A brief history of

R measurements & QCD studies at BES

Guangshun Huang

University of Science and Technology of China

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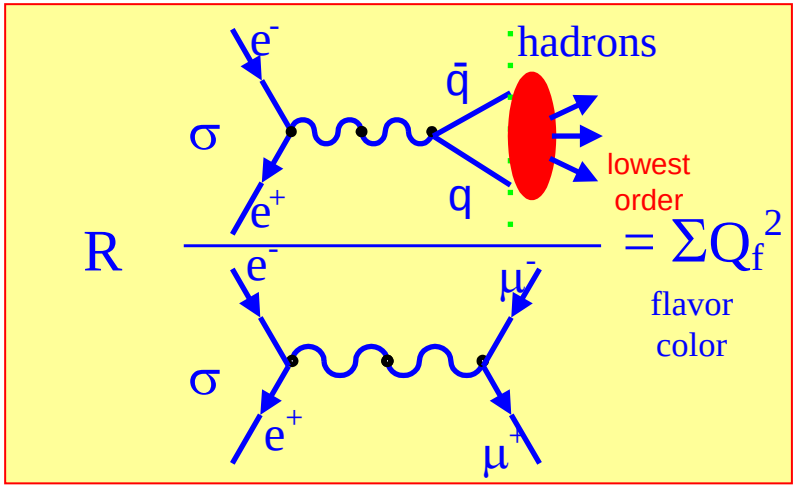
Outline

- Pre-study with BESI data
- R measurements at BESII
  - 6 points test run
  - 85 points fine scan
  - 3 points high statistics data
  - other approaches
- R scans at BESIII
  - 4 points test run
  - 104 points in 3.85-4.6 GeV
  - 22 points in 2.0-3.08 GeV
- QCD studies at BESII, BESIII
- Summary

Definition of R:



- At lowest order

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{\sum_q \sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_q Q_q^2$$

Number of quark colors

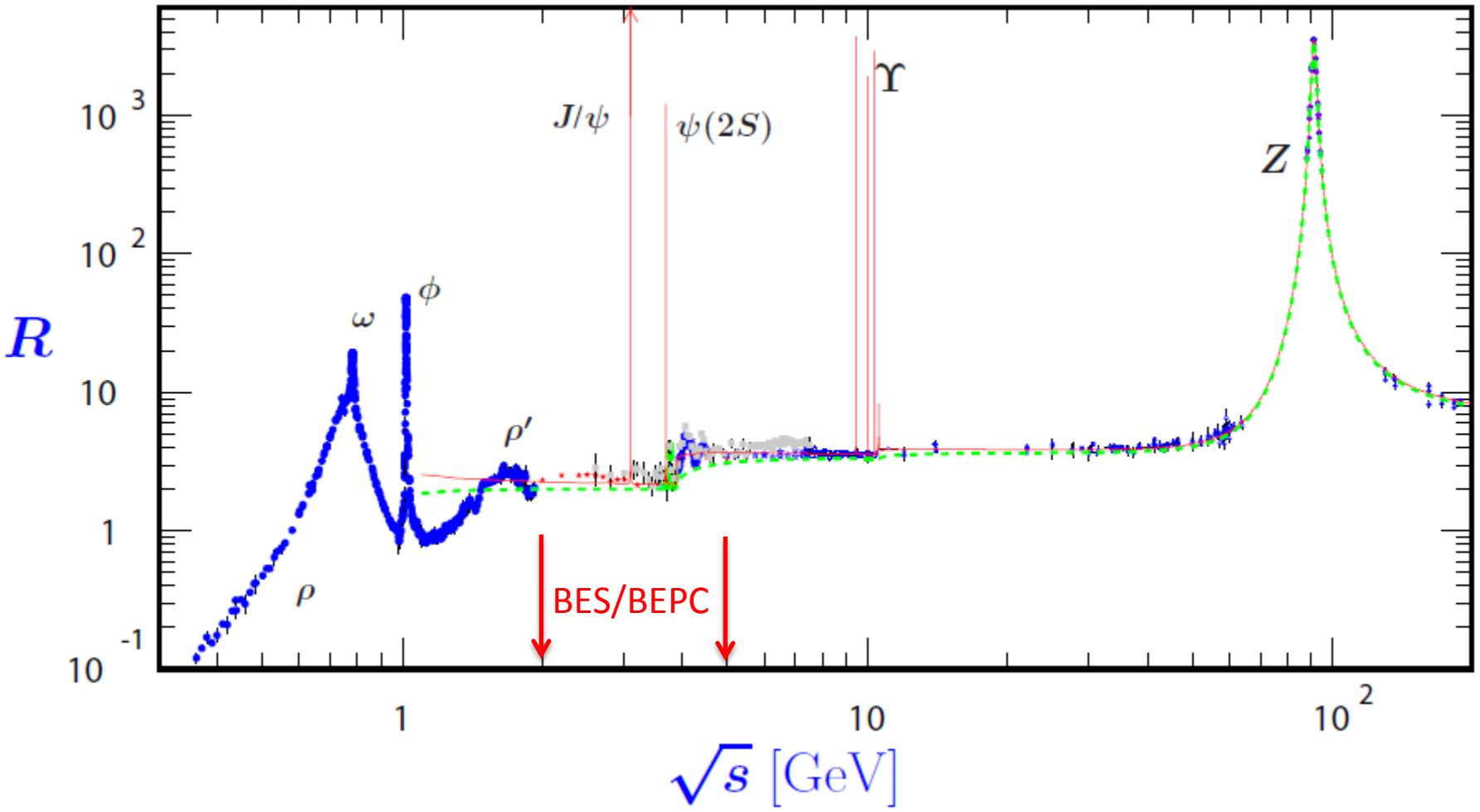
- At higher order

$$R = 3\, K_{QCD} \sum_q Q_q^2 ,$$

$$K_{QCD} = 1 + \frac{\alpha_S(\mu^2)}{\pi} + \sum_{n\geq 2} C_n \left(\frac{s}{\mu^2}\right) \left(\frac{\alpha_S(\mu^2)}{\pi}\right)^n$$

- R is one of the most fundamental quantities in particle physics that directly reflect the flavor and color of quarks.
- Directly test quark model & QCD, and discover new particles.

R: from threshold to Z



Measurement of R Values

$$R = \frac{1}{\sigma_{\mu+\mu-}} \cdot \frac{N_{had} - N_{bg}}{L \cdot \varepsilon_{had} \cdot (1+\delta)}$$

N_{had}: observed hadronic events

N_{bg}: background events

L: integrated luminosity

ε_{had}: detection efficiency for N_{had}

δ: radiative correction factor

$\sigma_{\mu\mu}$: can be precisely calculated(QED). Measurement of R is to measure the total $\sigma(e^+e^-\rightarrow hadrons)$

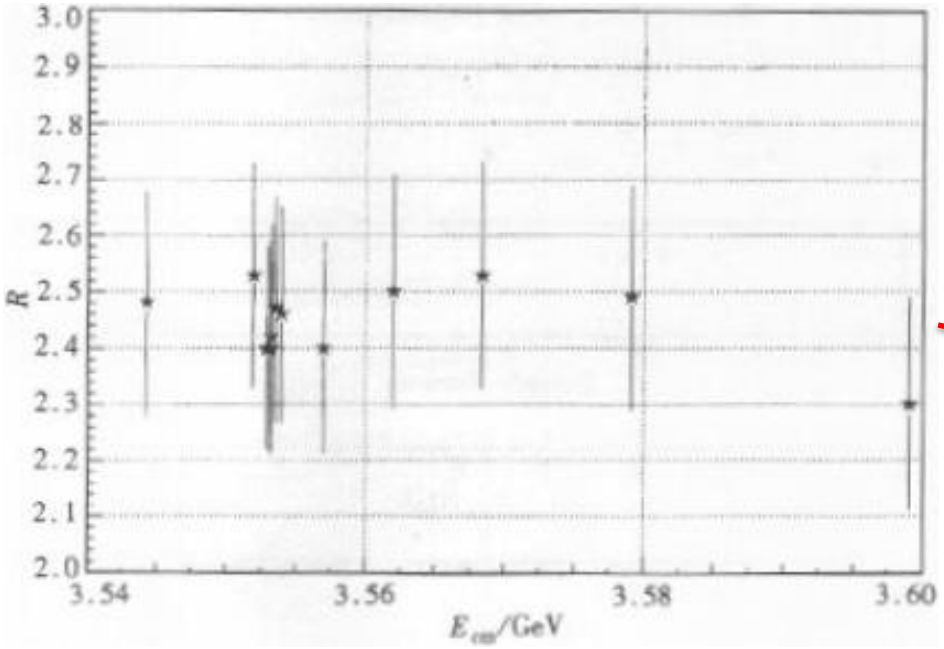
Except for controlling each item to the precision requested, stable long term machine and detector performance is crucial.

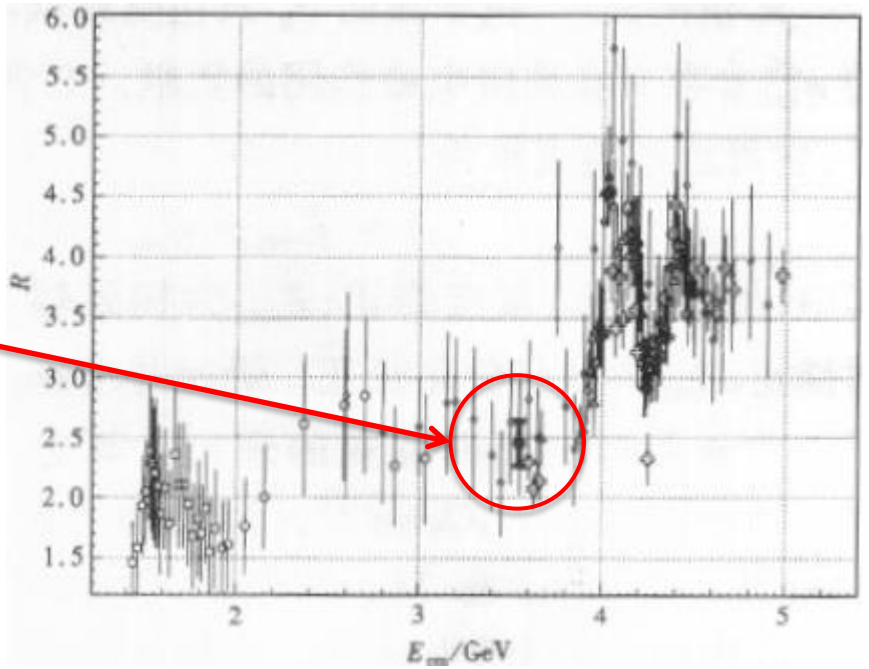
Starting R measurement at BES…

- Prof. Zhipeng Zheng and Jin Li initiated the important study in 1995, Zhengguo started investigation in ETHZ;
- Initial members were Prof. Shengtian Xue, Dr. Haiming Hu, Xinhua Li, Ms. Xiangrong Qi in IHEP;
- Prof. Zhengguo Zhao formally came back to lead the effort in 1997;
- More helpers joined: Mr. Guangshun Huang, Dr. Jiangchuan Chen, Mr. Zhiyong Wang, Zhongchao Li, Lei Zhang, Wenbiao Yan, …;
- Key partner Hawaii group: Prof. Fred Harris, Mr. Derrick Kong
- Effort by whole BES Collaboration and IHEP support!

R values near ττ threshold

- Pre-study, using BESI tau mass data, 12 points around 3.55 GeV, uncertainties ~8.5%

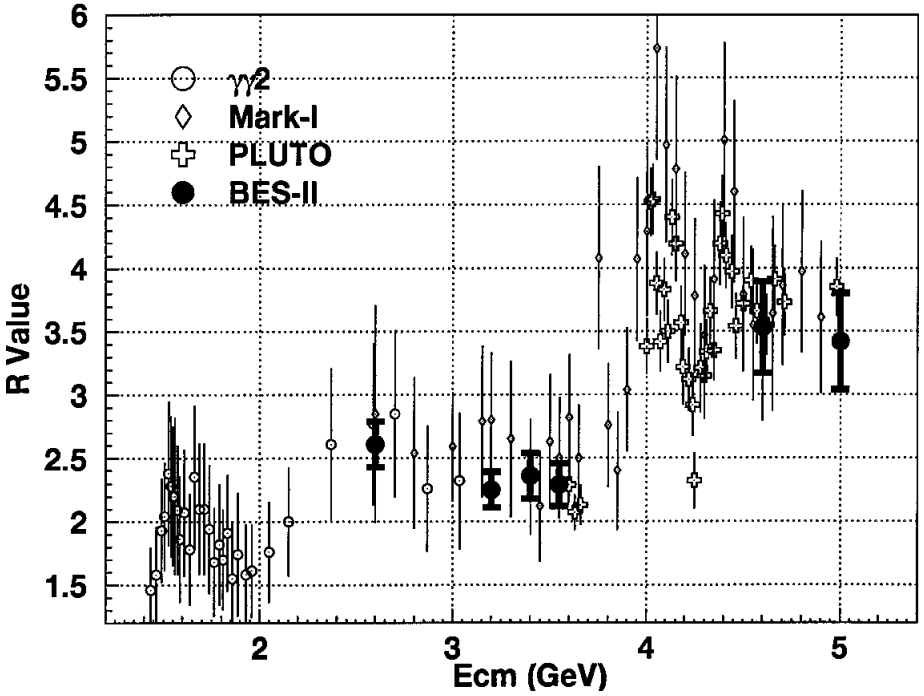




- HEP&NP (→CPC) 24, 609 (2000), in Chinese
- Ms. Xiangrong Qi's Ph.D thesis

First R scan at BESII

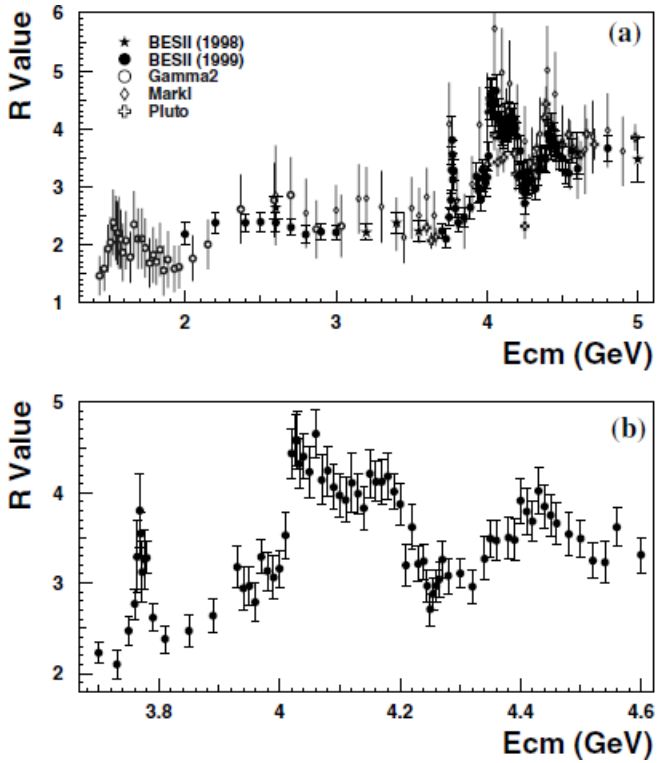
- Test run in 1998, 6 continuum points in 2.6 ~ 5.0 GeV, uncertainties (7~10)%



