$e^+e^- \rightarrow \pi^+\pi^-$ with ISR and the R_b Scan at BaBar

Francesco Renga

Università di Roma “La Sapienza” & INFN Roma

on behalf of the BaBar Collaboration

Introduction

- B-Factories showed an exciting capability for improving our experimental knowledge about *Hadronic Physics* (hadron production, mass spectra, hadron decays,...);
- Several fields involved:
  - Quark models and quarkonia;
  - QCD in the non-perturbative regime;
  - ...
- Impact on a wider range of fields:
  - measurement of SM parameters;
  - Tests of SM;
  - ...

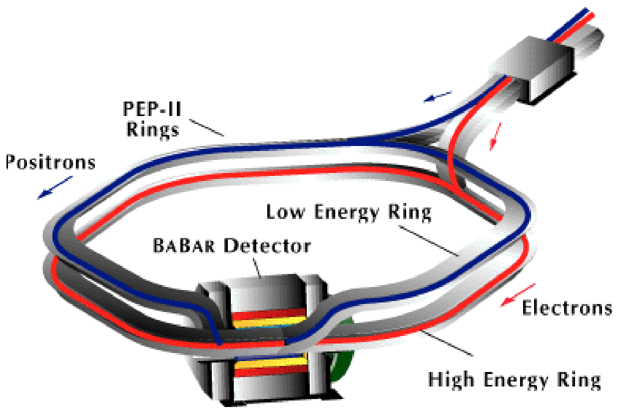
Introduction

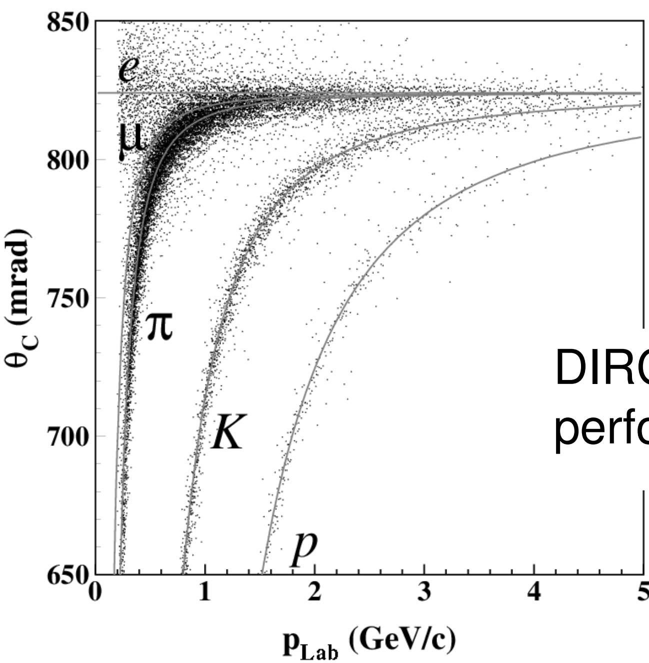
- B-Factories showed an exciting capability for improving our experimental knowledge about *Hadronic Physics* (hadron production, mass spectra, hadron decays,...);
- Several fields involved:
  - Quark models and quarkonia;
  - QCD in the non-perturbative regime;
  - ...
- Impact on a wider range of fields:
  - measurement of SM parameters;
  - Tests of SM;
  - ...

bottomonium above the open beauty threshold

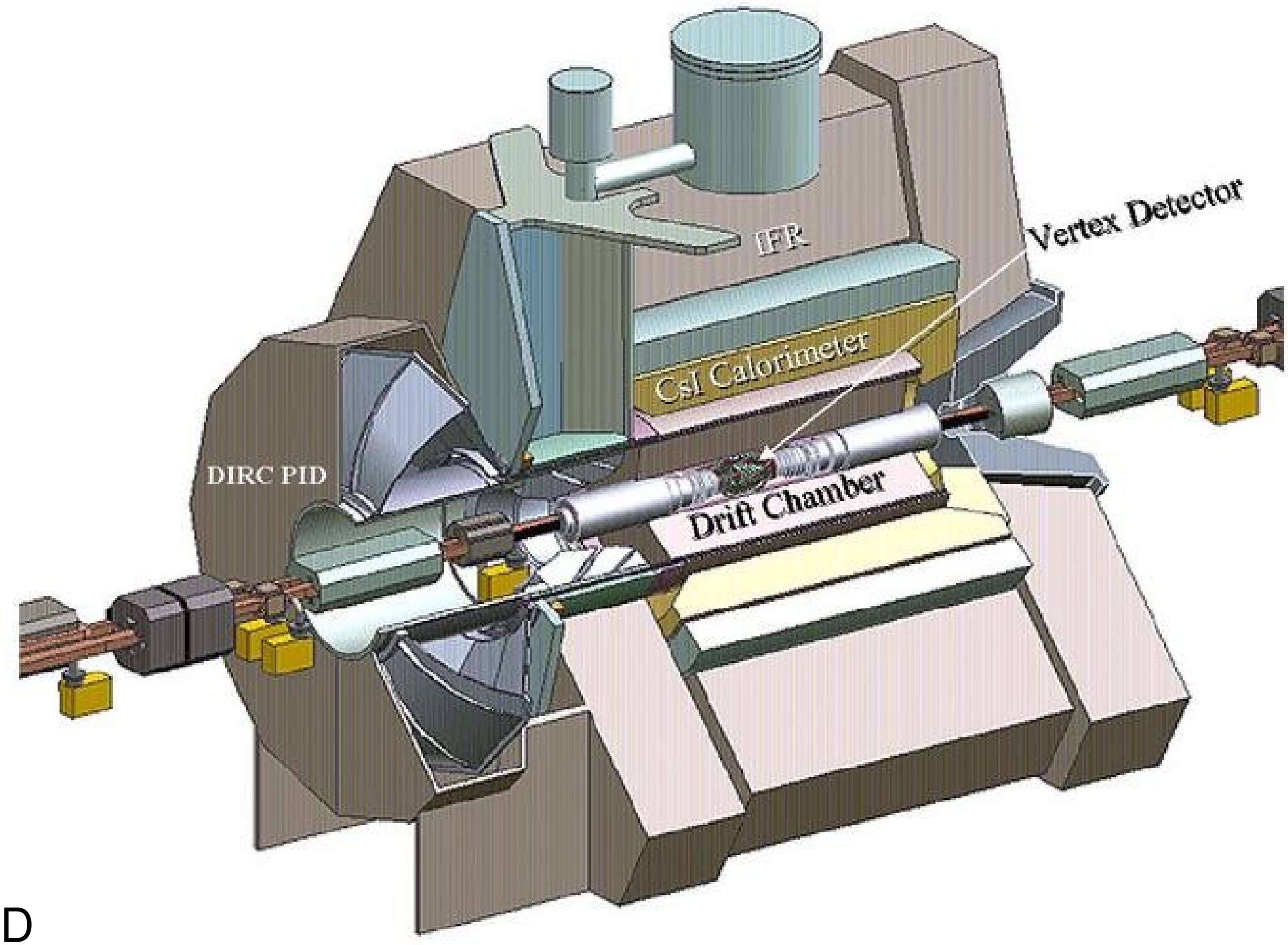
$e^+e^- \to \pi^+\pi^-$ and the anomalous magnetic moment of the muon

The BaBar Experiment

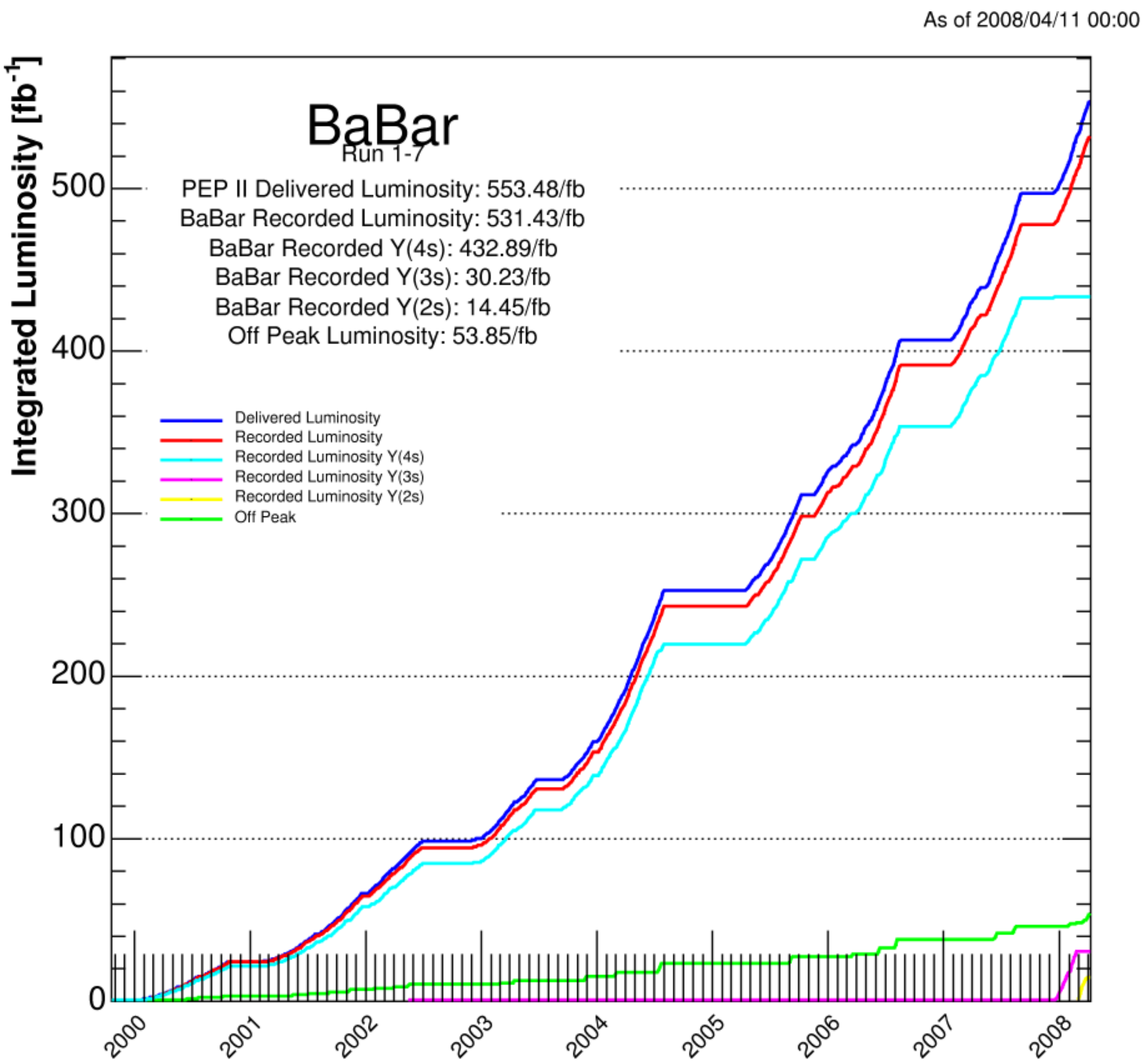




DIRC PID
performances



Collected Luminosity



$e^+e^- \rightarrow \pi^+\pi^-$ with ISR

(presented at TAU08)

$a_\mu=(g_\mu-2)/2$: SM & Experiment

- Best experimental measurement from E821 experiment at BNL:

$$a_\mu^{\exp} = 11\,659\,208.0(5.4)(3.3)\times 10^{-10}$$

- Some SM predictions show a disagreement (up to 3.5σ) with the experimental measurement;
- The disagreement depends on the method used to extract the SM predictions (details in the next slides).

