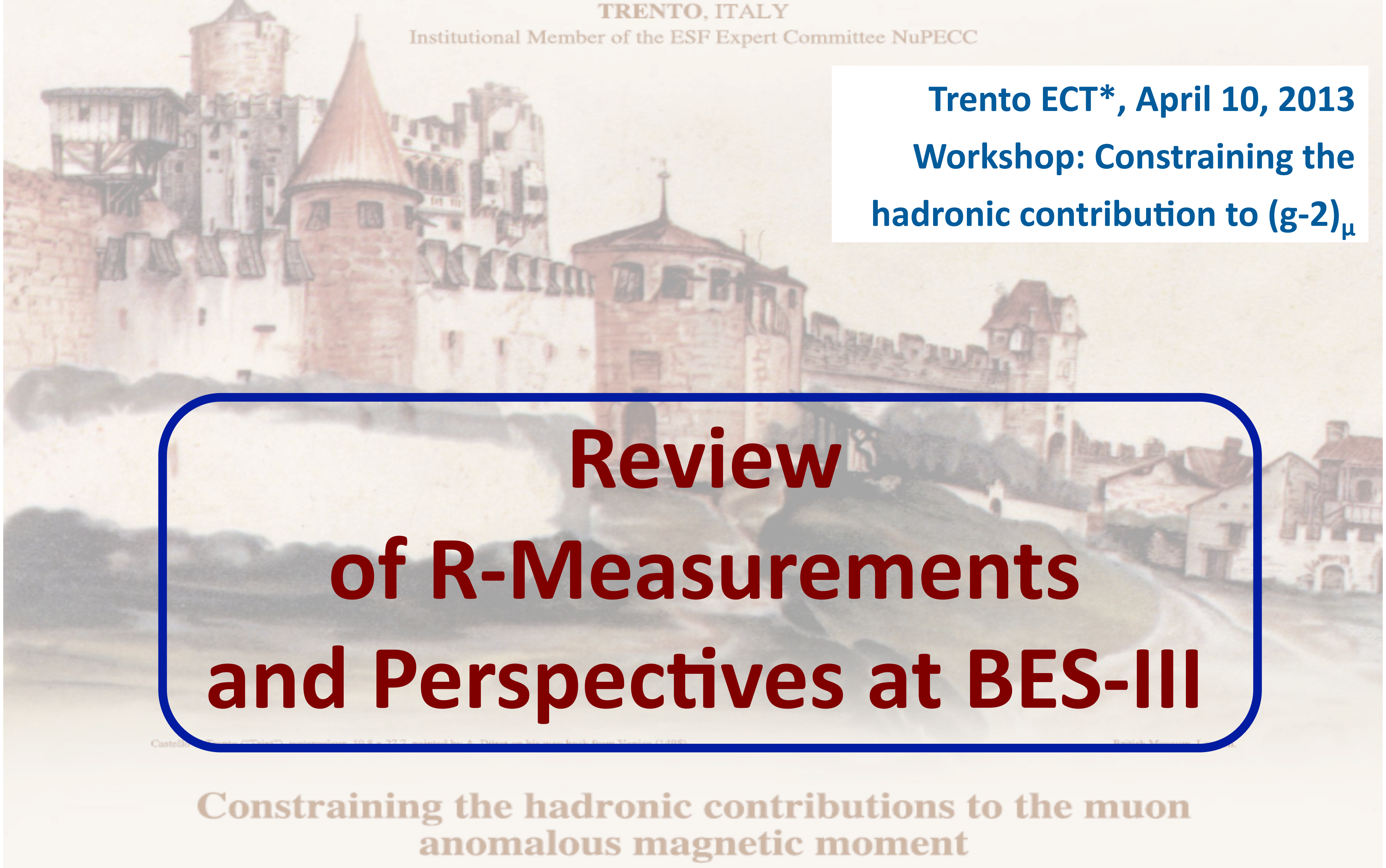


Trento ECT*, April 10, 2013
Workshop: Constraining the
hadronic contribution to $(g\text{-}2)_\mu$

Review of R-Measurements and Perspectives at BES-III

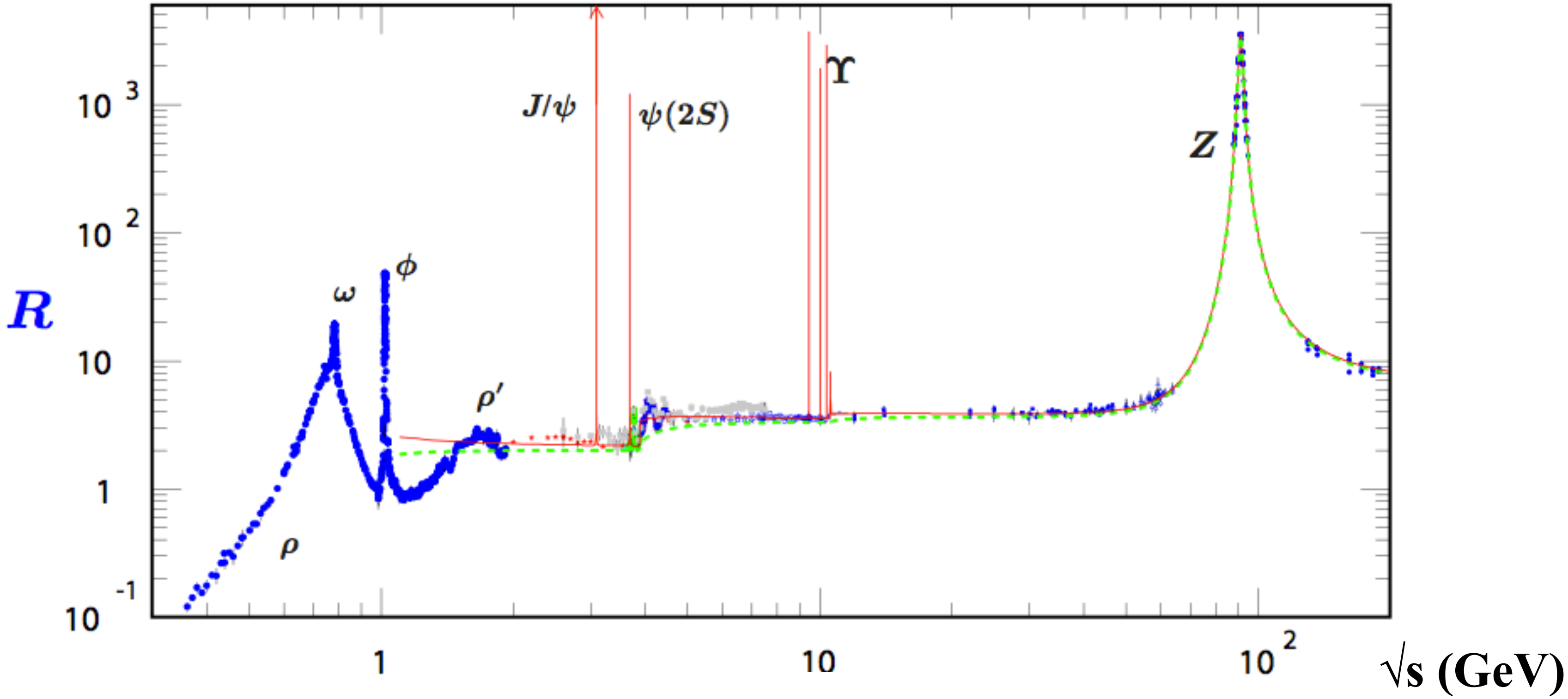
Achim Denig
University of Mainz
Institute for Nuclear Physics

The R Ratio

$$R = \frac{\sigma^{(0)}(e^+e^- \to \text{hadrons})}{\sigma^{(0)}(e^+e^- \to \mu^+\mu^-)}$$

R lead to formulation of Standard Model

- **Number of colours $N_c = 3$**
- **Number of quark flavours $N_f > 2$**



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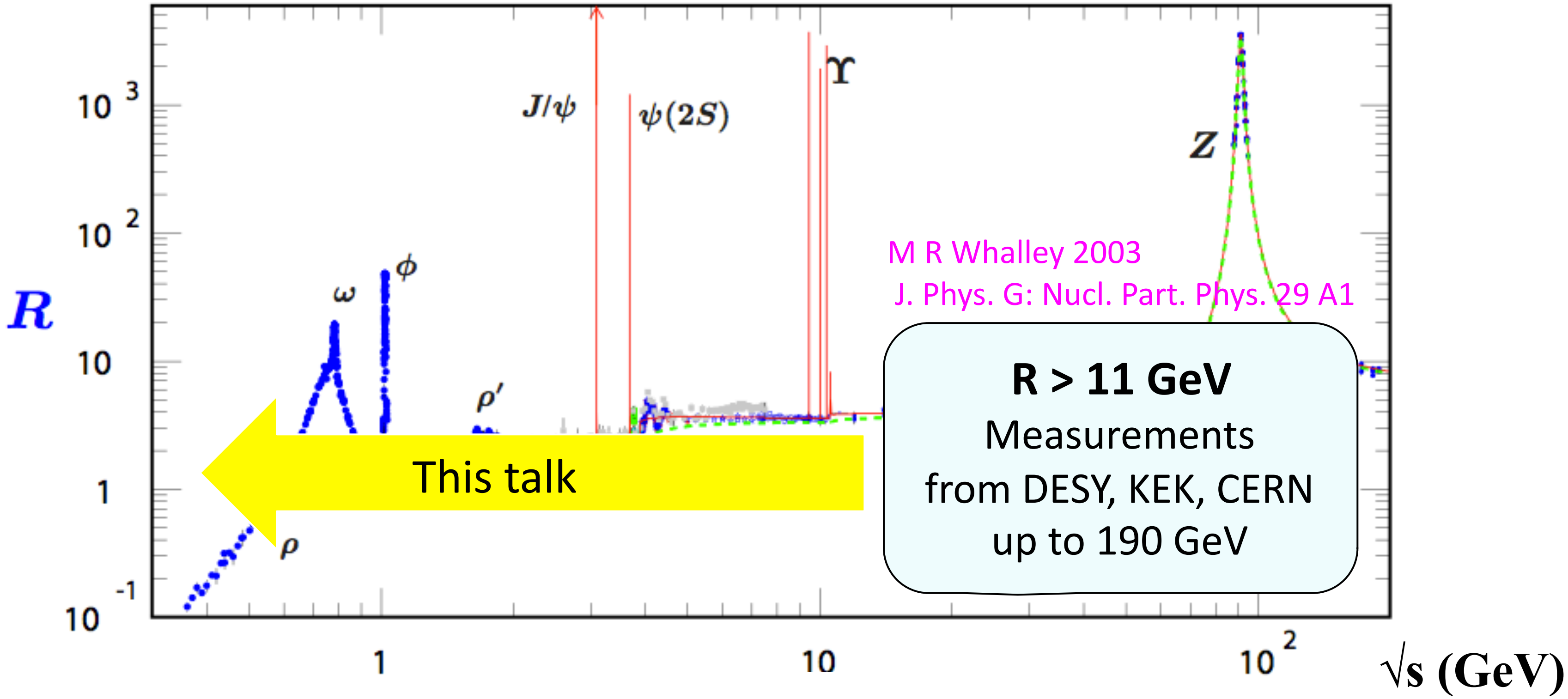
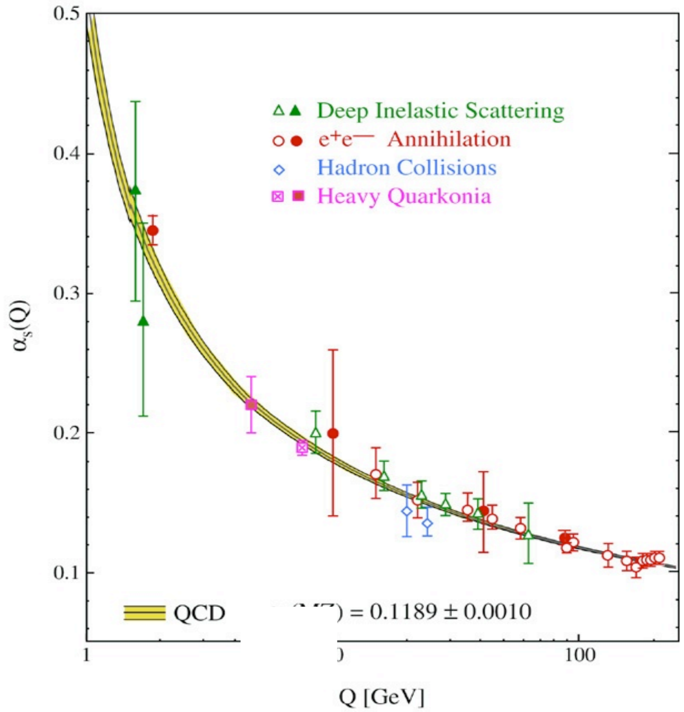
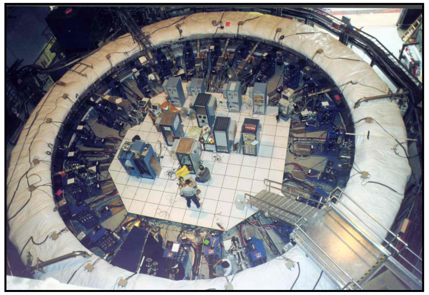
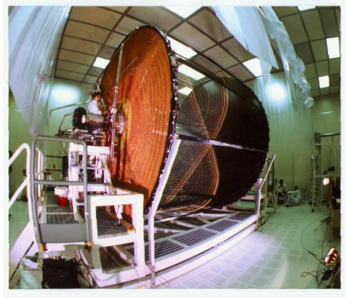


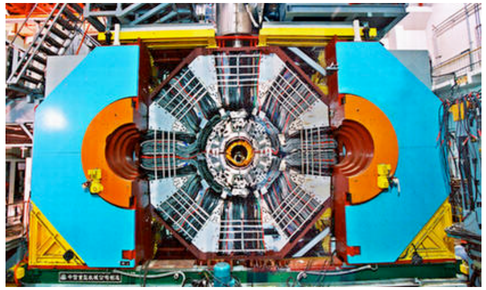
Extracting Fundamental Parameters of QCD from R Measurements

- **Extraction of quark masses (c, b)**
- **Chiral condensates**
- **Extraction of strong coupling constant**
- **Hadron spectroscopy**
- **Timelike nucleon EM Form Factors**

.....





Outline

- **Motivation: $(g\text{-}2)_\mu$ & $\alpha_{QED}(M_Z^2)$**
- **Results Energy Scan**
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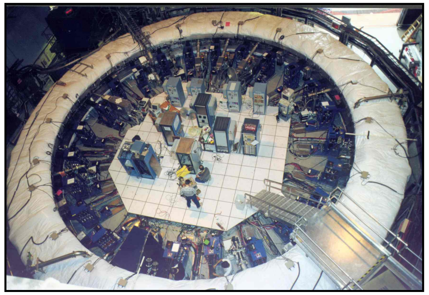
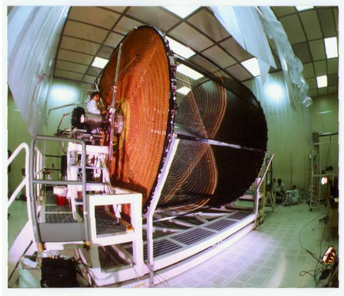
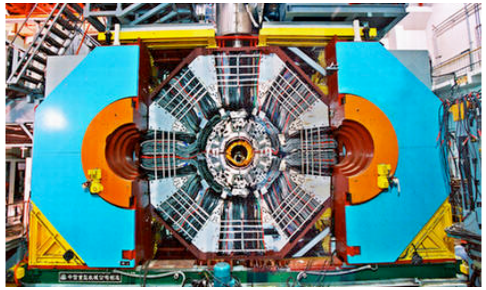
- **Conclusions and Future Perspectives**







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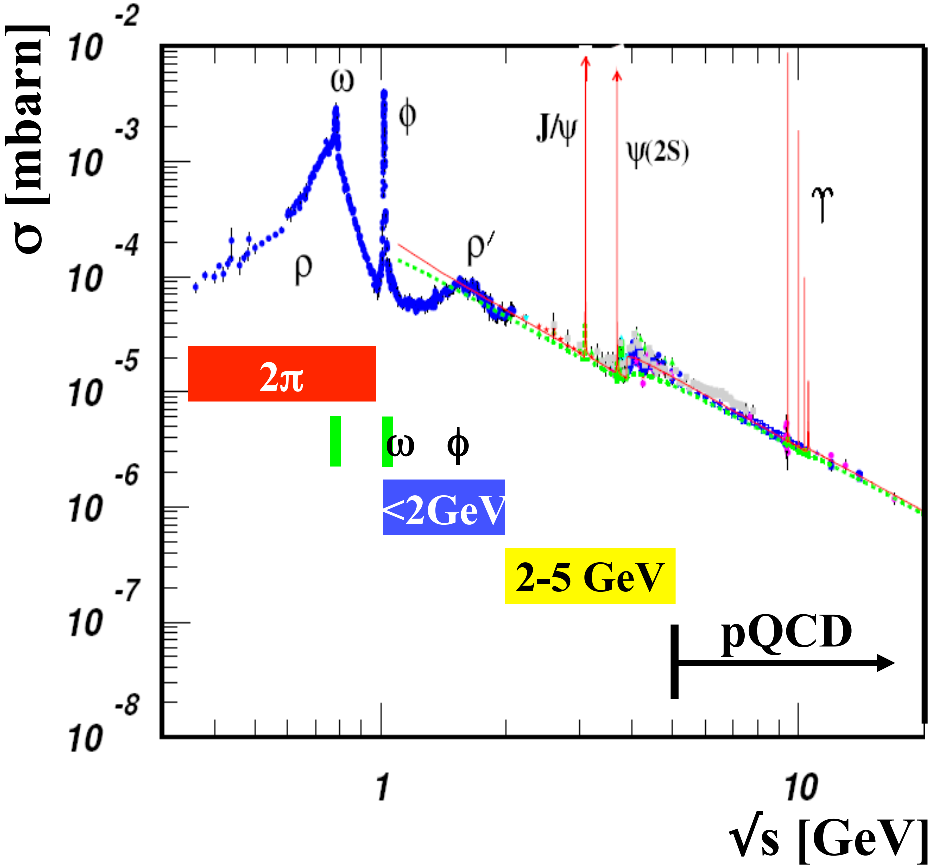
Hadronic Cross Section Data and $(g\text{-}2)_\mu$

Determine the hadronic contriution to $a_\mu=(g\text{-}2)_\mu$

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



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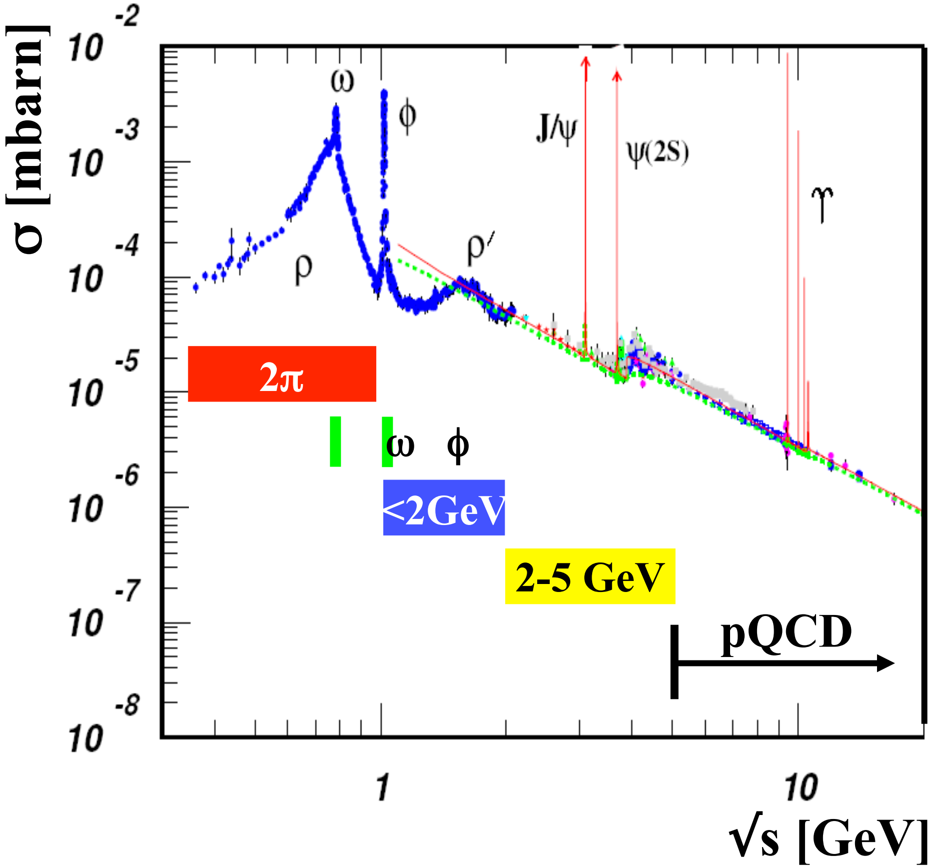
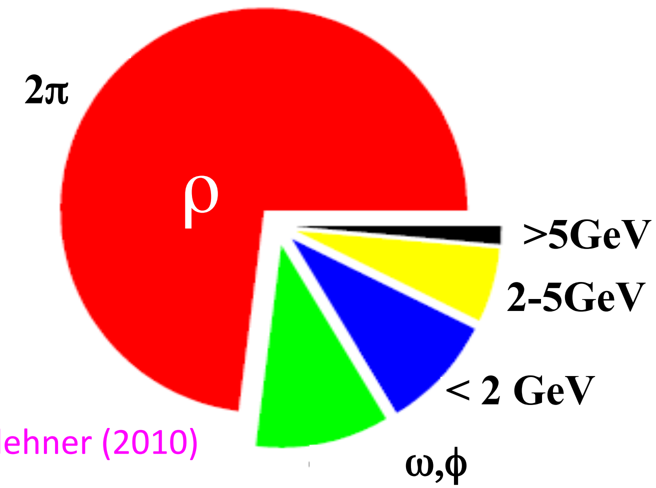
$$a_\mu^{had} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had}$$

Intrinsic ~ $1/s^2$
low energy contributions
especially important!

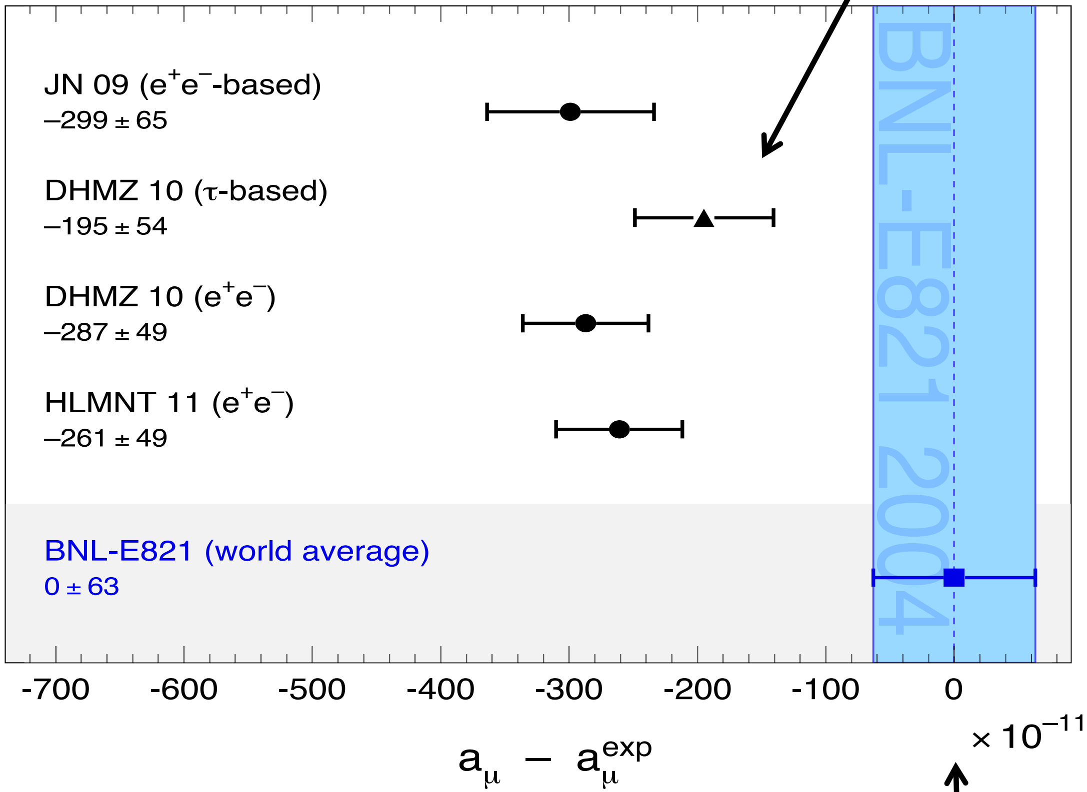




Jegerlehner (2010)

Muon Anomaly $(g\text{-}2)_\mu$

Standard Model predictions $(g\text{-}2)_\mu$



E821 measurement of $(g\text{-}2)_\mu$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} =$$

$$(28.7 \pm 8.0) \cdot 10^{-10} \quad (3.6\ \sigma)$$

Error(s) or New Physics ?

Muon Anomaly $(g\text{-}2)_\mu$

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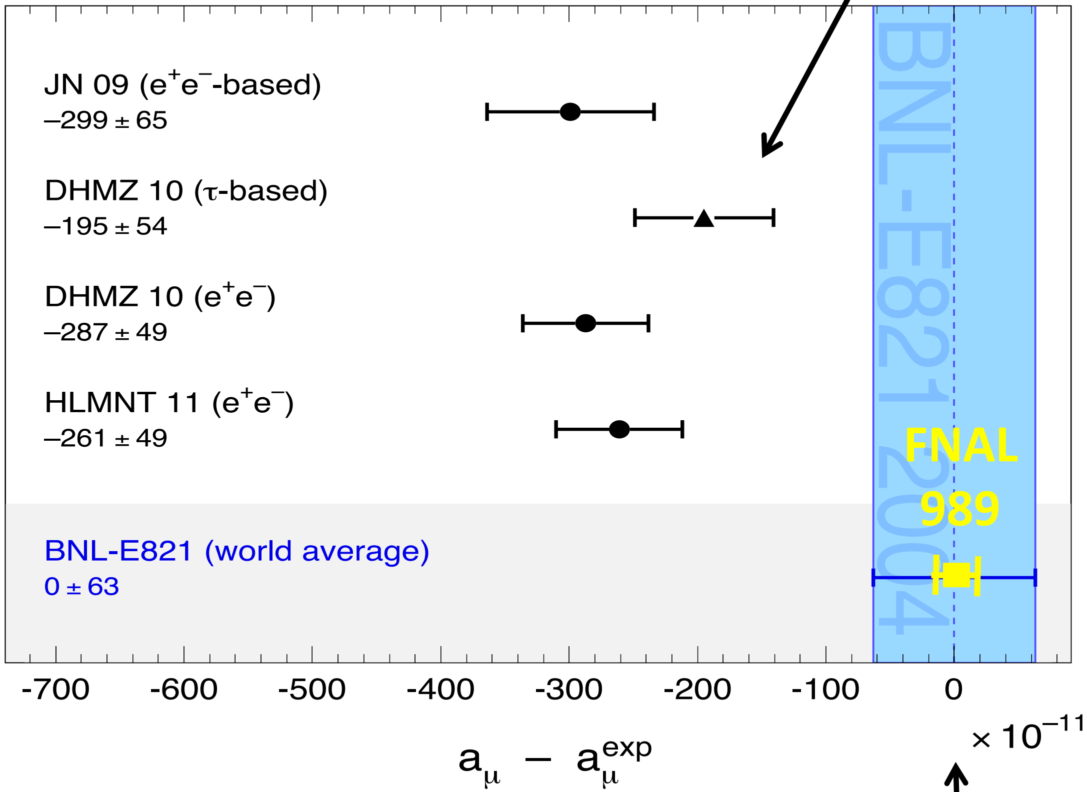

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$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} =$

$(28.7 \pm 8.0) \cdot 10^{-10}$ $(3.6\ \sigma)$

Error(s) or New Physics ?

