Tau-muon lepton flavor universality in Upsilon(3S) decays

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On behalf of the *BaBar* collaboration

Lepton Universality in Υ decays

Width of a spin-1 $q\bar{q}$ bound state (mass M) decaying into $\ell^+\ell^-$:

$$\Gamma_{\Upsilon\to\ell^+\ell^-} = 4\alpha^2 e_q^2 \frac{|\Psi(0)|^2}{M^2}\left(1 + 2\frac{m_\ell^2}{M^2}\right)\sqrt{1 - 4\frac{m_\ell^2}{M^2}}$$

Hadronic corrections cancel in the ratio:

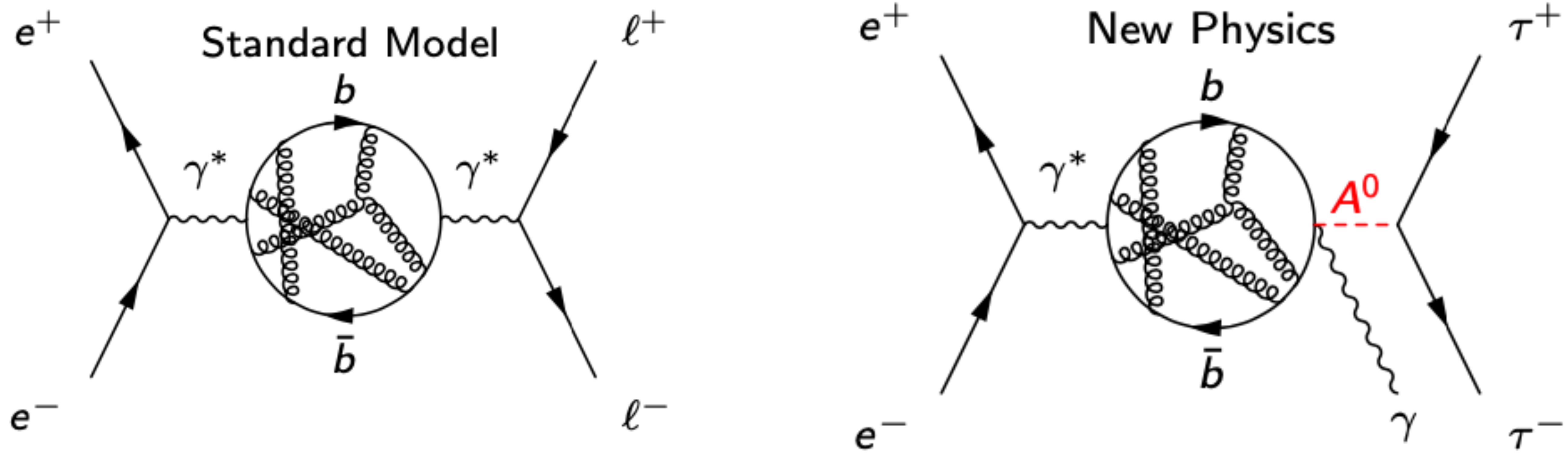
$$R_{\tau\mu} = \frac{\Gamma_{\Upsilon\to\tau^+\tau^-}}{\Gamma_{\Upsilon\to\mu^+\mu^-}} = \frac{M^2 + 2m_\tau^2}{M^2 + 2m_\mu^2}\sqrt{\frac{M^2 - 4m_\tau^2}{M^2 - 4m_\mu^2}}$$

Such ratios are very well known in the Standard Model (SM):

$V(nS)$	SM prediction
$\Upsilon(1S)$	$0.9924 \pm \mathcal{O}(10^{-5})$
$\Upsilon(2S)$	$0.9940 \pm \mathcal{O}(10^{-5})$
$\Upsilon(3S)$	$0.9948 \pm \mathcal{O}(10^{-5})$

