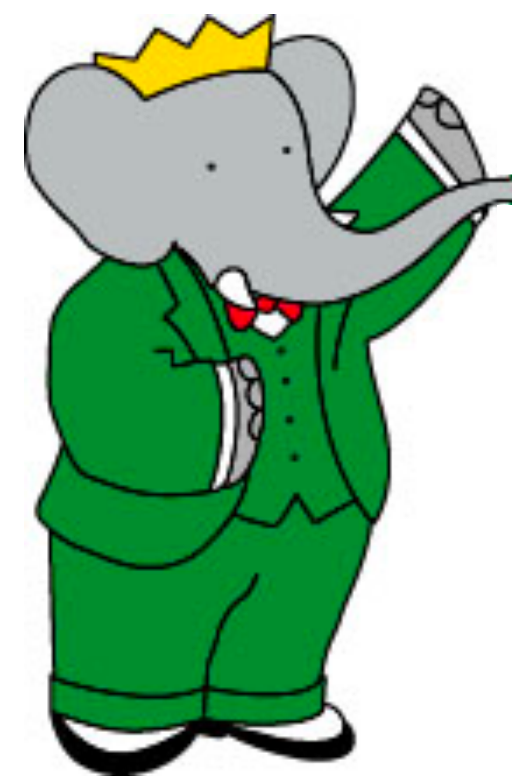
LEPTON FLAVOR UNIVERSALITY IN $\Upsilon(3S)$ DECAYS TO TAU LEPTONS AND MUONS WITH *BABAR*

Based on Lees et al., PRL 125, 241801 (2020)

Brian Shuve

on behalf of *BABAR* Collaboration

HARVEY MUDD COLLEGE



May 24, 2021

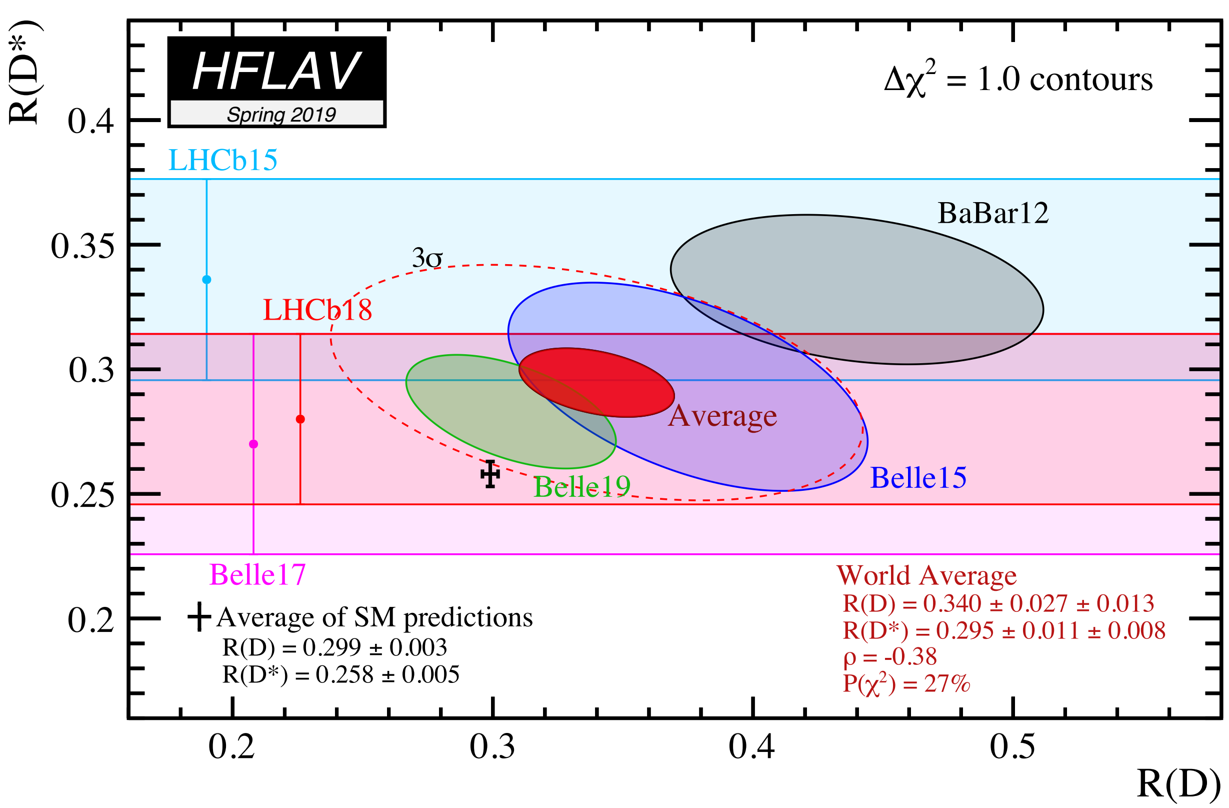
PHENO 2021

TESTS OF LEPTON FLAVOR UNIVERSALITY

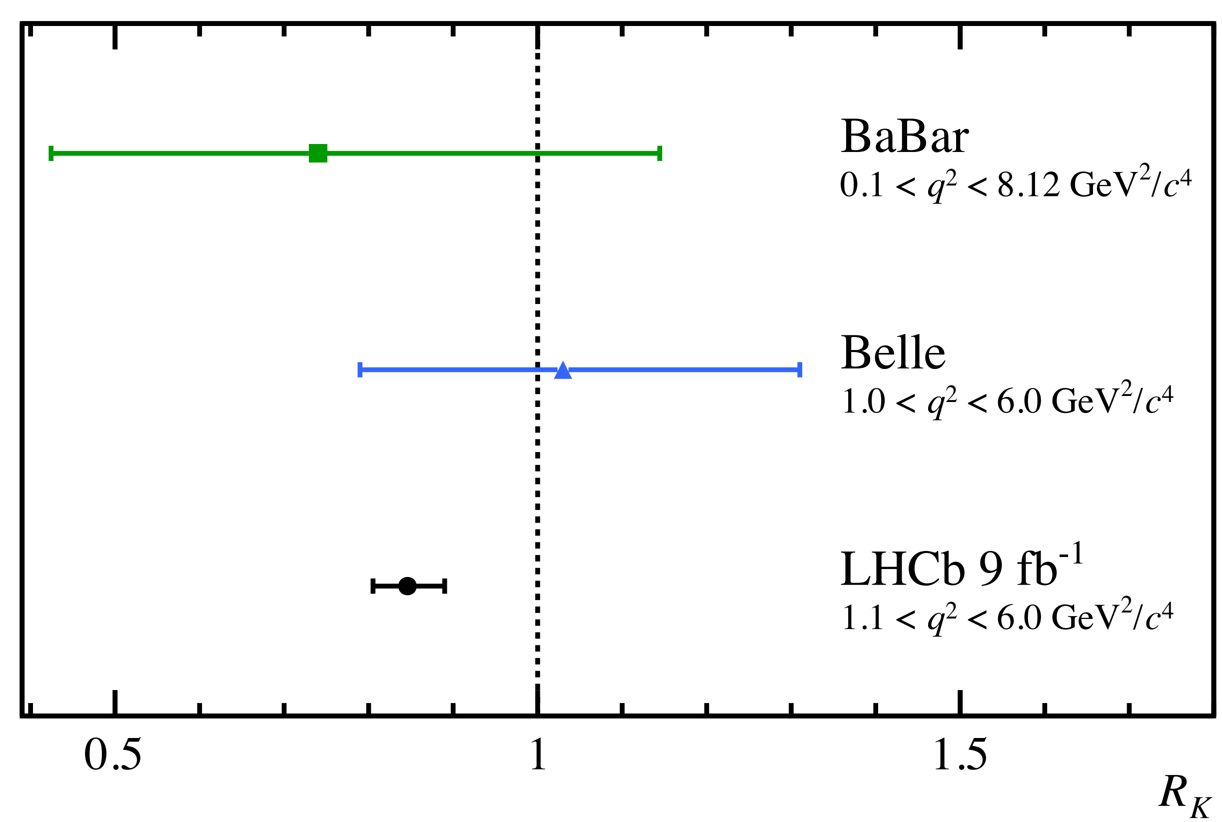
- Recent hints of possible violation of lepton flavor universality in B meson decays

$$\mathcal{R}(D^{(*)}) = \frac{\mathrm{BF}(B \to D^{(*)}\tau\nu)}{\mathrm{BF}(B \to D^{(*)}\ell\nu)} \qquad \mathcal{R}(K^{(*)}) = \frac{\mathrm{BF}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BF}(B \to K^{(*)}e^+e^-)}$$

HFLAV, Eur. Phys. J. C 81, 226 (2021)

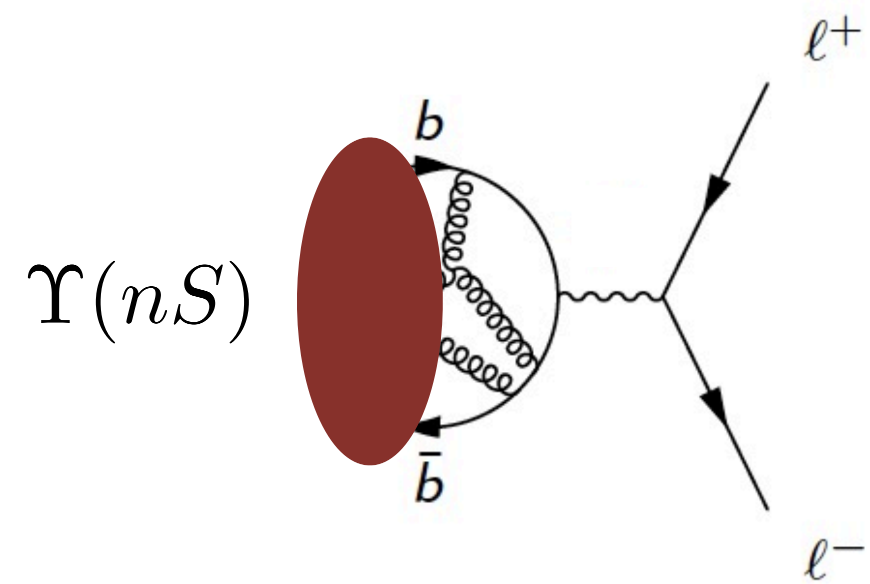


LHCb, arXiv:2103.11769



LEPTON UNIVERSALITY IN Υ DECAYS

- New physics contributions to charged-current semileptonic *B* decays can *also* contribute to neutral-current processes
- Deviations expected at 0.2%-4% level for models motivated by $\mathcal{R}(D^{(*)})$
  Aloni *et al.*, JHEP 06, 019 (2017); García-Duque *et al.*, PRD 103, 073003 (2021)



