τ–μ Lepton Flavour Universality in $\Upsilon(3S)$ Decays at the *BABAR* Experiment

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On behalf of the BABAR Collaboration

Motivation

Partial width of vector such as $\Upsilon \to \ell^+ \ell^-$ is:

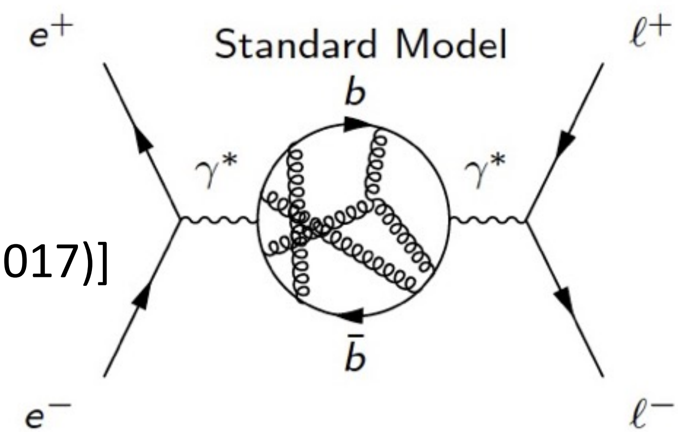
$$\Gamma_{\Upsilon \to \ell\ell} = 4\alpha^2 e_q{}^2 \frac{|\Psi(0)|^2}{M^2}(1 + 2m^2{}_\ell/M^2)\sqrt{1 - 4m^2{}_\ell/M^2}$$

$$\Rightarrow R_{\tau\mu} = \frac{\Gamma_{\Upsilon \to \tau\tau}}{\Gamma_{\Upsilon \to \mu\mu}} = \frac{(1 + 2m^2{}_\tau/M_\Upsilon{}^2)\sqrt{1 - 4m^2{}_\tau/M_\Upsilon{}^2}}{(1 + 2m^2{}_\mu/M_\Upsilon{}^2)\sqrt{1 - 4m^2{}_\mu/M_\Upsilon{}^2}}$$

$R_{\tau\mu}(3S)_{SM} = 0.9948 \pm \mathcal{O}(10^{-5})$

With radiative corrections

[Aloni , Efrati, Grossman& Nir, J. High Energ. Phys. 06, 019 (2017)]

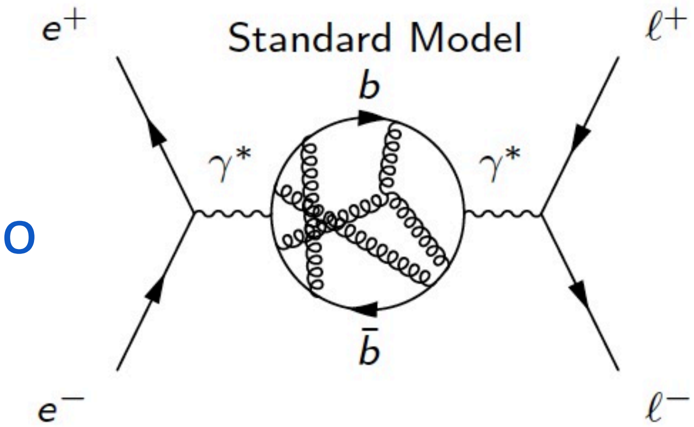


Ratio has no hadronic uncertainties

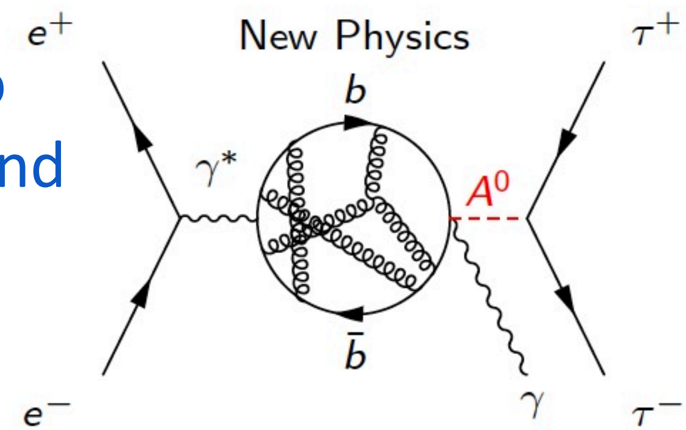
$\Rightarrow$ ideal probe for Physics Beyond the Standard Model

Motivation

In [Phys. Lett. B653, 67, 2007] a light CP-odd Higgs boson A^0 is proposed. In 2HDM(II) with large tanβ the A^0 boson exclusively decays into τ-pairs and thus New Physics effects might modify $R_{\tau\mu}$ in Υ(nS) decays.



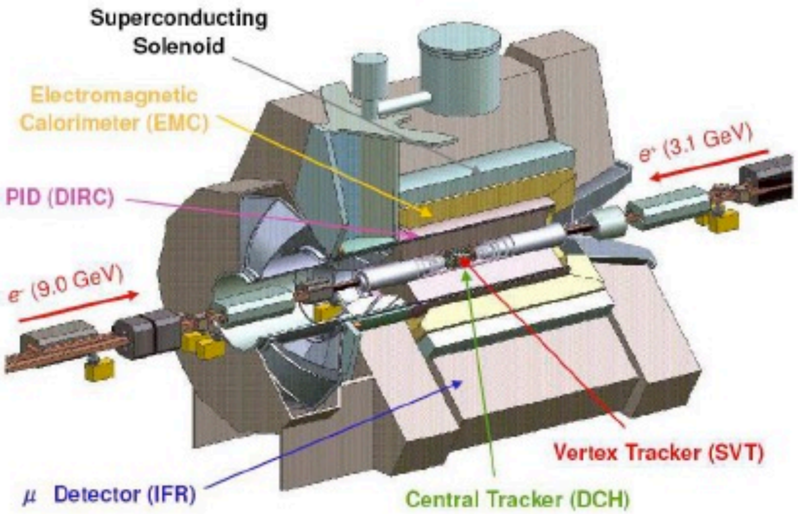
Aloni et al in [J. High Energ. Phys. 06, 019 (2017)] propose a New Physics contribution to $b \rightarrow c\tau\upsilon$ which explains the tension in R(D(*)) and which must also modify the $R_{\tau\mu}$ observable – encourage this measurement to be made

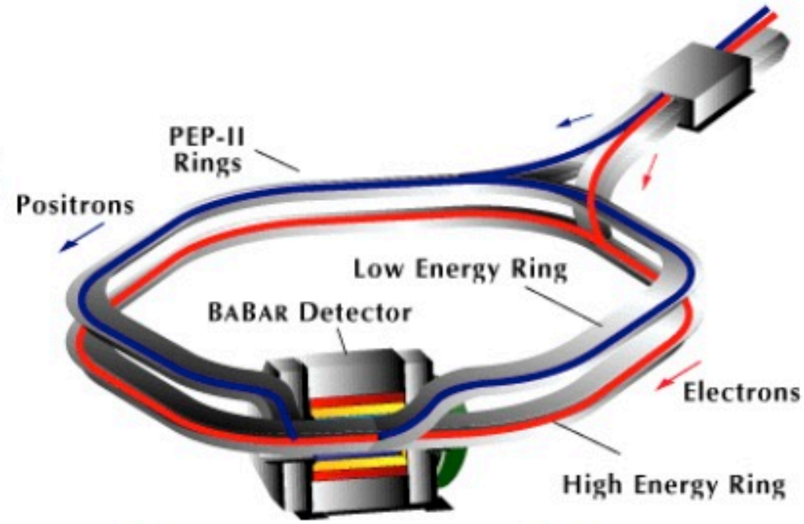


The only other measurement is by the CLEO collaboration [Phys.Rev.Lett. 98 (2007) 052002]: $R_{\tau\mu}$ = 1.05$\pm$0.08$\pm$0.05.

BABAR Datasets

BABAR and PEP-II operated in 1999 – 2008 at SLAC.





Data sample	On resonance fb^{-1}	Off resonance fb^{-1}
Run 7 $\Upsilon(3S)$	$27.96 = 25.55 + 2.41$	2.62
Run 6 $\Upsilon(4S)$	78.3	7.75

Total data (Run 1-7)

On resonances:

$\Upsilon(4S)$:	433 fb^{-1}
$\Upsilon(3S)$:	28 fb^{-1}
$\Upsilon(2S)$:	14 fb^{-1}
Off reson./scan:	54 fb^{-1}
Total:	529 fb^{-1}

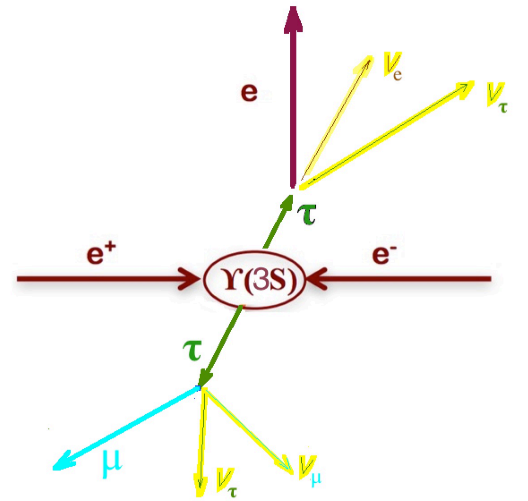
- Blind analysis technique – only 2.41 fb^{-1} of $\Upsilon(3S)$ on resonance and $\Upsilon(3S)$ and $\Upsilon(4S)$ off resonance data are used to tune selections.
- $\Upsilon(3S)$ off-resonance statistic is low $\Rightarrow$ Run 6 $\Upsilon(4S)$ on-resonance data with the same detector configuration is used to get the final result.