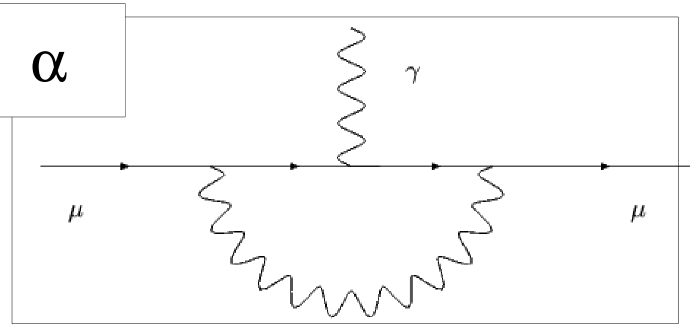
SM predictions

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLO} + a_\mu^{HHO}(\mathrm{vp}) + a_\mu^{HHO}(\mathrm{lbl})$$

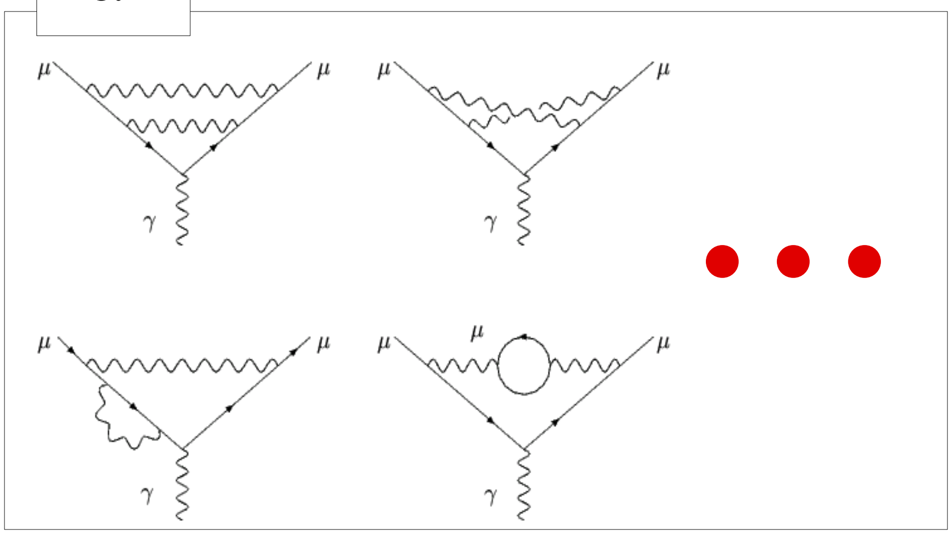
SM predictions

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{H\,LO} + a_\mu^{H\,HO}(\mathrm{vp}) + a_\mu^{H\,HO}(\mathrm{lbl})$$

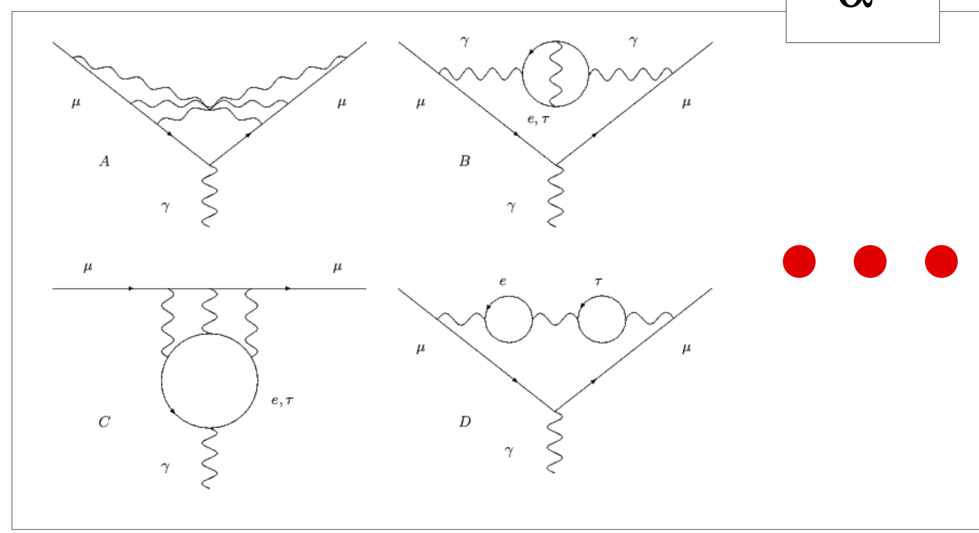
α



α^2



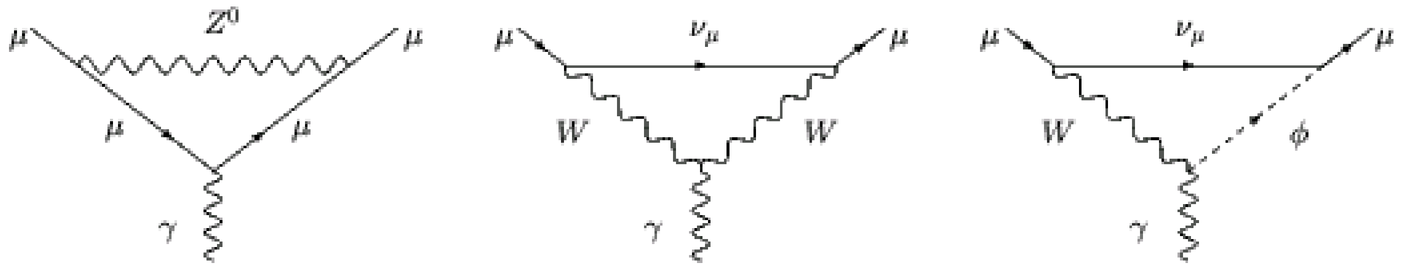
α^3



higher orders also available!

SM predictions

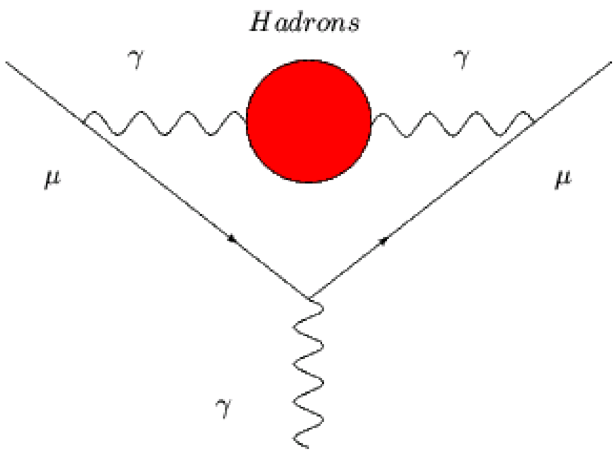
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLO} + a_\mu^{HHO}(\mathrm{vp}) + a_\mu^{HHO}(\mathrm{lbl})$$



+ higher orders

SM predictions

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLO} + a_\mu^{HHO}(\mathrm{vp}) + a_\mu^{HHO}(\mathrm{lbl})$$



QED Kernel (known function)

$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^{(0)}(s)$$

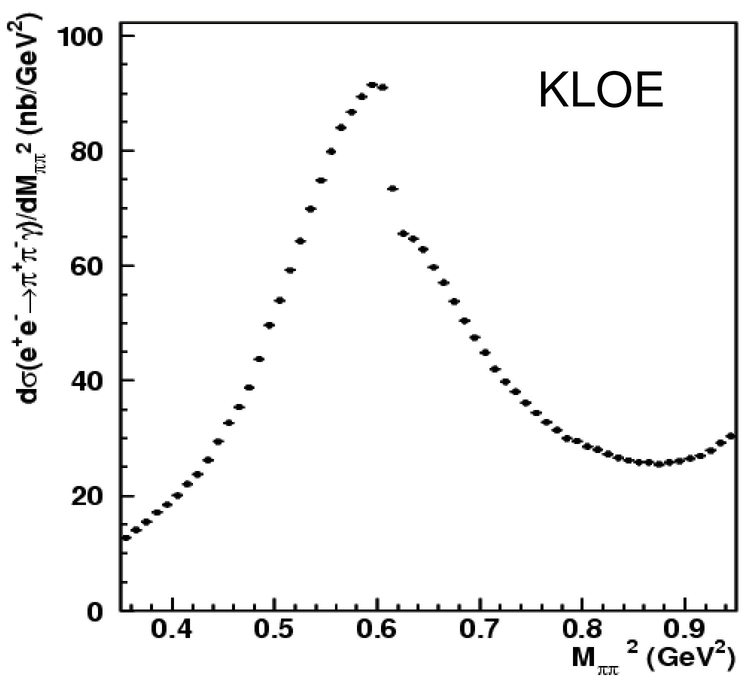
73% from $e^+e^- \rightarrow \pi^+\pi^-$

$e^+e^- \rightarrow$ hadrons cross section

- It dominates the final error on the SM prediction;
- Require exp. measurement of $e^+e^- \rightarrow$ hadrons:
  - Direct measurement at e^+e^- colliders;
  - τ hadronic decays.

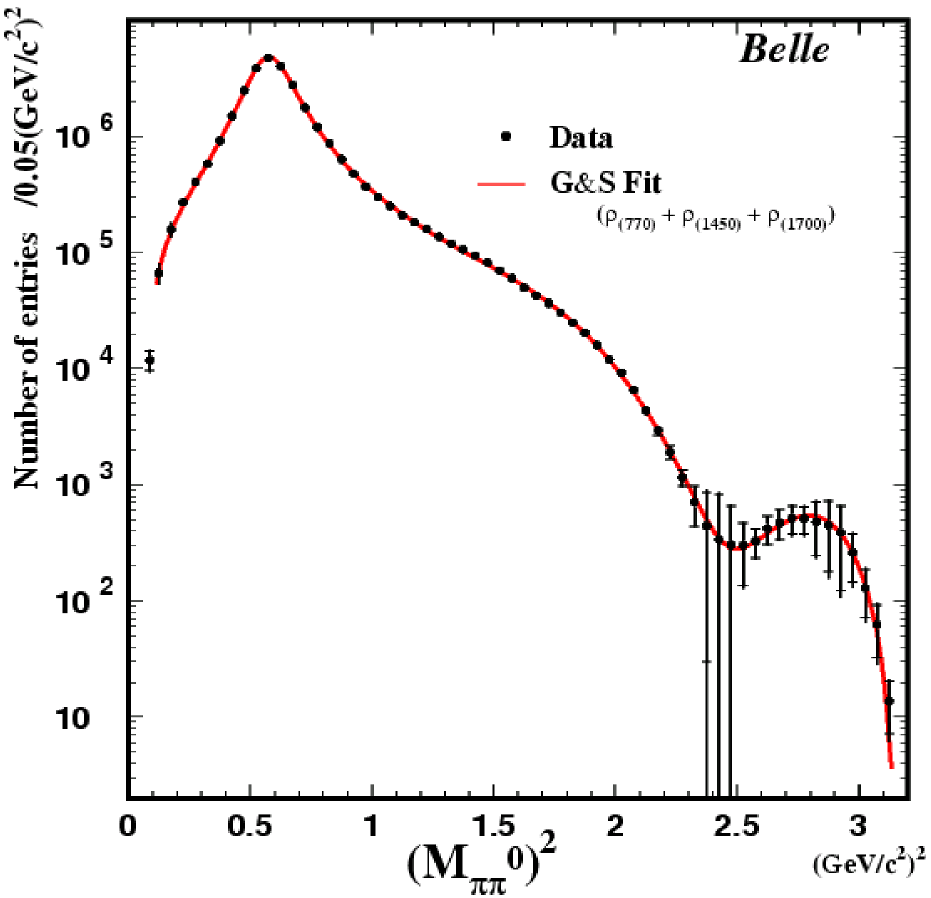
The e^+e^- Perspective

- Direct measurement of cross section at different energies;
- 2 methods:
  - Energy scan;
  - ISR production (automatic energy scan due to energy carried out by the ISR photon);
- Experiments:
  - SND (Novosibirsk): Scan;
  - CMD (Novosibirsk): Scan;
  - KLOE (Frascati): ISR;
  - ...



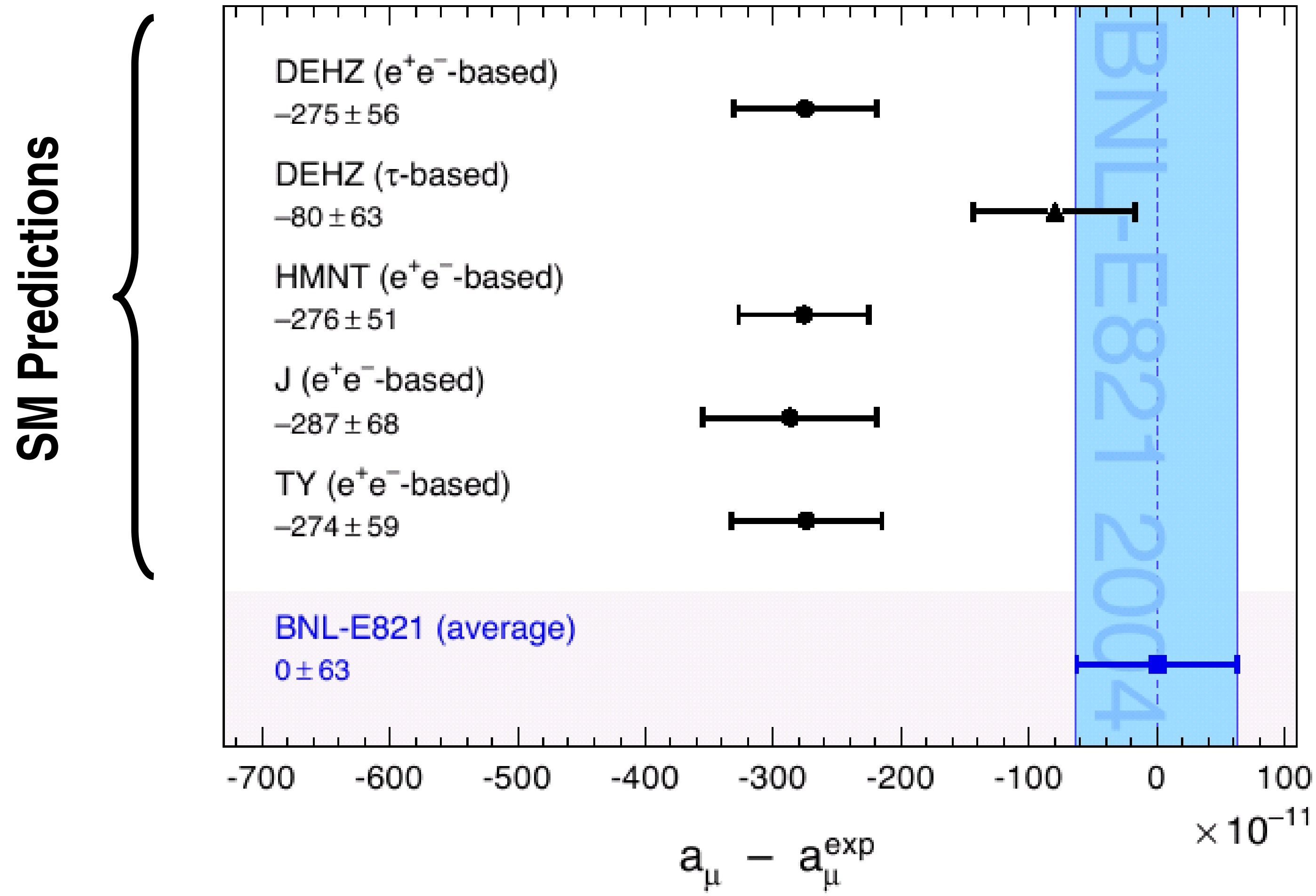
The τ Perspective

- The cross section of $e^+e^- \rightarrow \pi^+\pi^-$ can be related to the hadronic mass spectrum in $\tau^+ \rightarrow \nu\pi^+\pi^0$;
- Measurements available from:
  - ALEPH, OPAL (CERN);
  - CLEO (Cornell);
  - BELLE (KEK);