New FNAL 989 $(g\text{-}2)_\mu$ measurement (2015):

Factor 4 improvement
in experimental error

Hadronic Cross Section Data and $\alpha_{em}(M_Z^2)$

JG|U

Running of α_{em} (s) with s due to vacuum polarization corrections

- Leptonic Vacuum Polarization calculable within QED
- Hadronic Vacuum Polarization not accessible in pQCD → **Dispersion relation**

$$\alpha_{\rm em}(s) \quad = \quad \frac{\alpha(0)}{(1-\Delta\alpha_{\rm em}(s))} \qquad \alpha^{-1}(M_Z^2) = 128.962 \pm 0.014$$

Davier, et al.(2010)

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Davier, et al.(2010)

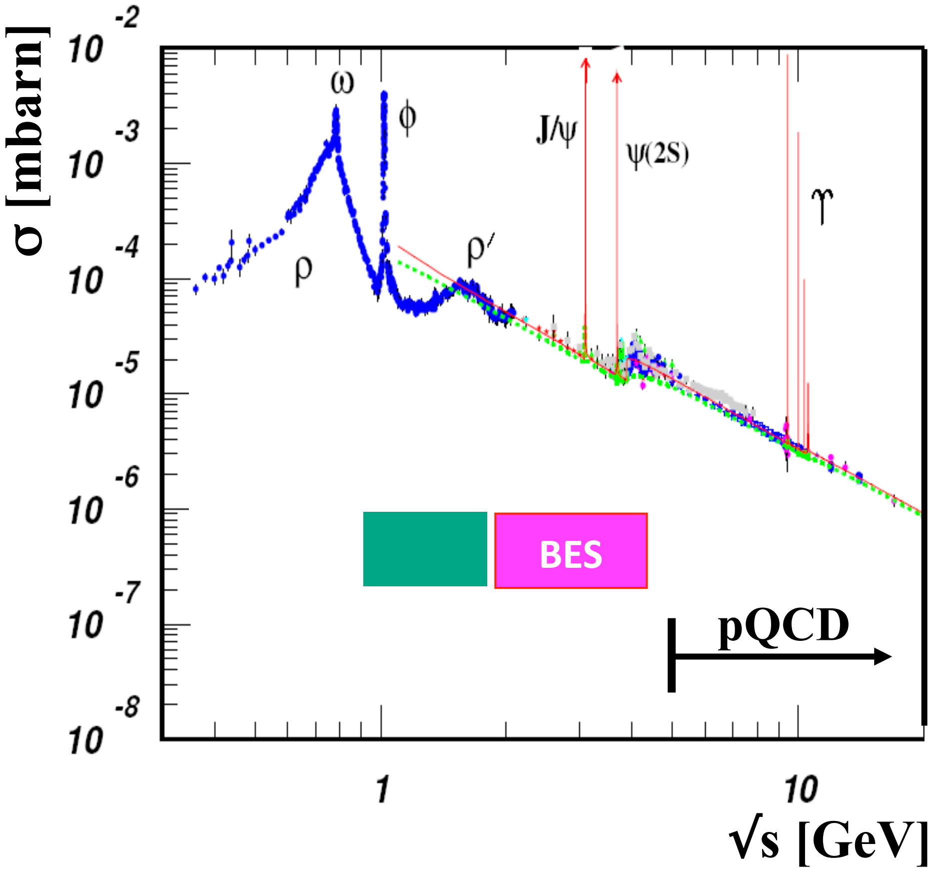
QED $\Delta\alpha_{\rm lep}(M_Z^2) = 314.97686 \cdot 10^{-4}$

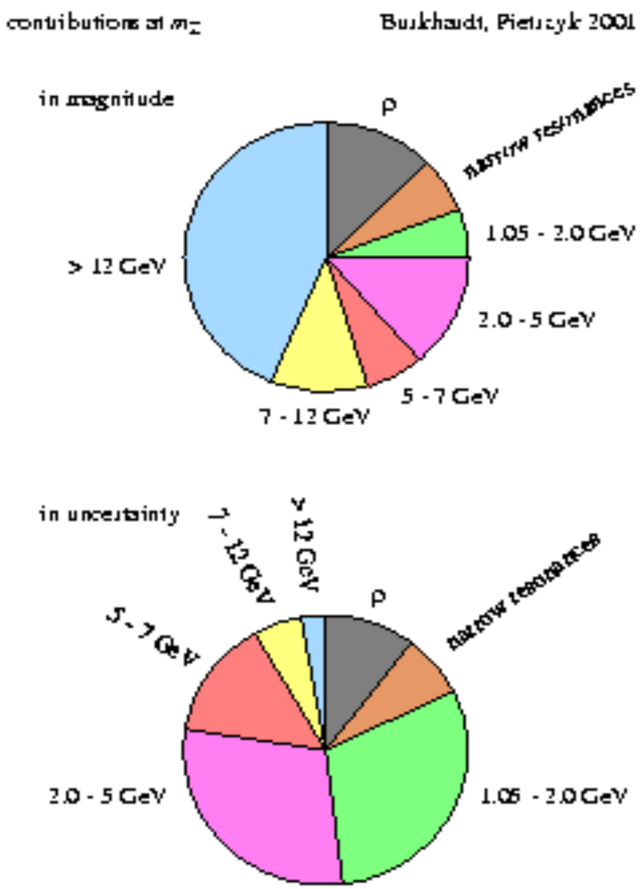
strong $\Delta\alpha_{\rm had}(M_Z^2) = (274.2 \pm 1.0) \cdot 10^{-4}$

dispersion integral relates σ_{had} with $\Delta\alpha_{em}^{had}$

→ R data up to few GeV essential, above use pQCD !

Hadronic Cross Section Data and $\alpha_{em}(M_Z^2)$

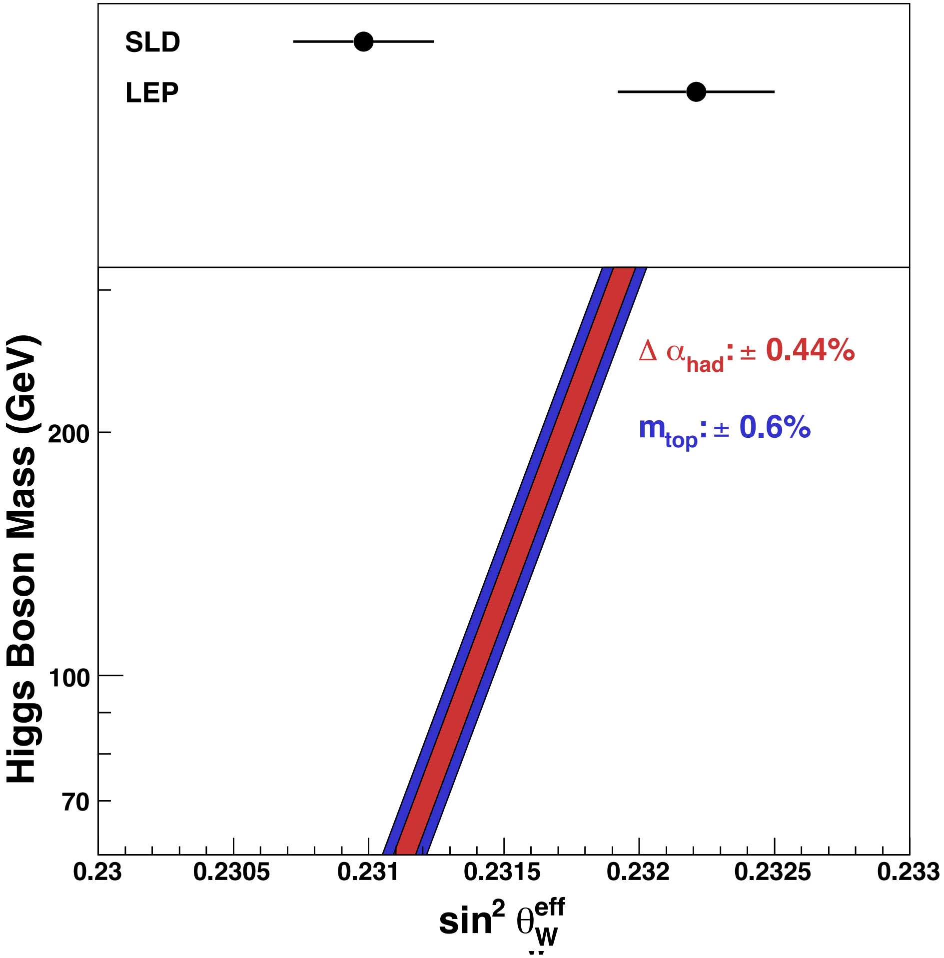




Electroweak Precision Physics

$\alpha_{em}(M_Z^2)$ limiting electroweak precision fits

→ Test overall consistency of the electroweak Standard Model
→ Since the discovery of the Higgs boson more timely than ever



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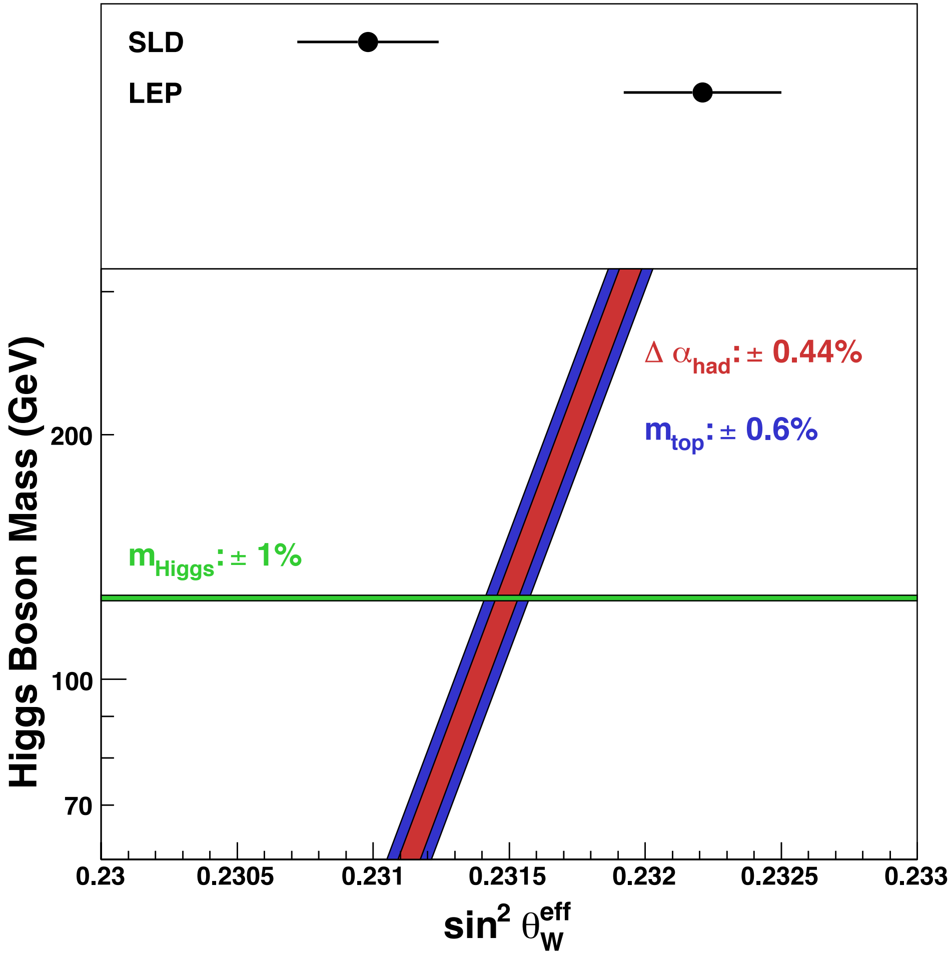

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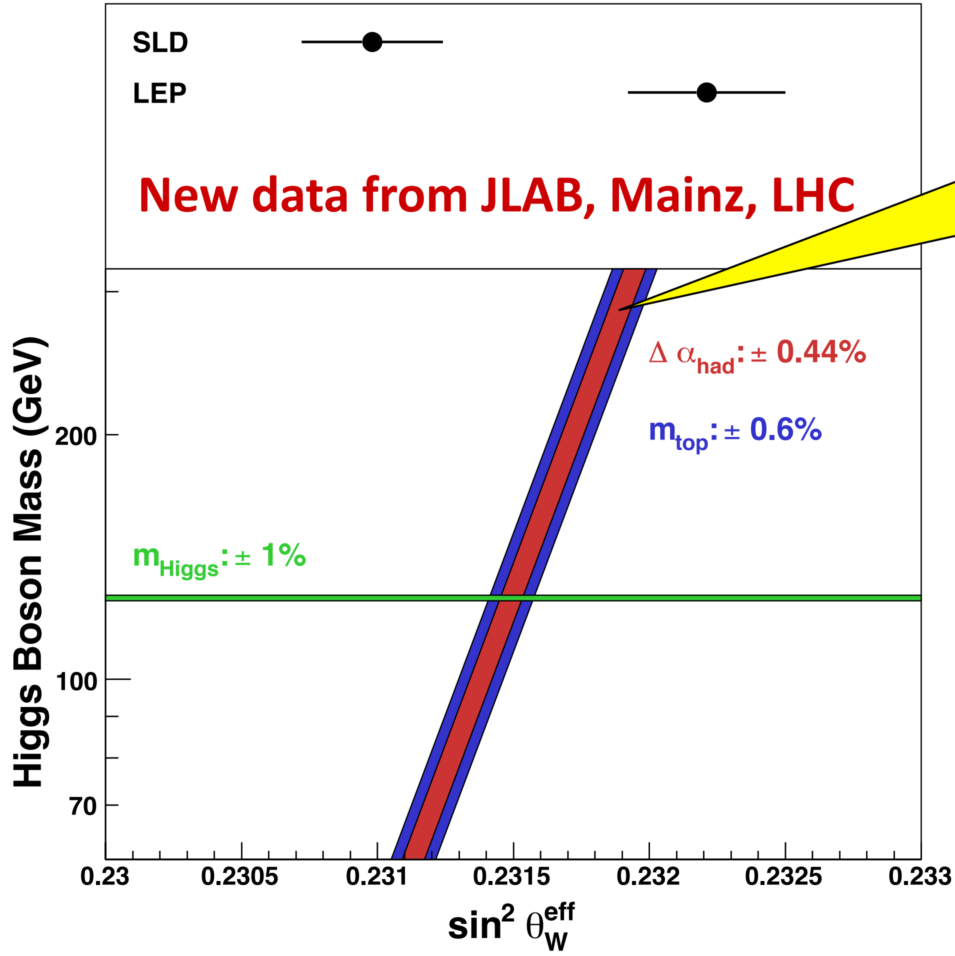
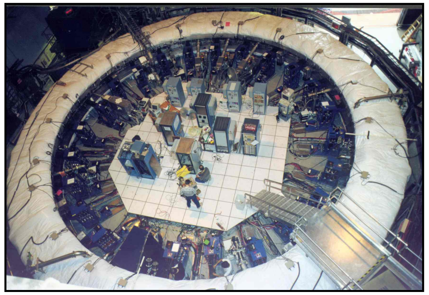
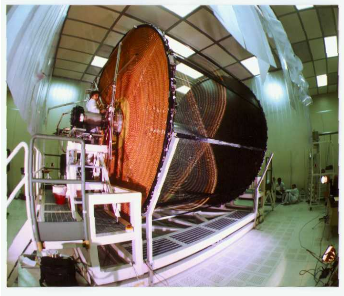
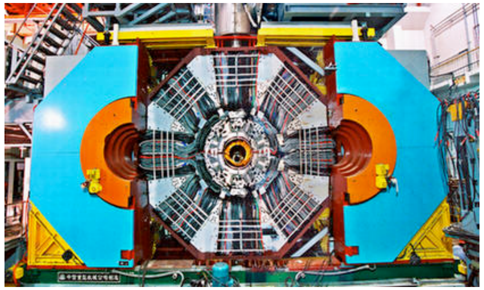


SM running $\sin^2\Theta_W\,(M_{Higgs})$ limited by α_{em}

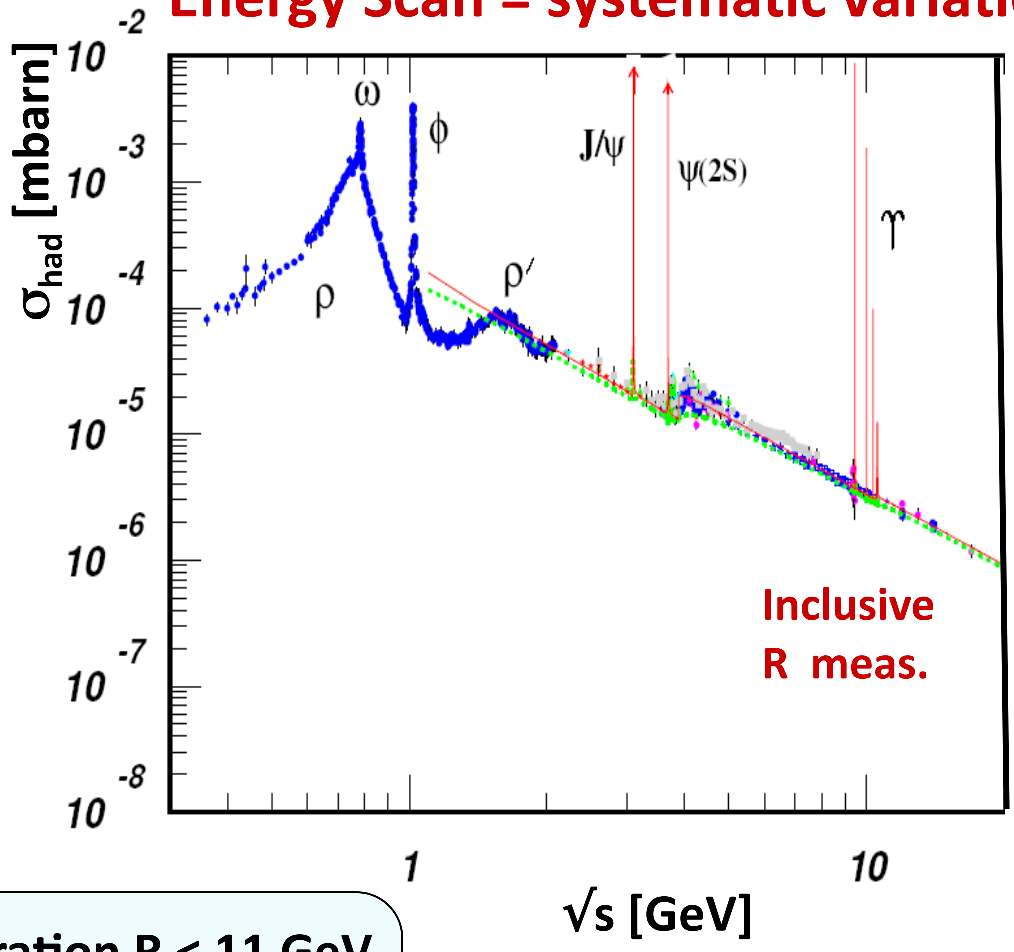


Outline

- Motivation: $(g\text{-}2)_\mu$ & $\alpha_{QED}(M_Z^2)$
- **Results Energy Scan and ISR**
- Perspectives at BES-III
- Conclusions and Future Perspectives

*Hadronic Cross Section via **Energy Scan***

Energy Scan = systematic variation of collider's √s



1^{st} Generation R < 11 GeV
→ 60's, 70's, 80's, 90's
measurements from Orsay, Frascati, SLAC, Novosibirsk

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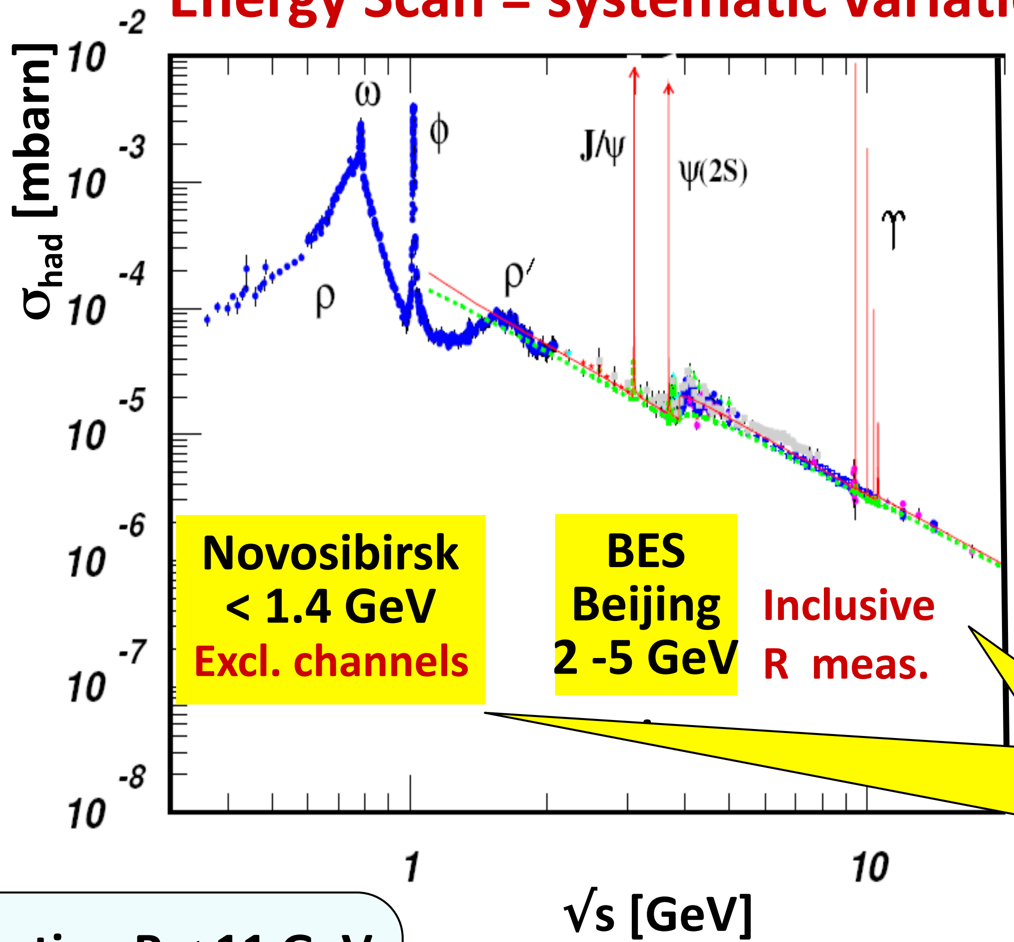
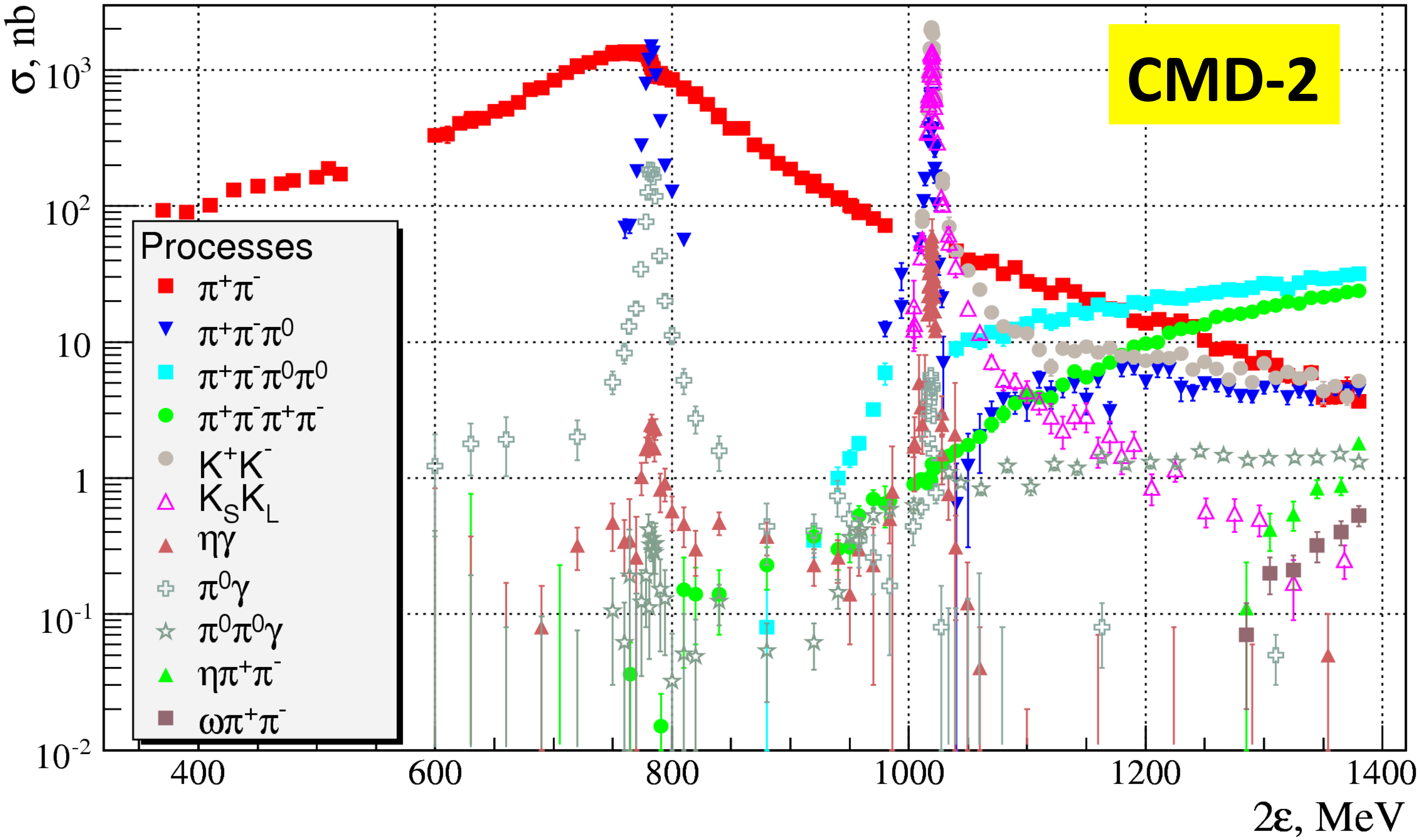


2nd Generation Expts.
→ new millenium
VEPP-2M Novosibirsk
BEPC Beijing

1st Generation R < 11 GeV
→ 60's, 70's, 80's, 90's
measurements from Orsay, Frascati, SLAC, Novosibirsk

Overview Novosibirsk Results

- **CMD-2: $\pi^+\pi^-$ <1%, higher multiplicities few % accuracy**
- **SND measurement of $\pi^+\pi^-$ with 1.2% accuracy**



VEPP-2000: Upgrade towards E_{max}=2.0 GeV

NEW

VEPP-2000 (since 2010):

