BES Highlights and R Measurement

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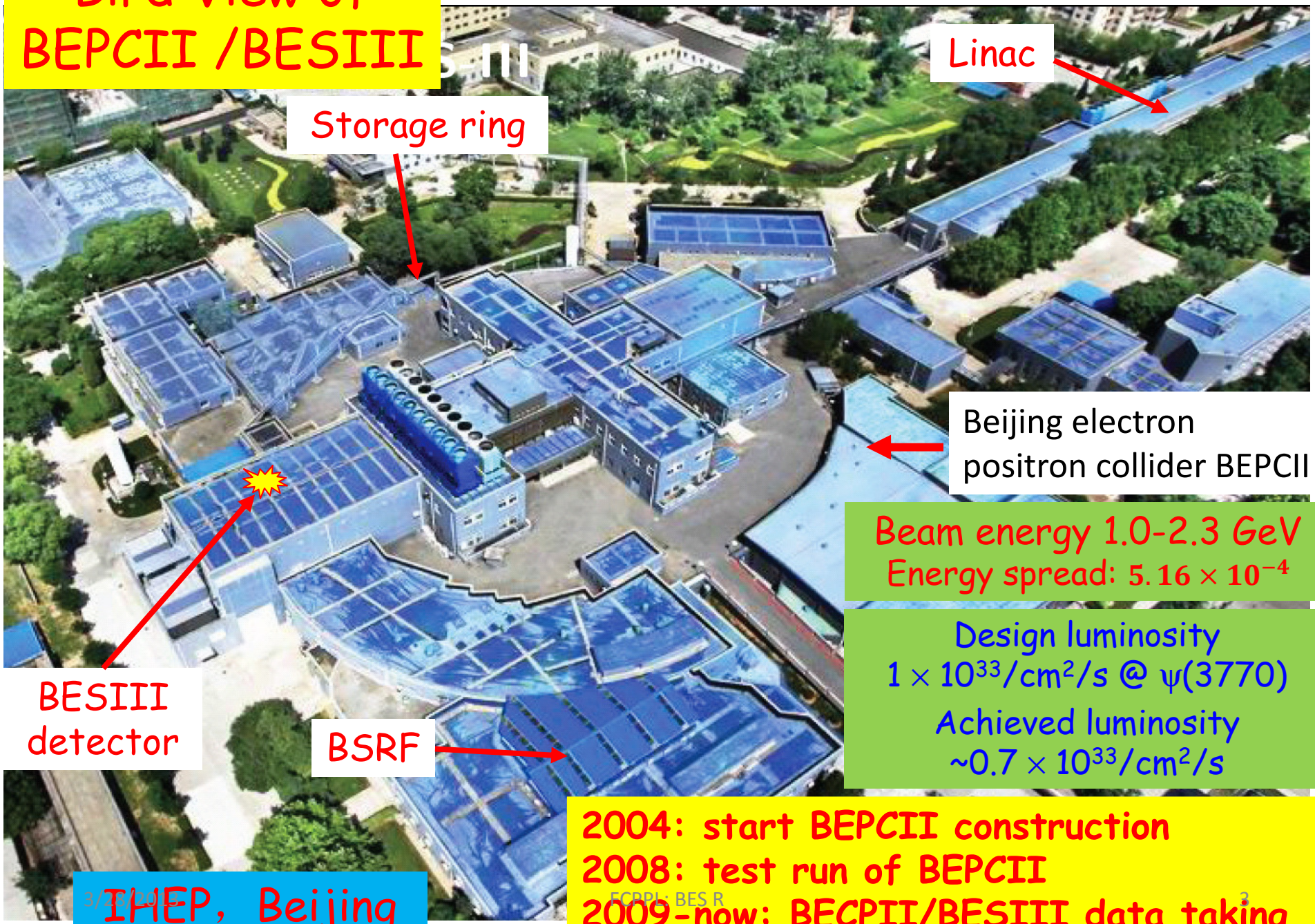
Outline

- Status of BEPCII/BESIII
- BESIII highlight: $Z_c^{\pm}$ observed
- R measurements at BES
  - A brief review for BESI/BESII
  - New efforts/prospects at BESIII
- Summary

Bird View of BEPCII /BESIII

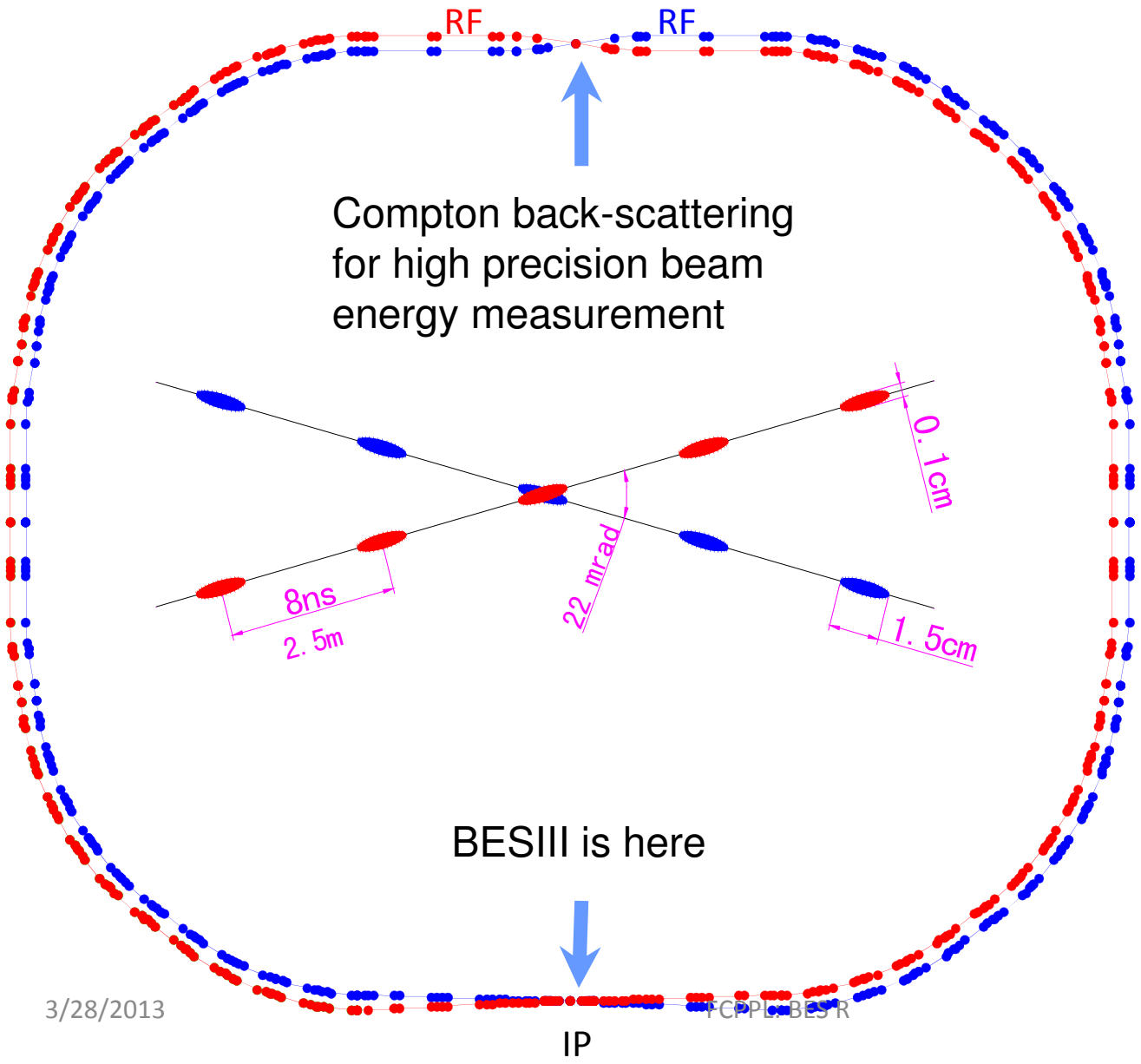


Beam energy 1.0-2.3 GeV
Energy spread: 5.16×10^{-4}

Design luminosity
$1 \times 10^{33}/cm^2/s$ @ $\psi(3770)$
Achieved luminosity
$\sim 0.7 \times 10^{33}/cm^2/s$

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:
1×10^{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

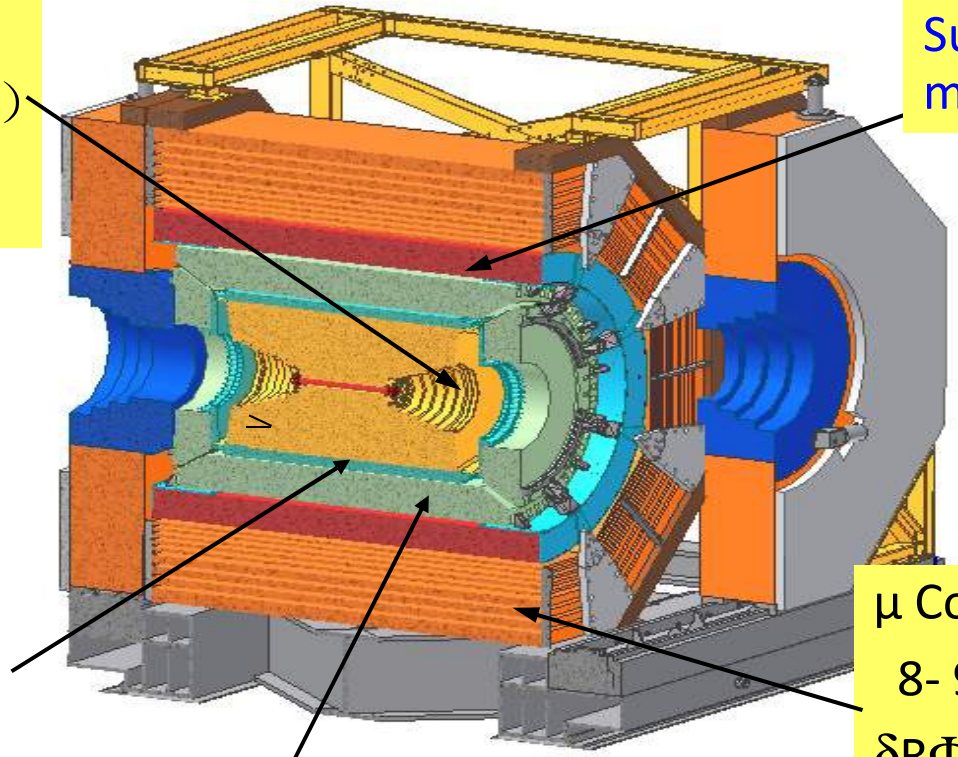
NIM A614, 345 (2010)

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

BESIII Data Taking

- July 19, 2008: first e^+e^- collision event in BESIII
- Nov. 2008: ~14M $\psi(2S)$ events for detector calibration
- 2009: 106M $\psi(2S)$ 4×CLEO-c
  225M J/ψ 4×BESII
- 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

World's largest sample of J/ψ,$\psi(2S)$ and $\psi(3770)$

- 2012: tau mass scan: ~5.0 pb^{-1} ; $\psi(2S)$: 0.4B; J/ψ: 1B;
  J/ψ lineshape, R scan (2.23, 2.4, 2.8, 3.4 GeV)
- 2013: ~0.5 fb^{-1} @ 4.26, 4.36 GeV and scan in vicinity

Future plans:
R scan, D_s physics (E_{cm}=4170 MeV), τ scan,
5-10 fb^{-1} $\psi(3770)$ for DD physics, ……

The BESIII Collaboration

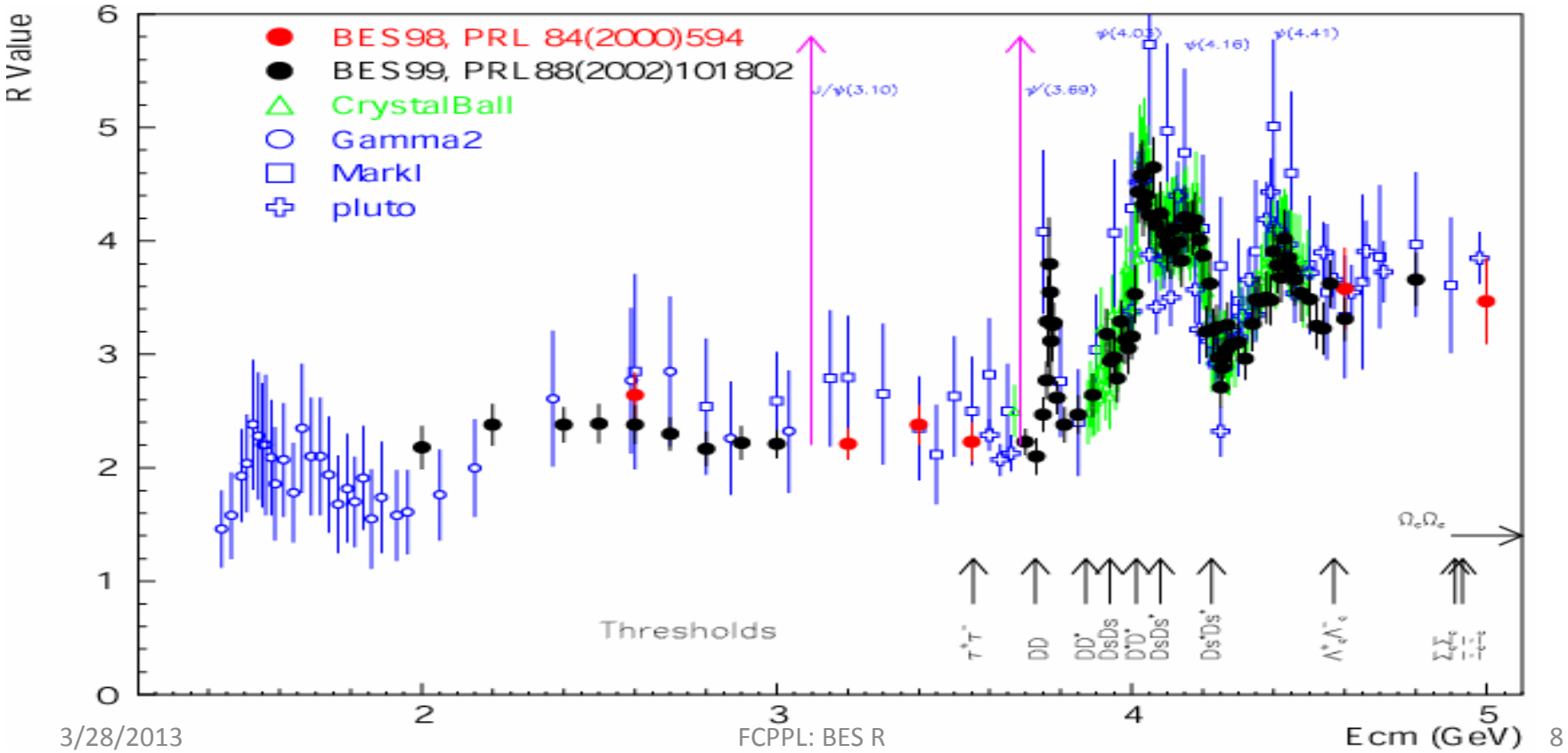
http://bes3.ihep.ac.cn

~350 physicists

50 institutions from 10 countries

Features of the BEPC Energy Region

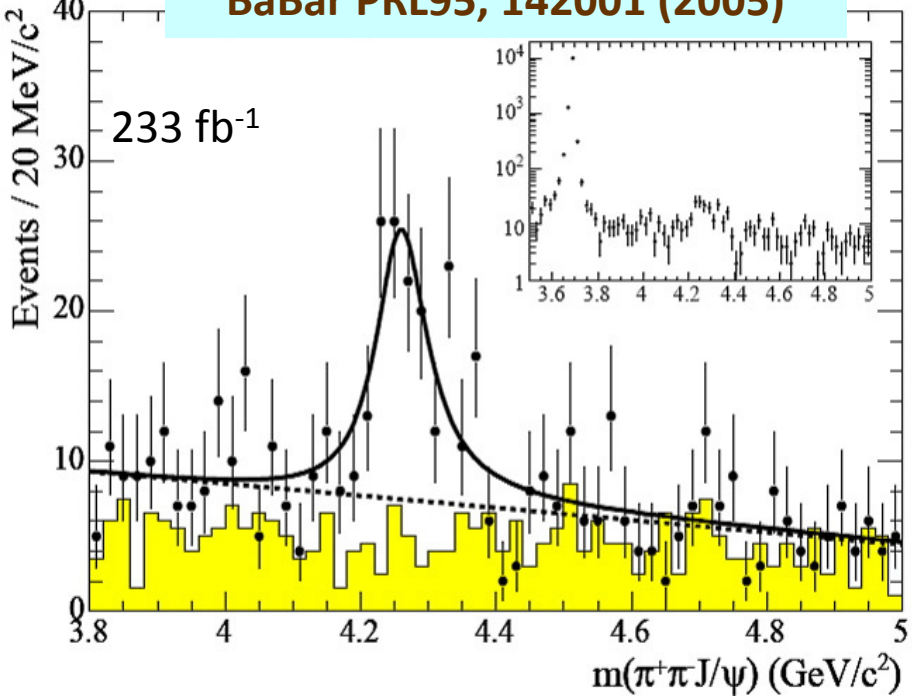
- Rich of resonances, charmonium and charmed mesons
- Threshold characteristics (pairs of τ, D, D_s, charmed baryons…)
- Transition between smooth and resonances, perturbative and non-perturbative QCD
- Energy location of the gluonic matter and glueball, exotic states and hybrid



