Hadronic Cross Section Measurements at BES-III

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Introduction

- Hadronic cross sections & R ratio
- Impact on a_μ and $\Delta\alpha_{\mathrm{had}}$

Physics with Initial State Radiation

- ISR technique
- Hadronic final states at $\sqrt{s} < 2.0$ GeV
- ISR physics with BES-III

Energy Scan measurements

- BES-III Energy Scan for $\sqrt{s} = 2.0 \ldots 4.5$ GeV

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

The R ratio

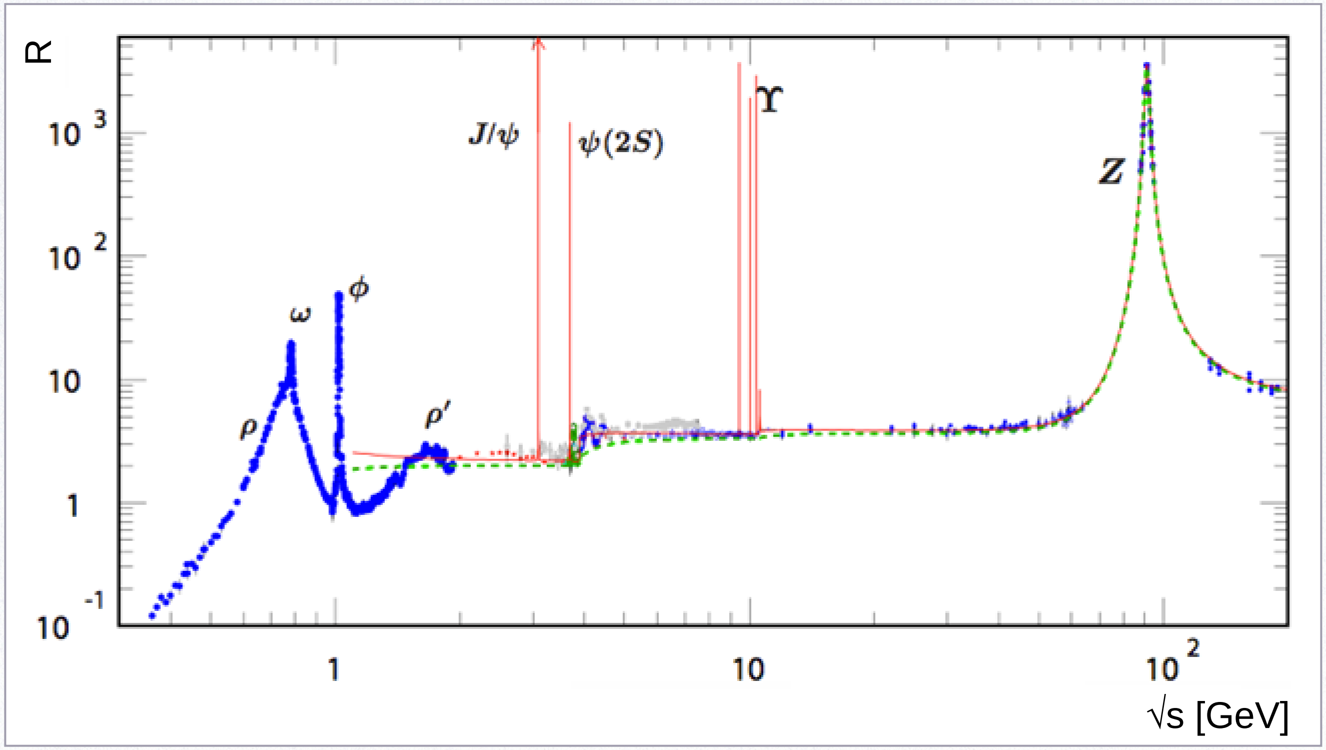
Hadronic cross section ratio R:

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

BES-III contributions to R data

Both ISR and Energy Scan measurements

Energy range $0 < \sqrt{s} < 4.5$ GeV



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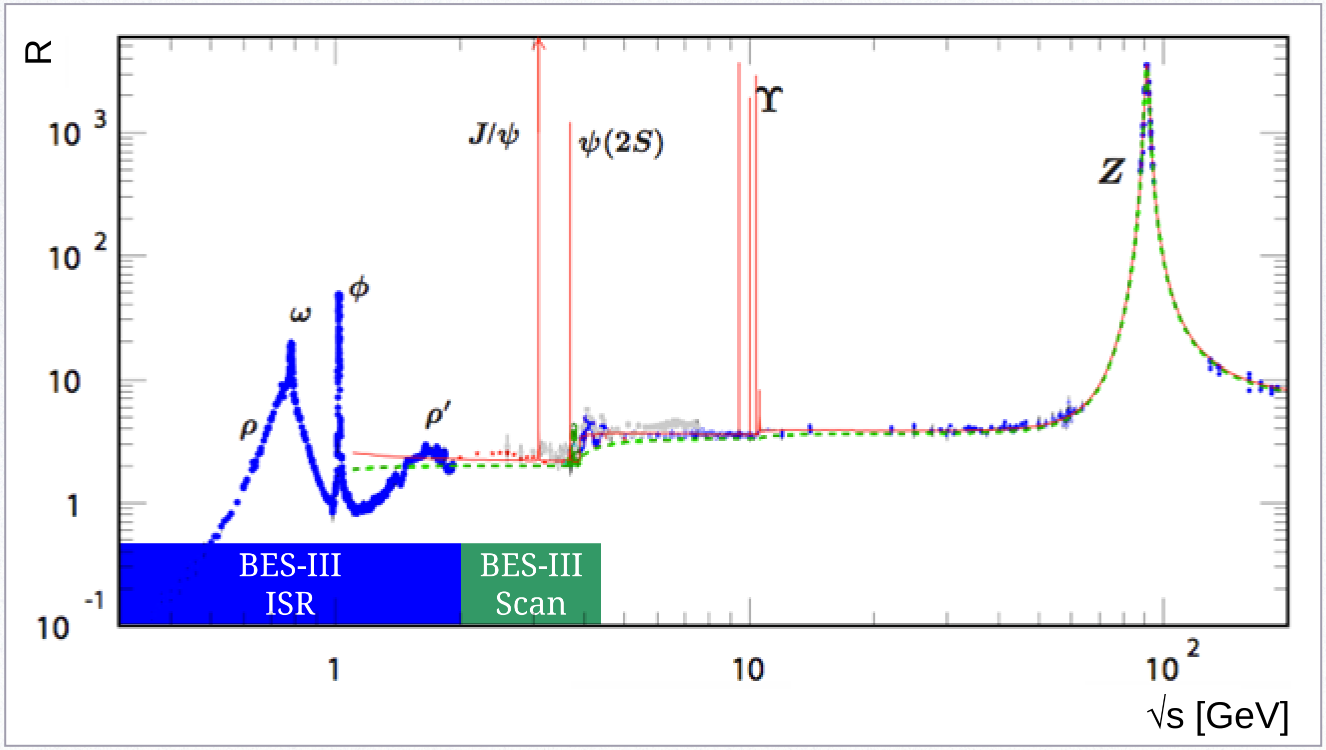
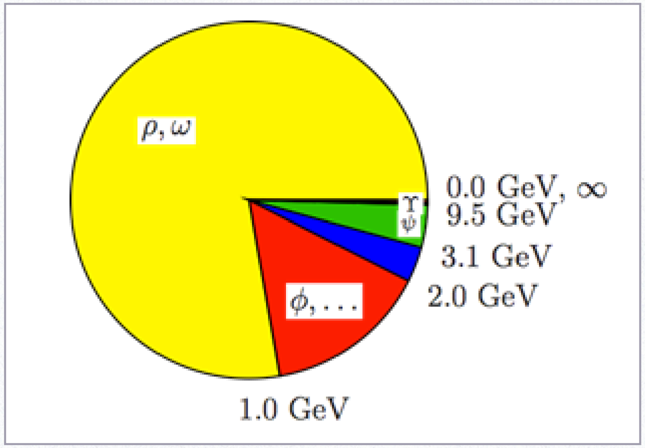


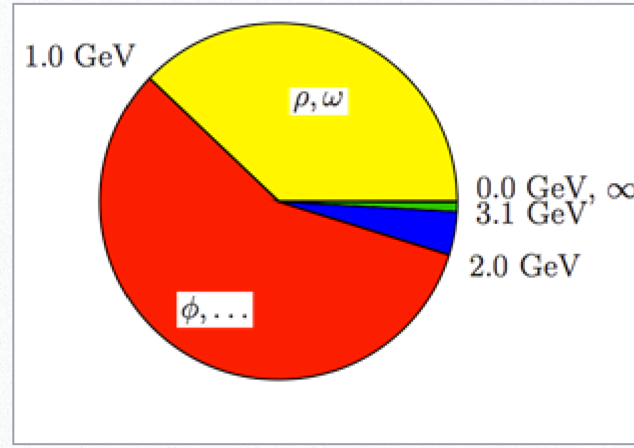
Contributions to a_μ and $\Delta\alpha_{\text{had}}$

Contributions to a_μ^{had}



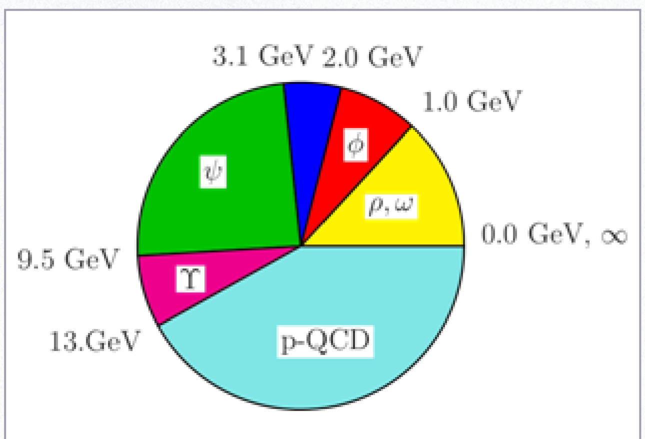
Dominated by energies $\sqrt{s} < 1$ GeV
ρ/ω resonances

