Lepton universality and lepton flavor violation in Υ decays

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(on behalf of **BABAR Collaboration**)

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Outline

- BABAR $\Upsilon(3,2S)$ datasets have led to recent results in:

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

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

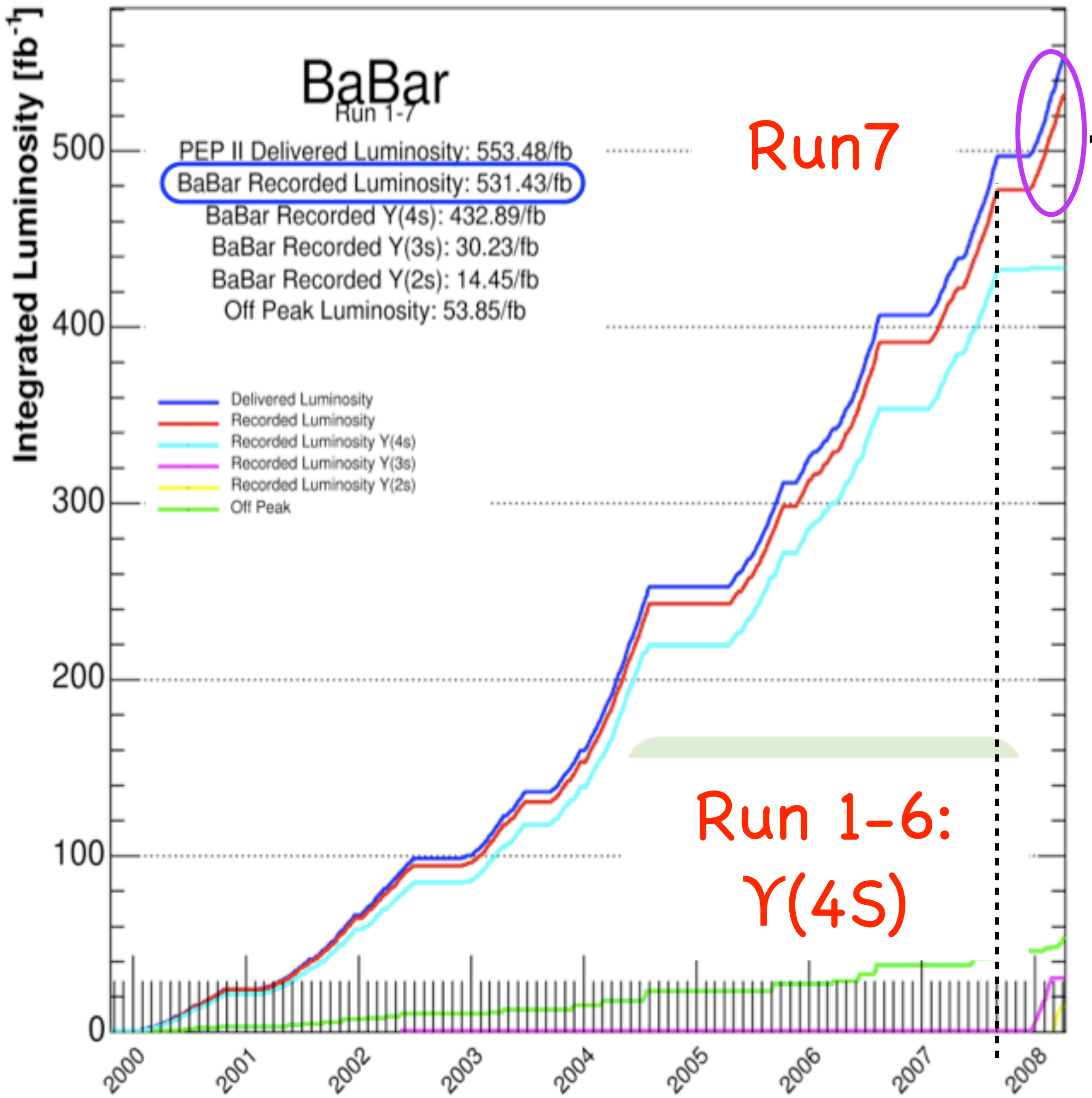
  ✓ Search for Charged Lepton Flavor Violation (LFV) in $\Upsilon(3,2S)\to e^{\pm}\tau^{\mp}$, $\mu^{\pm}\tau^{\mp}$ decays

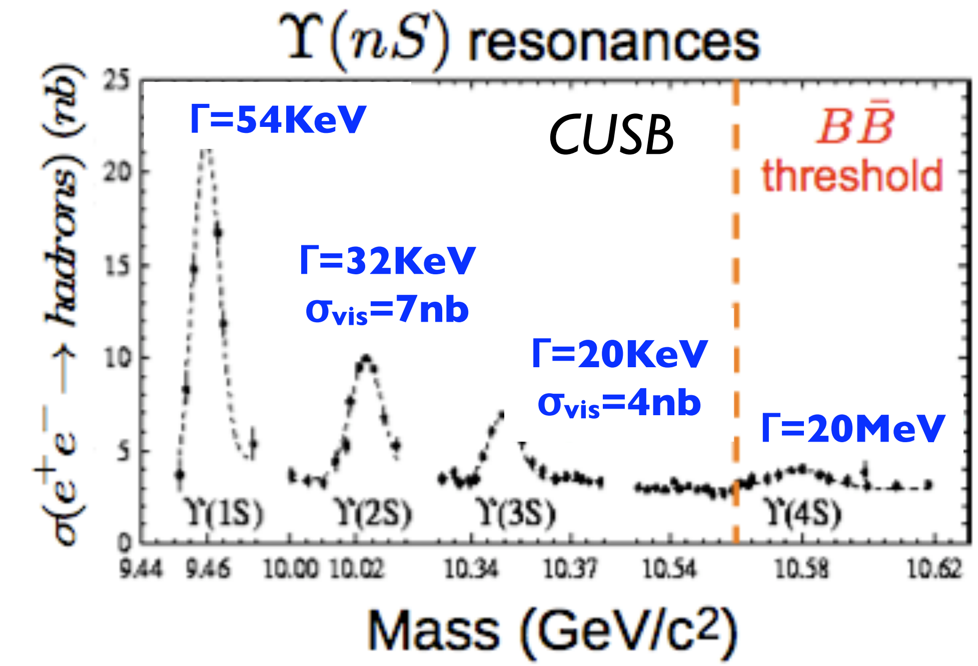
  PRL 104, 151802 (2010) [arXiv:1001.1883]

