Tau Lepton Physics @ STCF

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2025 a special year as it marks
- 50 anniversary of the tau lepton discovery
- 25 anniversary of 1st direct evidence for tau neutrino

Introduction

- Tau lepton physics already discussed in several excellent talks in the previous workshops

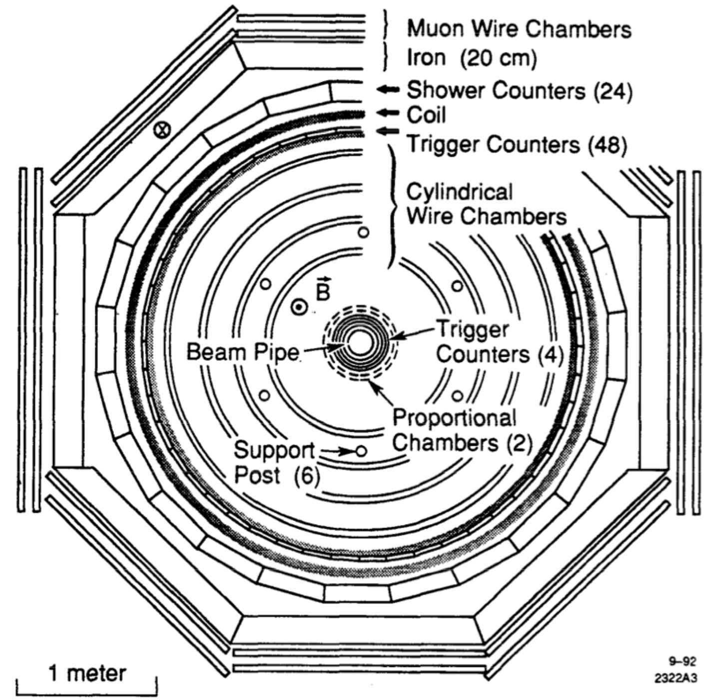
- Instead of repeating this, I would rather
  - Give a few examples from the discovery to precision measurements and comment on these
  - Point out a few open issues or possibilities
  - Whenever possible, I would use materials that I have worked on

Very General Comments

- The SM extremely successful
- Yet, it is believed that there must be physics beyond the SM
- Where to find new physics (NP)?
  - High / right energy (the tau discovery itself is a good example, see next slides)
  - High density / precision frontier ➔ STCF is a possibility

Tau Lepton Discovery in 1975 [SLAC-PUB-5937]

- SPEAR e^+e^- storage ring started operation in 1973 at $\sqrt{s}$ = 4.8 GeV
- Mark I detector, a first large solid angle, general purpose detector
- Theory guidance:
  - Decay correlation of heavy lepton in $e^+e^-\to\ell^+\ell^-$ (Paul Tsai 1971)
  - Spontaneously broken gauge theories of weak interactions and heavy leptons (James Bjorken and Chris Llewellyn Smith 1973)
- Discovery based on initial 24 $e\mu$ events ($e^+e^-\to\tau^+\tau^-$, $\tau\to e/\mu\nu_{e/\mu}\nu_\tau$) in 1974
- The new lepton was initially called U for Unknown, and was named later τ meaning third in greek
- Confirmed in 1977 by PLUTO@DORIS
- Nobel prize to Martin Perl in 1995



"Distribution of 513, 4.8 GeV, 2-prong, events which meet the criteria: $p_e > 0.65$ GeV/c, $p_\mu > 0.65$ GeV/c, $\theta_{copl} > 20°$."

	Total Charge = 0			Total Charge = ±2		
Number photons =	0	1	> 1	0	1	> 1
ee	40	111	55	0	1	0
$e\mu$	24	8	8	0	0	3
$\mu\mu$	16	15	6	0	0	0
eh	18	23	32	2	3	3
μh	15	16	31	4	0	5
hh	13	11	30	10	4	6
Sum	126	184	162	16	8	17

Tau Production

M. Perl 1991

SPEAR was at the right energy where the tau production cross section is the largest!

(J/ψ discovered at the same machine in 1974!)

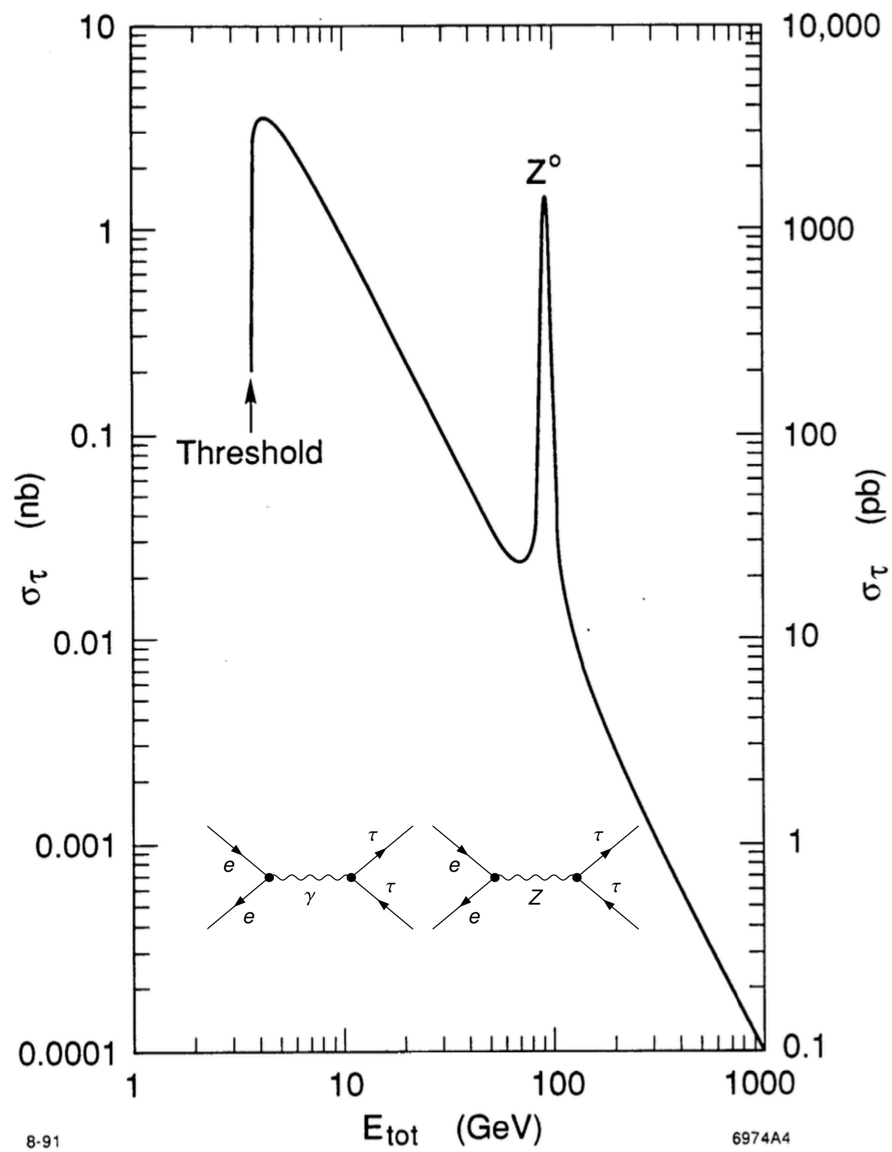
The production cross sections at B factories (~10 GeV) and at Z factories are both lower

$N_{\tau\tau} = \sigma_{\tau\tau} \times \mathcal{L}$

Large luminosity $\mathcal{L}$ is the other key factor

SuperKEKB reached $0.5 \times 10^{35}\ cm^{-2}s^{-1}$ in 2024 and is aiming for $> 1.0 \times 10^{35}\ cm^{-2}s^{-1}$

➔ SuperKEKB is an existing super tau factory!



Precision Measurements vs NP searches

- At (S)TCF, one can perform precision measurements: e.g. tau mass measurement
- Why it matters?
  - For measuring fundamental SM parameters and validating the SM
  - For finding deviations from SM predictions
    - Lepton Flavour Universality (LFU) tests
    - Rare and Lepton Flavour Violating (LFV) decays
    - Tau electric dipole moment (d_τ)
    - Tau magnetic moment anomaly (a_τ)
    - CP violation in tau decays?