- PRL84, 594 (2000)
- Mr. Guangshun Huang's Ph.D thesis

Finer R scan at BESII

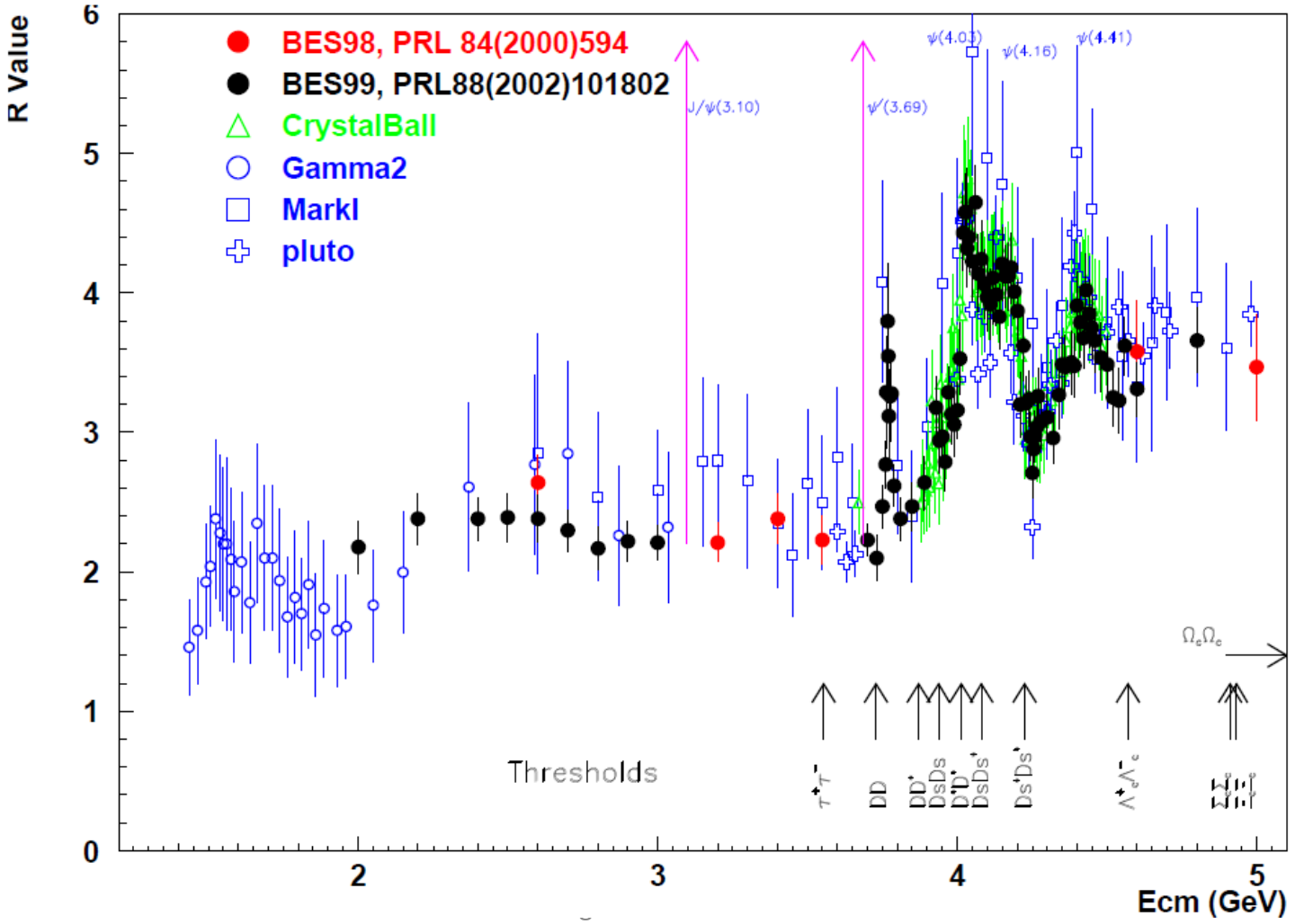
- Full scan in 1999, 85 points in 2~4.8 GeV, 4.6 pb^{-1} in total, uncertainties (5~12)%



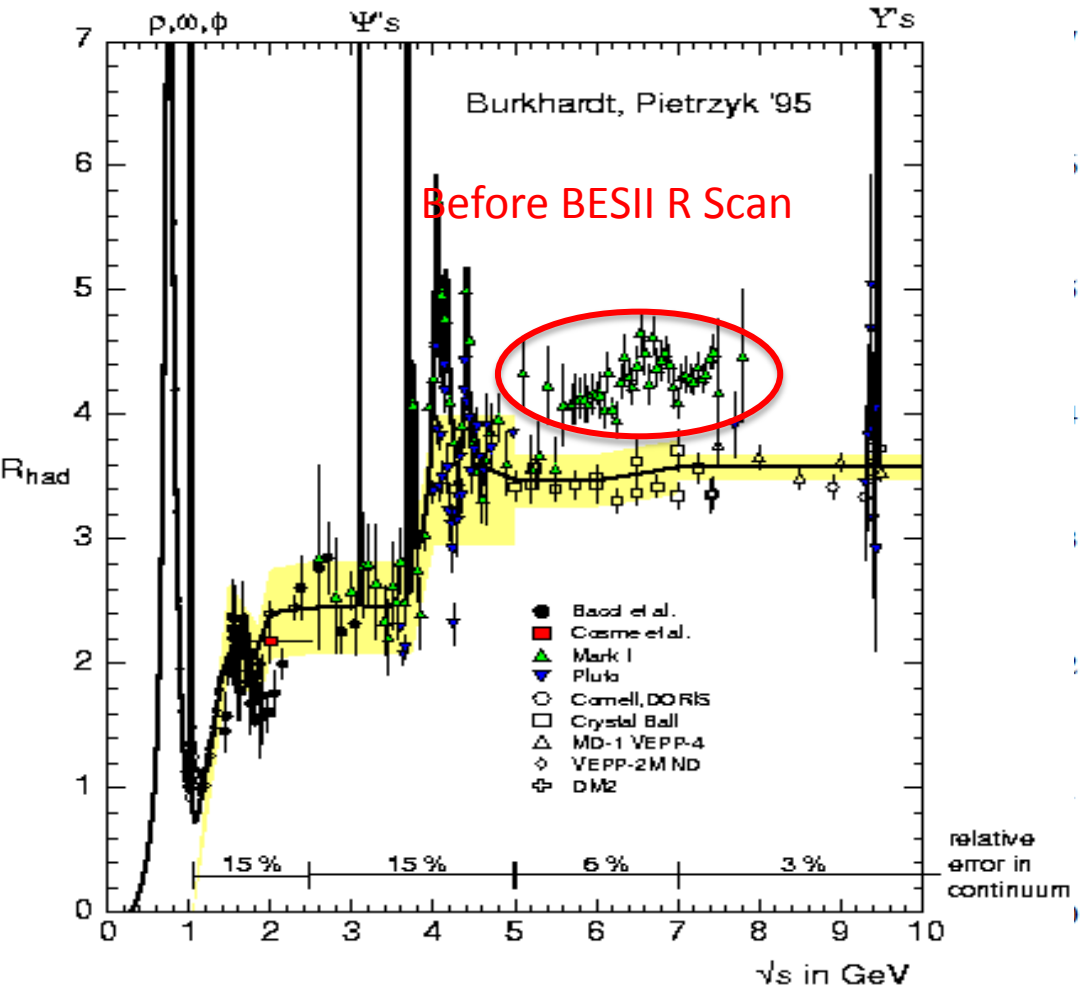
- PRL88, 101802 (2002)
- Mr. Derrick Kong/Zhiyong Wang's Ph.D thesis

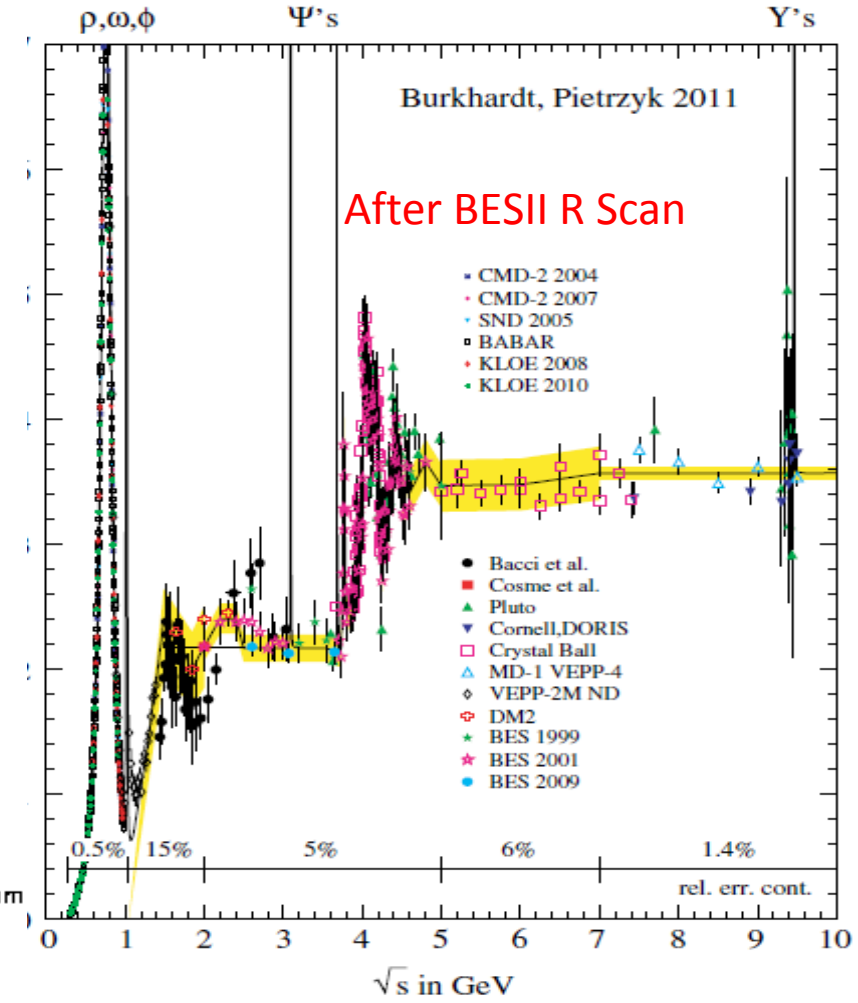
R Scans at BESII

- 6 + 85 energy points, total ~5 pb^{-1} data, average uncertainty 6.6%



BESII R Measurement: A big Improvement



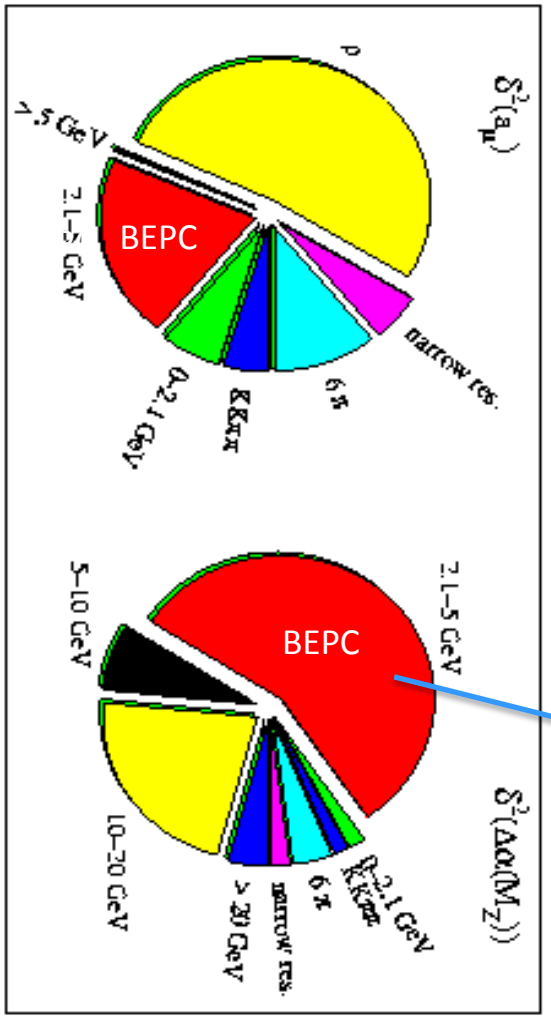


- ΔR/R ~15-20% below 5 GeV
- Unclear & complex structure in 3.7-5GeV
- Values from Mark I much higher than others

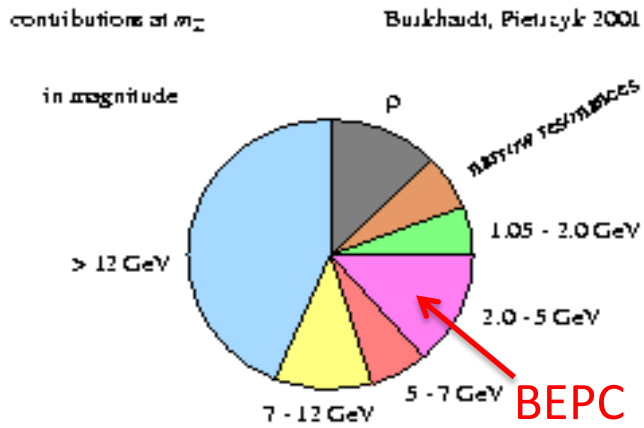
- ΔR/R **~6%** between 2 and 5 GeV
- Much clean structures in 3.7-5 GeV
- Mark I results is removed from PDG

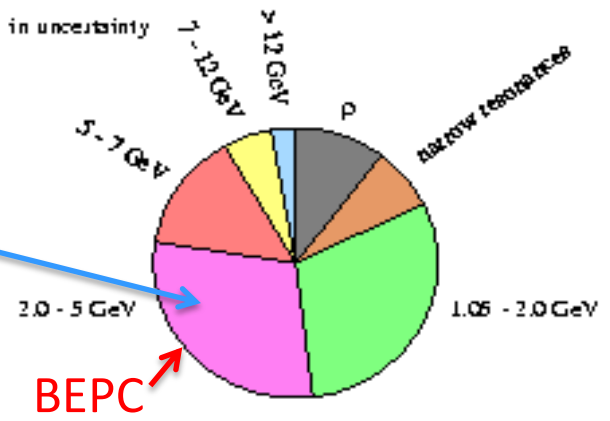
Relative Contributions to the Uncertainties of a_μ and $\Delta\alpha(M_Z^2)$

Before BESII R scan



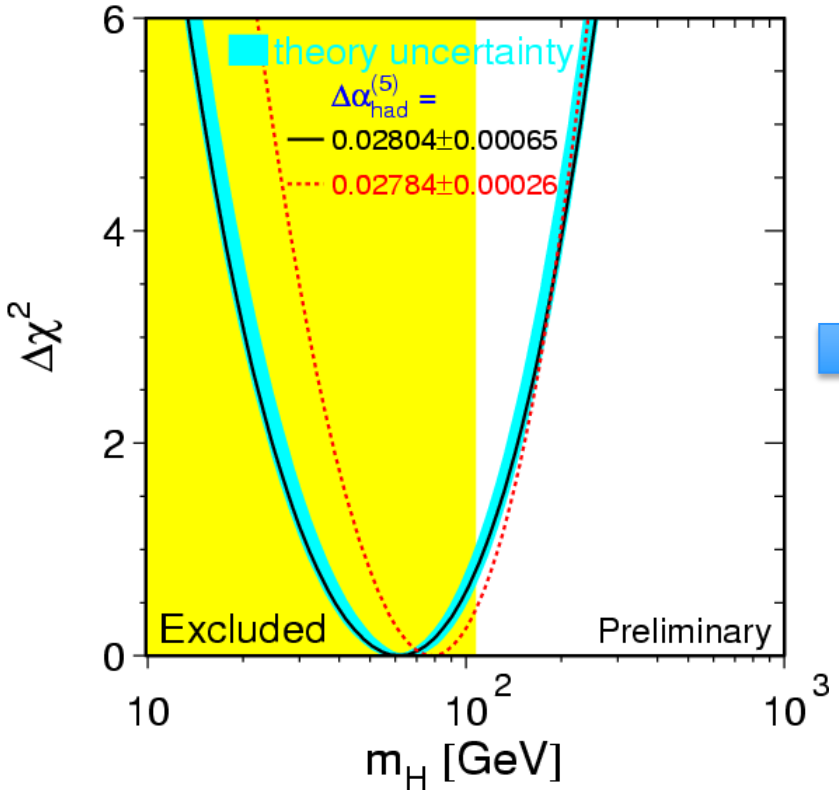
After BESII R scan

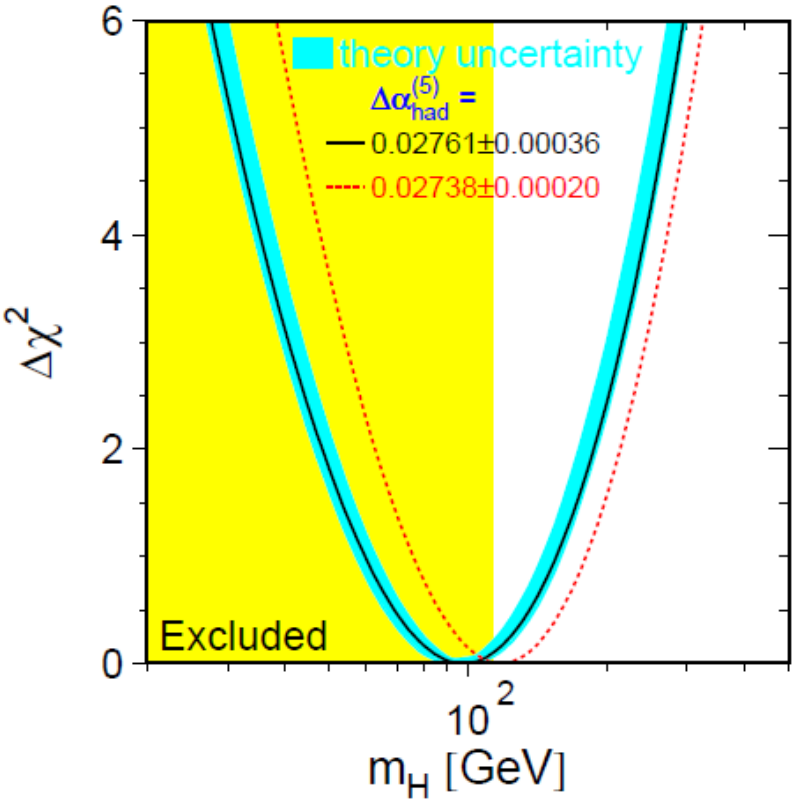




Impact of BESII R to Higgs mass

From SM fit:





before: $62^{+53}_{-30}\mathrm{GeV}$

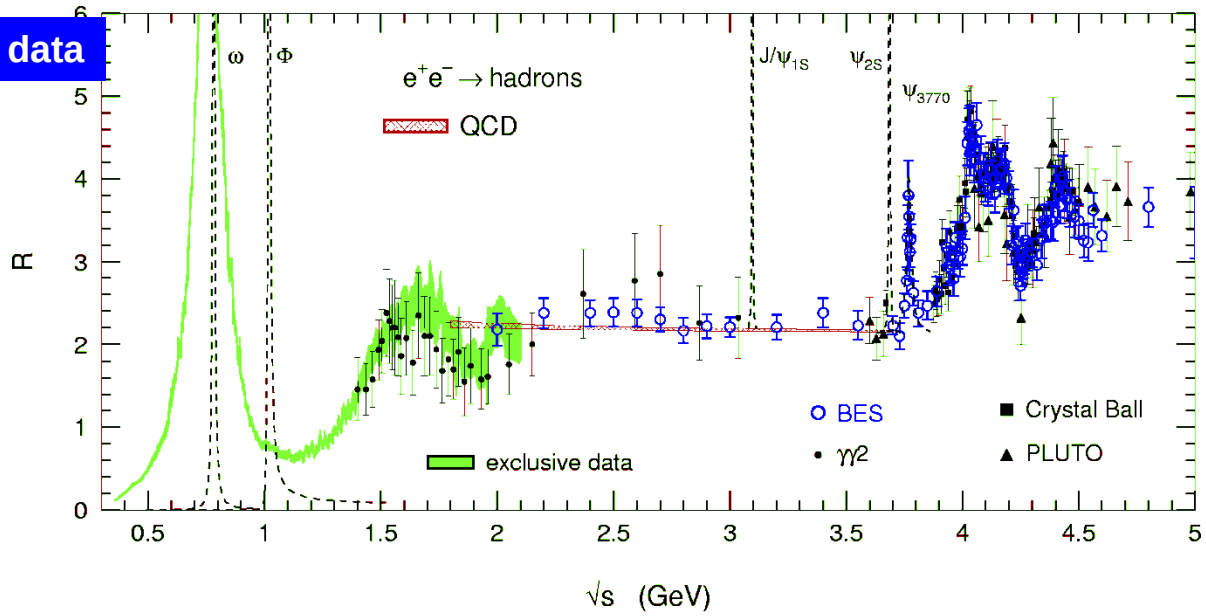
< 170 95%C.L.

after: $98^{+58}_{-38}\mathrm{GeV}$

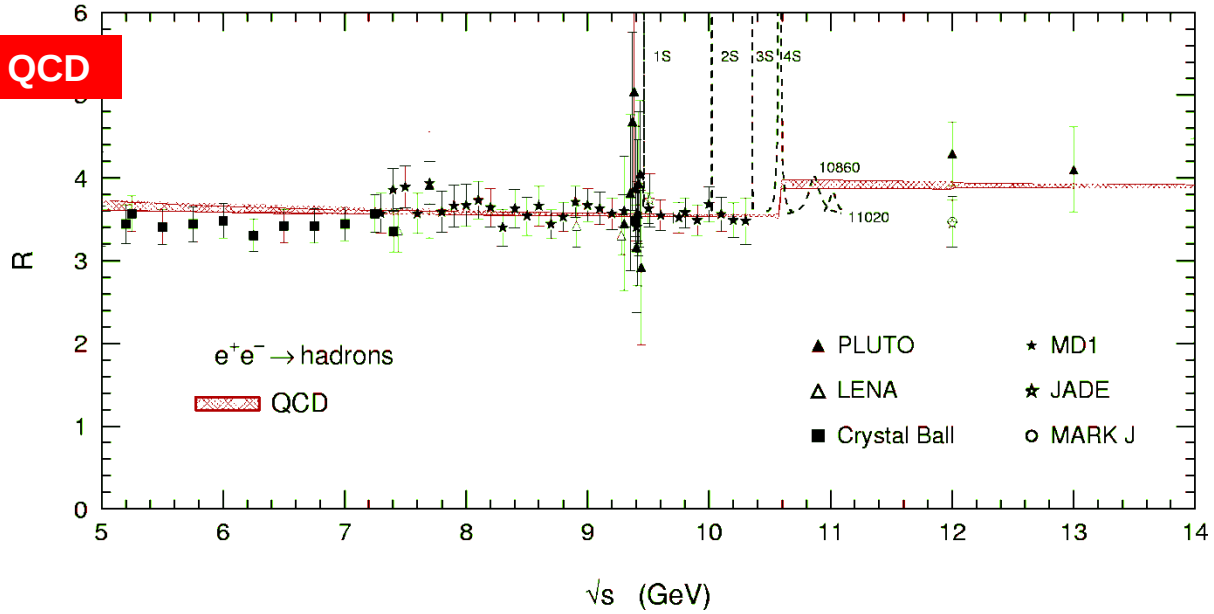
< 210 95%C.L.

Impact of BESII R to muon (g_μ–2)

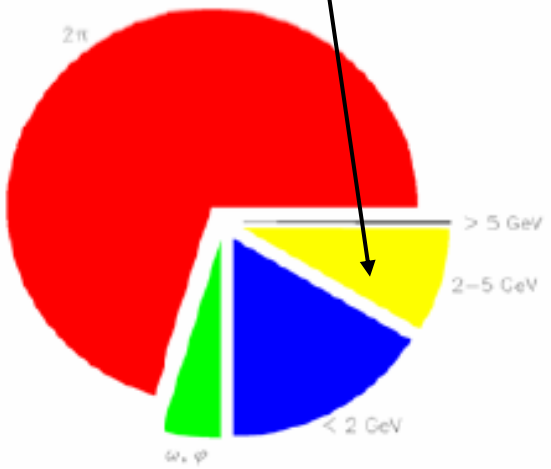
use data



use QCD



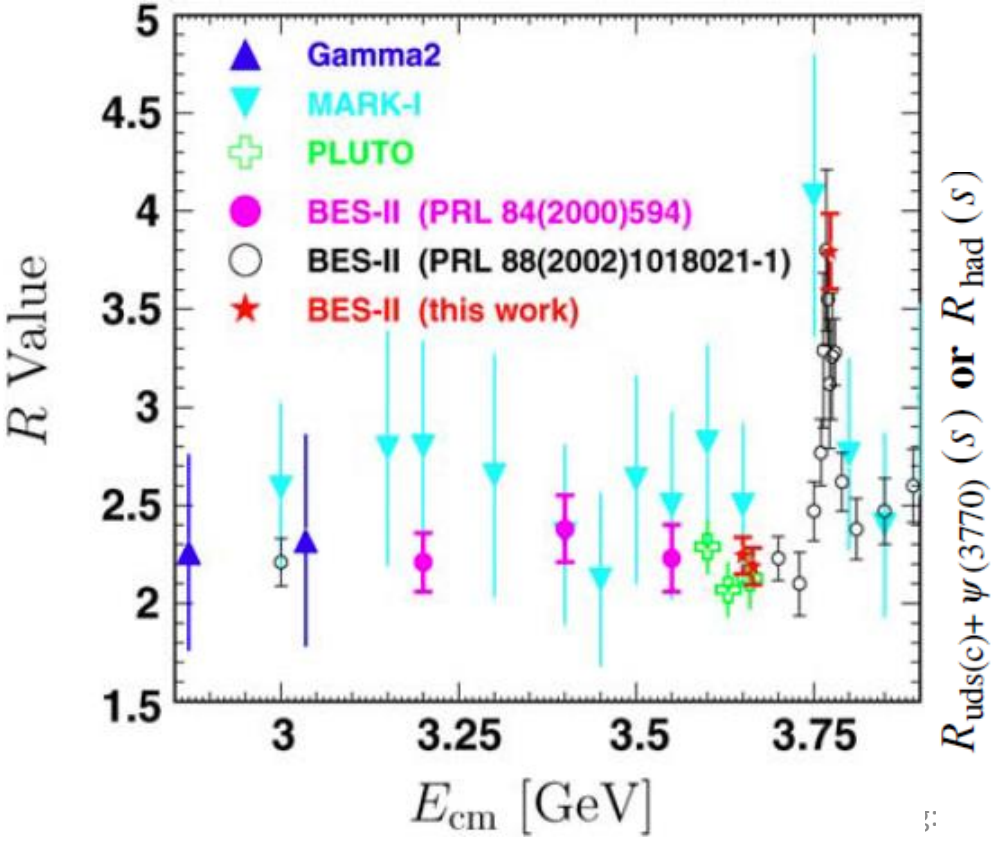
after

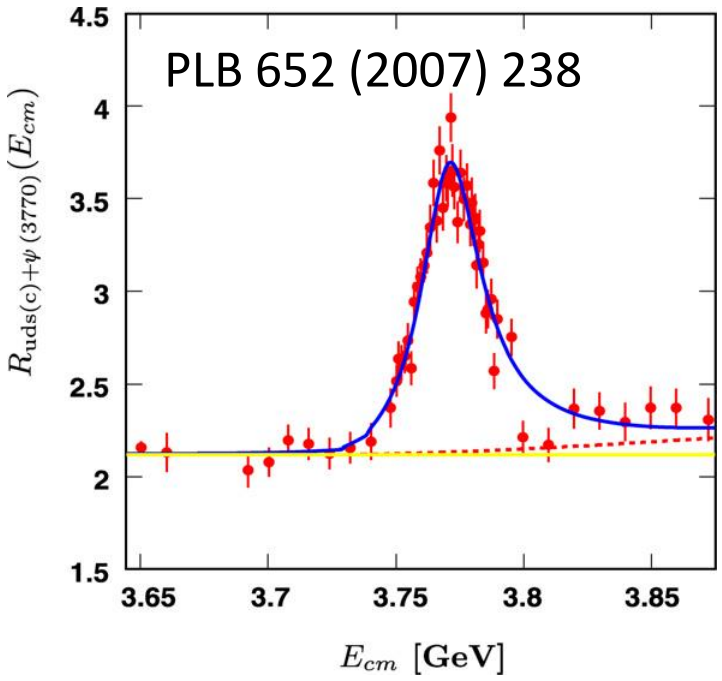


R around ψ(3770)

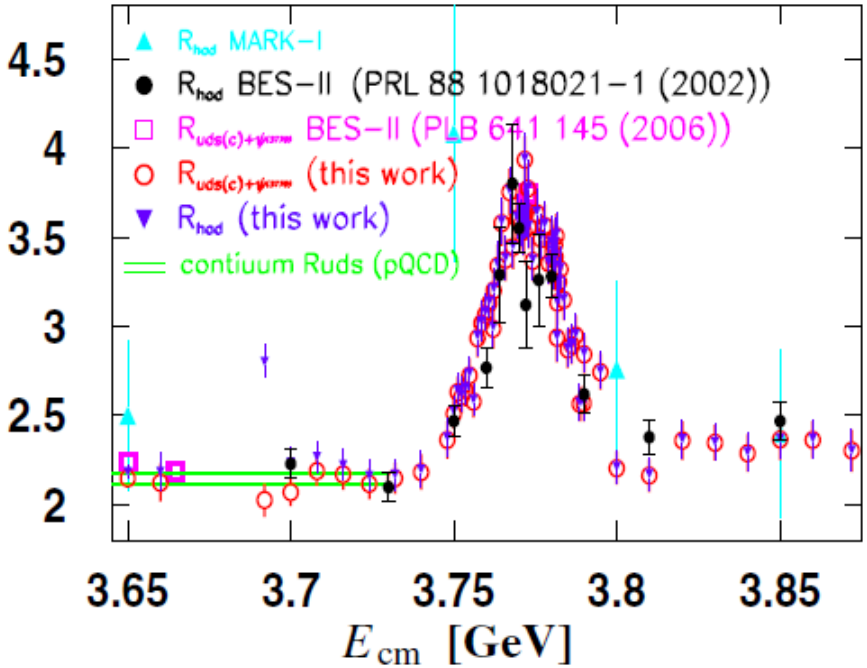
- Various R values, (4~5)%
- Prof. Gang Rong's great work

PLB641, 145 (2006)



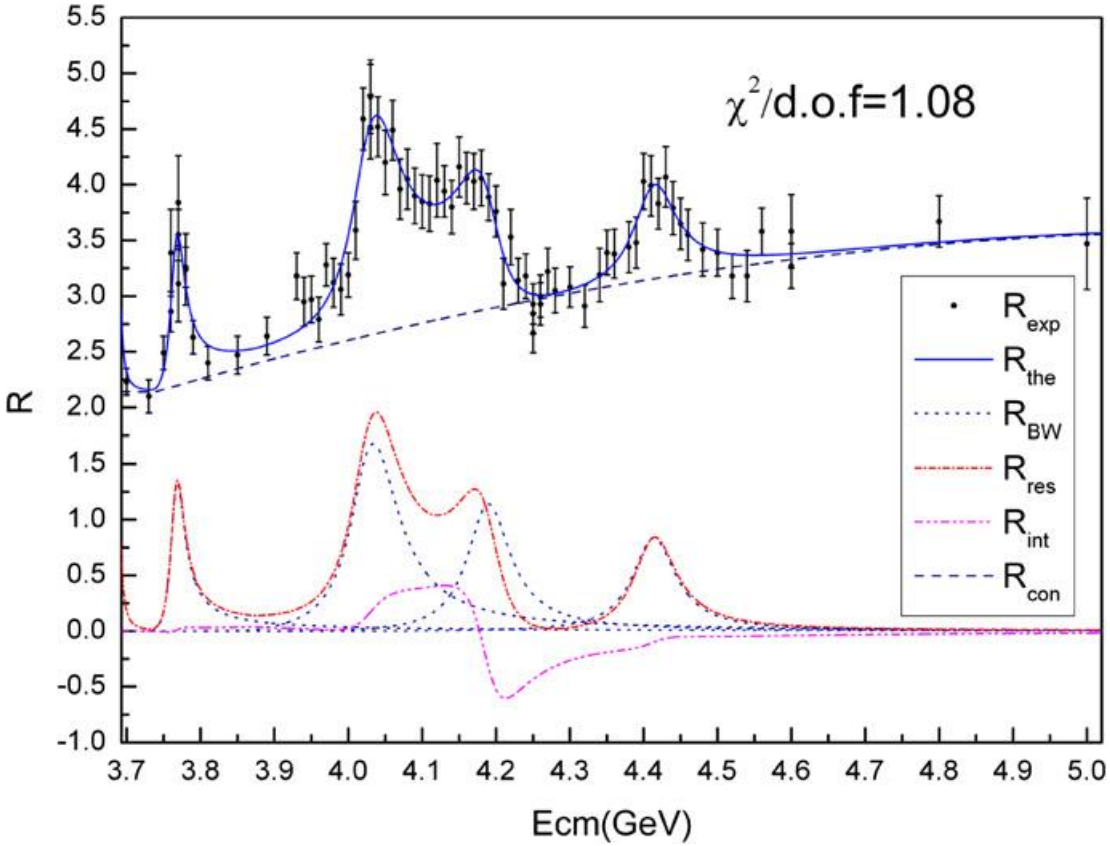


PRL 97, 262001 (2006)



