Measuring the CP state of the Higgs through its decay $H \to \tau\,\tau$

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The content of this talk is almost entirely derived from Marcel's thesis

Outline

1) A reminder of the method

2) Higgs production and background

3) Getting the tau direction in the Higgs frame

4) Current results

5) Conclusion: Is there any reason to pursue?

The differential partial width for a τ decay writes:

$$\frac{d\Gamma}{dLips}=\frac{1}{2m_\tau}G^2\frac{v^2+a^2}{2}\omega\left(1+\vec{h}\cdot\vec{s}\right)$$ with the **polarimeter vector *h*** and the spin ***s*.**

Reconstruction of *h* provides information about the τ spin state via the decay distribution

h for different τ decays:

$$\tau^- \to \nu_\tau l^- \bar{\nu}_l,\ (\ l\ =\ e,\mu\ )\ :\ \vec{h}\ \|\ \hat{\nu}_l$$

$$\tau^- \to \nu_\tau \pi^-\ :\ \vec{h}\ =\ -\hat{n}_\pi$$

$$\tau^- \to \nu_\tau \rho^- \to\ \nu_\tau \pi^-\ \pi^0\ :\ \vec{h}\ =\ Norm[2(q\cdot N)\vec{q}-q^2\vec{N}]$$

$$N\ =\ P_\tau - q_\rho\ ,\ q=q_\pi - q_\pi^0$$

$$\tau^- \to \nu_\tau a_1^- \to\ \nu_\tau 3\pi\ :\ need\ internal\ structure\ of\ a_1$$

$\tau^- \to X$	BR
$e^-\ \bar{\nu}_e \nu_\tau$	17.85%
$\mu^-\ \bar{\nu}_\mu \nu_\tau$	17.36%
$\pi^-\ \nu_\tau$	10.91%
$\rho^-\ \nu_\tau$	25.52%
$a_1^-\ \nu_\tau\ \ (a_1 \to \pi^-\ \pi^0\ \pi^0)$	9.27%
$a_1^-\ \nu_\tau\ \ (a_1 \to \pi^-\ \pi^+\ \pi^-)$	8.99%
other modes	10.10%

The hadronic decays, where the polarimeter can be reconstructed, offer the full sensitivity,
In the leptonic modes the polarimeter can be approximated by the lepton direction with a much reduced sensitivity and a problem for the tau reconstruction.

The general Yukawa coupling to τ of a CP mixed state H writes : $g\bar{\tau}(\cos\psi + i\sin\psi\gamma_5)\tau H$

$\frac{1}{\sqrt{2}}[|+-\rangle + |-+\rangle]$ is spin 0, CP even

$\frac{1}{\sqrt{2}}[|+-\rangle - |-+\rangle]$ is CP odd

The τ τ state is $\frac{1}{\sqrt{2}}[|+-\rangle + e^{i2\psi}|-+\rangle]$

$$\tau^- \quad |+\rangle \rightarrow \cos\frac{\theta^-}{2}\, e^{i\frac{\phi^-}{2}}$$
$$|-\rangle \rightarrow \sin\frac{\theta^-}{2}\, e^{-i\frac{\phi^-}{2}}$$
$$\tau^+ \quad |+\rangle \rightarrow -\sin\frac{\theta^+}{2}\, e^{i\frac{\phi^+}{2}}$$
$$|-\rangle \rightarrow \cos\frac{\theta^+}{2}\, e^{-i\frac{\phi^+}{2}}$$

With $\theta^\pm$ and $\varphi^\pm$ being the polar and azimuthal angles of the polarimeter in the $\tau^\pm$ rest frames wrt. a z-axis parallel to the τ^- direction for $\boldsymbol{h}^-$ and opposite to the τ^+ direction for $\boldsymbol{h}^+$

Taking into account the full helicity correlation

$$|+-\rangle = \cos\frac{\theta^-}{2}\cos\frac{\theta^+}{2}\, e^{\frac{i}{2}(\phi^- - \phi^+)}$$
$$|-+\rangle = -\sin\frac{\theta^-}{2}\sin\frac{\theta^+}{2}\, e^{\frac{-i}{2}(\phi^- - \phi^+)}$$
$$|++\rangle = -\cos\frac{\theta^-}{2}\sin\frac{\theta^+}{2}\, e^{\frac{i}{2}(\phi^- + \phi^+)}$$
$$|--\rangle = \sin\frac{\theta^-}{2}\cos\frac{\theta^+}{2}\, e^{\frac{-i}{2}(\phi^- + \phi^+)}$$

The correlated decay distribution writes :

$$W^H(\cos\theta+, \cos\theta-, \Delta\phi) \propto 1 + \cos\theta^- \cos\theta^+ - \sin\theta^- \sin\theta^+ \cos(\Delta\phi - 2\psi)$$

$$\Delta\phi = \phi^+ - \phi^-$$

Integrating over the polar angles $W^H(\Delta\phi) = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\cos(\Delta\phi - 2\psi)\right]$

15% loss of sensitivity

The distribution of Δφ provides information about Ψ
Reconstruct τ **directions** and **polarimeters !**

The study has been done with the simplest decay modes: π and ρ

Assumption: at ILC the transverse position of the interaction point is “perfectly” known run by run.
The longitudinal position is determined with an adequate accuracy by knowing the Z decay products.

