Υ(nS) at BaBar: New physics searches with lepton flavor violation, lepton universality, or final states with tau leptons

Elisa Guido
University & INFN Genova
(on behalf of **BaBar Collaboration**)

The 11th International Workshop on Tau Lepton Physics
Manchester, UK, 14th September 2010

Outline

BABAR $\Upsilon(3,2S)$ datasets have produced several results in the search for New Physics (NP) effects:

- ✓ Charged Lepton Flavor Violation as a probe of NP (search for LFV in $\Upsilon(3,2S) \to e^{\pm}\tau^{\mp}$, $\mu^{\pm}\tau^{\mp}$ decays)

  PRL 104, 151802 (2010)
  [arXiv:1001.1883]

- ✓ Searches for the beyond Standard Model-Higgs A^0:
  - ✓ in $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

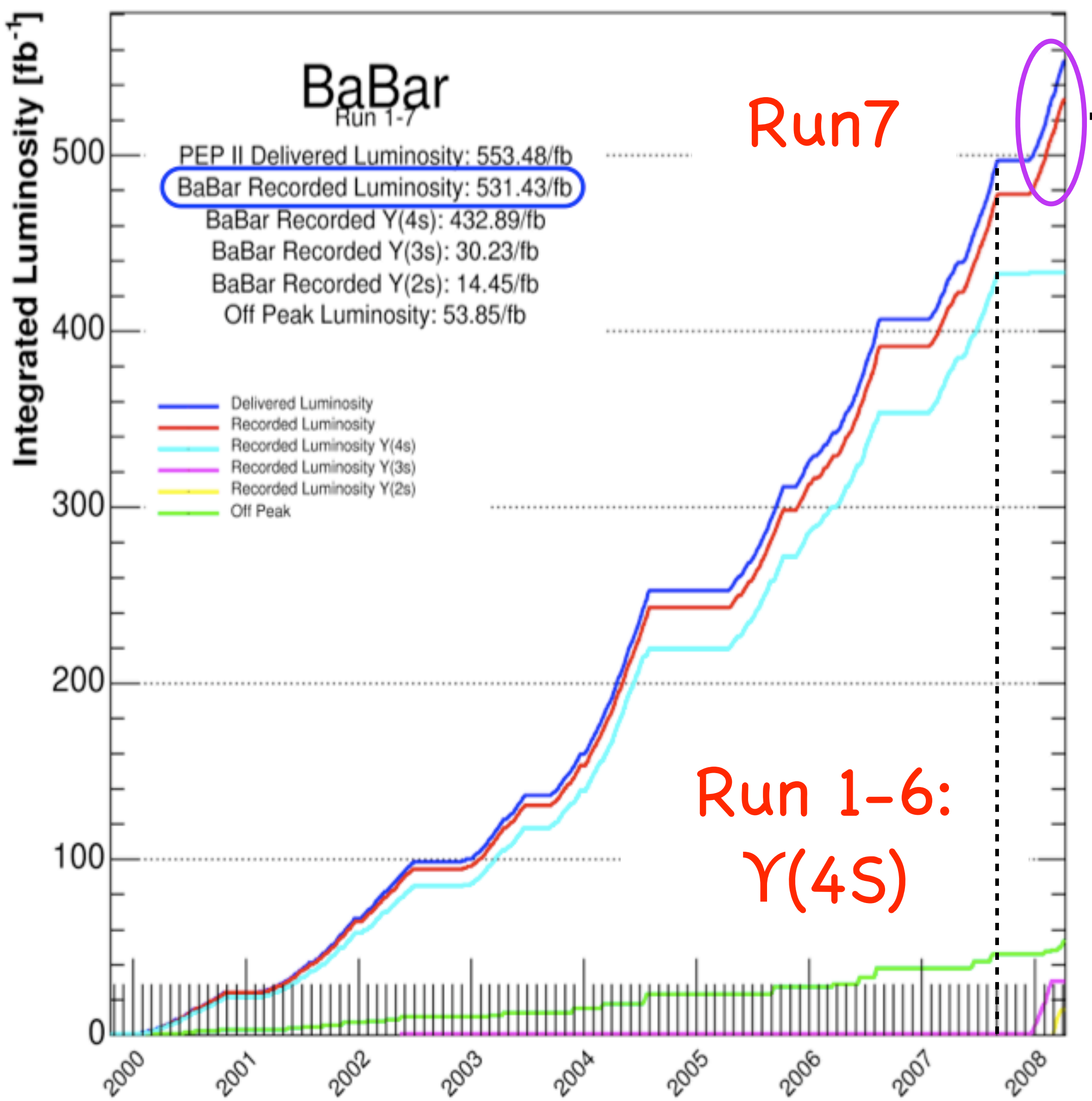
    PRL 103, 181801 (2009)
    [arXiv:0906.2219]

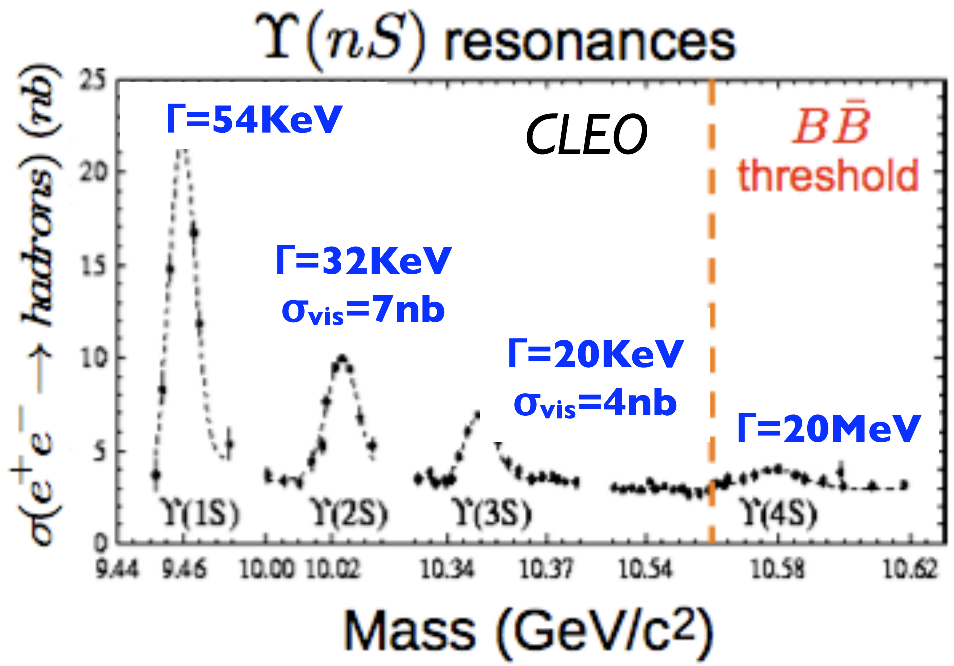
  - ✓ Lepton Universality test in $\Upsilon(1S)$ decays

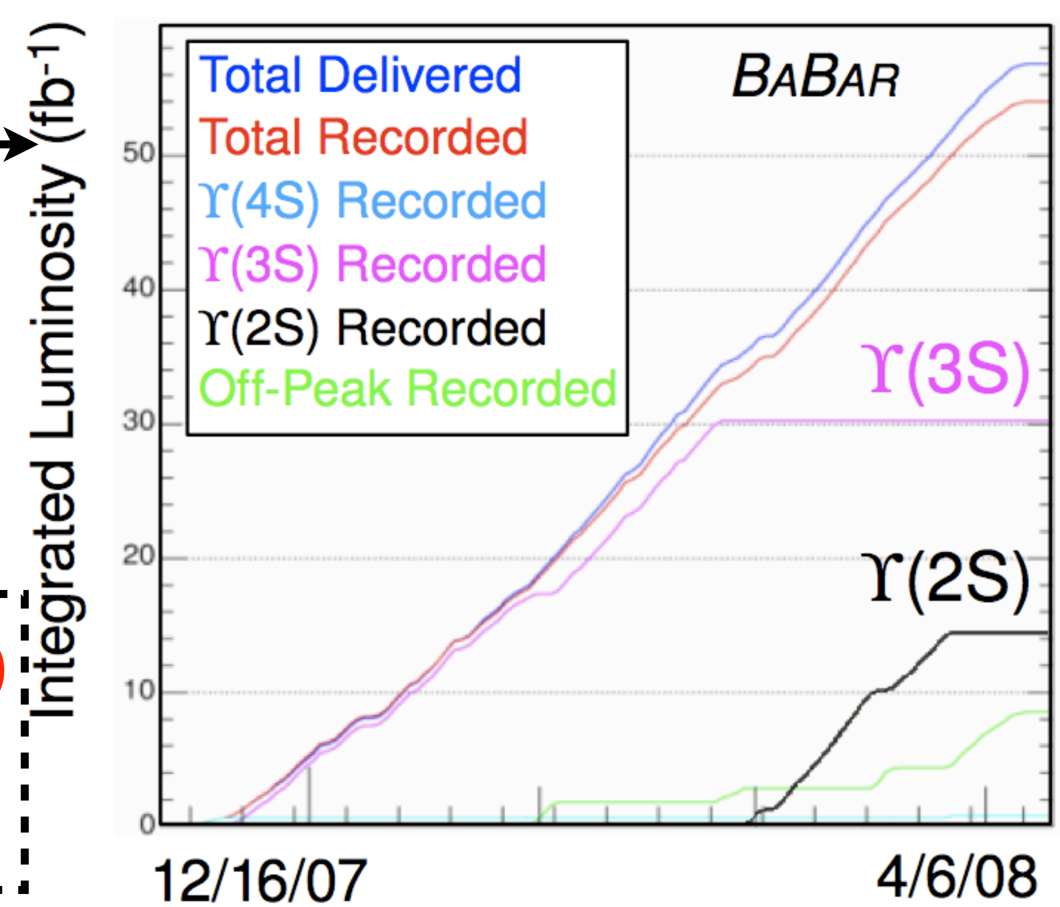
    PRL 104, 191801 (2010)
    [arXiv:1002.4358]

BaBar data samples

- ✓ PEP-II asymmetric energy e^+e^--collider operating at the Υ resonances
- ✓ BaBar recorded luminosity

