$t\bar{t}$ photoproduction in proton-proton colissions

Workshop on Medical and High Energy Physics

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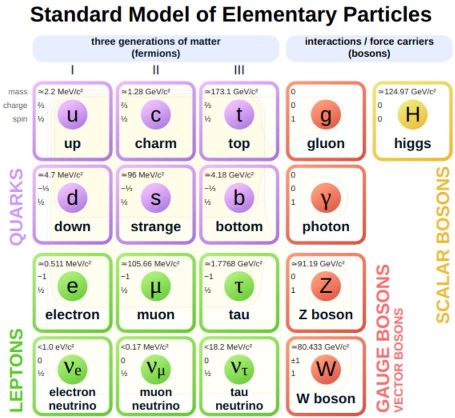
Foundations

- The Standard Model (SM) of particle physics is a theory that includes all known fundamental particles.
  - Currently have open issues:
    - Dark matter candidate.
    - Mass hierarchy.
    - W boson mass deviations [1].
  - It is a successful but incomplete theoretical model.

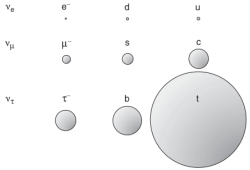


[1] K.S. Babu, et. al. Phys. Rev. Lett. 129, 121803. 2022

Foundations

The particle of interest for this work is the top quark.

- Its existence has been theorized since 1973.
- Its existence was predicted when its partner, the bottom quark, was discovered (1977).
- The top quark was discovered in 1995. [2] (CDF and DØ).
- It is the most massive quark in SM.
- It decays before hadronizing.
  - $t \longrightarrow$ Wb (99%).
- Provides an environment for testing of the SM and for new Physics searches beyond SM.



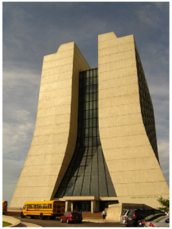


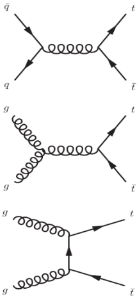
Figure: Tevatron/Fermilab Wilson Hall. Author: Chris Phan. Creative Commons 2.0.

[2] Phys.Rev.Lett.74:2626-2631,1995.

Foundations

How do we quantify/measure production of particles? $\longrightarrow$ Cross section ($[\sigma] = L^2$).

- Probability of occurrence in quantum mechanics.
- The observation of the top-quak pair was made based on quark annihilation interactions (10%);
$$q + \bar{q} \longrightarrow t\bar{t}$$
- More recently production has been dominated by gluon fusion (90%)
$$g + g \longrightarrow t\bar{t}$$



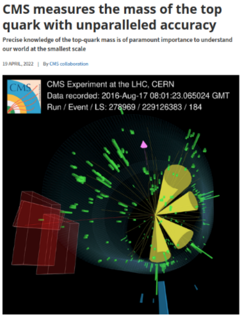
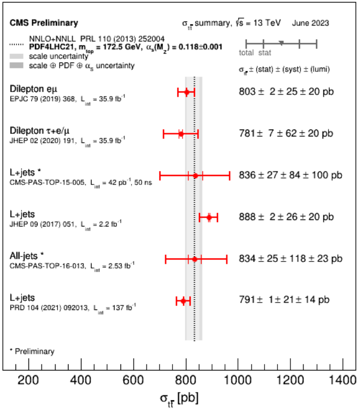
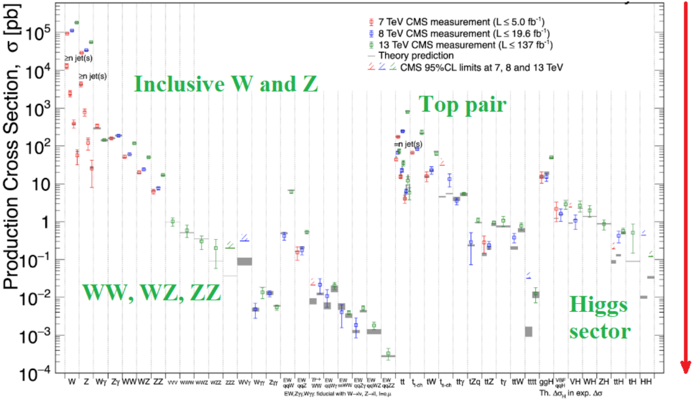


Figure: Pair production modes of the top-antitop system already observed and known as “gluon fusion” and “quark annihilation”.

