In search of new Physics with Lepton Flavor Violation in $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ at BABAR

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On behalf of the BaBar Collaboration

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Outline of the Talk

- Motivation: Charged Lepton Flavor Violation
- Theoretical Expectations and Experimental Limits
- Asymmetric PEP-II Collider and BaBar Detector
- Data, MC and Data Driven Background
- Analysis Strategy
    - ➢ Signal and Background Characteristic
    - ➢ A Selection Criterion
    - ➢ Validation of Using the Data Driven Background
- Results and Indication for New Physics
- Conclusion

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Motivation

- Lepton Flavor Violation (LFV) in the neutral lepton sector has already indicated by the observation of neutrino oscillations by the Super-Kamiokande Observatory and the Canadian Sudbury Neutrino Observatories (SNO).

- Such an oscillation mechanism cannot induce observable LFV in the charged lepton sector.

- Charged Lepton flavor violating (CLFV) processes are strongly suppressed in the standard model by powers of (small) neutrino masses, e.g. $\left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 \leq 10^{-48}$ [1]

- Observation of CLFV is, therefore, a clear sign of new physics (NP) beyond the SM.

[1] Phys. Rev. Lett. 104, 151802

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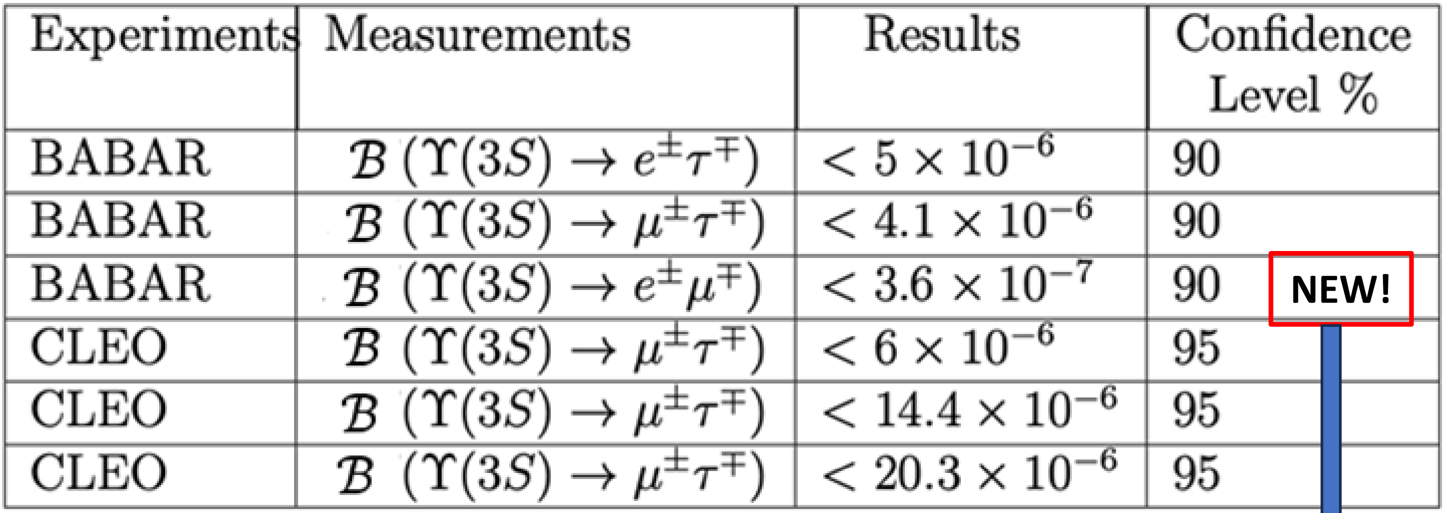
Motivation

Table: CLEO and BABAR results on different decay modes of Υ.



Experiments	Measurements	Results	Confidence Level %
BABAR	$\mathcal{B}\,(\Upsilon(3S) \to e^{\pm}\tau^{\mp})$	$< 5 \times 10^{-6}$	90
BABAR	$\mathcal{B}\,(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$< 4.1 \times 10^{-6}$	90
BABAR	$\mathcal{B}\,(\Upsilon(3S) \to e^{\pm}\mu^{\mp})$	$< 3.6 \times 10^{-7}$	90
CLEO	$\mathcal{B}\,(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$< 6 \times 10^{-6}$	95
CLEO	$\mathcal{B}\,(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$< 14.4 \times 10^{-6}$	95
CLEO	$\mathcal{B}\,(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$< 20.3 \times 10^{-6}$	95

NEW!

Phys. Rev. Lett. 128 (2022) 9, 091804

- BABAR reports the first search for electron-muon LFV in the decay of a ϒ (3S) resonance.
- With the results of ϒ(3S) we placed constraints on New Physics (NP) processes that include LFV.

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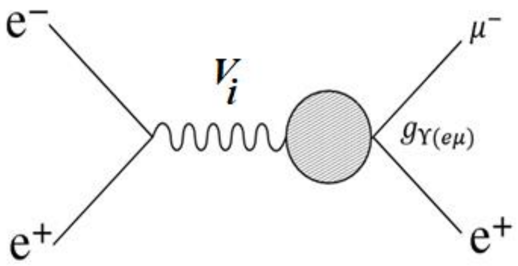
Theoretical Background

- Let us assume that a vector boson V_i (here V_i could be either a fundamental state, such as the Z^0, or a quark-antiquark bound state such as the $\phi,\ J/\psi$, or Υ) couples to $e^{\pm}\mu^{\mp}$. The effective coupling between the vector boson V_i and $e^{\pm}\mu^{\mp}$ can be written as

$$[\mathcal{B}(\mu\to 3e)]_{V-\text{exch.}} \approx \frac{\Gamma(V\to e^+e^-)\Gamma(V\to e^{\pm}\mu^{\mp})}{\Gamma^2(W\to e\nu)}\left(\frac{M_W}{M_V}\right)^6 .$$



Using $\mathcal{B}$ ($\mu \to eee$) $<1.0 \times 10^{-12}$ [2] and other data pertaining to the e^+e^-widths of the various vector mesons V_i, we find

$$\boxed{\mathcal{B}\left(\Upsilon(3S) \to e^{\pm}\mu^{\mp}\right) \leq 2.5 \times 10^{-8}}$$

- $\mu \longrightarrow eee$ decay amplitude can be significantly reduced if there are kinematical suppressions. Such suppressions are possible when the effective vector boson couplings involve momentum factors. According to Nussinov [3], the size of the vector boson exchange contribution reduce by a factor of $\frac{M_\mu^2}{2M_{\Upsilon(3S)}^2}$ which is $\mathbf{3 \times 10^{-5}}$.

