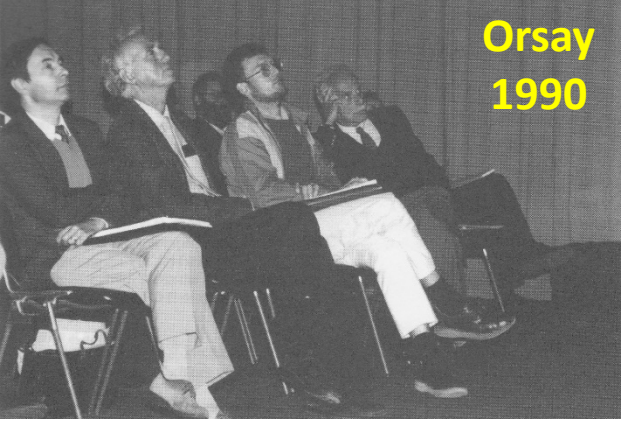
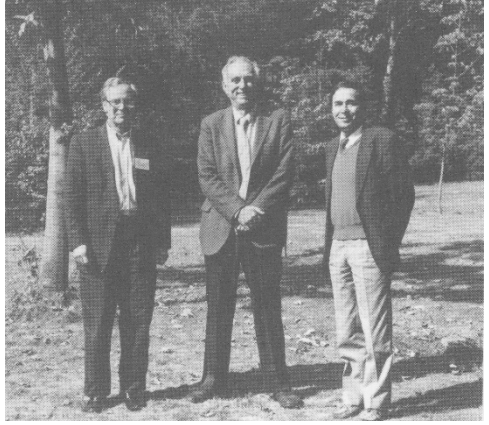




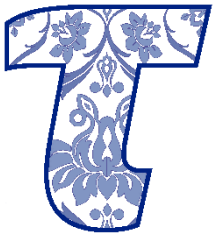
Workshop on Tau Lepton Physics @ 30th Anniversay

Antonio Pich

IFIC, Univ. Valencia - CSIC

The 16th International Workshop on Tau Lepton Physics (TAU2021)
Indiana University (online), 27 September – 1 October 2021

Olga Igonkina (Moscow 1973 – Amsterdam 2019)



- Chair of TAU 2018 Organizing Committee
- ARGUS → HERA-B → BaBar → ATLAS
- ITEP → U. Oregon (SLAC & CERN) → Nikhef & Radboud U. in Nijmegen
- Convener of BaBar τ working group (work on LFV τ decays)
- ATLAS trigger-menu coordinator
- 2018 ATLAS Oustanding Achievement Award (B-hadron triggers, LFV)

Simon Eidelman (Odessa 1948 – Novosibirsk 2021)

- Co-Chair of TAU 2008 (and sτcF 2018) Organizing Committee
- VEPP-2(M), OLYA, CMD-2, CMD-3, Belle, Belle-II, LHCb
- Budker Institute of Nuclear Physics & Physics Department, Novosibirsk
- Member of the Particle Data Group (1992-2021)
- Editorial Board of EPJC (2019-2021)
- Summary talk @ TAU 2018

Workshops on Tau Lepton Physics

1. Orsay, France, 1990. Michel Davier – Bernard Jean-Marie
2. Columbus, Ohio, USA, 1992. K.K. Gan
3. Montreux, Switzerland, 1994. Luigi Rolandi
4. Estes Park, Colorado, USA, 1996. James G. Smith – Walter Toki
5. Santander, Spain, 1998. Antonio Pich – Alberto Ruiz
6. Victoria, BC, Canada, 2000. Randall J. Sobie – J. Michael Roney
7. Santa Cruz, California, USA, 2002. Terry Schalk – Abe Seiden
8. Nara, Japan, 2004. H. Hayashii
9. Pisa, Italy, 2006. Fabrizio Cei – Isidoro Ferrante - Alberto Lusiani
10. Novosibirsk, Russia, 2008. Alexander Skrinsky – Alexander Bondar – Simon Eidelman
11. Manchester, UK, 2010. George Lafferty – Stefan Söldner-Rembold
12. Nagoya, Japan, 2012. Kiyoshi Hayasaka – Toru Iijima
13. Aachen, Germany, 2014. Achim Stahl – Ian M. Nugent
14. Beijing, China, 2016. Xiaohu Mo – Changzheng Yuan
15. Amsterdam, Netherlands, 2018. Olga Igonkina – Cristina Galea
16. Indiana, USA, 2021. Emilie Passemar – Swagato Banerjee – Jon Urheim

Tau-Charm Factory Workshops

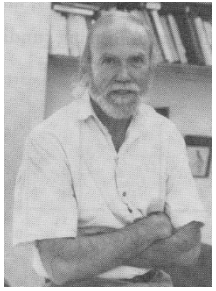
- SLAC, California, USA, 1989. K.L. Brown et al
- Sevilla, Spain, 1991. Jasper Kirkby – Juan Antonio Rubio
- JINR, Dubna, SLAC…
- Marbella, Spain, 1993. Jasper Kirkby
- Argonne, Illinois, USA, 1995. José Repond
- Beijing, China, 1996. Z.P. Zheng
- Beijing, China, 2006 (CHARM06). Yifang Wang

➡ **BESIII @ BEPCII** (main focus charm & charmonium)

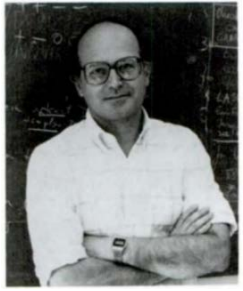
- …

- Orsay, France, 2018. V. Balagura et al.
- Novosibirsk, Russia, 2018. Alexander Bondar – Simon Eidelman
- Moscow, Russia, 2019.
- Guangzhou, China, 2020 (online). A. Barnyakov et al.

} **STCF**



1990 Status



- Previous knowledge summarized by Barry C. Barish and Ryszard Stroynowski in "The Physics of the tau Lepton", Phys. Rep. 157 (1988) 1
- Not a field on its own: *"by-product of general purpose e^+e^- detectors"* (Barish)
- Relatively large uncertainties. Inconsistencies in the data.

- **τ Anomalies:** (HRS $\tau \to \nu_\tau \pi\eta$ signal already gone)

  - **The one-prong problem**

    $B_1^{incl} = (86.1 \pm 0.3)\%$, $B_1^{excl} = (81.0 \pm 1.5)\%$ [3.3 σ]

  - **Discrepancy between the τ lifetime and electronic branching ratio**

    $B_e = (17.78 \pm 0.32)\%$ ➡ $\tau_\tau^{SM} = (2.81 \pm 0.06) \cdot 10^{-13}$ s

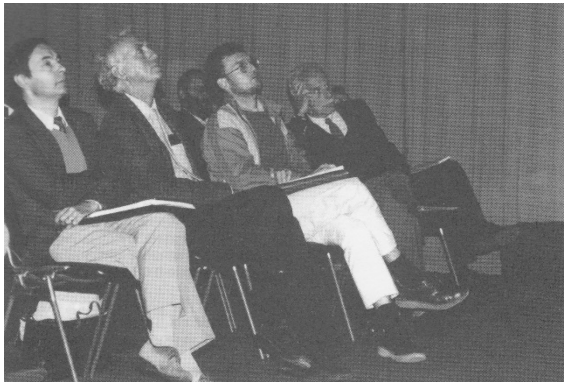
    $\tau_\tau^{exp} = (3.04 \pm 0.06) \cdot 10^{-13}$ s [2.7 σ]

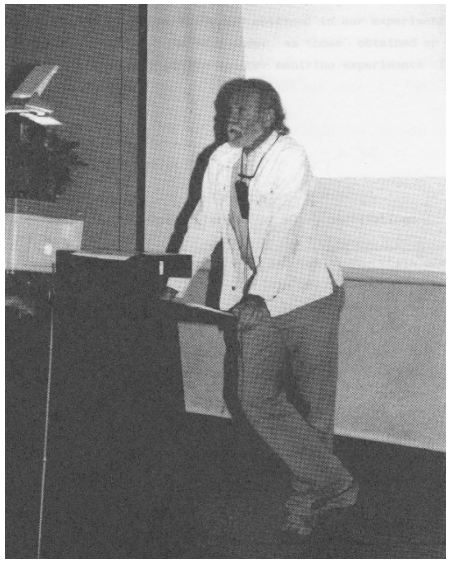
- **LEP started its operation in August 1989**

Orsay 1990: Successful & Inspiring Meeting

Orsay 1990: Successful & Inspiring Meeting

- Many ideas, suggestions & alive discussions
- 117 participants
- First (very preliminary) LEP analyses





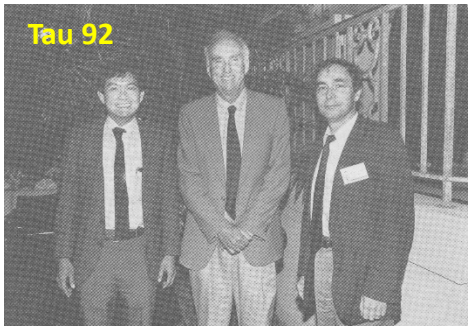
e^+e^- annihilation into hadrons and exclusive τ decays

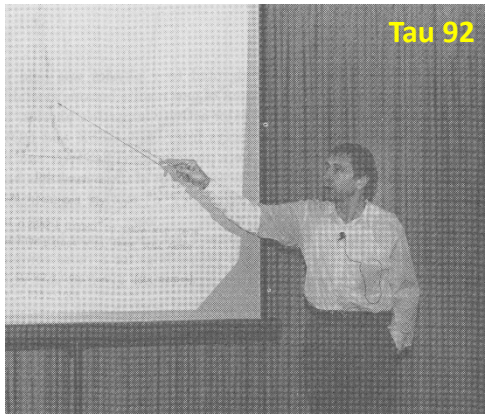
Resonance studies in τ decays

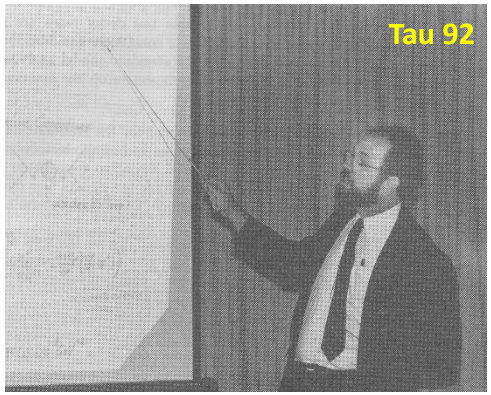
Hadronic τ decays and QCD

The Golden Age

Columbus 1992, Montreux 1994
Estes Park 1996, Santander 1998
Victoria 2000







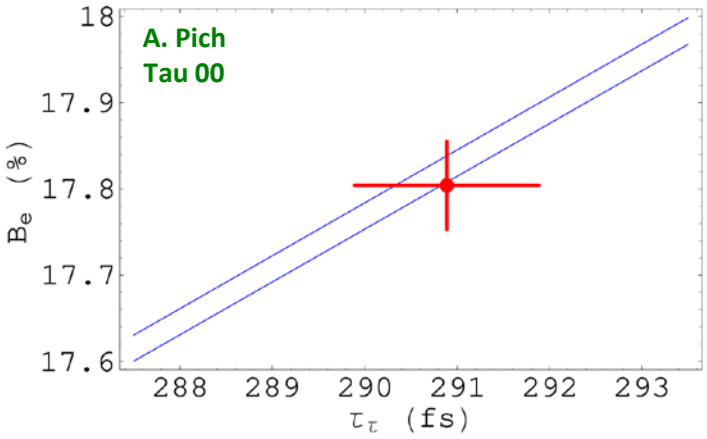
- Lots of new data: LEP, CLEO, SLD, ARGUS
- Accurate m_τ measurement at BES
- Main τ anomalies solved