Aloni, Efrati, Grossman & Nir
JHEP 06 (2017) 019

Lepton Universality in Υ decays

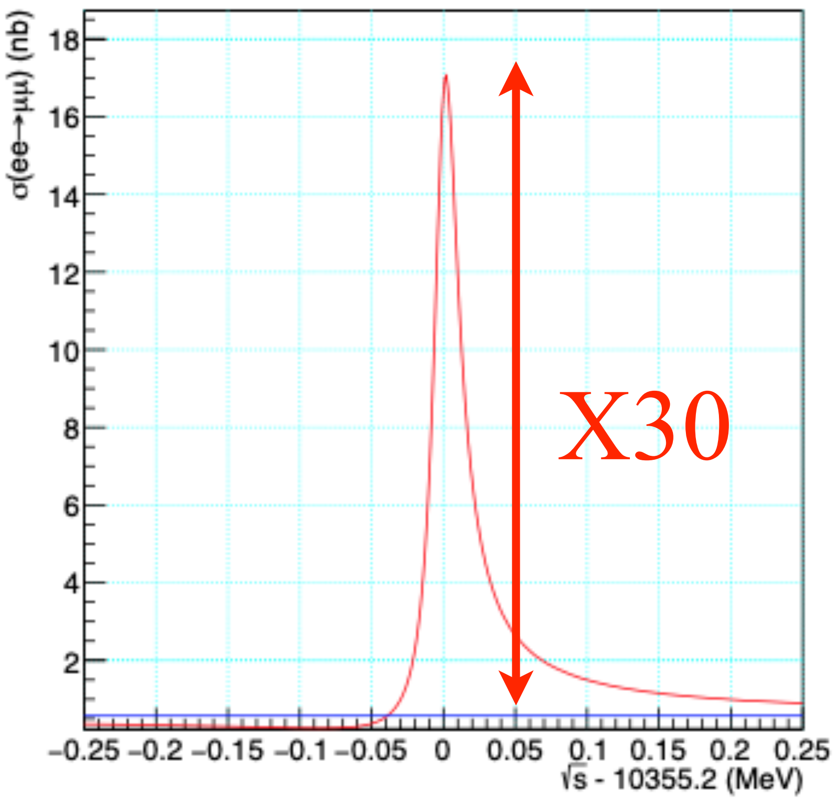


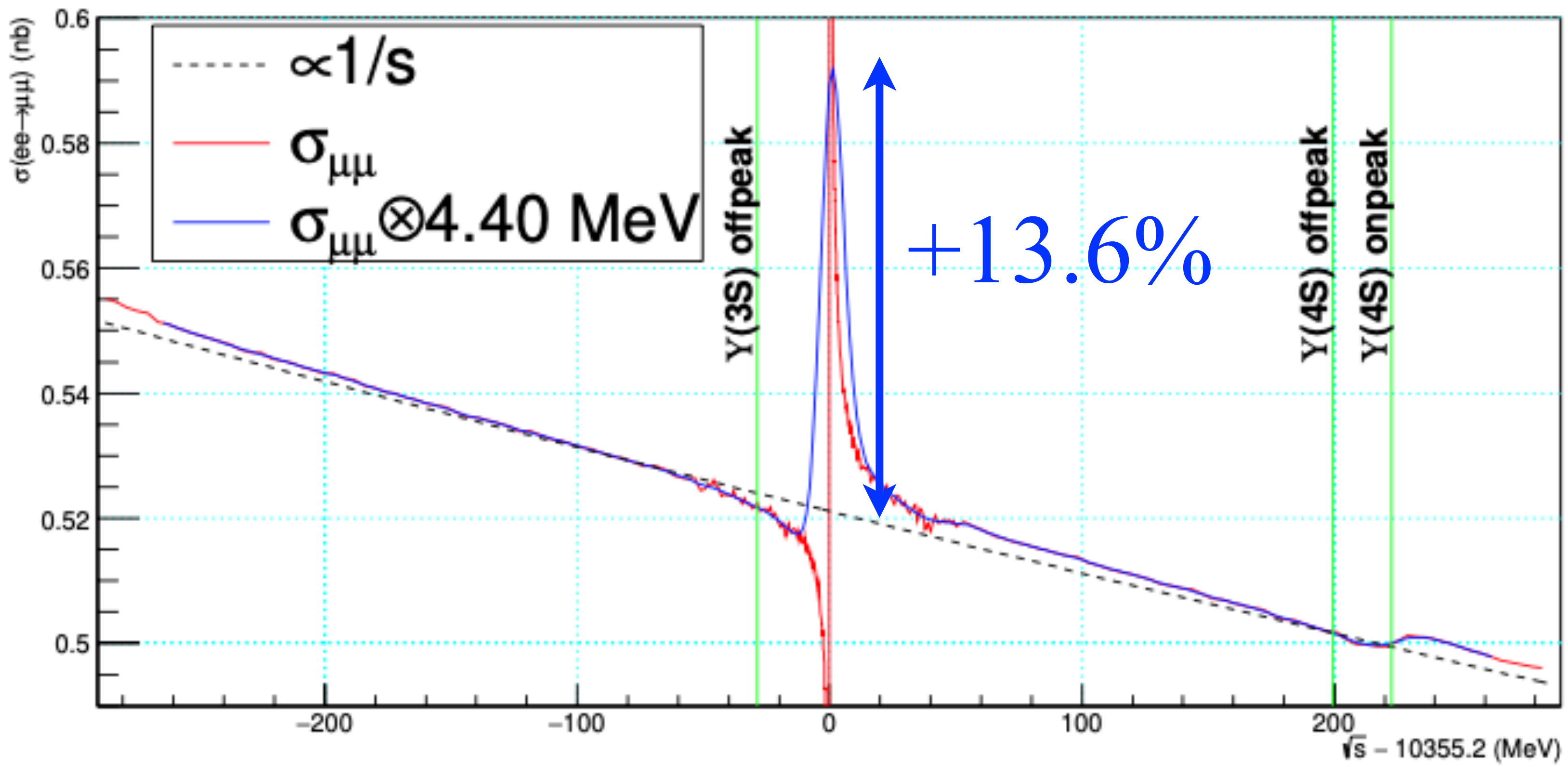
Excellent probe for new physics:

- Light CP-odd Higgs (A^0) in 2HDM (Type-II) models with large tanβ can increase $R_{\tau\mu}$ [Sanchis-Lozano, Int.J.Mod.Phys.A 19 (2004) 2183]
- New physics contribution in $b \rightarrow c\tau\nu$ decays that resolves the existing tension in $R(D^*)$ measurements can modify $R_{\tau\mu}$ [Aloni, Efrati, Grossman & Nir, JHEP 06 (2017) 019]

Di-muon production cross-section

- MCGPJ, a high precision (<0.2%) generator, shows at $\Upsilon(3S)$ the resonance production is a factor of 30 larger than continuum production [Arbuzov, Fedotovich, Ignatov, Kuraev, Sibidanov, Eur.Phys.J.C46 (2006) 689]