Contributions to $\Delta a_\mu^{\text{had}}$

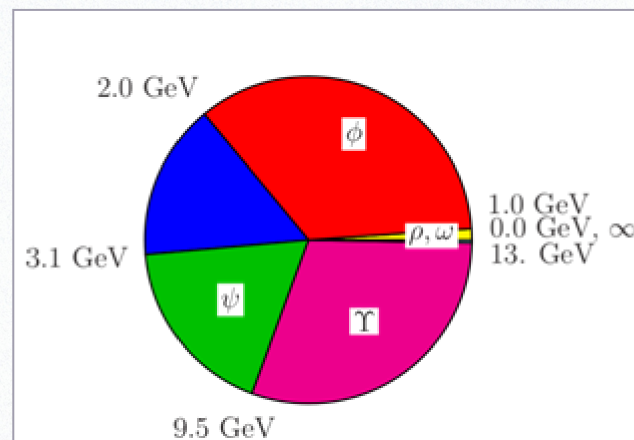


Dominated by energies $\sqrt{s} < 2$ GeV

Contributions to $\Delta\alpha_{\text{had}}$



Contributions to $\delta\Delta\alpha_{\text{had}}$



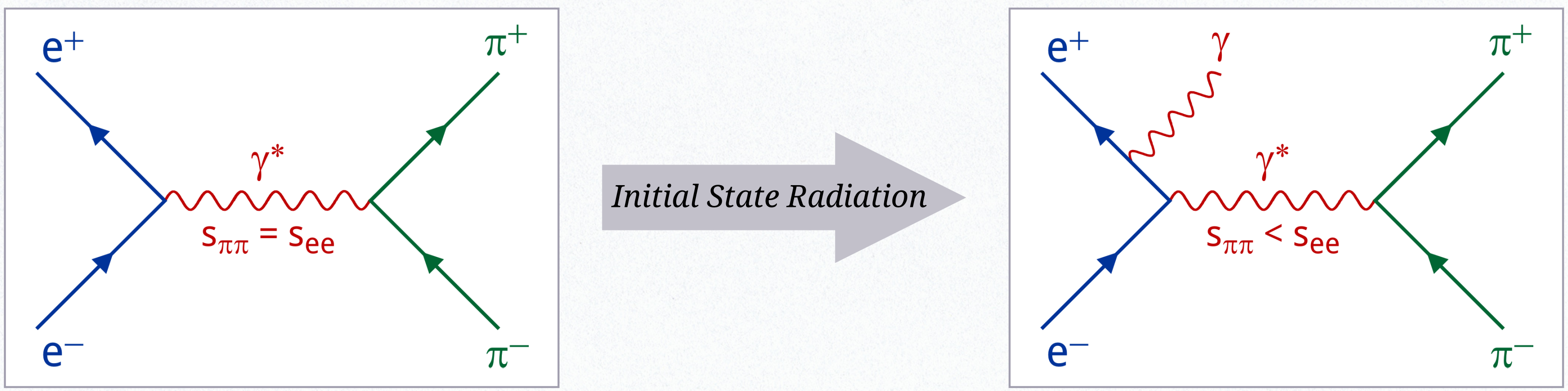
ISR physics with BES-III

Initial State Radiation

- Hadronic cross sections for a_μ and $\Delta\alpha$ required over wide energy range

- e+e- colliders at fixed (design) energy
  BEPC-II / BES-III: $\sqrt{s} = m_{\Psi(3770)} = 3.77$ GeV
  PEP-II / BABAR: $\sqrt{s} = m_{\Upsilon(4S)} = 10.58$ GeV
  DAΦNE / KLOE: $\sqrt{s} = m_{\phi(1020)} = 1.02$ GeV

- Use *Initial State Radiation (ISR)* from e^+ or e^- to decrease effective $\sqrt{s}$



- Measure cross sections for radiative process, *e.g.* $e^+e^- \to \pi^+\pi^-\gamma$

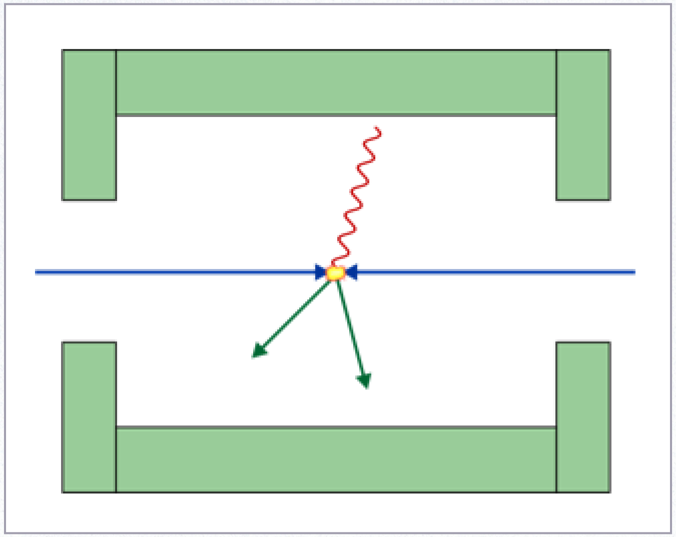
$$\frac{d\sigma(e^+e^- \to \pi^+\pi^-\gamma)}{dM_{\pi\pi}{}^2} = \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} \quad \Rightarrow \quad M^2_{\pi\pi}\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi}(s) \times H(s)$$

with Radiator function $H(s)$

Tagged and untagged ISR

Different analysis types:

- Tagged analyis: ISR photon detected in EMC

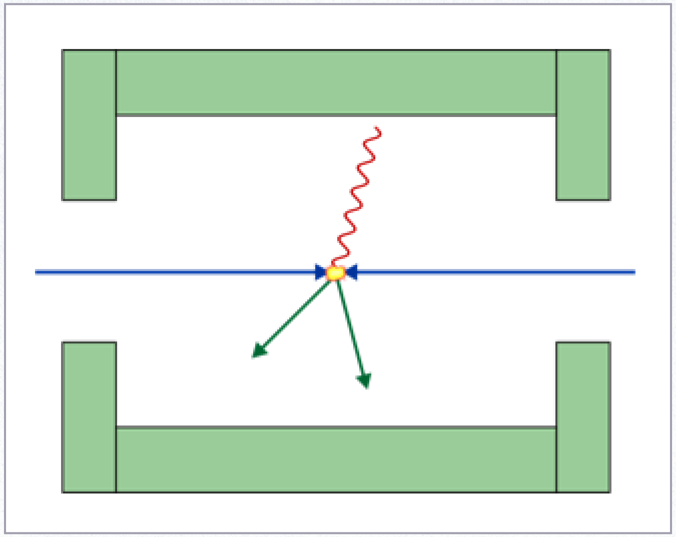


Tagged ISR

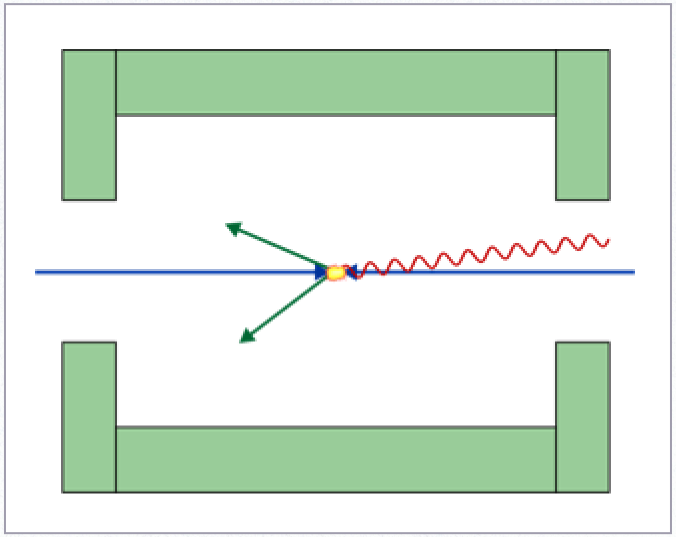
Tagged and untagged ISR

Different analysis types:

- Tagged analyis: ISR photon detected in EMC
- Untagged analysis: ISR photon leaves detector
  Most probable case
  Photon emitted close to e^+/e^- beam direction



