Measurement of W Boson Helicity in Top Quark Decay

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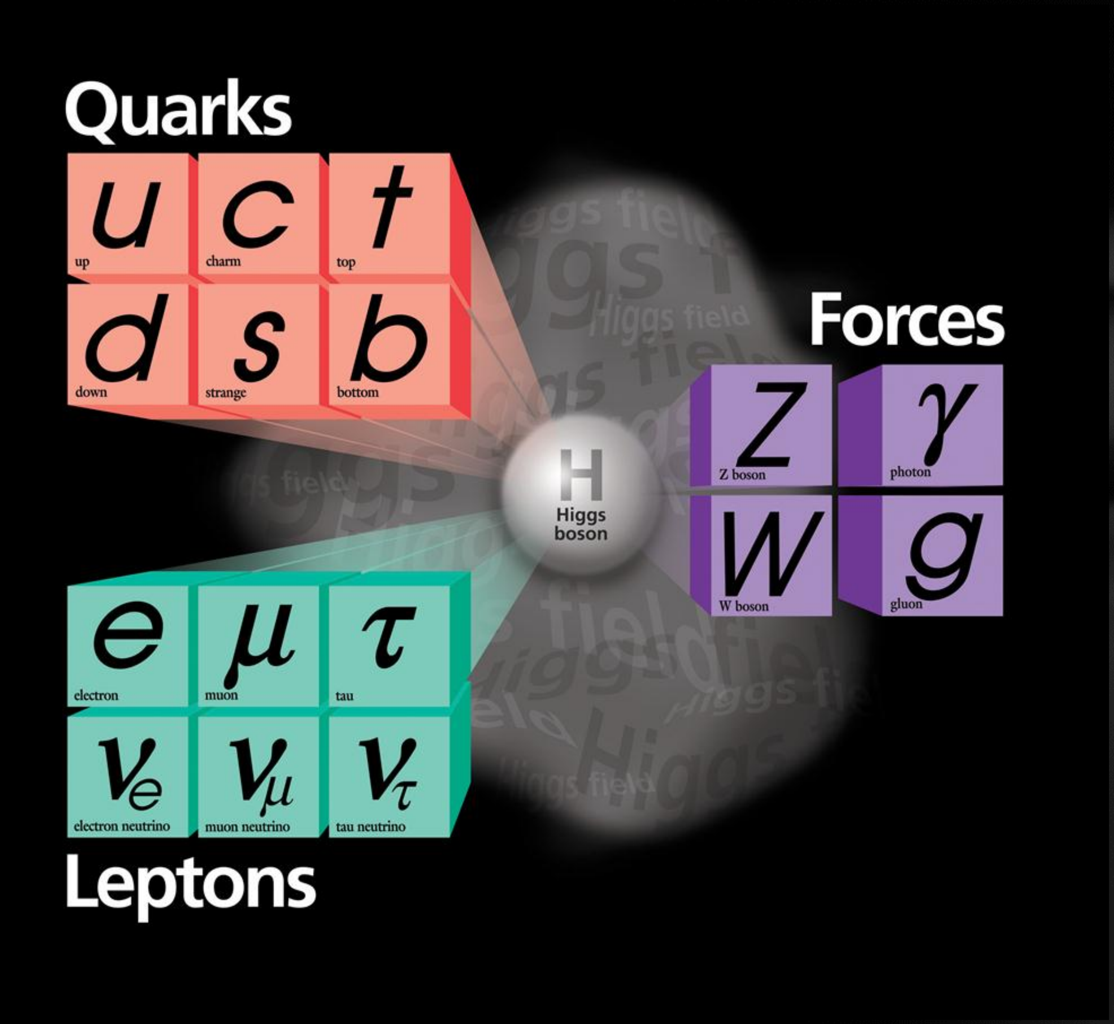
OUTLINE

- **Introduction**
- **Experimental apparatus**
- **Analysis**
- **Conclusion**

INTRODUCTION

Particle Physics

Study the fundamental particles and forces of nature



The Standard Model

- Theoretical basis of modern particle physics.
- All the fundamental particles proposed by the SM, except the Higgs boson, have been observed experimentally.
- However that is not the end of the story !

- Despite the success, the Standard Model is **still not a complete theory** of fundamental particles and forces. There are still many questions unanswered. Some of them are
  - ✓ Why gravity is not included in the standard model?
  - ✓ Why we have more matter than anti-matter?

- Broadly speaking, most of the particle physics experiments are aimed at :
  - Doing precision measurements like measuring top quark mass or W boson mass
  - Searching for evidence of new physics beyond the standard model which can be done in two ways :

1. Search for a signal proposed by some new theory
2. Put the standard model into test - Measure a parameter in standard model and look for any deviation from the standard model prediction

The analysis I am going to present today fall into this 2nd category.

So let's stop for a while and look at the title of this talk :

- **Measurement of** - We know what that means!
- **W boson** – know that too…
- **Helicity** – What is that ? How do we measure that?
- **in Top Quark Decay** – Why top quark?

What is so unique about top quark?

❑ The top quark is the most recently discovered quark , discovered at Fermilab in 1995

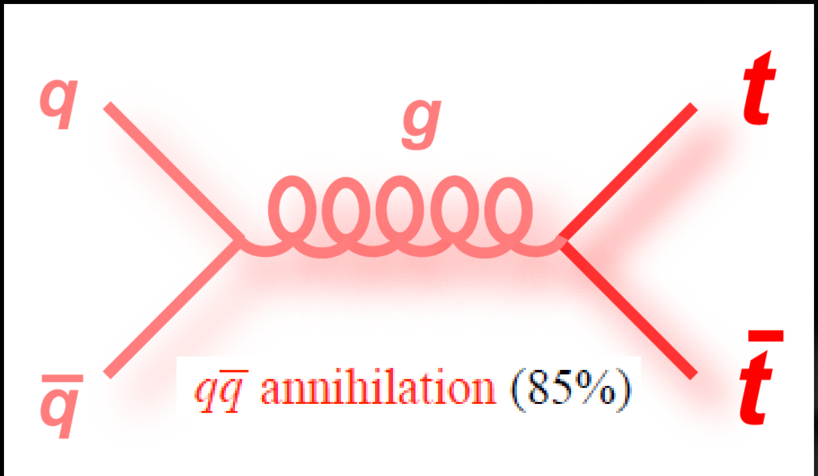
✓ It is the most massive quark

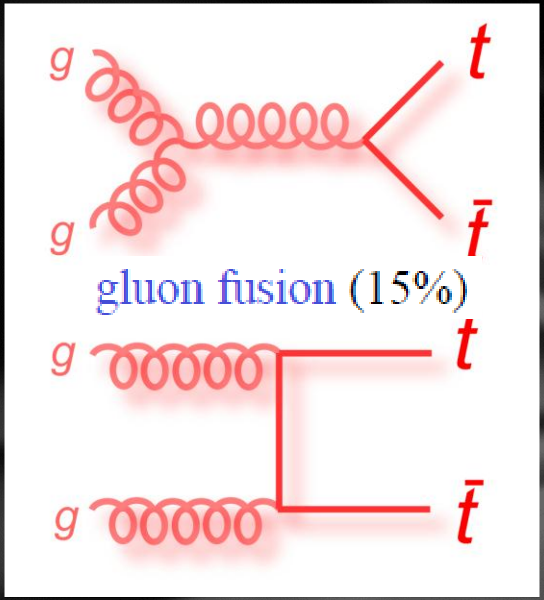
✓ The coupling of the top quark to Higgs ~ 1

✓ It decays before hadronizing, transferring its properties to the decay products, which we can observe and study experimentally.

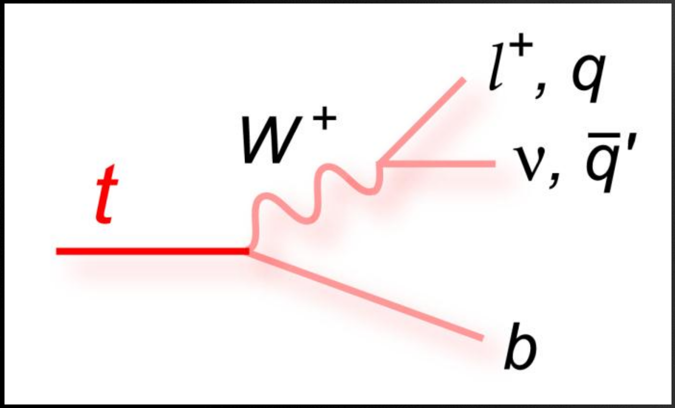
❑ After 15 years and almost 100 times more data now we have thousands of top events and increasing….

Top quark pair production at Tevatron



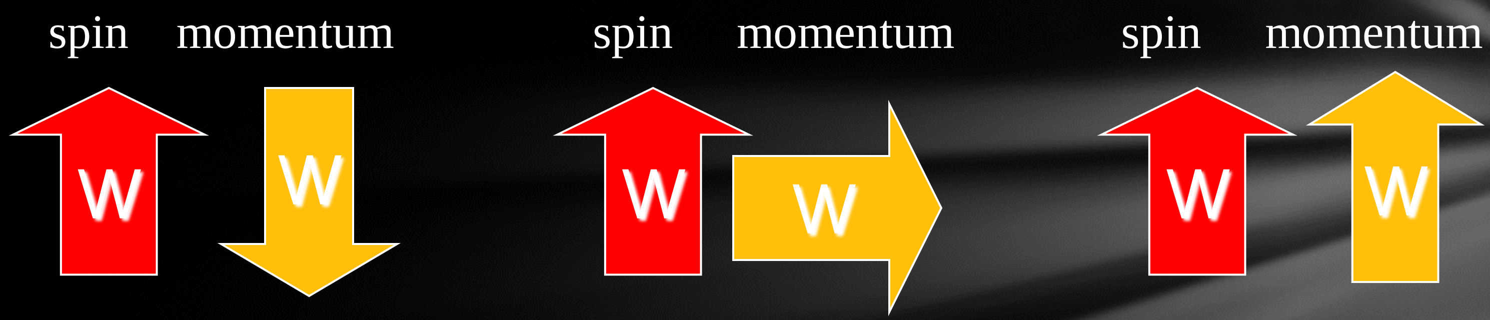


Top quark decays ~100% to W and b quark



What is W boson Helicity ?