- Upgrade towards E_{max}=2.0 GeV
- $L_{max} = 1 \cdot 10^{32}$ cm^{-2} s^{-1} at 2 GeV
- Upgrade of detectors CMD-3, SND

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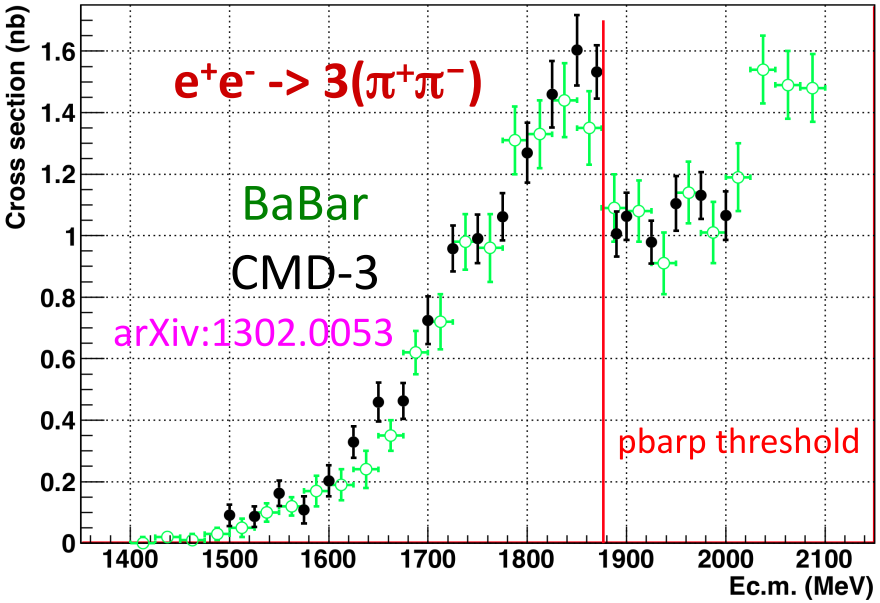
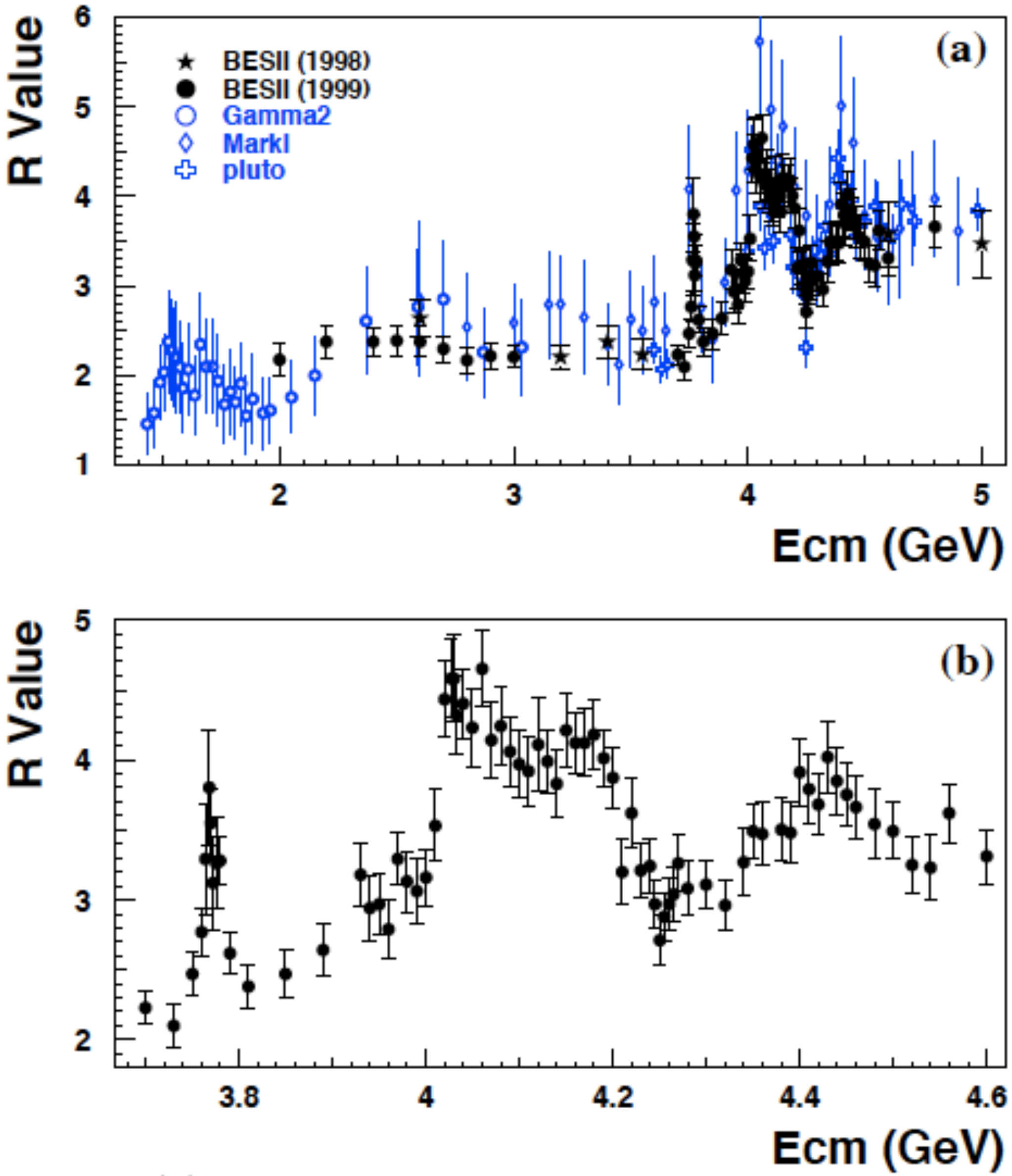


Brief History of BES R Measurements

- 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 $\psi(3770)$, 2 points off-resonance, 1 on-resonance, PLB641, 145 (2006);
- Improvements at 3 continuum points, PLB677, 239 (2009).

BEPC: $\sigma_{incl}(e^+e^- \rightarrow Hadrons)$



Results

- 3-5 % statistical accuracy per scan point
- Systematic uncertainty: ~5 …8%

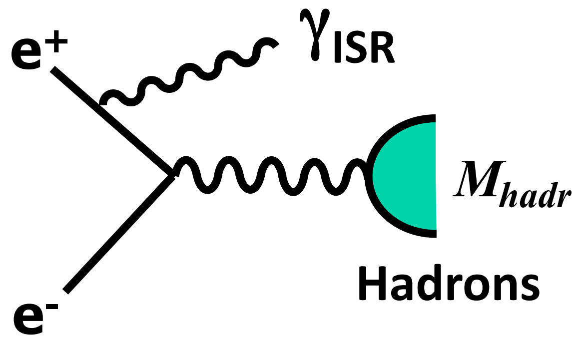
- **Major improvement of R**
- **Best measurement to date**
- **Important QCD test**
- **Of utmost importance for $\alpha_{em}(m_Z^2)$**

Initial State Radiation (ISR)

New and completely complementary ansatz:
Consider events with **Initial State Radiation (ISR)**

W. Kluge: "A success story"

Binner, Kühn, Melnikov, Phys.Lett. B459 (1999) 279
Benayoun, Eidelman, Invanchenko, Silagadze, 1999, Mod. Phys. Lett. 14, 2605
Druzhinin, Eidelman, Serednyakov, Solodov, Rev. Mod. Phys. 83 (2011) 1545

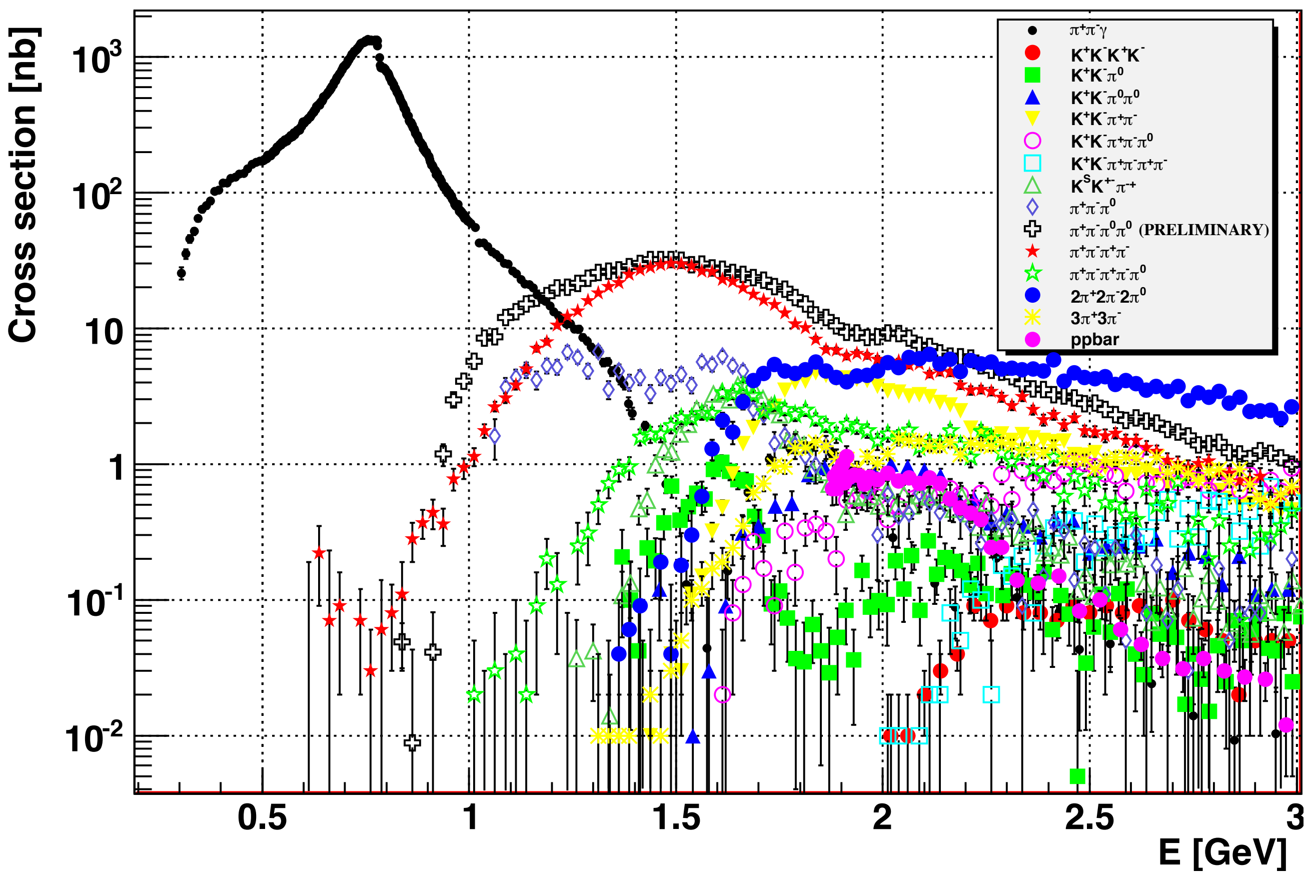


Charmonium production
Spectroscopy
e.g. Y(4260)

Multihadronic form factors
$e^+e^- \rightarrow 2\pi, 3\pi, 4\pi, >4$ hadr.
$(g-2)_\mu$, $\alpha_{em}(M_Z^2)$
Light hadron spectroscopy

Timelike baryon form factors
Hadron structure

BABAR Summary of ISR Results



Precision:

2π: < 1%

3π: ~10%

4π: ~ 3%

≥ 5π: 10% and higher

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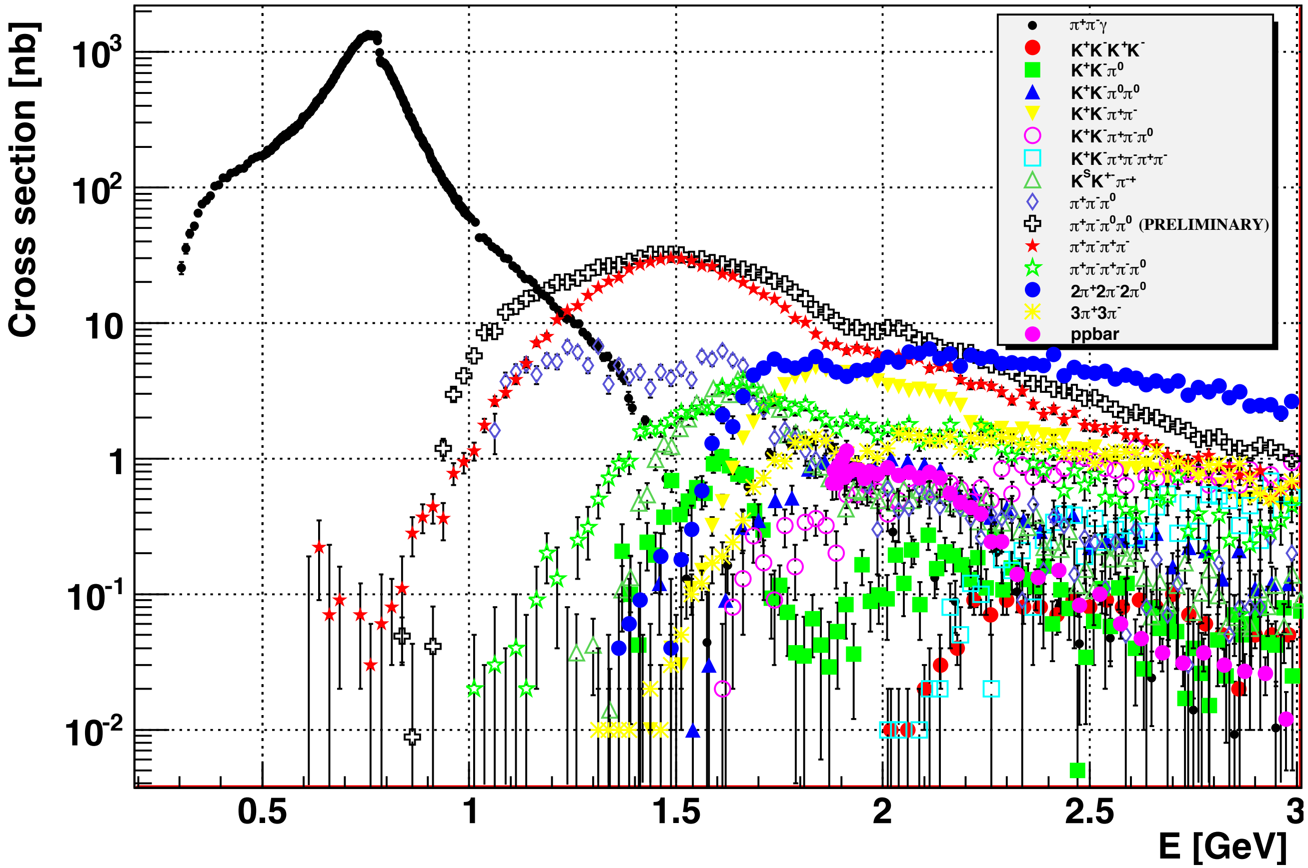


Precision:

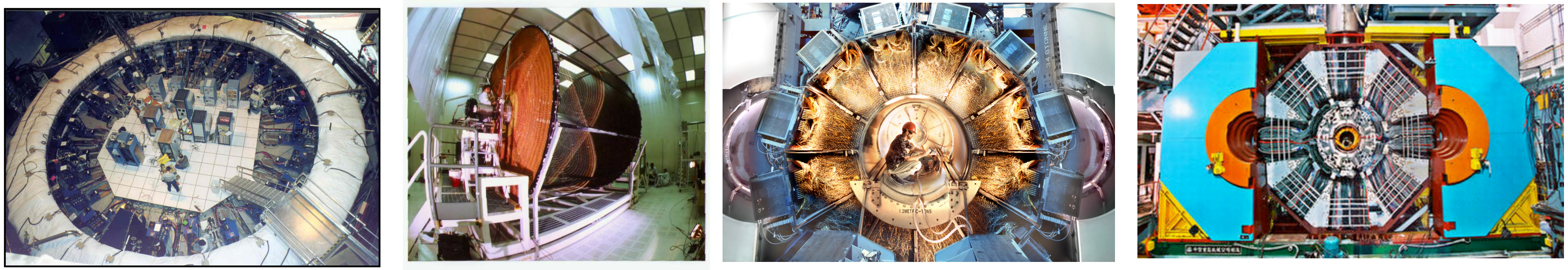
2π: < 1%

3π: ~10%

4π: ~ 3%

≥ 5π: 10% and higher

Measurement of exclusive channels:
Utmost importance for $(g-2)_\mu$ but not (yet) competitive with R_{incl} > 2 GeV



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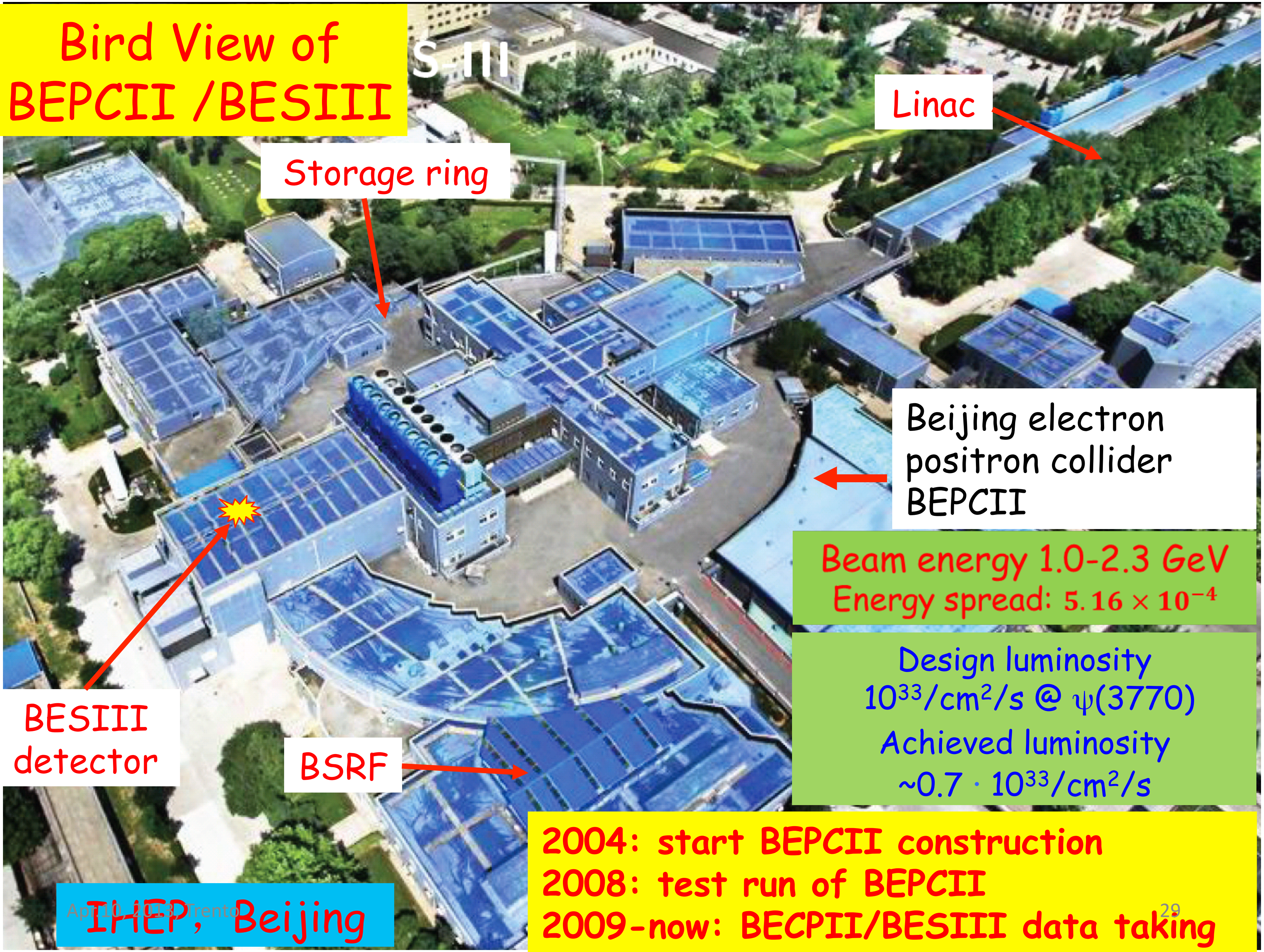
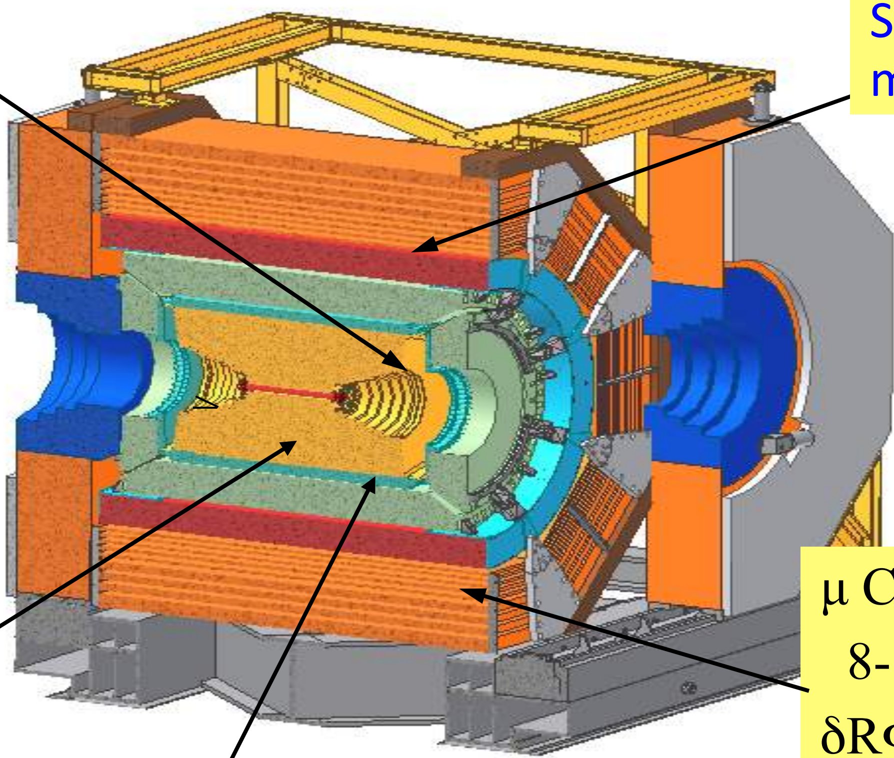
Bird View of BEPCII /BESIII



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/$\sqrt{E}$

NIM A614, 345 (2010)

Run Planning

R measurement foreseen in 3 phases

Phase 1: **R in range 2 – 4.5 GeV**

~10^4 events per scan point, 3% systematic accuracy

→ improve $\alpha_{QED}(m_Z^2)$ by factor 2

Phase 2: **R in range 2 – 3 GeV, high statistics**

>10^5 events per scan point

→ Improve nucleon $|G_E|/|G_M|$ ratio, Nucleon FF

Phase 3: **Fine binning R ratio in charmonium region**

→ charmonium spectroscopy

Phase 1: Precision R Scan

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

N_{had}: observed hadronic events

N_{bg}: background events

L: integrated luminosity

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

δ: radiative correction factor

$\sigma_{\mu\mu}$: calculated within QED.

Measurement of R is a measurement of $\sigma(e^+e^- \rightarrow \text{hadrons})$

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

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Measurement of R is a measurement of $\sigma(e^+e^- \rightarrow \text{hadrons})$

Our goal: 3% precision

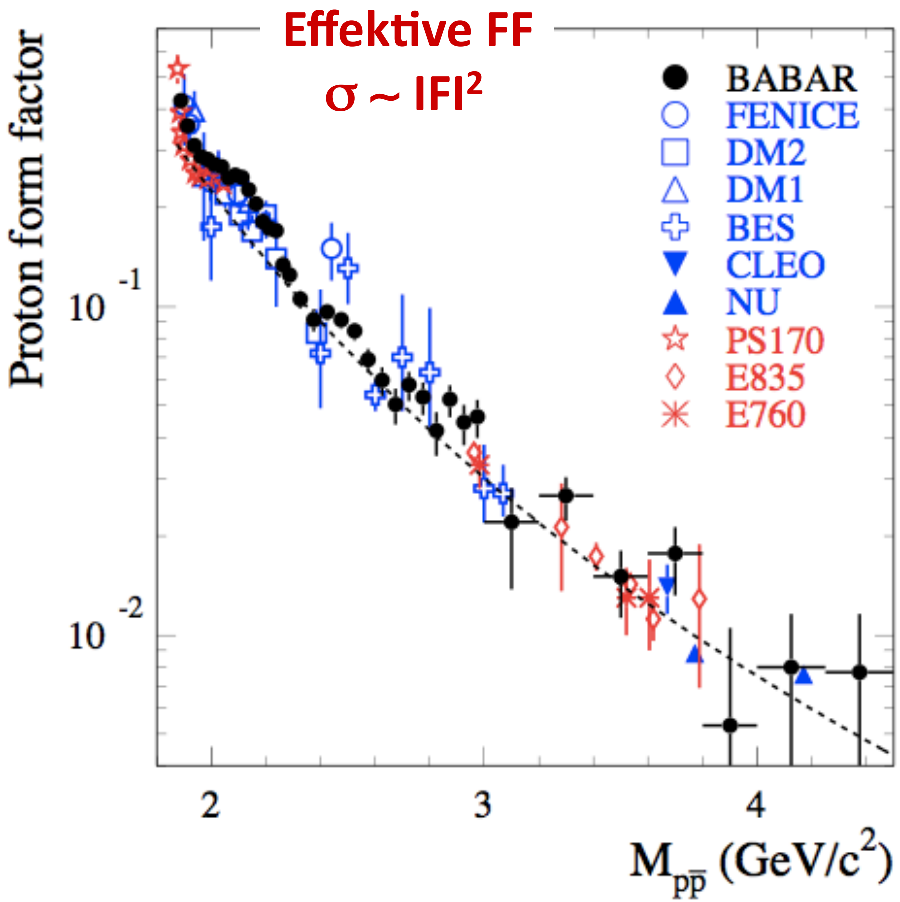
Except for controlling each item to the precision requested, stable long term machine and detector performance is crucial.

Phase 1: Mini R Scan (2012)

- 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.

