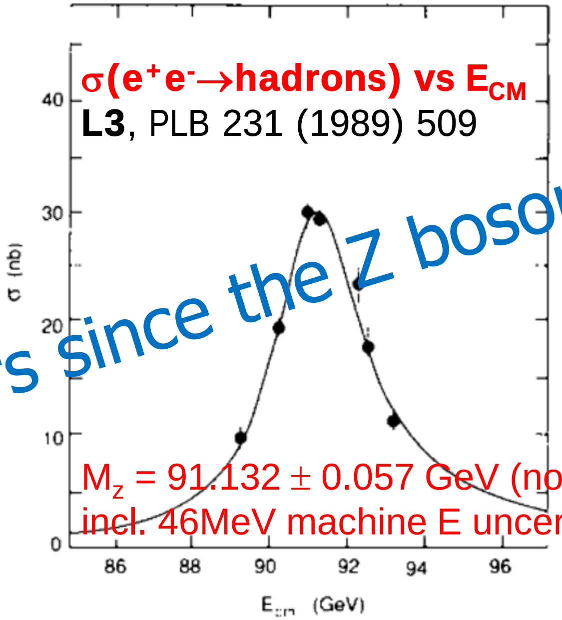
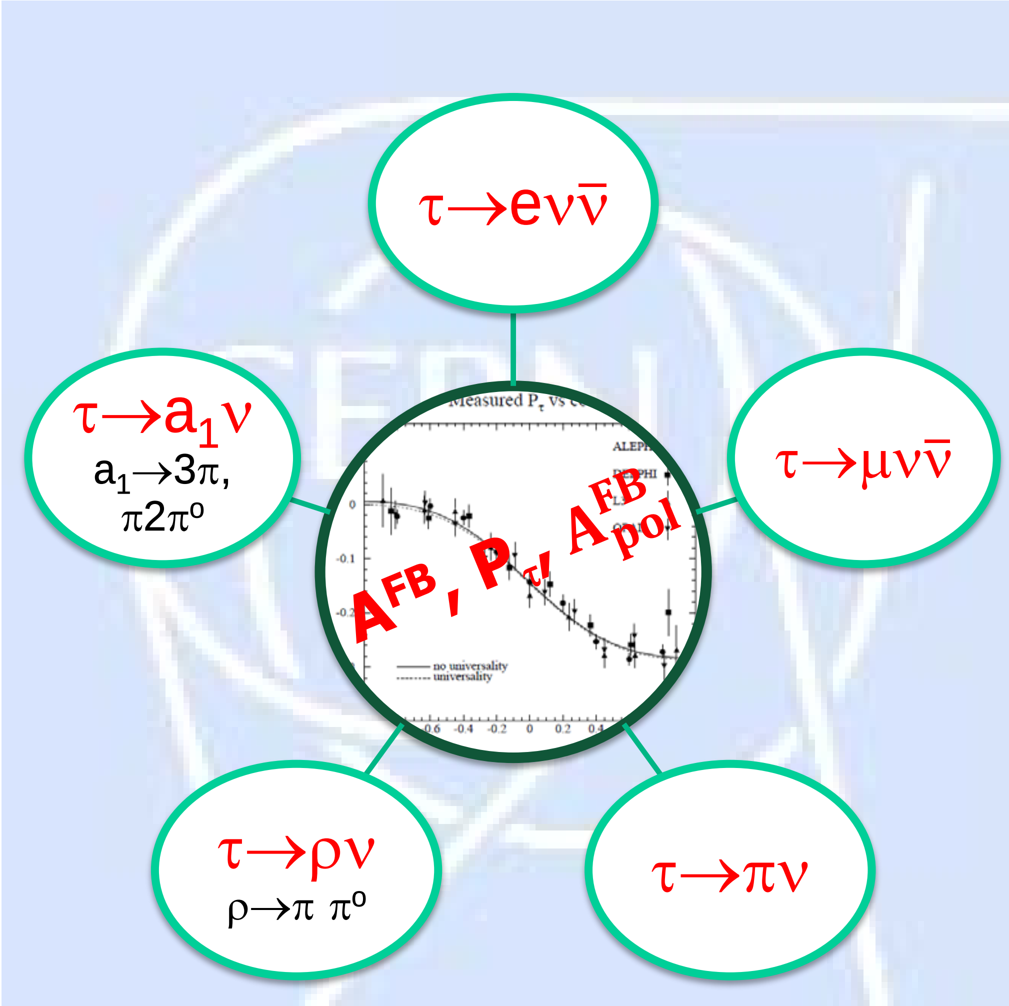
Challenges for τ polarisation: LEP $\rightarrow$ FCC-ee

Manuella G. Vincter (Carleton University, Ottawa, Canada)

- LEP@CERN: a trip down memory lane (ADLO)
- Asymmetries with $e^+e^- \rightarrow \tau^+\tau^-$ at LEP-I
  - Relation to SM couplings/Weinberg angle
  - Radiative corrections
  - τ decays and kinematic variables
  - Measured asymmetries and systematics
- Interspersed thoughts about τ polarisation at FCC-ee