$e^+e^- \rightarrow \tau^+\tau^-$ Signal Selection

2.17×10^6 $\tau\tau$ candidates
Purity = 98.9%

$\tau_1 \rightarrow e\ \nu\nu$, $\tau_2 \rightarrow \mu\ \nu\nu$ || $h\ n\pi^0\ \nu$ n=0,1,2,..

- Two and only two opposite charged charged particles, each with polar angle acceptance designed to be insensitive to CM energy: $41^o < \theta^{CM} < 148^o$
- Tracks roughly backed-to-back in CM: angle > 110°
- PID one track as electron AND the other must fail the same electron PID requirements: e and not-e



Require Presence of neutrinos from τ decays

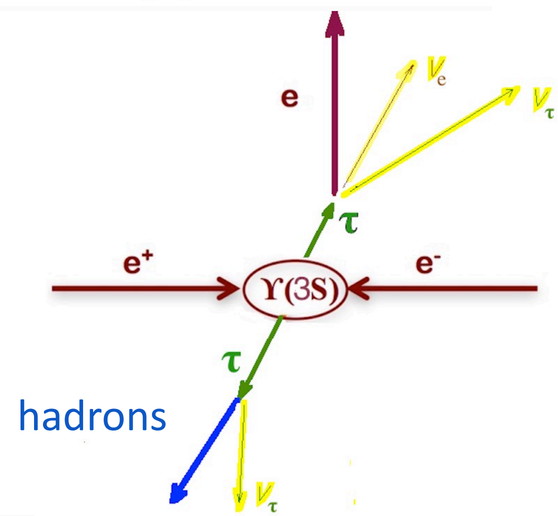
- Track azimuthal acollinearity > 3°
- Total calorimeter energy < 0.70 x $[E_{beam}(e-)+E_{beam}(e+)]$
- $|M^2_{MISS}| > 0.01 \times E^2_{cm}$
- $|\cos\theta^{CM}_{MISS}| < 0.85$

Suppress Bhabha backgrounds

- Both azimuthal and polar angle acollinearity of not-e and $[e+\gamma] > 2^o$

Suppress of Two-photon backgrounds

- Cuts on transverse momenta of the two tracks



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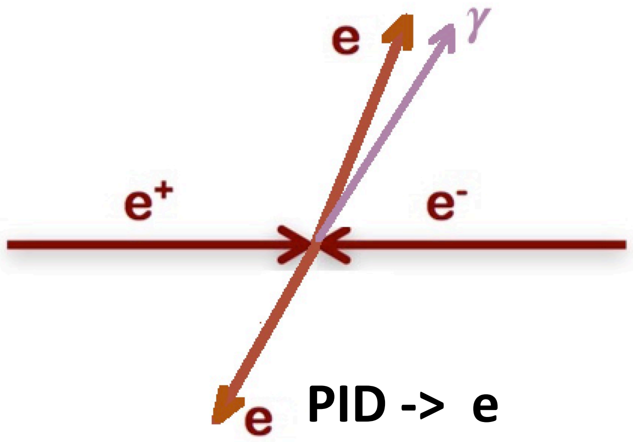

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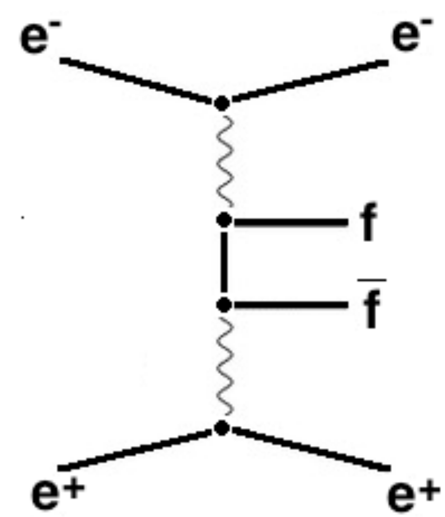


$e^+e^- \to \mu^+\mu^-$ Signal Selection

18.8×10^6 $\mu\mu$ candidates
Purity = 99.9%

Two High Momentum Back-to-Back Charged Particles

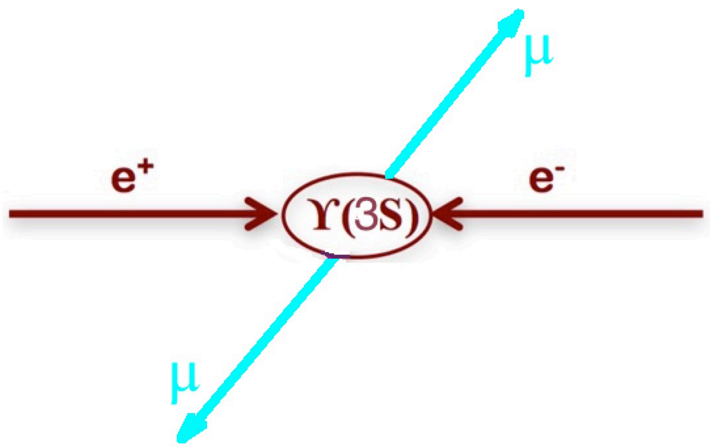
- Two and only two opposite charged charged particles each within polar angle acceptance designed to be insensitive to CM energy:
  $0.65 \text{ rad} < \theta^{CM}(-) < 2.5 \text{ rad}$ && $0.58 \text{ rad} < \theta^{CM}(+) < 2.56 \text{ rad}$
- CM opening angle between charged particles > 160°
- CM polar angle back-to-back in Filter: $2.8 \text{ rad} < \theta^{CM}(-) + \theta^{CM}(+) < 3.5 \text{ rad}$
- P^{CM}high > 4 GeV || P^{CM}low > 2 GeV

Invariant mass of two charged particles near CM energy

- $0.8 < M_{\mu\mu}/E_{cm} < 1.1$

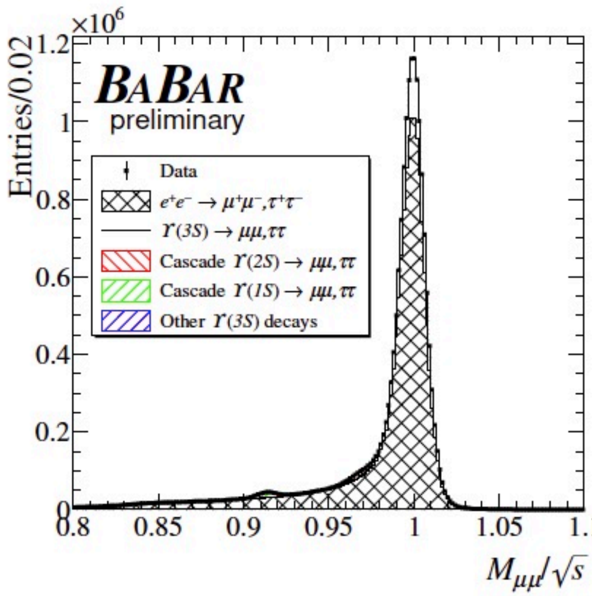
Tracks are muon-like: suppress Bhabha backgrounds

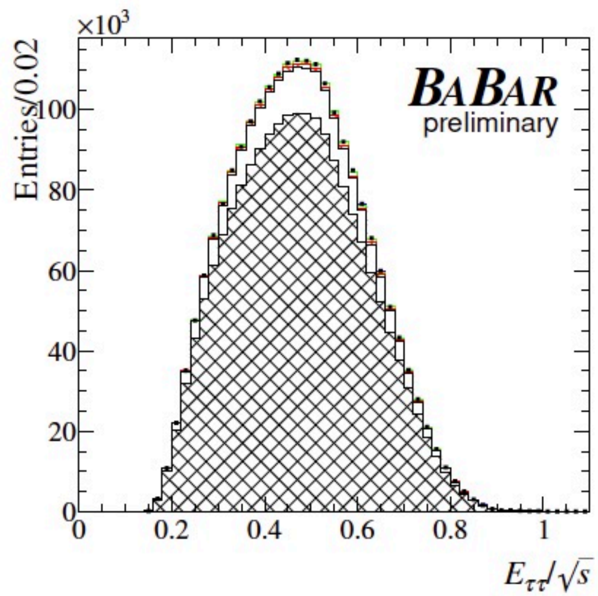
- Total EM calorimeter energy associated with both tracks < 2GeV
- At least one particle has response in the Instrumented Flux Return (IFR)



