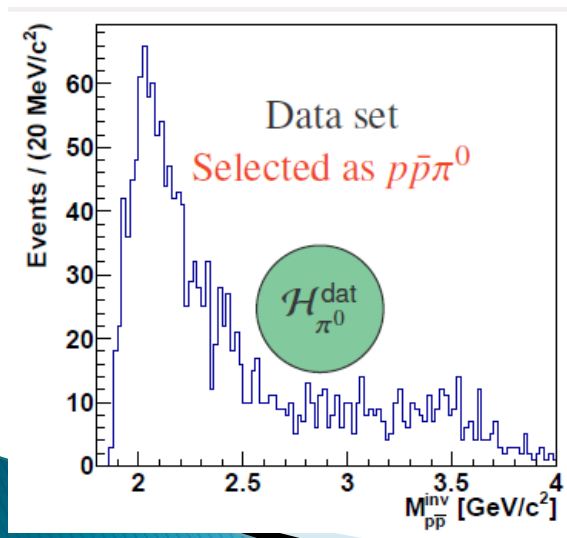


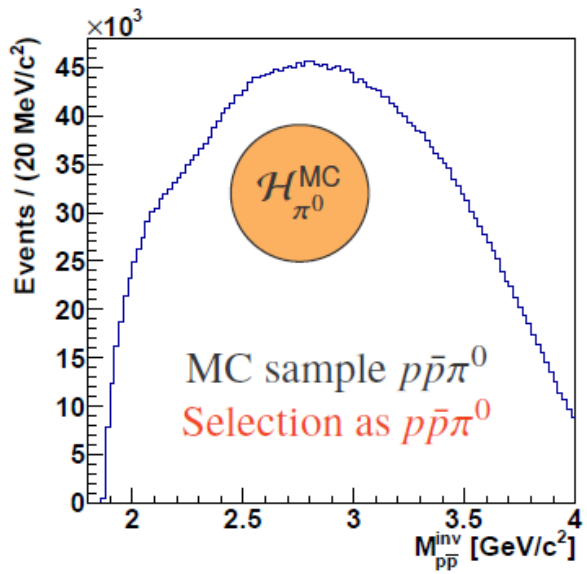
ISR tagged: background subtraction

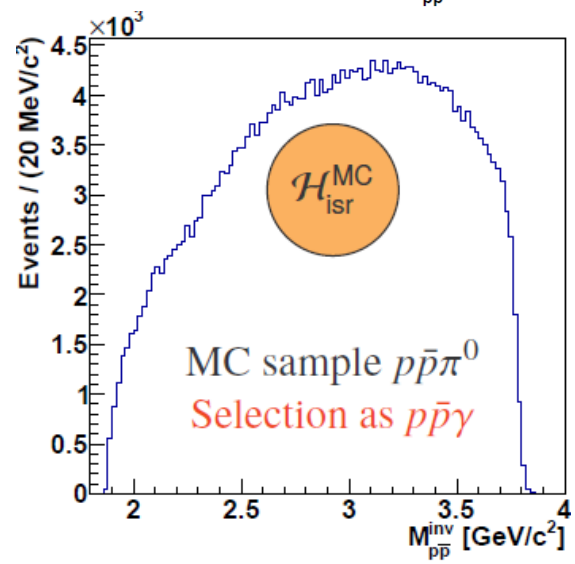
- Dominant background $p\bar{p}\pi^0$: one photon from π^0 decay miss identified as ISR photon
- Estimated with phasespace $p\bar{p}\pi^0$ MC weighted by data:

$$\mathcal{H}_{ISR}^{Bkg} = \frac{\mathcal{H}_{ISR}^{MC}}{\mathcal{H}_{\pi^0}^{MC}}$$









ISR: Form Factor ratio

- Extracted from distribution of the helicity angle θ_p
- θ_p is defined as the angle between proton momentum in the $p\bar{p}$ rest frame and the momentum of the $p\bar{p}$ system in the e^+e^- rest frame
- Analytic for $e^+e^- \to p\bar{p}$:

$$\frac{dN}{d\cos\theta_p} = \frac{L\hbar c\pi\alpha^2\beta C}{2E_{cm}^2}|G_M|^2\left(\left(1+\cos^2\theta_p\right)\tau + \left(1-\cos^2\theta_p\right)\frac{1}{\tau}\frac{|G_E|^2}{|G_M|^2}\right)$$