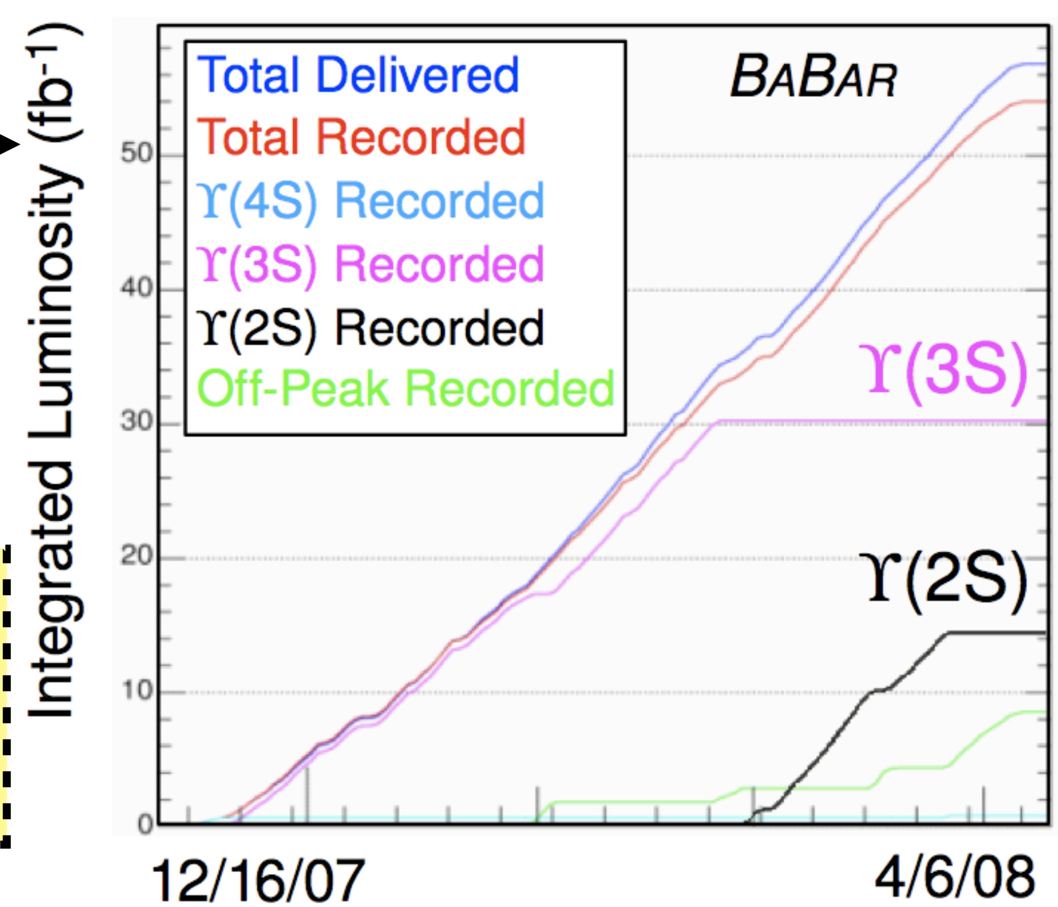
- SM precision tests and New Physics (NP) probes

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 $\Upsilon(3S)$ → ~$122\cdot10^6$ $\Upsilon(3S)$
- ✓ 14.4 fb^{-1} of data at $\Upsilon(2S)$ → ~$99\cdot10^6$ $\Upsilon(2S)$

Lepton Universality test

PRL 104, 191801 (2010)

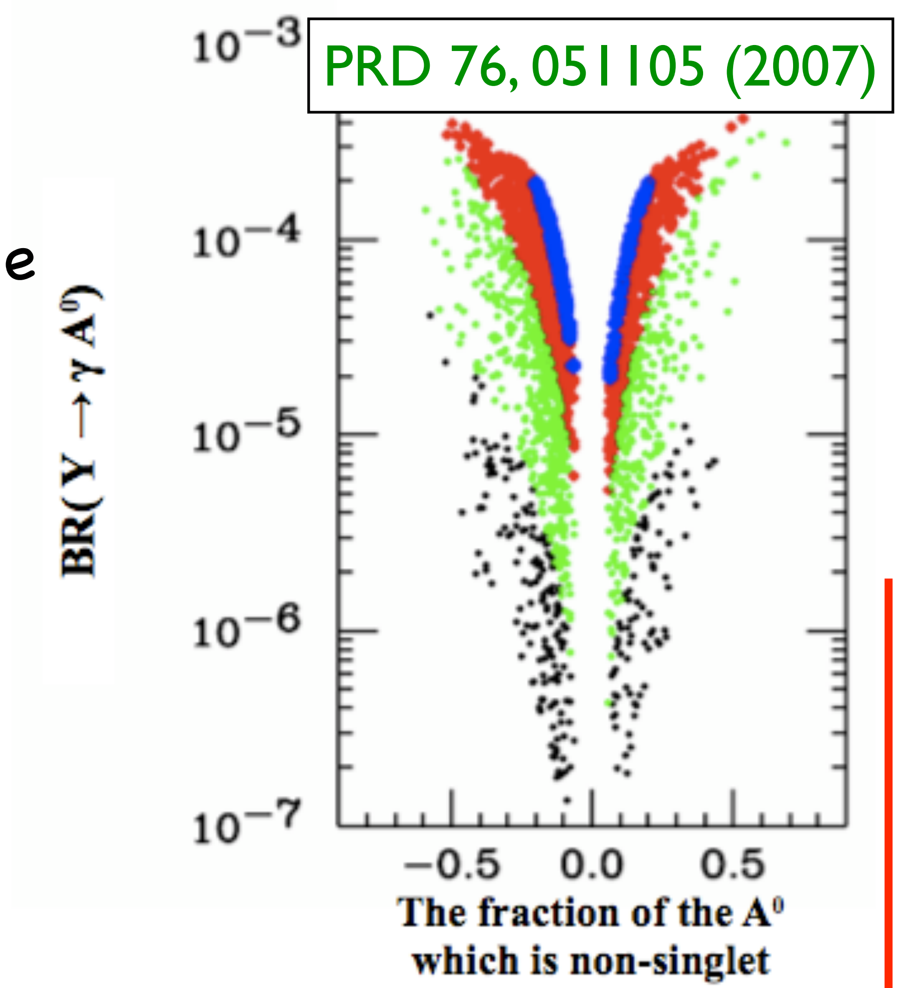
1. Theory

- 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 $\sim\mathcal{O}(10^{-4})$:
  - $\Upsilon(nS) \rightarrow \gamma A^0$, with $A^0 \rightarrow l^+ l^-$ ($l = \mu, \tau$) or $A^0 \rightarrow$ invisible