- Hadronic uncertainties cancel in ratio:

$$\mathcal{R}_{\tau\mu}^{\Upsilon(nS)} = \frac{\mathrm{BF}(\Upsilon(nS) \to \tau^+\tau^-)}{\mathrm{BF}(\Upsilon(nS) \to \mu^+\mu^-)}$$

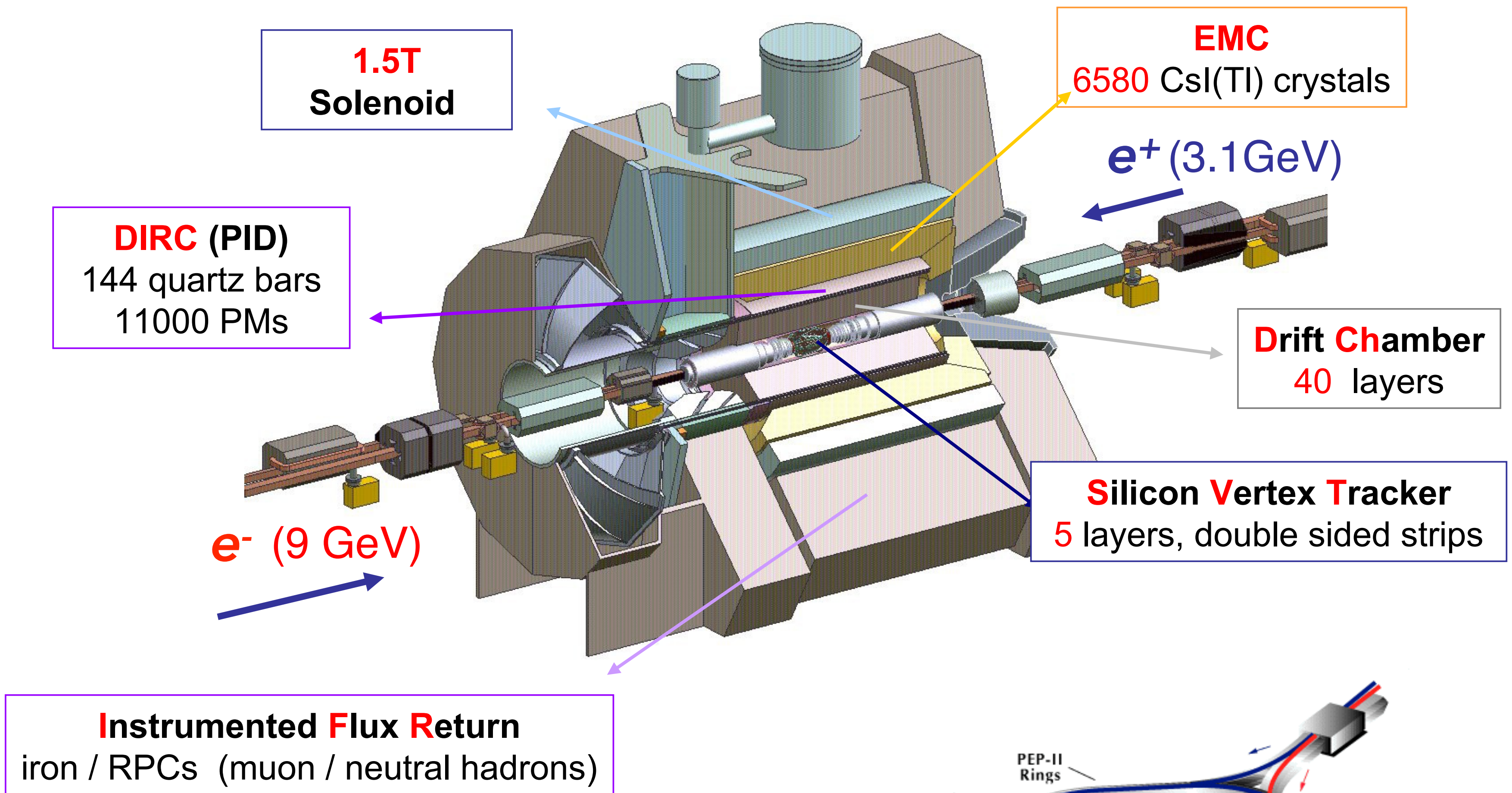
$$\mathcal{R}_{\tau\mu}^{\Upsilon(1S)} = \begin{cases} \text{BABAR-10: } 1.005 \pm 0.013 \pm 0.022 \\ \text{SM: } 0.9924 \end{cases}$$

$$\mathcal{R}_{\tau\mu}^{\Upsilon(2S)} = \begin{cases} \text{CLEO-07: } 1.04 \pm 0.04 \pm 0.05 \\ \text{SM: } 0.9940 \end{cases}$$

this talk

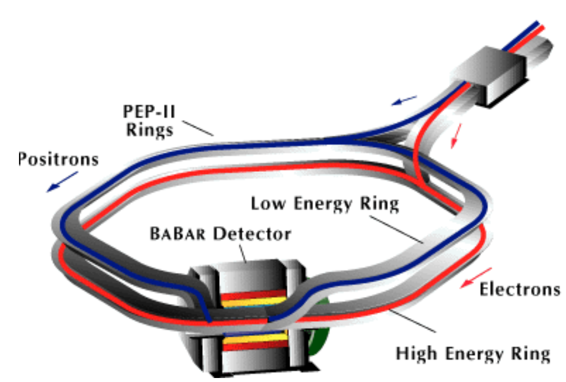
$$\mathcal{R}_{\tau\mu}^{\Upsilon(3S)} = \begin{cases} \text{CLEO-07: } 1.05 \pm 0.08 \pm 0.05 \\ \text{SM: } 0.9948 \end{cases}$$

BaBar EXPERIMENT



- 529/fb data collected at $\Upsilon(2S)/\Upsilon(3S)/\Upsilon(4S)$ and off-peak
- We use 27.96/fb at $\Upsilon(3S)$, 78.3/fb at $\Upsilon(4S)$, and 10.37/fb off-peak

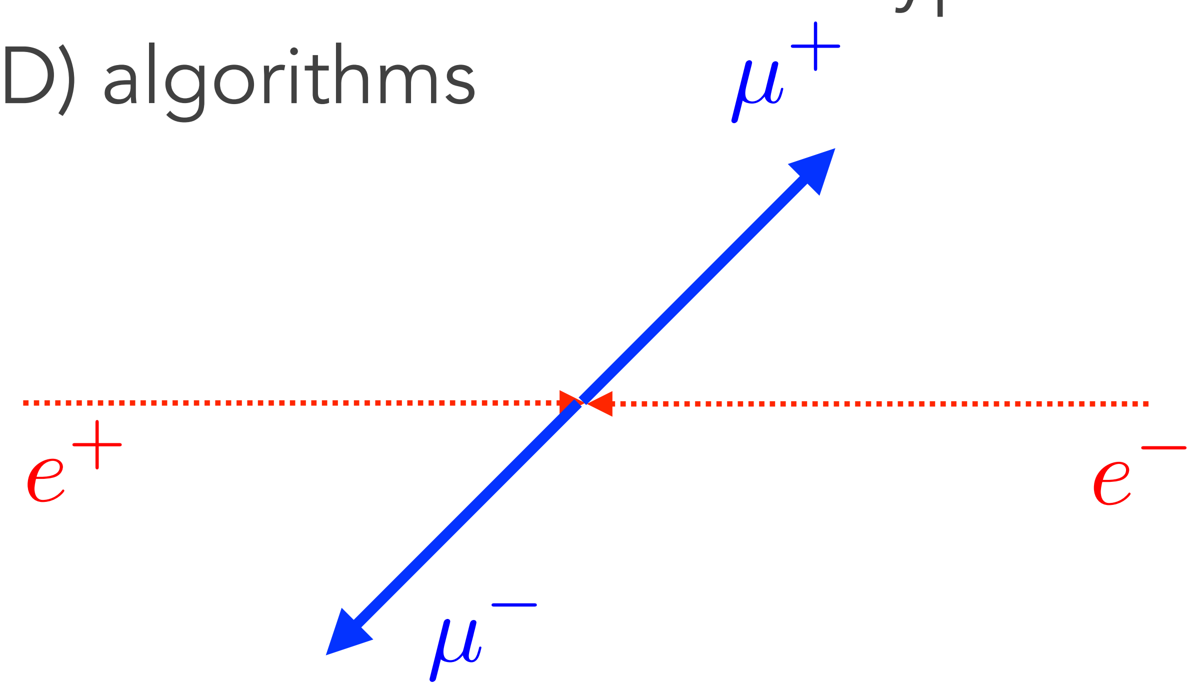
1999-2008



- Blind analysis strategy: use 9% of $\Upsilon(3S)$ dataset as optimization sample used to determine analysis method, discard for final results