The *W* boson from top quark decay is produced in one of three polarization states



In Standard Model :

Negative helicity $f_- \sim 30\%$
(left handed, W_-)

Zero helicity $f_0 \sim 70\%$
(longitudinal, W_0)

Positive helicity $f_+ \sim 0\%$
(right handed, W_+)

What we measure is the helicity fraction

$$f_o = \Gamma\left(t \to W_0 b\right) / \Gamma\left(t \to Wb\right)$$

$$f_+ = \Gamma\left(t \to W_+ b\right) / \Gamma\left(t \to Wb\right)$$

$$f_- = 1 - f_o - f_+$$

MOTIVATION

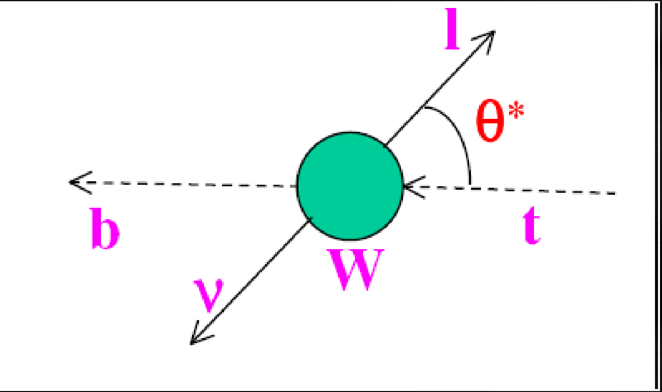
The uncertainties in the Standard Model prediction are far smaller than the precision we can achieve experimentally.

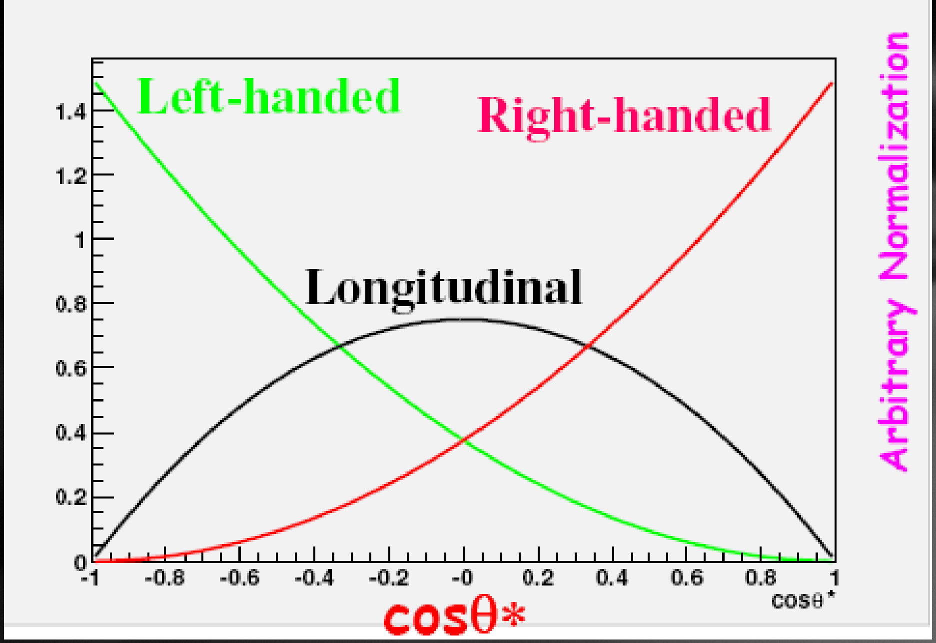
Any significant deviation from the SM values would be a clear signature of new physics.

How do we measure *W* Helicity

We can get *W* helicity fractions (f_0 and f_+) from the cosθ* distribution

$$c = \cos\theta^* = \frac{-(\vec{l}.\vec{b})}{|\vec{l}||\vec{b}|}$$



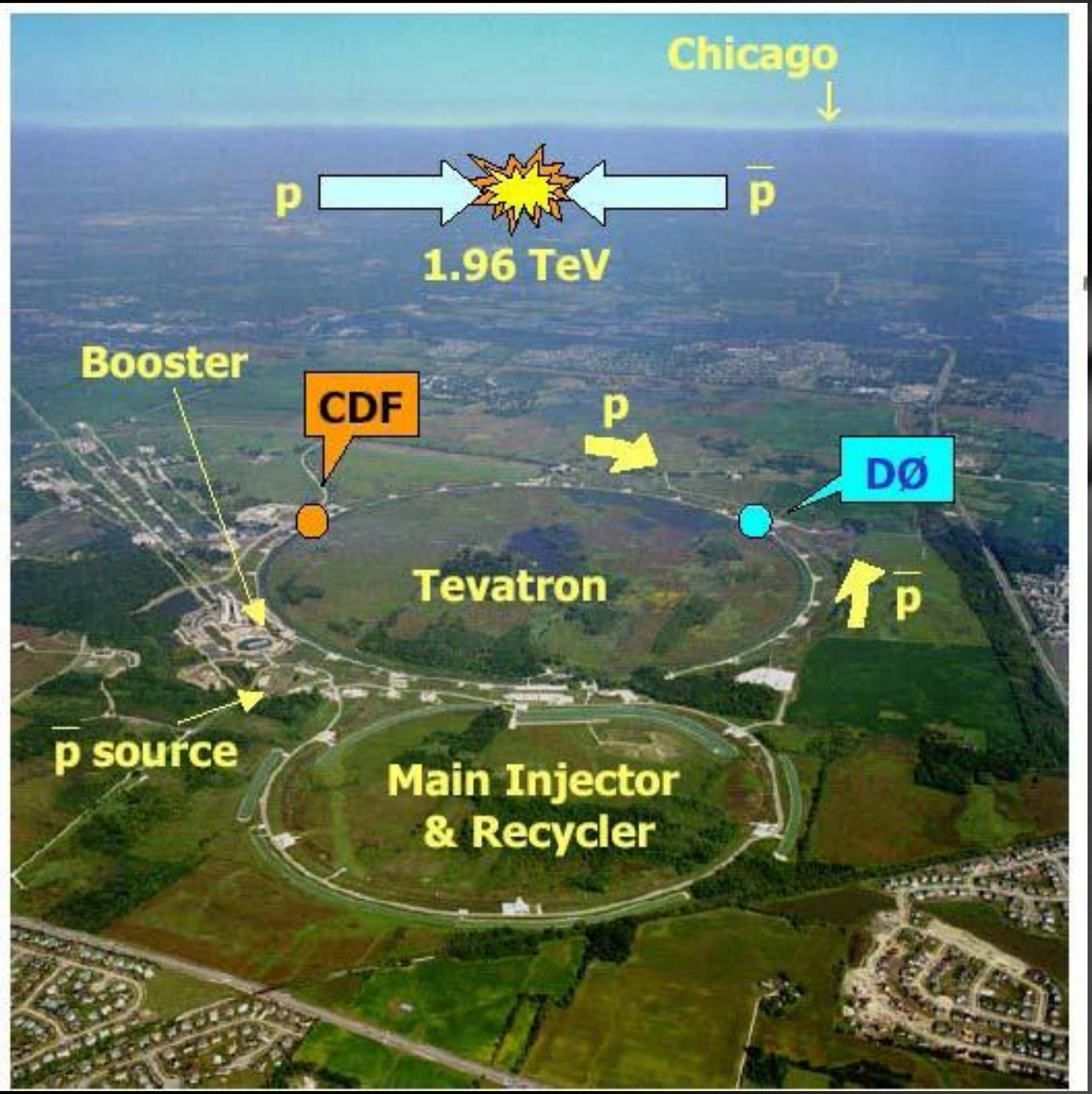


$$\omega(c) \propto 2(1-c^2)f_0 + (1-c)^2 f_- + (1+c)^2 f_+$$

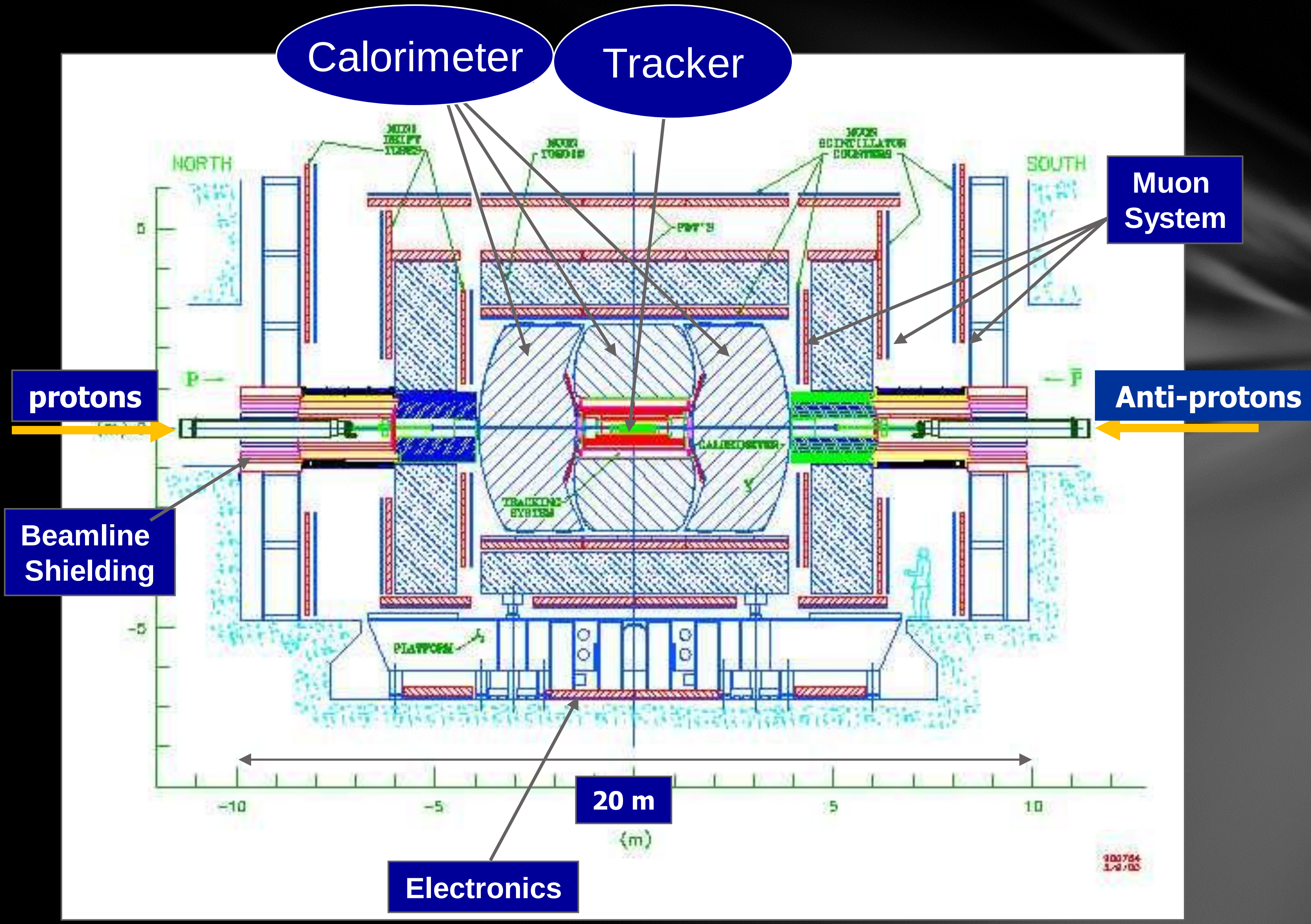
This is the basis of this measurement.