Phase 2: Nucleon EM Form Factors

$$\sigma_{e^+e^-\to N\bar{N}} = \frac{4\pi\alpha^2\beta}{3s}\,C_N(s)\,\left[\left|G_M^N(q^2)\right|^2 + \frac{2M_N^2}{s}\left|G_E^N(q^2)\right|^2\right]$$



Cross section parametrized by magnetic and electric form factors G_M and G_E

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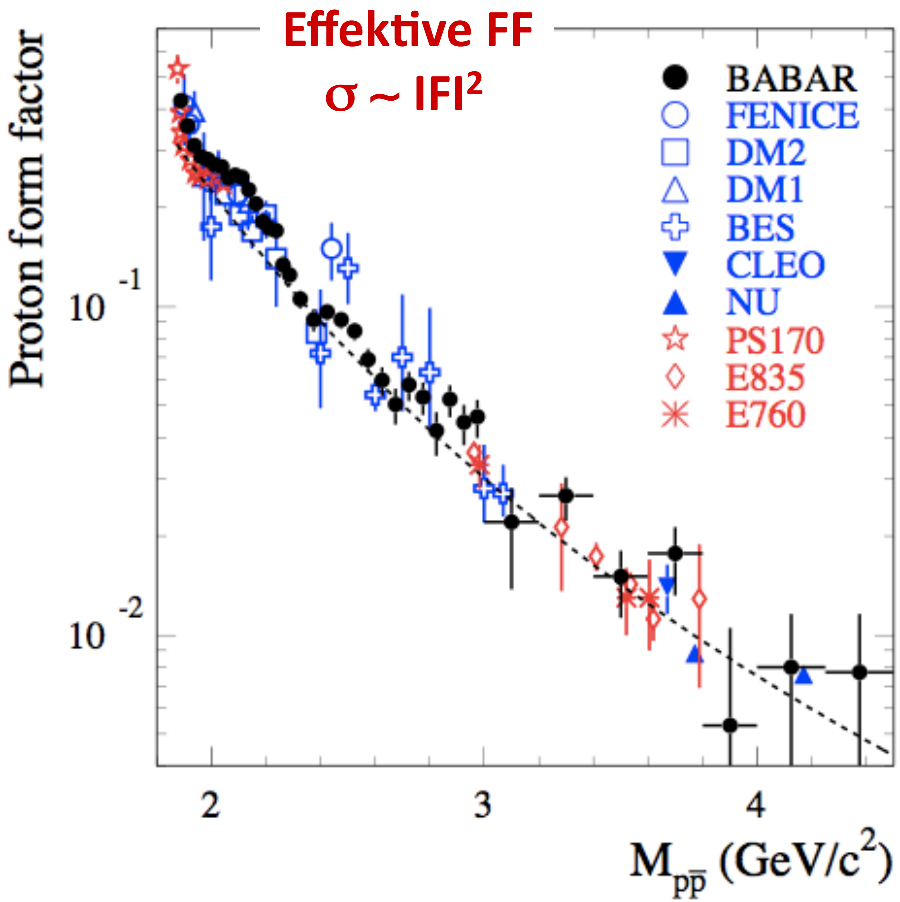

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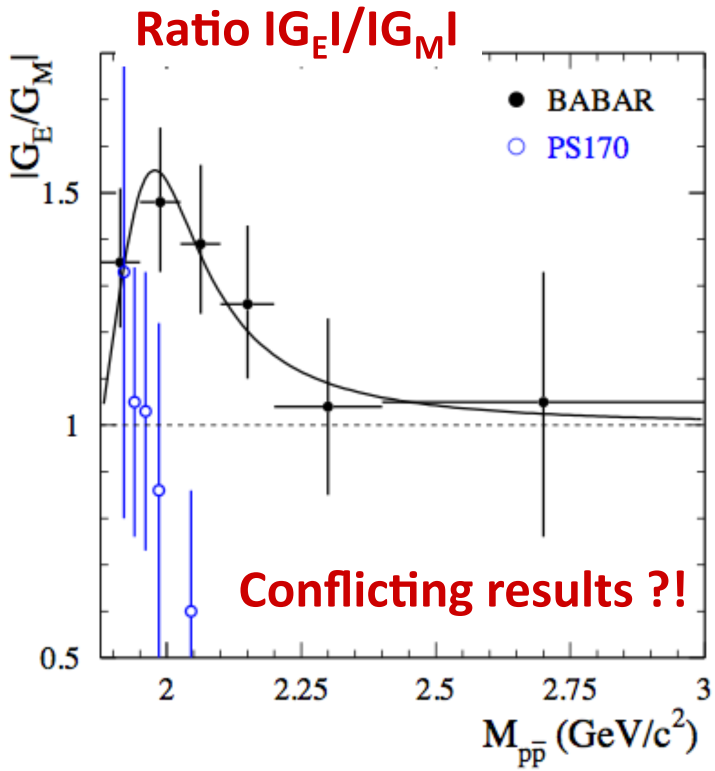

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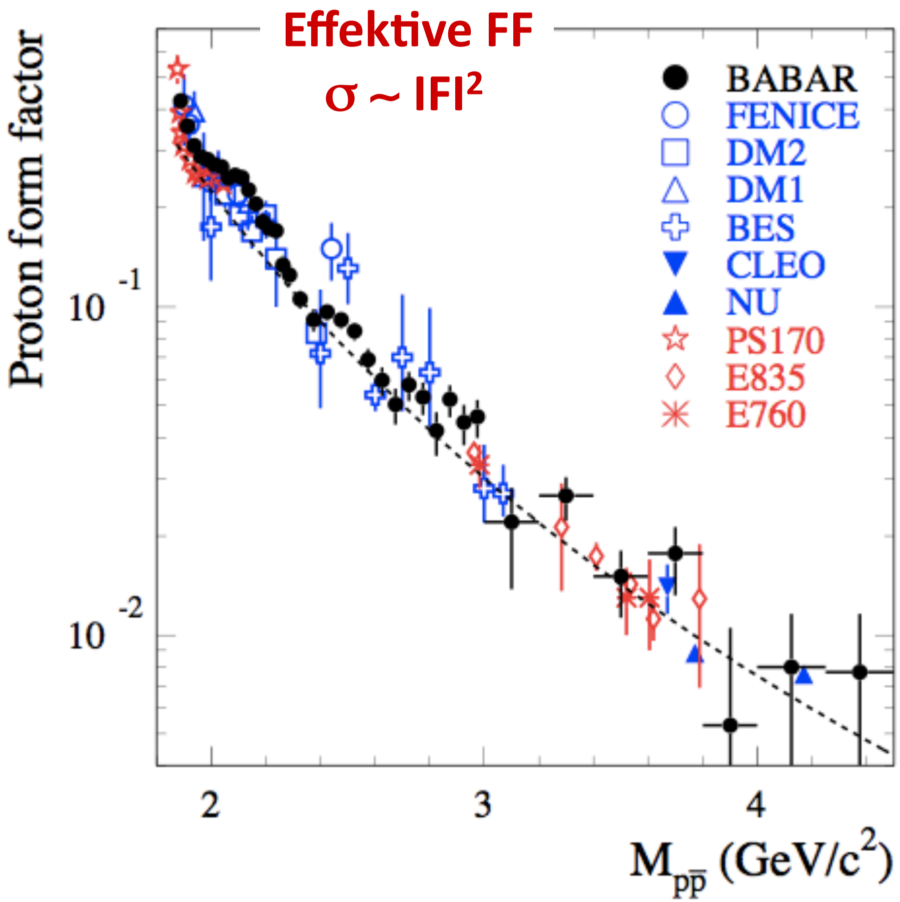

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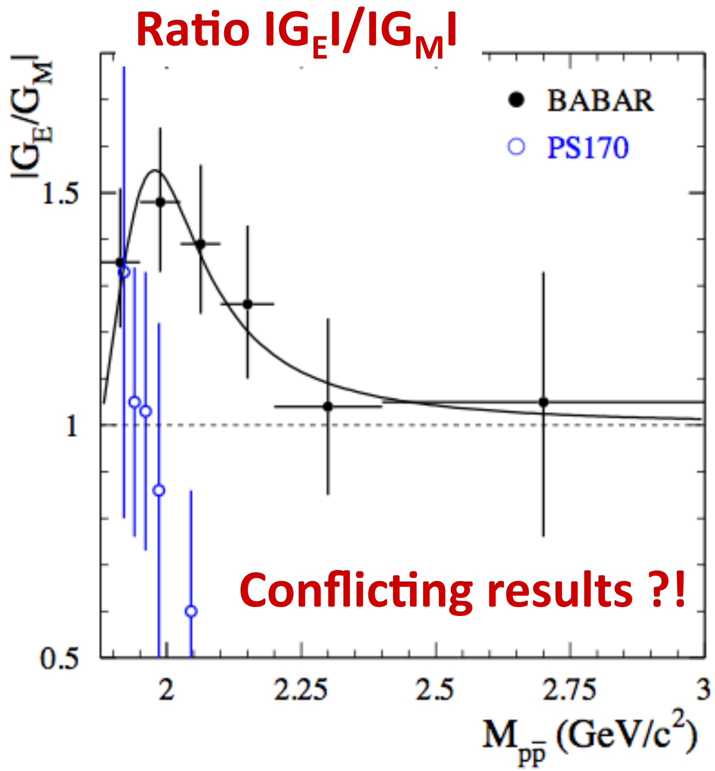
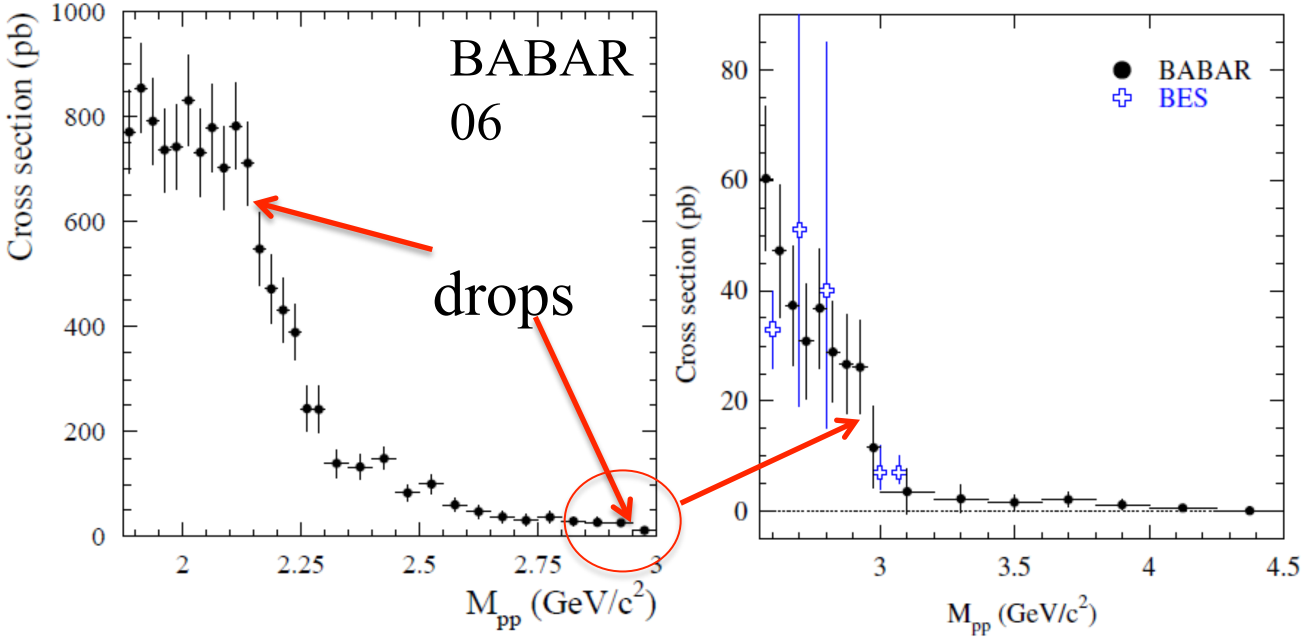


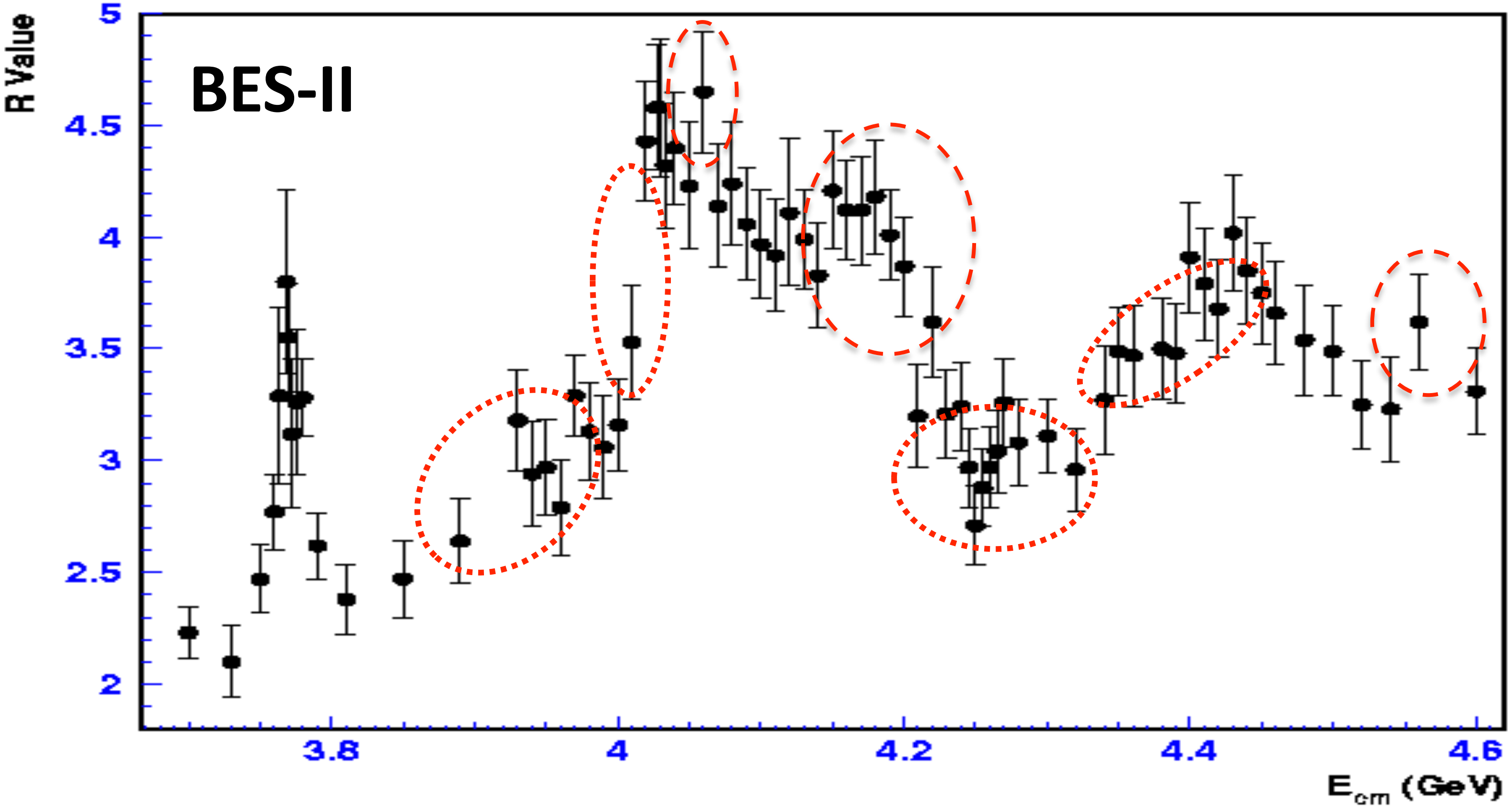
Goal: Improve knowledge of $|G_E|/|G_M|$ by factor 10

Phase 2: Nucleon EM Form Factors

- 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 ? → ISR, Scan?

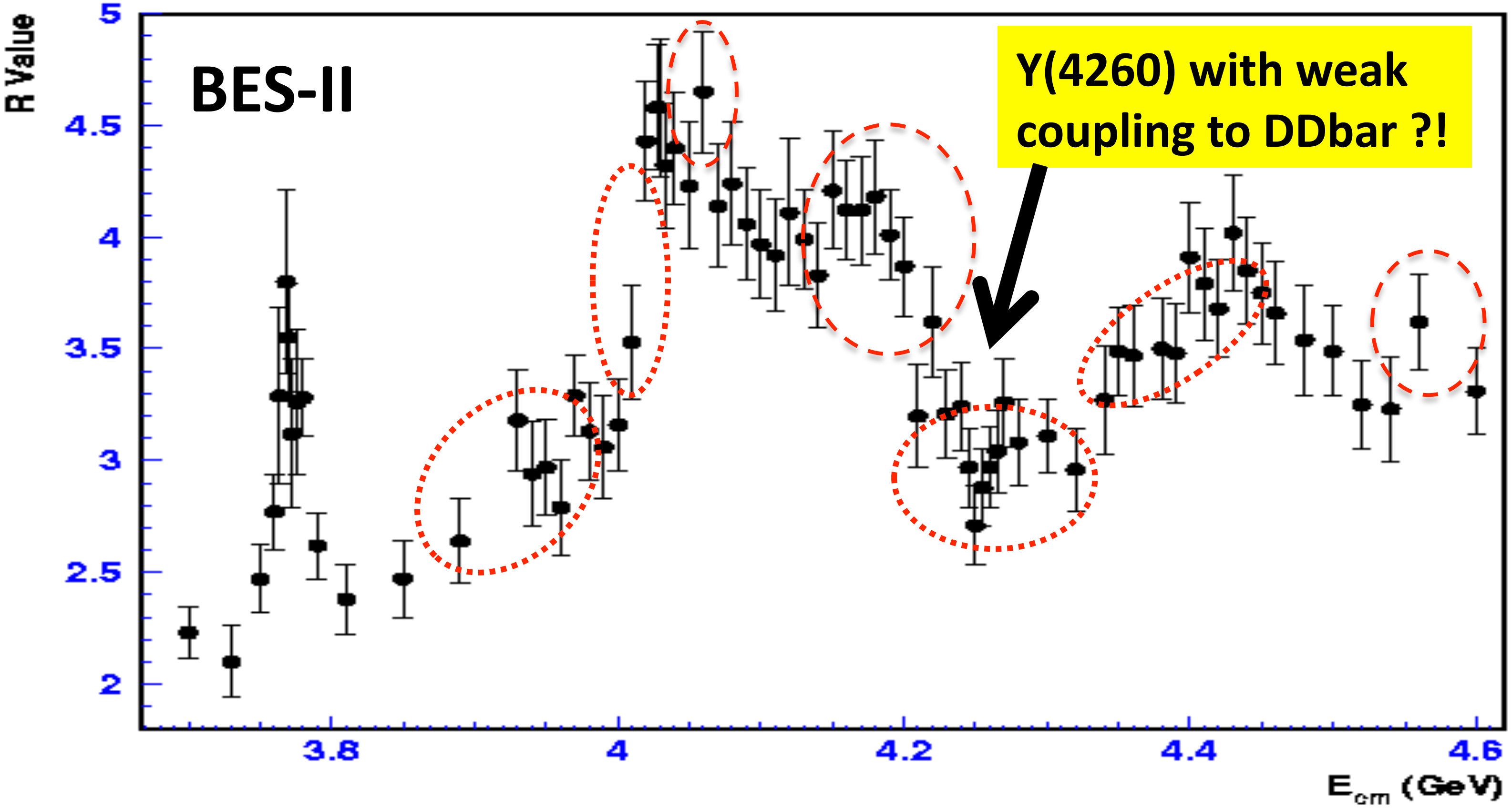


Phase 3: Charmonium Spectroscopy



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

Phase 3: Charmonium Spectroscopy



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

Phase 3: Charmonium Spectroscopy

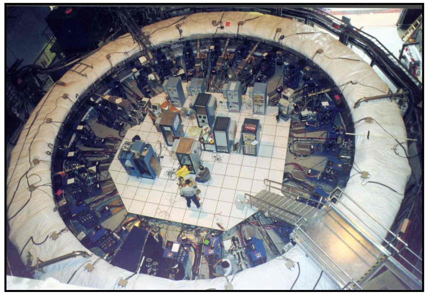
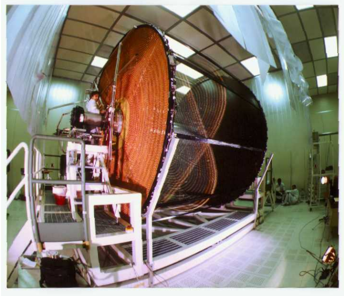
Understanding the nature of charmonium resonances:

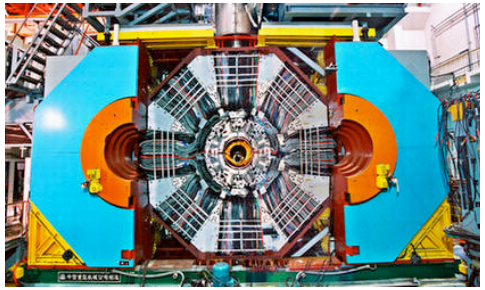
All possible two-body decays of ψ(3770), ψ(4040), ψ(4160), ψ(4415) need to be included in the fit

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

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

- Non-resonant contribution
- Open charm threshold



Outline

- Motivation: $(g-2)_\mu$ & $\alpha_{QED}(M_Z^2)$
- Results Energy Scan
- Results Radiative Return
- **Conclusions and Future Perspectives**

Summary

- Tremendous progress over past years in our knowledge of R at low energies
- Pivotal role of Radiative Return technique
- Relevant for determination of QCD parameters
- Precision Test of the Standard Model

  - Muon anomaly $(g\text{-}2)_\mu$:

    Improvement by ~factor 3 in knowledge of hadronic vacuum polarization; in ca. 10 years; Timely topic: new FNAL experiment

  - Electromagnetic fine stucture constant $\alpha_{em}(m_Z^2)$:

    After Higgs discovery new quality of electroweak precision fits possible

Outlook

New e+e- facilities have started data taking or will start shortly

- Upgraded DAPHNE Frascati
  - ISR < 1 GeV
- VEPP-2000 Novosibirsk
  - Energy Scan < 2 GeV
- BES-III @ BEPC-II
  - ISR < 3 GeV, R scan 2-5 GeV
- BELLE-2 @ Super-KEKB
  - ISR < 5 GeV

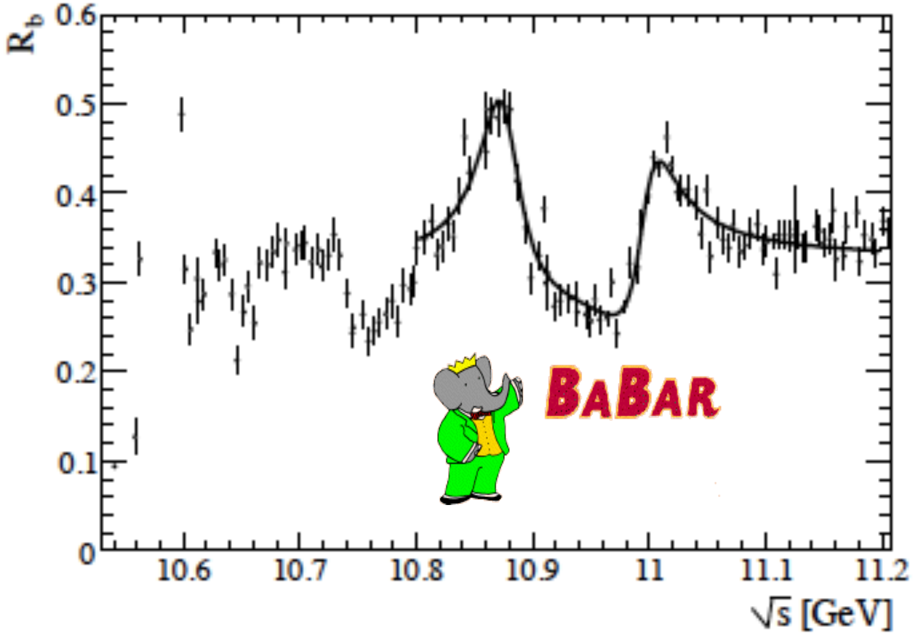
Within this decade (likely earlier?) further reduction of factor 2 in precision on our knowledge of R not impossible !

Additional slides

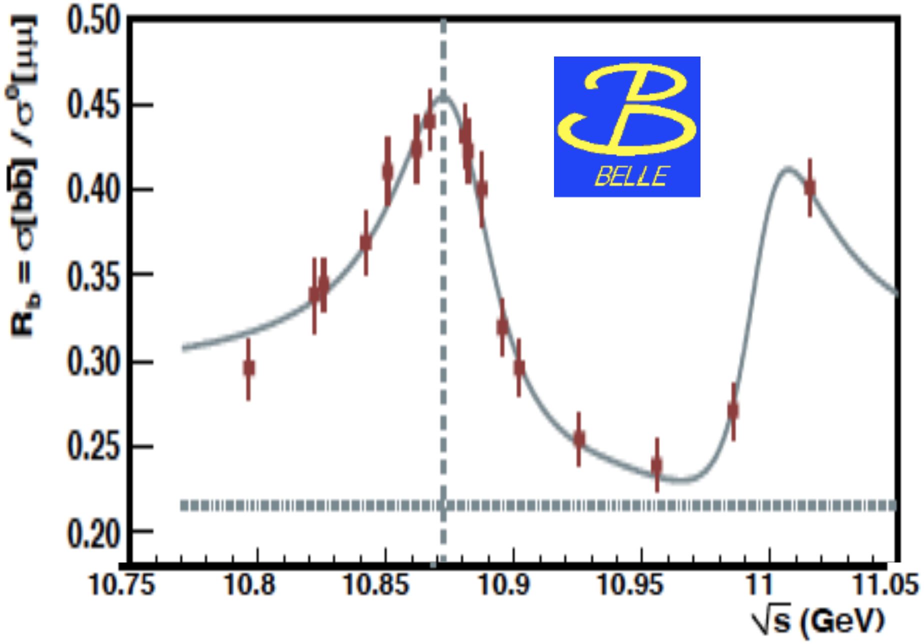
BABAR and BELLE Scan Bottominium

Scan of R_b = σ(e+e-→bbar)/σ(e+e-→μ+μ-) in Bottomonium region

arXiv:0808.2445



arXiv:0710.2577



- Identify bbar by event shape
- Asymmetric Y(5S) peak oberserved
- Difficult interpretation (many channels)

- Y(5S) peak obsesved as in BABAR
- Anomalous decay patterns of decays from Y(5S) in lower lying Y resonances

BESIII Data Taking

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

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

- 2010: ~0.9 fb^{-1} ψ(3770)
- 2011: ~2.0 fb^{-1} ψ(3770)
  ~0.5 fb^{-1} @ 4.01 GeV

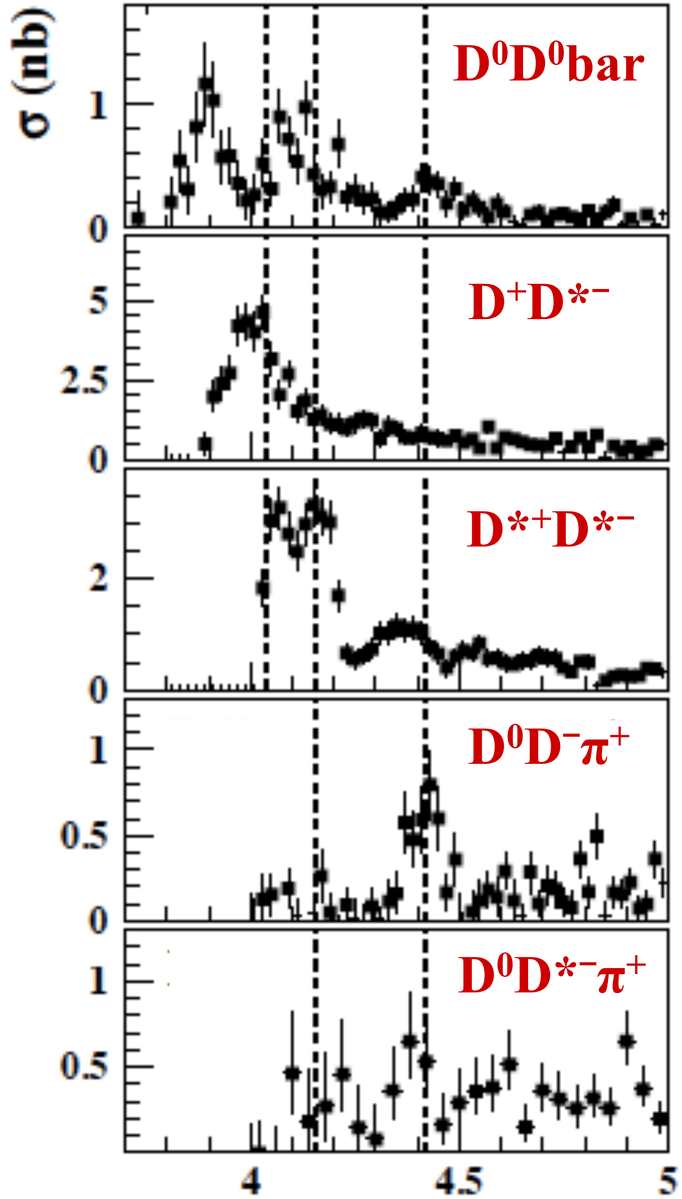
(2010–2011 ψ(3770): 3.5×CLEO-c)