DIMUON SAMPLE

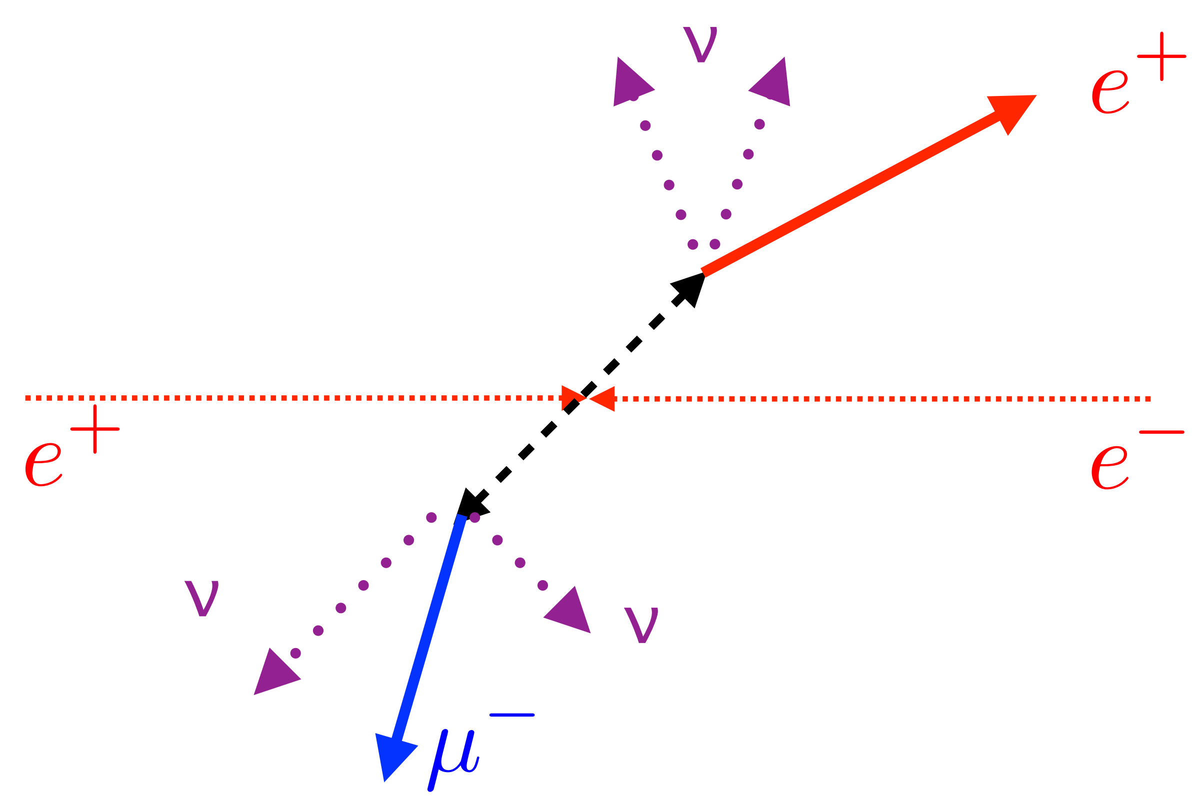
- Only 2 oppositely charged particles in the event, back-to-back (< 20°) in center-of-mass (CM) frame
- Dimuon mass most of CM collision energy, $0.8 < M_{\mu\mu}/\sqrt{s} < 1.1$
- At least one track consistent with muon hypothesis using particle identification (PID) algorithms



- These selections are sufficient to obtain **99.9% purity**

DITAU SAMPLE

- Only 2 oppositely charged, roughly back-to-back in CM (< 70°) particles in the event, large transverse momentum
- Tracks are acollinear in CM (> 3°) *and* (electron+most energetic photon) must be acollinear with other track (> 2°)
- One track passes electron PID, the other one fails electron PID
- Missing momentum within detector acceptance, missing mass exceeds 10% of CM energy, restrictions on total calo energy
- **Purity of 99%**



EFFICIENCY CORRECTIONS

- Off-peak samples in the vicinities of $\Upsilon(3S)$, $\Upsilon(4S)$ are used to determine relative efficiencies of muon/tau, and to derive data/MC corrections

- $N_{\tau\tau}/N_{\mu\mu} = 0.11665 \pm 0.0017$ at $\Upsilon(4S)$, 0.11647 ± 0.0029 at $\Upsilon(3S)$

- $N_{\tau\tau}/N_{\mu\mu}$ is independent of energy in both data and MC

- Data/MC ratios also independent of energy (from known continuum dilepton cross sections):

$$\frac{(\varepsilon_{\tau\tau}/\varepsilon_{\mu\mu})_{\mathrm{data}}}{(\varepsilon_{\tau\tau}/\varepsilon_{\mu\mu})_{\mathrm{MC}}} = 1.0146 \pm 0.0016$$

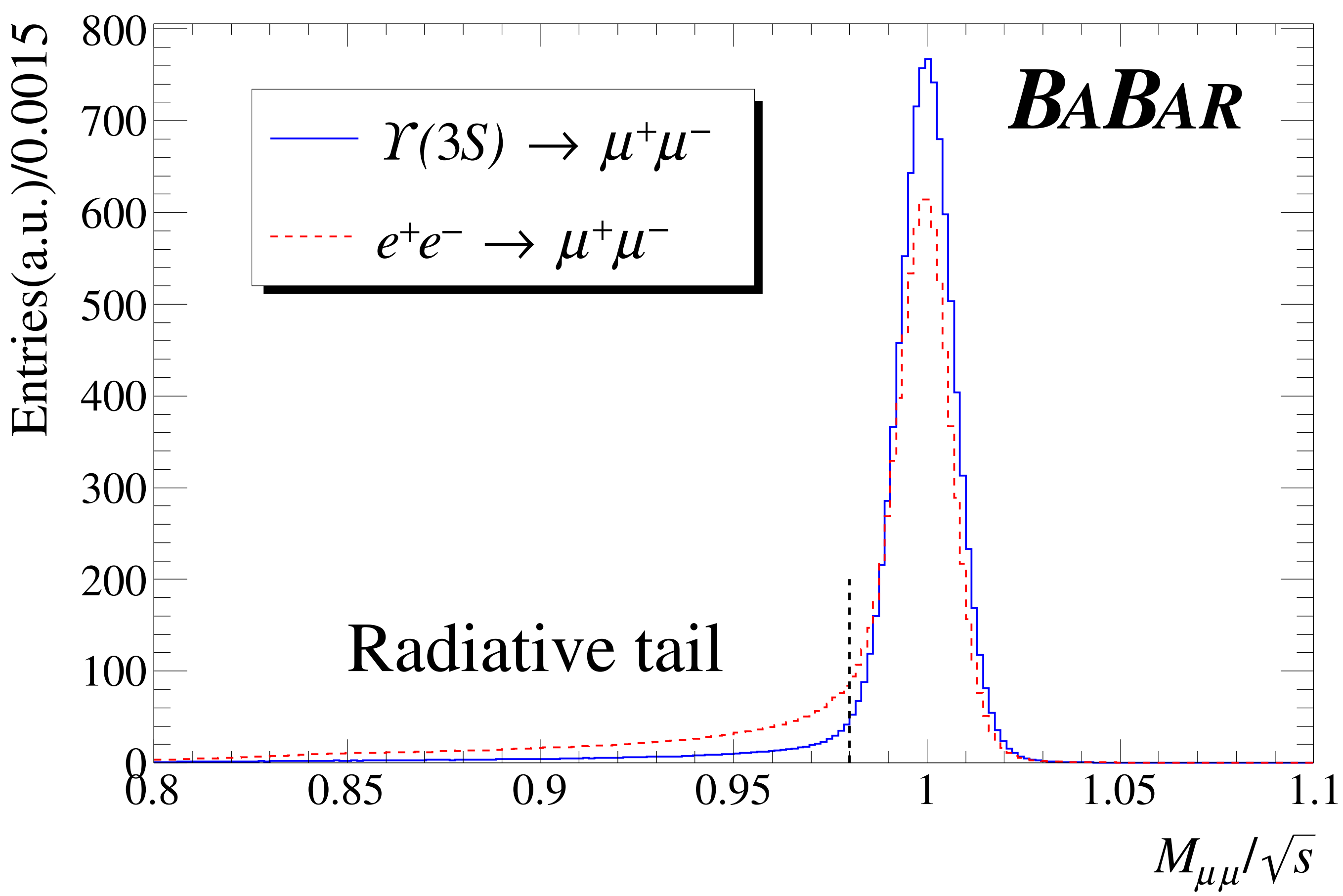
DISTINGUISHING CONTINUUM

- Need to distinguish $\Upsilon(3S) \to \ell^+\ell^-$ from continuum $\ell^+\ell^-$

- Continuum dilepton sample has more significant tail from ISR

- Radiative tail only visible in dimuon sample

- Fix relative muon/tau contribution in continuum and simultaneously fit both $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$



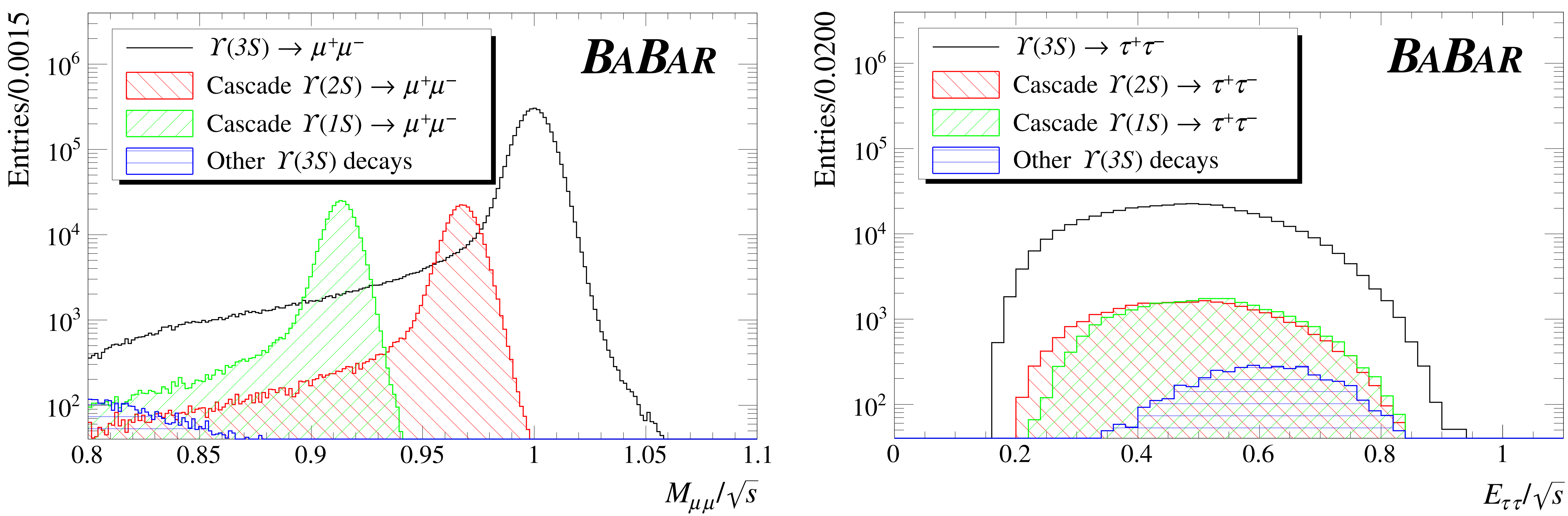
COMPONENTS FOR FIT

- Signal template taken from MC
- Continuum template taken Run6 on-peak $\Upsilon(4S)$ sample (78/fb), which has negligible leptonic BF
- Radiative return production of $\Upsilon(1S)/\Upsilon(2S)/\Upsilon(3S)$ at 10.58 GeV is estimated & subtracted from continuum template
- There is a small contamination of low-multiplicity $B\overline{B}$ in tau continuum sample at $\Upsilon(4S)$ energy
  - We leave template as-is, but apply 0.42% correction to tau rate obtained from fit