Experimental Apparatus

D0 detector at Fermilab



D0 is a general purpose detector capable of variety of physics measurements.



THE GOAL

IDENTIFY THE PARTICLE

and

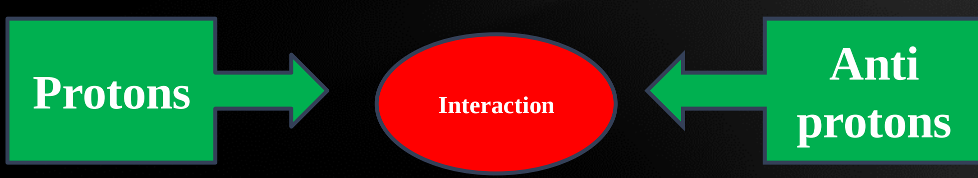
MEASURE THE ENERGY OR MOMENTUM OF THE PARTICLE

Muon : Identify muons

Calorimeter : measurement of particle energy and particle identification.

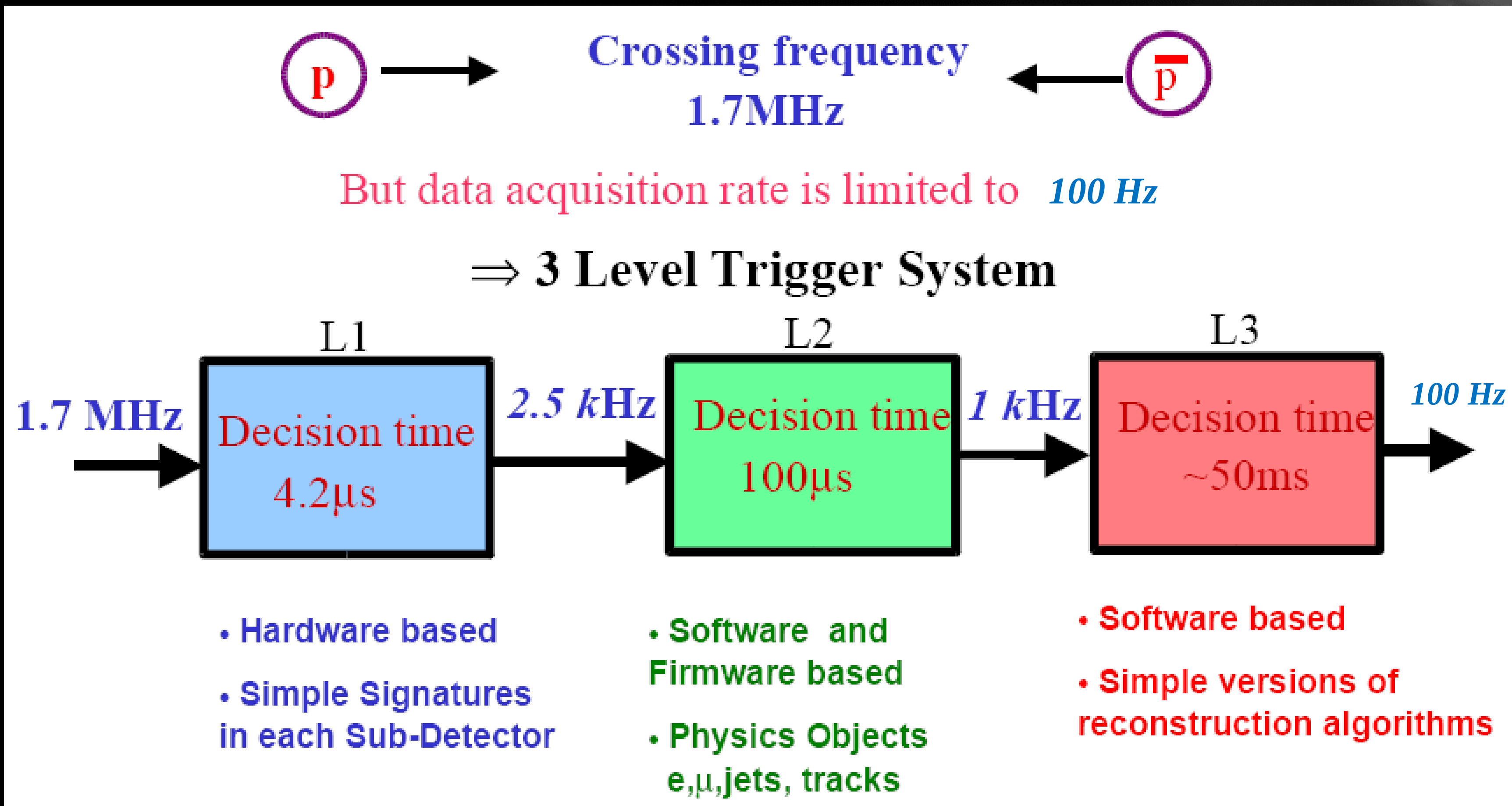
Tracker : track reconstruction of charged particles

Particle moving



D0 Trigger System

Through a fast selection, only keep the events which have properties matching the characteristics of physics events of interest.



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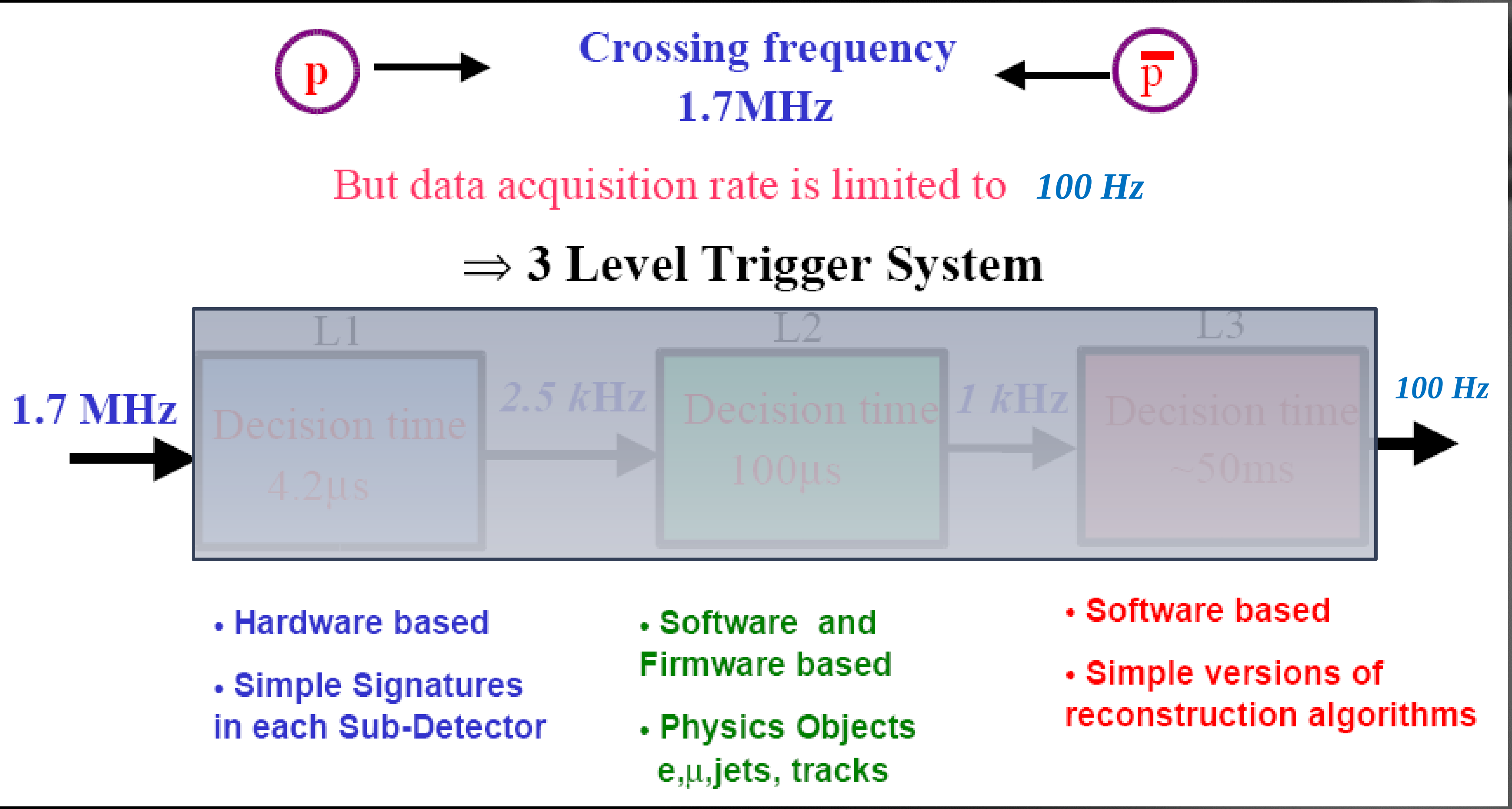
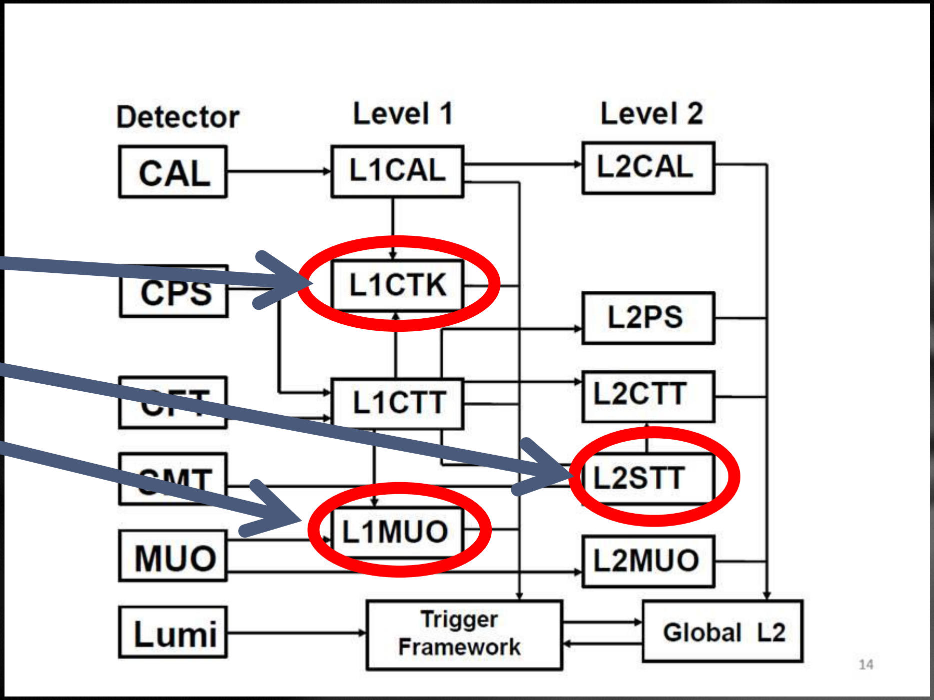


D0 Trigger System

The hardware I worked on



Silicon Track Trigger (L2STT) **:** Fast selection of events with ‘b’ quarks

Level 1 Muon (L1MUO) **:** Fast selection of events with muons based on inputs from all the muon sub-detectors and tracker.