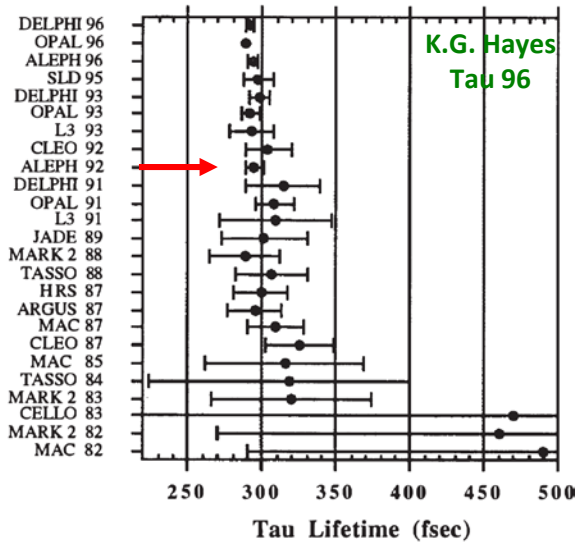
$Br_{unseen} < 0.11\%$ (95% CL) M. Davier, Tau 92

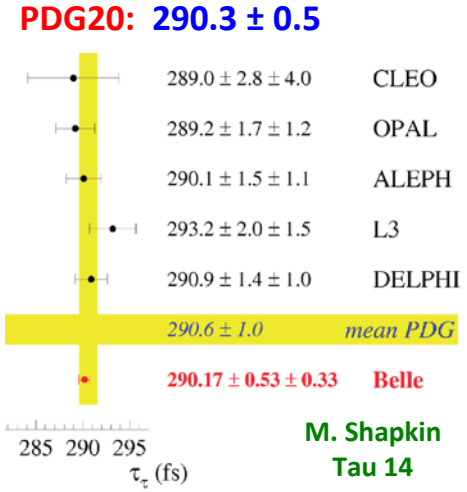
- Precision era: SM tests (QCD, EW)
- Many theory developments:
  - QCD: Braaten-Narison-A.P.-Le Diberder, Prades…
  - Hadronic structure: Kühn-Santamaria-Mirkes, A.P., Decker-Finkemeier-Heiliger-Jonsson, Colangelo-Urech,…
  - EW corrections: Marciano-Sirlin, Braaten-Li, Decker-Finkemeier,…
  - Polarization analyzers: Davier-Duflot-Le Diberder-Rouge, Alemany-Rius-Bernabéu-Gómez-A.P.,…
  - TAUOLA: Jadach-Kühn-Was-Jezabek,…

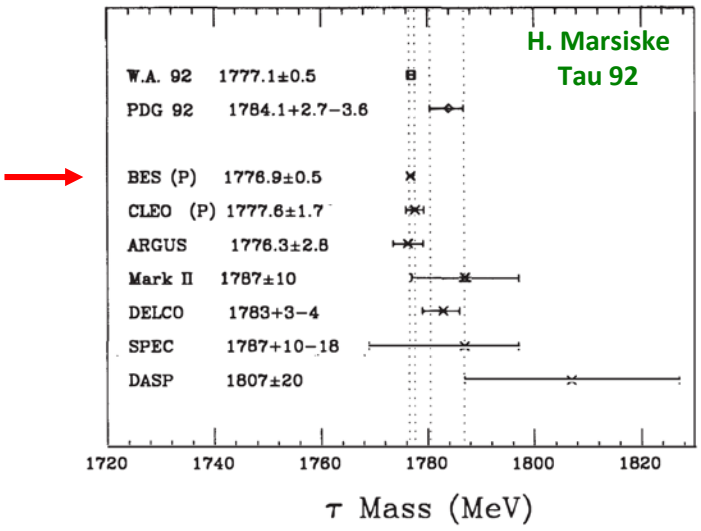
Shifts on τ_τ and m_τ

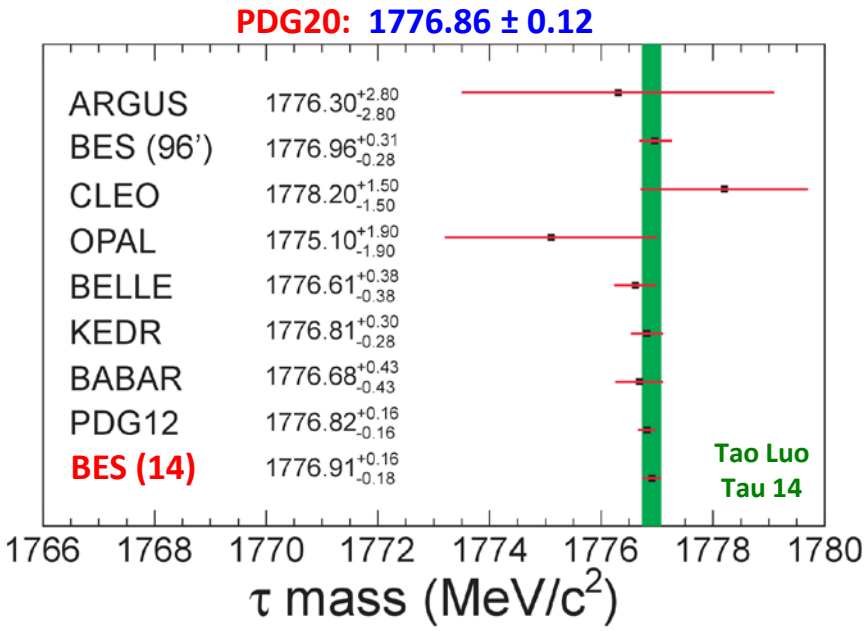
$$\Gamma(\tau \to e\bar{\nu}_e\nu_\tau) = B_e/\tau_\tau \propto m_\tau^5$$











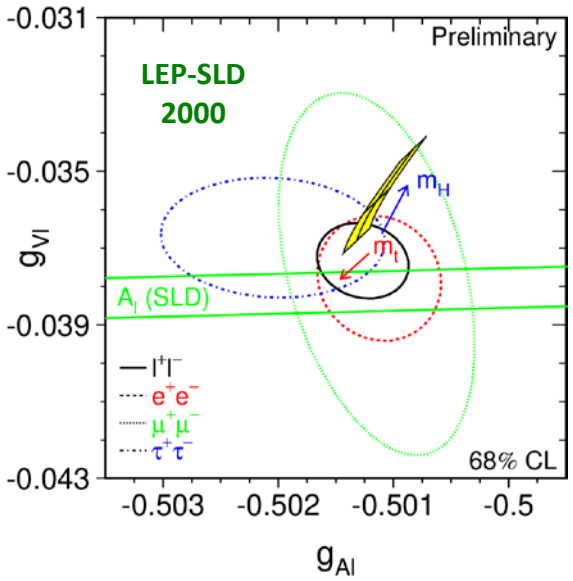
Leptonic Universality

A. Pich
Tau 00

W couplings

	$\lvert g_\mu/g_e\rvert$
B_μ/B_e	1.0006 ± 0.0021
$B_{\pi\to e}/B_{\pi\to\mu}$	1.0017 ± 0.0015
$B_{W\to\mu}/B_{W\to e}$	0.999 ± 0.013
	$\lvert g_\tau/g_\mu\rvert$
$B_e\tau_\mu/\tau_\tau$	0.9995 ± 0.0023
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	1.005 ± 0.007
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.977 ± 0.016
$B_{W\to\tau}/B_{W\to\mu}$	1.022 ± 0.014
	$\lvert g_\tau/g_e\rvert$
$B_\mu\tau_\mu/\tau_\tau$	1.0001 ± 0.0023
$B_{W\to\tau}/B_{W\to e}$	1.021 ± 0.015

Z couplings

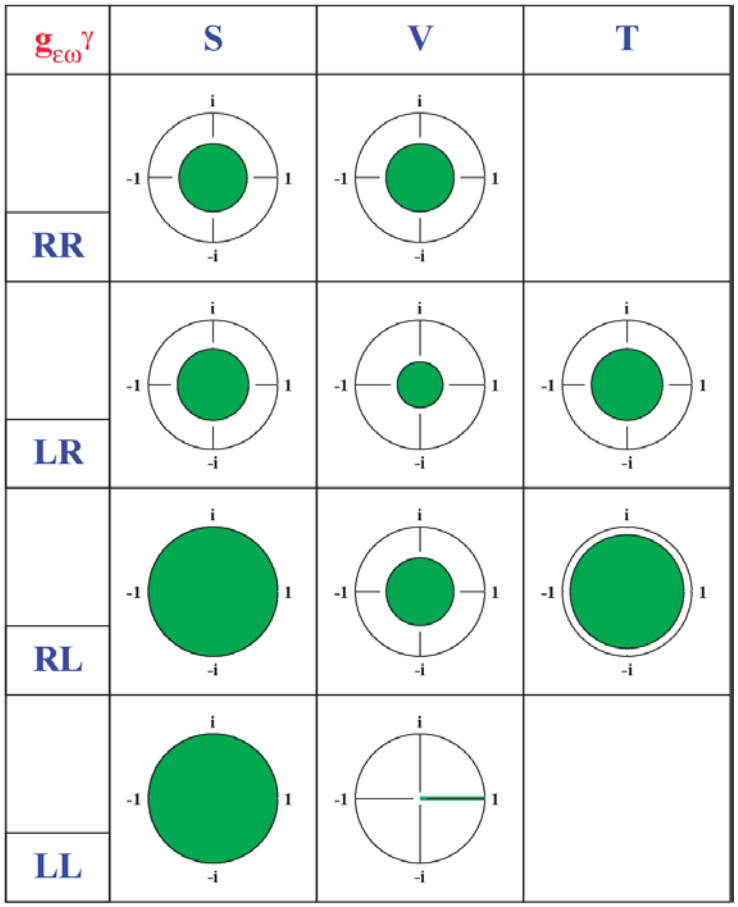


Michel parameters

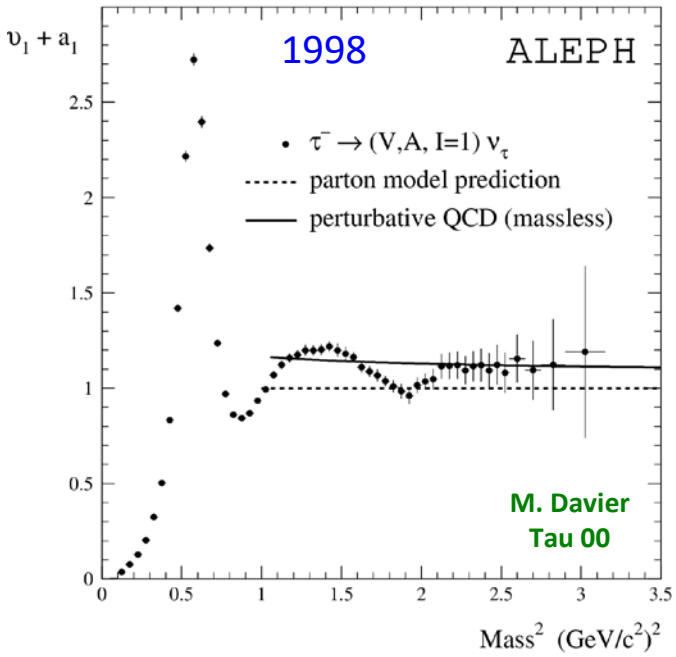
$$H = 4\frac{G_{\ell'\ell}}{\sqrt{2}}\sum_{n,\epsilon,\omega} g^n_{\epsilon\omega}\left[\overline{\ell'_\epsilon}\Gamma^n(\nu_{\ell'})_\sigma\right]\left[\overline{(\nu_\ell)_\lambda}\Gamma_n\ell_\omega\right]$$

