Tau lepton couplings to the Z and Higgs bosons

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Tau Lepton

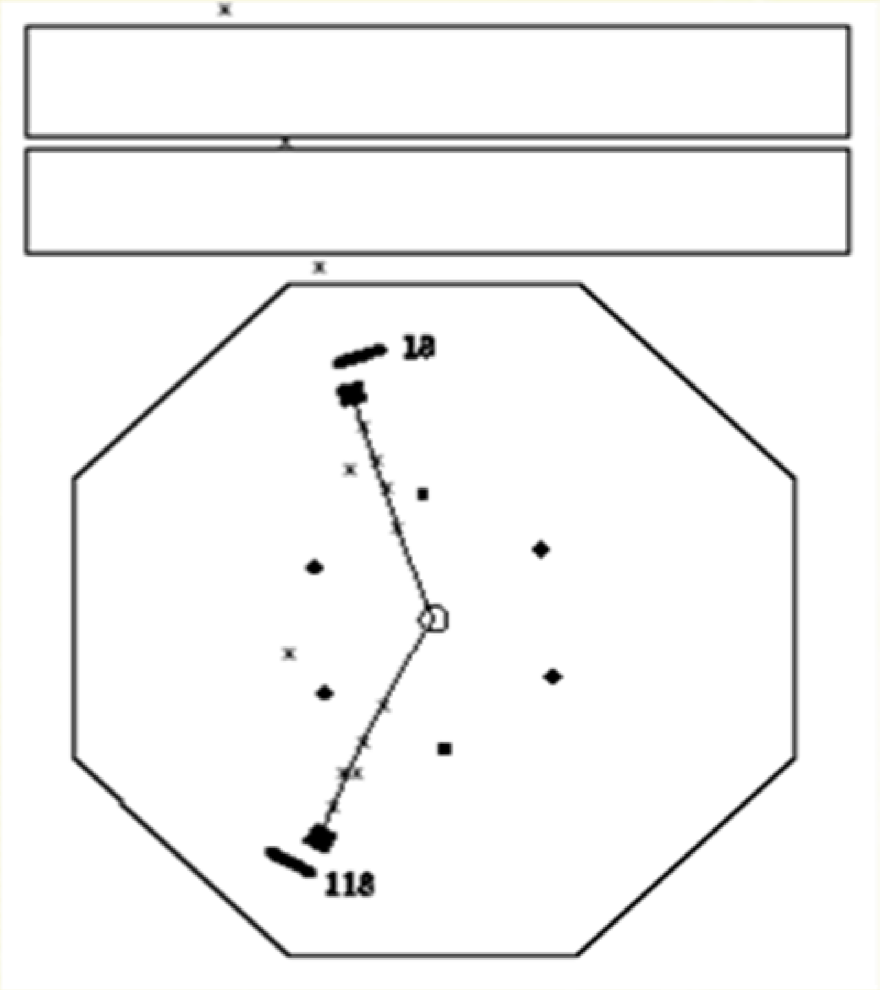
The τ lepton was discovered in SLAC in 1975 (Nobel prize for Martin Perl in 1995)

appearance of events with an electron and a muon in the final state

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

$$\tau^- \rightarrow \mu^-\nu\nu$$

$$\tau^+ \rightarrow e^+\nu\nu$$



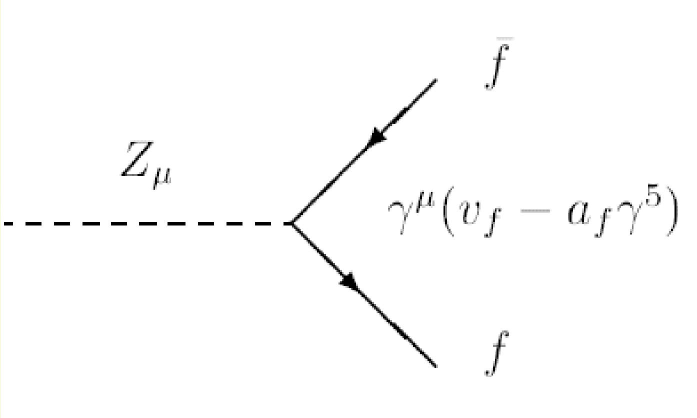
It is the heaviest lepton we know

Mass : 1777 MeV

Lifetime: 290.6 fs (87 μm)

Couplings to the neutral current

The $SU(2)_L \oplus U(1)$ gauge invariance determines the structure of the weak neutral current as:



and the vector- and axial-vector coupling vf and a_f

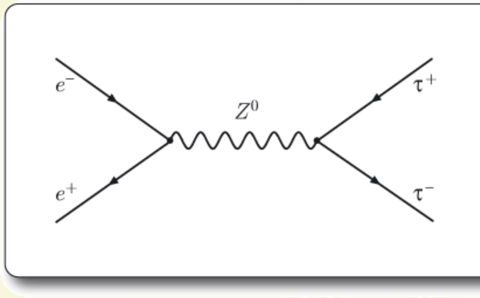
$$v_f = T_3 - 2Q\sin^2\theta_W$$

$$a_f = T_3$$

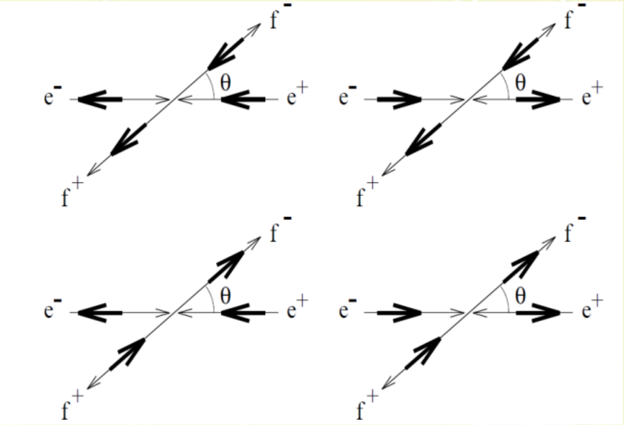
with T_3 the third component of the weak isospin, Q the electric charge and $\sin^2\theta_W$ the weak mixing angle, a free parameter of the theory

neutral current coupling measurements in e^+e^- annihilations

$$\frac{d\sigma_{\mathrm{Born}}}{d\cos\theta}(s,\cos\theta;p) = (1+\cos^2\theta)F_0(s) + 2\cos\theta F_1(s) + p\left[(1+\cos^2\theta)F_2(s) + 2\cos\theta F_3(s)\right]$$



$$A_{fb} = \frac{\sigma(\cos\theta<0)-\sigma(\cos\theta>0)}{\sigma(\cos\theta<0)+\sigma(\cos\theta>0)} = \frac{3}{4}\frac{F_1(s)}{F_0(s)} = \frac{3}{4}\,\frac{2vea_e}{v_e{}^2+ae^2}\,\frac{2v_\tau a_\tau}{v_\tau{}^2+a_\tau{}^2}$$

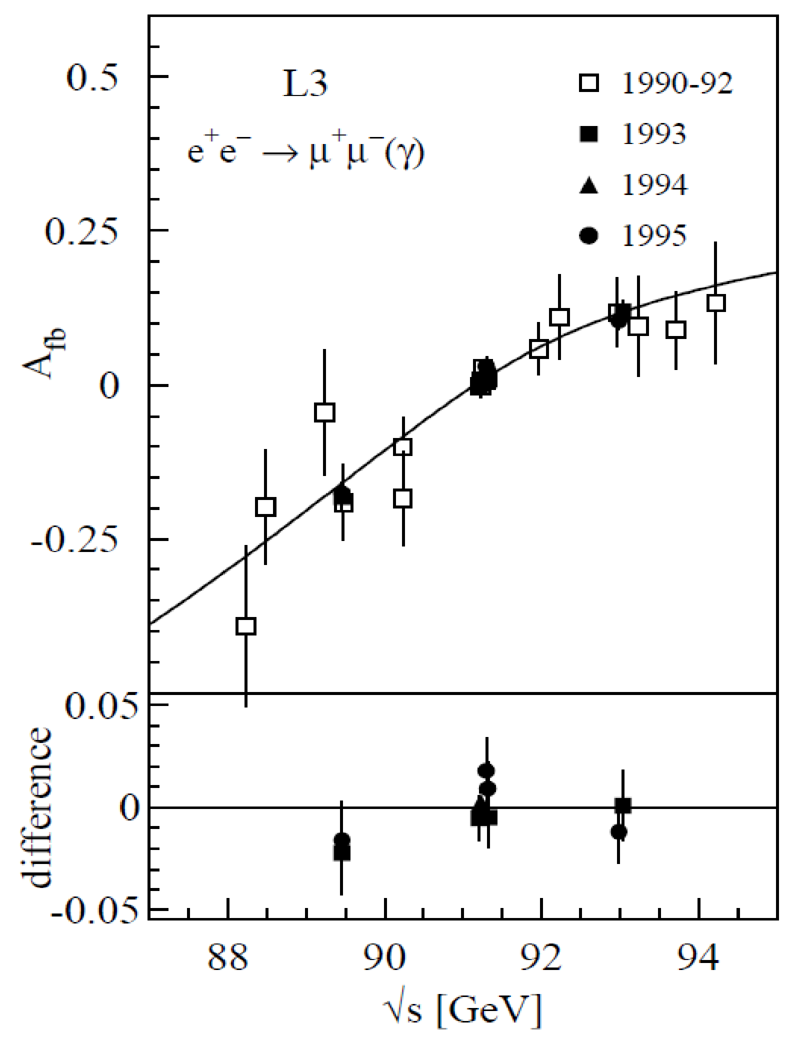


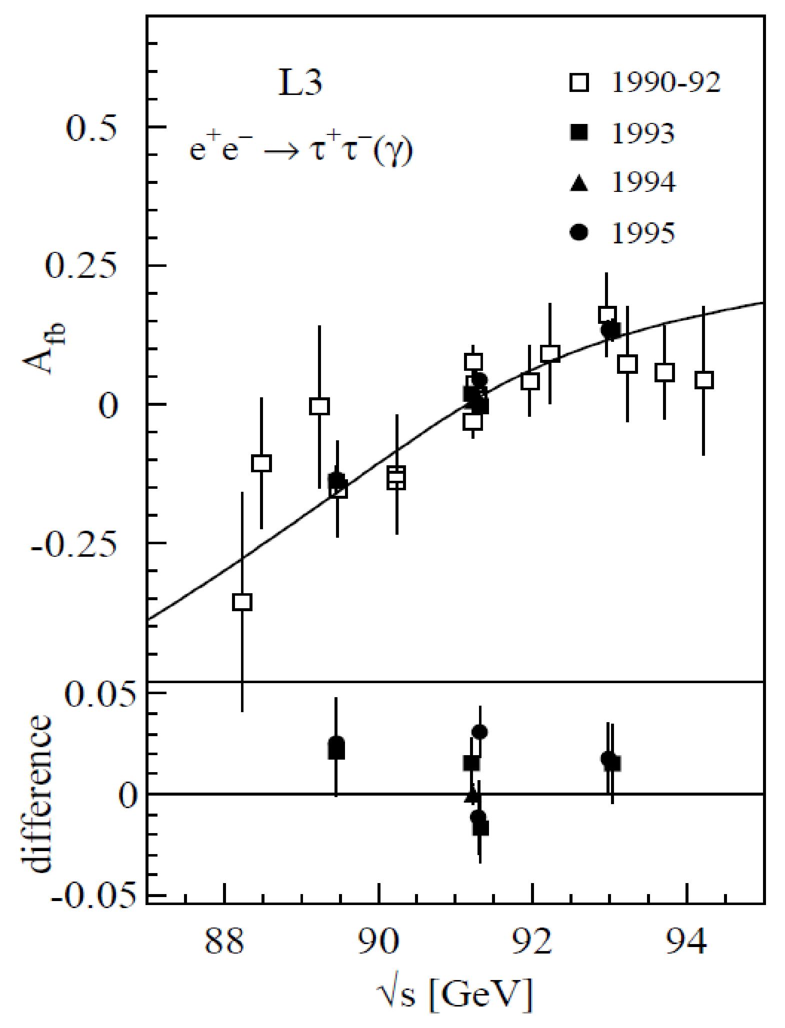
$$P_\tau = \frac{\sigma(s,h_\tau=+1)-\sigma(s,h_\tau=-1)}{\sigma_{total}} = -\frac{F_2(s)}{F_0(s)} = \frac{2v_\tau a_\tau}{v_\tau{}^2+a_\tau{}^2}$$

$$A_{FB}^{pol} = \frac{[\sigma^F(s,h_\tau=+1)-\sigma^F(s,h_\tau=-1)]-[\sigma^B(s,h_\tau=+1)-\sigma^B(s,h_\tau=-1)]}{\sigma_{total}} = -\frac{3F_3(s)}{4F_0(s)} = -\frac{3}{4}\,\frac{2vea_e}{v_e{}^2+ae^2}$$