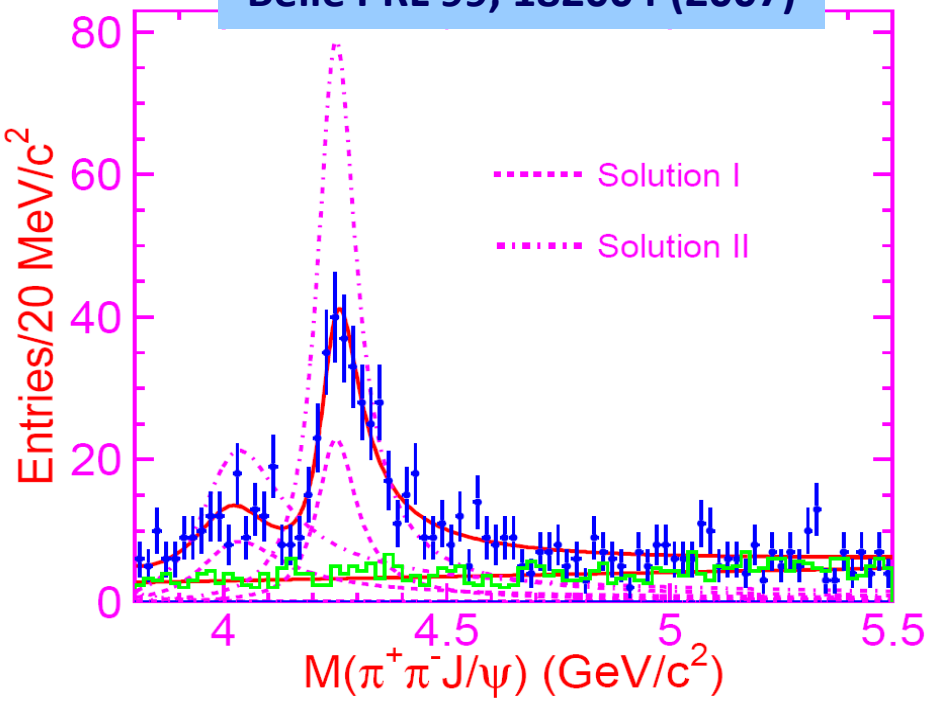
BESIII Highlight: XYZ search

- Y(4260) was first observed in ISR process by BaBar, then confirmed by CLEO and Belle, not seen in BESII R scan;
- BESIII just collected ~0.5 fb^{-1} data @ 4.26, 4.36 GeV, and more data is coming…

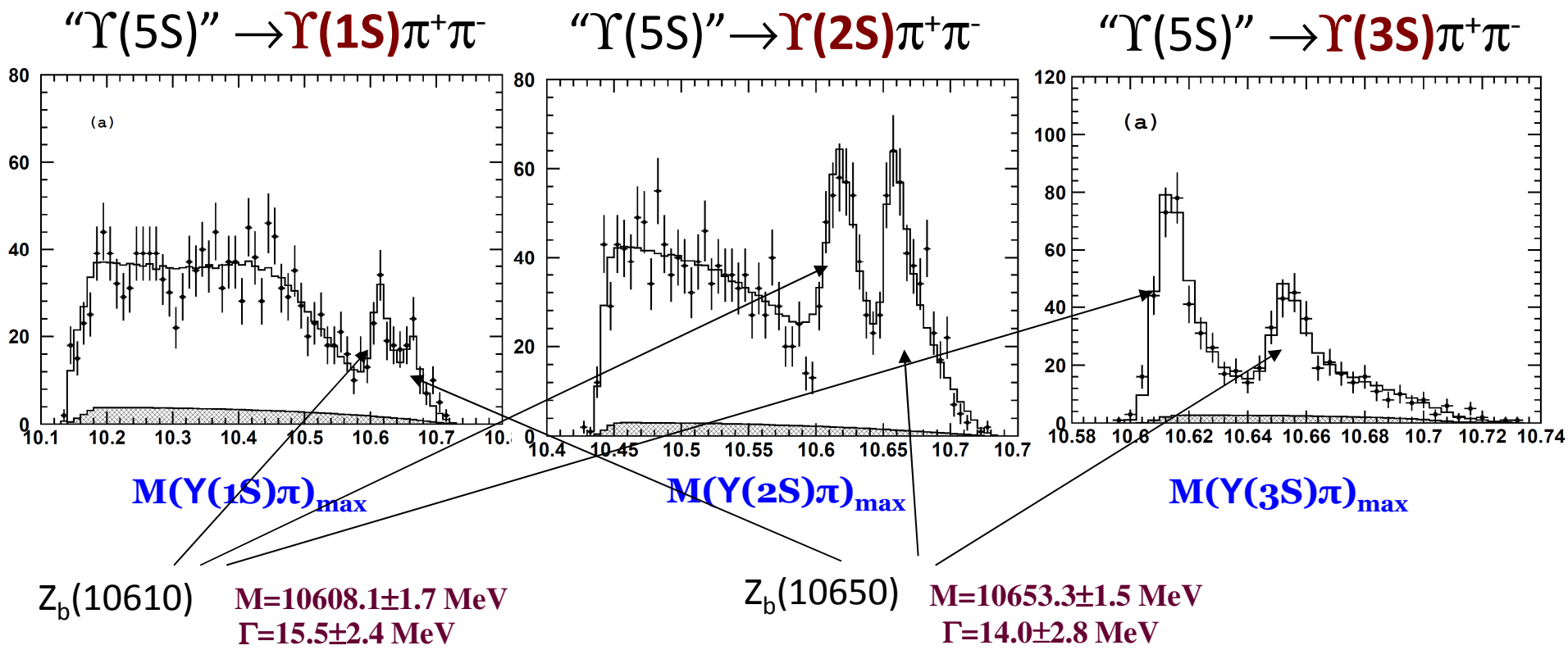
BaBar PRL95, 142001 (2005)



Belle PRL 99, 182004 (2007)



Belle observed "$Z_b^{\pm}$" mesons

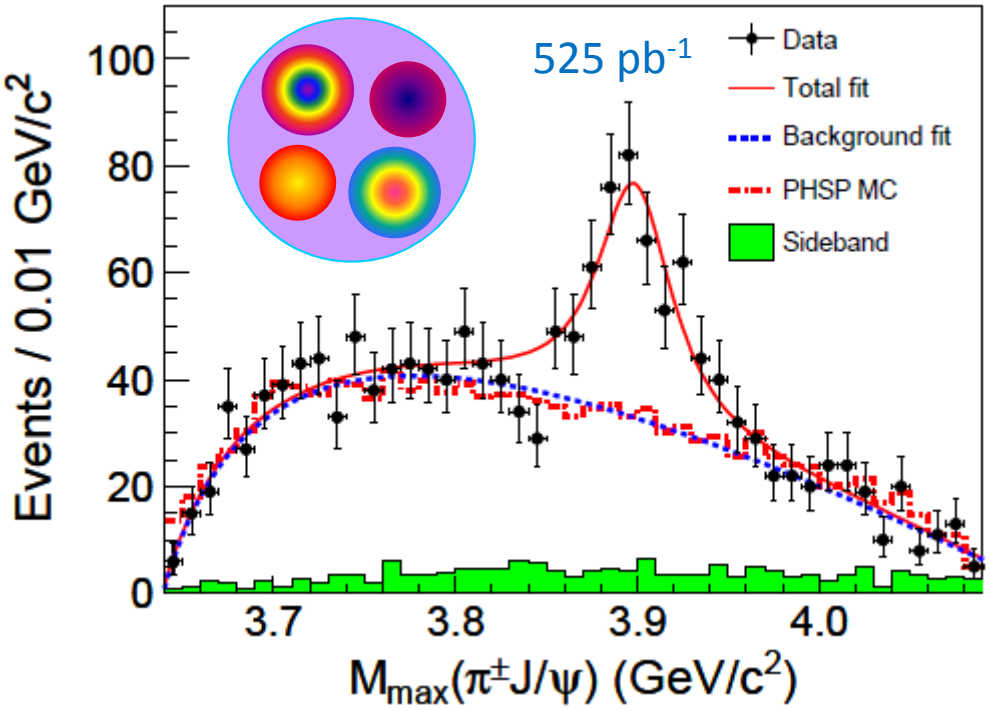


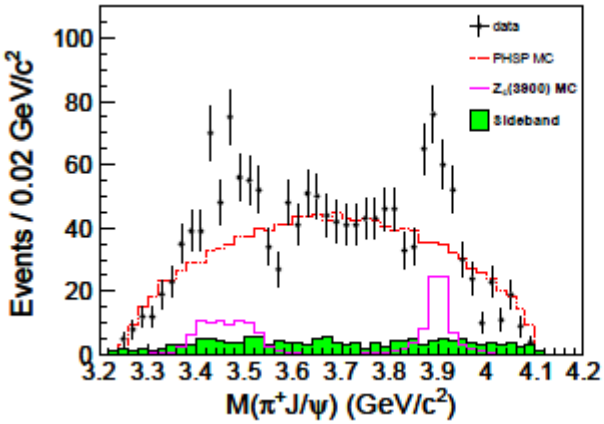
Belle: PRL 99, 182004 (2007)

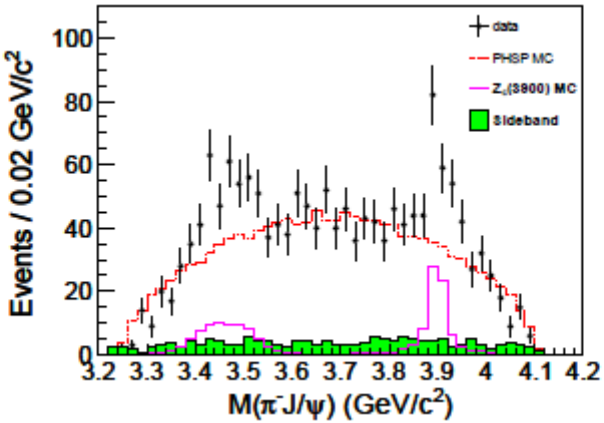
Should $Z_c^{\pm}$ show up in Y(4260) decays?

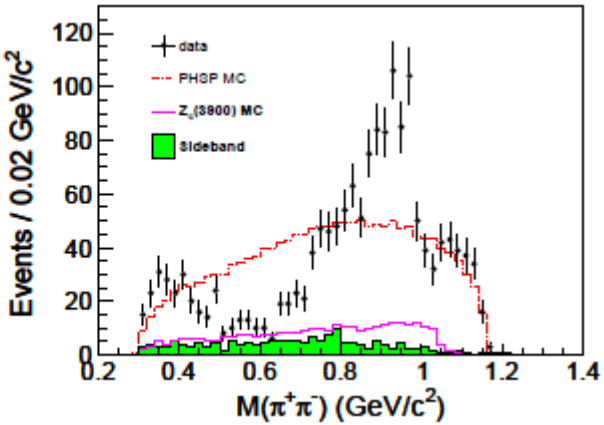
$Z_c^{\pm}$ observed at BESIII

- Significance > 8σ;
- Mass (3899.0±3.6±4.9) MeV;
- Width (46±10±20) MeV;
- arXiv:1303.5949, Submitted to PRL;
- More results to come!





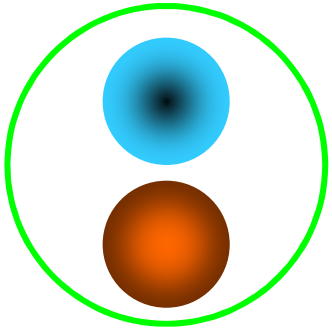




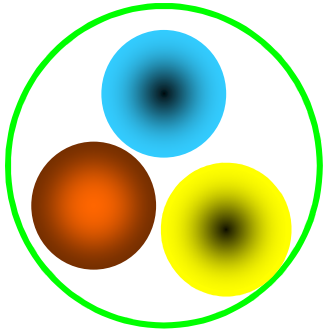
$Z_b^{\pm}$, $Z_c^{\pm}$: Exotic Hadrons

- In Quark Model, hadron has 2 or 3 quarks;

meson:
2 quarks

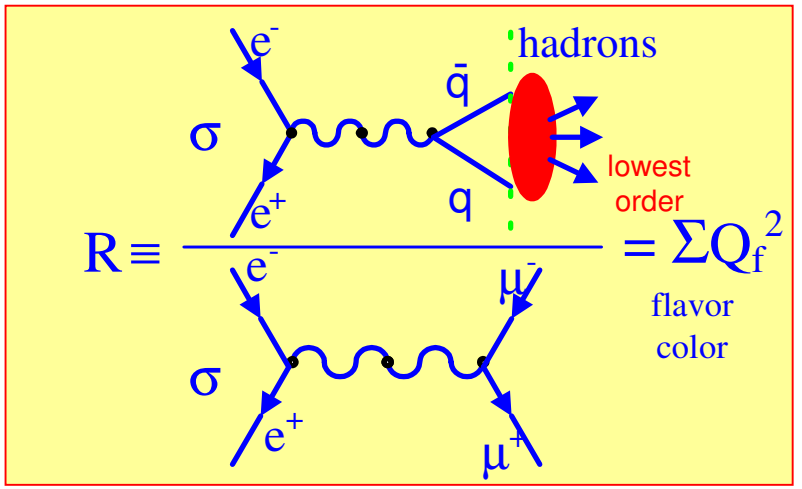


baryon:
3 quarks



- QCD allows hadrons with $N_{quarks} \neq 2, 3$
  - glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - hybrid : $N_{quarks} = 2$ + excited gluon
  - multiquark state : $N_{quarks} > 3$
  - molecule : bound state of more than 2 hadrons
- $Z_b^{\pm}$, $Z_c^{\pm}$ are special, because they apparently have 4 quarks ($b\bar{b}/c\bar{c}$ + 2 light quarks): $\pi^{\pm}\Upsilon$(nS), $\pi^{\pm}\psi$(nS).

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.

