Elementary Particle Physics Report

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In this report, we compute the cross-section for the production of top quark pairs ($t\bar{t}$) in proton-proton collisions at the Large Hadron Collider (LHC) with a centre-of-mass energy of $\sqrt{s} = 7$ TeV and an integrated luminosity of 50 pb^{-1}. We obtained a cross-section of $163.40 \pm (21.39)_{stat} \pm (16)_{sys}$ pb that is consistent with the theoretically predicted value of $173.60^{+11.24}_{-11.78}$ pb computed at next-to-next-to leading order in QCD.

In the second part of this report, we study the charge asymmetry of the pair of W bosons. As W bosons are heavy, they decay before they can be reconstructed by the detector. Therefore, in our analysis, we study the reconstructed μ's produced from the decay of W bosons. We obtain a charge asymmetry of 0.137 ± 0.008 for $|\eta| < 0.4$ of the muons. This result is also consistent with the theoretical predictions.

I. INTRODUCTION

Elementary particle physics explores the most fundamental constituents of matter and the forces that govern their interactions. At present, the Standard Model (SM) provides the best description of all the forces in nature except gravity. However, there must be physics beyond the SM, as it cannot explain dark matter, dark energy, neutrino oscillation, matter-antimatter asymmetry, etc. One of the common techniques to unviel New Physics (NP) is to study the scattering of fundamental particles at high energies in particle colliders and to analyze the kinematics of final decay products.

One of the most powerful and largest colliders is the Large Hadron Collider (LHC) at CERN that has been running since 2008. One of the major discoveries of the LHC is the Higgs boson in 2012 [1, 2], which is the first fundamental scalar particle observed in nature. Although, since 2012 no new fundamental particle has been discovered at the LHC but with the high-lumionisty upgrade of the LHC in the next few years, the potential to discover NP is promising. Events at the LHC are stored in the form of `ROOT` files which we analyze in this report for two different analyses. The events analyzed in the reports were collected at the LHC at a center-of-mass energy of $\sqrt{s} = 7$

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TeV and for an integrated luminosity of 50 pb^{-1}.

At first, we focus on computing the production cross section of top-quark pairs ($t\bar{t}$). The top quark is the heaviest elementary particle in the SM and they decay almost 100 % to the b quark and W bosons, as shown in Fig. 1. By analyzing these decay products, we can measure the $t\bar{t}$ production cross section and compare it with theoretical predictions.

In the second part, we investigate the charge asymmetry of the W bosons ($W^{\pm}$). This study examines the difference in production rates of these two bosons, which is influenced by the distribution of quarks within the protons. Measuring this asymmetry in the muon decay channel provides insight into the proton's internal structure and tests the accuracy of parton distribution functions (PDFs).

Both analyses are essential for testing the robustness of the SM and exploring potential new physics. The report outlines the methods used for these measurements, discusses the results obtained, and compares them with theoretical predictions.

II. PRODUCTION CROSS-SECTION OF TOP QUARK PAIRS

We start with our analysis to compute the cross section of the process $pp \to t\bar{t}$ from the data collected at the LHC. The dominant gluon-fusion Feynman diagram of this process is shown in Fig. 1 for the $t\bar{t}$ process. The mean lifetime of the top quarks is too short to enable top-quark reconstruction. Therefore, the final-state decay products of the top quark from energy deposits in the detector are measured, and the top quark is indirectly reconstructed.

As shown in Fig. 1, decay of the top-quark pair produces different jets and leptons, which can be reconstructed by the detector. Here, we consider the semileptonic decay of the top quark pair, which means that one W decays to two quarks and another W to μ and neutrino. In the following, I describe my analysis and cuts to compute the $t\bar{t}$ cross-section.