- Thus, **new modified bound on $\mathcal{B}(\Upsilon\ (3S) \to e^{\pm}\mu^{\mp})$** reduced by $\boldsymbol{\leq 1 \times 10^{-3}}$

[2] Bellgardt, et al., Nucl.Phys. B299 (1988)
[3] S. Nussinov, et. al. PRD 63 (2001)

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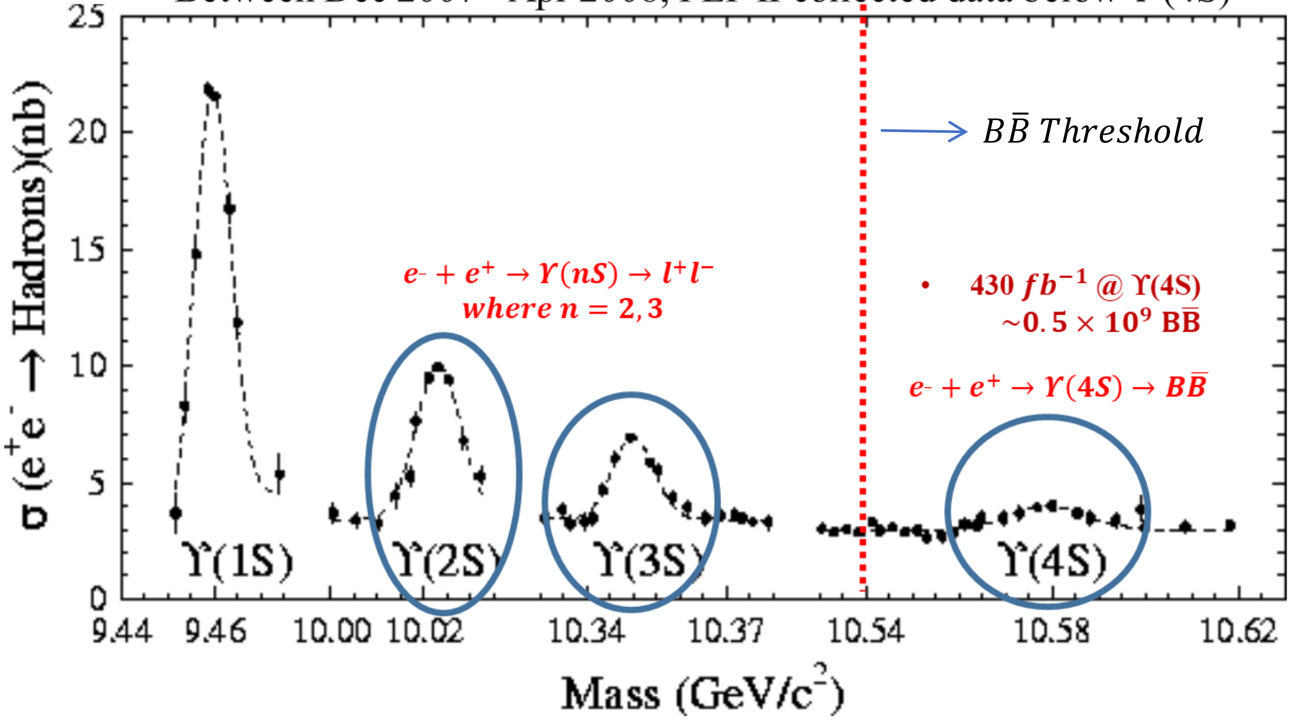
Charged Lepton Flavor Violation in Upsilon Decays

Between Dec 2007 - Apr 2008, PEP II collected data below Υ (4S)



$B\bar{B}$ *Threshold*

$e^- + e^+ \rightarrow \Upsilon(nS) \rightarrow l^+l^-$
where $n = 2, 3$

- **430 fb^{-1} @ Υ(4S)**
  $\sim 0.5 \times 10^9$ $B\bar{B}$

$e^- + e^+ \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

- **30 fb^{-1}@ Υ(3S) 122 M Υ decays**
  ~ 10 × Belle
  ~ 20 × CLEO
- **15 fb^{-1}@ Υ(2S) 100 M Υ decays**
  ~ 12 × CLEO

Dramatic Increase in sensitivity to rare decays: $\Gamma_{\Upsilon(4S)}/\Gamma_{\Upsilon(nS)} \approx 10^3$

Upsilon System: **CUSB detector, CLEO Collaboration**
T. Bohringer et al., Phys. Rev. Lett. 44, 1111 (1980) and P. Finocchiaro et al., Phys. Rev. Lett. 45, 222 (1980)