- 2012: tau mass scan: ~5.0 pb^{-1} ; ψ(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

Radiative Return at BELLE

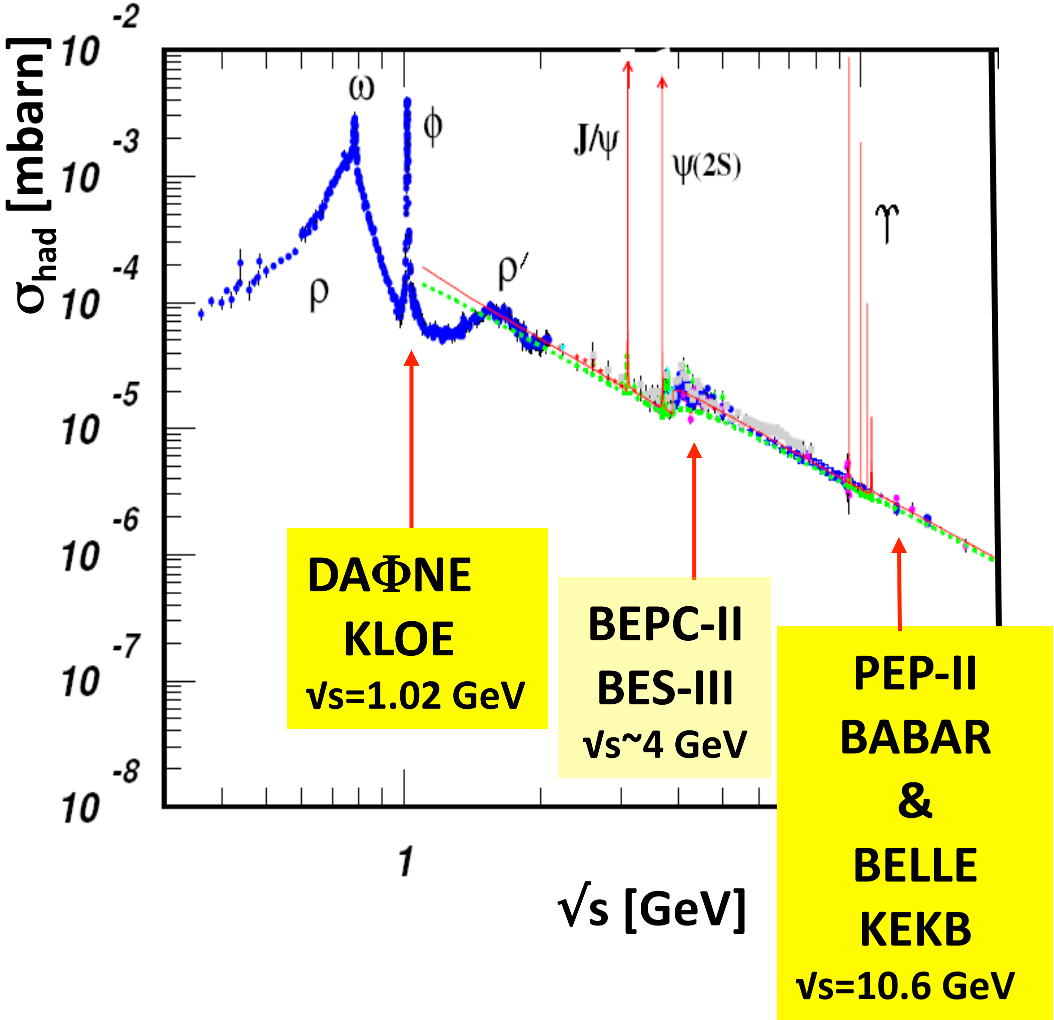
- BELLE ISR programme lead to important results on charmonium spectroscopy
- So far no publication on light hadron systems below 3 … 4 GeV (prelimary result on e+e- → $\pi^+\pi^-\pi^0$)
- No clear indication of e.g. Y(4260) resonance which is seen in J/ψ ππ

PRL 98 (2007) 092001	e+e- → D*+D*-, D+-D*-+
PRL 99 (2007) 182004	e+e- → π+π- J/ψ
PRL 99 (2007) 142002	e+e- → π+π- ψ(3685)
PRD 77(2008) 011103	e+e- → D^0+D^0bar-, D+-D-
PRL 100 (2008) 062001	e+e- → D^0+D-π+
PRL 101 (2008) 172001	e+e- → $\Lambda_c^+ \Lambda_c^-$, $\Lambda_c^0 \Lambda_c^0$bar

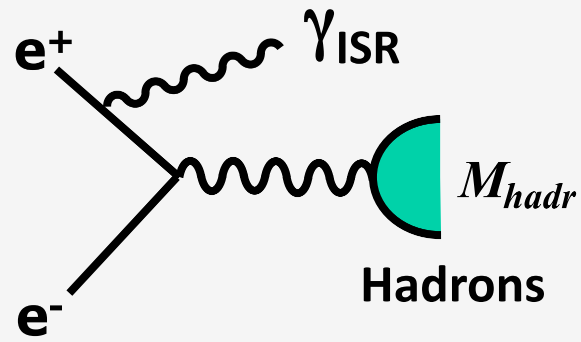


Hadronic Cross Section via ***Radiative Return***

Rev. Mod. Phys. 83, 1545–1588 (2011)



Initial State Radiation (ISR)
aka Radiative Return



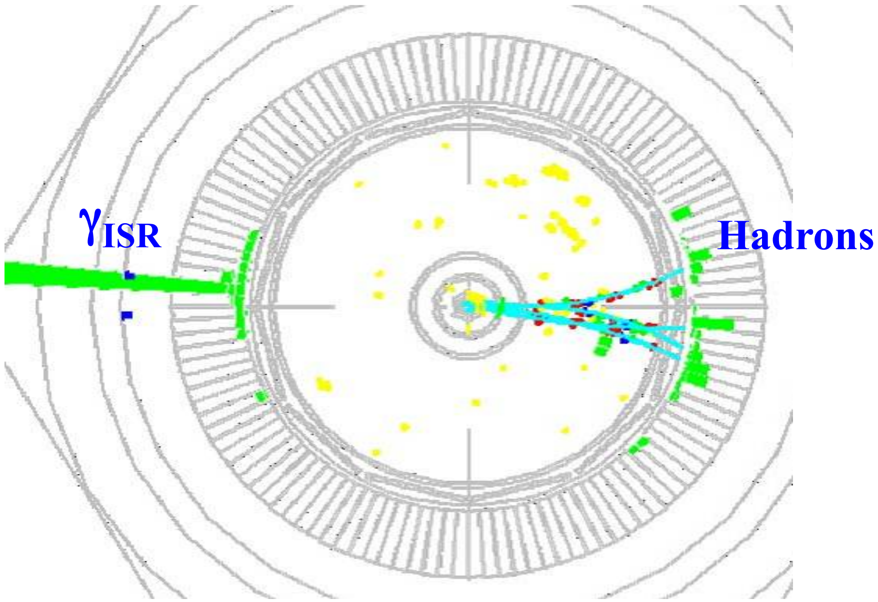
- Possible at modern particle factories
- Needs no systematic variation of beam energy
- High statistics due to high integrated luminosities

→ Entire E range <√s accessible

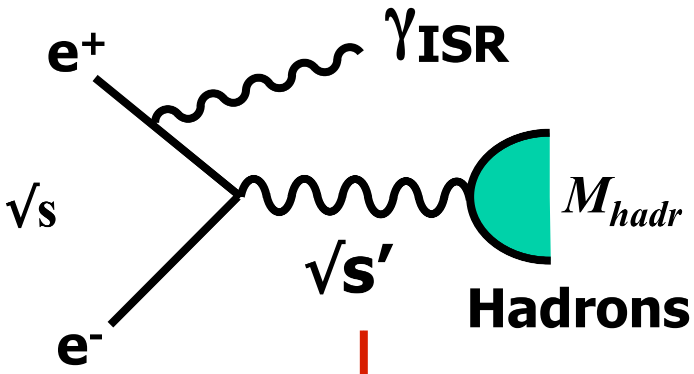
BABAR: ISR at 10.6 GeV

Features:

- Rely on **tagged (=measured) photon** for identifying ISR-events
- High **fiducial efficiency** :
  wide-angle ISR-g forces hadronic system into detector fiducial region at large polar angles
- Harder momentum spectrum due to boost
  - **fewer problems with soft particles;**
  - **allows to go down to threshold**
- Can access a very **wide mass range** in one single experiment:
  from threshold to **4 ... 5 GeV**

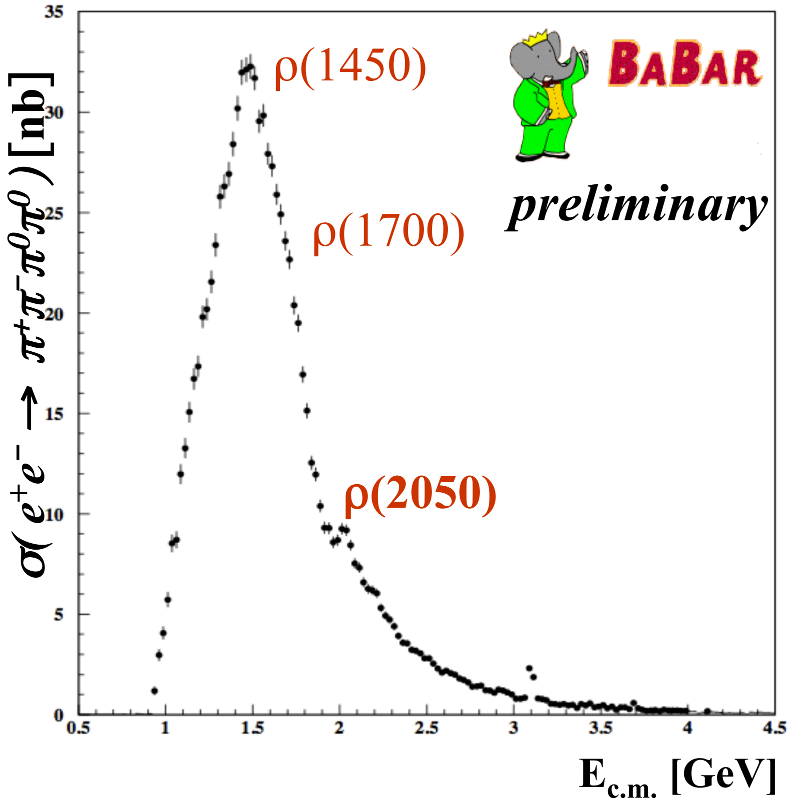


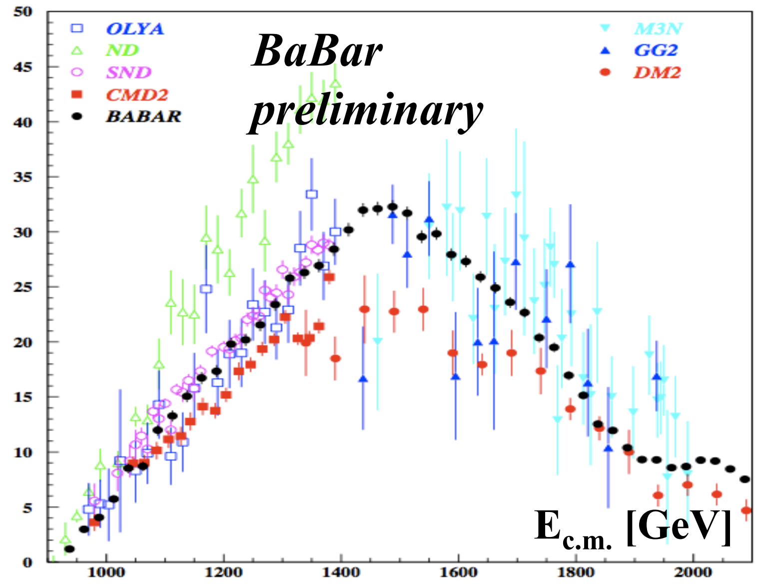
Initial State Radiation (ISR)

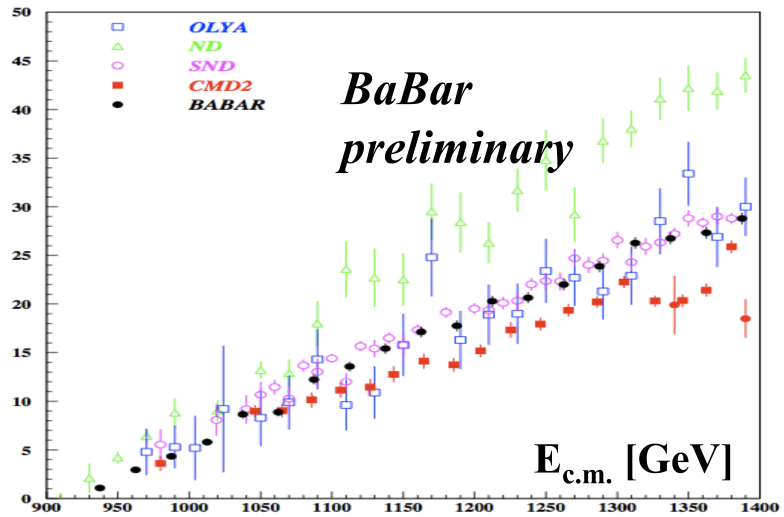


Charmonium production	Multihadronic form factors	Timelike baryon form factors
Spectroscopy	$e^+e^- \rightarrow 2\pi, 3\pi, 4\pi, >4$ hadr.	Hadron structure
e.g. Y(4260)	$(g\text{-}2)_\mu$, $\alpha_{em}(M_Z^2)$	
	Light hadron spectroscopy	
BaBar, Belle	BaBar, KLOE	BaBar

ISR-channel $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$







Typical features:

- Second most important contribution for $(g-2)_\mu$
- Precision (preliminary result): 8%
- Analysis on full data (454 fb^{-1}) sample almost ready: ~4% systematic uncertainty

Cross Section Data from e^+e^-

Experiments CMD-2 / SND

Energy scan < 1.4 GeV

➔ $\pi^+\pi^-$ channel O(1%) !

Novosibirsk

Beijing

R - scan 2 - 5 GeV

Inclusive meas. ~ 7%

BABAR

SLAC/Stanford

PEP-II

√s=10.58 GeV

'B-Factory'

LNF/Frascati

DAΦNE

√s=1.02 GeV

'φ-Factory'

Energy-Scan e+e-

Radiative Return e+e-

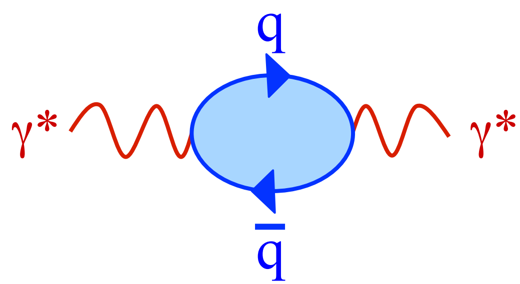
Running Fine Structure Constant

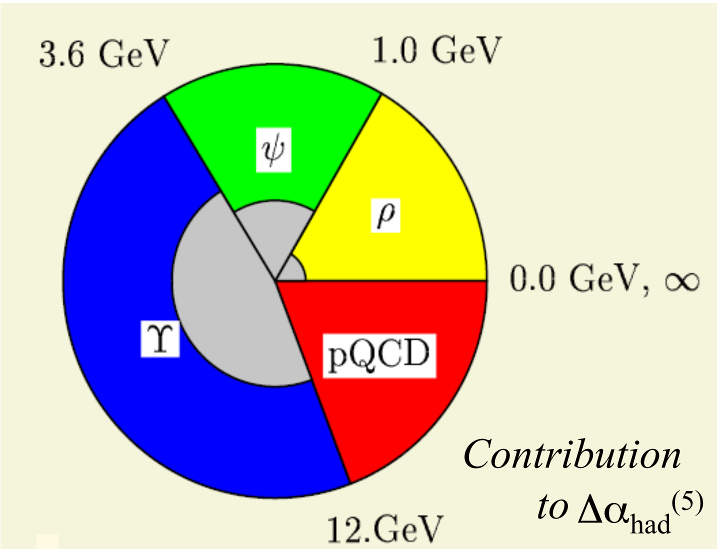
$\alpha_{QED}(0) = 1 / 137$

$\alpha_{QED}(M_Z^2) = 1 / 129$

$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)} \quad \begin{cases} \Delta\alpha_{lept}(M_Z^2)=0.0314 \\ \Delta\alpha_{had}^{(5)}(M_Z^2)=0.027515\pm0.000149 \end{cases}$$

$$\Delta\alpha_{had}^{(5)}(s) = -\frac{\alpha s}{3\pi} \int_{4m_\pi^2}^{E_{cut}^2} ds' \frac{R_\gamma^{data}(s')}{s'(s'-s)}$$





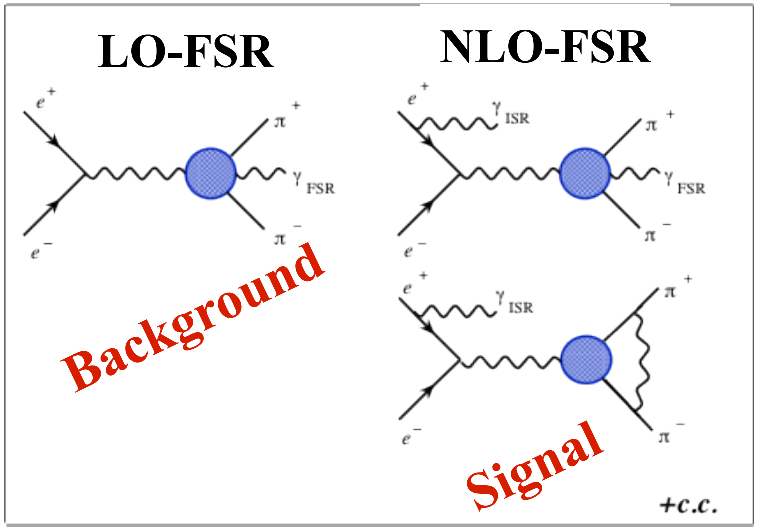
[F. Jegerlehner ArXiv:0807.4206]

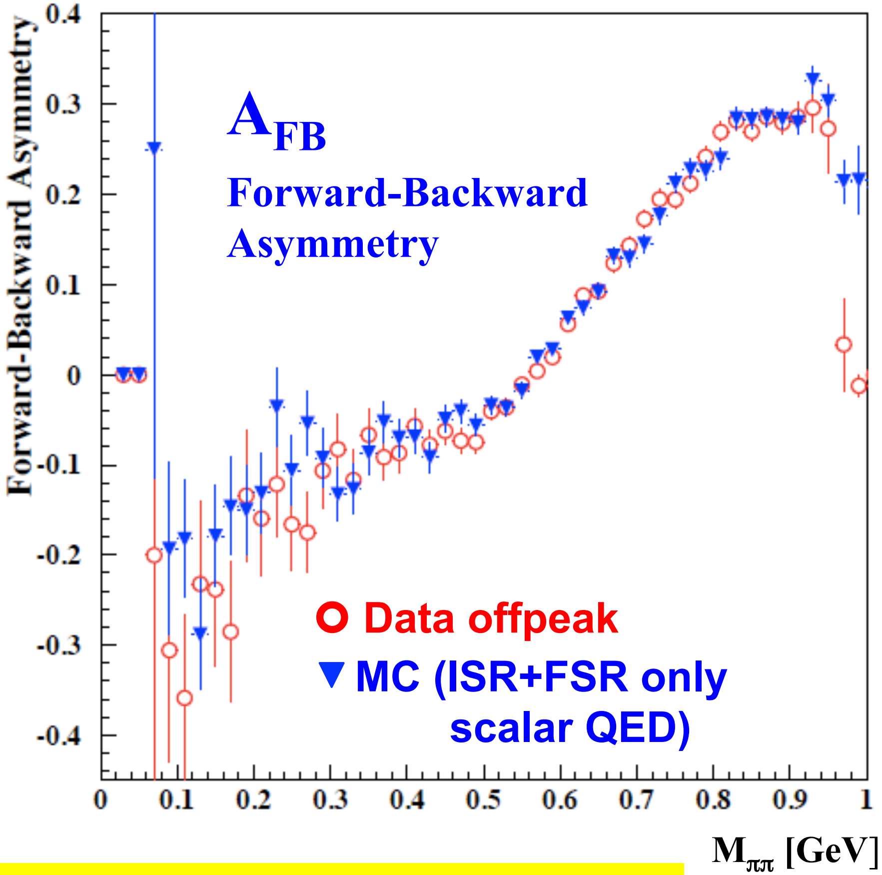
- $\Delta\alpha_{had}^{(5)}$ is the hadronic vacuum polarization contribution of the five lightest quarks u,d,s,c,b
- Low energy contributions are less weighted in dispersion integral

  ⇒ **from which energy range on use pQCD?**

The Issue of Final State Radiation

FSR - corrections are model dependent, typically model of scalar QED is used



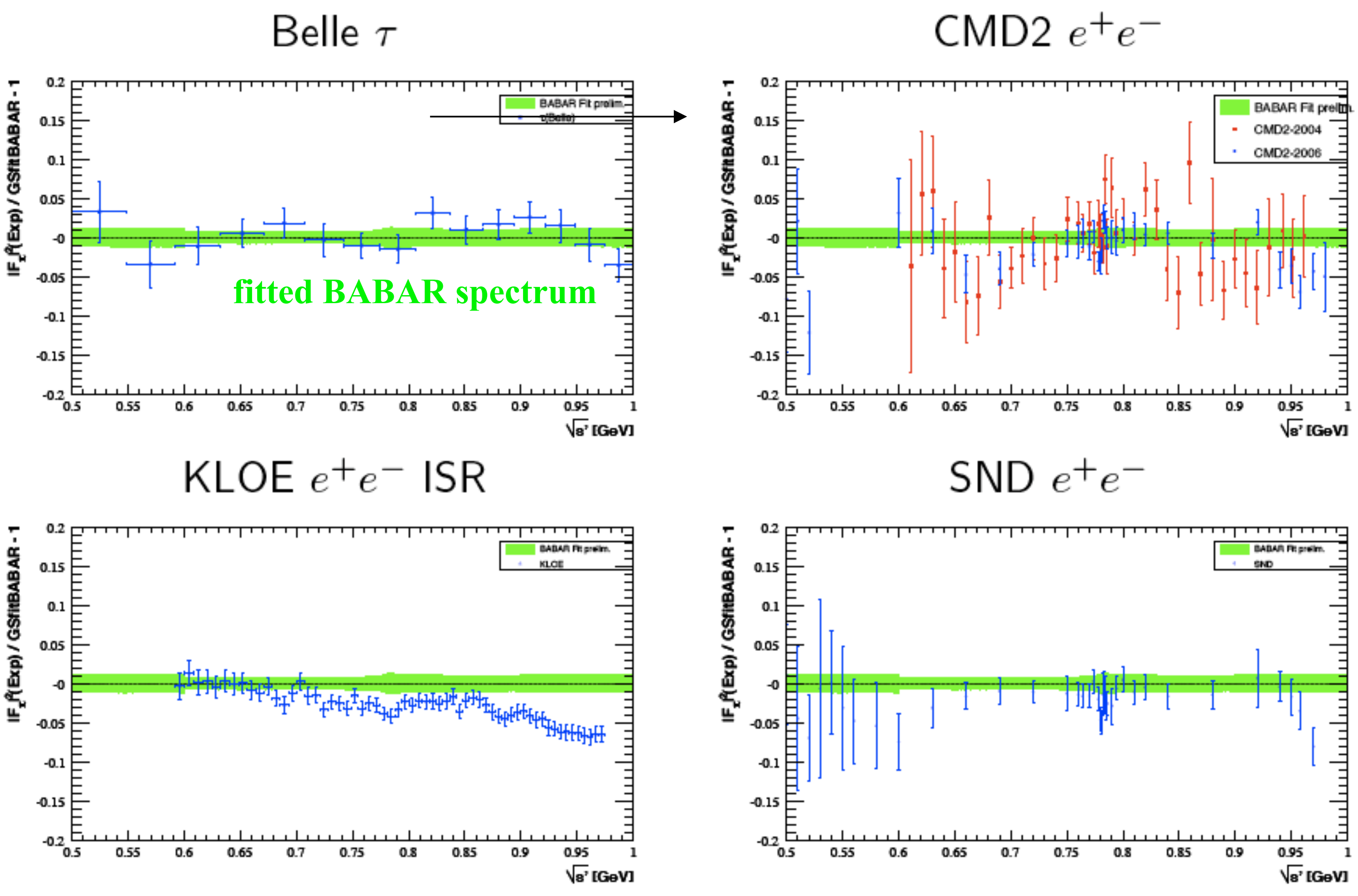


F-B- Asymmetry is a consequence of ISR-FSR-interference and is a direct **test of model of scalar QED for FSR**!