Resonance structure measurement

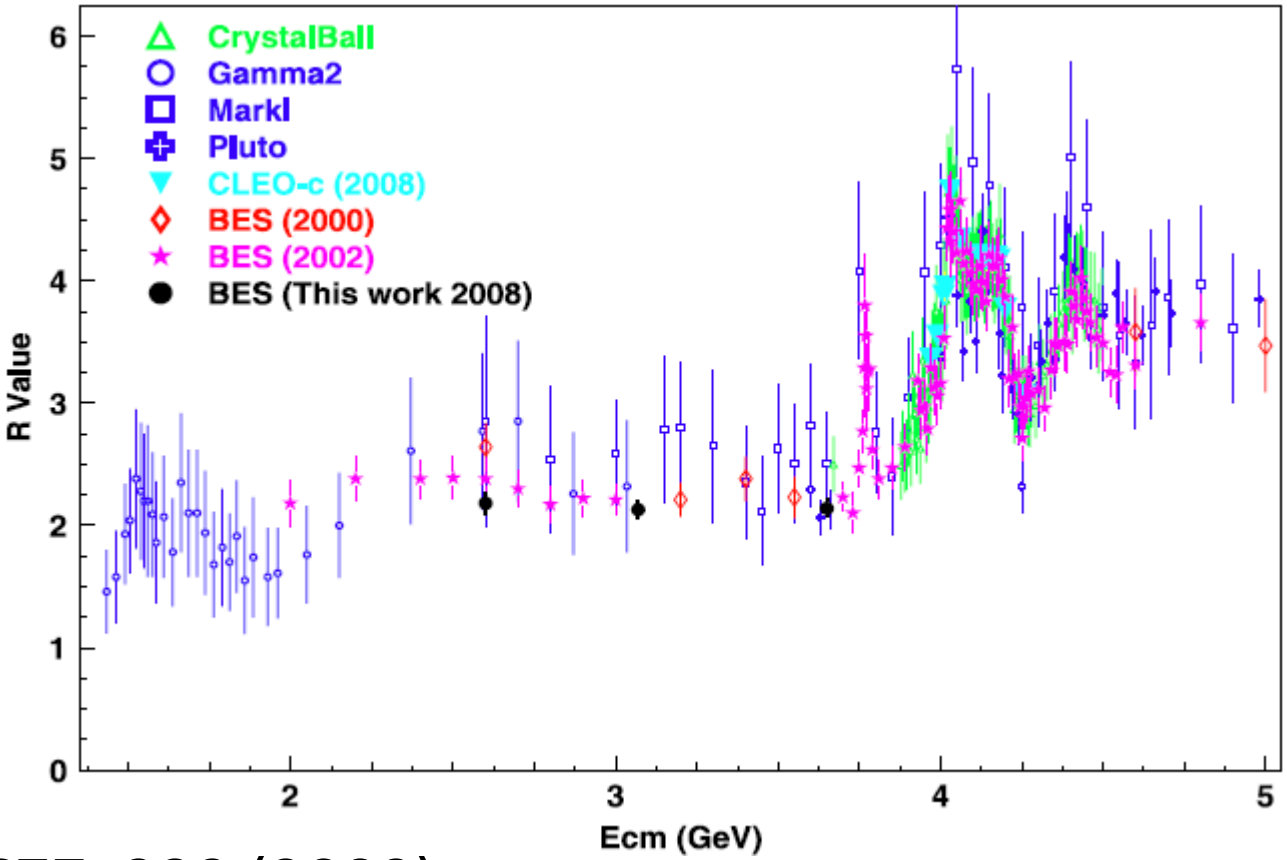
- Interference, phase, energy-dependent width included



- PLB660, 315 (2008)
- Prof. Haiming Hu's hard work

Last Attempt at BESII

- **Large samples at 2.6, 3.07, 3.65 GeV just before shutdown, ~10 pb^{-1}, uncertainties ~3.5%**



- PLB677, 239 (2009)
- Prof. Haiming Hu's hard work

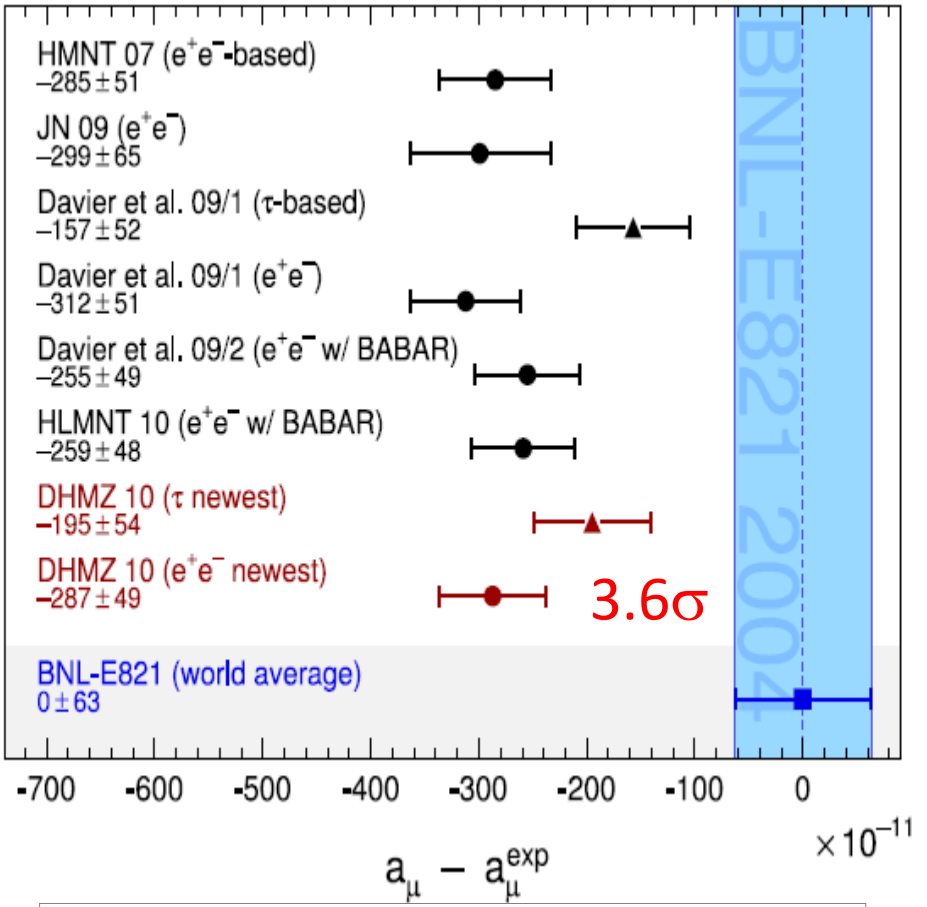
$\Delta\alpha(M_Z^2)$ and a_μ: Status BESIII starting

Burkhardt, Pietrzyk 2011

TABLE I. Contributions to $\Delta\alpha^{(5)}_{had}(m_Z^2)$.

Range $\sqrt{s}$, GeV	$\Delta\alpha$	Relative error
$\rho\,(\pi^+\pi^-)$	0.00349	0.5%
Narrow resonances	0.00184	3.1%
1.05–2.0	0.00156	15%
2.0–5.0	0.00371	5.0%
5–7	0.00183	6%
7–12	0.00304	1.4%
>12	0.01203	0.2%
	0.02750	1.2%

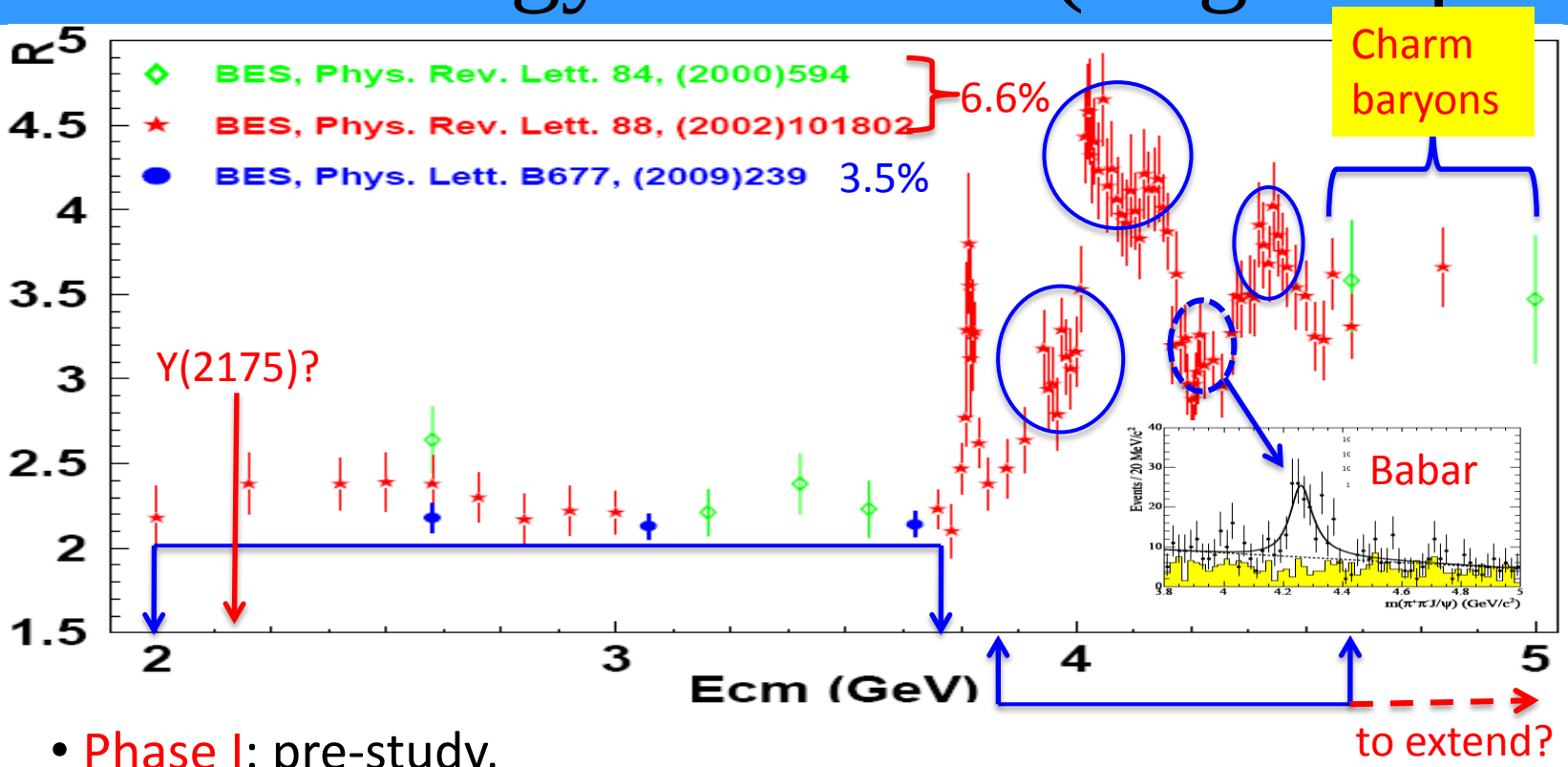
Still the 2nd largest one.



$a_\mu^{exp} = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$ (E821)
$a_\mu^{SM} = (11\,659\,180.2 \pm 4.9) \times 10^{-10}$

Davier 2010

R Scan Strategy at BESIII (original plan)

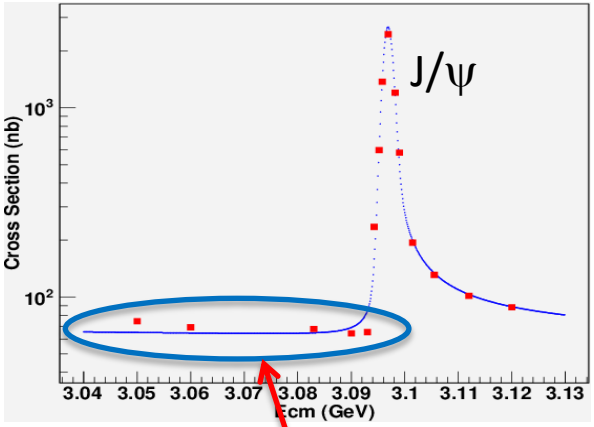


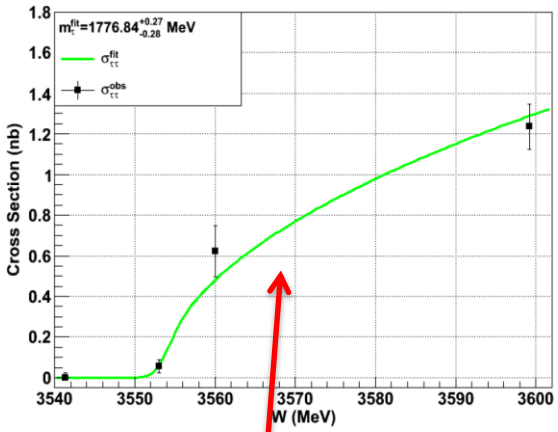
- Phase I: pre-study,
  Machine study at 2.0, 2.5 and 4.2(4.6) GeV, MC tuning, …
- Phase II: scan continuum region,
  15 points in 2.0–3.6 GeV, step 100 MeV, 100k+ hadrons<3 GeV.
- Phase III: scan resonance region,
  ~100 points in 3.8–4.6 GeV, 100k events, step 2, 5,10, 20 MeV.
  (10^8 hadrons at 4040, 4160, 4415 for radiative decay search?)

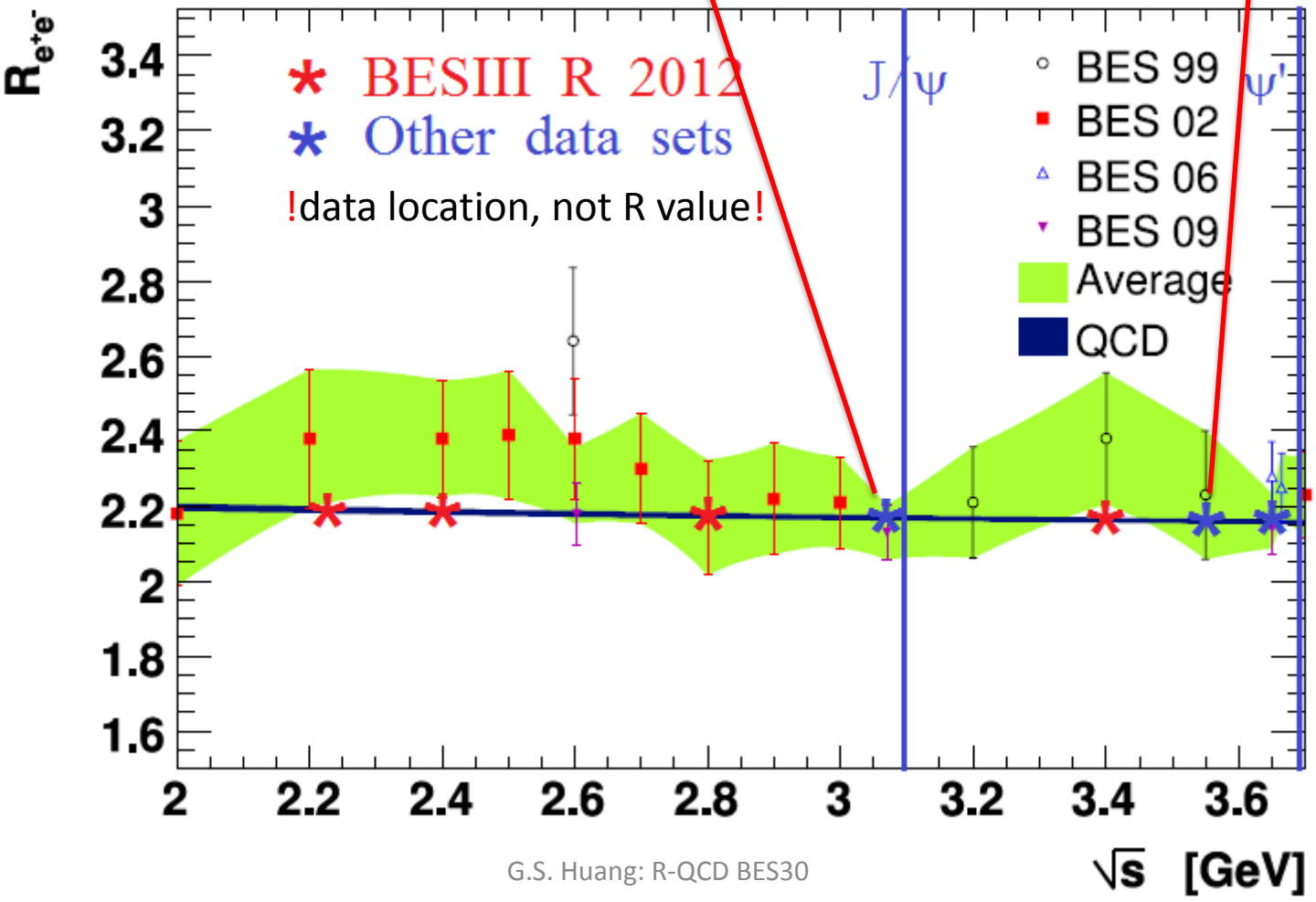
First R-QCD Run at BESIII

- BESIII collected data at 2.23, 2.4, 2.8 and 3.4 GeV during June 8–16, 2012;
- Total integrated luminosity ~12 pb^{-1};
- Useful information for machine at low energy;
- Essential for MC generator tuning;
- Necessary to establish analysis chain;
- Excellent results on baryon form factors, threshold effect of baryon pair production, …