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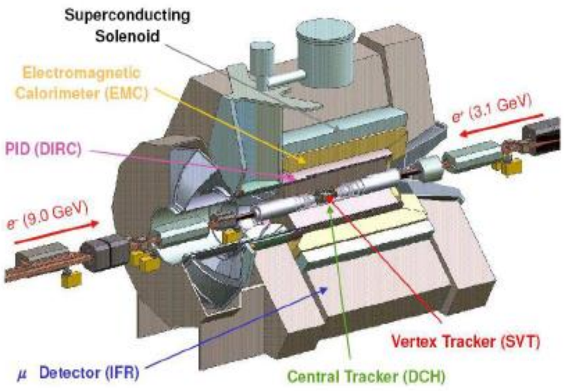
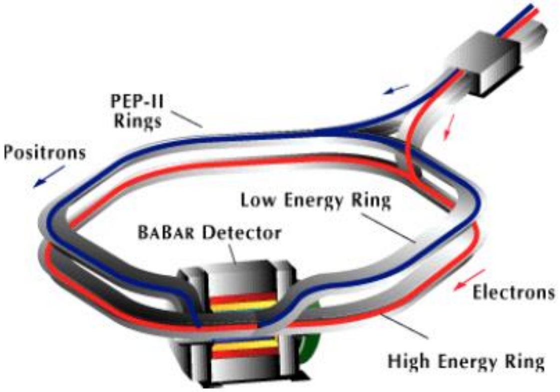
Data, MC Sample

BABAR and PEP-II operated from 1999-2008 at SLAC





Data Sample	On resonance (fb^{-1})	Off resonance (fb^{-1})
Run 7 $\boldsymbol{\Upsilon(3S)}$ **(Data)**	27.9 = 27.0 + (0.9 **Blinded Analysis**)	2.62 To validate the systematic study
Run 6 $\boldsymbol{\Upsilon(4S)}$ **Data driven continuum background**	78.31 **Systematic study** pre-selected as $e^{\pm}\mu^{\mp}$and $\mu^{\pm}\mu^{\mp}$	7.75 To validate the systematic study
MC signal: $\boldsymbol{e^+e^- \to \Upsilon(3S) \to e^{\pm}\mu^{\mp}}$: 103000 events		

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Signal and Background

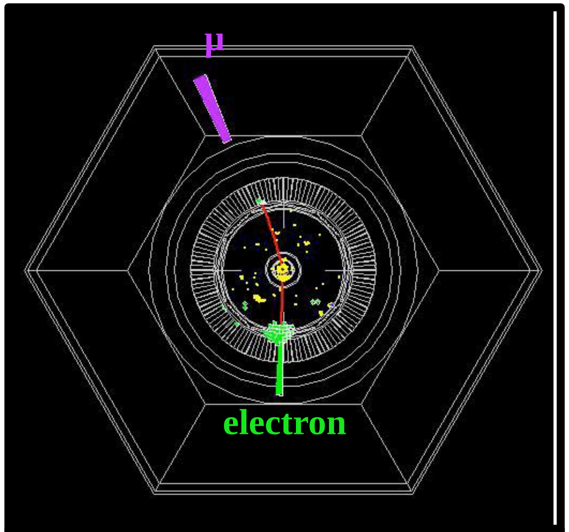
- $\boldsymbol{\Upsilon}(\mathbf{3}\boldsymbol{S}) \rightarrow \boldsymbol{e}^{\pm}\boldsymbol{\mu}^{\mp}$: required two primary track signal of $\boldsymbol{e}^{\pm}$ $\boldsymbol{and}$ $\boldsymbol{\mu}^{\mp}$
- Centre of Mass (CM) momentum:

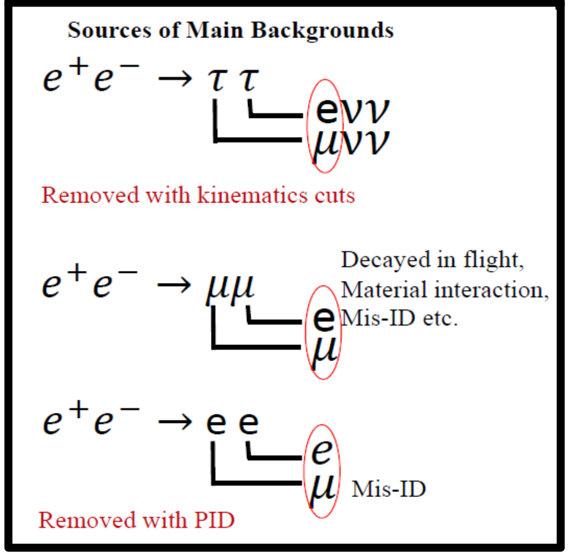
  $\boldsymbol{p}_{\boldsymbol{e}^{\pm}} \sim \frac{\sqrt{\boldsymbol{s}}}{\mathbf{2}} = \boldsymbol{E}_{\boldsymbol{B}}$ and $\boldsymbol{p}_{\boldsymbol{\mu}^{\pm}} \sim \frac{\sqrt{\boldsymbol{s}}}{\mathbf{2}} = \boldsymbol{E}_{\boldsymbol{B}}$

  where $\boldsymbol{E}_{\boldsymbol{B}}$ = beam energy in CM
- Angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179^{\circ}$ to emerge as back-to-back.
- Energy deposit by $\boldsymbol{\mu}^{\mp}$ track on the Electromagnetic Calorimeter (EMC) > 50 MeV
- EMC acceptance $24^{\circ} < \theta_{Lab} < 130^{\circ}$ etc.
- Optimized PID selection for $\boldsymbol{e}^{\pm}$ $\boldsymbol{\mu}^{\mp}$ track

Sample Background Event

$\boldsymbol{e}^{-}\boldsymbol{e}^{+} \rightarrow \boldsymbol{\tau}^{\pm}\boldsymbol{\tau}^{\mp} \rightarrow \boldsymbol{e}^{\pm}\boldsymbol{\mu}^{\mp} + \mathbf{4}\boldsymbol{\nu}$





Sources of Main Backgrounds

$e^{+}e^{-} \rightarrow \tau\,\tau$ — $e\nu\nu$, $\mu\nu\nu$

Removed with kinematics cuts

$e^{+}e^{-} \rightarrow \mu\mu$ — e, μ

Decayed in flight,
Material interaction,
Mis-ID etc.