First Precise Mass Measurement from BES in 1992

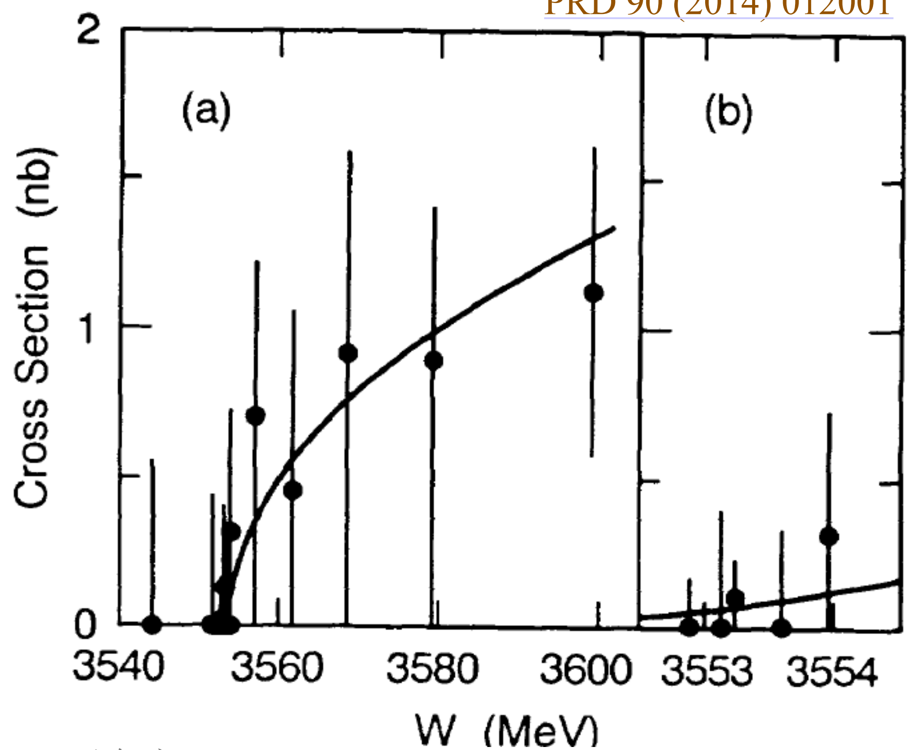
- Before 1992, m_τ is known with un uncertainty of 3-4 MeV
- 1st BES measurement of $1776.9^{+0.4}_{-0.5} \pm 0.2\,\mathrm{MeV/c^2}$ based on 14 $e\mu$ events selected near threshold
  - Uncertainties improved later in 1996 and 2014 $1776.91 \pm 0.12^{+0.10}_{-0.13}\,\mathrm{MeV/c^2}$
  - Dominant uncertainty sources (2014)
    - (Fitted) efficiency uncertainty [−0.034, +0.038] MeV
    - Background shape [±0.040] MeV
    - Selections; misID [±0.050; ±0.048] MeV
    - Beam energy scale [−0.086, +0.022] MeV
    - Beam energy spread [±0.016] MeV

PRL 69 (1992) 3021
PRD 53 (1996) 20
PRD 90 (2014) 012001

➔ Demonstrating (S)TCF's advantage in measuring m_τ

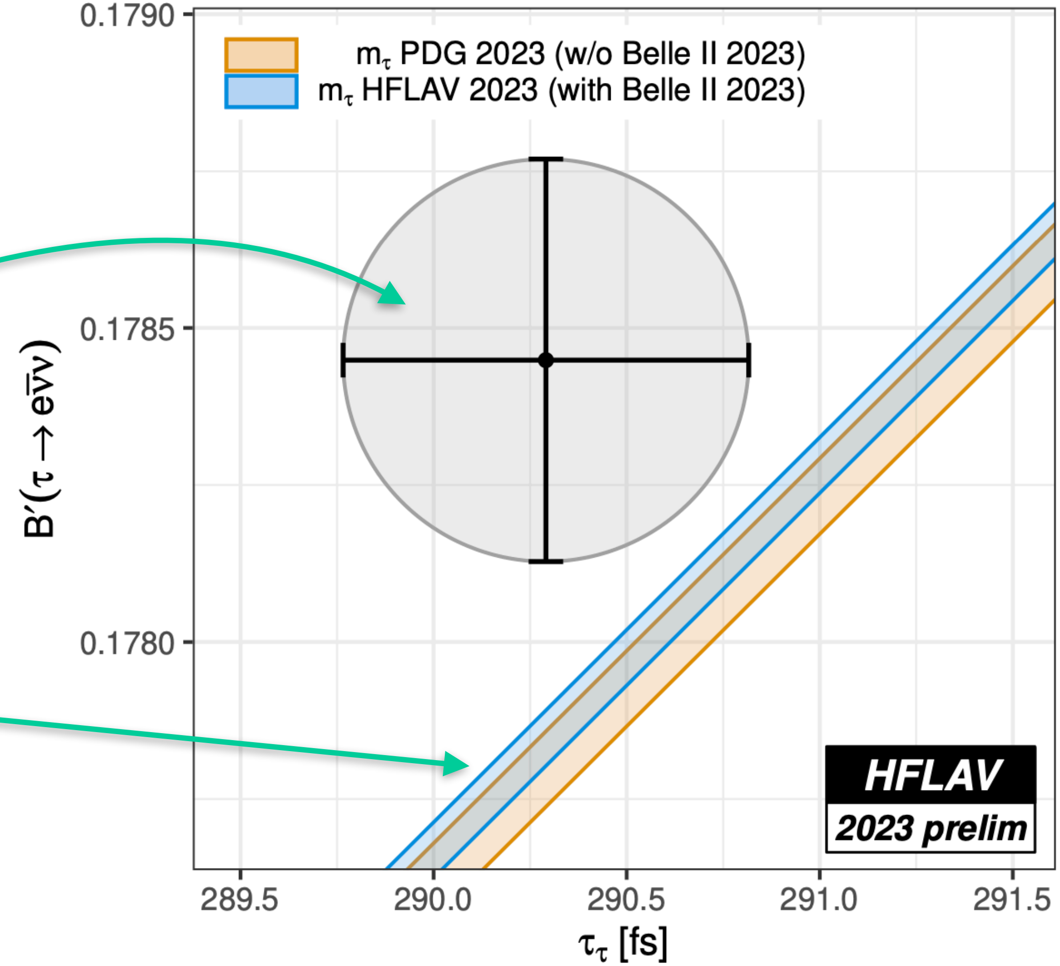
To be compared with the most recent measurement of Belle 2 [PRD 108 (2023) 032006]:
$1777.09 \pm 0.08 \pm 0.11$ MeV/c^2
based on 175 M tau pair events using 3π pseudo-mass endpoint

➔ Showing the complementary of different colliders/experiments



Limiting Factors in LFU Test

Lusiani, TAU2023



The test is currently limited by the precision of the leptonic branching fraction and lifetime measurements

and by the tau mass uncertainty on the prediction side using

$$\frac{B_{\tau\to\nu_\tau e\bar{\nu}_e}}{\tau_\tau} = \frac{B_{\mu\to\nu_\mu e\bar{\nu}_e}}{\tau_\mu}\left(\frac{m_\tau}{m_\mu}\right)^5$$

➔ STCF can improve the branching fraction and mass measurements

➔ LFU tests are important as it may unveil some clue on the puzzling family structure of matter

Tau lifetime measurements need boost

High energy collider provides boost to tau before it decays:

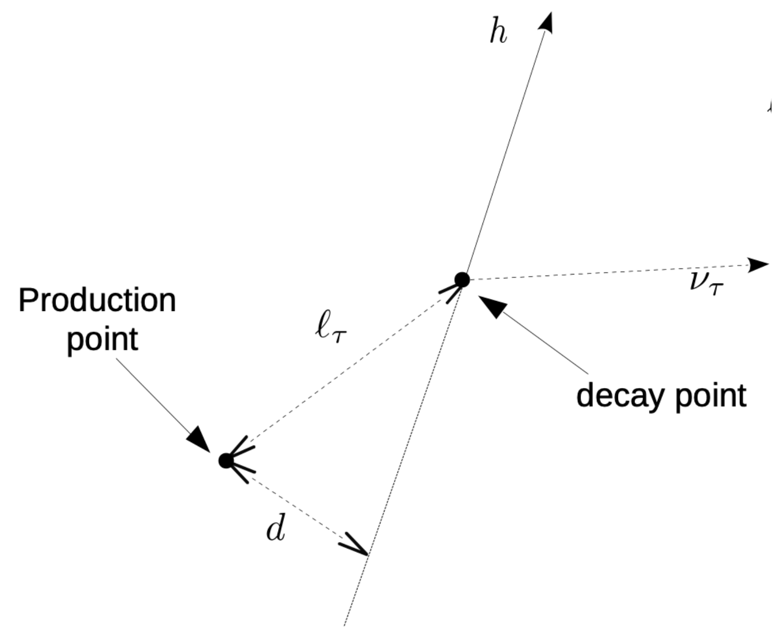
- At B factories, the mean decay length is ~250 μm
- At Z factories, the mean decay length is ~2.2 mm

Precision measurements need high resolution vertex detector + high statistics

For many years LEP experiments dominate
The best precision is achieved at Belle (II)

➔ Showing again the complementary of different colliders/experiments

➔ Precision lifetime measurement needed for other tests

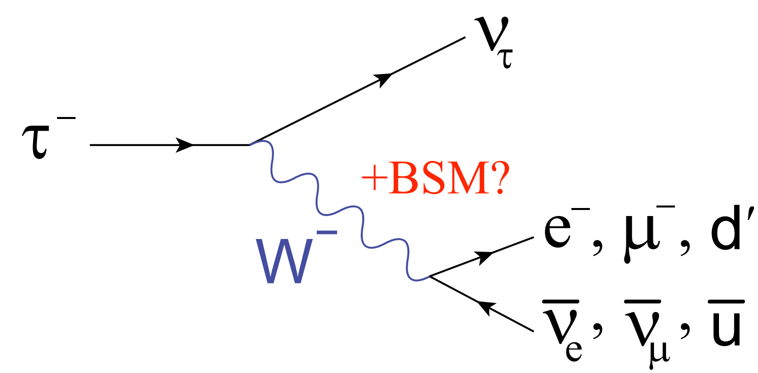


Tau Decays

Tau lepton has a mass around 1776.9 MeV/c^2

The only lepton heavy enough to have hadronic decay modes

$|d'\rangle = V_{ud}\,|d\rangle + V_{us}\,|s\rangle$



The branching fractions (BFs) used to be measured individually by different experiments
➔ a longstanding puzzle of "one-prong problem", namely the BF of the inclusive decay modes containing one-prong does not correspond to the sum of the exclusive decay modes

The problem was resolved by ALEPH by measuring simultaneously the BFs of all the (dominant) decay modes
➔ ALEPH's measurement remains the most precise one for many decay modes

BFs Measured by ALEPH 20 years ago!