CASCADE & HADRONIC BKDS

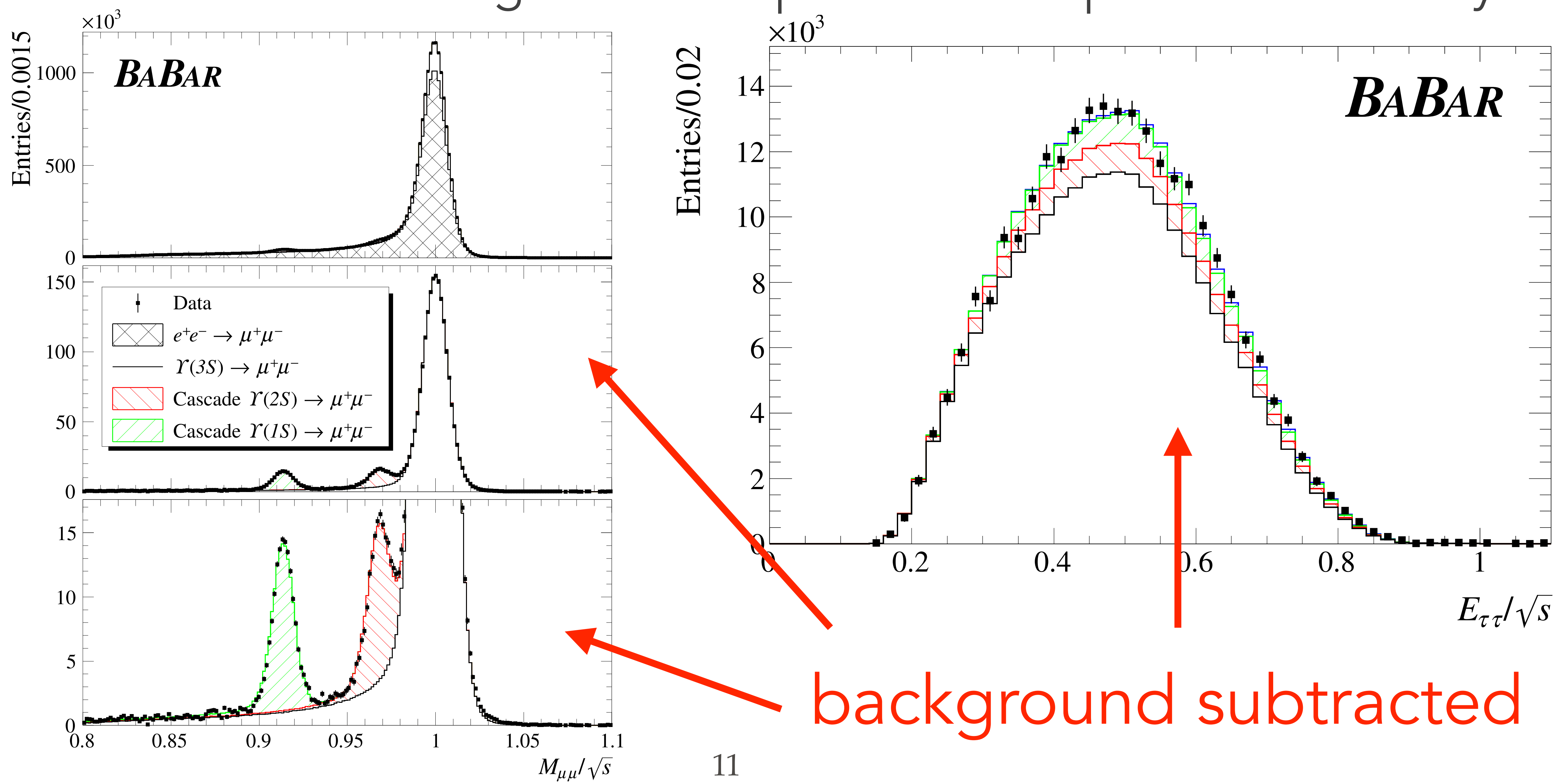
- Other backgrounds include cascade decays $\Upsilon(3S) \to \Upsilon(nS) + X$, $n = 1, 2$ and hadronic decays that nevertheless pass dilepton selections

- These templates are taken from MC (EvtGen)



$\Upsilon(3S) \to \ell^+\ell^-$ EXTRACTION

- Binned maximum-likelihood template fit to $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$
- $N_{\mu\mu}$ and the ratio $N_{\tau\tau}/N_{\mu\mu}$ are free parameters, as are normalizations of background components except hadronic decays



SYSTEMATIC UNCERTAINTIES

- Dominant PID uncertainty comes from varying electron PID requirements used
- Relax assumption of LFU in cascade decays, error captures spread

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

- Vary selections on track transverse momentum to eliminate two-photon production, difference in result taken as uncertainty
- Hadronic backgrounds varied by 50% to assess systematic
- MC shape: compare results of different generators (EvtGen+PHOTOS vs. KKMC) and vary signal resolution
- ISR: vary subtraction by 10% to account for uncertainties in radiative return, vary masses/widths within PDG values

RATIO OF BRANCHING FRACTIONS

$$\mathcal{R}_{\tau\mu} = \frac{N_{\tau\tau}}{N_{\mu\mu}} \frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}} (1 + \delta_{B\overline{B}}) = 0.9662 \pm 0.0084_{\text{stat}} \pm 0.014_{\text{syst}}$$

BaBar, PRL 125, 241801 (2020)

$$\mathcal{R}_{\tau\mu}^{\Upsilon(3S)}(\text{SM}) = 0.9948$$

- Total uncertainty of 0.016, 6x more precise than CLEO
- Agreement with SM at level of 2σ

SUMMARY

$$\mathcal{R}_{\tau\mu}^{(3S)} = \frac{\text{BF}(\Upsilon(3S) \to \tau^+\tau^-)}{\text{BF}(\Upsilon(3S) \to \mu^+\mu^-)} = 0.9662 \pm 0.0084_{\text{stat}} \pm 0.014_{\text{syst}}$$

- High-purity dimuon and ditau samples at *BABAR* allow precise measurement of ratio of $\Upsilon(3S)$ BFs to taus and muons
- New method using radiative tail on dimuon distribution allows separation of signal and continuum backgrounds
- Factor of 6 improvement over previous measurement at CLEO
- Agrees with the SM value of 0.9948 at the 2σ level
- *BABAR* still producing leading flavor results 12 years after end of data taking!

BACKUP SLIDES

THEORY PREDICTIONS

TABLE III: *The simplified (single boson) models and the predicted range for $R^V_{\tau/\ell}$ for $V = \Upsilon(1S), \psi(2S)$. The achievable and projected uncertainties are our estimations, see the text for more details.*

UV field content	$R^{\Upsilon(1S)}_{\tau/\ell}$	$R^{\psi(2S)}_{\tau/\ell}$	Predicted modification to $R^{\Upsilon(1S)}_{\tau/\ell}$
$W'_\mu \sim (1,3)_0$	0.989-0.991	0.390	Decrease by $0.2\% - 0.4\%$
$U_\mu \sim (3,1)_{+2/3}$	0.952-0.990	SM	Decrease by $0.3\% - 4.0\%$
$S \sim (3,1)_{-1/3}$	SM	0.389-0.390	–
$V_\mu \sim (3,2)_{-5/6}$	0.976-0.987	SM	Decrease by $0.5\% - 1.6\%$
SM	0.992	0.390	
Current measurement	1.005 ± 0.025	0.39 ± 0.05	
Achievable uncertainty (with current data)	± 0.01	± 0.02	
Projected uncertainty ($\mathcal{L}^{\Upsilon(3S)} = 1/\text{ab}$ in Belle II)	± 0.004	–	

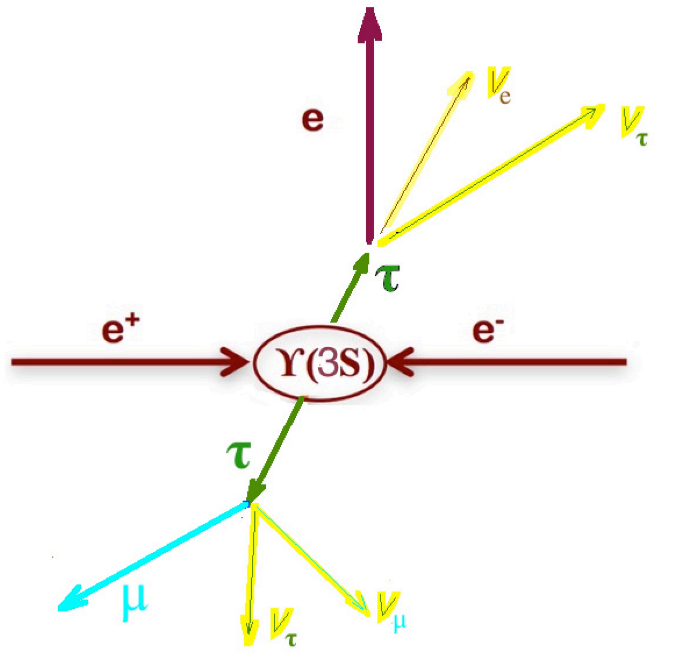
Aloni *et al.*, JHEP 06, 019 (2017)