Motivations

- Hadronic contribution to
  - QED running coupling constant $\alpha_{QED}(M_Z)$

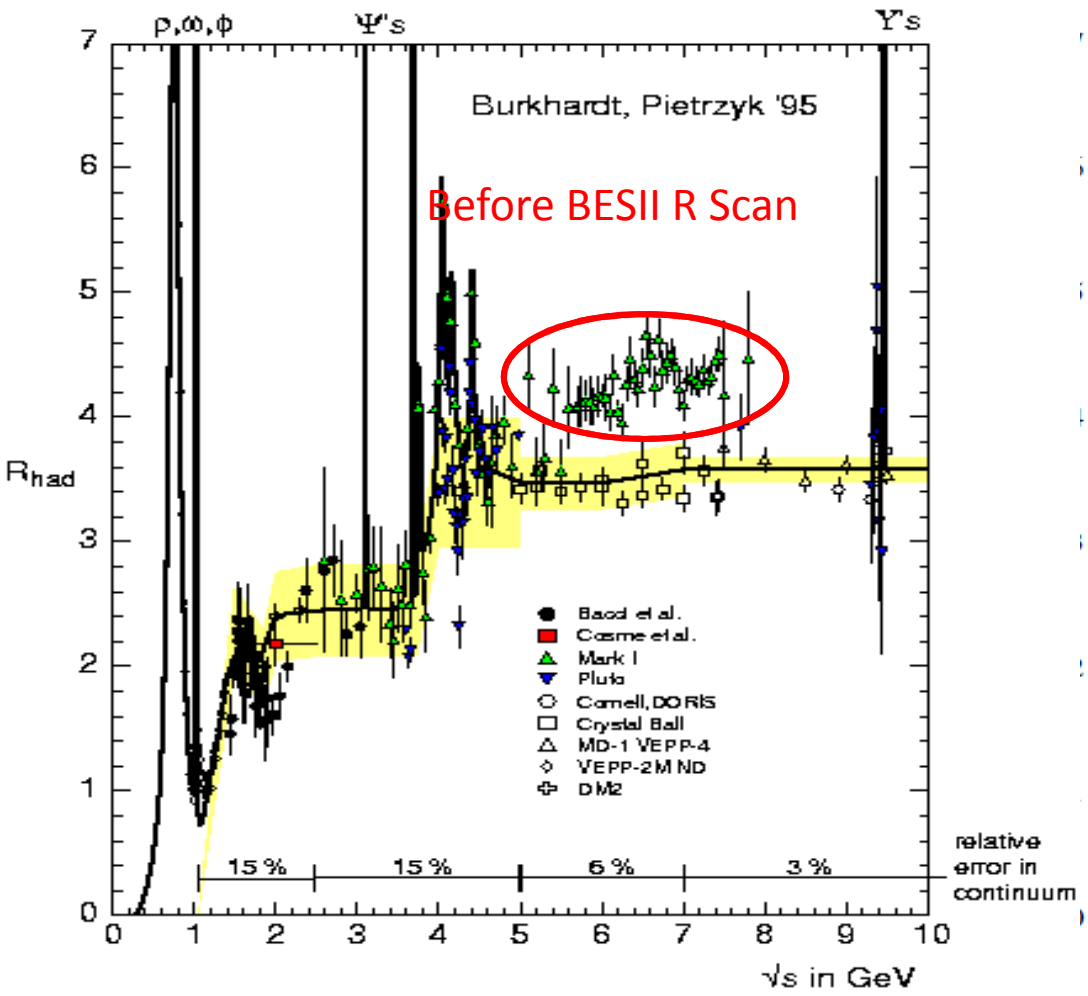
$$\Delta\alpha^{(5)}_{had}(s) = -\frac{\alpha s}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds' \frac{R(s')}{s'-s-i\varepsilon}$$

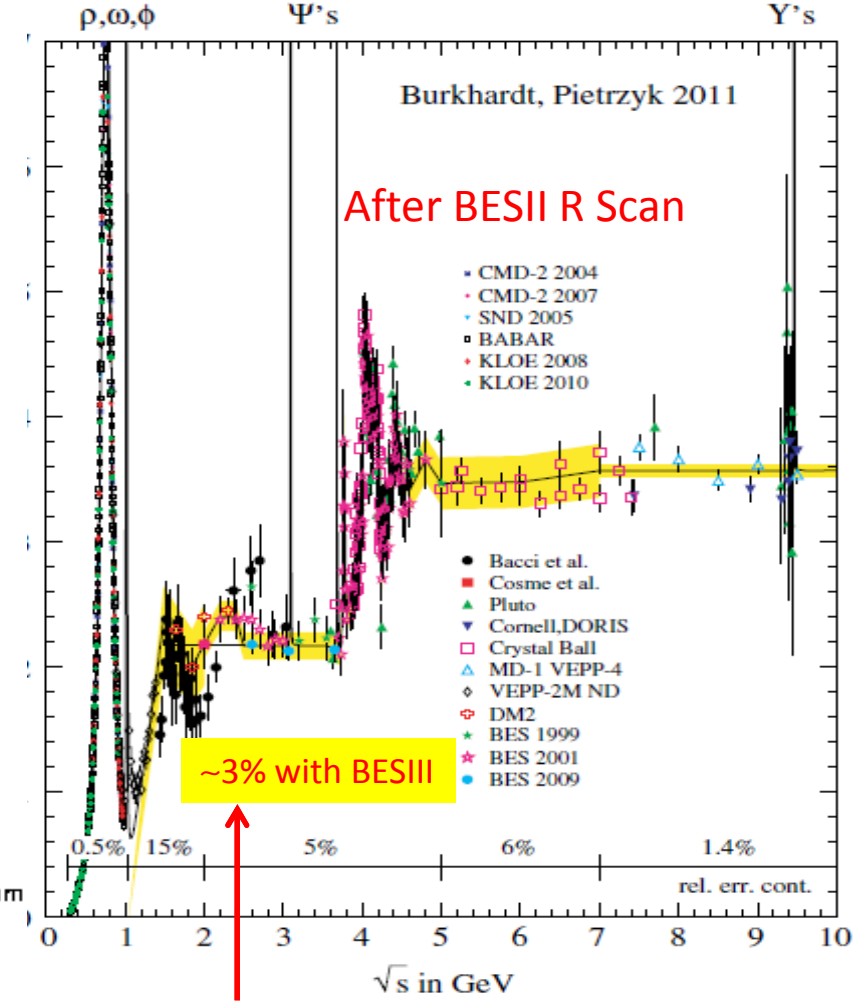
  - Anomalous magenet moment of the muon a_μ, or $(g_\mu - 2)$

$$a_\mu^{had} = (\frac{\alpha m_\mu}{3\pi})^2 \int_{4m_\pi^2}^{\infty} ds' \frac{\hat{K}(s')}{s'^2} R(s')$$

- Resonance structure and component in open charm region;
- Strong coupling constant α_s determination;
- Baryon form factors;
- Charm quark mass m_c determination;
- X, Y, Z particles and other possible new resonances;
- Physics with D_s, Charmed baryons, ……

R Below 10 GeV



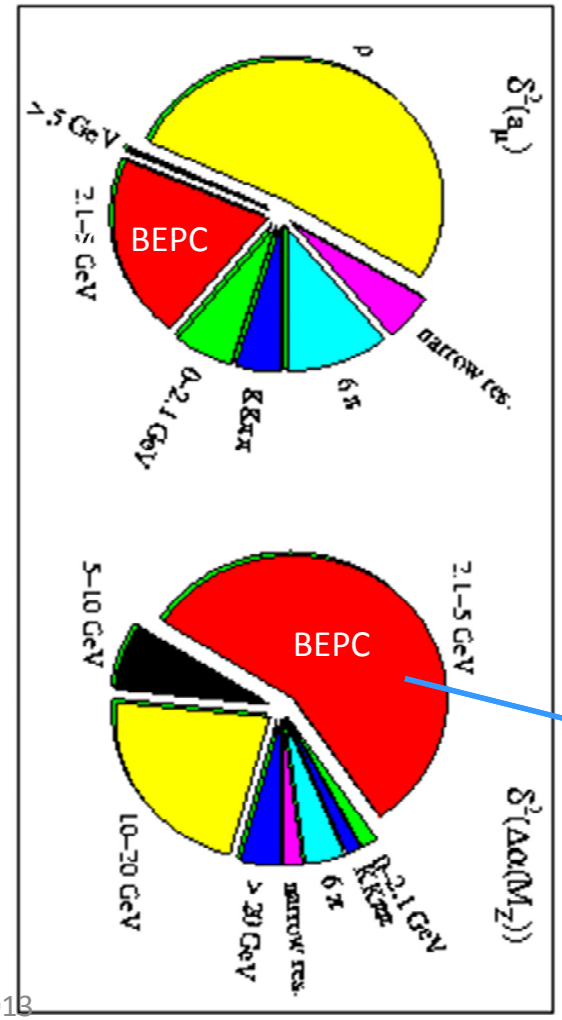


- ΔR/R~15-20% below 5 GeV
- Unclear & complex structure in 3.7-5GeV
- Values from Mark I much higher than others

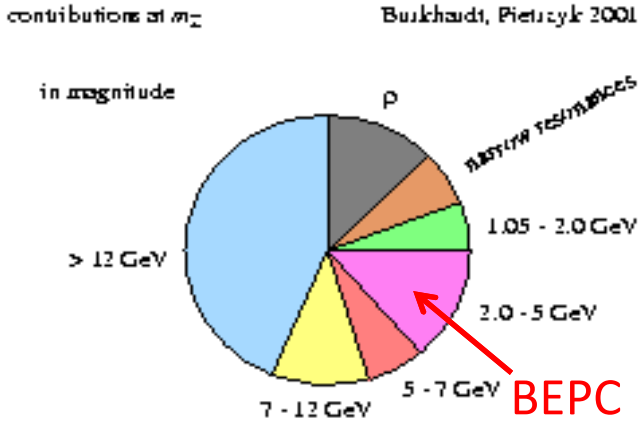
- ΔR/R~6% between 2 and 5 GeV
- Much clean structures in 3.7-5 GeV
- Mark I results is removed from PDG

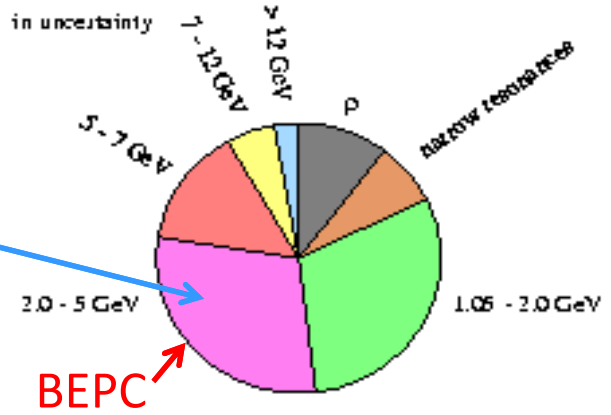
Relative Contributions to the Uncertainties of a_μ and $\Delta\alpha(M_Z^2)$

Before BESII R scan



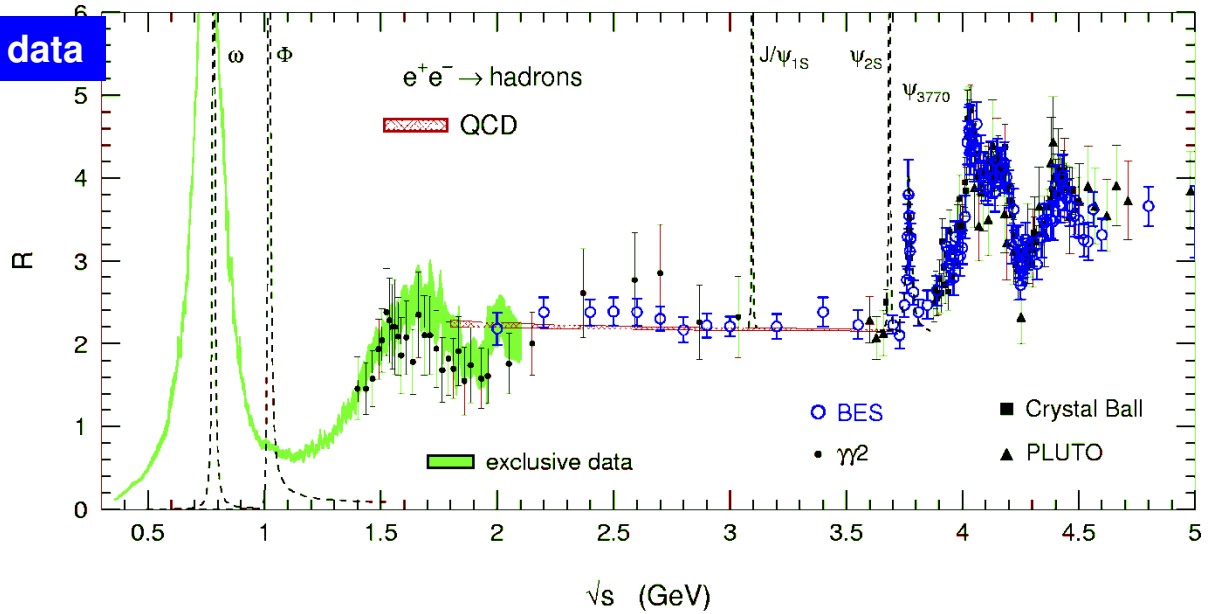
After BESII R scan



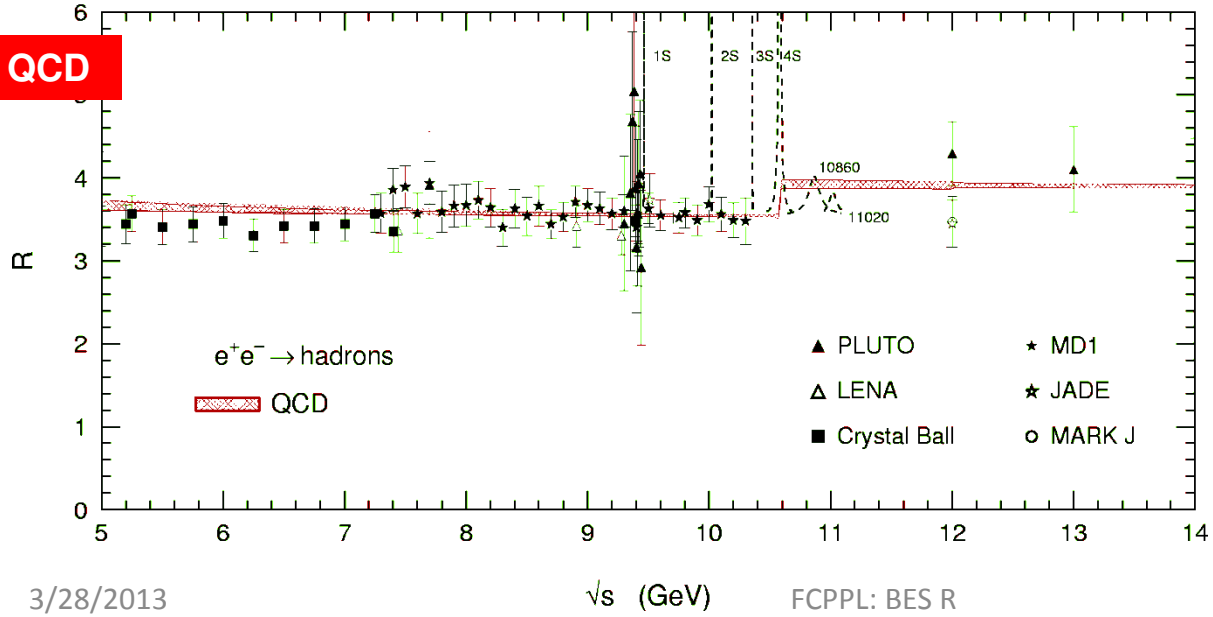


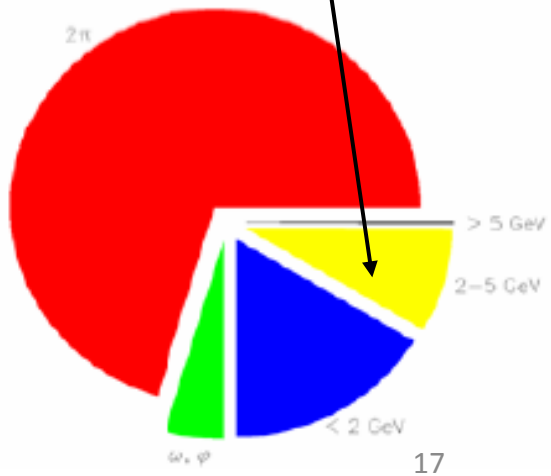
Impact of BESII R to muon (g_μ–2)