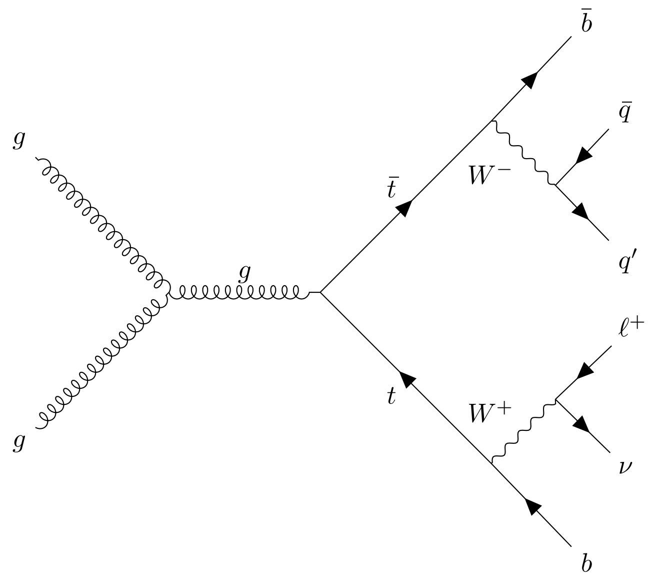

FIG. 1: Feynman diagram for $t\bar{t}$ production via the dominant gluon fusion process at the LHC subsequently decaying to four quarks, one lepton, and one neutrino.

A. Object and Event Selection

We have been provided with 9 `ROOT` files, of which `data.root` contains the actual events recorded in the LHC and the other root files `ttbar.root`, `qcd.root`, `dy.root`, `single_top.root`, `ww.root`, `wjets.root` and `wz.root` contain events generated using automated software based on Monte Carlo algorithms. As actual events, stored in `data.root`, have events other than $t\bar{t}$ events, we need to apply conditions (cuts) on the final decaying particles before computing the $t\bar{t}$ cross section. For this reason, simulated data using the Monte Carlo simulation (MC) are used to check the effectiveness of the cuts applied and estimate the number of background events to calculate the final cross section. Therefore, we must apply some conditions (cuts) on both the data and the backgrounds to remove the backgrounds from the real data. Comparing the kinematic properties of the simulated $t\bar{t}$ and other processes with the actual data, we can calculate the final cross section. In the following, we describe the object selection cuts applied on muons, jets, etc. to determine which decay particles will be considered subsequently while applying event selections conditions.

1. **Muons** : To make sure that the muons were produced from hard scattering and satisfy the online and offline trigger requirements, we imposed the condition that its transverse momentum is $\mu_{\mathrm{PT}} \geq 25$ GeV. Next, to make sure that it is isolated we applied $\mu_{\mathrm{Iso}}/\mu_{\mathrm{PT}} < 0.05$. The isolation condition is essential as we expect the muons decaying from W bosons in

$t\bar{t}$ to be isolated. Furthermore, due to constraints from the angular width of the calorimeter to apply the condition $|\eta| < 2.1$, where $\eta = -\log(\tan(\theta/2)$ and θ is the angle between the particle momentum and positive direction of the beam axis.

2. **Jets** : To make sure that the jets were produced from hard scattering and satisfy the online and offline trigger requirements, we imposed the condition $j_{\rm PT} > 35$ GeV on the transverse momentum of all the jets. Furthermore, to tag b-jets we used the condition Jet_btag > 2, where Jet_btag is the b-tagging discriminator obtained from an algorithm that identifies the secondary vertex due to the decay of B mesons.

After applying the above object selection conditions, we apply event selection cuts to reduce the signal-to-background ratio and subsequently compute the $t\bar{t}$ cross section.

1. **nIsoMu $\geq$ 1:** This condition is imposed to ensure that at least one isolated muon is present in the event. By requiring the presence of at least one isolated muon, we can enhance the signal-to-background ratio by reducing contributions from background processes that do not produce isolated muons, such as QCD multijet events. This enhances the signal, as we expect muons from the leptonic decays of W bosons produced from decay $t\bar{t}$.

2. **Njets $\geq$ 4:** As can be seen in Fig. 1, another characteristic feature of the $t\bar{t}$ events is the presence of at least 4 jets (taking into account initial and final-state radiation). Hence, this enhances the signal, while reducing background from processes such as in `single_top.root`,etc, which are expected to have fewer than 4 jets.

3. **Nbjets $\geq$ 2.0:** We apply this condition because we expect at least two b-jets from the decay of $t\bar{t}$ events as we know t decays almost 100 % to the b and W boson.