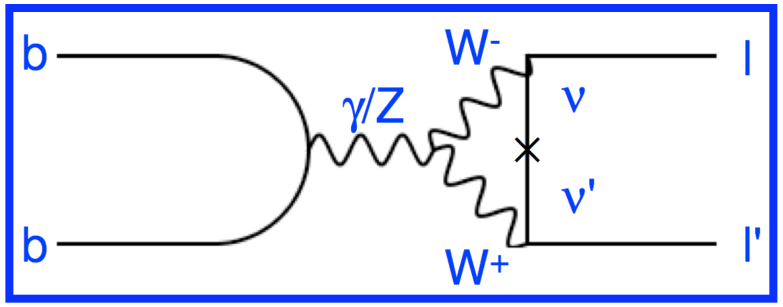




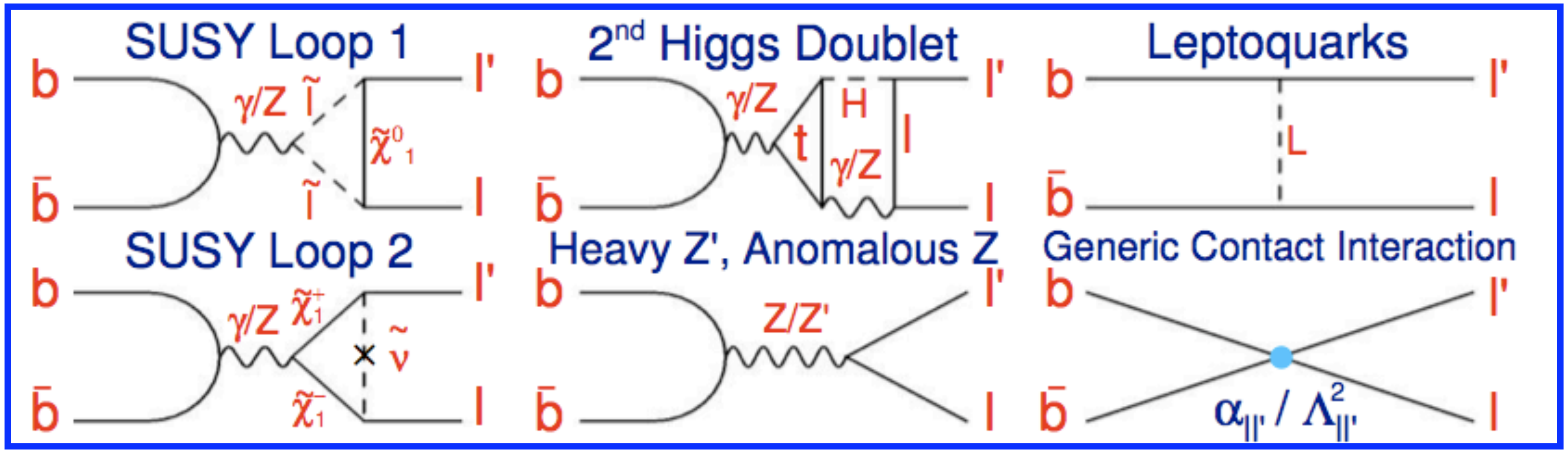


- ✓ 28.5 fb^{-1} of data at $\Upsilon(3S)$ → **~122·10⁶ $\Upsilon(3S)$**
- ✓ 14.4 fb^{-1} of data at $\Upsilon(2S)$ → **~99·10⁶ $\Upsilon(2S)$**

Charged LFV as a NP probe



- ✓ In the SM with ν-masses oscillation LFV can occur
- ✓ Never observed in processes involving **charged** LFV, for instance **Υ→ll'** decays: tree-level contribution suppressed by $(\Delta m_\nu^2/M_W^2)^2 \lesssim 10^{-48}$ to undetectable levels
- ✓ Enhancements close to experimental sensitivity (BR~$\mathcal{O}(10^{-8})$) in many extensions of the SM



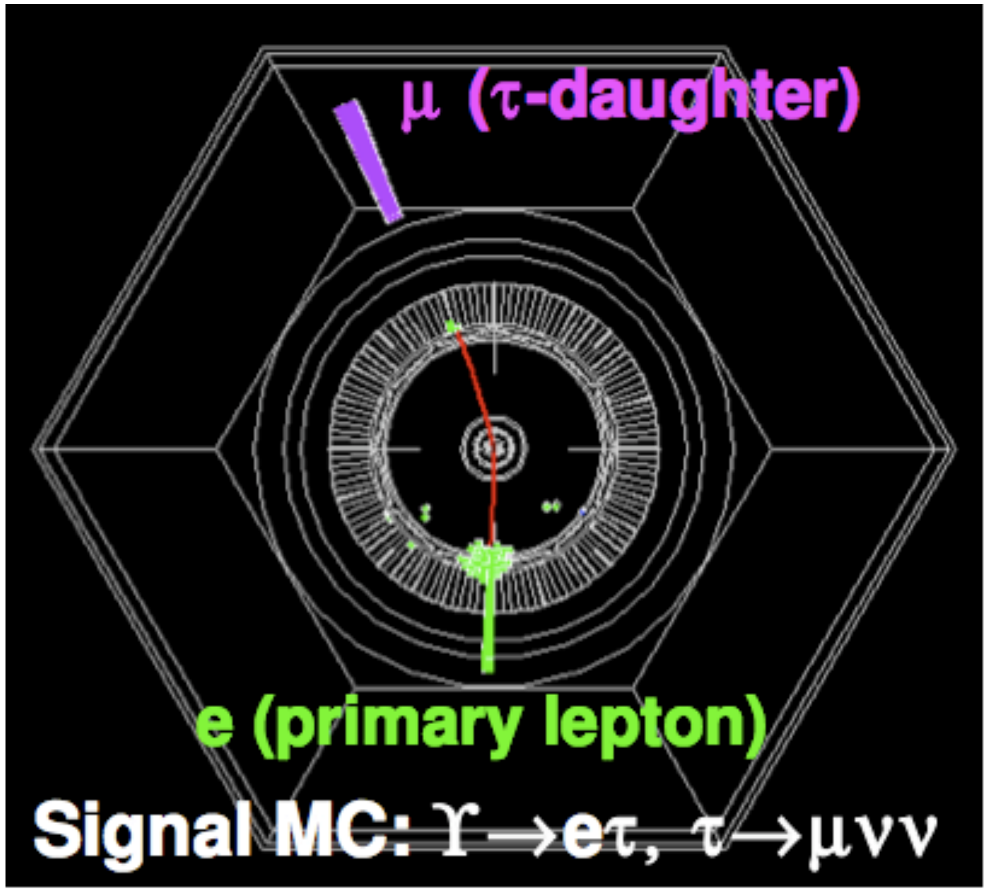
- ✓ Observation of charged LFV clear signature of NP
- ✓ Search for charged LFV at BABAR in several other decays (see talks in the LFV sections)

LFV in Υ decays

PRL 104, 151802 (2010)

1. Strategy

- ✓ Search for **Υ(nS)→$l^{\pm}\tau^{\mp}$** with n=2,3 and l=e,μ
- ✓ Signature:
  - 1 primary lepton (e or μ)
  - 1 τ detected through a leptonic (μ or e) or hadronic ($\pi^{\pm}$+π^{0}) decay
  - ✓ in case of a leptonic τ decay, the τ-daughter is opposite in flavor w.r.t. the primary lepton



Process	τ decay	Channel
Υ(3,2S)→eτ	τ→μνν	leptonic eτ
Υ(3,2S)→eτ	τ→$\pi^{\pm}\pi^{0}\nu$/$\pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic eτ
Υ(3,2S)→μτ	τ→eνν	leptonic μτ
Υ(3,2S)→μτ	τ→$\pi^{\pm}\pi^{0}\nu$/$\pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic μτ

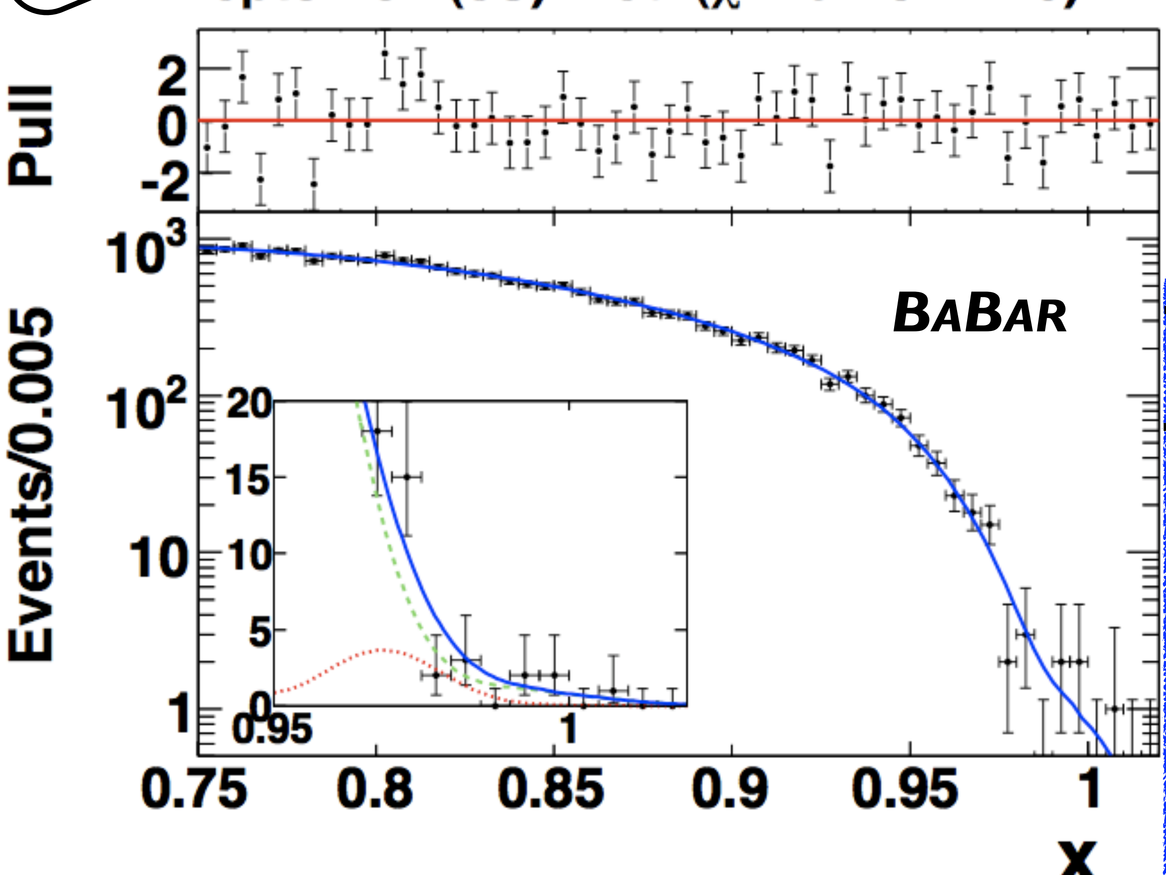
- ✓ Background events:
  - Bhabha and μ-pair (and mis-ID)
  - τ-pair
  - multiple π and additional γ
- ✓ Selection partially common to the 4 channels, partially channel-specific (particle-ID, τ-daughter kinematics)