use data



use QCD





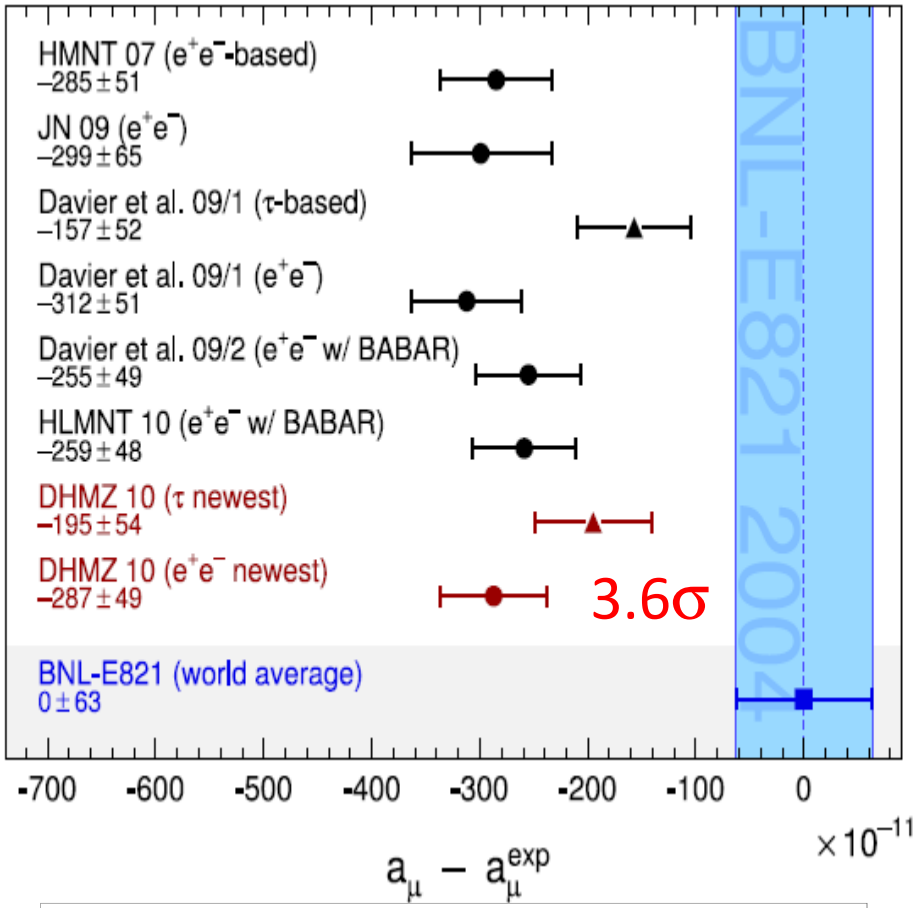
$\Delta\alpha(M_Z^2)$ and a_μ: Current Status

Burkhardt, Pietrzyk 2011

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

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.



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

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

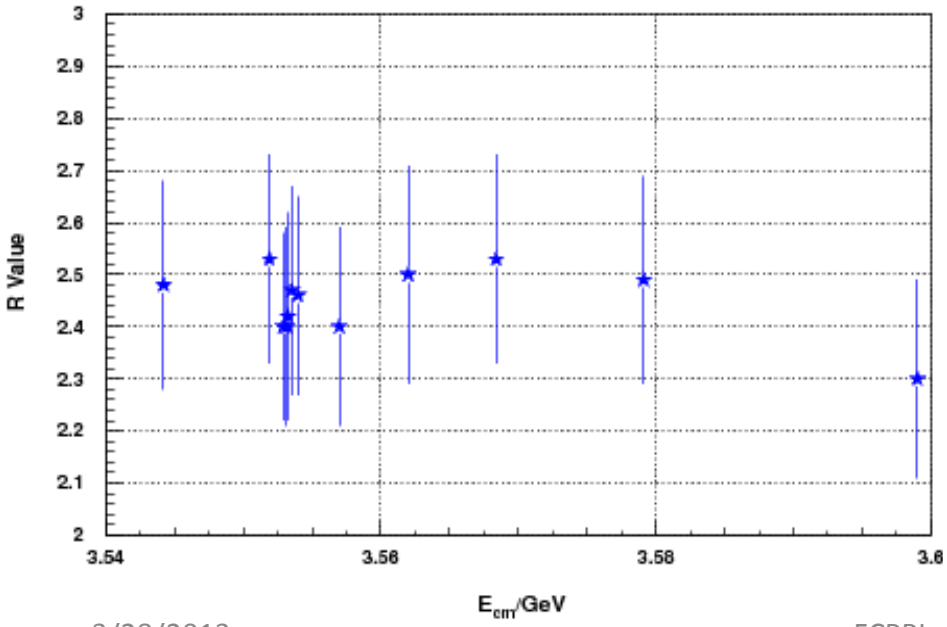
Davier 2010

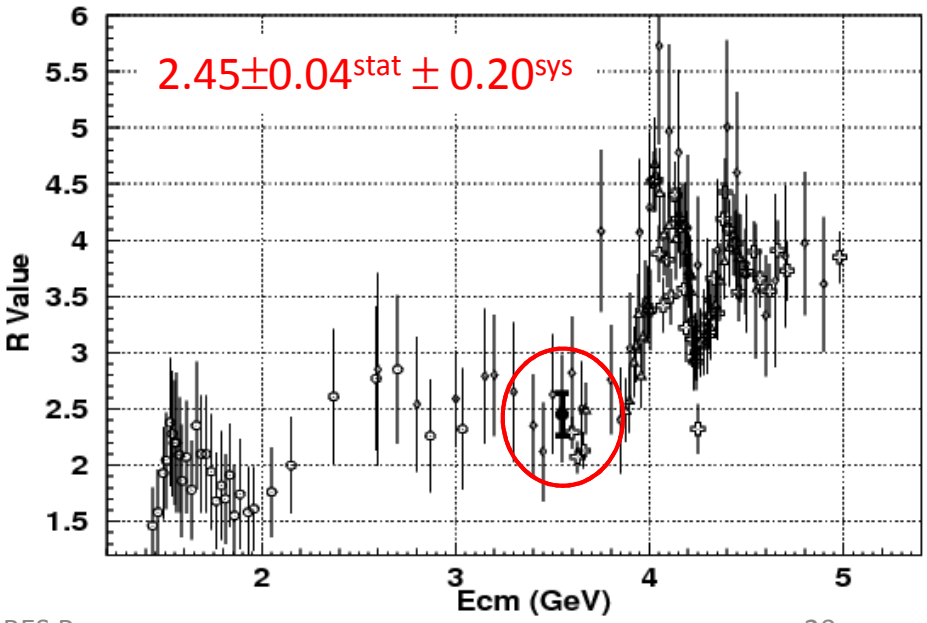
Brief Review on BES R Measurements

- Pre-study, using BESI tau mass data, 12 points around 3.55 GeV, ~8.5%, HEP&NP24, 609 (2000);
- Test run, 6 continuum points in 2.6 ~ 5.0 GeV, PRL84, 594 (2000);
- Full scan, 85 points in 2 ~ 4.8 GeV, PRL88, 101802 (2002);
- R around ψ(3770), 2 points off-resonance, 1 on-resonance, PLB641, 145 (2006);
- Improvements at 3 continuum points, PLB677, 239 (2009).

Pre-study near ττ Threshold

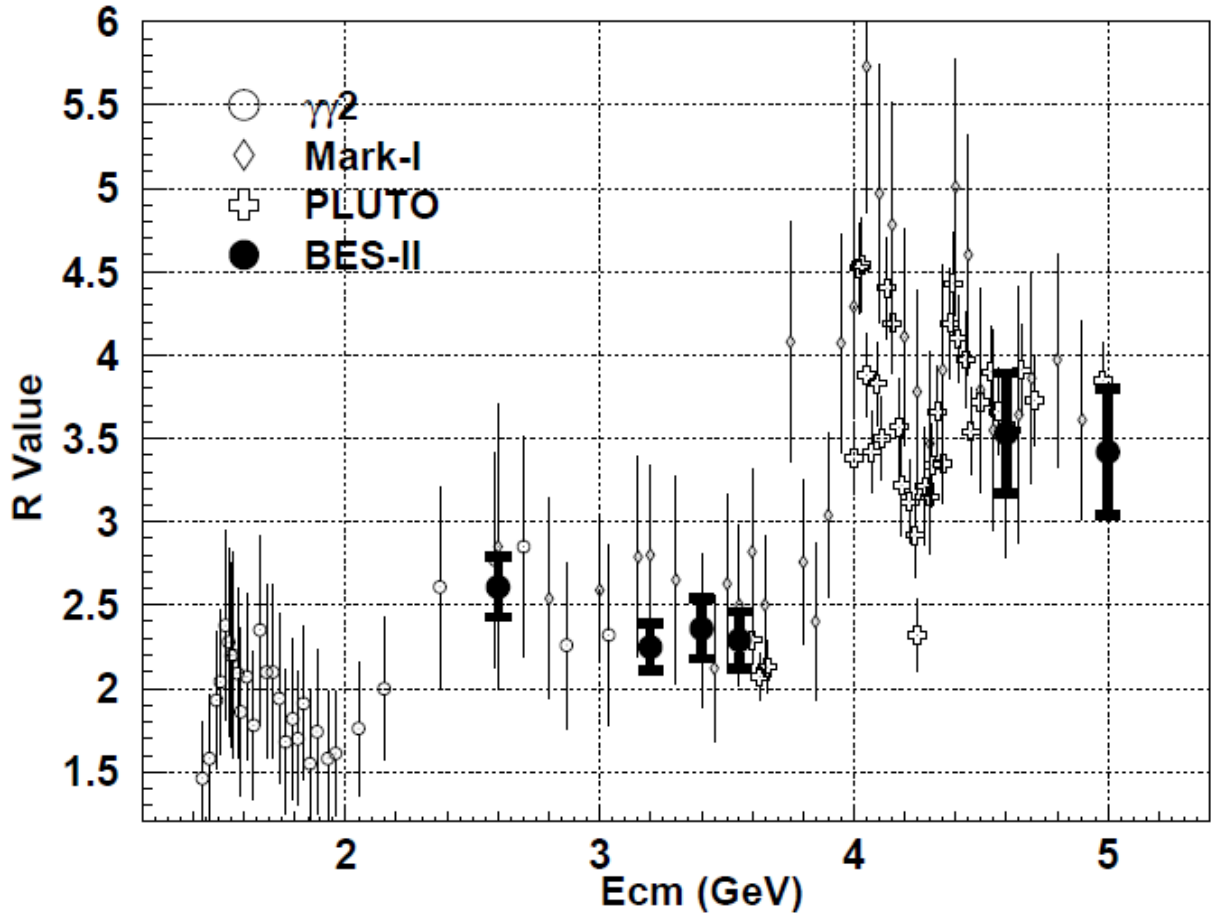
- BESI tau mass data, 12 energy points around 3.55 GeV, total ~5 pb^{-1} data, uncertainty on average ~8.5%, HEP&NP24, 609 (2000). (in Chinese)
- Analysis chain established.





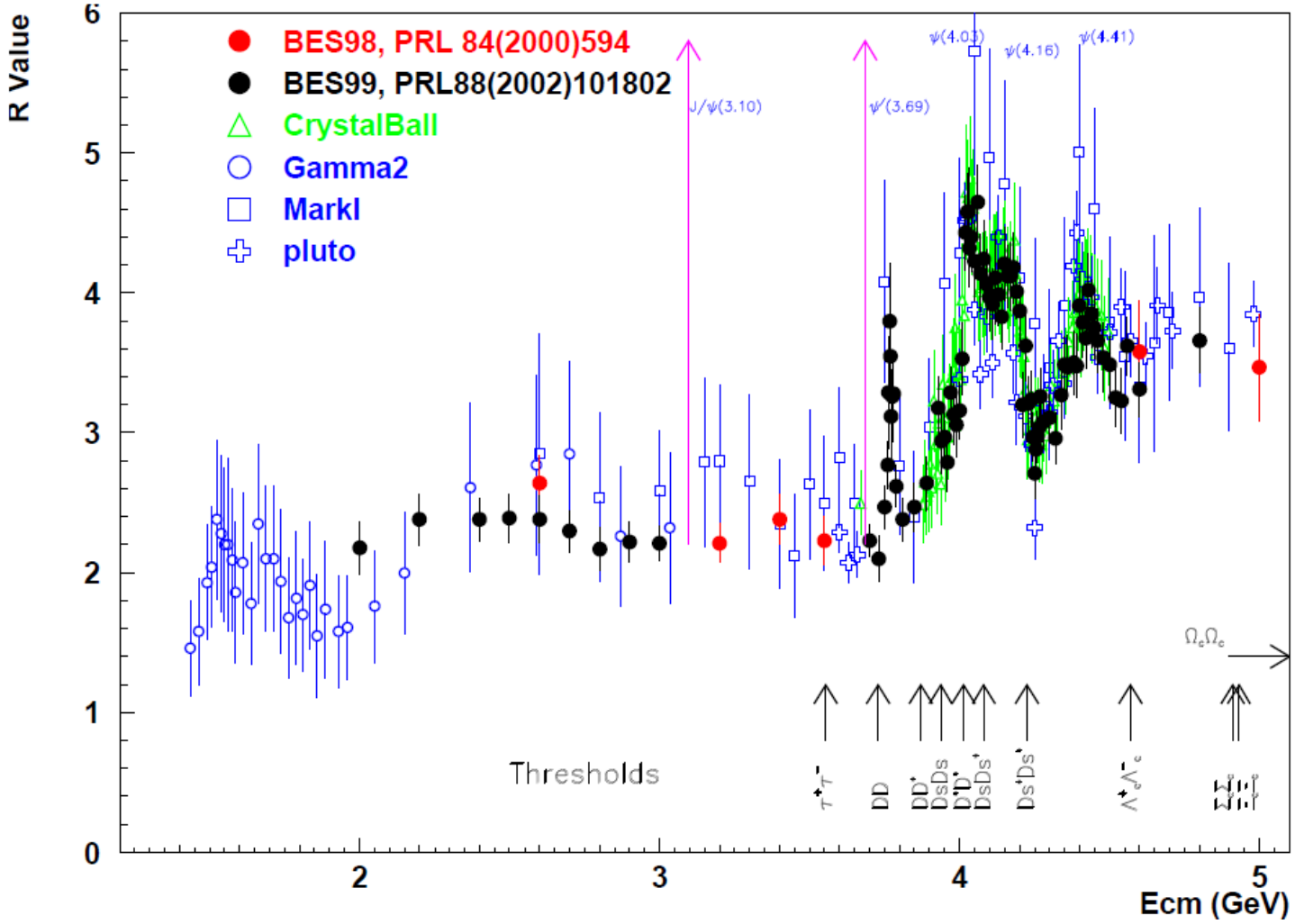
Test Run: 6 Points in 2.6 ~ 5.0 GeV

- The first project after BES upgrade, 6 energy points at 2.6, 3.2, 3.4, 3.55, 4.6 and 5.0 GeV, total ~1 pb^{-1} data, uncertainties 6~12%, PRL84, 594 (2000).



