UNIVERSITY OF OREGON

Tau Physics@BaBar

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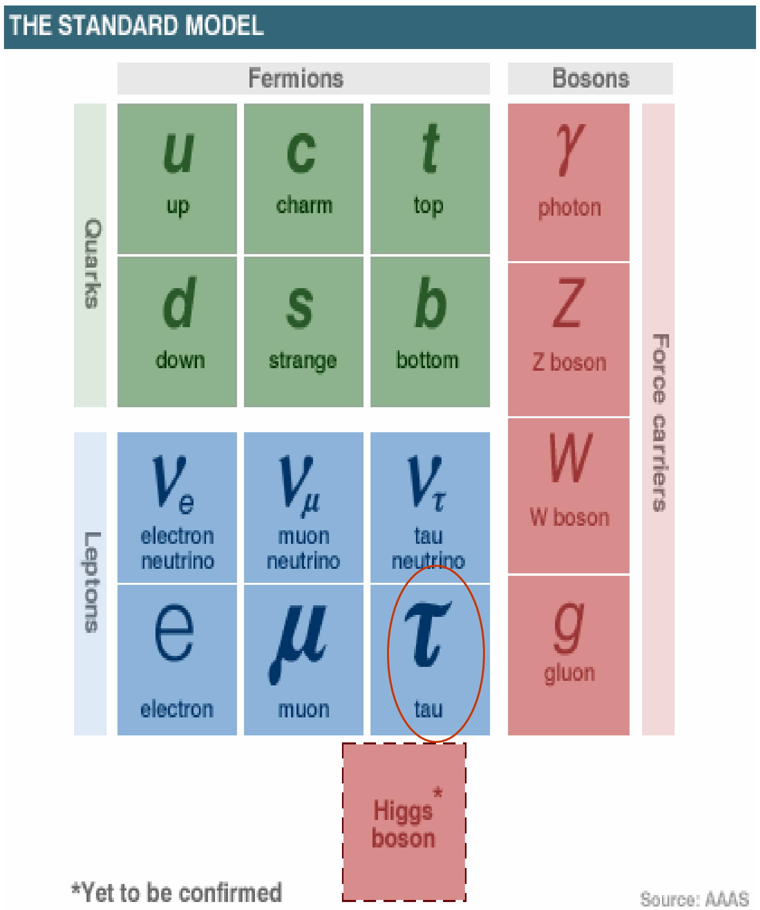
Outlines

- Tau Lepton
- BaBar Detector
- Lepton Flavor Violation
- Hadronic Spectrum of Tau Decay
- Summary

Tau Lepton

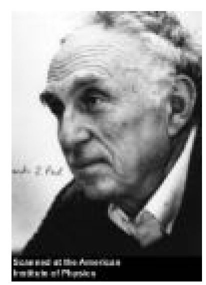


The tau lepton belongs to the 3rd generation of lepton. It is the third generation counterpart of the electron (1st generation) and the muon (2nd generation).

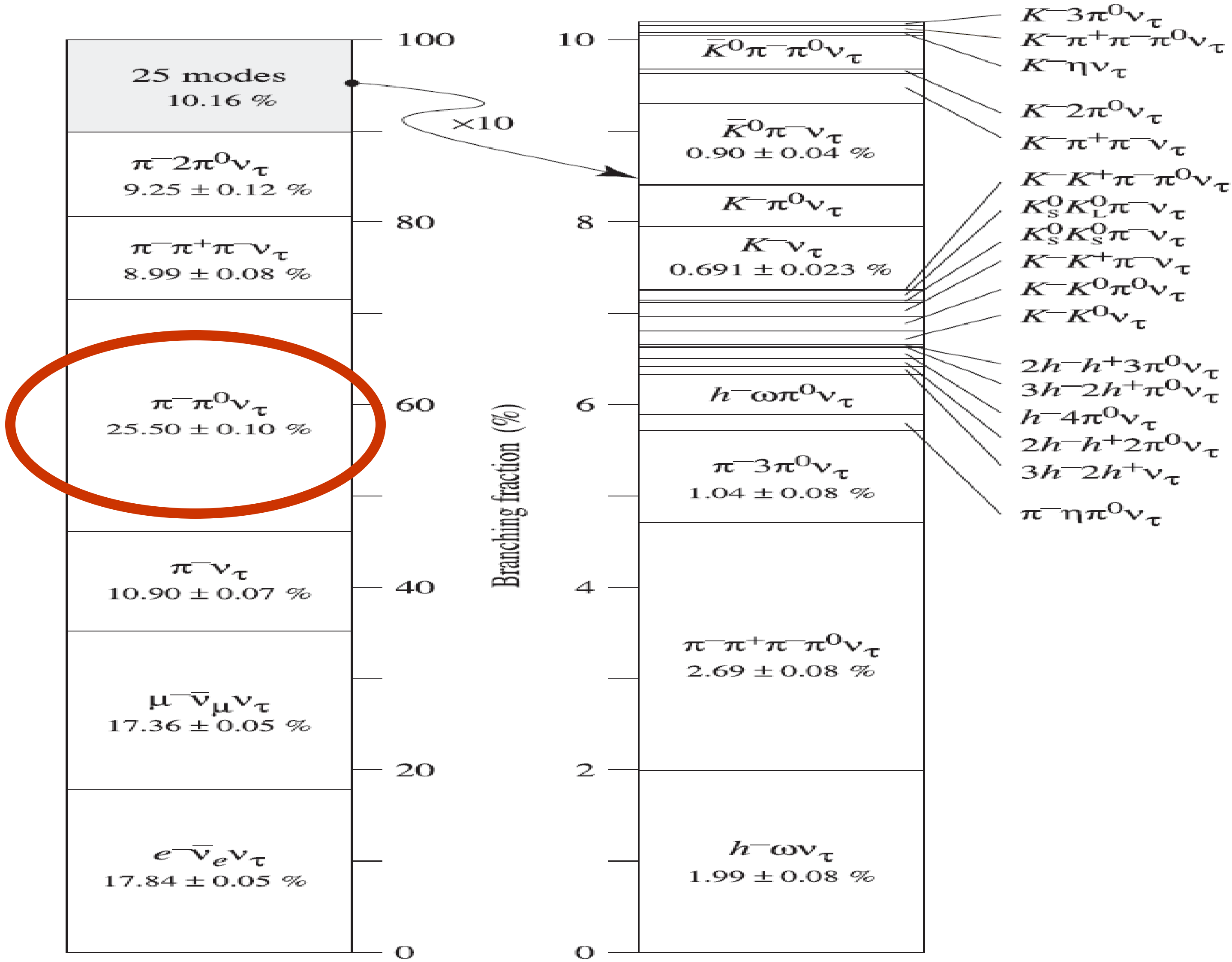
Tau Mass = 1776.90 ± 0.20 MeV (PDG 2007)

Tau Lifetime = (290.6±1) x 10^{-15} s (PDG 2007)

Tau is the only lepton which can decay to hadron



Tau Decays



25 modes
10.16 %
×10
$\pi^- 2\pi^0 \nu_\tau$
9.25 ± 0.12 %
$\pi^- \pi^+ \pi^- \nu_\tau$
8.99 ± 0.08 %
$\pi^- \pi^0 \nu_\tau$
25.50 ± 0.10 %
$\pi^- \nu_\tau$
10.90 ± 0.07 %
$\mu^- \bar{\nu}_\mu \nu_\tau$
17.36 ± 0.05 %
$e^- \bar{\nu}_e \nu_\tau$
17.84 ± 0.05 %
100
80
60
40
20
0
Branching fraction (%)
10
8
6
4
2
0
$\bar{K}^0 \pi^- \pi^0 \nu_\tau$
$\bar{K}^0 \pi^- \nu_\tau$
0.90 ± 0.04 %
$K^- \pi^0 \nu_\tau$
$K^- \nu_\tau$
0.691 ± 0.023 %
$h^- \omega \pi^0 \nu_\tau$
$\pi^- 3\pi^0 \nu_\tau$
1.04 ± 0.08 %
$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$
2.69 ± 0.08 %
$h^- \omega \nu_\tau$
1.99 ± 0.08 %
$K^- 3\pi^0 \nu_\tau$
$K^- \pi^+ \pi^- \pi^0 \nu_\tau$
$K^- \eta \nu_\tau$
$K^- 2\pi^0 \nu_\tau$
$K^- \pi^+ \pi^- \nu_\tau$
$K^- K^+ \pi^- \pi^0 \nu_\tau$
$K^0_S K^0_L \pi^- \nu_\tau$
$K^0_S K^0_S \pi^- \nu_\tau$
$K^- K^+ \pi^- \nu_\tau$
$K^- K^0 \pi^0 \nu_\tau$
$K^- K^0 \nu_\tau$
$2h^- h^+ 3\pi^0 \nu_\tau$
$3h^- 2h^+ \pi^0 \nu_\tau$
$h^- 4\pi^0 \nu_\tau$
$2h^- h^+ 2\pi^0 \nu_\tau$
$3h^- 2h^+ \nu_\tau$
$\pi^- \eta \pi^0 \nu_\tau$

SLAC as an International Research Facility

- 3000 scientists from ~25 nations use SLAC facilities to do their research

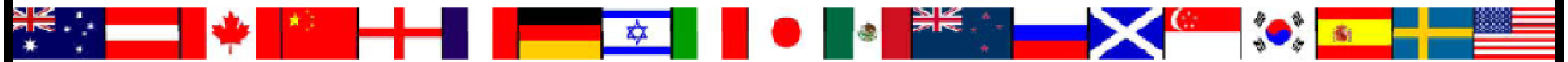
  The facilities require:

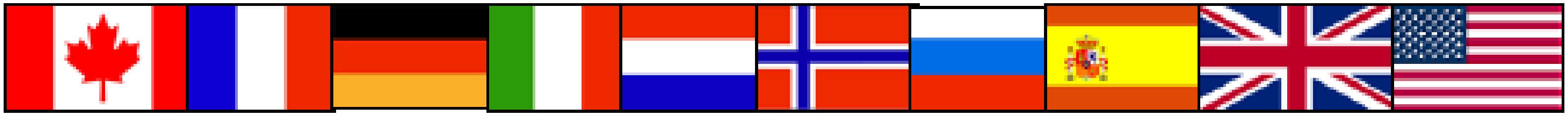
  a) Highly specialized technical staff and extensive infrastructure to design, construct and maintain large accelerator-facilities and detectors

  b) Extremely efficient operation of complex accelerators and detectors

  c) State of the art computing systems (running 24/7/12) for the analysis and worldwide distribution of data

- Science program at SLAC generates 800-900 publications per year





The *BABAR* Collaboration

10 Countries

74 Institutions

459 Physicists

USA [32/223]

California Institute of Technology
UC, Irvine
UC, Los Angeles
UC, Riverside
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
Harvard U
U of Iowa
Iowa State U
Johns Hopkins U
LBNL
LLNL
U of Louisville
U of Maryland
U of Massachusetts, Amherst
MIT
U of Mississippi
SUNY, Albany
U of Notre Dame
Ohio State U
U of Oregon
Princeton U
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Austin
U of Texas at Dallas
U of Wisconsin