2. Signal extraction and results

- ✓ Discriminating variable: **x** = primary lepton momentum/beam energy
- ✓ Unbinned extended maximum-likelihood fit
- ✓ PDFs chosen for: - signal (peaks at $x=x_{MAX}\sim0.97$) ⟶ from extracted signal yields, BR calculated
  - τ-pair bkg (smooth, endpoint at x_{MAX})
  - Bhabha/μ-pair bkg (peaks at x~1)
  - hadron bkg (smooth, endpoint at x_{MAX})

$$\mathcal{B} = N_{SIG}/(\epsilon_{SIG} \times N_{\Upsilon(nS)})$$

An example of fit:



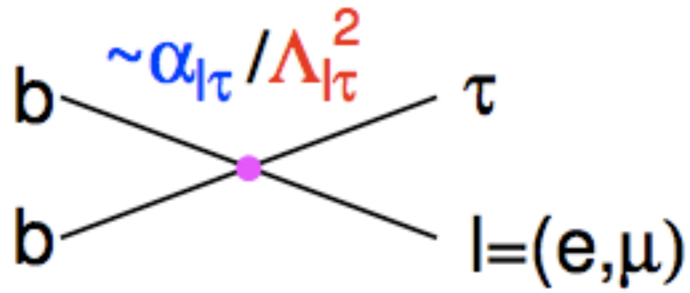
Systematic uncertainties (mainly from PDF shapes) and corrections applied

PRL101, 201601 (2008)

	$\mathcal{B}$ (10^{-6})	UL (10^{-6})	Improvement factor
$\mathcal{B}(\Upsilon(2S) \to e^{\pm}\tau^{\mp})$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	< 3.2	**first**
$\mathcal{B}(\Upsilon(2S) \to \mu^{\pm}\tau^{\mp})$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	< 3.3	**5.5**
$\mathcal{B}(\Upsilon(3S) \to e^{\pm}\tau^{\mp})$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	< 4.2	**first**
$\mathcal{B}(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$-0.8^{+1.5+1.4}_{-1.5-1.3}$	< 3.1	**3.7**

3. Constraints on NP

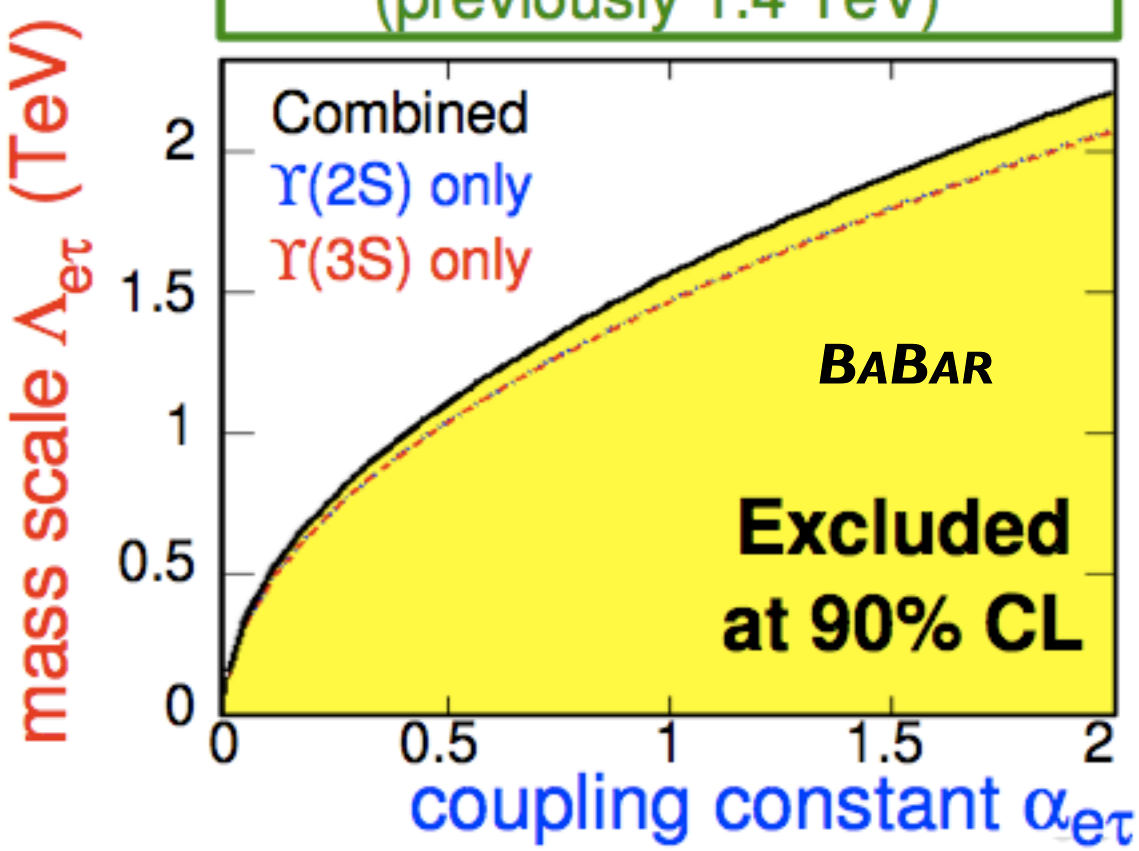
- ✓ NP constraint using effective field theory
- ✓ Charged LFV-Υ decays parameterized as a $b\bar{b}l^{\pm}\tau^{\mp}$ contact interaction with a NP coupling constant ($\alpha_{l\tau}$) and a mass scale ($\Lambda_{l\tau}^2$)



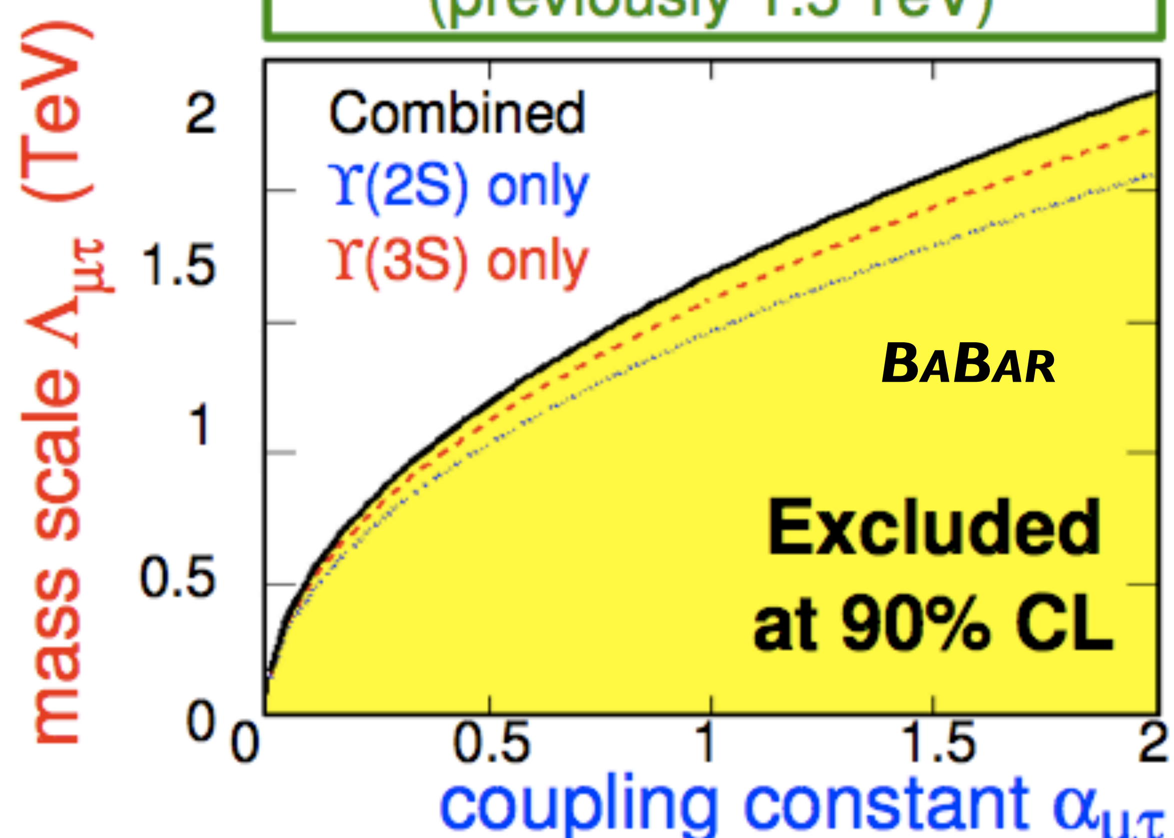
$$\frac{\alpha_{l\tau}^2}{\Lambda_{l\tau}^4} = \frac{BF(\Upsilon(3S)\to l\tau)}{BF(\Upsilon(3S)\to ll)} \frac{2q_b\alpha^2}{(M_{\Upsilon(nS)})^4} \quad l = (e,\mu)$$

Silagadze Phys.Scripta 64,128 (2001) & Black et al. PRD66, 053002 (2002)

$\alpha_{e\tau} = 1 \to \Lambda_{e\tau} > 1.6$ TeV
(previously 1.4 TeV)



$\alpha_{\mu\tau} = 1 \to \Lambda_{\mu\tau} > 1.7$ TeV
(previously 1.5 TeV)