Tagged ISR

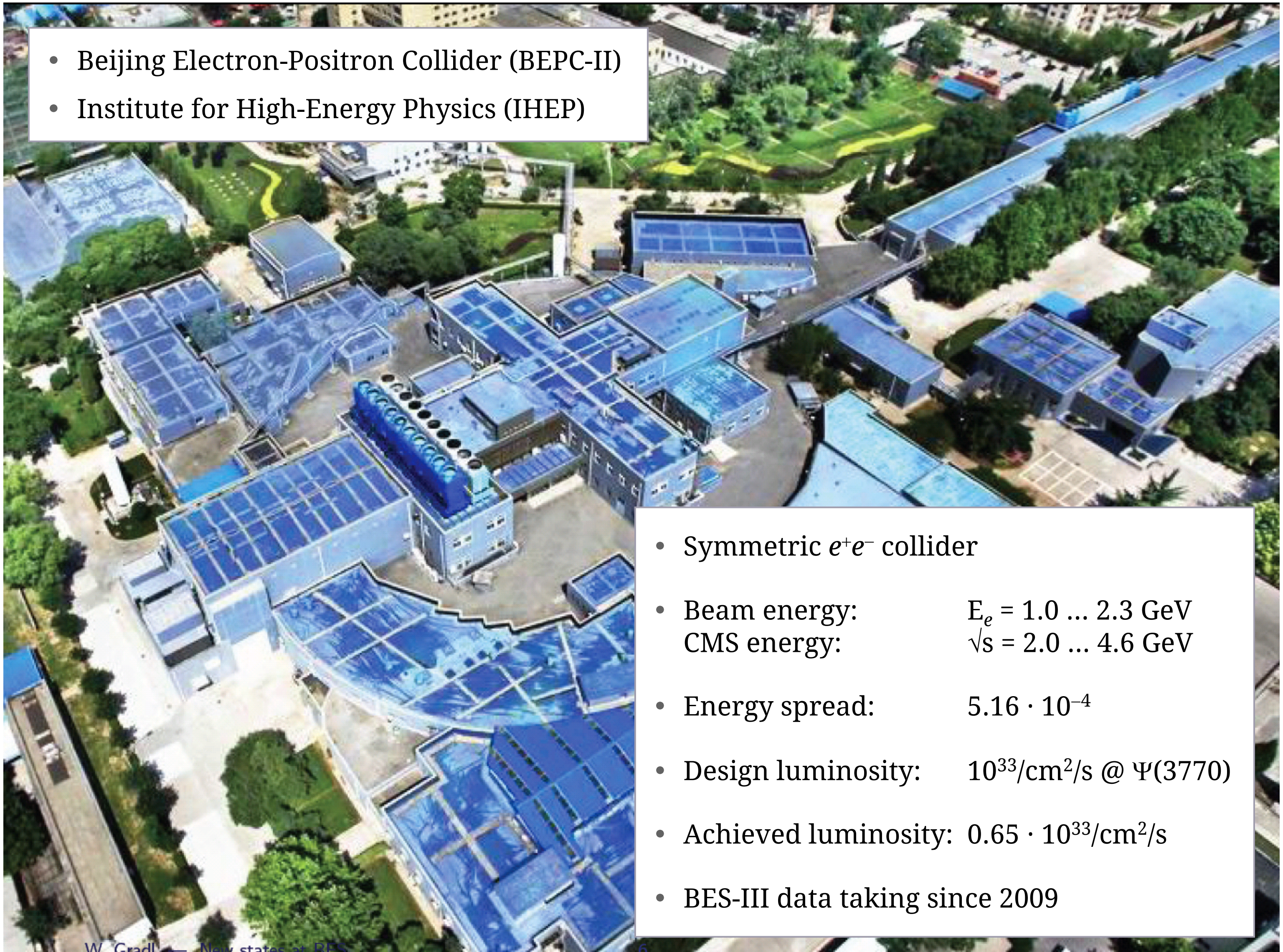


Untagged ISR

BES-III and BEPC-II

- Beijing Electron-Positron Collider (BEPC-II)
- Institute for High-Energy Physics (IHEP)

BES-III and BEPC-II



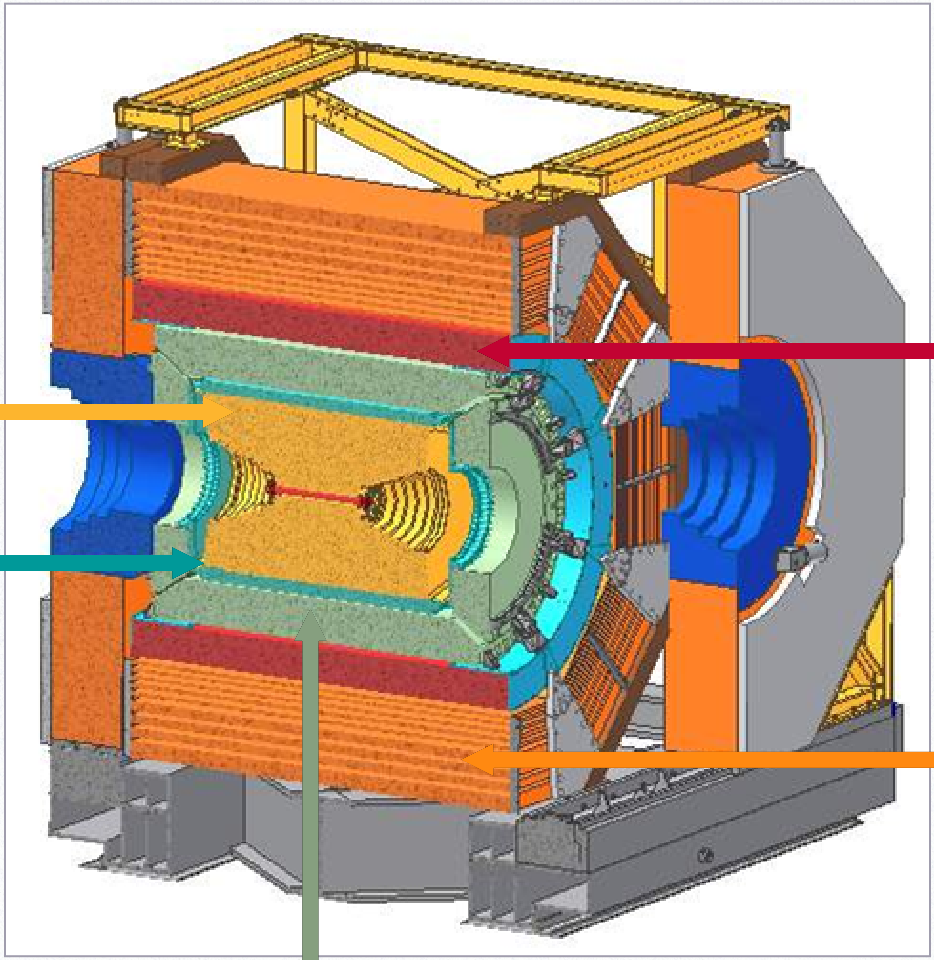
- Beijing Electron-Positron Collider (BEPC-II)
- Institute for High-Energy Physics (IHEP)

- Symmetric e^+e^- collider
- Beam energy: E_e = 1.0 ... 2.3 GeV
  CMS energy: $\sqrt{s}$ = 2.0 ... 4.6 GeV
- Energy spread: $5.16 \cdot 10^{-4}$
- Design luminosity: $10^{33}/cm^2/s$ @ $\Psi(3770)$
- Achieved luminosity: $0.65 \cdot 10^{33}/cm^2/s$
- BES-III data taking since 2009

BES-III detector systems

Cylindrical drift chamber
- σ_p/p = 0.5% @ 1 GeV

Super-conducting magnet
- B = 1.0 T



Time of Flight
- σ_T = 90 ps (Barrel)
  110 ps (Endcap)

EM calorimeter (CsI)
- $\sigma_E/\sqrt{E}$ = 2.5% @ 1 GeV

Muon chamber
- 8-9 layers RPC

BES-III data taking

July 19, 2008	First e^+e^- collision event in BES-III
11/2008	$14 \cdot 10^6$ $\Psi(2S)$ events for detector calibration
2009	$106 \cdot 10^6$ $\Psi(2S)$ events $225 \cdot 10^6$ J/Ψ events
2010	$0.9\ \mathrm{fb}^{-1}$ @ $\Psi(3770)$
2011	$2.0\ \mathrm{fb}^{-1}$ @ $\Psi(3770)$ $0.5\ \mathrm{fb}^{-1}$ @ 4.10 GeV
2012	$0.4 \cdot 10^9$ $\Psi(2S)$ events $1.0 \cdot 10^9$ J/Ψ events
2013	$1.0\ \mathrm{fb}^{-1}$ @ 4.23 GeV $0.8\ \mathrm{fb}^{-1}$ @ 4.26 GeV $0.5\ \mathrm{fb}^{-1}$ @ 4.36 GeV $0.3\ \mathrm{fb}^{-1}$ @ 4.19 ... 4.42 GeV $0.5\ \mathrm{fb}^{-1}$ @ 4.01 GeV

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- World‘s largest set on J/Ψ, $\Psi(2S)$, $\Psi(3770)$
- $2.9\ \mathrm{fb}^{-1}$ @ $\Psi(3770)$
  used for ISR physics

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- World‘s largest set on J/Ψ, $\Psi(2S)$, $\Psi(3770)$
- 2.9 fb^{-1} @ $\Psi(3770)$
  used for ISR physics

- 3.1 fb^{-1} @ XYZ region
  usable for ISR physics

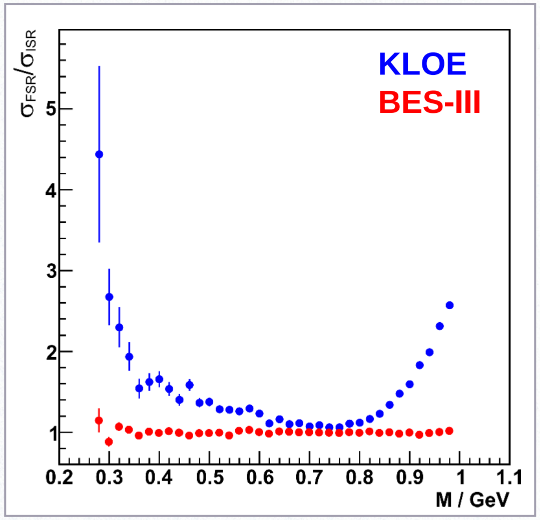
BES-III compared to KLOE:

☺ Higher energy range covered
up to $\sqrt{s}$ ~ 3.5 GeV with BES
max. $\sqrt{s}$ ~ 1.0 GeV with KLOE

☺ Less Final State Radiation (FSR)

☹ Worse statistics for $\pi^+\pi^-$ final state

☹ Worse mass resolution
Larger drift chamber of KLOE

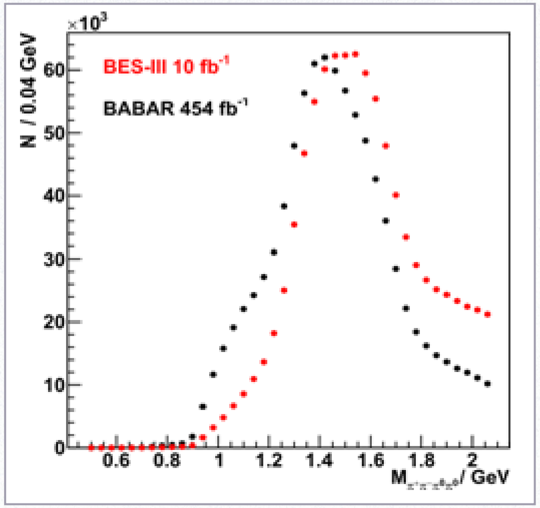


BES-III compared to *B*-factories:

😐 Similar effective luminosities
Smaller integrated luminosity
More advantageous Radiator function

☺ Untagged ISR measurements possible already at ~ 1 GeV

😐 Similar mass resolution

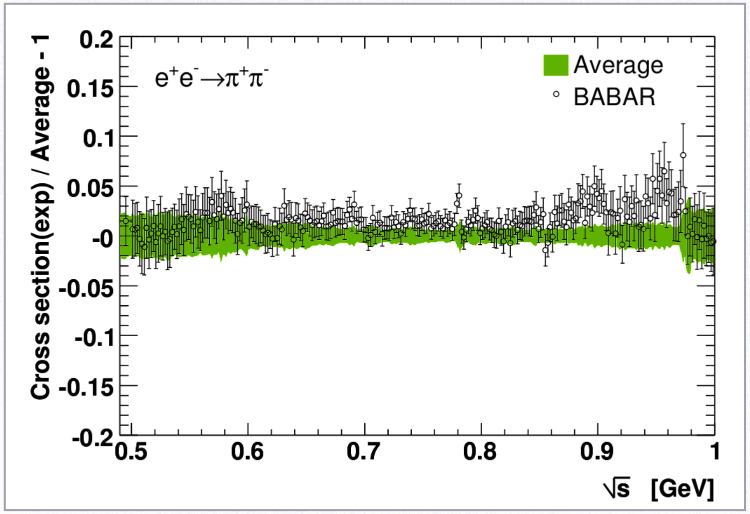


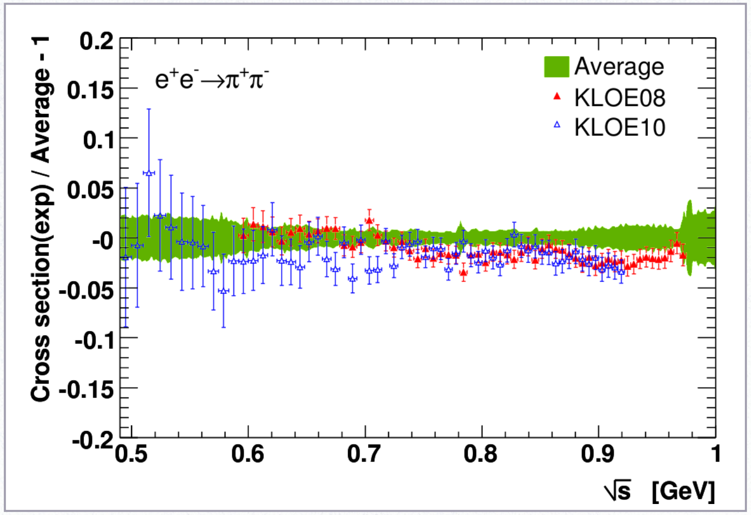
BES-III programme on ISR

ISR measurements for 3 main channels contributing to a_μ^{had} :

① $\pi^+\pi^-$ cross section for $\sqrt{s} < 1$ GeV:

- Precise measurements of π form factor in ρ/ω region from BABAR & KLOE
  BABAR: *PRL 103, 131801 (2009)*
  KLOE: *PLB 670, 285 (2009), PLB 700, 102 (2011)*
- Both experiments claiming ~1% precision





- Discrepancy between both experiments

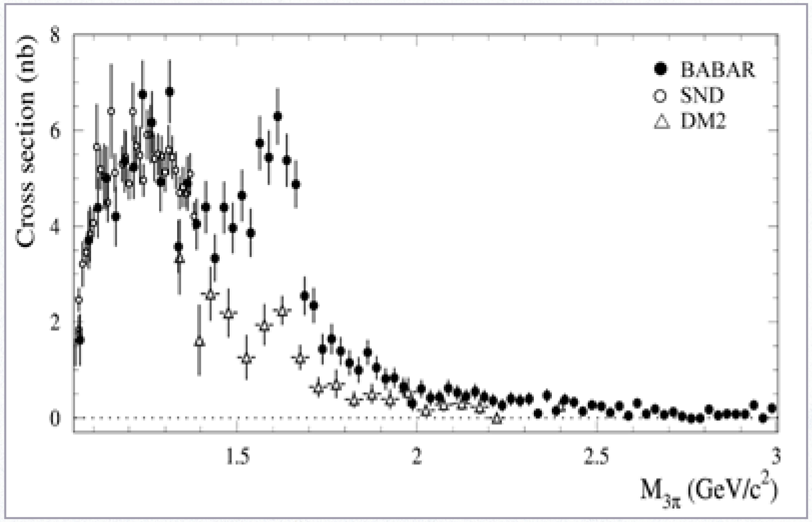
⇒ Additional measurement for $\pi^+\pi^-$ cross section needed

BES-III programme on ISR

(2) $\pi^+\pi^-\pi^0$ cross section:

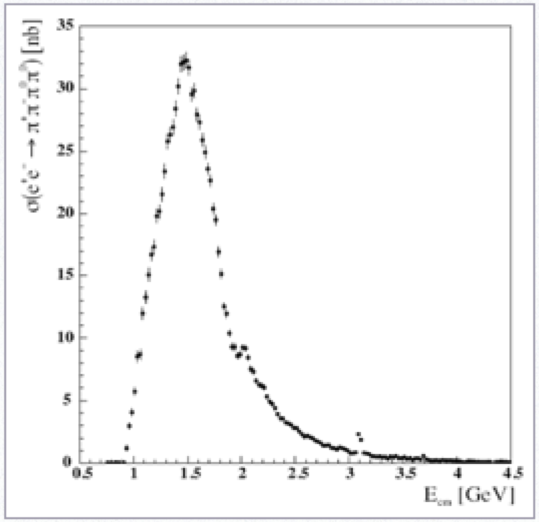
- VEPP-2000 precision data up to $\sqrt{s}$ = 1.4 GeV
- High-statistics data from BABAR for $\sqrt{s}$ > 1.4 GeV
- Large deviation of BABAR & DM2 results

→ Cross-check with BES-III ISR



(3) $\pi^+\pi^-\pi^0\pi^0$ cross section :

- High statistics BABAR ISR results
  Huge improvement for $\sqrt{s}$ > 1.4 GeV
  First measurement for $\sqrt{s}$ > 2.5 GeV
- Competitive statistics at BES-III
  BABAR: 454 fb^{-1} @ 10.58 GeV
  BES-III: 10 fb^{-1} @ 3.77 GeV
  Advantageous BES-III radiator function



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

Goal: Measurement of $R_{\pi\pi}$:

$$R_{\pi\pi} = \frac{\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-\gamma)} = \frac{N(e^+e^- \rightarrow \pi^+\pi - \gamma)}{N(e^+e^- \rightarrow \mu^+\mu^-\gamma)}$$

with

$$\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma) = \frac{N(e^+e^- \rightarrow \pi^+\pi^-\gamma) - N_{\mathrm{Bkg}}}{\varepsilon \cdot \int Ldt \cdot H}$$

Main issue: π/μ separation ✓

- Using Artificial Neural Network (ANN)
- ANN trained with $\mu^+\mu^-\gamma$ and $\pi^+\pi^-\gamma$ MC samples
- Correct for efficiency differences between data and MC

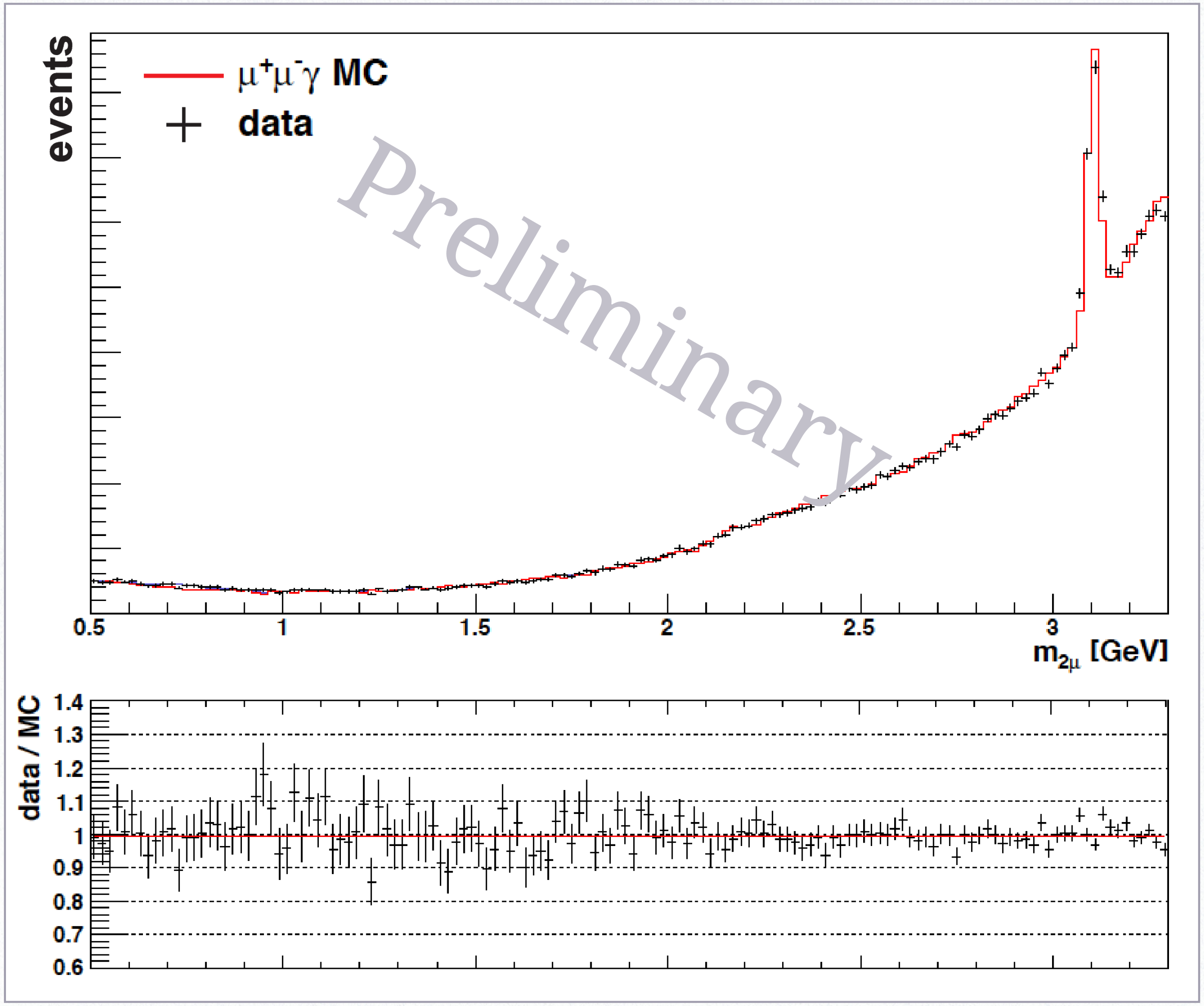
Other analyis steps:

- μ, π tracking efficiency ✓
- Photon efficiency ✓
- Kinematic fit ✓
- Unfolding of mass resolution ✓
- FSR corrrection —

Dedicated results for $\pi^+\pi^-\gamma$ analysis

$e^+e^- \rightarrow \mu^+\mu^-\gamma$ mass distribution (*preliminary*)

$\mu^+\mu^-$ mass distribution – tagged ISR:

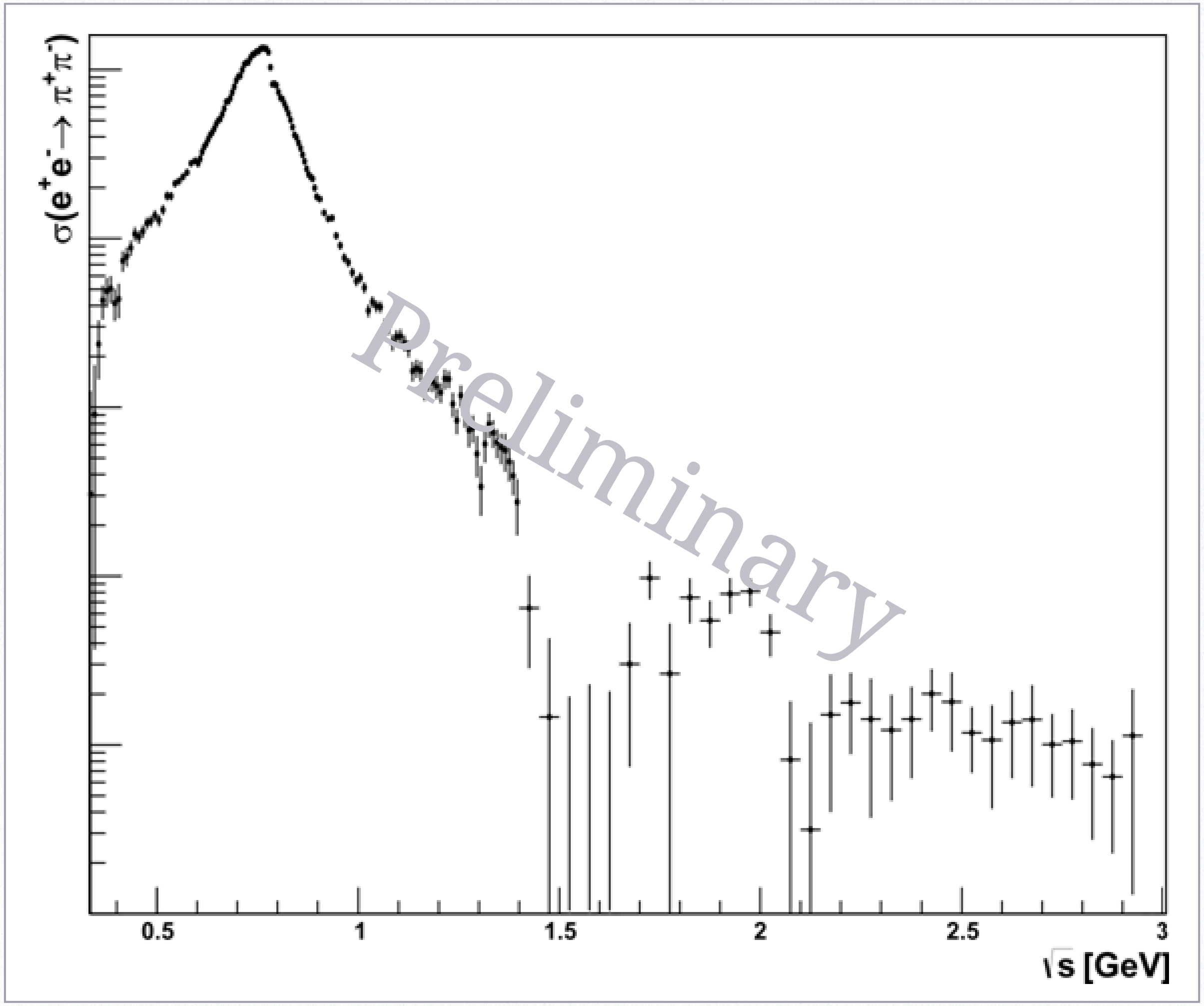


- BES-III data
  2.9 fb^{-1} @ 3.770 GeV, tagged ISR
- Simulation
  PHOKHARA 7.0, $e^+e^- \rightarrow \mu^+\mu^-\gamma$
- Very good agreement
- Data & MC difference of

  $(0.5 \pm 0.3)\%$

$e^+e^- \to \pi^+\pi^-$ cross section *(preliminary)*

$\pi^+\pi^-$ cross section – extracted from ISR $\pi^+\pi^-\gamma$ data



- BES-III data
  2.9 fb^{-1} @ 3.770 GeV, tagged ISR
- Wide energy range
  up to ~3 GeV
- No FSR correction yet

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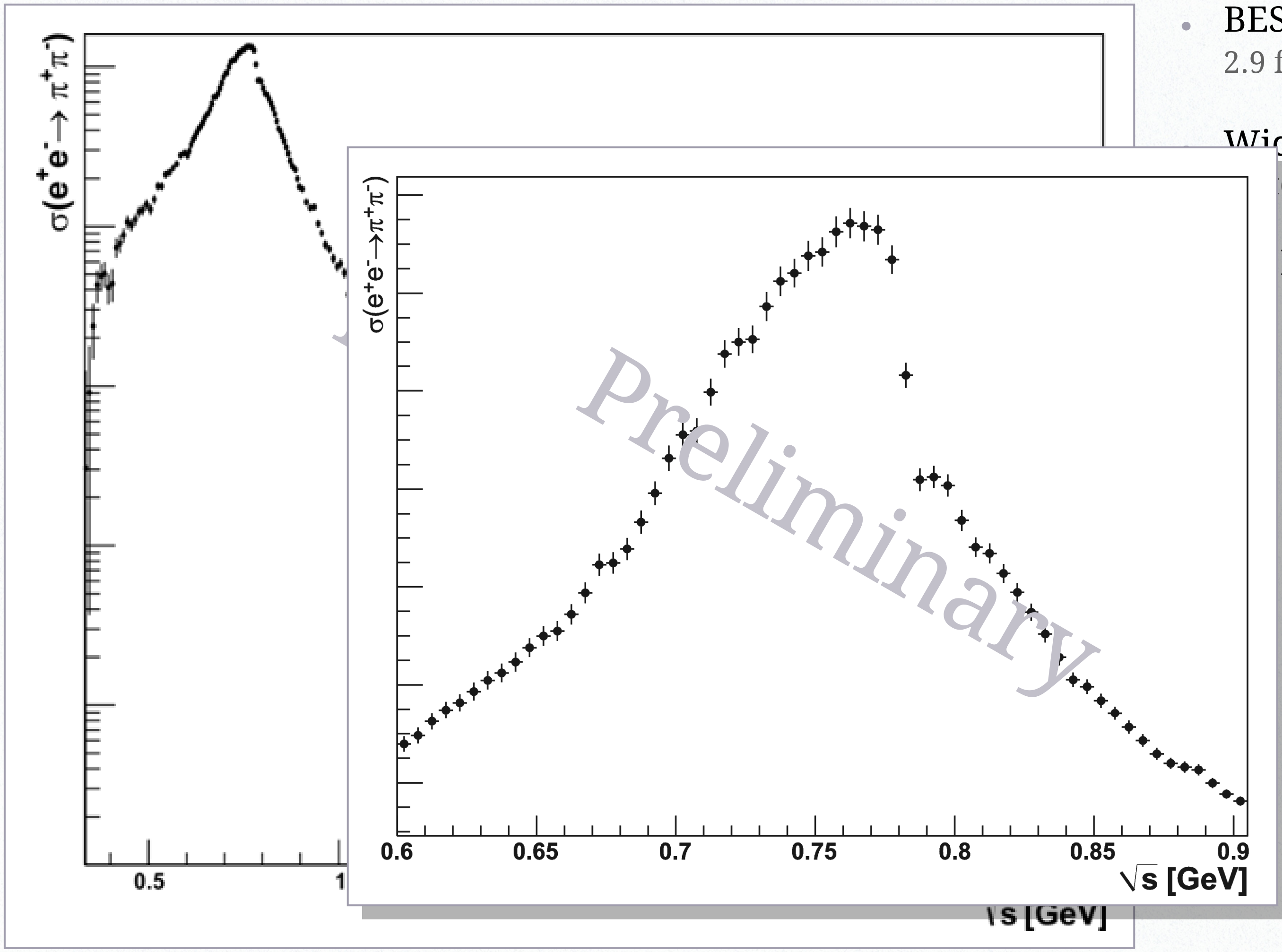