4. **metPt $>$ 30 GeV:** In the leptonic decays of W bosons in $t\bar{t}$ events, neutrinos are produced. However, as neutrinos interact feebly with other particles, they escape the detector and therefore cannot be reconstructed. Therefore, they manifest as missing transverse momentum (MET) in the detector. By setting a threshold of 30 GeV for MET, we ensure that the event has a sufficient amount of missing transverse momentum, which is a characteristic feature of $t\bar{t}$ events. This criterion helps suppress background events where neutrinos are not expected.

We applied the above cuts on all the simulated `ROOT` files and observed that our cuts were able to remove most background events, except for events in `single_top.root`. We then applied the cuts of the real events stored in `data.root` and counted the number of events that passed all cuts. We show various kinematic properties of the final decay particles in Fig. 2.

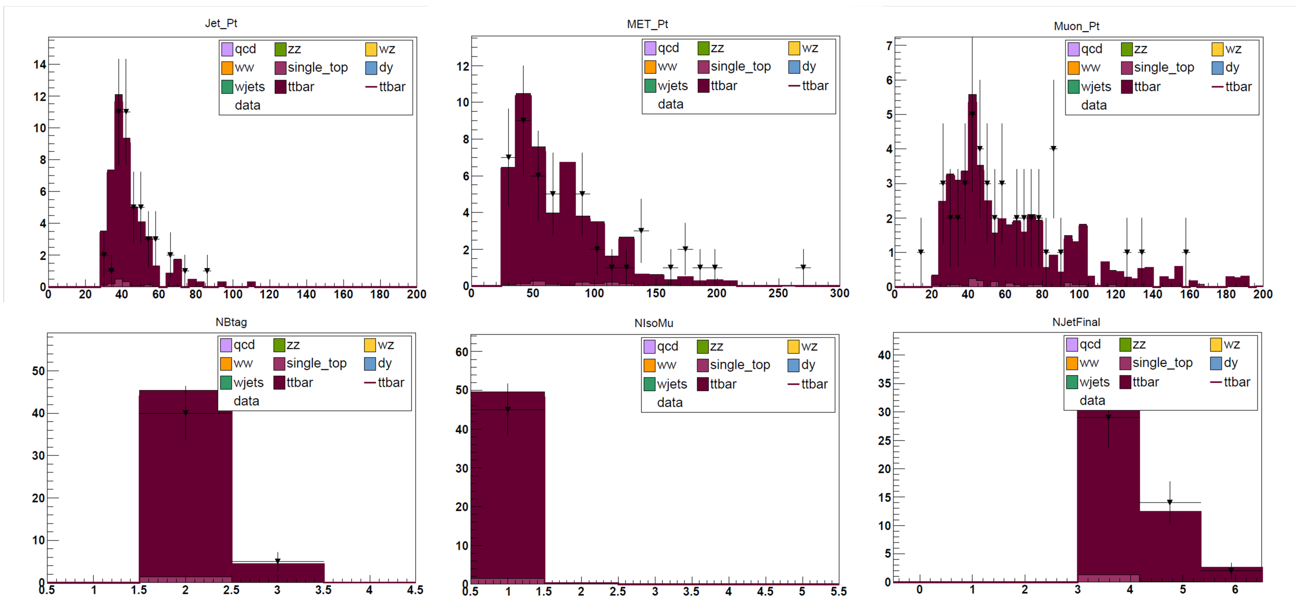

FIG. 2: Various kinematic distributions of final particles of events in `data.root`, `ttbar.root` and other simulated background samples passing the event selection cuts. We observe that the cuts were good enough to remove most of the background events expect for `single_top.root` events.

B. Numerical results and $t\bar{t}$ cross-section

The numerical results are in Table I. It is shown that most of the backgrounds are removed with the applied cuts, such as DY, QCD, W+Jets, WW, ZZ, and WZ, and the only remaining background is for the single top. The remaining background can be removed using background subtraction. We should first calculate the signal-to-background ratio (S/B), which gives us only 3% of the MC are from single tops. Therefore, it means 3% of the actual data is also from the single top and should be removed, leaving only 44 of the remaining data.