Fitting for $R_{\tau\mu}$

- $R_{\tau\mu}$ obtained with binned maximum-likelihood template fit to $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$ distributions [Barlow&Beeston, Comp.Phys Comm. 77, 2019 (1993)]
- $M_{\mu\mu}$: $\mu^+\mu^-$ invariant mass in $\mu^+\mu^-$ sample
- $E_{\tau\tau}$: total reconstructed energy in $\tau^+\tau^-$ sample using the measured momenta of charged particles and up to 10 most energetic photons
- $N_{\mu\mu}$ (no. $\Upsilon(3S) \to \mu^+\mu^-$ events) and $\tilde{R}_{\tau\mu} = N_{\tau\tau} / N_{\mu\mu}$ are free parameters in the fit (N$_{\tau\tau}$ = no. $\Upsilon(3S) \to \tau^+\tau^-$ events)



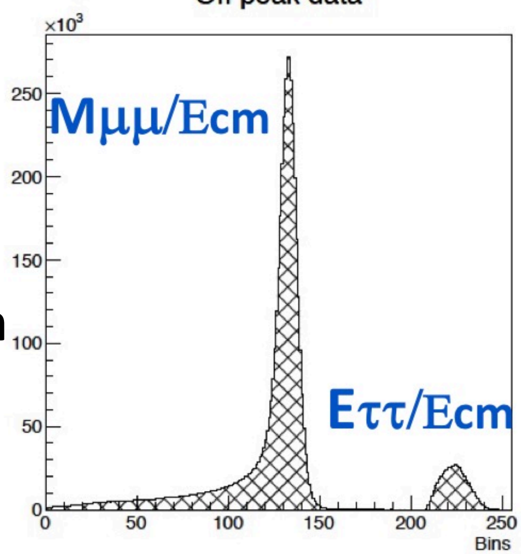


Fitting for $R_{\tau\mu}$

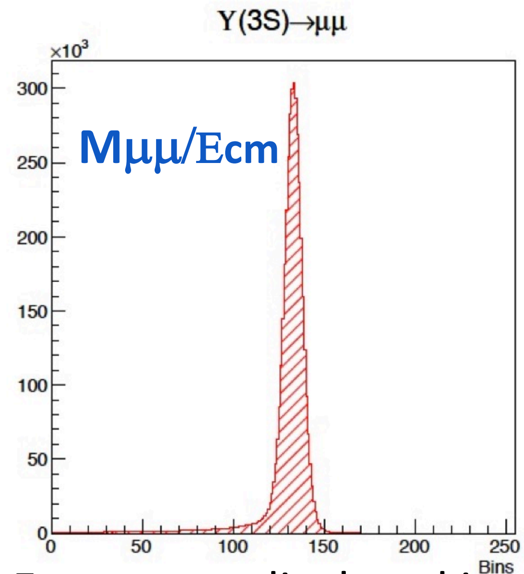
- Signal templates from KKMC-based MC without ISR
- Non-Υ(3S) data gives templates of continuum background
- There is insufficient Υ(3S) off-resonance data->we use high-statistics Υ(4S) sample having identical detector configuration (Run 6) as the Υ(3S) sample (Run 7) - 10x larger than Υ(3S) off-resonance sample
- Run 6 gives 44M selected $\mu^+\mu^-$ events and 5M selected $\tau^+\tau^-$ events

Shapes of Continuum Templates obtained from Υ(4S) data

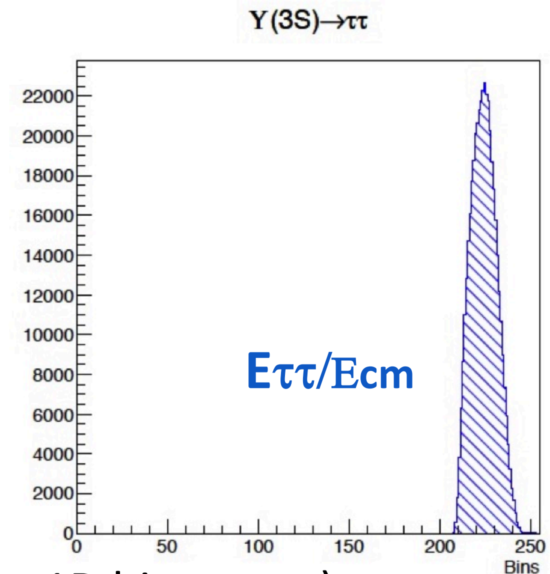
Run 6 Υ(4S) data



Signal μμ MC no ISR

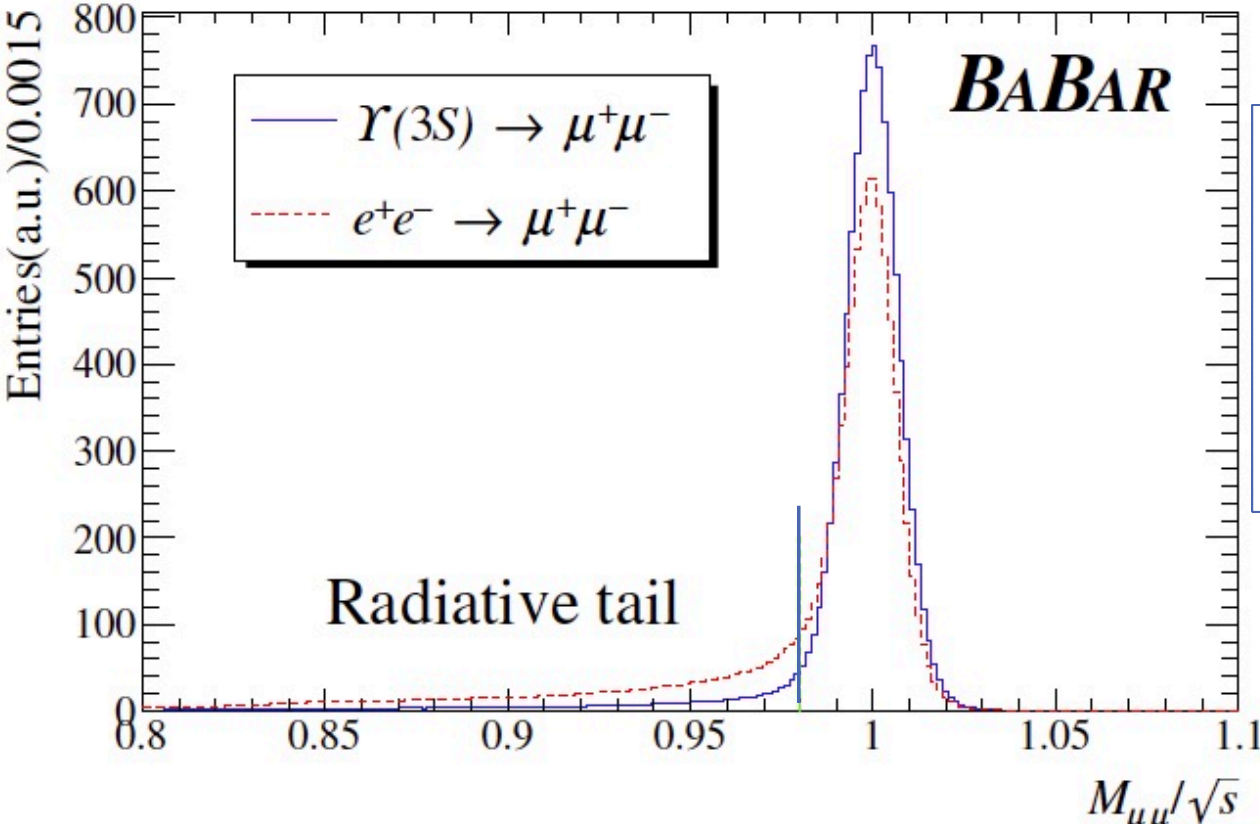


Signal ττ MC no ISR



(Note: Here Mμμ/Ecm and Eττ/Ecm are displayed in same 1D histogram)

Separating $\Upsilon(3S) \rightarrow \mu^+\mu^-$ from continuum



Continuum has substantially larger radiative tail than $\Upsilon(3S) \rightarrow \mu^+\mu^-$

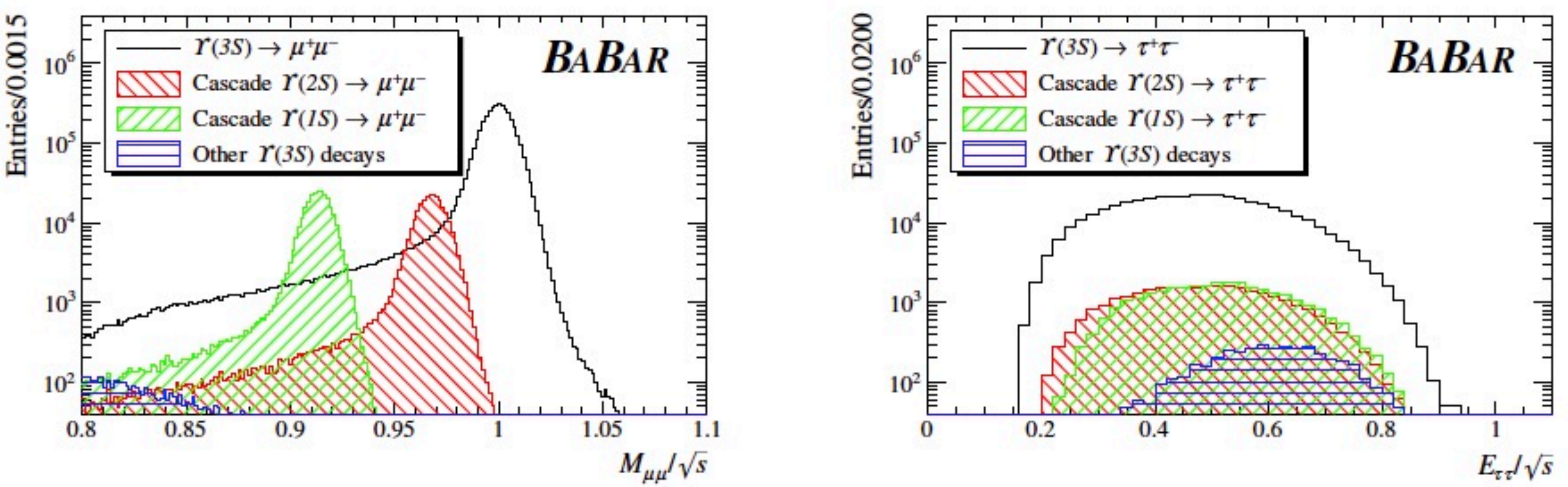
Exploit difference in invariant mass shapes arising from initial state radiation effects to distinguish resonant decays from continuum in fit