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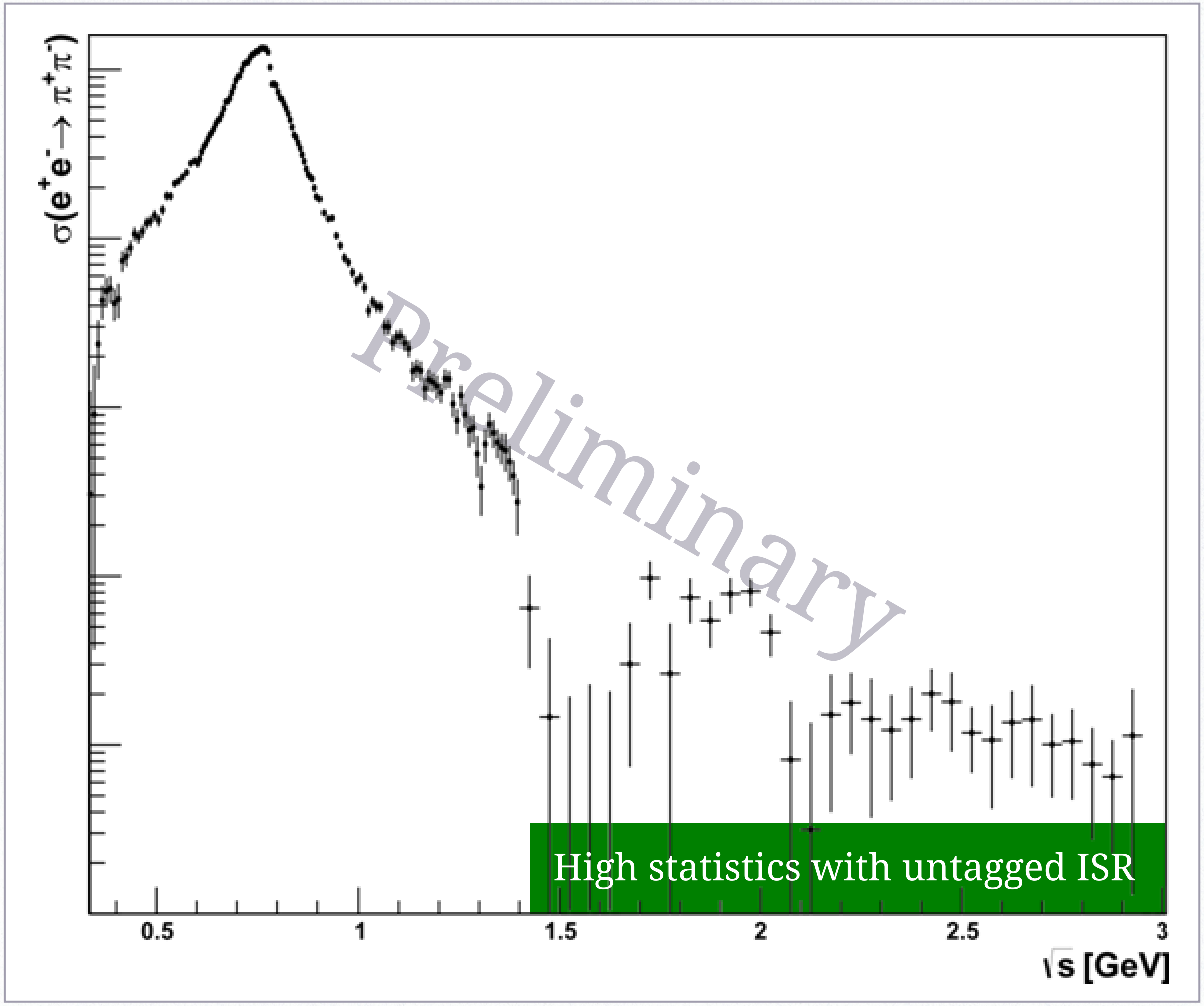

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  2.9 fb^{-1} @ 3.770 GeV, tagged ISR
- Wide energy range
  up to ~3 GeV
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Energy scan measurements with BES-III

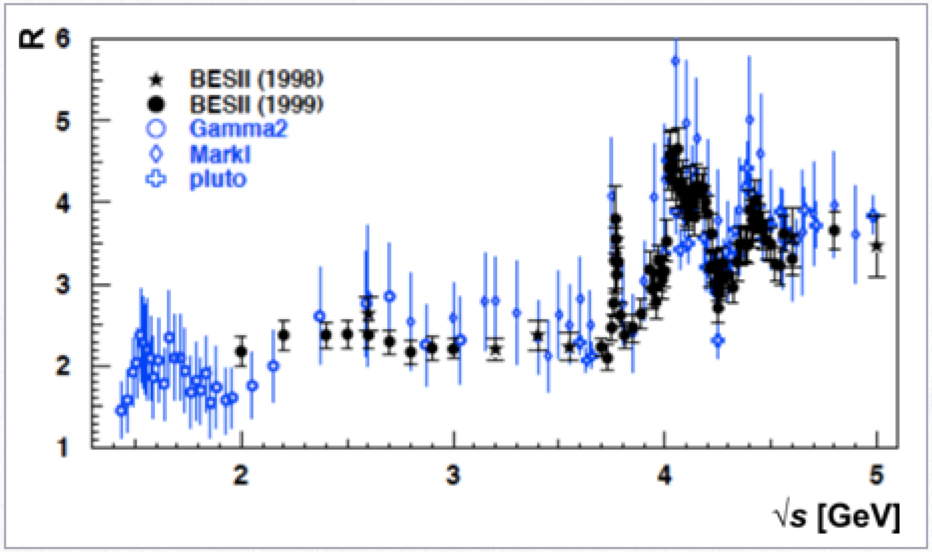
Previous R measurements with BES

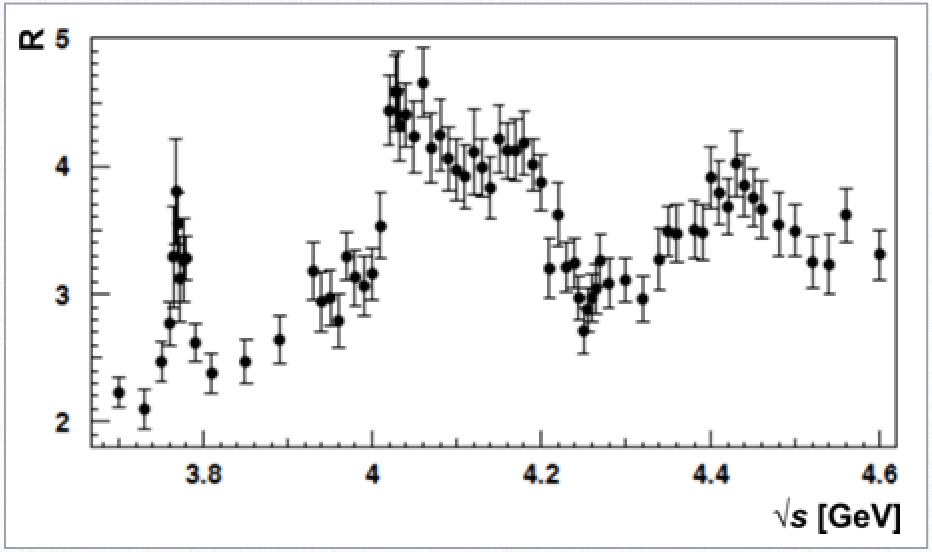
Energy scan experiments at BEPC:

- Pre-studies with BES-I τ mass data
  12 continuum data points
  $\sqrt{s}$ ~ 3.55 GeV
  HEP&NP 24, 609 (2000)
- Test run
  6 data points
  $\sqrt{s}$ = 2.6 … 5.0 GeV
  PRL 84, 594 (2000)
- Full scan
  85 data points
  $\sqrt{s}$ = 2.0 … 4.8 GeV
  PRL 88, 101802 (2002)
- R around $\Psi(3770)$
  2 data points off-resonance
  1 data point on-resonance
  PLB 641, 145 (2006)
- Improvements at 3 continuum points
  PLB 677, 239 (2009)

Statistical accuracy:	3 … 5%
Systematic uncertainty:	5 … 8%

→ Major improvement on R





New energy scan experiments at BEPC-II:

- Phase 1

  Energy range $\sqrt{s}$ = 2.0 … 4.5 GeV
  about 10^4 events per scan point
  about 3% systematic accuracy

  ➡ Improvement on $\alpha_{\text{em}}(M_Z^2)$ by factor 2

- Phase 2

  Energy range $\sqrt{s}$ = 2.0 … 3.0 GeV
  about 10^5 events per scan point
  high statistics
  Time-like p, n, Λ form factors G_E, G_M

  ➡ Improvement on $|G_E|/|G_M|$ by factor 10

- Phase 3

  Fine energy binning in charmonium region
  Determination of R_c

  ➡ Charmonium spectroscopy

Phase 1: Mini *R* Scan (2012)

BES-III data taking during June 8-16, 2012:

- 4 energy points
  $\sqrt{s}$ = 2.23 GeV ($\Lambda\underline{\Lambda}$ threshold)
  $\sqrt{s}$ = 2.40 GeV
  $\sqrt{s}$ = 2.80 GeV
  $\sqrt{s}$ = 3.40 GeV
- Total integrated luminosity ~12pb^{-1}

- Useful information for BEPC-II performance at low energies
- Preparations for extended Phase 1 scan
- Data used to establish analysis chain

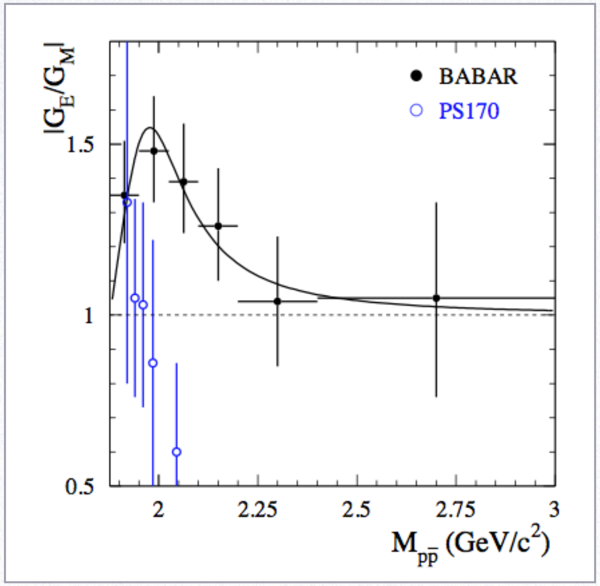
↳ Studies of baryon form factors, fragmentation function, ...