TABLE I: Analysis Summary

Process	**Entries**	**MC percentage (%)**	**Integral after cut**	**Percentage (%)**
ttbar	36941	15.35	48.3±3.6	97
DY	77729	32.30	0	0
QCD	142	0.05	0	0
Single Top	5684	2.36	1.5±0.3	3
W+Jets	109737	45.60	0	0
WW	4580	1.90	0	0
ZZ	2421	1.00	0	0
WZ	3367	1.39	0	0
Data	469384	-	45	-

The cross-section can be calculated using this formula:

$$\sigma = \frac{N}{L \times \epsilon_{\text{trigger}} \times A} \tag{1}$$

Here, L, $\epsilon_{\text{trigger}}$, and A are luminosity, trigger efficiency, and acceptance, respectively, and you can see the calculated amounts in the Table II. In this report, we considered luminosity to be 50 pb^{-1}. To compute the cross-section, we first need to compute the Acceptance and Triggered efficiency and then use Eq. 1 we can compute the cross-section of $163.40 \pm (21.39)_{stat} \pm (16)_{sys}$ pb. By comparing this result with $173.60^{+11.24}_{-11.78}$ pb [3], we can see it is nearly the same as in the literature, although it is not the same, maybe it is due to the more accurate cuts they applied.

TABLE II: Summary of parameters

Parameter	**Value**	**Uncertainty**
Integral without Cut	7929.47	45.47
Integral with Cut	48.36	3.60
Acceptance	**0.0061**	**2.07e-07**
Events Passed	208	-
Events Passed with Trigger	42.45	-
Trigger Efficiency	**0.878**	**0.0086**
Cross-section	**163.40 pb**	**21.39 pb**
Cut Efficiency	0.563	-

III. W CHARGE ASYMMETRY MEASUREMENT

In the second part of this report, we calculate the charge asymmetry of $W^{\pm}$ bosons in events stored in `data.root`. As the W boson has a short lifetime, it decays to a pair of quarks or to a lepton and antineutrino, which can be subsequently reconstructed by the detector. In this analysis, we study the leptonic decays of W bosons to muons and compute the difference in the number of positive and negative muons as a function of pseudo-rapidity. Hence, the analysis is performed by selecting $W^{\pm}$ bosons decaying in the muon channel, $W^{\pm} \to \mu^{\pm}\nu$. Like our previous analysis to compute the $t\bar{t}$ cross section, we apply object selection cuts and then event selection cuts.

A. Object and Event Selection

As in this analysis only muons are relevant, therefore, object selection cuts are applied only to the muons as described below.

1. **Muons** : To ensure that the muons were produced from hard scattering and not from pileup, we imposed the condition that its transverse momentum is $\mu_{\mathrm{PT}} \geq 30$ GeV. Next, to ensure that it is isolated, we applied $\mu_{\mathrm{Iso}}/\mu_{\mathrm{PT}} < 0.05$, as in $t\bar{t}$. Finally, as in this analysis we aim to study the asymmetry as a function of pseudo-rapidity, we considered the following conditions on $|\eta|$ independently.

$$|\eta| < 0.4, \quad 0.4 < |\eta| < 0.8, \quad 0.8 < |\eta| < 1.5, \quad 1.5 < |\eta| < 1.8, \quad 1.8 < |\eta| < 2.1 \tag{2}$$

After object selection, we apply the following conditions to select events that are retained to compute the charge asymmetry of W bosons.

1. **nIsoMu $\geq$ 1:** This condition is imposed to ensure that at least one isolated muon is present in the event. This is necessary for our analysis as we want to consider only those events which has atleast one muon due to the leptoni decay of W bosons.

2. **metPt $>$ 30 GeV:** Leptonic decays of W bosons would produce neutrinos. However, because they will escape the detector, they manifest as missing transverse momentum (MET) in the detector. Hence, this cut will reduce the background. In Fig. 3, (a) and (b) are without metPt, and (c) and (d) are with this cut, and we can see it nearly removed most DY backgrounds.