ALEPH 2005

mode	$B \pm \sigma_{stat} \pm \sigma_{syst}$ [%]	
e	$17.837 \pm 0.072 \pm 0.036$	
μ	$17.319 \pm 0.070 \pm 0.032$	
π^-	$10.828 \pm 0.070 \pm 0.078$	
$\pi^-\pi^0$	$25.471 \pm 0.097 \pm 0.085$	
$\pi^-2\pi^0$	$9.239 \pm 0.086 \pm 0.090$	
$\pi^-3\pi^0$	$0.977 \pm 0.069 \pm 0.058$	
$\pi^-4\pi^0$	$0.112 \pm 0.037 \pm 0.035$	
$\pi^-\pi^-\pi^+$	$9.041 \pm 0.060 \pm 0.076$	
$\pi^-\pi^-\pi^+\pi^0$	$4.590 \pm 0.057 \pm 0.064$	
$\pi^-\pi^-\pi^+2\pi^0$	$0.392 \pm 0.030 \pm 0.035$	
$\pi^-\pi^-\pi^+3\pi^0$	$0.013 \pm 0.000 \pm 0.010$	estimate
$3\pi^-2\pi^+$	$0.072 \pm 0.009 \pm 0.012$	
$3\pi^-2\pi^+\pi^0$	$0.014 \pm 0.007 \pm 0.006$	
$\pi^-\pi^0\eta$	$0.180 \pm 0.040 \pm 0.020$	ALEPH [13]
$\pi^-2\pi^0\eta$	$0.015 \pm 0.004 \pm 0.003$	CLEO [27]
$\pi^-\pi^-\pi^+\eta$	$0.024 \pm 0.003 \pm 0.004$	CLEO [27]
$a_1^-(\to \pi^-\gamma)$	$0.040 \pm 0.000 \pm 0.020$	estimate
$\pi^-\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.253 \pm 0.005 \pm 0.017$	ALEPH [13]
$\pi^-\pi^0\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.048 \pm 0.006 \pm 0.007$	ALEPH [13] + CLEO [26]
$\pi^-2\pi^0\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.002 \pm 0.001 \pm 0.001$	CLEO [27]
$\pi^-\pi^-\pi^+\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.001 \pm 0.001 \pm 0.001$	CLEO [27]

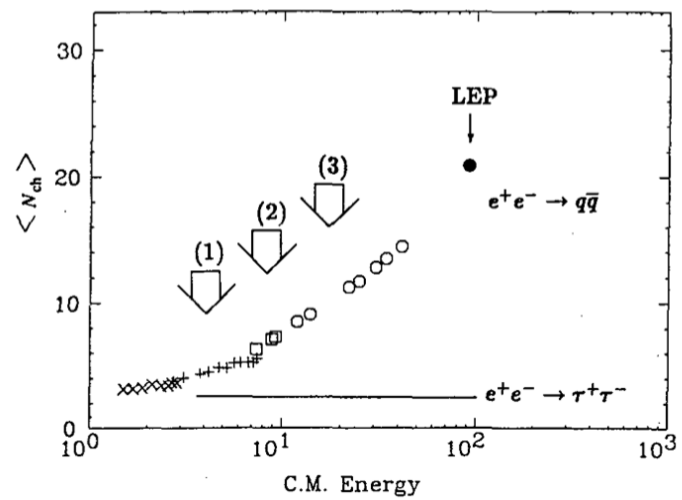
The contribution of the kaon modes (ALEPH '99) having a BF of (2.87±0.12)% has been subtracted from the relevant decay modes

BF ↔ the normalisation of each mode, shape info ↔ spectral function (SF, slides 18+)

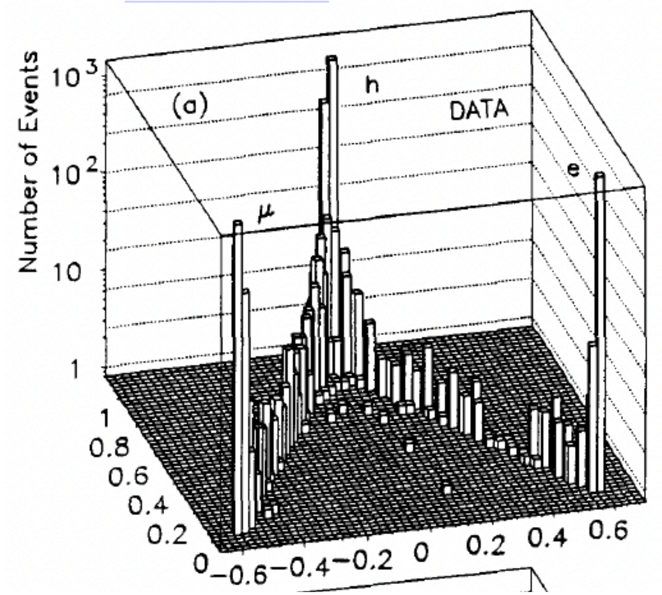
Why could ALEPH do so well?

- ➢ Good acceptance/efficiency ~90% for all dominant channels!
- ➢ Hadronic background (<1%, easy signal / background separation)
- ➢ Excellent particle separation / identification (e / μ / hadrons)

Zhang, LAL-92-15



ALEPH 1992



➔ STCF can and should play a role in improving the precision and measuring rare decays

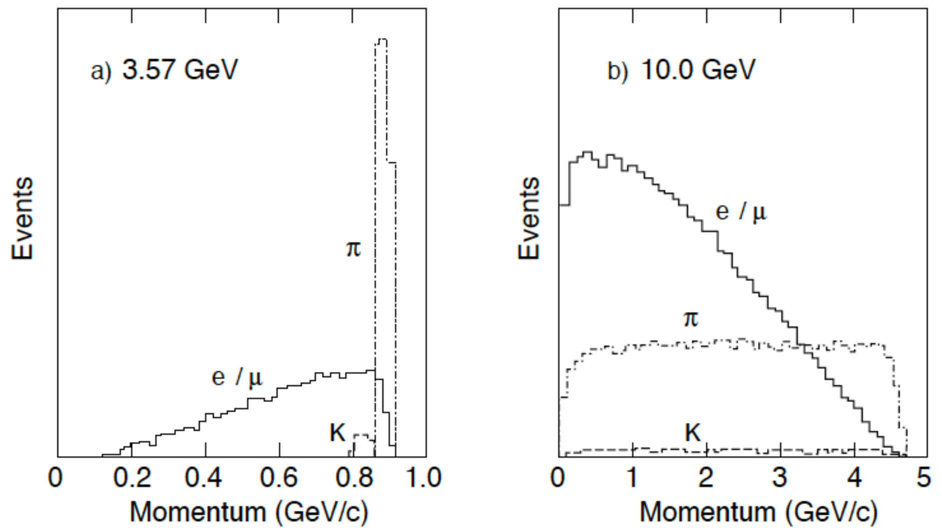
Several other LFU tests need improved tau BF measurements

Should Exploit Fully the Advantage of STCF

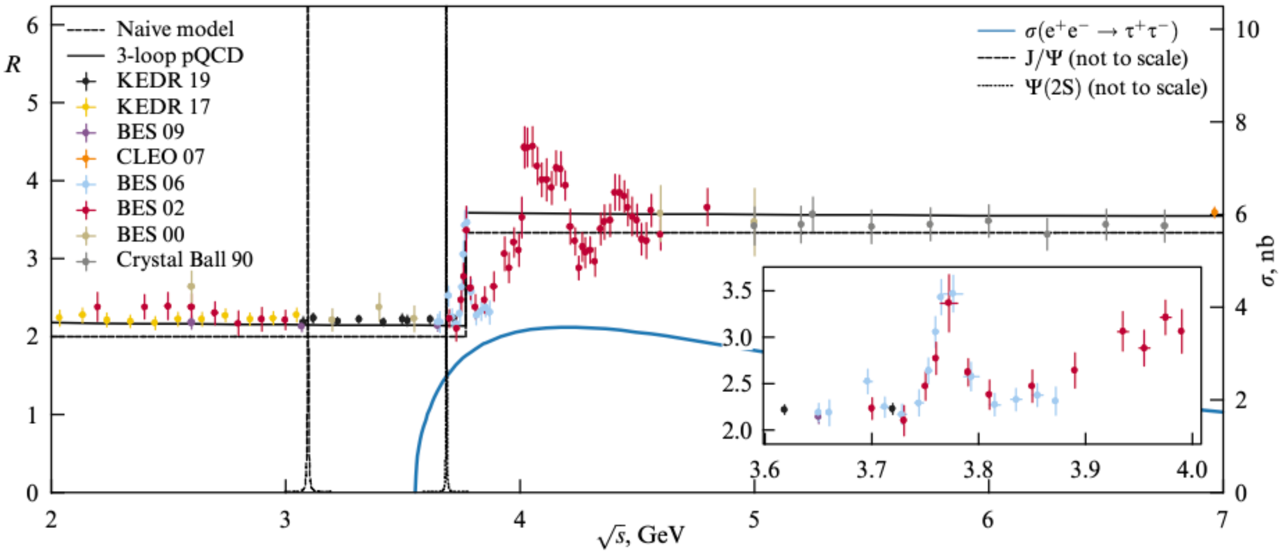
Pich, CERN-th.7065/93

➢ Excellent particle identification provided by redundant sub-detectors

➢ Additional kinematic separation using monochromatic distributions for tau pairs produced near threshold