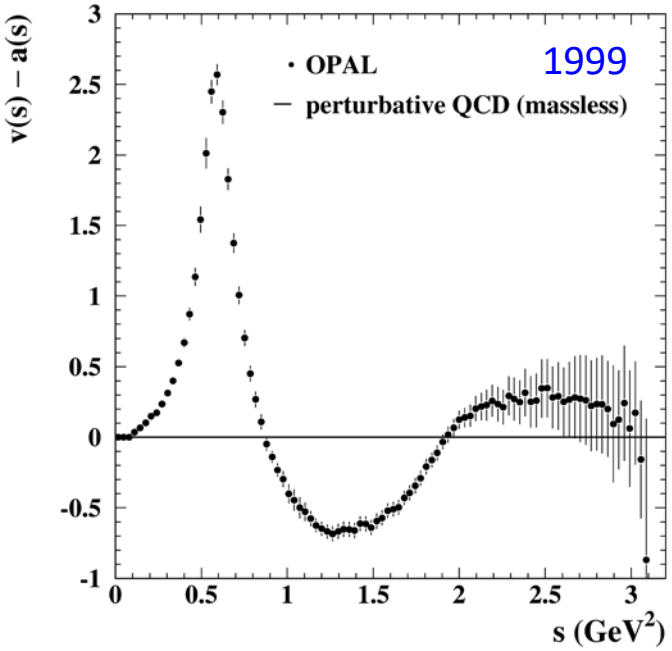
OPAL 99 $\tau \to l\nu\nu$

A. Stahl
Tau 98



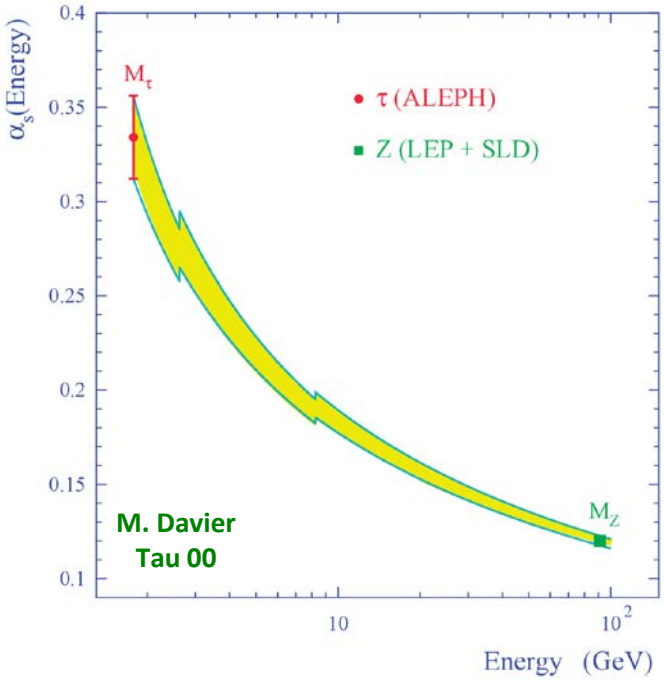
Spectral Functions





Strong Coupling

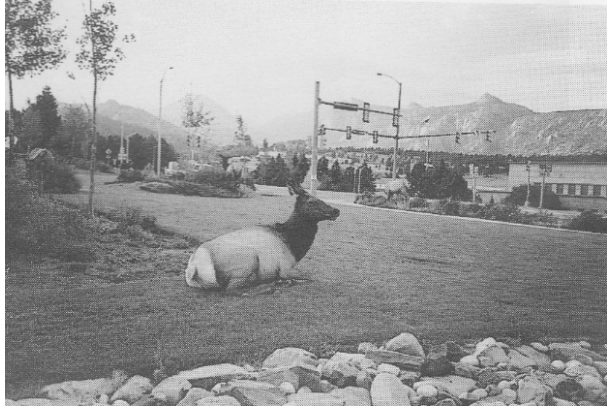
Detailed experimental analyses by ALEPH, CLEO & OPAL



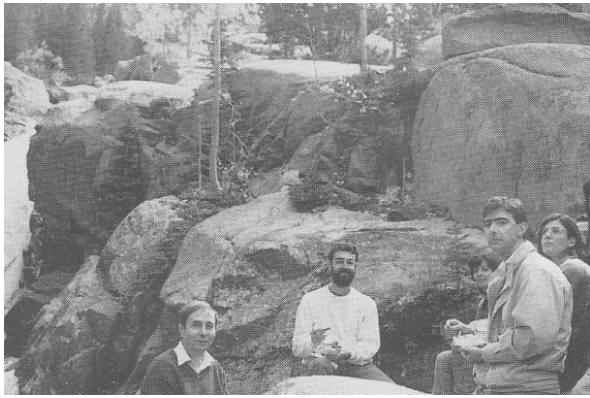
$$\alpha_s(M_Z) = \begin{cases} 0.1202 \pm 0.0027 & (\tau) \\ 0.1183 \pm 0.0027 & (Z) \end{cases}$$

- Pre-LEP value (Altarelli, APS 90): 0.11 ± 0.01
- 1st Lattice determination: 0.105 ± 0.004 (El-Khadra et al, PRL 92)
- PDG94 Lattice Average: 0.110 ± 0.006

Enjoying Life



Estes Park 96

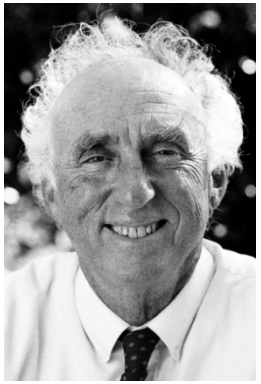


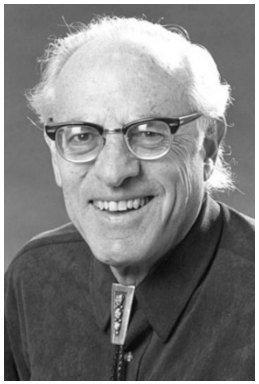
Victoria 00

The Nobel Prize in Physics 1995

Martin L. Perl

(New York 1927 – Palo Alto 2014)

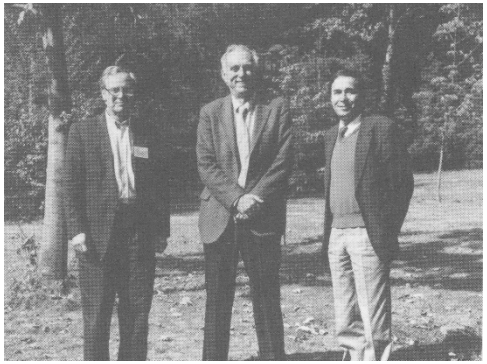




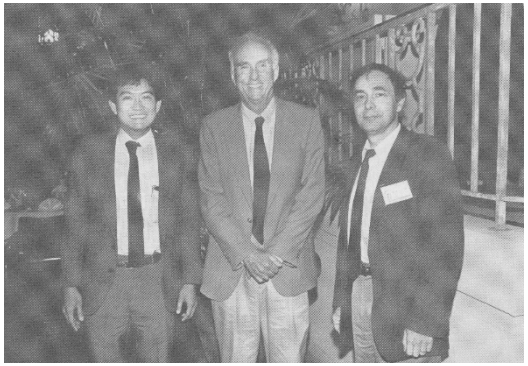
Frederick Reines

(Paterson 1918 – Orange 1998)

Orsay 90



Columbus 92



Estes Park 96

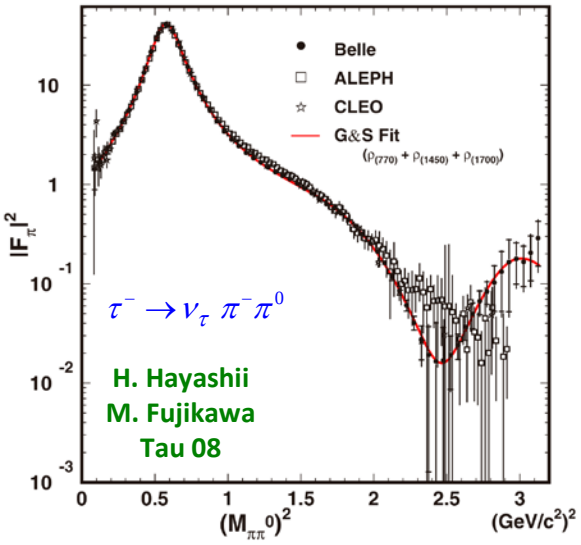
Montreux 94

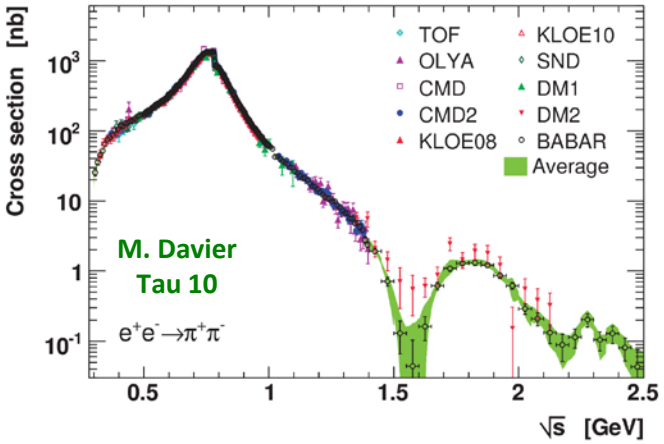
Victoria 00

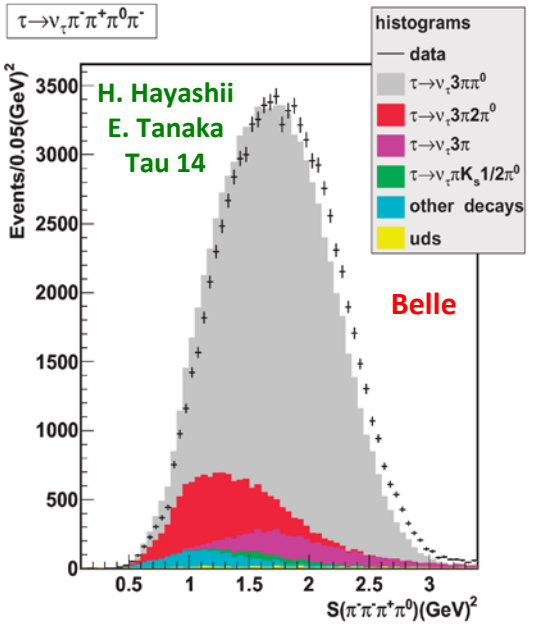
Santander 98

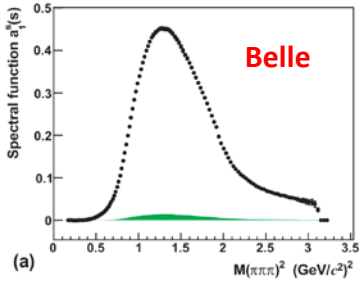
The B-Factory Era

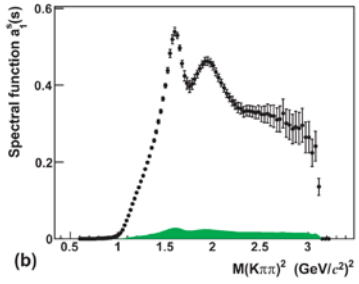
Victoria 2000, Santa Cruz 2002, Nara 2004
Pisa 2006, Novosibirsk 2008, Manchester 2010

