Precision measurement of the $\mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)/\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$ ratio at the *BABAR* experiment

Alexei Sibidanov

University of Victoria
on behalf of the *BABAR* collaboration

The 16th International Workshop on Tau Lepton Physics
TAU 2021
(Virtual Edition)
September 27, 2021 – October 1, 2021
Indiana University, Bloomington, USA

Introduction

The result of the analysis is published in [Phys.Rev.Lett. **125** (2020) 241801].

Vector $q\bar{q}$ resonance decay width into $\ell\ell$

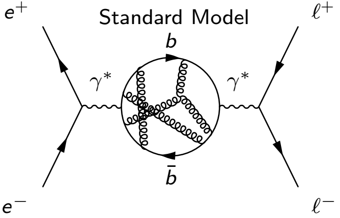
$$\Gamma_{\ell\ell} = 4\alpha^2 e_q^2 \frac{|\Psi(0)|^2}{M^2}\left(1 + 2\frac{m_\ell^2}{M^2}\right)\sqrt{1 - 4\frac{m_\ell^2}{M^2}}$$

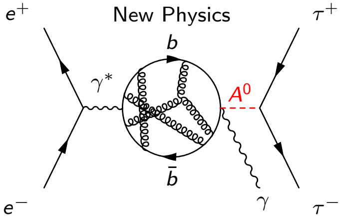
$R_{\ell\ell'} = \dfrac{\Gamma_{\ell\ell}}{\Gamma_{\ell'\ell'}}$ – free of hadronic uncertainties, good probe of the SM.

New Physics Contribution to $R_{\ell\ell'}$

In [Phys. Lett. B **653**, 67-74 (2007)] a light CP-odd Higgs boson A^0 is proposed. In 2HDM(II) with large $\tan\beta$ the A^0 boson exclusively decays into $\tau\tau$ pair and thus New Physics effects might modify visible $R_{\tau\ell}$ in $\Upsilon(nS)$ decays.

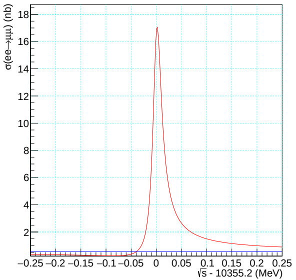
In [JHEP **06**, 019 (2017)] a new physics contribution to $b \to c\tau\nu$ which explains a tension in $R(D^{(*)})$ also necessarily modifies the $R_{\tau\ell}$ observable.

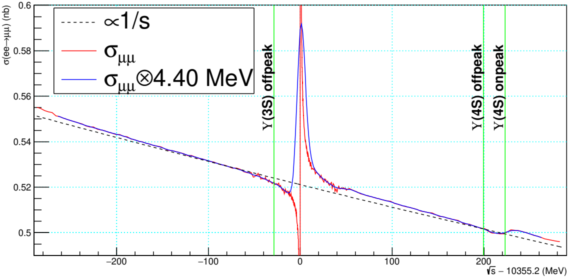




$e^+e^- \to \mu^+\mu^-$ cross section

- MCGPJ [Eur. Phys. J. C **46**, 689-703 (2006)], 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.

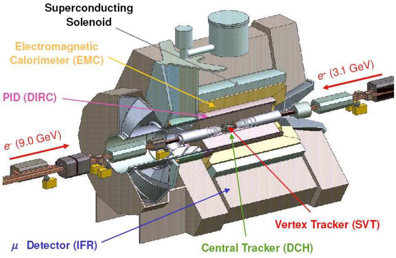


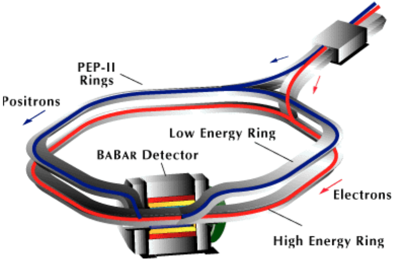


- Due to strong interference between resonance and continuum dilepton production there is an ambiguity in how to extract the leptonic branching fractions.
- In the ratio $R_{\tau\mu}$ the ambiguity is significantly mitigated as well as other factors e.g. instability of the collider interaction energy.
- At the peak $\sigma(ee \to \Upsilon(3S) \to \mu\mu)/\sigma(ee \to \gamma^* \to \mu\mu) = 1.136$ with 4.4 MeV beam energy spread.
- Continuum cross section of $e^+e^- \to e^+e^-$ is more than 500 times larger than the resonance one $\Rightarrow$ only $\tau^+\tau^-$ and $\mu^+\mu^-$ decays of $\Upsilon(3S)$ are considered.

