Tau polarization in Z to ditau decays

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Outline

- Physical motivation.
- Theoretical aspects.
- Experimental observables.
- Summary.
- References.

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Goal

Develop a technique and tools necessary to infer the polarization of the parent particle by knowing the final decay products for proton-proton collisions.

- Z boson would correspond to the test case.

- A polarization observable could enhance an AI discriminator for detecting high-mass particles with preferred third-generation fermion couplings.

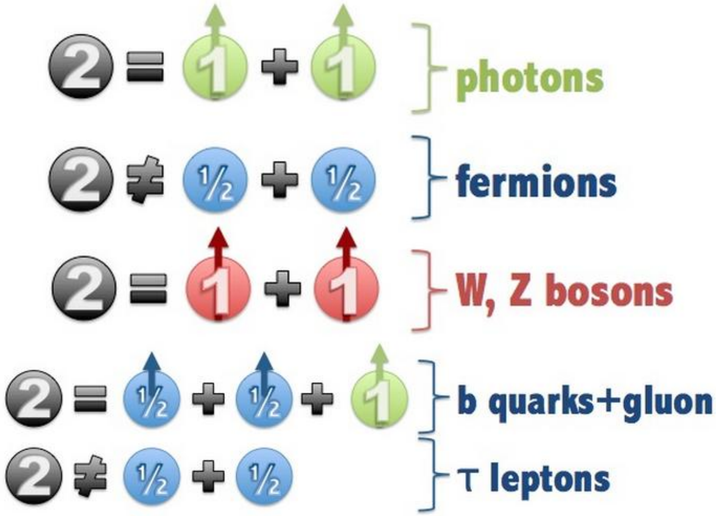
We would like to distinguish particles such as Z', high-mass neutral Higgs, scalar resonances in simplified models, and LQs.

Motivation

Child particles contain information from mother particle.

- *Total charge.*
- *Tranverse momentum (mother).*
- *Total energy.*
- *Etc.*

What about spin?[1]



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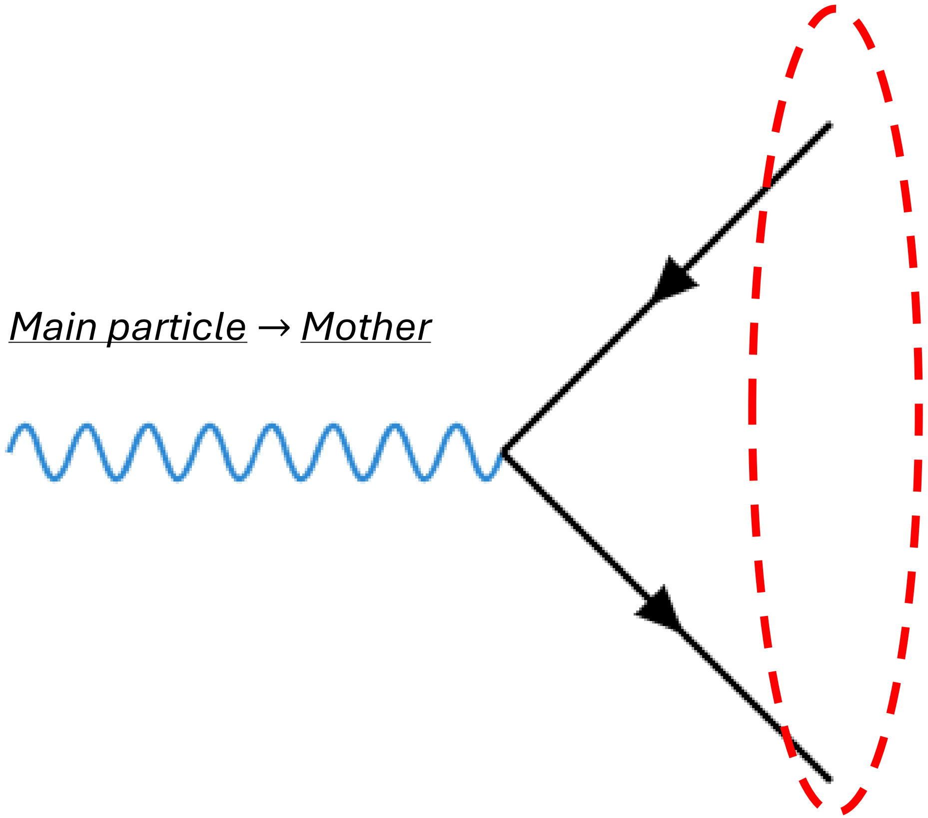
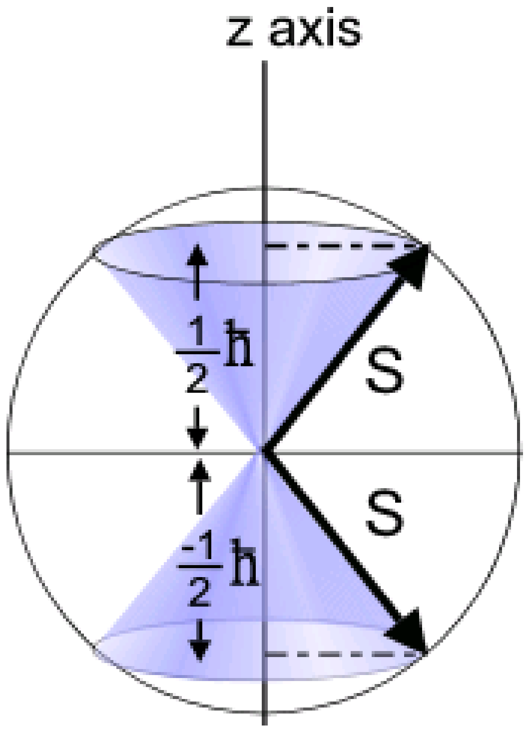
Product decays → *Childrens*

Main particle → *Mother*



Measuring the spin of a particle requires projecting that spin onto a certain axis (or direction in which we measure).



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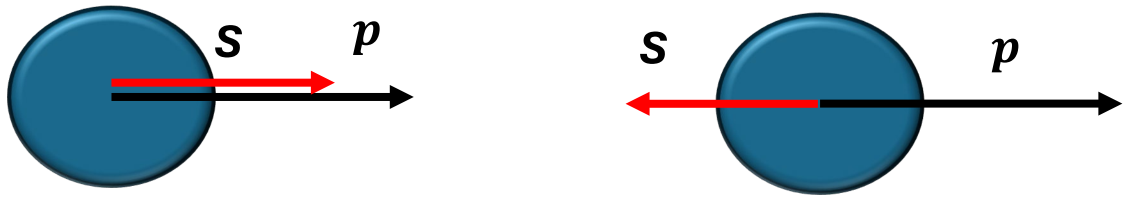
E.j:

Particles With spin ½ can be proyected along the z axis as:

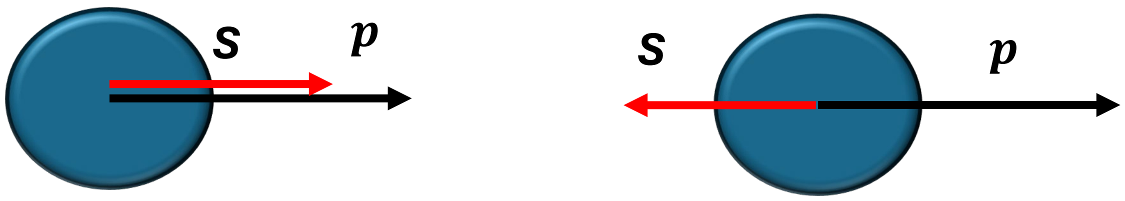
$$\left\{-\frac{\hbar}{2},\frac{\hbar}{2}\right\} \to \left\{-\frac{1}{2},\frac{1}{2}\right\} \to \{-,+\}$$

Helicity:

Spin projection onto the momentum direction.



$h = +$ $h = -$



$h = +$ $\qquad\qquad$ $h = -$

$$h = \frac{\hat{\boldsymbol{S}} \cdot \boldsymbol{p}}{|\hat{\boldsymbol{p}}|} = \hat{\boldsymbol{S}} \cdot \hat{\boldsymbol{p}}$$

- ***p** depends on the reference frame.*

$$\boldsymbol{p} = (p_x, p_y, p_z) \rightarrow \boldsymbol{p}' = (-p_x, -p_y, -p_z) = -(p_x, p_y, p_z) = -\boldsymbol{p}$$

$$h = \hat{\boldsymbol{S}} \cdot \hat{\boldsymbol{p}}$$

$$h' = \hat{\boldsymbol{S}} \cdot \hat{\boldsymbol{p}}' = -\hat{\boldsymbol{S}} \cdot \hat{\boldsymbol{p}} = -h$$

Helicity is not invariant under transformations.