The knowledge of the centre of mass and of the Z provides a way to determine the Higgs 4-vector up to radiation effects, in particular beamstrahlung.
We will first make use explicitly of this knowledge in the reconstruction of the taus then will show that in fact we need only two constraints and then be insensitive to beamstrahlung.

Method

Simple kinematical description in the tau CM, in the” Higgs CM and in the laboratory
for the pion case

In the τ CM

π et ν are back to back

$$\mathbf{P}_\tau \cdot \mathbf{P}_\pi = E_\pi{}^* m_\tau = \frac{m_\tau^2 + m_\pi^2}{2}$$

In the Higgs CM

the two taus are back to back up to a radiation from a τ.
their energy and momentum modulus are known ($m_H/2$)
as well as the angle between the momentum and the π .

$$\mathbf{P}_\tau \cdot \mathbf{P}_\mathbf{H} = E_\tau{}^* m_H = \frac{m_H^2}{2}$$

The τ momentum lies then on a sphere and on a cone around the π.
Its locus is then a circle intersection of the sphere and the cone. It lies then in a plane.

In the laboratory

Going from the Higgs CM to the laboratory,
the sphere becomes an ellipsoid
and the plane a plane.
The locus is then an ellipse.

The Higgs γ being close to 1 it is almost a circle.

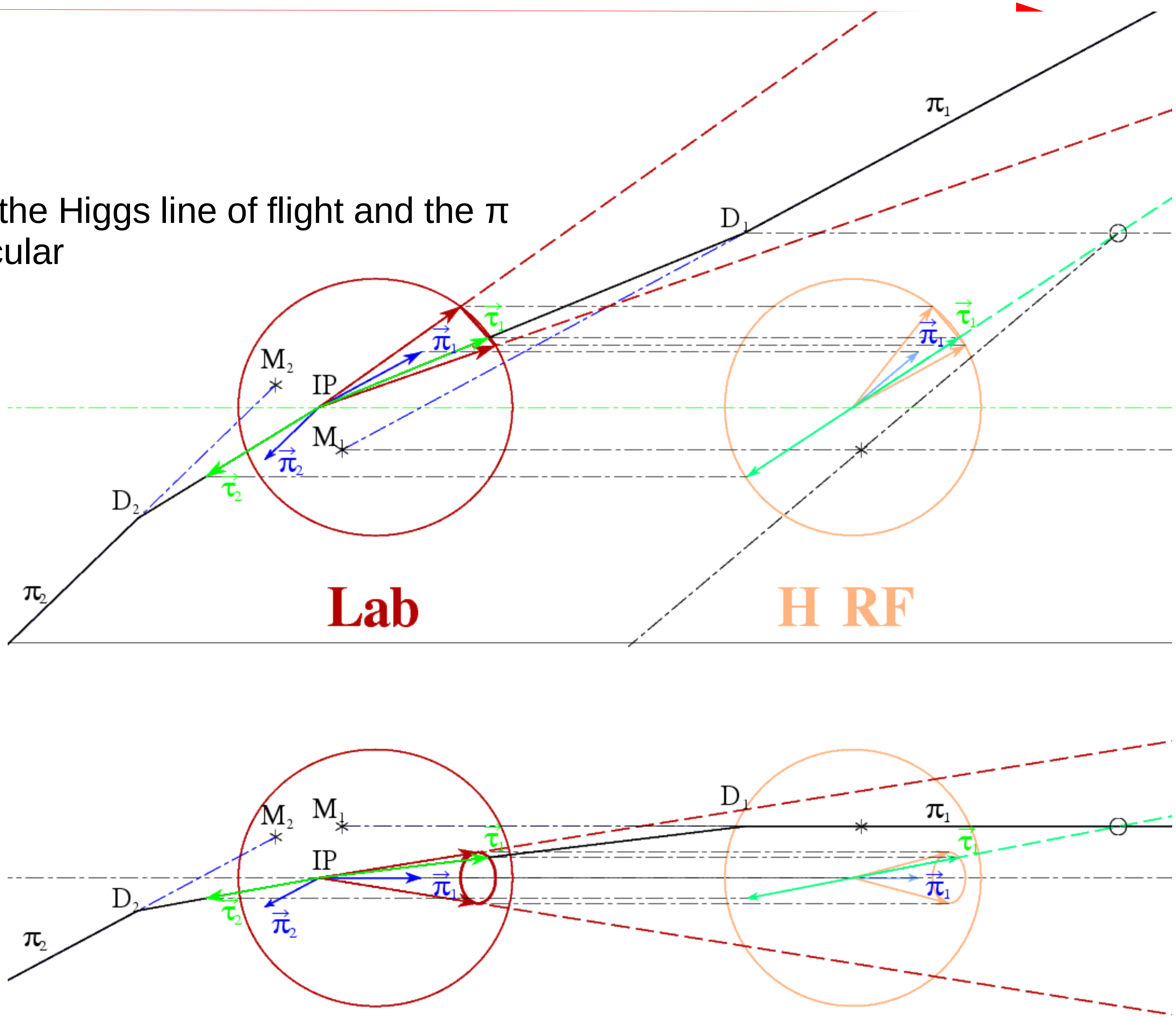
In view of the τ decay length, its trajectory can be treated as a straight line.
In the same way the π trajectory can be approximated by a straight line passing through the point of closest approach to the interaction point and following the momentum.