BABAR and analyzed data

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





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}

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

- 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.

Signal selections

$\mu^+\mu^-$ selections

1. Two and only two charged particles with opposite charges
2. $P_{\text{high}}^{\text{cm}} > 4\,\text{GeV}/c$ and $P_{\text{low}}^{\text{cm}} > 2\,\text{GeV}/c$
3. $2.8\,\text{rad} < \theta_-^{\text{cm}} + \theta_+^{\text{cm}} < 3.5\,\text{rad}$
4. $E_+^{\text{EMC}} + E_-^{\text{EMC}} < 2\,\text{GeV}$
5. $0.65\,\text{rad} < \theta_-^{\text{cm}} < 2.5\,\text{rad}$ and $0.58\,\text{rad} < \theta_+^{\text{cm}} < 2.56\,\text{rad}$
6. $\psi^{\text{cm}} = \arccos \dfrac{\vec{P}_+^{\text{cm}} \cdot \vec{P}_-^{\text{cm}}}{|\vec{P}_+^{\text{cm}}| \cdot |\vec{P}_-^{\text{cm}}|} > 160^\circ$
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. $41^\circ < \theta_\pm^{\text{cm}} < 148^\circ$.
3. $\psi^{\text{cm}} > 110^\circ$
4. $E_{\text{tot}}^{\text{EMC}} < 0.7 \times E_{\text{PEP-II}}$
5. One of the particles must be an electron and the other not [$e\not{e}$]
6. $||\phi_+ - \phi_-| - 180^\circ| > 3^\circ$
7. $|M_{\text{miss}}^2| > 0.01 \times s$
8. $|\cos\theta_{\text{miss}}| < 0.85$
9. $P_\pm^\perp \notin \gamma^*\gamma^*$ region
10. $|\Delta\phi| = ||\phi_{e\gamma} - \phi_{\not{e}}| - 180^\circ| > 2^\circ$ and $|\Delta\theta| = |\theta_{e\gamma} + \theta_{\not{e}} - 180^\circ| > 2^\circ$

99% purity

All selections are designed to be beam-energy insensitive.

MC selection efficiency correction

Precision measurement ⇒ data driven efficiency correction is needed!
The $\Upsilon(3S)$ and $\Upsilon(4S)$ off-resonance date samples are used derive and test the correction to the efficiency ratio.

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	$N_{\mu\mu}^{\text{data}}$	$N_{\mu\mu}^{\text{MC}}$	$N_{\tau\tau}^{\text{data}}$	$N_{\tau\tau}^{\text{MC}}$	$\tilde{R}_{\tau\mu}^{\text{data}}/\tilde{R}_{\tau\mu}^{\text{MC}}$
$\Upsilon(3S)$ 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

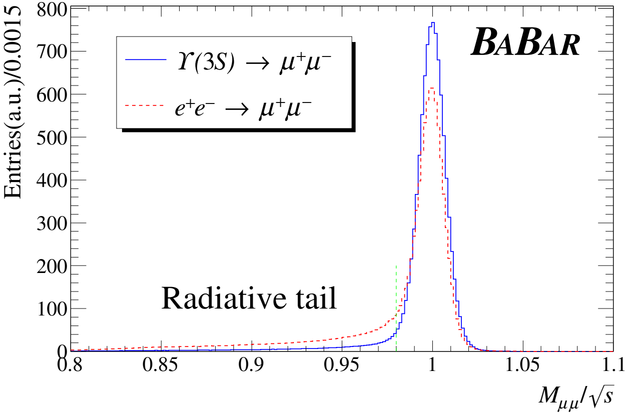
$\tilde{R}_{\tau\mu}(3S) = 0.11665 \pm 0.00029(0.25\%)$
$\tilde{R}_{\tau\mu}(4S) = 0.11647 \pm 0.00017(0.15\%)$
$\tilde{R}_{\tau\mu}(4S)/\tilde{R}_{\tau\mu}(3S) - 1 = -0.0015 \pm 0.0029$

Off-peak MC

$\tilde{R}_{\tau\mu}(3S) = 0.11489 \pm 0.00018(0.16\%)$
$\tilde{R}_{\tau\mu}(4S) = 0.11483 \pm 0.00014(0.13\%)$
$\tilde{R}_{\tau\mu}(4S)/\tilde{R}_{\tau\mu}(3S) - 1 = -0.0006 \pm 0.0020$

The ratio of τ-μ candidates does not depend on energy in data and MC!