After applying the above cuts, we compute the transverse mass (m_T) of the W boson, which is defined as the sum of the transverse momentum of the selected muon and MET. In Fig. 3 we show the distribution of m_T for both positive and negative W bosons. It is important to note that we have more events in W^+ compared to W^-. The reason is that $W^\pm$ bosons can be produced through the processes $u + \bar{d} \rightarrow W^+$ and $d + \bar{u} \rightarrow W^-$ at the LHC. Since a proton consists of two u valence quarks and one d valence quark, there is a higher production of W^+ compared to W^- due to the higher density of u valence quarks compared to d valence quarks [4].

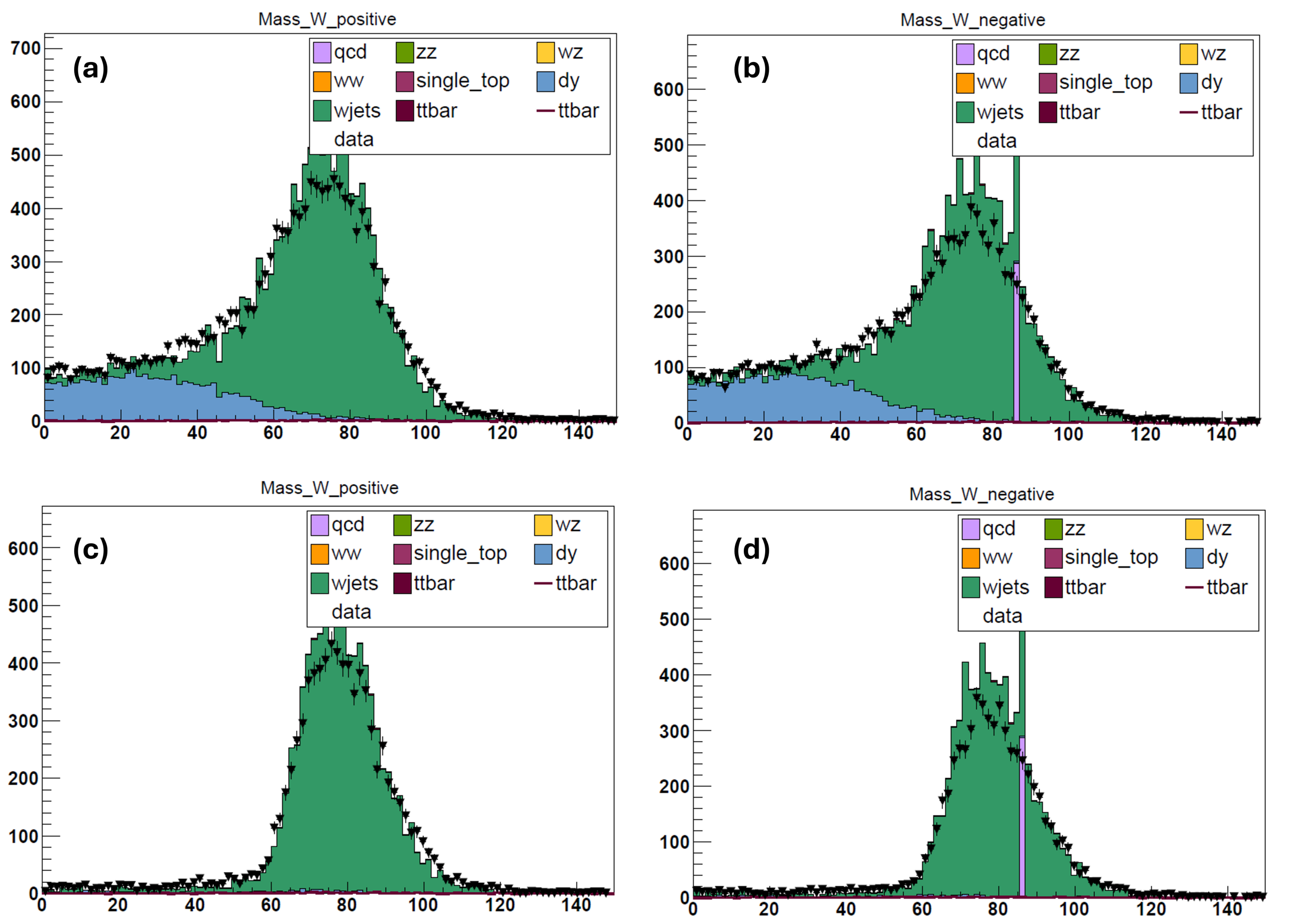

FIG. 3: Distribution of the transverse momentum of W bosons for the selected events. (a) and (b) without metPt > 30 GeV cut and (c) and (d) with this cut.