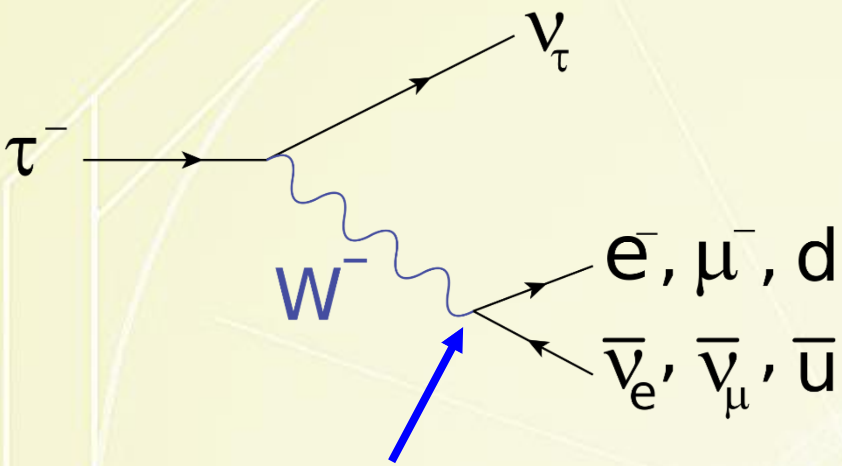
Measurements at LEP and SLD

examples





Measurements at LEP and SLD

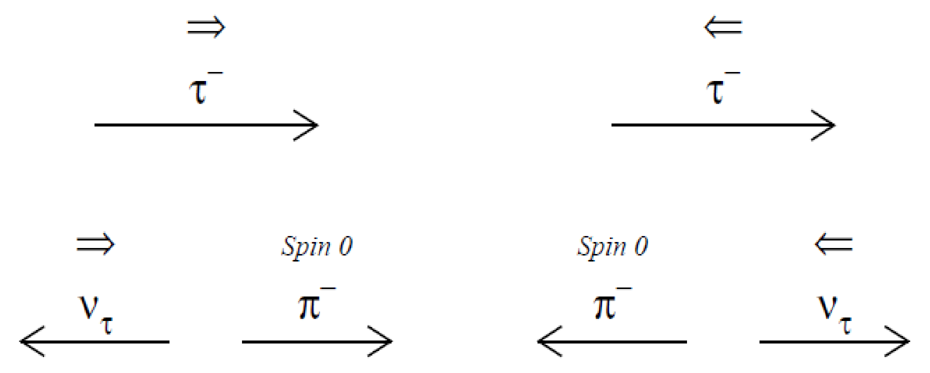


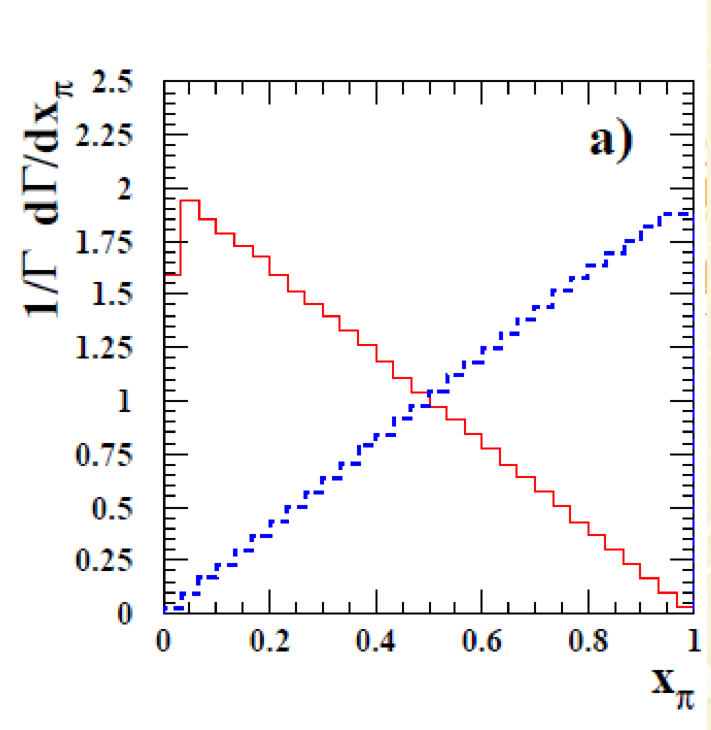
Assuming (V-A}

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\pi} = \frac{1}{2}\left(1+\mathcal{P}_\tau\cos\theta_\pi\right)$$

$$x_\pi = \frac{E_\pi}{E_\tau}$$

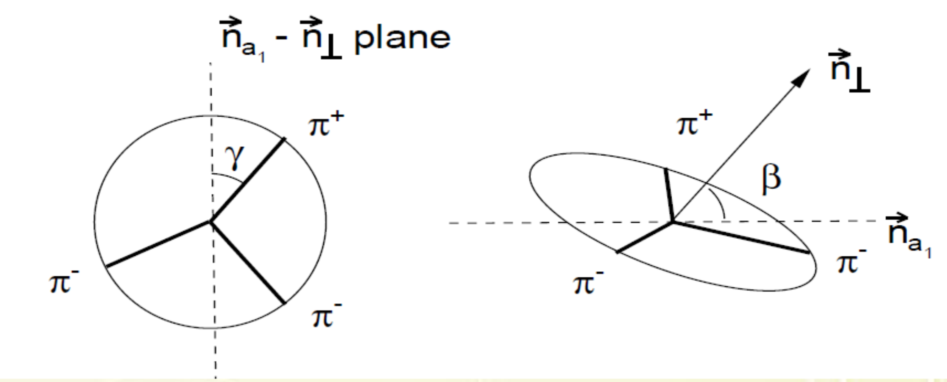
In the lab frame





Measurements at LEP and SLD

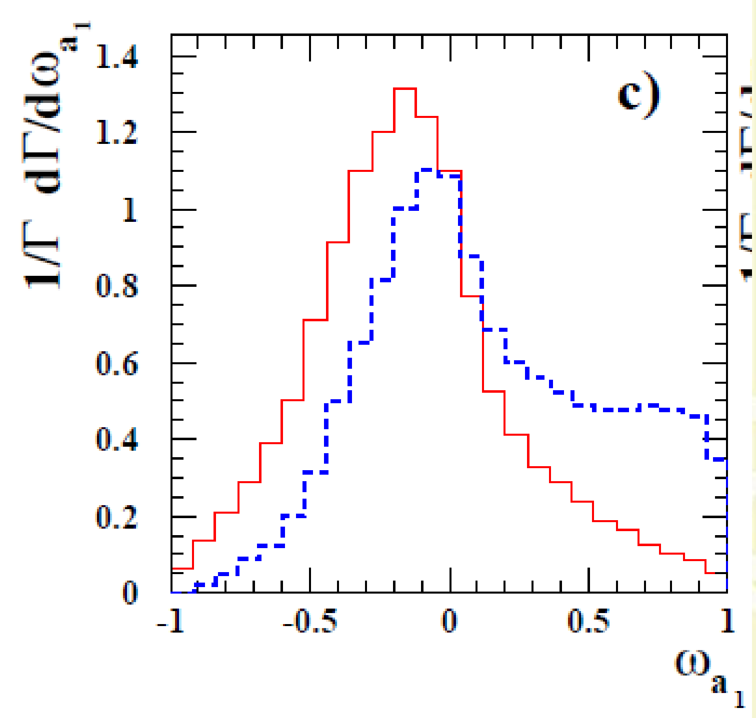
Analysis of the $\tau \to a_1 \nu$ decay



$$\frac{1}{\Gamma}\frac{d^n\Gamma}{d^n\xi} = f(\xi) + P_\tau g(\xi),$$

$$\xi = \xi\,(\cos(\theta)\,,\beta,\gamma)$$

$$\omega = \frac{g(\xi)}{f(\xi)} = \frac{|M_+(\xi)|^2 - |M_-(\xi)|^2}{|M_+(\xi)|^2 + |M_-(\xi)|^2}$$



Measurements at LEP and SLD

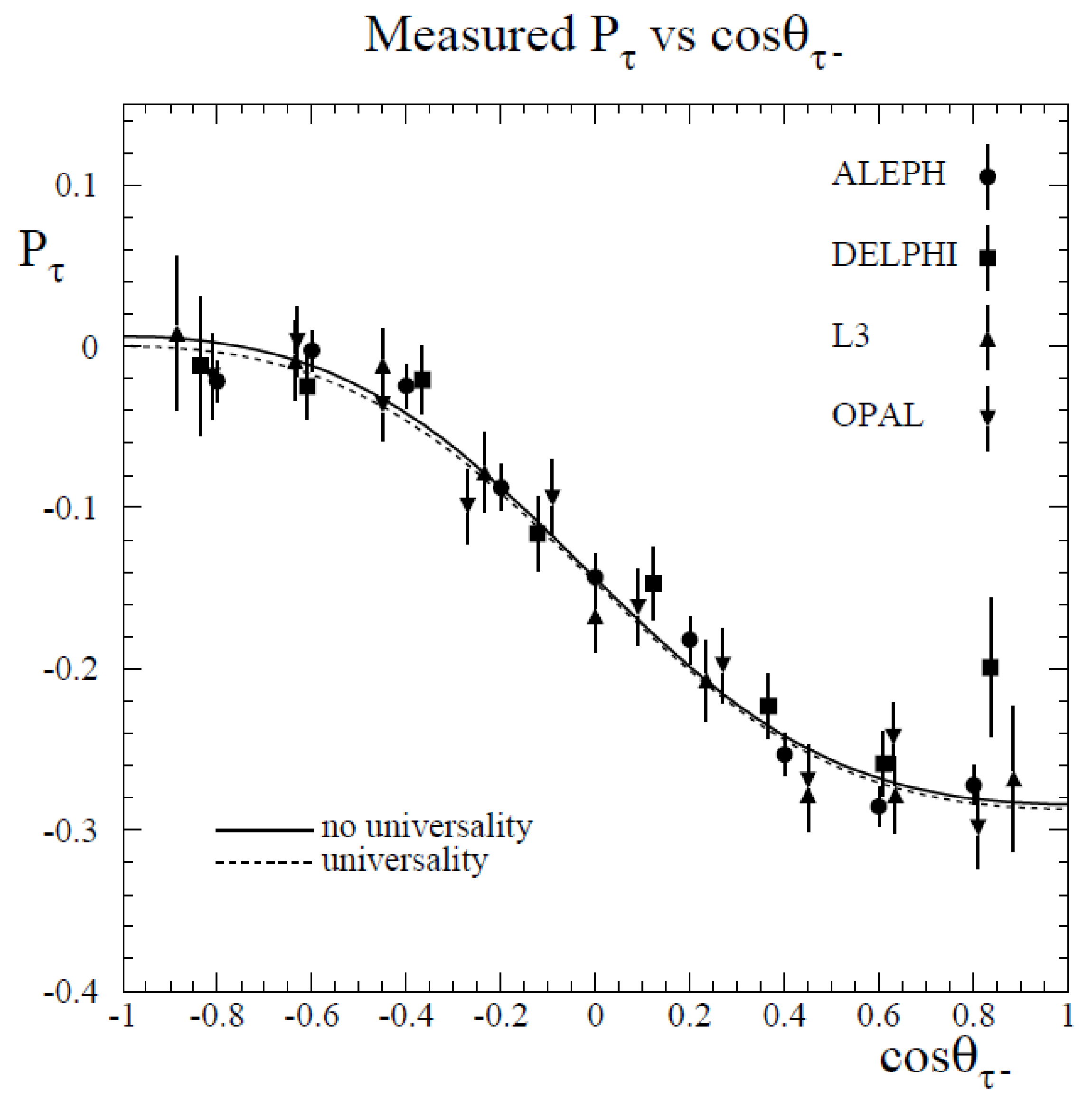
$$\mathcal{A}_e = \frac{2veae}{v_e{}^2 + ae^2} = 0.1498 \pm 0.0049$$

$$\mathcal{A}_\tau = \frac{2v_\tau a_\tau}{v_\tau{}^2 + a_\tau{}^2} = 0.1439 \pm 0.0043$$

$$= -\ \mathrm{P}_\tau$$

$$\sin^2\theta_W = \frac{1}{8}\mathrm{P}_\tau + \frac{1}{4}$$
$$= 0.23159 \pm 0.00041$$

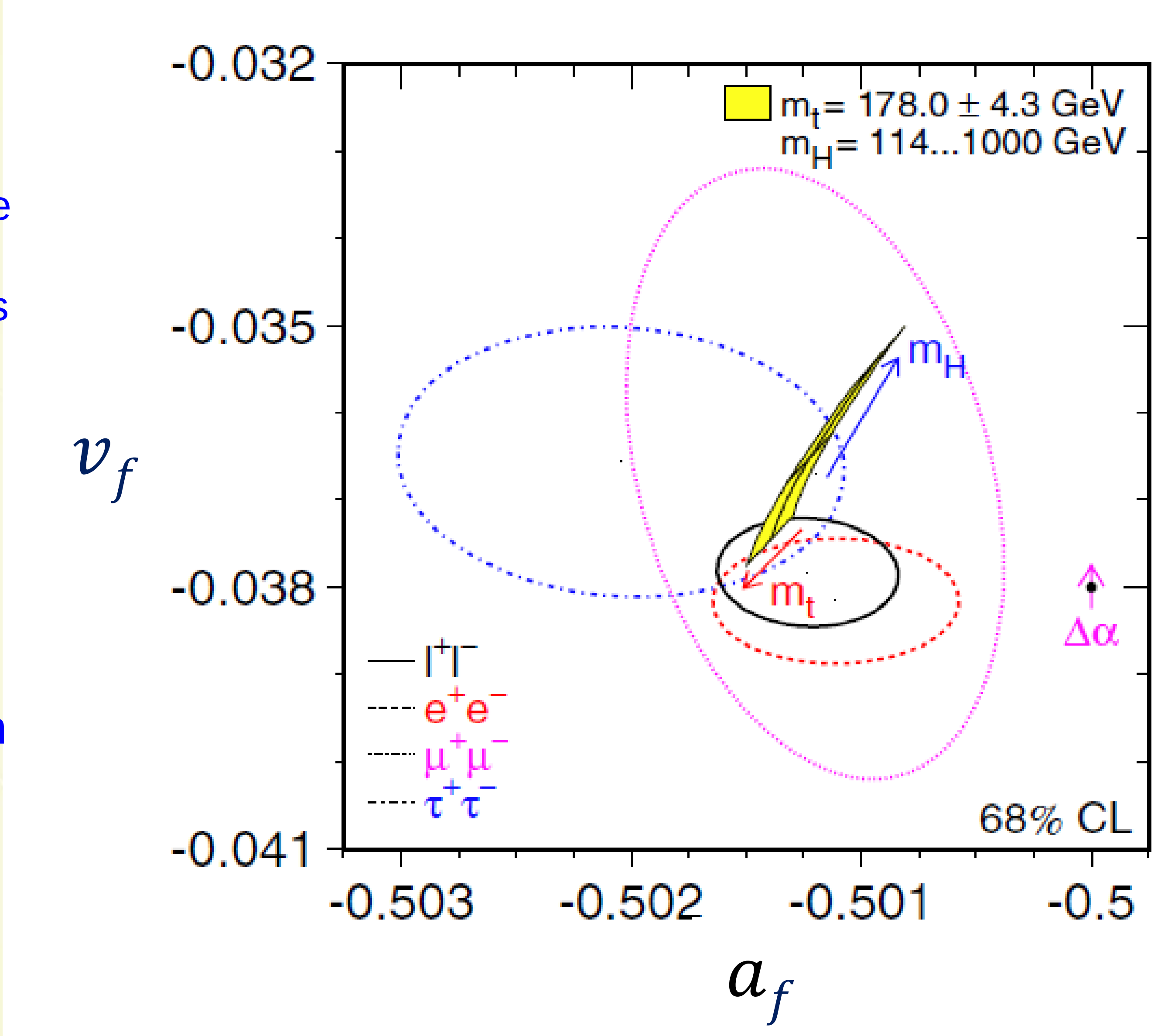
$\sin^2\theta_W$ contains some weak higher order corrections, hence it is called the effective mixing angle from lepton observables