The τ momentum is collinear to its trajectory and leans on the π trajectory.
It is then in the plane containing the interaction point, the decay point
and the π momentum.
This plane intersects the ellipse in two points exhibiting two solutions,
but one only, in the case of the π corresponds to a decay after the interaction.

For the ρ two solutions are possible,
most of the time only one physical

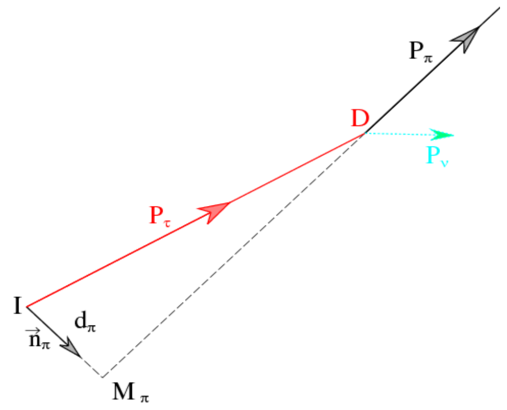
Geometrical vision:

on the left the lab system
on the right the Higgs system
on the top view plane containing the Higgs line of flight and the π
on the bottom the view perpendicular



Method

Parametrisation of a τ decaying into π ν knowing the creation point I, and the π trajectory



The τ trajectory is, at the size of the decay (mm), a straight line, the π trajectory as well.
The latter is defined by the point of closest approach to I, M_π and the π momentum.

The τ decay space-time point D is on the π trajectory

In 4 dimensions, calling **I** the interaction point:

$$\mathbf{I} = (0, \vec{0})$$
$$\mathbf{M}_\pi = (t_\pi, d_\pi \hat{n}_\pi)$$
$$\mathbf{P}_\pi = (E_\pi, \vec{p}_\pi)$$

By construction of M_π

$$\hat{n}_\pi \cdot \vec{p}_\pi = 0$$
$$\hat{n}_\pi \cdot \hat{n}_\pi = 1$$

$$\mathbf{P}_\tau = (E_\tau, \vec{p}_\tau)$$
$$\mathbf{D} = a \mathbf{P}_\tau$$
$$\mathbf{D} = \mathbf{M}_\pi + b \mathbf{P}_\pi$$

There are three unknowns: $a \quad b \quad t_\pi$

and two equations

$$\mathbf{P}_\tau \cdot \mathbf{P}_\pi = \frac{m_\tau^2 + m_\pi^2}{2}$$
$$\mathbf{P}_\tau \cdot \mathbf{P}_\tau = m_\tau^2$$

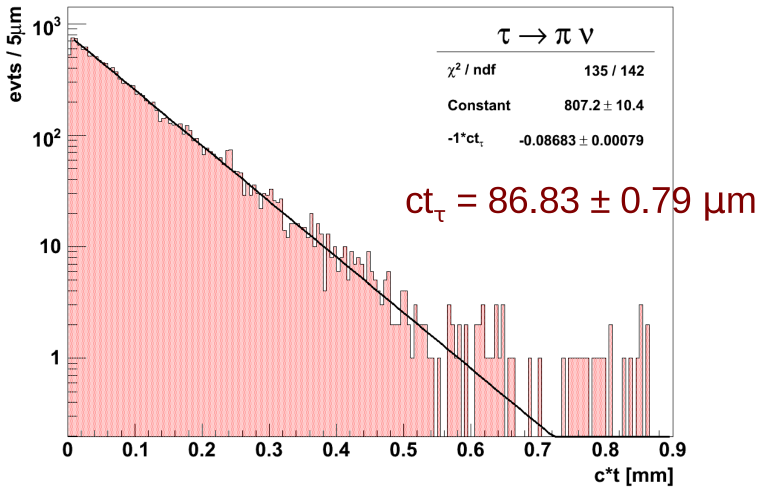
The decay can therefore be expressed as a function of only one parameter, idem for the ρ decay.

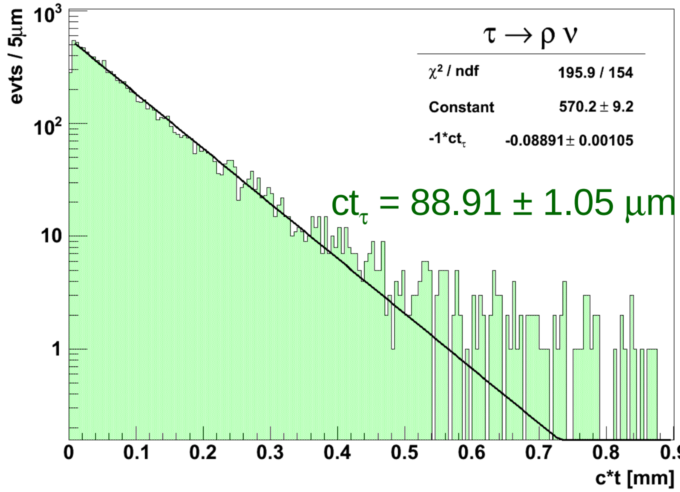
Two parameters define the ττ system which has to be the H system: 2 constraints only needed, for example mH and 1 momentum component orthogonal to the beam!