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

2.17×10^6 ττ candidates
Purity = 98.9%

$\tau_1 \to e\,\nu\nu$, $\tau_2 \to \mu\,\nu\nu$ || $h\,n\pi^0\,\nu$ 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^o
- 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

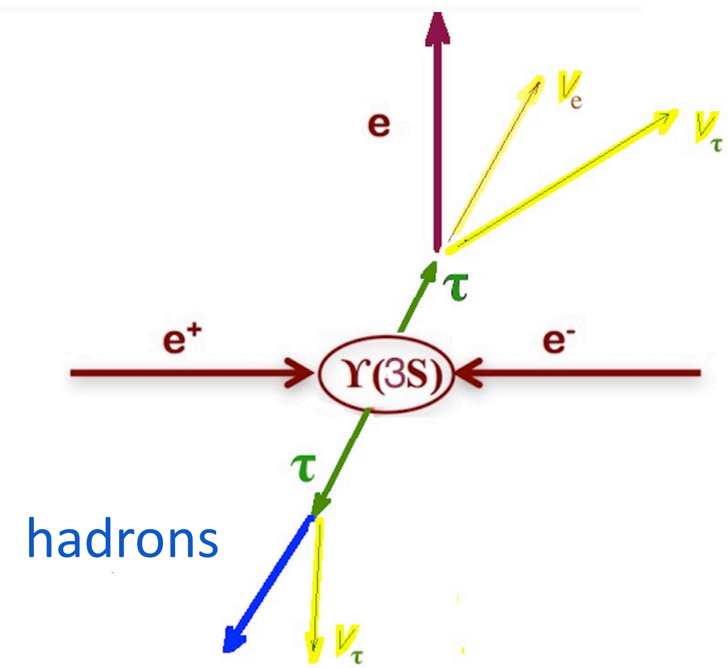
- Track azimuthal acollinearity > 3^o
- Total calorimeter energy < 0.70 x $[E_{beam}(e-)+E_{beam}(e+)]$
- $|M^2_{MISS}| > 0.01 \times E^2_{cm}$
- $|\cos\theta^{CM}{}_{MISS}| < 0.85$

Suppress Bhabha backgrounds

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

Suppress of Two-photon backgrounds

- Cuts on transverse momenta of the two tracks



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

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

Two High Momentum Back-to-Back Charged Particles

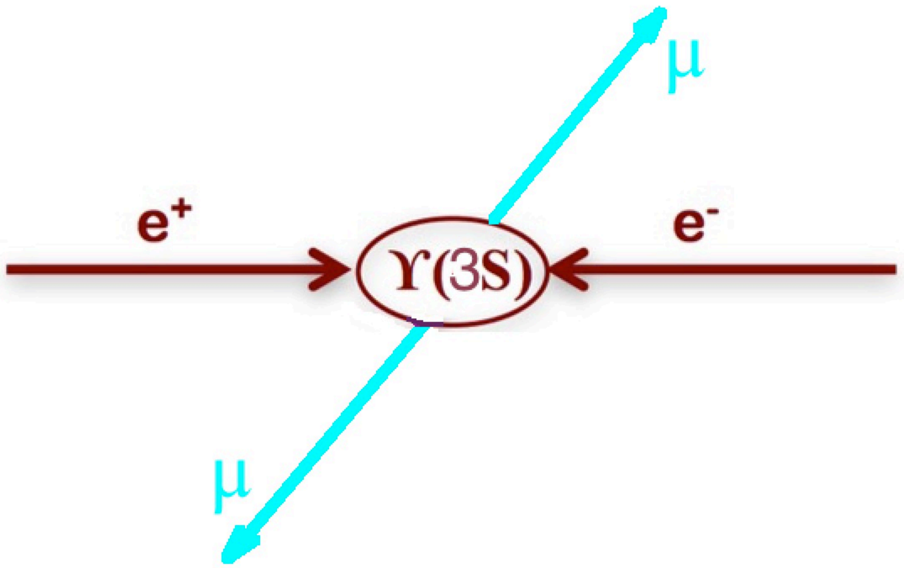
- Two and only two opposite charged charged particles
  each within polar angle acceptance designed to be insensitive to CM energy:
  0.65 rad $< \theta^{CM}(-) < 2.5$ rad && 0.58 rad $< \theta^{CM}(+) < 2.56$ rad
- CM opening angle between charged particles > 160^o
- CM polar angle back-to-back in Filter: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

Invariant mass of two charged particles near CM energy

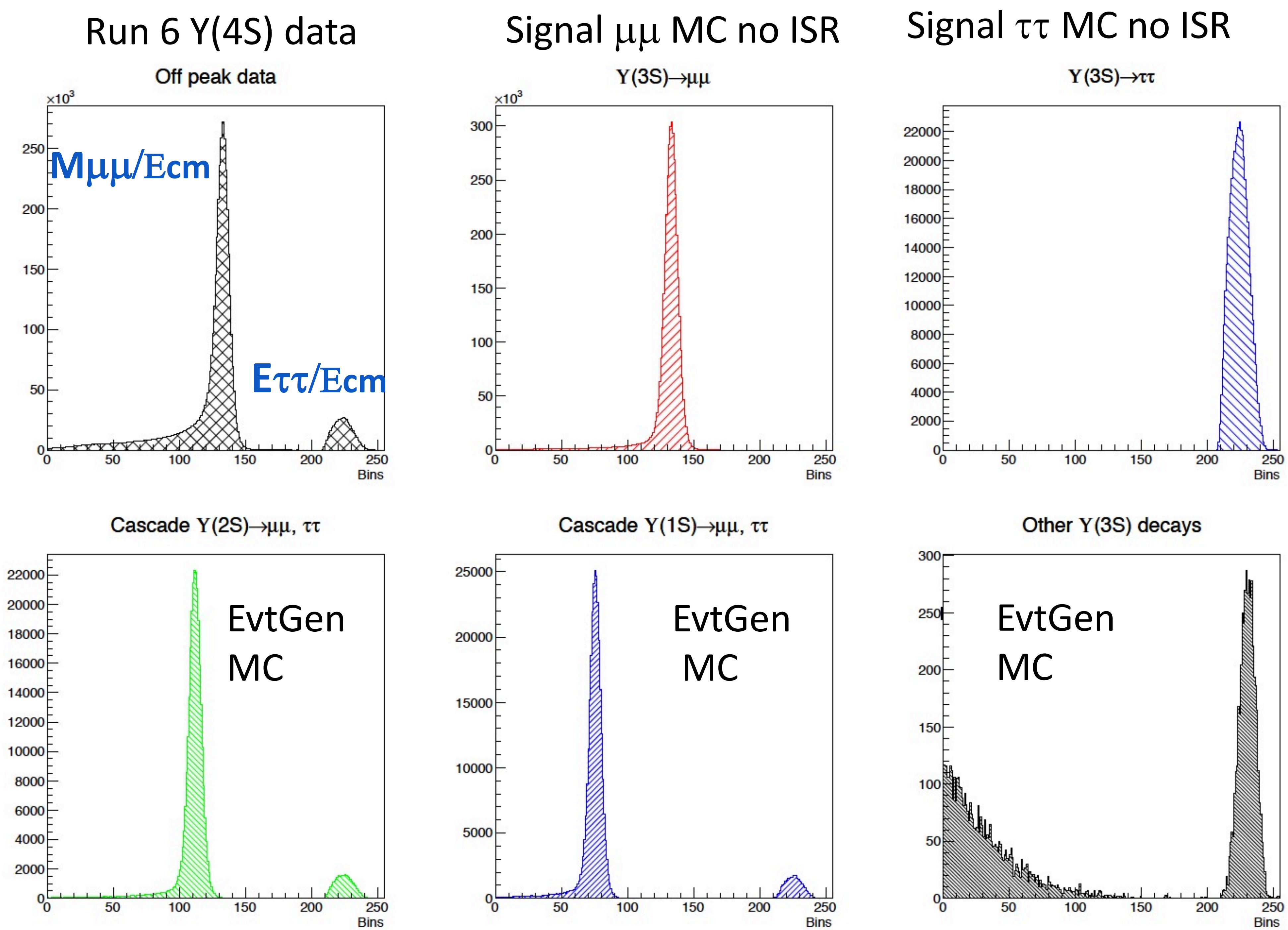
- $0.8 < M_{\mu\mu}/E_{cm} < 1.1$

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)