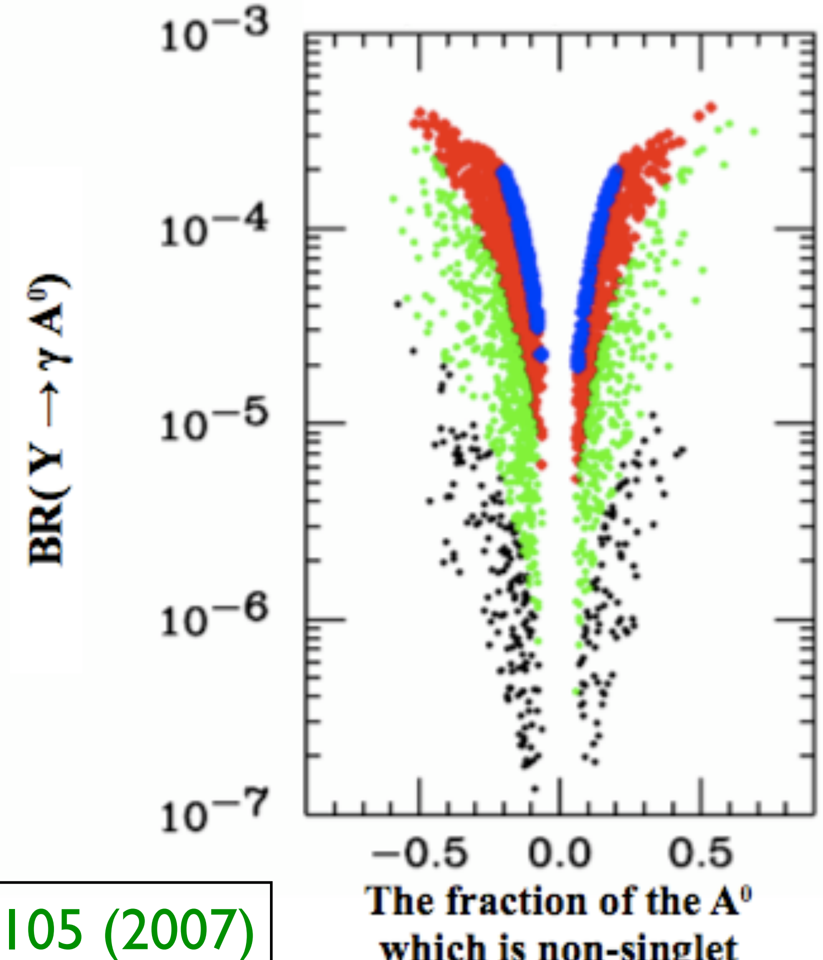


A^0: a light CP-odd Higgs boson

- Next to Minimal Super-symmetric SM (**NMSSM**) foresees a light pseudo-scalar Higgs boson $A^0 = \cos(\theta_A) a_{MSSM} + \sin(\theta_A) a_{singlet}$
  - Not excluded by LEP limits
  - Light -> accessible to B-factories
- Radiative decays of narrow Υ resonances have predicted BRs up to $\sim\mathcal{O}(10^{-4})$:
  - $\Upsilon(nS)\to\gamma A^0$, with $A^0\to l^+l^-$ ($l=\mu,\tau$)
  - $\Upsilon(nS)\to\gamma A^0$, with $A^0\to$invisible

  (with the different A^0 decays dominant for different mass regions)
- If the photon is energetic enough, it can be detected in the energy spectrum

$M(A^0)<2M(\tau)$
$2M(\tau)<M(A^0)<7.5$ GeV/c^2
$7.5<M(A^0)<8.8$ GeV/c^2
$8.8<M(A^0)<9.2$ GeV/c^2

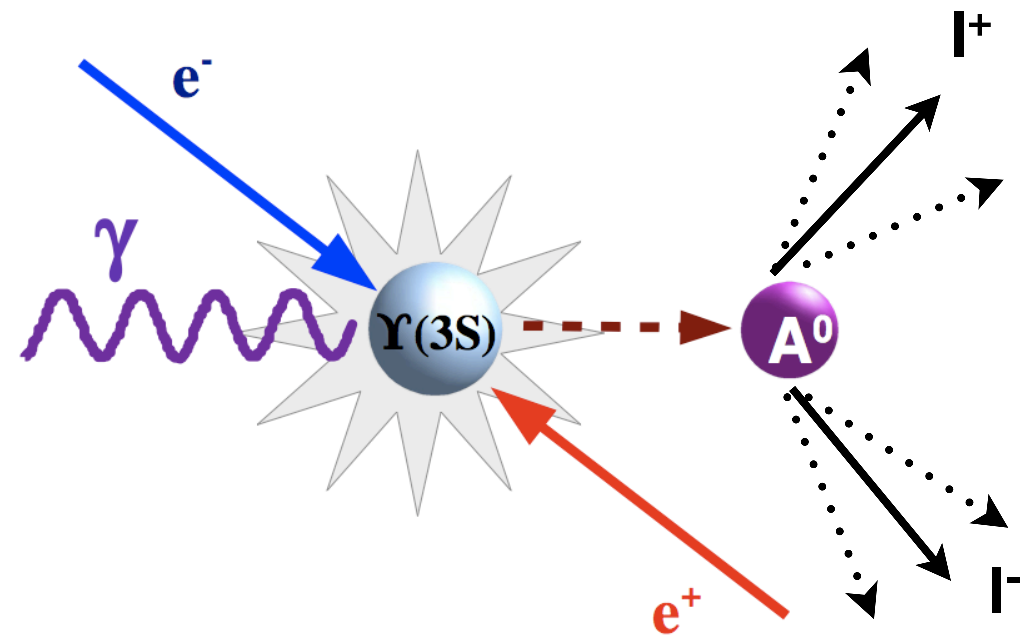


PRD 76, 051105 (2007)

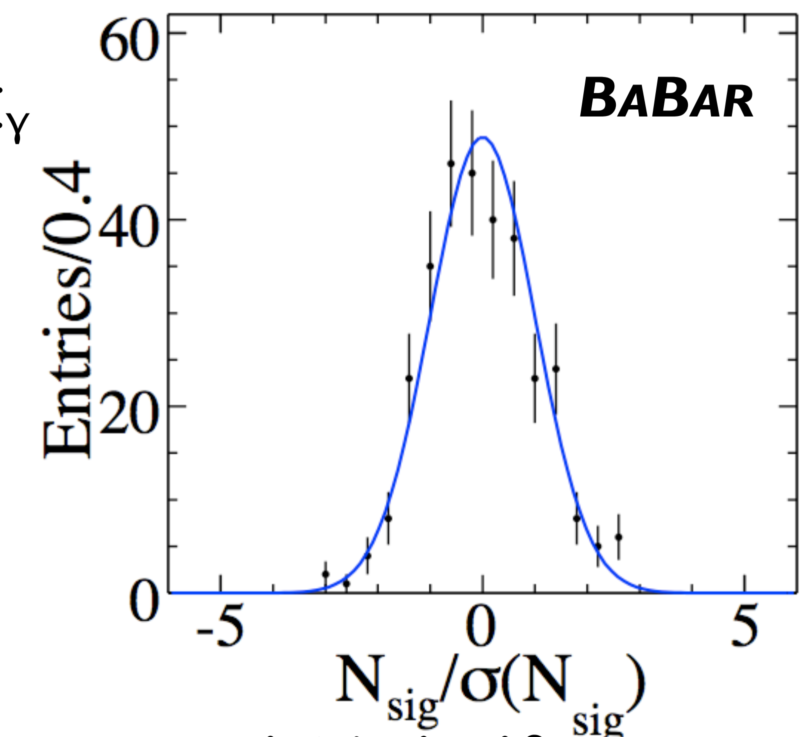
$\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

PRL 103, 181801 (2009)

1. Strategy



- 1 photon with $E_\gamma > 100$ MeV
- τ reconstructed through $\tau \to l\nu_l\bar{\nu}_\tau$ with $l=e,\mu$
  - 2 oppositely-charged leptons
  - final state not fully reconstructed
  - 3 samples: γee, $\gamma\mu\mu$ and $\gamma e\mu$
- Bkg: QED events ($e^+e^- \to \gamma\tau^+\tau^-$, and higher-order processes) and peaking events $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma\Upsilon(nS)$, with J=0,1,2 and n=1,2
- Event selection optimized in 5 overlapping regions of E_γ
- Signal extraction:
  - scan for peaks in the E_γ distribution in a range corresponding to $4.03 < M(A^0) < 10.10$ GeV/c^2
  - set of binned maximum-likelihood fits
  - distribution of fit results agrees with the null hypothesis