(with the different A^0 decays dominant for different mass regions)

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

PRD 76, 051105 (2007)



- If the **photon** is **energetic** enough, its energy spectrum can be measured

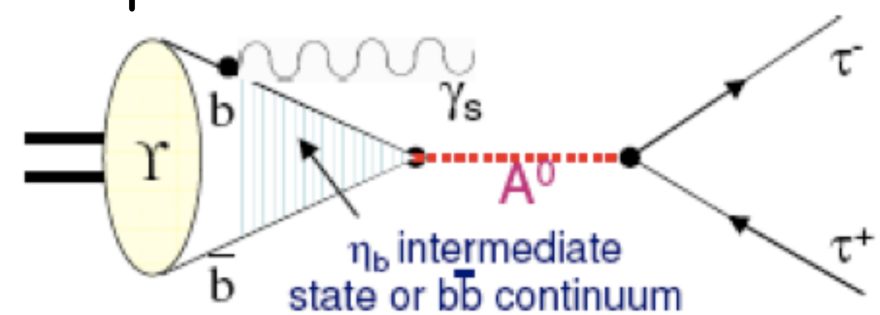
A set of searches at BABAR: **see Y.Kolomensky's talk**

- 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 due to the existence of the A^0

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



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

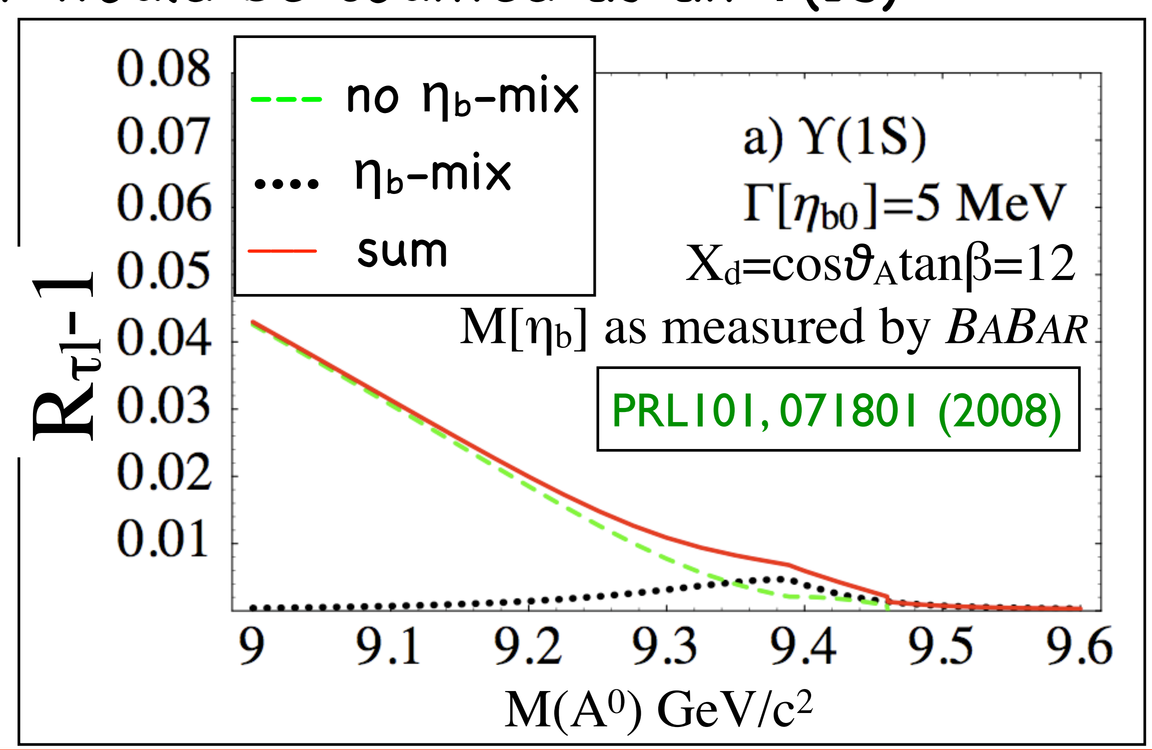
$\Upsilon(1S)\to \eta_b(1S)\gamma,\ \eta_b(1S)\leftrightarrow A^0\to l^+l^-$

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

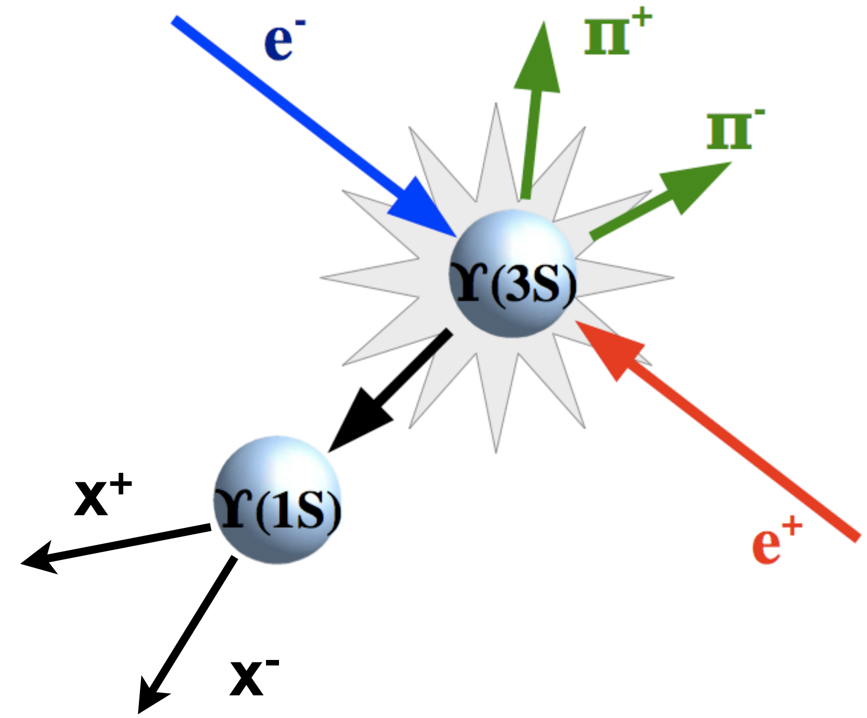
- If the **photon** is **low energy**, the lepton pair would be counted as an $\Upsilon(1S)$