Measurements at LEP and SLD

Experiments at
LEP and SLC:

- Measurement of the neutral current couplings of leptons
- Lepton universality
- Measurement of $sin^2\theta_W$
- Preference for a light Higgs boson



Measurements at LHC

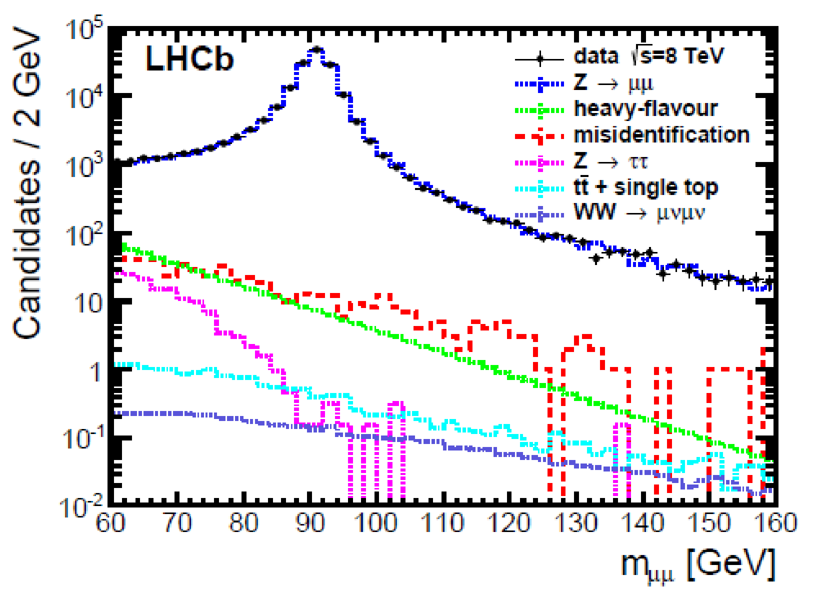
At LHC the luminosity is 10^3 times larger

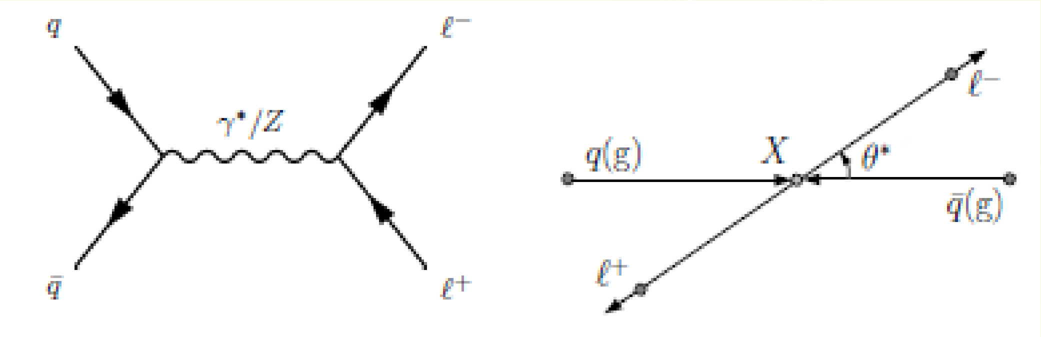
However:

- The Z is produced in $q\bar{q}$ annihilations
- the Z is not at rest in the centre-of-mass system (or lab system)
- Pile up of many interactions

$sin^2\theta_W$ from A_{FB}

Process: $q\bar{q} \longrightarrow Z \longrightarrow \mu^+\mu^-$





$$F_0(s) = \frac{\pi\alpha}{4s}\left[q_q^2 q_\ell^2 + 2Re\chi(s) q_q q_\ell v_q v_\ell + |\chi(s)|^2 (v_q^2 + a_q^2)(v_\ell^2 + a_\ell^2)\right],$$

$$F_1(s) = \frac{\pi\alpha}{4s}\left[2Re\chi(s) q_q q_\ell a_q a_\ell + |\chi(s)|^2 2 v_q a_q 2 v_\ell a_\ell\right],$$

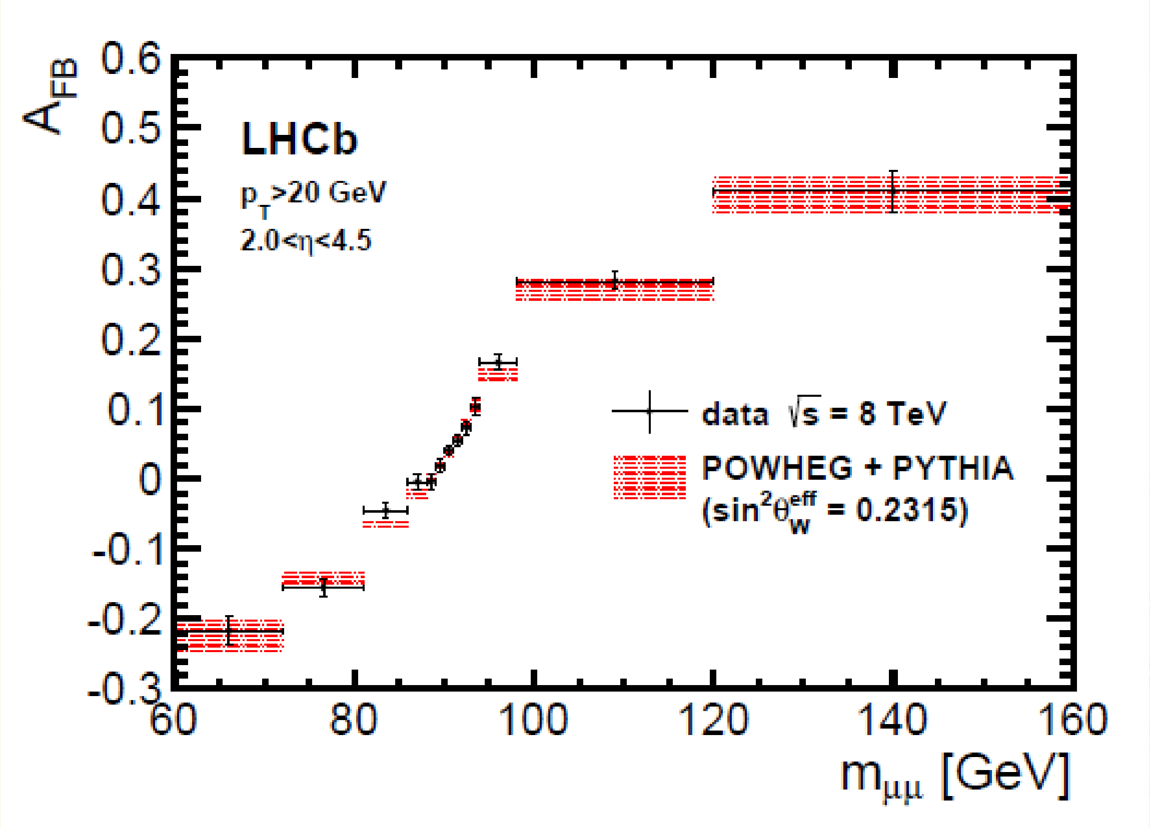
The Z tends to be boosted in the direction of the valence quark q

For the Z production from sea quarks either a correction to A_{FB} is derived using MC simulations, or the measured value of A_{FB} is compared to Monte Carlo templates including the sea quark contribution

Axial and vector couplings of quarks and leptons in $F_0(s)$ and $F_1(s)$!

$sin^2\theta_W$ from A $_{FB}$

A_{FB} as a function of $m(\mu^+\mu^-)$

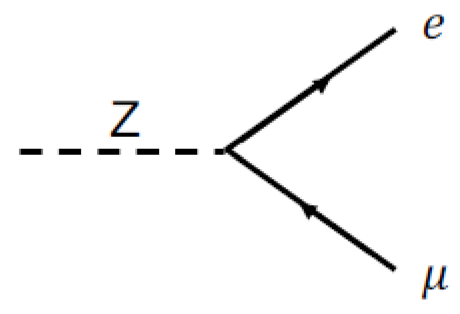


Currently best result at a hadron collider (LHCb):

$sin^2\theta_W$ = 0.23142 ± 0.00073± 0.00052 ±0.00056

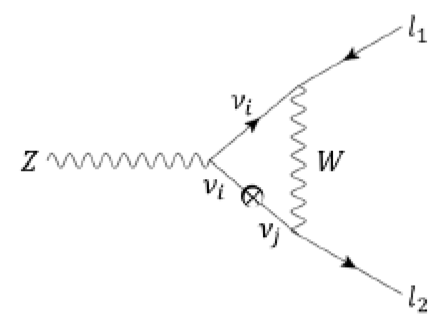
stat sys th

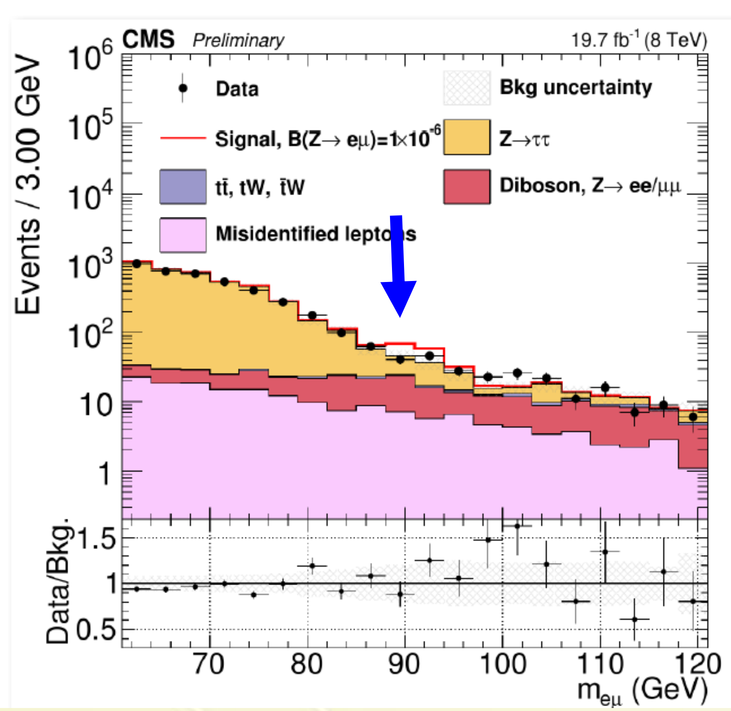
Flavour changing neutral current



Lepton flavor is conserved in the standard model, however there is no underlying symmetry, and it does not hold for neutrinos

Contribution to charged lepton flavor violation is $B(Z \to e\mu) < 10^{-60}$



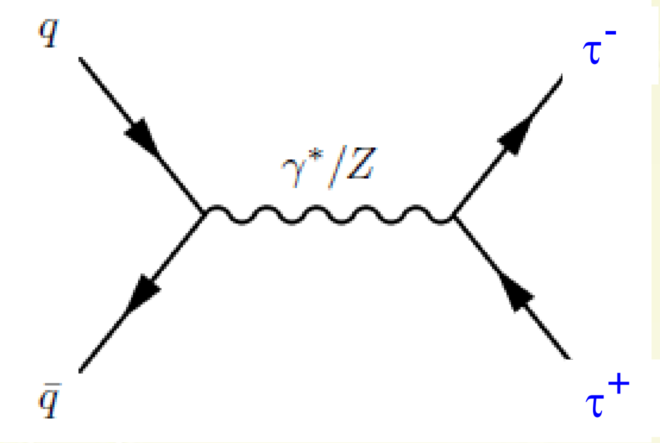


Indirect searches from $\mu \to 3e$:
$B(Z \to e\mu) < 10^{-13}$

Direct search (CMS):
$B(Z \to e\mu) < 7.3 \cdot 10^{-7}$ (expected $< 6.7 \cdot 10^{-7}$)