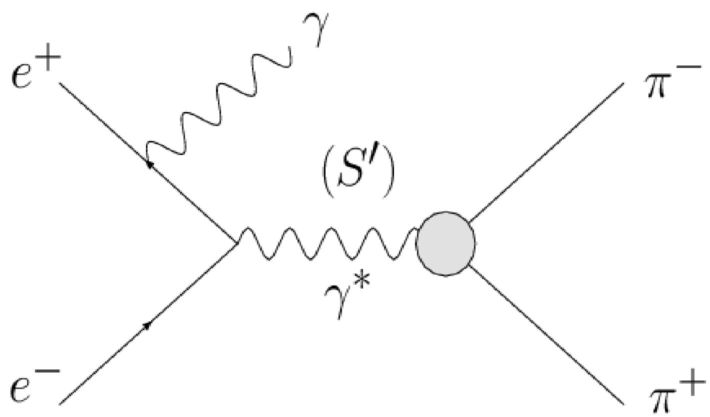


SM vs. Experiment

$$a_\mu^{\mathrm{exp}} = 11\,659\,208.0(5.4)(3.3) \times 10^{-10}$$



$e^+e^- \rightarrow \pi^+\pi^-$ with ISR

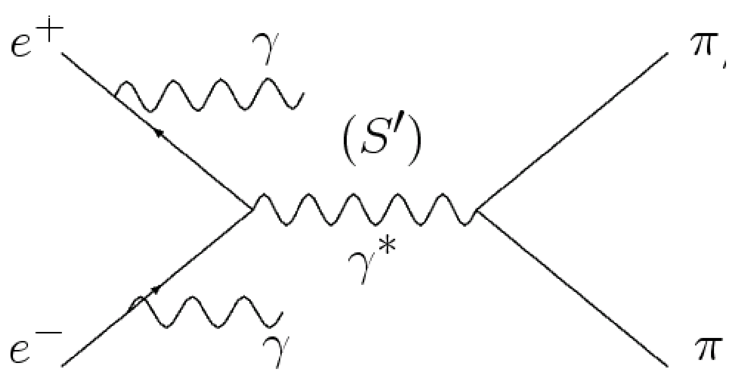


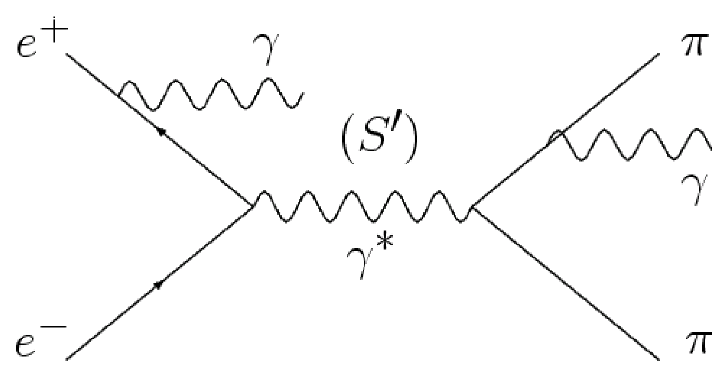
$$\frac{d\sigma_{\pi\pi\gamma}}{dx_\gamma \, d\cos\theta} = W(x_\gamma, s, \theta)\, \sigma_{\pi\pi}(s')$$

ISR production

automatic energy scan

To be taken into account...





Analysis Strategy

- Measurement of the *ratio* of $e^+e^- \to \pi^+\pi^-(\gamma)\gamma_{ISR}$ and $e^+e^- \to \mu^+\mu^-(\gamma)\gamma_{ISR}$ yields:
  - Allows to remove common systematic uncertainties related to the ISR photon.

$$\frac{dN_{\pi\pi\gamma(\gamma)}}{d\sqrt{s'}} \Bigg/ \frac{dN_{\mu\mu\gamma(\gamma)}}{d\sqrt{s'}} = \frac{\sigma^0_{\pi\pi(\gamma)}(\sqrt{s'})}{\sigma_{pt}(\sqrt{s'})} \cdot \kappa(\sqrt{s'})$$

$\kappa(\sqrt{s'})$ → efficiencies, corr. for μ FSR, etc.

$\sigma_{pt}(\sqrt{s'})$ → $\frac{4\pi\alpha^2}{3s'}$

DATA SAMPLES

- $\Upsilon(4S)$ data: ~513000 pion events, ~446000 muon events (231 fb^{-1});
- MC samples for $e^+e^- \to \pi^+\pi^-(\gamma)\gamma_{ISR}$, $e^+e^- \to \mu^+\mu^-(\gamma)\gamma_{ISR}$, $e^+e^- \to qq$.

ISR/FSR simulation (*AfkQED*) includes LO ISR + LO FSR (*PHOTOS*) + interference + approx. additional ISR/FSR + corrections using *Phokara*

Selection (I)

ISR photon

- $E > 3$ GeV;
- $0.35 < \theta < 2.4$ rad.

μμ pair

- 2 tracks:
  - opposite charge;
  - $p_{trk} > 1$ GeV;
  - $0.40 < \theta_{trk} < 2.45$ rad.
  - PID based on IFR and EMC variables ($\varepsilon \sim 90\%$, muon-to-pion mis/ID ~ 10%);

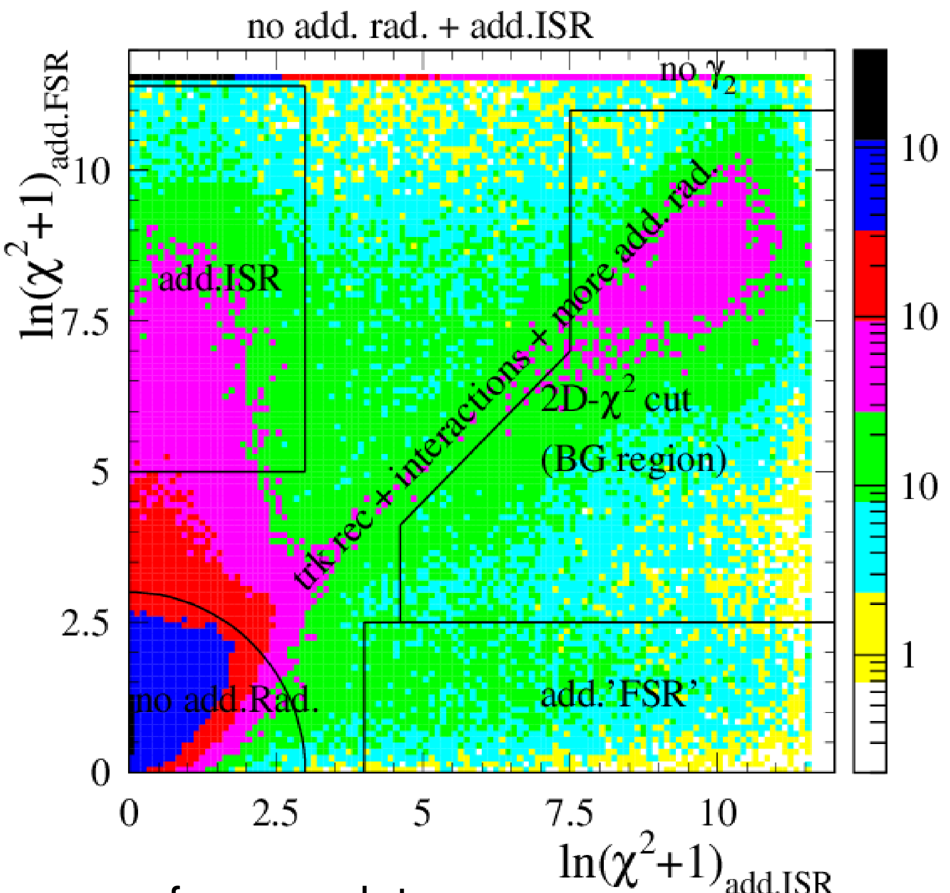
ππ pair

- 2 tracks:
  - opposite charge;
  - $p_{trk} > 1$ GeV;
  - $0.40 < \theta_{trk} < 2.45$ rad;
  - NOT SATISFYING either muon or kaon PID ($\varepsilon \sim$ 80 to 90%);

Selection (II)

- Further selection based on 2 kinematic fits:
  - 2C "ISR" fit (assume a second undetected ISR photon);
  - 3C "FSR" fit (if more than 1 reconstructed photon, assume that one of the non-ISR photons is FSR or large-angle ISR).

χ^2's used to define a background region (BG)

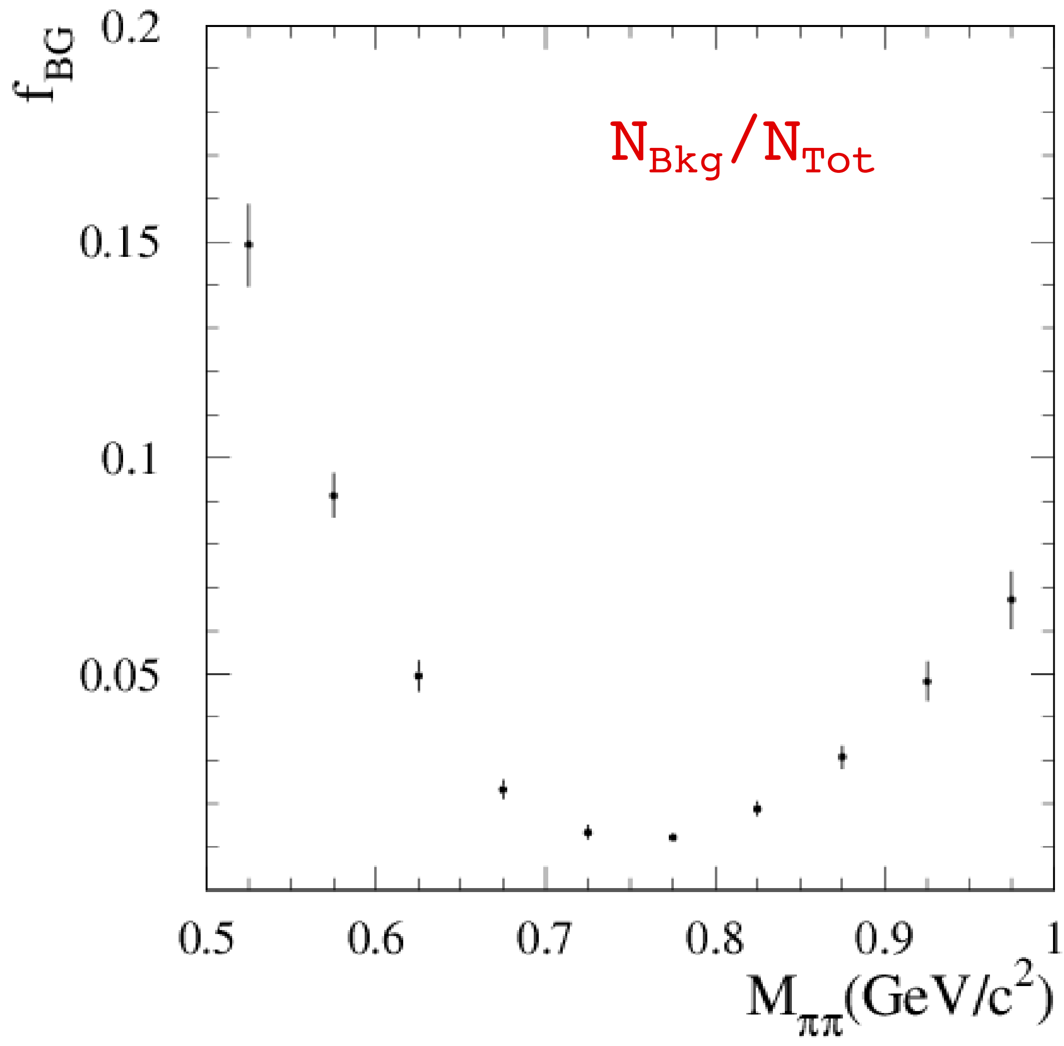


from ππ data

Background (I)