e.g. 7% of the selected $\Upsilon(3S) \rightarrow \mu^+\mu^-$ events have invariant mass <0.98 E_{CM}

cf 23% of the selected continuum $e^+e^- \rightarrow \mu^+\mu^-$ events have invariant mass <0.98 E_{CM}

$\Upsilon(3S) \to \mu^+\mu^-$ in presence of 'cascade decays'

- 'Cascade decays' here refer to $\Upsilon(3S) \to \ell^+\ell^-$ decays through intermediate states, including the $\Upsilon(2S)$ and $\Upsilon(1S)$
- Separate the cascade decays from signal in $\Upsilon(3S) \to \mu^+\mu^-$ in fit to $M_{\mu\mu}/\sqrt{s}$ and use those fits to fix them for $\Upsilon(3S) \to \tau^+\tau^-$
- Cascade templates and small contributions from $\Upsilon(3S) \to$ hadrons are from EvtGen-based MC



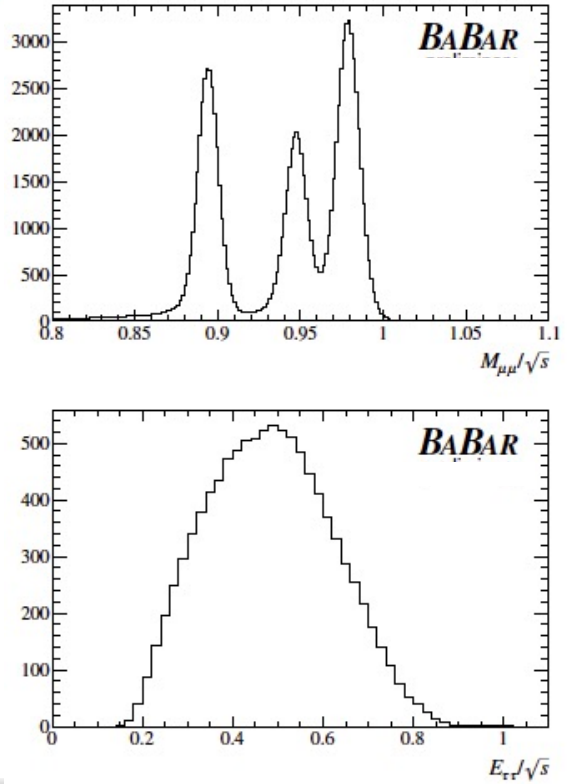
Correct for ISR-produced ϒ(nS) in ϒ(4S) Data

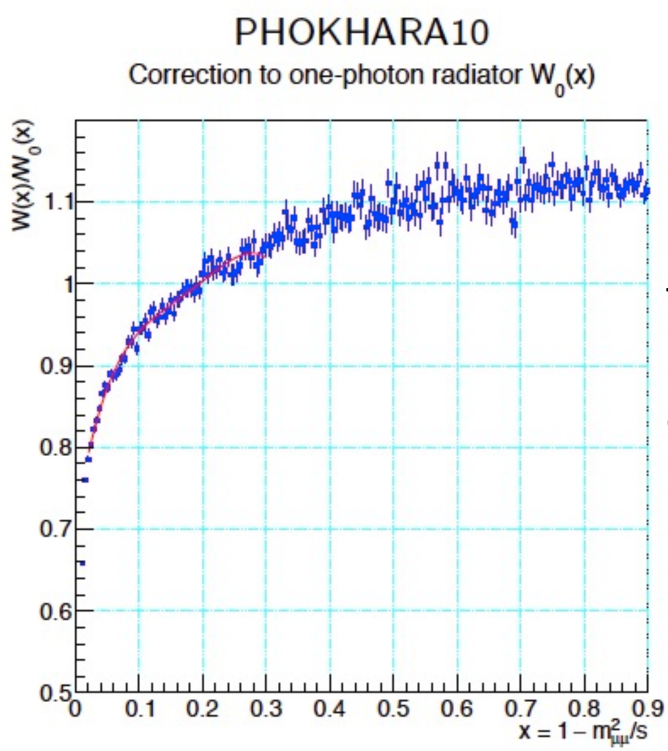
Templates intended to describe Continuum only

The Run 6 continuum template is corrected to take into account $\Upsilon(nS)$ produced by the radiative return process. Total ISR cross section for a narrow resonance is

$$\sigma(s) = \frac{12\pi^2\Gamma_{ee}\Gamma_{\mu\mu}}{sM\Gamma} W(s,x_0),\ x_0 = 1 - \frac{M^2}{s},\ W_0(s,x) = \frac{\alpha}{\pi x}\left(\ln\frac{s}{m_e^2} - 1\right)(2-2x+x^2),$$

where W_0 is one photon radiator function, since all $\Upsilon(nS)$ resonances are close to each other – photon emission is soft and corrections have to be evaluated.