30 years since the Z boson at LEP



FCC WEEK 2019
BRUSSELS, BELGIUM
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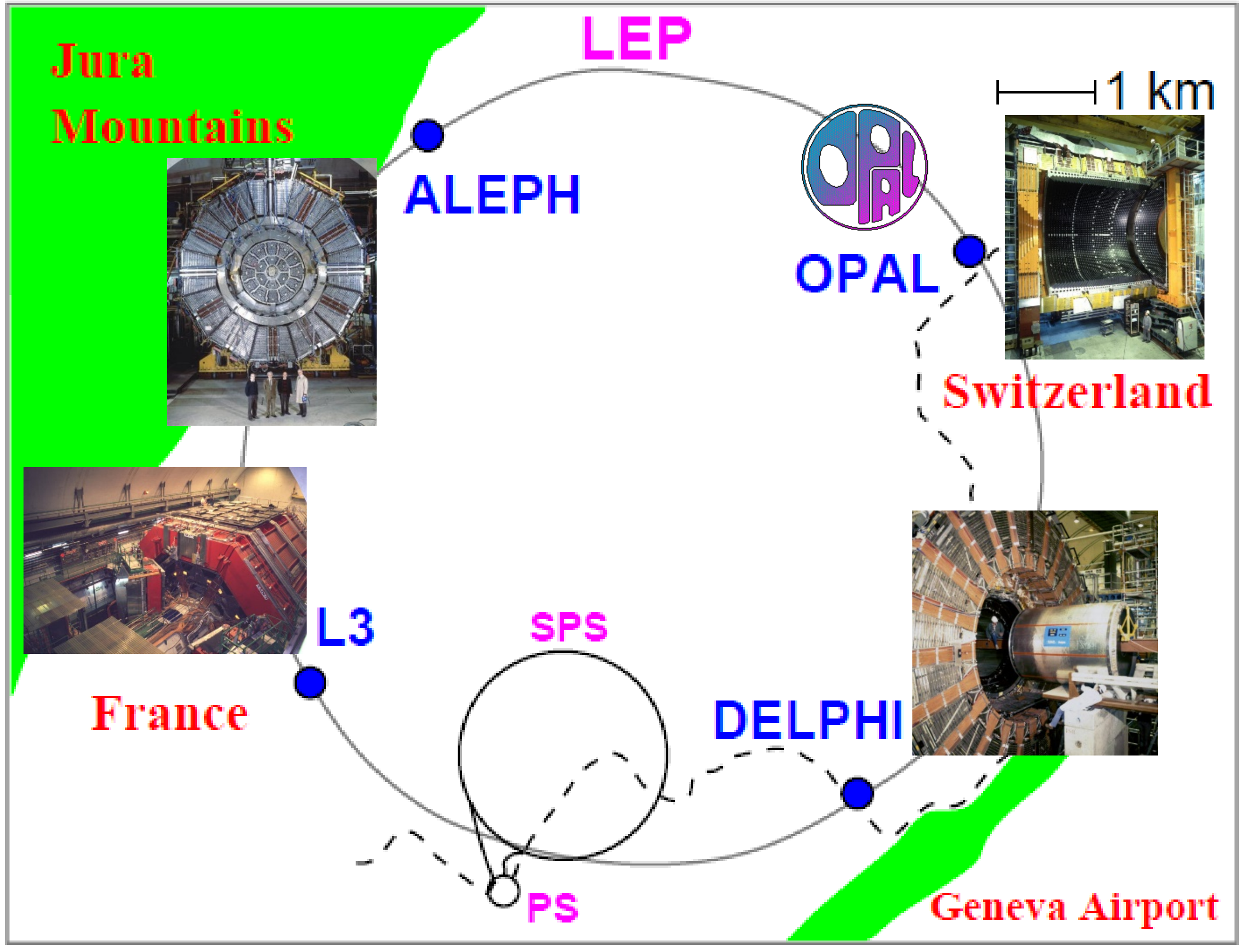
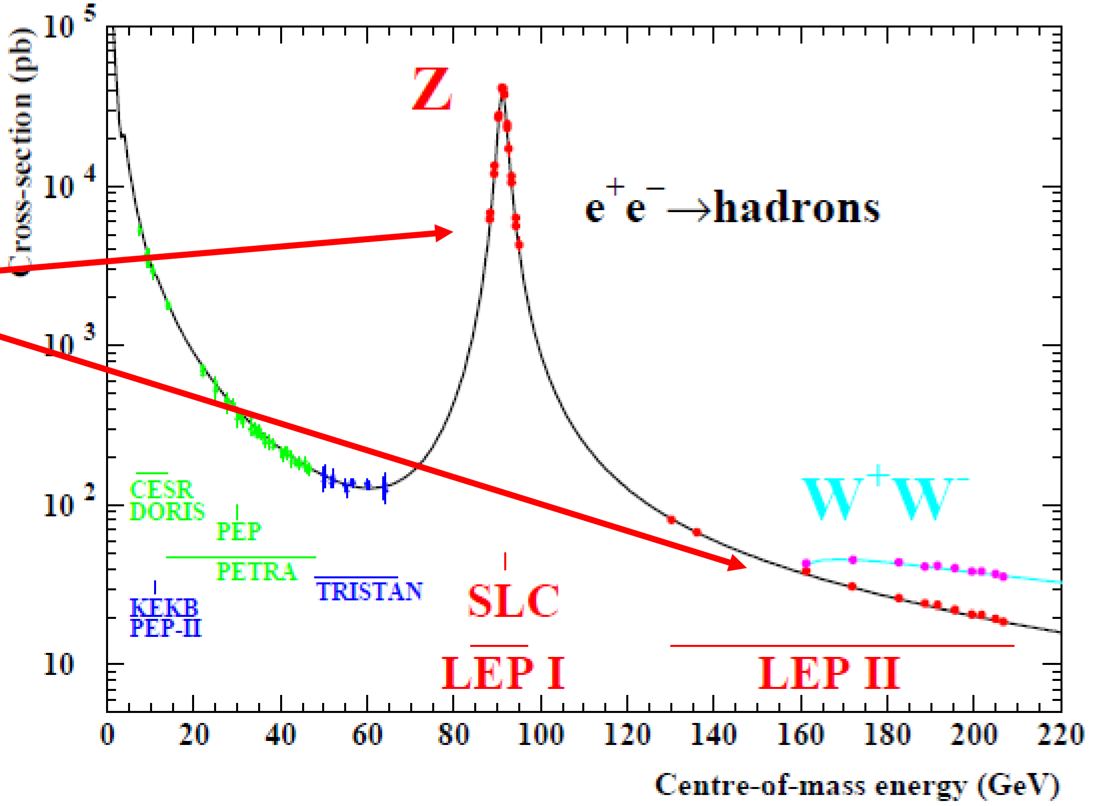
Special thanks to Mike Roney for his wise comments...

ADLO@LEP

ALEPH (A), DELPHI (D), L3 (L), OPAL (O)

- LEP (1989-2000) e^+e^- machine at Z pole and at W^+W^-
- Focus on LEP-I: at its best, 1000 Z/hour recorded by each expt (17M Z total)! Machine energy was known to ~2 MeV.





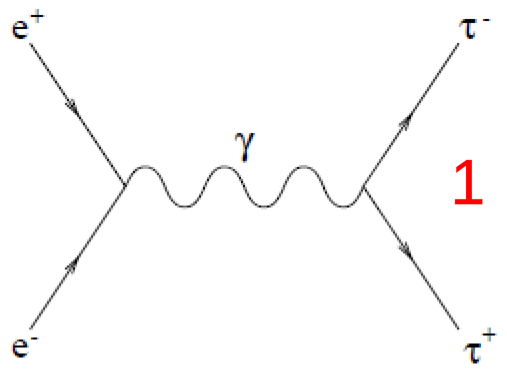
LEP-I (1989-1995): around the Z pole (~200pb^{-1})

Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

	$Z \to \ell^+\ell^-$ x10^3				
Year	A	D	L	O	LEP
1990/91	53	36	39	58	186
1992	77	70	59	88	294
1993	78	75	64	79	296
1994	202	137	127	191	657
1995	90	66	54	81	291
Total	500	384	343	497	1724

LEP EWWG, Phys. Rept. 427, 257-454 (2006)

What happens near the Z pole: $e^+e^- \rightarrow \tau^+\tau^-$...