B. Computing $W^\pm$ asymmetry

In this final part of this report, we calculate the charge asymmetry for different ranges of the pseudorapidity of the selected muons. The $W^\pm$ boson charge asymmetry is defined in Eq. 3;

alternatively, we can also use Eq. 4 because the triggered efficiency is 100%, and we assume that the acceptance of μ^+ and μ^- is nearly equal. Therefore, they cancel out from the numerator and denominator.

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu_\mu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\bar{\nu}_\mu)}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu_\mu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\bar{\nu}_\mu)} \tag{3}$$

$$\mathcal{A} = \frac{N(W^+) - N(W^-)}{N(W^+) - N(W^-)} \tag{4}$$

Initially, we put the $|\eta| < 0.4$, and as you can see in Table III, our value 0.137 ± 0.008, compared to the other papers [5], is consistent with theoretical predictions. Furthermore, we varied the range of $|\eta|$ and observed that the asymmetry value increases as the pseudorapidity increases.

TABLE III: Asymmetry with different pseudorapidity

Pseudorapidity	**N(W^-)**	**S/B (%)**	**N(W^+)**	**S/B(%)**	**Asymmetry**
$\lvert\eta\rvert < 0.4$	6522±81	92	8231±90	96	0.137±0.008
$0.4 < \lvert\eta\rvert < 0.8$	7050±83	96	8898±94	96	0.12±0.008
$0.8 < \lvert\eta\rvert < 1.5$	11246 ± 106	94	15338 ± 123	95	0.16 ± 0.006
$1.5 < \lvert\eta\rvert < 1.8$	4331 ± 65	92	6315.0± 79.46	93	0.19 ± 0.01
$1.8 < \lvert\eta\rvert < 2.1$	3950± 62	89	5953 ± 77	93	0.22 ± 0.01

IV. CONCLUSION

This report presents an analysis of the production cross-section of top quark pairs ($t\bar{t}$) and the charge asymmetry of W bosons ($W^\pm$) in proton-proton collisions at the Large Hadron Collider (LHC). The events used were collected at a center-of-mass energy of $\sqrt{s} = 7$ TeV and an integrated luminosity of 50 pb^{-1}.

Our findings for the $t\bar{t}$ production cross-section, determined to be $163.40 \pm (21.39)_{stat} \pm (16)_{sys}$ pb, align closely with theoretical predictions, confirming our measurement techniques. The detailed analysis procedures, including background subtraction and selection, are fully explained in the report.

Furthermore, we studied $W^\pm$ boson charge asymmetry, particularly in the muon decay channel, which provides significant insights into the internal structure of the proton and the behavior of parton distribution functions (PDFs). A charge asymmetry of 0.137 ± 0.008 for $|\eta| < 0.4$ was obtained.

The observed asymmetry values, increasing with pseudorapidity, match well with expectations and further validate the accuracy of the SM.

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[2] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," *Phys. Lett. B* **716** (2012) 30–61, arXiv:1207.7235 [hep-ex].

[3] M. l Czakon, P. Fiedler, and A. Mitov, "The total top quark pair production cross-section at hadron colliders through O(α_s^4)," *Phys. Rev. Lett.* **110** (2013) .

[4] A. Collaboration, "Measurement of the w charge asymmetry in the $w\,\mu\nu$ decay mode in pp collisions at $\sqrt{s} = 7$ tev with the atlas detector," *Phys. Lett. B* **701** (2011) .

[5] V. I. M. Outschoorn, *Measurement of the Charge Asymmetry of W Bosons Produced in pp Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector*. PhD thesis, Harvard University, Cambridge, MA, May, 2011. Available at: https://lppc.physics.harvard.edu/files/lppc/files/martinez-outschoorn-2.pdf.