- $\mu\mu$ background contamination:
  - Negligible.
- $\pi\pi$ background contamination:
  - $e^+e^- \rightarrow pp\gamma$ (due to proton-to-pion mis-ID)
  - $e^+e^- \rightarrow qq$
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma_{ISR}$;
  - Estimated in the MC and corrected by data/MC comparisons;

Background (II)



Yield extraction

- Once data are selected and background is subtracted, ππ and μμ yields are extracted taking into account PID cross-feed:

$$
\begin{aligned}
N_{'\pi\pi'} &= N^{(0)}_{\mu\mu}\varepsilon_{\mu\mu\to'\pi\pi'} + N^{(0)}_{\pi\pi}\varepsilon_{\pi\pi\to'\pi\pi'} + N^{(0)}_{KK}\varepsilon_{KK\to'\pi\pi'} + N_{ee/'\pi\pi'} \\
N_{'\mu\mu'} &= N^{(0)}_{\mu\mu}\varepsilon_{\mu\mu\to'\mu\mu'} + N^{(0)}_{\pi\pi}\varepsilon_{\pi\pi\to'\mu\mu'} + N^{(0)}_{KK}\varepsilon_{KK\to'\mu\mu'}
\end{aligned}
$$

Observed events in the PID category μμ

Probability of a μμ pair to be identified as μμ

Probability of a ππ pair to be identified as μμ

measured from data

PID measurements

- PID efficiencies measured using $xx\gamma_{ISR}$ data, where x is a track;
- Example of procedure (for muons):
  - Look for xx pairs where *one* of the x is *identified* as a muon;
  - require xx mass > 2.5 GeV (assuming both x to be muons) to reduce $\pi\pi$ and KK contamination;
  - Evaluate the PID efficiency and mis-ID for the second track.
- Take into account correlations due to overlapping tracks.

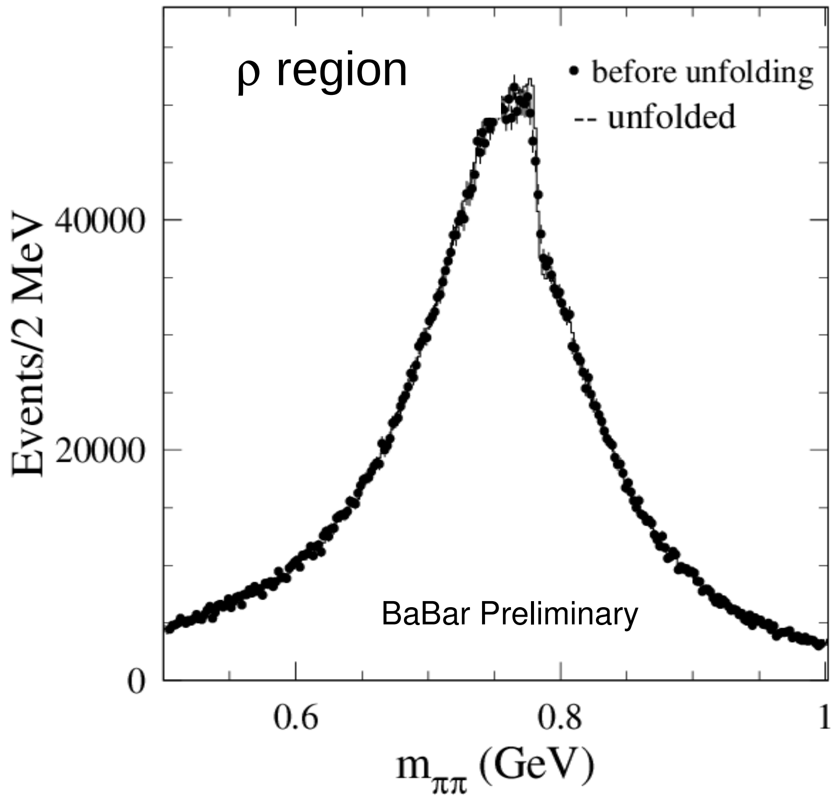
$\pi^+\pi^-$ mass spectrum

- $\pi\pi$ yields used to build the mass spectrum;
- *Unfolding* (transfer matrix method) to correct for resolution effects.

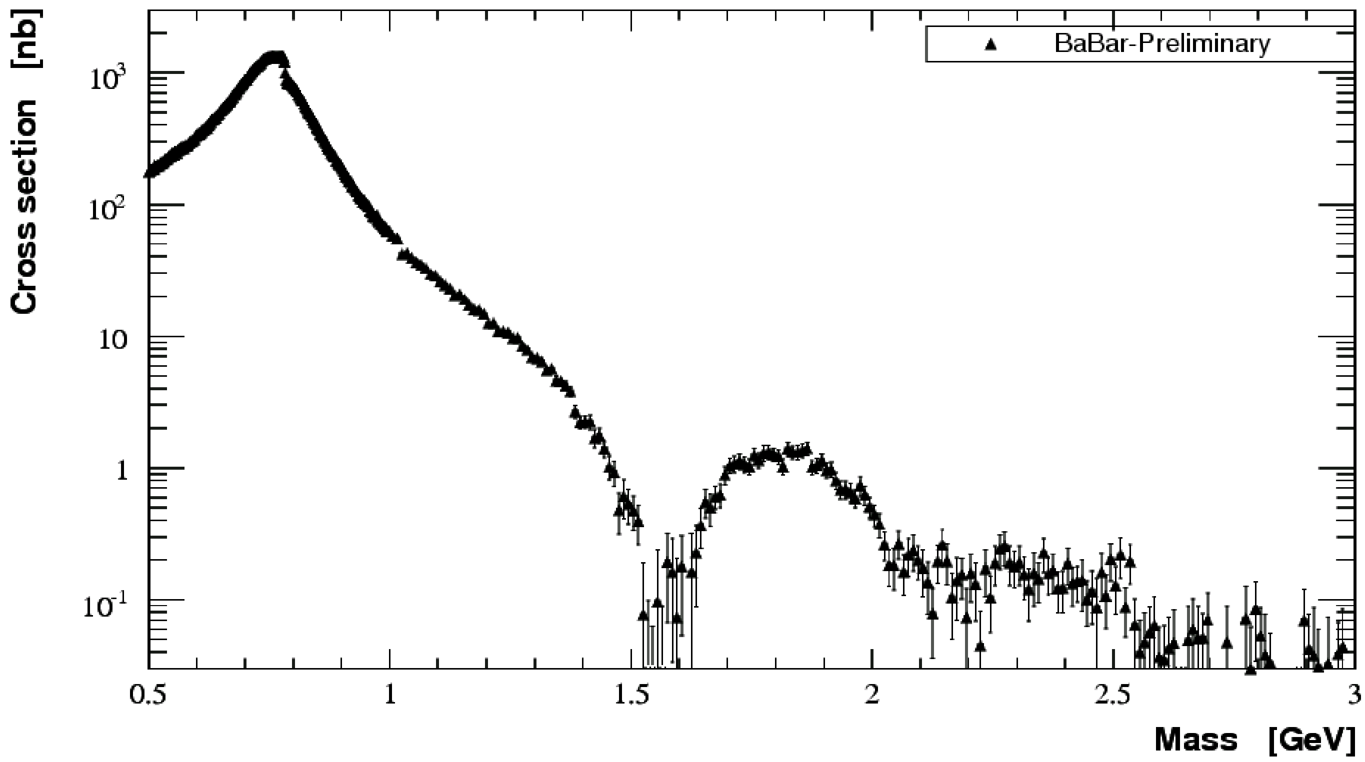
Systematics (in 10^{-3})

$\sqrt{s}$ range (GeV)

sources	0.4–0.6	0.6–0.9	0.9–1.2	1.2–1.4	1.4–3.0
trigger/ filter	1.5	0.8	0.5	0.5	0.5
tracking	2.1	1.1	1.7	3.1	3.1
π-ID	5.2	2.4	4.2	10.1	10.1
background	5.2	0.4	1.0	7.0	12.0
acceptance	1.0	1.0	1.0	1.0	1.0
kinematic fit (χ^2)	1.8	0.7	1.8	2.8	2.8
correlated $\mu\mu$ ID loss	3.0	1.3	2.0	3.0	10.0
sum $\pi\pi$	7.5	3.3	5.5	13.4	19.1

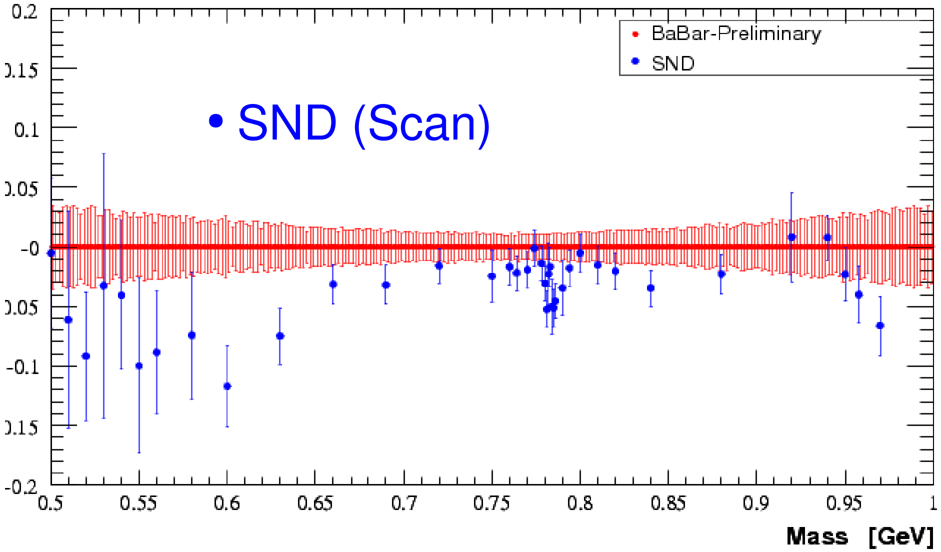


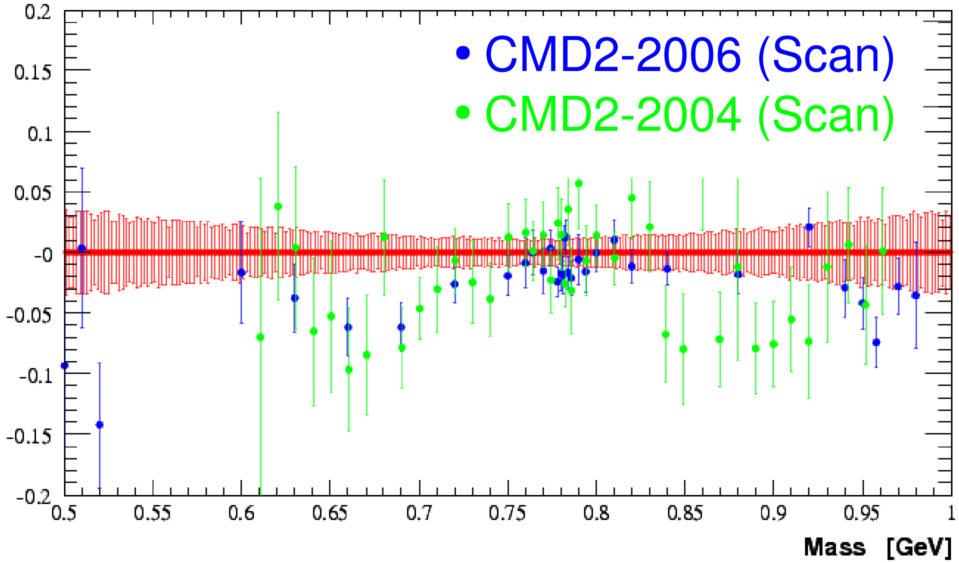
Cross Section



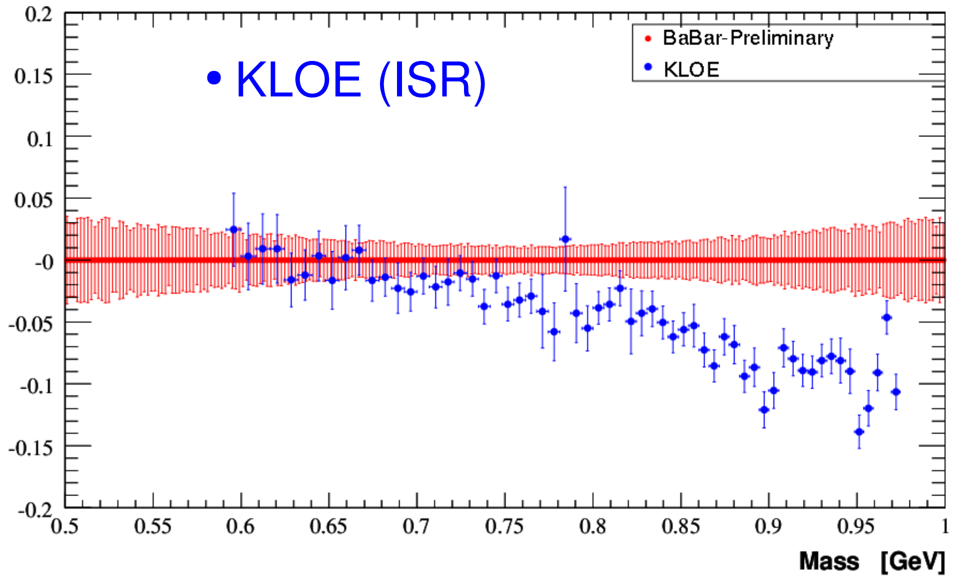
$$|F_\pi|^2(s') = \frac{3s'}{\pi\alpha^2(0)\beta_\pi^3}\,\sigma_{\pi\pi}(s')$$