Consistent with ATLAS:
$B(Z \to e\mu) < 7.5 \cdot 10^{-7}$

Tau Polarisation at LHC



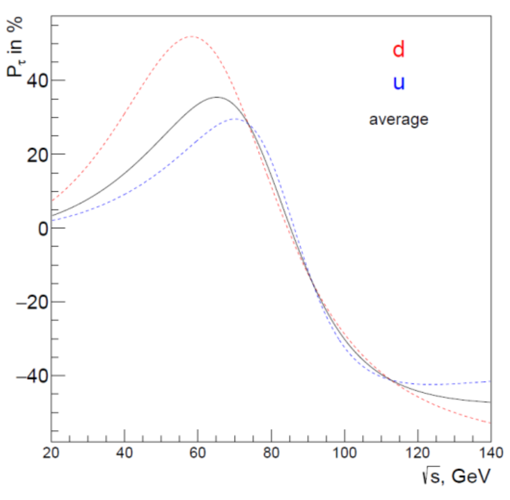
$$F_0(s) = \frac{\pi\alpha}{4s}\left[q_q^2 q_\tau^2 + 2Re\chi(s)q_q q_\tau v_q v_\tau + |\chi(s)|^2\boxed{(v_q^2 + a_q^2)}(v_\tau^2 + a_\tau^2)\right]$$

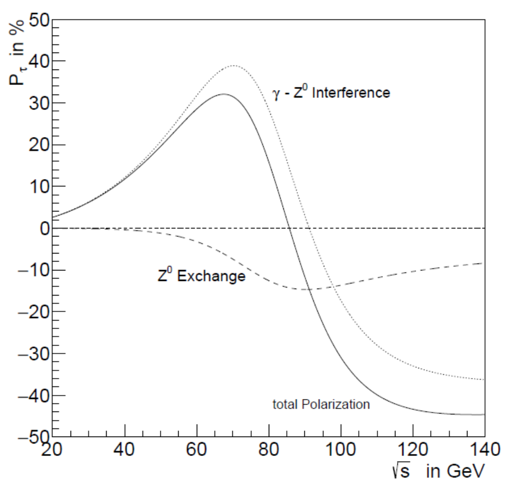
$$F_2(s) = \frac{\pi\alpha}{4s}\left[2Re\chi(s)q_q q_\tau v_q a_\tau + |\chi(s)|^2\boxed{(v_q^2 + a_q^2)}2v_\tau a_\tau\right]$$

since $P_\tau = -\frac{F_2}{F_0}$

⇒ the quark couplings cancel out at the Z pole

Away from the Z pole u and d type quarks give slightly different contributions, and γZ interference matters



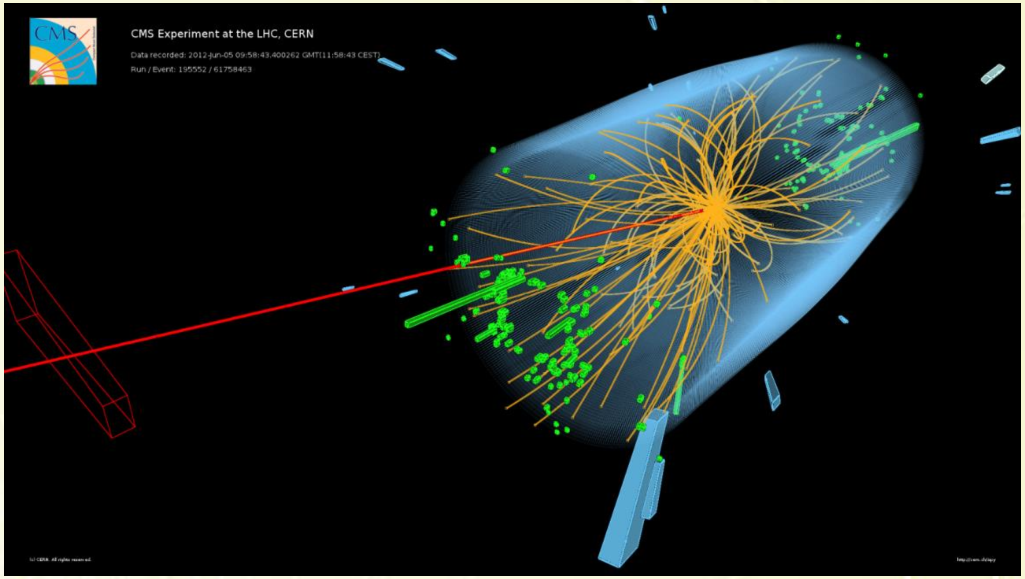


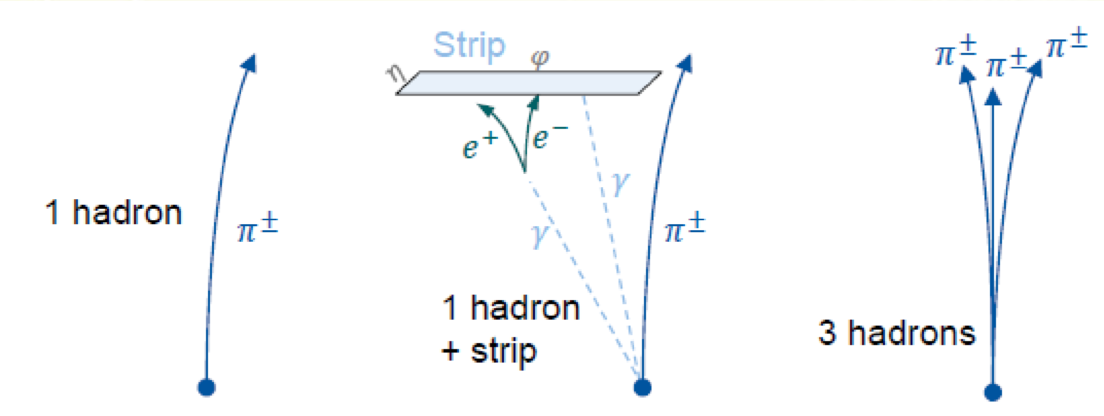
Tau Leptons at LHC

Signatures of τ pairs in an event:

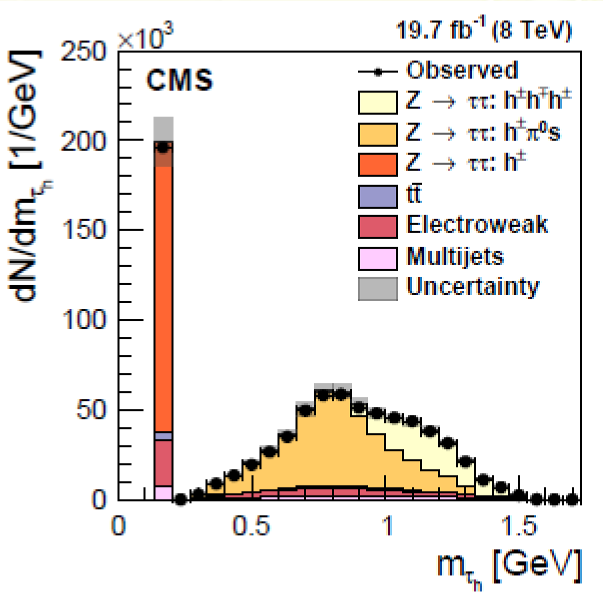
- Two electrons
- Two muons
- One electron and one muon
- One electron/muon and a low multiplicity hadronic jet
- Two low multiplicity hadronic jets

In all cases missing transverse momentum





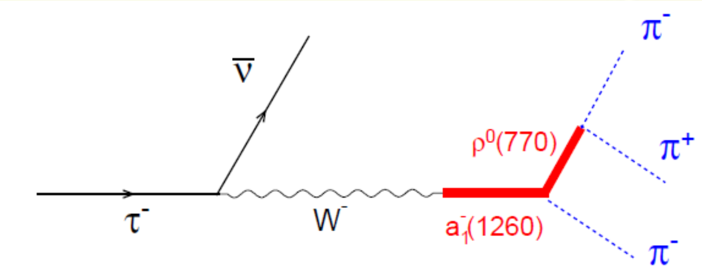
$\tau \to \pi \nu$ $\quad$ $\tau \to \varrho \nu \to \pi^{\pm} \pi^0 \nu$ $\quad$ $\tau \to a_1 \nu \to \pi^+ \pi^- \pi^{\pm} \nu$

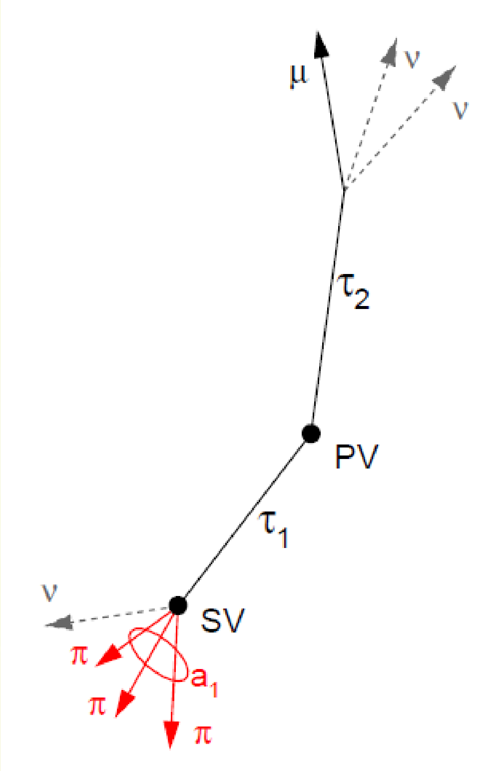


Tau Polarisation in $\tau \to a_1 \nu$

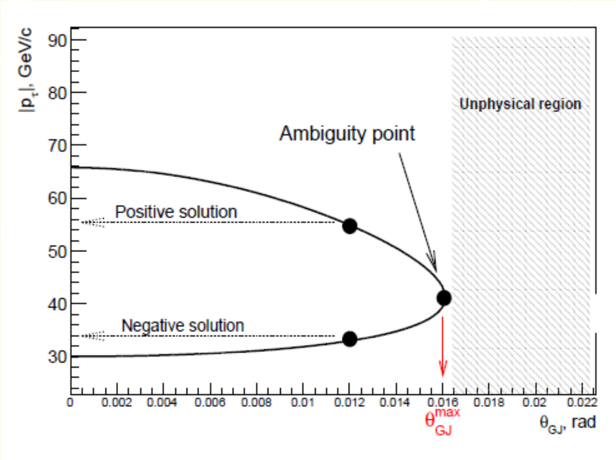
Analysis of the $\tau \ \to a_1 \nu$ decay

Branching fraction 9.8 %



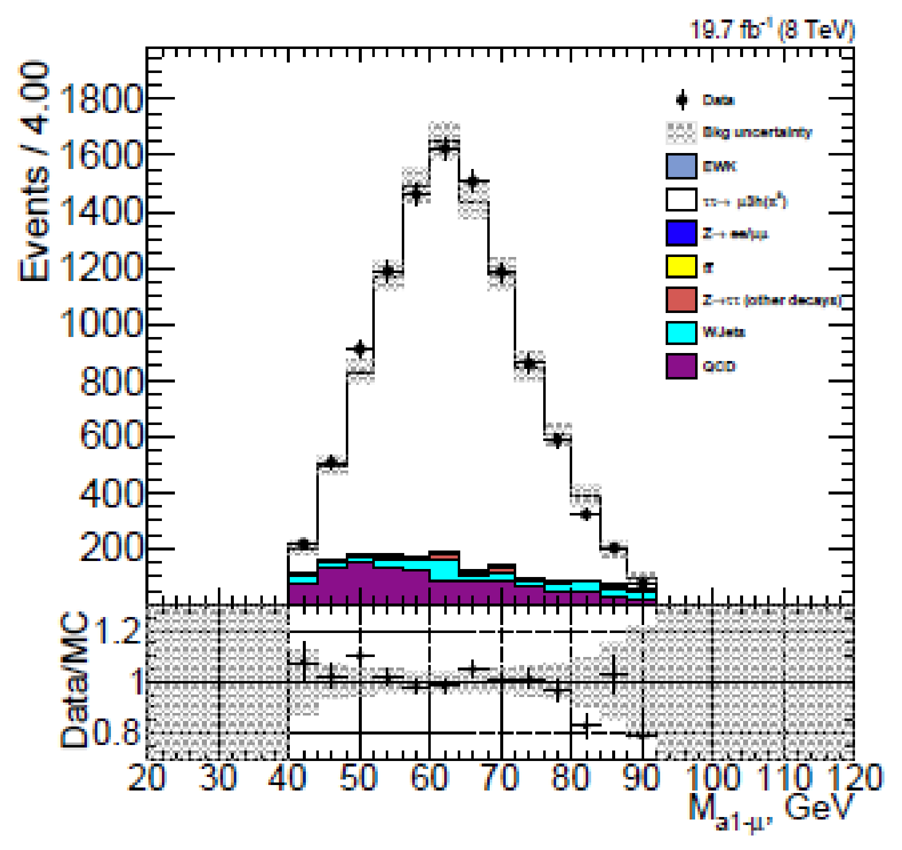


- Events with one μ and a three prong jet
- Three pion vertex (SV) separated from the primary vertex (PV)→ τ direction
- Calculate τ momentum
  $$p_\nu{}^2 = (p_\tau - pa_1)^2 = 0$$
- Solve the ambiguity (partially) by fit to fully reconstruct the event