Canada [4/19]

University of British Columbia
McGill University
University de Montréal
University of Victoria

France [5/41]

LAPP, Annecy
LAL Orsay
LPNHE des Universités Paris VI et VII
Ecole Polytechnique, Laboratoire Leprince-Ringuet
CEA, DAPNIA, CE-Saclay

Germany [6/28]

Ruhr Universitaet Bochum
Universitaet Dortmund
Technische Univeritaet Dresden
Universitaet Heidelberg
Universitaet Rostock
Universitaet Karlsruhe

Italy [12/83]

INFN, Bari
INFN, Ferrara
Lab. Nazionali di Frascati dell' INFN
INFN, Genova & Univ
INFN, Milano & Univ
INFN, Napoli & Univ
INFN, Padova & Univ
INFN, Pisa & Univ & Scuola Normale Superiore
INFN, Perugia & Univ
INFN, Roma & Univ "La Sapienza"
INFN, Torino & Univ
INFN, Trieste & Univ

The Netherlands [1/2]

NIKHEF, Amsterdam

Norway [1/3]

U of Bergen

Russia [1/11]

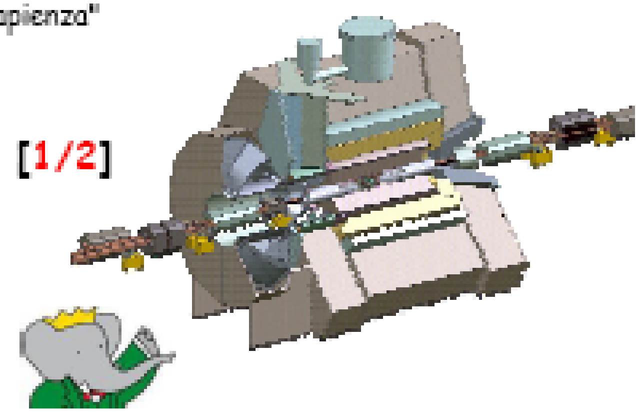
Budker Institute, Novosibirsk

Spain [2/7]

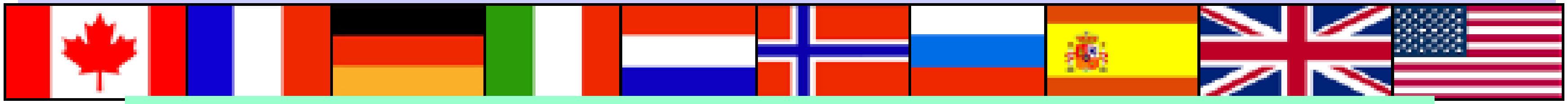
IFAE-Barcelona
IFIC-Valencia

United Kingdom [10/43]

U of Birmingham
Brunel U
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary , U of London
U of London, Royal Holloway
U of Manchester
Rutherford Appleton Laboratory
U of Warwick



The BaBar Collaboration

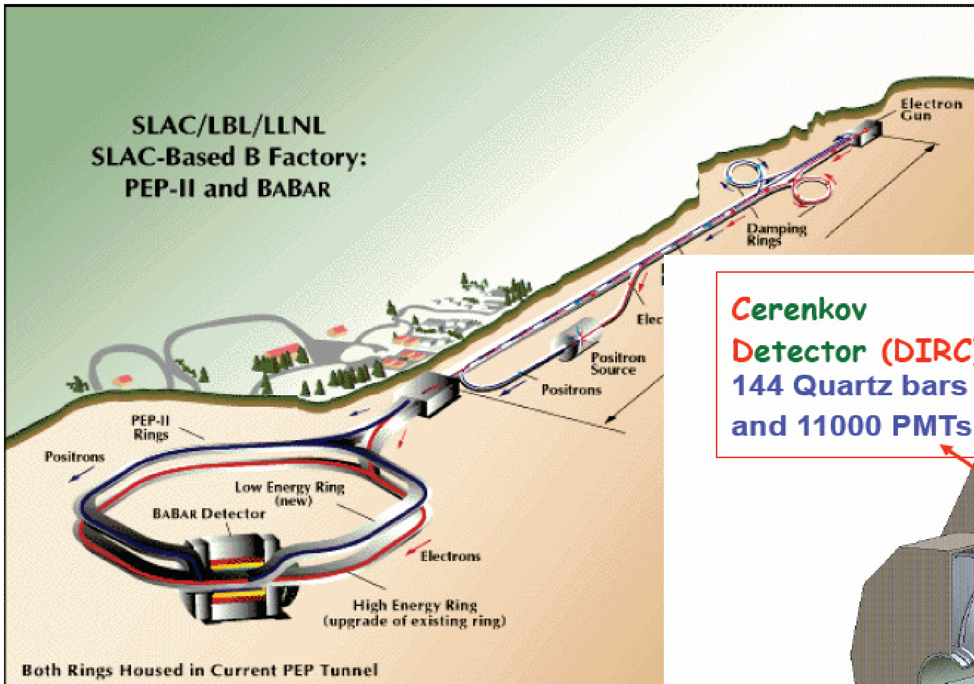


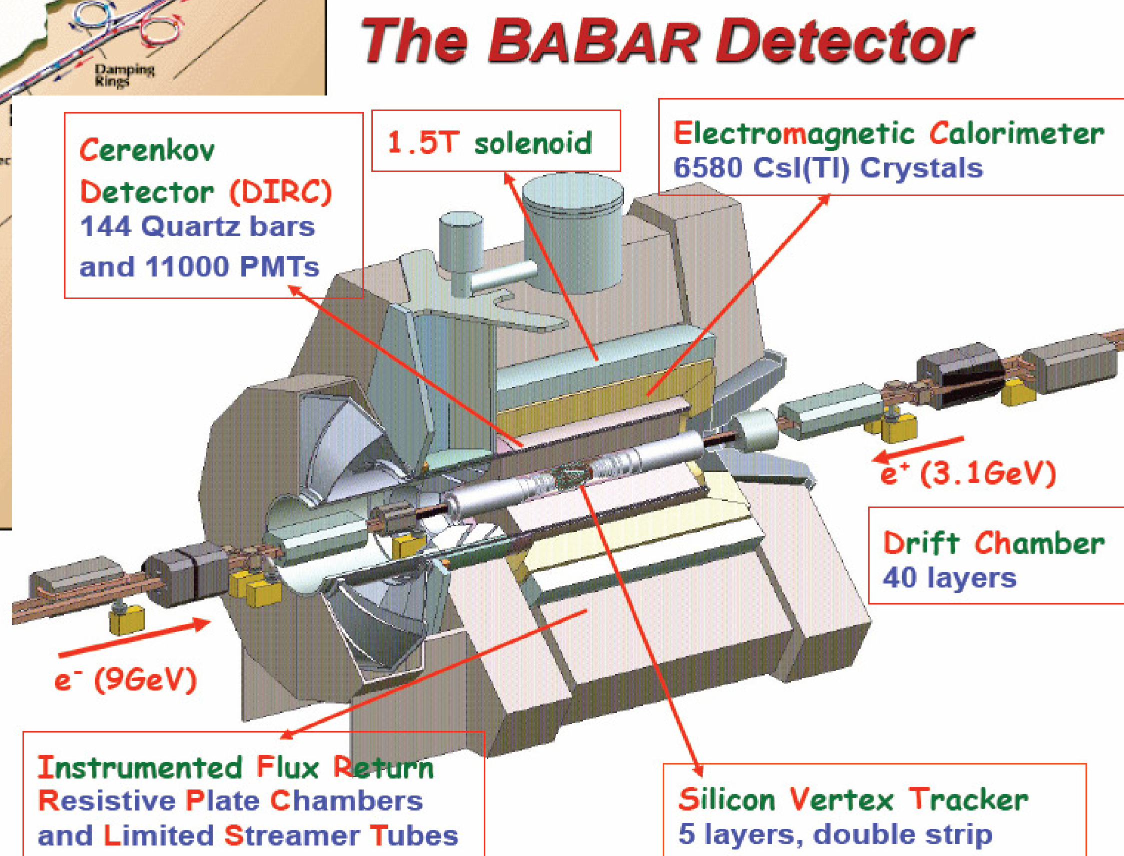
74 Institutions in 10 countries

	Faculty	PhD Staff	Postdoc	Grad	Non-PhD	Totals
Canada	10		2	7		19
France	14	12	3	12	4	45
Germany	7	4	1	15		27
Italy	27	28	15	14		84
Netherlands	1			1		2
Norway	2			1		3
Russia	2	6		2	1	11
Spain		3	2	3		8
United Kingdom	18	1	12	12	1	44
United States	72	47	40	64	19	242
Totals	**153**	**101**	**75**	**131**	**25**	**485**

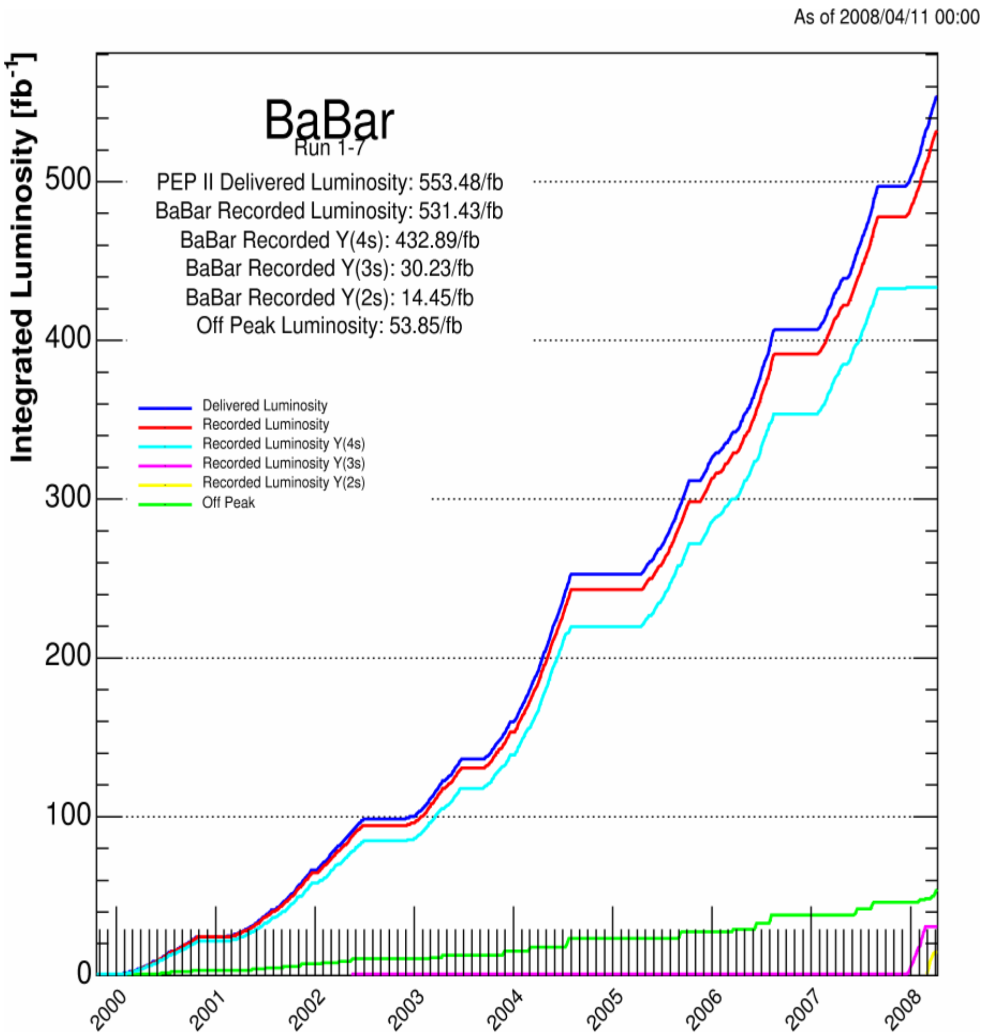
With more than 200 students and postdocs the collaboration continues to be on a very strong foundation.