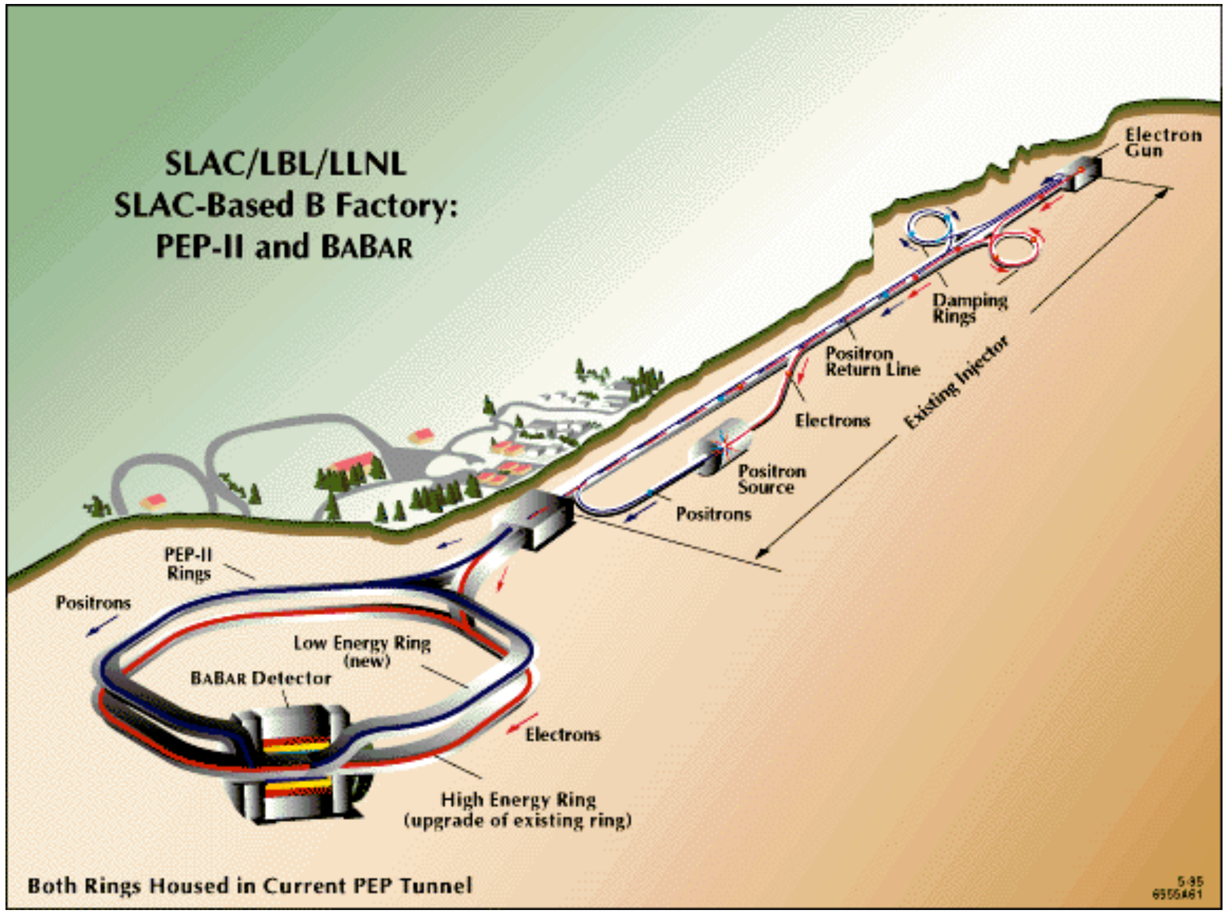




- However, after smearing with realistic beam spread at $\Upsilon(3S)$,

$$\frac{\sigma(e^+e^- \to \Upsilon(3S) \to \mu^+\mu^-)}{\sigma(\sigma(e^+e^- \to \gamma^\star \to \mu^+\mu^-)} = 1.136$$

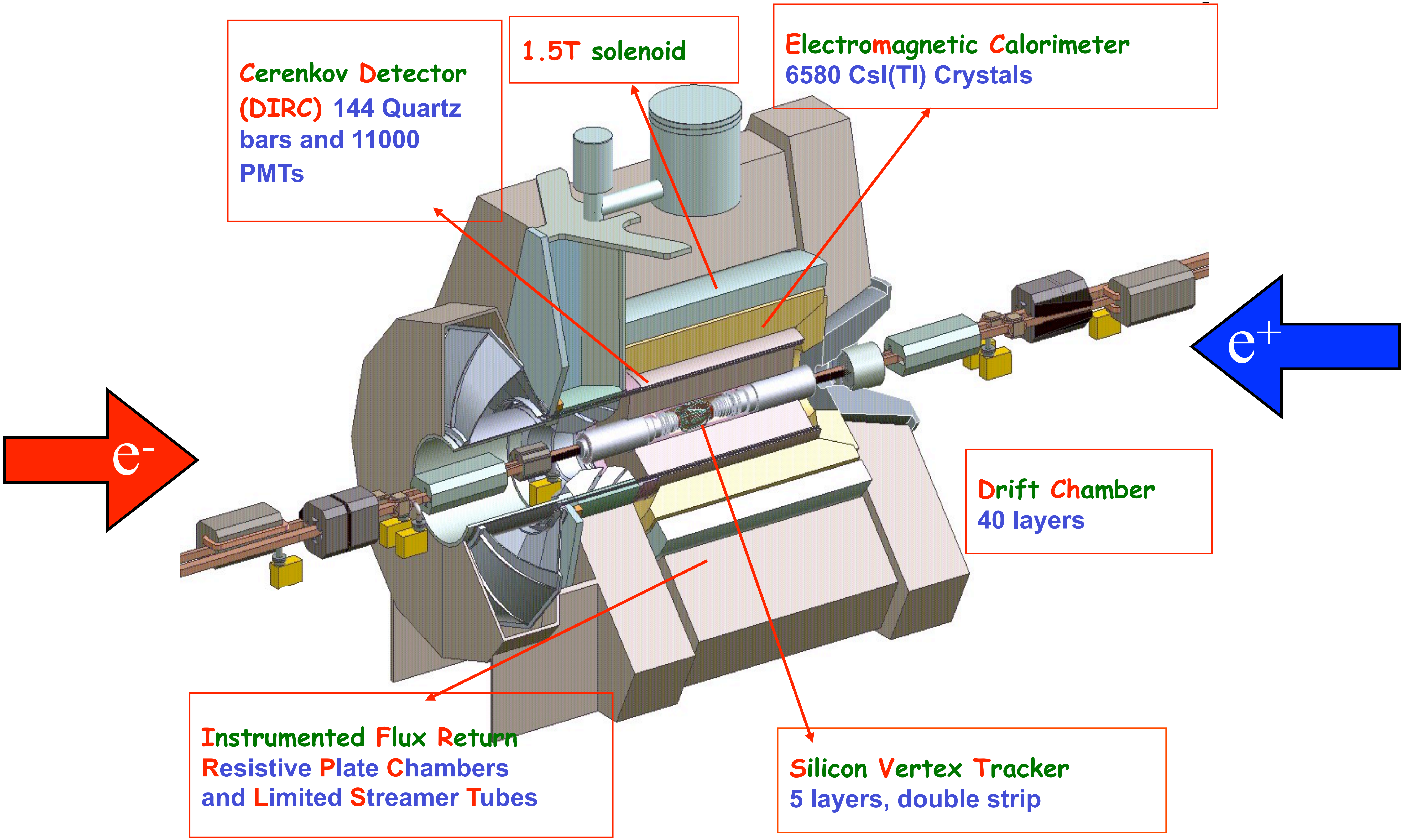
The PEP-II Accelerator



Datasets used in this analysis:

	$\sqrt{s}$	e^-	e^+	On-peak Luminosity	Off-peak Luminosity	Year
Υ(3S)	10.355 GeV	8.6 GeV	3.1 GeV	27.96 fb^{-1}	2.62 fb^{-1}	2008
Υ(4S)	10.58 GeV	9.0 GeV	3.1 GeV	78.3 fb^{-1}	7.72 fb^{-1}	2007

The BaBar Detector



Analysis overview

Select μμ events

- 2 high-momentum & back-to-back tracks identified as muons
- Invariant mass close to $\sqrt{s}$ used as the discriminating fit variable
- Parameterize the shape of $\Upsilon(3S)$ and continuum contributions

Select ττ events

- 2 tracks in the event which are not back-to-back; one track identified as an electron and the other track fails electron identification
- Total reconstructed energy used as the discriminating fit variable
- Parameterize the shape of $\Upsilon(3S)$ and continuum contributions

Measure yields of μμ and ττ events

- Simultaneous binned maximum likelihood fit to data
- Blind analysis strategy: 2.41 fb^{-1} of on-peak data at $\Upsilon(3S)$ as well as the off-peak data at $\Upsilon(3S)$ and $\Upsilon(4S)$ used to optimize analysis

Event Selection

$\mu^+\mu^-$ selections

1. Two and only two charged particles with opposite charges
2. $P^{cm}_{high} > 4\,\text{GeV}/c$ and $P^{cm}_{low} > 2\,\text{GeV}/c$
3. $2.8\,\text{rad} < \theta^{cm}_- + \theta^{cm}_+ < 3.5\,\text{rad}$
4. $E^{EMC}_+ + E^{EMC}_- < 2\,\text{GeV}$
5. $0.65\,\text{rad} < \theta^{cm}_- < 2.5\,\text{rad}$ and $0.58\,\text{rad} < \theta^{cm}_+ < 2.56\,\text{rad}$
6. $\psi^{cm} = \arccos \dfrac{\vec{P}^{cm}_+ \cdot \vec{P}^{cm}_-}{|\vec{P}^{cm}_+| \cdot |\vec{P}^{cm}_-|} > 160°$
7. $0.8 < M_{\mu\mu}/\sqrt{s} < 1.1$
8. At least one particle having IFR response

99.9% purity

$\tau^+\tau^-$ selections

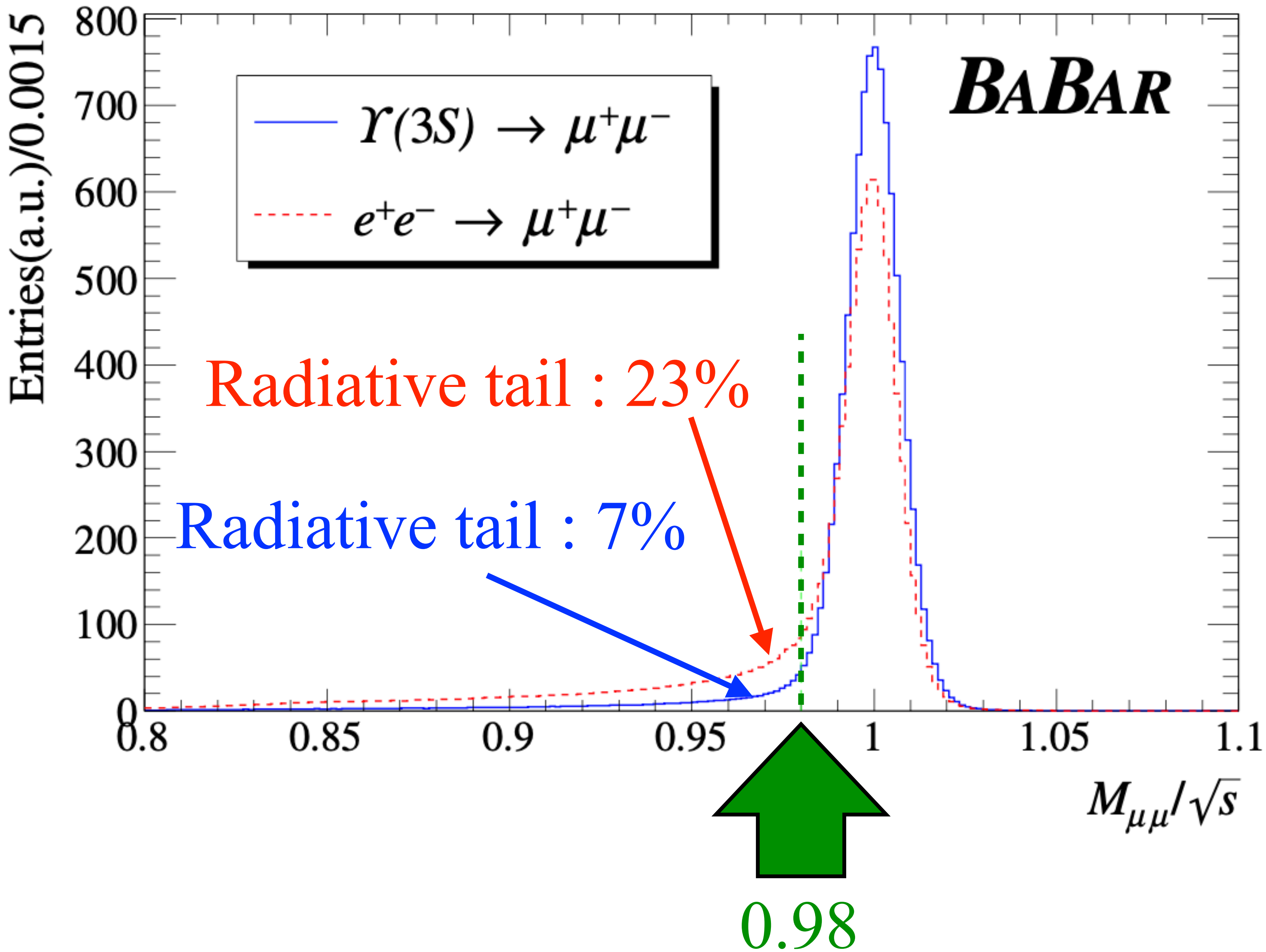
1. Two and only two charged particles with opposite charges
2. $41° < \theta^{cm}_\pm < 148°$.
3. $\psi^{cm} > 110°$
4. $E^{EMC}_{tot} < 0.7 \times E_{PEP\text{-}II}$
5. One of the particles must be an electron and the other not electron
6. $||\phi_+ - \phi_-| - 180°| > 3°$
7. $|M^2_{miss}| > 0.01 \times s$
8. $|\cos\theta_{miss}| < 0.85$
9. $P^\perp_\pm \notin \gamma^*\gamma^*$ region
10. $|\Delta\phi| = ||\phi_{e\gamma} - \phi_{\not{e}}| - 180°| > 2°$ and $|\Delta\theta| = |\theta_{e\gamma} + \theta_{\not{e}} - 180°| > 2°$