Comparisons (e^+e^-)

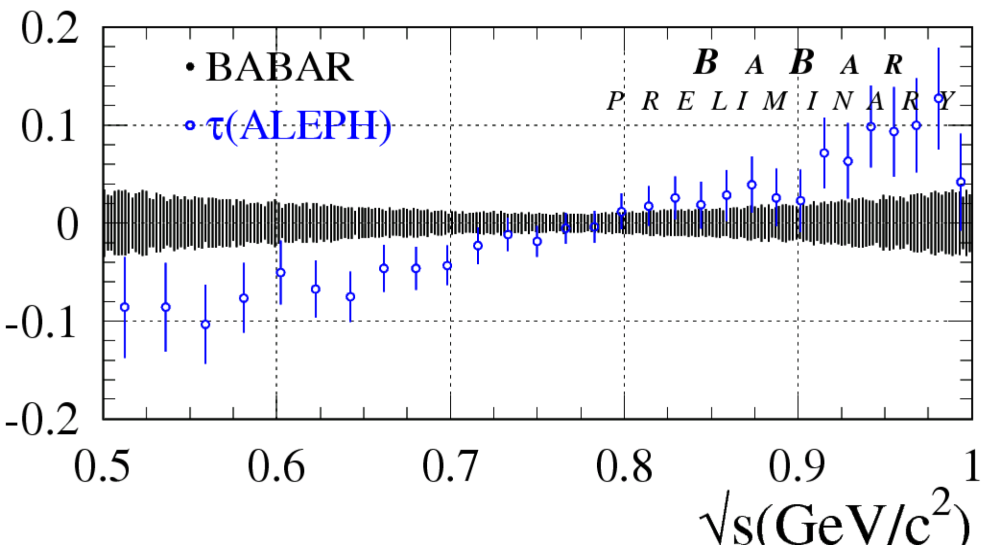


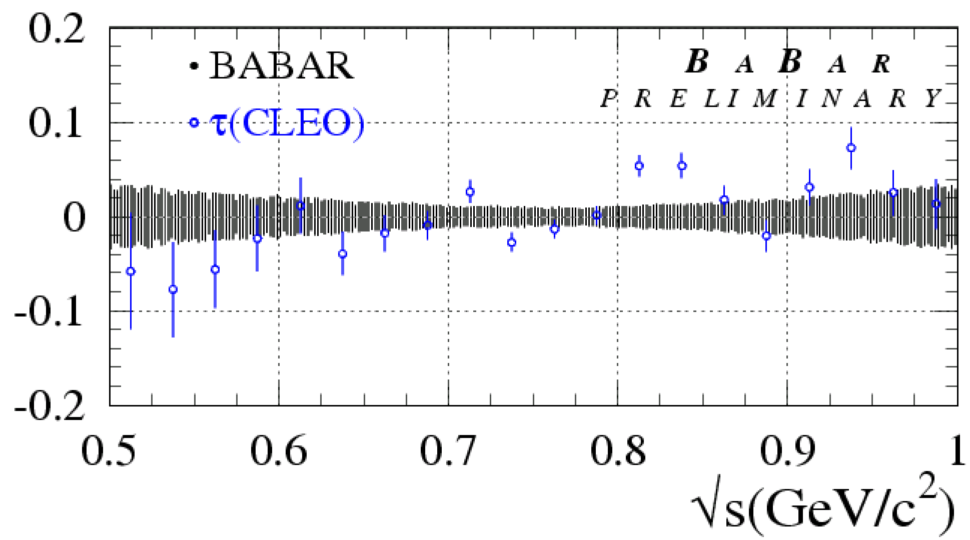


$$\frac{|F_\pi|^2(BaBar) - |F_\pi|^2(OTHER\ EXP.)}{|F_\pi|^2(BaBar)}$$

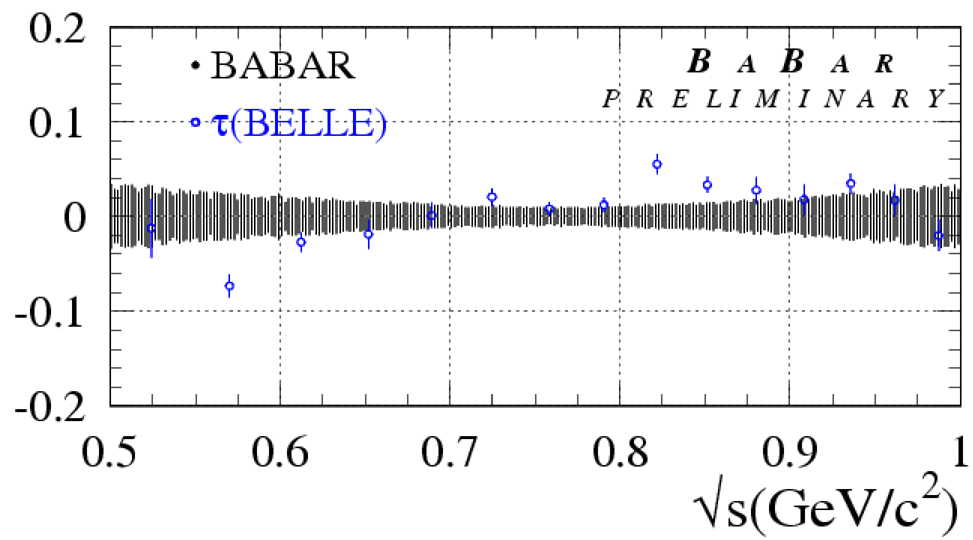


Comparisons (τ)





$$\frac{|F_\pi|^2(BaBar) - |F_\pi|^2(OTHER\ EXP.)}{|F_\pi|^2(BaBar)}$$



Summary

- Measurement of $e^+e^- \rightarrow \pi^+\pi^-$ cross section with ~0.6% precision in the ρ region;
- Comparison with other e^+e^- experiment shows some significant disagreement;
- Better agreement with τ data;
- Measurement of cross section above 0.5 GeV allows to extract the corresponding contribution to a_μ.

$$a_\mu^{HLO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^{(0)}(s)$$

$$a_\mu^{\pi\pi LO,\sqrt{s}>0.5GeV} = (462.5 \pm 0.9 \pm 3.1) \times 10^{-10}$$

$$a_\mu(\exp) - a_\mu(SM) = (14.8 \pm 8.4) \times 10^{-10}$$

PRELIMINARY!

R_b Scan above $\Upsilon(4S)$

(arXiv:0809.4120 [hep-ex])

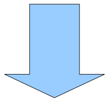
A new charm spectroscopy

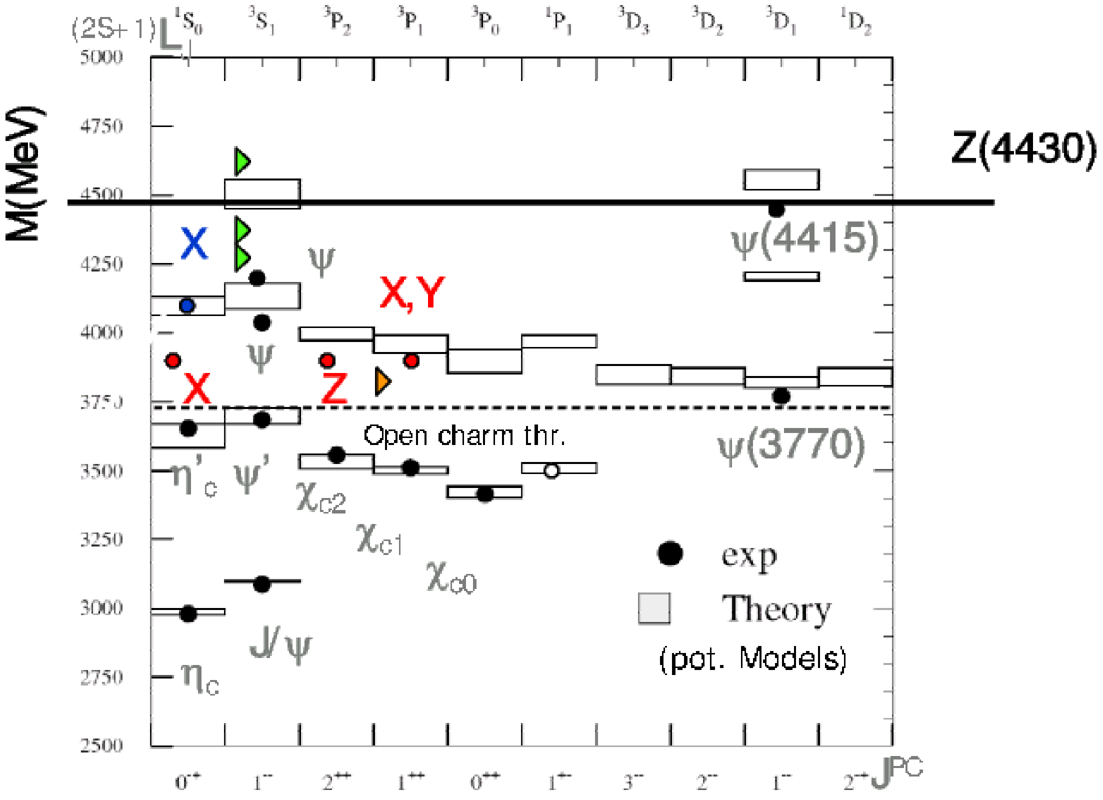
- New charmonium-like resonances, recently discovered, do not fit in the "standard" $c\bar{c}$ charmonium schema;

✗ Masses far from predicted states;

✗ Widths too small;

✗ Unusual decay rates.





Tetraquarks $[qq][\bar{q}\bar{q}]$?
Hybrids $q\bar{q}g$?
Molecules $[q\bar{q}][q\bar{q}]$?

A new bottom spectroscopy?

- New charmonium-like resonances could have bottom companions;
- Mass of new bottom resonances could be guessed just applying a shift to the new charmonium resonances:

$$m(bottomonium) = m(charmonium) + m(\Upsilon(1S)) - m(J/\Psi)$$

Works fine for standard bottomonium!

$$Y(4260) \rightarrow Y_b(10620)???$$

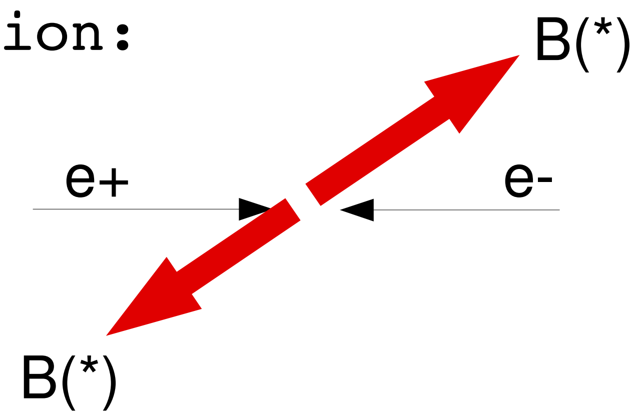
$$Y(4350) \rightarrow Y_b(10710)???$$

$$Y(4660) \rightarrow Y_b(11020)???$$

Energy Scan

- New bottomonium resonances can be searched for with an energy scan above the $\Upsilon(4S)$ resonance;
- *Inclusive approach:*
  - Search for unexpected structures in the inclusive hadronic cross section:

$$R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma^0_{\mu\mu}(s)}$$

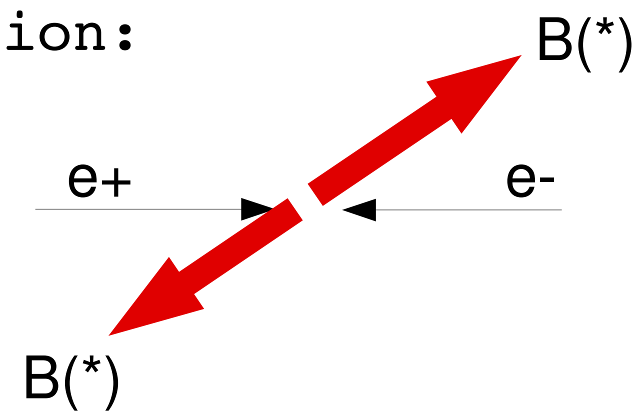


- *Exclusive approach:*
  - Look for signals in specific decay channels (like $\Upsilon(nS)\pi\pi$) inspired by the new charmonia decay channels (like $J/\Psi\pi\pi$)