Level 1 Cal Track (L1CTK) **:** Gives the D0 Level 1 trigger system additional rejection power required to accommodate Tevatron’s high luminosity based on inputs from calorimeter and tracker.

ANALYSIS

Identify DATA sample and model signal and background

Event Selection

Reconstruct $\cos\theta^*$ for selected events

Measure W helicity fraction and evaluate systematics

Identify DATA sample and model signal and background

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Event Selection

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Reconstruct $\cos\theta^*$ for selected events

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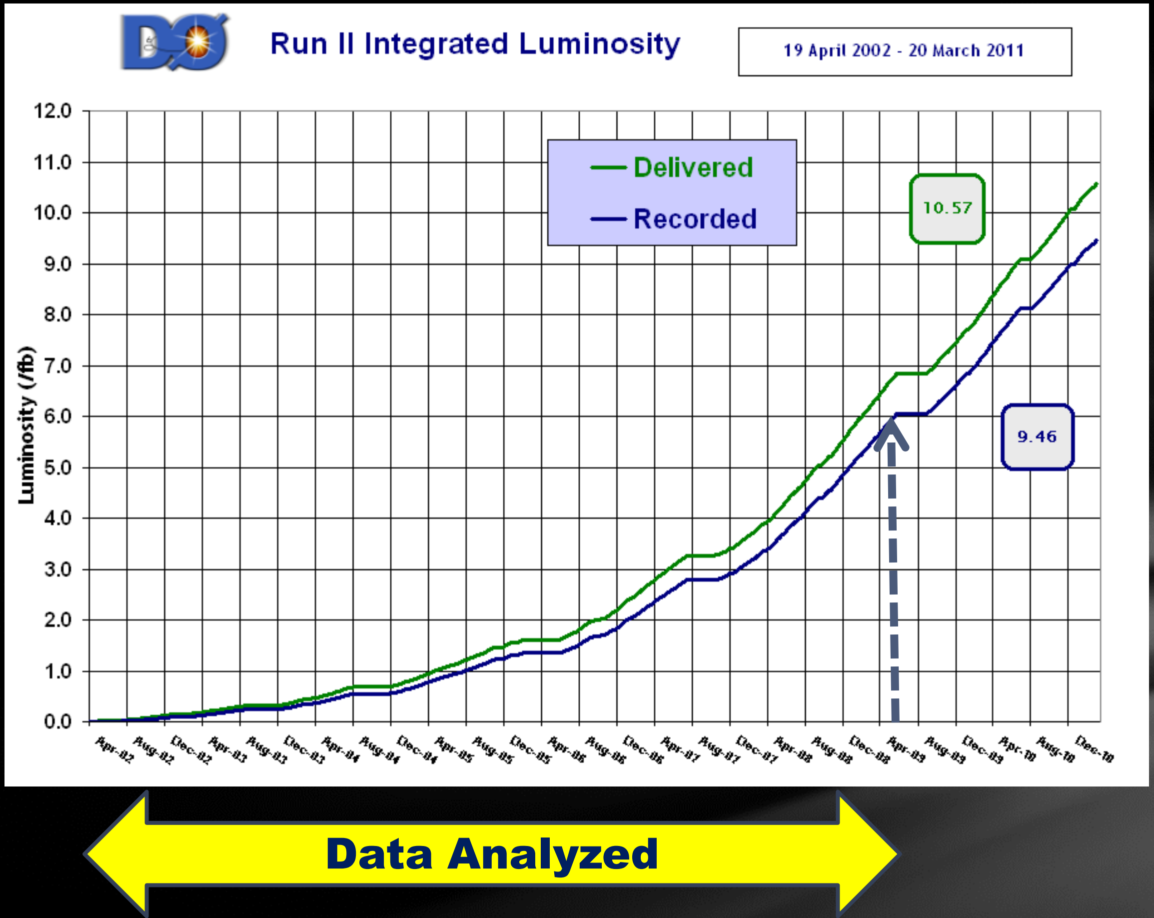
Measure W helicity fraction and evaluate systematics



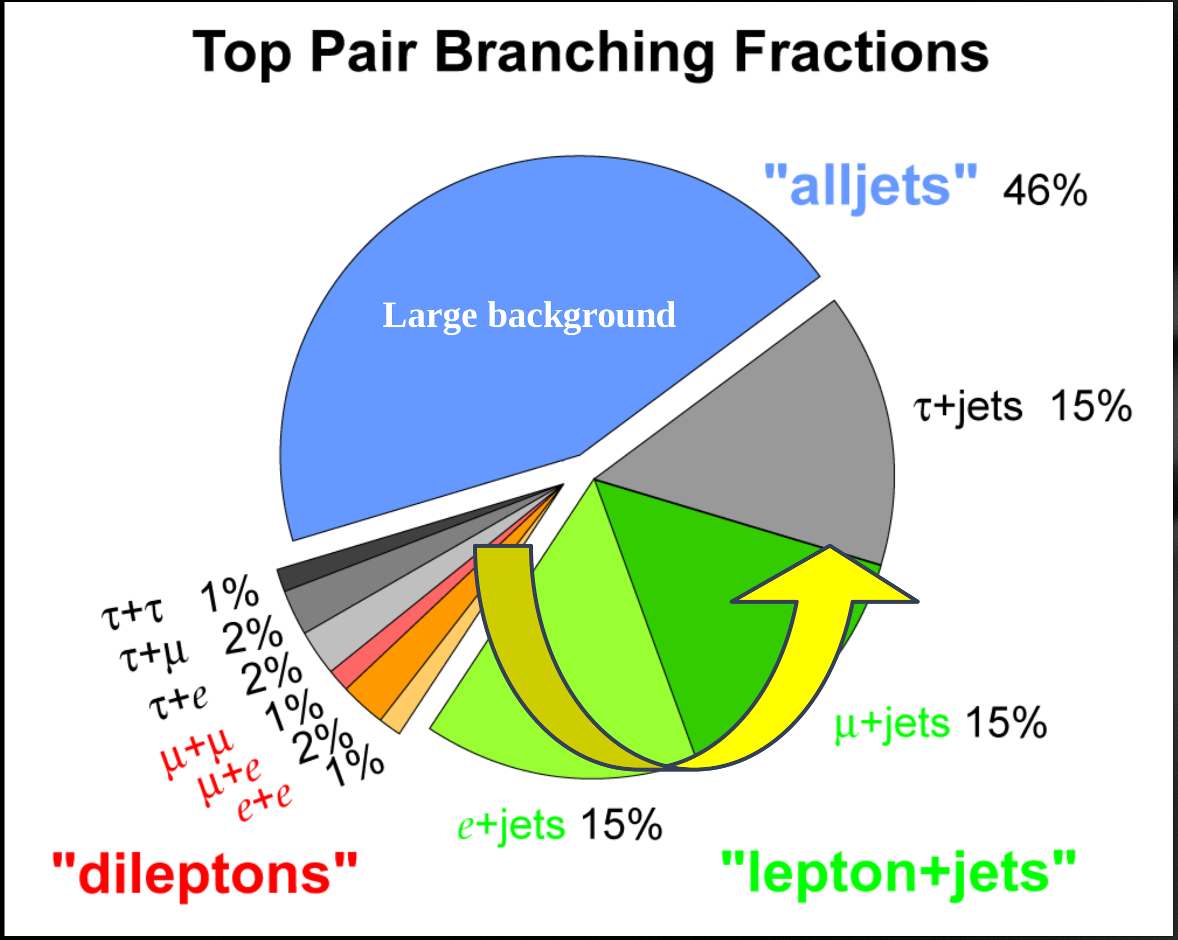
Integrated Luminosity x Cross-section = Number of events

- Data used for this analysis was collected between April 2002 and June 2009 which corresponds to a total integrated luminosity of 5.4 fb^{-1}.

- Simulated samples (Monte Carlo) were used to model the data.

We are doing this measurement in top quark decay.

So what final state do we look at??