Foundations

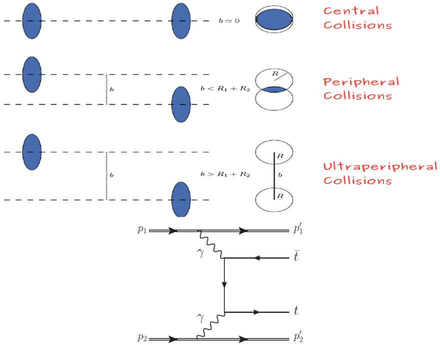
- The cross section σ or production rate has been measured for different final states of particles[4]
- By analyzing the final state particles, we can accurately determine the production mechanisms and decay channels, enhancing our understanding of $t\bar{t}$ events.





Foundations

- Within the category of top quark pair production is the subcategory of photoproduction in ultraperipheral collisions.



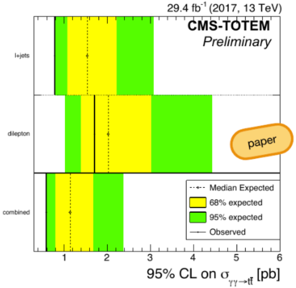


Figure: Theoretical and experimental results of the cross section with photon-photon mechanism. [5]

[5] arXiv:2310.11231v1 [hep-ex], 2023.

Evidence of photo induced process with intact protons and Pb

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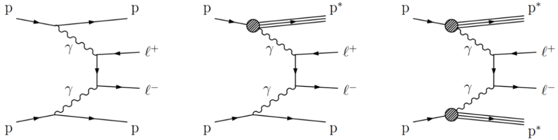
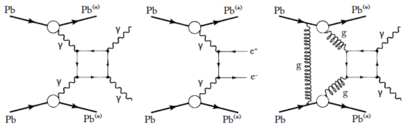
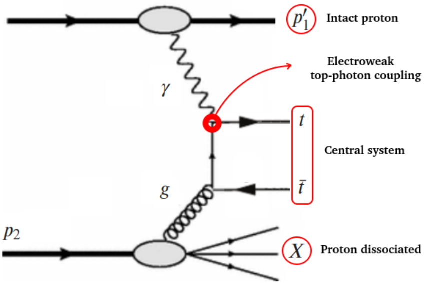
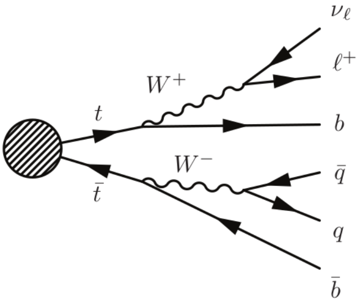


- Detection of intact protons at the LHC / Production of lepton pairs.
  - Exclusive (two intact protons) and semi exclusive production of lepton pairs.
  - Observed for the first time at the LHC in pp collisions at $\sqrt{s} = 13$ TeV.
- Detection of intact lead nuclear at the LHC / Light by light scattering.
  - Evidence of light-by-light scattering. CMS-FSQ-16-012.



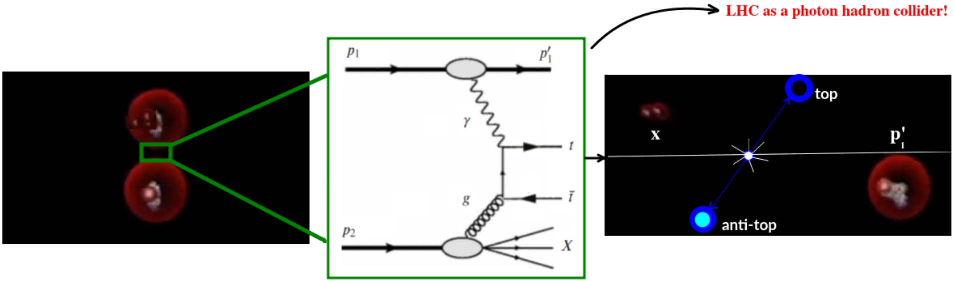
The photoprodution $\gamma p \to t\bar{t}X$ process





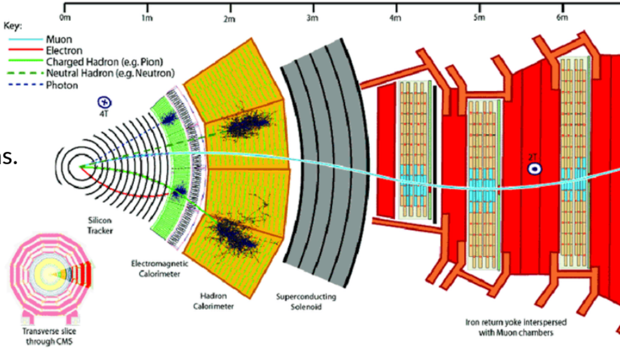
- Production of $t\bar{t}$ in association with an elastic proton via photon-gluon interaction (semi leptonic channel.
- Observing deviations from expected results in this process could signal new physics beyond the Standard Model.
- Studying this process helps probe the internal structure of the proton, revealing how quarks and gluons interact with photons at a fundamental level.