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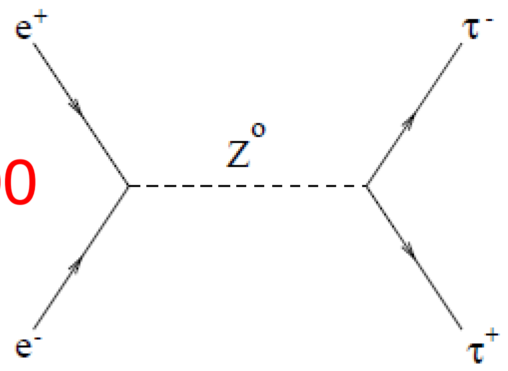
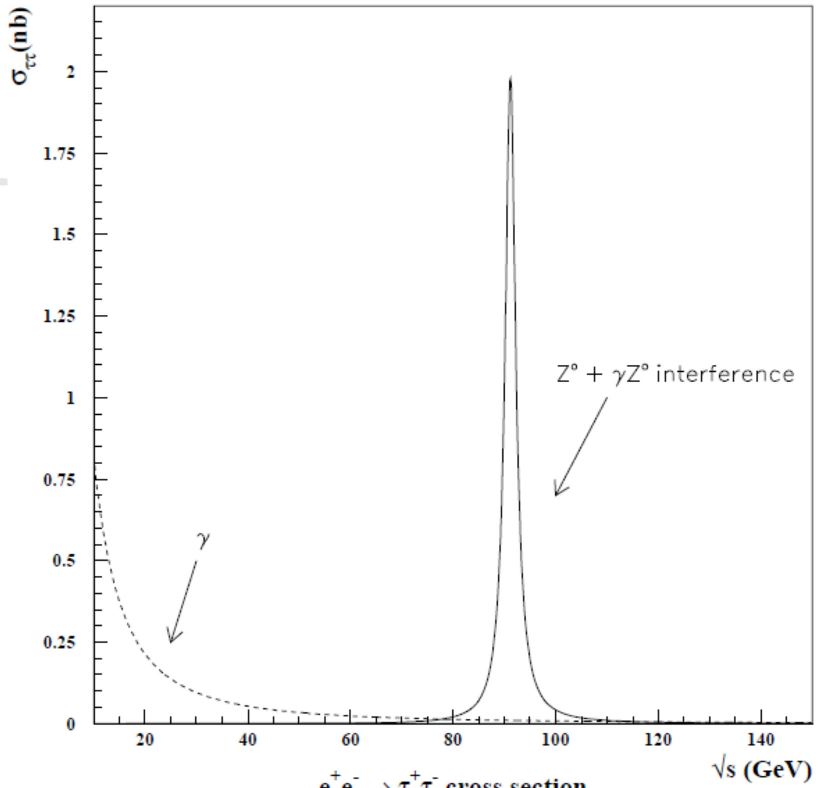
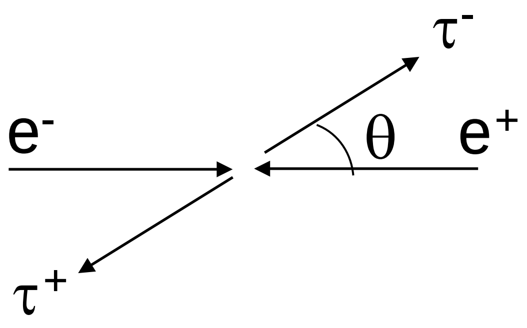




$e^+e^- \rightarrow \tau^+\tau^-$ cross section

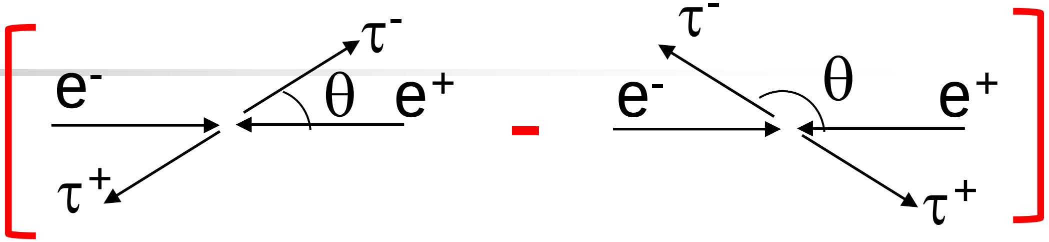
- γ - Z interference ~ 10^{-3} x smaller than Z exchange ($\equiv$ 0 at the mass peak)
- The neutral weak force couples unequally to left-handed and right-handed fermions
  - → parity violation

$$\frac{d\sigma}{d\cos\theta} = A\,(1+\cos^2\theta) + \boxed{B\cos\theta}$$



manifestation of the parity violation of the weak interaction

The three types of asymmetries*



- **A^{FB}** : forward ($\cos\theta > 0$) – backward ($\cos\theta < 0$) scattering

$$A^{FB} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}$$

- **P_τ** : polarisation of the Z induces an angular dependence on the polarisation of the τ

$$P_\tau(\cos\theta) = \frac{\left.\frac{d\sigma}{d\cos\theta}\right|_R - \left.\frac{d\sigma}{d\cos\theta}\right|_L}{\left.\frac{d\sigma}{d\cos\theta}\right|_R + \left.\frac{d\sigma}{d\cos\theta}\right|_L}$$

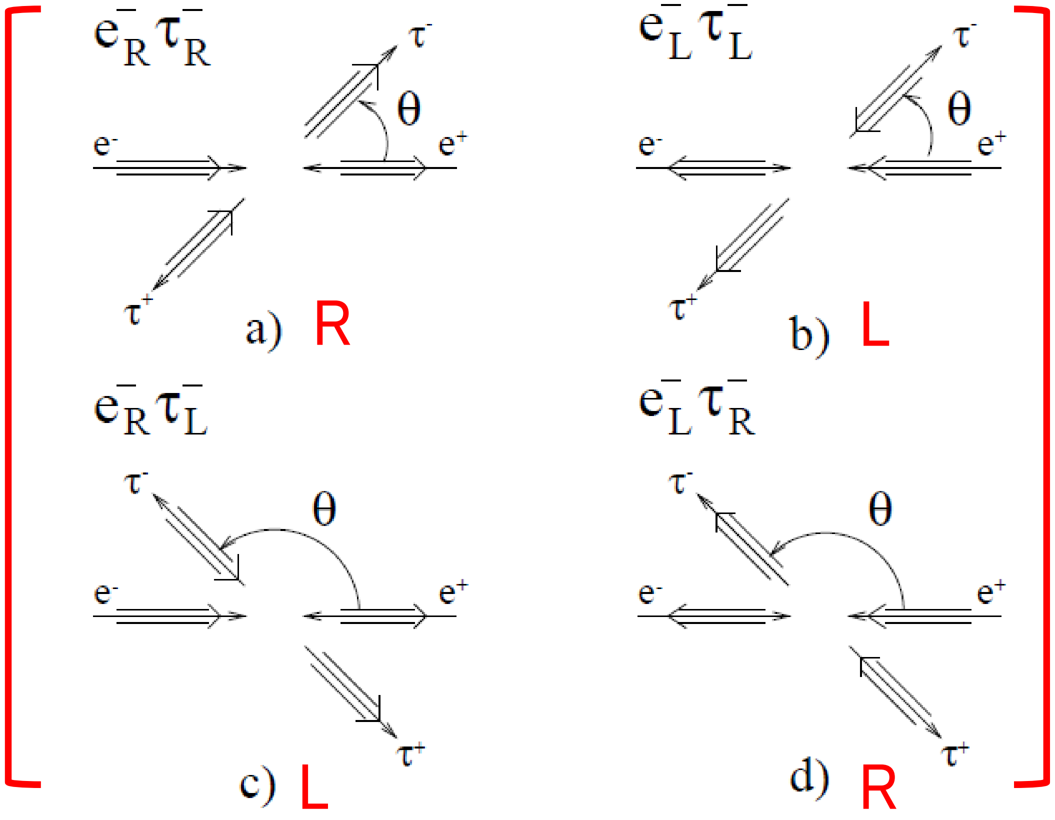
$$\langle P_\tau \rangle = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$P_{\tau^-} = -P_{\tau^+} = P_\tau$$