$e^{+}e^{-} \rightarrow e\,e$ — e, μ

Mis-ID

Removed with PID

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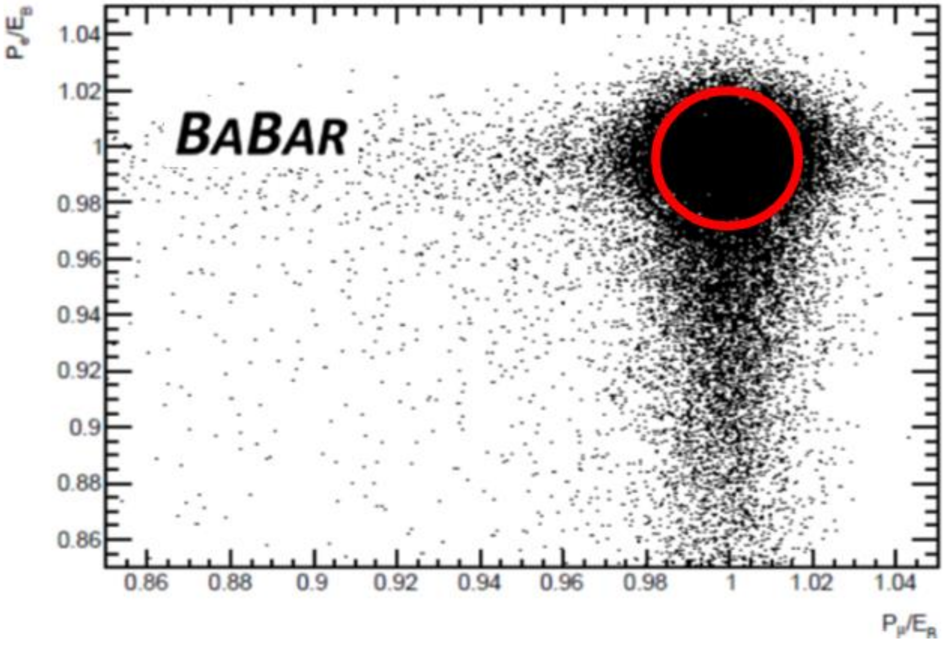
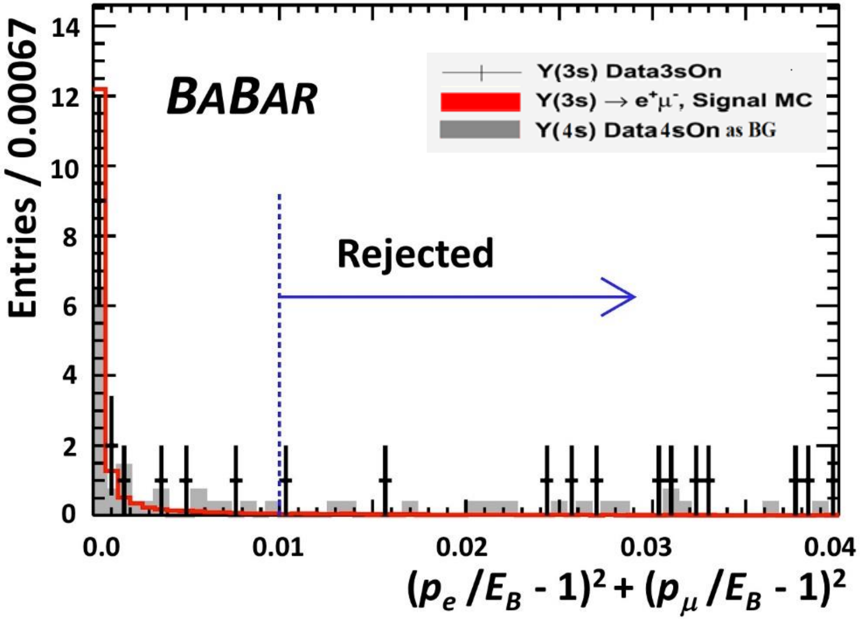
Selection criteria on the lepton momentum plane

Signal Monte Carlo



Distribution of the squared distance from the point (1,1) in the plane of the scaled electron vs muon momenta for events satisfying all other selection criteria in the data.



The lepton momenta must satisfy the condition which is defining a circle of radius

$$\left(\frac{p_e}{E_B}-1\right)^2+\left(\frac{p_\mu}{E_B}-1\right)^2 = (0.1)^2 = 0.01$$ Where, $p_{e^\pm,\mu^\pm} \sim \frac{\sqrt{s}}{2} = E_B$