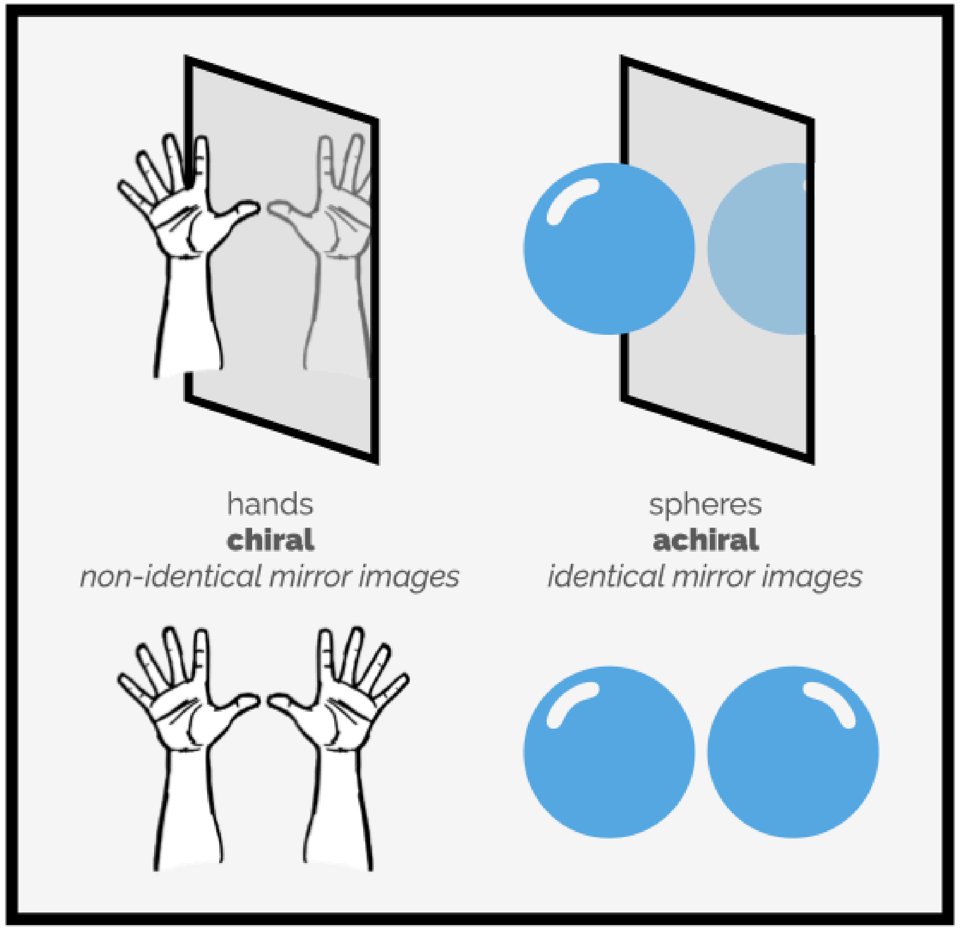
Chirality

Chirality

- ✓ An object is *chiral* if we can distinguish from its mirror image.
- ✓ Intrinsic property that distinguishes between left-hand and right-hand components of a **Dirac Spinor**.

$$\psi_L = \left(\frac{1-\gamma^5}{2}\right)\psi \qquad \psi_R = \left(\frac{1+\gamma^5}{2}\right)\psi$$

No reference frame dependance



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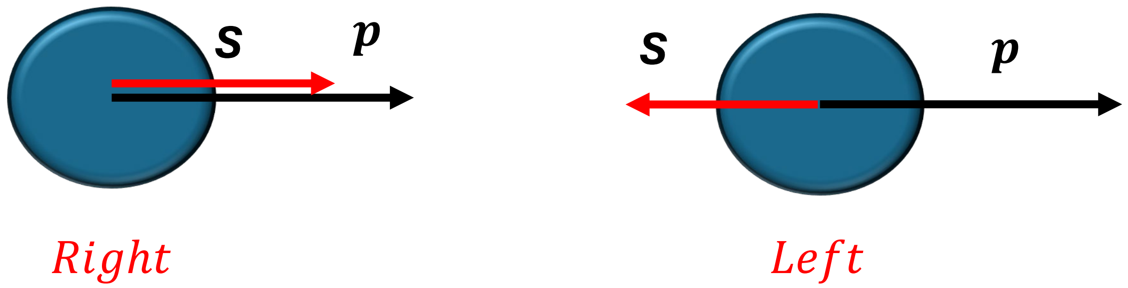
SM distinguishes between Left and Right particles.

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

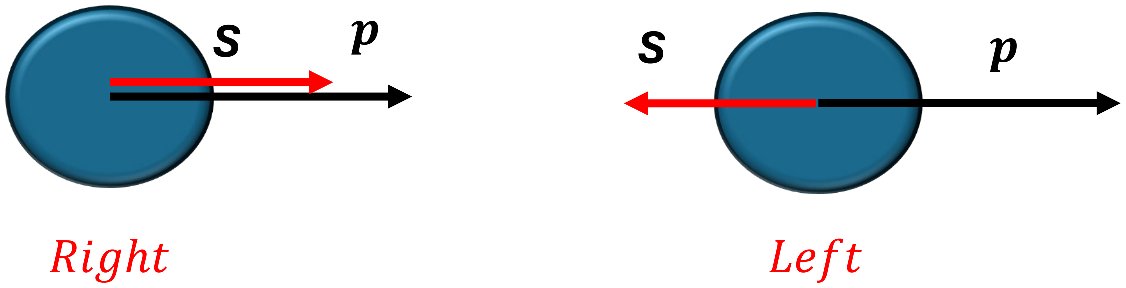
Equivalence Chirality and Helicity:

- **Massless particles:**
  - It does not exist a reference frame where momentum invert its direction.
  - There is not mixing between Left-hand and Right-Hand in the Dirac equation.
- **Ultrarelativistic**
  - $\boldsymbol{v} \sim \boldsymbol{c}$
  - $|\boldsymbol{p}| \gg m.$
  - $E \sim |\boldsymbol{p}|$



$\boldsymbol{Z \rightarrow \tau^{-}\tau^{+}}$

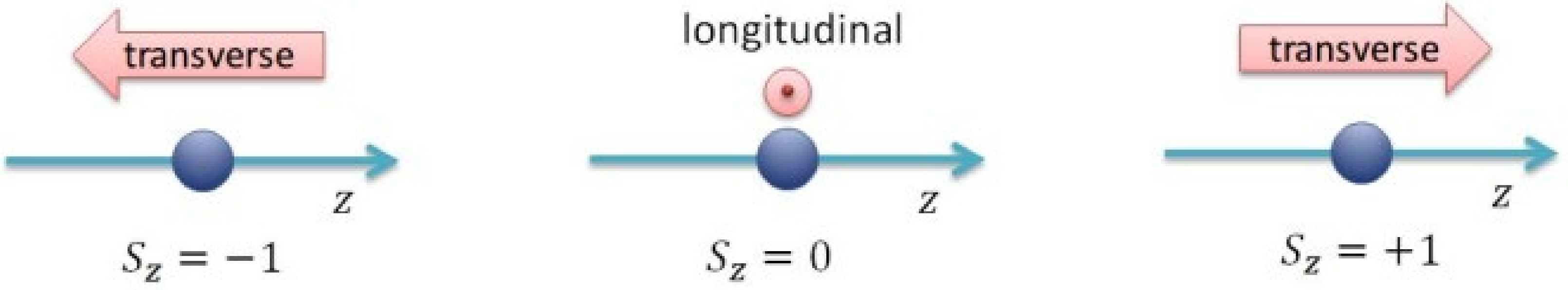
- Z boson couples to left-hand and right-hand particles with different strengths, so the decay amplitude favors configurations in which:
  - $Z\colon\ \tau^{-} = \tau_{L}^{-}$
  - $Z\colon\ \tau^{-} = \tau_{R}^{+}$



- **Ditau combination:**
  - $Q(Z) = Q(\tau^{-}) + Q(\tau^{+}) = 0$ "Neutral bosón"
  - $Z \rightarrow \{\tau_{R}^{-}\tau_{L}^{+}, \tau_{L}^{-}\tau_{R}^{+}\}$

Z: $\boldsymbol{Polarization}$

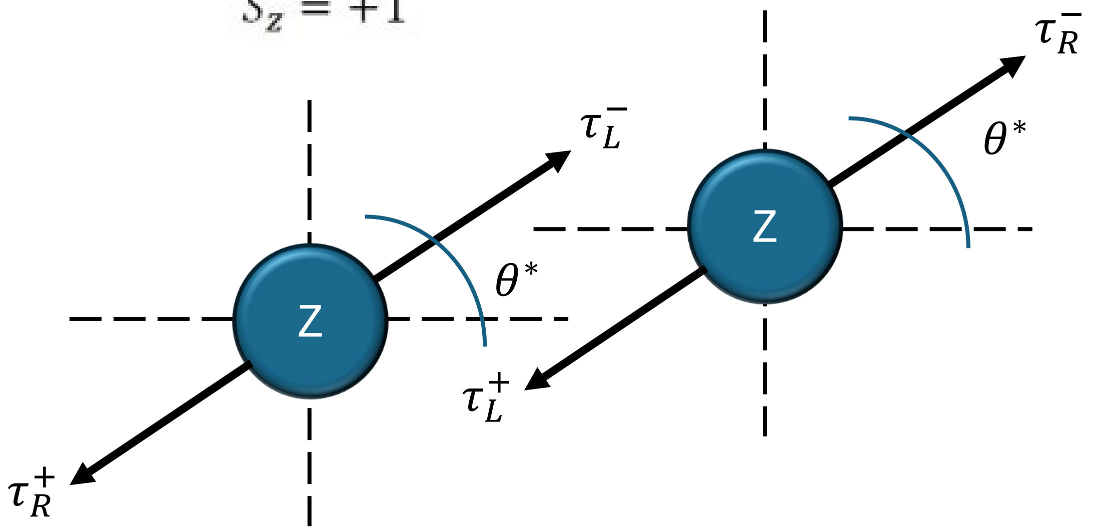
- $S(Z) = 1 \rightarrow \quad S_Z = \{-1, 0, +1\}$



- Z reference frame (rest frame).