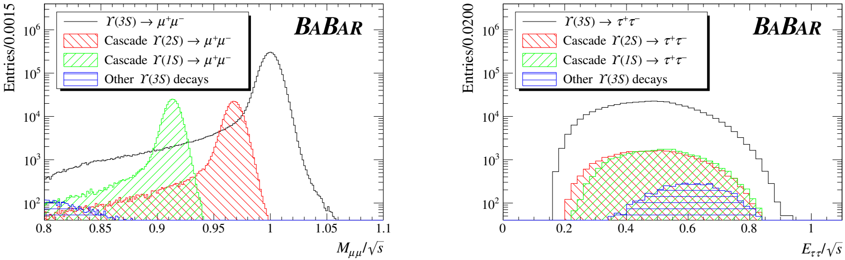
Signal/background separation – continuum



Only about 7% of the selected dimuon events from $\Upsilon(3S)$ decays have invariant mass $M_{\mu\mu}$ less than 98% of interaction energy due to final state radiation whereas in the continuum selected events this fraction is 23% because of initial state radiation.

Exploit this difference in shape to distinguish resonance decays from continuum one.

Signal/background separation – cascade decays



- "Cascade" decays or leptonic decays of $\Upsilon(1S)$ or $\Upsilon(2S)$ are also there.
- Only in the $M_{\mu\mu}$ variable cascade decays can be separated from $\Upsilon(3S)$ decays. In all $\tau\tau$ distributions they are indistinguishable so use information from the $\mu\mu$ channel to fix them in $\tau\tau$.
- Use off-resonance data to describe the shape of the continuum background in on-resonance data in $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$ variables.
- Combine available $M_{\mu\mu}$ shape information in a template-based fit to extract the number of $\Upsilon(3S)$ decayed into $\mu\mu$ and $\tau\tau$ pairs.
- To overcome low statistic of the $\Upsilon(3S)$ off-resonance data sample use high statistic Run 6 experimental data where about 44×10^6 $\mu^+\mu^-$ and 5×10^6 $\tau^+\tau^-$ pairs are selected.
- MC based cascade decay templates.

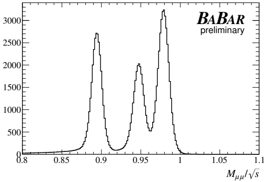
ISR produced $\Upsilon(nS)$

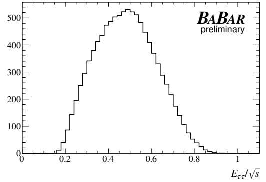
The Run 6 continuum template is corrected to take into account $\Upsilon(nS)$ produced by the radiative return process. Total ISR cross section for a narrow resonance is

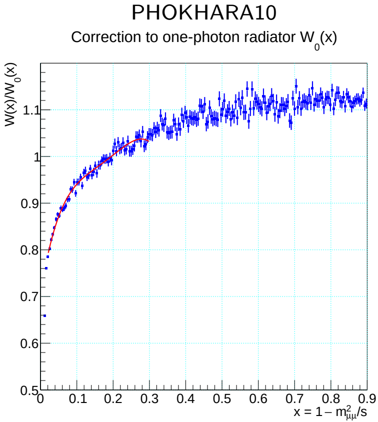
$$\sigma(s) = \frac{12\pi^2\Gamma_{ee}\Gamma_{\mu\mu}}{sM\Gamma} W(s, x_0),\ x_0 = 1 - \frac{M^2}{s},\ W_0(s,x) = \frac{\alpha}{\pi x}\left(\ln\frac{s}{m_e^2} - 1\right)(2 - 2x + x^2),$$

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.