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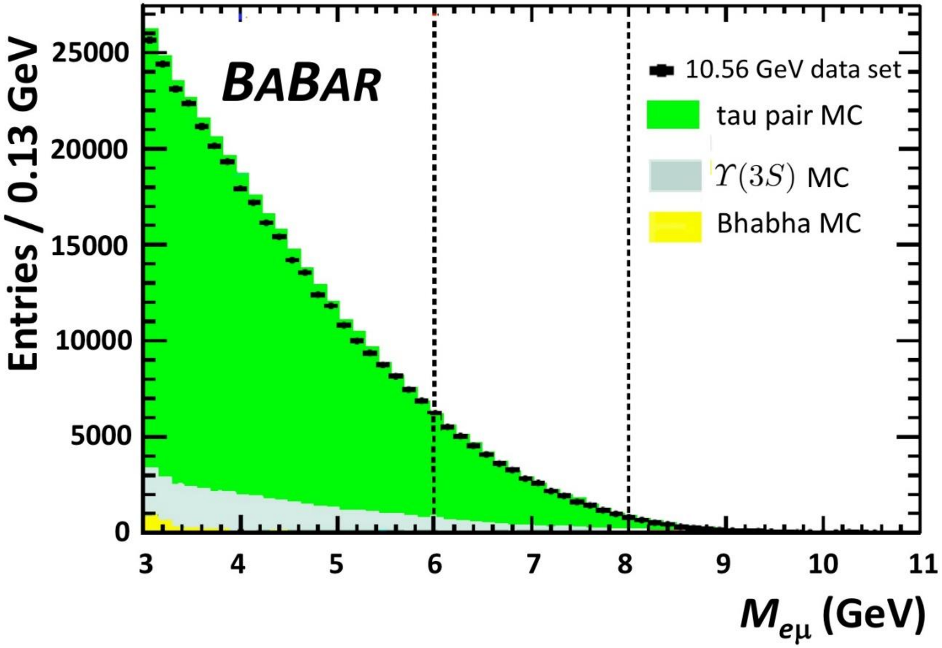
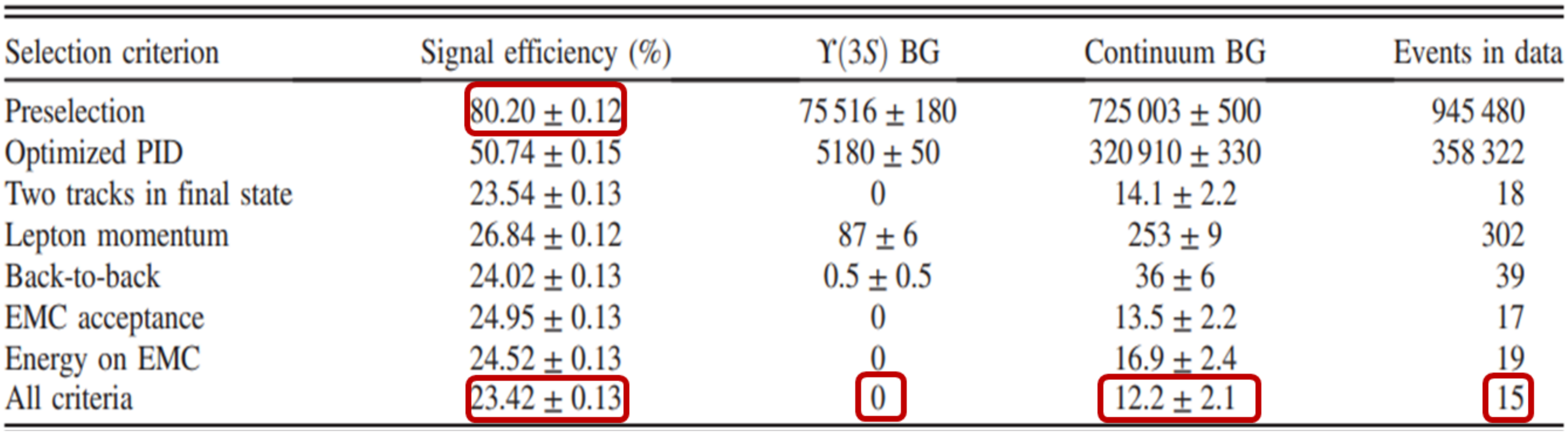
Systematic Study



- We reversed two major cuts to check the $\Upsilon(4S)$data/MC agreement.
- $e^+e^- \rightarrow \Upsilon(4S)$ of 78.31/fb pre-selected as $e^\pm\mu^\mp$and $\mu^\pm\mu^\mp$
- Disagreement arises due to uncertainties in PID, Tracking, kinematics, trigger etc.
- The difference in continuum background and MC background (in the energy band 6-8 GeV) was 1.2%



Selection criterion	Signal efficiency (%)	$\Upsilon(3S)$ BG	Continuum BG	Events in data
Preselection	80.20 ± 0.12	75 516 ± 180	725 003 ± 500	945 480
Optimized PID	50.74 ± 0.15	5180 ± 50	320 910 ± 330	358 322
Two tracks in final state	23.54 ± 0.13	0	14.1 ± 2.2	18
Lepton momentum	26.84 ± 0.12	87 ± 6	253 ± 9	302
Back-to-back	24.02 ± 0.13	0.5 ± 0.5	36 ± 6	39
EMC acceptance	24.95 ± 0.13	0	13.5 ± 2.2	17
Energy on EMC	24.52 ± 0.13	0	16.9 ± 2.4	19
All criteria	23.42 ± 0.13	0	12.2 ± 2.1	15

Impact of each component of the selection on the signal efficiency, background and data