- Tau information should allow inference of Z polarization.

- We can study the Z polarization identification from the taus (test case): Differential xsection as a function of θ^*.



Theoretical aspects

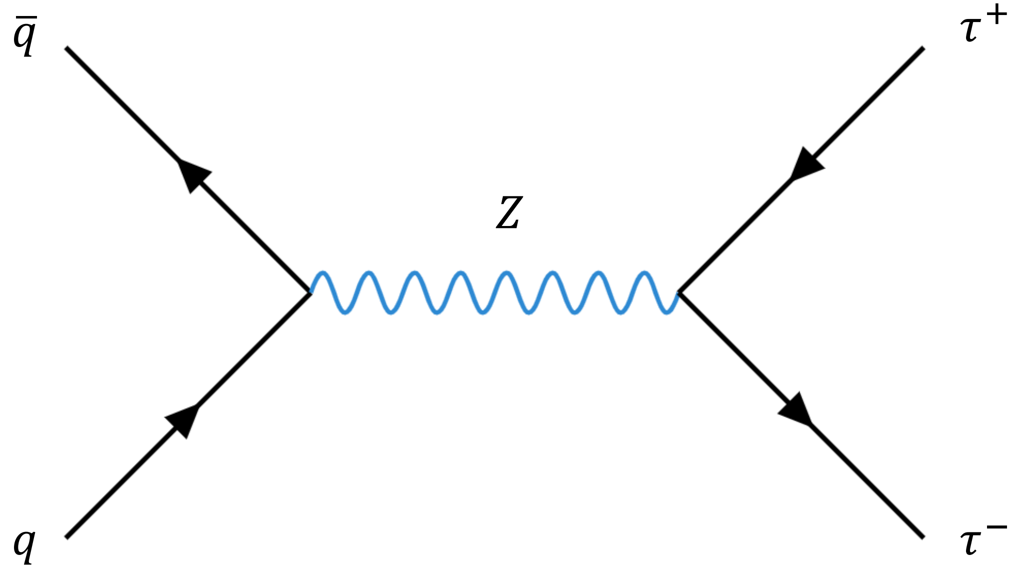
- Z boson mediates the weak interaction, and couple to chiral Fermions (Left/Right).
  - Z couples differently to right-handed, and left-handed.
  - Total helicity have to be zero.
  - Total charge have to be zero.

- g_V: Left and Right-hand particle coupling.
- g_A: Left-hand particle coupling.

- Z decays in two taus.

- Z is produced in quark – antiquark processes.

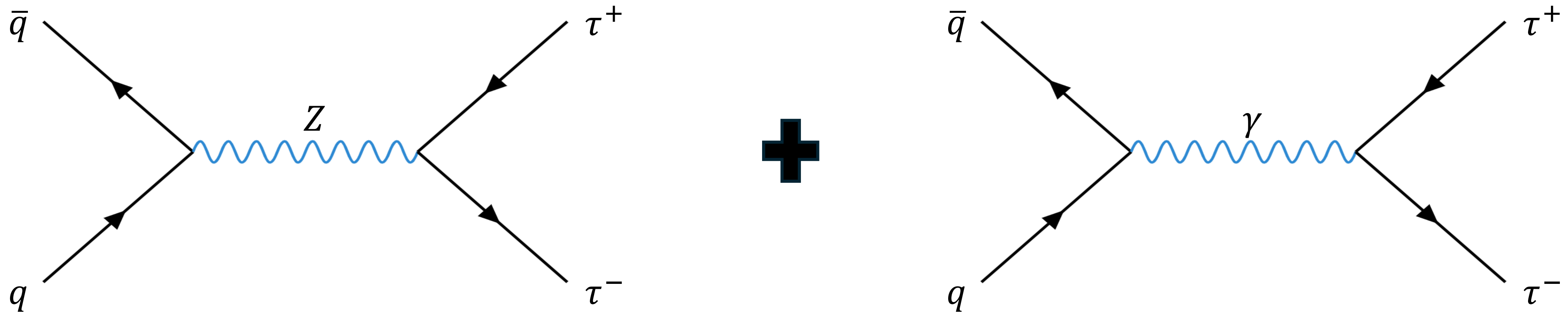
$$q\bar{q} \rightarrow Z \rightarrow \tau^- \tau^+$$



$$g_V = T_3 - 2Q_f sen^2\theta_W$$

$$g_A = T_3$$

- Quark pairs can also create off-shell, virtual photons, causing interference between contributions from γ and contributions from Z.



S channel

$$q\bar{q} \rightarrow Z/\gamma \rightarrow \tau^-\tau^+$$

Xsection for the process is given by:

$$d\sigma_T(s) = d\sigma_\gamma(s) + d\sigma_Z(s) + d\sigma_{\gamma Z}(s)$$

Interference term

Transition probability amplitude, $|M|^2$, is proporcional to $d\sigma$.

$$|M|^2 = |M_\gamma + M_Z|^2 = |M_\gamma|^2 + |M_Z|^2 + 2Re\{M_\gamma M_Z\}$$

Interference term

¡Feynman rules!

Feynman rules

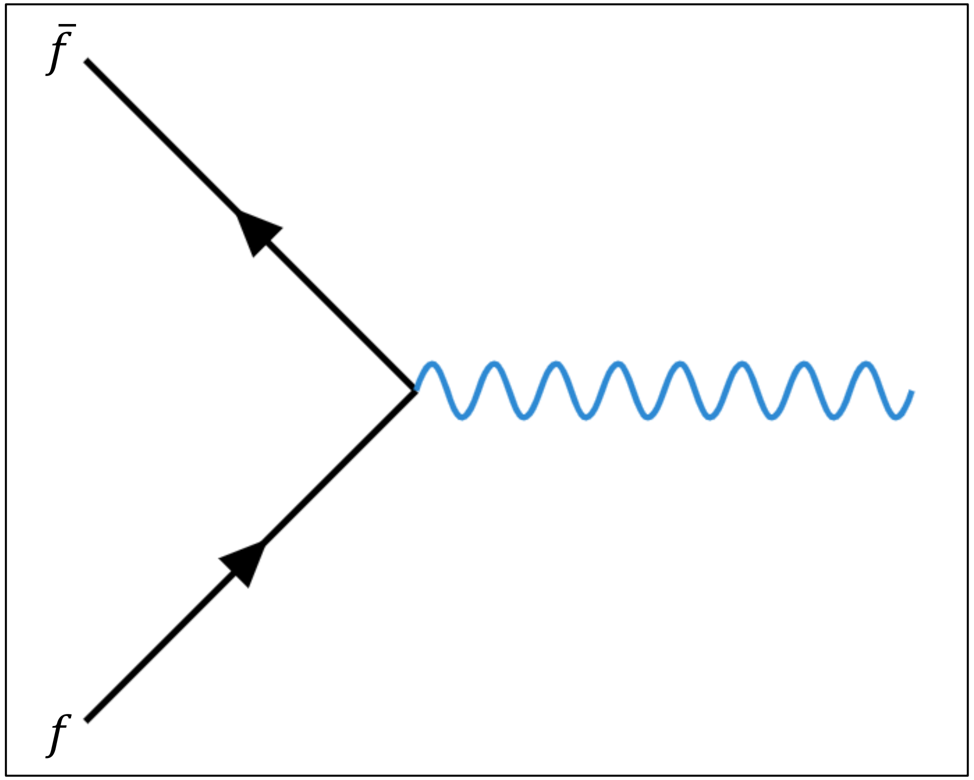
Photon:

- γ propagator:

$$D_{\mu\nu}(q) = -\frac{ig_{\mu\nu}}{s}$$

- Vertex factor:

$$-ieQ\gamma^{\mu}$$



Z boson:

- Z propagator:

$$D_{\mu\nu}(q) = -\frac{ig_{\mu\nu}}{s - m_Z^2 + im_Z\Gamma_Z}$$

- Vertex factor:

$$-\frac{ig_Z}{2}\gamma^{\mu}\left[g_V^{(q/f)} - g_A^{(q/f)}\gamma^5\right]$$

f	T_3^f	Q_f	g_A^f	g_V^f
ν_τ	1/2	0	1/2	1/2
τ^-	-1/2	-1	-1/2	-0.04
u	1/2	2/3	1/2	0.19
d	-1/2	-1/3	-1/2	-0.35

Incoming fermión/antifermion:

$$u(p_i) \;/\; \bar{v}(p_j)$$

Outcoming fermión/antifermion:

$$\bar{u}(p_i) \;/\; v(p_j)$$

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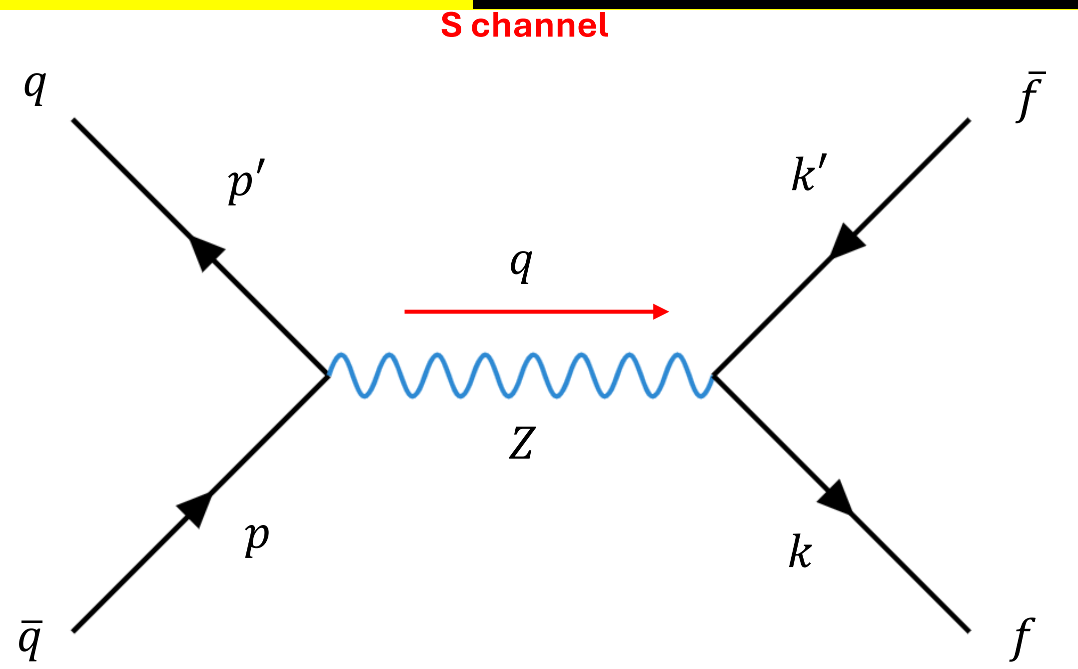


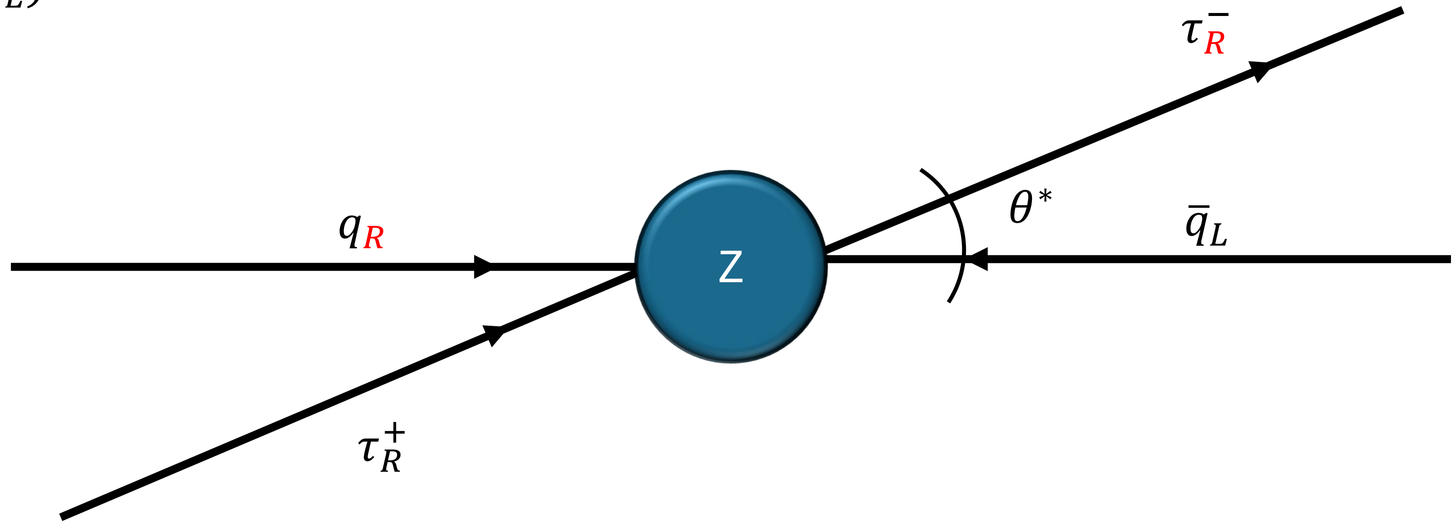
$$iM_Z = \left\{-\frac{ig_Z}{2}\bar{v}(p')\gamma^\mu\left[g_V^{(q)}-g_A^{(q)}\gamma^5\right]u(p)\right\}\times\left\{-\frac{ig_{\mu\nu}}{s-m_Z^2+im_Z\Gamma_Z}\right\}\times\left\{-\frac{ig_Z}{2}\bar{u}(k)\gamma^\nu\left[g_V^{(f)}-g_A^{(f)}\gamma^5\right]v(k')\right\}$$

$$= \frac{ig_Z^2}{4(s-m_Z^2+im_Z\Gamma_Z)}\bar{v}(p')\gamma^\mu\left[g_V^{(q)}-g_A^{(q)}\gamma^5\right]u(p)\bar{u}(k)\gamma_\mu\left[g_V^{(f)}-g_A^{(f)}\gamma^5\right]v(k')$$

$$= \frac{ig_Z^2}{(s-m_Z^2+im_Z\Gamma_Z)}\left\{g_L^{(f)}g_L^{(q)}\bar{v}_\uparrow(p')\gamma^\mu u_\downarrow(p)\bar{u}_\uparrow(k)\gamma_\mu v_\downarrow(k') + g_R^{(f)}g_L^{(q)}\bar{v}_\uparrow(p')\gamma^\mu u_\downarrow(p)\bar{u}_\downarrow(k)\gamma_\mu v_\uparrow(k')\right.$$
$$\left. + g_L^{(f)}g_R^{(q)}\bar{v}_\downarrow(p')\gamma^\mu u_\uparrow(p)\bar{u}_\uparrow(k)\gamma_\mu v_\downarrow(k') + g_R^{(f)}g_R^{(q)}\bar{v}_\downarrow(p')\gamma^\mu u_\uparrow(p)\bar{u}_\downarrow(k)\gamma_\mu v_\uparrow(k')\right\}$$

How to understand each term?