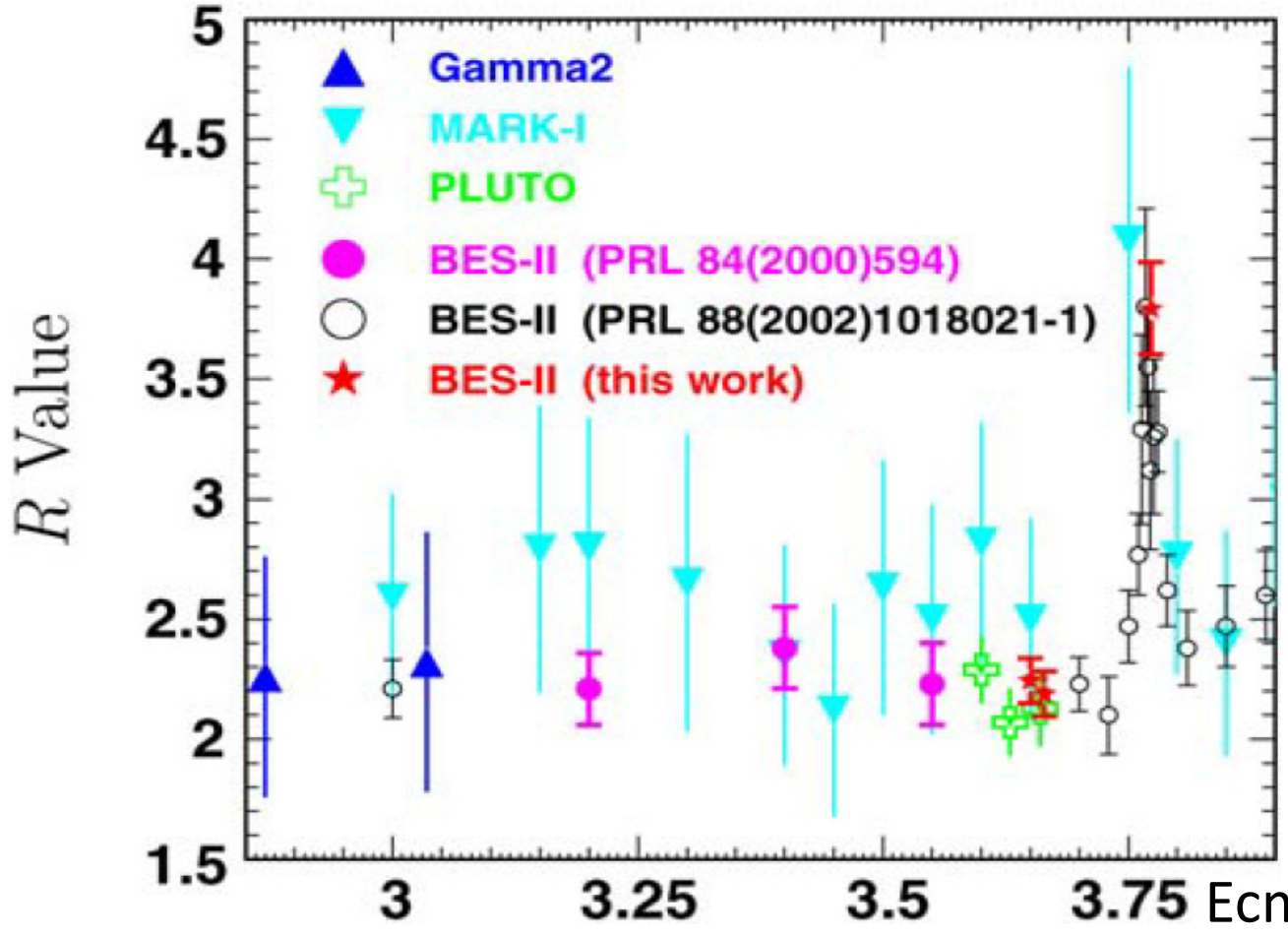
Full Scan in 2.0 ~ 4.8 GeV

- 85 energy points, 24(7) with separated(single)-beam run, total ~5 pb^{-1} data, uncertainties 5~10% (average 6.6%), PRL88, 101802 (2002).

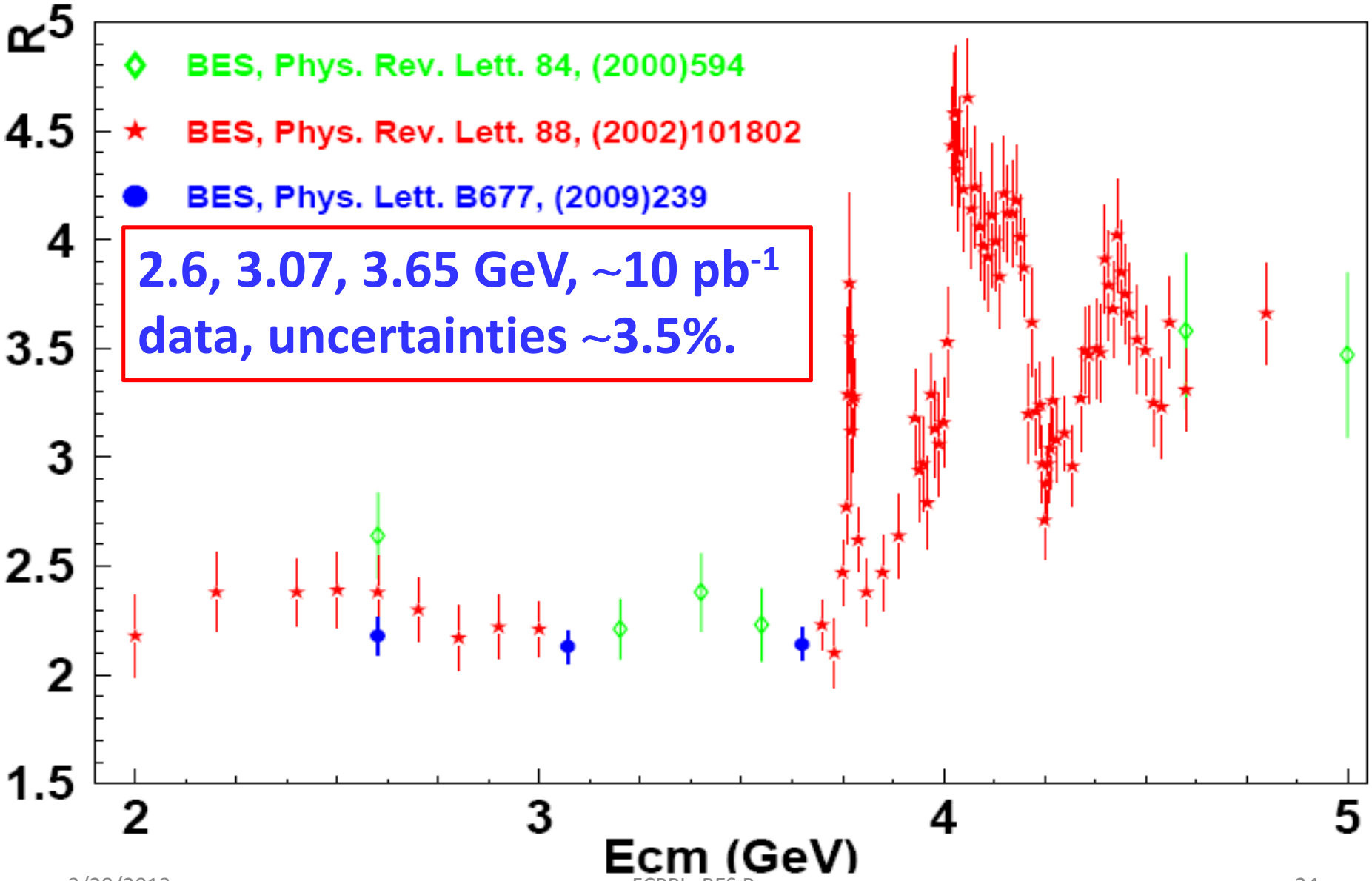


On/off ψ(3770)

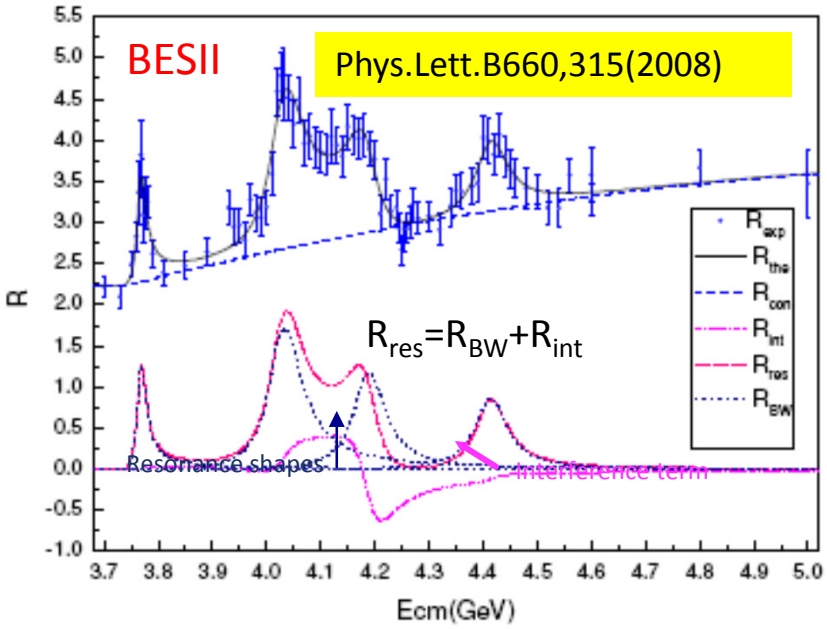
- 2 off-, 1 on-resonance energy points at 3.650, 3.6648, 3.773 GeV, total ~6.5 + 17.3 pb^{-1} data, uncertainties 4.1~5.1%, PLB641, 145 (2006).



Last Attempt at BESII



Resonances in the Open Charm Region



- All possible two-body decays of ψ(3770), ψ(4040), ψ(4160), ψ(4415) are included in the fit.
- Interference, phase and energy-dependent width must be taken into account in the fit.

$$
\begin{aligned}
\psi(3770) &\Rightarrow D\bar{D};\\
\psi(4040) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s;\\
\psi(4160) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*;\\
\psi(4415) &\Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*.
\end{aligned}
$$

We need high statistic data taken at each peak position to measure the resonance parameters by knowing the cross section of their exclusive decay channels.

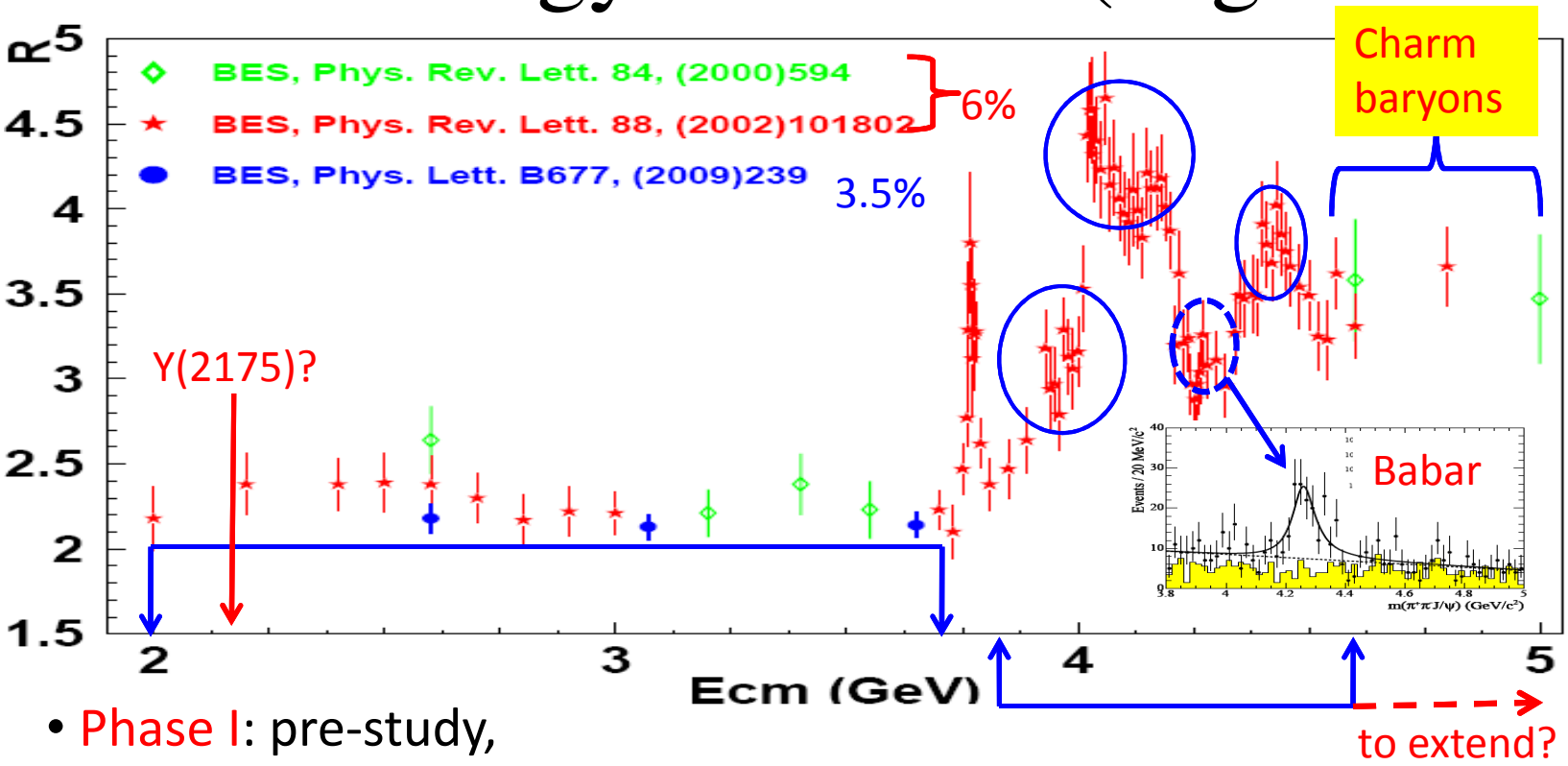
- Non-resonant contribution
- Open charm threshold

Parameters of the Broad Resonances

Parameters (M, Γ_{tot}, Γ_{ee}) of the $J^{PC} = 1^{--}$ conventional charmonia $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ remain quite uncertain and model dependent:

	M, MeV	Γ_{tot}, MeV	Γ_{ee}, keV	δ, deg	
$\psi(3770)$	3772.92 ± 0.35	27.3 ± 1.0	0.265 ± 0.018		PDG09
	3772.0 ± 1.9	30.4 ± 8.5	0.22 ± 0.05	0	BES08
$\psi(4040)$	4039 ± 1	80 ± 10	0.86 ± 0.07		PDG09
	4039.6 ± 4.3	84.5 ± 12.3	0.83 ± 0.20	130 ± 46	BES08
$\psi(4160)$	4153 ± 3	103 ± 8	0.83 ± 0.07		PDG09
	4191.7 ± 6.5	71.8 ± 12.3	0.48 ± 0.22	293 ± 57	BES08
$\psi(4415)$	4421 ± 4	62 ± 20	0.58 ± 0.07		PDG09
	4415.1 ± 7.9	71.5 ± 19.0	0.35 ± 0.12	234 ± 88	BES08

R Scan Strategy at BESIII (Big Picture)



- 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?)