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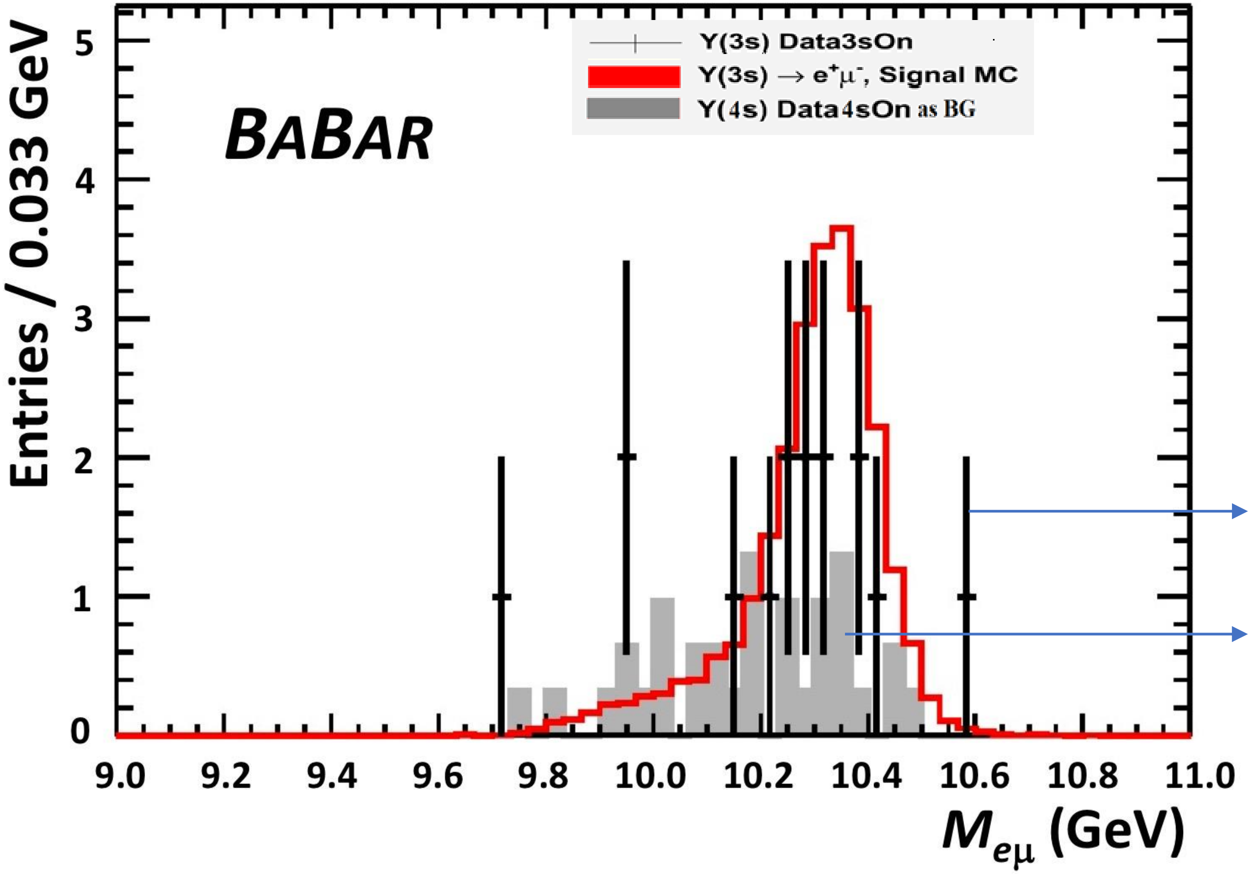
Final Invariant Mass Distribution of $e^{\pm}\mu^{\mp}$

After all selection criteria are applied



Candidate Events:15 (black)

Data Driven Estimated Background from $\boldsymbol{\Upsilon}(\mathbf{4}\boldsymbol{S})$: 12.2 (grey)

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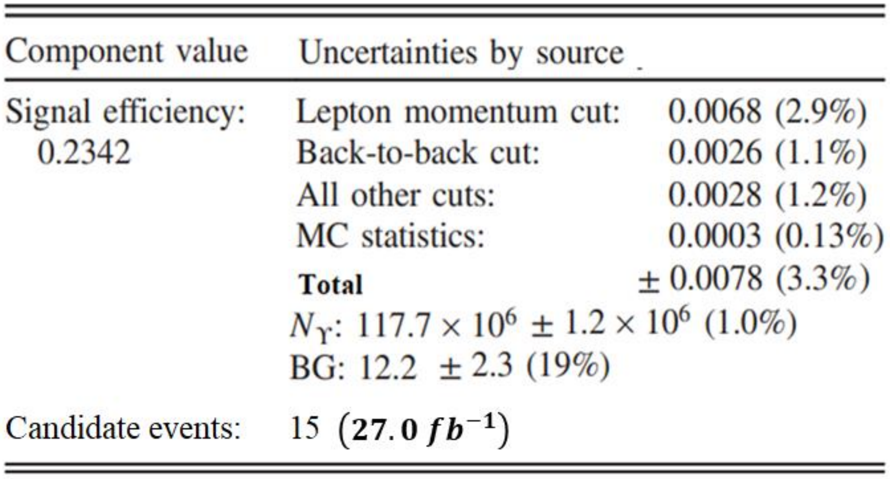
Summary and Result $\Upsilon\,(3S) \to e^{\pm}\mu^{\mp}$



Component value	Uncertainties by source	
Signal efficiency: 0.2342	Lepton momentum cut:	0.0068 (2.9%)
	Back-to-back cut:	0.0026 (1.1%)
	All other cuts:	0.0028 (1.2%)
	MC statistics:	0.0003 (0.13%)
	Total	± 0.0078 (3.3%)
	N_Υ: $117.7 \times 10^6 \pm 1.2 \times 10^6$ (1.0%)	
	BG: 12.2 ± 2.3 (19%)	
Candidate events:	15 $(27.0\ fb^{-1})$	

Table: Summery of systematic uncertainties. The values of efficiency, background, and number of $\Upsilon(3S)$ decays are presented in the first column and their uncertainties in the second column.

- Calculating the branching fraction from $\dfrac{N_{\text{Candidate}} - N_{BG}}{\varepsilon_{sig} \times N_\Upsilon}$ gives

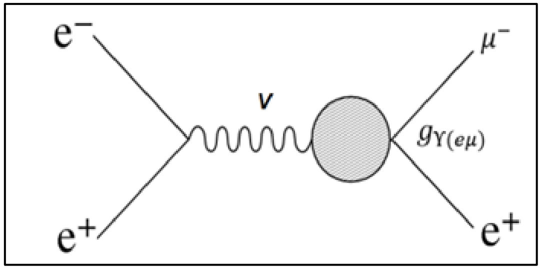
$$\boxed{\mathcal{B}[\Upsilon(3S) \to e^{\pm}\mu^{\mp}] = [1.0 \pm 1.4(\text{stat}) \pm 0.8(\text{syst})] \times 10^{-7}}$$

- We set an upper limit at 90% confidence level (C.L.) on the branching fraction by using the "CLs" method.

$$\boxed{\mathcal{B}[\Upsilon(3S) \to e^{\pm}\mu^{\mp}] < 3.6 \times 10^{-7}\ @\ 90\%\ \text{C.L.}}$$

- This result is the first reported experimental upper limit on $\Upsilon\,(3S) \to e^{\pm}\mu^{\mp}$.