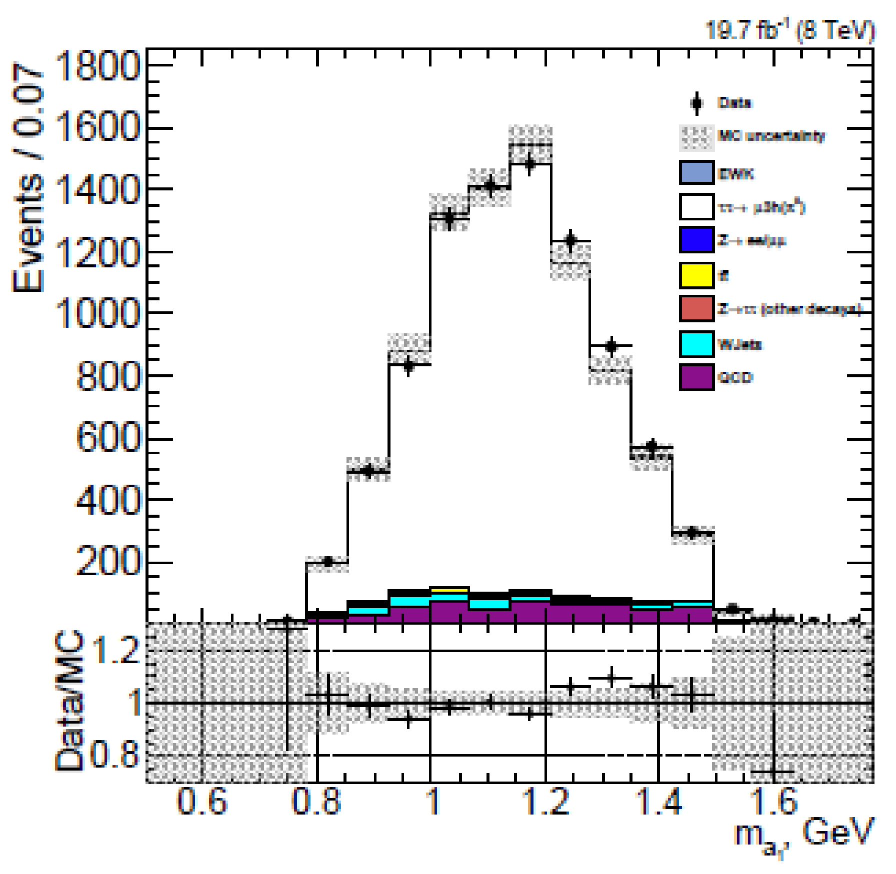


Tau Polarisation in $\tau \rightarrow a_1\nu$

Comparison between data and simulated event samples



Visible mass m($a_1\mu$)



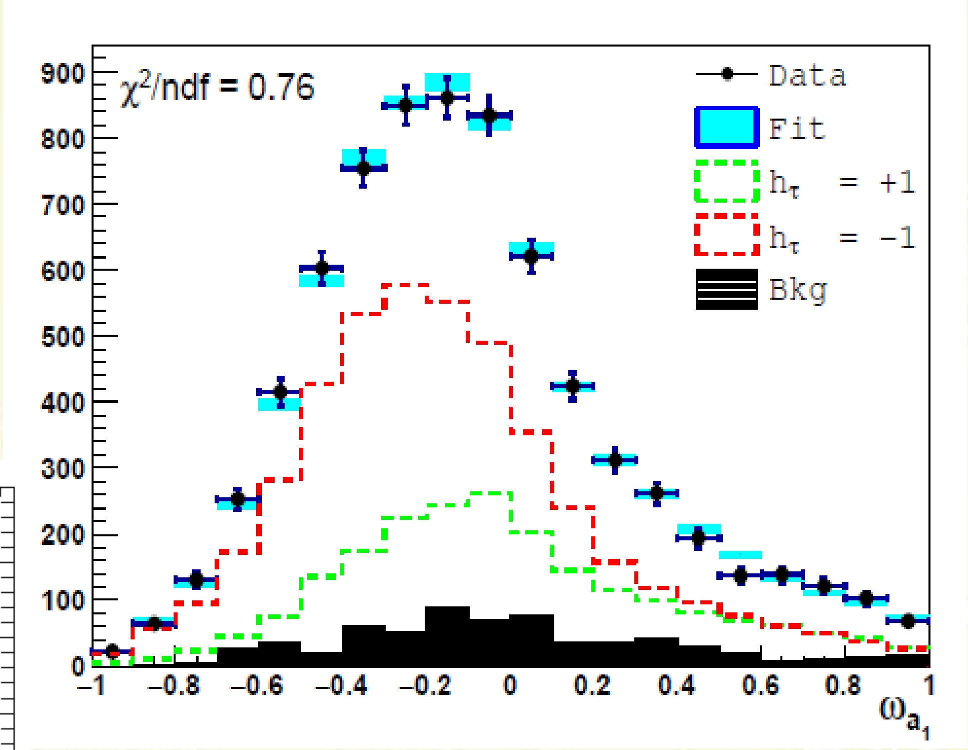
3 π mass

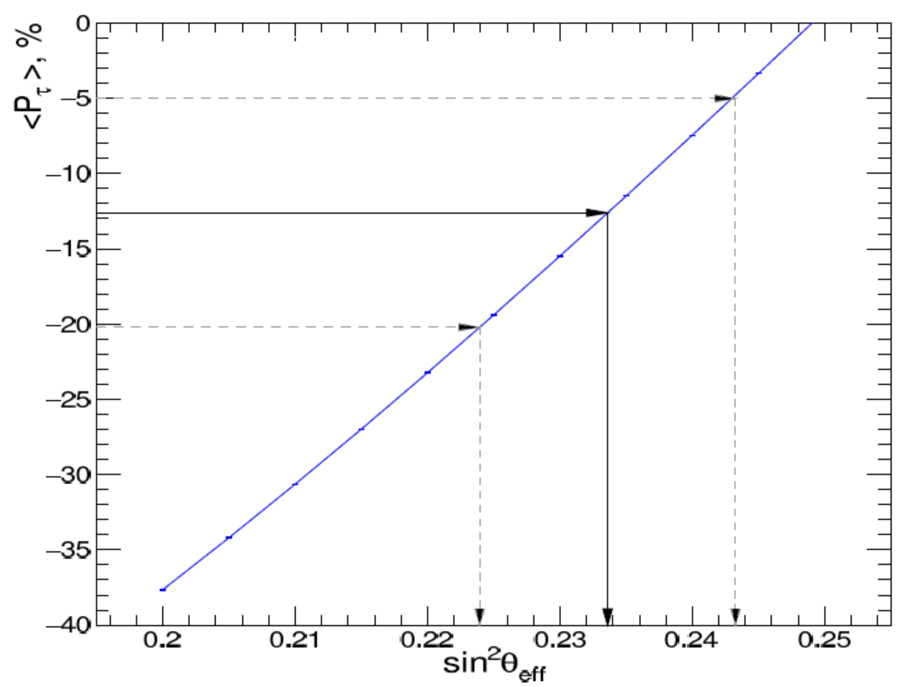
Tau Polarisation in $\tau \rightarrow a_1\nu$

$$P_\tau = -12.6 \pm 0.066 \pm 0.032 \pm 0.017$$

stat(data) stat(MC) sys

This is the polarisation averaged over the Z resonance shape!





Gauge obtained using ZFITTER and proton pdfs

$$sin^2\theta_W = 0.2326 \pm 0.0096$$

Measured with only small impact of the quark couplings

Tau Polarisation in $\tau \to \rho\nu$

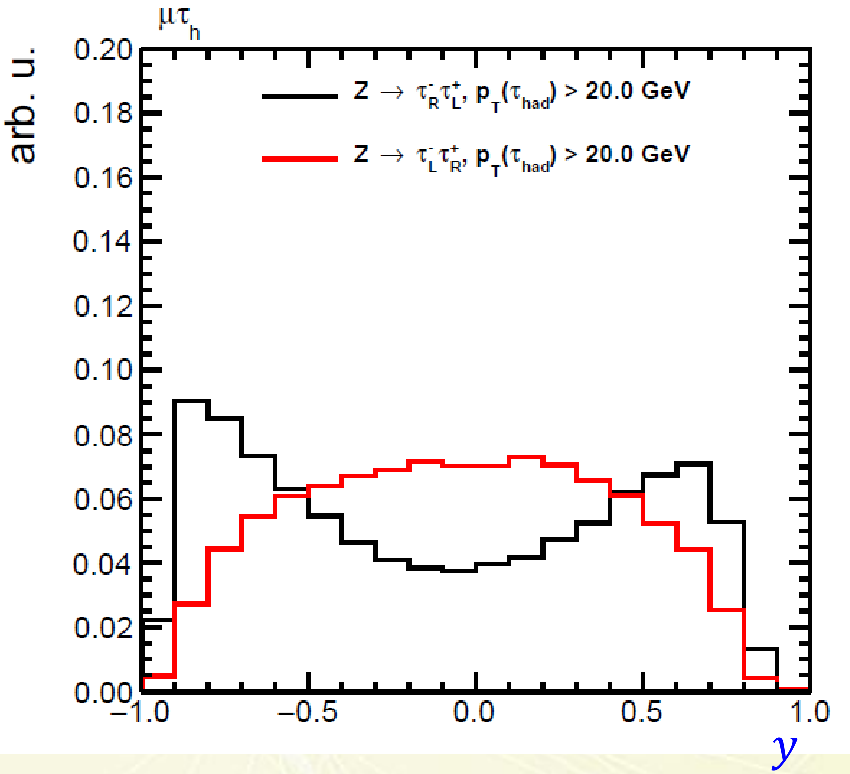
Branching fraction 26 %

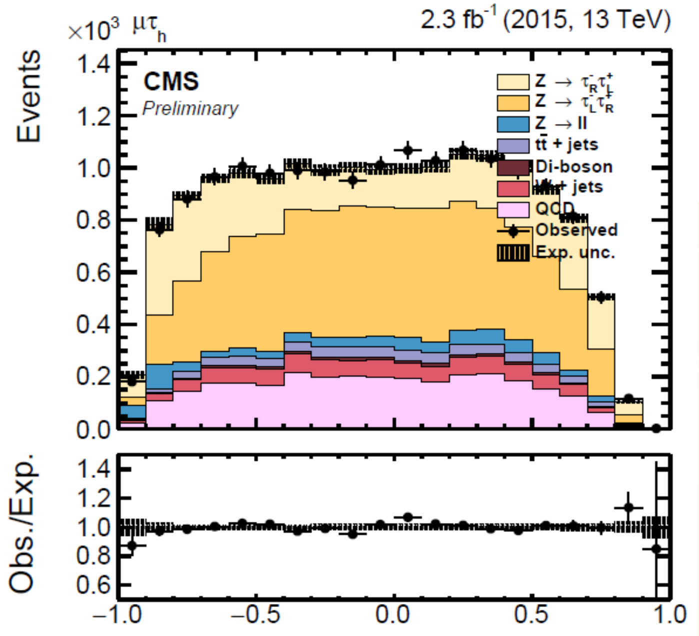
decay:

$$\tau^{\pm} \to \rho^{\pm}\nu \to \pi^{\pm}\pi^{0}\nu$$

Observable:

$$y = \frac{E(\pi^{\pm}) - E(\pi^{0})}{E(\pi^{\pm}) + E(\pi^{0})}$$

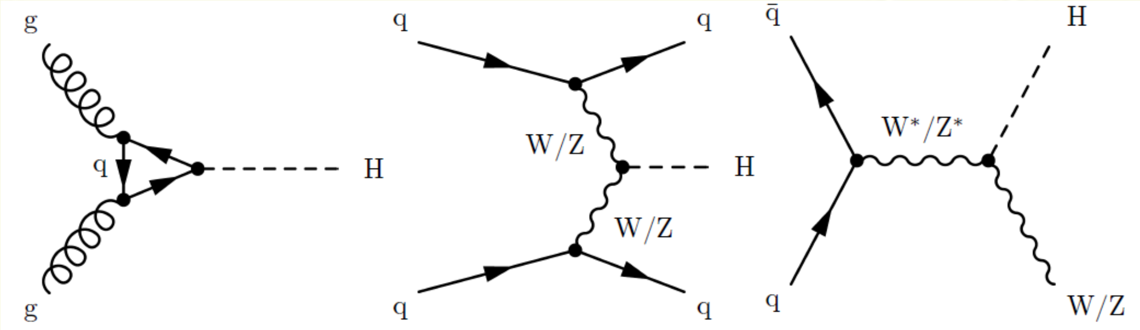


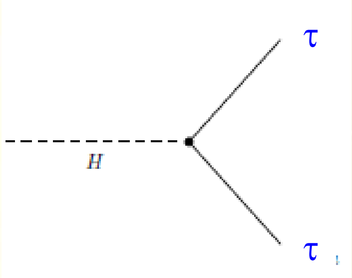


Results in progress

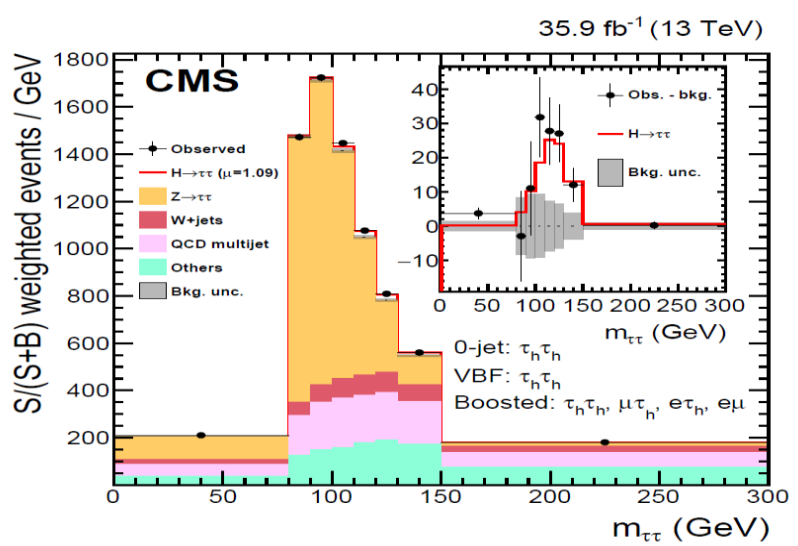
Couplings to the Higgs boson

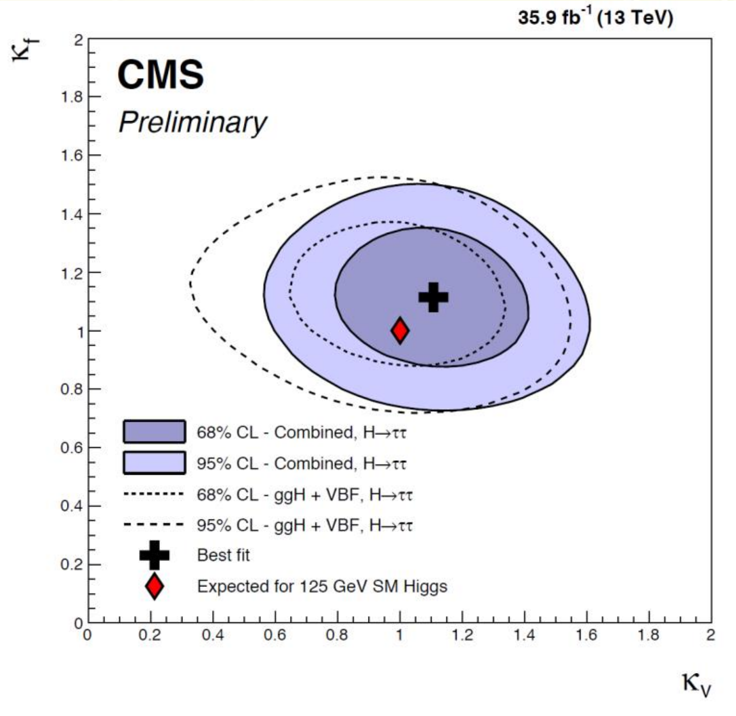
Couplings to gauge bosons and quarks manifest in the production cross section