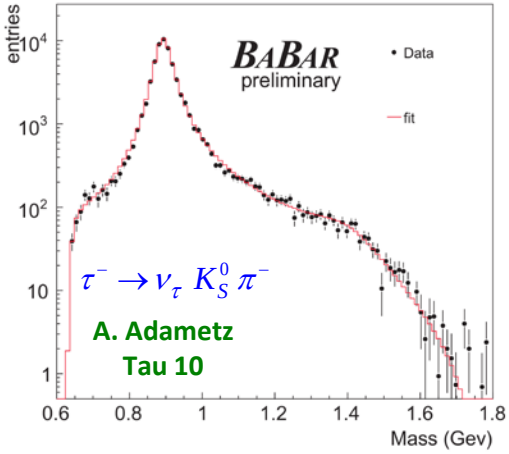


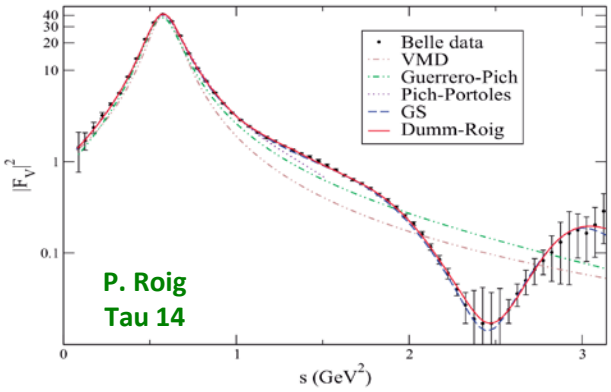


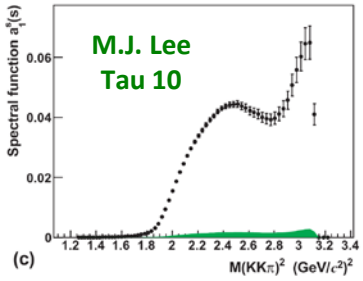


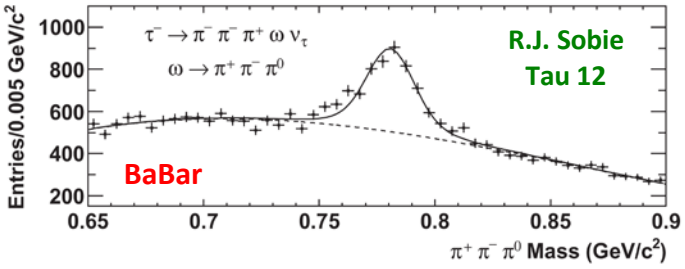










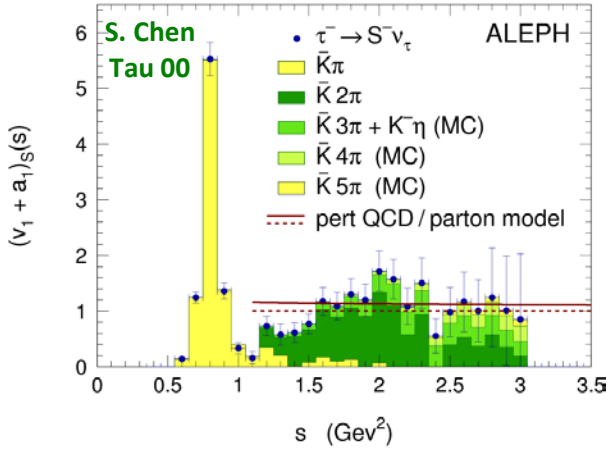


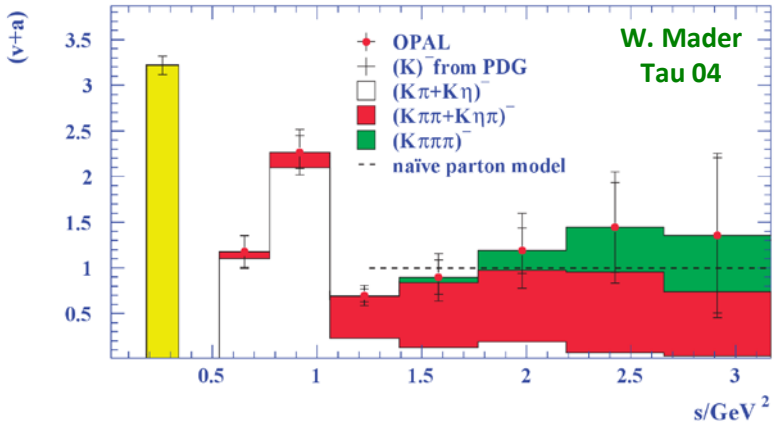
M. Davier, TAU 04

The Complete List of ALEPH Branching Ratios

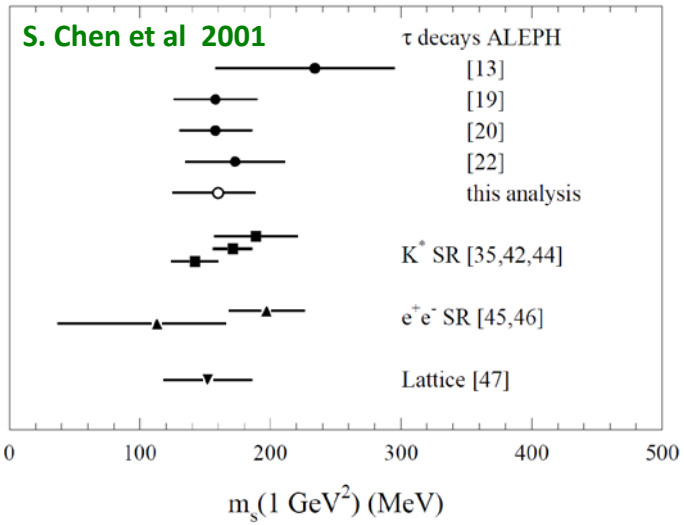
mode	B $\pm\sigma_{\rm tot}$ [%]	ALEPH prelim.	
e	17.837 ± 0.080		
μ	17.319 ± 0.077		
π^-	10.828 ± 0.105		A
$\pi^-\pi^0$	25.471 ± 0.129		V
$\pi^-2\pi^0$	9.239 ± 0.124		A
$\pi^-3\pi^0$	0.977 ± 0.090		V
$\pi^-4\pi^0$	0.112 ± 0.051		A
$\pi^-\pi^-\pi^+$	9.041 ± 0.097		A
$\pi^-\pi^-\pi^+\pi^0$	4.590 ± 0.086		V
$\pi^-\pi^-\pi^+2\pi^0$	0.392 ± 0.046		A
$\pi^-\pi^-\pi^+3\pi^0$	0.013 ± 0.010		V
$3\pi^-2\pi^+$	0.072 ± 0.015		A
$3\pi^-2\pi^+\pi^0$	0.014 ± 0.009		V
$\pi^-\pi^0\eta$	0.180 ± 0.045		V
$(3\pi)^-\eta$	0.039 ± 0.007		A
$a_1^-(\to \pi^-\gamma)$	0.040 ± 0.020		A
$\pi^-\omega$ (*)	0.253 ± 0.018		V
$\pi^-\pi^0\omega$ (*)	0.048 ± 0.009		A
$(3\pi)^-\omega$ (*)	0.003 ± 0.003		V
K^-K^0	0.163 ± 0.027		V
$K^-\pi^0K^0$	0.145 ± 0.027	$(75 \pm 25)\%$	A
$\pi^-K^0\overline{K^0}$	0.153 ± 0.035	$(75 \pm 25)\%$	A
$K^-K^+\pi^-$	0.163 ± 0.027	$(75 \pm 25)\%$	A
$(K\overline{K}\pi\pi)^-$	0.05 ± 0.02	$(50 \pm 50)\%$	A
K^-	0.696 ± 0.029		S
$K^-\pi^0$	0.444 ± 0.035		S
$\overline{K^0}\pi^-$	0.917 ± 0.052		S
$K^-2\pi^0$	0.056 ± 0.025		S
$K^-\pi^+\pi^-$	0.214 ± 0.047		S
$\overline{K^0}\pi^-\pi^0$	0.327 ± 0.051		S
$(K3\pi)^-$	0.076 ± 0.044		S
$K^-\eta$	0.029 ± 0.014		S

Strange Spectral Function: SU(3) Breaking





$$\delta R_\tau^{kl} \equiv \frac{R_{\tau,V+A}^{kl}}{|V_{ud}|^2} - \frac{R_{\tau,S}^{kl}}{|V_{us}|^2} \approx 24\,\frac{m_s^2(m_\tau^2)}{m_\tau^2}\,\Delta_{kl}(\alpha_s) \quad \Rightarrow \quad \mathbf{m_s} \text{ and/or } \mathbf{V_{us}}$$



Gámiz et al, Tau 04

$$|V_{us}| = 0.2208 \pm 0.0033_{\mathrm{exp}} \pm 0.0009_{\mathrm{th}}$$

- Slightly lower values preferred by BF data
- Small tensión with K data (Antonelli et al)
- Many complementary tests (Maltman et al)
- More data needed

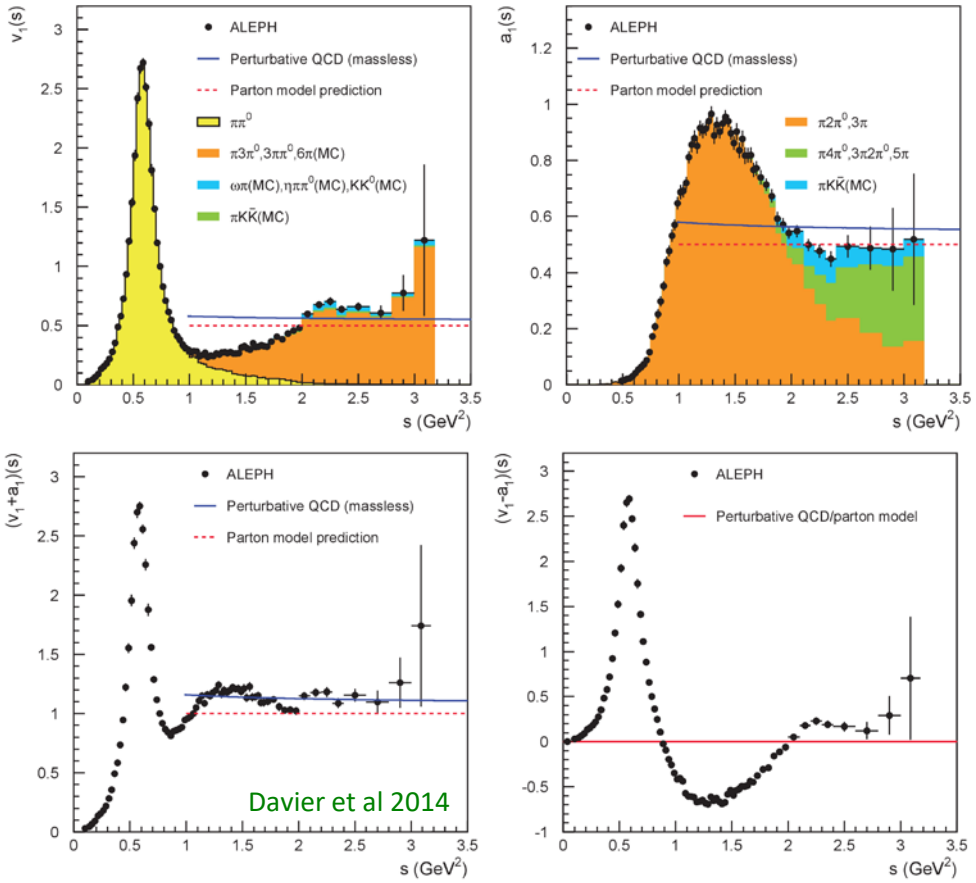
Ximo Prades

(Castellón 1963 - Granada 2010)