Expected ISR contributions to the continuum templates for 78/fb @ $\Upsilon(4S)$:



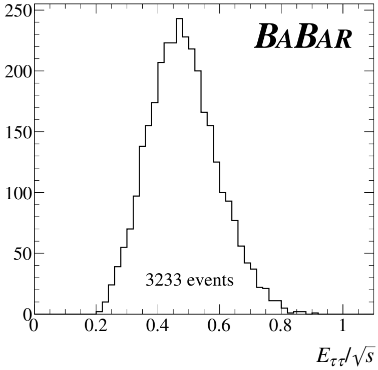




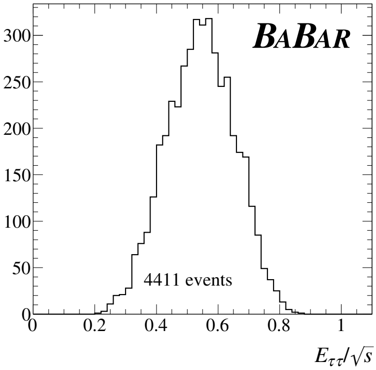
MC based $B\bar{B}$ correction

Since the continuum template is taken @ $\Upsilon(4S)$ – there are plenty of $B\bar{B}$ events and some of the low multiplicity B decays (e.g. charmless semileptonic) might mimic τ decays and modify the template. From more than 265 million of generated $B\bar{B}$ ($\times 3$ data) events only 15 were selected as dimuon candidates whereas 7644 were selected as $\tau\tau$.

$\Upsilon(4S) \to B^0\bar{B}^0$

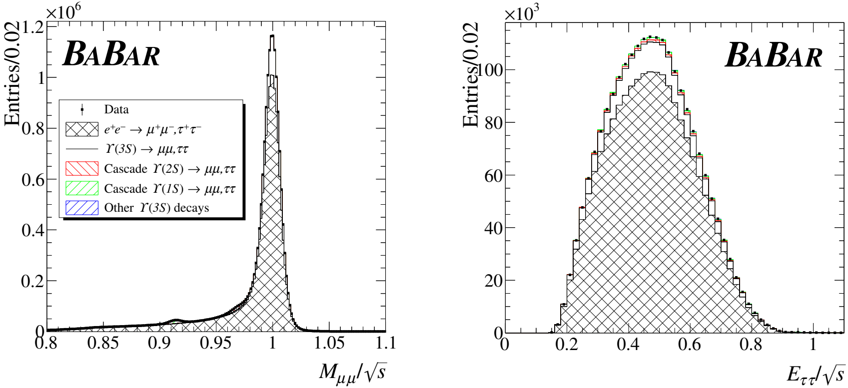


$\Upsilon(4S) \to B^+B^-$



Amount of $B\bar{B}$ misidentified as $\tau\tau$ translates to $\delta_{B\bar{B}} = 0.4\%$ of $\Upsilon(3S) \to \tau\tau$ events. This contribution is taken into account as a correction in the final result.

Fit result

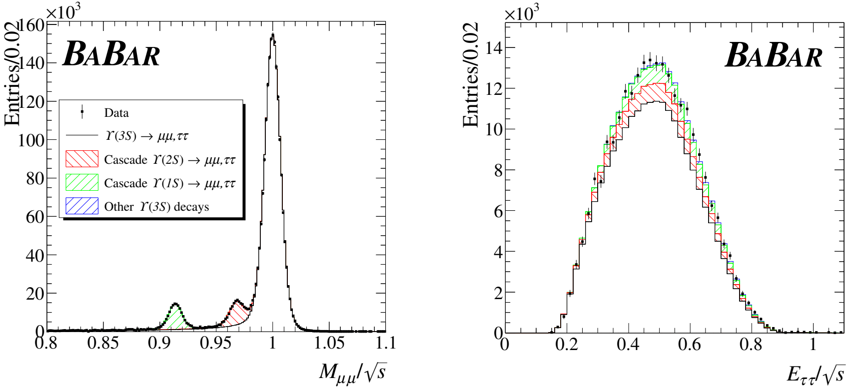


Dominant continuum $e^+e^- \to \ell^+\ell^-$ background (cross-hatched histogram) is mainly visible.