Energy Scan

- New bottomonium resonances can be searched for with an energy scan above the $\Upsilon(4S)$ resonance;
- *Inclusive approach:*
  - Search for unexpected structures in the inclusive hadronic cross section:

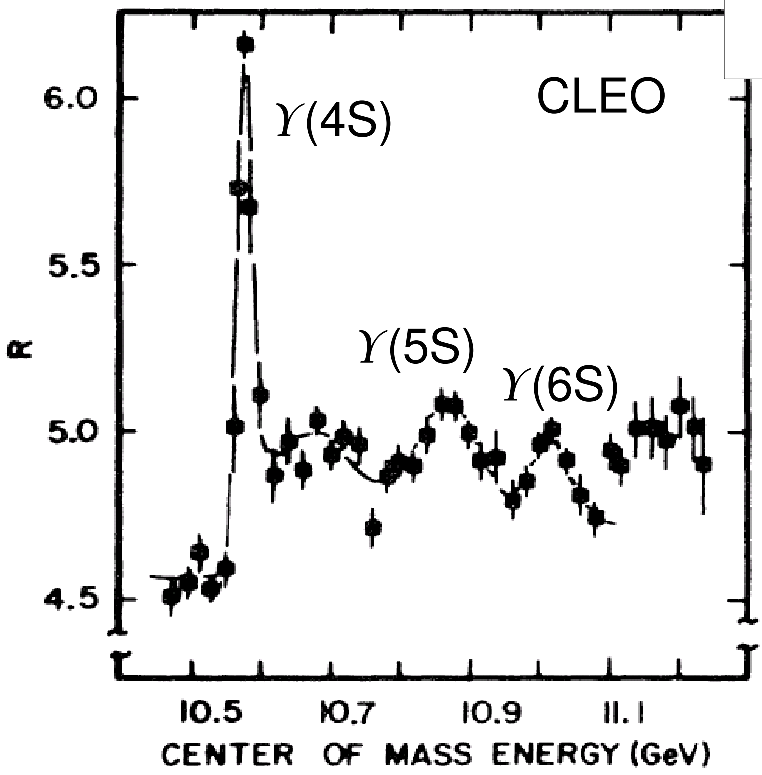
$$R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma^0_{\mu\mu}(s)}$$

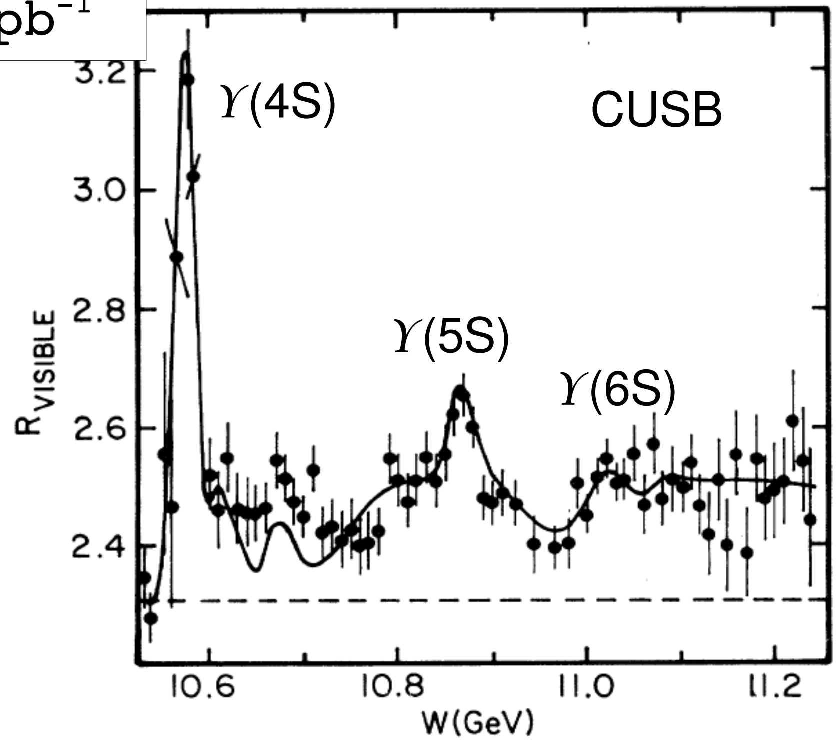


- *Exclusive approach:*
  - Look for signals in specific decay channels (like $\Upsilon(nS)\pi\pi$) inspired by the new charmonia decay channels (like $J/\Psi\pi\pi$)

Previous Measurements

CESR
~130 pb^{-1}





CUSB: Phys.Rev.Lett.54:377,1985

CLEO: Phys.Rev.Lett.54:381,1985

BaBar Scan

- BaBar performed a 10 days long energy scan starting on March 28th, 2008:
  - Steps of 5 MeV from 10.54 to 11.20 GeV;
  - about 25 pb^{-1} per step (3.3 fb^{-1} total);
  - 8 additional steps in the $\Upsilon(6S)$ region (10.96 to 11.10 GeV) corresponding to 600 pb^{-1}.

30 times more luminosity
and
4 times finer steps
w.r.t. CESR scan

Measurement Strategy

- For each point and for a "reference" point (10.54 GeV) we select:
  - bb-enriched sample, according to a multi-hadron selection (see later);
  - μμ sample (see later);
- At the "reference" point:
  - Estimate of backgrounds, scaled to other energies according to the expected *s* dependence;
- Across the scan:
  - R_b extracted from a combination of the bb and μμ yields, subtracting the non-bb background.

Multi-Hadrons Selection

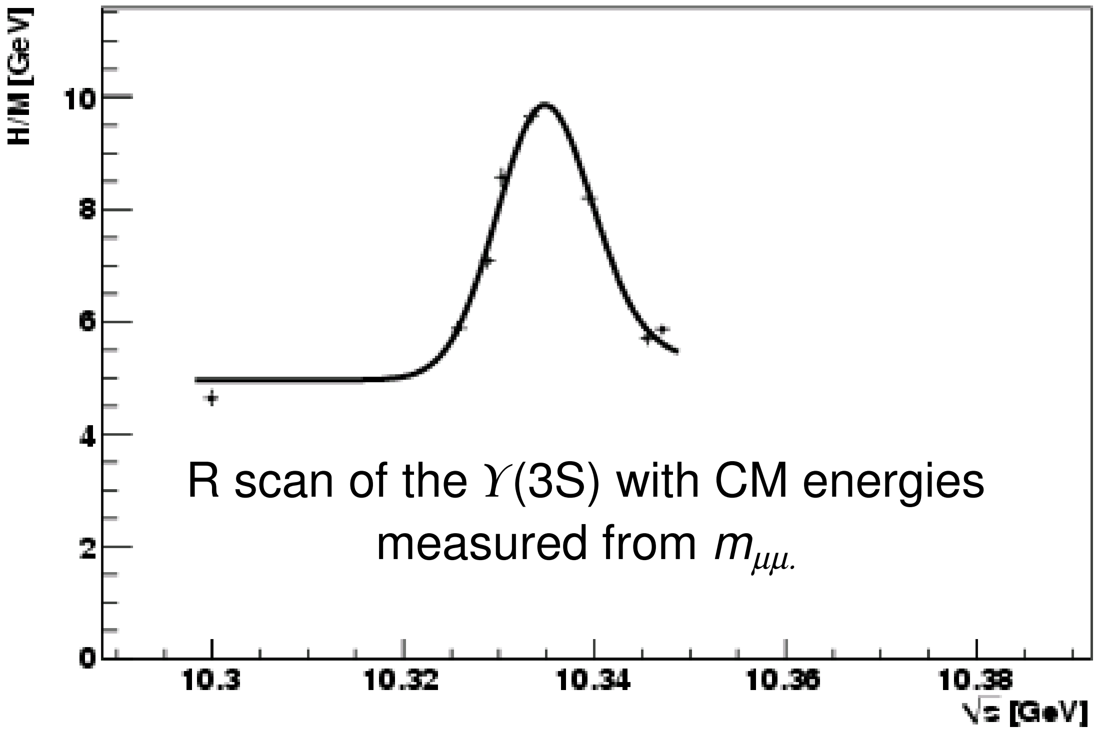
- bb-enriched sample:
  - > 3 tracks;
  - reconstructed energy > 4.5 GeV;
  - vertex of tracks within 5mm of beam crossing in the transverse plane, 6cm along the beam;
  - Cut on the ratio of 0th and 2nd Fox-Wolfram moments: $R_2 < 0.2$ (spherical event);

Background & ISR

- $e^+ e^- \rightarrow e^+ e^- \gamma^* \gamma^* \rightarrow e^+ e^- X_h$ (two-photon events):
  - cross-section estimated at the reference point and scaled according to *log(s)*;
  - efficiency supposed flat across the scan;
- $e^+e^- \rightarrow qq$:
  - cross-section estimated at the reference and scaled according to $\sqrt{s}$;
  - efficiency, estimated from MC simulations for different energies, follows a slow linear trend in $\sqrt{s}$.
- $e^+e^- \rightarrow \Upsilon(nS)\gamma_{ISR}$:
  - NOT A BACKGROUND, BUT A SIGNAL COMPONENT!!!

Muon Pairs Selection

- $\mu\mu$ events given by 2 tracks with:
  - $m_{\mu\mu}$ > 7.5 GeV;
  - θ < 0.7485 in the center-of-mass frame;
  - collinearity better than 10°.

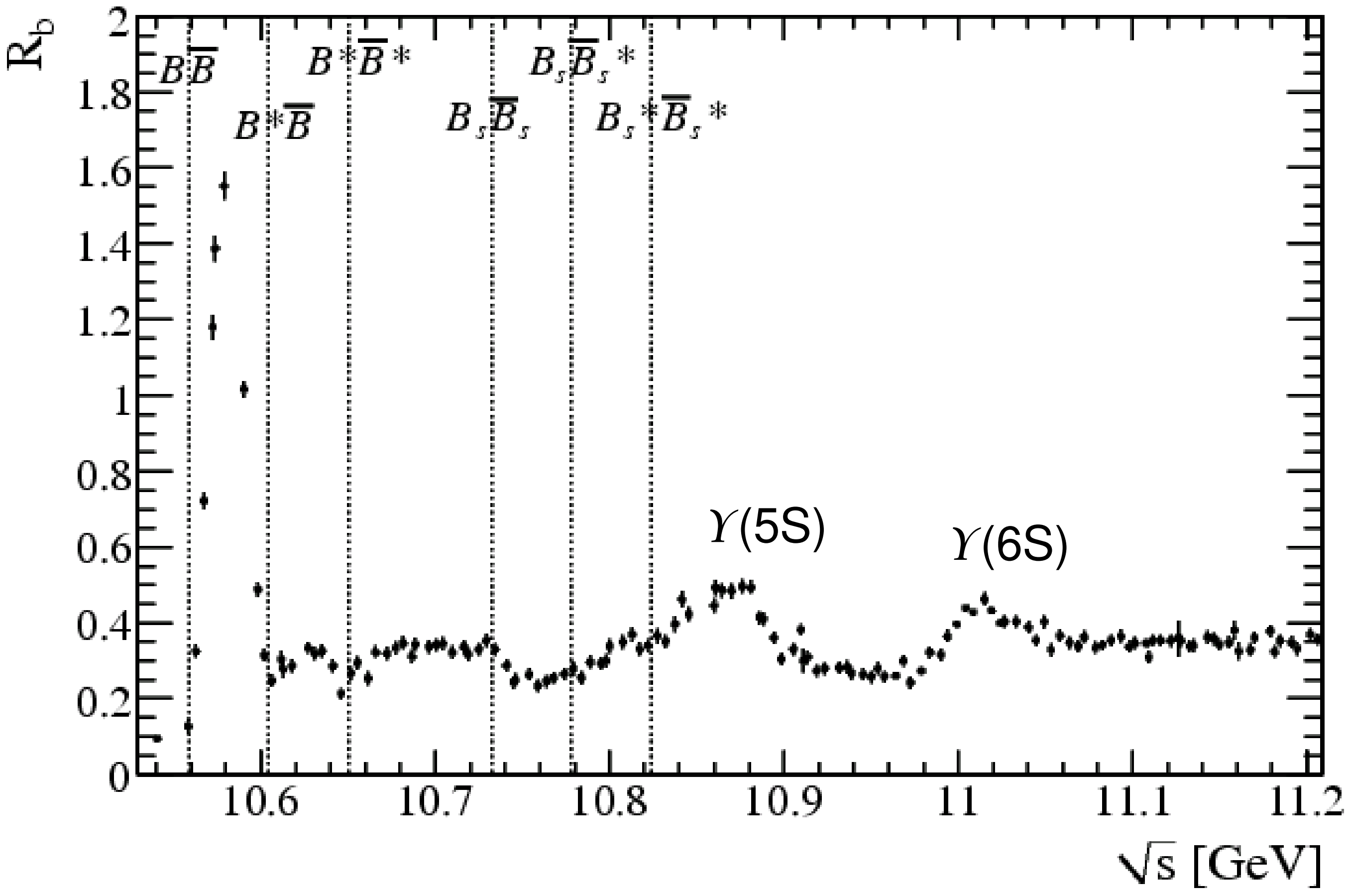


R scan of the Υ(3S) with CM energies measured from $m_{\mu\mu}$.