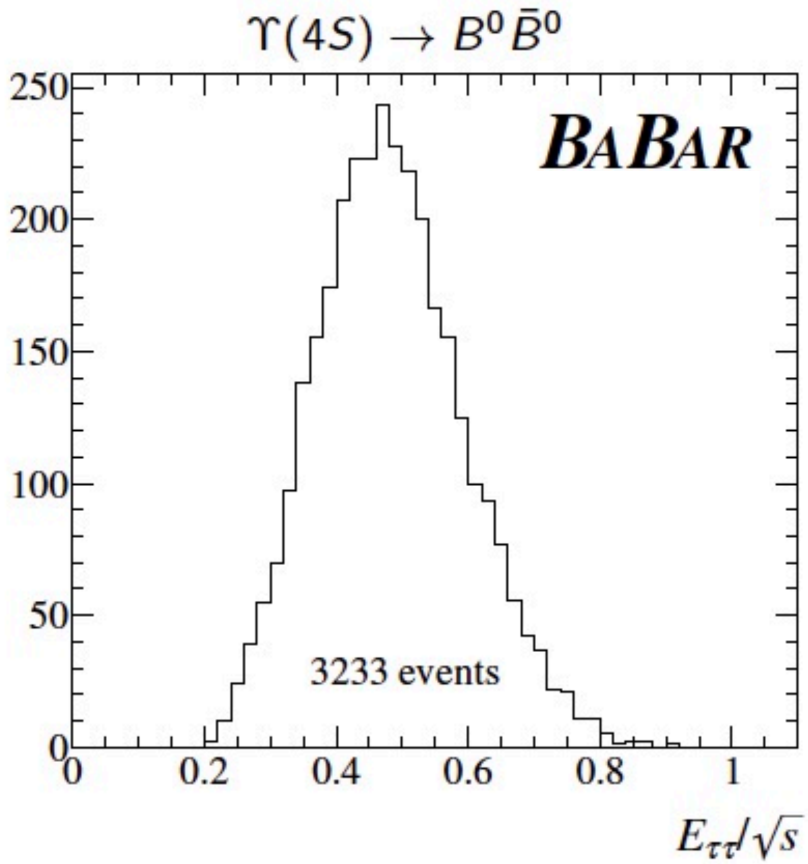


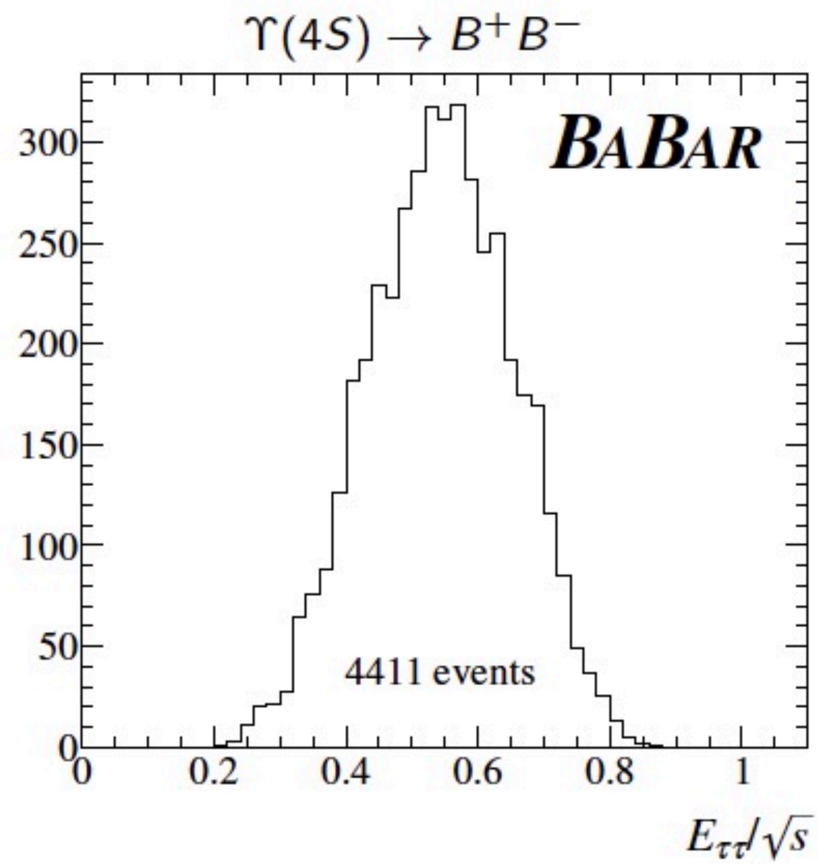


PHOKHARA MC Correction to above formula For soft photon emission

Accounting for $B\bar{B}$ Background

Continuum template uses RUN 6 data at Υ(4S) and low multiplicity B meson decays can contaminate the sample: in MC that is 3x data sample 15 $\mu^+\mu^-$ events and 7644 $\tau^+\tau^-$ events are selected





Results in a δ_{BB} = 0.42% correction to $R_{\tau\mu}$

Data-driven corrections to MC efficiencies

Sample	$\varepsilon_{\mu\mu}$	$\varepsilon_{\tau\tau}$	$\varepsilon_{\tau\tau}/\varepsilon_{\mu\mu}$
MC $\Upsilon(3S)$	69.951 ± 0.018	7.723 ± 0.010	0.11041 ± 0.00015
MC $\Upsilon(3S)$ off peak	49.250 ± 0.017	7.018 ± 0.010	0.14249 ± 0.00021
MC $\Upsilon(4S)$ off peak	48.997 ± 0.016	6.979 ± 0.007	0.14245 ± 0.00015

DATA/MC efficiency correction $\tilde{R}_{\tau\mu} = N_{\tau\tau}/N_{\mu\mu}$

Sample	$N^{\text{data}}_{\mu\mu}$	$N^{\text{MC}}_{\mu\mu}$	$N^{\text{data}}_{\tau\tau}$	$N^{\text{MC}}_{\tau\tau}$	$\tilde{R}^{\text{data}}_{\tau\mu}/\tilde{R}^{\text{MC}}_{\tau\mu}$
$\Upsilon(3S)$ off peak	1,538,569	1,554,208	179,466	178,569	1.0152 ± 0.0030
$\Upsilon(4S)$ off peak	4,422,407	4,398,983	515,067	505,133	1.0143 ± 0.0020
Efficiency correction C_{MC}					1.0146 ± 0.0016

Off-peak DATA

$\tilde{R}_{\tau\mu}(3S) = 0.11665 \pm 0.00029 (0.25\%)$

$\tilde{R}_{\tau\mu}(4S) = 0.11647 \pm 0.00017 (0.15\%)$

$\tilde{R}_{\tau\mu}(4S)/\tilde{R}_{\tau\mu}(3S) - 1 = -0.0015 \pm 0.0029$

Off-peak MC

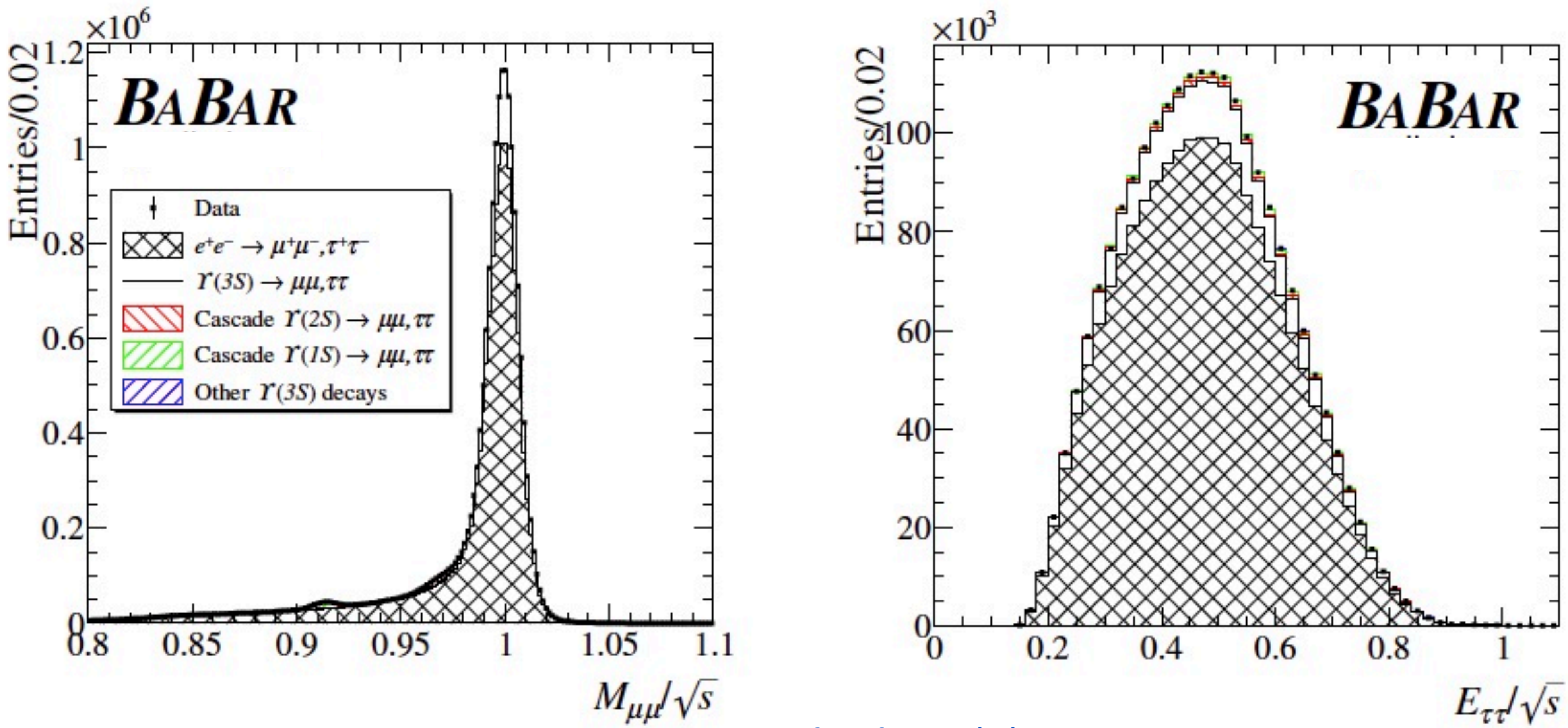
$\tilde{R}_{\tau\mu}(3S) = 0.11489 \pm 0.00018 (0.16\%)$

$\tilde{R}_{\tau\mu}(4S) = 0.11483 \pm 0.00014 (0.13\%)$

$\tilde{R}_{\tau\mu}(4S)/\tilde{R}_{\tau\mu}(3S) - 1 = -0.0006 \pm 0.0020$

Ratio of No. of ττ to μμ candidates is independent of CM Energy in both Data and MC