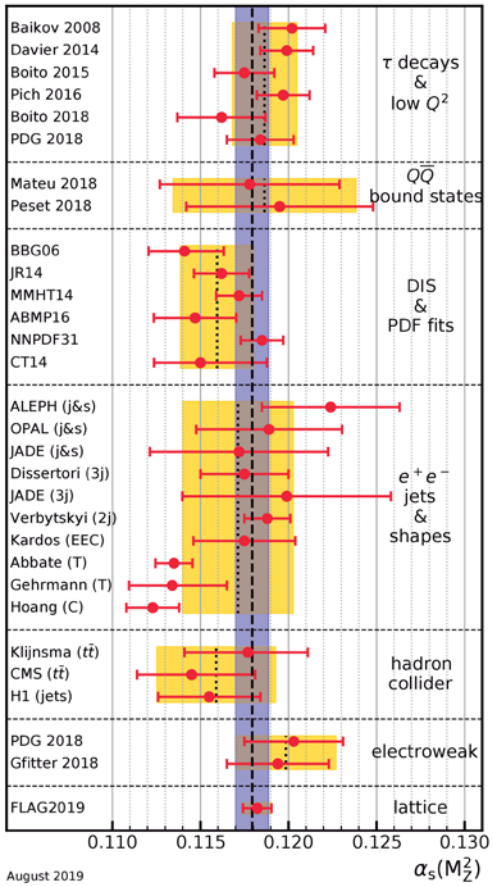
The Strong Coupling at N^{3}LO

- Impressive $O(\alpha_s^4)$ calculation of R_τ **(Baikov- Chetyrkin-Kühn, Tau 08)**
- QCD β function computed to 5 loops **(Baikov- Chetyrkin-Kühn Tau 16)**
- Update of the ALEPH Spectral Functions **(Davier et al 2014, Z. Zhang Tau 14)**

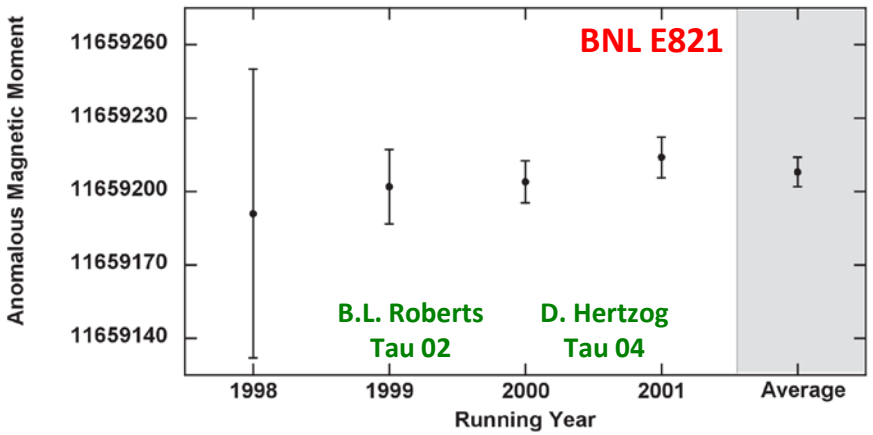
Huge theoretical activity (many discussions): Moment analyses, OPE, Renormalons, Duality Violations…
(Baikov et al, Beneke et al, Boito et al, Caprini et al, Cvetic et al, Davier at al, Groote et al, Hoang-Regner, Menke, A.P.-Rodríguez…)



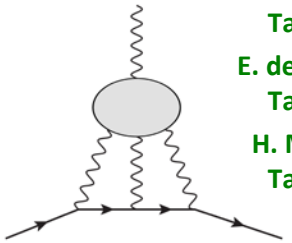
PDG 2020



$(g-2)_\mu$



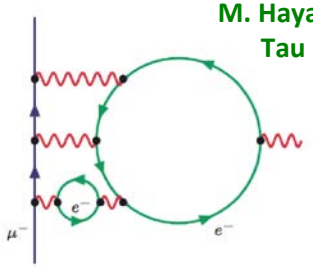
Light-by-Light



A. Vainshtein
Tau 06

E. de Rafael
Tau 12

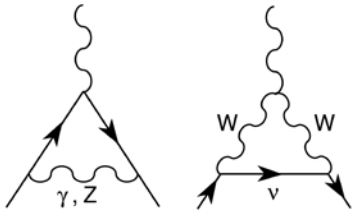
H. Meyer
Tau 18



T. Kinoshita
Tau 04

M. Hayakawa
Tau 12

QED

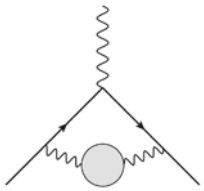


Electroweak

A. Czarnecki
Tau 02

Vacuum polarization

A. Hoecker
Tau 02
+ …



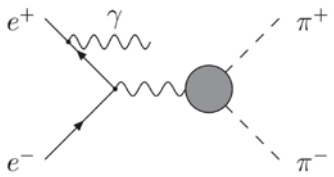
$$a_\mu^{\rm HVP,LO} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{s_{\rm th}}^{\infty} \frac{ds}{s^2}\, \hat{K}(s)\, R(s)$$

Many experimental contributions

BaBar, BES, CLEO, CMD, KEDR, KLOE, SND…

M. Davier, Tau 16
B. Shwartz, Tau 18

Radiative return: PHOKHARA



G. Rodrigo
Tau 02, 06

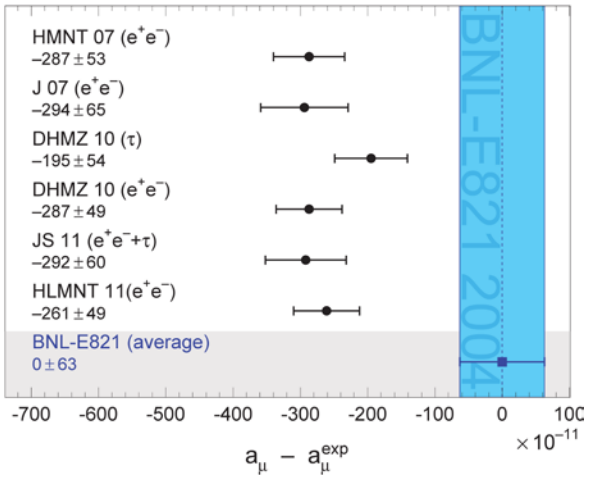
J. Kühn
Tau 00, 04

$\tau^- \to \nu_\tau V^-$ & $e^+e^- \to V^0$

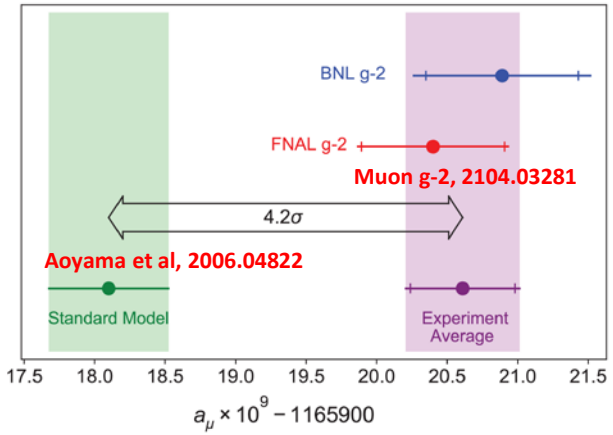
related by isospin

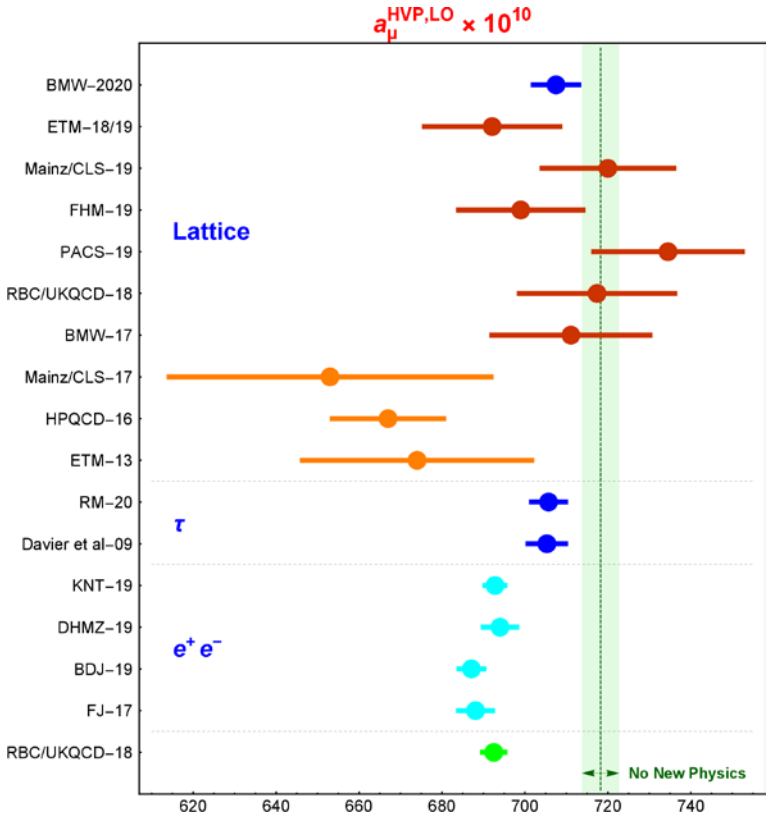
S.I. Eidelman - V.N. Ivanchenko, Tau 90
S.I. Eidelman, Tau 00
Davier at al, Tau 00, 02…