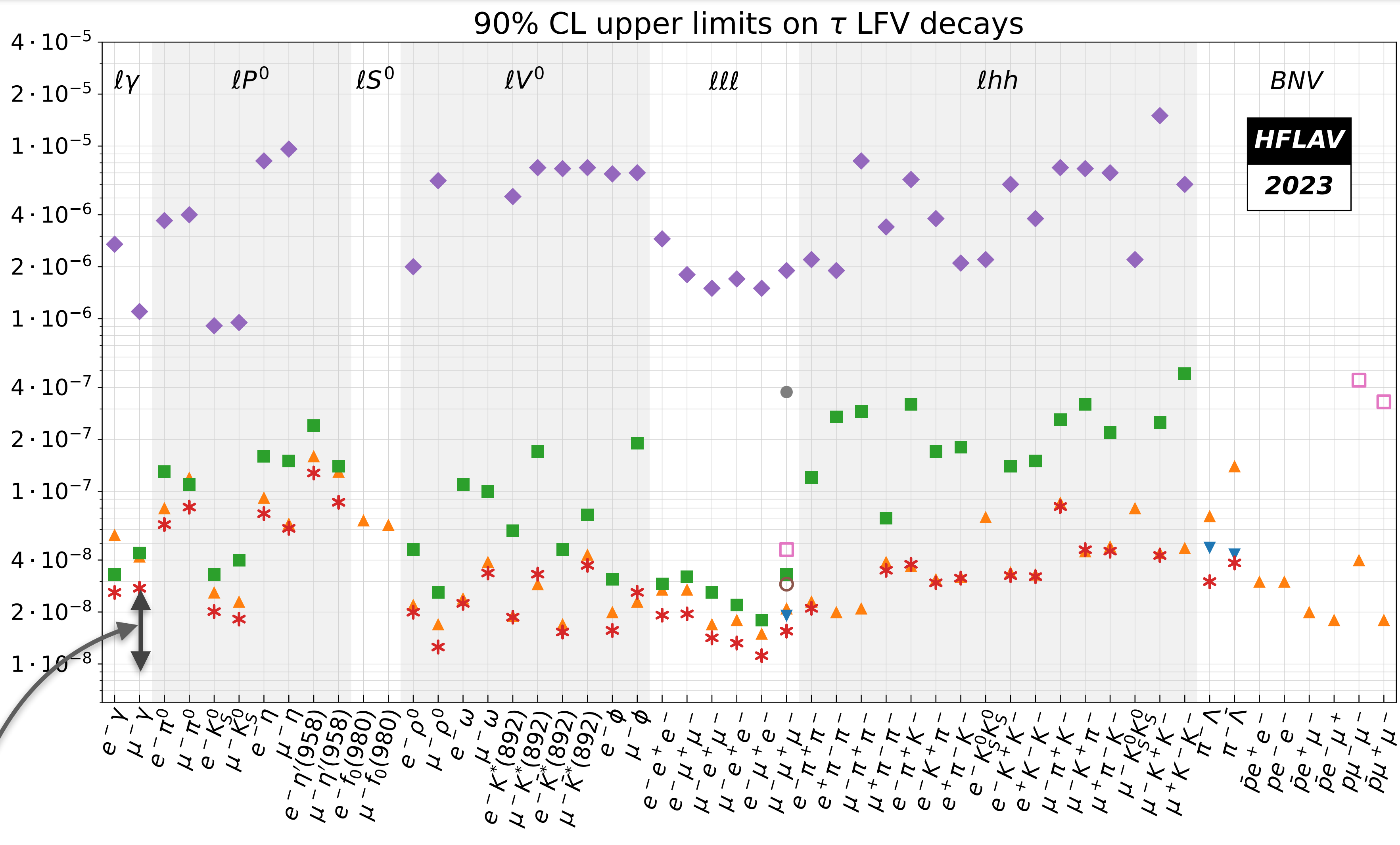
Physics - Uspekhi 67 (2024) 55



➢ (Light) quark background near threshold can be well controlled, measured and extrapolated

➢ What about beam-related background?

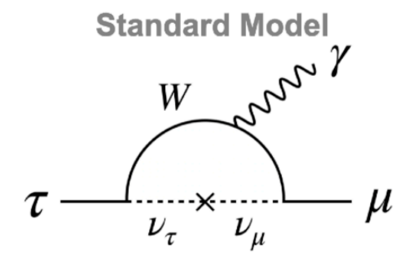
Rare and LFV Decays

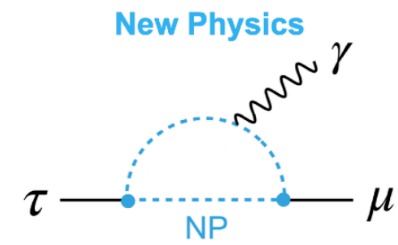


STCF study:
Xiang-Shi-Wang-Zhou
EPJC 83 (2023) 908

Why LFV Decays?

- SM predicts BF $\propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 < 10^{-50}$ thus negligible
- NP models predict much larger BFs up to 10^{-8}
- Therefore any observation such a LFV decay a sign of NP
- There are many competing experiments (+ those (Mu2e@FermiLab, Mu3e@PSI, MEG II@PSI, COMET@J-PARC) for non tau processes)
- STCF should not be too much delayed in order not to miss a chance



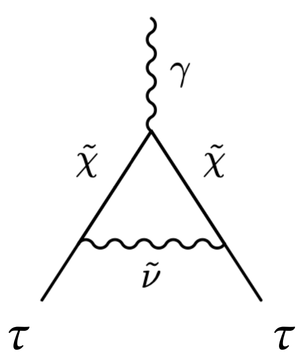


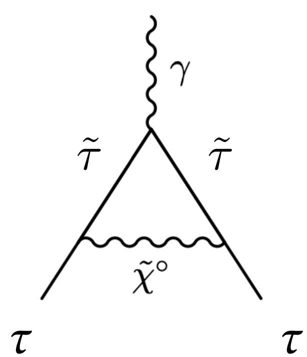
Electric Dipole and Anomalous Magnetic Moments

Joël Gogniat, Tau2025

	e^-		μ^-		τ^-	
d_ℓ^{exp}	$\lesssim 10^{-30}$	Roussy et al. 2023	$\lesssim 10^{-19}$	BNL 2009	$\lesssim 10^{-17}$	Belle 2022
Δa_ℓ^{exp}	$\simeq 10^{-13}$	Northwestern 2022	$\simeq 10^{-10}$	Fermilab 25	$\simeq 10^{-3}$	CMS 2024
Δa_ℓ^{SM}	$\simeq 10^{-12}$	Parker et al. 2018 Morel et al. 2020	$\lesssim 10^{-9}$	Muon g-2 TI 25	$\simeq 10^{-7}$	Keshavarzi et al. 2024

Tau lepton expected to be more sensitive to NP contributions: $a_\tau \propto (m_\tau / \Lambda)^2$





Recent STCF study:
Sun-Wu-Zhou
Chin. Phys. C 49 (2025) 113001
$|d_\tau| < 3.89 \times 10^{-18}$ ecm @ 68%CL

CP Violation in Tau Decays?

CP violation observed in the quark sector cannot explain the baryon asymmetry of the Universe

Tau leptons, being heavier than electrons and muons, can decay into hadrons, providing a unique opportunity to study and search for new CP violation in the lepton sector

CP asymmetry in $\tau\to\nu_\tau\pi K_S(\to 2\pi)$

$$\mathcal{A}_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

is expected due to the K-Kbar mixing and predicted to be +0.36(0.01)% [BS 2005, GN 2012]

This process can be served as a calibration for searching for additional CP violation in tau decays

BABAR's measurement: −0.36(0.23)(0.11)% [BABAR 2011]

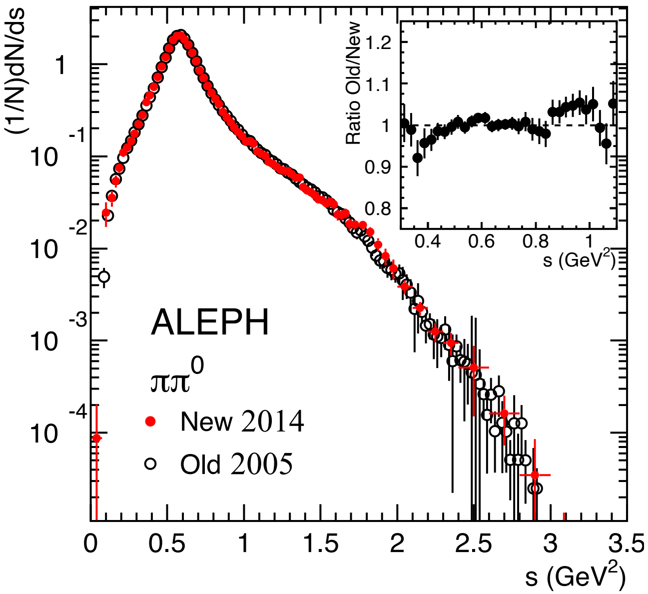
Need independent measurements to cross check the result of BABAR

STCF study: Xiang-Shi-Zhou-Kang-Liu, Chin. Phys. C 45 (2021) 053003
See also H.Y. Cheng et al., arXiv:2502.08907

Hadronic Decays, Spectral Functions and Its Applications

- Spectral functions (SFs) of (semi)hadronic decay modes
  - Measurements
  - Applications (see e.g. Davier-Hoecker-Zhang, RMP 78 (2006) 1043)
    - Muon g-2 predictions
    - Precise determination of the strong coupling constant
    - Determination of the V_{us} entry of the CKM matrix
    - Determination of the strange quark mass
    - As a probe of new physics (see e.g. JHEP 04 (2022) 152)