Final Fit

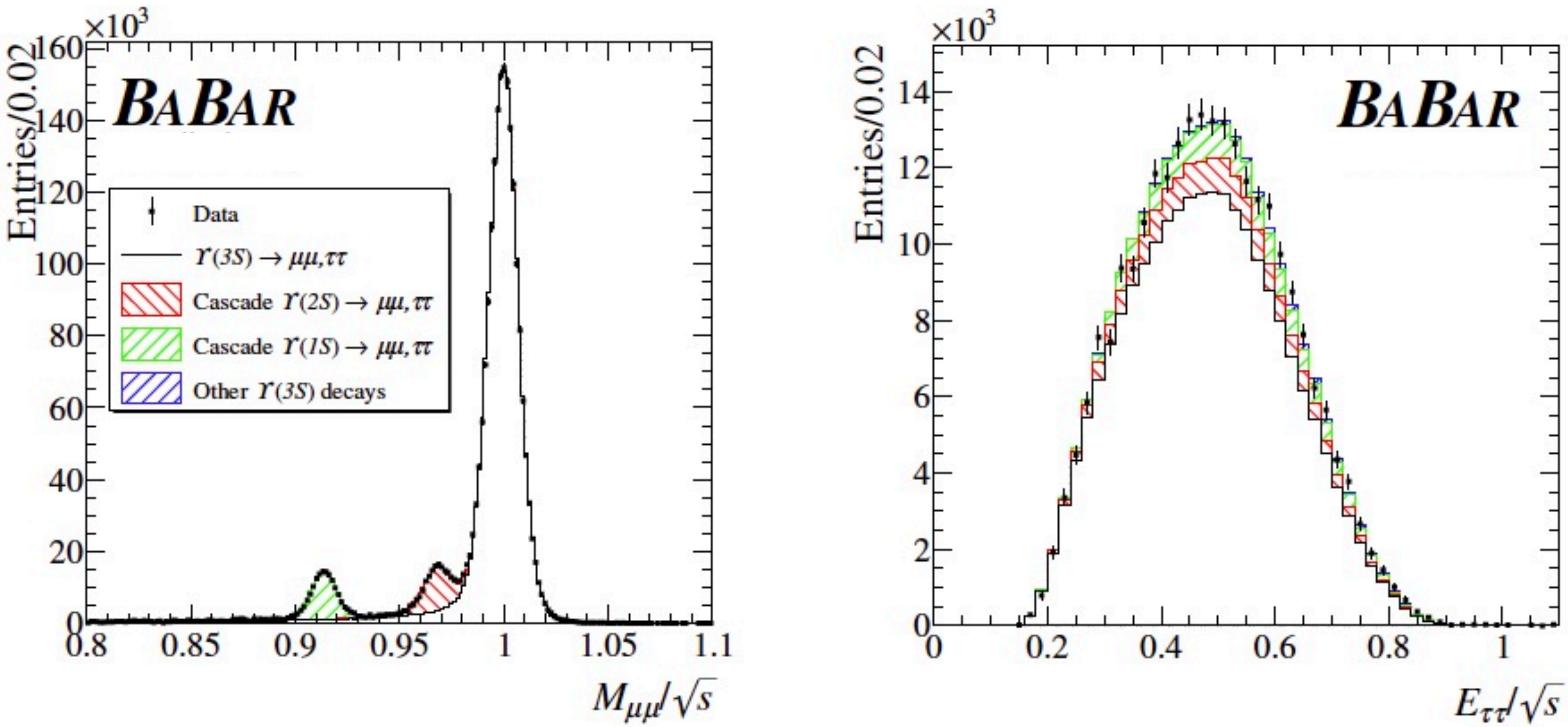


Dominance of the continuum $\Upsilon(3S) \rightarrow \ell^+\ell^-$ is evident

Fit Result: $\tilde{R}_{\tau\mu} = N_{\tau\tau} / N_{\mu\mu} = 0.10778 \pm 0.00091$ (stat)

$$R_{\tau\mu} = \tilde{R}_{\tau\mu} \frac{1}{C_{MC}} \frac{\mathcal{E}_{\mu\mu}}{\mathcal{E}_{\tau\tau}} . (1 + \delta_{BB}) = 0.9662 \pm 0.0084_{stat} \pm 0.014_{syst}$$

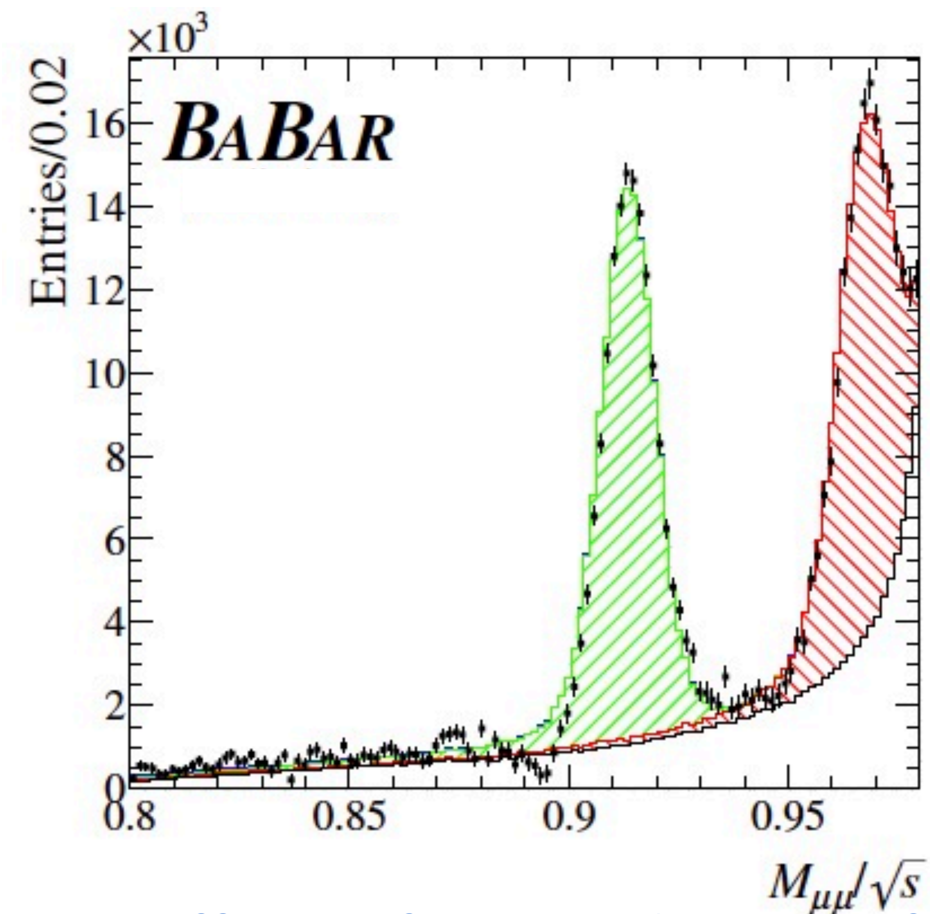
Final Fit with continuum subtracted



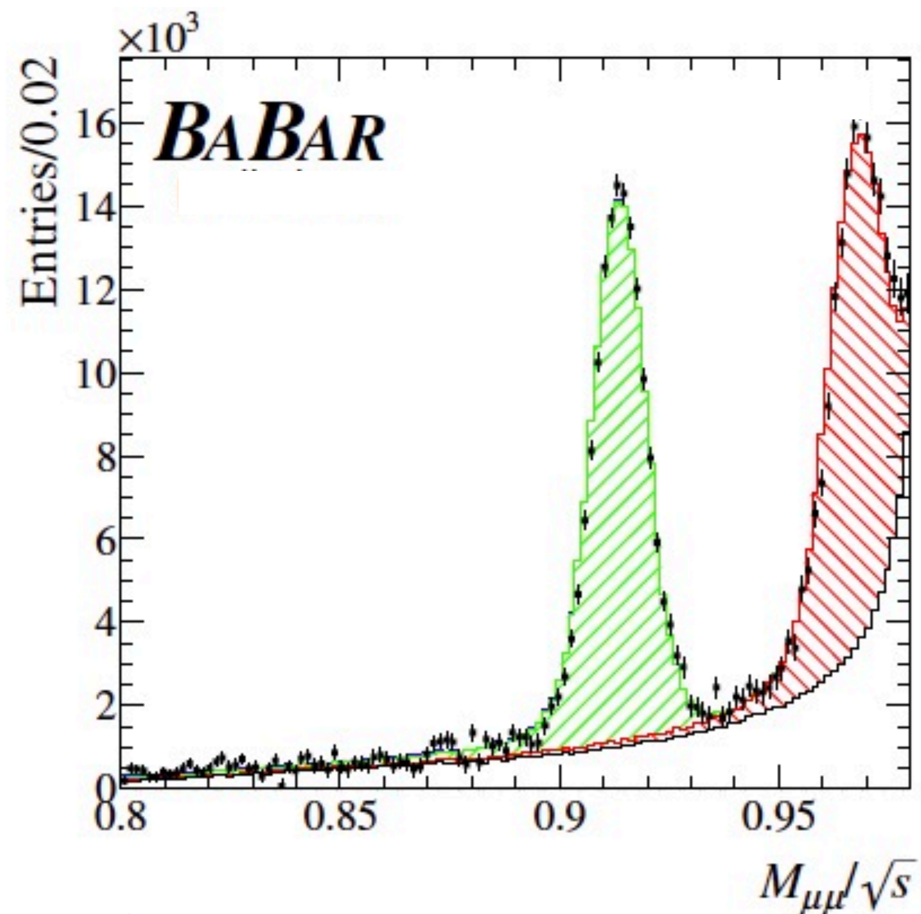
- **'Cascade' backgrounds clearly seen**
- **Radiative tail is very well described**

Final Fit with continuum subtracted

Continuum template is NOT corrected For ISR production of Υ(nS)



Continuum template IS corrected For ISR production of Υ(nS)



Effects of ISR production of ϒ(nS) evident in continuum-subtracted distribution … ϒ (1S) particularly clear

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

- Various particle identification criteria were applied to estimate the PID uncertainty e.g. explicit muon ID. All used data-driven corrections. Error captures spread
- In cascade decays the ratios for lower ϒ resonances were varied within experimental uncertainties around the SM value.
- Two-photon: Various $P_\perp$ selections are applied giving up to twice the loss in efficiency.

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- $B\bar{B}$ and generic $\Upsilon(3S)$ backgrounds conservatively varied by $\pm$50% about nominal MC values
- Possible effects of MC shapes on the ratio: radiative effects are modelled by PHOTOS and KKMC generators separately and the invariant mass resolution is varied up to 10%
- ISR subtraction has uncertainties in $\Upsilon(nS)$ total width and leptonic BR and varying overall amount by $\pm$10% to conservatively account for radiator function uncertainties.