Implication For New Physics (NP)



- Using the relationship, $$\frac{\left(\frac{g^2_{NP}}{\Lambda_{NP}}\right)^2}{\left(\frac{4\pi\alpha_{QED}Q_b}{M_{\Upsilon(3S)}}\right)^2} = \frac{\mathcal{B}(\Upsilon(3S)\to e\mu)}{\mathcal{B}(\Upsilon(3S)\to\mu\mu)}$$

we can set an upper limit on NP $\boxed{\frac{\Lambda_{NP}}{g^2_{NP}} \geq 80\,\text{TeV}}$ @90% C.L.

where, $$\frac{g^2_{\text{NP}}}{\Lambda_{NP}} = \frac{\text{Effective coupling of the new physics}}{\text{Energy scale of the NP, given by the mass of the NP propagator.}}$$

- $Q_b = -\frac{1}{3}$ is the b-quark charge
- α_{3S} is the fine structure constant at the $M_{\Upsilon(3S)}$ energy scale.
- Using the world average $\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 2.18 \pm 0.21$ [4]

[4] P. A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

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Conclusion

- **Upper limit at 90% confidence level (C.L.) on the branching fraction**

$$\boxed{\mathcal{B}[\Upsilon(3S) \to e^{\pm}\mu^{\mp}] < 3.6 \times 10^{-7} \text{ @ } 90\% \text{ C.L.}}$$

- **A limit on NP is** $\boxed{\frac{\Lambda_{NP}}{g_{NP}^2} \geq 80 \text{ TeV}}$ @90% CL [Phys. Rev. Lett. 128 (2022) 9, 091804]

- **This is the first reported experimental upper limits on the branching fraction of $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$.**

- **The measurement we report here is several orders of magnitude more sensitive than the indirect limit $\mathcal{B}(\Upsilon(3S) \to e^{\pm}\mu^{\mp}) \leq 1 \times 10^{-3}$.**

Thanks

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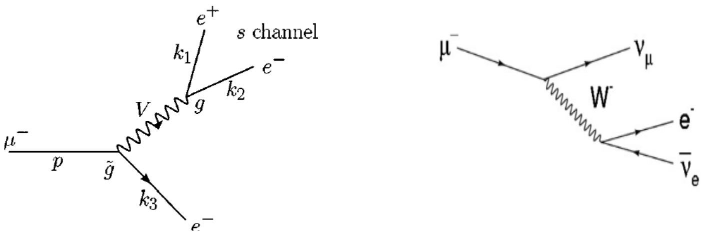
Back up: Theoretical Upper limit (Indirect)

Nussinov, Peccei, Zhang [1]

- Assume coupling of ϒ to eμ looks like: $L_{eff} = gV_{e\mu}\bar{\mu}\gamma_\alpha e V^\alpha$
- Through Fig 1. this coupling contributes to $A\ (\mu \rightarrow 3e)$



(Left) A vector exchange diagram contributing to $\mu \rightarrow 3e$
(Right) Ordinary muon decay, $\mu \rightarrow e\nu\bar{\nu}$, which proceeds via W exchange.

$$A(\mu \to 3e) = (\bar{u}_\mu(p)\gamma^\alpha u_e(k_3))(\bar{v}_e(k_1)\gamma_\alpha u_e(k_2))\frac{g_{V_{e\mu}}g_{V_{ee}}}{M_V^2 - S} \quad \text{----(1)}$$

$$\frac{[\Gamma(\mu \to 3e)]_{V-exch}}{[\Gamma(\mu \to e\nu\bar{\nu})]} \approx \frac{g^2V_{e\mu}g^2V_{ee}}{M_V^4} / \frac{g_W^4}{M_W^4} \quad \text{----(2)}$$

$$\text{Since } [\Gamma(\mathrm{V} \to \mathrm{e}^+\mathrm{e}^-)] \sim \mathrm{g}^2\ \mathrm{V}_{ee}\ \mathrm{M}_V \text{ and}$$
$$[\Gamma(\mathrm{V} \to \mathrm{e}^\pm\mu^\mp)] \sim \mathrm{g}^2\ \mathrm{V}_{e\mu}\ \mathrm{M}_V, \text{ while } [\Gamma(\mathrm{W} \to \mathrm{e}\nu)] \sim \mathrm{g}_W^2\ \mathrm{M}_W$$

$$[BR(\mu \to 3e)]_{V-exch} \approx \frac{[\Gamma(V \to e^+e^-)][\Gamma(V \to e^\pm\mu^\mp)]}{[\Gamma^2(W \to e\nu)]}\left(\frac{M_W}{M_V}\right)^6 \quad \text{----(3)}$$

$$BR(\Upsilon \to e\mu) = BR(\mu \to eee)\frac{\Gamma(W \to e\nu)^2}{\Gamma(\Upsilon)\Gamma \to ee}\left(\frac{M_\Upsilon}{M_W}\right)^6 \quad \text{----(4)}$$

$$\mathrm{BR}(\Upsilon(3S)) \to e^\pm\mu^\mp \le 2.5 \times 10^{-8}.$$

- $\mathrm{BF}(\mu \to \mathrm{eee}) \le 1.0 \times 10^{-12}$
- $\mathrm{BF}(\mu \to e\nu\bar{\nu}) \simeq 100\ \%$
- $\mathrm{BF}(\mathrm{W} \to \mathrm{e}^+\nu) \simeq (10.71 \pm 0.09)\ \%$
- $\mathrm{BF}(\Upsilon(3S) \to \mathrm{l}^+\mathrm{l}^-) \simeq (2.18 \pm 0.21)\ \%$
- $\Gamma(\Upsilon(3S)) = (20.32 \pm 1.85)\ keV$
- $\Gamma(\mathrm{W}) = (2.046 \pm 0.049)\ GeV$