RR: $(q_R \bar{q}_L \to Z \to f_R f_L)$

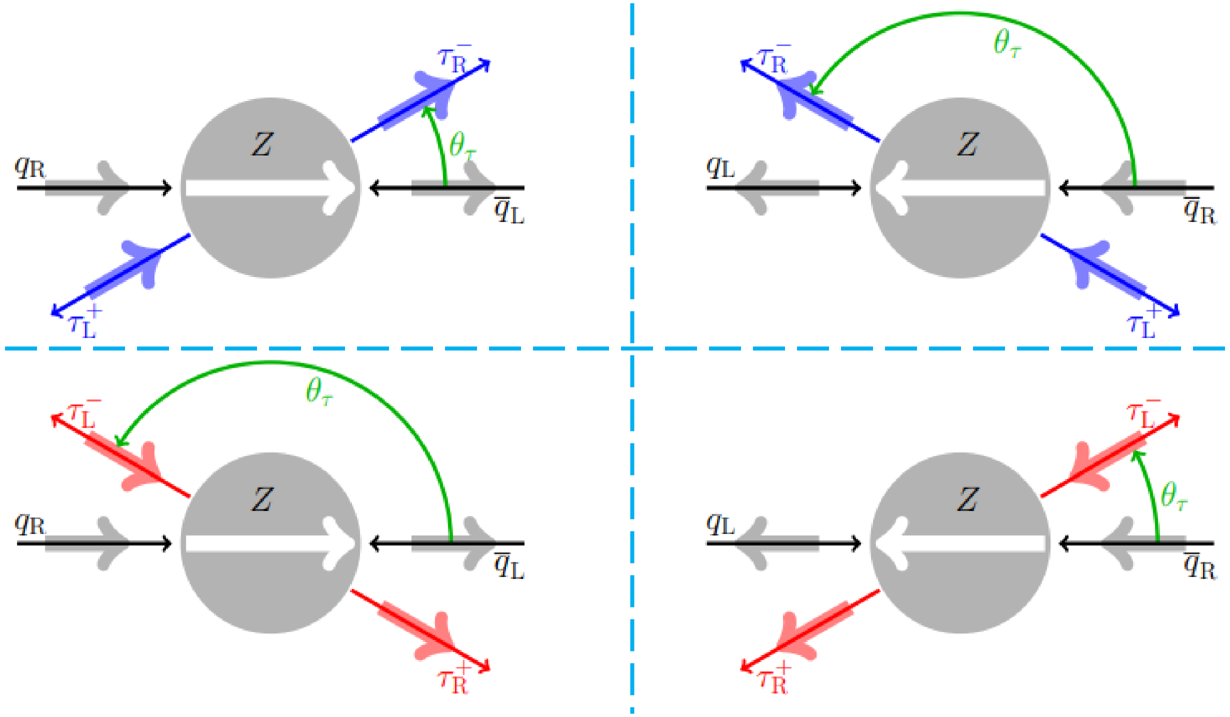


$$iM_{RR}(Z) = \frac{ig_z^2}{(s - m_Z^2 + im_Z\Gamma_Z)} g_R^{(f)} g_R^{(q)} \bar{v}_\downarrow(p')\gamma^\mu u_\uparrow(p) \bar{u}_\uparrow(k)\gamma_\mu v_\downarrow(k') = \frac{ig_z^2}{(s - m_Z^2 + im_Z\Gamma_Z)} g_R^{(f)} g_R^{(q)} s(1 + cos\theta^*)$$

$$|M_{RR}|^2 = \frac{s^2 g_z^4 \left[g_R^{(f)} g_R^{(q)}\right]^2}{(s - m_Z^2)^2 + (m_Z\Gamma_Z)^2} [1 + cos\theta^*]^2$$

$$q_R\bar{q}_L \rightarrow Z \rightarrow \tau_R^-\tau_L^+$$

$$q_L\bar{q}_R \rightarrow Z \rightarrow \tau_R^-\tau_L^+$$



$$q_R\bar{q}_L \rightarrow Z \rightarrow \tau_L^-\tau_R^+$$

$$q_L\bar{q}_R \rightarrow Z \rightarrow \tau_L^-\tau_R^+$$

Figure 1: The four possible helicity states of incoming quarks and outgoing τ leptons. Thin arrows depict the direction of movement and the thick arrows show the spin of the particles. The angle θ_τ is the scattering angle of the τ^- lepton with respect to the quark momentum in the rest frame of the Z boson.

Scheme taken from [2]

Equivalence between photons and Z:

$$g_R^{(f)} \to Q^{(f)};\quad g_L^{(q)} \to -Q^{(q)};\quad g_z^4 \to e^4;\quad \frac{1}{(s-m_Z^2)^2+(m_Z\Gamma_Z)^2} \to \frac{1}{s^2}\ \text{because } m_\gamma = 0$$

	RR	RL	LR	LL
$\lvert M_Z\rvert^2$	$\frac{s^2 g_z^4\left[g_R^{(f)} g_R^{(q)}\right]^2}{(s-m_Z^2)^2+(m_Z\Gamma_Z)^2}[1+cos\theta^*]^2$	$\frac{s^2 g_z^4\left[g_R^{(f)} g_L^{(q)}\right]^2}{(s-m_Z^2)^2+(m_Z\Gamma_Z)^2}[1+cos\theta^*]^2$	$\frac{s^2 g_z^4\left[g_L^{(f)} g_R^{(q)}\right]^2}{(s-m_Z^2)^2+(m_Z\Gamma_Z)^2}[1+cos\theta^*]^2$	$\frac{s^2 g_z^4\left[g_L^{(f)} g_L^{(q)}\right]^2}{(s-m_Z^2)^2+(m_Z\Gamma_Z)^2}[1+cos\theta^*]^2$
$\lvert M\gamma\rvert^2$	$e^4\left[Q^{(f)}Q^{(q)}\right]^2[1+cos\theta^*]^2$	$e^4\left[Q^{(f)}Q^{(q)}\right]^2[1-cos\theta^*]^2$	$\left[Q^{(f)}Q^{(q)}\right]^2[1-cos\theta^*]^2$	$e^4\left[Q^{(f)}Q^{(q)}\right]^2[1+cos\theta^*]^2$
$M_\gamma M_Z$	$\frac{g_Z^2 e^2 Q^{(f)}Q^{(q)} g_R^{(f)} g_R^{(q)}}{(s-m_Z^2+im_Z\Gamma_Z)} s(1+cos\theta^*)^2$	$\frac{g_Z^2 e^2 Q^{(f)}Q^{(q)} g_R^{(f)} g_L^{(q)}}{(s-m_Z^2+im_Z\Gamma_Z)} s(1-cos\theta^*)^2$	$\frac{g_Z^2 e^2 Q^{(f)}Q^{(q)} g_L^{(f)} g_R^{(q)}}{(s-m_Z^2+im_Z\Gamma_Z)} s(1-cos\theta^*)^2$	$\frac{g_Z^2 e^2 Q^{(f)}Q^{(q)} g_L^{(f)} g_L^{(q)}}{(s-m_Z^2+im_Z\Gamma_Z)} s(1+cos\theta^*)^2$

$$\left|M^{(RR)}\right|^2 = \left|M_\gamma^{(RR)}\right|^2 + \left|M_Z^{(RR)}\right|^2 + 2Re\left\{M_\gamma^{(RR)} M_Z^{(RR)}\right\}$$

With the table we can calculate any combination

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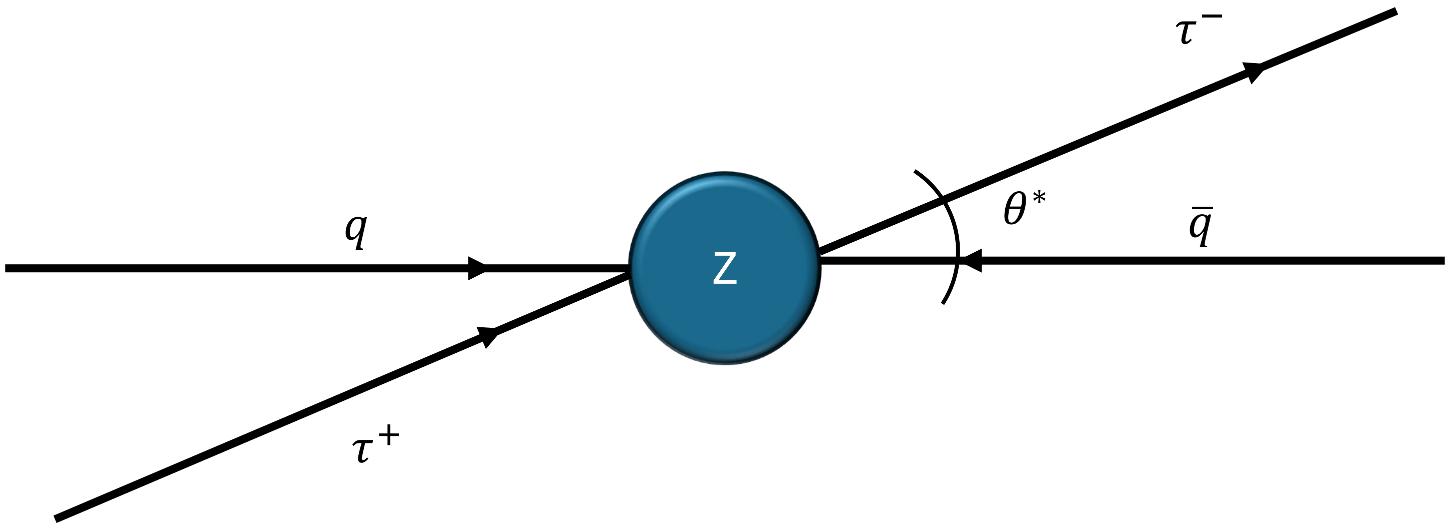
Differencial xsection

- In the M calculation, we have observed a dependence with the angle θ^* in the Z frame reference.