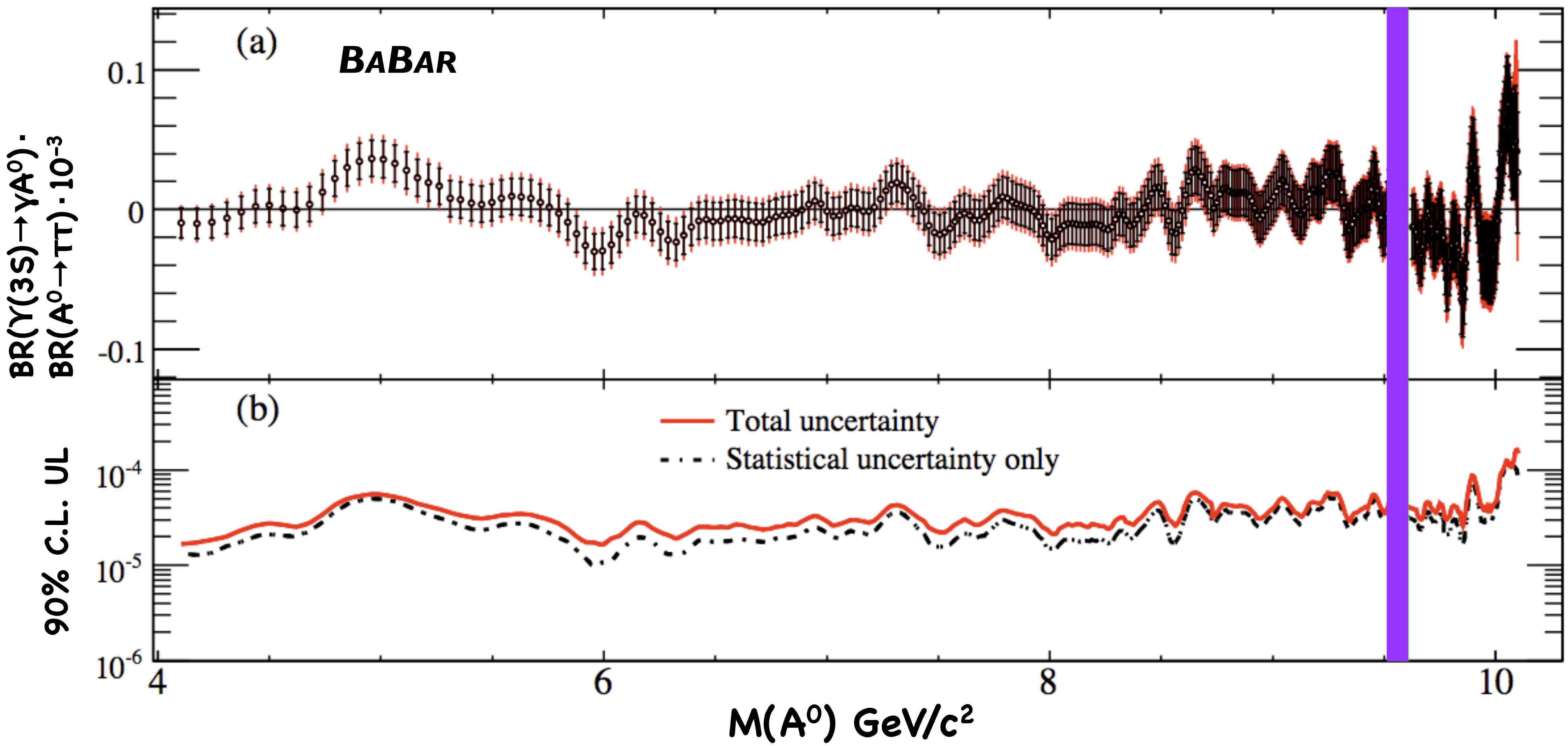


yield significance

2. Constraints on NP

- no statistically significant signal yield -> 90% C.L. upper limits
- **$BR(\Upsilon(3S)\to\gamma A^0)\cdot BR(A^0\to\tau\tau) < (1.5\text{-}16)\cdot 10^{-5}$**

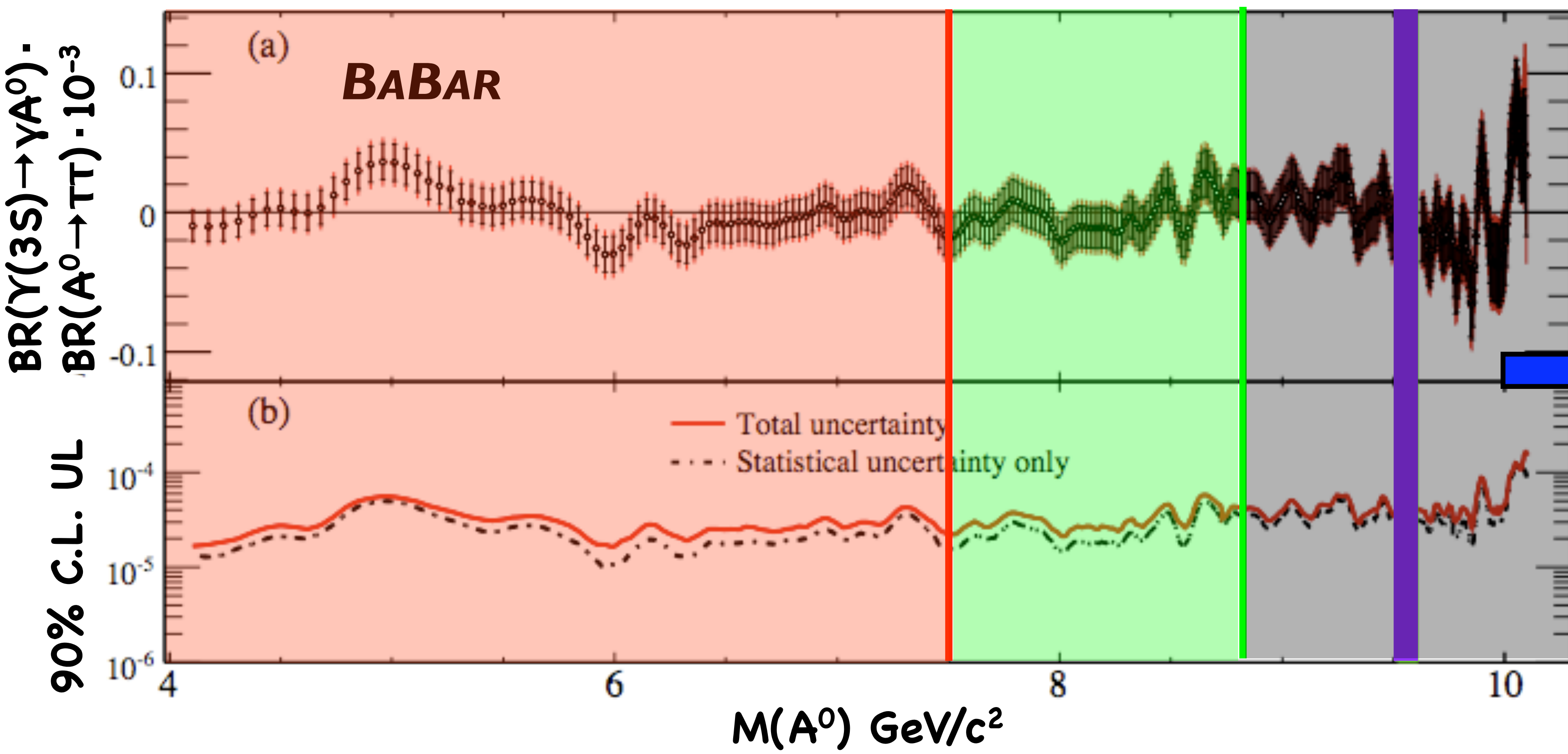
region $\chi_{bJ}(2P)\to\gamma\Upsilon(1S)$ excluded
$[9.52 < M(A^0) < 9.61\ GeV/c^2]$



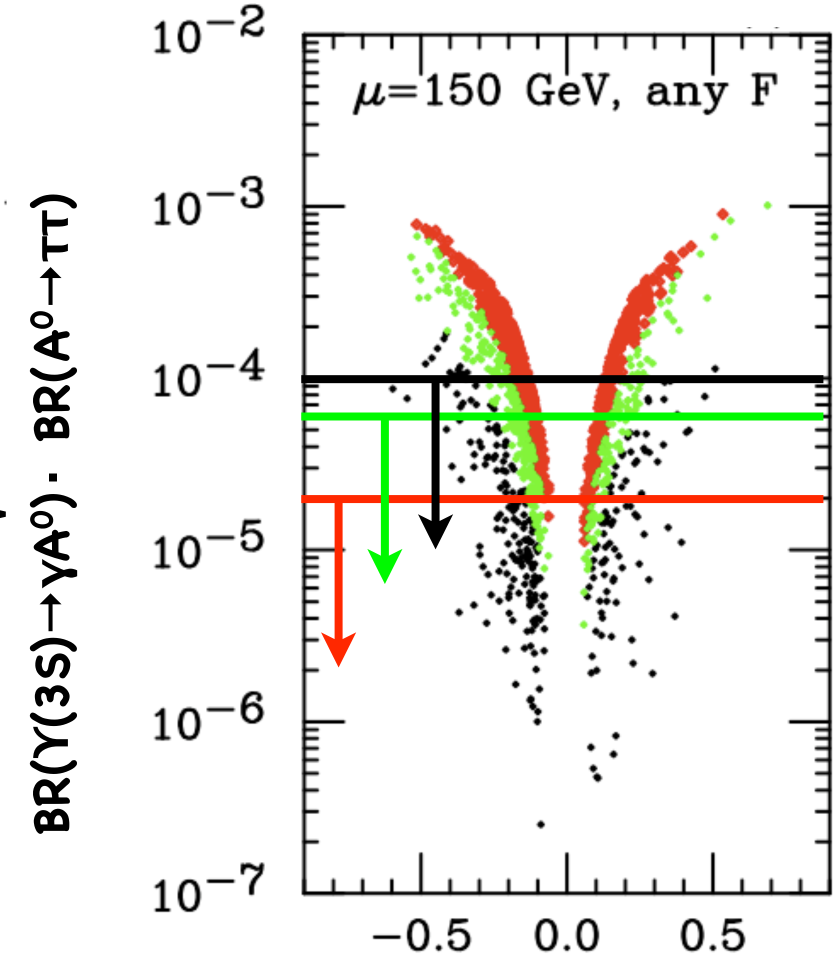
2. Constraints on NP

- no statistically significant signal yield -> 90% C.L. upper limits
- $BR(\Upsilon(3S)\to\gamma A^0)\cdot BR(A^0\to\tau\tau) < (1.5\text{-}16)\cdot 10^{-5}$

region $\chi_{bJ}(2P)\to\gamma\Upsilon(1S)$ excluded



PRD 81, 075003 (2010)



$2M(\tau)<M(A^0)<7.5$ GeV/c^2
$7.5<M(A^0)<8.8$ GeV/c^2
$8.8<M(A^0)<2M(b)$ GeV/c^2

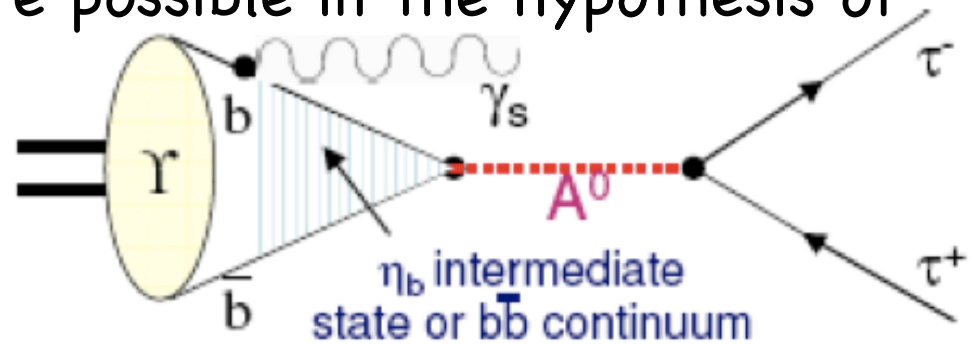
Lepton Universality test

(see M.A.Sanchis-Lozano's talk)