BABAR


SLAC/LBL/LLNL
SLAC-Based B Factory:
PEP-II and BABAR
Electron Gun
Damping Rings
Positron Source
Positrons
PEP-II Rings
Positrons
Low Energy Ring (new)
BABAR Detector
Electrons
High Energy Ring (upgrade of existing ring)
Both Rings Housed in Current PEP Tunnel


The BABAR Detector
Cerenkov Detector (DIRC)
144 Quartz bars
and 11000 PMTs
1.5T solenoid
Electromagnetic Calorimeter
6580 CsI(Tl) Crystals
e^+ (3.1GeV)
Drift Chamber
40 layers
e^- (9GeV)
Instrumented Flux Return
Resistive Plate Chambers
and Limited Streamer Tubes
Silicon Vertex Tracker
5 layers, double strip

Integrated Luminosity



Cross Section

$\sigma(e^+e^- \rightarrow \tau^-\tau^+) = 0.89$ nb

450 million τ pairs

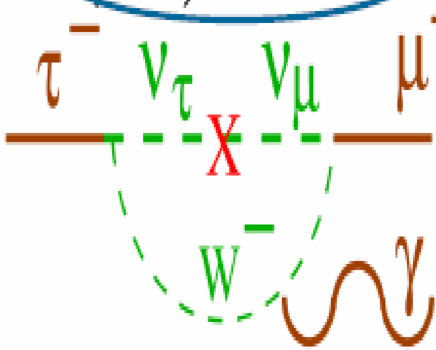
BaBar is a τ Factory

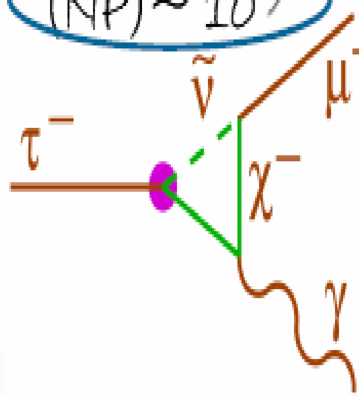
Lepton Flavor Violation

Lepton Flavor Violation

- ✓ Lepton Flavour Violation (LFV) prohibited in Standard Model (SM) with massless neutrinos
- ✓ observed neutrino oscillation

  → extension of SM allow for LFV processes BUT BR not experimentally accessible
- ✓ New Physics (NP) allow for LFV with $BR_{NP} \gg BR_{SM}$
  - i.e. $BR(\tau \to \mu\gamma)$ $(SM) \sim 10^{-54}$ $(NP) \sim 10^{-7}$



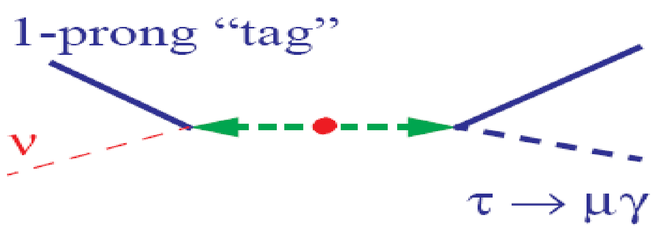


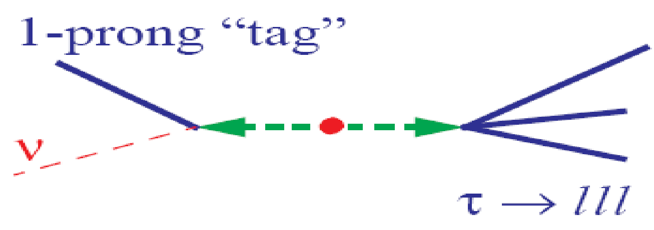
mSUGRA+ seesaw

Ellis et al. EPJ c14 (2002) 319

Ellis et al. PRD 66 (2002) 115013

LFV signature





- One prong on "tag" side ($\pi\nu$, $\rho\nu$, $e\nu\nu$, $\mu\nu\nu$,...) ~ 85%
- Strict lepton identification
- No missing momentum on signal side

"Neutrinoless" Decay

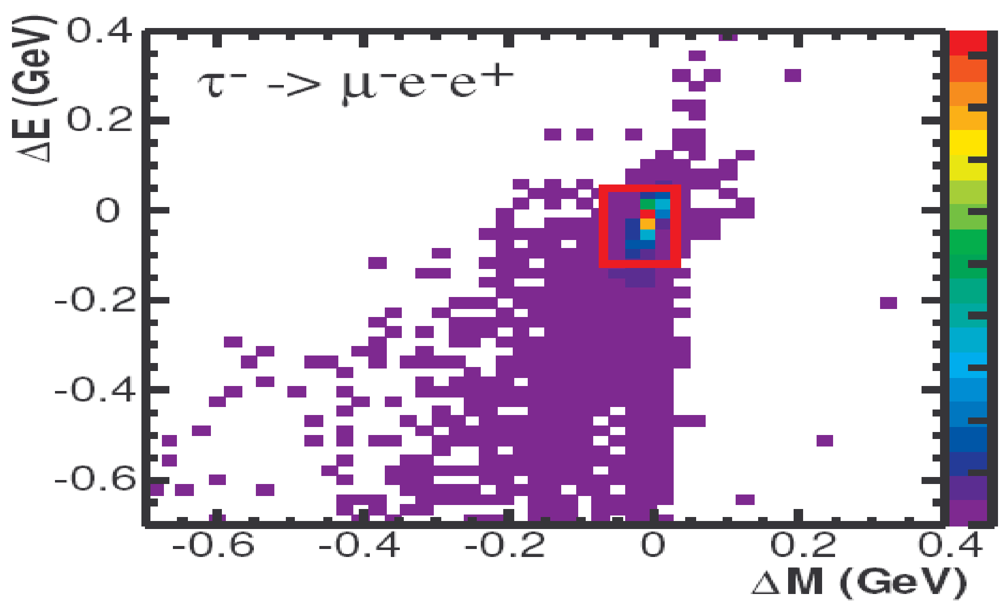
$$\Delta m = m_{rec} - m_\tau$$

$$\Delta E = E_{rec} - E_{beam}$$

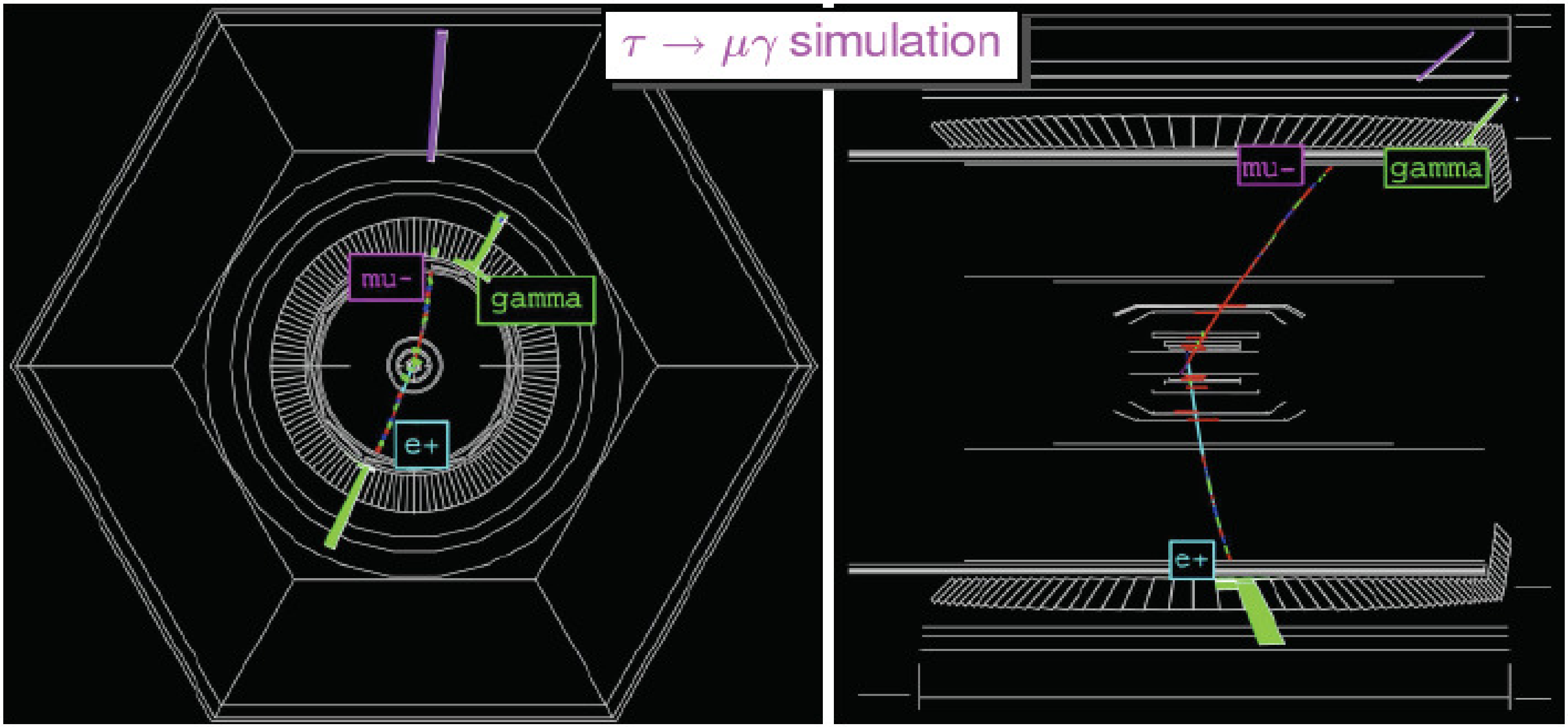
Smeared by resolution and radiative effects