- 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 $\mathbf{x}^{\pm} = \mu^{\pm}$ or $\mathbf{x}^{\pm}$ = charged track from $\tau^{\pm}$ decay (accompanied by neutral particles)

- ✓ $122 \cdot 10^6$ $\Upsilon(3S)$ from BABAR
- ✓ Tag $\Upsilon(1S)$ exploiting $\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-$, with $\Upsilon(1S)\to\tau^+\tau^-$ or $\Upsilon(1S)\to\mu^+\mu^-$ events:
  - ✓ BF($\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-$) ~ 4.5%
  - ✓ select τ 1-prong decays
  - ✓ 4-charged tracks final state topology
- ✓ Any number of extra photons allowed
- ✓ Separate selections for $\Upsilon(1S)\to\tau^+\tau^-$ and $\Upsilon(1S)\to\mu^+\mu^-$ 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 using MC simulations):

$$\epsilon_{\mu\mu} \sim 45\%$$
$$\epsilon_{\tau\tau} \sim 17\%$$

3. Signal extraction

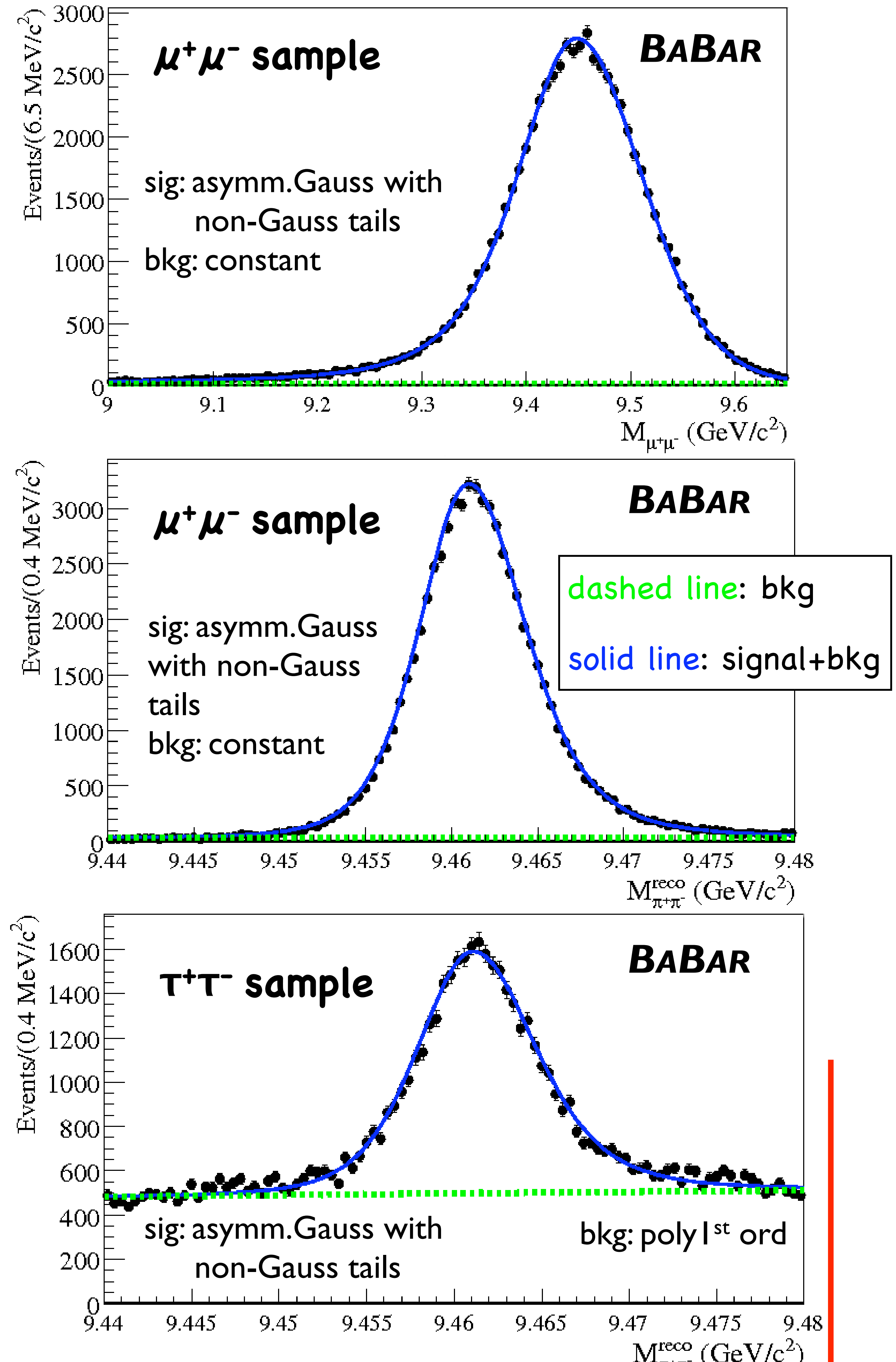
- Extended and unbinned maximum-likelihood fit:
  - in $\mu^+\mu^-$ channel a 2-dim likelihood based on $M_{\pi+\pi-}^{reco}$ and $M_{\mu+\mu-}$
  - in $\tau^+\tau^-$ channel a 1-dim likelihood based on $M_{\pi+\pi-}^{reco}$

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

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

(momentum of the ππ-system in the CM frame)

- PDFs chosen from a data sub-sample (~1/10 of the total) and applied to the remaining data
- 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 (**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.)