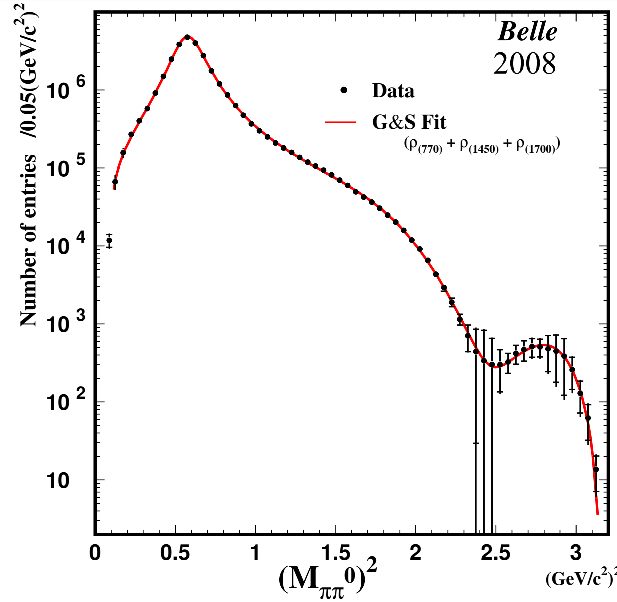
Measurements Performed Long Time Ago!

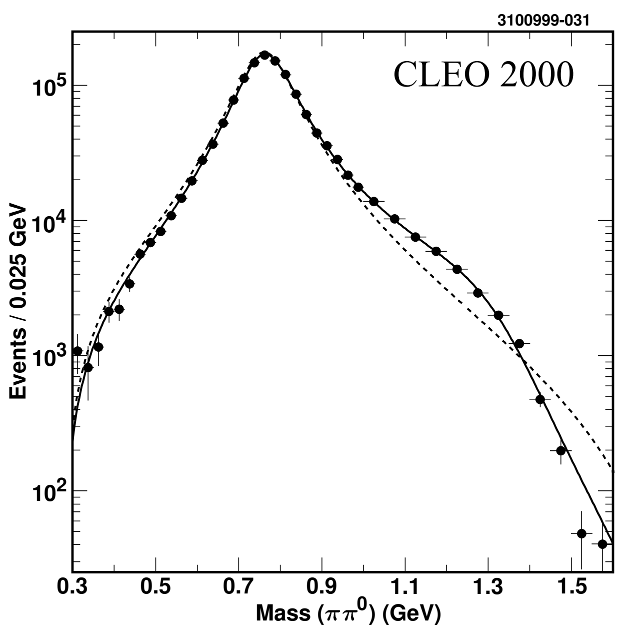


DHMYZ 2014

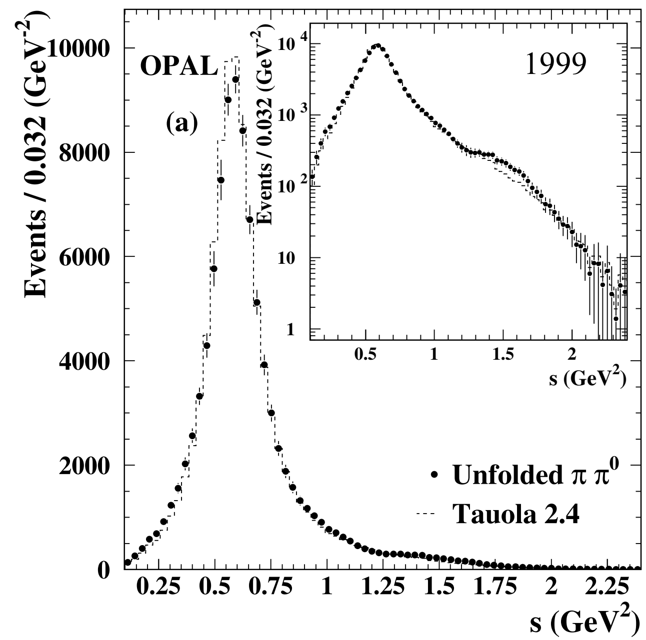
SFs measured under very different exp. conditions

ALEPH had the best branching fraction (normalisation) measurement, while Belle had the best shape measurement



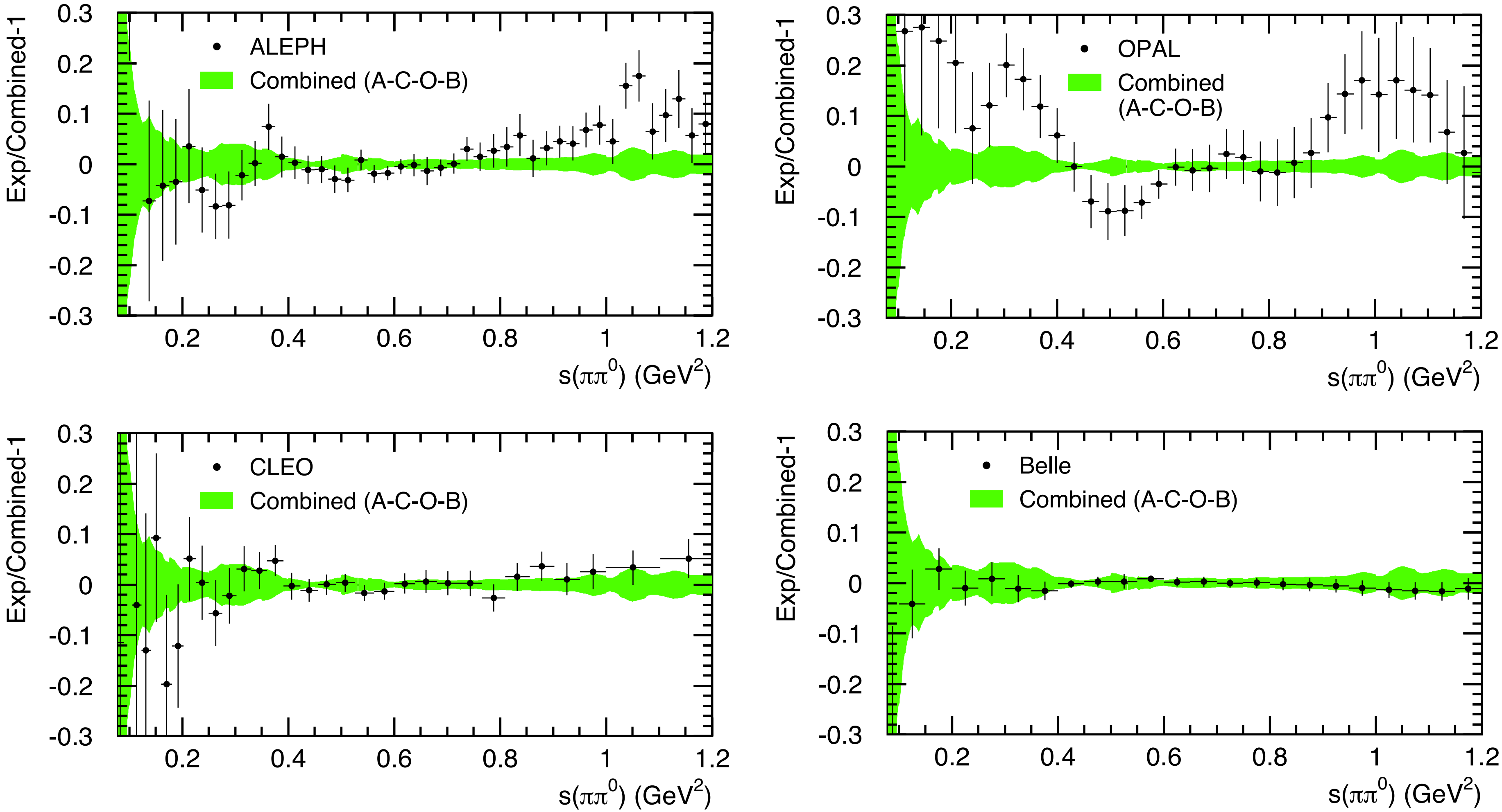


ALEPH: Phys. Rept. 421 (2005) 191, Eur. Phys. J. C 74 (2014) 2803
Belle: Phys. Rev. D 78, 072006 (2008)
CLEO: Phys. Rev. D 61, 112002 (2000)
OPAL: Eur. Phys. J. C 7, 571 (1999)



Data Combination for the $\pi\pi^0$ Channel

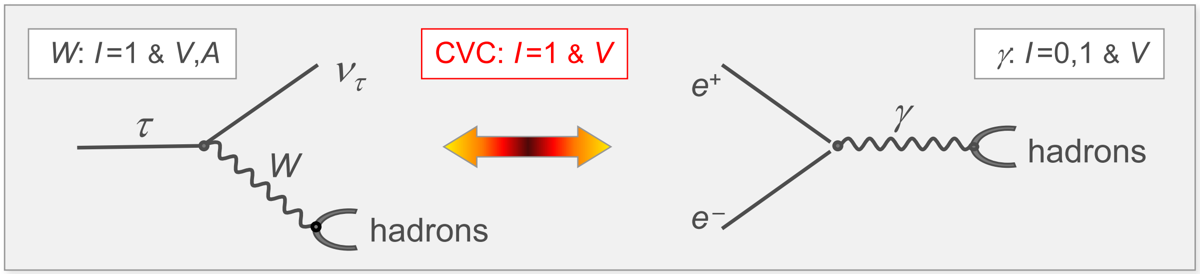
Figures from DHMYZ 2014



The normalisation is constrained dominantly by ALEPH while the shape by Belle

Use tau Spectral Functions

- The use of tau spectral functions for the leading-order (LO) hadronic vacuum polarisation (HVP) evaluation was originally proposed by Alemany-Davier-Hoecker [ADH 1997]
  - Based on CVC (conserved vector current) relations:



$$\sigma^{I=1}_{e^+e^-\to\pi^+\pi^-} = \frac{4\pi\alpha^2}{s} \upsilon_{1,\pi^-\pi^0\nu_\tau}$$

$$\sigma^{I=1}_{e^+e^-\to\pi^+\pi^-\pi^+\pi^-} = 2\cdot\frac{4\pi\alpha^2}{s} \upsilon_{1,\pi^-3\pi^0\nu_\tau}$$