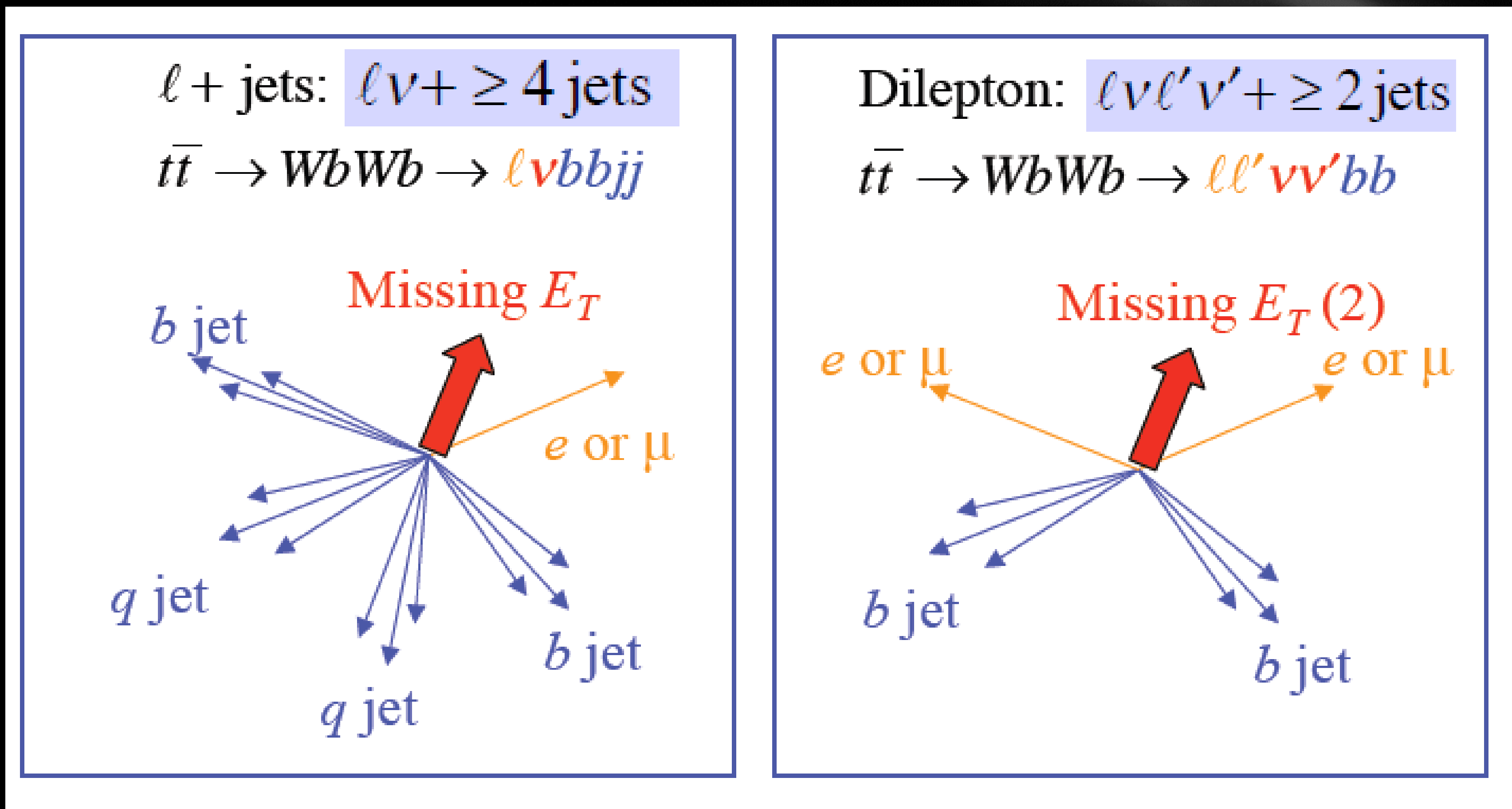
- **For this analysis, we used events with the following 5 final states or channels:**

1. **Electron + Jet**
2. **Muon + Jet**
3. **Di-electron**
4. **Di-muon**
5. **Electron + Muon**

The quarks and gluons produced in the final state develops into a shower of particles (called hadronization). We call this shower, observed in the detector, a <u>JET</u>.

Signal Events for this analysis

Final state **Final state**



Background events for this analysis

There are two categories of background

1. Physics background from standard model physics process having similar final state as from top pair, e.g.

$$W + \geq 4\,\text{jets} \rightarrow \ell\nu + \geq 4\,\text{jets}$$

$$Z + \geq 2\,\text{jets} \rightarrow \tau\tau + \geq 2\,\text{jets} \rightarrow \ell\nu\ell'\nu' + \geq 2\,\text{jets}$$

Simulated sample (MC) used to model the physics background

2. Instrumental background where a final state object is misidentified, e.g. a hadronic jet misidentified as an electron.

Data control sample is used to model the instrumental background

Identify DATA sample and model signal and background

↓

Event Selection

↓

Reconstruct $\cos\theta^{*}$ for selected events

↓

Measure W helicity fraction and evaluate systematics

The event selection is done in two steps

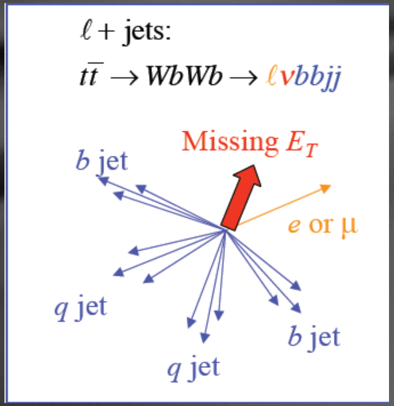
Remember : Our goal is to get a sample enriched with pure top pair events

Pre-selection

Apply well understood selection criteria to identify each object expected in the final state of an event with top pair.

Example : for lepton+jet final state, we select events with

- At least 4 or more jets with a minimum energy
- 1 well identified lepton (electron or muon) depending on the final state
- Missing energy to account for the neutrino



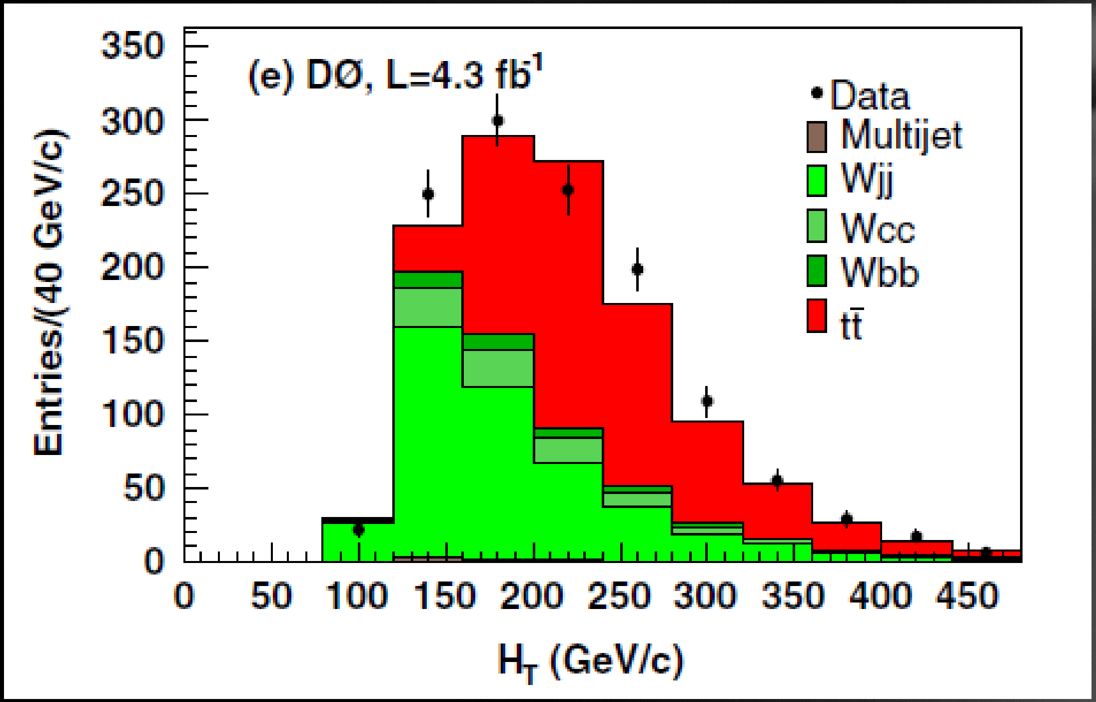
Final selection

Use a multivariate discriminant to separate background from signal events and apply a cut to get a sample enriched with top quark.

Final Selection

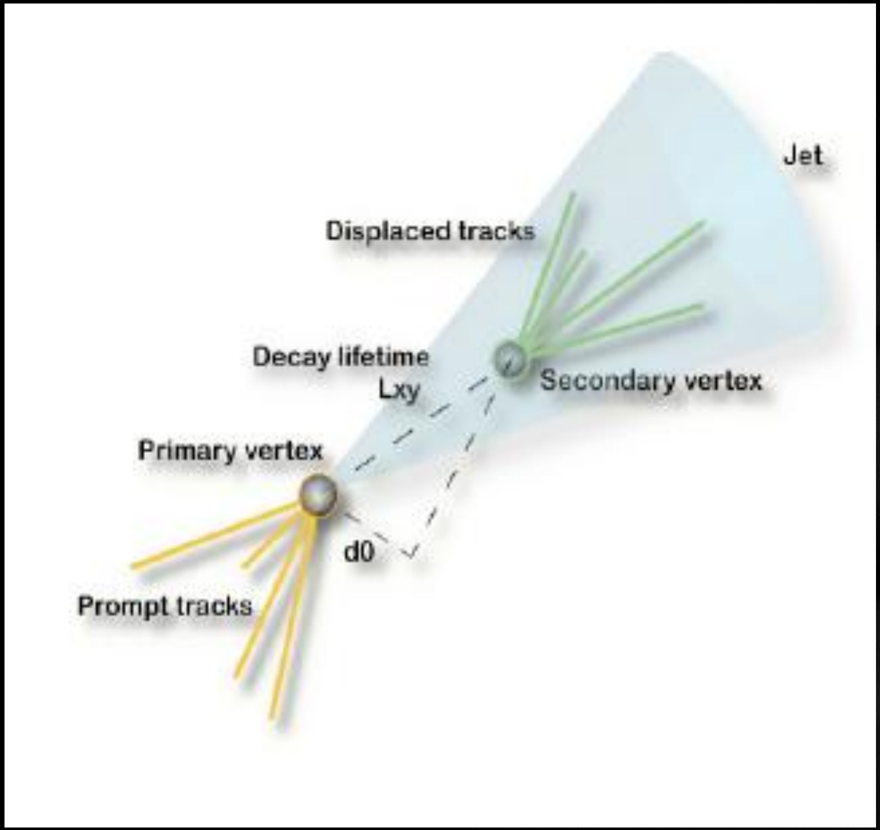
- The final selection is done using a **classical likelihood** that combines all the information we have in terms of several variables. Example, one such variable:

H_T – Scalar sum of the pre-selected jet transverse energies. Jets originating from gluon radiation are less energetic from those originating from top pair decay.



H_T distribution of signal (red), background and data (points) sample after pre-selection.

Another very powerful tool used : b quark identification



- In top quark pair production we have 2 b quarks in the final state.