We can estimate:

$$\frac{d\sigma}{dcos\theta^*} = \frac{|M|^2}{32\pi s}$$

Undefined polarization state

Longitudinal and transversal

$$\frac{d\sigma}{dcos\theta^*} = \frac{1}{3}\left(\frac{|M|^2}{32\pi s}\right) \rightarrow \frac{d\sigma_{RR}}{dcos\theta^*} = \frac{1}{3}\left(\frac{|M_{RR}|^2}{32\pi s}\right)$$

Test

$$\frac{d\sigma_{RR}}{d[cos\theta^*]} = \frac{1}{3}\left(\frac{1}{32\pi s}\right)\left[e^4\left[Q^{(f)}Q^{(q)}\right]^2 + \frac{s^2 g_Z^4\left[g_R^{(f)}g_R^{(q)}\right]^2}{(s-m_Z^2)^2+(m_Z\Gamma_Z)^2} + 2e^2Q^{(f)}Q^{(q)}g_R^{(f)}g_R^{(q)}Re\left\{\frac{sg_Z^2}{(s-m_Z^2+im_Z\Gamma_Z)}\right\}\right](1+cos\theta^*)^2$$

$$\frac{d\sigma_{RR}}{d[cos\theta^*]} = \frac{1}{3}\left(\frac{4\pi\alpha^2}{s}\right)\frac{1}{2}\left[\frac{1}{4}\left[Q^{(f)}Q^{(q)}\right]^2 + 2Q^{(f)}Q^{(q)}g_R^{(f)}g_R^{(q)}Re\{\chi(s)\} + |\chi(s)|^2\left[g_R^{(f)}g_R^{(q)}\right]^2\right](1+cos\theta^*)^2$$

Where:

$$\alpha = \frac{e^2}{4\pi} \qquad \chi(s) = \frac{sG_F m_Z^2}{2\pi\sqrt{2}\alpha(s-m_Z^2+im_Z\Gamma_Z)}$$

We can extend our result to the 4 possible combinations

$$\frac{d\sigma_{LL}}{d[cos\theta^*]} = \frac{1}{3}\left(\frac{4\pi\alpha^2}{s}\right)\frac{1}{2}\left[\frac{1}{4}\left[Q^{(f)}Q^{(q)}\right]^2 + 2Q^{(f)}Q^{(q)}g_L^{(f)}g_L^{(q)}Re\{\chi(s)\} + |\chi(s)|^2\left[g_L^{(f)}g_L^{(q)}\right]^2\right](1+cos\theta^*)^2$$

$$\frac{d\sigma_{RL}}{d[cos\theta^*]} = \frac{1}{3}\left(\frac{4\pi\alpha^2}{s}\right)\frac{1}{2}\left[\frac{1}{4}\left[Q^{(f)}Q^{(q)}\right]^2 + 2Q^{(f)}Q^{(q)}g_L^{(f)}g_R^{(q)}Re\{\chi(s)\} + |\chi(s)|^2\left[g_L^{(f)}g_R^{(q)}\right]^2\right](1+cos\theta^*)^2$$

$$\frac{d\sigma_{LR}}{d[cos\theta^*]} = \frac{1}{3}\left(\frac{4\pi\alpha^2}{s}\right)\frac{1}{2}\left[\frac{1}{4}\left[Q^{(f)}Q^{(q)}\right]^2 + 2Q^{(f)}Q^{(q)}g_R^{(f)}g_L^{(q)}Re\{\chi(s)\} + |\chi(s)|^2\left[g_R^{(f)}g_L^{(q)}\right]^2\right](1+cos\theta^*)^2$$

We will describe the differential cross section as a function of the **final-state fermion polarization**, averaging over the possible states of the quarks in the initial configuration.

$$\frac{d\sigma_{XR}}{dcos\theta^*} = \frac{1}{2}\left(\frac{d\sigma_{RR}}{d[cos\theta^*]} + \frac{d\sigma_{LR}}{d[cos\theta^*]}\right) \qquad \frac{d\sigma_{XL}}{dcos\theta^*} = \frac{1}{2}\left(\frac{d\sigma_{RL}}{d[cos\theta^*]} + \frac{d\sigma_{LL}}{d[cos\theta^*]}\right)$$

$$\frac{d\sigma(\lambda)}{dcos\theta^*} = (1+\cos^2\theta^*)\left\{\frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_1+\mathfrak{J}_2+\mathfrak{J}_3)\right\} + 2cos\theta^*\left\{\frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_6+\mathfrak{J}_7)\right\} - \lambda\left[(1+\cos^2\theta^*)\left\{-\frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_4+\mathfrak{J}_5)\right\} + 2cos\theta^*\left\{-\frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_8+\mathfrak{J}_9)\right\}\right]$$

$$\lambda = \begin{cases} +1 & f\to R \\ -1 & f\to L \end{cases}$$

$$F_0^f = \frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_1+\mathfrak{J}_2+\mathfrak{J}_3) \qquad F_1^f = \frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_6+\mathfrak{J}_7) \qquad F_2^f = -\frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_8+\mathfrak{J}_9) \qquad F_3^f = -\frac{1}{2}\left(\frac{2\pi\alpha^2}{3s}\right)(\mathfrak{J}_4+\mathfrak{J}_5)$$

$$\frac{d\sigma(\lambda)}{dcos\theta^*} = (1+\cos^2\theta^*)F_0^f + 2cos\theta^* F_1^f - \lambda\left[(1+\cos^2\theta^*)F_2^f + 2cos\theta^* F_3^f\right]$$

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Tau polarization

We can define **polarization asymmetry** as the asymmetry between the number of Right-hand and Left-hand τ^- [6].

$$P_{\tau^-} = \frac{N_R - N_L}{N_R + N_L} = \frac{\left.\frac{d\sigma_{XR}}{dcos\theta^*}\right|_{\tau^-} - \left.\frac{d\sigma_{XL}}{dcos\theta^*}\right|_{\tau^-}}{\left.\frac{d\sigma_{XR}}{dcos\theta^*}\right|_{\tau^-} + \left.\frac{d\sigma_{XL}}{dcos\theta^*}\right|_{\tau^-}} = \frac{\frac{d\sigma(\lambda=-1)}{dcos\theta^*} - \frac{d\sigma(\lambda=+1)}{dcos\theta^*}}{\frac{d\sigma(\lambda=-1)}{dcos\theta^*} + \frac{d\sigma(\lambda=+1)}{dcos\theta^*}}$$

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

$$P_{\tau^-} = \frac{(1+\cos^2\theta^*)F_2^f + 2cos\theta^* F_3^f}{(1+\cos^2\theta^*)F_0^f + cos\theta^* F_1^f}$$

Integrating over all possible values $cos\theta^*$.

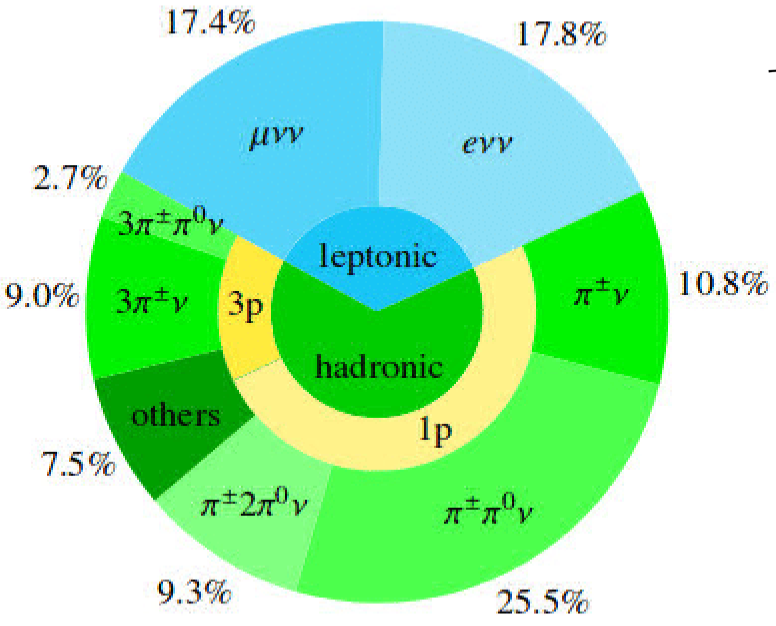
$$\langle P_{\tau^-}\rangle = \int_{-1}^{1} \frac{(1+\cos^2\theta^*)F_2^f + 2cos\theta^* F_3^f}{(1+\cos^2\theta^*)F_0^f + cos\theta^* F_1^f}\, dcos\theta^* = -\frac{F_2^f}{F_0^f}$$

f	T_3^f	Q_f	g_A^f	g_V^f	$\mathcal{A}_f$
ν_τ	1/2	0	1/2	1/2	1
τ^-	-1/2	-1	-1/2	-0.04	0.16
u	1/2	2/3	1/2	0.19	0.67
d	-1/2	-1/3	-1/2	-0.35	0.94

$$\langle P_{\tau^-}\rangle = -\frac{2g_V^{(f)}g_A^{(f)}}{\left[g_V^{(f)}\right]^2 + \left[g_A^{(f)}\right]^2} = -A_{\tau^-}$$