Count events in signal box

ΔE vs. Δm for MC signal



Looking for new physics



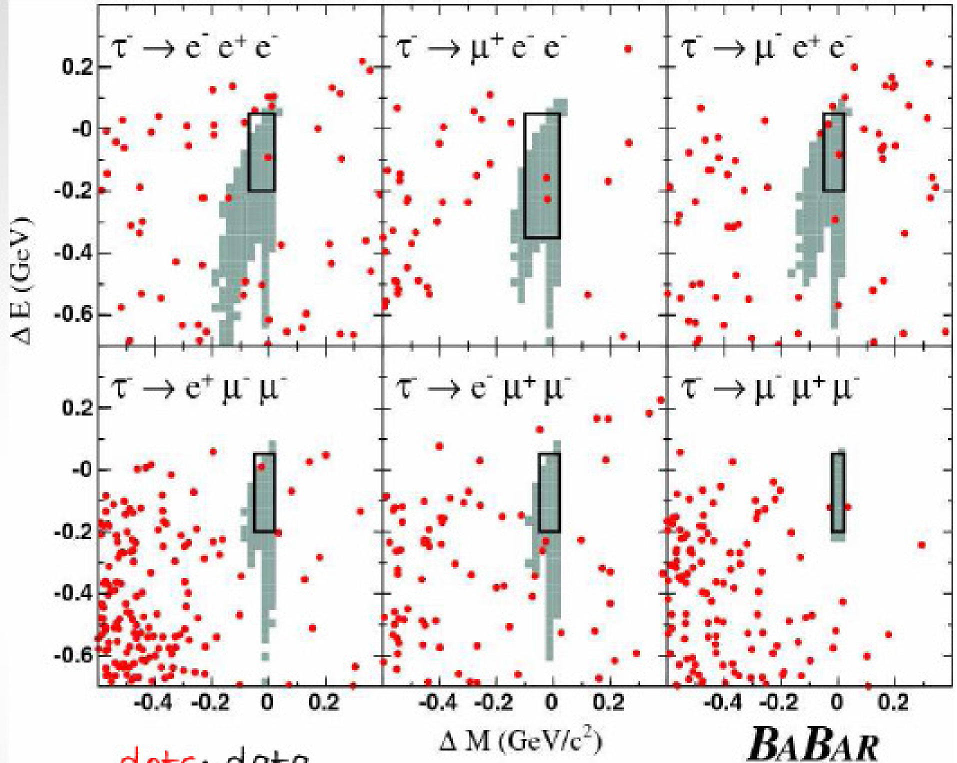
...unambiguous signature of new physics!

$\tau^- \to l^- l^+ l^-$: results

PRL99(2007)251803

- ✓ 376 fb^{-1}
- ✓ observed data in Δm-ΔE plane
- ✓ signal efficiencies : $(5.5 \div 12.4)\%$
- ✓ total expected background (combining 6 channels) (4.2 ± 0.8) events
- ✓ observed 6 events

→ no evidence for signal



dots: data

grey region: 90% MC signal events

Mode	Eff. [%]	N_{bgd}	N_{obs}	UL_{90}^{obs}
$e^-e^+e^-$	8.9 ± 0.2	1.33 ± 0.25	1	4.3
$\mu^-e^+e^-$	8.3 ± 0.6	0.89 ± 0.27	2	8.0
$\mu^+e^-e^-$	12.4 ± 0.8	0.30 ± 0.55	2	5.8
$e^+\mu^-\mu^-$	8.8 ± 0.8	0.54 ± 0.21	1	5.6
$e^-\mu^+\mu^-$	6.2 ± 0.5	0.81 ± 0.31	0	3.7
$\mu^-\mu^+\mu^-$	5.5 ± 0.7	0.33 ± 0.19	0	5.3

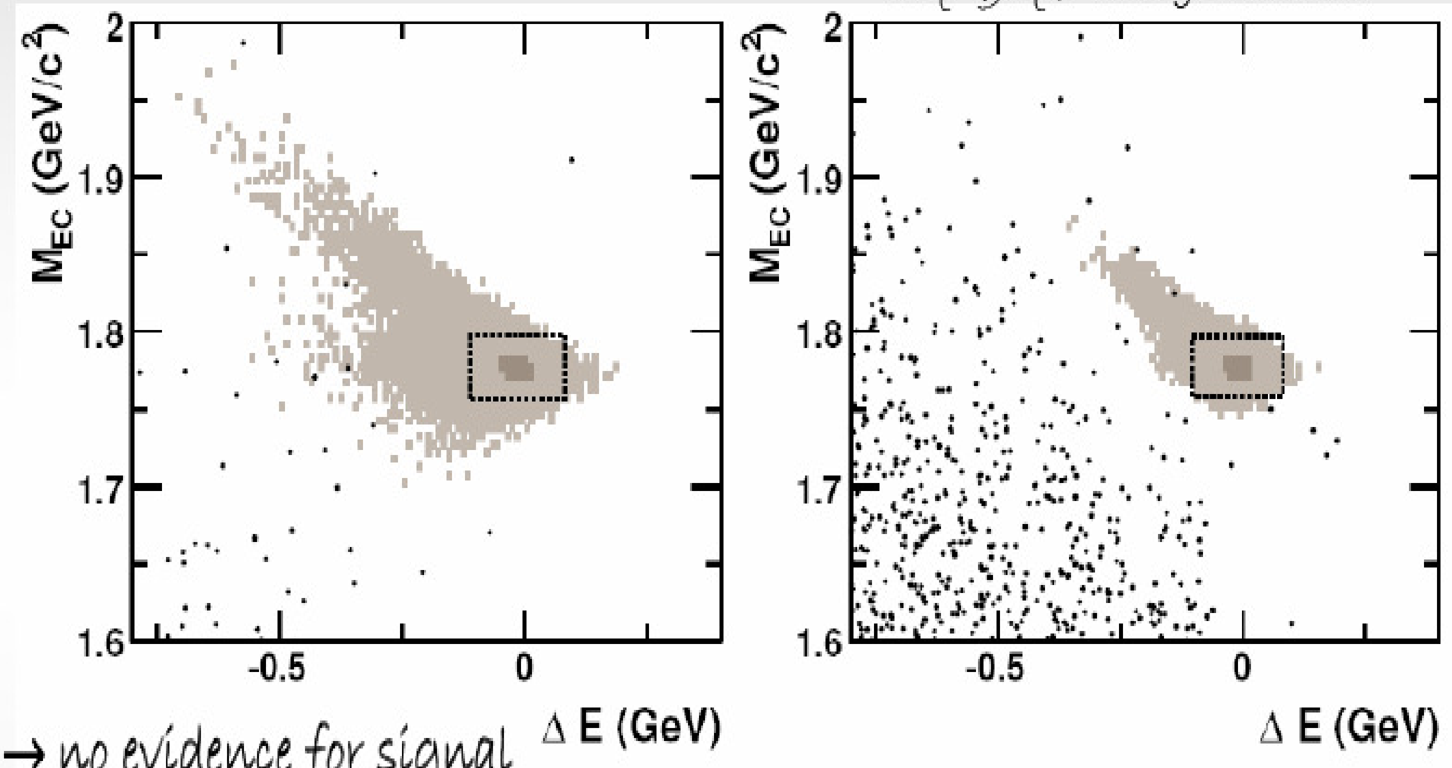
$BR(\tau^- \to l^- l^+ l^-) < (3.7\text{-}8.0)\ 10^{-8}$ @90% C.L.

$\tau^{\pm} \to l^{\pm}\omega$: results

hep-ex/0711.0980
accepted by PRL

✓ 384.1 fb^{-1}

dots: data
dark (light) gray region:
50% (90%) MC signal events



→ no evidence for signal

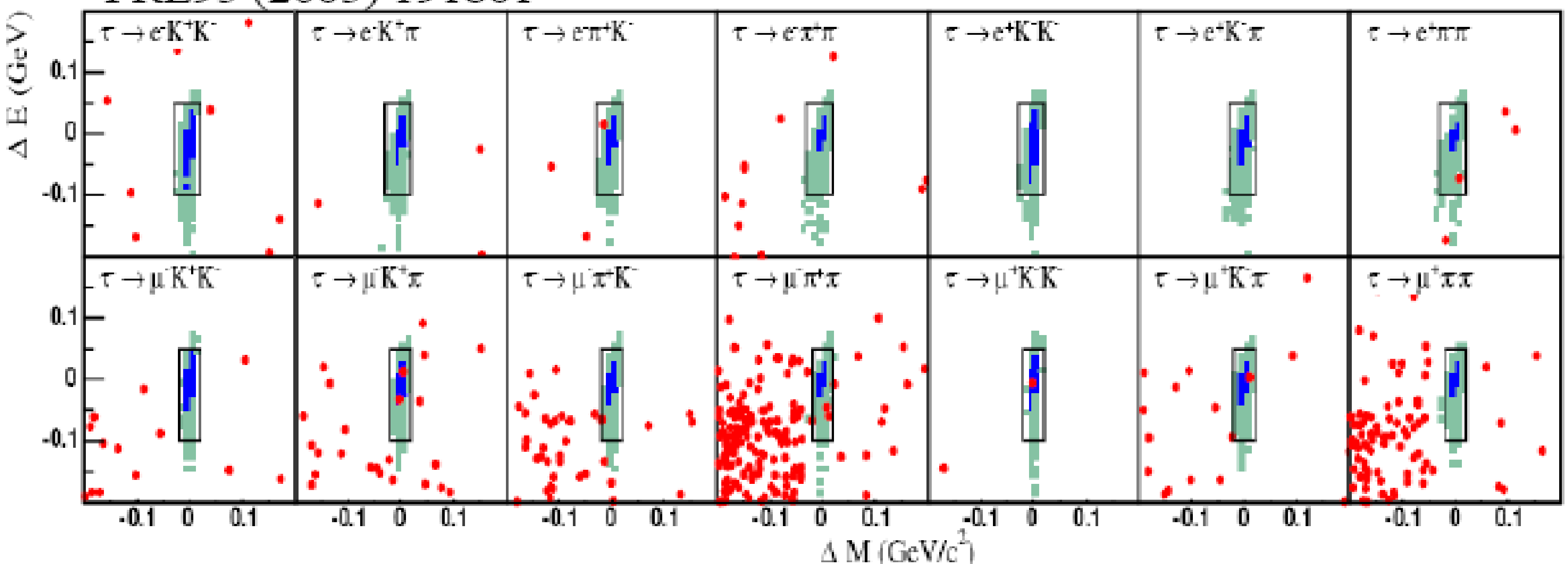
$BR(\tau^{\pm} \to e^{\pm}\omega) < 11 \times 10^{-8}$ @90% C.L.

$BR(\tau^{\pm} \to \mu^{\pm}\omega) < 10 \times 10^{-8}$ @90% C.L.