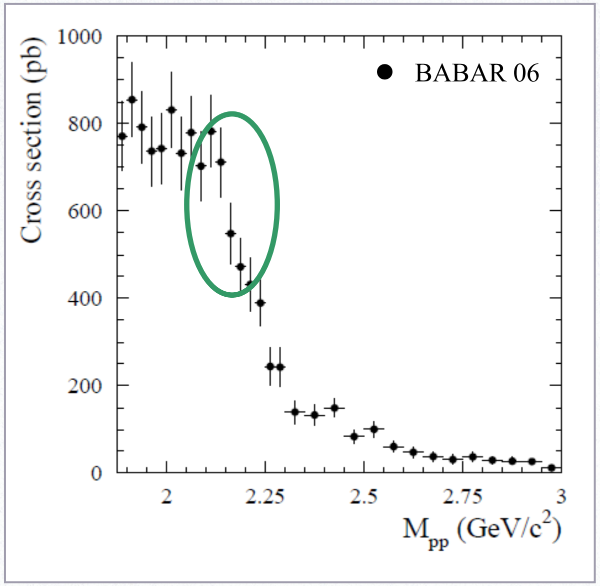
Phase 2: Nucleon Form Factors

$e^+e^- \rightarrow N\underline{N}$ cross section and time-like baryon form factors:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta_N}{4Q^2}\left(|G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta\right)$$

- Parametrised by electric and magnetic form factors G_E, G_M
- Energy region $\sqrt{s}$ ~ 2.0 … 2.5 GeV
- Previous data on $|G_E|/|G_M|$ inconclusive
- Investigate cross section drop around ~2.15 GeV

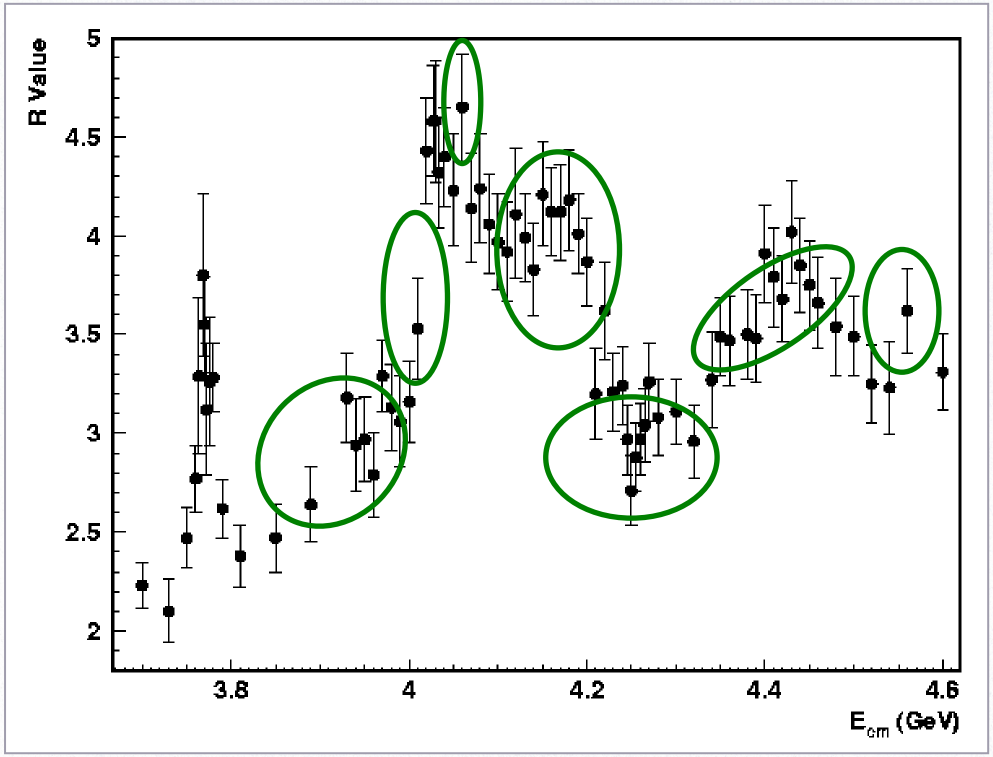




Phase 3: Charmonium spectroscopy

Understanding the nature of charmonium resonances:

- All possible two-body decays of $\Psi(3770)$, $\Psi(4040)$, $\Psi(4160)$, $\Psi(4415)$ need to be considered
- High statistic data at peak positions required
  Measure the resonance parameters
  Determine cross section of exclusive decay channels



- Investigate possible broad resonance structures
- Mass region where some X, Y, Z particles are found
- Possible new resonances, which are not yet discovered?

Summary & Outlook

- Hadronic cross section measurements important for a_μ and $\Delta\alpha_{had}$
  - Precise data at low energies required
  - ISR and Energy Scan measurements

- ISR physics programme at BES-III
  - 2.9 fb^{-1} @ Ψ(3770), 3.1 fb^{-1} @ XYZ region
  - Highly competitive with other facilities
  - Precise measurements of hadronic final states for $\sqrt{s} < 2$ GeV
  - Significant contributions to a_μ and $\Delta\alpha_{had}$ expected

- Energy Scan measurements at BES-III
  - Covering energy range from $\sqrt{s} = 2.0 \ldots 4.5$ GeV
  - Complementary to ISR programme
  - Impact on $\Delta\alpha_{had}$ and baryon form factors
  - Phase 1 (Mini R Scan) currently being analysed

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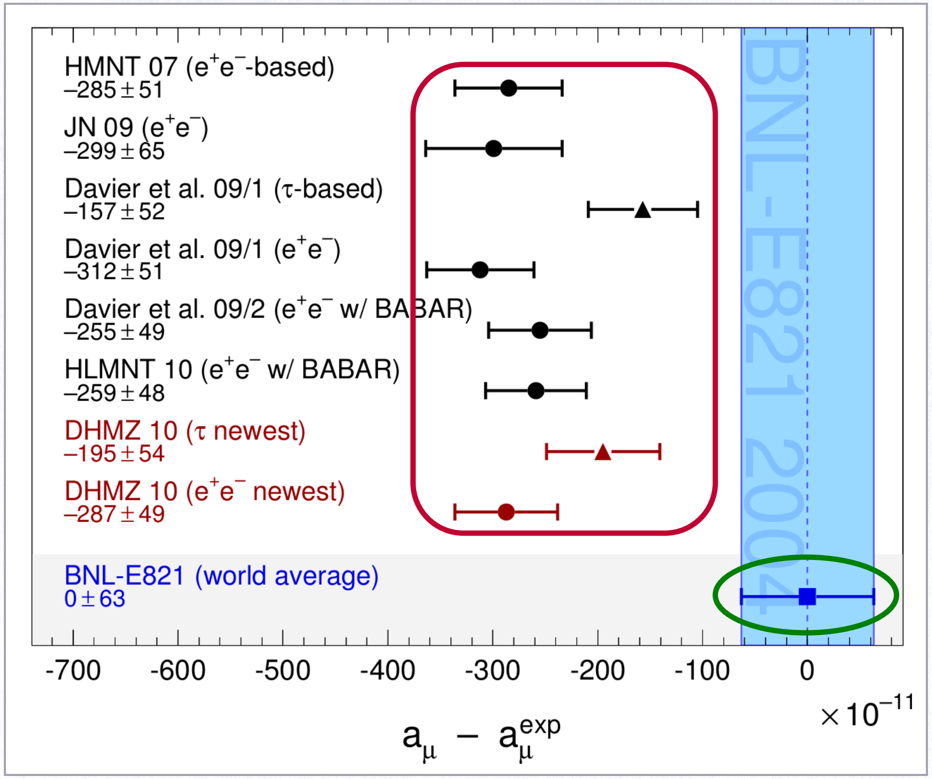
Thank you for your attention

The muon anomaly: $(g-2)_\mu$

Experimental value and Standard model predictions of $a_\mu = (g-2)_\mu$
BNL-E821

$$\boxed{\Delta a = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} \simeq 3.6\sigma}$$