Measurement of R Values

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

Our goal:
3% precision

N_{had}: observed hadronic events

N_{bg}: background events

L: integrated luminosity

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

δ: radiative correction factor

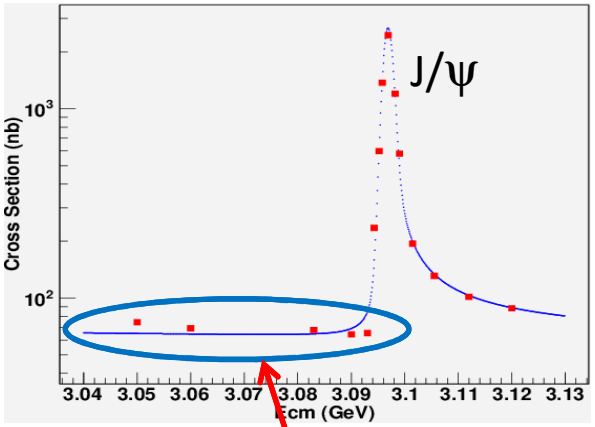
$\sigma_{\mu\mu}$: can be precisely calculated(QED). Measurement of R is to measure the total $\sigma(e^+e^- \rightarrow \text{hadrons})$

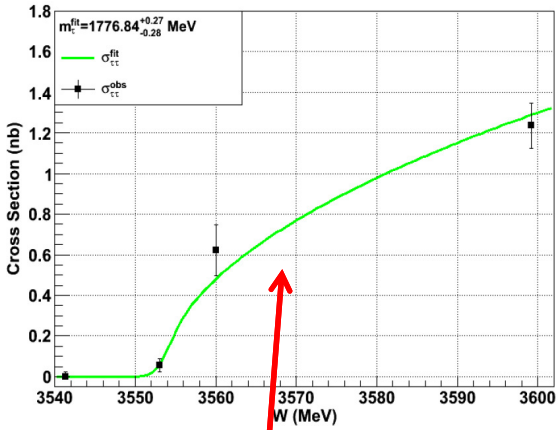
Except for controlling each item to the precision requested, stable long term machine and detector performance is crucial.

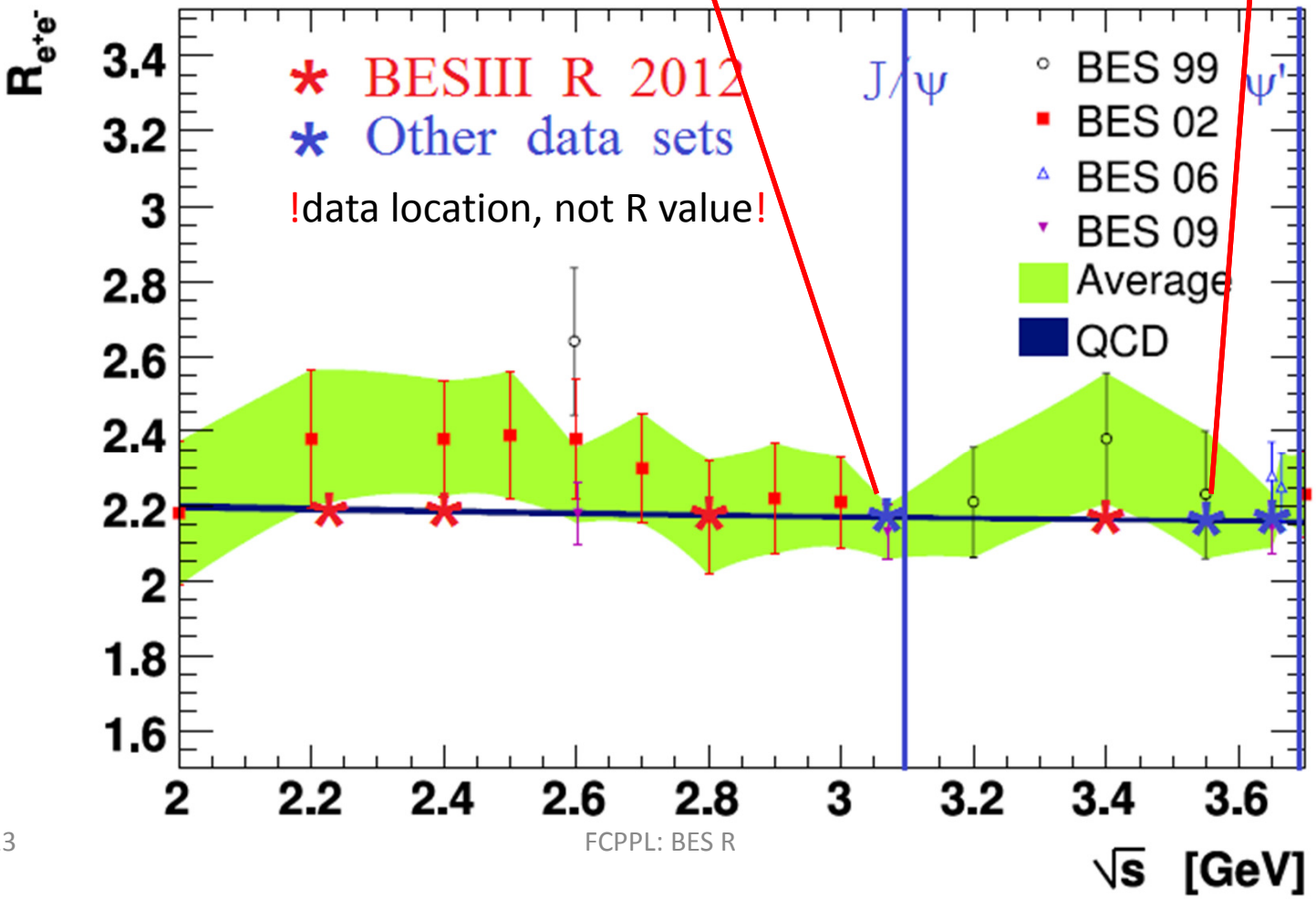
First R-QCD Run at BESIII

- 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;
- The data being used for MC generator tuning;
- Necessary to establish analysis chain;
- Baryon form factors, fragmentation function study underway.

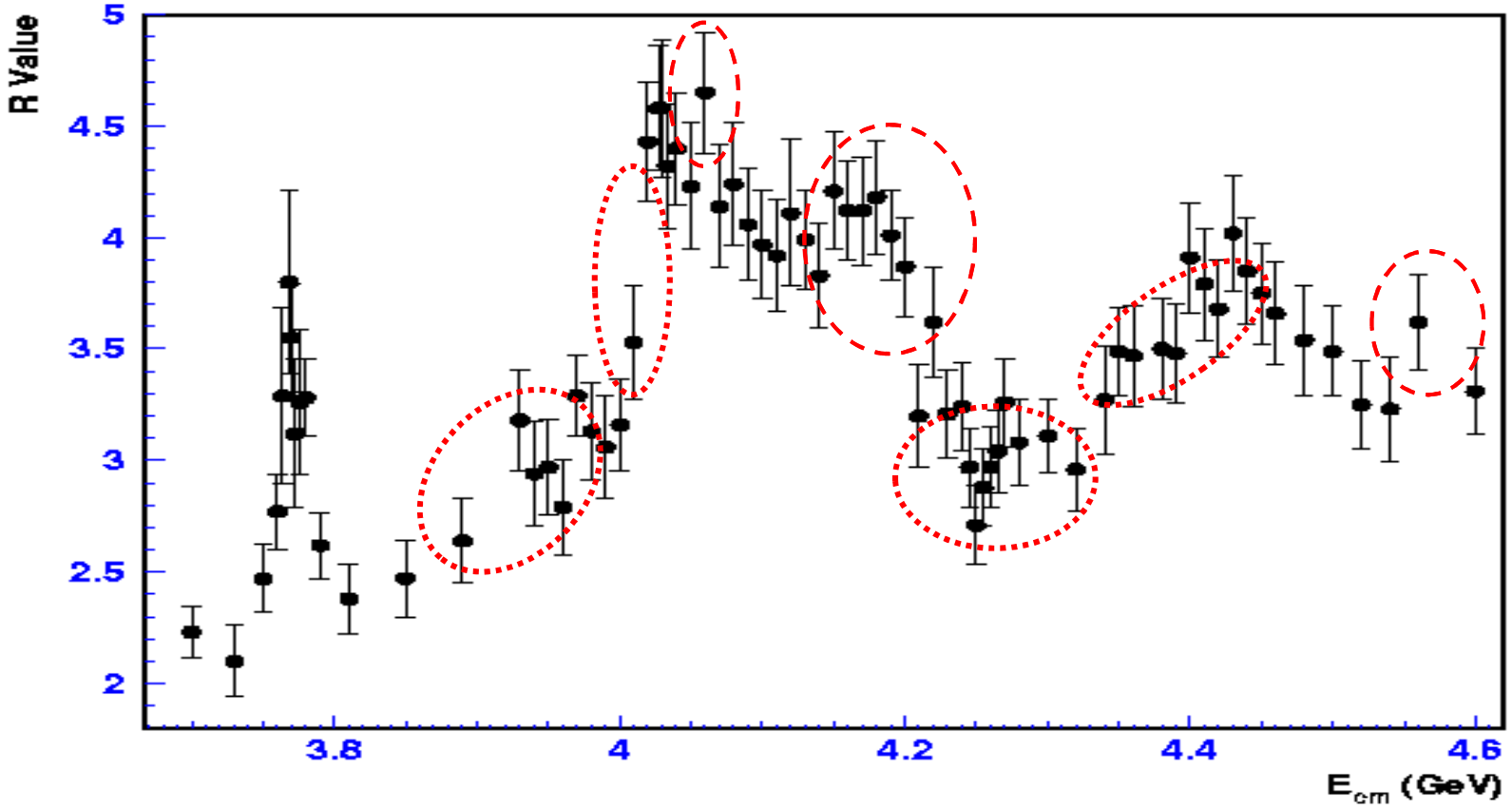
BESIII continuum data overview







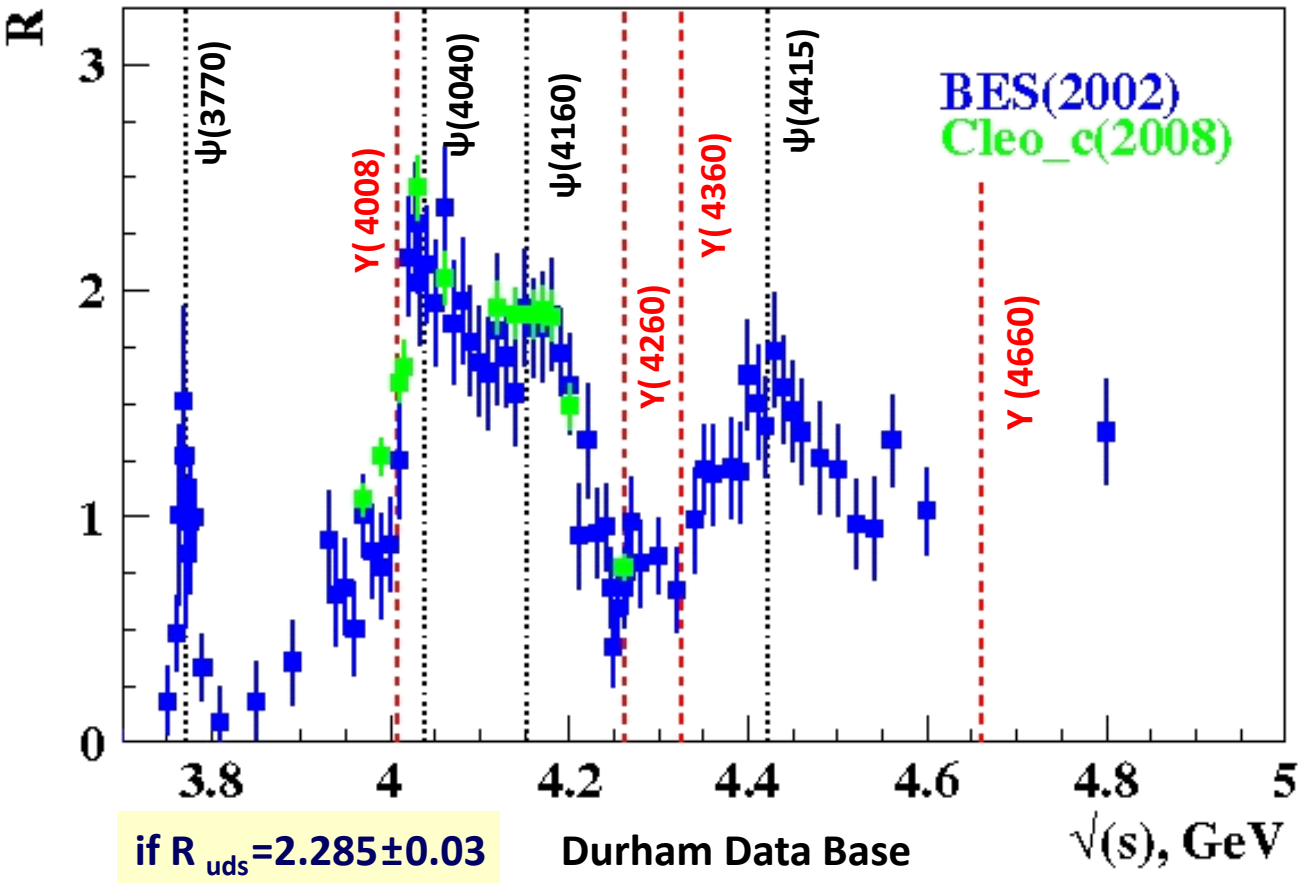
Resonance Structure in High Energy Region



- What are these broad resonances?
- Mass resgion where some X, Y, Z particles are found.
- Possible new resonance that not yet discovered?