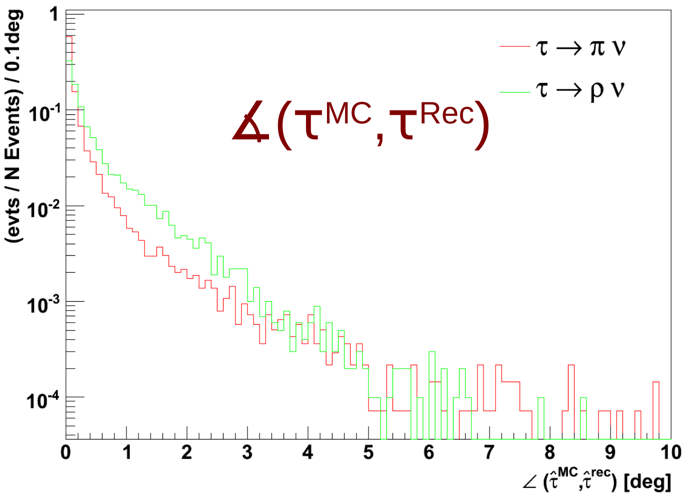
Quality of the reconstruction

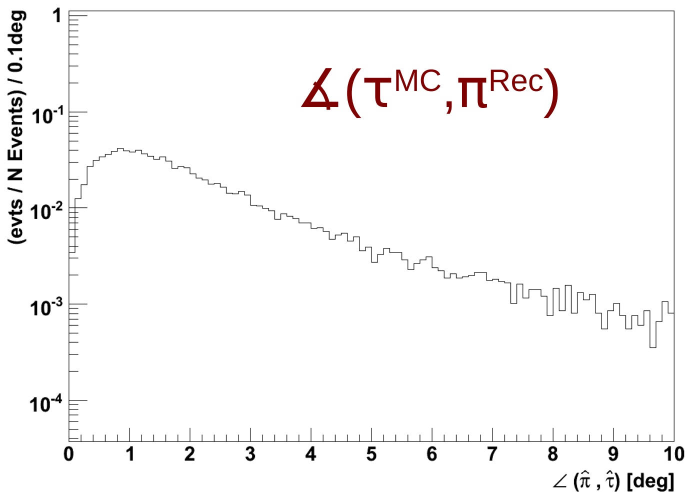
τ lifetime measurement provides a **criterion for the reconstruction quality**

$ct_{\tau}^{input} = 87.11\ \mu m$









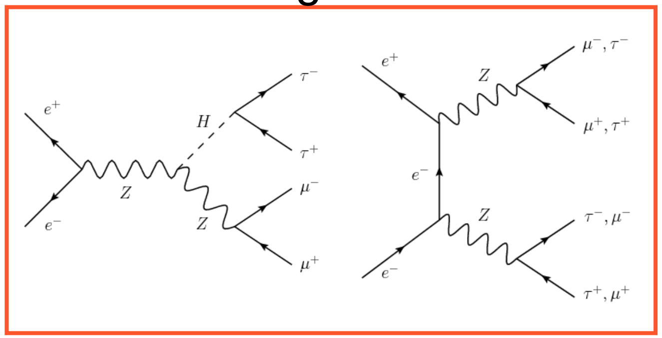
Measurement error smaller than the decay angle

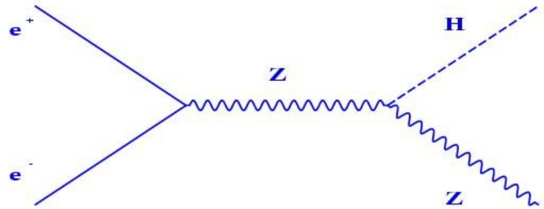
Production and background

We consider a Higgs of mass 120 GeV produced by Higgsstrahlung at 230 GeV peak of the cross section.

The study is done with $Z \to \mu\mu$

The ZZ background





No **CP-odd** ZZH coupling at tree level !

→ suppression with $\cos^2\psi$

effect of beam polarisation

Polarisation (e^-; e^+)	σ(ZZ) fb	σ(ZH) fb	σ(ZH) / σ(ZZ) %
0.0; 0.0	1139	214.4	18.8
0.8; 0.3	1860.1	306.8	16.5
0.8; 0.6	2347.9	384.4	16.4
0.8; 0.0	1517..3	252.9	16.7

Few numbers:
E_{CM} = 230. GeV
m_Z = 91 GeV
m_H = 120 GeV
γ_H = 1.0725
β_H = 0.36
$\beta\gamma_H$= 0.388
p_H = 46.5 GeV
BR($H \to \tau\tau$)=8%
BR($Z \to \mu\mu$)=3.4%

$\mathscr{L} = 500 fb^{-1}$	$\tau \to X$	$\tau \to \pi, \rho$
$e^+ e^- \to ZH \to \mu^+ \mu^- \ \tau^+ \tau^-$	417	54
$e^+ e^- \to ZZ \to \mu^+ \mu^- \ \tau^+ \tau^-$	2150	279

$$\frac{S}{B} \approx \frac{1}{5}$$

Z $\rightarrow \mu^+\mu^-$ decay is chosen for excellent determination of the Z ($\rightarrow$H) RF