The photoprodution $\gamma p \rightarrow t\bar{t}X$ process

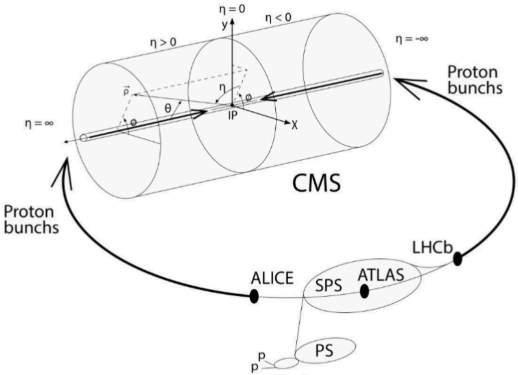


- **Motivations**
  - First semi-exclusive search of $t\bar{t}$ via photon-gluon interaction.
  - SM $\sigma_{p\gamma\rightarrow t\bar{t}p}$ is 10^4 times higher than $\sigma_{\gamma\gamma\rightarrow pt\bar{t}p}$ exclusive analysis
  - Sensitive to electroweak top-photon coupling $t\bar{t}\gamma$.
- **Goal**: Set limits on cross section and compare it with Standard Model prediction.

CMS detector



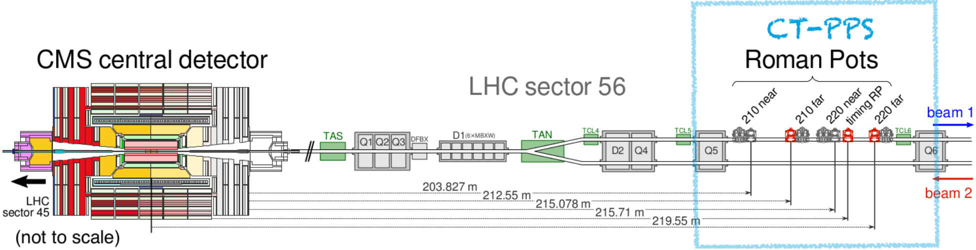
- The CMS detector captures resulting particles from interactions, except for intact protons.



- The LHC provides a proton beam at a center-of-mass energy of 13 TeV

- Data from Run 2 (2017) with an integrated luminosity of 29.4 fb^{-1}.

- In the case of the measurement of the intact proton, we are using the CT-PPS detector (CMS TOTEM Precision Proton Spectrometer)



- **CT-PPS detector**
  - Localized at $\sim$ 200 m from the interaction point on both sides of CMS
  - It is possible to tag protons and measure fraction of momentum loss

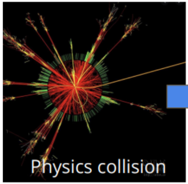
$$\xi = \frac{|\overrightarrow{p_f}| - |\overrightarrow{p_i}|}{|\overrightarrow{p_i}|} \quad (1)$$

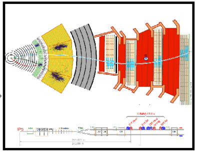
  - Can measure protons that lost $\sim 2-20\%$ of their momentum