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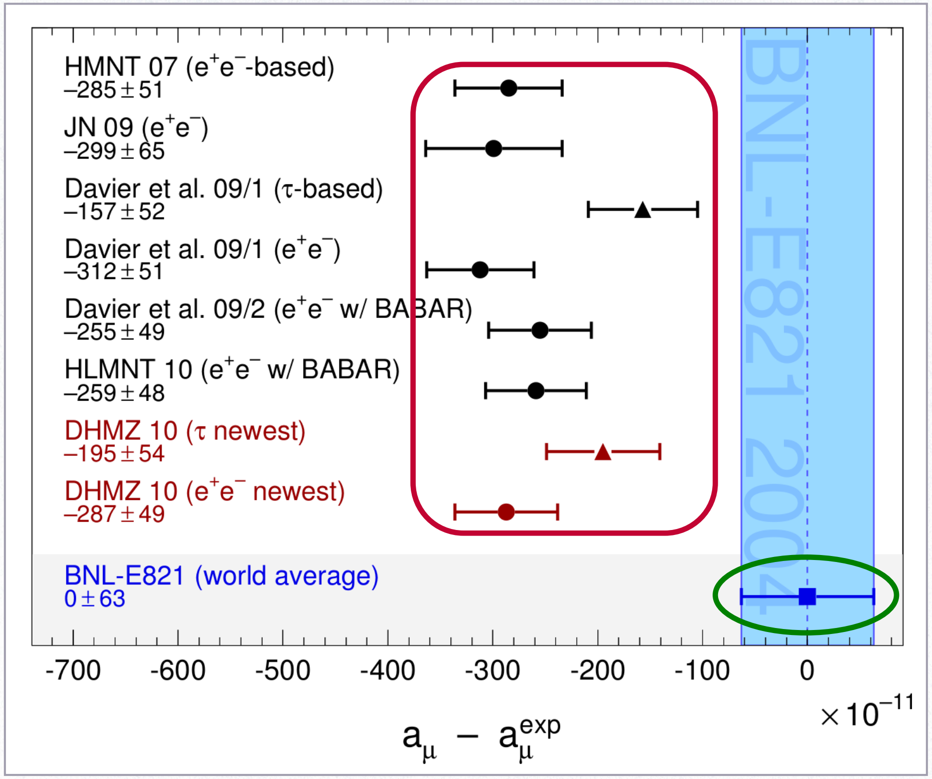


- Standard model contributions to a_μ

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{weak}} + a_\mu^{\mathrm{had}}$$

- a_μ^{had} needs experimental input

$$\sigma^{\mathrm{had}} = \sigma(e^+e^- \to \mathrm{hadrons})$$

- Exp. uncertainty on σ^{had} limits SM precision

- Low-energy contributions important

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

$$K(s)\,\sigma^{\mathrm{had}} \sim \frac{1}{s^2}$$

Hadronic cross section data & $\alpha_{em}(s)$

Vacuum polarisation corrections → Running of $\alpha_{em}(s)$

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

Davier, et al. (2010)

- Leptonic vacuum polarisation calculable within QED

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

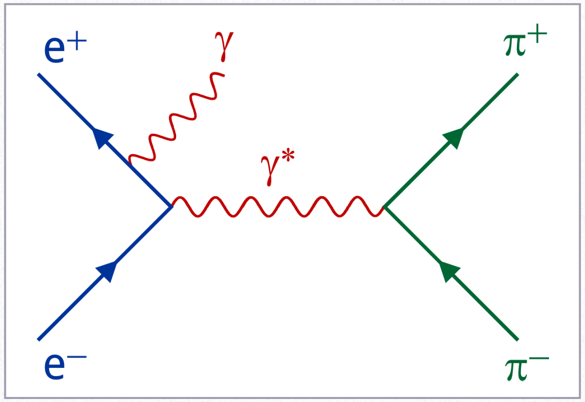
- Hadronic vacuum polarisation not accessible in *p*QCD

- Dispersion integral relates $\Delta\alpha_{em}^{had}$ with σ^{had}

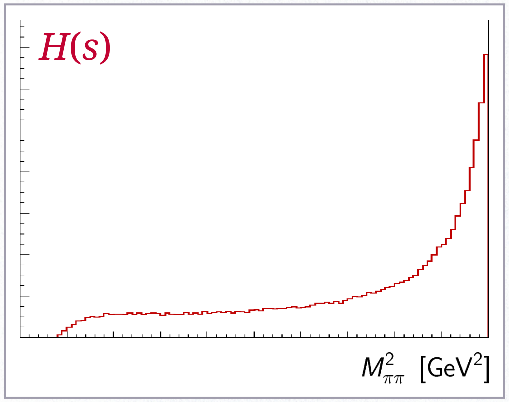
$$\Delta\alpha_{had}(M_Z^2) = (274.2 \pm 1.0) \cdot 10^{-4}$$

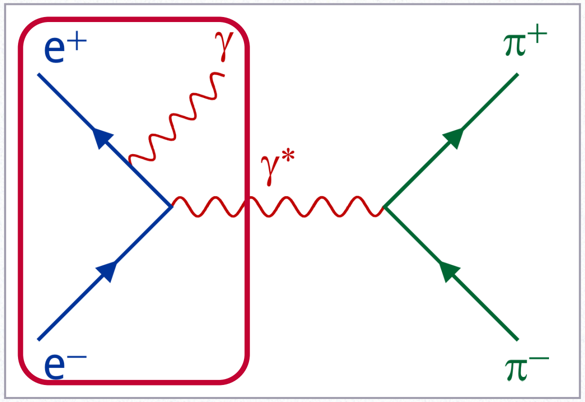
→ Experimental *R* data essential up to ~5 GeV
*p*QCD for higher energies

Initial State Radiation



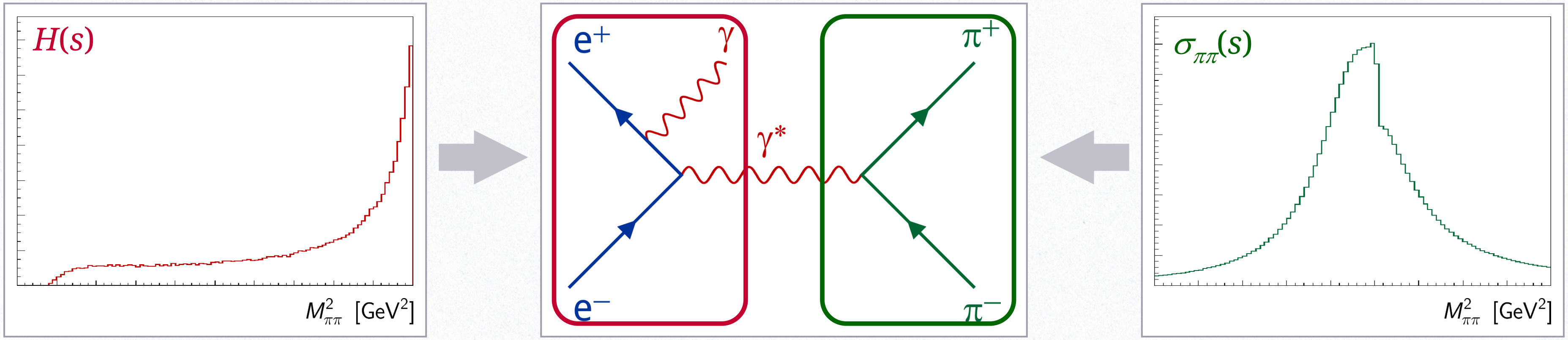
Initial State Radiation





- Radiator function $H(s)$
  PHOKHARA MC generator

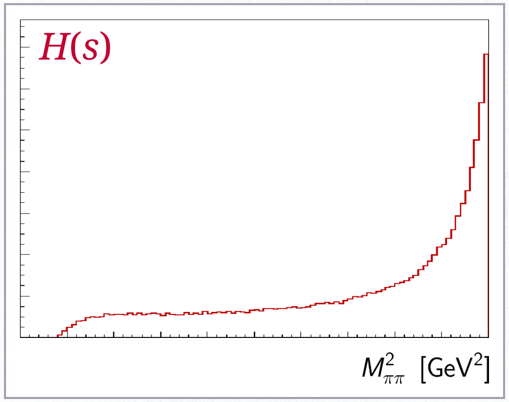
Initial State Radiation

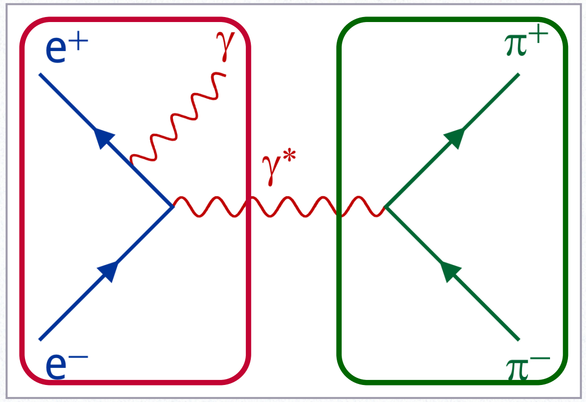


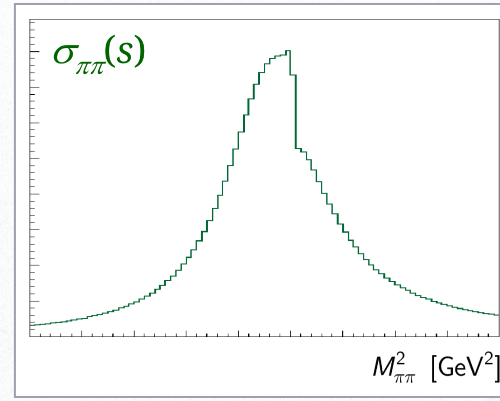
- Radiator function $H(s)$
  PHOKHARA MC generator

- Cross section $\sigma_{\pi\pi}(s)$
  for non-radiative process
  $e^+e^- \rightarrow \pi^+\pi^-$

Initial State Radiation

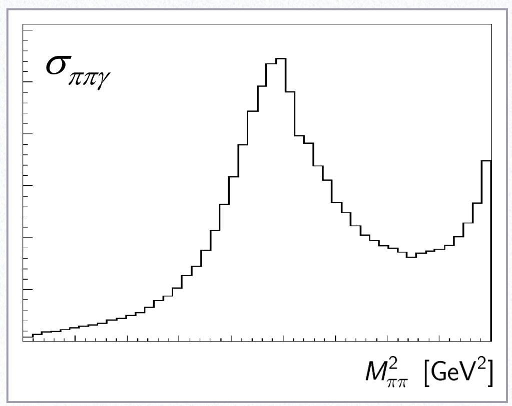






- Radiator function $H(s)$
  PHOKHARA MC generator

- Cross section $\sigma_{\pi\pi}(s)$
  for non-radiative process
  $e^+e^- \to \pi^+\pi^-$



Cross section $\sigma_{\pi\pi\gamma}$
for ISR process $e^+e^- \to \pi^+\pi^-\gamma$

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