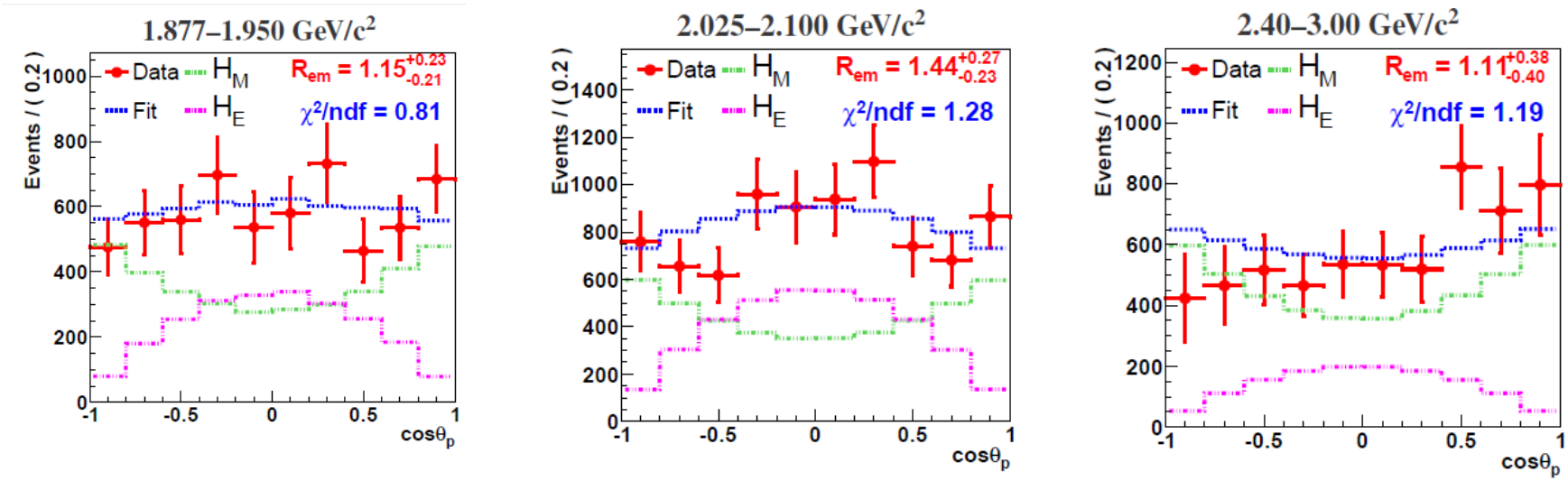
- For ISR process, histograms $\mathcal{H}_E$ and $\mathcal{H}_M$ obtained from MC simulation with $G_E = 0$ and $G_M = 0$ are used:

$$\frac{dN}{d\cos\theta_p} = A\left(\mathcal{H}_M\left(\cos\theta_p, M_{p\bar{p}}\right) + \left|\frac{G_E}{G_M}\right|^2 \mathcal{H}_E\left(\cos\theta_p, M_{p\bar{p}}\right)\right)$$