Experimental observables

τ^{-} *decay*



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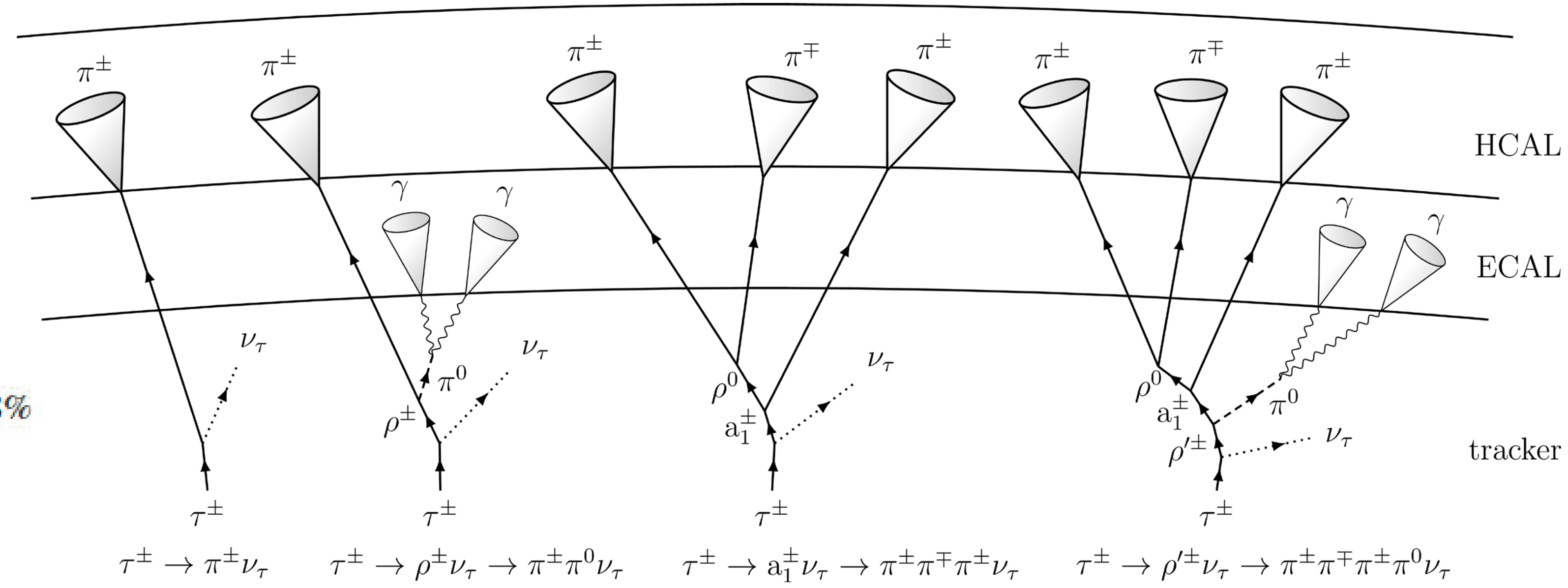

Tau parameters:

$$m_{\tau^-} = (1776.86 \pm 0.12)\text{MeV}$$

$$\tau = (290.3 \pm 0.5)\text{fs}$$

"In the case of a tau decaying to a pion and a neutrino, the neutrino is preferably emitted opposite the spin orientation of the tau to conserve angular moment"

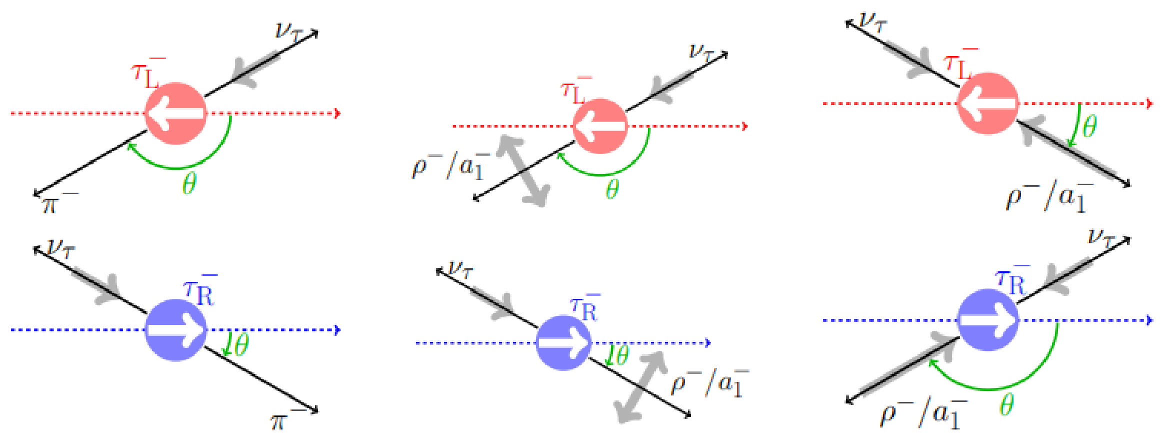

Figure 2: Definition of the angle θ in the τ^- lepton rest frame for the decays $\tau^- \rightarrow h^-\nu$ ($h^- = \pi^-, \rho^-, a_1^-$), upper row for left-handed τ lepton τ_L^-, lower row for right-handed τ lepton τ_R^-. The thick arrows indicate the spin directions of the particles.

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$$\frac{d\sigma(\lambda)}{d\cos\theta^*} = (1+\cos^2\theta^*)F_0^f + 2\cos\theta^* F_1^f - \lambda\left[(1+\cos^2\theta^*)F_2^f + 2\cos\theta^* F_3^f\right]$$

$$\lambda = \begin{cases} +1 & f \rightarrow R \\ -1 & f \rightarrow L \end{cases}$$

$$\cos\theta = \hat{\boldsymbol{n}}_{\tau^-} \cdot \hat{\boldsymbol{n}}_{h^-} \approx 2x - 1$$

$$\gamma = \frac{E_{h^\pm} - E_{h^0}}{E_{Total}}$$

Where:

$$x = \frac{E_{h^\pm}}{E_\tau}$$

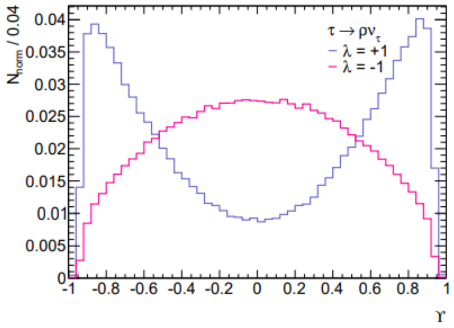

Figure 3.11: The distribution of the charged energy asymmetry, Υ, from rho decays divided into left-handed (pink) and right-handed (blue) samples. Each sample is normalized to one.

$\tau^- \rightarrow \pi\nu$ $\tau^- \rightarrow \rho\nu$

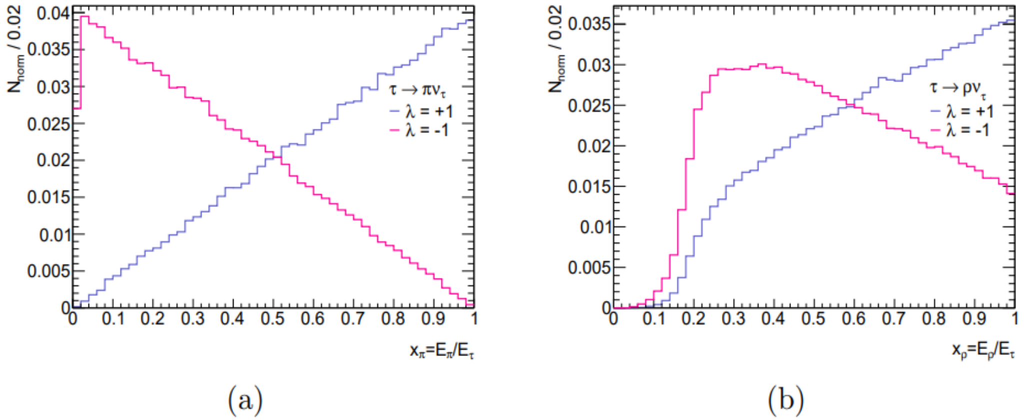

Figure 3.7: Distribution of fraction of visible energy, x, in pion (a) and rho (b) decays divided into left-handed (pink) and right-handed (blue) samples.