Summary

- $e^+e^- \to \mu^+\mu^-$ sample cleanly selected, with ~0.1% backgrounds
- $e^+e^- \to \tau^+\tau^-$ sample selected with ~1% backgrounds
- A binned likelihood template fit developed to avoid problems with luminosity determination and to account for cascade decays in the ratio
- Correction to continuum template due to background events produced via Radiative Return Process is implemented
- Contribution of $B\bar{B}$ events is evaluated
- Systematic uncertainties are estimated and found to be dominated by particle ID effects

Conclusion

Using a 26.9 fb^{-1} data sample collected at the Υ(3S) and 78.3 fb^{-1} data sample at the Υ(4S) to describe the continuum, *BABAR* measures:

$$R_{\tau\mu} = \frac{\mathcal{B}(\Upsilon(3S)\rightarrow\tau^+\tau^-)}{\mathcal{B}(\Upsilon(3S)\rightarrow\mu^+\mu^-)} = \mathbf{0.9662 \pm 0.0084_{stat} \pm 0.014_{syst}}$$

$$= \mathbf{0.9662 \pm 0.016tot}$$

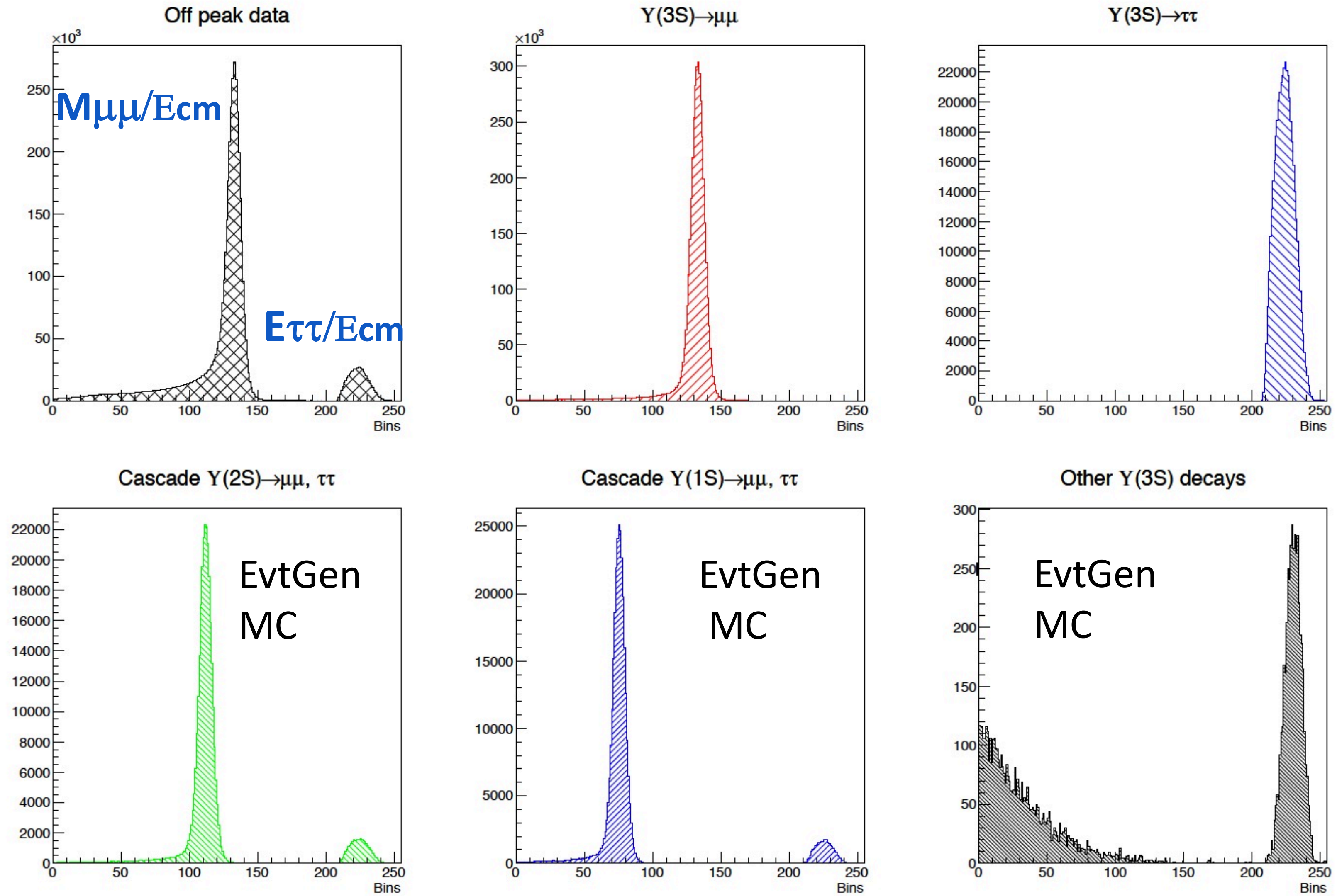
This measurement is 6 x more precise than CLEO's result and is within 2σ of the SM value of 0.9948

paper on this work (arXiv:2005.01230) has been submitted to PRL

Additional Supporting Material

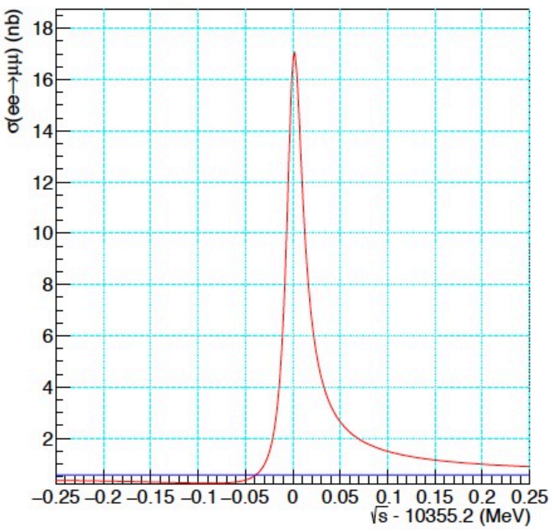
Fitting Templates
(Mμμ/Ecm and Eττ/Ecm displayed in same 1D histo)

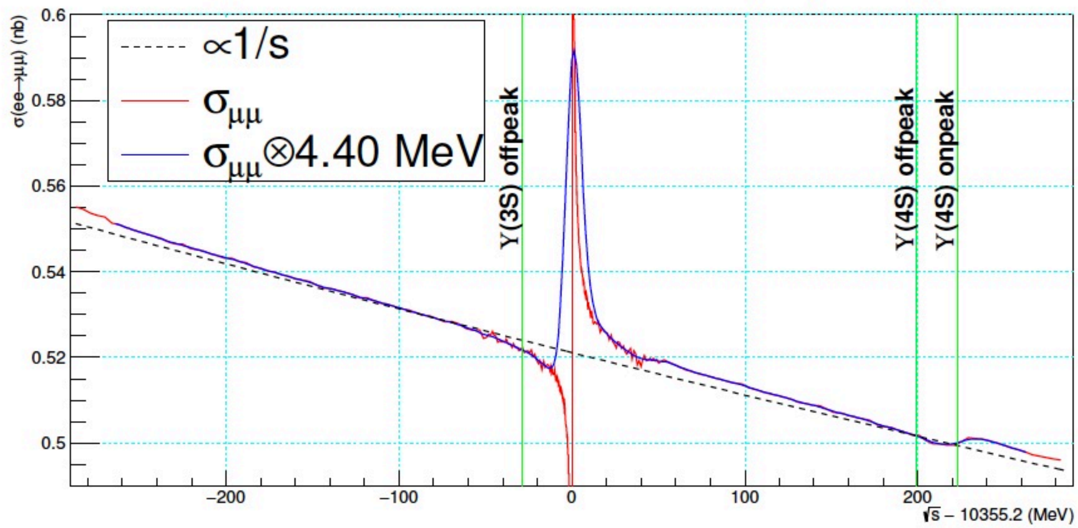
Run 6 Υ(4S) data | Signal μμ MC no ISR | Signal ττ MC no ISR



$e^+e^- \rightarrow \mu^+\mu^-$ Cross section

- MCGPJ, a high precision ($< 0.2\%$) MC generator with radiative corrections where $\Upsilon(nS)$ embedded via vacuum polarization, shows that the resonance production is more than 30 times larger than continuum one at $\Upsilon(3S)$ energy.