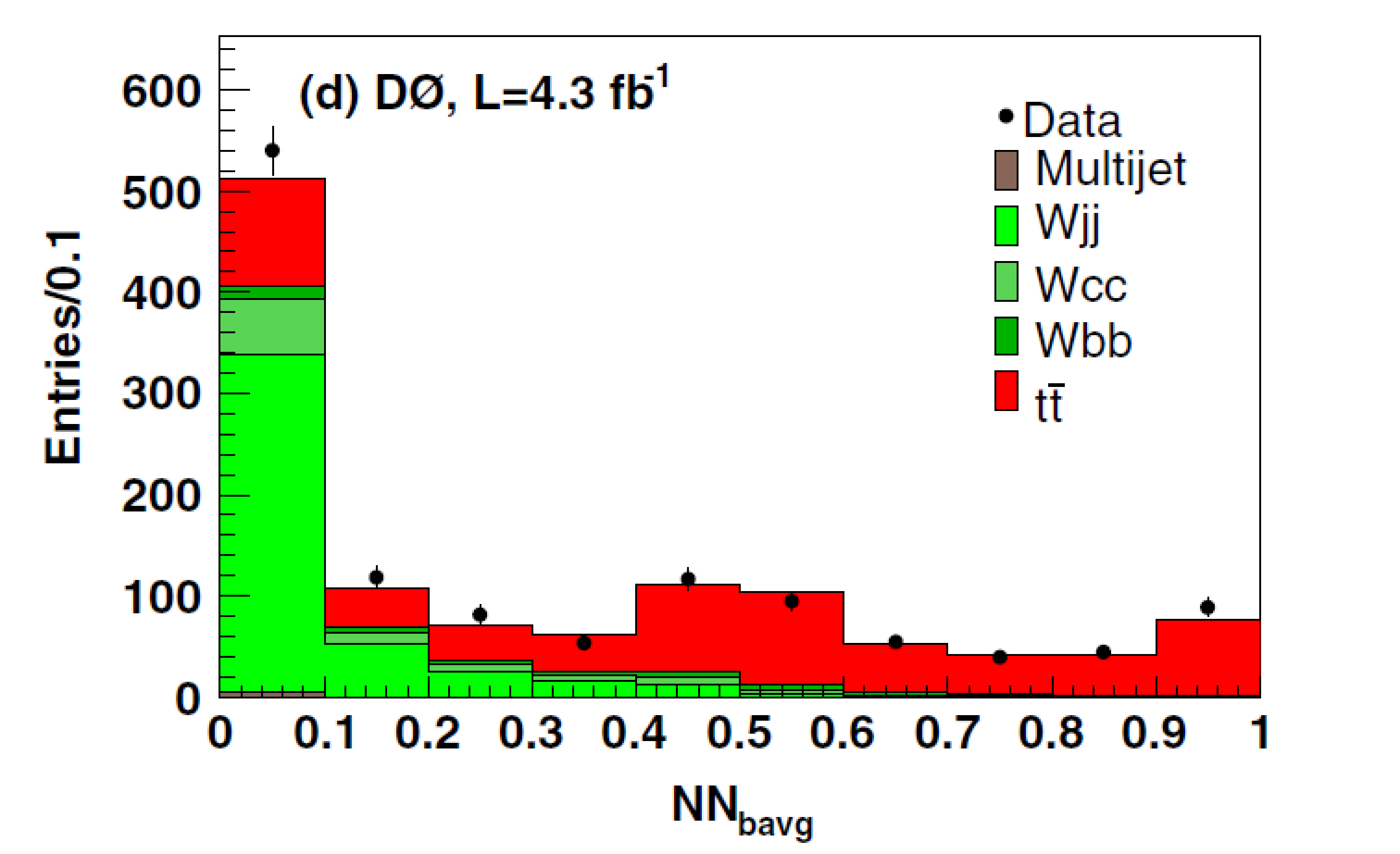
- b quark is unique from other quarks because they have sufficient lifetime and travel some distance before decaying.

- We make use of this property to identify b quarks, called b-tagging.

- A multivariate discriminant (Neural Net) is developed using several track and secondary vertex variables.

- The output of this neural net is called NN_b

- Instead of applying a cut on NN_b , we use this as an input variable to our Likelihood used for final selection.



Optimization of final selection

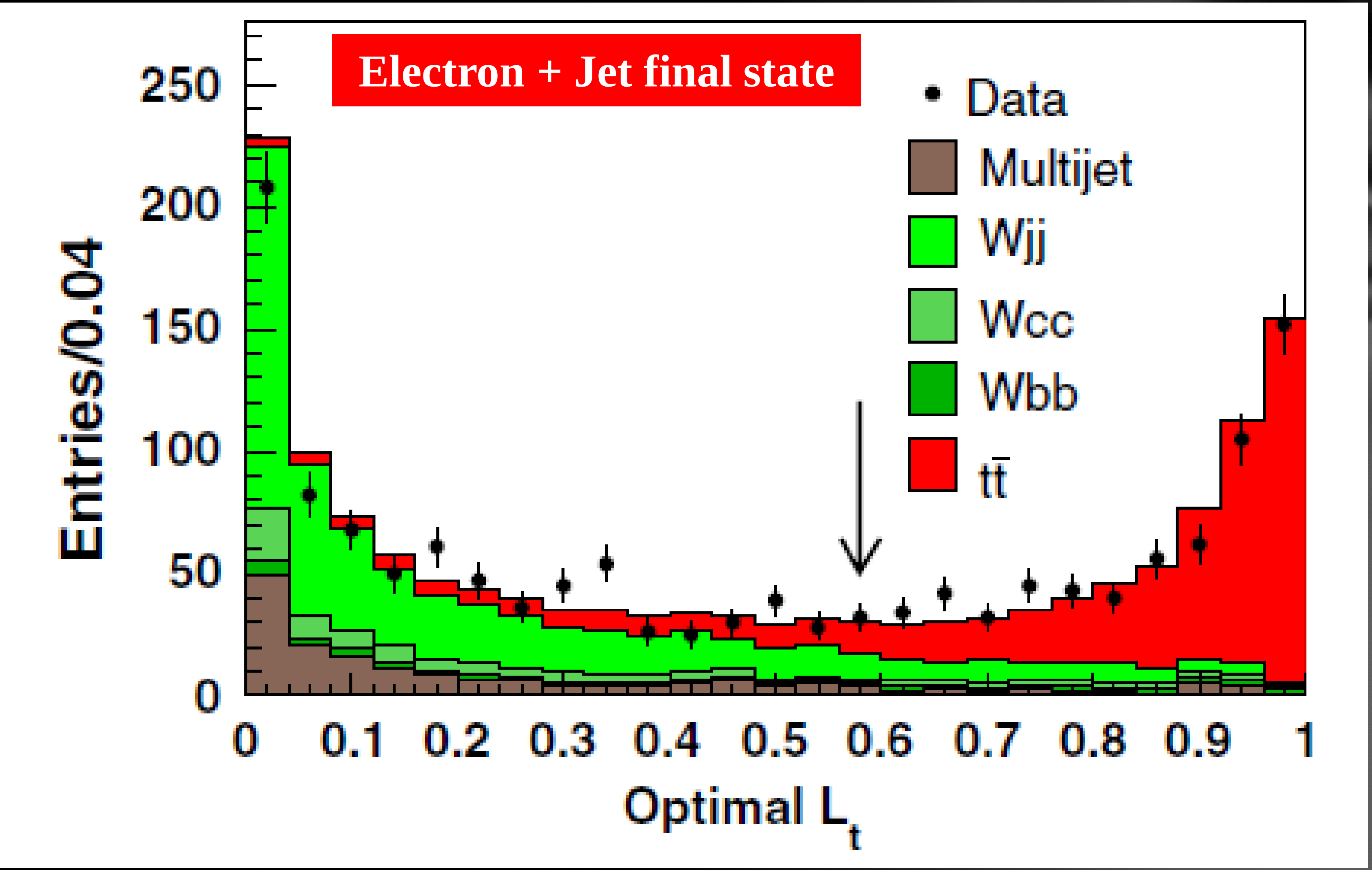
Optimization is done by trying all possible combinations of variables, and all possible cut points on the likelihood, to find the one that maximizes the following figure of merit:

$$\mathrm{FOM} = \frac{S}{\sqrt{S + B + \sigma_B^2}}$$

S = Signal
B = Background

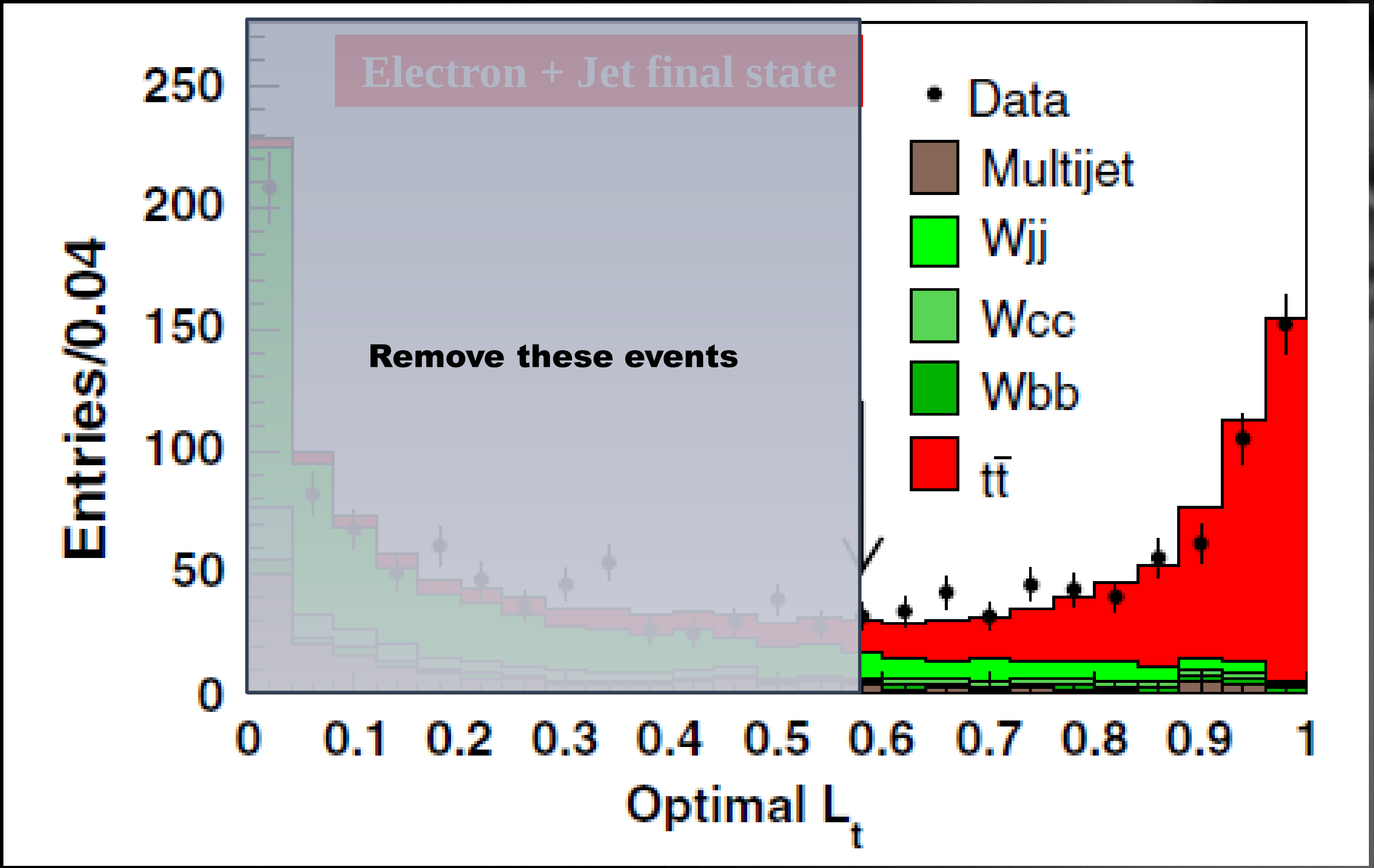
σ_B is a term that reflects the quality of data/MC agreement in the variables used in the likelihood