LFV in lhh

- Lepton Flavor violating modes: $\tau^- \rightarrow l^- h^+ h'^-$
- Lepton Number violating modes: $\tau^- \rightarrow l^+ h^- h'^-$

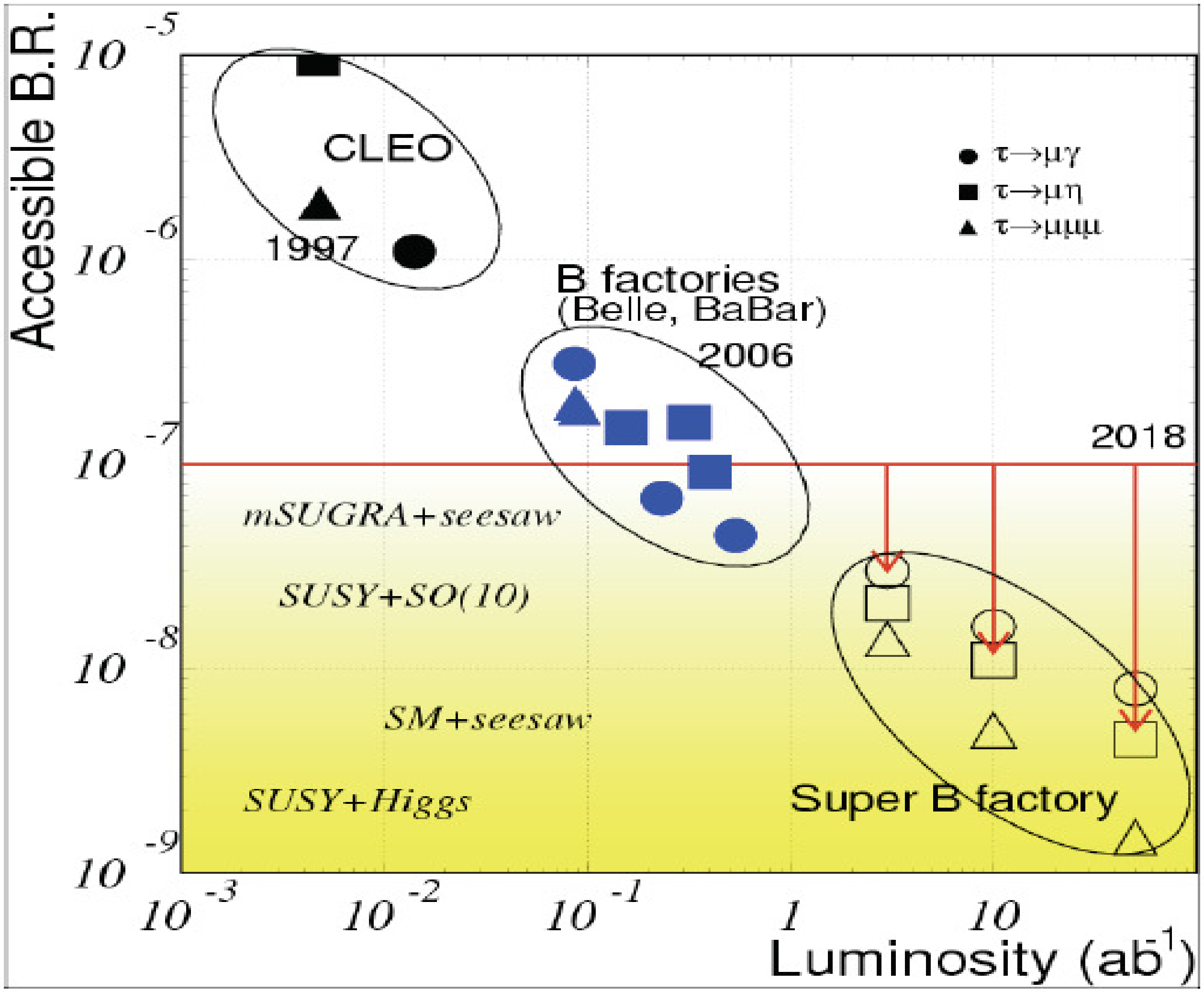
PRL95 (2005) 191801



$B(\tau \rightarrow lhh) < (0.7\text{-}4.8) \times 10^{-7}$ at 90% C.L.

Phys. Rev. Lett. **95**, 191801 (2005)

Future of Lepton Flavor Violation in τ Decays



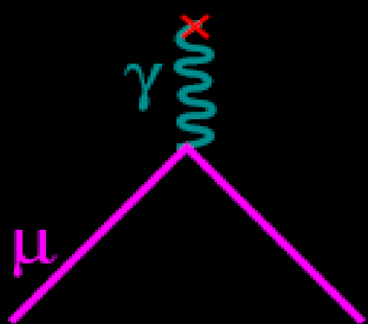
Anomalous magnetic moment of muon

Magnetic Moments, g-Factors, etc.

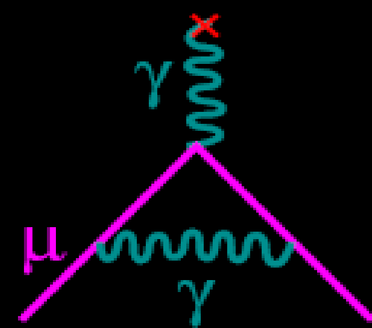
$$\vec{\mu}_s = g_s\left(\frac{e}{2m}\right)\vec{s}$$

$\vec{\mu}$ - magnetic moment; g - gyromagnetic ratio
$\vec{s}$ is the spin.

- Dirac Equation Predicts $g \equiv 2$
- In nature radiative corrections make $g \neq 2$.



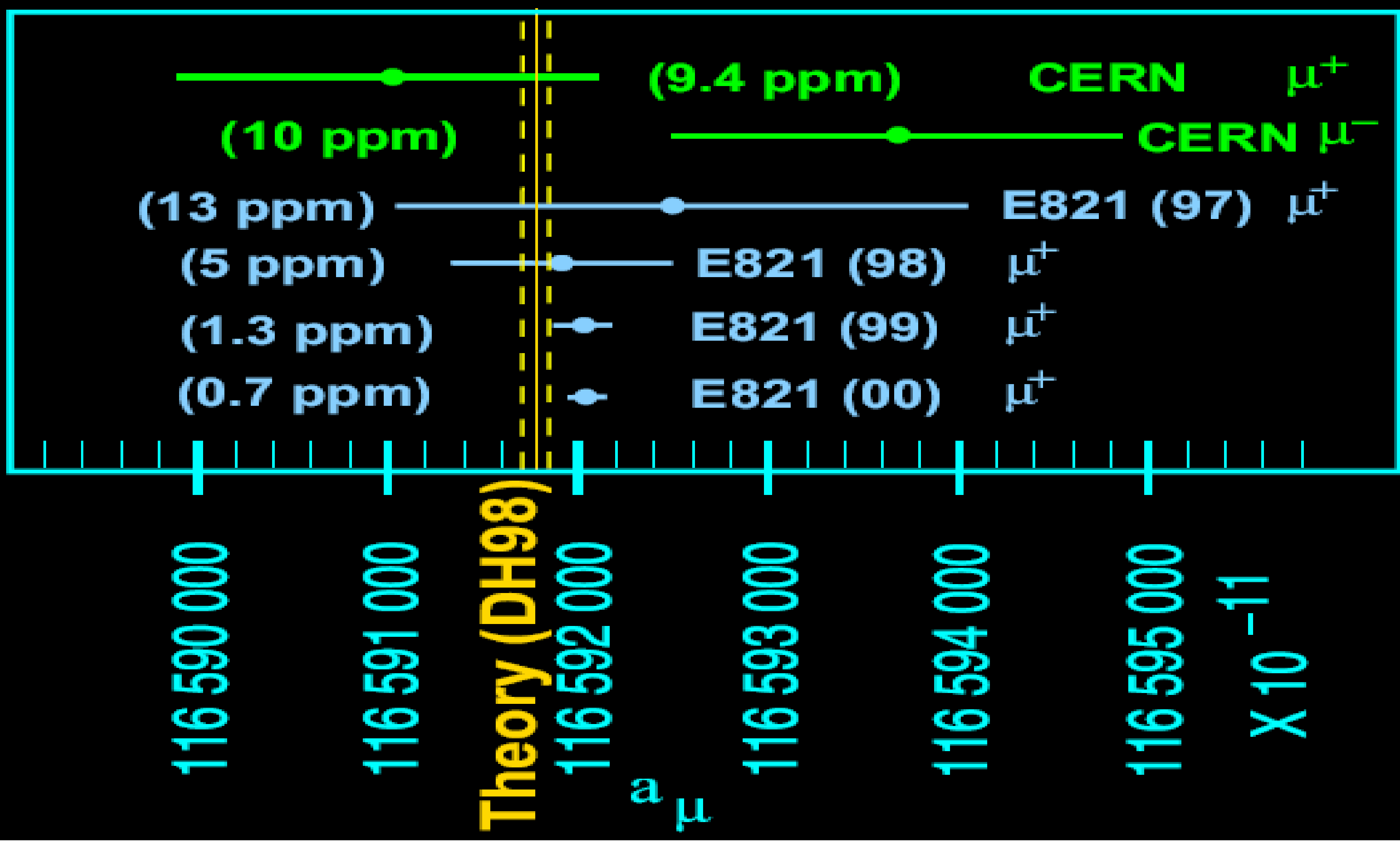
$$g = 2 + \frac{\alpha}{\pi} \quad + \cdots$$



Dirac

Kusch and Foley, Schwinger, 1947

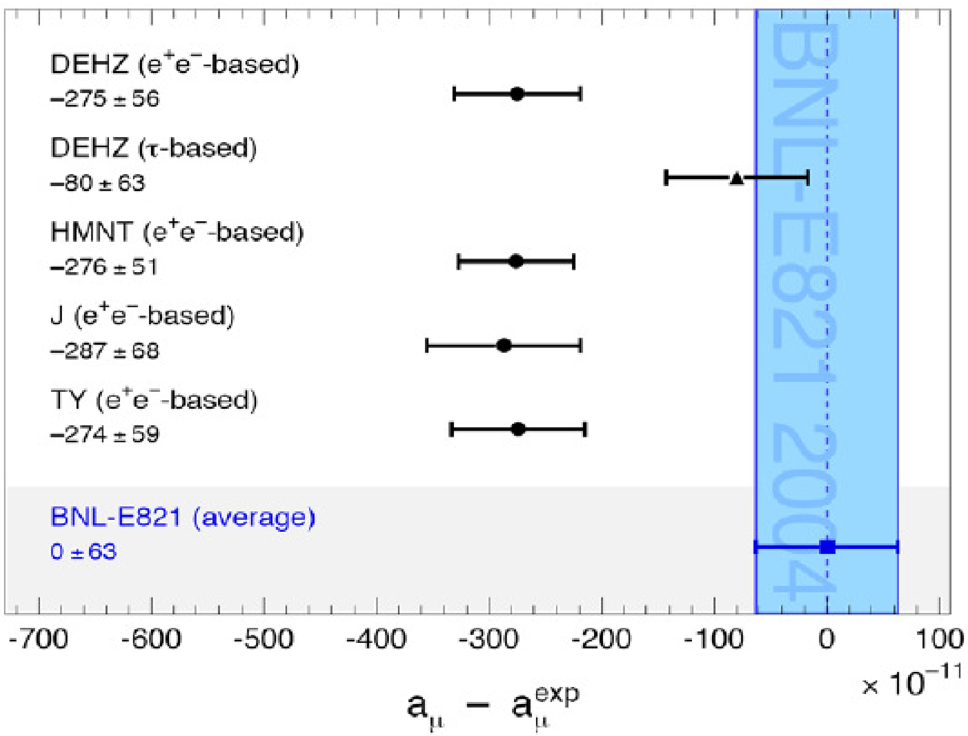
Measurements of a_μ



a_μ

$$a_\mu^{SM}[e^+e^-] = (11\,659\,180.5 \pm 4.4_{had,LO} \pm 3.5_{LBL} \pm 0.2_{QED+weak}) \times 10^{-10}$$