99% purity

All selections are designed to be beam-energy insensitive.

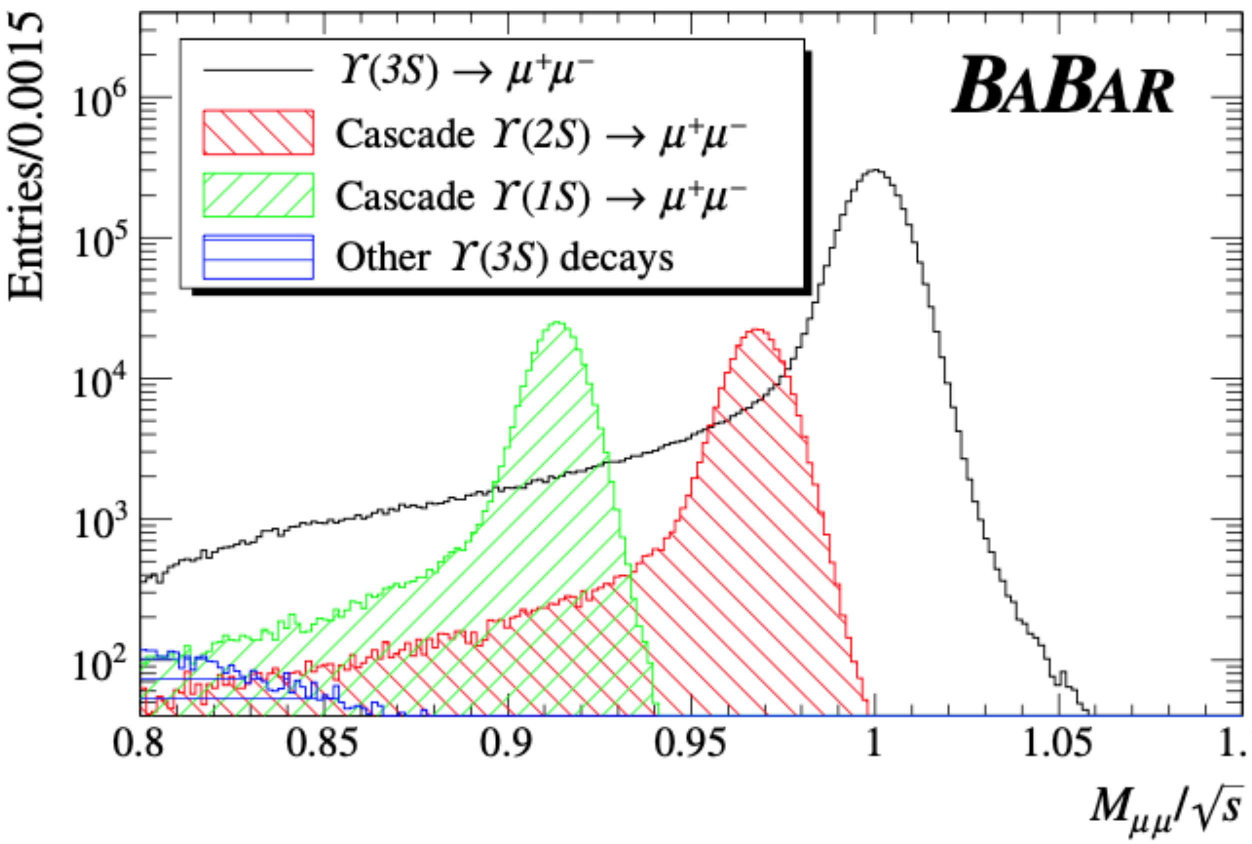
Continuum modeling

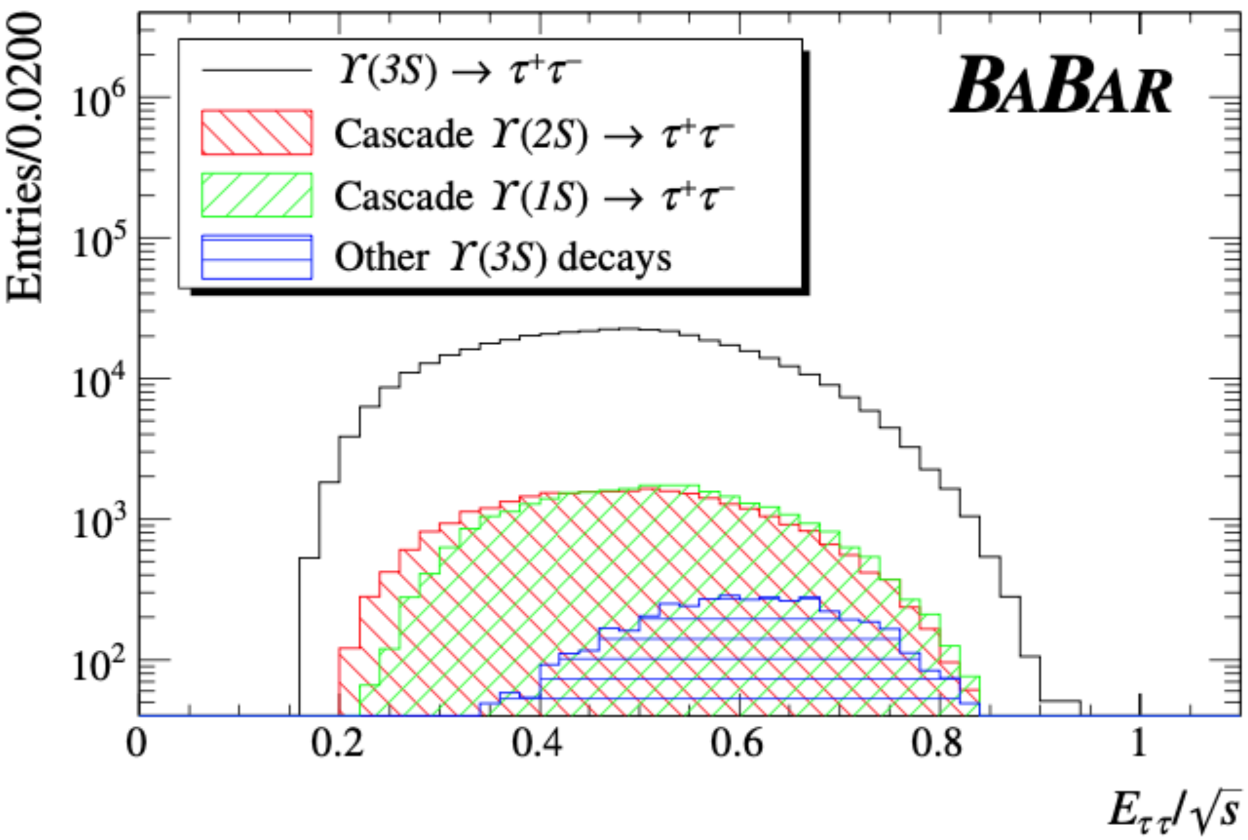
Template fit exploits differences in shapes of ϒ(3S) and continuum, where the latter is described by high-statistics ϒ(4S) & off-peak data