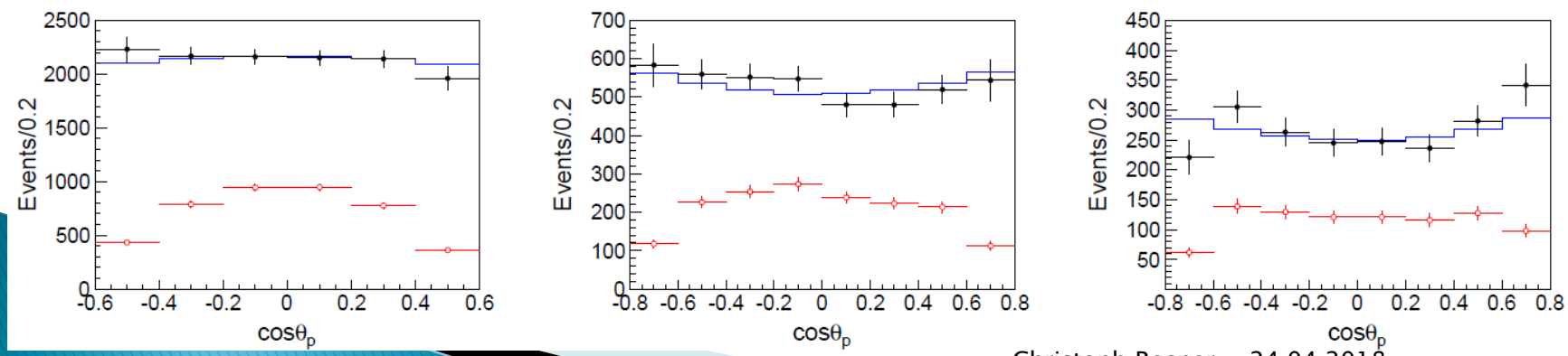
ISR: Form Factor ratio

- Angular distributions fitted after efficiency correction and background subtraction for each cos(θ) intervall
- Reduced fitting range leads to higher uncertainty in untagged case

Tagged:



Untagged:



ISR: systematic uncertainty of ratio

Tagged:

- Background:
  - Generate 890 random Bkg. distributions based on $p\bar{p}\pi^0$ data
  - Extract R for each distribution
  - Difference of mean to nominal result as error
- 4C Fit: change cut on χ^2_{4c} from 50 to 45 and 60
- Bins: change number of bins from 10 to 8 and 15

$M_{P\bar{P}}[GeV/c^2]$	Bkg.	4C Fit	Bins	total
1.877–1.950	2.0%	2.0%	6.1%	6.7%
1.950–2.025	1.6%	2.0%	3.7%	4.5%
2.025–2.100	2.1%	2.8%	2.3%	4.2%
2.100–2.200	1.3%	7.6%	9.0%	11.9%
2.200–2.400	1.0%	8.0%	13.1%	15.6%
2.400–3.000	6.0%	3.8%	7.7%	10.5%

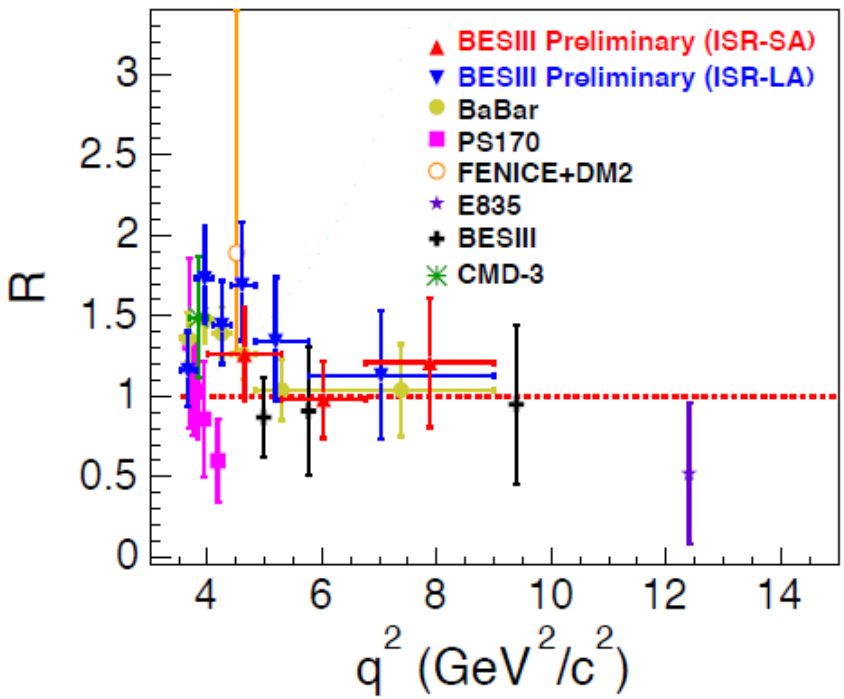
Untagged:

- Background: difference of R with and without subtraction
- Varying fitting range to [-0.5,0.5] or [-0.7,0.7]
- θ_{miss}, M^2_{miss}: reducing selection windows by 20%

$M_{P\bar{P}}[GeV/c^2]$	Bkg.	Fitrange	θ_{miss}	M^2_{miss}	total
2.0–2.3	3%	2%	4%	5%	7%
2.3–2.6	2%	1%	4%	2%	5%
2.6–3.0	16%	1%	4%	2%	16%

ISR: Form Factor ratio

- Measured in 3 (6) mass intervalls between 2.0 and 3.0 GeV (1.877 and 3.0 GeV) for the untagged (tagged) case
- Total uncertainties between 23% and 33% (19% and 35%)



Tagged:

$M_{P\bar{P}}[GeV/c^2]$	R
1.877–1.950	1.16±0.24
1.950–2.025	1.73±0.33
2.025–2.100	1.44±0.28
2.100–2.200	1.69±0.39
2.200–2.400	1.34±0.40
2.400–3.000	1.13±0.40

untagged:

$M_{P\bar{P}}[GeV/c^2]$	Fit range	R
2.0–2.3	$[-0.6, 0.6]$	1.26±0.29
2.3–2.6	$[-0.8, 0.8]$	0.98±0.24
2.6–3.0	$[-0.8, 0.8]$	1.21±0.40

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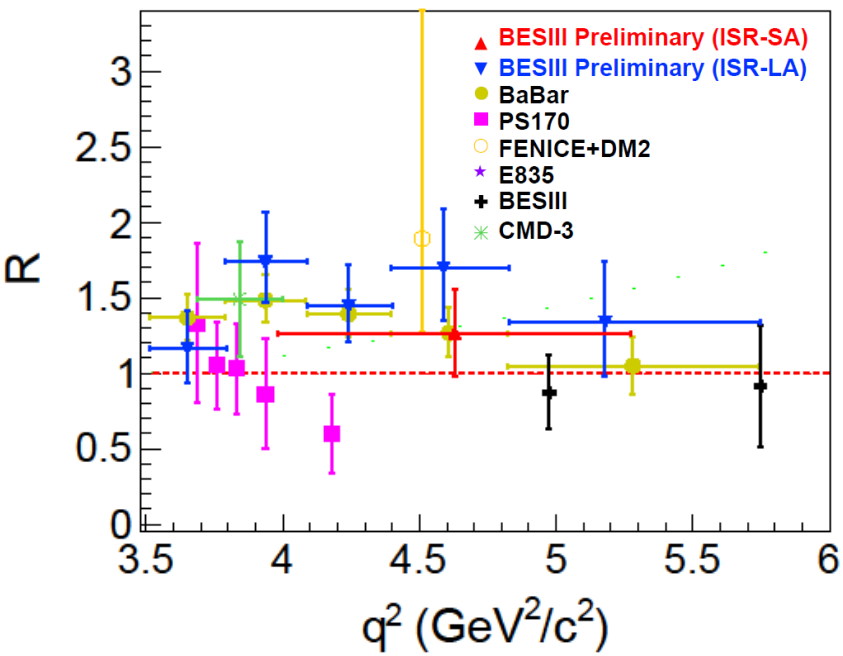

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ISR: cross section and eff. FF

- Cross section of $e^+e^- \to p\bar{p}$ calculated for each invariant mass intervall i by:

$$\sigma_i = \frac{N_i}{\varepsilon_i (1+\delta)_i L_i}$$

with:

  - N_i: number of events after selection and bkg. Subtraction
  - ε_i: efficiency obtained from phokhara signal MC, including NNLO radiative corrections, FSR and VP
  - $(1+\delta)_i$: radiative correction factor
  - L_i: differential Luminosity $L_i = \sum_k \int W(s_k, x_{ik})\, L_k dx_{ik}$, $W(s_k, x_{ik})$: radiator function