- ✓ **Significant improvement in precision**

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

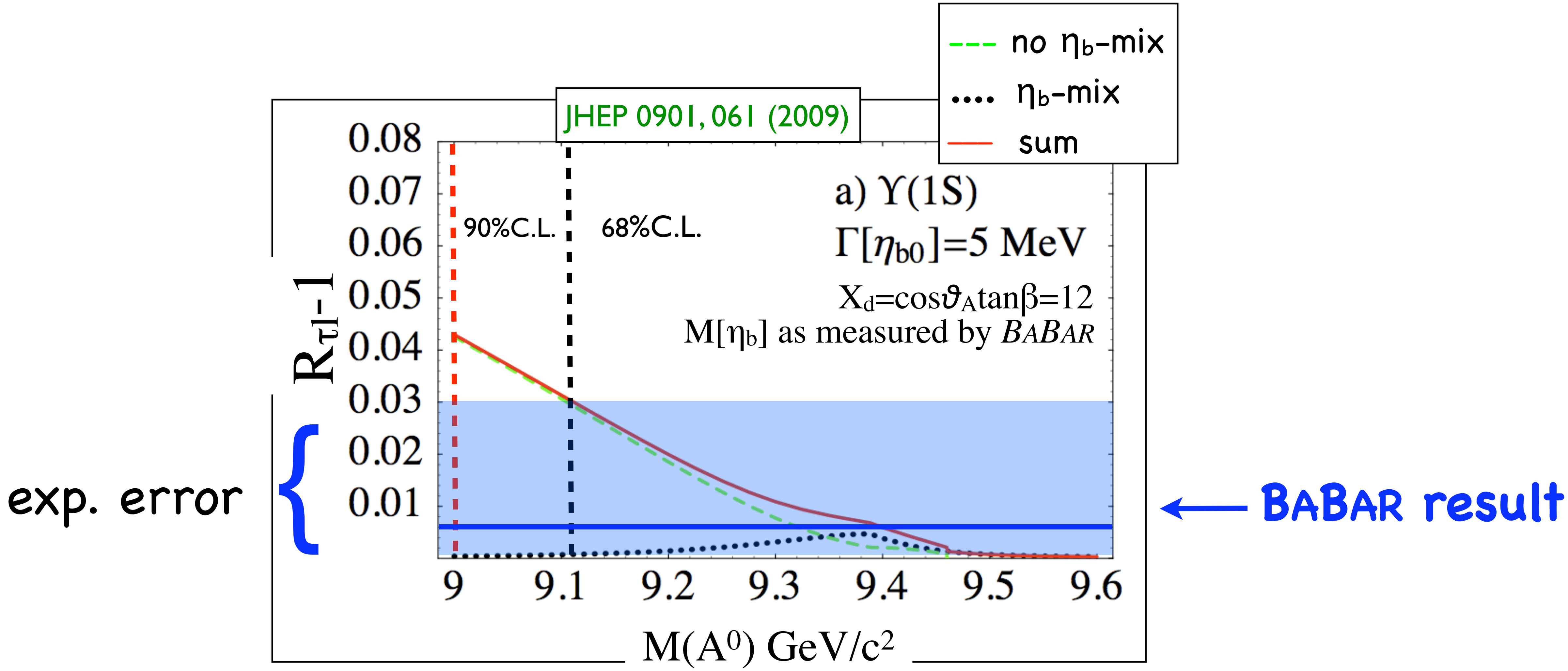
  PRL98, 052002 (2007)

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

5. Constraints on NP

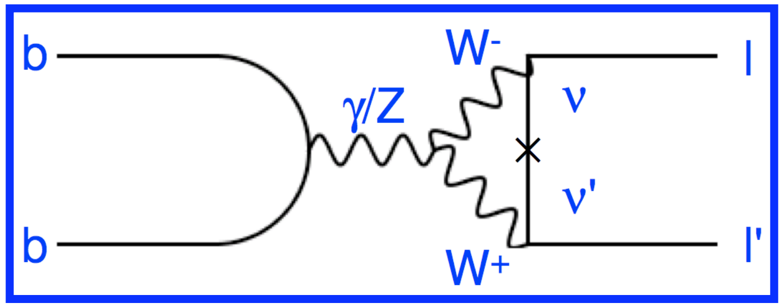
✓ **Excluded $M(A^0)<9$ GeV/c² @90%C.L.** (for large couplings)

$\Upsilon(1S)\to A^0\gamma,\ A^0\to l^+l^-$	(no η_b-mix)
$\Upsilon(1S)\to\eta_b(1S)\gamma,\ \eta_b(1S)\leftrightarrow A^0\to l^+l^-$	(η_b-mix)

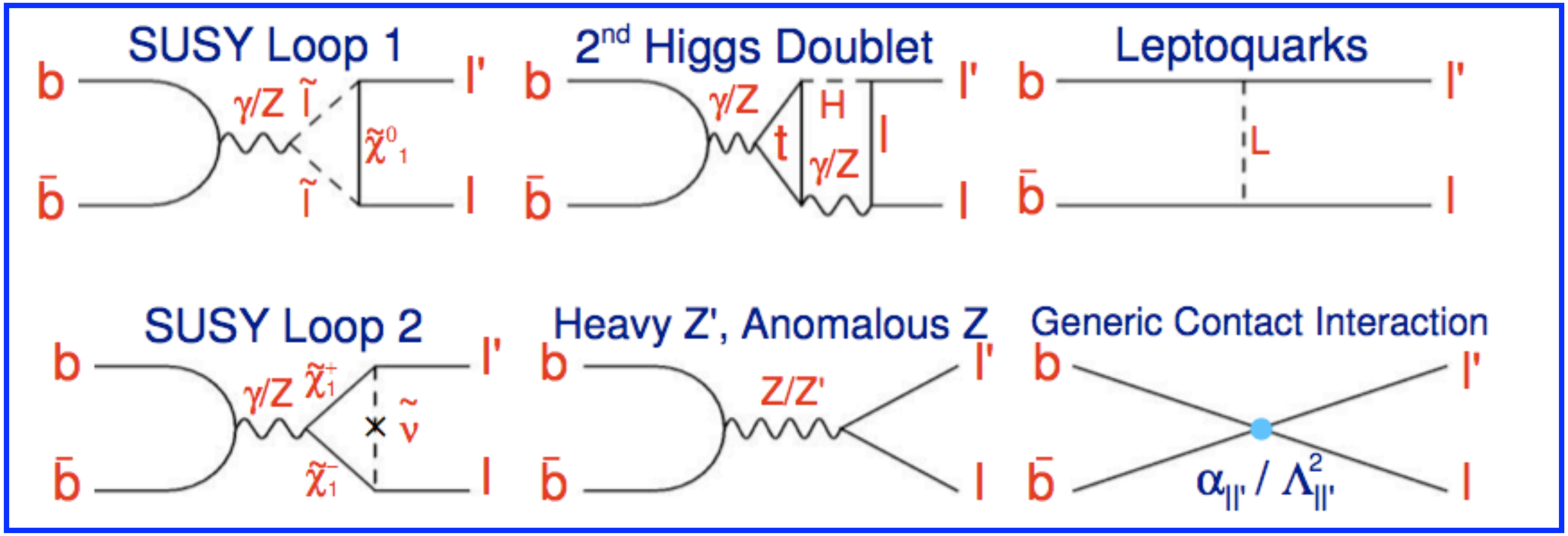


Charged LFV as a NP probe

- In the SM with ν oscillations LFV can occur
  - Never observed in processes involving **charged leptons**, 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