- **A^{FB}_{pol}** : forward-backward asymmetry of the polarisation

$$A^{FB}_{pol} = \frac{\left[\int_0^1 \left.\frac{d\sigma}{d\cos\theta}\right|_R - \int_0^1 \left.\frac{d\sigma}{d\cos\theta}\right|_L\right] - \left[\int_{-1}^0 \left.\frac{d\sigma}{d\cos\theta}\right|_R - \int_{-1}^0 \left.\frac{d\sigma}{d\cos\theta}\right|_L\right]}{\int_0^1 \left.\frac{d\sigma}{d\cos\theta}\right|_R + \int_0^1 \left.\frac{d\sigma}{d\cos\theta}\right|_L + \int_{-1}^0 \left.\frac{d\sigma}{d\cos\theta}\right|_R + \int_{-1}^0 \left.\frac{d\sigma}{d\cos\theta}\right|_L}$$

$$= \frac{[a-b]-[d-c]}{\text{Sum}}$$



*Neglecting radiative corrections and the contribution from photon exchange, at $\sqrt{s} = M_Z$

Relating three asymmetries to SM: couplings and Weinberg angle

- Asymmetries related to vector, axial-vector couplings:

$$A^{FB} \approx \frac{3}{4} A_e A_\tau$$

$$\langle P_\tau \rangle \approx -A_\tau$$

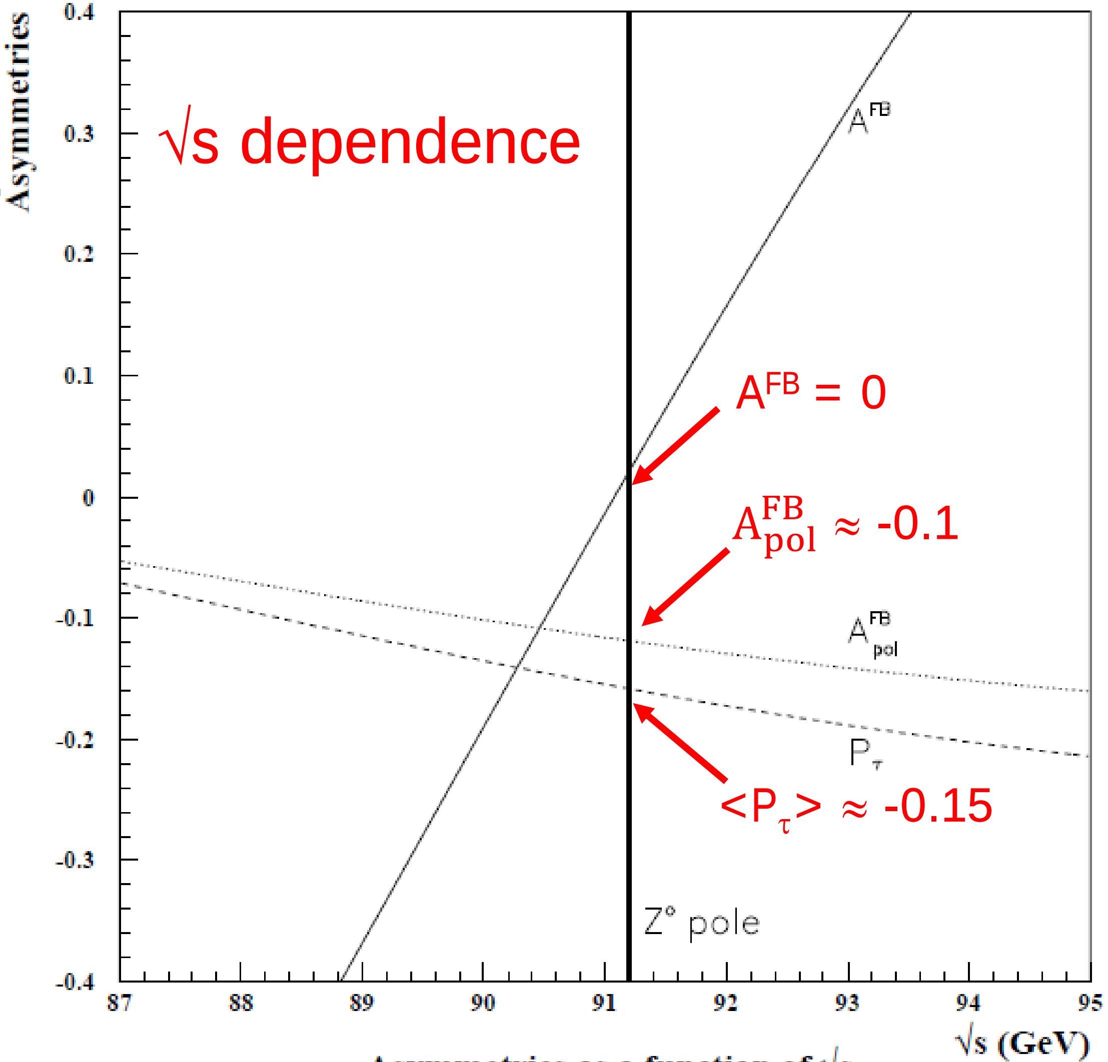
$$A^{FB}_{pol} \approx -\frac{3}{4} A_e .$$

$$A_\ell \equiv \frac{2 g_v^\ell g_a^\ell}{({g_v^\ell}^2 + {g_a^\ell}^2)}$$

Near Z pole: $A_\ell \approx 2 \frac{g_v^\ell}{g_a^\ell}$

$$\frac{g_v^\ell}{g_a^\ell} = 1 - 4 \sin^2 \theta_W$$

$$P_\tau(\cos\theta) \approx -\left[\frac{A_\tau (1 + \cos^2\theta) + 2 A_e \cos\theta}{1 + \cos^2\theta + \frac{8}{3} A^{FB} \cos\theta} \right]$$

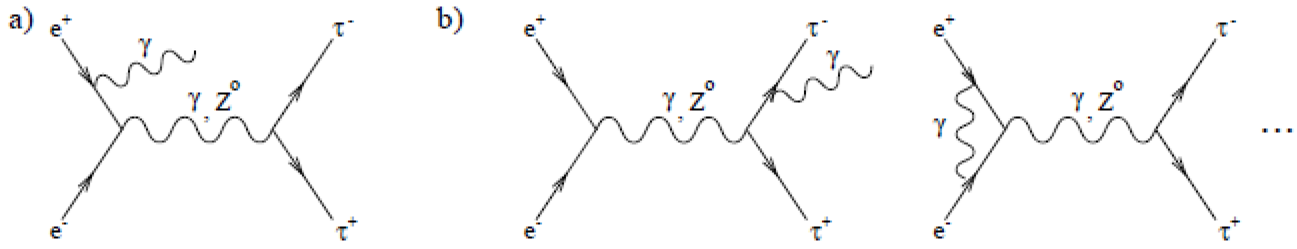


Asymmetries as a function of √s

- Sensitivity to $\sin^2\theta_W$ (assuming lepton universality, $\sin^2\theta_W = 0.23$)
  - $\delta A^{FB} \approx -1.9\ \delta \sin^2\theta_W$
  - $\delta \langle P_\tau \rangle \approx -7.8\ \delta \sin^2\theta_W$
  - $\delta A^{FB}_{pol} \approx -5.5\ \delta \sin^2\theta_W$

$\langle P_\tau \rangle$, A^{FB}_{pol} significant sensitivity to Weinberg angle.