PRL 104, 191801 (2010)

1. Theory

- ✓ In the SM couplings between gauge bosons and leptons are independent of lepton flavor
- ✓ SM expectation for $R_{ll'} = BR(\Upsilon(1S)\to l^+l^-)/BR(\Upsilon(1S)\to l'^+l'^-)$ is ~ 1 (except for small lepton-mass effects, $R_{\tau\mu} \sim 0.992$)
- ✓ NMSSM: deviations of $R_{ll'}$ from SM expectation are possible in the hypothesis of existence of A^0



- ✓ A^0 may mediate the decay chain of the $\Upsilon(1S)$:

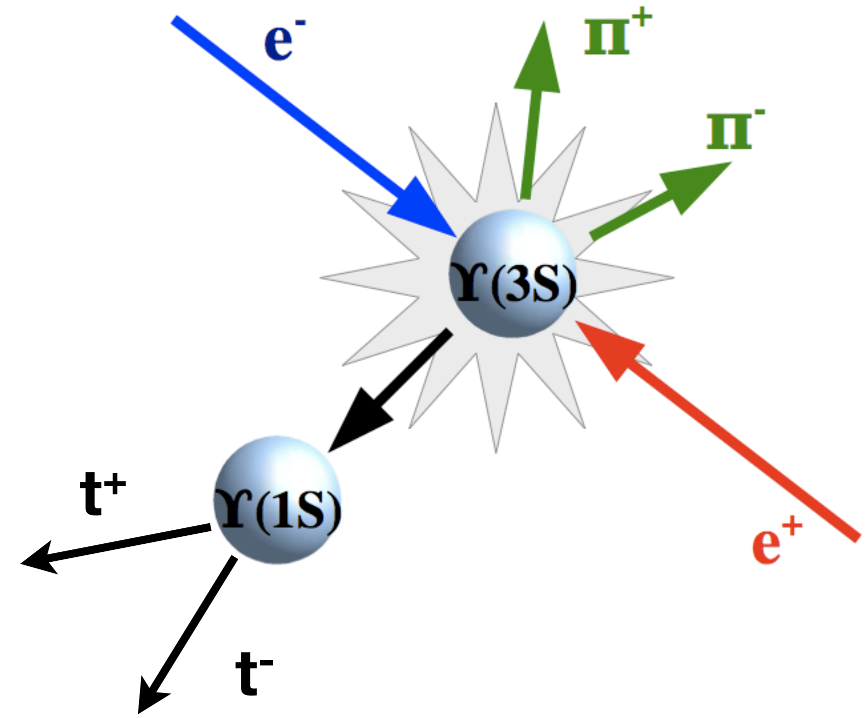
$$\Upsilon(1S)\to A^0\gamma,\ A^0\to l^+l^- \quad (1)$$

$$\Upsilon(1S)\to \eta_b(1S)\gamma,\ \eta_b(1S)\leftrightarrow A^0\to l^+l^- \quad (2)$$

Int.J.Mod.Phys.A19, 2183 (2004);
PL B653, 67 (2007);
JHEP 0901, 061 (2009)

- ✓ If the photon is undetected, the lepton pair would be ascribed to the $\Upsilon(1S)$
  - ✓ It can result in a deviation of $R_{ll'}$ from SM expectation (**lepton universality breaking**) -> NP effect
  - ✓ Effect more evident when one of the leptons is a τ (up to 4%) -> $R_{\tau\mu}$

2. Strategy



where **t**$^{\pm}$= $\mu^{\pm}$ or **t**$^{\pm}$ = charged track from $\tau^{\pm}$ decay (accompanied by neutral particles)

- ✓ $122 \cdot 10^6$ $\Upsilon(3S)$ from BABAR
- ✓ Tag $\Upsilon(1S)$ exploiting $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$, with $\Upsilon(1S)\rightarrow\tau^+\tau^-$ or $\Upsilon(1S)\rightarrow\mu^+\mu^-$ events:
  - ✓ BF($\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$) ~ 4.5%
  - ✓ select τ 1-prong decays
  - ✓ 4-charged tracks final state topology
- ✓ Any number of extra photons allowed
- ✓ Separate selections for $\Upsilon(1S)\rightarrow\tau^+\tau^-$ and $\Upsilon(1S)\rightarrow\mu^+\mu^-$ events
- ✓ Bkg: $q\bar{q}$ events, τ-pairs, QED events, $\Upsilon(1S)$ generic decays
- ✓ A multivariate analysis approach in $\tau^+\tau^-$ channel
- ✓ Signal extraction efficiencies (estimated on MC simulations):

$\epsilon_{\mu\mu} \sim 45\%$

$\epsilon_{\tau\tau} \sim 17\%$

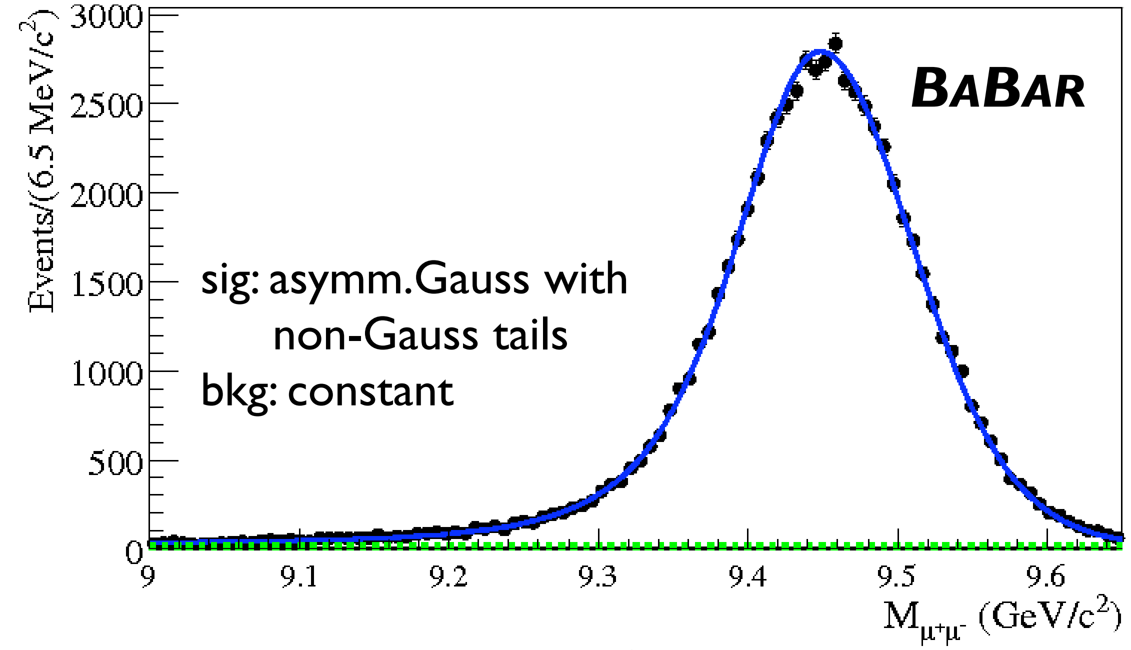
3. Signal extraction

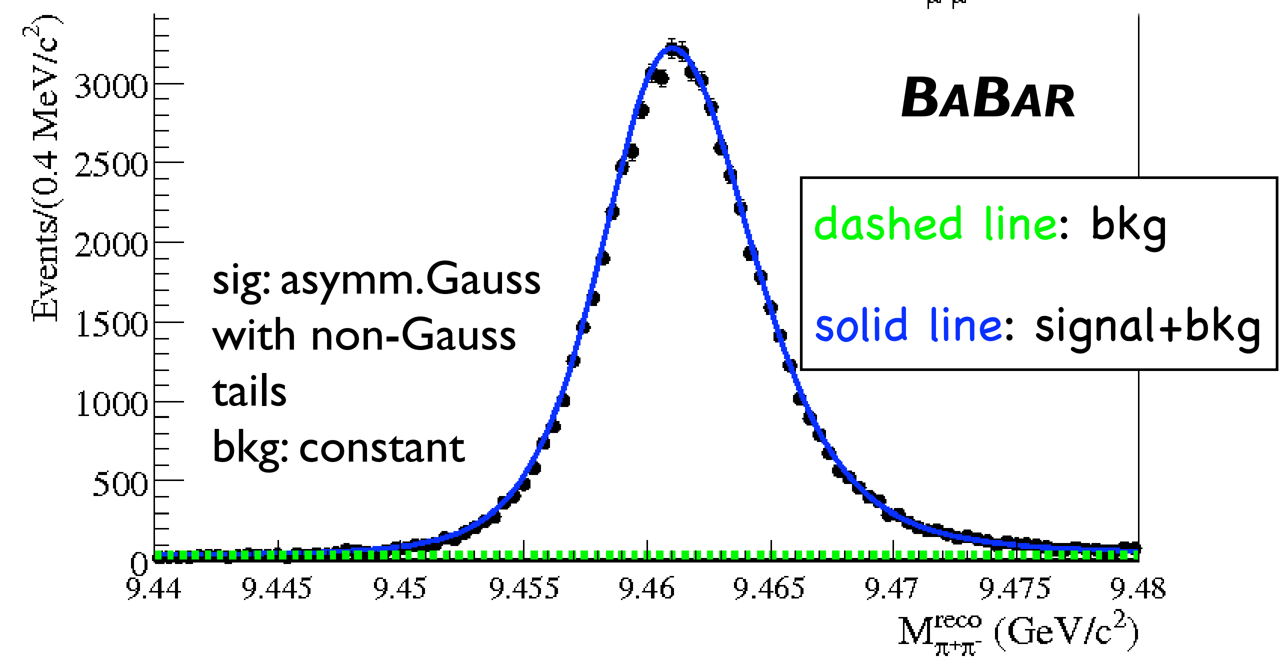
- Extended and unbinned maximum-likelihood fit:
  - in $\mu^+\mu^-$ channel a 2-dim likelihood based on $M_{\pi+\pi-}^{reco}$ and $M_{\mu+\mu-}$
  - in $\tau^+\tau^-$ channel a 1-dim likelihood based on $M_{\pi+\pi-}^{reco}$