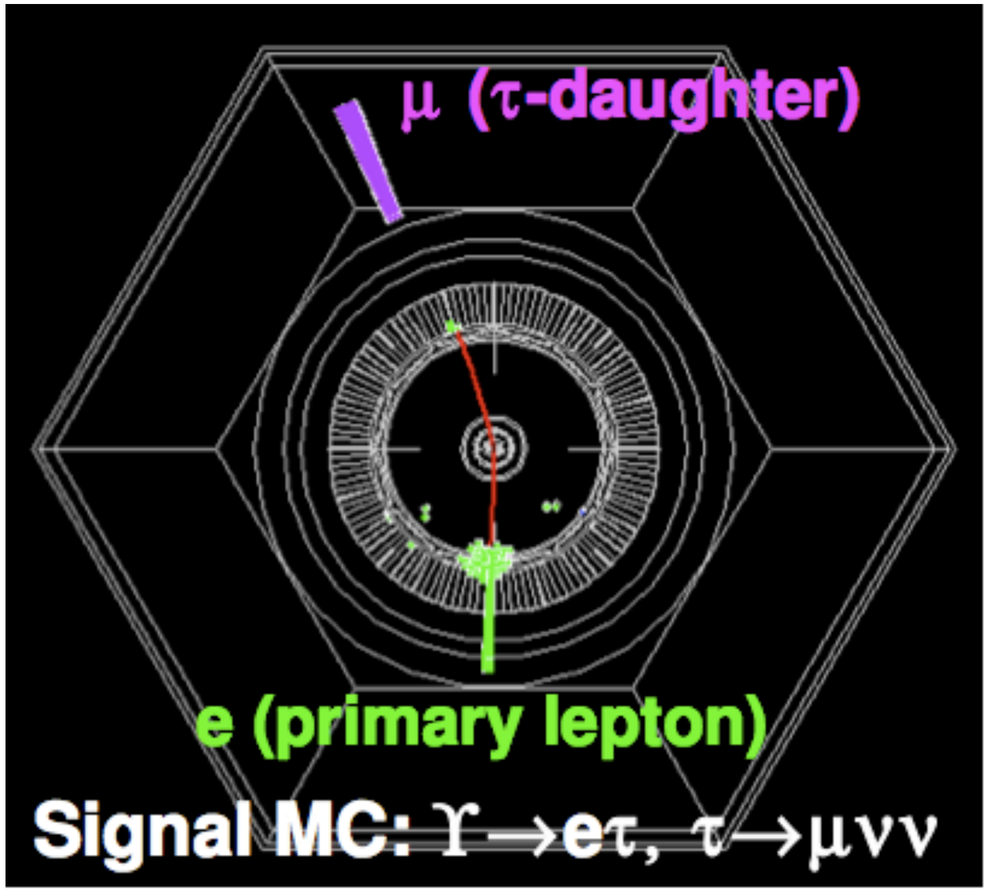
- Observation of charged LFV: clear signature of NP
- Search for charged LFV at BABAR in several other decays

LFV in Υ decays

PRL 104, 151802 (2010)

1. Strategy

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



Process	τ decay	Channel
$\Upsilon(3,2S) \to e\tau$	$\tau \to \mu\nu\nu$	leptonic eτ
$\Upsilon(3,2S) \to e\tau$	$\tau \to \pi^{\pm}\pi^{0}\nu / \pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic eτ
$\Upsilon(3,2S) \to \mu\tau$	$\tau \to e\nu\nu$	leptonic $\mu\tau$
$\Upsilon(3,2S) \to \mu\tau$	$\tau \to \pi^{\pm}\pi^{0}\nu / \pi^{\pm}\pi^{0}\pi^{0}\nu$	hadronic $\mu\tau$

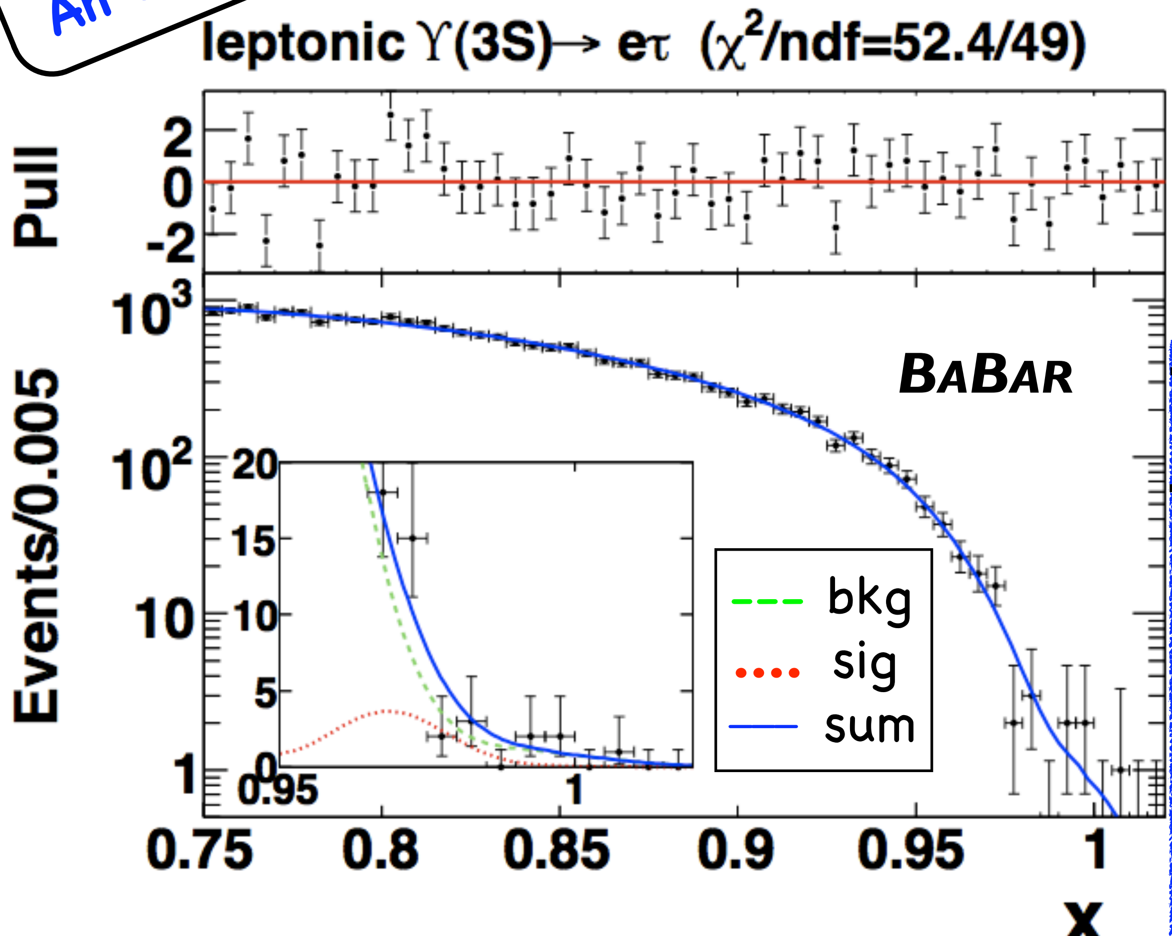
- ✓ Background events:
  - Bhabha and μ-pair (and mis-ID)
  - τ-pair
  - multiple π and additional γ
- ✓ Selection partially common to the 4 channels, partially channel-specific (particle-ID, τ-daughter kinematics)