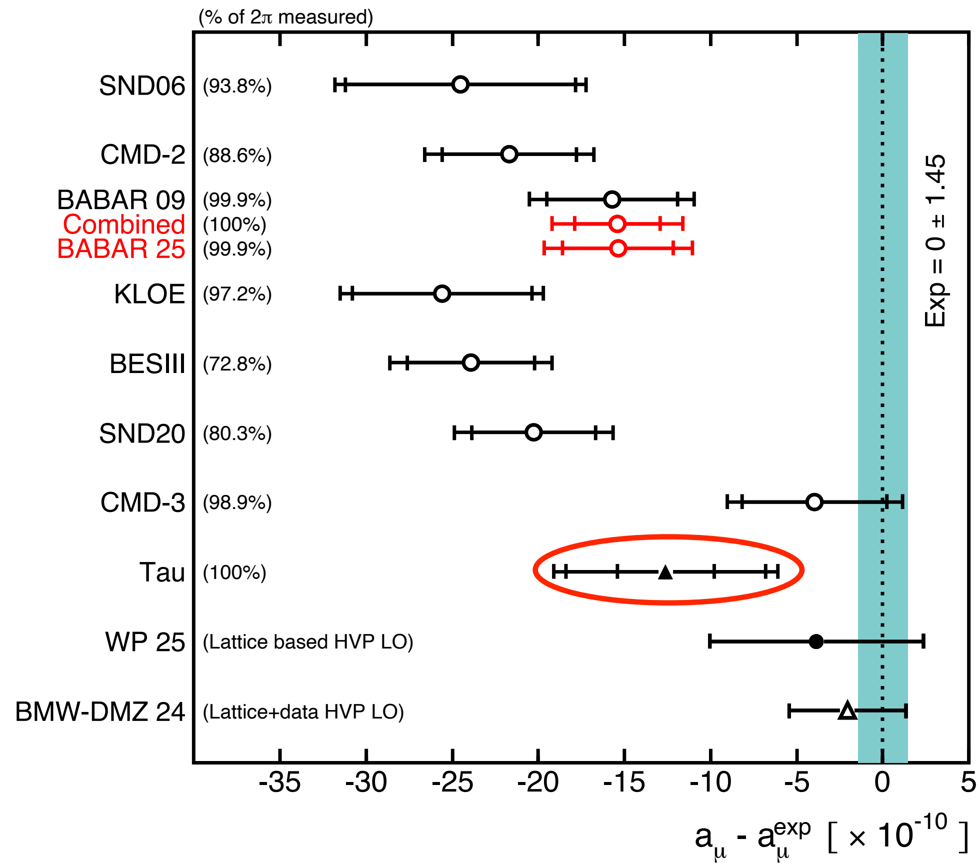
$$\sigma^{I=1}_{e^+e^-\to\pi^+\pi^-\pi^0\pi^0} = \frac{4\pi\alpha^2}{s} \left[\upsilon_{1,2\pi^-\pi^+\pi^0\nu_\tau} - \upsilon_{1,\pi^-3\pi^0\nu_\tau}\right]$$

where υ are the relevant spectral functions in the 2π and 4π tau decay channels

- Isospin-breaking corrections are needed to take into account
  - EW radiative corrections
  - Mass difference between charged and neutral pions
  - Mass and width differences between charged and neutral rho resonances

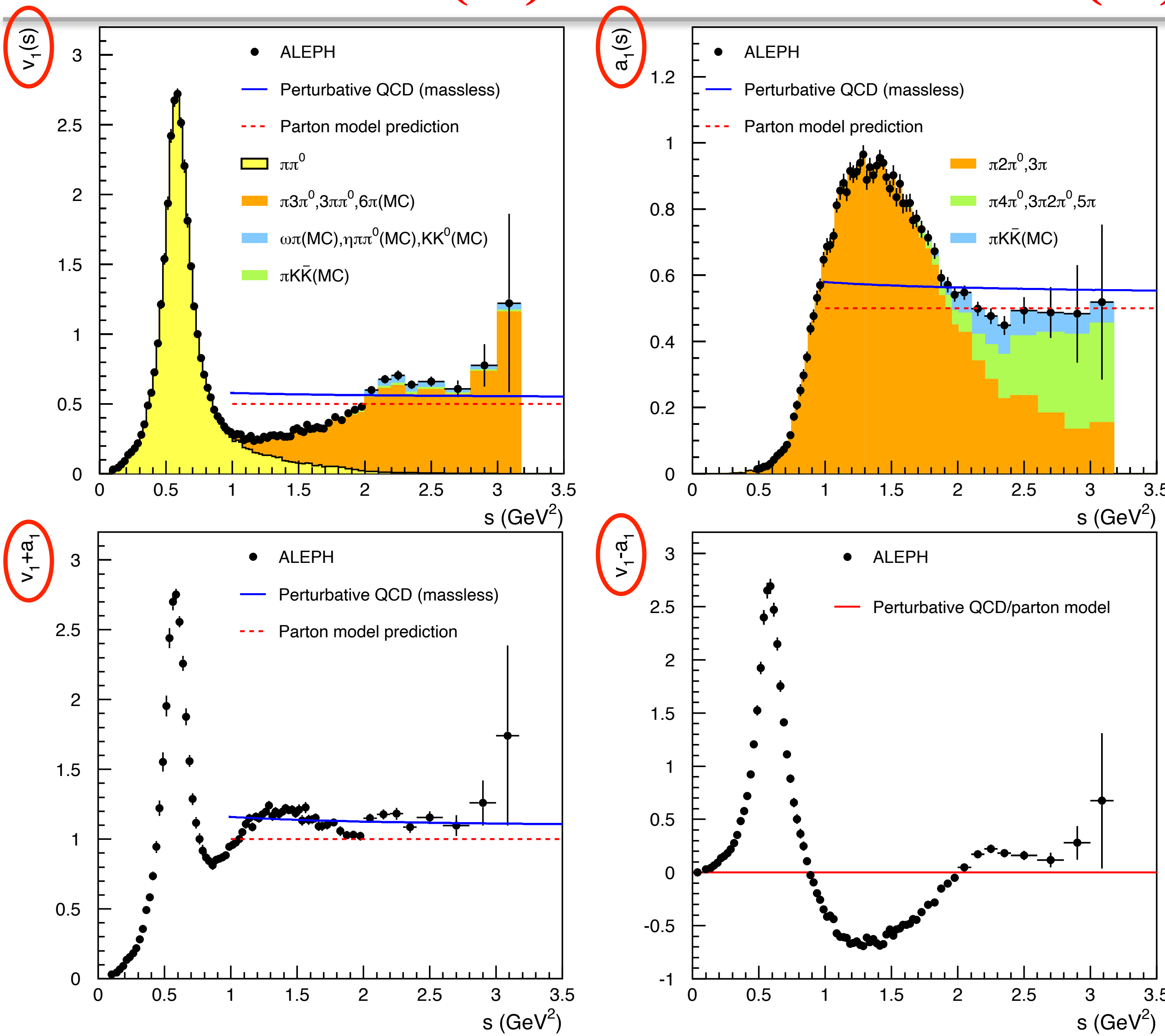
Current Status of the Muon g-2

- Tau data provide an alternative prediction to clarify the current confusing situation in the measurements of $e^+e^- \to \pi^+\pi^-$ among different experiments
- The 2π channel gives ~73% of the LO HVP contribution to muon g-2
- Uncertainties of model dependent isospin breaking (IB) corrections for the tau prediction inflated for white paper (WP) 2025 version for the muon g-2 Theory Initiative
- Need both improved spectral function measurements of the tau data and IB corrections



- Inner error: uncertainty of the 2π channel <1.8 GeV (non-100% part from combined 2π data)
- Outer one: uncertainty of other components
- Intermediate one for tau: inflated uncertainty of isospin breaking corrections

Vector (v_1) and Axial-Vector (a_1) SFs



DHMYZ 2014

Limited precision at high energy tails

Unmeasured modes based on MC

v_1+a_1 at high energy tail reaches the asymptotic limit in agreement with pQCD prediction
➔ α_s determination