Cascade contributions

Model prompt di-lepton production from $\Upsilon(3S)$ decays as well as contributions from cascade $\Upsilon(2S)$ & $\Upsilon(1S)$ decays:



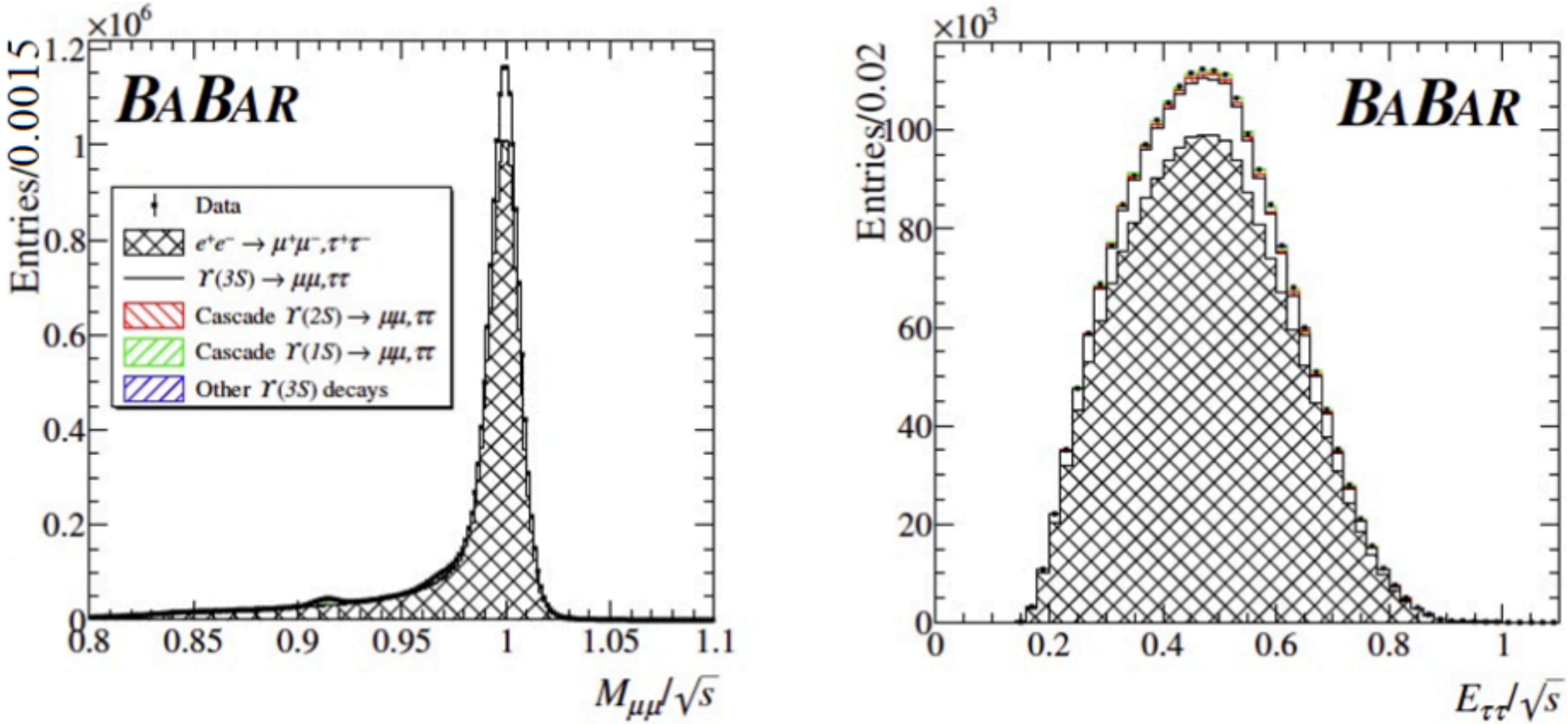


Monte Carlo (MC) based templates used:

- $\Upsilon(3S) \to \mu^+\mu^-$ and $\Upsilon(3S) \to \tau^+\tau^-$ are taken from KKMC
- $\Upsilon(2S) \to \ell^+\ell^-$ and $\Upsilon(1S) \to \ell^+\ell^-$ are from EvtGen MC

Fit results

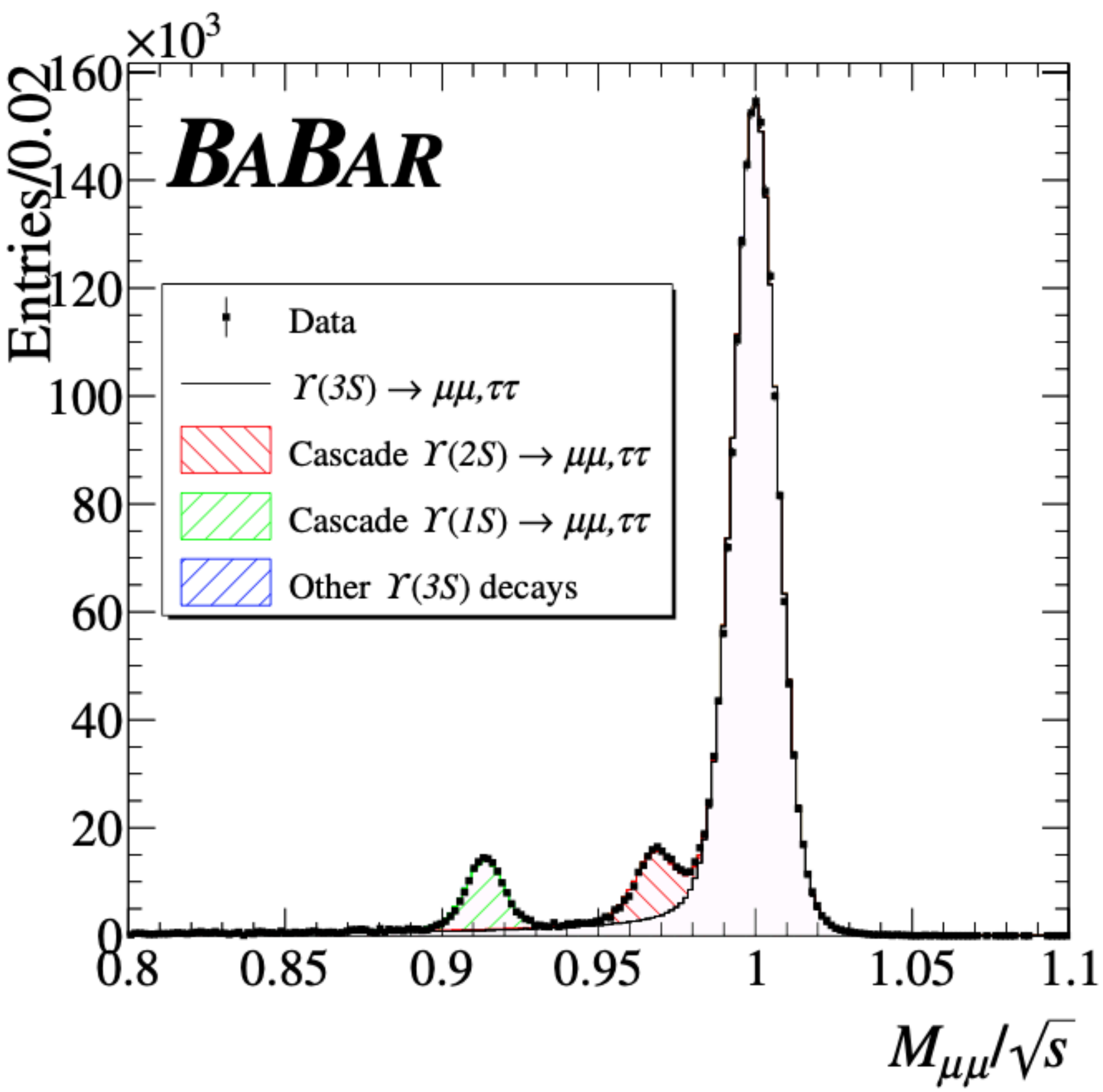
- Simultaneous fit to distributions of $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$
- Fit yields number of $\Upsilon(3S) \to \mu^+\mu^-$ events $(N_{\mu\mu})$ and the ratio $(\tilde{R}_{\tau\mu})$ of number of $\Upsilon(3S) \to \tau^+\tau^-$ events $(N_{\tau\tau})$ to $N_{\mu\mu}$