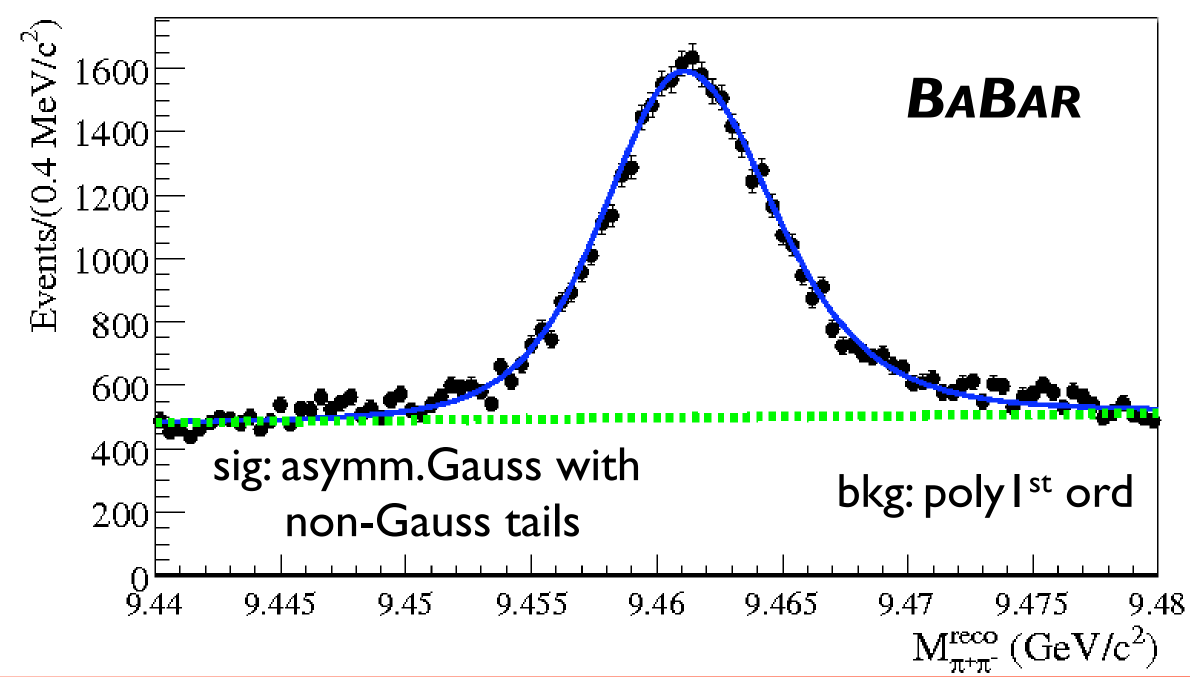
$M_{\mu+\mu-}$ invariant $\mu^+\mu^-$ mass

$$M_{\pi+\pi-}^{reco} = \sqrt{s + M^2_{\pi^+\pi^-} - 2\cdot\sqrt{s}\cdot\sqrt{M^2_{\pi^+\pi^-} + p^{*2}_{\pi^+\pi^-}}}$$

- PDFs chosen from a data sub-sample (~1/10 of the total), then discarded
- Fit performed simultaneously to the 2 datasets
- $R_{\tau\mu}$ returned







4. Results

- ✓ Correction for known differences between data and simulation efficiencies
- ✓ Systematic uncertainty contributions (up to 2.2%):
  - ✓ event selection efficiency
  - ✓ μ identification
  - ✓ trigger efficiency
  - ✓ imperfect knowledge of signal and bkg shapes
  - ✓ peaking background yield

$R_{\tau\mu}(\Upsilon(1S))$: 1.005 ± 0.013 (stat.) ± 0.022 (syst.)

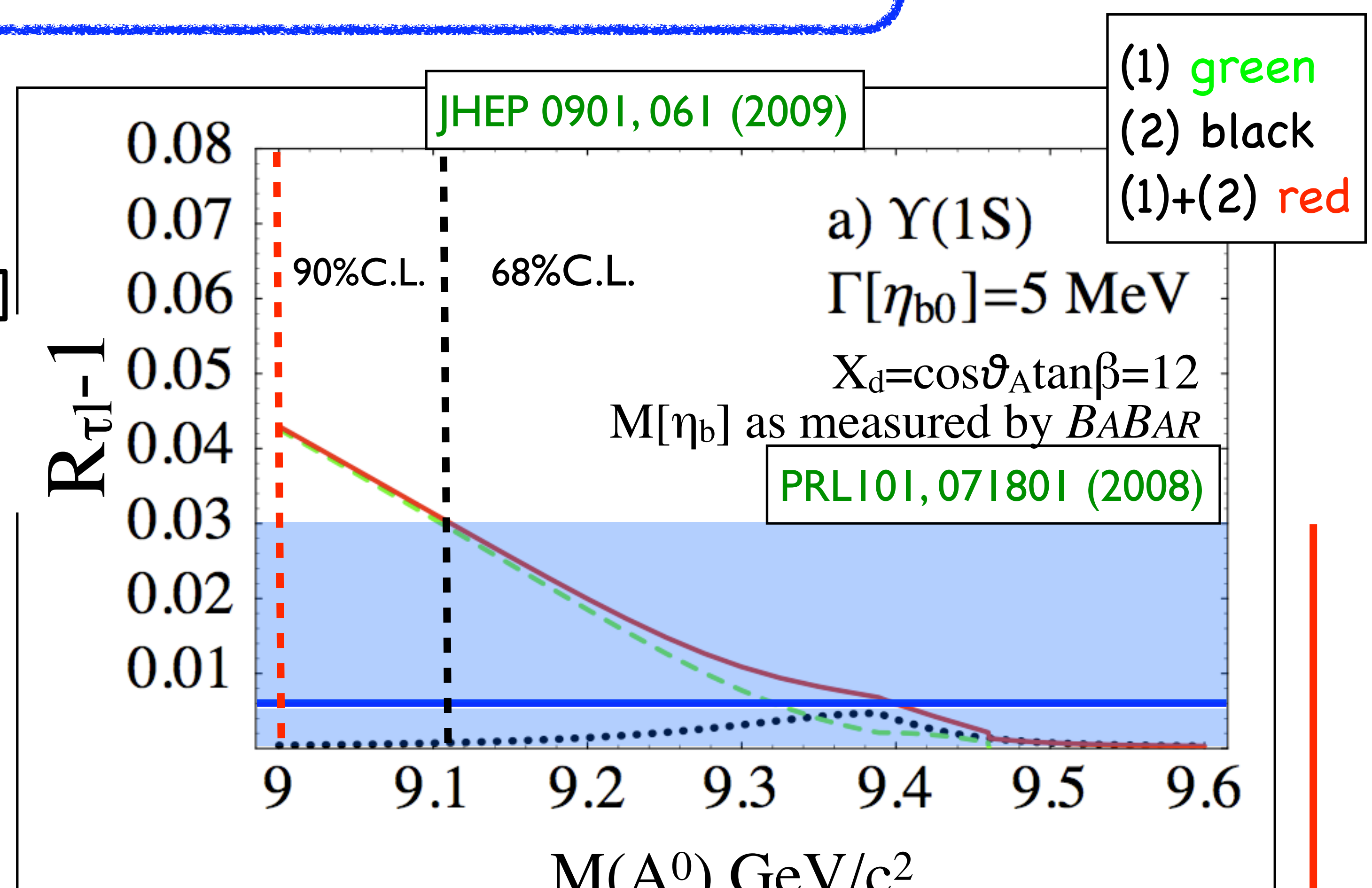
1. **Significant improvement in precision**

[Previous best result by CLEO:
$R_{\tau\mu}(\Upsilon(1S))$: 1.02 ± 0.02 (stat.) ± 0.05 (syst.)]

PRL98, 052002 (2007)

2. **No significant deviations w.r.t. SM expectations** ($R_{\tau\mu}(\Upsilon(1S))$ ~ 0.992)

3. **Excluded $M(A^0)$<9 GeV/c^2 @90%C.L.** (for large couplings)



Conclusions

- BABAR data are a rich harvest for several important searches beyond the SM
- $\Upsilon(3S)$ and $\Upsilon(2S)$ datasets give important results
- Recent results on:
  - LFV searches in Υ decays
  - Searches for A^0 in final states with τ leptons
  - Lepton Universality in $\Upsilon(1S)$ decays
- BABAR results are now able to dialogue with theoretical limits and able (or near) to exclude some foreseen parameters' space regions for several models

A list of all NP recent results @ BABAR

1. Search for Production of Invisible Final States in Single-Photon Decays of $\Upsilon(1S)$: submitted to PRL, arXiv:1007.4646
2. Test of Lepton Universality in $\Upsilon(1S)$ decays at BaBar: PRL 104, 191801 (2010)
3. Search for Charged Lepton Flavor Violation in Narrow Υ Decays: PRL 104, 151802 (2010)
4. A Search for Invisible Decays of the $\Upsilon(1S)$: PRL 103, 251801 (2009)
5. Search for a low-mass Higgs boson in $\Upsilon(3S)\to\gamma A^0$, $A^0\to\tau^+\tau^-$ at BaBar: PRL 103, 181801 (2009)
6. Search for Dimuon Decays of a Light Scalar Boson in Radiative Transitions $\Upsilon\to\gamma A^0$: PRL 103, 081803 (2009)