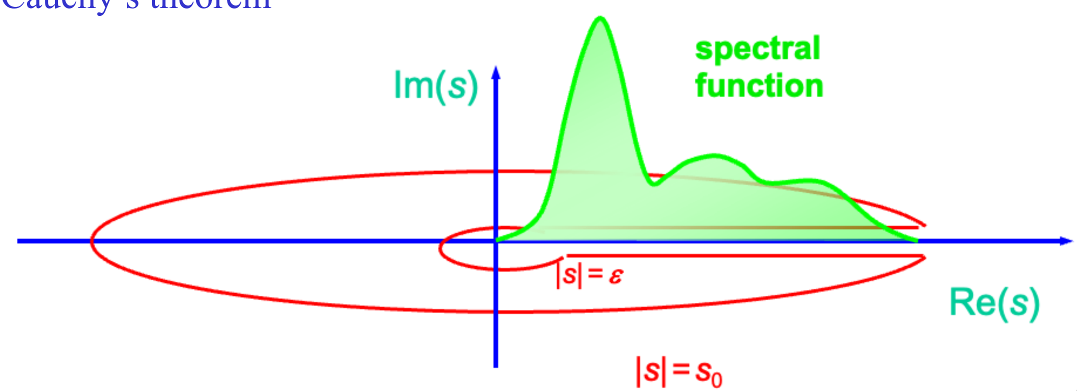
v_1-a_1 purely non-perturbative contribution

Connection to Theoretical Predictions

$$R(s_0) \propto \int_0^{s_0} ds\, w(s)\, \mathrm{Im}\Pi(s+i\epsilon) \Longleftrightarrow -\frac{1}{2i}\oint_{s=s_0} ds\, w(s)\, \Pi(s)$$

$$\propto |V_{\mathrm{CKM}}|^2 S_{\mathrm{EW}} \left(1 + \delta^{(0)}_{\mathrm{pQCD}}(\alpha_s) + \delta'_{\mathrm{EW}} + \delta^{(2)}(m_q) + \sum_{D=4,6,\cdots} \delta^{(D)}_{\mathrm{non\text{-}pQCD}}\right)$$

Cauchy's theorem



$\delta^{(0)}_{\mathrm{pQCD}}(\alpha_s)$ Dominant pQCD contribution, expansion known up to 5th order

$\delta'_{\mathrm{EW}} \simeq 0.0010$ Non-logarithmic EW correction (Braaten-Li, 1990)

$\delta^{(2)}(m_q)$ Dimension 2 pQCD contribution from quark mass (<0.1% for *u*, *d* quarks)

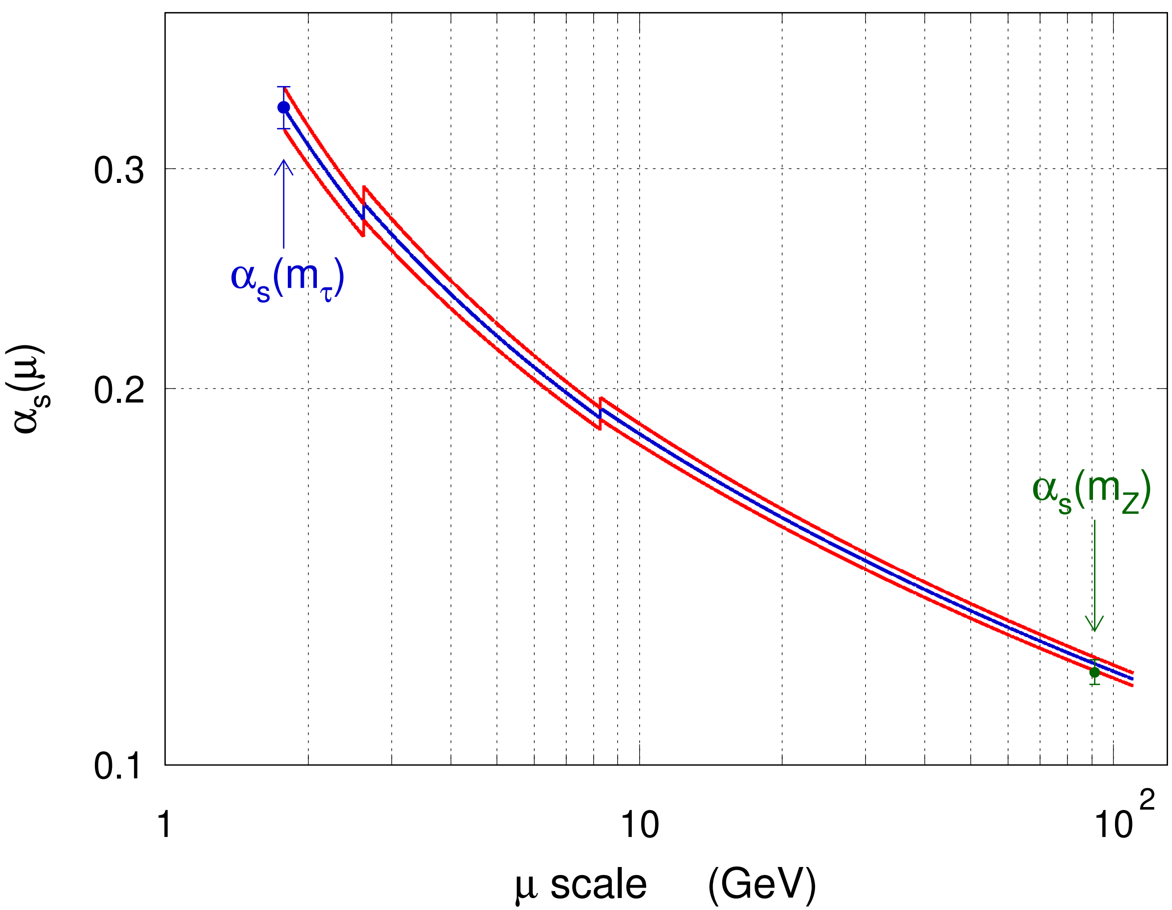
$\delta^{(D)}_{\mathrm{non\text{-}pQCD}}$ Dimension D non-pQCD contributions

Running Strong Coupling Constant

Tau α_s determination evolved to M_Z:

$$\alpha_s(M_Z^2) = 0.1209 \pm 0.0006_{\rm exp} \pm 0.0016_{\rm th} \pm 0.0005_{\rm evol} = 0.1209 \pm 0.0018 \;.$$

ALEPH 2005



to be compared with

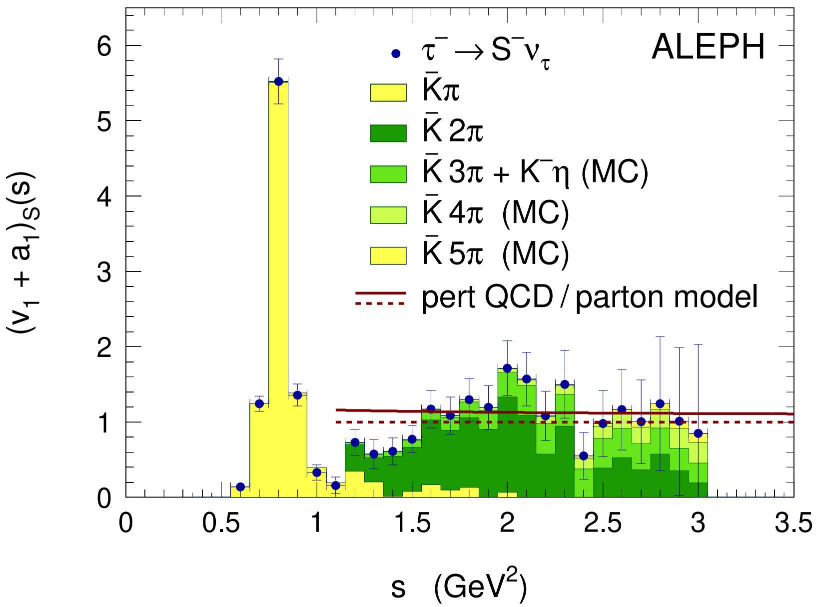
$$\alpha_s(M_Z^2)_{\rm Z\ width} = 0.1186 \pm 0.0027$$

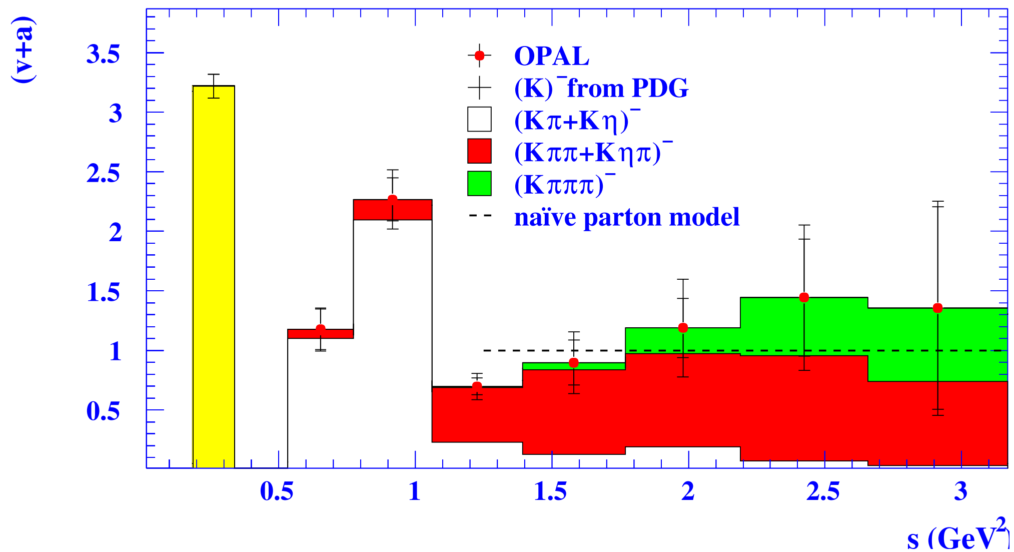
provides a powerful test of the evolution of α_s over a large energy range