➡ **low statistics**

Need to extend the event sample:

- Z $\rightarrow e^+e^-$, $q\bar{q}$ (q=u,d,s) , **multiply signal statistics by 14.6**
  for c and b need to sign the absence of ν
- Include **a_1** channels (also **3-prong) gain 2.25,** but model
- Include leptonic channels?
  it I possible to reconstruct the tau direction from
  the Higgs system and the opposite tau, but reduced sensibility

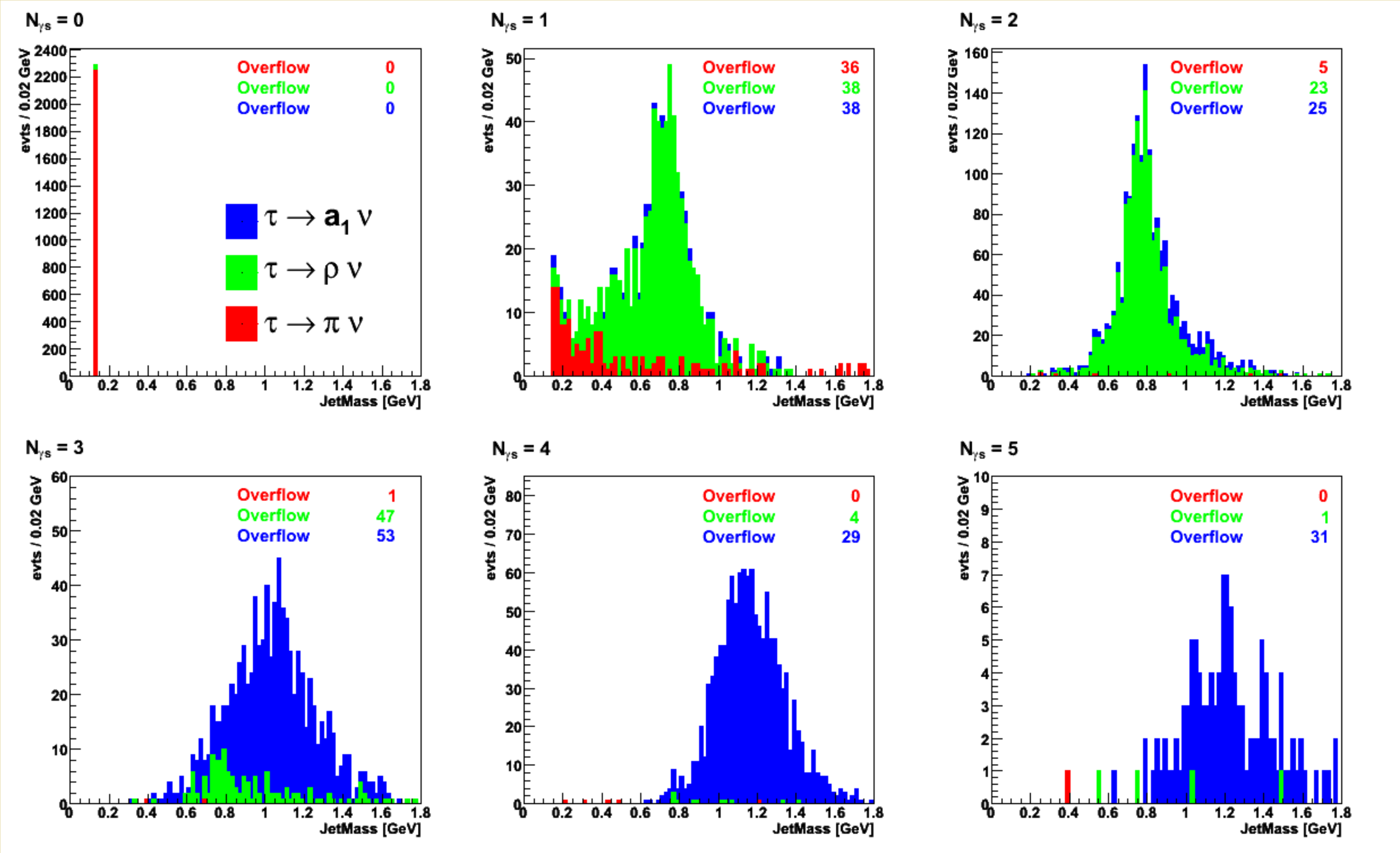
10.91 (p) + 25.52(r) = 36.43%
$0.3643^2 = 0.13$
with a1(18.26) goes to 0.30

As the polarimeters depend on the decay channel
we need to identify the different channels