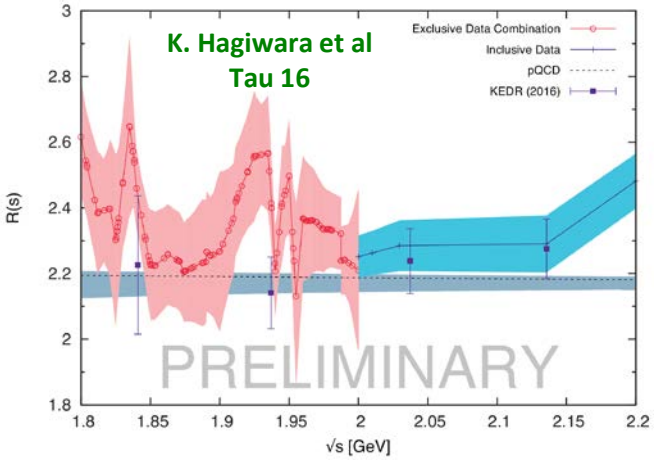
Z. Zhang
Tau 12

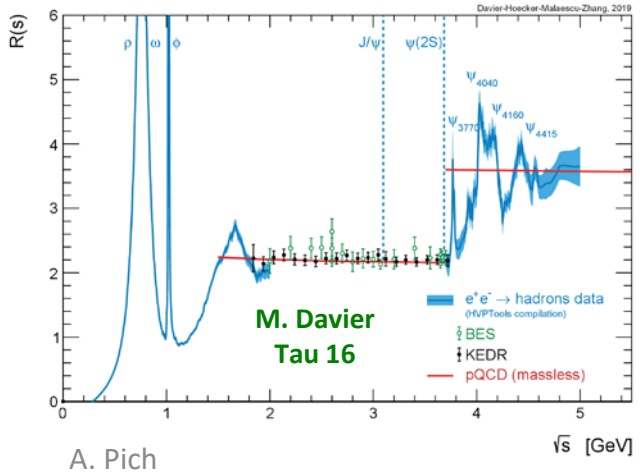


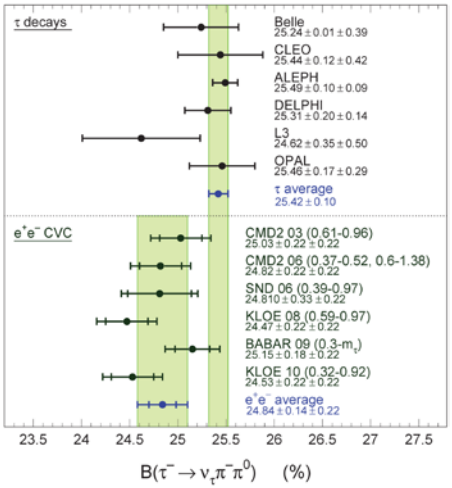
2021 Status

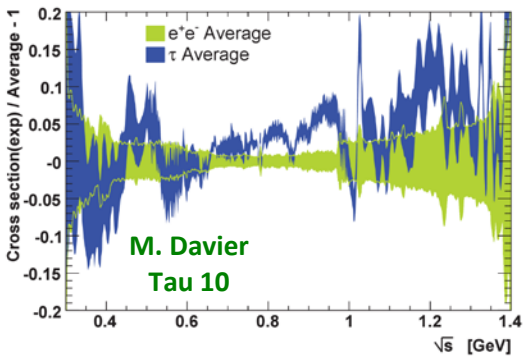

BNL g-2
FNAL g-2
Muon g-2, 2104.03281
4.2σ
Aoyama et al, 2006.04822
Standard Model
Experiment Average
17.5 18.0 18.5 19.0 19.5 20.0 20.5 21.0 21.5
$a_\mu \times 10^9 - 1165900$


$a_\mu^{HVP,LO} \times 10^{10}$
BMW–2020
ETM–18/19
Mainz/CLS–19
FHM–19
Lattice
PACS–19
RBC/UKQCD–18
BMW–17
Mainz/CLS–17
HPQCD–16
ETM–13
RM–20
τ
Davier et al–09
KNT–19
DHMZ–19
e^+e^-
BDJ–19
FJ–17
RBC/UKQCD–18
No New Physics
620 640 660 680 700 720 740


K. Hagiwara et al
Tau 16
Exclusive Data Combination
Inclusive Data
pQCD
KEDR (2016)
PRELIMINARY
R(s)
√s [GeV]

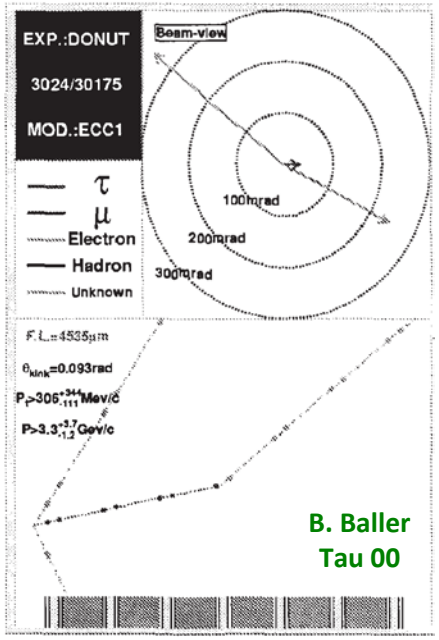

Davier-Hoecker-Malaescu-Zhang, 2019
ρ ω φ J/ψ ψ(2S)
ψ4040
ψ4160
ψ3770
ψ4415
M. Davier
Tau 16
$e^+e^- \to$ hadrons data
(HVPTools compilation)
BES
KEDR
pQCD (massless)
R(s)
√s [GeV]


τ decays
Belle 25.24 ± 0.01 ± 0.39
CLEO 25.44 ± 0.12 ± 0.42
ALEPH 25.49 ± 0.10 ± 0.09
DELPHI 25.31 ± 0.20 ± 0.14
L3 24.62 ± 0.35 ± 0.50
OPAL 25.46 ± 0.17 ± 0.29
τ average 25.42 ± 0.10
e^+e^- CVC
CMD2 03 (0.61-0.96) 25.03 ± 0.22 ± 0.22
CMD2 06 (0.37-0.52, 0.6-1.38) 24.82 ± 0.22 ± 0.22
SND 06 (0.39-0.97) 24.810 ± 0.33 ± 0.22
KLOE 08 (0.59-0.97) 24.47 ± 0.22 ± 0.22
BABAR 09 (0.3-m_τ) 25.15 ± 0.18 ± 0.22
KLOE 10 (0.32-0.92) 24.53 ± 0.22 ± 0.22
e^+e^- average 24.84 ± 0.14 ± 0.22
23.5 24 24.5 25 25.5 26 26.5 27 27.5
$B(\tau^- \to \nu_\tau \pi^- \pi^0)$ (%)

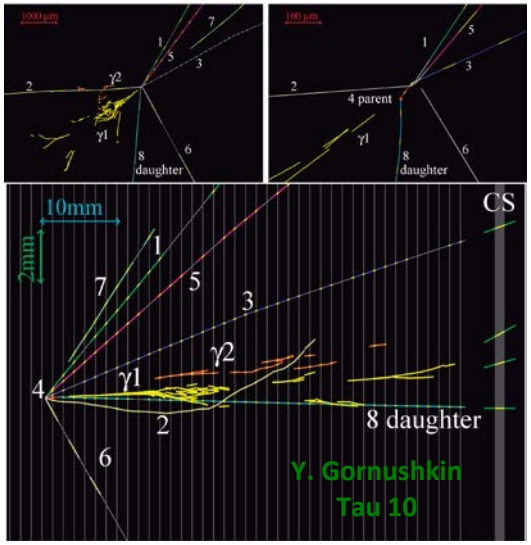

e^+e^- Average
τ Average
Cross section(exp) / Average - 1
M. Davier
Tau 10
√s [GeV]