- Eff. FF derived from cross section, assuming $G_E = G_M$:

$$|G_{eff}|^2 = \frac{3q^2 \sigma_{p\bar{p}}}{4\pi\alpha^2 C \left(1 + \frac{2M_p^2}{q^2}\right)}$$

ISR: systematic uncertainty of cross section

Tagged:

Trk.	PID	E/P	Lum.	Bkg	4C fit	Total
2.0%	2.0%	1.0%	1.0%	0.4%–6.0%	0.5%–23.6%	3.3%–24.0%

Untagged:

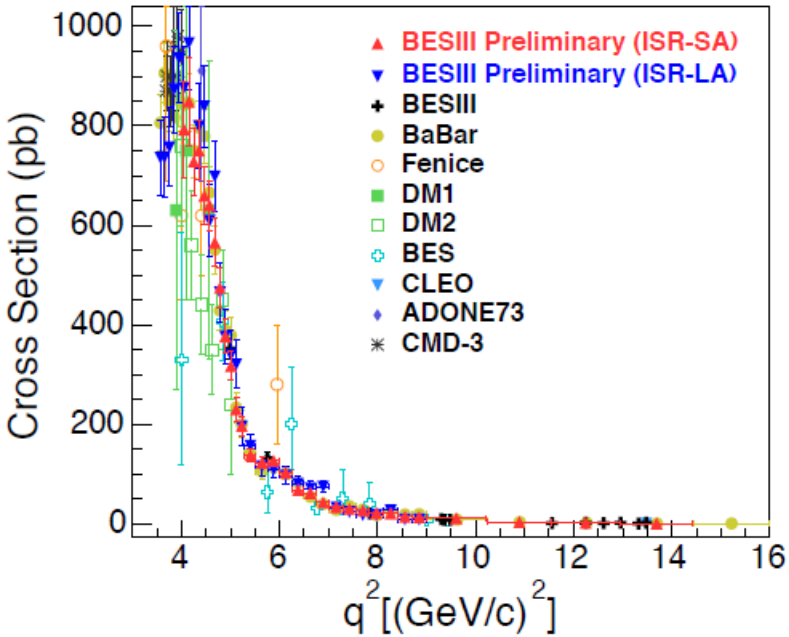
Trk.	PID	E/P	Lum.	Bkg.	θ_{miss}	M^2_{miss}	Rad. Func.	FSR	model	Total
2.0%	2.0%	1.0%	1.0%	1.5%–8.2%	6%	5%	0.5%	1%	3%–8%	5.3%–18.2%

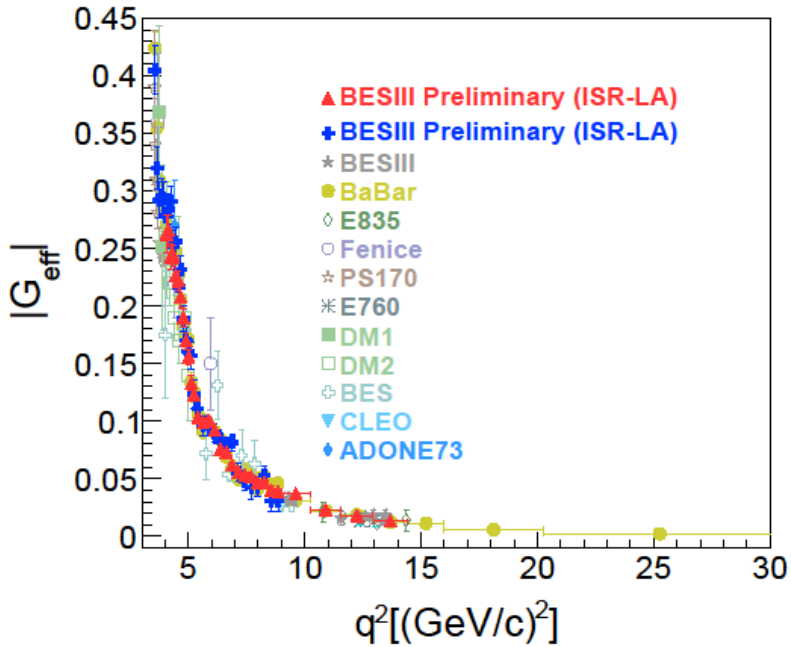
- Systematic uncertainties from tracking efficiency (2%) and E/p requirement (1%) from published analysis PRD 91(2015) 112004
- Uncertainty from Luminosity measurement: 1%
- PID uncertainty (2%) studied through $e^+e^- \to p\bar{p}\pi^0$
- Same methods for background uncertainties as for the ratio