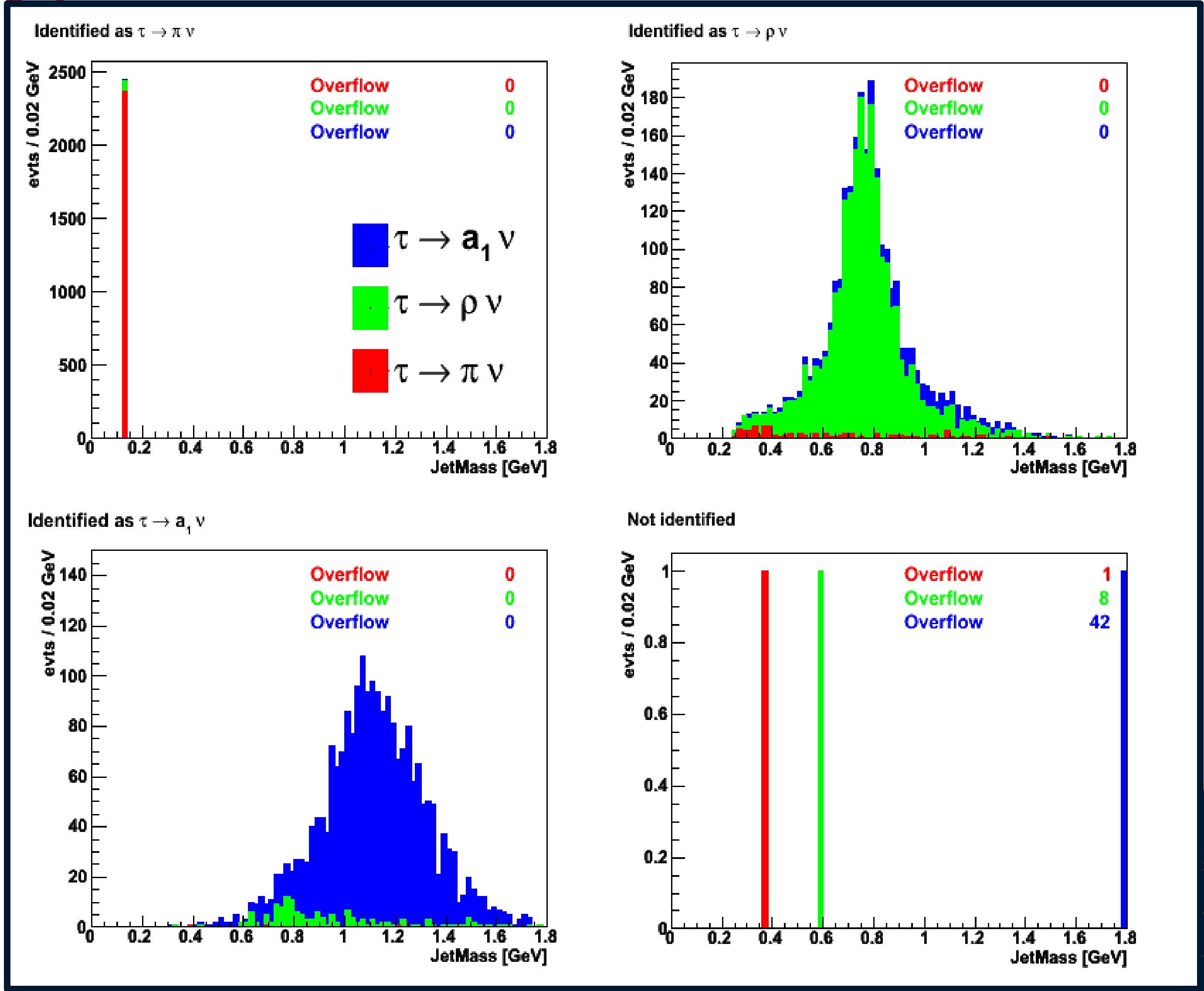
Distinguish between hadronic decay channels mostly by counting associated photons !