Early continuum data at BESIII

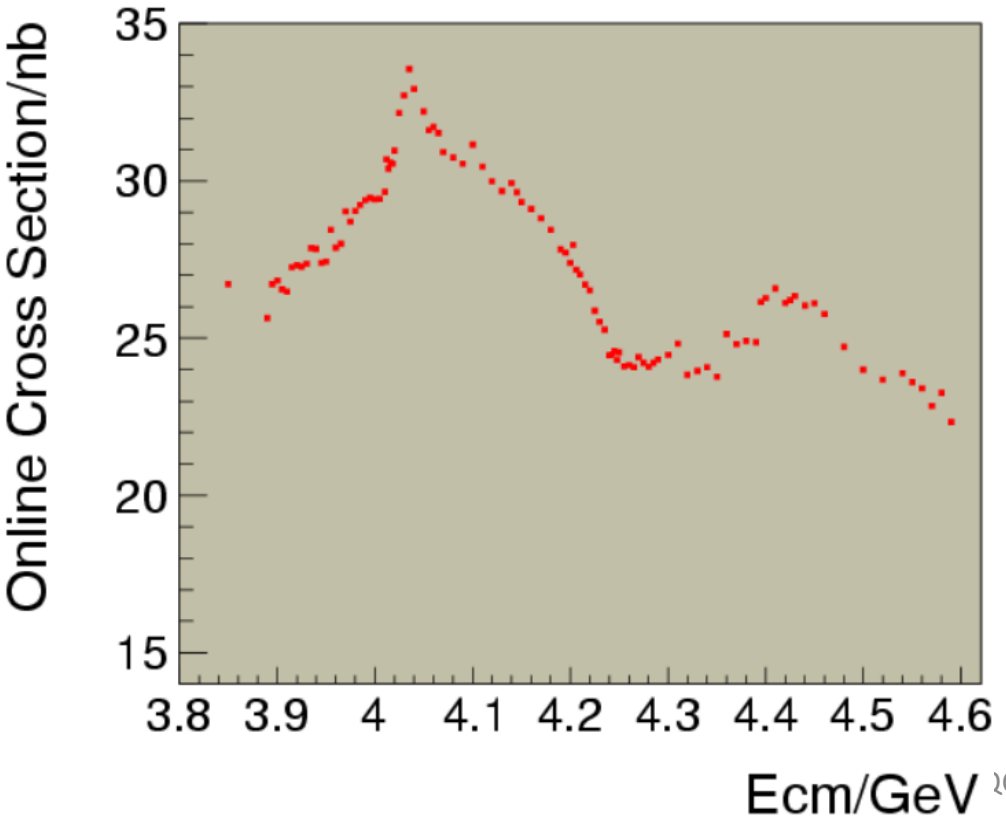


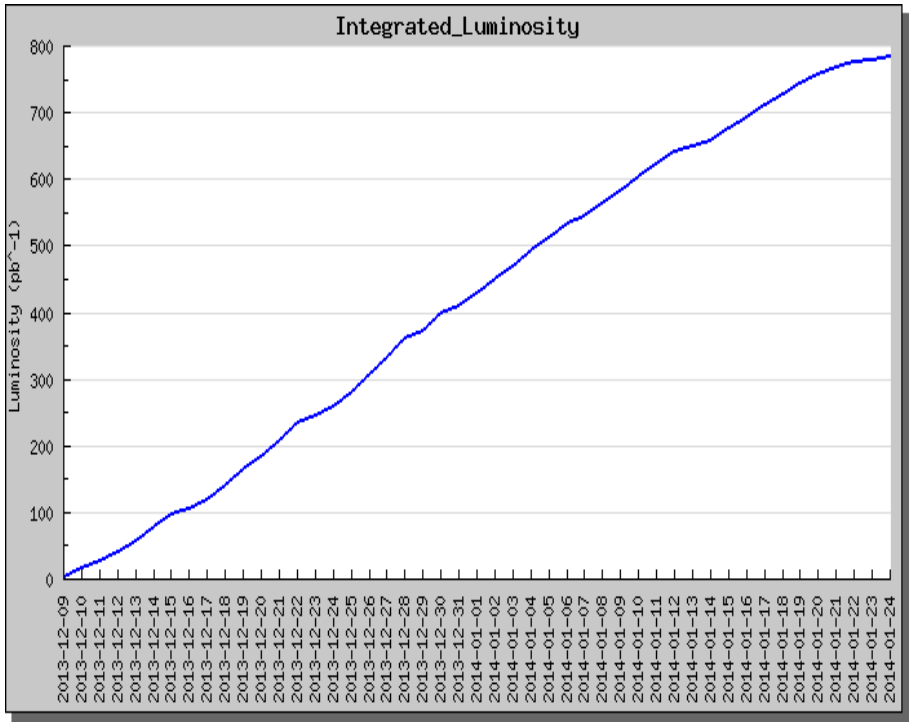




R Scan in 3.8 - 4.6 GeV

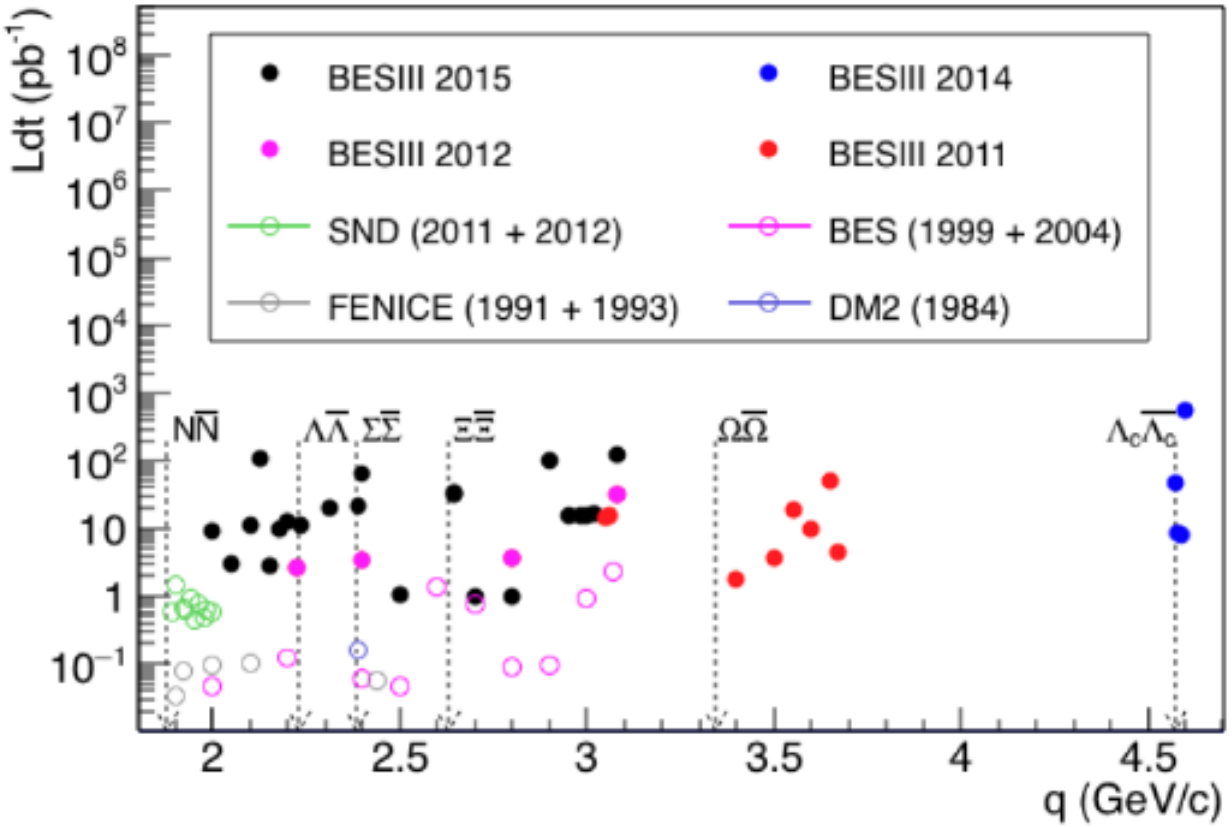
- Data taken in 2013.12.9 – 2014.1.24;
- 104 energy points in total, ~800 pb^{-1};
- >100k hadronic events each points.





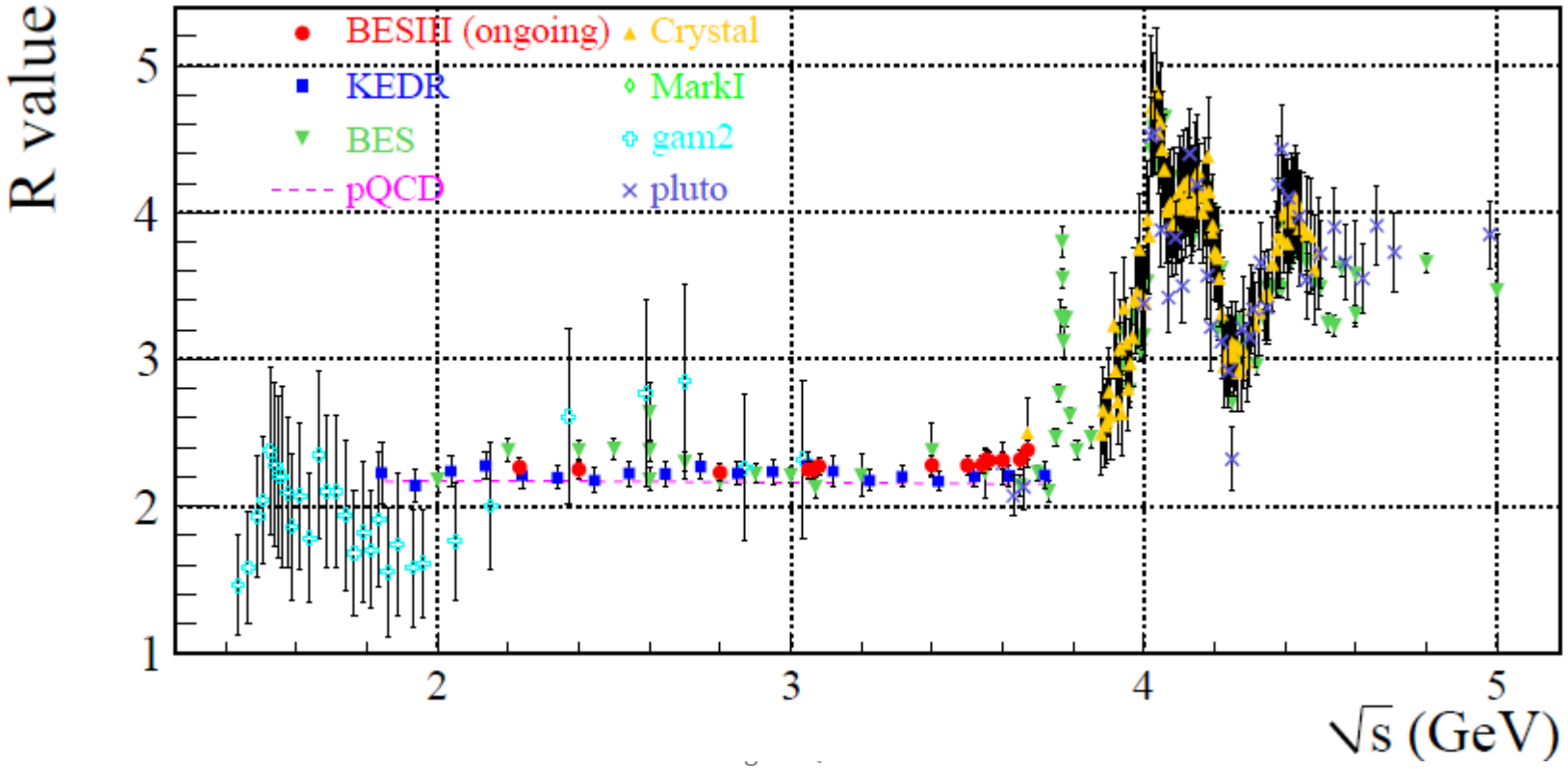
Low energy run in 2.0 – 3.08 GeV

- Data taken in 2014.12.30 – 2015.6.16;
- 22 points, ~650 pb^{-1};
- Unique sample in the energy range.



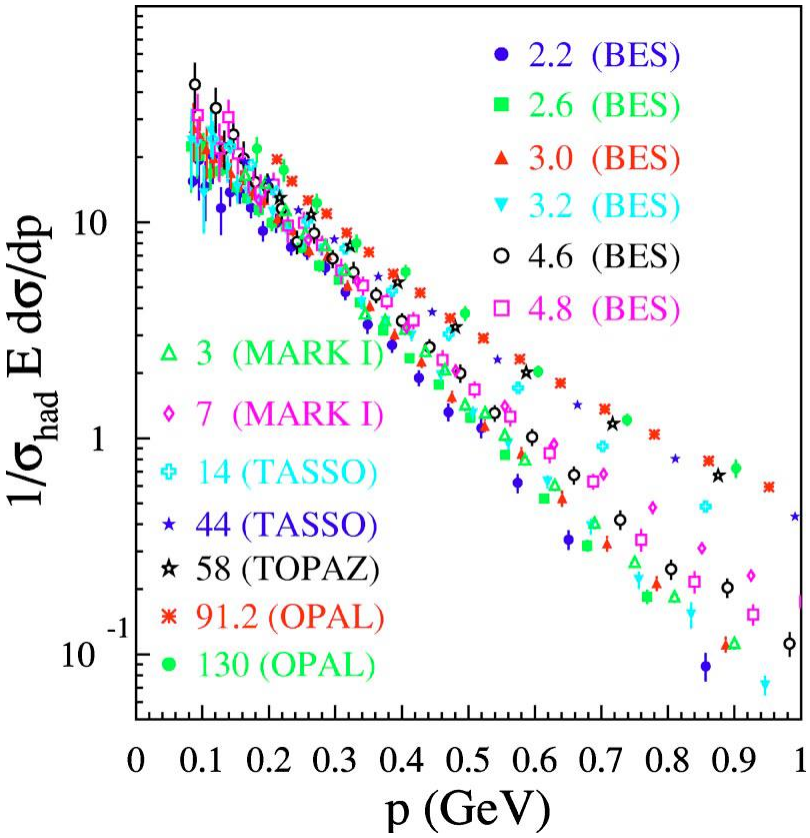
R measurement at BESIII

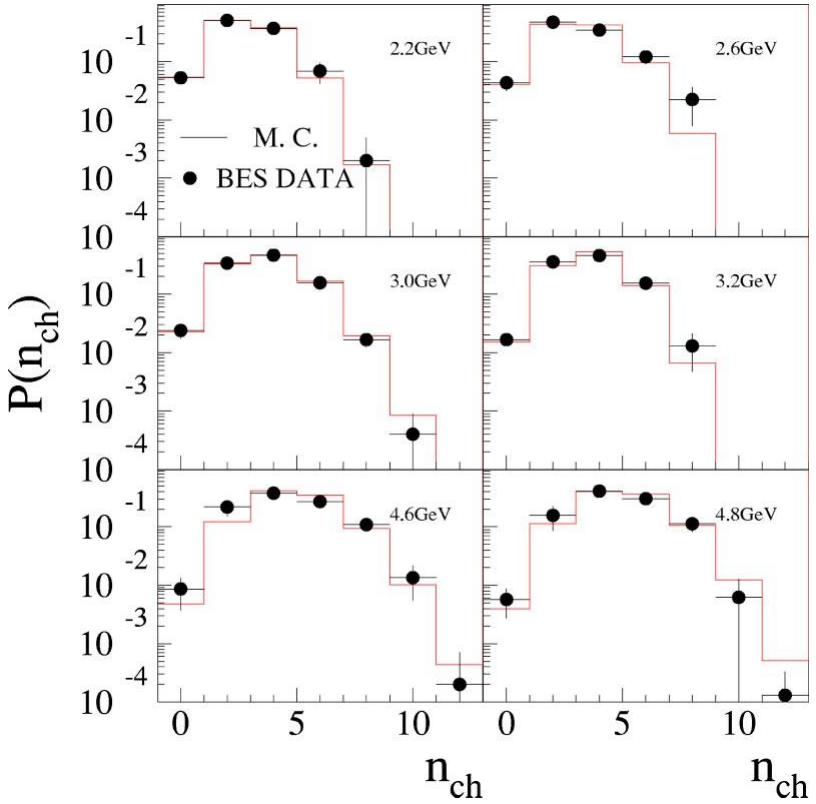
- Analysis ongoing. Goal: 3% precision;
- Key issue: MC generator:
  - ✓ Inclusive (LUARLW)
  - ✓ known exclusives (ConExc) + inclusive (LUARLW)