The raw result of the fit $\tilde{R}_{\tau\mu} = N_{\tau\tau}/N_{\mu\mu} = 0.1079 \pm 0.0009$

$$R_{\tau\mu} = \tilde{R}_{\tau\mu} \frac{1}{C_{\mathrm{MC}}} \frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}} \cdot (1 + \delta_{B\bar{B}}) = 0.966 \pm 0.008_{\mathrm{stat}} \pm 0.014_{\mathrm{syst}} = 0.966 \pm 0.016_{\mathrm{tot}}$$

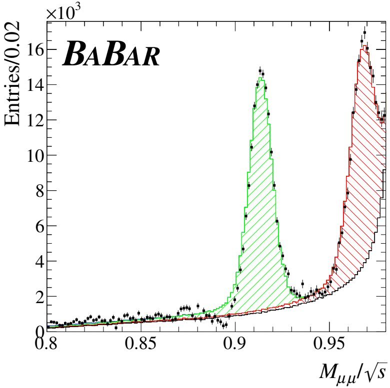
Fit result – continuum subtracted



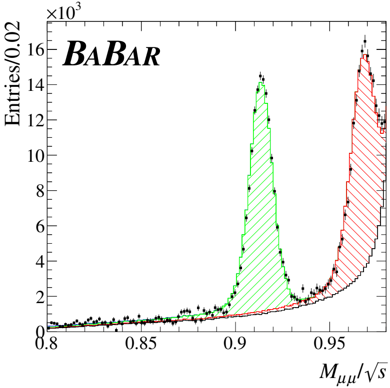
When the continuum background is subtracted the "cascade" backgrounds are clearly visible in the dimuon invariant mass distribution.

Fit result – effect of ISR produced $\Upsilon(nS)$

If the continuum template were NOT corrected for ISR produced $\Upsilon(nS)$



The continuum template IS corrected for ISR produced $\Upsilon(nS)$



Note that ISR produced $\Upsilon(nS)$ are clearly visible in the continuum subtracted distribution especially $\Upsilon(1S)$ as a statistically significant dip. Radiative tail well matches to MC prediction.

Systematic uncertainty estimation

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 other particle identification criteria were applied to estimate the PID uncertainty e.g. explicit muon ID.
- In cascade decays the ratios for lower Υ resonances were varied within experimental uncertainties around the SM value.
- Various other $P_{\perp}$ selections are tested up to 2 times loss in efficiency.
- In order to estimate possible effect of MC shapes to the ratio radiative effects are modelled by PHOTOS and KKMC generators. Invariant mass resolution varied up to 10% off.
- $\Upsilon(nS)$ cross sections are varied according uncertainties as well as overall uncertainty of 10% applied.
- Remaining small background from $\Upsilon(3S)$ decays fixed to MC prediction as well as $B\bar{B}$ contribution varied as much as 50% to conservatively estimate their contribution to the systematic uncertainty.

Conclusion

- The large *BABAR* data set of $\Upsilon(nS)$ decays is still a valuable source of new physical results!
- With the excellent and well studied performance of the *BABAR* detector $\tau^+\tau^-$ and $\mu^+\mu^-$ events are purely selected with virtually no background and only small corrections are needed to apply on MC based parameters.
- Simultaneous binned likelihood fit to $M_{\mu\mu}$ and $E_{\tau\tau}$ distributions is developed to directly extract the $N_{\tau\tau}/N_{\mu\mu}$ ratio and avoid problems with luminosity determination and the cascade decays in the ratio.
- The high statistic continuum templates based on 78.3/fb of $\Upsilon(4S)$ on-peak data and corrected for Radiative Return Processes and a tiny remaining contribution from the $B\bar{B}$ events improve statistical precision of the ratio.
- Systematic uncertainties are rigorously estimated.
- Based on 27.96/fb collected at $\Upsilon(3S)$ energy the ratio is

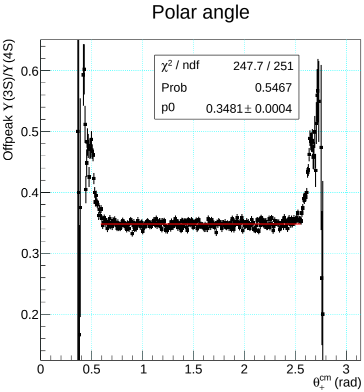
$$R_{\tau\mu} = \frac{\mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)}{\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)} = 0.966 \pm 0.008_{\text{stat}} \pm 0.014_{\text{syst}}.$$