Done with GARLIC

Decay selection: signal channels



Production and background

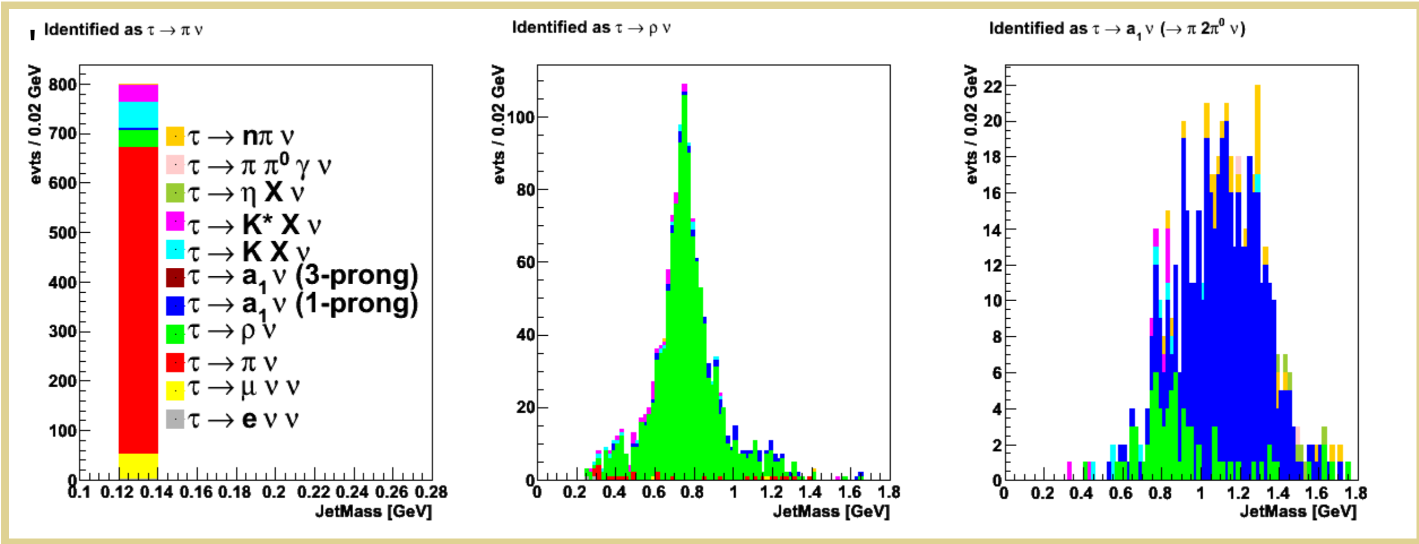


mass cuts defined
for each number of
photons in the hemisphere

[%]	π^{sim}	ρ^{sim}	a_1^{sim}
π^{rec}	95.9	2.8	0.6
ρ^{rec}	3.9	90.8	11.2
a_1^{rec}	0.1	6.1	86.8
not identified	0.1	0.3	1.4

Excellent separation and mass peaks!

Decay selection

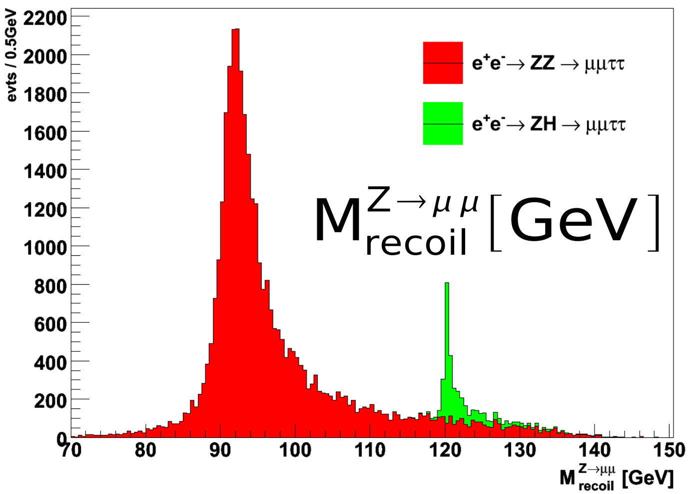


[%]	π^{sim}	ρ^{sim}	a_1^{sim}	other
π^{rec}	95.5	2.7	0.6	49.1
ρ^{rec}	4.2	90.2	12.5	21.8
a_1^{rec}	0.0	5.9	85.0	19.7
rejected	0.3	1.2	1.9	9.3

[%]	$\pi\pi^{sim}$	$\pi\rho^{sim}$	πa_1^{sim}	$\rho\rho^{sim}$	ρa_1^{sim}	$a_1 a_1^{sim}$	other
$\pi\pi^{rec}$	59.4	1.4	0.5	0.2	0	0	0.6
$\pi\rho^{rec}$	8.7	46.5	8.1	3.3	0.4	0	1.0
πa_1^{rec}	0	3.8	46.7	0	0.8	0	0.4
$\rho\rho^{rec}$	0	1.6	0.9	41.8	4.6	1.0	0.4
ρa_1^{rec}	0	0	0.5	5.6	39.6	9.4	0.6
$a_1 a_1^{rec}$	0	0	0	0	2.5	30.2	0.1
other	31.9	46.7	43.3	49.1	52.1	59.4	96.9

High signal rejection due to efficiency (mostly in the Z reconstruction) **with standard ILD particle ID**

Improve also event selection

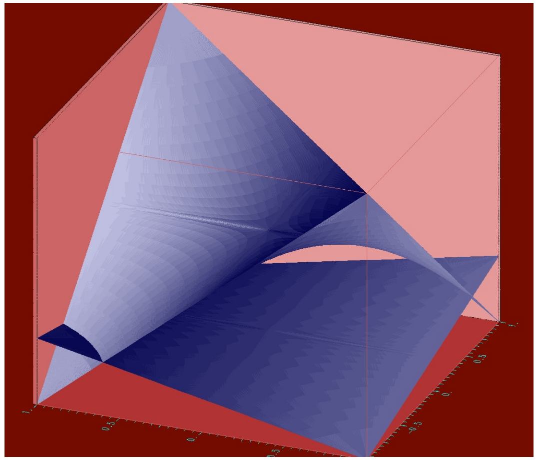


Cut on **recoil mass** to reject **ZZ background** and **beamstrahlung**

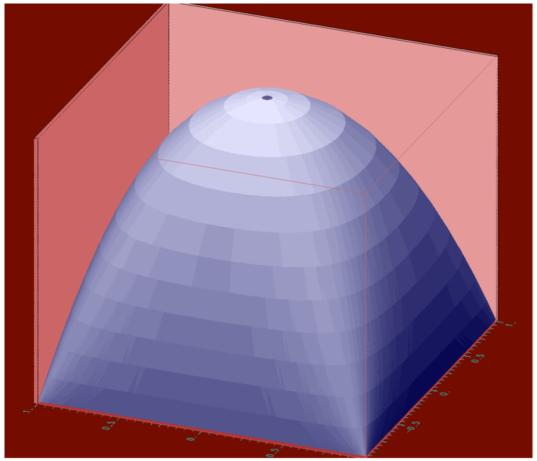
$$119\mathrm{GeV} < M^{Z\to\mu\mu}_{recoil} < 129\mathrm{GeV}$$