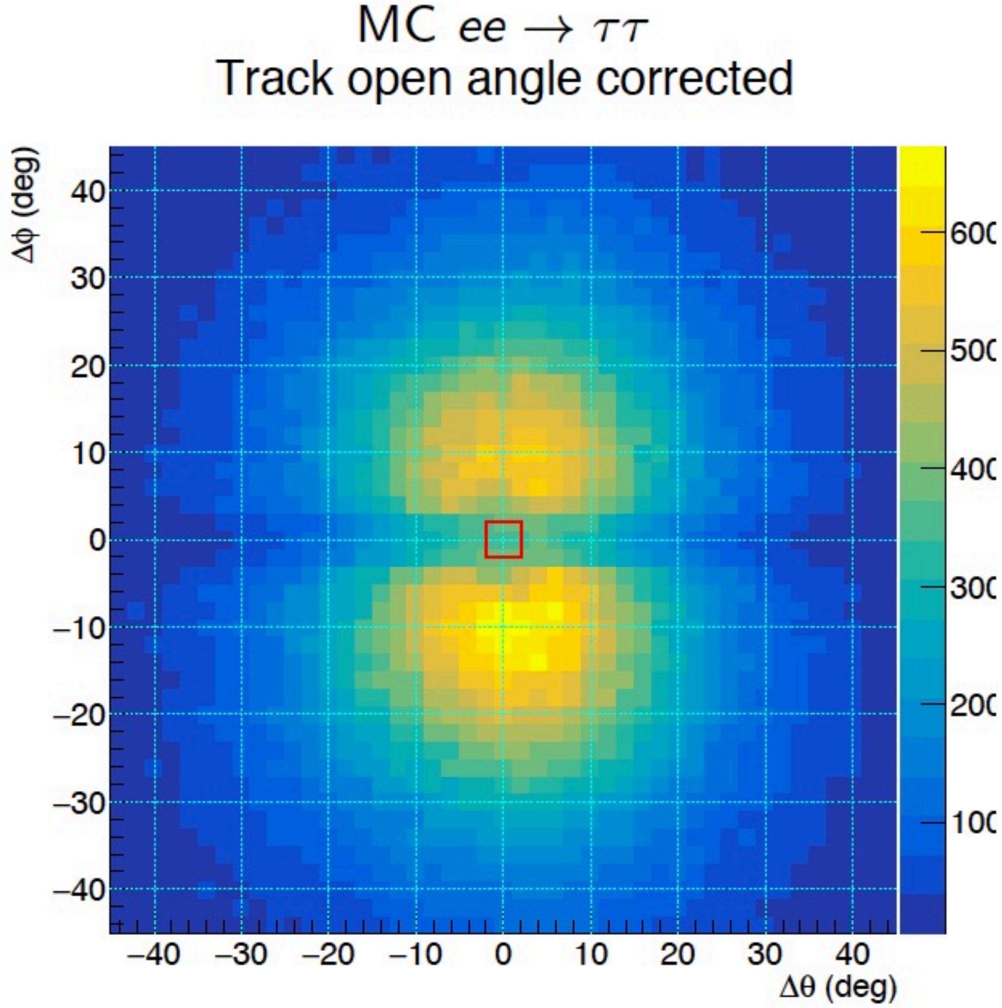


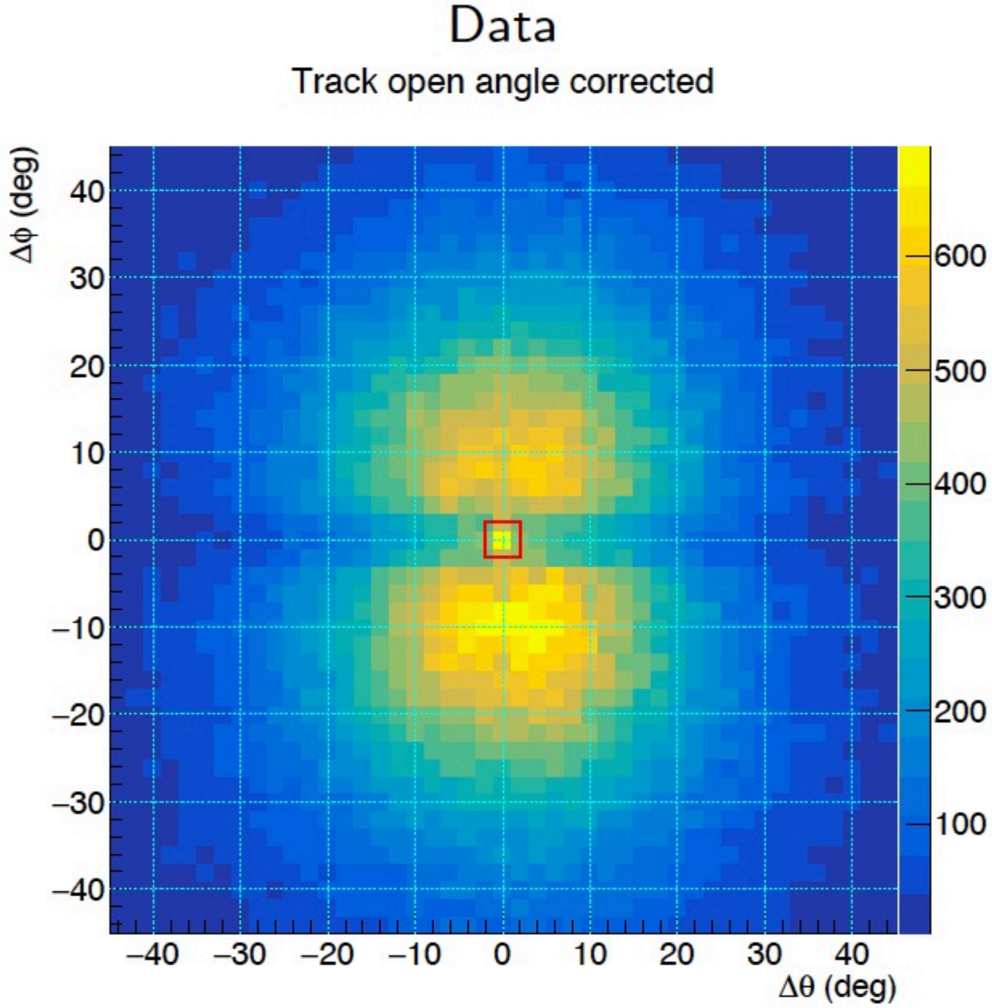
FITTING TEMPLATES



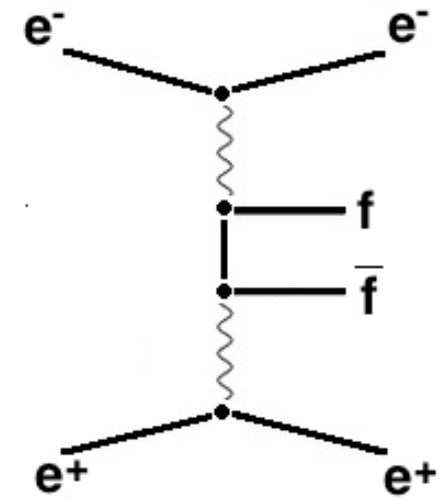
$\tau^+\tau^-$ Selection: Bhabha background suppression

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 $\Delta\phi = |\phi(\vec{P}_{e\gamma}) - \phi(\vec{P}_{\not{\phi}})| - 180^\circ$ and $\Delta\theta = \theta(\vec{P}_{e\gamma}) + \theta(\vec{P}_{\not{\phi}}) - 180^\circ$