Radiative corrections…



- If only pure Z exchange, $\langle P_\tau \rangle$ and A_{pol}^{FB} simply related to A_τ and A_e

- Photonic corrections ~30% effect on cross section, but much smaller on asymmetries. Well understood.
- At LEP, ZFITTER used correct for contributions from γ propagator, γ-Z interference and radiative corrections for initial state and final state radiation
  - ~0.005 correction to $\langle P_\tau \rangle$, A_{pol}^{FB}
  - LEP EWWG: "effects are theoretically well defined and have been calculated to more than adequate precision for the measurement at hand… ZFITTER error of ±0.0002 is included as a common systematic error in the LEP combination"

  → **Will not be sufficient for FCC-ee measurement of τ polarisation! May need a lot of work to get there.**

- Non-photonic corrections: higher-order processes affect the strength of γ and Z exchange contributions. Important vertex corrections: heavy bosons are exchanged between final and initial state charged particles.
  - modify the Born-level cross section by replacing
    - fine structure constant α by an s-dependent coupling,
    - Z width, Γ_Z, by an s-dependent width.
    - vector and axial-vector couplings by s (and t) dependent effective couplings
      - → effective weak mixing angle $g_v^f \to \hat{g}_v^f(s)$ $g_a^f \to \hat{g}_a^f(s)$.

τ polarisation from decay products

- $<P_\tau>$, A^{FB}_{pol} require knowledge of the helicity of the τ: extracted from kinematic variables of τ decay products

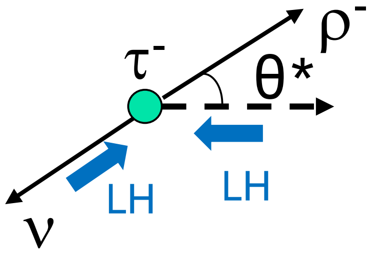
	BR (%)	Observable	Max sensitivity (with 3D τ dir)	"Ideal weight" (with 3D τ dir)
$\tau \to e\nu\bar{\nu}$	18	$X_e=E_e/E_\tau$	0.27	0.07
$\tau \to \mu\nu\bar{\nu}$	17	$X_\mu=E_\mu/E_\tau$	0.27	0.07
$\tau \to \pi\nu$	12	$X_\pi=E_\pi/E_\tau$	0.58	0.22
$\tau \to \rho\nu$	25	ω_ρ	0.58	0.47
$\tau \to a_1\nu$ ($a_1 \to \pi^\pm\pi^+\pi^-$)	9	ω_{a1}	0.58	0.17

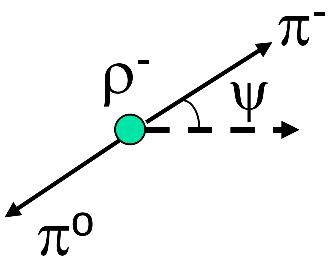
Selection efficiencies etc..
Will impact these weights

The case of the ρ (vector meson) $\rho \to \pi\ \pi^o$

- Comes longitudinally and transversely polarised
- Sensitivity diminished unless spin analyse ρ: cos θ^*, ψ
- "Optimal variable" $\propto$ differential decay with of $\pm$ helicity τ: ω_ρ

Same story for a_1 but more complicated! Axial-vector meson.



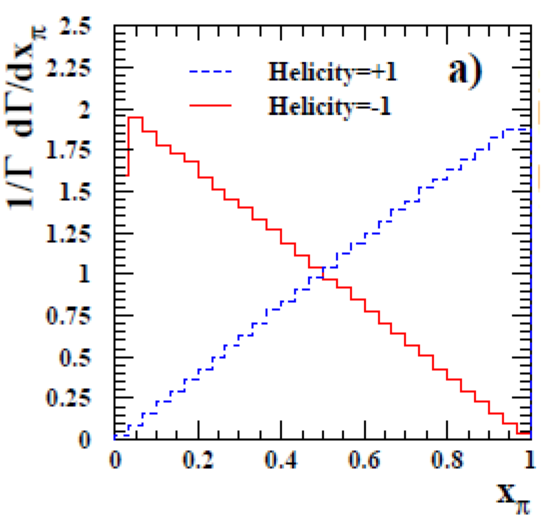


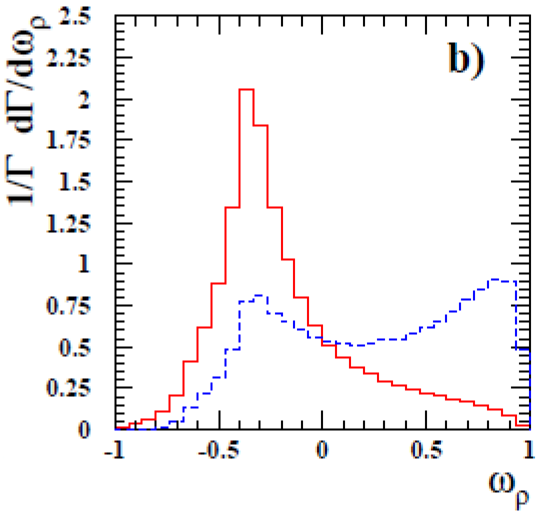
LEP EWWG, Phys. Rept. 427, 257-454 (2006)

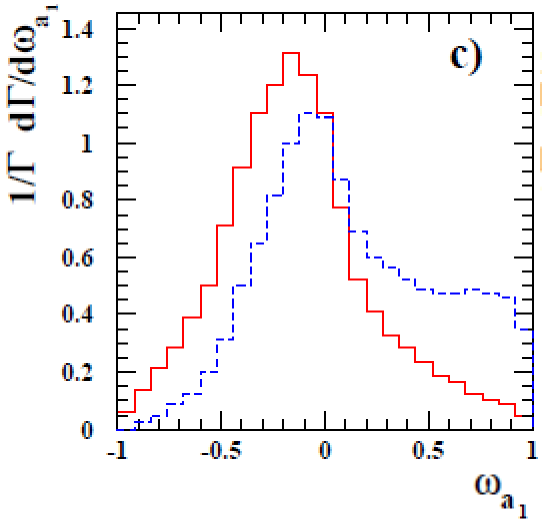
Kinematic observables

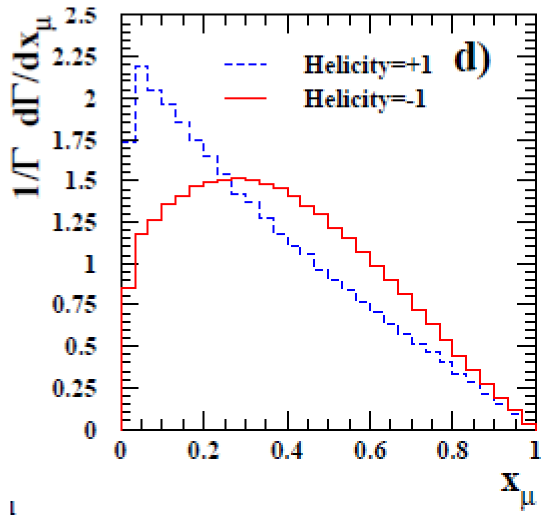
ADLO τ polarisation measurements based on ~150 pb^{-1} (~150k $e^+e^- \to \tau^+\tau^-$) per expt