DEHZ (Tau 2006)



BNL E821 (2004):

$$a_\mu^{exp} = (11\,659\,208.0 \pm 6.3)\ 10^{-10}$$

Observed Difference with Experiment:

$$a_\mu^{exp} - a_\mu^{SM} = (27.5 \pm 8.4) \times 10^{-10}$$

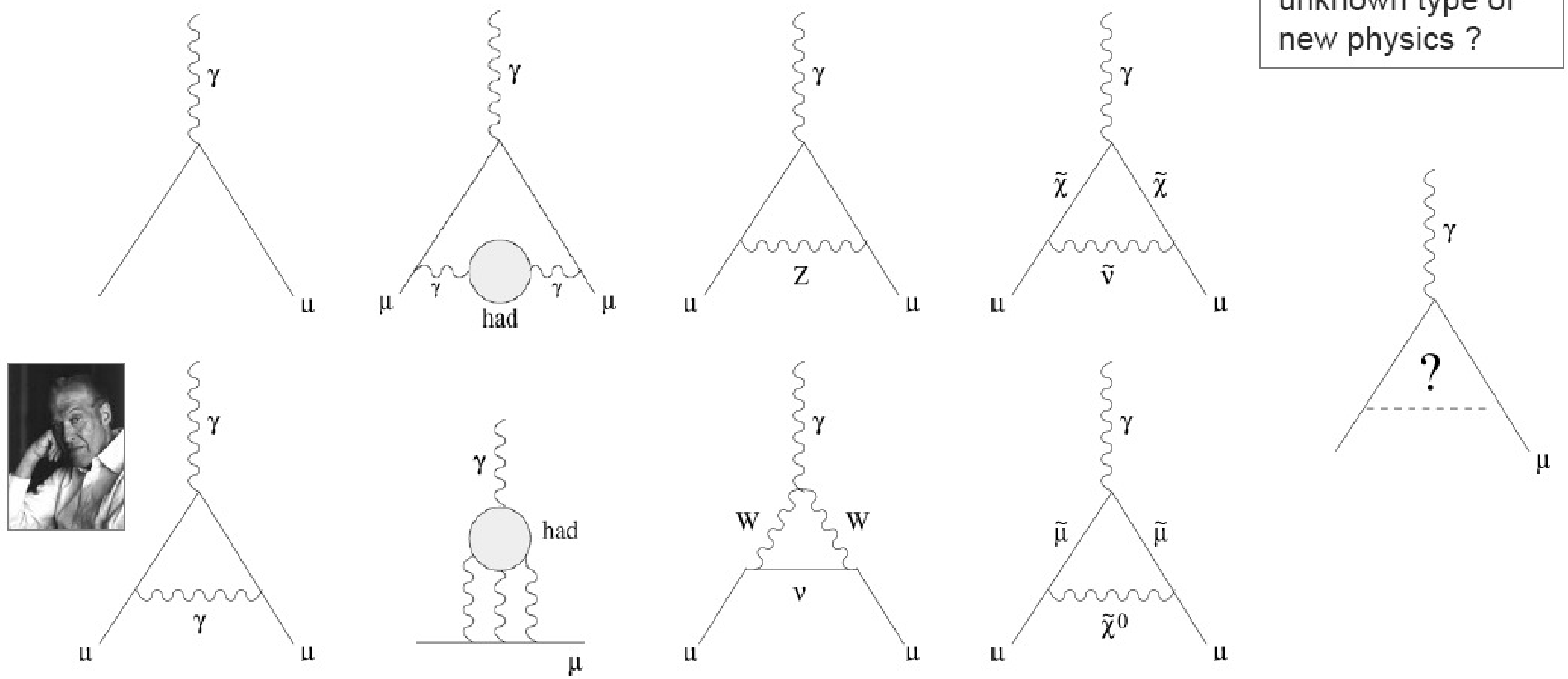
➡ 3.3 "standard deviations"

The Standard Model prediction of a_μ is decomposed in its main contributions:

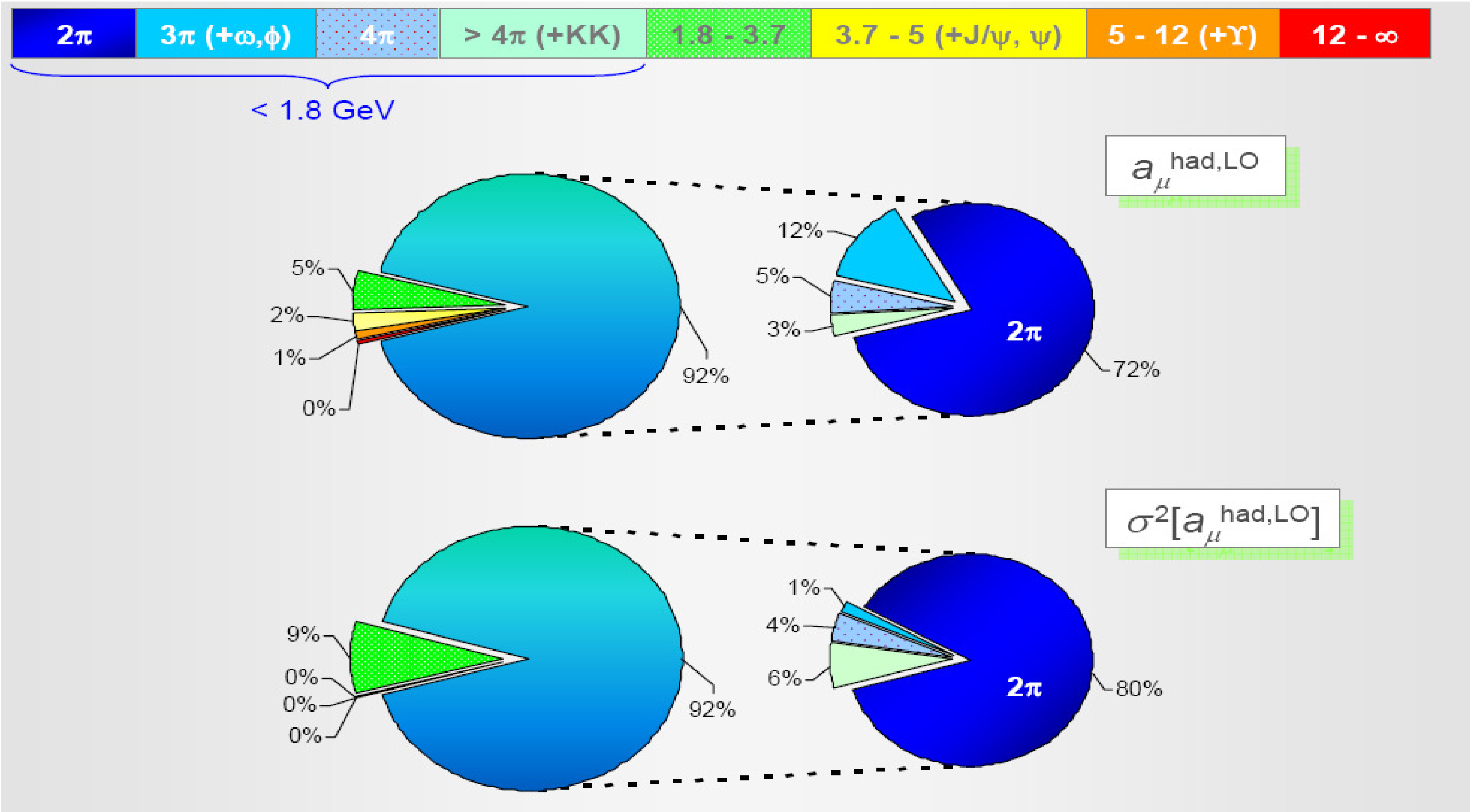
$$a_\mu^{SM} \equiv \left(\frac{g-2}{2}\right)_\mu = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak}$$

of which the hadronic contribution has the largest uncertainty

QED | Hadronic | Weak | SUSY... | ... or some unknown type of new physics ?



Component of a_μ



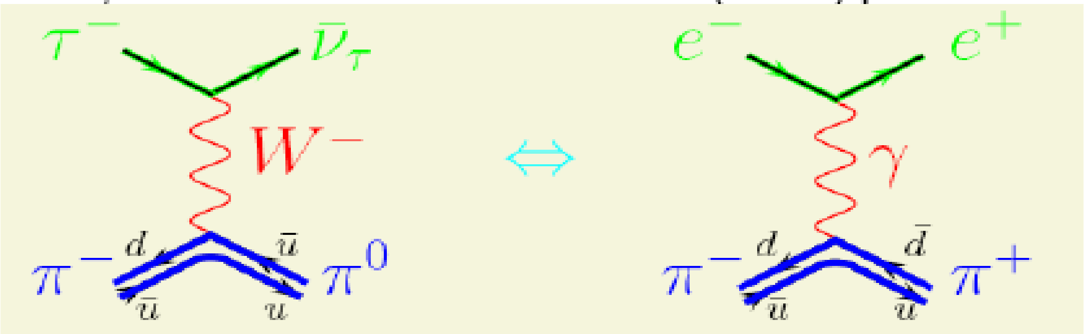
Conserved Vector Current

Because 73% of $a_\mu^{had,LO}$ is covered by 2π final state which is dominated by the $\rho(770)$ final state, let's deal with it.