QCD studies at BESII

- Inclusive momentum spectra and charged multiplicity distributions



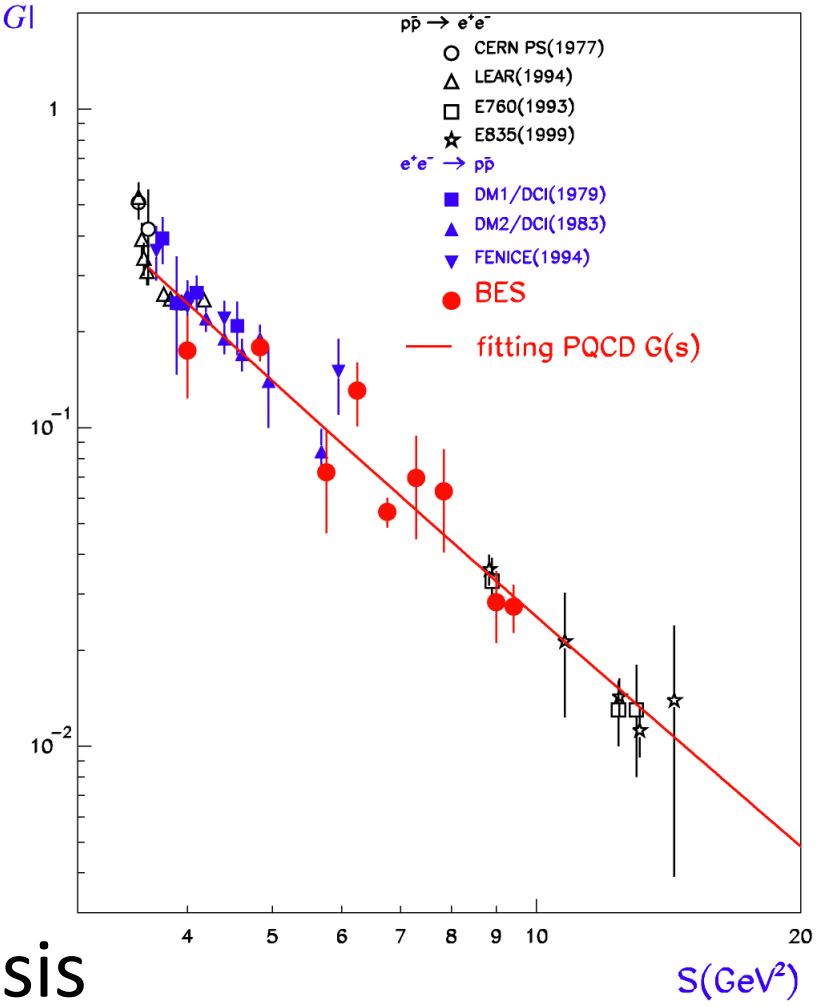


- PRD69, 072002 (2004), first QCD paper at BES
- Mr. Wenbiao Yan's Ph.D thesis

QCD studies at BESII

- Proton form factor from $e^+e^- \rightarrow p\bar{p}$ in [2.0, 3.07] GeV
- Statistics limited.

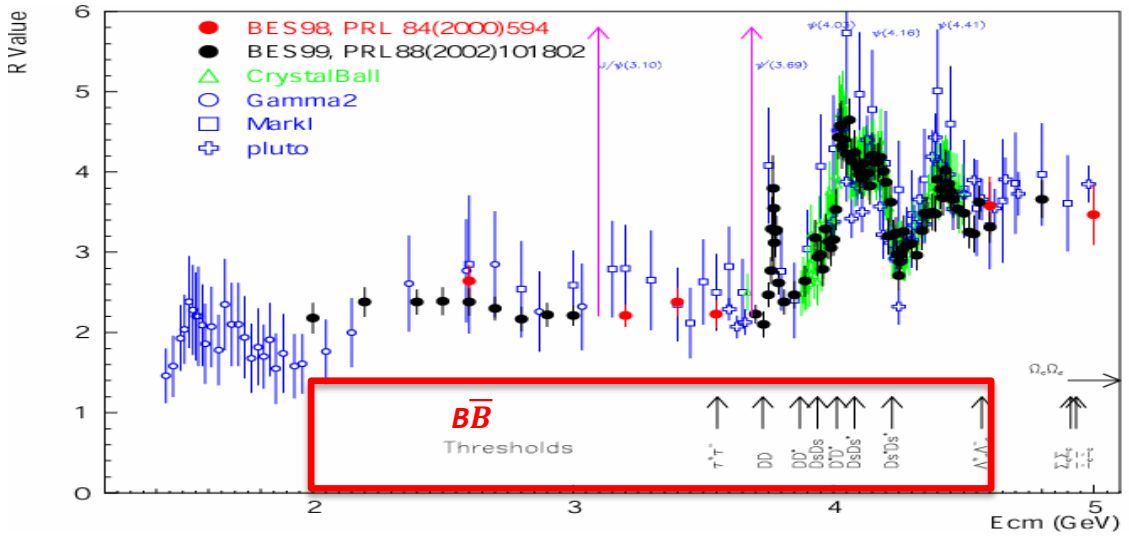
$\sqrt{s}$ (GeV)	N	$\mathcal{L}$ (nb^{-1})
2.0	$3^{+2.3}_{-1.9}$	45.8 ± 1.4
2.2	29 ± 5.4	123.5 ± 3.7
2.4	$2^{+2.2}_{-1.3}$	61.0 ± 1.6
2.5	$5^{+2.8}_{-2.2}$	47.0 ± 1.0
2.6	24 ± 4.9	1351 ± 24
2.7	$2^{+2.2}_{-1.3}$	71.6 ± 2.1
2.8	$2^{+2.2}_{-1.3}$	89.0 ± 1.8
2.9	0	94.0 ± 2.6
3.0	$4^{+2.8}_{-1.7}$	947 ± 22
3.07	$9^{+3.8}_{-2.7}$	2347 ± 59



- PLB630, 14 (2005)
- Ms. Huihong Li's Ph.D thesis

Now, it's turn of BESIII

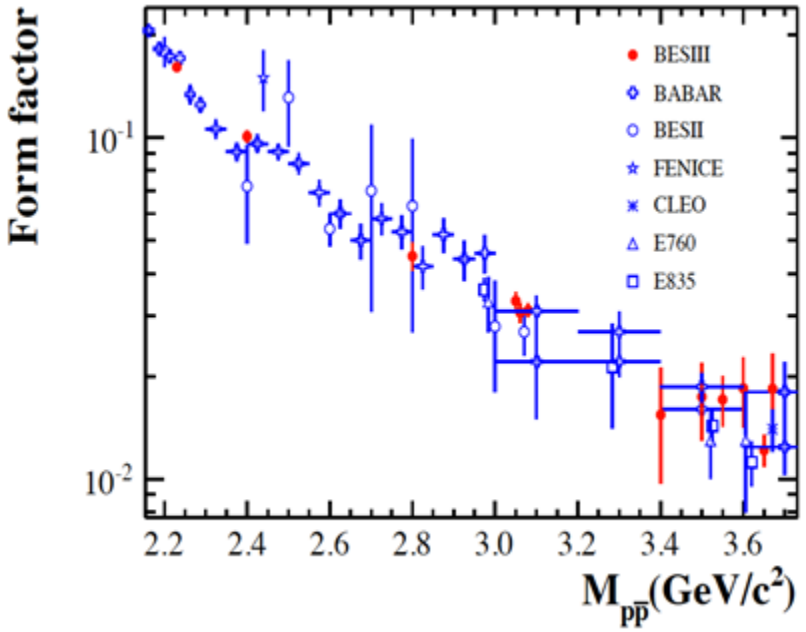
- Large statistics make it possible for QCD studies, example $B\overline{B}$ production near threshold.
- Not possible to list all works in this talk…

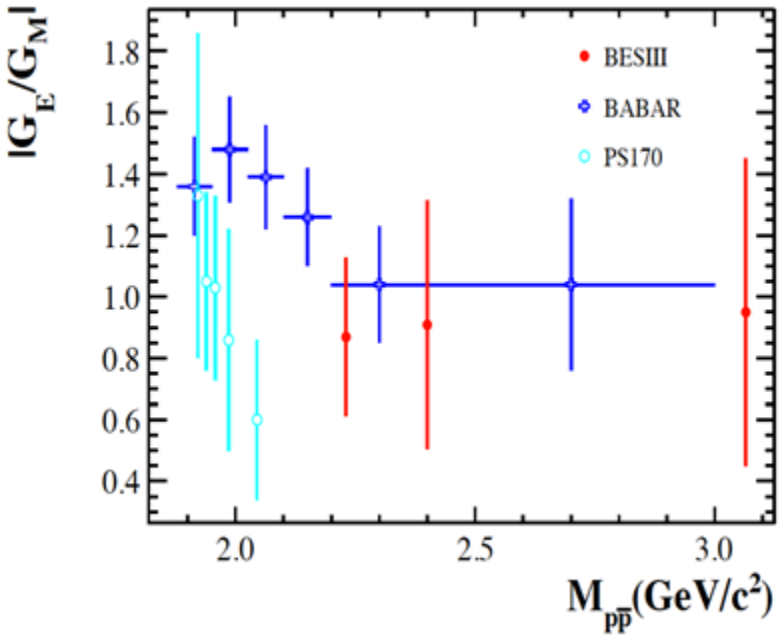


Proton form factor

- Based on 2012 test run data：
  Phys. Rev. D91, 112004 (2015);
- Much precision better than BESII;
- First measurement of G_E/G_M at BES, consistent with BaBar.
- Ms. Xiaorong Zhou's Ph.D thesis

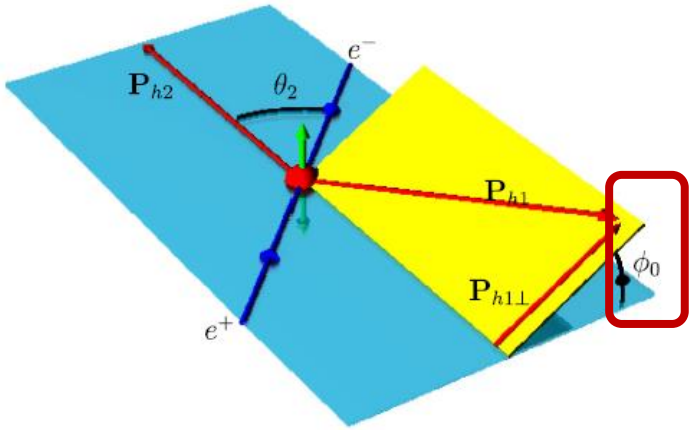
E_{cm}/GeV	L_{int} / pb^{-1}
2.23	2.6
2.40	3.4
2.80	3.8
3.05, 3.06, 3.08	60.7
3.40, 3.50, 3.55	23.3
3.60, 3.65, 3.67	63.0





Measurement of Collins Effect

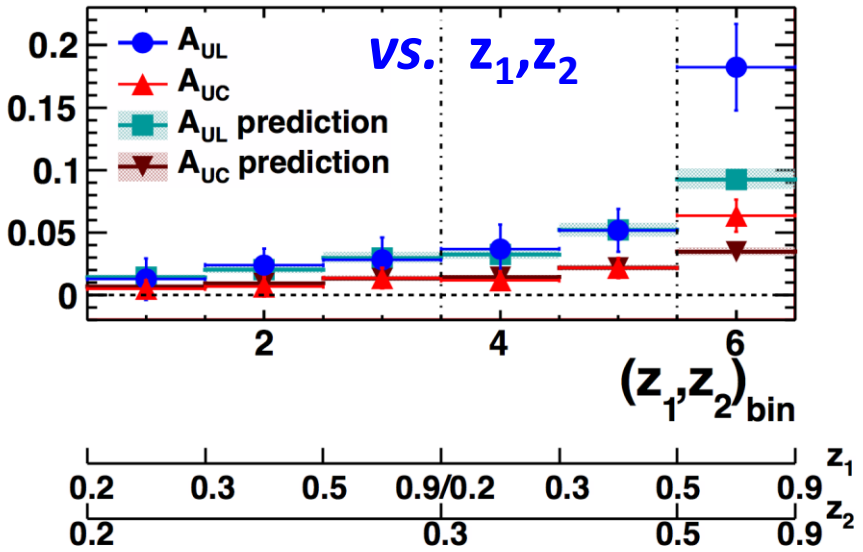
- **Motivation:** Input for SIDIS experiments to extract spin-dependent parton distribution without energy evolution
- **Method:** Probing azimuthal asymmetries of di-hadron.

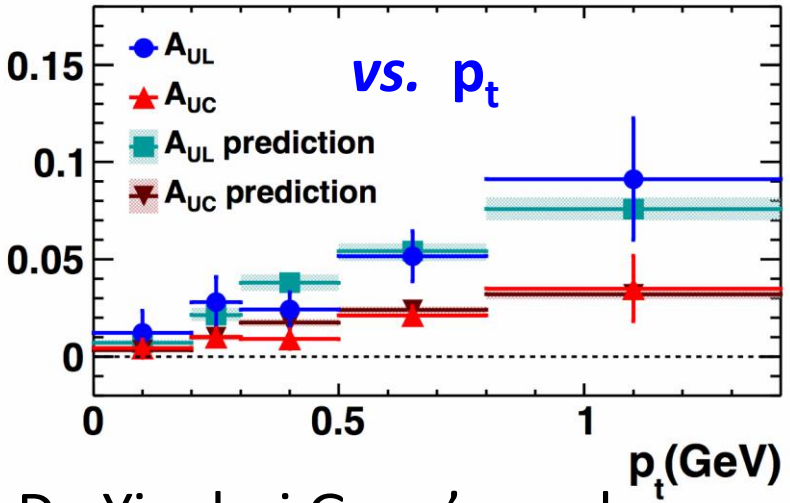


$$A(\theta_2, z_1, z_2) = \frac{sin^2\theta_2}{1+cos^2\theta_2} \frac{F\left(H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)/M_1M_2\right)}{D_1^q(z_1)\bar{D}_1^q(z_2)}$$

Phys. Rev. Lett. 116, 042001 (2016)

- **non-zero asymmetries**
- **growing with fractional energy z**





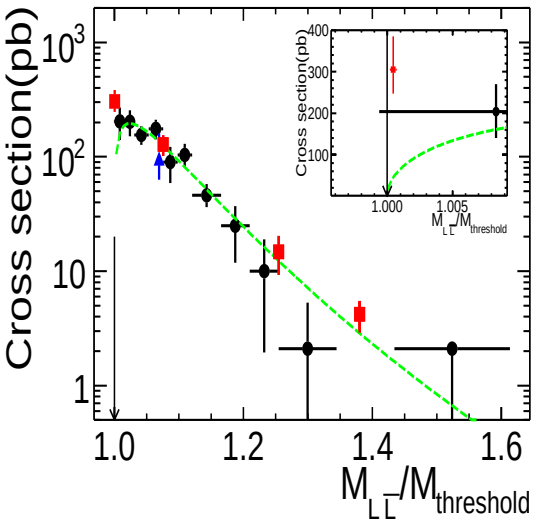
Dr. Yinghui Guan's work

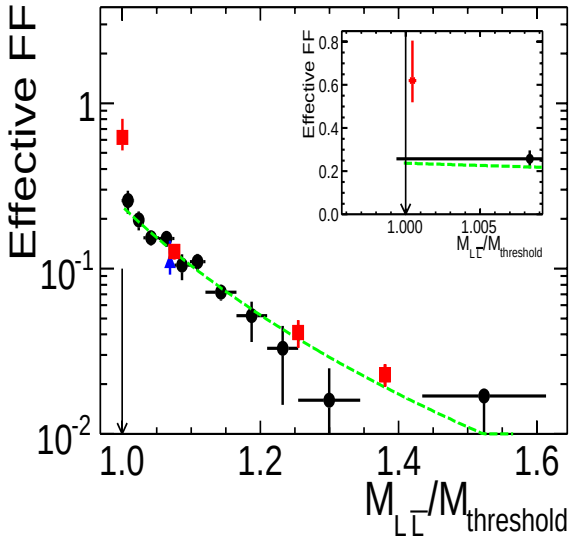
$\Lambda\bar{\Lambda}$ pair production near threshold

$$\sigma_{\Lambda\Lambda} = \frac{2\pi\alpha^2}{W^2}\,\beta\,G^2_{eff}(W^2)$$

$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})	N_{obs}	$\epsilon(1+\delta)$ (%)	σ^B (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2.2324_1	2.63	43 ± 7	12.9	$312 \pm 51^{+72}_{-45}$	
2.2324_2	2.63	22 ± 6	8.25	$288 \pm 96^{+64}_{-36}$	
2.2324_c				$305 \pm 45^{+66}_{-36}$	$61.9 \pm 4.6^{+18.1}_{-9.0}$
2.400	3.42	45 ± 7	25.3	$128 \pm 19 \pm 18$	$12.7 \pm 0.9 \pm 0.9$
2.800	3.75	8 ± 3	36.1	$14.8 \pm 5.2 \pm 1.9$	$4.10 \pm 0.72 \pm 0.26$
3.080	30.73	13 ± 4	24.5	$4.2 \pm 1.2 \pm 0.5$	$2.29 \pm 0.33 \pm 0.14$

Zero production cross section expected at threshold. 2.2324 GeV, only 1 MeV above, shows non-zero cross section, from 2 modes. Coulomb interaction at quark level? Final state interaction? Resonance effect?