- Without selection requirements: the observables in MC

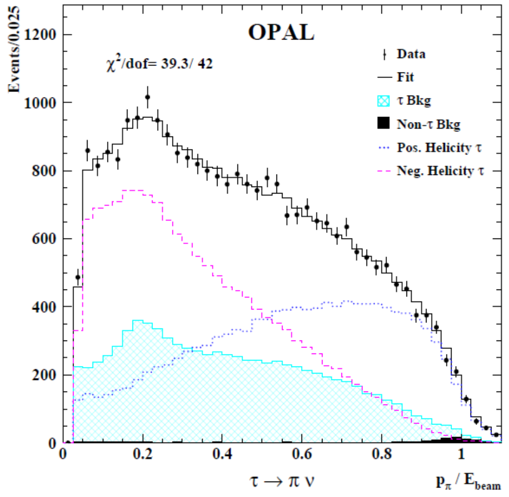


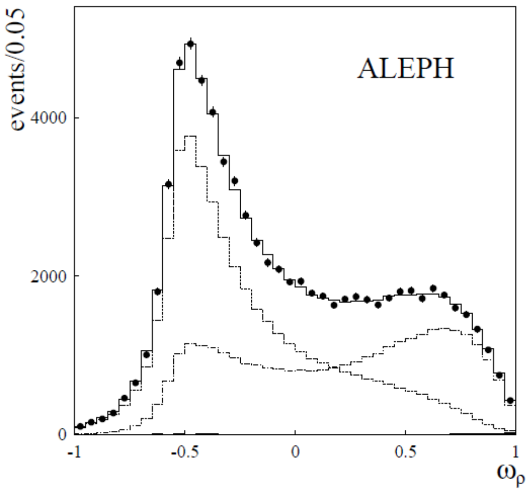


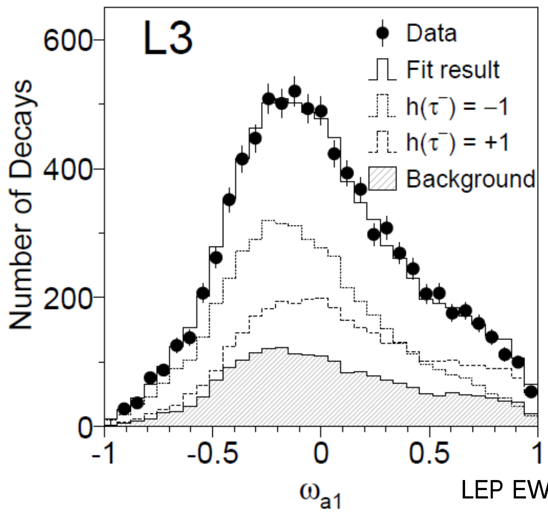


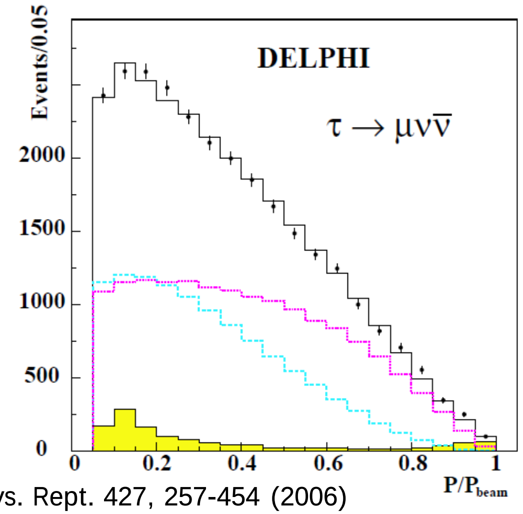


- With selection requirements: Fit linear combinations of ± helicity using the observables in MC (KORALZ+TAUOLA)



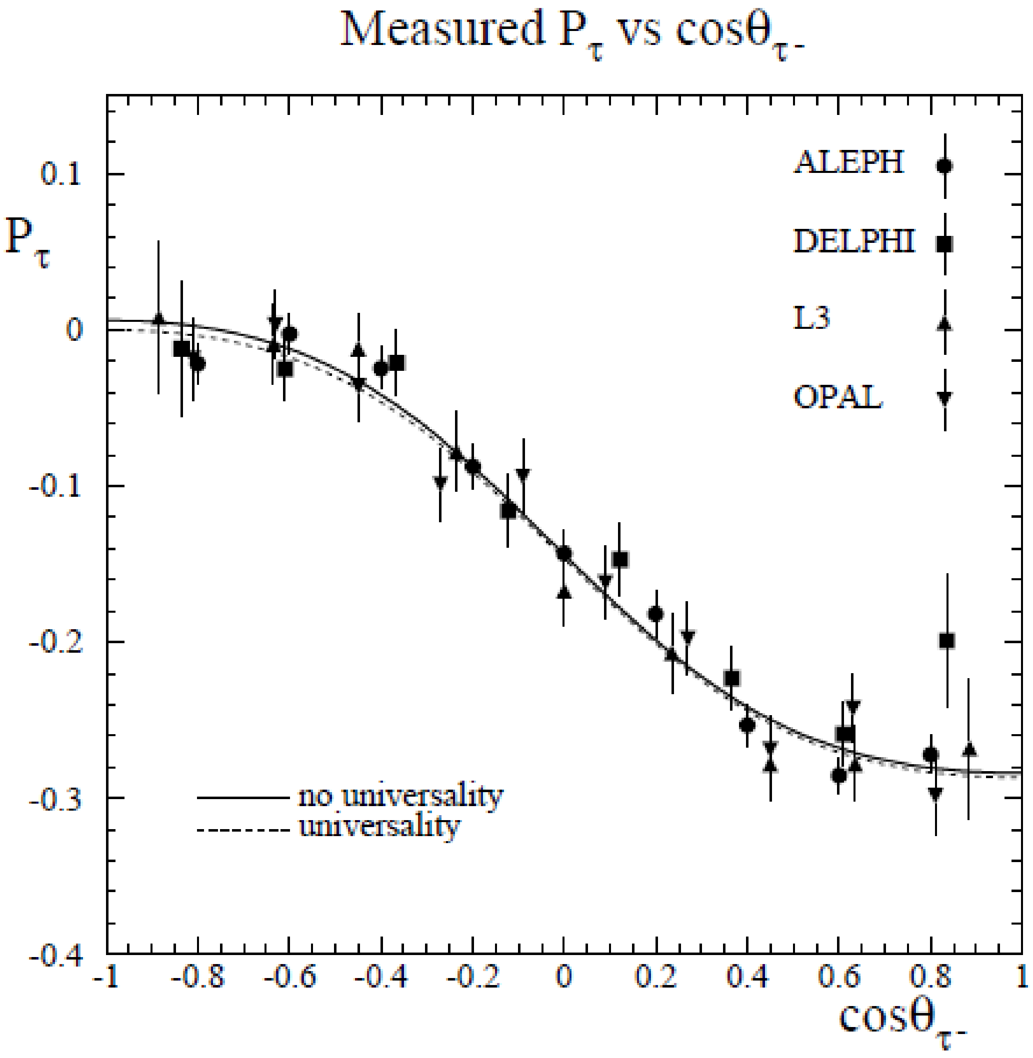






LEP EWWG, Phys. Rept. 427, 257-454 (2006)

Measured P_τ and LEP EWWG extraction of A_τ and A_e



Value ± stat.± syst.

Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$

- Some systematic uncert at LEP related to the sample size
- Statistical uncertainty at FCC-ee on A_τ and A_e <0.00002 (~10^5 x more Z than at LEP i.e. $\sqrt{10^5}$ =300 improvement)

→ FCC-ee: will have negligible statistical uncertainties. It will be all about controlling systematics!

→ FCC-ee: need to perform simultaneous fit across all decay modes with all systematic errors.

→ Modes with higher syst uncert will feed into those with better controlled syst uncert as backgrounds.

LEP EWWG, Phys. Rept. 427, 257-454 (2006)

Common systematic uncertainties on LEP measurements

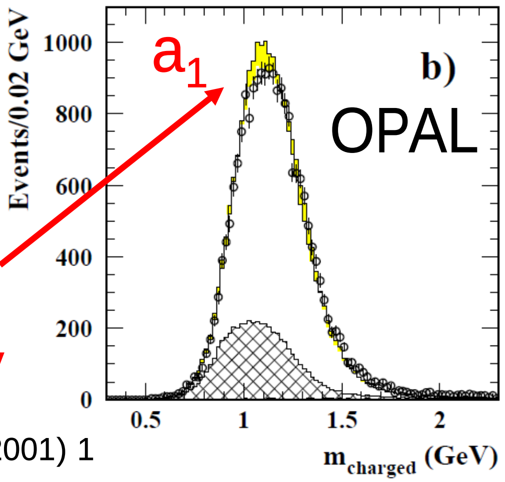
LEP EWWG, Phys. Rept. 427, 257-454 (2006)	ALEPH		DELPHI		L3		OPAL	
	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$	$\delta\mathcal{A}_\tau$	$\delta\mathcal{A}_e$
ZFITTER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
τ branching fractions	0.0003	0.0000	0.0016	0.0000	0.0007	0.0012	0.0011	0.0003
two-photon bg	0.0000	0.0000	0.0005	0.0000	0.0007	0.0000	0.0000	0.0000
had. decay model	0.0012	0.0008	0.0010	0.0000	0.0010	0.0001	0.0025	0.0005

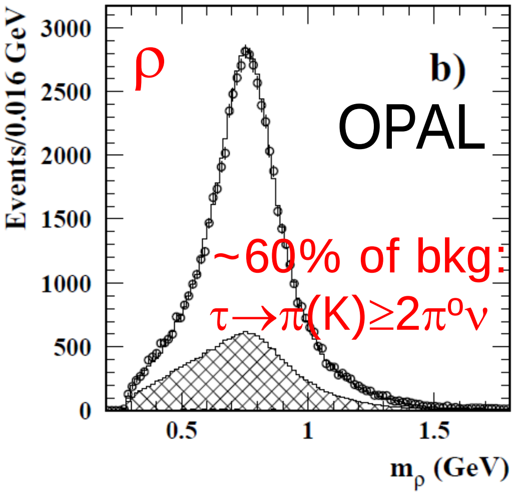
τ branching ratios (BR)	δ BR (%) LEP	δ BR (%) PDG18
$\tau\to\pi\nu$	0.13	0.05
$\tau\to\rho\nu$	0.15	0.09
$\tau\to a_1\nu$ ($\pi^\pm\pi^+\pi^-$)	0.11	0.05
$\tau\to a_1\nu$ ($\pi 2\pi^o$)	0.14	0.10

Uncertainties reduced by ~1.5-2.5

- τ BR measurement uncertainties @LEP dominated by stats or stat≈syst. Syst sometimes dominated by sample size.
  - Must be measured again at FCC-ee with negligible stat uncertainties. Important to control the systematics!
  - At Belle-II? Improve modes with K & π^o $\to$ May improve TAUOLA & treatment of radiation in τ decays
- Significant modeling uncertainties in $\tau\to a_1\nu$ either directly as signal or as part of the $\tau\to\rho\nu$ background
  - Mass & width of a_1, $\tau\to a_1\nu$ decays, modeling of $\tau\to 3\pi\geq 1\pi^o\nu$

Reco mass $a_1\to 3\pi$ modeling uncertainty





OPAL, EPJC 21 (2001) 1

- Are our MC tools good enough e.g. τ decay MC?
- At LEP, could ignore entanglement of τ pairs (KORALZ MC gave helicity states). Might not be good enough for FCC-ee.

→May all be an issue for FCC-ee measurement of τ polarisation unless better understood!

Experimental systematic uncertainties on LEP measurements

FCC-ee: is shower simulation ready for the required precision?

ALEPH, EPJC 20, 401-430 (2001) A_τ

Source	ρ	$3h$	$h2\pi^0$
selection	0.01	-	-
tracking	-	0.22	-
ECAL scale	0.11	0.21	1.10
PID	0.06	0.04	0.01
misid.	-	-	-
photon	0.24	0.37	0.22
non-τ back.	0.08	0.05	0.18
τ BR	0.04	0.10	0.26
modelling	-	0.70	0.70
MC stat	0.26	0.49	0.63
TOTAL	0.38	1.00	1.52

FCC-ee stat uncert on A_τ <0.002%

An example:

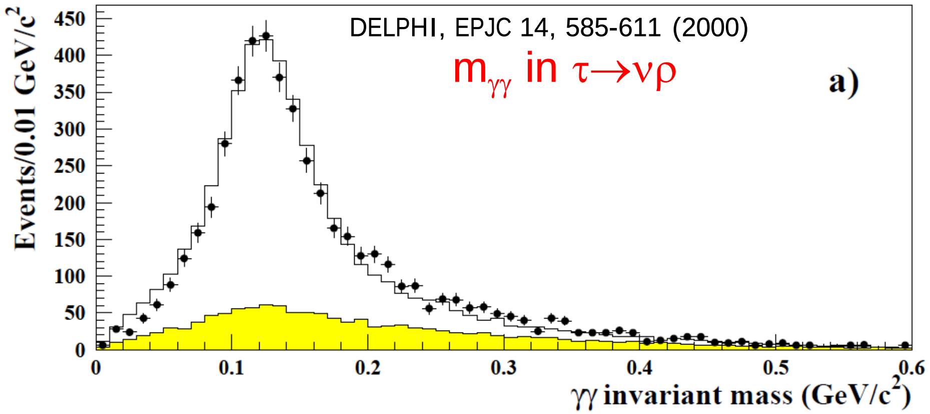
- EM calorimetry a limiting factor in the most sensitive decay modes at LEP
- FCC-ee would need
  - exceptionally good (fine-grained, precisely calibrated) calorimeter for γ, π^0 reconstruction coupled to excellent detector simulation to model for e.g. shower shapes that are input to the τ decay spectra (and a lot of compute power to generate that many events! MC stats a significant uncert at LEP!)
- Too simplistic to just look at dominant experimental uncertainties at LEP and think to attack the major ones.
  - Improvements needed on all fronts to take advantage of stat precision!