$$\sigma(e^+e^- \longrightarrow \pi^+\pi^-) = \frac{4\pi\alpha_0^2}{s} v_0(s)$$

In the limit of isospin invariance, Conserved Vector Current (CVC) predict :

$$v_-(s) = v_0^{I=1}(s)$$



$$v_-(s) = \frac{\beta_-^3(s)}{12\pi} |F_\pi^-(s)|^2$$

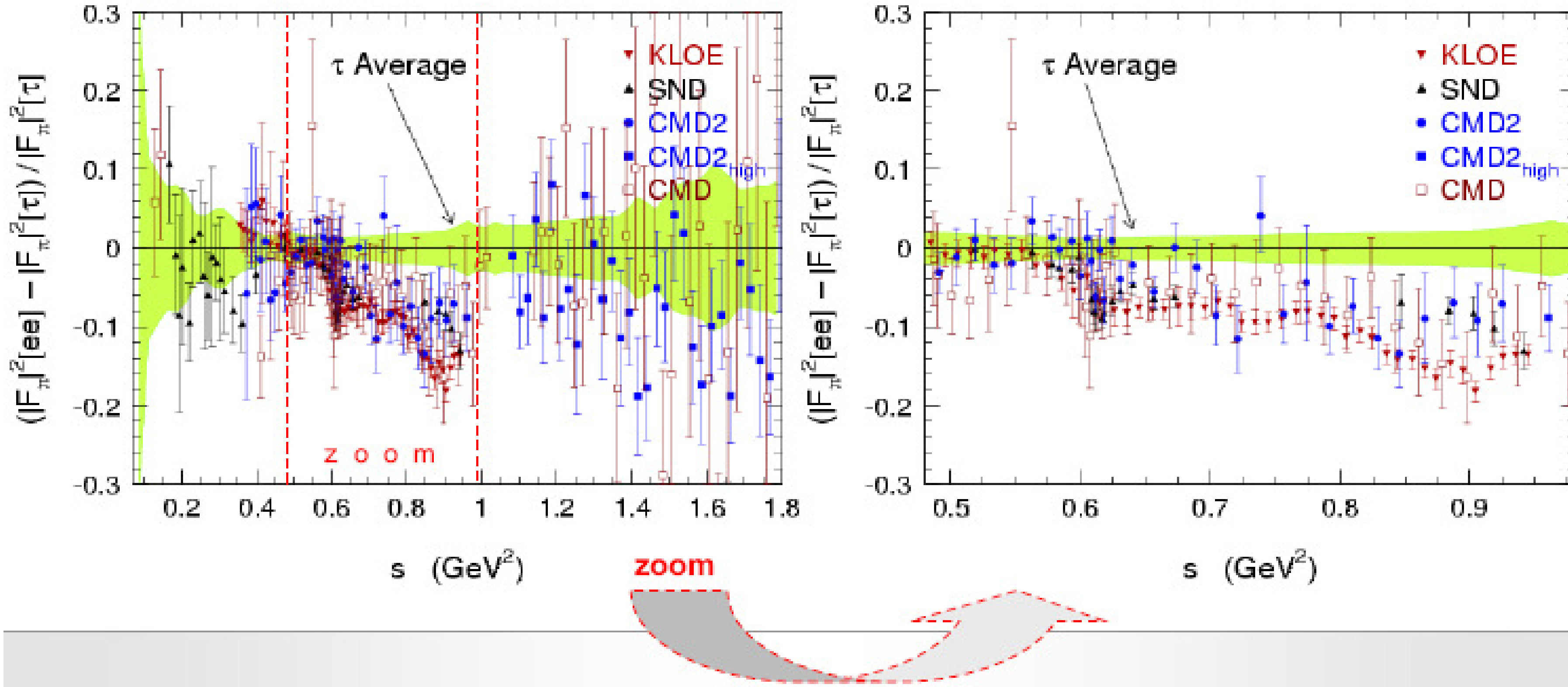
$$v_0(s) = \frac{\beta_0^3(s)}{12\pi} |F_\pi^0(s)|^2$$

$$\beta_{0,-} = \beta(s, m_{\pi^-}, m_{\pi^{+,0}})$$

$$\beta(s, m_1, m_2) = \left[\left(1 - \frac{(m_1+m_2)^2}{s}\right)\left(1 - \frac{(m_1-m_2)^2}{s}\right)\right]^{1/2}$$

The Problem

Relative difference between τ and e^+e^- data (form factors)

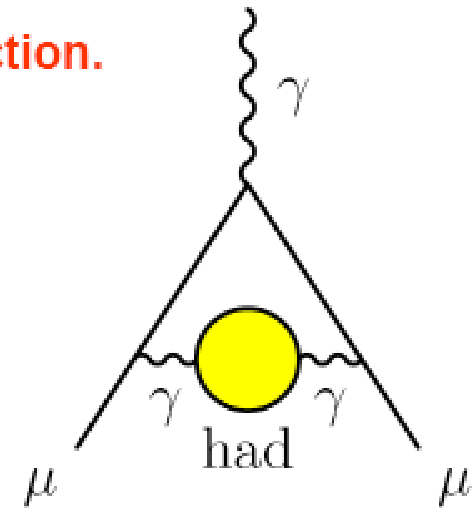


➔ Clear difference on s dependence in particular for s at 0.7 – 1.0 GeV^2

Lowest order in hadronic

the main error contributor to the a_μ theoretical prediction.

$$a_\mu^{\mathrm{had,LO}} = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \, \frac{K(s)}{s} R^{(0)}(s)$$



$$K(s) = x^2\left(1-\frac{x^2}{2}\right) + (1+x)^2\left(1+\frac{1}{x^2}\right)\left[\ln(1+x) - x + \frac{x^2}{2}\right] + x^2 \ln x \frac{1+x}{1-x}$$

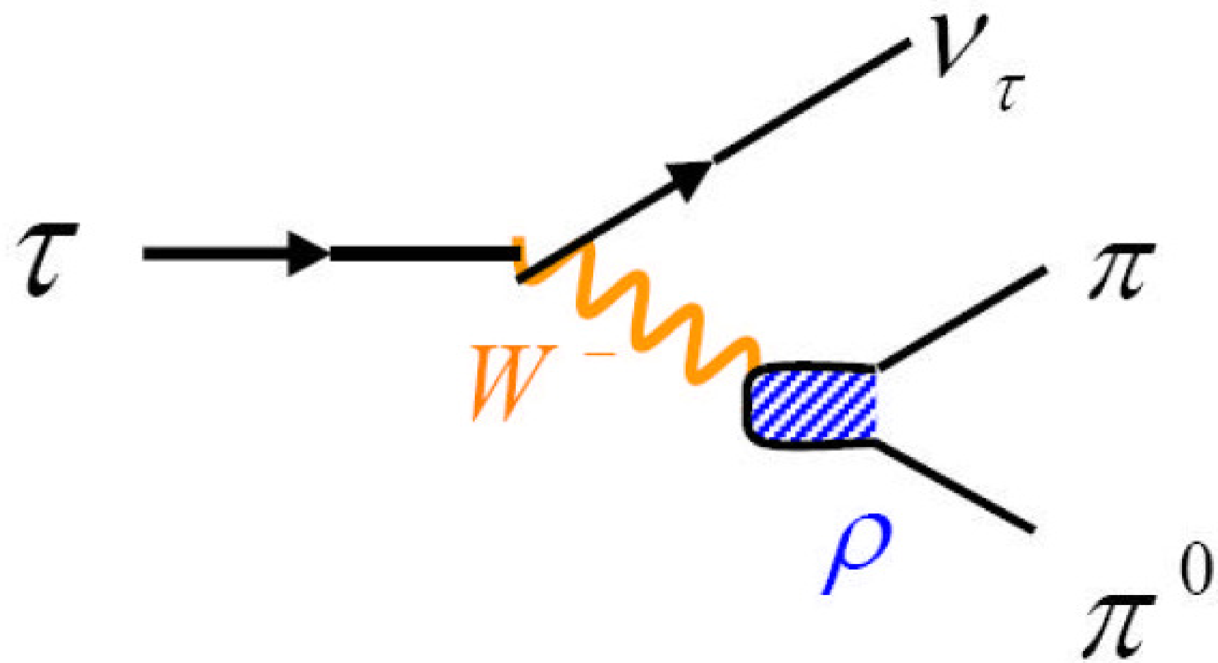
$$x = (1-\beta_\mu)/(1+\beta_\mu)$$

$$\beta_\mu = (1-4m_\mu^2/s)^{1/2}$$

As QCD is a non-Abelian theory with massless gauge bosons, its perturbative expansion at low energies is not well behaved, so experimental results are needed to complete the theory

Signal

The signal consists of π^- and π^0 (reconstructed from 2 photons)



Systematic ; we are varying every input which goes into rho mass by uncertainties derived from independent data-MC control samples.

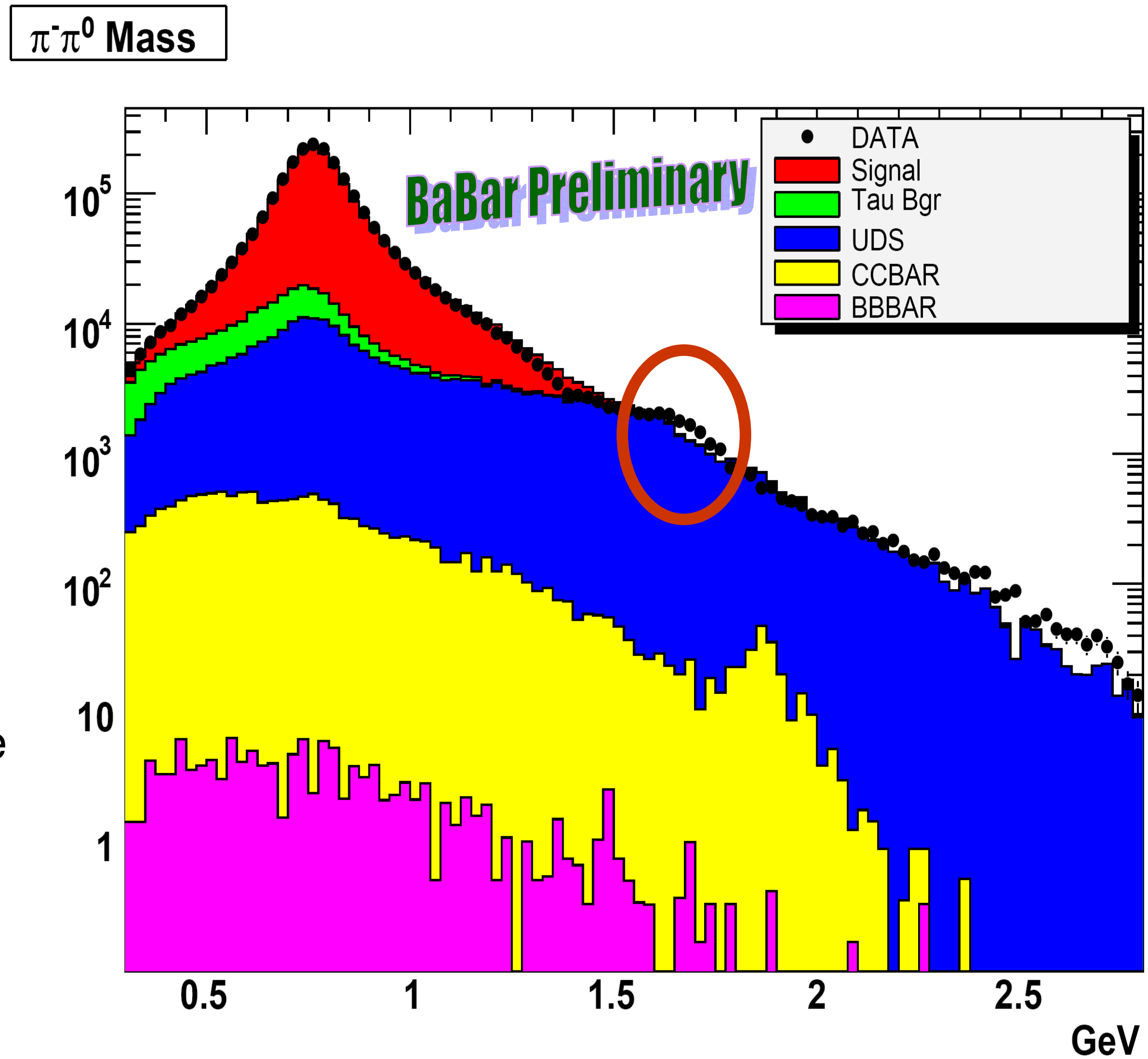
Invariant $\pi^{-}\pi^{0}$ Mass Spectrum

Comparison between Data and MonteCarlo, shows good agreement, except about ρ”(1.7 GeV).