Binner, Kühn, Melnikov, Phys. Lett. B 459, 1999

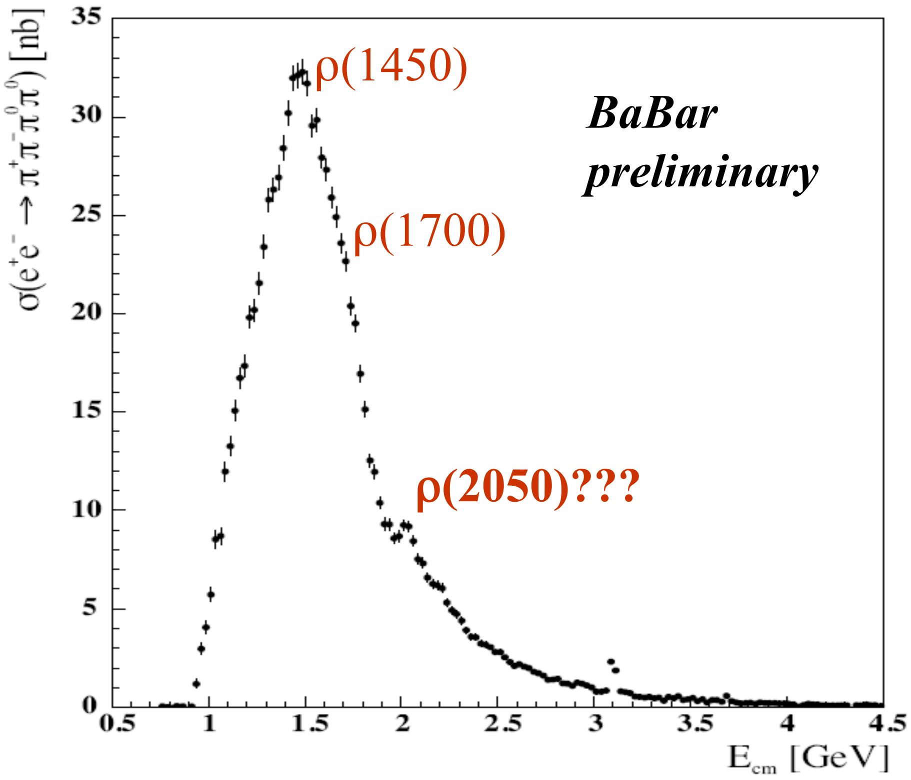
A_{FB}: unique opportunity to test final state radiation

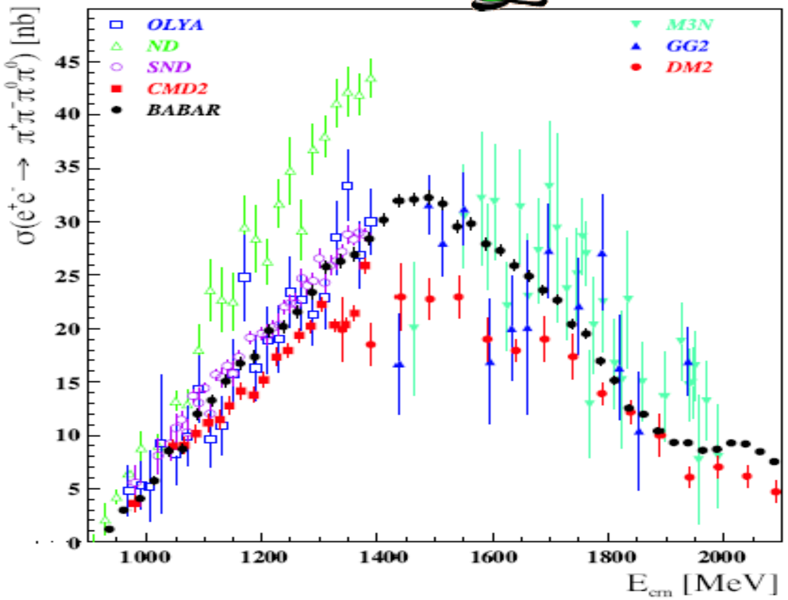
Fractional Difference BABAR-other Expts.

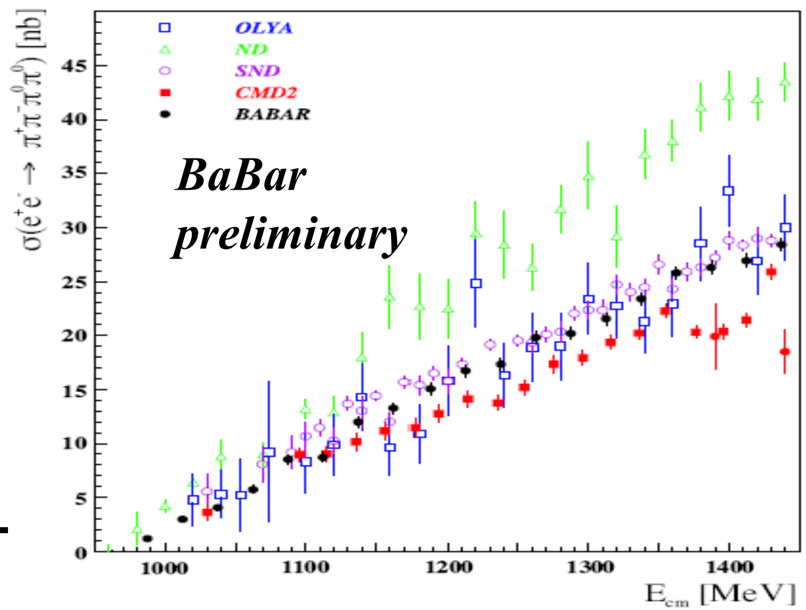


Relatively large deviations seen ?!

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





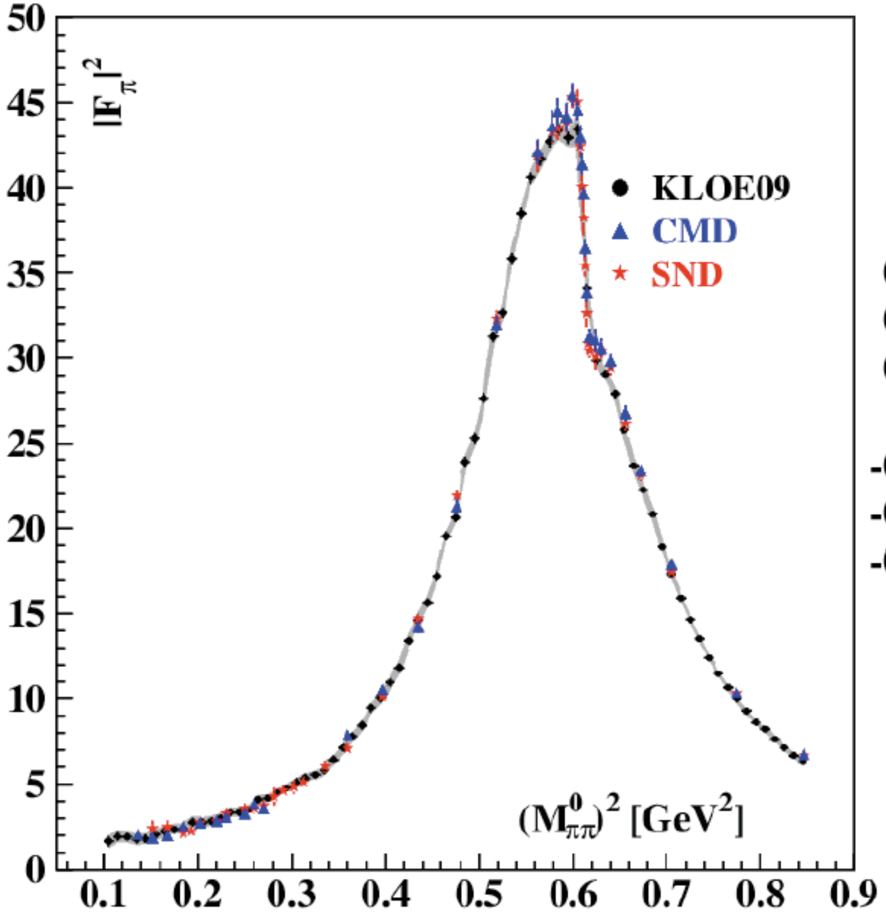


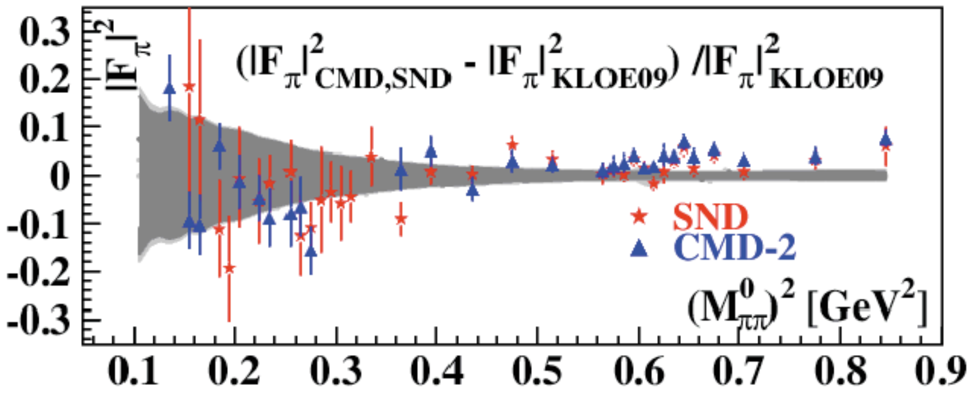
Features:

- Important mode for a_μ and $\boldsymbol{\alpha}_{\mathbf{QED}}$
- Preliminary precision: 8% in peak → 5%
- Good agreement with SND <1.4 GeV
- Huge improvement >1.4 GeV
- First measurement >2.5 GeV

Comparison KLOE vs. Novosibirsk Experim.

CMD and SND results compared to KLOE09: Fractional difference





band: KLOE09 error

Fair agreement btw. energy scan and radiative return experiments

BABAR *Radiative Return Ergebnisse*

Ein erfolgreiches Forschungsgebiet bei BABAR/Stanford:

- $e^+e^- \rightarrow \pi^+\pi^-\pi^0$
- $e^+e^- \rightarrow 2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$
- $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$
- $e^+e^- \rightarrow 3(\pi^+\pi^-)$, $3(\pi^+\pi^-\pi^0)$, $2(\pi^+\pi^-)K^+K^-$
- $e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-K^+K^-\pi^0$, $\pi^+\pi^-K^+K^-\eta$
- $e^+e^- \rightarrow K^+K^-\pi^0$, $K^+K_S\pi^-$, $K^+K_S\eta$
- $e^+e^- \rightarrow p\bar{p}$
- $e^+e^- \rightarrow \Lambda^0\bar{\Lambda}^0$, $\Lambda^0\bar{\Sigma}^0$, $\Sigma^0\bar{\Sigma}^0$

1) Relevante Kanäle für $(g\text{-}2)_\mu$
2) Hadronspektroskopie und J/ψ - Verzweigungsverhältnisse
3) Nukleon-Struktur durch Messung der zeitartigen Baryon-Formfaktoren

BABAR Radiative Return Resultate

BABAR

- $e^+e^- \rightarrow \pi^+\pi^-$
- $e^+e^- \rightarrow \pi^+\pi^-\pi^0$
- $e^+e^- \rightarrow 2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$
- $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$

Höchst relevant für $(g-2)_\mu$

- $e^+e^- \rightarrow 3(\pi^+\pi^-)$, $3(\pi^+\pi^-\pi^0)$, $2(\pi^+\pi^-)K^+K^-$
- $e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-K^+K^-\pi^0$, $\pi^+\pi^-K^+K^-\eta$
- $e^+e^- \rightarrow K^+K^-\pi^0$, $K^+K_S\pi^-$, $K^+K_S\eta$
- $e^+e^- \rightarrow p\bar{p}$
- $e^+e^- \rightarrow \Lambda^0\bar{\Lambda}^0$, $\Lambda^0\bar{\Sigma}^0$, $\Sigma^0\bar{\Sigma}^0$

Weniger relevant für $(g-2)_\mu$
Mesonspektroskopie
Nukleonstruktur

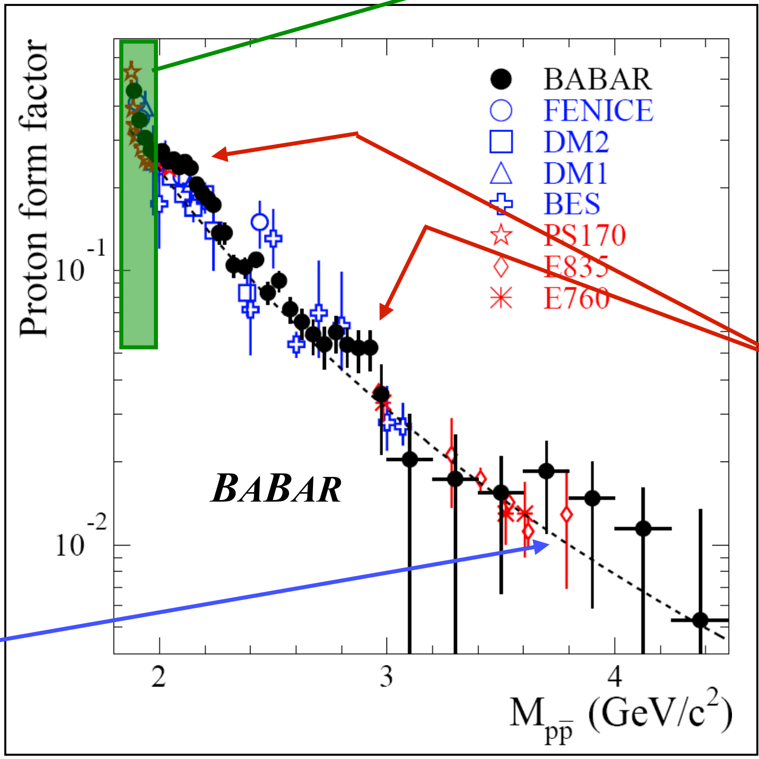
$e^+e^- \rightarrow p\bar{p}$

Defining the effective form factor |F| ($|G_E| = |G_M|$):

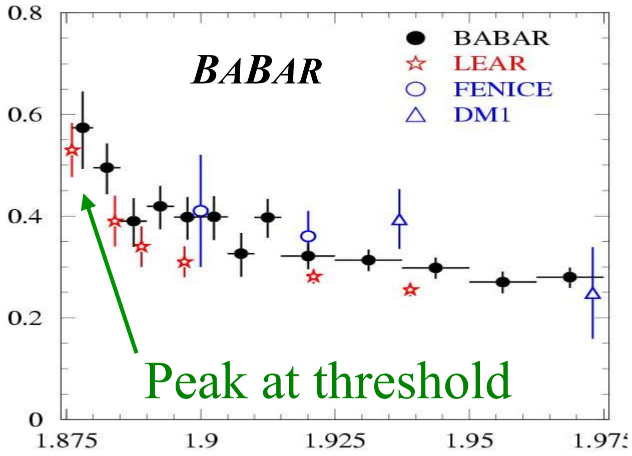
$$\sigma = \frac{4\pi\alpha^2\beta C}{3m_{p\bar{p}}^2}\cdot\left(1+\frac{2m_p^2}{m_{p\bar{p}}^2}\right)\cdot|F|^2$$

allows comparison with other experiments ($p\bar{p}\rightarrow e^+e^-$, $e^+e^- \rightarrow p\bar{p}$)

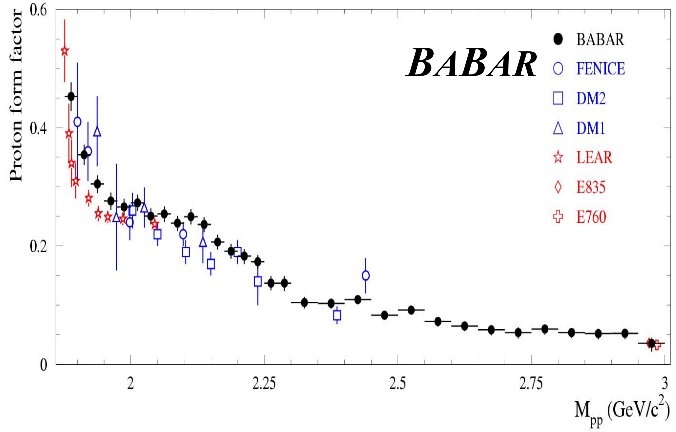
Complicated structure observed:



Agreement with pQCD-fit at high masses



Similar feature in $M_{p\bar{p}}$ seen by *BABAR* for $B\rightarrow p\bar{p}X$ and by BES in $J/\psi\rightarrow\gamma\, p\bar{p}$!



Sharp dips at 2.25 and 3.0 GeV

Impact of $\alpha_{em}(M_Z^2)$

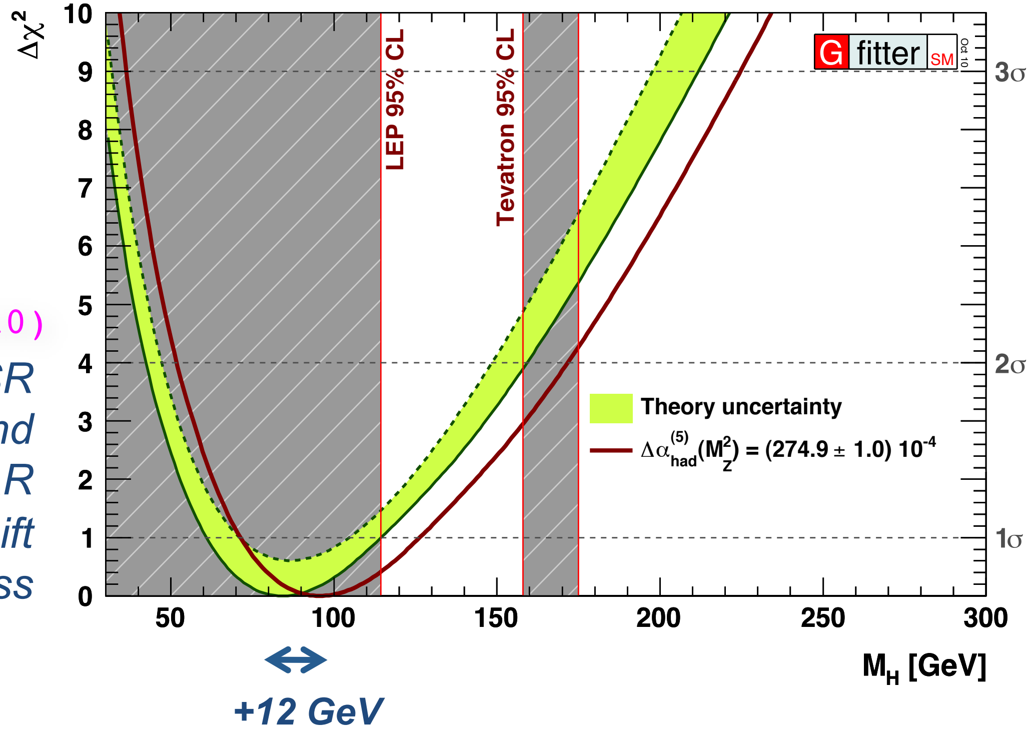
Reduction of uncertainty of $\alpha_{em}(M_Z^2)$: Needed for electroweak physics

→ *least known input for electroweak precision fits to SM, e.g. Higgs mass prediction*

→ Project P2

Davier *et al.* (2010)

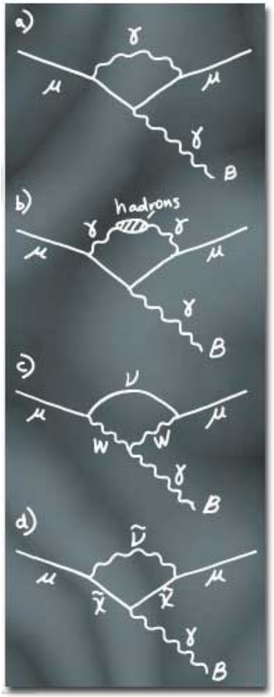
Including recent ISR data by KLOE and BABAR lead to significant shift of predicted Higgs mass



→ Project P1: Reduce uncertainty of $\Delta\alpha_{em}^{had(5)}$ by ~factor 2

A must for future International Linear Collider ILC

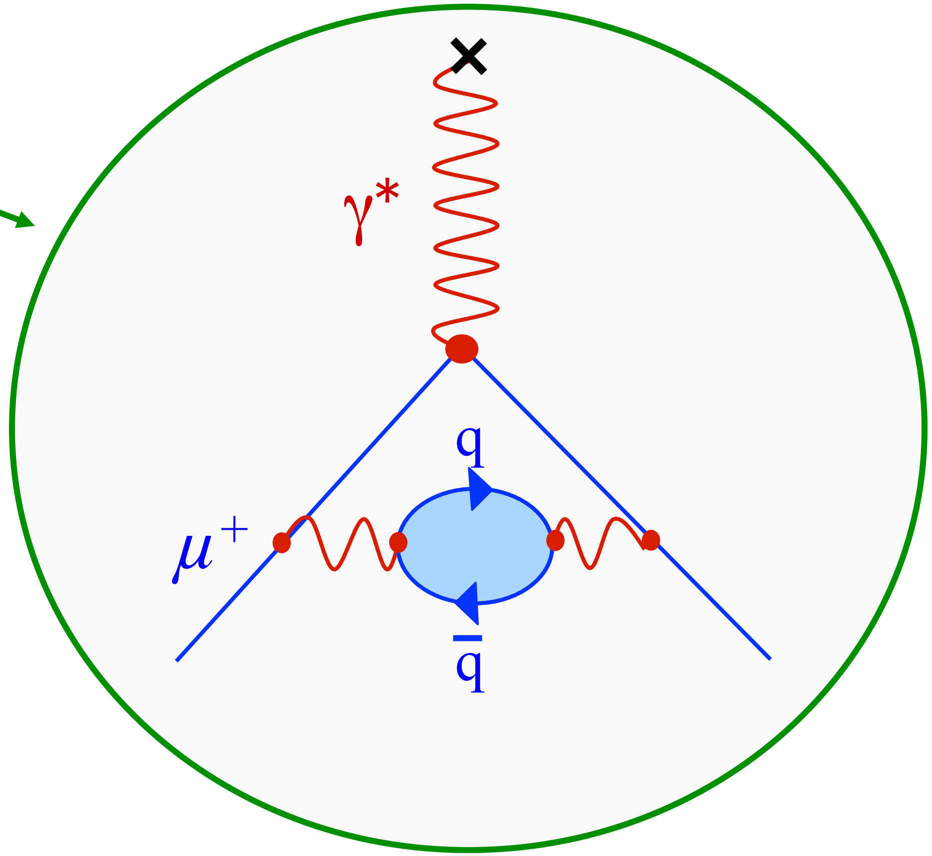
Theory contributions to (g-2)$_\mu$



QED contribution

Hadronic vacuum polarizatio n

Electroweak contribution



Muon Anomaly $(g\text{-}2)_\mu$

Magnetic Moment: $\vec{m} = \mu_B \; g \; \vec{S}$ *μ_B: Bohr magneton, g: gyromagnetic factor ~ 2*

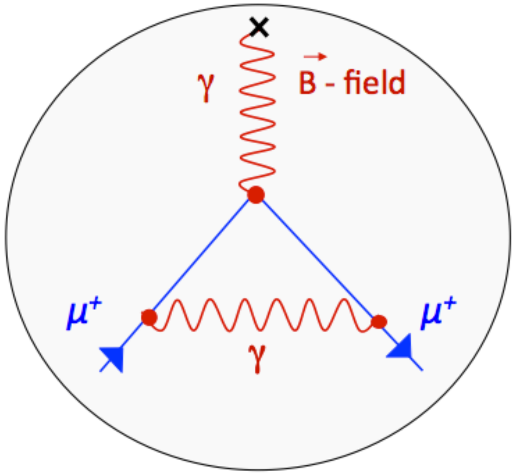
Muon Anomaly: $a_\mu = (g\text{-}2)_\mu / 2 = \alpha_{em} / 2\pi + \ldots = 0.001161\ldots.$

- **Standard Model (SM) prediction a_μ^{SM}:**

  - QED: a_μ^{QED} = $(11\,658\,471.809 \pm 0.015) \cdot 10^{-10}$
  - weak: a_μ^{weak} = $(15.4 \pm 0.2) \cdot 10^{-10}$
  - strong: a_μ^{strong} = $\mathbf{(693.0 \pm 4.9) \cdot 10^{-10}}$

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

  SM prediction entirely limited by **strong interactions** !



- **Direct measurement BNL-E821 a_μ^{exp}:**

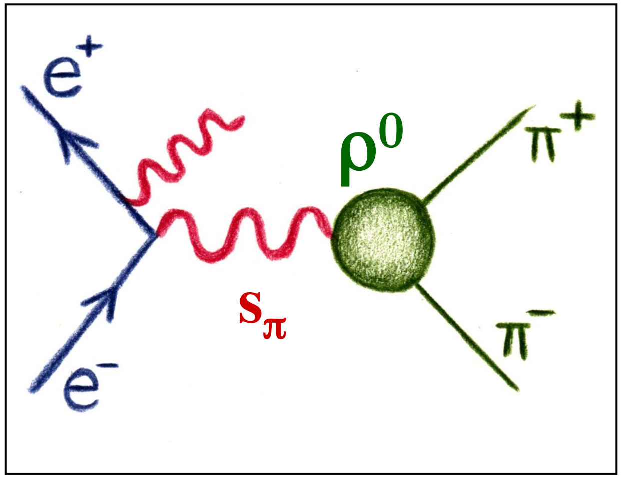
  $a_\mu^{exp} = (11\,659\,208.9 \pm 6.3) \cdot 10^{-10}$

Initial State Radiation (ISR)

Modern e^+e^- particle factories : $\sqrt{s} = m_{\phi(1020)} = 1.02$ GeV bei DAΦNE
$\sqrt{s} = m_{\Upsilon(4S)} = 10.6$ GeV bei PEP-II

energy scan impossible over a wide energy range!