Strange SFs and its Applications

Spectral functions (SFs)

DHZ, RMP 78 (2006) 1043





OPAL normalised each channel with branching fraction from PDG, dominated by ALEPH
Belle also measured $K_S\pi$ in 2007

Very limited precision in the strange spectral functions.
There is large room for improvement

Connection to Theoretical Predictions

$$R_\tau(m_\tau^2) = 12\pi S_{\rm EW} \int_0^{m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 \left[\left(1+2\frac{s}{m_\tau^2}\right){\rm Im}\Pi^{(1+0)}(s+i\epsilon) \;-\; 2\frac{s}{m_\tau^2}{\rm Im}\Pi^{(0)}(s+i\epsilon)\right]$$

$$R_{\tau,S} = 3|V_{us}|^2 S_{\rm EW}\left(1+\delta^{(0)}+\delta'_{\rm EW}+\delta_S^{(2,m_q)}+\sum_{D=4,6,\dots}\delta_S^{(D)}\right)$$

$\delta^{(0)}$ perturbative part of mass dimension D = 0

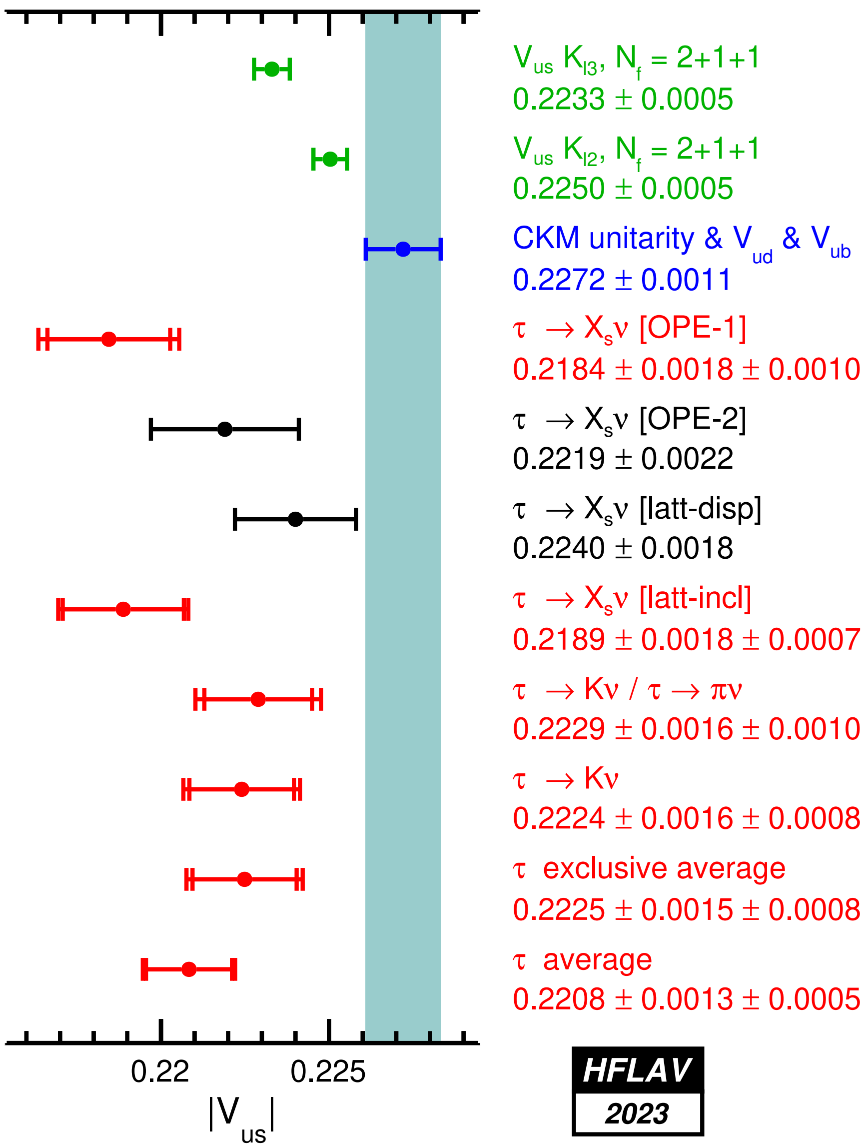
$\delta'_{\rm EW} \simeq 0.0010$

$$\delta_S^{(2,m_s)} = -\,8\frac{m_s^2(m_\tau^2)}{m_\tau^2}\left[1+\frac{16}{3}a_s+46.00\,a_s^2+\left(283.6+\frac{3}{4}\,x_3^{(1+0)}\right)a_s^3+\cdots\right]$$

The dimension-2 term is sensitive to strange quark mass

V_{us}, and/or m_s can be extracted from strange SFs and their moments

Current Status of V_{us} Determinations



We really need high precision BFs and SFs measurements in the strange decay modes to clarify the discrepancies!

Other Topics

- ➢ Dark sector searches for dark matter or axion-like candidates
- ➢ Michel parameters - tau decay parameters (study if the Lorentz structure of charged weak currents is SM like)
- ➢ Quantum entanglement (Loophole? See e.g. arXiv:2507.15949)
- ➢ Ditauonium (if discovered, provides the most precise (25 keV) determination of m_τ, see e.g. arXiv:2302.07365)
- ➢ Search for new physics using effective field theory (EFT) approaches

General Comment STCF vs Other existing colliders

As far as the tau physics is concerned

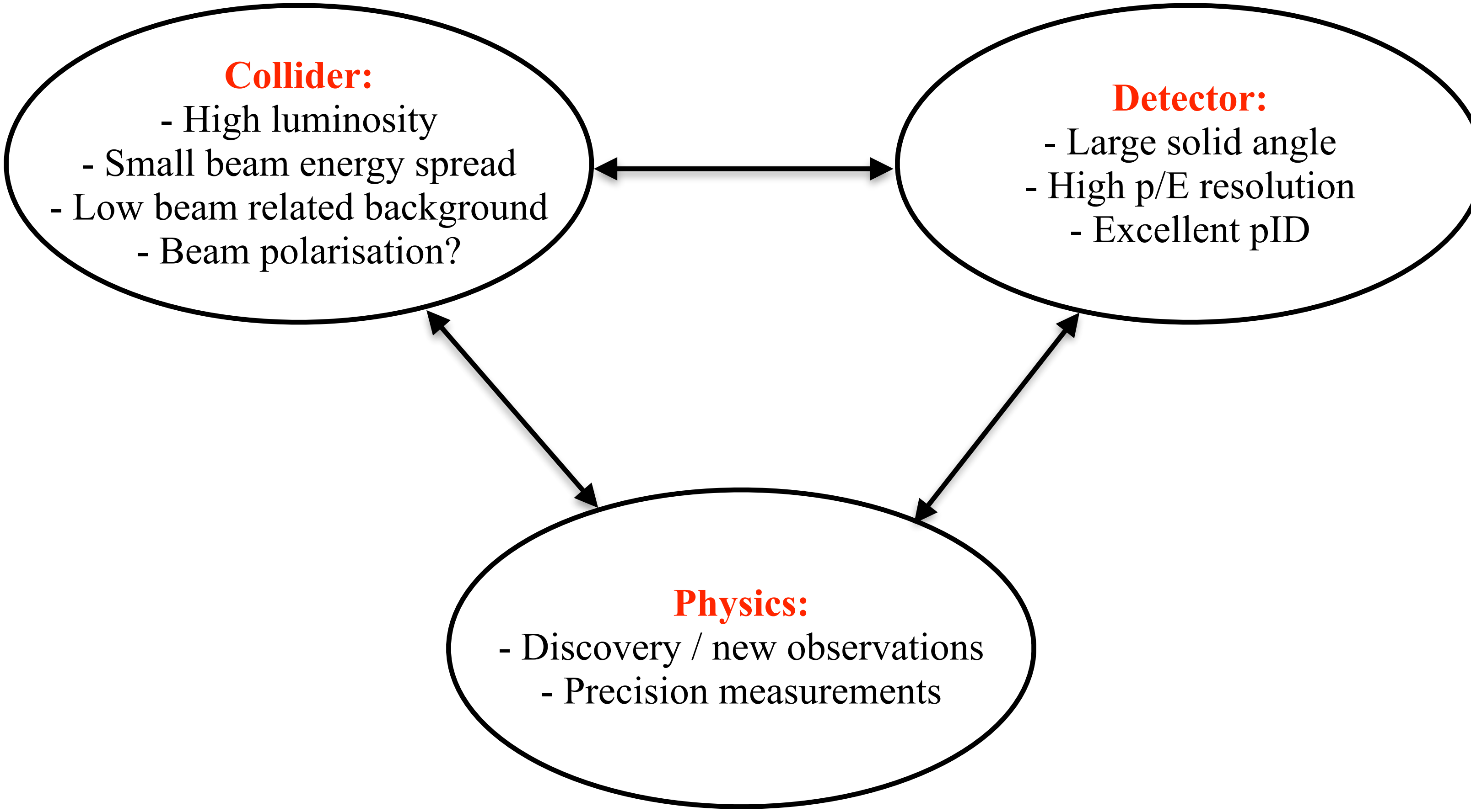
STCF is unique for some of observations / measurements

Most observations / measurements can be realised at all colliders

In this sense, we should not wait too long before constructing STCF, as the other existing experiments won't wait for STCF

To have different experiments is also important to verify any new observation

Interplay between Collider, Detector and Physics



- It's important to have the best accelerator and detector possible and upgradable
- Desirable to have more feasibility studies for accelerator/detector optimisation