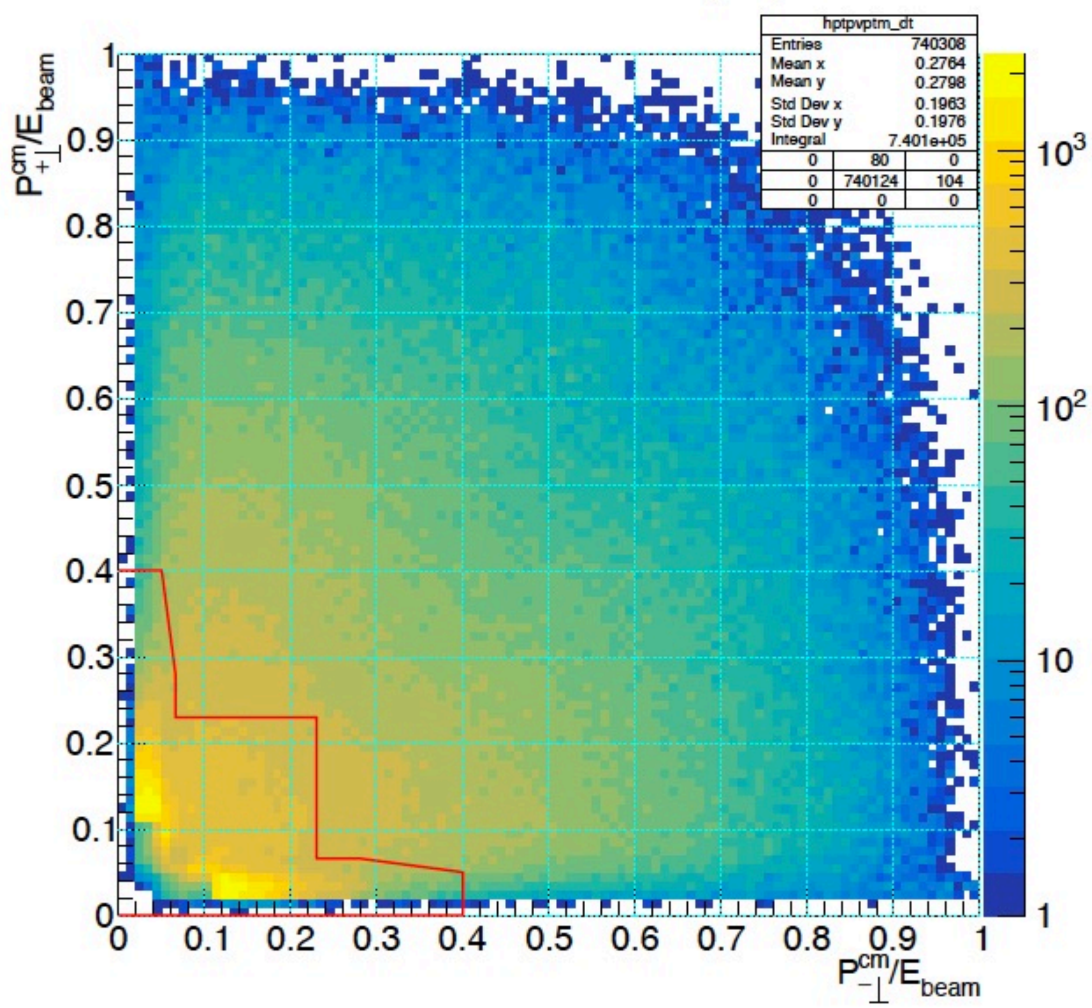


$\tau^+\tau^-$ Selection: 2-photon background suppression

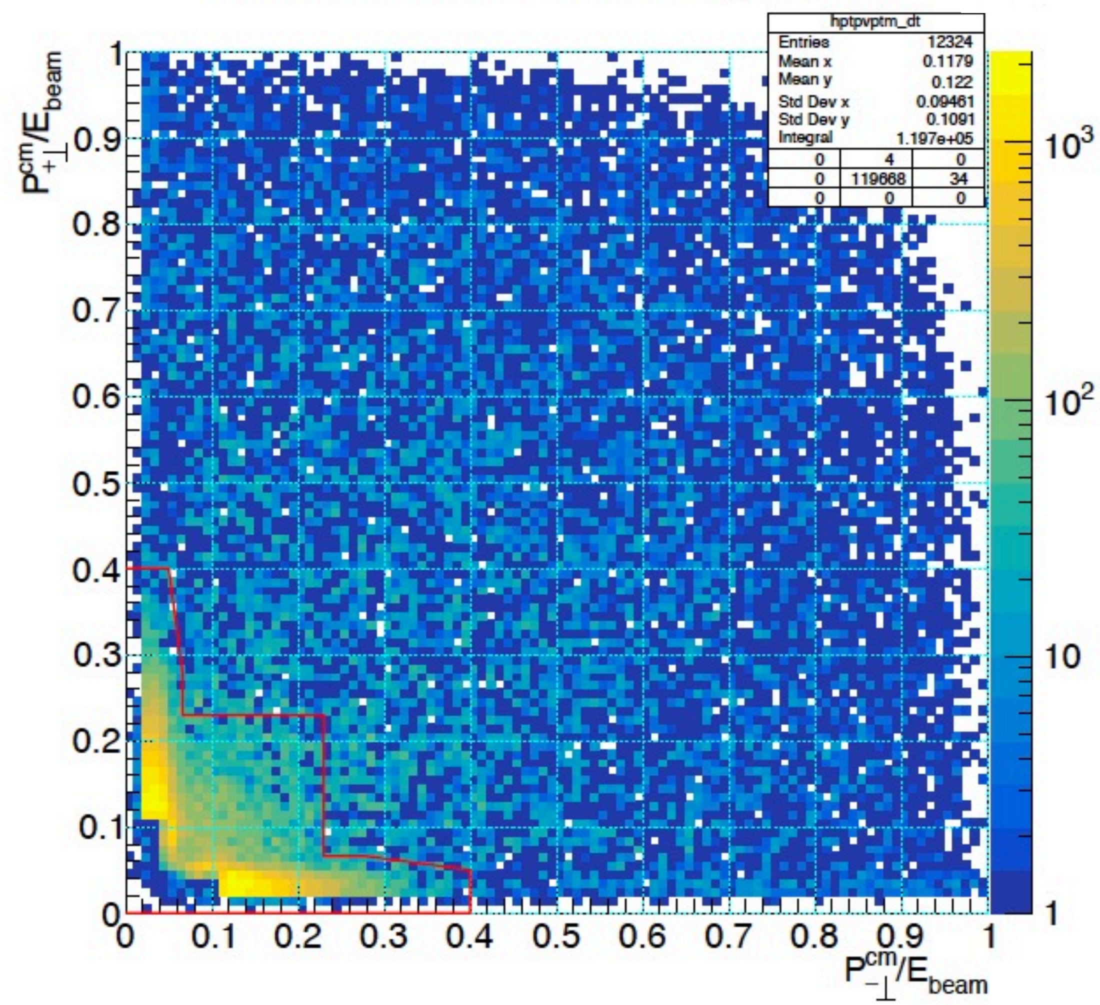


Since momenta of particles of two-photon production are correlated, a two-dimensional selection is applied to maintain good efficiency for signal and reject two-photon background.

Data



Data



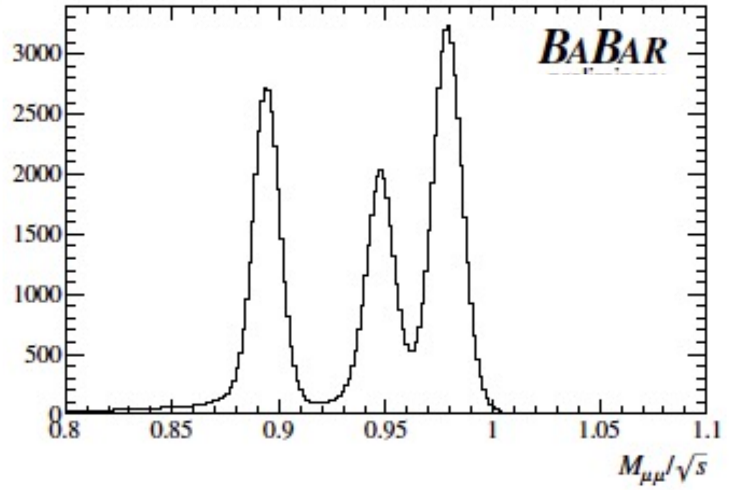
Known MC backgrounds are subtracted.

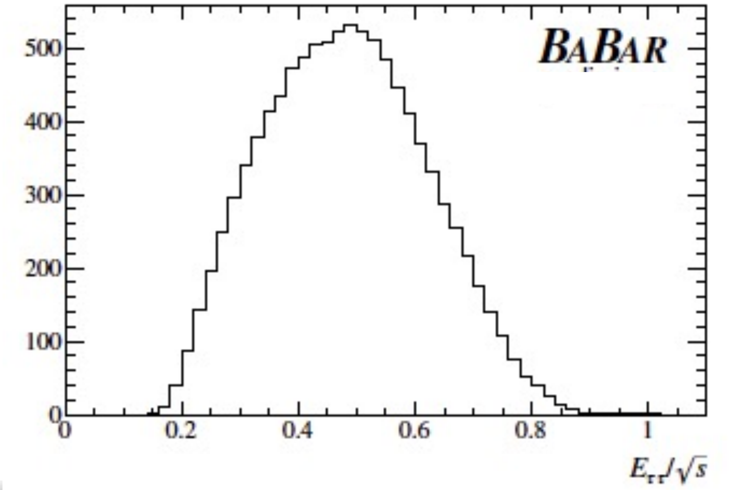
Correct for ISR-produced ϒ(nS) in ϒ(4S) Data
Templates intended to describe Continuum only

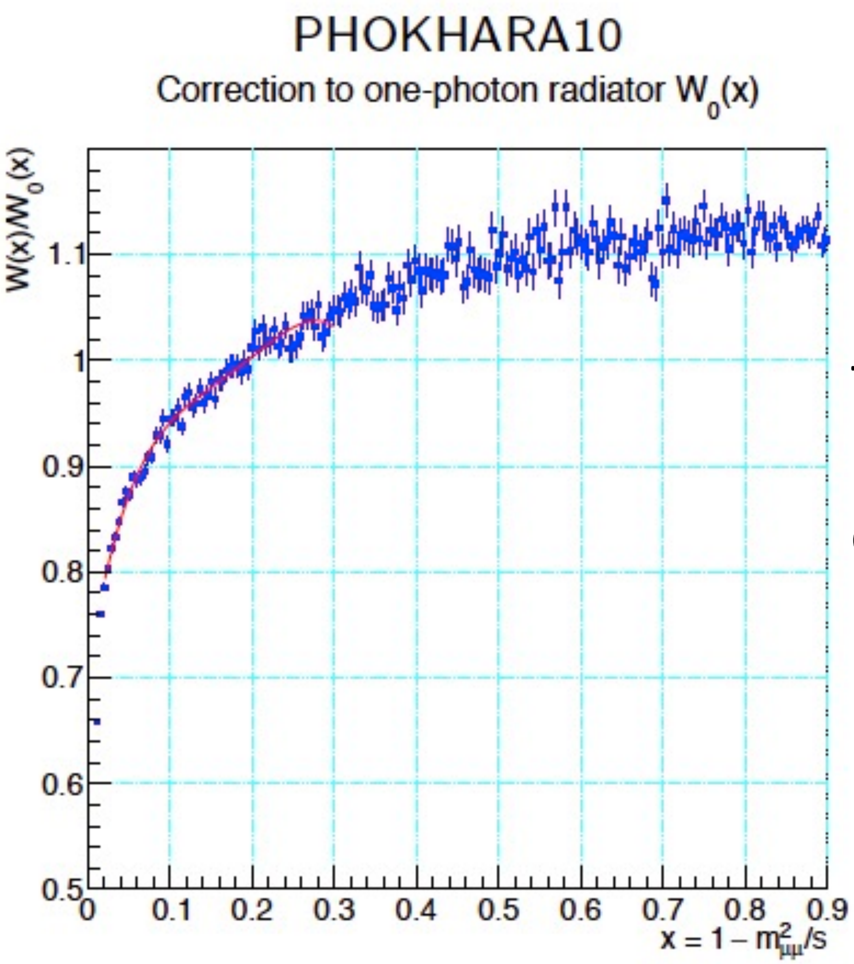
The Run 6 continuum template is corrected to take into account $\Upsilon(nS)$ produced by the radiative return process. Total ISR cross section for a narrow resonance is

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

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.