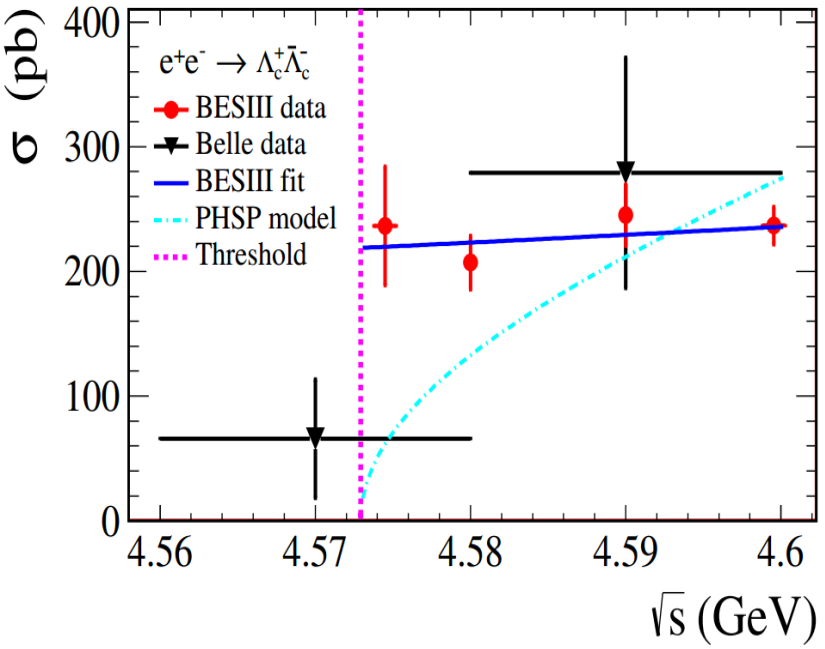




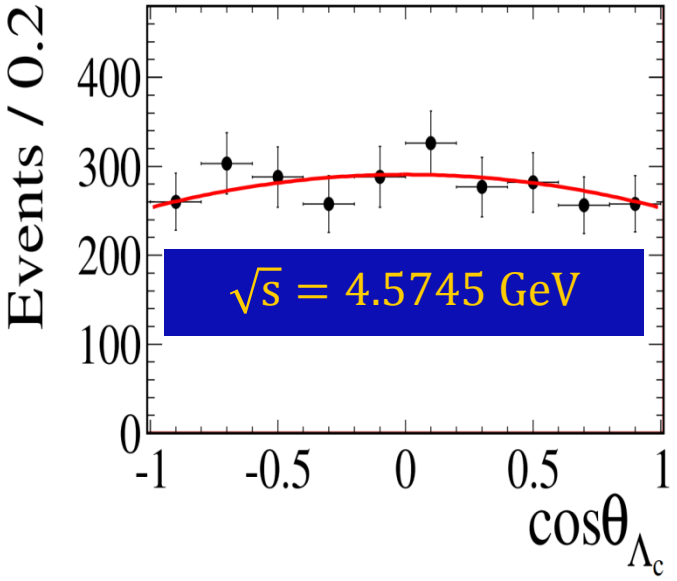
Phys. Rev. D 97, 032013 (2018), Dr. Xiaorong Zhou/Liang Yan's work, thanks to Rinaldo Baldini.

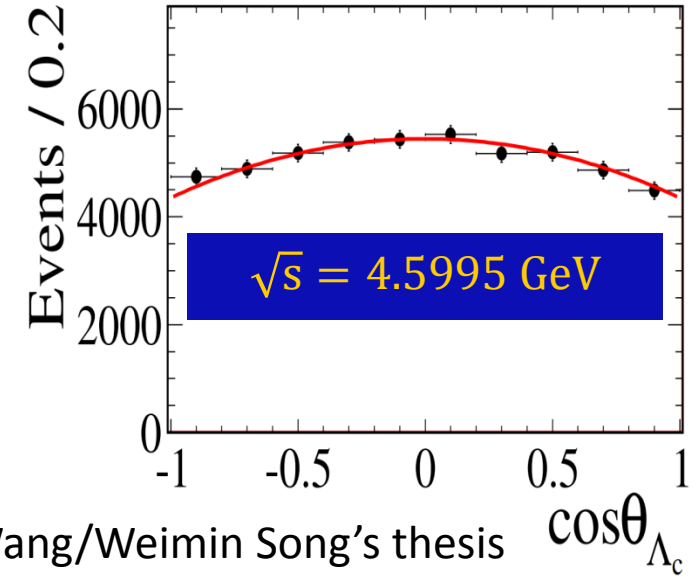
$\Lambda_c\overline{\Lambda}_c$ pair production near threshold

Non-zero cross section again !



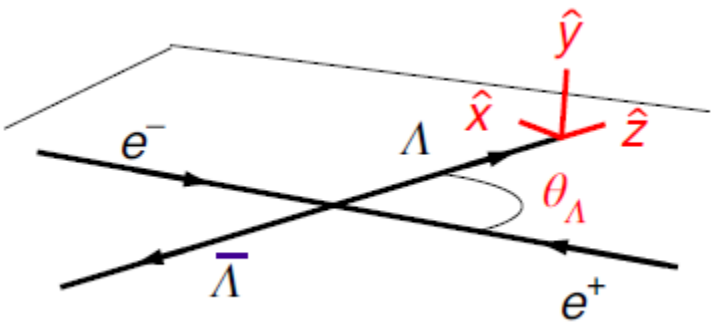
Energy (GeV)	$\lvert G_E/G_M \rvert$
4.5745	$1.14 \pm 0.14 \pm 0.07$
4.5995	$1.23 \pm 0.05 \pm 0.03$

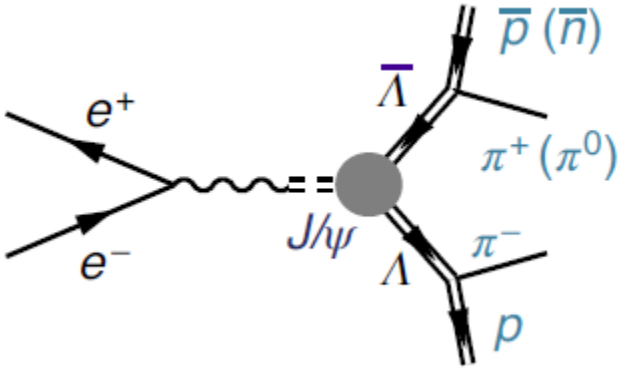


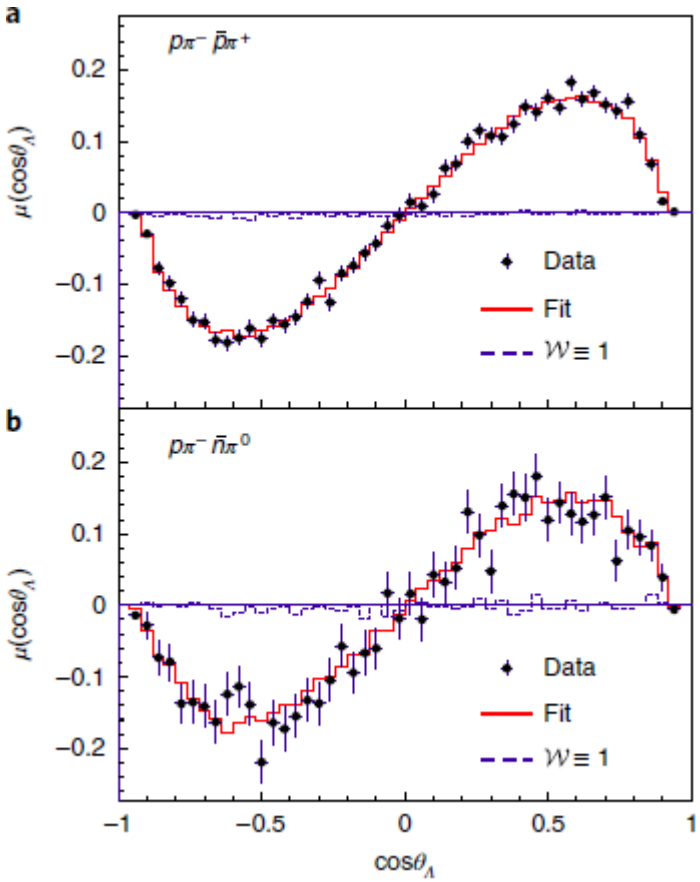


Phys. Rev. Lett. 120, 132001 (2018), Mr. Weiping Wang/Weimin Song's thesis

Polarization in $\Lambda\bar{\Lambda}$ production







Nature Physics (2019.5.6)

https://doi.org/10.1038/s41567-019-0494-8

Work by Jie, Ronggang , Andrzej et al.

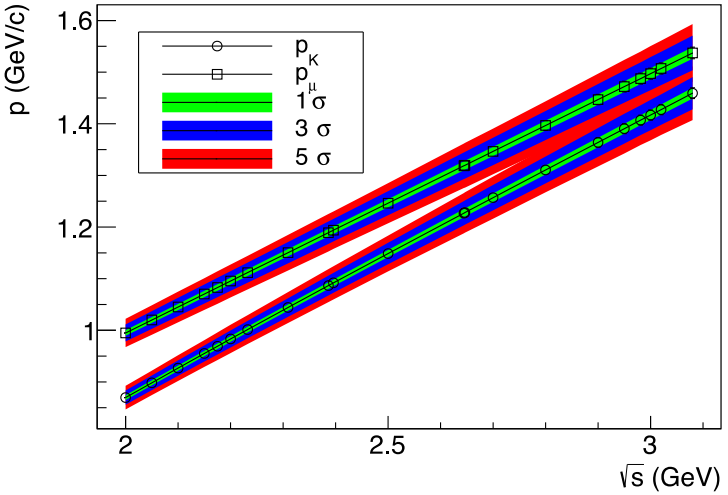
Table 1 | Summary of the results

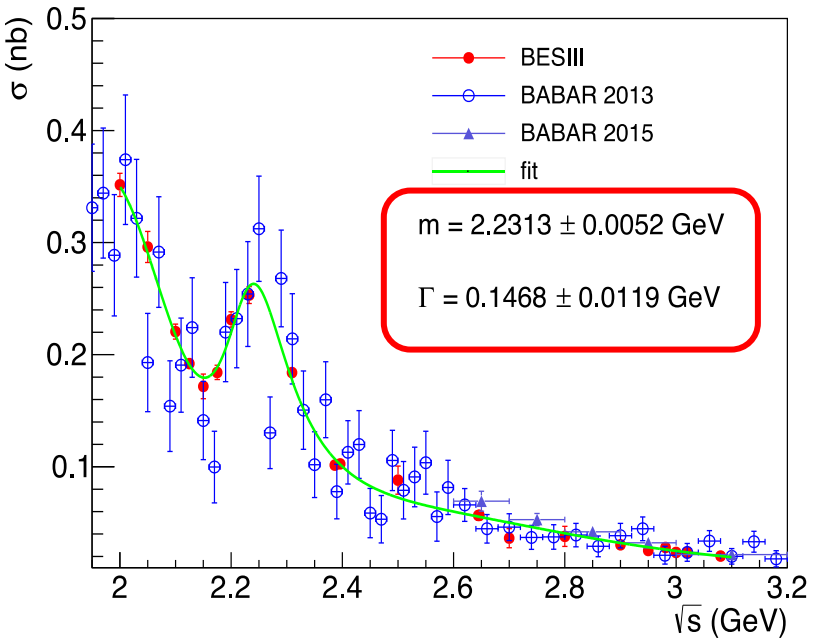
Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 (ref. [14])
$\Delta\Phi$	$42.4 \pm 0.6 \pm 0.5^\circ$	-
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 (ref. [6])
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 (ref. [6])
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	-
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 (ref. [6])
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	-

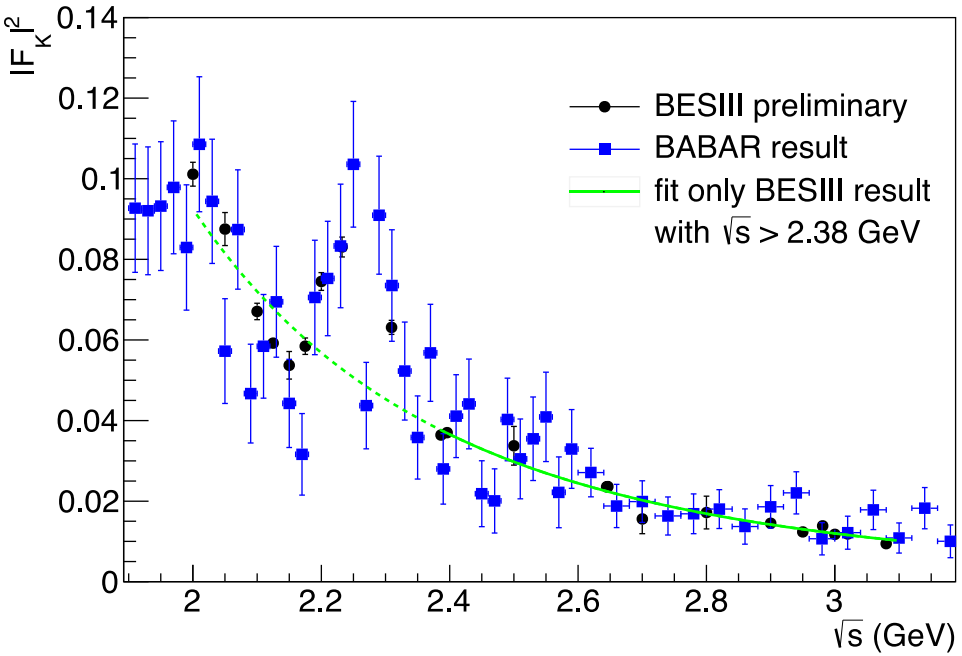
Parameters: $J/\psi \to \Lambda\bar{\Lambda}$ angular distribution parameter α_ψ, helicity phase $\Delta\Phi$, asymmetry parameters for the $\Lambda \to p\pi^-$ (α_-), $\bar{\Lambda} \to \bar{p}\pi^+$ (α_+) and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\bar{\alpha}_0$) decays, CP asymmetry A_{CP} and ratio $\bar{\alpha}_0/\alpha_+$. The first uncertainty is 1 s.d. statistical, and the second is systematic, calculated as described in the Methods.