BABAR will be able to confirm ρ”(1.7 GeV)

Plot after Montecarlo samples are normalized to Data Luminosity

After Background subtracted, we can use Gounaris-Sakurai function to study its properties



What will we measure?

- $M\rho, \Gamma\rho$ (Mass and width of ρ)
- $M\rho', \Gamma\rho'$ (Mass and width of ρ')
- $M\rho'', \Gamma\rho''$ (Mass and width of ρ'')
- β, ϕ_β (contribution of ρ' and its phase)
- γ, ϕ_γ (contribution of ρ'' and its phase)
- $a_\mu^{\pi\pi}$($\pi\pi$ part of muon anomalous magnetic moment and the most interesting part)

Gounaris-Sakurai Fitting Function

$$F_\pi^{I=1}(q^2) = \frac{1}{1+\beta+\gamma}(BW_\rho + \beta\, BW_{\rho'} + \gamma\, BW_{\rho''\ldots})$$

$$BW_\rho = \frac{M_\rho^2 + M_\rho \Gamma_\rho d}{(M_\rho^2 - q^2) + f(q^2) - i\sqrt{q^2}\Gamma_\rho(q^2)}$$

$$d = \frac{3m_\pi^2}{\pi p_0^2} ln \frac{M_\rho + 2p_0}{2m_\pi} + \frac{M_\rho}{2\pi p_0} - \frac{m_\pi^2 M_\rho}{\pi p_0^3}$$

$$f(q^2) = \frac{\Gamma_\rho M_\rho^2}{p_0^3}\left[p_\pi^2(q^2)[h(q^2) - h(M_\rho^2)] - p_0^2(q^2 - M_\rho^2)\frac{dh}{dq^2}|_{q^2=M_\rho^2}\right]$$

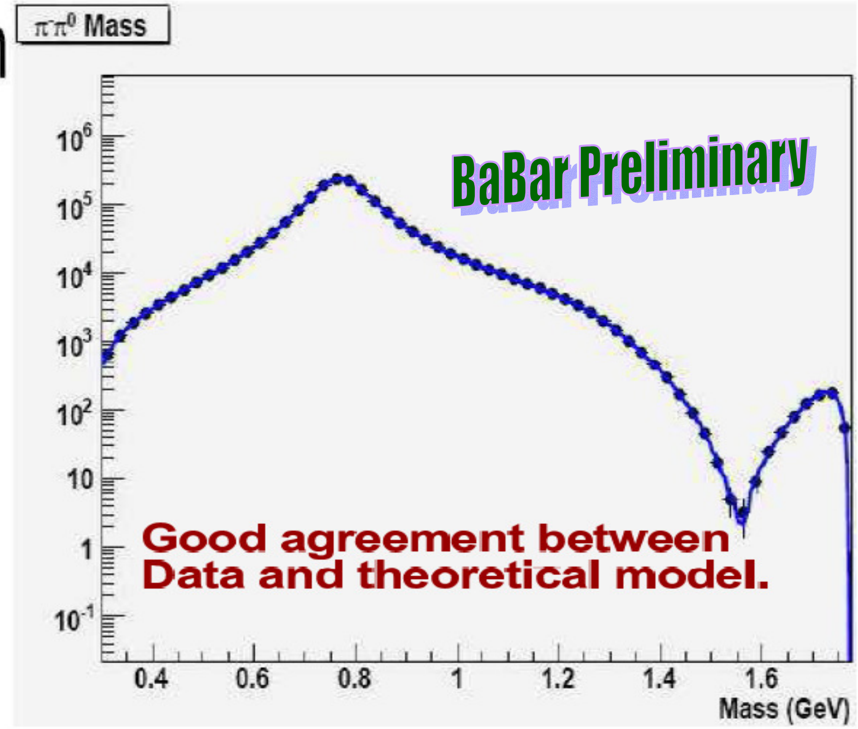
$$h(q^2) = \frac{2p_\pi(q^2)}{\pi\sqrt{q^2}} ln \frac{\sqrt{q^2} + 2p_\pi(q^2)}{2m_\pi}$$

$$\Gamma_\rho(q^2) = \Gamma_\rho \frac{M_\rho^2 p_\pi^3}{q^2 p_0^3}$$

$$\frac{dh}{dq^2}|_{q^2=M_\rho^2} = h(M_\rho^2)\left[\frac{1}{8p_0} - \frac{1}{2M_\rho^2}\right] + \frac{1}{2\pi M_\rho^2}$$

$$p_\pi = \frac{1}{2}\sqrt{q^2 - 4m_\pi^2}$$

$$p_0 = \frac{1}{2}\sqrt{M_\rho^2 - 4m_\pi^2}$$



- **Blue** line is the Fitting line.
- Dots are "Background-Subtracted Data"

The free parameters are $M_\rho, M_{\rho'}, M_{\rho''}, \Gamma_\rho, \Gamma_{\rho'}, \Gamma_{\rho''}, \beta, \gamma, \phi_\beta, \phi_\gamma$

Fitting parameters

BaBar Preliminary	BaBar	Belle	ALEPH(τ)	CMD-2(e^+e^-)
M ρ(GeV)	0.7745 ± 0.0006	0.7735 ± 0.0002	0.7755 ± 0.0007	0.7733 ± 0.0006
$\Gamma\rho$(GeV)	0.1493 ± 0.0013	0.1492 ± 0.0004	0.1490 ± 0.0012	0.1452 ± 0.0013
M ρ'(GeV)	1.2993 ± 0.0034	1.4530 ± 0.0070	1.3280 ± 0.0150	1.3370 ± 0.0350
$\Gamma\rho'$(GeV)	0.4990 ± 0.0133	0.4376 ± 0.0199	0.4680 ± 0.0410	0.5690 ± 0.0810
M ρ''(GeV)	1.6614 ± 0.0170	1.7300 ± 0.0220	1.7130(fixed)	1.7130 ± 0.0150
$\Gamma\rho''$(GeV)	0.2433 ± 0.0366	0.1379 ± 0.0500	0.2350(fixed)	0.2350(fixed)
β	0.090 ± 0.013	0.167 ± 0.005	0.210 ± 0.008	0.123 ± 0.011
γ	0.060 ± 0.009	0.031 ± 0.011	0.023 ± 0.008	0.048 ± 0.008
$\|\phi_\beta\|$	118.9 ± 8.3	210.3 ± 6.3	153.0 ± 7.0	139.4 ± 6.5
$\|\phi_\gamma\|$	59.4 ± 8.3	44.2 ± 17	0(fixed)	0(fixed)

Using the Gounaris-Sakurai function, we can extract some important parameters

Result

Using the spectral that we get from BABAR, we can calculate $a_\mu^{\pi\pi}$

BaBar Preliminary

	$a_\mu^{\pi\pi}(10^{-10})$
BaBar	$458.45 \pm 0.40(\text{stat}) \pm 0.76(\text{int sys}) \pm 2.70(\text{ext sys}) \pm 2.30_{SU(2)}$
Belle	$459.80 \pm 0.50(\text{stat}) \pm 1.00(\text{int sys}) \pm 3.00(\text{ext sys}) \pm 2.30_{SU(2)}$
ALEPH(τ)	$464.0 \pm 3.2 \pm 2.3_{SU(2)}$
CMD-2(e^+e^-)	$450.2 \pm 4.9 \pm 1.6_{SU(2)}$

BABAR will publish the most precise of in $a_\mu^{\pi\pi}$ the world

Results: the Compilation (including newest data)

Contributions to $a_\mu^{had,LO}$ [in 10^{-10}] from the different energy domains:

Modes	Energy [GeV]	e^+e^-	τ
Low s expansion	$2m_\pi - 0.5$	$55.6 \pm 0.8 \pm 0.1_{rad}$	$56.0 \pm 1.6 \pm 0.3_{SU(2)}$
$\pi^+\pi^-$ (+SND+CMD-2)	$0.5 - 1.8$	$449.0 \pm 3.0 \pm 0.9_{rad}$	$464.0 \pm 3.0 \pm 2.3_{SU(2)}$
$\pi^+\pi^- 2\pi^0$	$2m_\pi - 1.8$	$16.8 \pm 1.3 \pm 0.2_{rad}$	$21.4 \pm 1.3 \pm 0.6_{SU(2)}$
$2\pi^+ 2\pi^-$ (+BABAR)	$2m_\pi - 1.8$	$13.1 \pm 0.4 \pm 0.0_{rad}$	$12.3 \pm 1.0 \pm 0.4_{SU(2)}$
ω (782)	$0.3 - 0.81$	$38.0 \pm 1.0 \pm 0.3_{rad}$	–
ϕ (1020)	$1.0 - 1.055$	$35.7 \pm 0.8 \pm 0.2_{rad}$	–
Other excl. (+BABAR)	$2m_\pi - 1.8$	$24.3 \pm 1.3 \pm 0.2_{rad}$	–
J/ψ, ψ(2S)	$3.08 - 3.11$	$7.4 \pm 0.4 \pm 0.0_{rad}$	–
R [QCD]	$1.8 - 3.7$	$33.9 \pm 0.5_{theo}$	–
R [data]	$3.7 - 5.0$	$7.2 \pm 0.3 \pm 0.0_{rad}$	–
R [QCD]	$5.0 - \infty$	$9.9 \pm 0.2_{theo}$	–
Sum (w/o KLOE)	$2m_\pi - \infty$	$690.8 \pm 3.9 \pm 1.9_{rad} \pm 0.7_{QCD}$	$710.1 \pm 5.0 \pm 0.7_{rad} \pm 2.8_{SU(2)}$

BaBar Preliminary

<< BABAR08

Summary

- LFV results from τ Decays are very competitive
- BaBar will have the most precise calculation of $\pi\pi$ part of muon anomalous magnetic moment in the world BaBar Preliminary (prepared for ICHEP 2008)
- There is a lot of physics to be extracted from this huge data sample