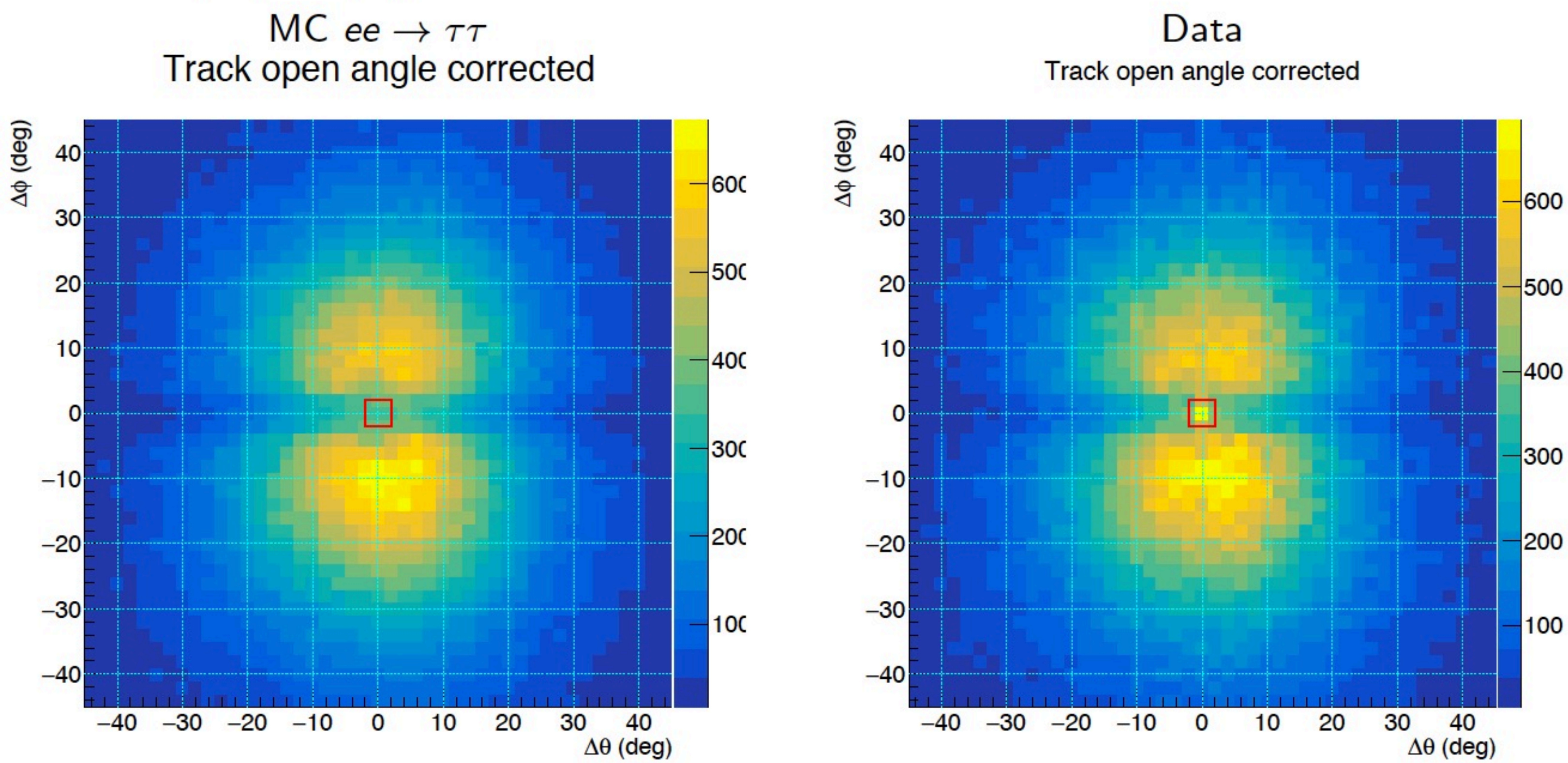




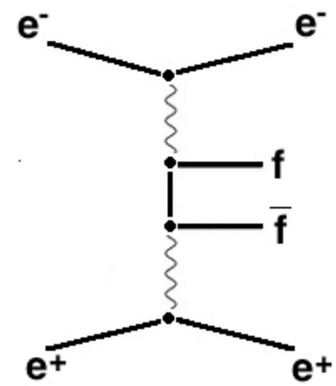
- Due to strong interference between resonance and continuum dilepton production there is an ambiguity in how to extract the leptonic branching fractions.
- In the ratio $R_{\tau\mu}$ the ambiguity is significantly mitigated as well as other factors e.g. instability of the collider interaction energy.
- At the peak $\sigma(ee \to \Upsilon(3S) \to \mu\mu)/\sigma(ee \to \gamma^* \to \mu\mu) = 1.136$ with beam spread.
- Similar continuum cross section of $e^+e^- \to e^+e^-$ is more than 500 times larger than the resonance one $\Rightarrow$ only dimuon decays of $\Upsilon(3S)$ are considered.

$\tau^+\tau^-$ Selection: Bhabha background suppression

To further suppress radiative Bhabha events when a hard photon is emitted at large angle the direction of the electron is corrected using the most energetic photon found in the calorimeter $\vec{P}_{e\gamma} = \vec{P}_e + \vec{P}_\gamma$ to restore collinearity and then reject collinear events: $|\Delta\phi| < 2^\circ$ and $|\Delta\theta| < 2^\circ$ with $\Delta\phi = |\phi(\vec{P}_{e\gamma}) - \phi(\vec{P}_{\not{e}})| - 180^\circ$ and $\Delta\theta = \theta(\vec{P}_{e\gamma}) + \theta(\vec{P}_{\not{e}}) - 180^\circ$

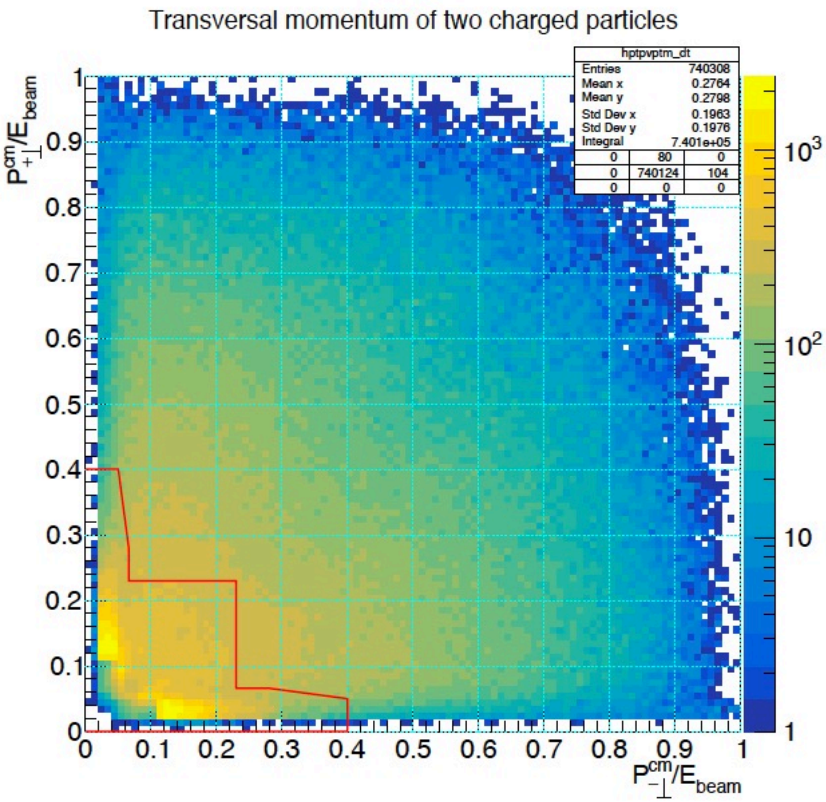


$\tau^+\tau^-$ Selection: 2-photon background suppression

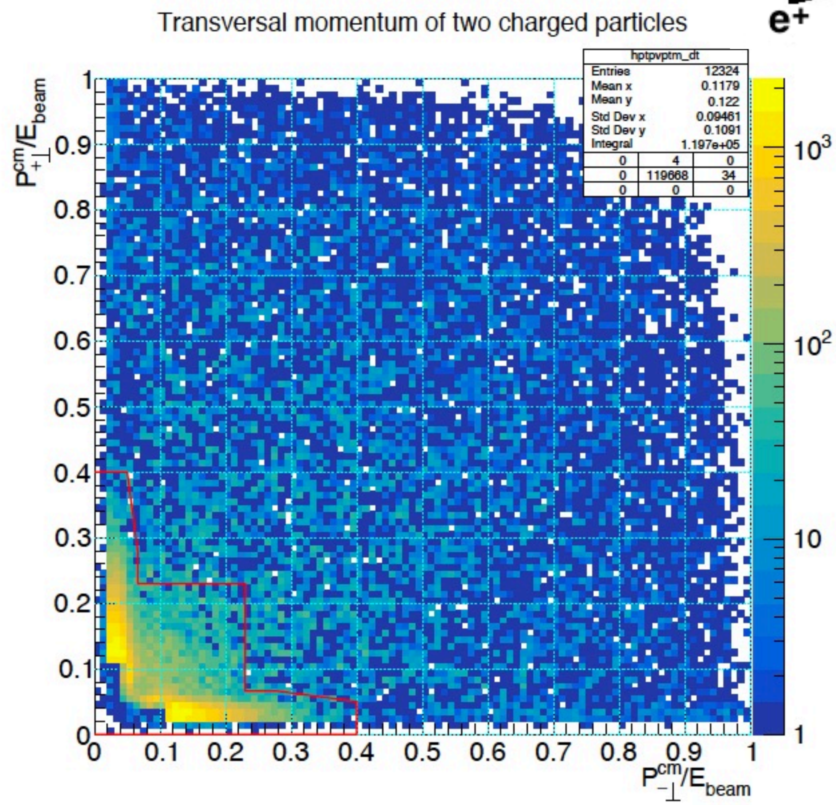


Since momenta of particles of two-photon production are correlated, a two-dimensional selection is applied to maintain good efficiency for signal and reject two-photon background.

Data



Data



Known MC backgrounds are subtracted.