$m_{\mu\mu}$ distribution also fitted to have a ***precise measurement of the CM energy*** *(tuned with Υ(3S) scan data).*

Results

- Region explored with *unprecedented detail*;
- Interpretation made difficult by *thresholds*.



Coupled Channel Models

- Interpretation requires explicit treatment of coupling between quarkonia & continuum (Coupled Channel Model, Eichten *et al.*, 1978);
- Effective Hamiltonian from a quark-level potential:

$$H_{eff} = H_{\Upsilon} + H_B + U$$

quarkonium binding

Coupled Channel Models

- Interpretation requires explicit treatment of coupling between quarkonia & continuum (Coupled Channel Model, Eichten *et al.*, 1978);
- Effective Hamiltonian from a quark-level potential:

$$H_{eff} = H_{\Upsilon} + H_{B} + U$$

quarkonium binding (H_{Υ})

B meson binding (H_{B})

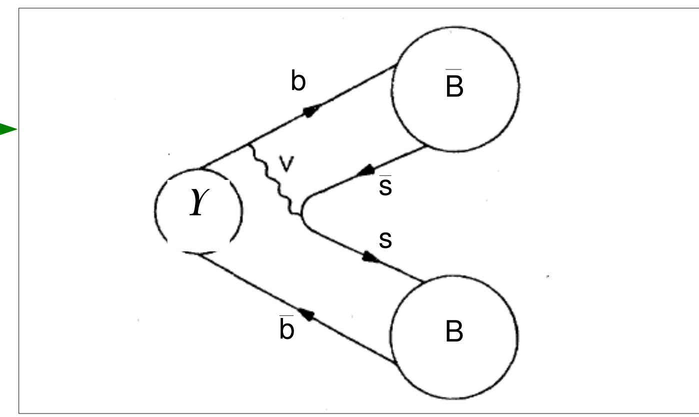
Coupled Channel Models

- Interpretation requires explicit treatment of coupling between quarkonia & continuum (Coupled Channel Model, Eichten *et al.*, 1978);
- Effective Hamiltonian from a quark-level potential:

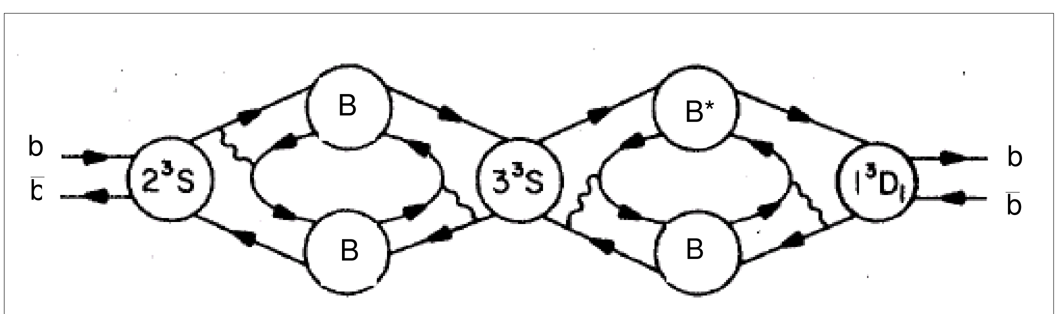
$$H_{eff} = H_{\Upsilon} + H_B + U$$

quarkonium binding

B meson binding

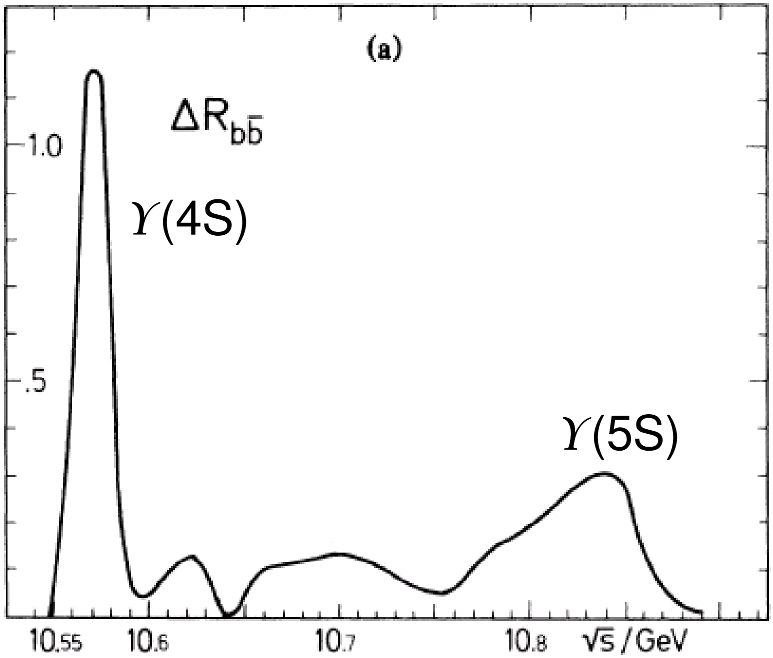


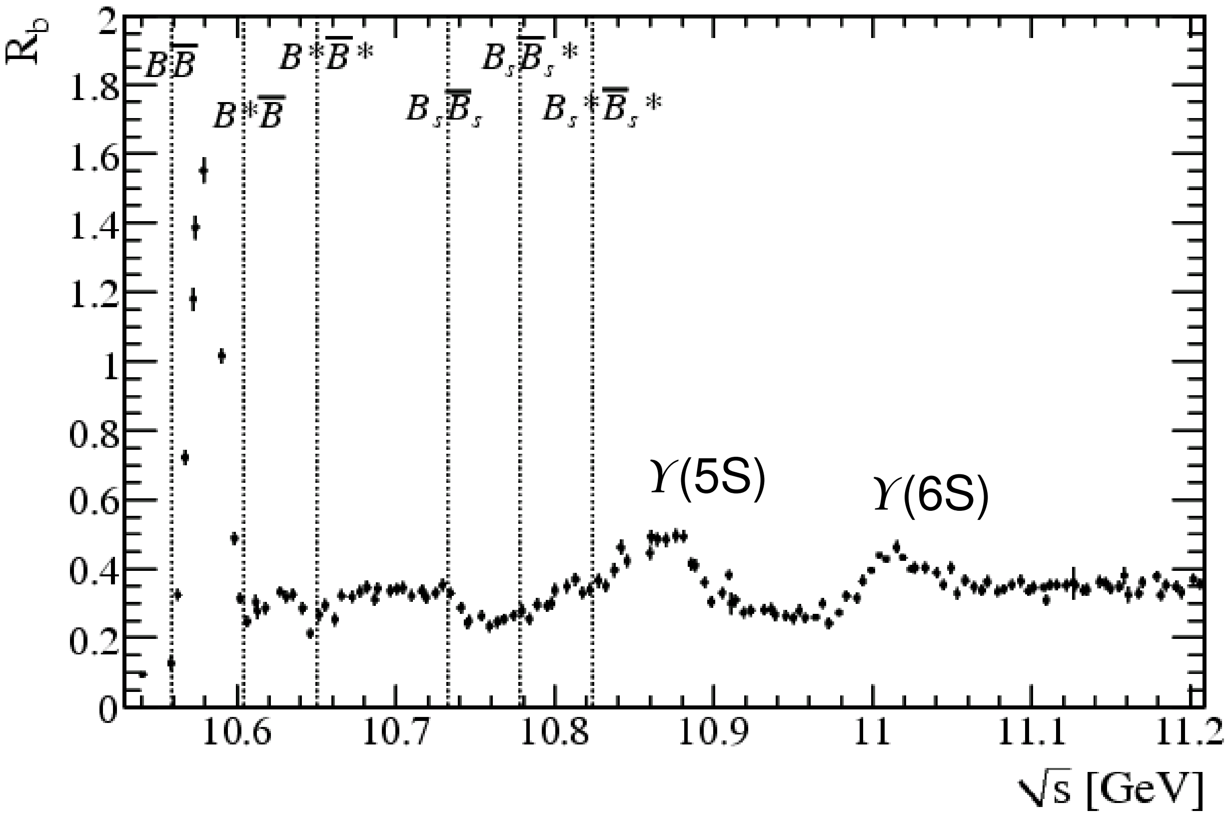
coupling
resonance – continuum



Interpretation

N. Törnqvist,
Phys.Rev.Lett.53:878,1984

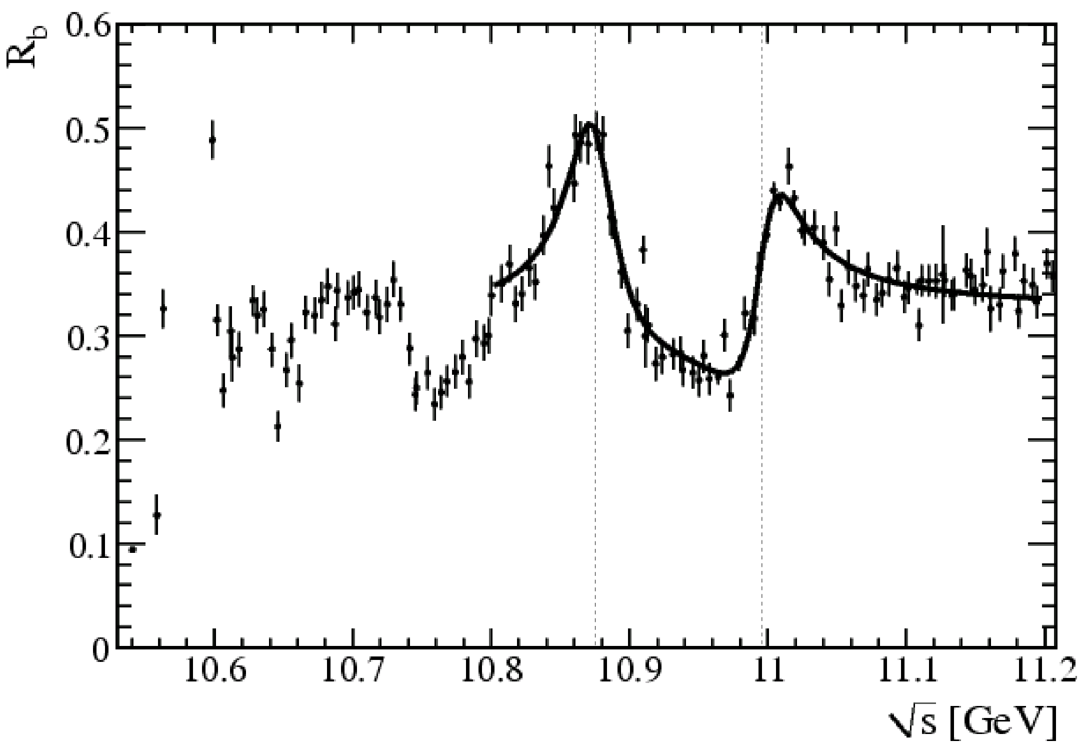




N. Törnqvist (1984) predicted structures between Υ(4S) and Υ(5S) and an asymmetric Υ(5S) shape with NO NEW RESONANCES!

$\Upsilon(5S)$ and $\Upsilon(6S)$

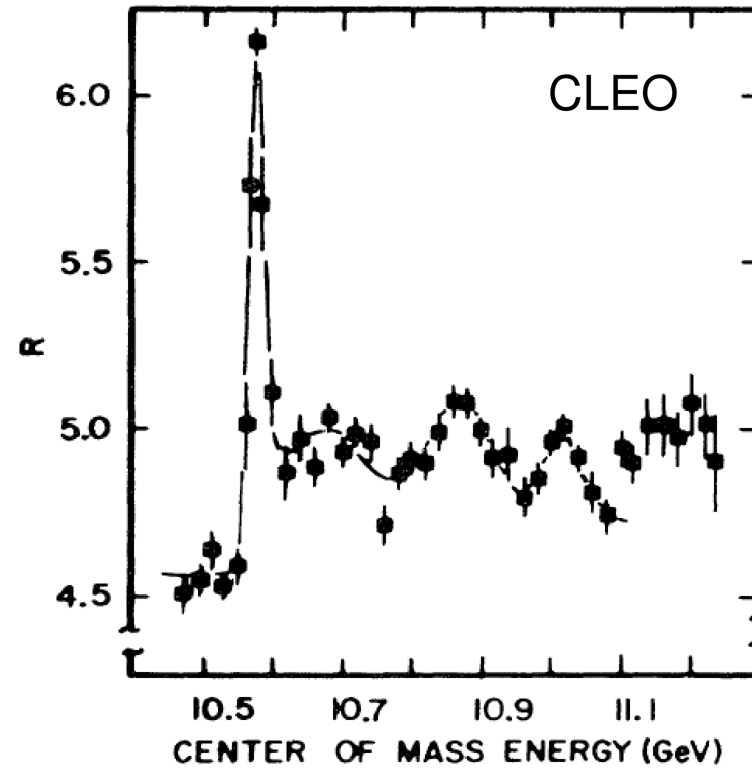
- Thresholds and interferences make also difficult the extraction of the $\Upsilon(5S)$ and $\Upsilon(6S)$ parameters;
- Realistic fit should explicitly include Couple Channel effects.
- We tried a simpler fit, with $\Upsilon(5S)$, $\Upsilon(6S)$ (Breit-Wigner PDFs) and continuum (flat), interfering.