$e^+e^- \to K^+K^-$

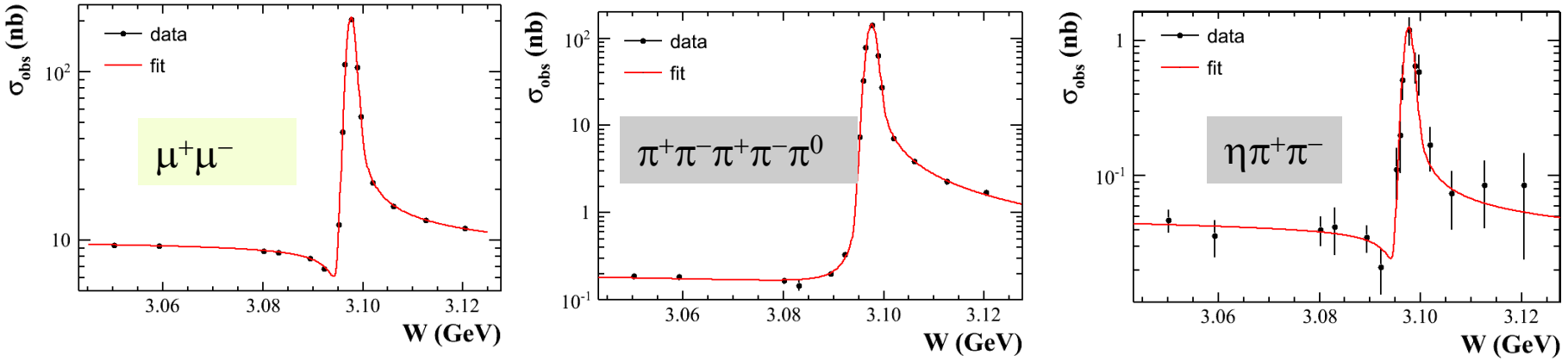
- Signal well separated from bkgd;
- Much better precision than BaBar;
- Confirmed 1/s rule of pQCD;
- Unknown structure around 2.23GeV.
- Phys. Rev. D 99, 032001 (2019).
- Mr. Dong Liu's Ph.D thesis







Phase angle between EW and strong



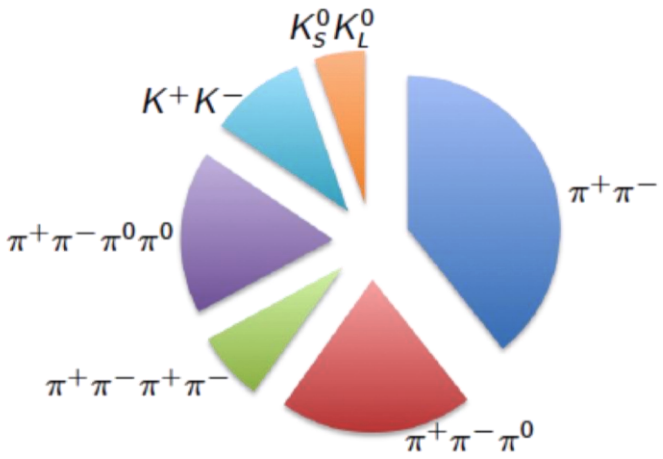
$\Phi' = (-5 \pm 9.7)°$, $\Phi' = (84.9 \pm 3.6)°/(-84.7 \pm 3.1)°$, $\Phi' = (-2 \pm 39)°$

- **Phys. Lett. B 791, 375 (2019),** **Dr. Yadi Wang's work**
- **Other ongoing analyses (efforts by Italian groups):**
  - ✓ $e^+e^- \to p\,\bar{p}$
  - ✓ $e^+e^- \to K^+K^-$
  - ✓ $e^+e^- \to K_sK_L$ and K_sK^*
  - ✓ $e^+e^- \to \Lambda\,\bar{\Lambda}$ and $\Sigma^0\overline{\Sigma^0}$

ISR physics

Hadronic vacuum polarization a_μ^{HVP}

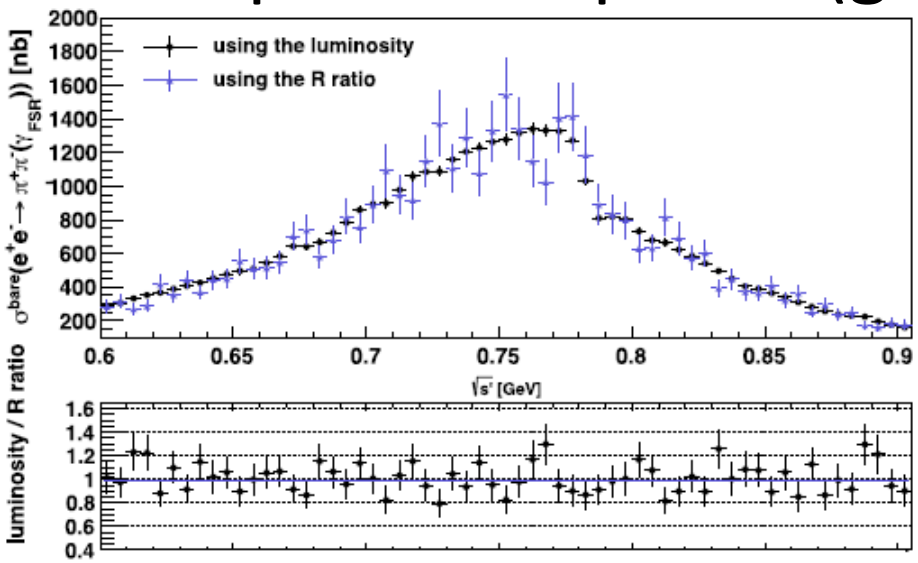
$$a_\mu^{HVP} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had}(s)$$

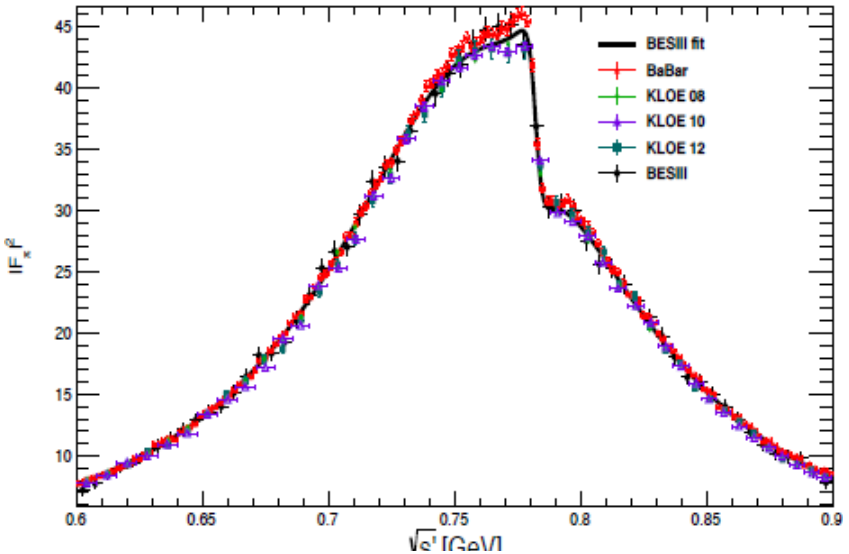


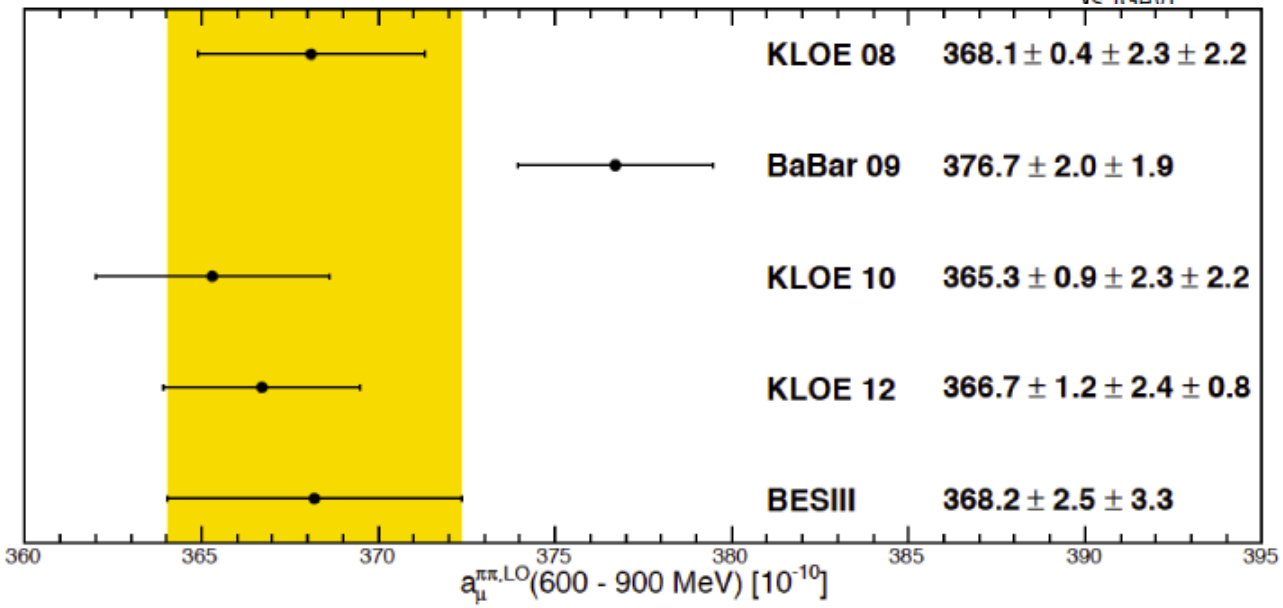
- $e^+e^- \to \pi^+\pi^-$
  - ✓ Phys. Lett. B753, 629 (2016)
- $e^+e^- \to \pi^+\pi^-\pi^0$
  - ✓ BAM-206
- $e^+e^- \to \pi^+\pi^-\pi^0\pi^0(\pi^0)$
  - ✓ tagged & untagged analysis
  - ✓ BAM-271
- $e^+e^- \to p\,\bar{p}$
  - ✓ tagged: BAM-230
  - ✓ untaged: PRD 99, 092002 (2019)

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

- Important input to (g-2). PLB 753, 629 (2016).

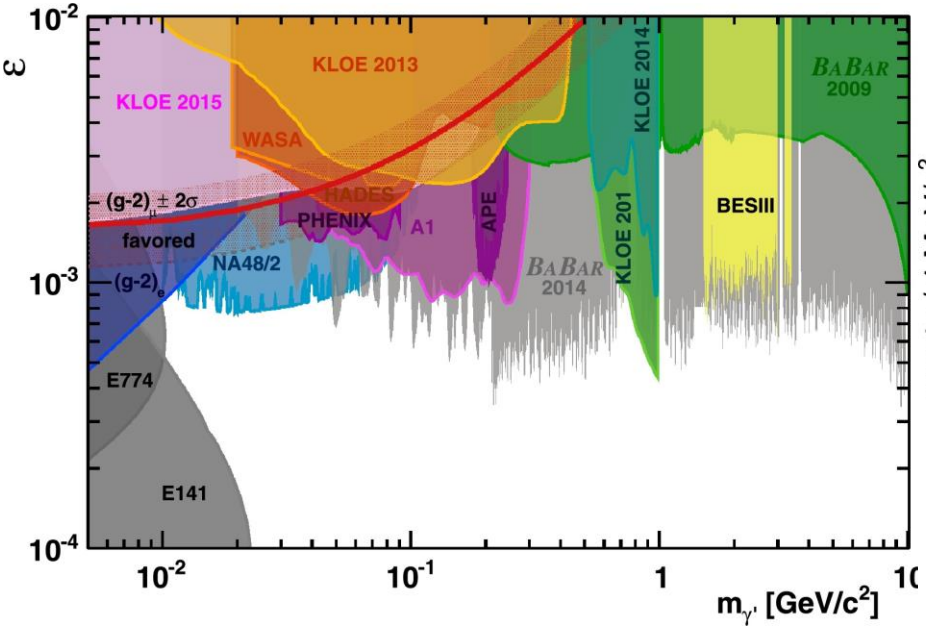


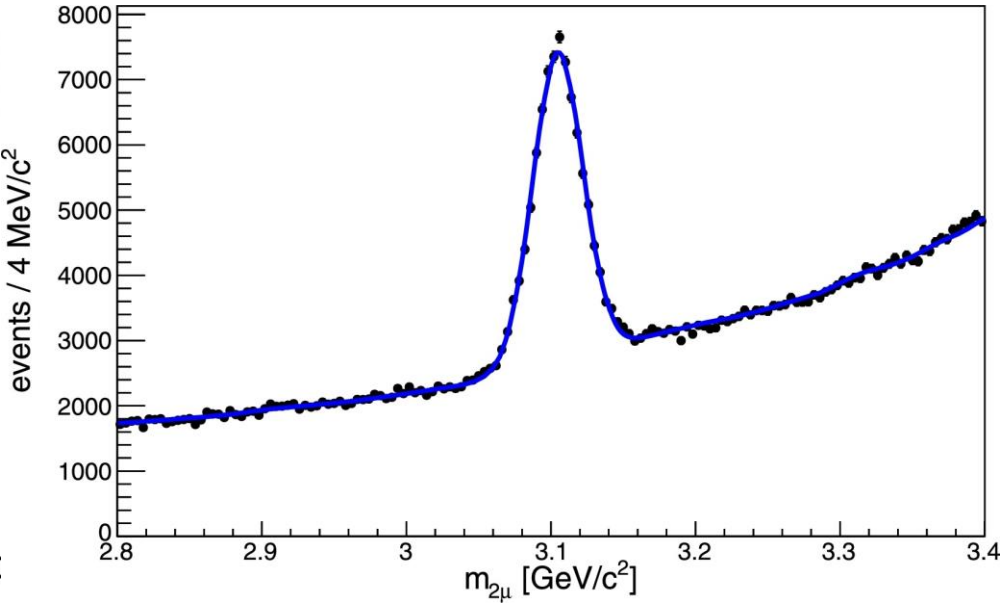




By-products of ISR $e^+e^- \to \pi^+\pi^-$ study

- Using the background process $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$



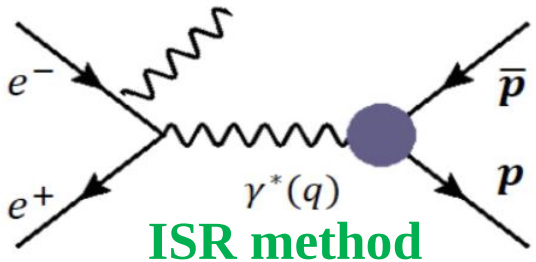


Dark photon search in [1.5, 3.4] GeV
Phys. Lett. B774, 252 (2017)

The electronic width of J/ψ
Phys. Lett. B761, 98 (2016)

Mr. Benedikt Kloss's Ph.D thesis

ISR $e^+e^- \to p\,\bar{p}$ (proton form factor)

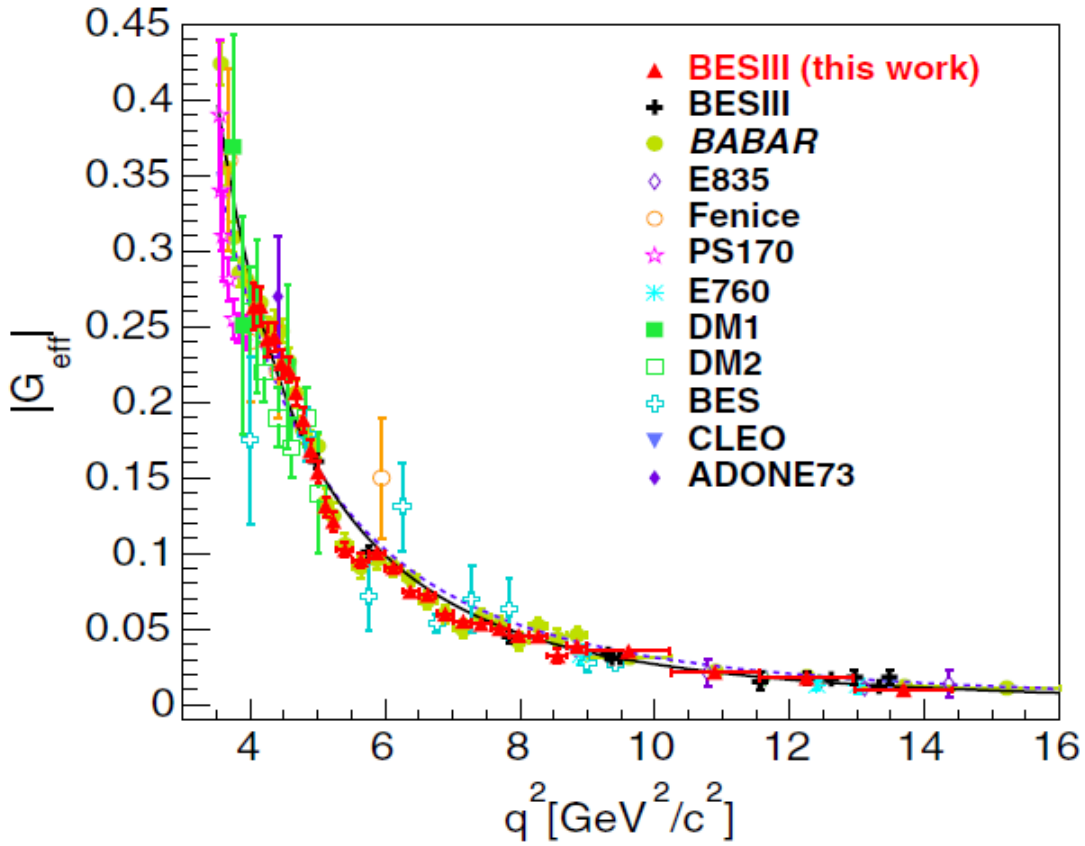


ISR method

untagged analysis

PRD 99, 092002 (2019)

Dr. Alaa Dbeyssi's work



Summary

- R measurements at BESII were a great success: 5(+10) pb^{-1}
  - R values around $\tau\tau$ threshold using BESI data;
  - Test run at 6 continuum points + 85 points scan in the full energy region. R uncertainties in 2–5 GeV reduced to ~6% (improved by factor of 2~3);
  - 3.5% precision reached at 3 energies with high statistics.
- Hard efforts at BESIII aiming for ~3% in 2–5 GeV: 1.5 fb^{-1}
  - Test run at 4 points in the low energy region;
  - A 104-point fine scan from 3.8 GeV to 4.6 GeV;
  - Data taken at 22 points between 2.0 GeV to 3.08 GeV.
- Few QCD studies at BESII due to limited data;
- Fruitful results on QCD studies at BESIII.

Stolen from Fred Harris