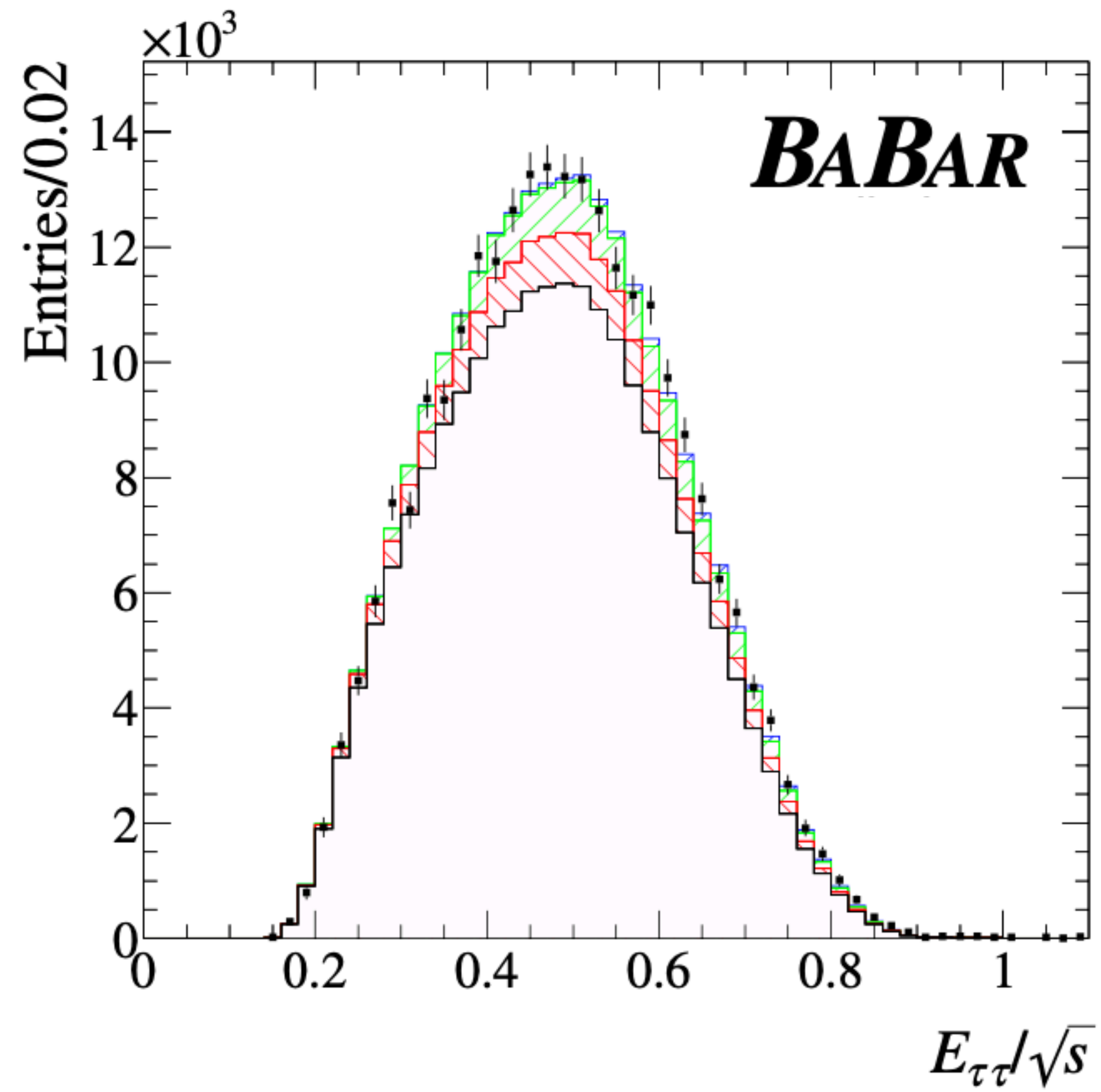


$$N_{\mu\mu} = (2.02 \pm 0.02) \times 10^6, \ \tilde{R}_{\tau\mu} = 0.10778 \pm 0.00091$$

Fit results (continuum subtracted)

- Dominant contribution to the above fit comes from continuum
- When the continuum background is subtracted, $\Upsilon(3S)$ signal & "cascade" backgrounds can be seen in $M_{\mu\mu}/\sqrt{s}$ distribution





Correction factors & systematics

$$R_{\tau\mu}^{\Upsilon(3S)} = \tilde{R}_{\tau\mu} \frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}} \frac{1}{C_{MC}} \left(1 + \delta_{B\bar{B}}\right)$$

$$= 0.9662 \pm 0.0084_{\text{stat}} \pm 0.0135_{\text{syst}} = 0.9662 \pm 0.0159_{\text{tot}}$$

- $\frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}} = 0.11041 \pm 0.00015_{\text{stat}}$ is the ratio of MC efficiencies
- $C_{MC} = 1.0146 \pm 0.0016_{\text{stat}}$ is the data/MC correction factor
- $\delta_{B\bar{B}} = (0.4 \pm 0.2)\ \%$ corrects for a small amount of $B\bar{B}$ in the $\tau\tau$ sample

Summary of systematic uncertainties

Source	Uncertainty (%)
Particle identification	0.9
Cascade decays	0.6
Two-photon production	0.5
$\Upsilon(3S) \to$ hadrons	0.4
MC shape	0.4
$B\bar{B}$ contribution	0.2
ISR subtraction	0.2
Total	1.4

Comparison with previous measurement

$$R_{\tau\mu}^{\Upsilon(3S)} = \tilde{R}_{\tau\mu}\frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}}\frac{1}{C_{MC}}\left(1+\delta_{B\bar{B}}\right)$$

$$= 0.9662 \pm 0.0084_{\text{stat}} \pm 0.0135_{\text{syst}} = 0.9662 \pm 0.0159_{\text{tot}}$$

- This result is 6 times more precise than the only previous measurement:

$$R_{\tau\mu}^{\Upsilon(3S)} = 1.05 \pm 0.08 \pm 0.05$$

D. Besson et. al. (CLEO) PRL 98 (2007) 052002

- CLEO analysis used 1.2 fb^{-1} of data at the $\Upsilon(3S)$ resonance
- *BaBar* statistical uncertainty is 2 times more precise, which scales as:

$$\sigma_{stat}^{BABAR} = \frac{\sigma_{stat}^{CLEO}}{\sqrt{\mathcal{L}_{BABAR}/\mathcal{L}_{CLEO}}} = \frac{0.08}{\sqrt{27.96/1.2}} = 0.0166$$

- Careful modeling of continuum using $\Upsilon(4S)$ and off-peak data and radiative returns allowed inclusion of low mass tail in the *BaBar* fit, whereas the CLEO analysis suppressed the backgrounds using cuts

Summary

- The *BABAR* datasets of ϒ(nS) decays are excellent probes of new physics

- Using 27.96 fb^{-1} of data collected at the ϒ(3S) resonance and 78.3 fb^{-1} of data collected at the ϒ(4S) resonance as well as off-peak data, a precise measurement of the following ratio is obtained:

$$R_{\tau\mu}^{\Upsilon(3S)} = \frac{\Gamma_{\Upsilon\to\tau^+\tau^-}}{\Gamma_{\Upsilon\to\mu^+\mu^-}} = 0.966 \pm 0.008_{\mathrm{stat}} \pm 0.014_{\mathrm{syst}}$$

J.P. Lees et. al. (*BABAR*)
PRL 125 (2020) 241801

- The result agrees with the SM prediction of 0.9948 within ± 2σ

- Almost an order of magnitude more precise than previous measurement