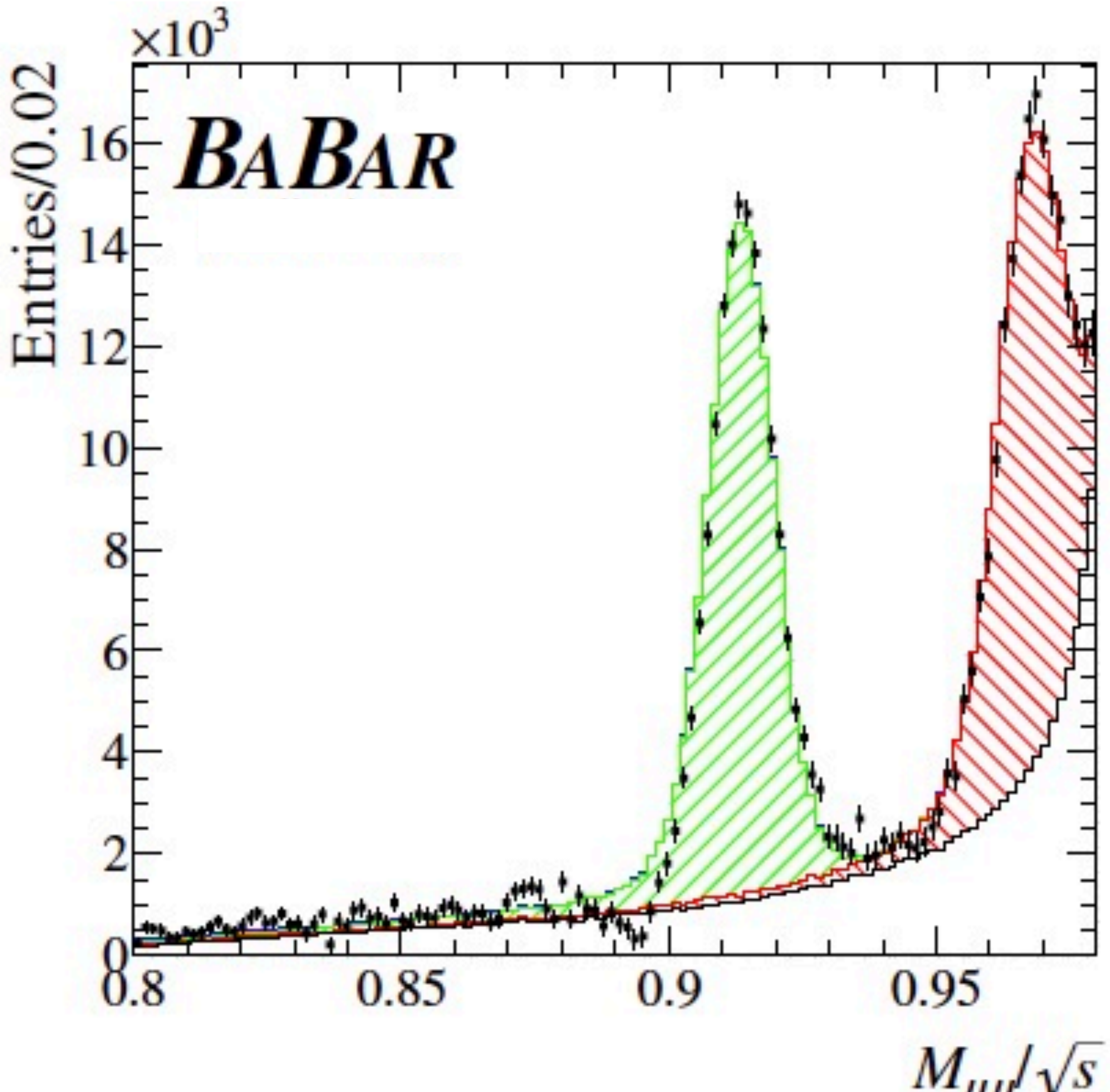




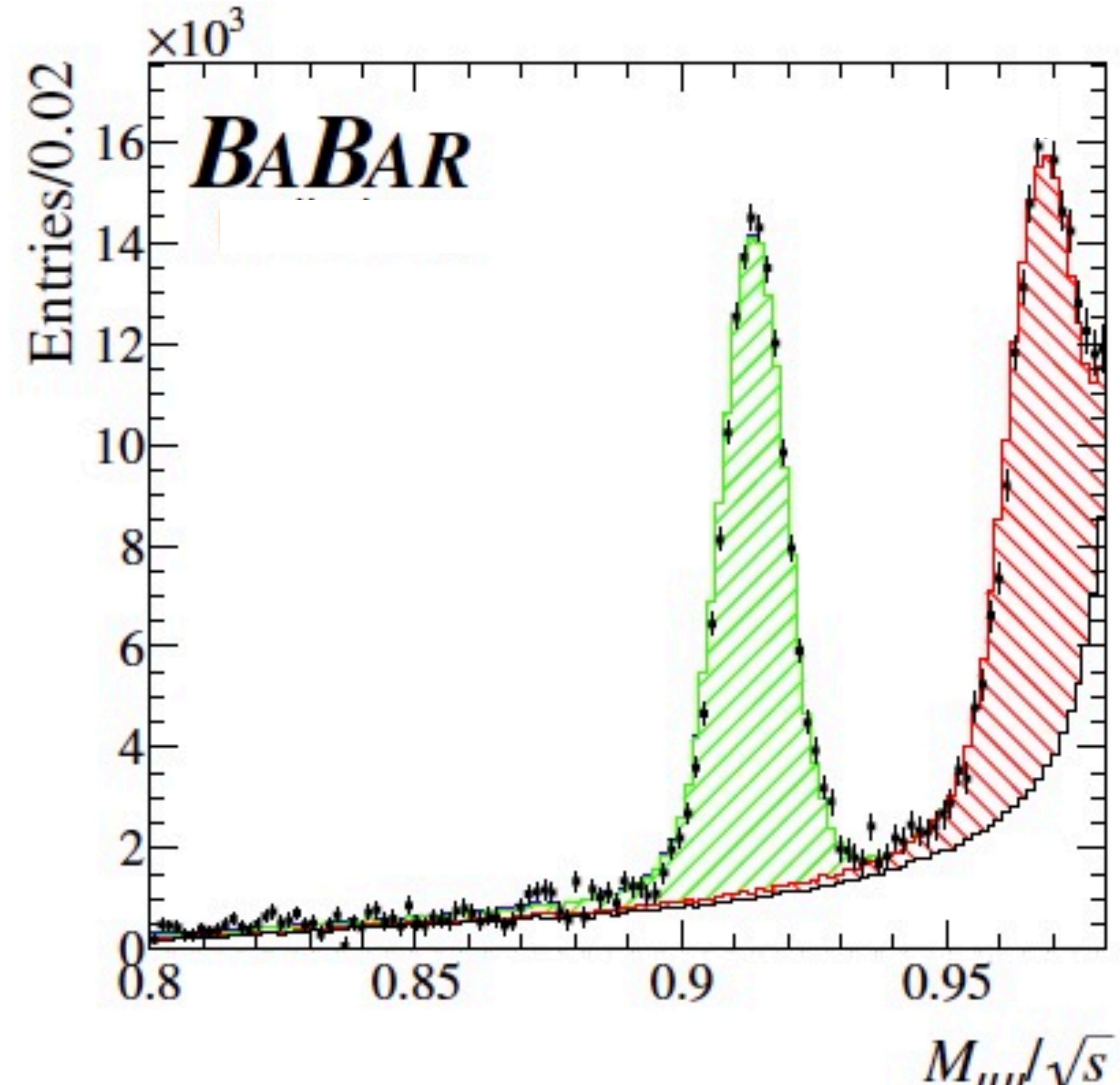
PHOKHARA MC Correction to above formula For soft photon emission

SUBTRACTING RADIATIVE RETURN

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



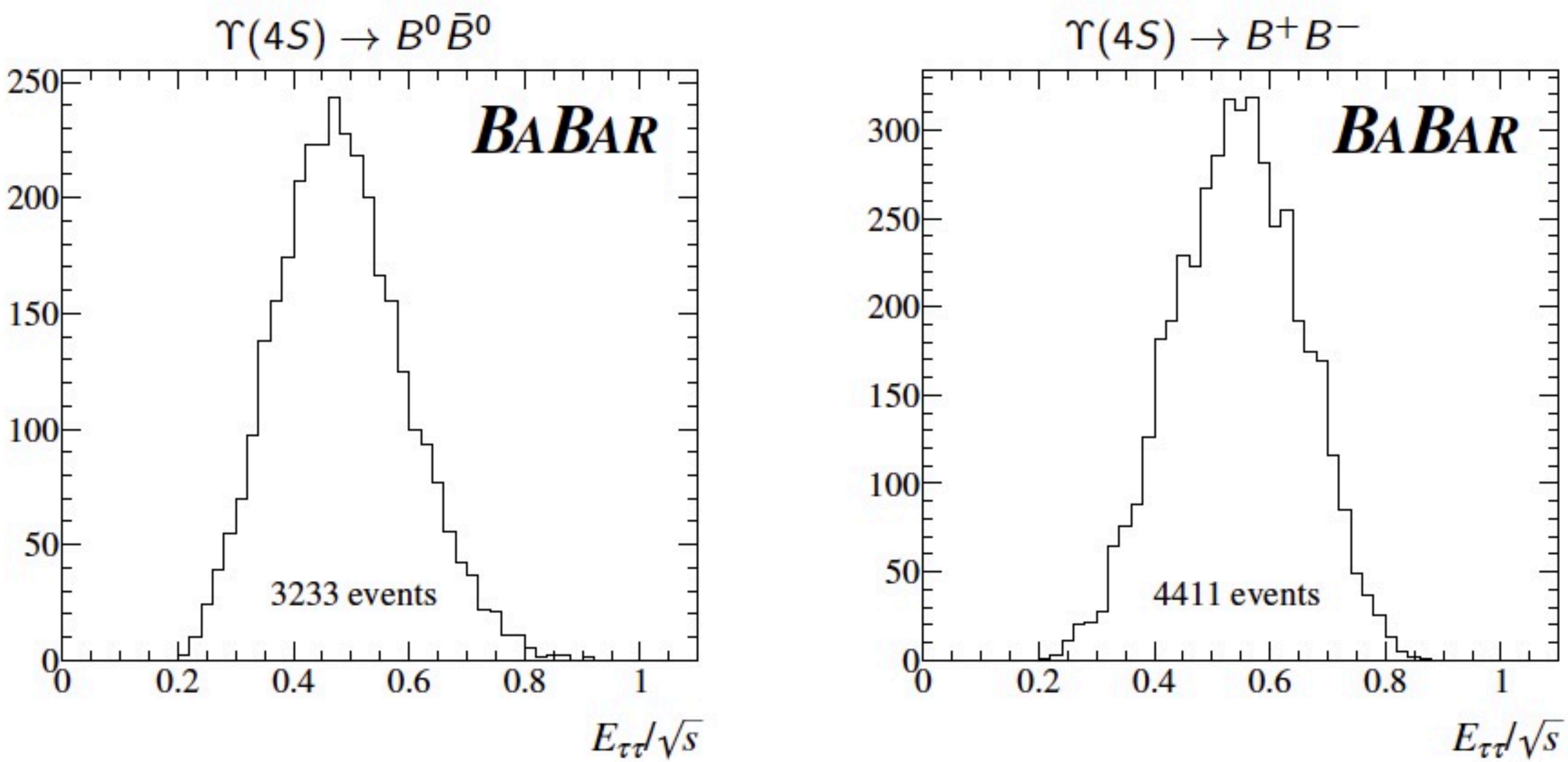
Continuum template IS corrected
For ISR production of Υ(nS)



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

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 $R_{\tau\mu}$