- Tagged: uncertainty from 4C kinematic fit for each invariant mass bin
- Untagged:
  - uncertainty from θ_{miss} and M^2_{miss}: same as for cross section
  - Uncertainty from radiator function and calculation of FSR assumed to be 0.5% and 1%, respectively
  - Model uncertainty estimated by varying R within ist statistical uncertainty

ISR: cross section and eff. FF

- Measured in 30 (31) mass intervalls between 2.0 and 3.8 GeV (1.877 and 3.0 GeV) for the untagged (tagged) case





- Total uncertainties: 8% to 37% (untagged) and 9% to 68% (tagged)
- constistent with previous measurements
- similar precision as BaBar in the untagged case despite much smaller Luminosity

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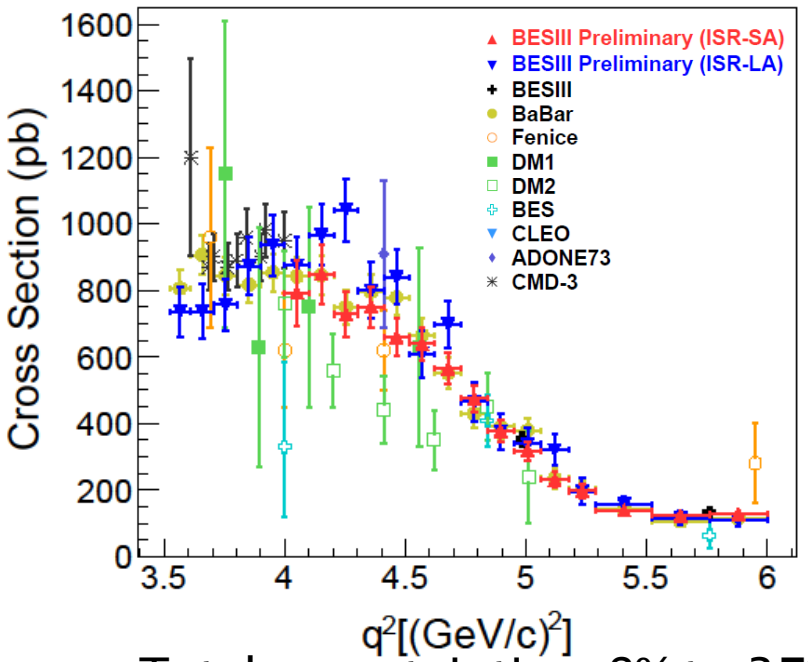