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:



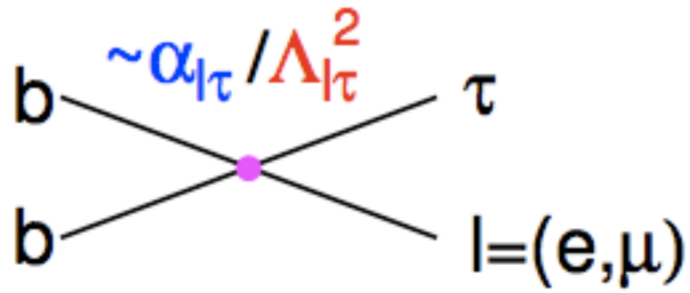
Systematic uncertainties (mainly from PDF shapes) and corrections applied

PRL101, 201601 (2008)

	$\mathcal{B}$ (10^{-6})	90% 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 ($\Lambda_{l\tau}^2$)



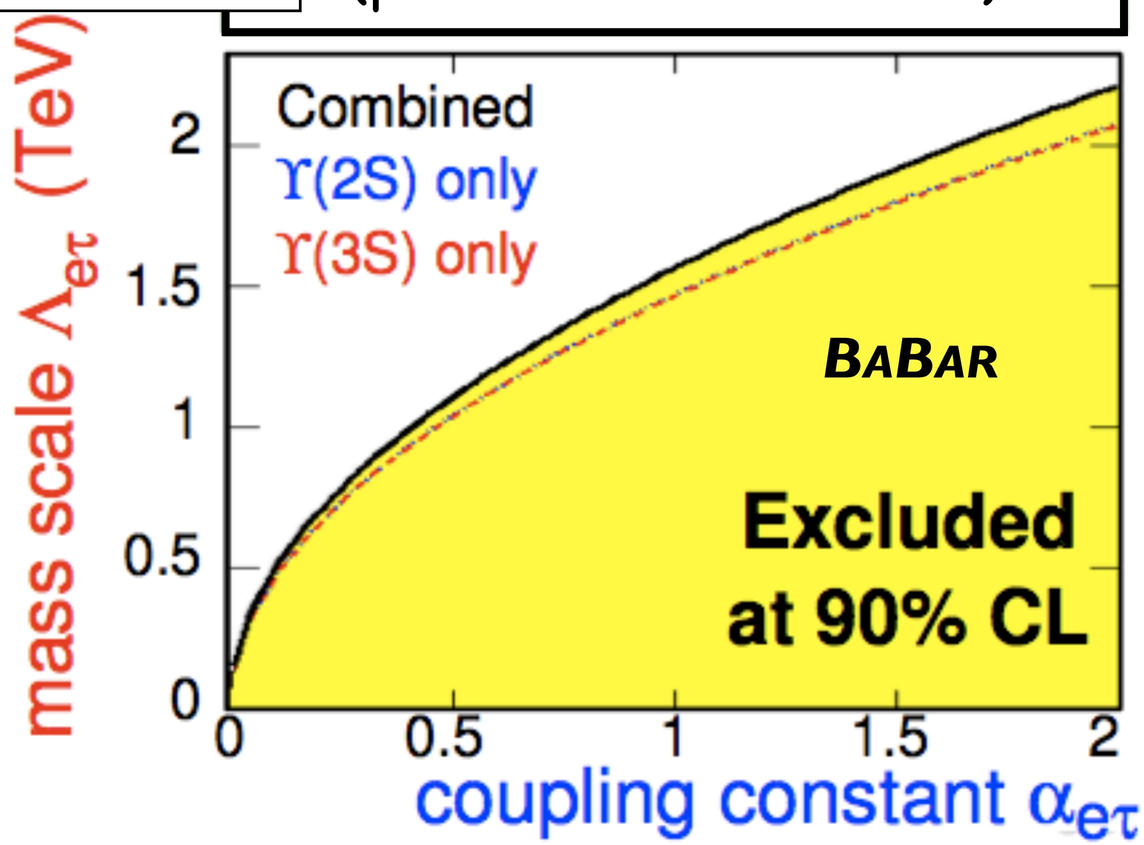
$$\frac{\alpha_{l\tau}^2}{\Lambda_{l\tau}^4} = \frac{BF(\Upsilon(3S)\to l\tau)}{BF(\Upsilon(3S)\to ll)} \frac{2q_b\alpha^2}{(M_{\Upsilon(nS)})^4} \qquad l = (e,\mu)$$

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

PRL101,201601(2008)