Complementary ansatz:
Consider events via **Initial State Radiation (*ISR*)**



"**Radiative Return**" to ρ-resonance:

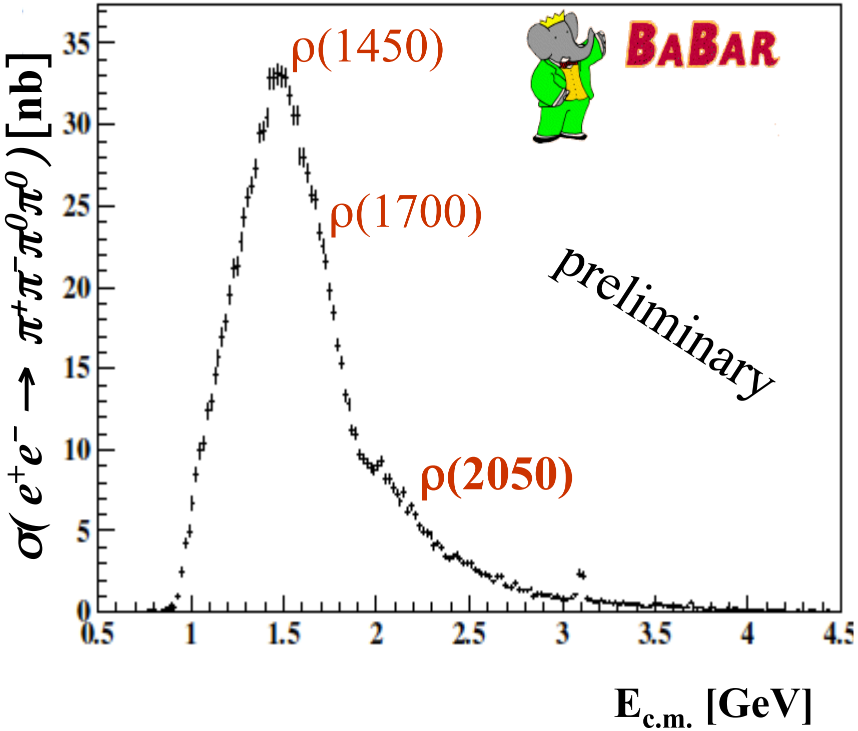
$e^+e^- \rightarrow \rho + \gamma \rightarrow \pi^+\pi^- + \gamma$

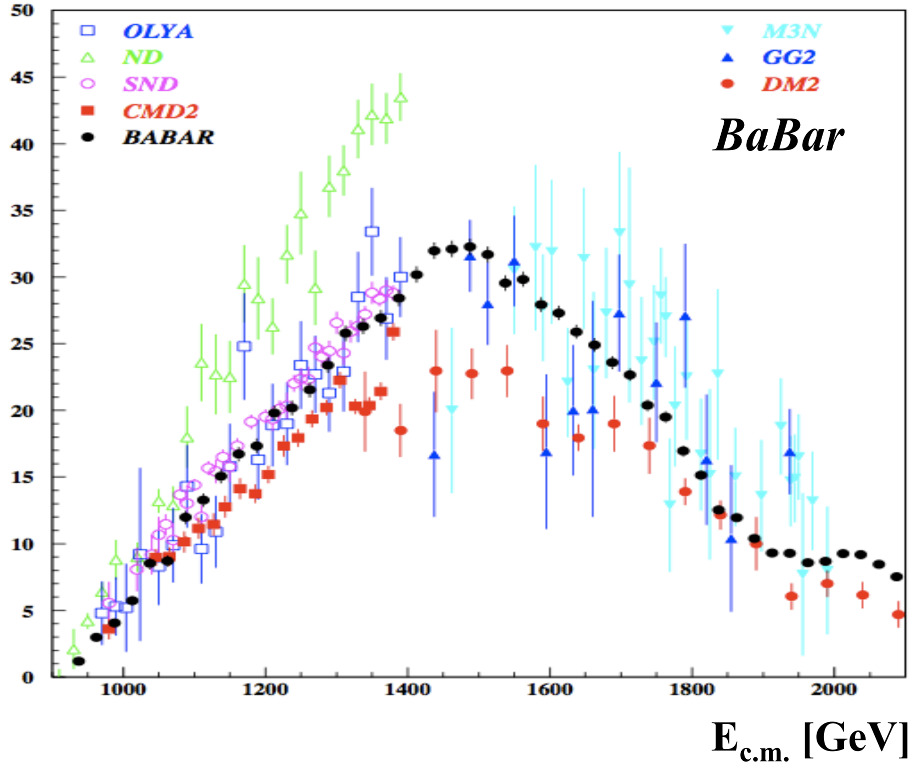
Measure 2π invariant mass

$\mathbf{s_\pi = M_{\pi\pi}^2}$

$$\frac{d\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)}{dM_{\pi\pi}^2}$$

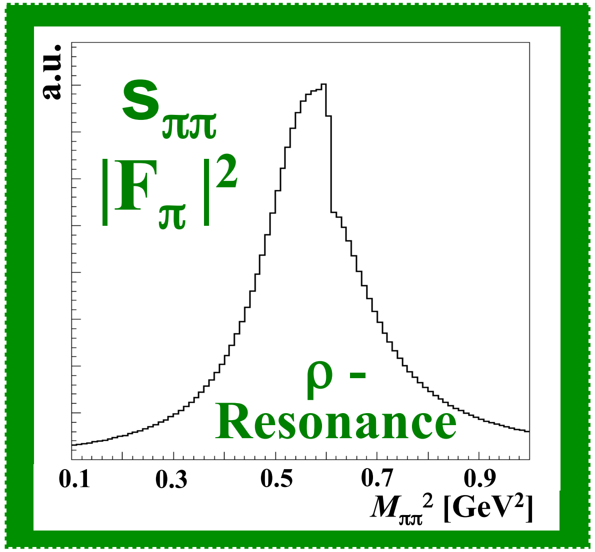
BABAR Example 2: $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$





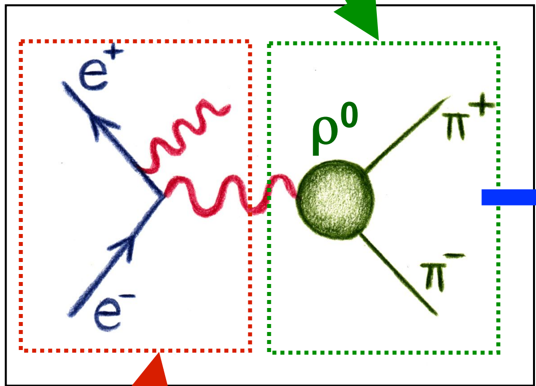
- Second most important contribution for $(g\text{-}2)_\mu$
- Significant improvement >1.4 GeV
- Precision (preliminary result): 8%
- Analysis on full data (454 fb^{-1}) sample ongoing: ~4% or lower

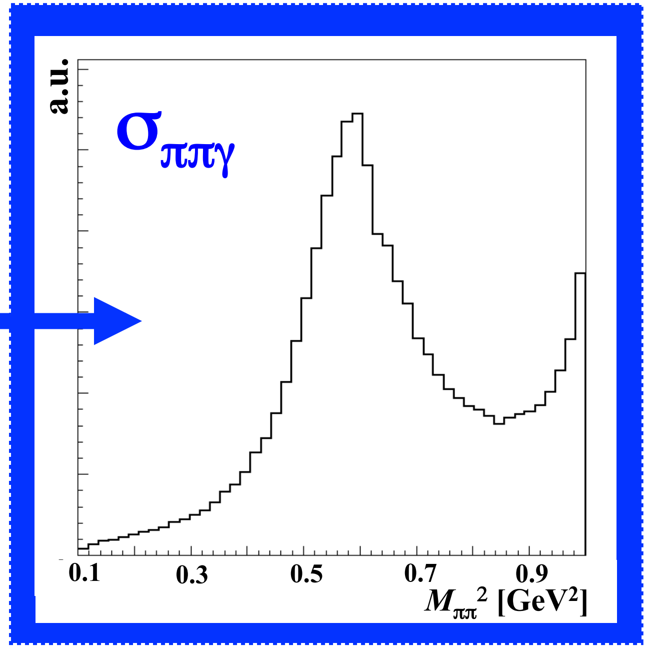
Radiative Return



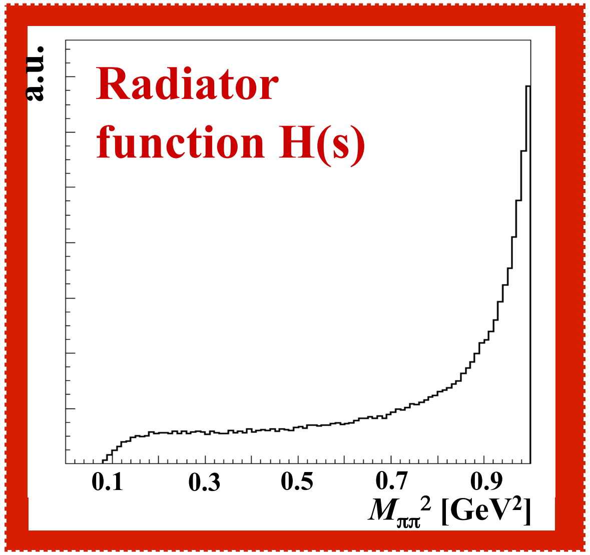
Non-radiative cross section

$$M^2_{\pi\pi}\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi}(s)\times \mathrm{H(s)}$$





radiative cross section



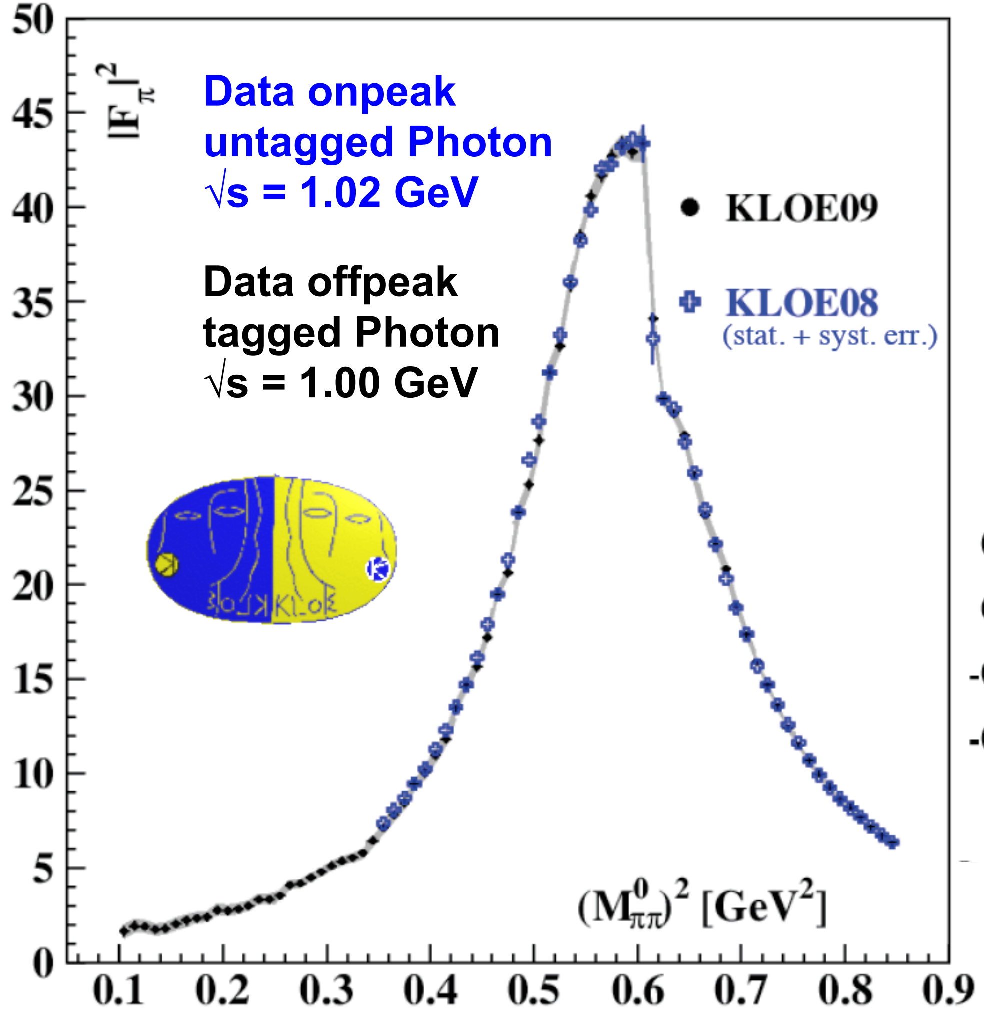
J. Kühn, H. Czyż, G. Rodrigo

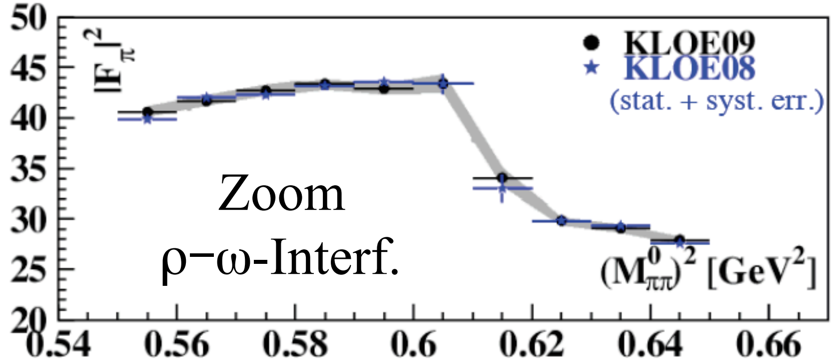
Radiator function

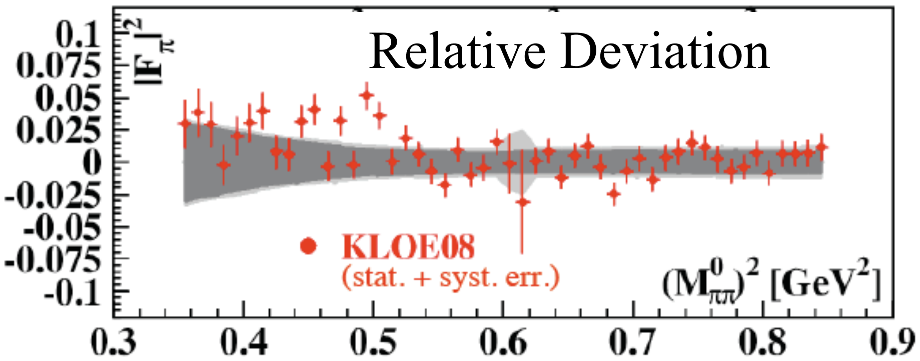
MC- Generator PHOKHARA

Pion Formfactor: KLOE Results

PLB 670 (2009) 285







Good agreement
with ~1% systematic uncertainty

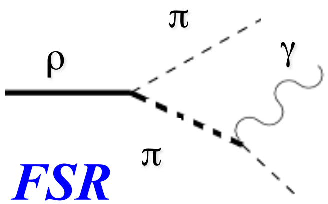
New

Forward-Backward-Asymmetry

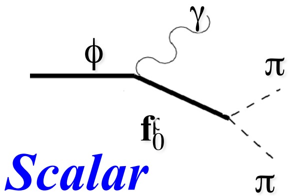
Forward-Backward-Asymmetry

$$A = \frac{N(\theta^+ > 90^o) - N(\theta^+ < 90^o)}{N(\theta^+ > 90^o) + N(\theta^+ < 90^o)}$$

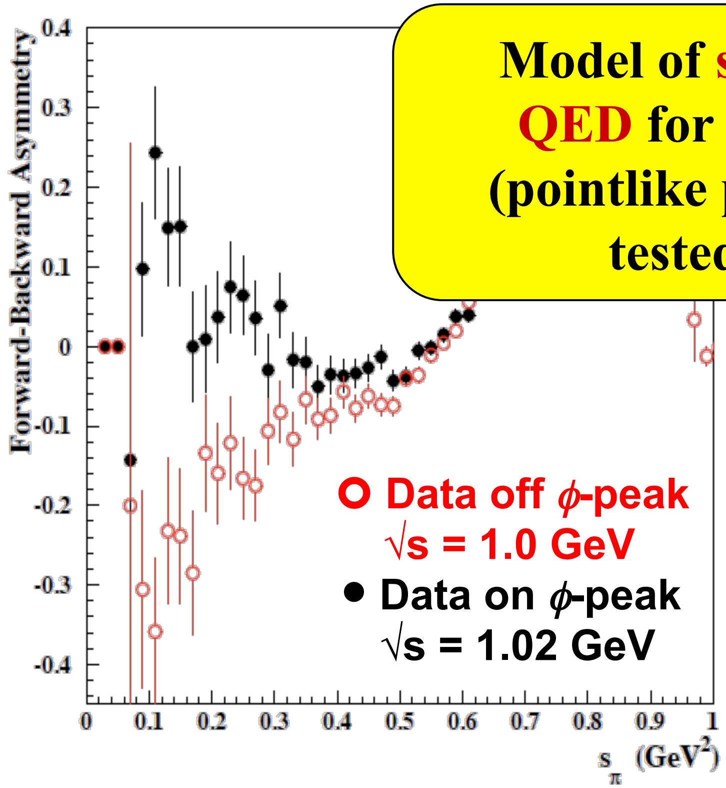
A very sensitive to:



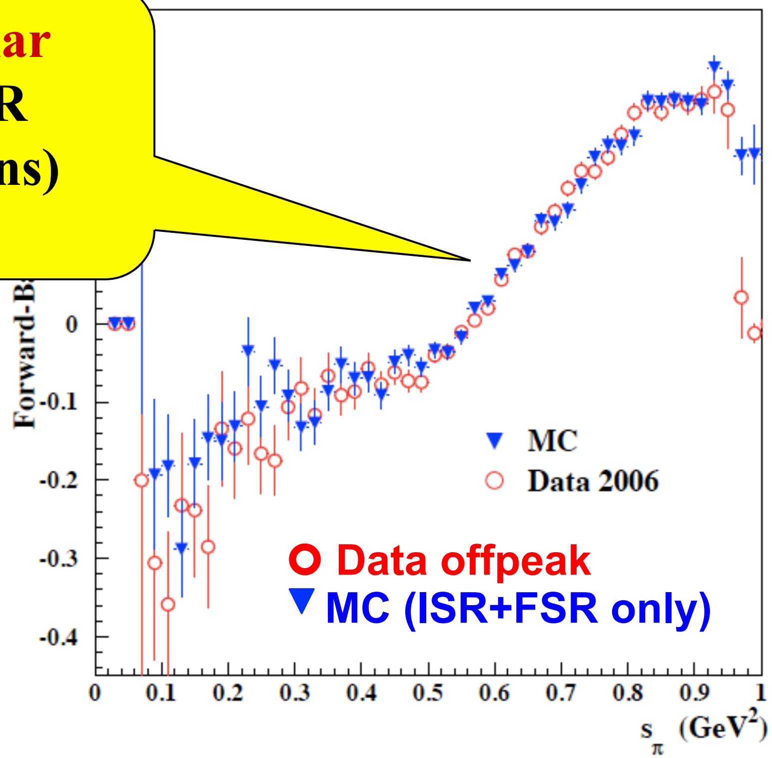
FSR



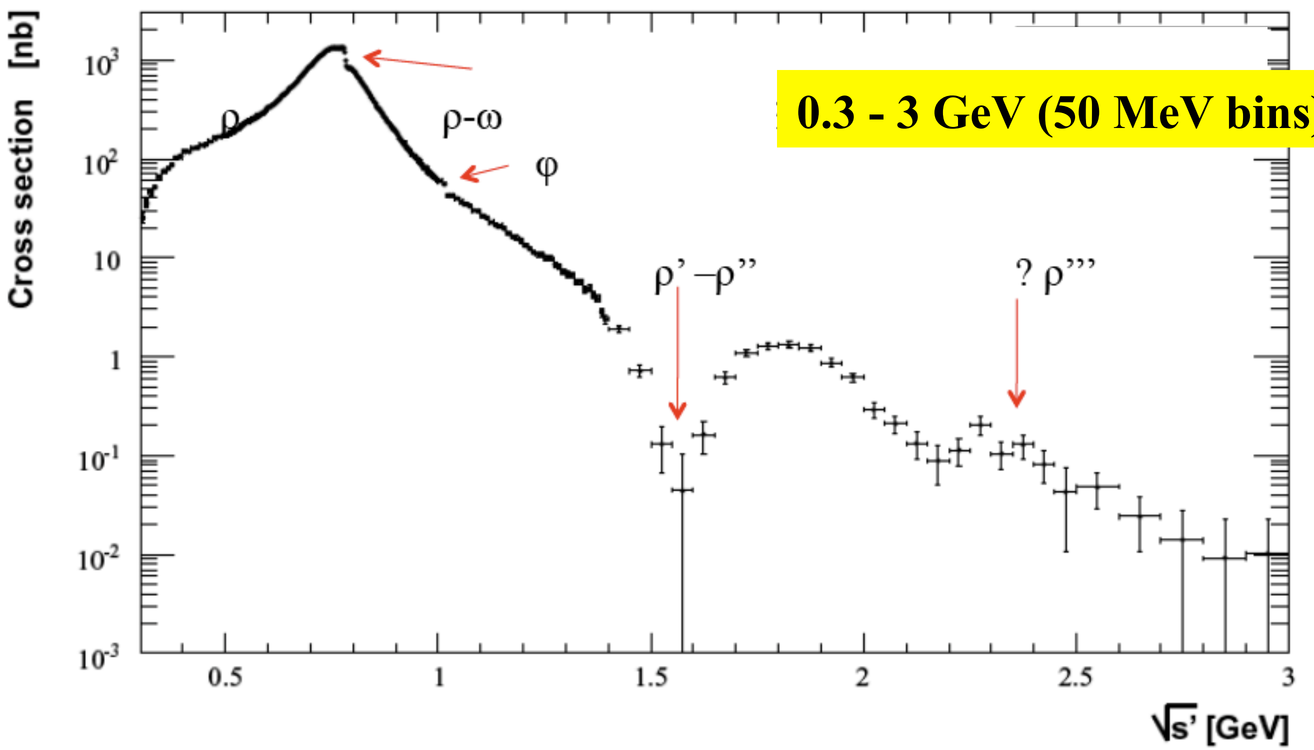
Scalar Mesons



Model of scalar QED for FSR (pointlike pions) tested

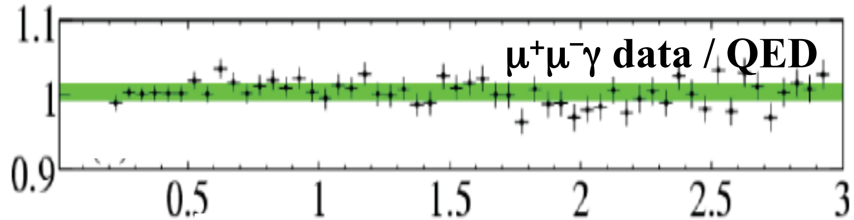


Pion Formfactor: BABAR Results

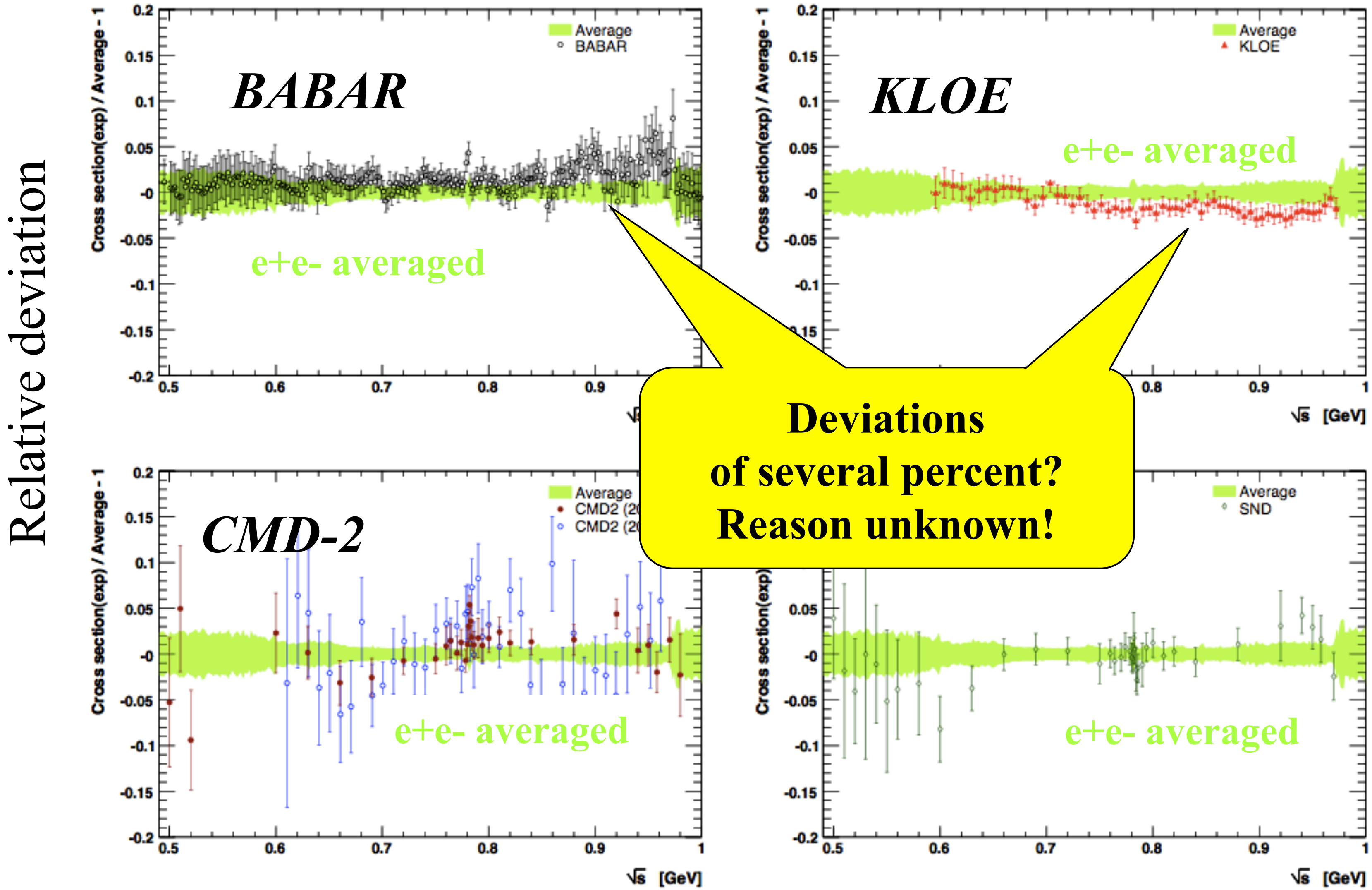


- Tagged ISR photons
- Wide energy range < 3 GeV
- Systematic uncertainty: 1.4% at threshold
  0.6% on ρ peak

- Normalized to $\mu^+\mu^-\gamma$ events:



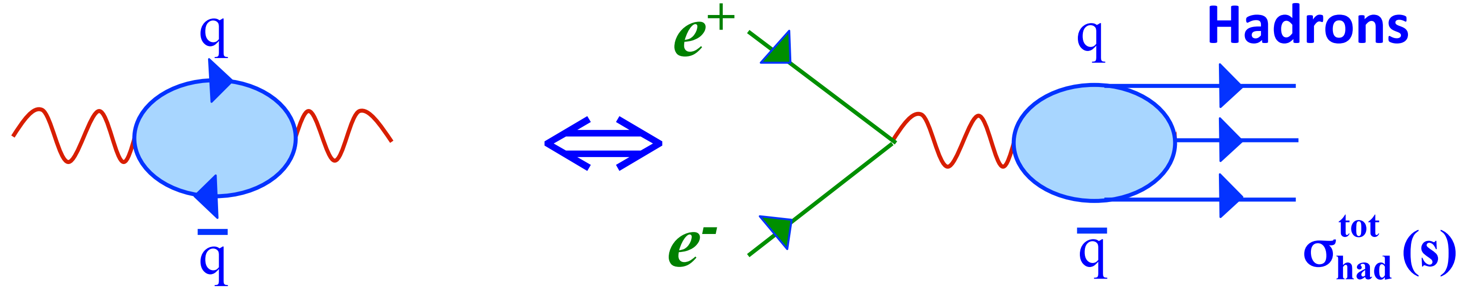
Comparison F_π among e^+e^- Experiments



M. Davier et al. ArXiv: 0908.4300

Optical Theorem & Dispersion Relation

Optical theorem:



Hadronic contribution a_μ^{had} can be computed using as input **e^+e^- annihilation data**

Dispersion integral:

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

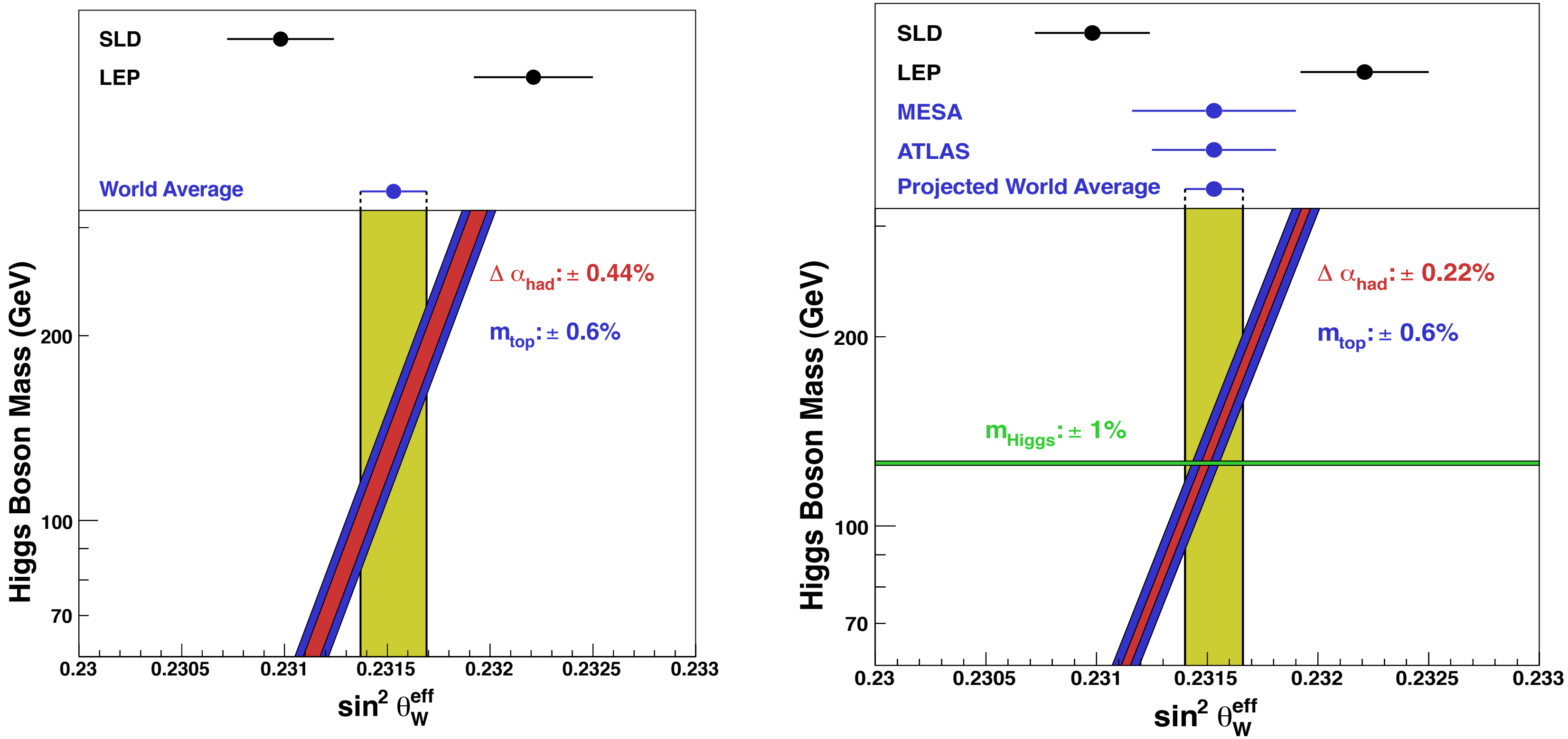
$s = (p_{e+}^{(4)} + p_{e-}^{(4)})^2$

$K(s)$ analytically known ~1/s

Input: **hadronic electron-positron cross section data**
or hadronic τ-decays → next talk