M. Dam SciPost Phys. Proc. 1, 041 (2019)

Quantity			LEP	FCC-ee
Impact parameter resolution	$\sigma_d = a \oplus \frac{b \cdot \text{GeV}}{p_T \sin^{2/3}\theta}$	a	20 µm	3 µm
		b	65 µm	15 µm
Momentum resolution	$\frac{\sigma(p_T)}{p_T} = \frac{a \cdot p_T}{\text{GeV}} \oplus b$	a	6×10^{-4}	2×10^{-5}
		b	5×10^{-3}	1×10^{-3}
ECAL energy resolution	$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b$	a	0.2	0.15
		b	0.01	0.01
ECAL transverse granularity			15 × 15 mrad^2	3 × 3 mrad^2

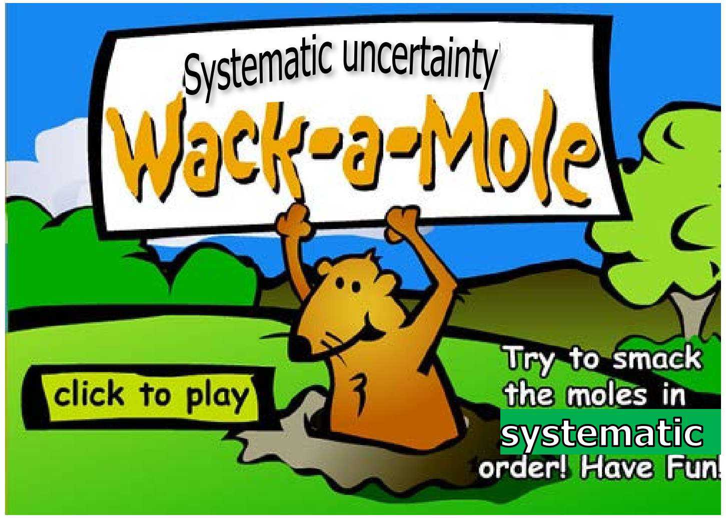
25x finer granularity

DELPHI

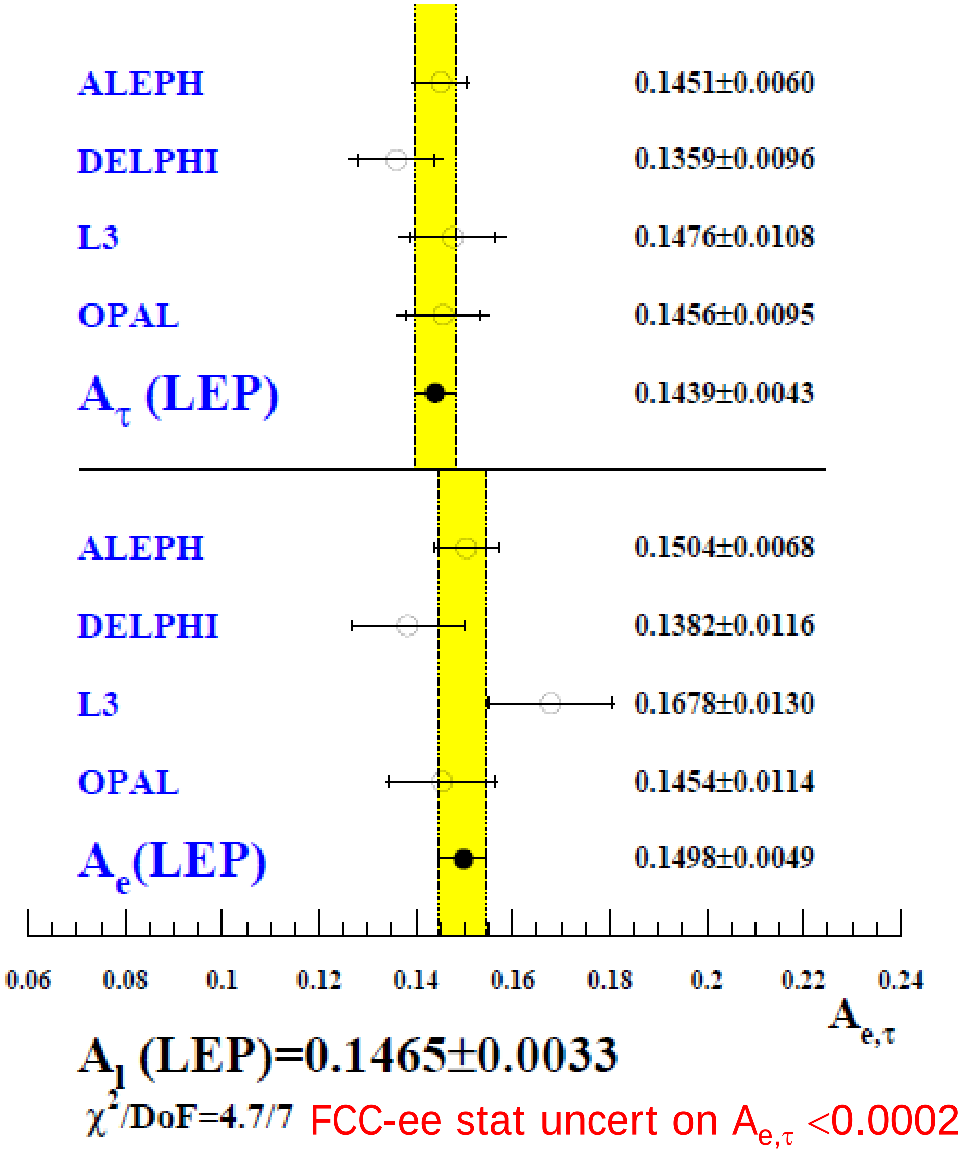


Conclusions

- Measurements of τ polarisation at LEP-I resulted in
  - $\sin^2\theta_{eff}^{lept}$=0.23159 ±0.00041
  - LEP+Tevatron+LHC: increased precision by a factor of ~3
- Challenge at FCC-ee: take full advantage of the stat precision!
  - Systematic uncertainties: both theoretical and experimental.
  - Prepare our tools to meet the challenge!



LEP EWWG, Phys. Rept. 427, 257-454 (2006)



FCC-ee stat uncert on $A_{e,\tau}$ <0.0002

Note: Proposal to introduce polarised electron beams to the SuperKEKB e^+e^- collider in order to measure the L-R asymmetry (like SLD). FPCP2019 talk. Interested? Contact mroney@uvic.ca

Thanks for inviting me!
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