Y states vs Inclusive Cross Section $e^+e^- \rightarrow hadrons$

$$R(s) = \sigma(e^+e^- \rightarrow hadrons)/\sigma(e^+e^- \rightarrow \mu^+\mu^-) - R_{uds}$$

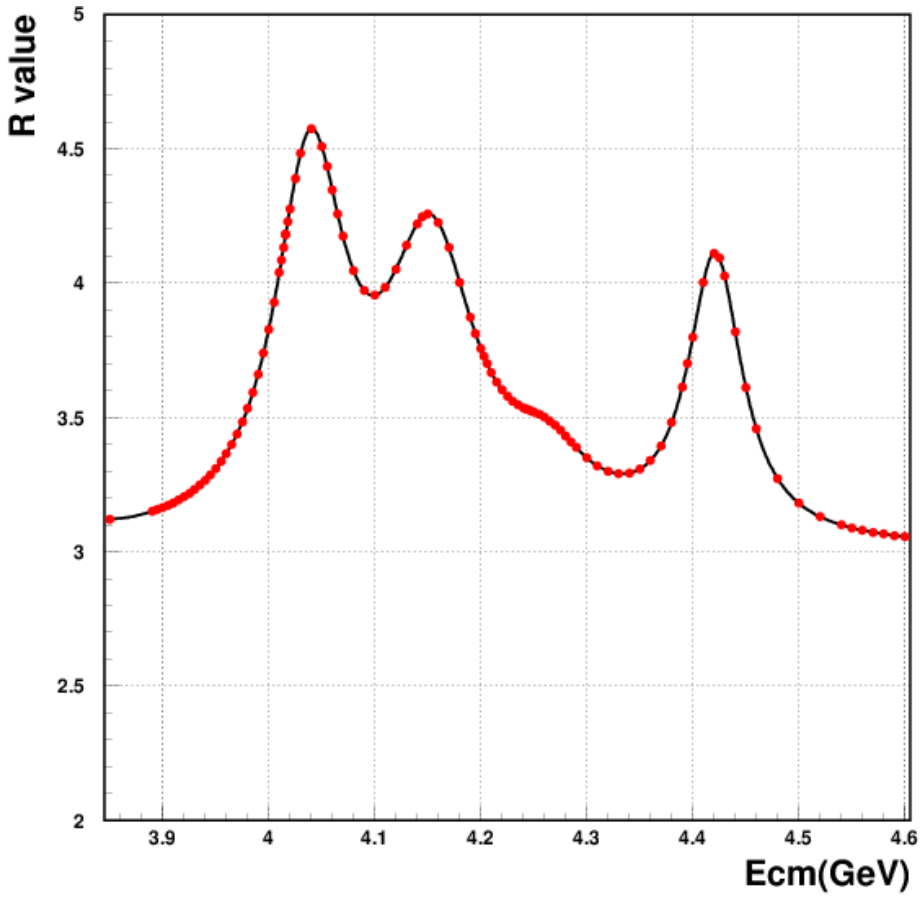


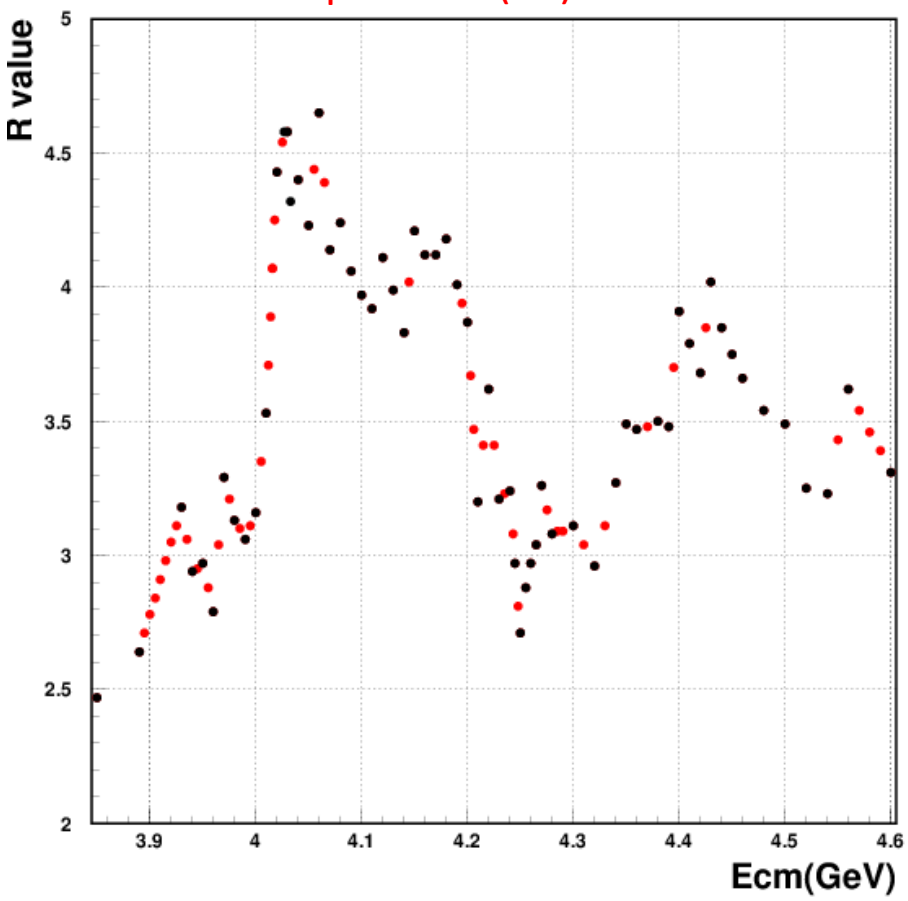
- Peak positions for M(J/ψππ) & M(ψ(2S)ππ) significantly different
- Y(4260) mass corresponds to dip in inclusive cross section

Run Plan: R Scan above 3.85 GeV

105 in total, 100k events each

- R measured by BESII (63)
- R interpolated (42)





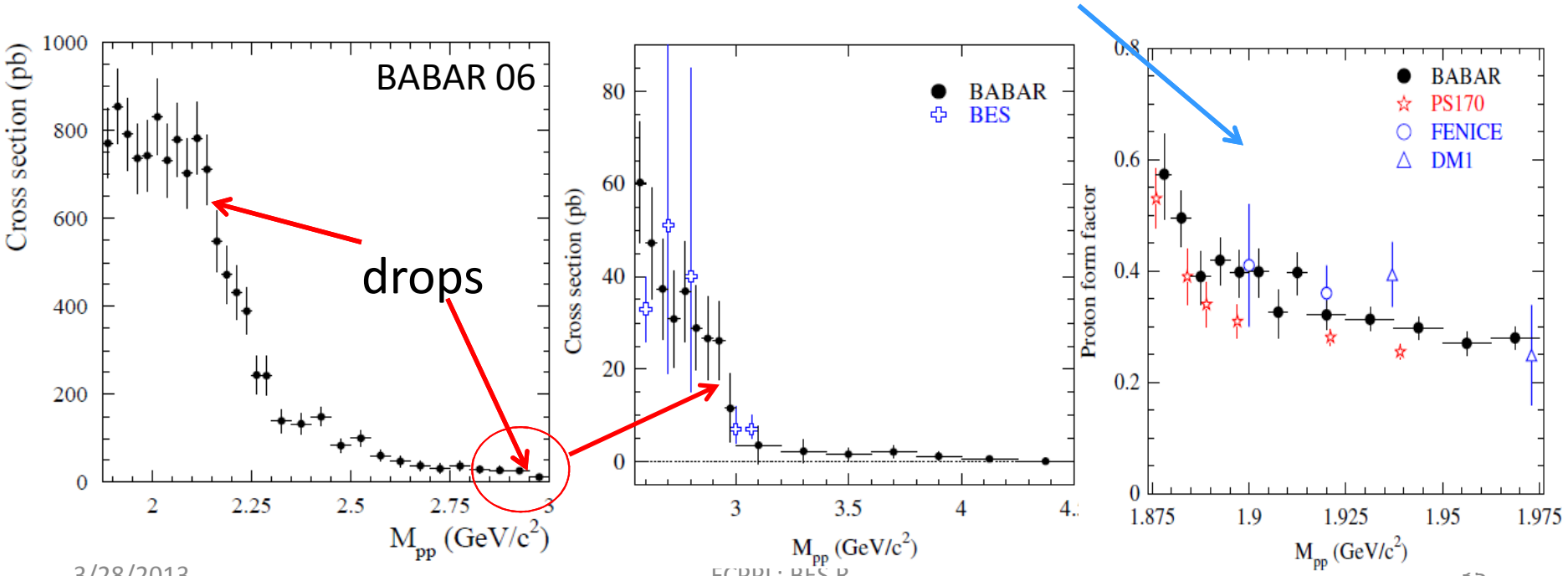
Low Energy Region: R and Beyond

E_{cm} (GeV)	N_{had} (10^5)	L (pb^{-1})
2.000	1.0	4.17
2.100	1.5	6.28
2.200	2.0	8.42
2.300	3.0	13.3
2.400	3.5	16.3
2.500	4.0	19.6
2.600	5.0	25.7
2.700	5.0	33.3
2.800	7.0	43.0
2.900	8.0	50.4

- For R, 10k hadronic events is enough;
- ~1000 observed $p\bar{p}$ events each point;
- To measure proton $|G_E/G_M|$;
- Highly desired for baryon (p, n, Λ, …) form factor studies;

Other Optional Projects

- Finer scan around 2.15 GeV: Y(2175)? Where there is also a drop in the pp invariant mass;
- And another drop at 2.9 GeV;
- To explore even lower energy 1.8–2 GeV.



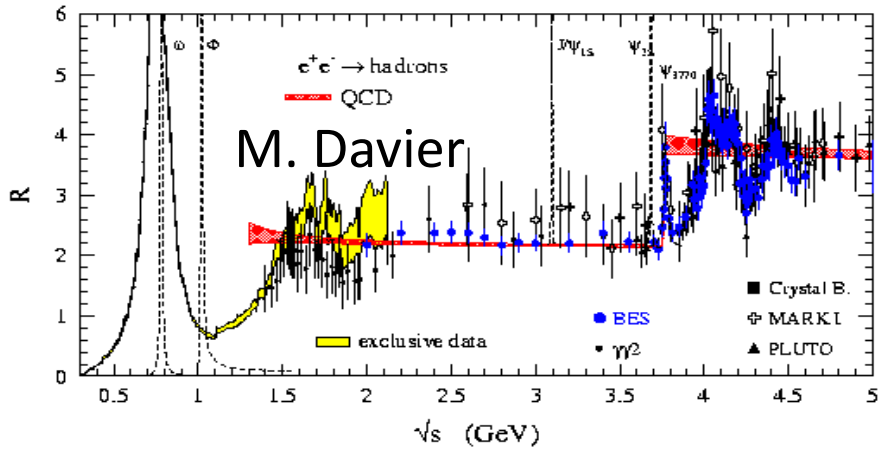
R Value and QCD Studies

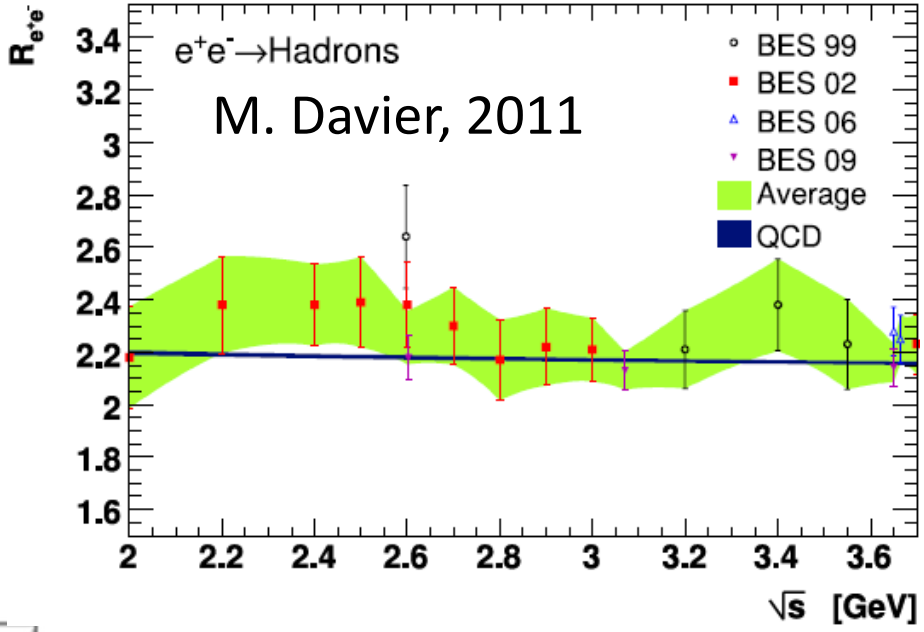
- R, α_s and charm quark mass
- Quark fragmentation functions
- Form factor of baryon (p, n, Λ, …)
- MLLA/LPHD predictions

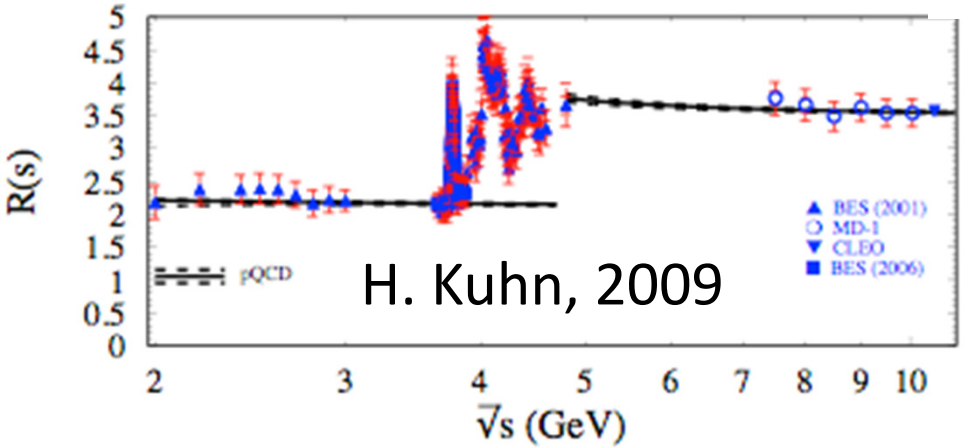
  - ξ distribution (ξ=-ln(2p/$\sqrt{s}$), parameter Λ & KLPHD

  - Multiplicity, 2nd binomial moment R_2

R (pQCD) and R (BES)

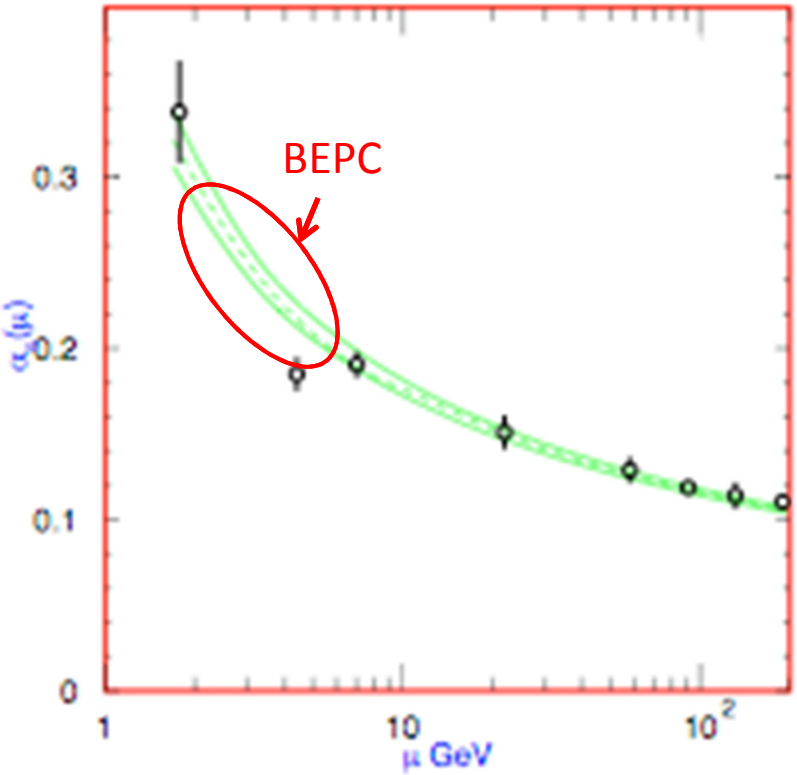


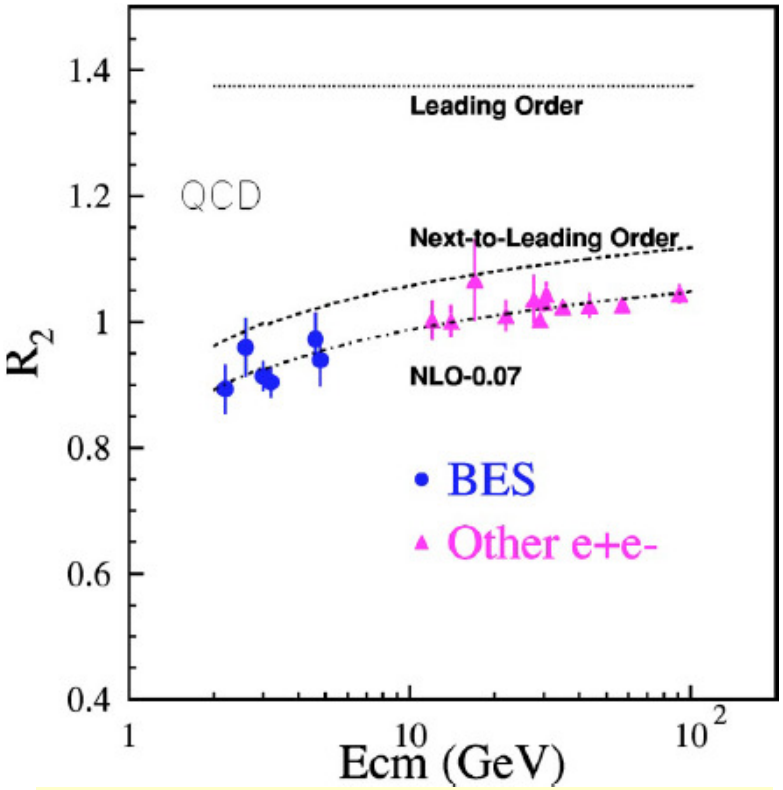




- pQCD calculation agrees well with BES data,
- with slight deviation in 2.2–2.5 GeV.