BACKUP SLIDES

The BaBar detector

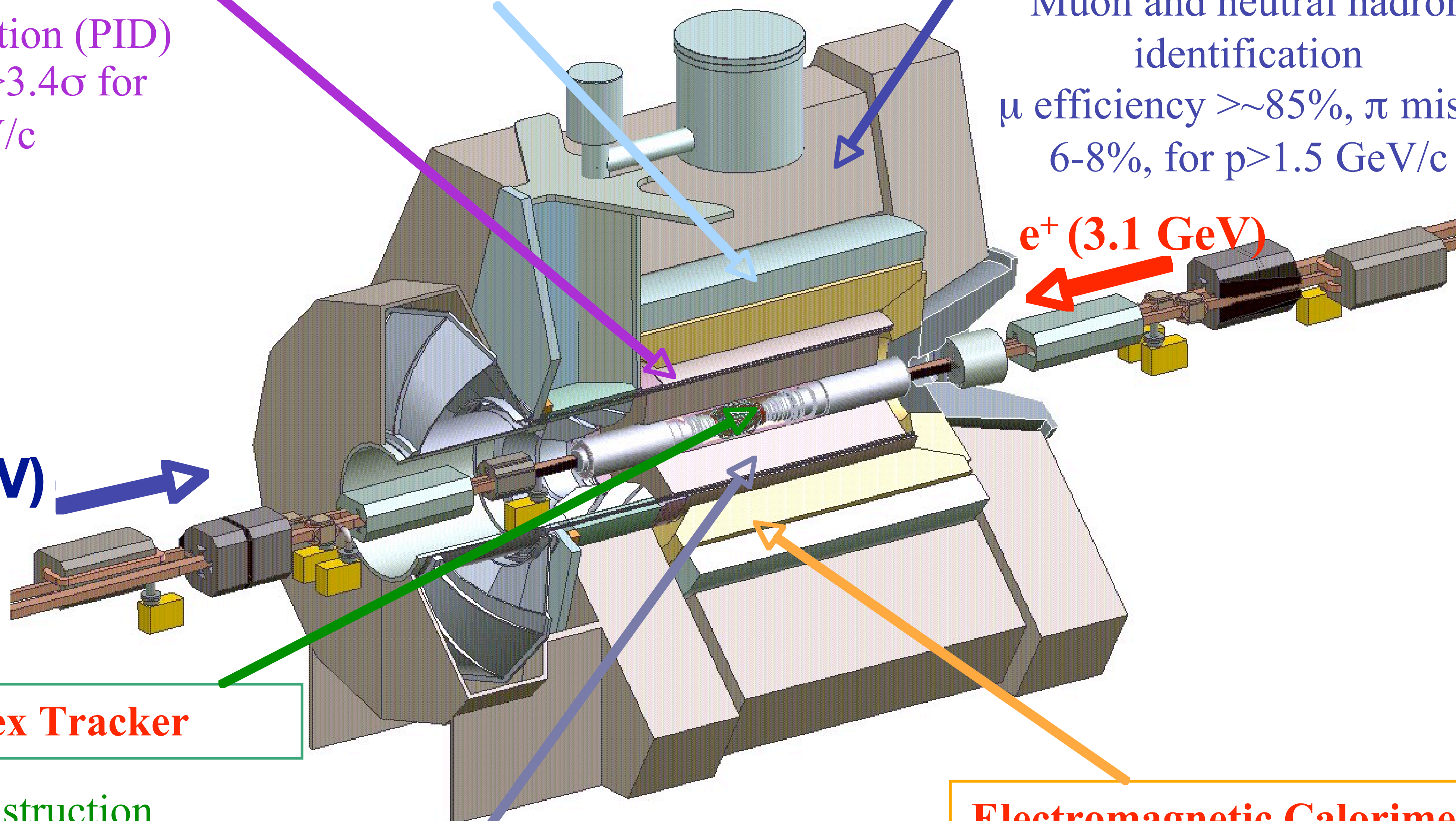
Cherenkov Detector

Particle identification (PID)
K-π separation >3.4σ for p<3.5GeV/c

Solenoid 1.5T

Instrumented Flux Return

Muon and neutral hadron identification
μ efficiency >~85%, π mis-id 6-8%, for p>1.5 GeV/c



Silicon Vertex Tracker

Vertex reconstruction and tracking + dE/dx.
Efficiency ~ 97%

Drift Chamber

Momentum measurement for charged particles + dE/dx.
$\sigma(p_T)/p_T = 0.13\% p_T \oplus 0.45\%$

Electromagnetic Calorimeter

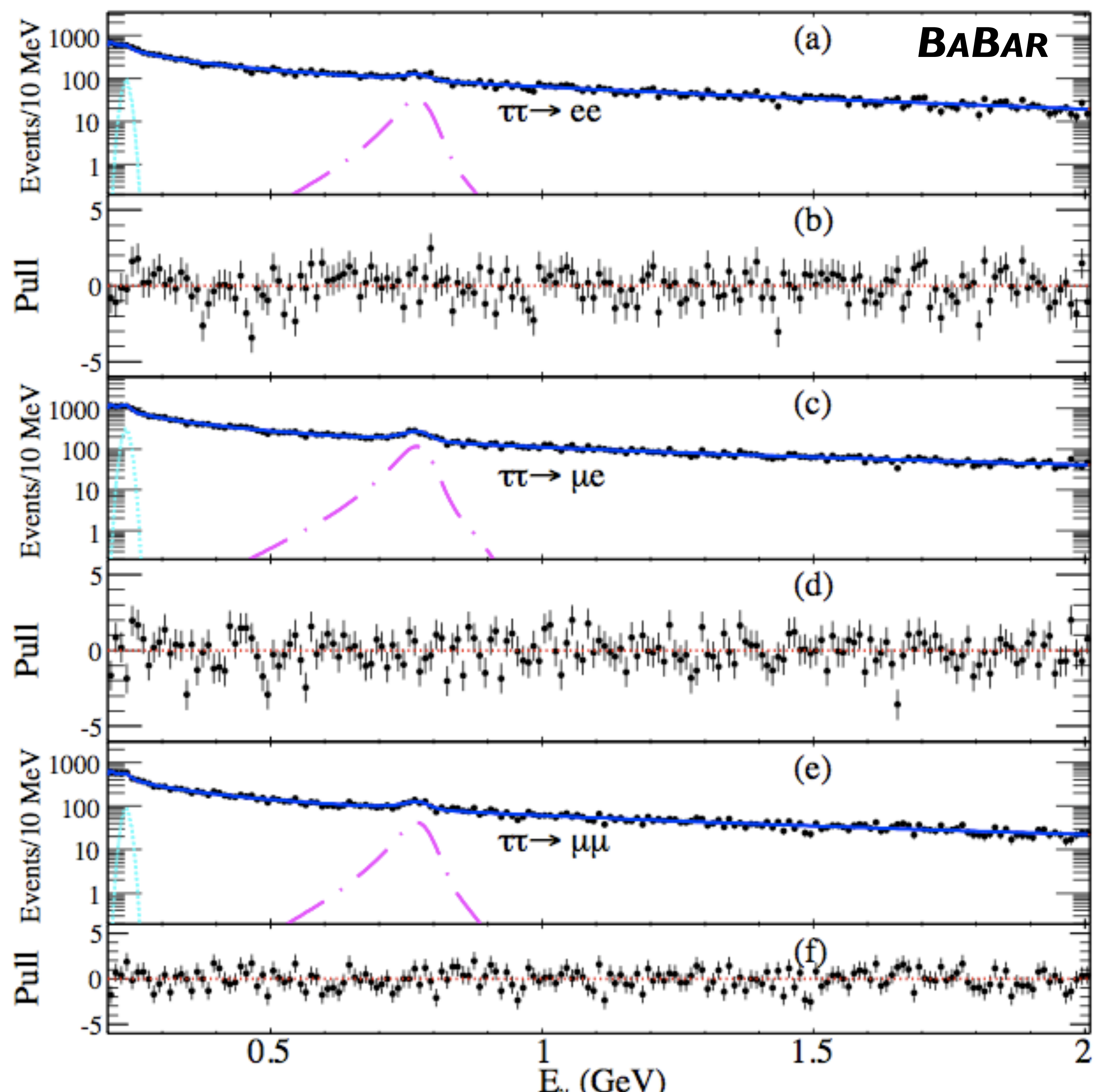
Electron and photon energy measurement. $\sigma(E)/E = 1.33\% E^{-1/4} \oplus 2.1\%$

$\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

- ✓ Bkg (smooth distribution):

$$f = (p(1-x)^r/E_\gamma^q + s/E_\gamma^5)\cdot\beta(x)\cdot(3-\beta^2(x))$$
$$\beta(x) \equiv \sqrt{1-4m_\tau^2/(m_{3S}^2(1-x))} \qquad x \equiv 2E_\gamma/m_{3S}$$

- ✓ $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma\Upsilon(nS)$: Crystal Ball
- ✓ Signal: Crystal Ball
- ✓ E_γ distributions for the different ττ decay modes
- ✓ Fit results superimposed, with bkg components highlighted



Lepton Universality Test

- Likelihood written as: $\mathcal{L}_{ext} = \mathcal{L}^{\mu}_{ext} \cdot \mathcal{L}^{\tau}_{ext}, \qquad \mathcal{L}^{i}_{ext} = \frac{e^{-N'_i}(N'_i)^{N_i}}{N_i!} \prod_{k=1}^{N_i} \mathcal{P}^i_k$

$$\mathcal{P}^{\mu}_k \equiv \frac{N_{sig\mu}}{N'_{\mu}} \mathcal{P}^{\mu}_k(M^{reco}_{\pi^+\pi^-}) \cdot \mathcal{P}^{\mu}_k(M_{\mu^+\mu^-}) + \frac{N_{bkg\mu}}{N'_{\mu}} \mathcal{P}^{bkg\mu}_k(M^{reco}_{\pi^+\pi^-}) \cdot \mathcal{P}^{bkg\mu}_k(M_{\mu^+\mu^-})$$

$$\mathcal{P}^{\tau}_k \equiv \frac{\epsilon_{\tau\tau}}{\epsilon_{\mu\mu}} \frac{N_{sig\mu}}{N'_{\tau}} R_{\tau\mu} \mathcal{P}^{\tau}_k(M^{reco}_{\pi^+\pi^-}) + \frac{N_{bkg\tau}}{N'_{\tau}} \mathcal{P}^{bkg\tau}_k(M^{reco}_{\pi^+\pi^-})$$

- Asymmetric Gaussian with non-Gaussian tails functional form:

$$\mathcal{F}(x) = exp\left\{ - \frac{(x-\mu)^2}{2\sigma^2(L,R) + \alpha(L,R)(x-\mu)^2} \right\}$$

- Summary of systematic uncertainties:

	$\mu^+\mu^-$	$\tau^+\tau^-$
event selection	1.2%	
PID	1.2%	—
Trigger	0.18%	0.10%
BGF	negl.	negl.
PDFs parameters	1.1%	
Bkg PDF	0.22%	
Agreement $\mu^+\mu^-$ *vs.* $\tau^+\tau^-$ in *MassPiPiReco*	0.6%	
Peaking bkg	—	0.4%
MC statistics	0.08%	0.09%
TOTAL	2.2%	
Corrections to efficiency:		
PID	1.023	—
Trigger	—	1.020
Corrections to signal yield:		
Peaking bkg	—	0.996