Plots taken from [7]

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Partonic level — **MadGraph** → *Hadronization* — **Pythia** → *Detector* — **Delphes**

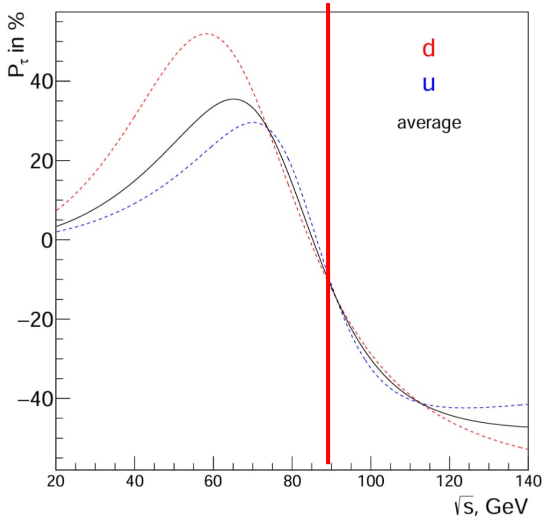
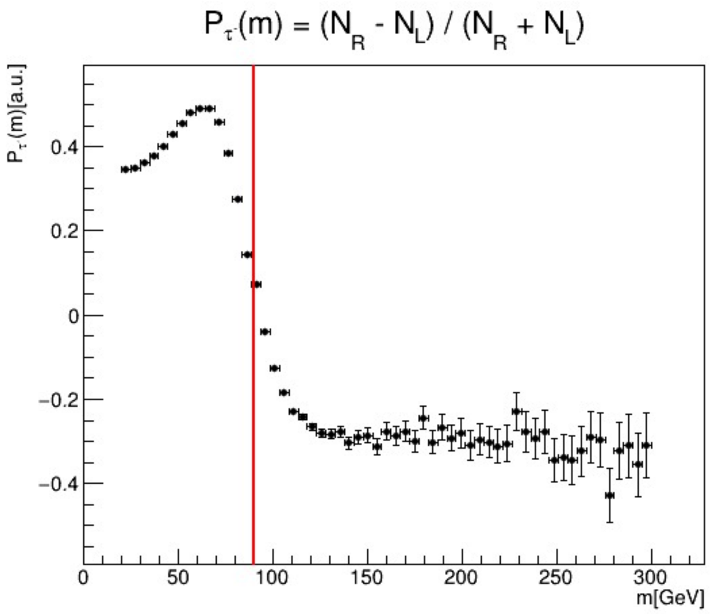


Figure 7: The τ polarization as a function of $\sqrt{s}$. *Dashed blue curve* polarization for $u\bar{u}$ in the initial state, *Dashed red curve* for $d\bar{d}$. *Solid curve* the average with the factor α_u = 0.423 taken from Monte Carlo simulation. The parameters $m_Z = 91.1867GeV$, $\Gamma_Z = 2.4939GeV$, $\sin^2\theta_W = 0.23155$ are used in the tree-level calculation.

Reference plot taken From [8]



Our results

Jet:

- TauTag: 0 or 1 for a jet that has been tagged as a tau
- Nneutrals: number of neutral constituents.
- Ncharged: number of charged constituents: (1)
- Constituents: references to constituents: (-211)

Click here

Summary

Theoretical calculations of the tau polarization study were developed for the scenario $q\bar{q} \rightarrow Z \rightarrow \tau^{-}\tau^{+}$.

- Interferences between virtual photons and Z bosons were considered.
- The differential xsection was obtained for the 4 possible combinations of final and initial states (RR, RL, LR, LL).
- The dependence of xsection with tau polarization was quantified using the λ parameter.
- Some observables to be considered were identified: x and $cos\theta$ (work is in progress).

References

[1] https://www.quantumdiaries.org/2012/07/16/spinning-out-of-control/

[2] https://arxiv.org/pdf/2309.12408

[3] *https://cds.cern.ch/record/1464097/files/CERN-THESIS-2012-091.pdf*

[4] https://cds.cern.ch/record/1537953/files/ms_salvatore_di_guida.pdf

[5] *https://www.hep.phy.cam.ac.uk/~thomson/partIIIparticles/handouts/Handout_14_2011.pdf*

[6] *https://inis.iaea.org/collection/NCLCollectionStore/_Public/27/020/27020655.pdf (p.27)*

[7] *https://cds.cern.ch/record/1464097/files/CERN-THESIS-2012-091.pdf*

[8] *https://cds.cern.ch/record/2206964/files/TS2016_014_2.pdf*

THANKS!

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Backup

Coupling constants: Weak interaction

$$\begin{bmatrix} A_\mu \\ Z_\mu \end{bmatrix} = \begin{bmatrix} cos\theta_W & sen\theta_W \\ -sen\theta_W & cos\theta_W \end{bmatrix} \begin{bmatrix} B_\mu \\ W_\mu^{(3)} \end{bmatrix}$$

$$Q = \frac{Y}{2} + T_3 \rightarrow Y = 2[Q - T_3]$$

$$g_V = T_3 - 2Q_f sen^2\theta_W$$

$$g_A = T_3$$

$$g_L^{(q)} = T_3^{(q)} - Q^{(q)} sen^2\theta_W \quad y \quad g_R^{(q)} = -Q^{(q)} sen^2\theta_W$$

$$g_L^{(f)} = T_3^{(f)} - Q^{(f)} sen^2\theta_W \quad y \quad g_R^{(f)} = -Q^{(f)} sen^2\theta_W$$

$Cos\theta^*$

$$S_z = -1$$

Polarización transversal:

$$\epsilon_-^\mu = \frac{1}{\sqrt{2}}(0,1,-i,0)$$

$$S_z = 0$$

Polarización longitudinal:

$$\epsilon_0^\mu = \frac{1}{m}(p_z, 0,0,E)$$

$$S_z = +1$$

Polarización transversal:

$$\epsilon_+^\mu = -\frac{1}{\sqrt{2}}(0,1,i,0)$$

- Polarización transversal negativa:

$$iM_- = -\frac{i}{\sqrt{2}}\left[\frac{1}{\sqrt{2}}(0,1,-i,0)\right]\cdot\left[2\frac{E g_V g_W}{2cos\theta_W}(0,-cos\theta^*,-i,sen\theta^*)\right] = \frac{1}{2}\frac{E g_V g_W}{cos\theta_W}[1+cos\theta^*]$$

- Polarización longitudinal:

$$iM_0 = -\frac{i}{\sqrt{2}}\left[\frac{1}{m_Z}(p_{z,Z},0,0,E_z)\right]\cdot\left[2\frac{E g_V g_W}{2cos\theta_W}(0,-cos\theta^*,-i,sen\theta^*)\right] = -\frac{1}{\sqrt{2}}\frac{E E_z g_V g_W}{cos\theta_W m_Z} sen\theta^*$$

- Polarización transversal positiva:

$$iM_+ = -\frac{i}{\sqrt{2}}\left[-\frac{1}{\sqrt{2}}(0,1,i,0)\right]\cdot\left[2\frac{E g_V g_W}{2cos\theta_W}(0,-cos\theta^*,-i,sen\theta^*)\right] = \frac{1}{2}\frac{E g_V g_W}{cos\theta_W}[1-cos\theta^*]$$

Variables used in the differencial xsection calculation

Variable	Value
$\mathfrak{J}_1$	$\frac{2}{4}\left[Q^{(f)}Q^{(q)}\right]^2$
$\mathfrak{J}_2$	$Q^{(f)}Q^{(q)}g_V^{(f)}g_V^{(q)}Re\{\chi(s)\}$
$\mathfrak{J}_3$	$\frac{\lvert\chi(s)\rvert^2}{8}\left(\left[g_V^{(f)}\right]^2+\left[g_A^{(f)}\right]^2\right)\left(\left[g_V^{(q)}\right]^2+\left[g_A^{(q)}\right]^2\right)$
$\mathfrak{J}_4$	$\frac{g_V^{(q)}g_A^{(q)}\lvert\chi(s)\rvert^2}{4}\left[\left[g_V^{(f)}\right]^2+\left[g_A^{(f)}\right]^2\right]$
$\mathfrak{J}_5$	$Q^{(f)}Q^{(q)}g_V^{(f)}g_A^{(q)}Re\{\chi(s)\}$
$\mathfrak{J}_6$	$Q^{(f)}Q^{(q)}g_A^{(f)}g_A^{(q)}Re\{\chi(s)\}$
$\mathfrak{J}_7$	$\frac{\lvert\chi(s)\rvert^2}{2}g_V^{(f)}g_V^{(q)}g_A^{(f)}g_A^{(q)}$
$\mathfrak{J}_8$	$\frac{g_V^{(f)}g_A^{(f)}\lvert\chi(s)\rvert^2}{4}\left[\left[g_V^{(q)}\right]^2+\left[g_A^{(q)}\right]^2\right]$
$\mathfrak{J}_9$	$Q^{(f)}Q^{(q)}g_A^{(f)}g_V^{(q)}Re\{\chi(s)\}$

Delphes: Studies

$$\text{Assymetry\_tau(antitau)} = \frac{2p_T^{(h^{\mp})}}{p_T^{(\tau^{\mp})}} - 1$$