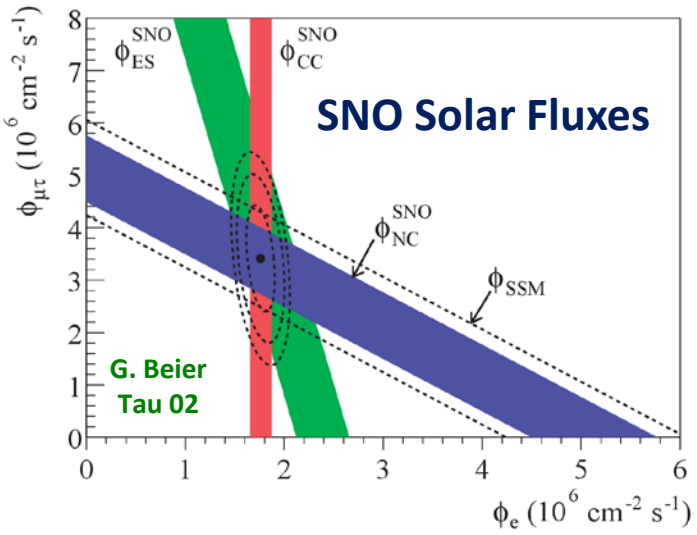
Neutrino Physics

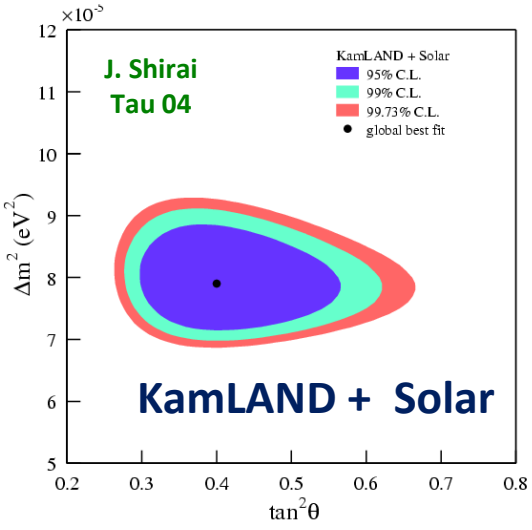
First ν_τ event



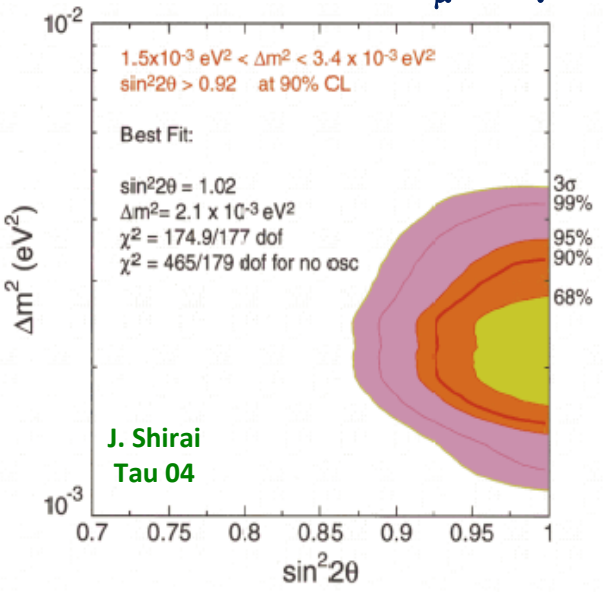
First OPERA event

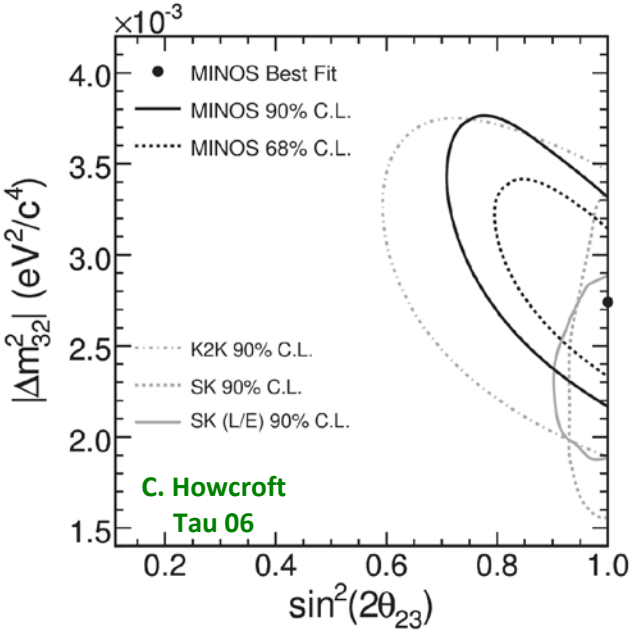






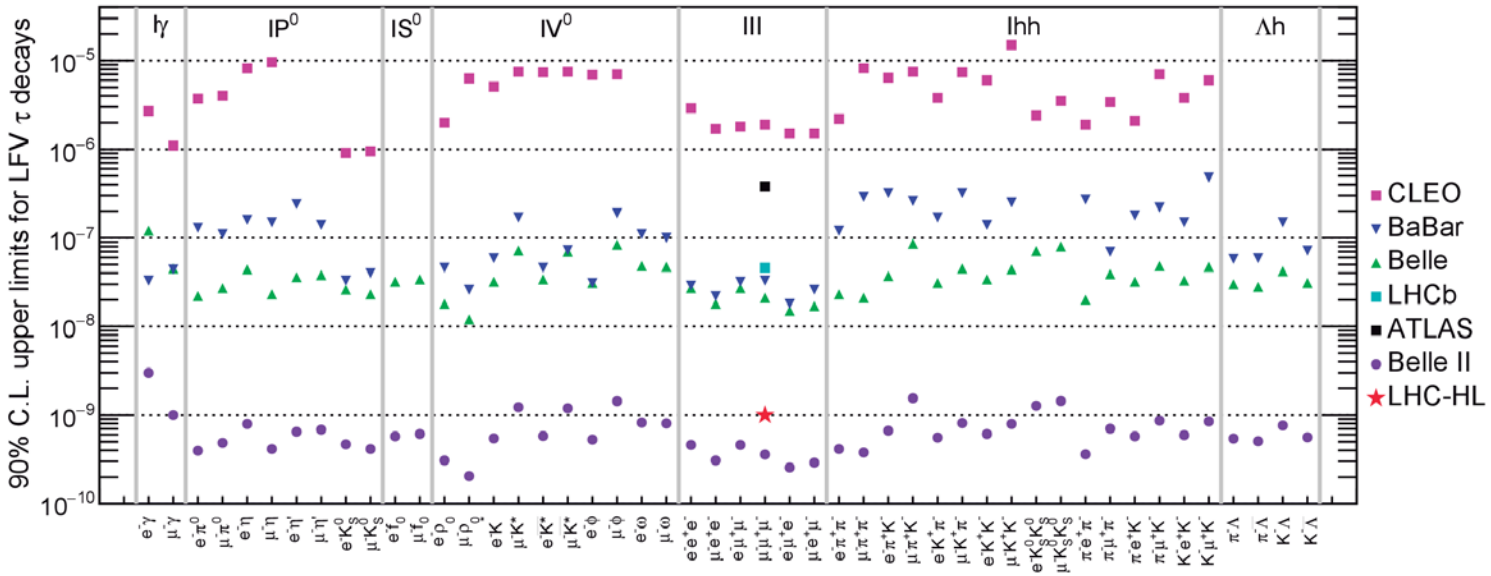
SK Atmospheric $\nu_\mu \rightarrow \nu_\tau$



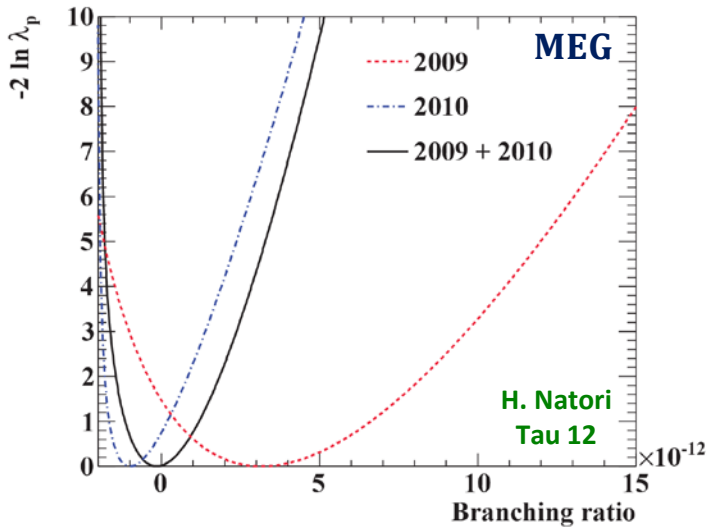


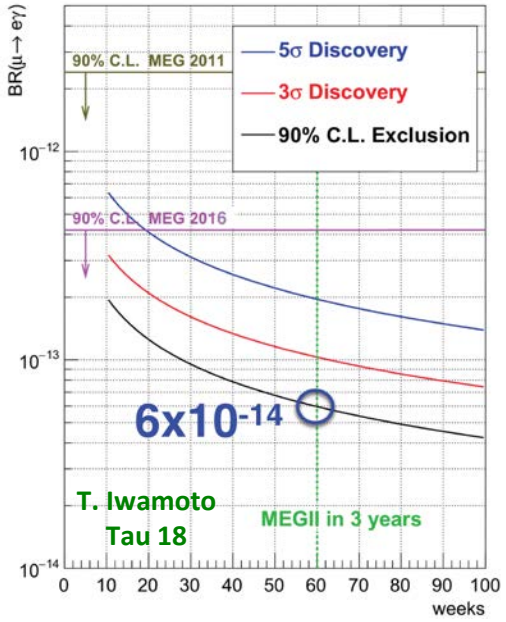
Lepton-Flavour Violation

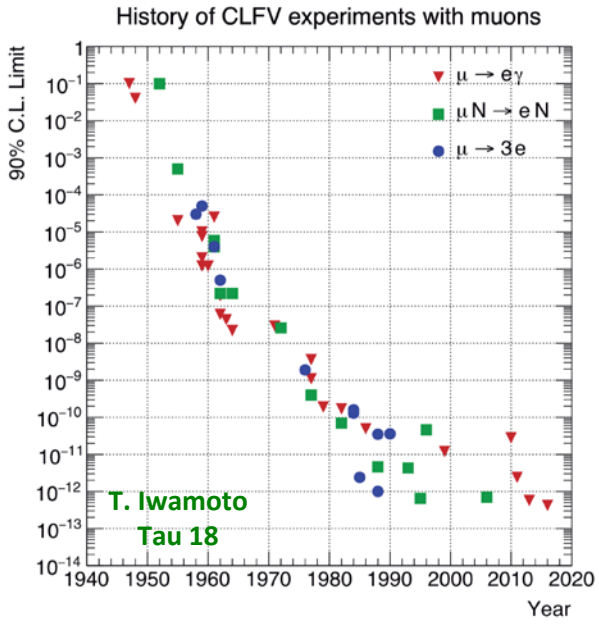
S. Eidelman
TAU 18



$\mathrm{Br}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$ (90% CL)





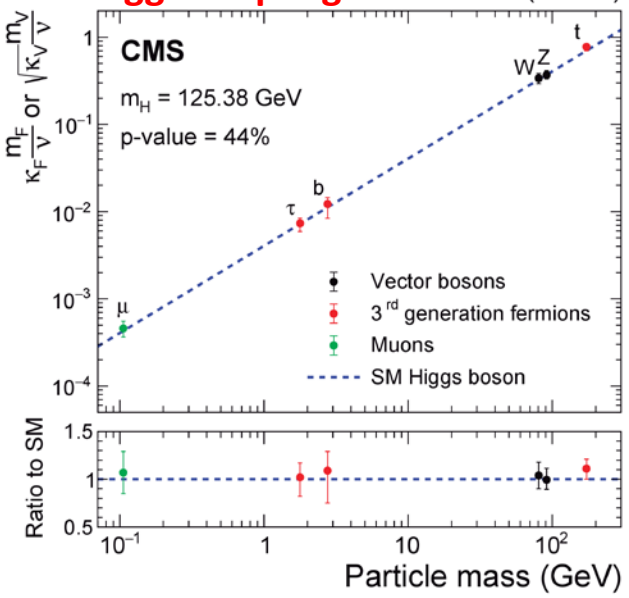


The LHC Times

Manchester 2010, Nagoya 2012, Aachen 2014, Beijing 2016, Amsterdam 2018, Indiana 2021

- **τ's are an excellent signature to probe New Physics**
  - Difficult to identify light objects (Z,W$^{\pm}$) with only Jets
  - QCD Jets orders of magnitude larger
  - Must rely on leptons
- **LHC produces high-momenta τ's**
  - Tightly collimated decay products (mini-jet like)
  - Momentum reconstruction possible
- **Low multiplicity.** Good tagging efficiency
- **Heaviest lepton coupling to the Higgs** (4th H Br)
- **Polarization information**

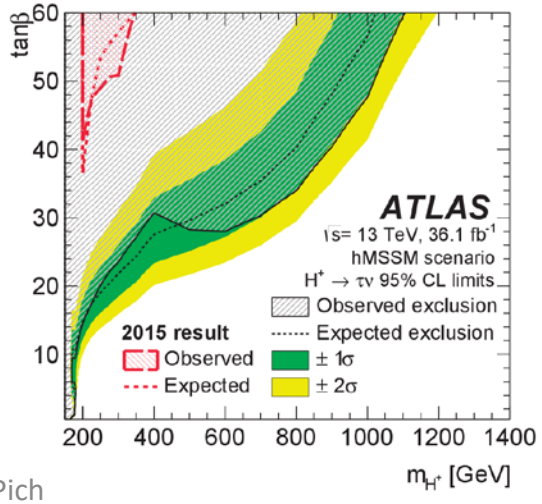
Higgs couplings 35.9-137 fb^{-1} (13 TeV)