One Example ……



Electron + Jet final state
Data
Multijet
Wjj
Wcc
Wbb
$t\bar{t}$
Entries/0.04
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Optimal L_t

One Example ……


Electron + Jet final state
Remove these events
Data
Multijet
Wjj
Wcc
Wbb
tt̄
Entries/0.04
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Optimal L_t

- For each of the 5 channels, we get one such optimized likelihood distribution

- We apply the optimized selection criteria

Final State	Electron + JETS	Muon + JETS	Electron + Electron	Muon + Muon	Electron + Muon
Signal purity before L_t cut (PRE-SELECTED SAMPLE)	**41%**	**49%**	**2%**	**2%**	**55%**
Signal Purity after L_t cut (FINAL SAMPLE)	**73%**	**71%**	**83%**	**65%**	**82%**

Now we have a highly pure top quark sample used for our measurement

Identify DATA sample and model signal and background

↓

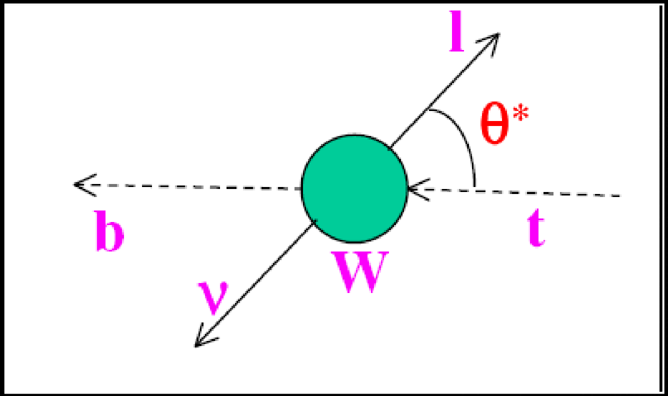
Event Selection

↓

Reconstruct $\cos\theta^*$ for selected events

↓

Measure W helicity fraction and evaluate systematics



$$c = \cos\theta^{*} = \frac{-(\vec{l}\,.\vec{b})}{|\vec{l}\,||\vec{b}\,|}$$

❑ For each event in the final sample we need to reconstruct the four momenta of the top quark and the W boson. For each event, we calculate 2 cos θ^* (one for each tWb vertex).

❑ This is done using the following constraints :

✓ The invariant mass of the lepton and neutrino is the *W* mass

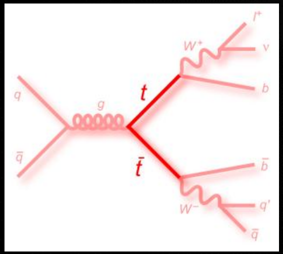
✓ In lepton+jet events, the invariant mass of the two jets is the *W* mass

✓ The top mass is 172.5 GeV

❑ Using these four-momenta, cos θ^* is calculated

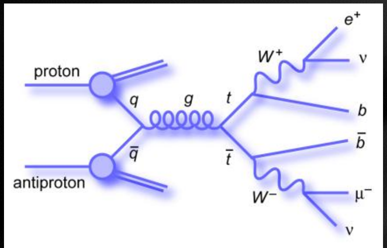
Further Challenges !!

Lepton + jet final state



- We have 4 jets but none are assigned to any initial parton. Total 12 possibilities

- Choose the combination with highest combined probability of kinematic and NN_b probability.



Di-lepton final state

- We have 2 leptons and 2 jets but there is an ambiguity of which lepton and jet should we pair.

- Take average over all solutions to get $\cos\theta^*$ for each tWb vertex.

Identify DATA sample and model signal and background

↓

Event Selection

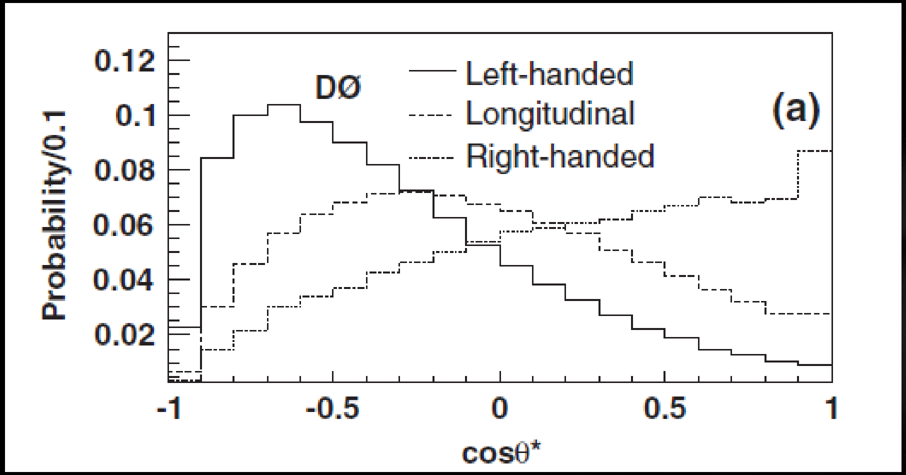
↓

Reconstruct $\cos\theta^{*}$ for selected events

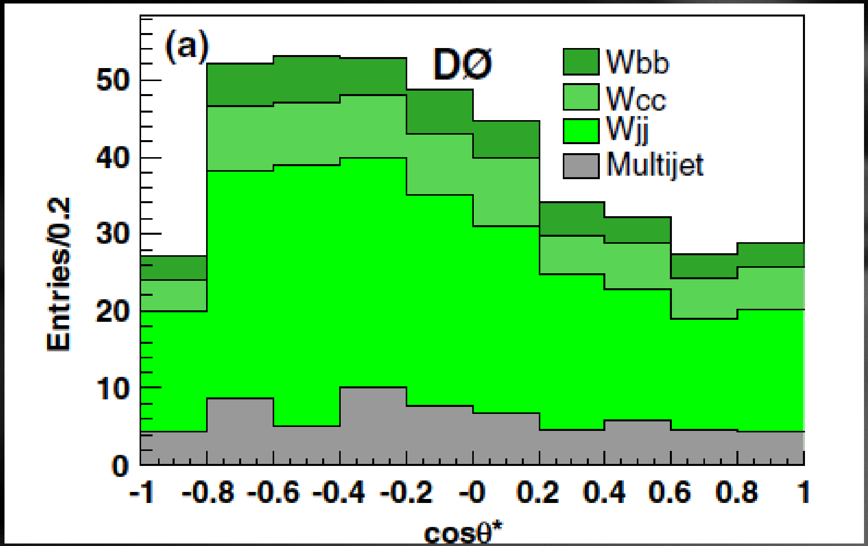
↓

Measure W helicity fraction and evaluate systematics

❑ Starting with the simulated signal samples (top pair sample), we model the expected distributions of $\cos\theta^*$ for left-handed, longitudinal and right-handed W's.



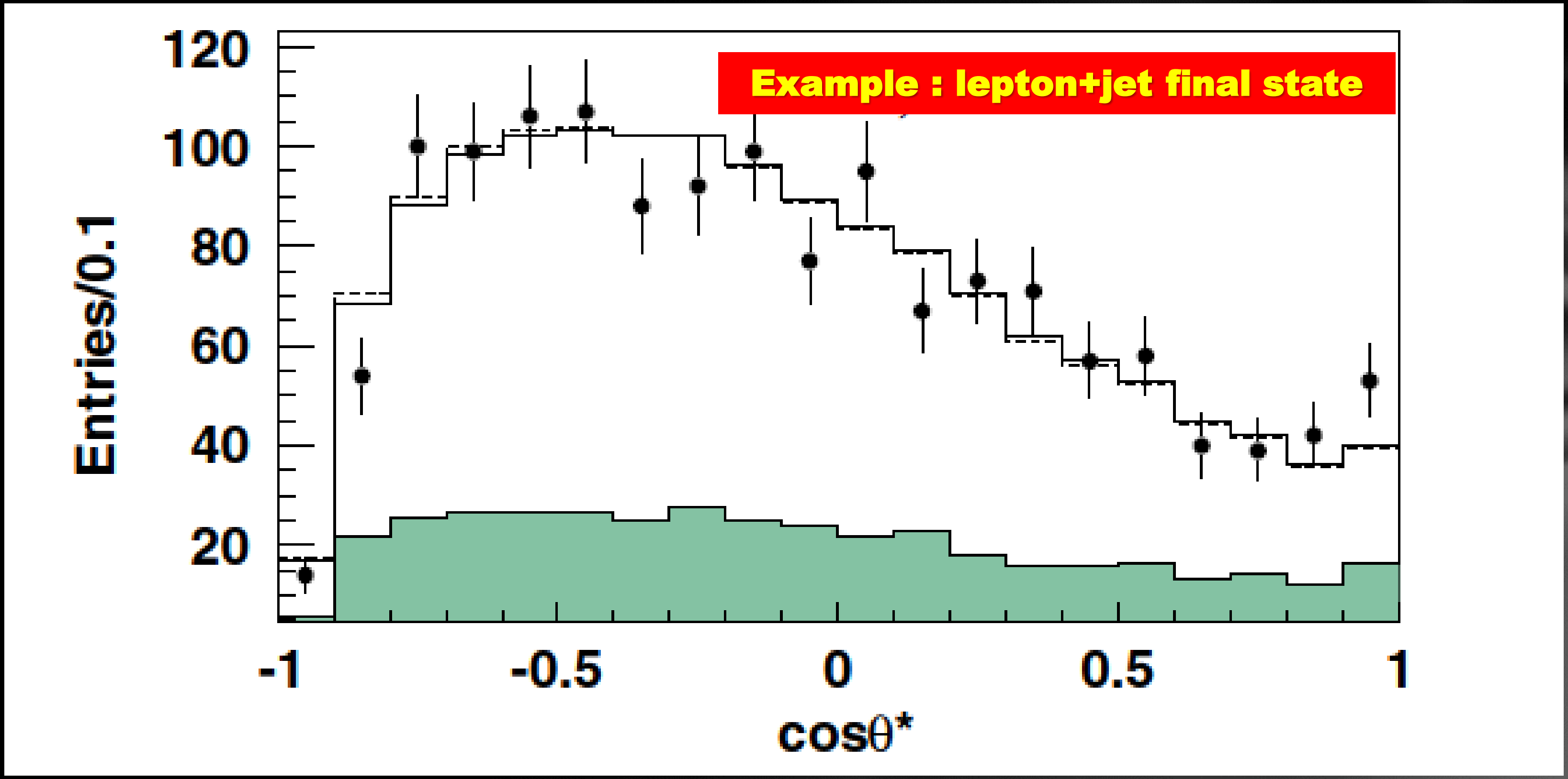
$\cos\theta^*$ distribution for simulated signal (top pair) sample (Lepton + Jet final state)



$\cos\theta^*$ distribution for background (Lepton + Jet final state)

❑ Once we have the $\cos\theta^*$ distributions for signal, background and data, we use a maximum likelihood fit for the data to be consistent with the sum of signal and background in the $\cos\theta^*$ distribution.