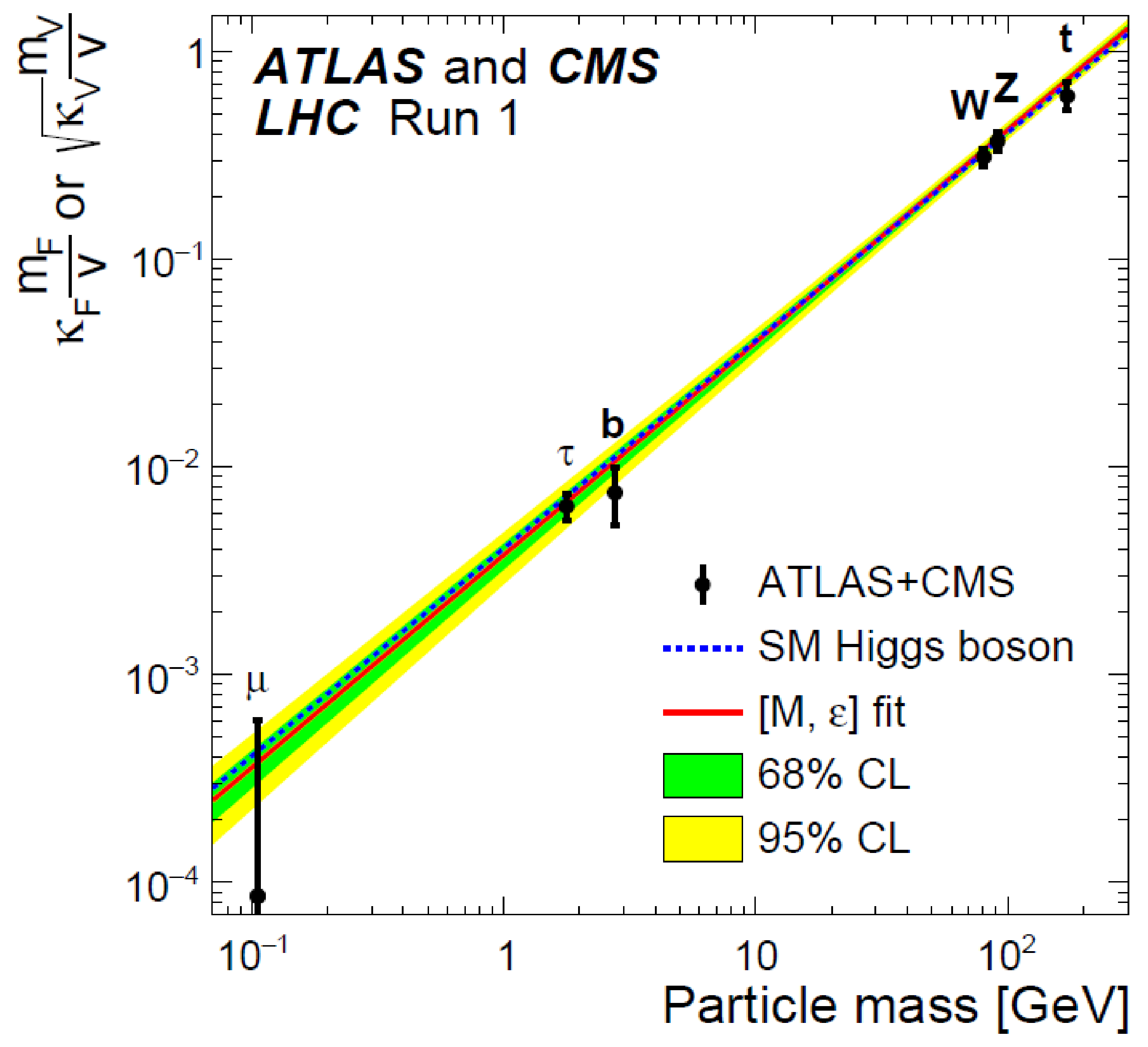


The Yukawa coupling to the tau-lepton is measured in the decay H ⟶ τ τ

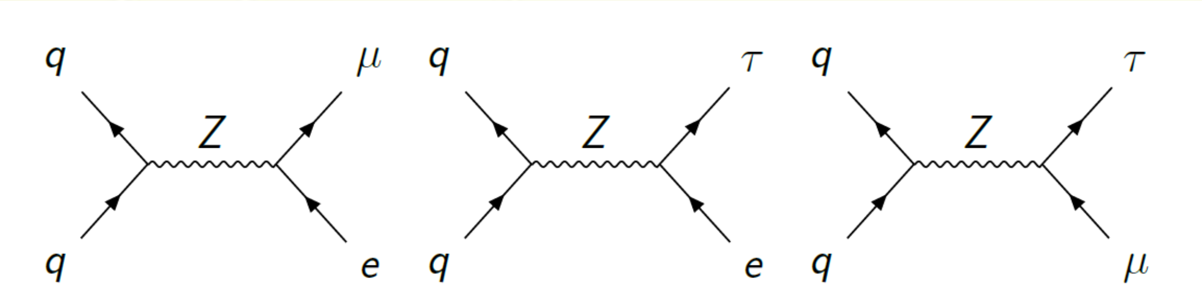




Couplings to the Higgs boson

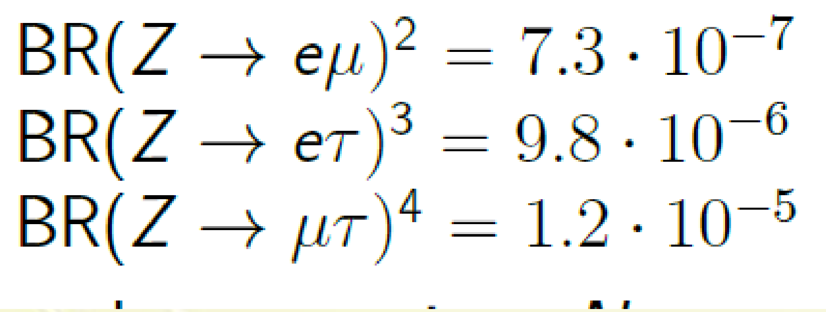


Lepton flavor violation Z boson decays



- number of Z bosons larger than at LEP
- challenge: precise estimate of background processes

Best limits so far:

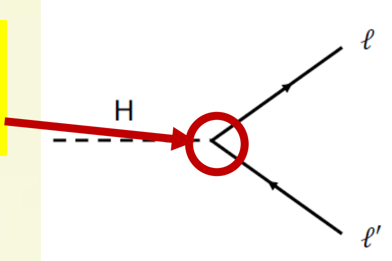


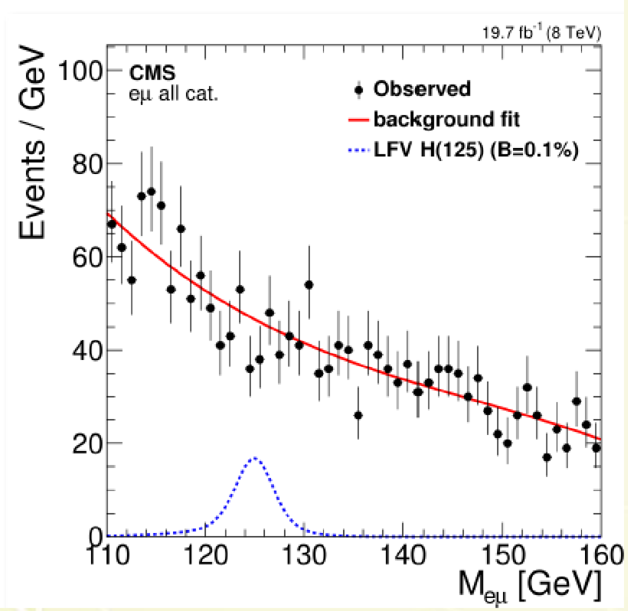
$$\mathrm{BR}(Z \to e\mu)^2 = 7.3 \cdot 10^{-7}$$
$$\mathrm{BR}(Z \to e\tau)^3 = 9.8 \cdot 10^{-6}$$
$$\mathrm{BR}(Z \to \mu\tau)^4 = 1.2 \cdot 10^{-5}$$

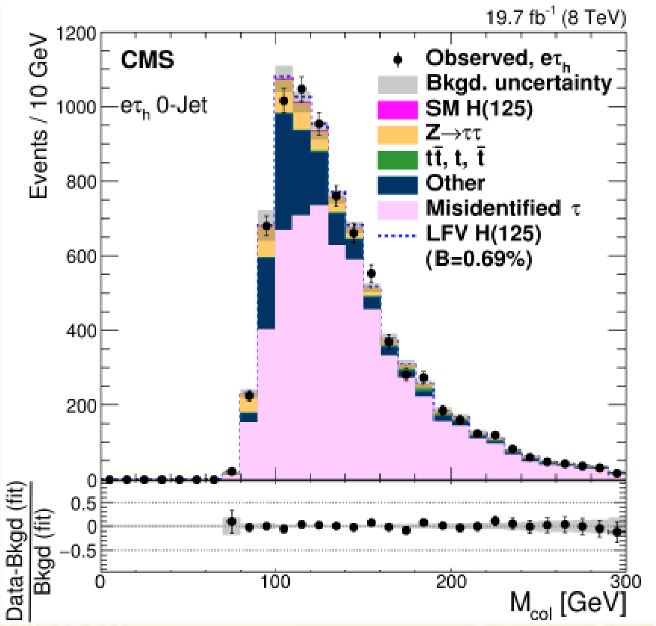
Lepton flavor violation in Higgs boson decays