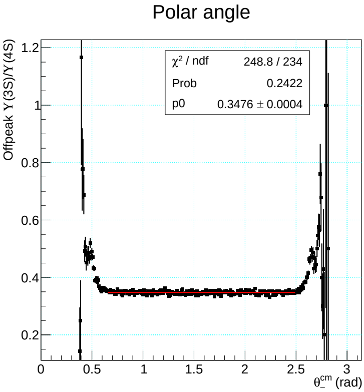
- This result is published in [Phys.Rev.Lett. **125** (2020) 241801] and a preprint is available [arXiv:2005.01230]. It can be compared with $R_{\tau\mu} = 0.9948$ in the Standard Model (radiation effects are included) as well as the only previous measurement reported by the CLEO collaboration [Phys.Rev.Lett.**98** (2007) 052002]: $R_{\tau\mu} = 1.05 \pm 0.08 \pm 0.05$.

BACKUP SLIDES

$\mu^+\mu^-$ selection – polar angle selection

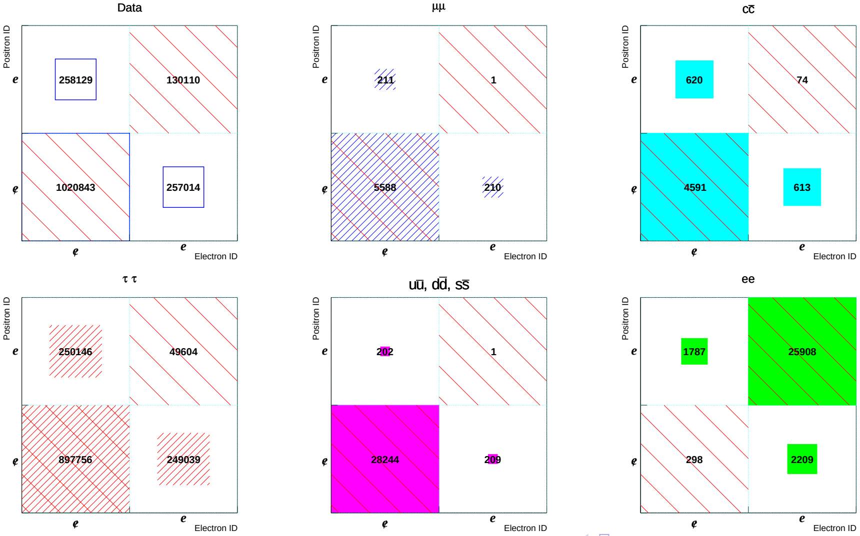
In order to maintain equal efficiency between $\Upsilon(3S)$ and $\Upsilon(4S)$ data samples more narrow angle selections are needed because different boost leads to different efficiency drop at the fiducial volume borders.
Selection criteria are derived from ratios of polar angle distributions for $\Upsilon(3S)$ and $\Upsilon(4S)$ off peak data.





$\tau^+\tau^-$ selection – $[e\not{e}]$

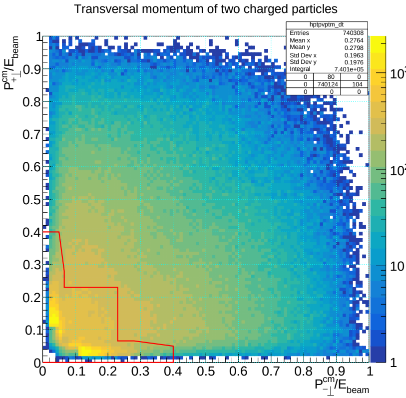
Electron identification is based on dE/dx measurements in the drift chamber and energy deposition in EMC. Among other tested PID selections it gives the best performance.



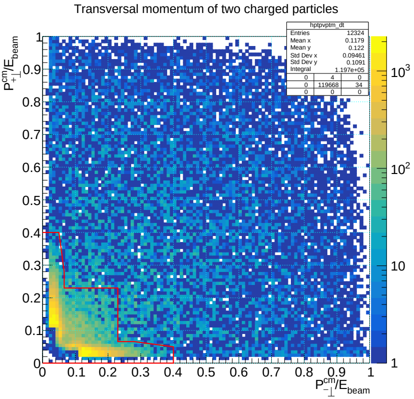
$\tau^+\tau^-$ selection – $P^{\perp}_{\pm} \notin \gamma^*\gamma^*$ region

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.

$\tau^+\tau^-$ selection #10

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