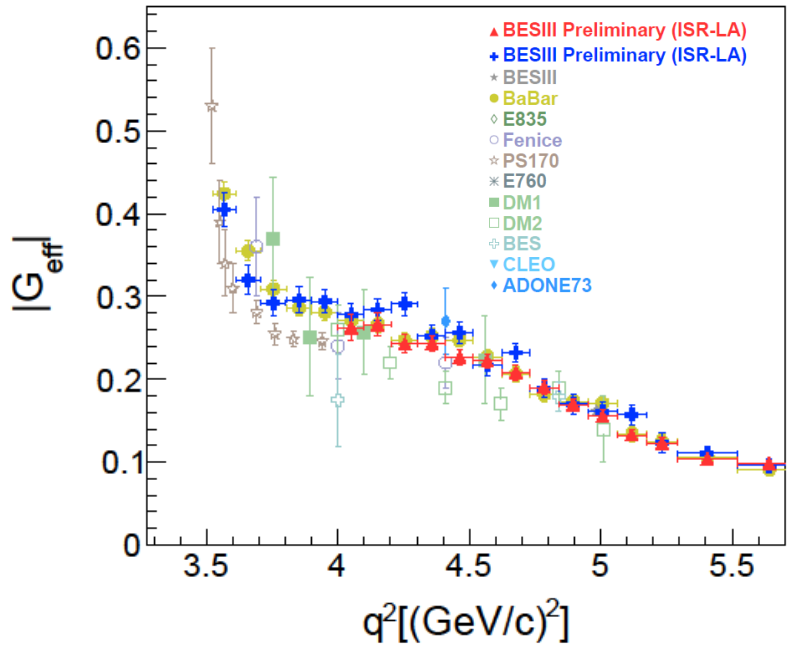

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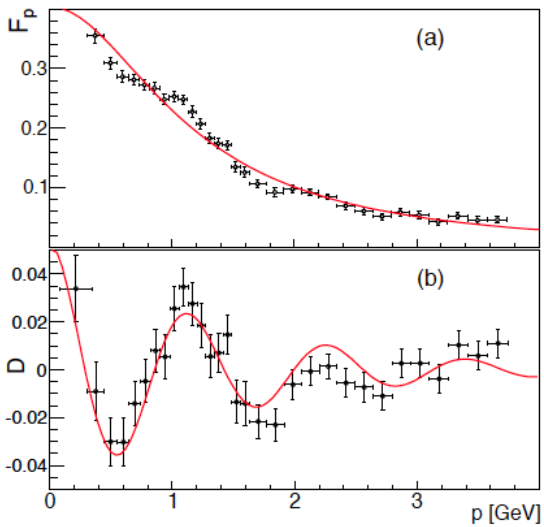
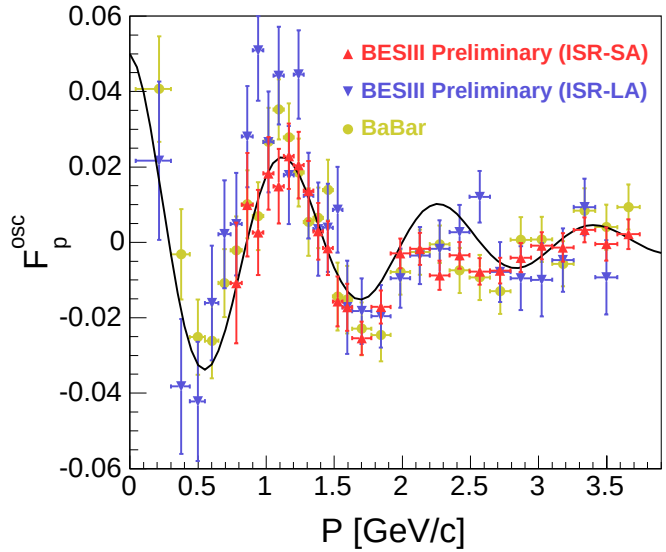
- similar precision as BaBar in the untagged case despite much smaller Luminosity

ISR: effective FF structure

- Effective form factor as a function of the 3-momentum (P) of the relative motion of the two protons
- The oscillations can be extracted from the effective form factor as $F^{osc}=|Geff|-F^0$ (F^0 describes the regular behavior of the form factor over the long range of the ppbar invariant mass)

Phys. Rev. Lett. 114,232301 (2015), Phys. Rev. C 93, 035201 (2016)





- Oscillations seen in eff. FF by BaBar reproduced by both ISR tagged and untagged

Summary and Prospects

- BESIII provides an excellent opportunity to study nucleon form factors, using both scan and ISR technique
- Scan data of 2012 has been analysed to extract proton form factors:
  - Good agreement in eff. FF and cross section with previous measurements, increased precision by ~30%
  - $|G_M|$ and $R = |G_E/G_M|$ extracted for 3 energy points, in agreement with Babar and R=1
- Preliminary results from ISR tagged and untagged analysis for Proton FFs:
  - Cross section, eff. FF and R extracted, in agreement with Babar
  - Oszillations seen by BaBar in eff. FF confirmed by both tagged and untagged analysis
- Prospects: 2015 scan data to will significantly improve the precision of proton FFs

Thank You!