S.Nussinov, et. al. estimate that the contribution of the virtual ϒ $(3S) \rightarrow e^\pm\mu^\mp$ to the μ $\rightarrow eee$ rate would be reduced by approximately $M^2_\mu / (2\ M^2_\Upsilon)$ leading to a re-calculated indirect bound:
BF(ϒ $(3S) \rightarrow e^\pm\mu^\mp) < 1\times 10^{-3}$

[1] Nussinov, et. al. PRD 63, 016003 (2001)

$$\frac{m_\mu^2}{2M_V^2} = \left\{ \begin{array}{ll} 3\times10^{-3} & V=\phi \\ 3\times10^{-4} & V=J/\psi \\ \boxed{3\times10^{-5} \quad V=\Upsilon} & \\ 3\times10^{-7} & V=Z^0 \end{array} \right\}.$$

Back up: Analysis Scheme

- **Blind Analysis:** To eliminate experimenter's bias.
- **Pre-Selection:** Needs a special background filter to collect $e^{\pm}\mu^{\mp}$ events efficiently.
- **Final Selection by the analyst:** Applied on the pre-selected events
- **PID Selection:** Multivariate Technique applied, tested 16 different PID selectors.
- **Optimized Electron and Muon selectors:** ${}^{\varepsilon_{e\mu}}\!/\!{}_{\sqrt{(1+N_{BG})}}$ where

  $\varepsilon_{e\mu}$ is the final efficiency as determined by signal MC and

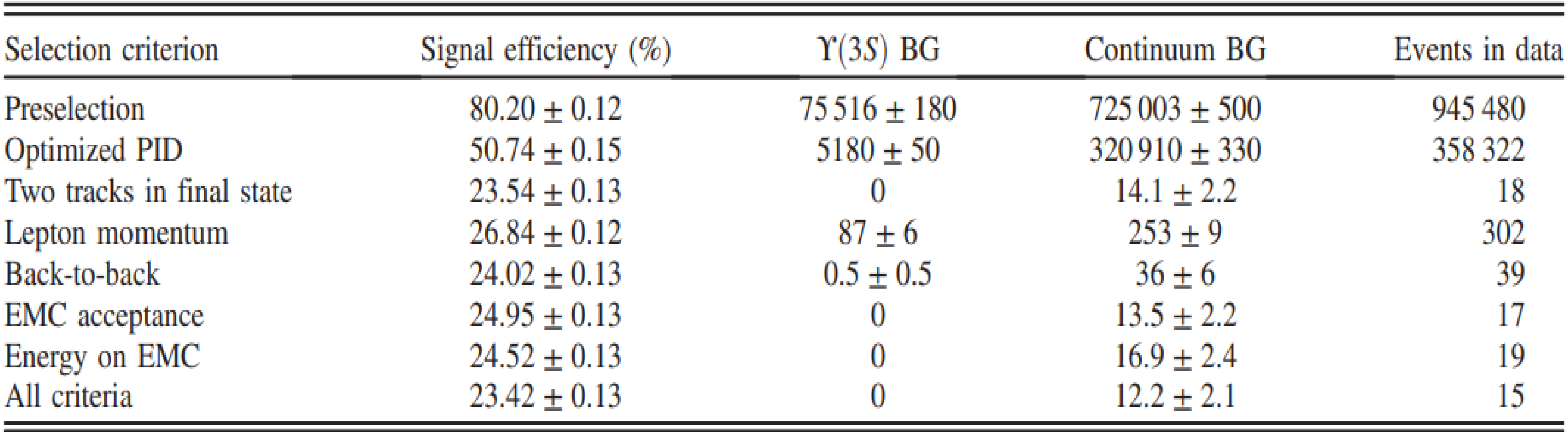
  N_{BG} is the number of expected background events

Final Selection:
2 tracks (1 electron and 1 muon in the final state), one in each hemisphere;
$24° < \theta_{Lab} < 130°$ EMC acceptance for both tracks.
The lepton momenta must satisfy the following condition $\left(\frac{p_e}{E_{Beam}} - 1\right)^2 + \left(\frac{p_\mu}{E_{Beam}} - 1\right)^2 < 0.01$ where $E_{Beam} = {}^{\sqrt{s}}\!/\!{}_2$
Angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179°$ to ensure they emerged as back to back.
Energy deposit by Muon track on the Electromagnetic Calorimeter should be greater than 50 MeV.

Peaking Background

Source of Background	**Data Driven Continuum Background Υ(4S)**	**Peaking Background from Generic Υ(3S) MC**
Tight PID selection	12.2 ± 2.1	0
Loose PID selection	N/A	1.80 ± 0.9

Back up: Impact of each component of the selection on the signal efficiency, background and data



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- The first row provides information on the pre-selection of the events as $\boldsymbol{\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}}$.
- The last row provides information after applying all selection criteria.
- Rows 2-7 provides information when all requirements are applied except the criterion associated with the particular row.
- Third column represents the background events from $e^+e^- \rightarrow \boldsymbol{\Upsilon(3S)}$ **defining as generic MC Background**.
- Fourth column represents the background events from $e^+e^- \rightarrow \boldsymbol{\Upsilon(4S)}$ **defining as data-driven Continuum Background.**
- Event numbers in the third and forth columns are luminosity-normalized.
- The last column gives the number of events in the 27 fb^{-1} data sample after unblinding.
- We have added an additional uncertainty of ± 0.9 any potential peaking background from the $\Upsilon(3S)$ decays which estimate the background events 12.2 ± 2.3

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