S. Choudhury, L. Schildgen, TAU 18

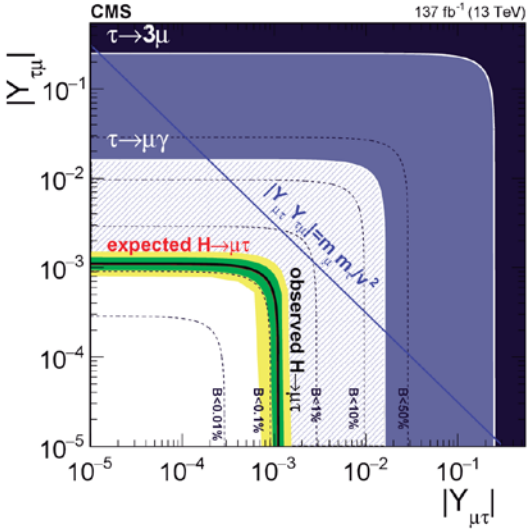
$H^+ \to \tau^+\nu$

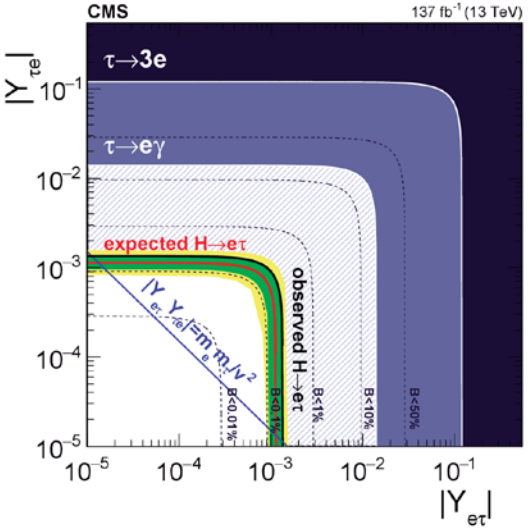
C. Caputo TAU 18



$H \to \tau\mu$, τe

B. Le, J. Wang, TAU 18



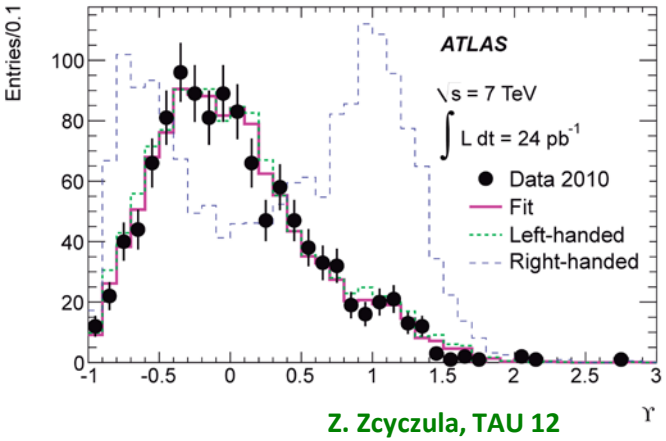


Nagoya 12

Beijing 16

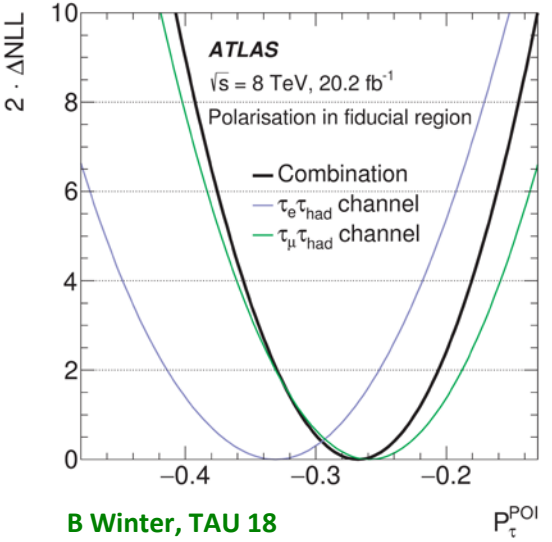
Amsterdam 18

$W \to \tau\nu$ $P_\tau = -1.05 \pm 0.07$



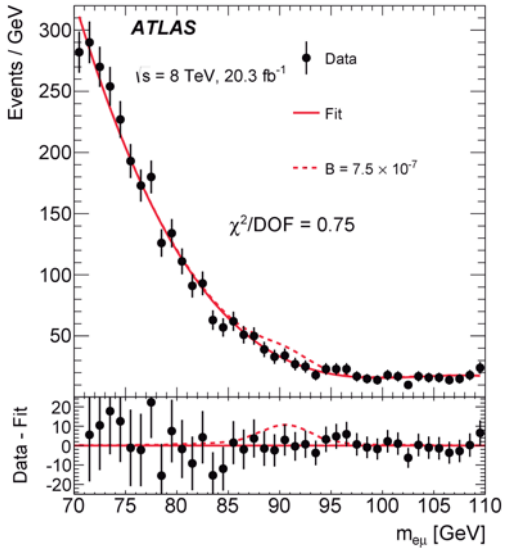
Z. Zcyczula, TAU 12

$Z/\gamma^* \to \tau^+\tau^-$ $P_\tau = -0.14 \pm 0.04$

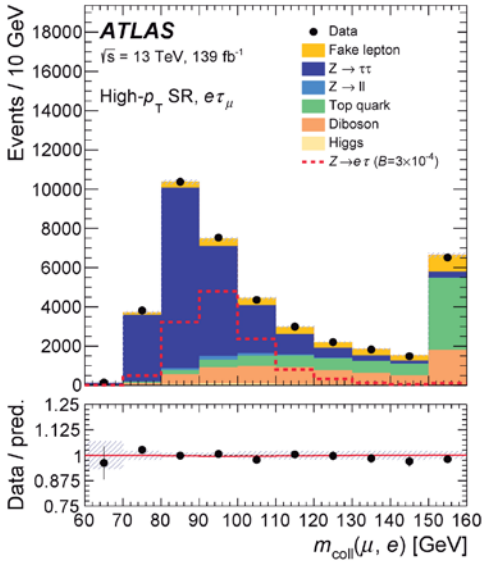


B Winter, TAU 18

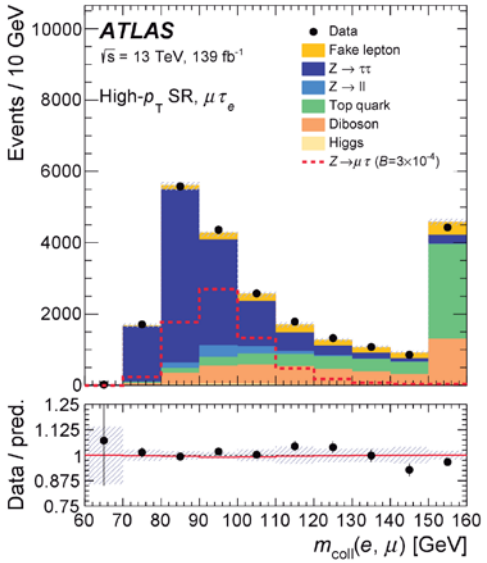
$Br(Z \to e\mu) < 7.5 \times 10^{-7}$



$Br(Z \to e\tau) < 7.0 \times 10^{-6}$

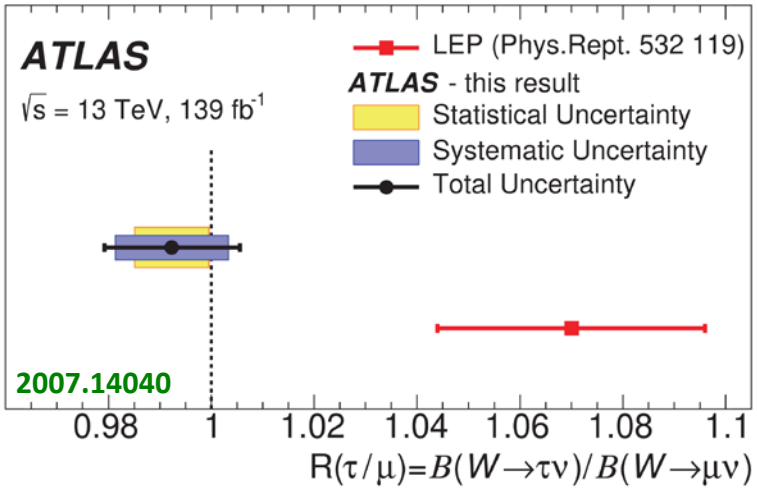


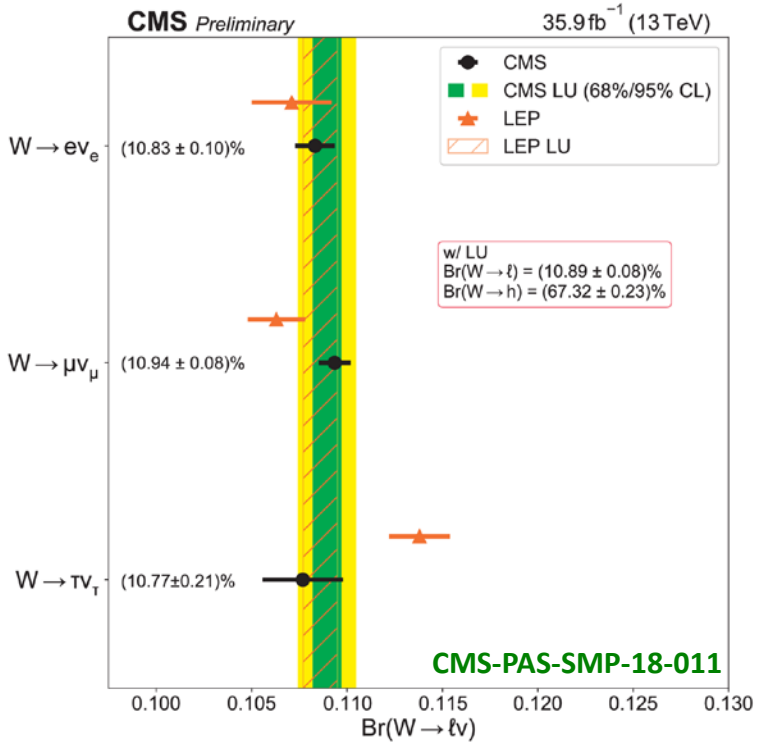
$Br(Z \to \mu\tau) < 7.2 \times 10^{-6}$



W.S. Chan, TAU 18

Lepton Universality



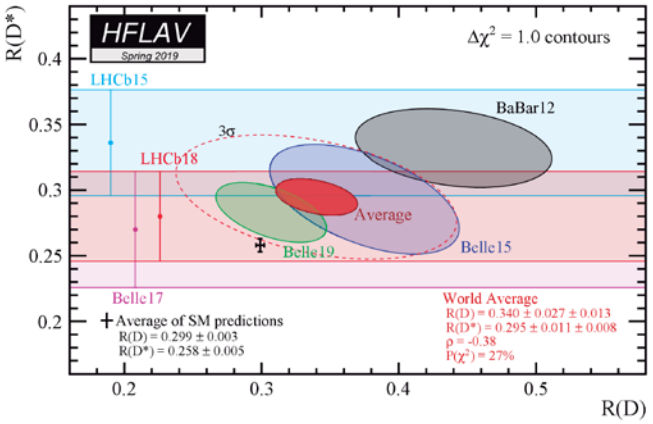


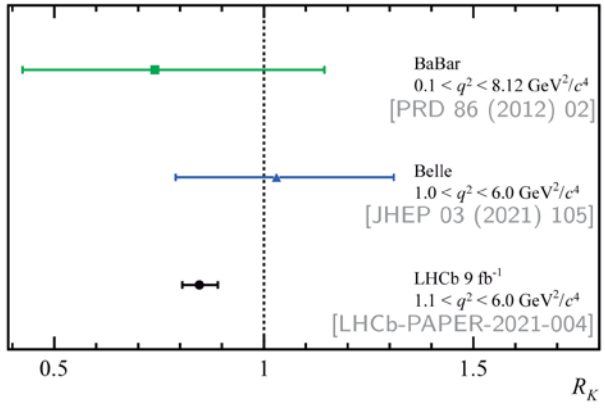
S. Benson, A. Rostomyan, TAU 18

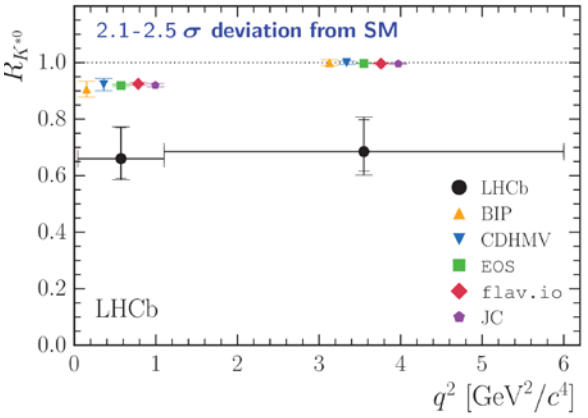
$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

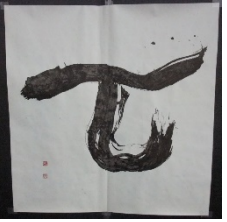
$$R_K \equiv \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$

$$\frac{\Gamma(B \to K^*\mu^+\mu^-)}{\Gamma(B \to K^*e^+e^-)}$$









Great Ongoing Physics

- Many interesting τ topics
  - Tests of QCD and the Electroweak Theory
  - Looking for Signals of New Phenomena
  - Superb Tool for New Physics Searches
- Current anomalies: Better data samples needed
- Lots of data will be produced @ Belle-II, LHC, …

Looking forward to new results @ Tau 21

Aachen 14

Pisa 06