α_s and R_2





PDG10: $\alpha_s(M_Z)=0.1184\pm0.0007$

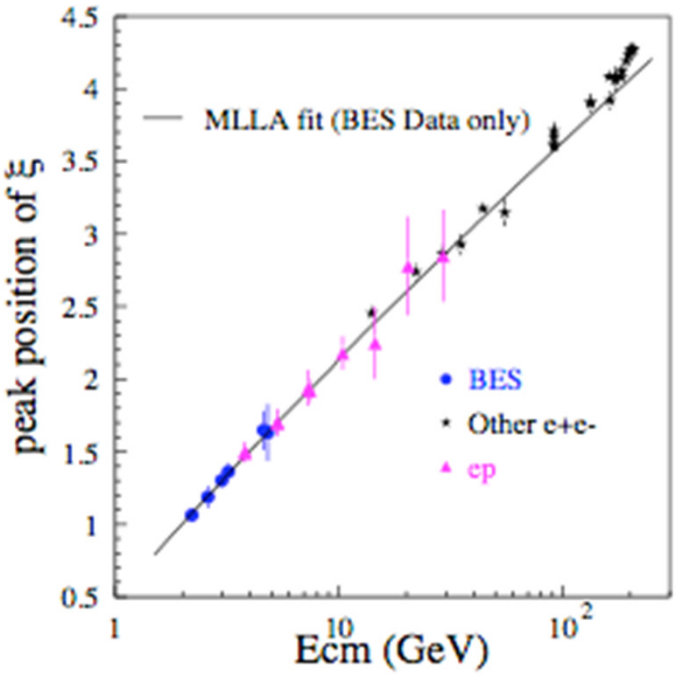
BESII $\sqrt{s}$=2.60, 3.07, 3.65GeV

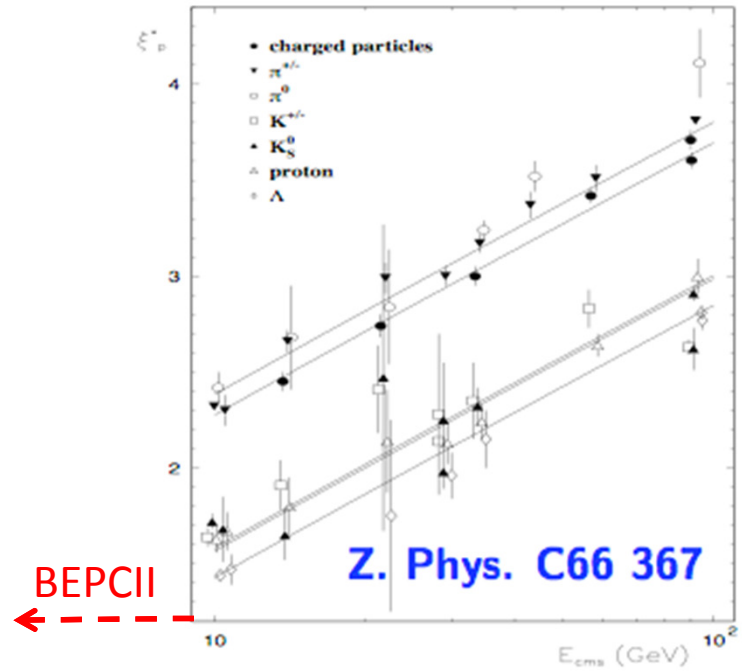
$\alpha_s(M_Z)=0.117^{+0.012}_{-0017}$

$$R_2 \equiv \frac{\langle n_{ch}(n_{ch}-1)\rangle}{\langle n_{ch}\rangle^2} = \frac{11}{8}(1-c\sqrt{\alpha_s(s)})$$

$$c=(4455-40n_f)/1728\sqrt{6\pi}$$

MLLA/LPHD Predictions



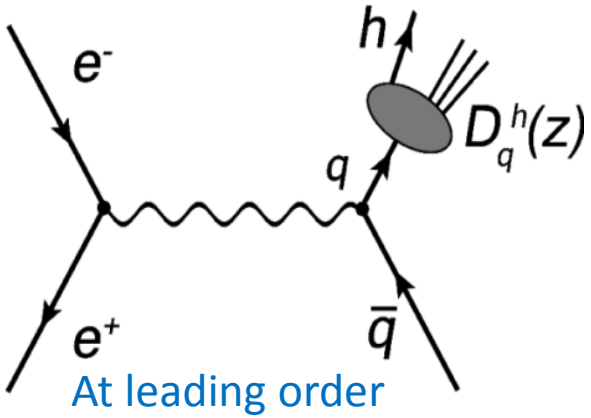


BESII R scan data: PRD69 (2004) 072002 for inclusive charged particle.

Consistant with high energy ep data at 5% level.

- Pretty large uncertainty
- No exclusive data yet
- BESIII can contribute

Fragmentation Function



At leading order

Fragmentation function $D^h_q(z)$: probability that hadron h is found in the debris of a parton (quark/gluon) carrying a fraction $z = 2E_h/\sqrt{s}$ of parton's energy.

LO: $d\sigma(e^+e^- \rightarrow h+X)/dz=\sum_q \sigma(e + e- \rightarrow q\underline{q})(D^h_q(z) + D^h_{\underline{q}}(z))$

No good data at $\sqrt{s} < 10$ GeV

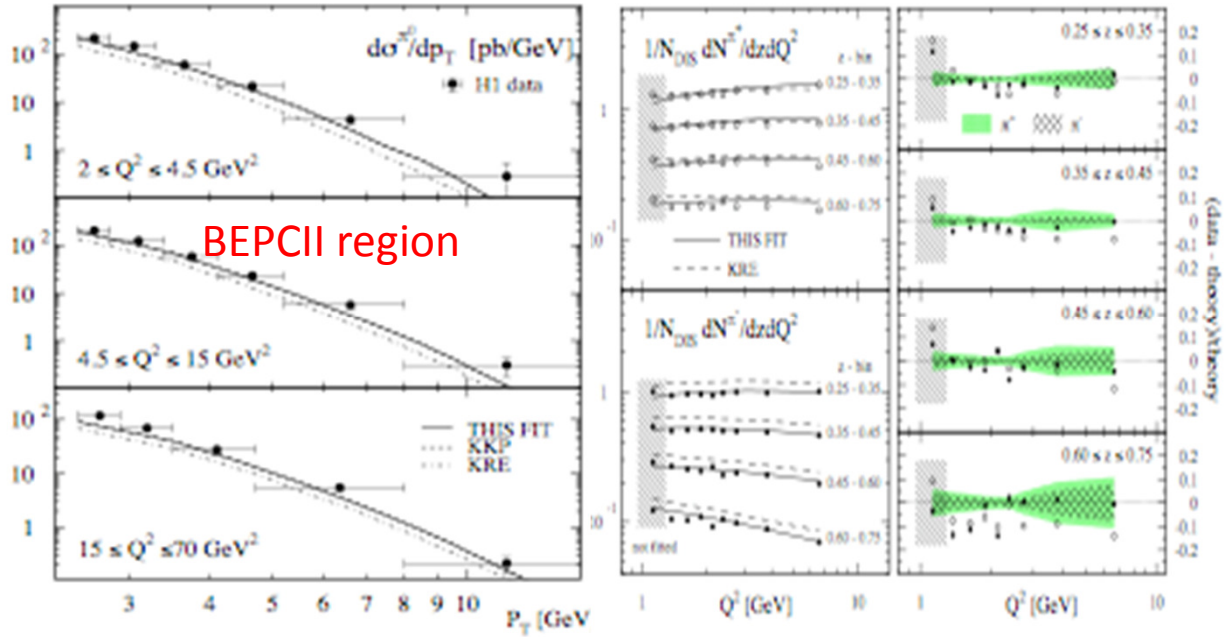
- DASP: $\pi^{\pm}$ at 3.6GeV; average stat. uncertainty 18%
- DASP: $k^{\pm}$ at 3.6GeV; average stat. uncertainty 55%

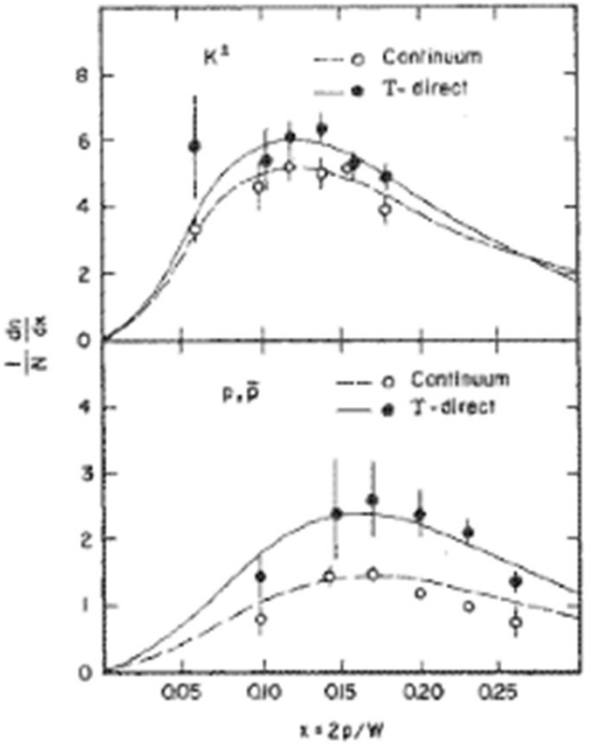
Frangmenation Function

ep collision, H1 data

Fix target experiment HEMES

CLEO





BESIII can provide e^+e^- data in 2-5 GeV

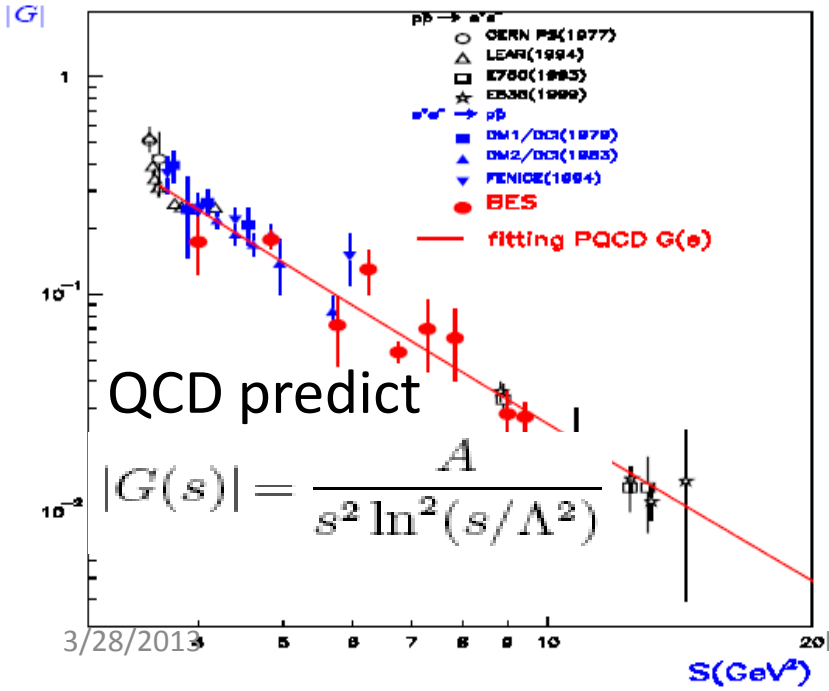
Form Factor: $p\bar{p}$

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

$$G_E = F_1 + \tau F_2 \qquad G_M = F_1 + F_2$$

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

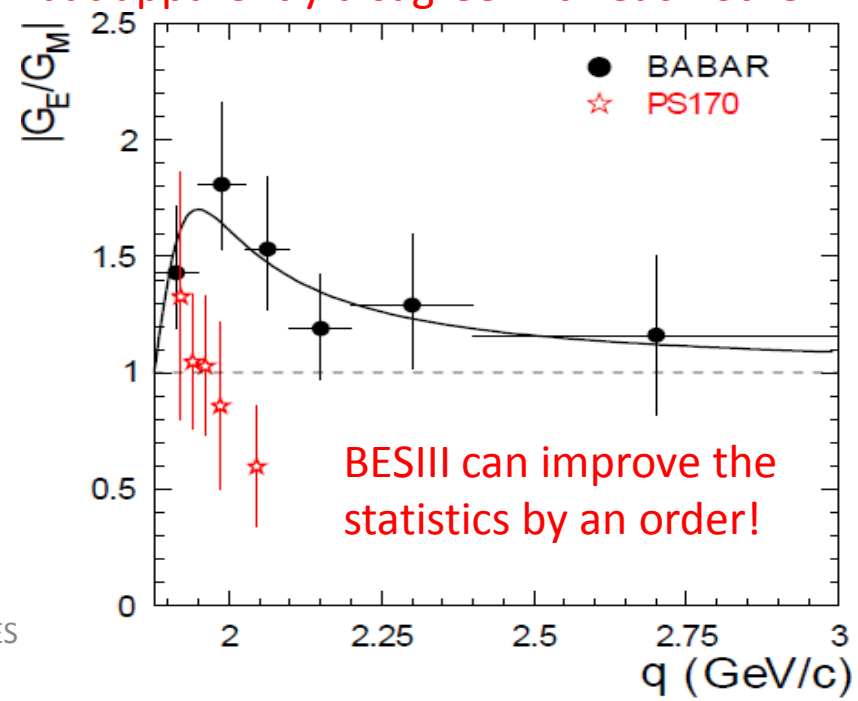
Most measurements assume G_E=G_M.



QCD predict

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

Only 2 experiments measured $|G_E/G_M|$, but apparently disagree with each other.



More on Form Factor

Puzzles related to proton timelike FF:

- Proton FF factor 2 higher in Timelike region compared to Spacelike Region (pQCD precicts them to be equal)

- Neutron FF ~ factor 2 higher than proton FF → measurement of Neutron FF at BESIII very important

- Steps at 2.2 and 2.9 GeV

- Threshold enhancement

Summary

- BEPCII/BESIII has been in excellent status;
- New 0.4B $\psi(2S)$, 1B J/ψ added to already largest samples;
- ~0.5 fb^{-1} @ 4.26, 4.36 GeV, and more is taking @ 4.26 GeV;
- Zc(3900) observed with ~0.5 fb^{-1} @ 4.26 GeV;
- BES reduced R uncertainty in 2–5 GeV to ~6% (a factor of 2~3);
- Precision R measurement still helps in $a_{QED}(M_Z)$ and a_μ evaluation, and a ~3% precision is expected at BESIII;
- BESIII collected data at 4 points in the low energy region;
- A detail scan between 3.8 GeV to 4.6 GeV is in plan;
- High statistics data in 2 – 3 GeV will significantly improve measurements like proton form factor, event shapes, etc.