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

Extended
Yukawa coupling



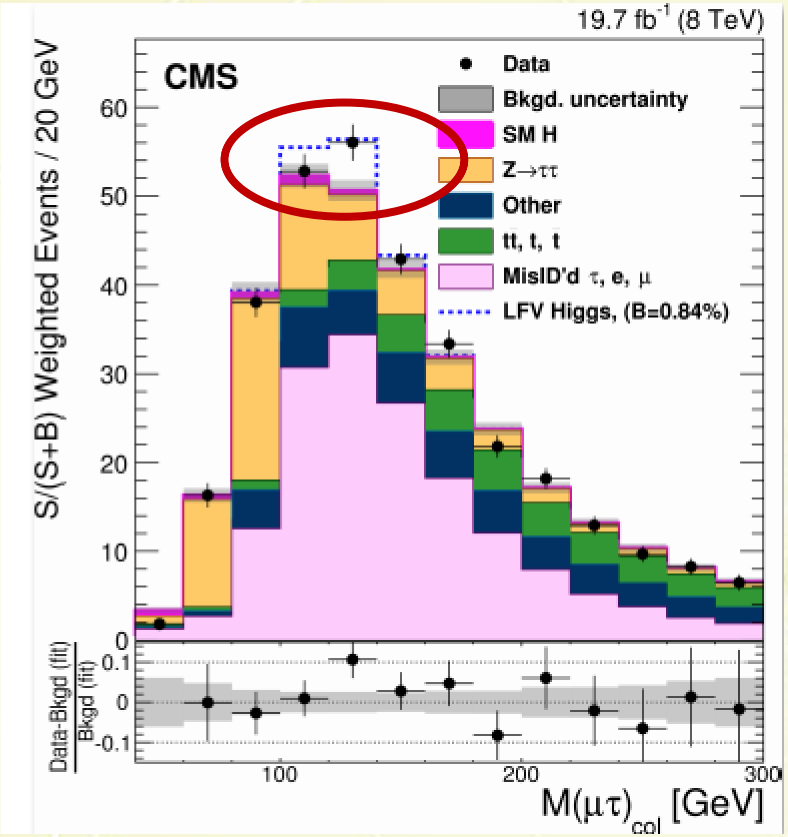


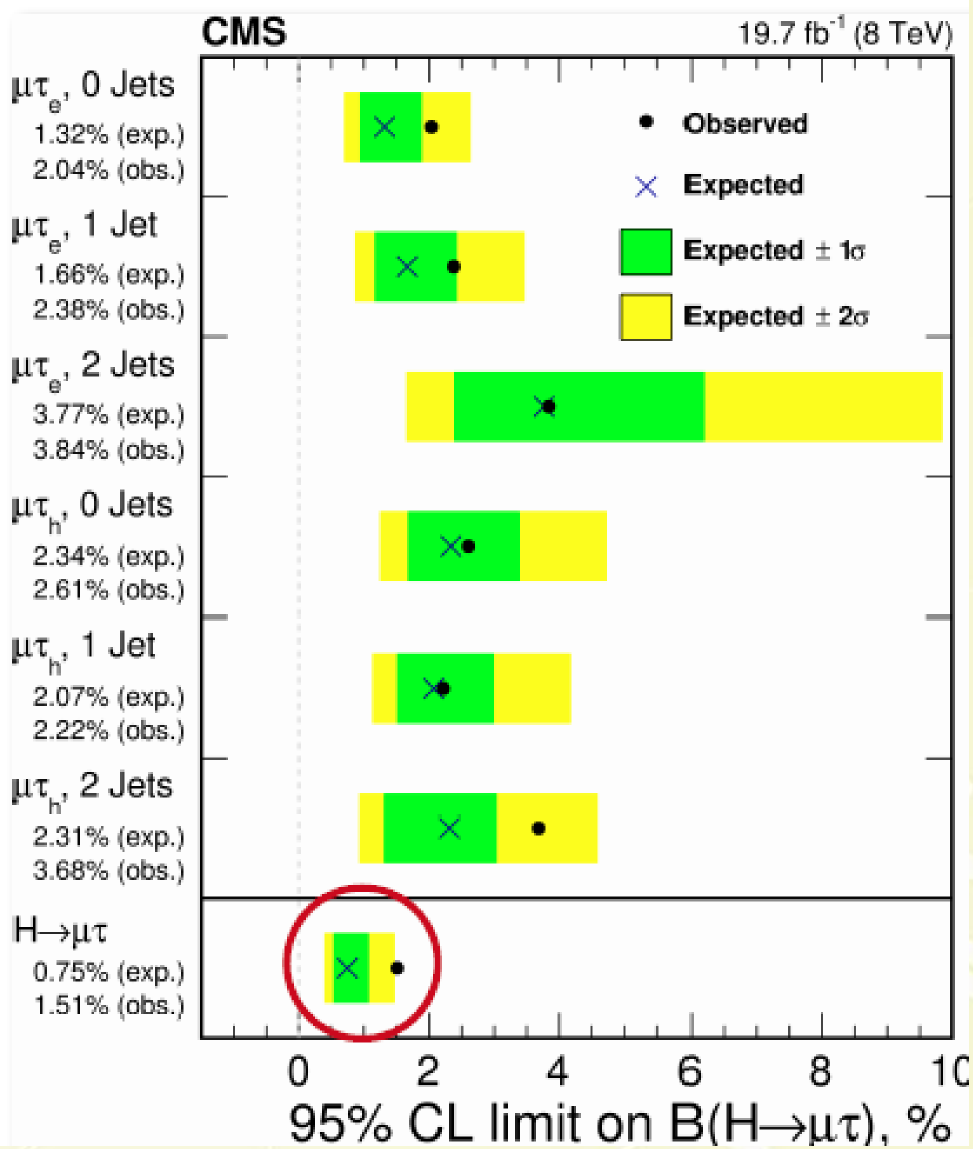


$B(H \rightarrow e\mu) < 0.035\%\ (95\%\ C.L.)$

$B(H \rightarrow e\tau) < 0.69\%\ (95\%\ C.L.)$

Lepton flavor violation in Higgs boson decays

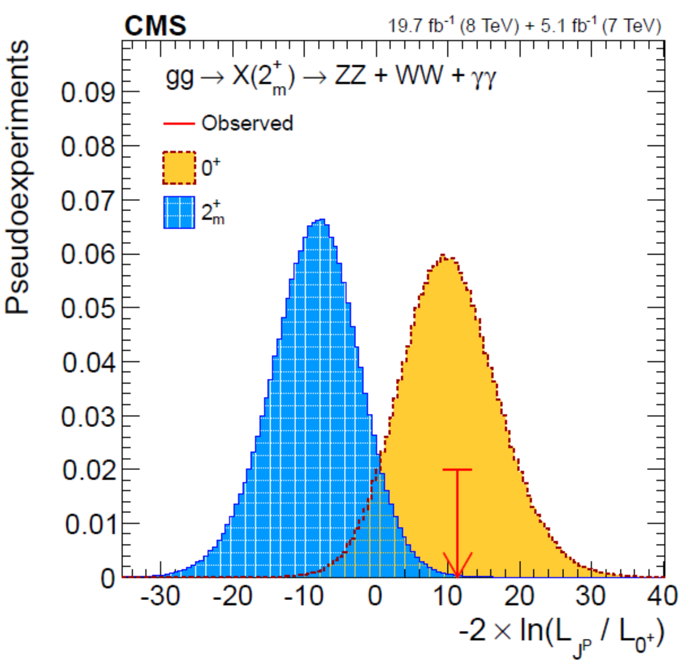


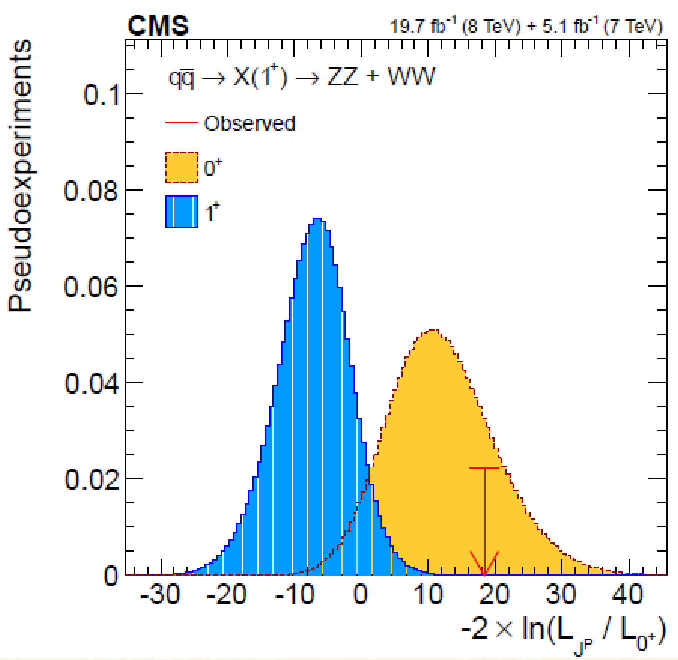


$$B(H \rightarrow \mu\tau) = 0.84 \pm {}^{0.39}_{0.37}$$

Higgs boson spin and parity

Spin 0 and parity + of the Higgs boson is preferred
(derived from H→ $\gamma\gamma$ and H→ ZZ decays



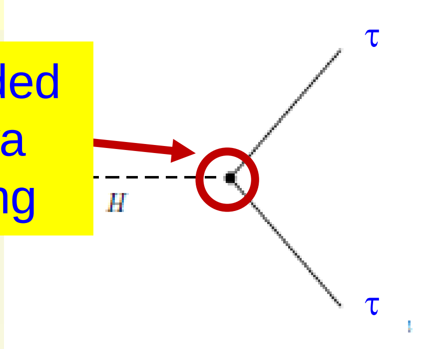


What about the CP quantum number ?

Couplings to the Higgs boson

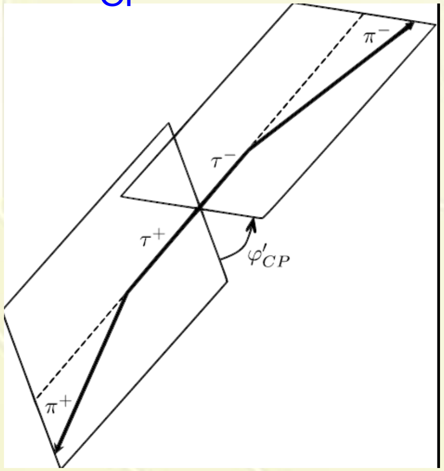
$$\mathcal{L}_Y = -g_\tau \left(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i \gamma_5 \tau\right) h$$

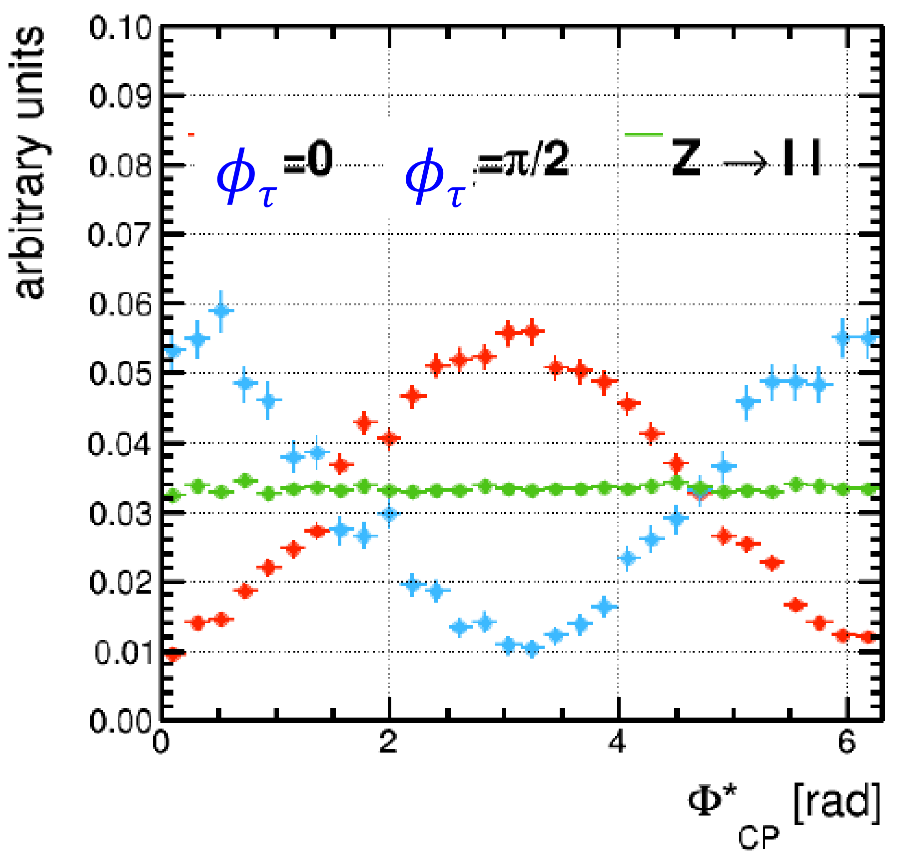
Extended Yukawa coupling



ϕ_τ is the mixing angle between a CP + and CP - state

It can be accessed from the distribution of the angle between the two τ decay planes Φ_{CP}, or, without loss of sensitivity, by the angle of the two impact parrameter planes of the τ decays Φ^*_{CP}



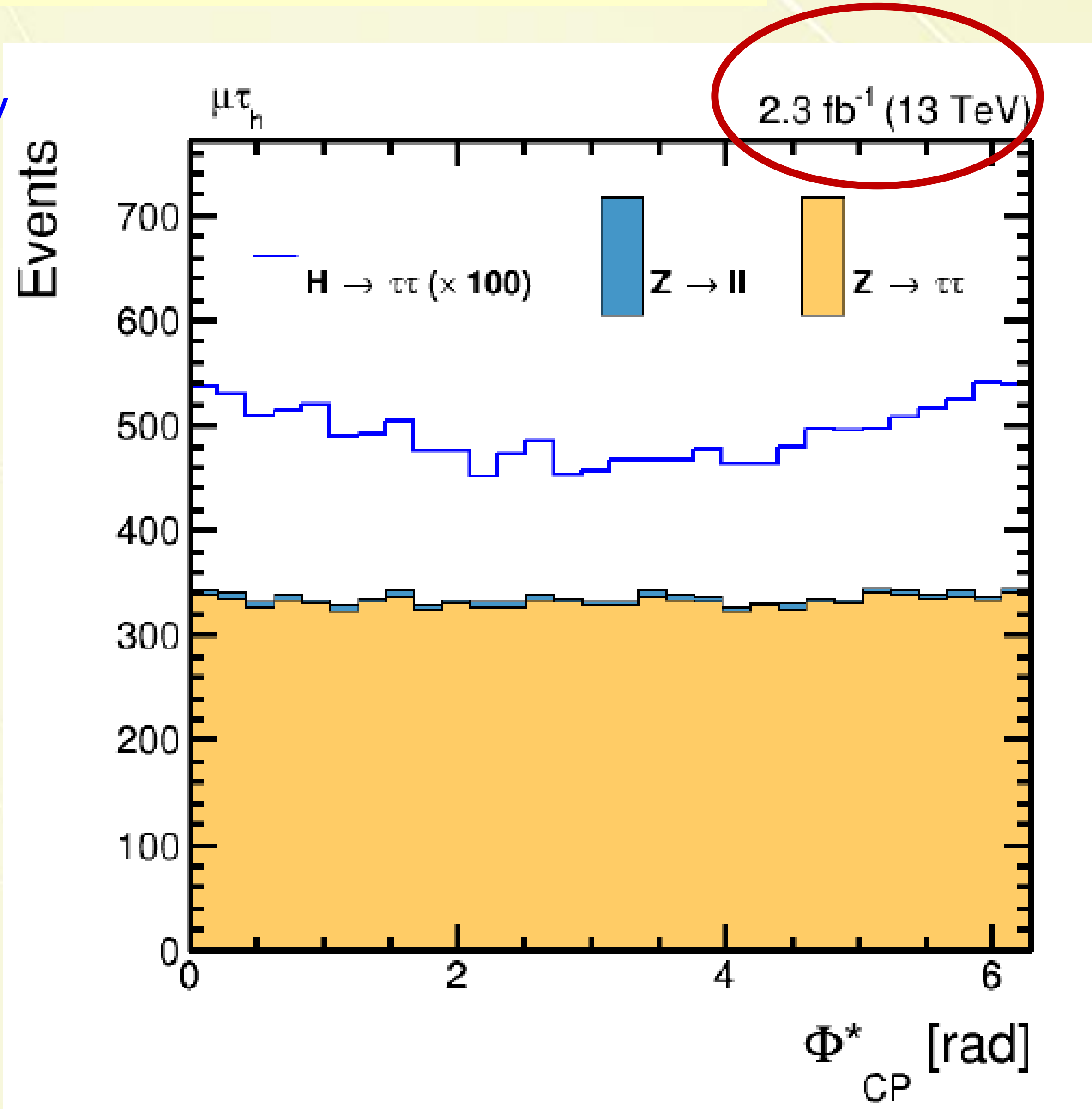


Sensitivity of the method

With the current luminosity the signal is too small,

But:

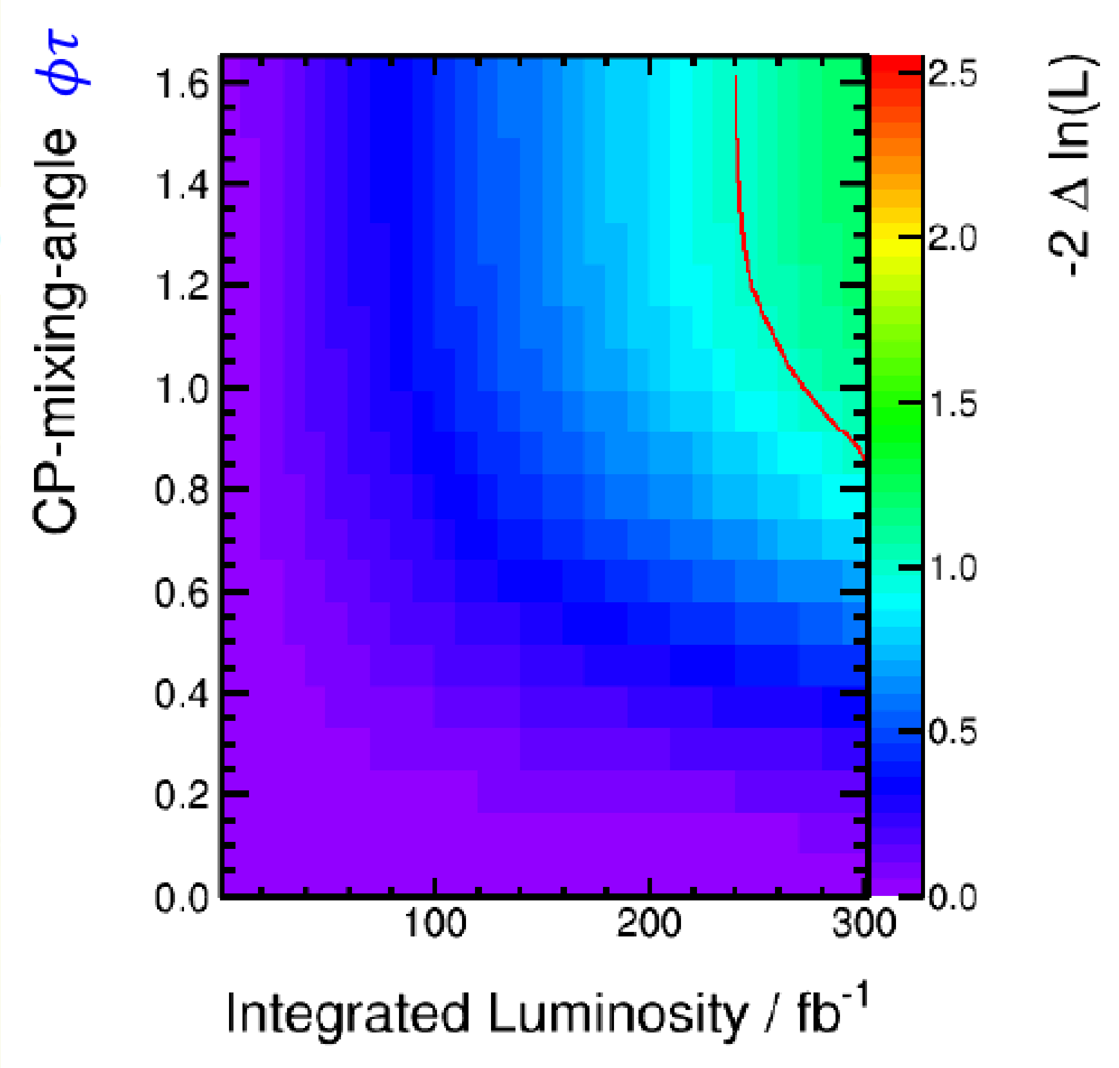
- Luminosity is growing now > 100 fb^{-1}
- Analysis method has room for improvements
- Fine tuning of the tracking/vertexing needed



Sensitivity of the method

Defining a likelihood function:

$$\mathcal{L}(n|\alpha_\tau) = \prod_i \frac{[s_i(\alpha_\tau) + b_i]^{n_i}}{n_i!} exp(-s_i(\alpha_\tau) - b_i)$$

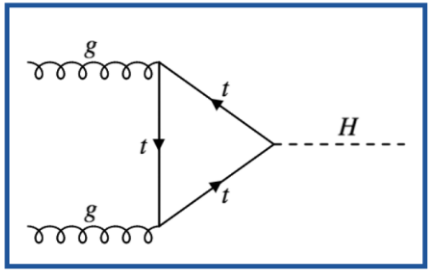


it is estimated at which luminosity we expect sufficient data to obtain sensitivity for $\phi\tau$

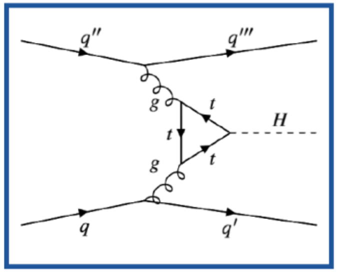
At the end of the current run of LHC some range of ϕ_τ we may expect to exclude

However: improvements are possible

Other Methods



(a) ggH



(b) ggH + 2 jets

Production process	Cross section / pb
ggH	43.92
ggH + 2 jets	3.98
VBF	3.75

H → ττ decay !

Extended Lagrangian

$$\mathscr{L}_{eff,ggH} = \underline{cos(\alpha_h)}\frac{\alpha_s}{12\pi v}hG^a_{\mu\nu}G^{a,\mu\nu} + \underline{sin(\alpha_h)}\frac{\alpha_s}{8\pi v}hG^a_{\mu\nu}G^a_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$

CP+

CP-

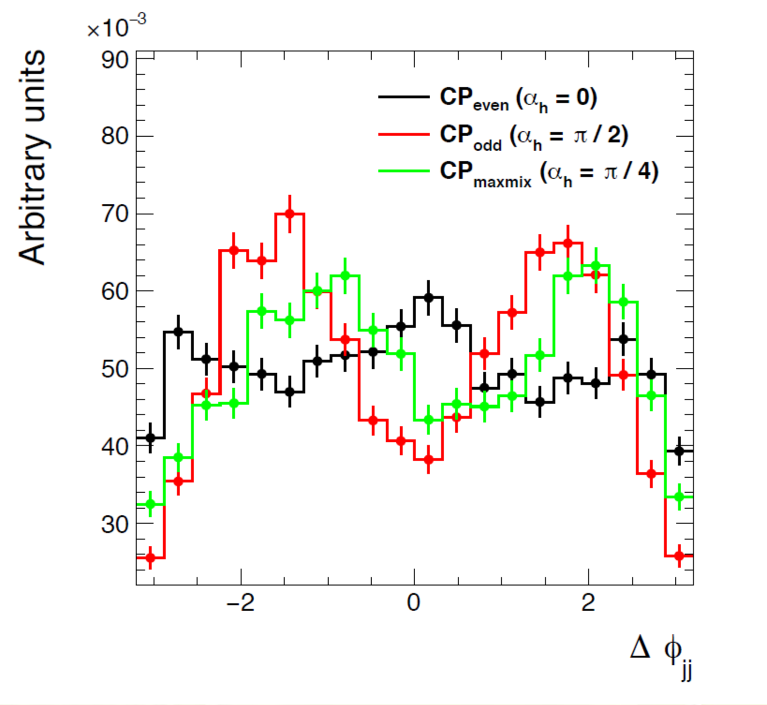
CP sensitive quantites, obtained from MELA (Matrix Element Likelihood Algorithm)

$$D_{0^-} \propto \frac{|M_{CP_{even}}|^2}{|M_{CP_{even}}|^2 + |M_{CP_{odd}}|^2}$$

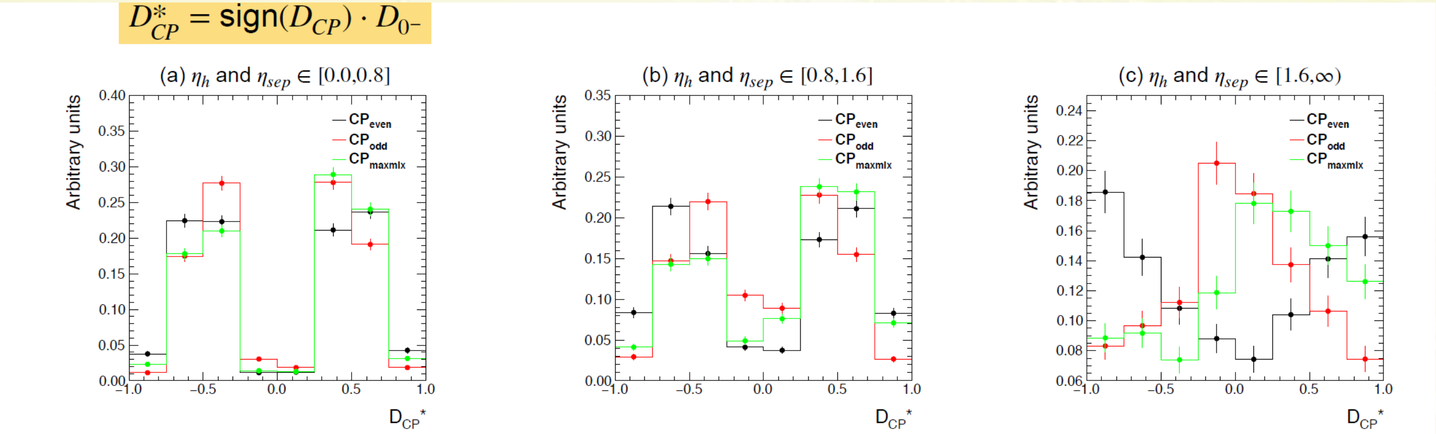
$$D_{CP} \propto \frac{|M_{CP_{maxmix}}|^2 - |M_{CP_{even}}|^2 - |M_{CP_{odd}}|^2}{|M_{CP_{even}}|^2 + |M_{CP_{odd}}|^2}$$

Other Methods

Most sensitive quantity: ϕ (J1, J2), azimuthal angle difference between jets



MELA variables



$$D^*_{CP} = \text{sign}(D_{CP}) \cdot D_{0-}$$

(a) η_h and $\eta_{sep} \in [0.0,0.8]$

(b) η_h and $\eta_{sep} \in [0.8,1.6]$

(c) η_h and $\eta_{sep} \in [1.6,\infty)$

Other methods

CP test in the production, using a CP odd (-) quantity and calculating its average value
For the vector boson fusion Higgs production the matrix element is extended:

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}}$$

Additional couplings HZZ, HWW, HWA

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d}\cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}}) + \tilde{d}^2\cdot|\mathcal{M}_{\mathrm{CP\text{-}odd}}|^2$$

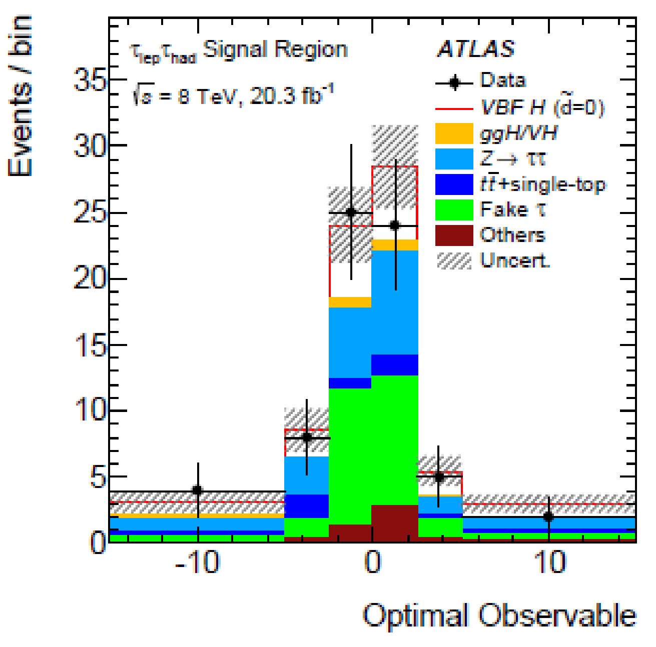
CP odd quantity

An optimal CP odd variable is defined:

$$\mathcal{OO} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

And distributed for the events with H→ $\tau\tau$ decays

$$-0.11 < \tilde{d} < 0.05\ (68\%\ C.L.)$$



Summary

τ leptons open unique, interesting ut challenging new fields of physics at the LHC

- Measurerment of the polarization in Z decays promises high precision measurements of $sin^2\theta_W$ solely from τ couplings
- Test of lepton universality in the neutral current
- Yukawa couplings to the Higgs boson
- CP mixing in H→ $\tau\ \tau$ final states
- Lepton flavor violation

Currently these studies are in most cases still limited by statistics. However, with growing luminosity very interesting and surprising results may appear.

I would like to thank the students of RWTH Aachen who worked with me the last year on many of the topics reported here: Claudia Pistone, Vladimir Cherepanov, Peter Fakeldey, Olena Hlushchenko, Bastian Kargoll, Thomas Müller, Alexander Nehrkorn, Hale Sert and Jann Aschersleben.