Rejection: 96% B, 9%S → $\frac{S}{B} \approx 4$

Cut on the correlation between polar angles



Signal and background



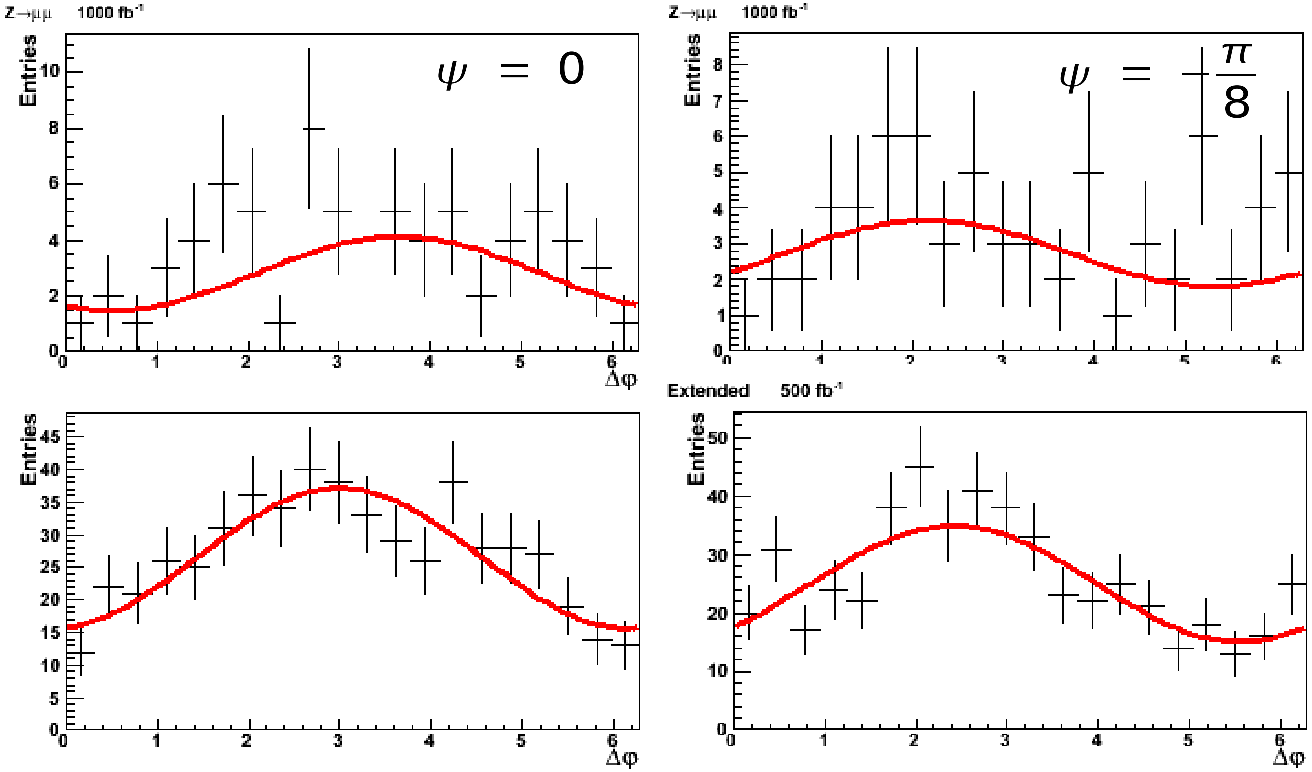
Sensitivity

H $W^H(\cos\theta^+, \cos\theta^-, \Delta\phi) \propto 1 + \cos\theta^-\cos\theta^+ - \sin\theta^-\sin\theta^+\cos(\Delta\phi - 2\psi)$ $\quad \Delta\phi = \phi^- - \phi^+$

Z $W^Z(\cos\theta^+, \cos\theta^-, \Sigma\phi) \propto 1 - \cos\theta^-\cos\theta^+ - \sin\theta^-\sin\theta^+\cos(\Sigma\phi)$ $\quad \Sigma\phi = \phi^- + \phi^+$

With $\cos\theta^+ \cos\theta^- > -0.4$:

Rejection: 19% B, 5% S, 3% weighted S → $\frac{S}{B} \approx 4.5$



$Z \rightarrow \mu^+ \mu^-$

$Z \rightarrow \mu^+ \mu^-$
$e^+ e^-$
$q\bar{q}$ q=u,d,s

χ^2 fit with the function

$$W_{fit}(\Delta\phi) = a(1 - b\cos(\Delta\phi - 2c))$$

With a sample of 300 fb^{-1} taking the Z decays in e, μ and light quarks

we can exclude a phase larger than π/8 at 4.5 σ

For such a phase the cross section is reduced by 15% (included in the analysis)
but the information from the measurement of the cross section is not included.
may well be, if CP violation proven, more effective than spin correlations!

using additional modes and with an adequate PID, could be done with 100 fb^{-1}

but that needs quite some work
specially to improve dramatically the quality of PID

Marginal?