Electroweak Precision Physics

- Running of **electroweak mixing angle $\sin^2\Theta_W$** as function of Higgs mass
- After Higgs discovery even more interesting
- Theory curve limited by electromagnetic fine structure constant



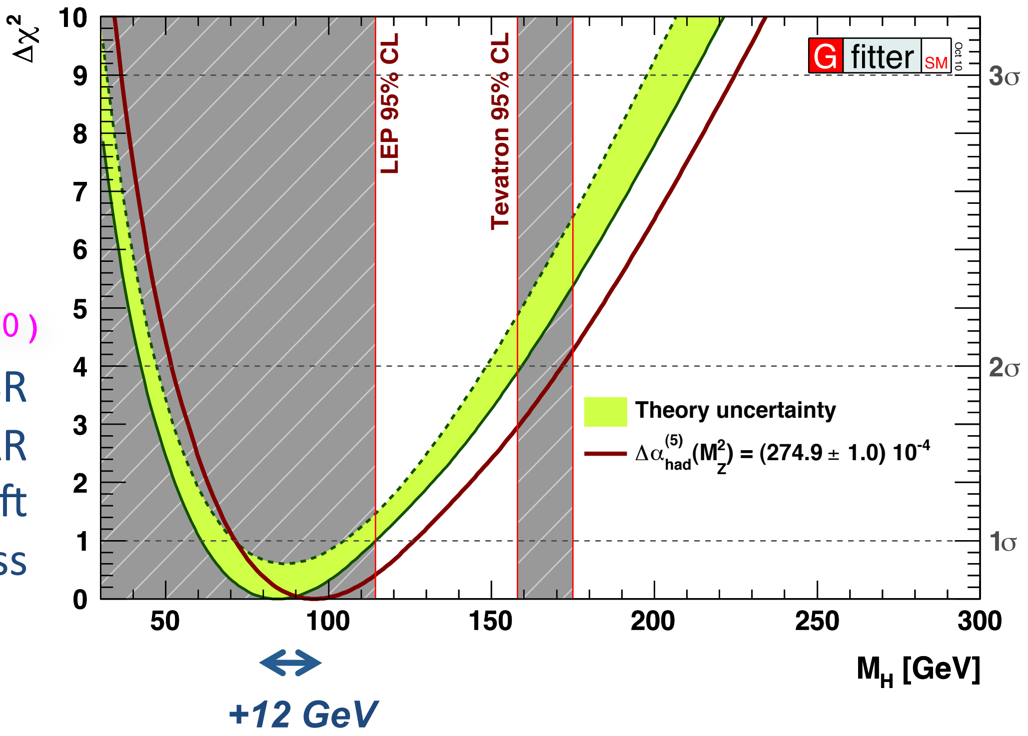
$\alpha_{em}(M_Z^2)$ and Electroweak Physics

$\alpha_{em}(M_Z^2)$ limiting electroweak precision fits

→ Test overall consistency of the electroweak Standard Model
→ Since the discovery of the Higgs boson more timely than ever

Davier *et al.* (2010)

Including recent ISR data by KLOE and BABAR lead to significant shift of predicted Higgs mass



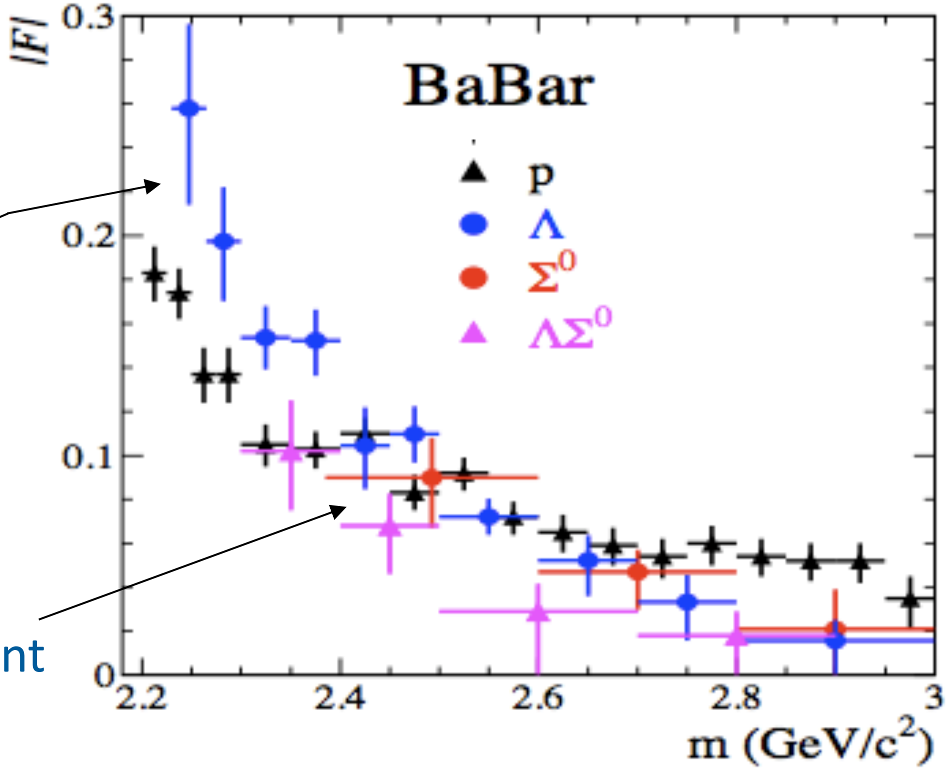
BABAR: Nucleon Form Factors

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

Cross section parametrized **by magnetic and electric form factors G_M and G_E**

$\tau = m^2/4m_B^2$

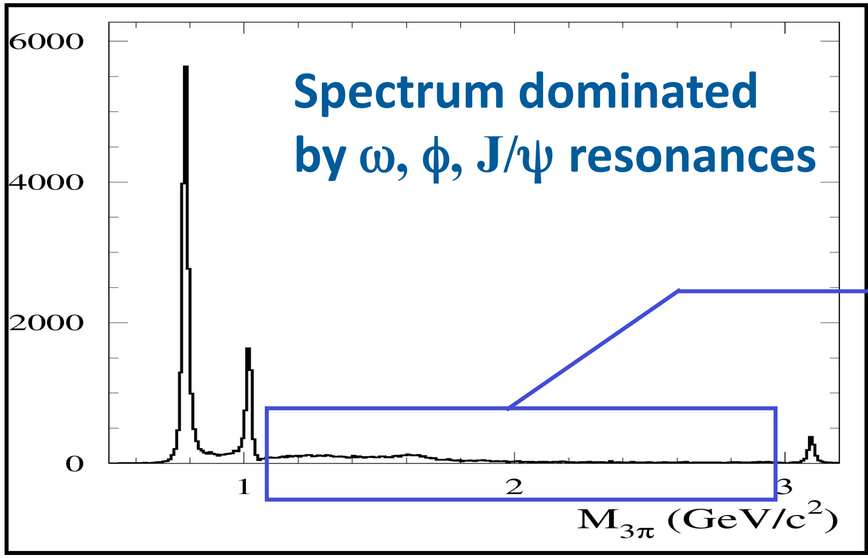
Effective FF:
$\sigma \sim |F|^2$

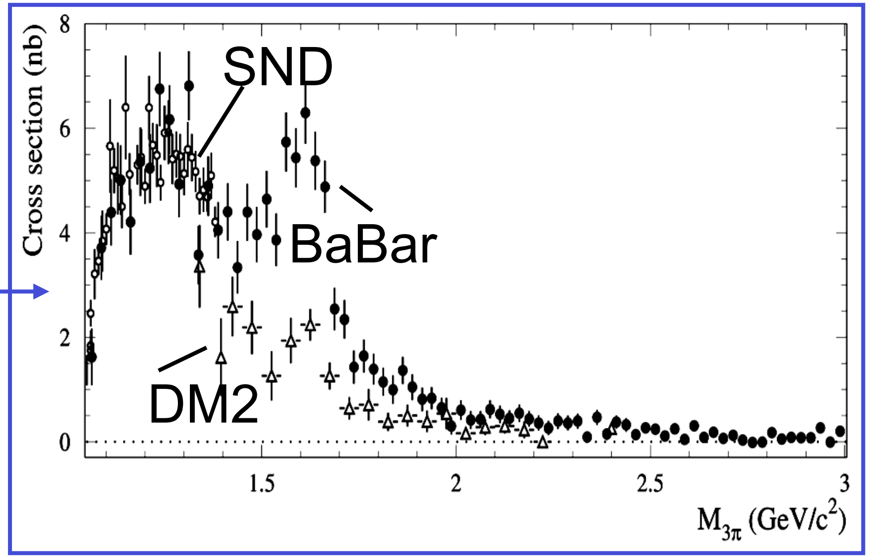


All FF's showing rising behaviour

All FF's seem to have consistent behaviour

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





Typical features:

- Precision data up to 1.4 GeV from VEPP-2M
- Above 1.4 GeV: BABAR data provides first high-statistics sample ever
- Large deviation seen with DM2
- World's most precise extraction of J/ψ branching ratio: $\mathcal{B}(J/\psi \to 3\pi) = (2.18 \pm 0.19)\%$

Muon Anomaly $(g\text{-}2)_\mu$

Magnetic Moment: $\vec{m} = \mu_B\ g\ \vec{S}$ *μ_B: Bohr magneton, g: gyromagnetic factor ~ 2*

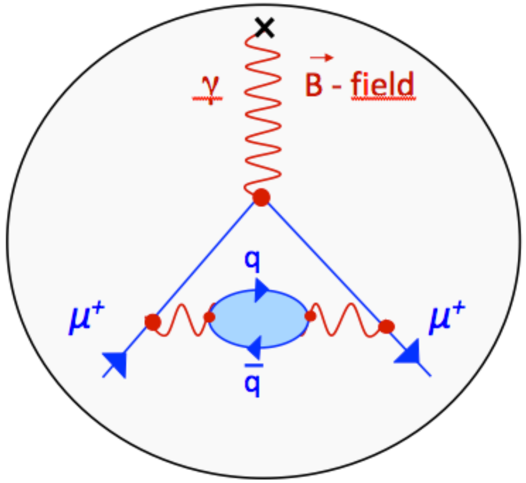
Muon Anomaly: $a_\mu = (g-2)_\mu / 2 = \alpha_{em} / 2\pi + \ldots = 0.001161\ldots.$

- **Standard Model (SM) prediction a_μ^{SM}:**

  - QED: $a_\mu^{QED} = (11\,658\,471.809 \pm 0.015) \cdot 10^{-10}$
  - weak: $a_\mu^{weak} = (15.4 \pm 0.2) \cdot 10^{-10}$
  - hadronic: $a_\mu^{hadr} =$ $\mathbf{(693.0 \pm 4.9) \cdot 10^{-10}}$

  $a_\mu^{SM} = (\,11\,659\,180.2 \pm 4.9\,) \cdot 10^{-10}$ Davier et al., 2010

  SM prediction entirely limited by **hadronic contribution**!



- **Direct measurement BNL-E821 a_μ^{exp}:**

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

Collider BEPC-II and BES-III

NEW

BEPC-II (since 2009):

- Major upgrade of BEPC and BES-III
- Design luminosity: 10^{33} $cm^{-2}s^{-1}$
- R-measurements btw. 2 – 4.5 GeV

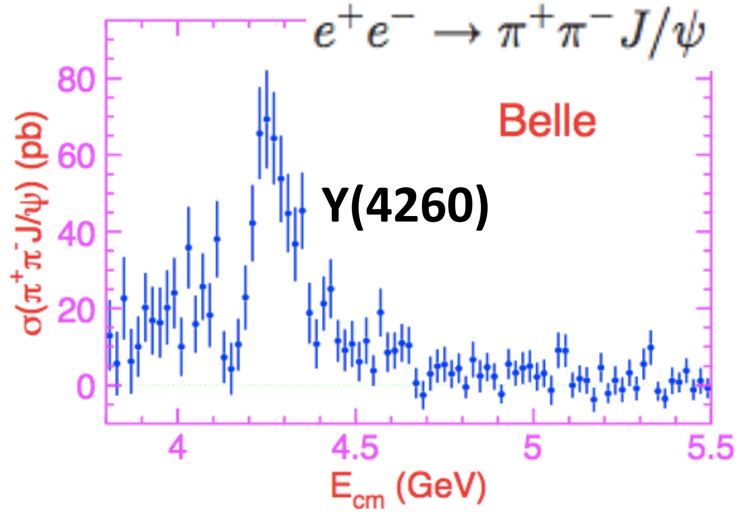
R measurement foreseen in 3 phases

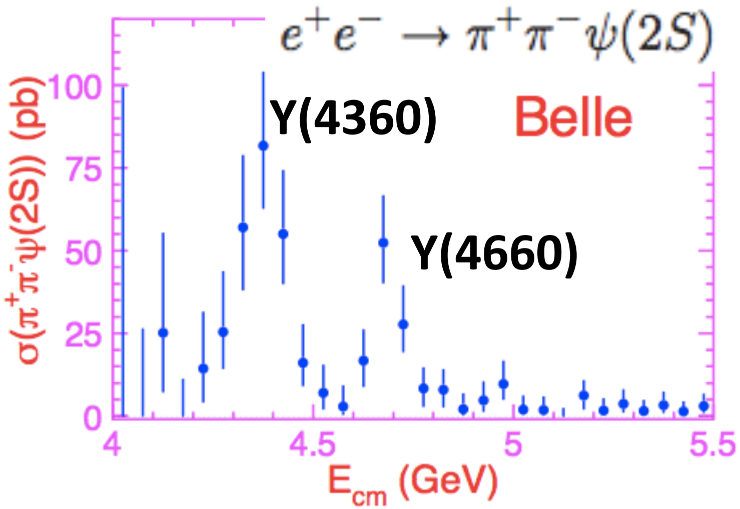
- R in range 2 – 4.5 GeV
  ~1% statistical, 3% systematic accuracy
  → improve $\alpha_{QED}(m_Z^2)$ by factor 2
- R in range 2 – 3 GeV, high statistics
  → Improve nucleon $|G_E|/|G_M|$ ratio
- Fine binning R ratio in charmonium region → charmonium spectroscopy

Radiative Return at BELLE

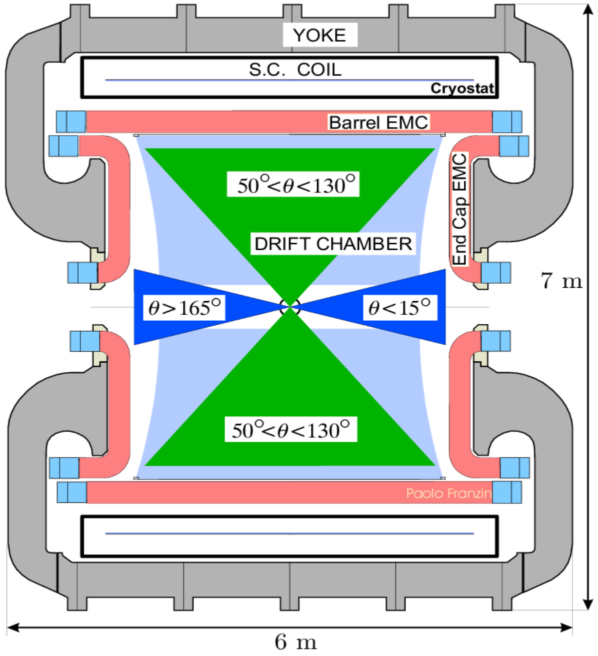
- ISR programme lead to important results on charmonium spectroscopy
- So far no publication on light hadron systems below 3 … 4 GeV (prelimary result on e+e- → $\pi^+\pi^-\pi^0$)

PRL 98 (2007) 092001	e+e- → D*+D*-, D+-D*-+
PRL 99 (2007) 182004	e+e- → π+π- J/ψ
PRL 99 (2007) 142002	e+e- → π+π- ψ(3685)
PRD 77(2008) 011103	e+e- → D^0+D^0bar-, D+-D-
PRL 100 (2008) 062001	e+e- → D^0+D-π+
PRL 101 (2008) 172001	e+e- → $\Lambda_c^+ \Lambda_c^-$, $\Lambda_c^0 \Lambda_c^0$bar





KLOE: ISR at 1.02 GeV (DAΦNE)



$$\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma_{\mathrm{ISR}})$$

Tagged analysis:

ISR photon measured in KLOE-Calorimeter

- Increased amount of Final State Radiation (FSR)

Untagged analysis:

No ISR detection; cut on missing momentum

- Threshold mass region not accessible

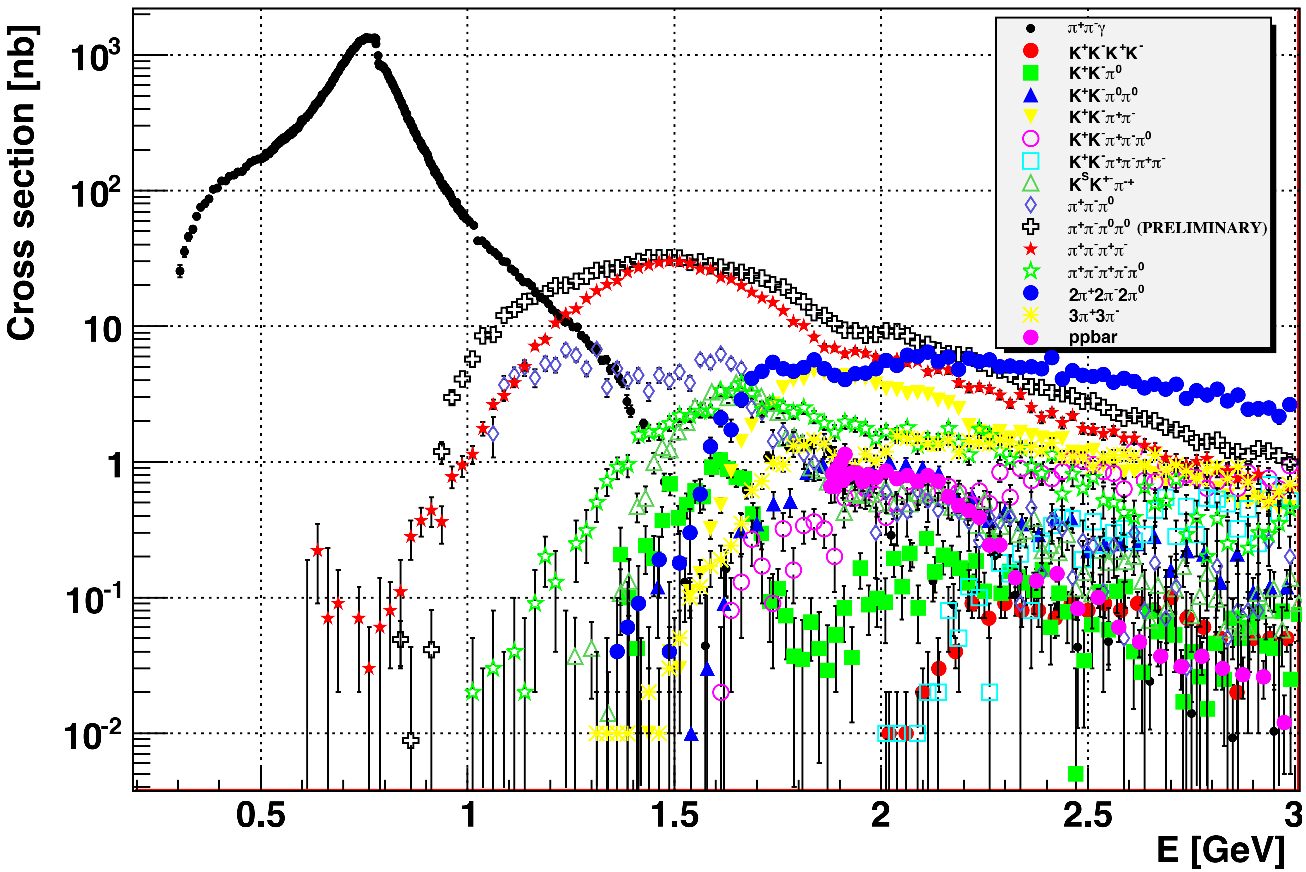
*full KLOE statistics 2,500 pb^{-1}

Publication	Mode	Normalization	Int. Luminosity*
Phys.Lett. B606 (2005) 12	untagged	Radiator	141 pb^{-1}
Phys.Lett. B670 (2009) 285	untagged	Radiator	240 pb^{-1}
Phys.Lett. B700 (2011) 102	tagged	Radiator	232 pb^{-1}
ArXiv:1212.4524	untagged	$\mu^+\mu^-\gamma$	240 pb^{-1}

NEW

BaBar

Summary of ISR Results



Precision:

2π: < 1%

3π: ~10%

4π: ~ 3%

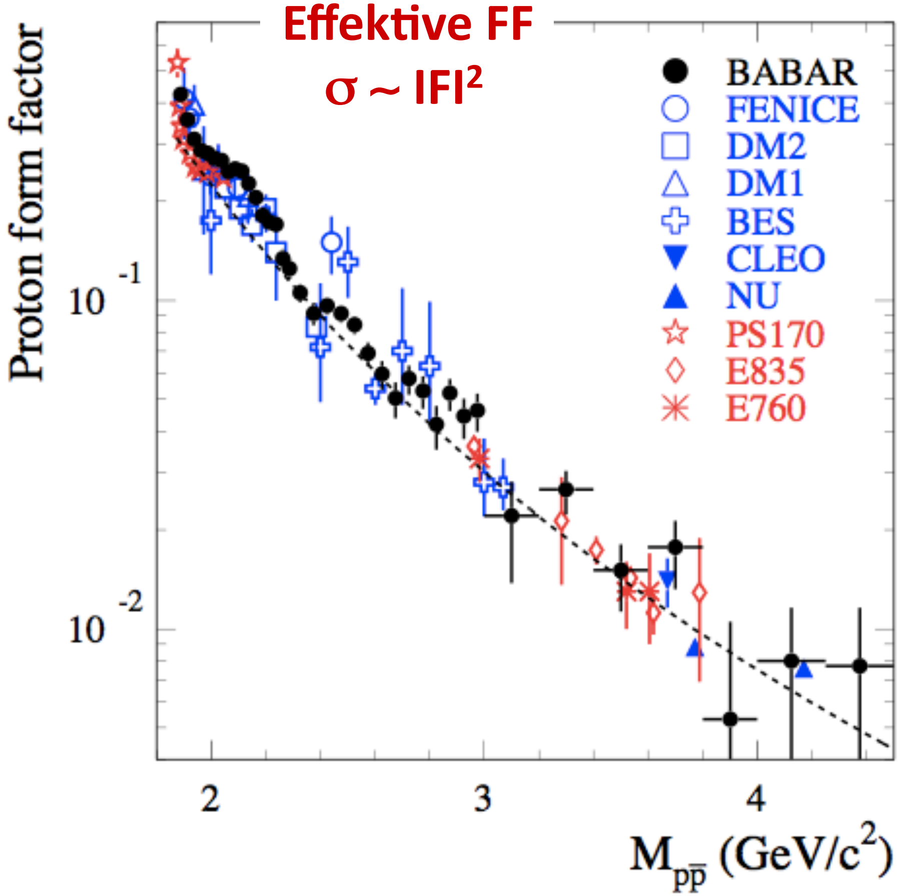
≥ 5π: 10% and higher

BABAR: Nucleon Form Factors

$$\sigma_{e^+e^-\to N\bar{N}} = \frac{4\pi\alpha^2\beta}{3s}\, C_N(s)\, \left[\left|G_M^N(q^2)\right|^2 + \frac{2M_N^2}{s} \left|G_E^N(q^2)\right|^2 \right]$$

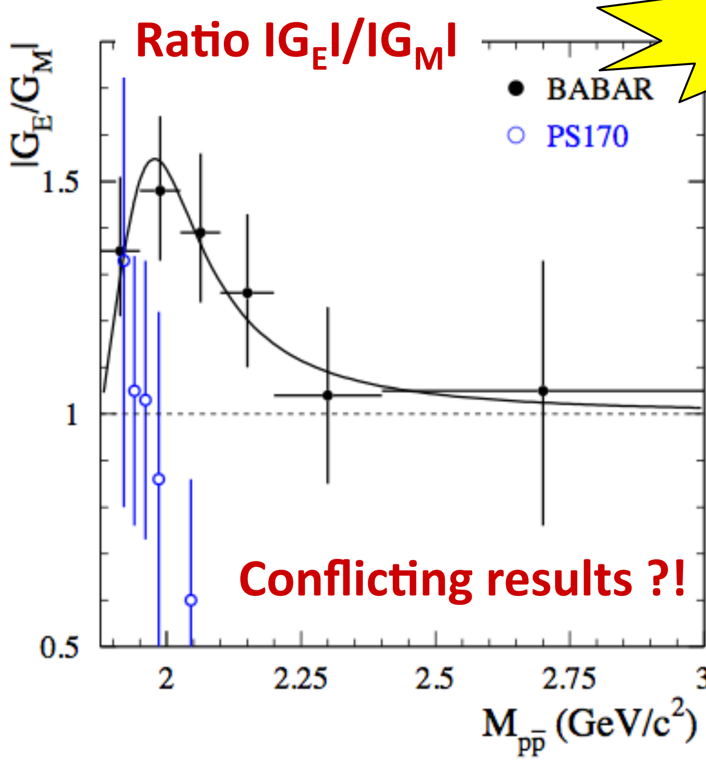
Cross section parametrized by magnetic and electric form factors G_M and G_E

Effektive FF
$\sigma \sim |F|^2$



Ratio $|G_E|/|G_M|$

NEW



Conflicting results ?!

arXiv:1302.0055: Analysis on full data set