Maximum Likelihood Fit to extract f_0 and f_+



Comparison of the cosθ* distribution in data (points with error bars) and the global best-fit model (solid open histograms) for lepton+jet events. The dashed open histograms show the SM expectation, and the shaded histograms represent the background contribution.

The fit parameters include the W helicity fractions f_0 and f_+

Cross check – Ensemble tests!

Make sure the maximum likelihood fit method actually works

- We create several toy experiments where we make mock data sample by using random events from the simulated samples.

- Each toy experiment gives us a mock data cosθ* distribution and we perform the maximum likelihood fit which returns a for f_0 and f_+

Known input values	Avg fit output f_o	Avg fit output f_+
$f_0 = 0.7$ & $f_+ = 0.3$	**0.708 ± 0.002**	**0.304 ± 0.001**
$f_0 = 0.7$ & $f_+ = 0.0$	**0.702 ± 0.002**	**-0.004 ± 0.001**

SYSTEMATIC UNCERTAINTIES

Source	Uncertainty (f_+)	Uncertainty (f_0)
Jet energy scale	0.009	0.010
Jet energy resolution	0.004	0.008
Jet ID	0.005	0.007
Top quark mass	0.012	0.009
Template statistics	0.011	0.021
$t\bar{t}$ model	0.024	0.039
Background model	0.008	0.023
Heavy flavor fraction	0.010	0.022
b fragmentation	0.002	0.004
PDF	0.000	0.001
Analysis consistency	0.004	0.006
Muon ID	0.002	0.017
Muon trigger	0.003	0.024
Total	0.034	0.065

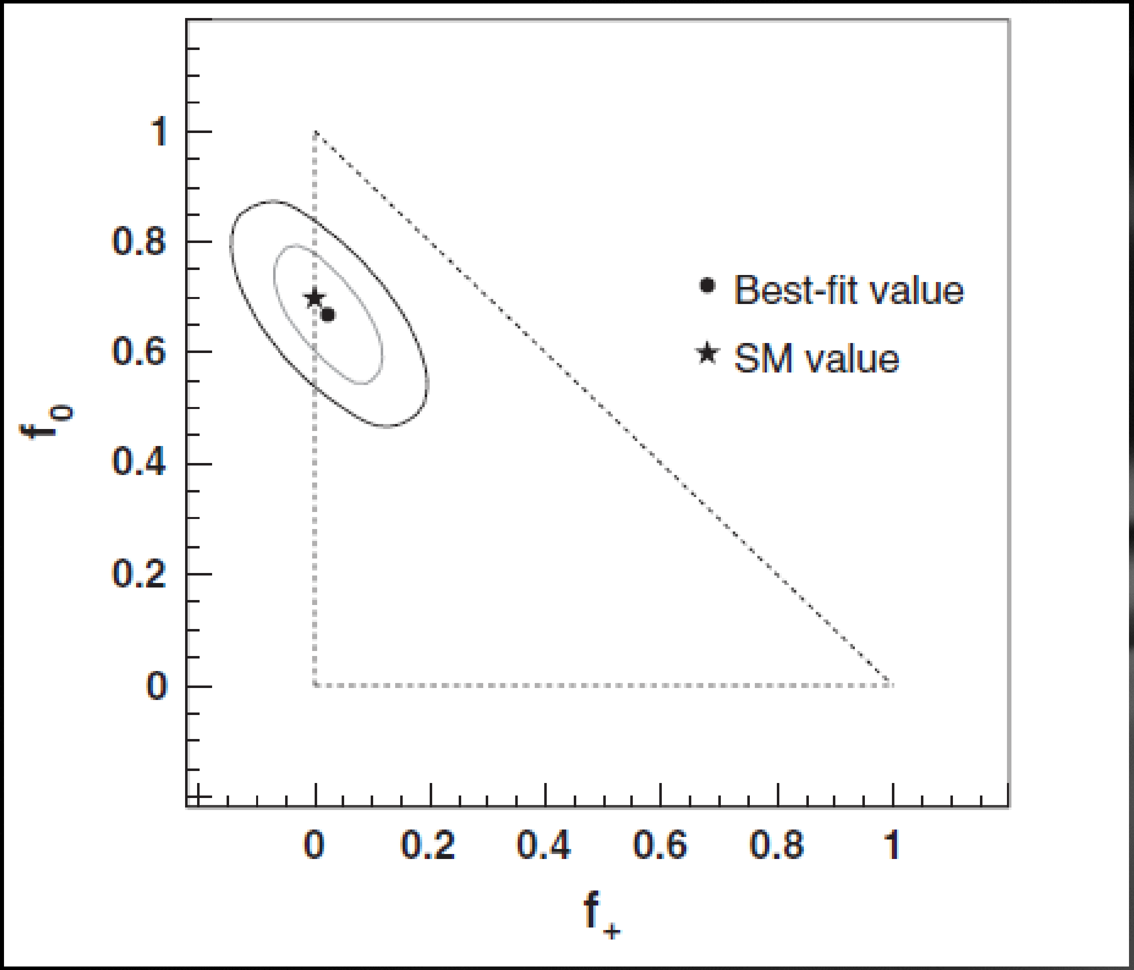
RESULT

Analyzing a data sample corresponding to 5.4 fb^{-1} of proton anti-proton collisions collected by the D0 detector at Fermilab

$$f_0 = 0.669 \pm 0.102[\pm 0.078(stat.) \pm 0.065(syst.)]$$
$$f_+ = 0.023 \pm 0.053[\pm 0.041(stat.) \pm 0.034(syst.)]$$

Compare to SM values : f_0 = 0.698 & $f_+ = 3.6 \times 10^{-4}$

The consistency of this result with the standard model value is 98%



The ellipses are the 68% and 95% C.L. contours, the triangle borders the physically allowed region where f_0 and f_+ sum to one or less, and the star denotes the SM values.

Future Prospects

Tevatron :

- There is no plan to update this measurement with full D0 dataset
- There is a plan to do a combination of the D0 and CDF result which is now underway

LHC :

- The top pair production cross-section at LHC will be almost 100 times more compared to the Tevatron.
- With full energy and high statistics of top sample with 10 fb^{-1} of data, the uncertainty for these measurements is expected to go down to ~ 1-2%.

CONCLUSION

After analyzing 5.4 fb^{-1} of data collected through the D0 detector, we find the measured values of the W helicity fractions consistent with the standard model value.

Hence we state that we found no evidence of new physics at the tWb decay vertex.

This is the world's most precise measurement of W boson helicity

published in PRD [Phys. Rev. D 83, 032009 (2011)]

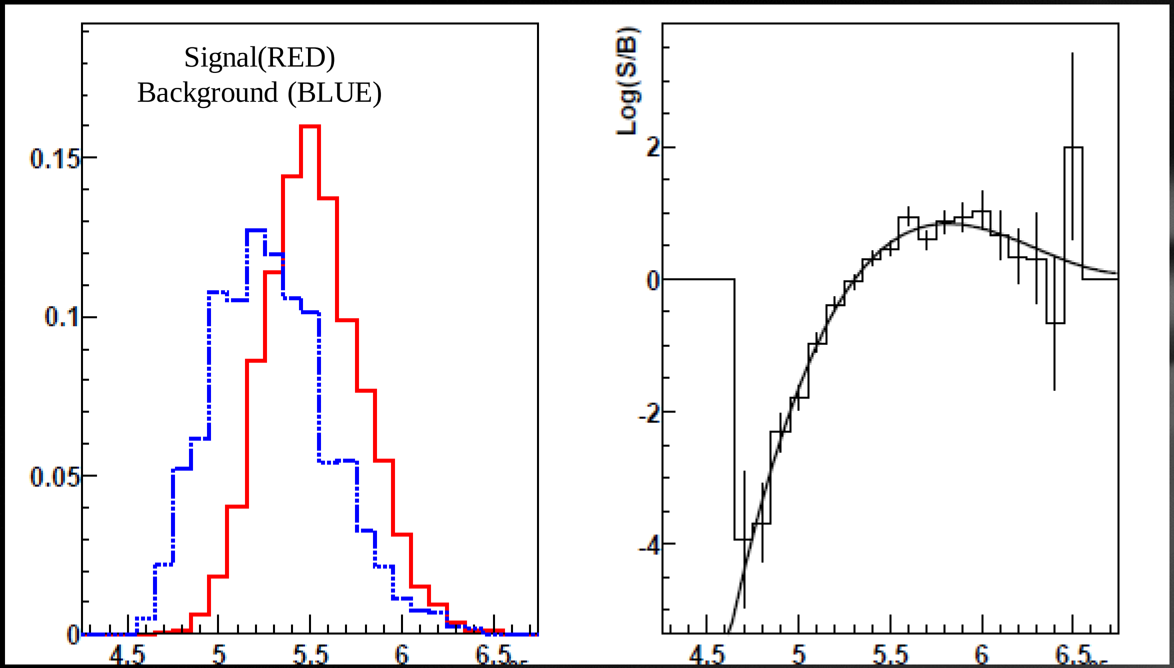
THANK YOU

BACKUP

Classical Likelihood

For each variable 'i' (e.g. H_T), we compute the functional form for Sig/Bkg

Example…



The likelihood is calculated using the equation

$$L_t(\mathrm{x}) = \frac{\exp(\sum_{i=1}^{N_{\text{var}}}(\ln(\frac{S}{B})_i^{fit}))}{\exp(\sum_{i=1}^{N_{\text{var}}}(\ln(\frac{S}{B})_i^{fit}))+1}$$