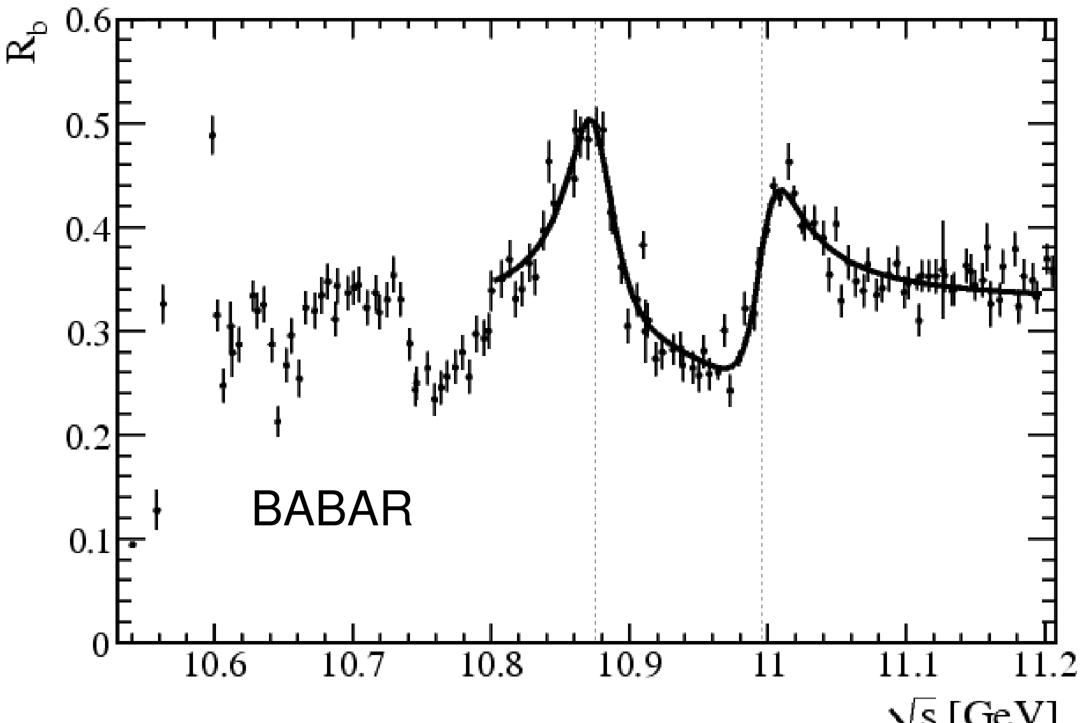


	$\Upsilon(10860)$	$\Upsilon(11020)$
mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16

Comparison with PDG

PDG: CLEO + CUSB

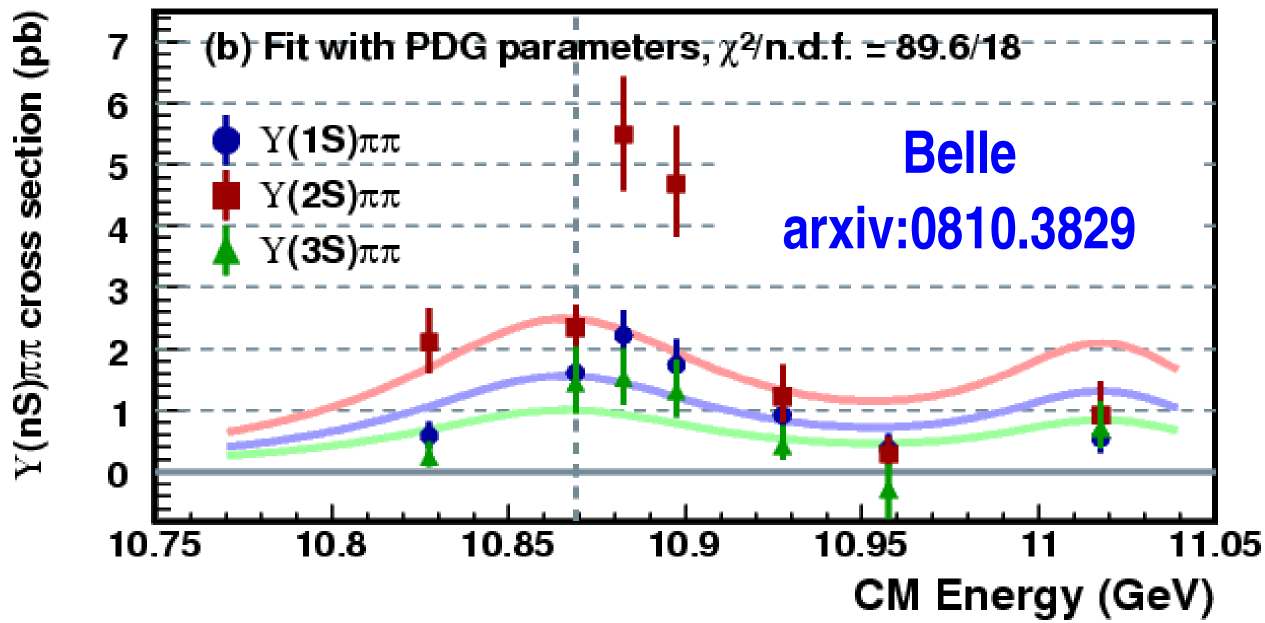


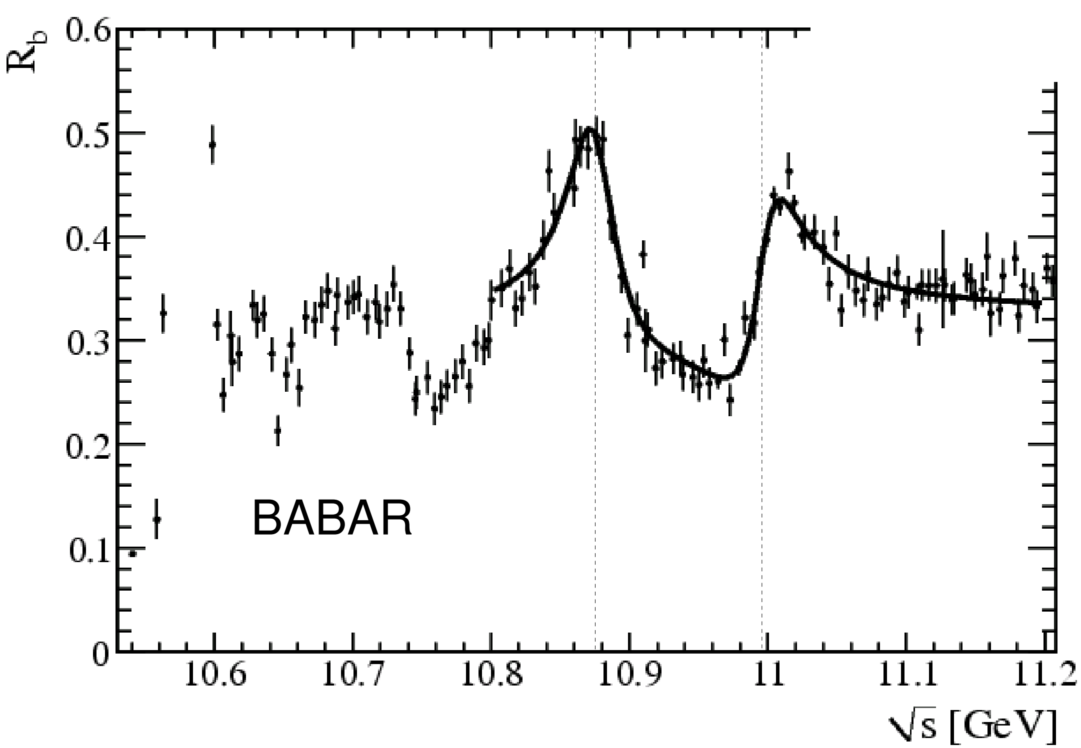


Comparison with Belle (I)

BELLE Statement:

DISAGREEMENT of $\Upsilon(5S)$ mass and width between exclusive (Belle) and inclusive (PDG) analysis





But...

$\Upsilon(5S)$ width

BaBar (Incl.): (43 ± 4) MeV

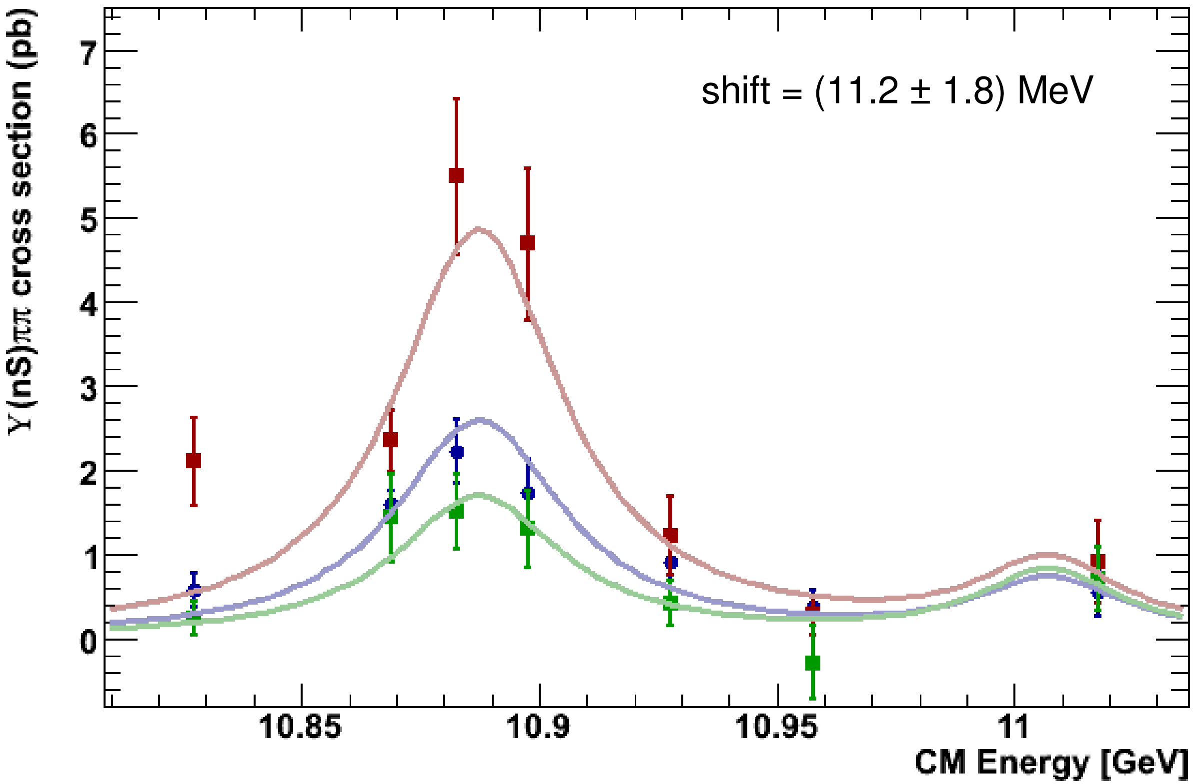
Belle(Excl.): $(54.7^{+8.5}_{-7.2} \pm 2.5)$ MeV

Comparison with Belle (II)

	BaBar (Inclusive)	Belle (Exclusive)
Υ(5S)		
Mass (GeV)	10.876 ± 0.002	10.8896 ± 0.0018 ± 0.0015
Width (MeV)	43 ± 4	$54.7^{+8.5}_{-7.2} \pm 2.5$

Comparison with Belle (III)

- Is there a bias in the CM energy measurement in BaBar or Belle?
  - Try fitting Belle data with BaBar parameters + a CM energy shift.



Conclusions

- B-Factories allow to significantly boost the experimental knowledge on Hadronic Physics;
- I presented two recent results from *BaBar*:
  - $e^+e^- \rightarrow \pi^+\pi^-$ with ISR;

    New contribution to the SM prediction of the anomalous magnetic moment of the muon

  - R_b scan above the $\Upsilon(4S)$;

    New estimate of the $\Upsilon(5S)$ and $\Upsilon(6S)$ shapes
    &
    improved knowledge of the open beauty threshold region

    NEXT STEP: EXCLUSIVE ANALYSIS

Backup

Scan Systematics

- Uncorrelated Systematics: NO point-by-point correlation;
- Correlated Systematics: FULL point-by-point correlation.

$$V_{ij} = \left[\sigma^2_{stat}(s_i) + \sigma^2_{unc}(s_i)\right]\delta_{ij} + \sigma_{corr}(s_i)\sigma_{corr}(s_j)$$

Correlated Systematics

Contribution	Relative error (%)
$\mu\mu$ MC statistics	0.2
$\mu\mu$ radiative corrections	1.4
ϵ_μ	1.3
ϵ_B	1.3
ϵ_{cont}	< 2.0
ϵ_{ISR}	< 0.7
$\sigma_{\gamma\gamma}\epsilon_{\gamma\gamma}$	< 0.2