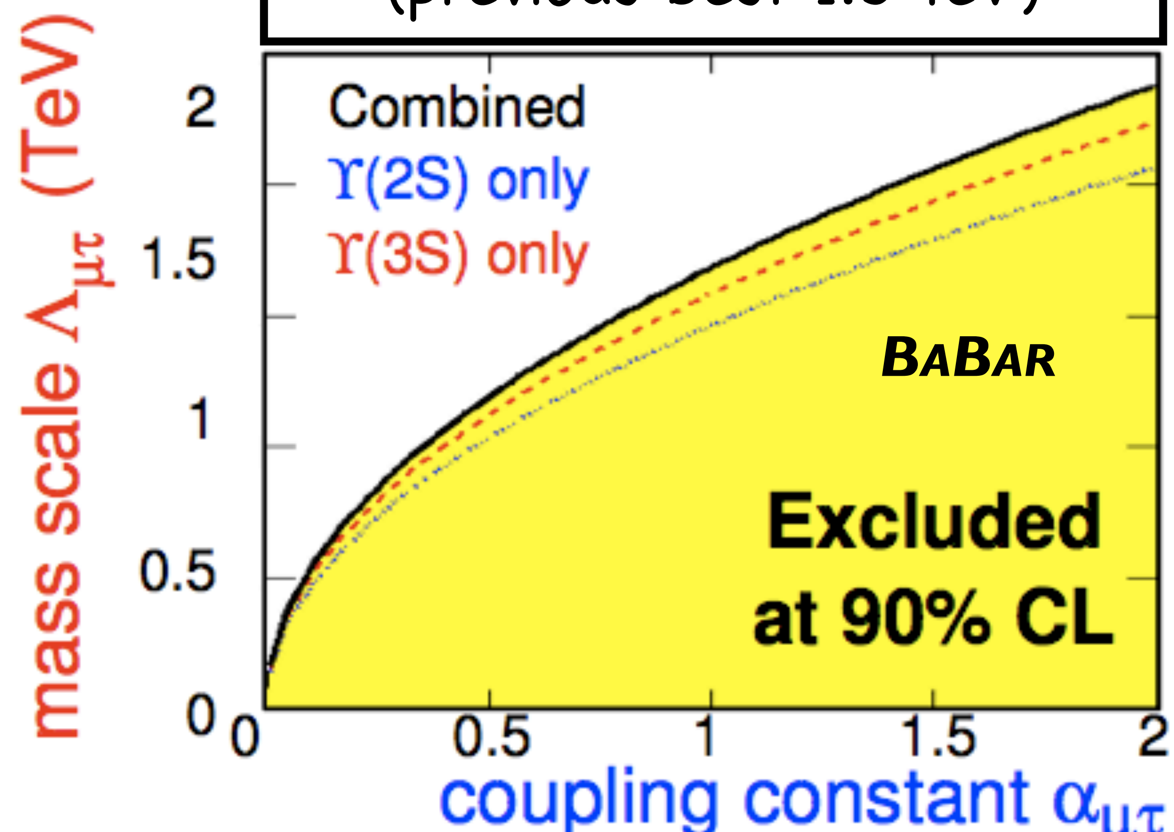
$\alpha_{e\tau} = 1 \rightarrow \Lambda_{e\tau} > 1.6$ TeV

(previous best 1.4 TeV)



$\alpha_{\mu\tau} = 1 \rightarrow \Lambda_{\mu\tau} > 1.7$ TeV

(previous best 1.5 TeV)



Conclusions

- ✓ BABAR $\Upsilon(3S)$ and $\Upsilon(2S)$ data have led to several important results:
  - ✓ **Lepton Universality in $\Upsilon(1S)$ decays**
  - ✓ **LFV searches in $\Upsilon(3,2S)$ decays**
- ✓ BABAR results have:
  - ✓ improved the precision of Lepton Universality measurement in Υ decays
  - ✓ put important constraints on physics beyond the SM

BACKUP SLIDES

The BABAR detector

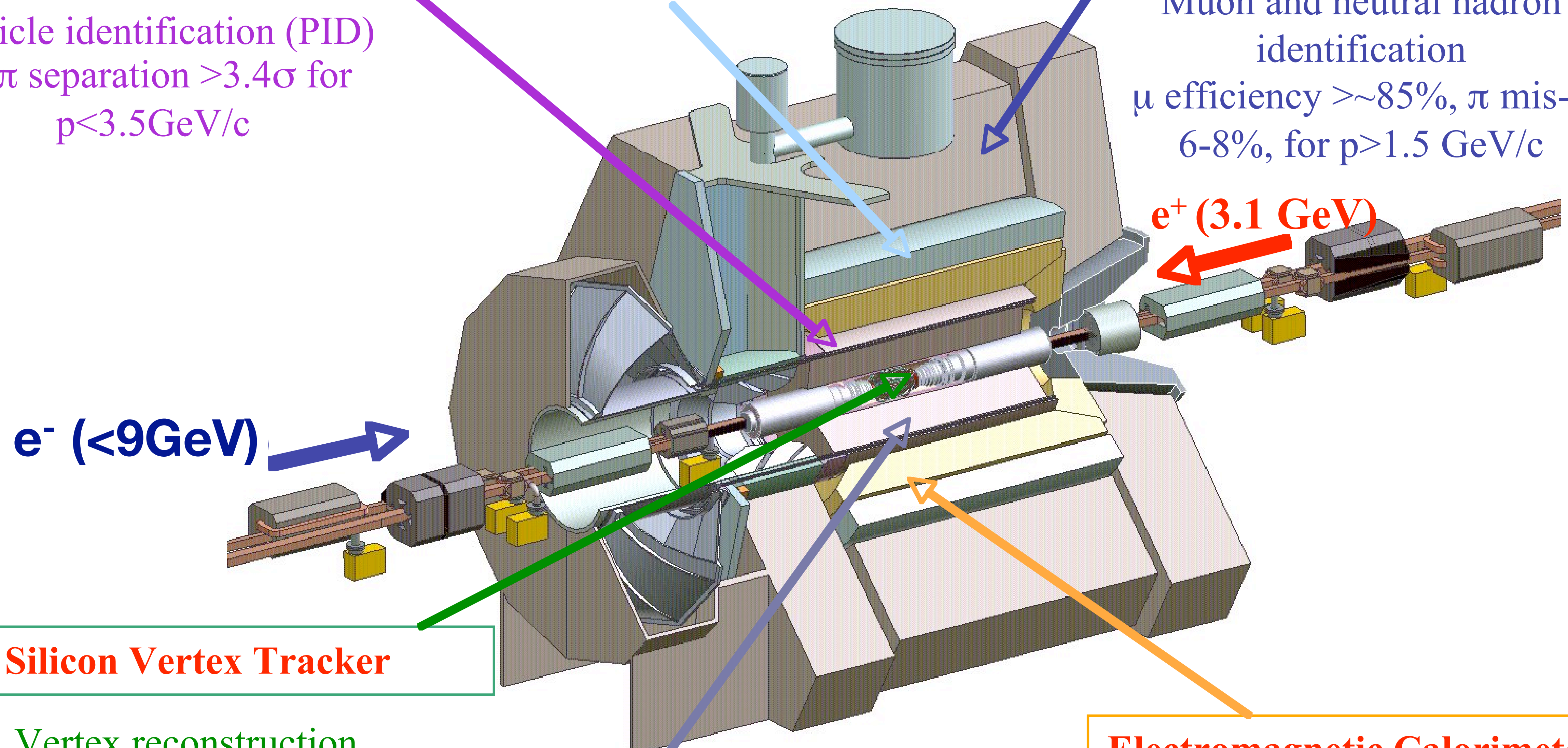
Cherenkov Detector

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. $\sigma(E)/E = 1.33\% E^{-1/4} \oplus 2.1\%$

Lepton Universality Test

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

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

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

- 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