Analysis Workflow

Measurement Roadmap

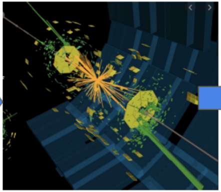
E
X
P





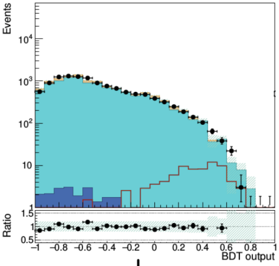
Detector interaction

Detector reconstruction



Event selection

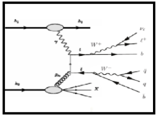
Analysis



Fit to extract cross section

Physics model

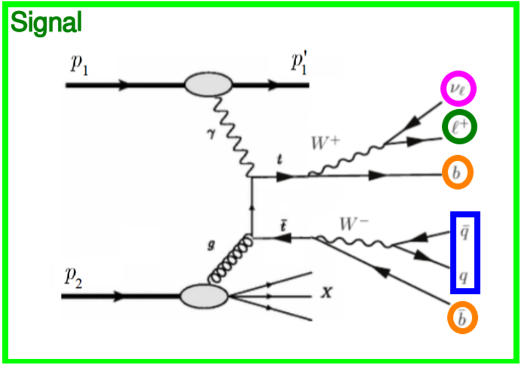
T

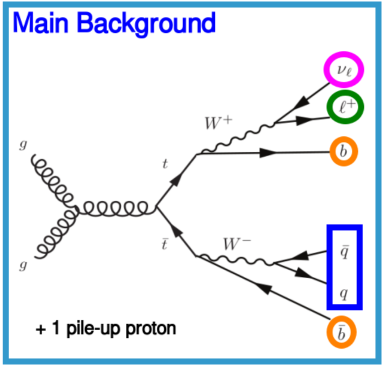


Detector simulation

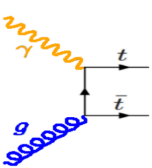
Simulation and Background Modelling

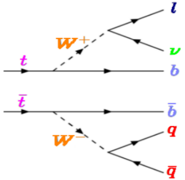
- Collision events are simulated using software such as MadGraph at generator level.
- Besides simulating the photoproduction of the top quark (signal), it is necessary to simulate other processes that produce top quarks. The main background is gluon fusion $\sigma_{t\bar{t}}$

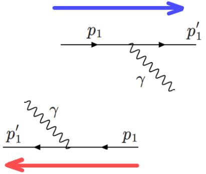


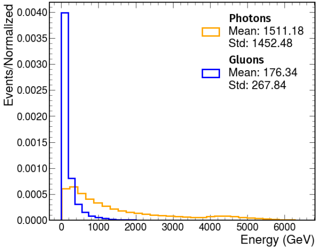


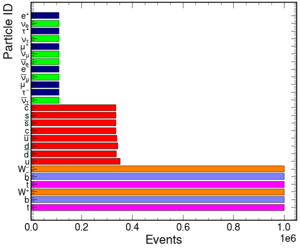
- Using the equivalent photon approximation method, photons and gluons achieve the high energies necessary for top quark pair creation.
- Particle ID shows the dominance of hadronic over leptonic parts in top quark decays.
- η distribution of muons in positive and negative directions indicates dependence on the direction of the intact proton.

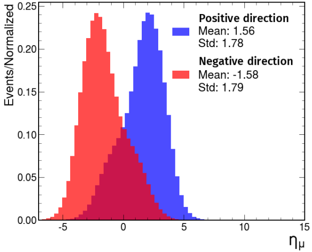


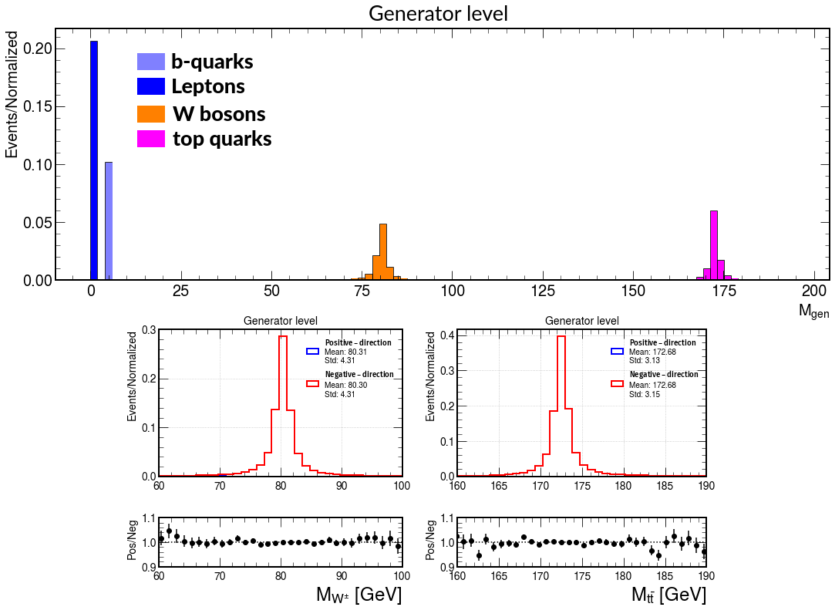








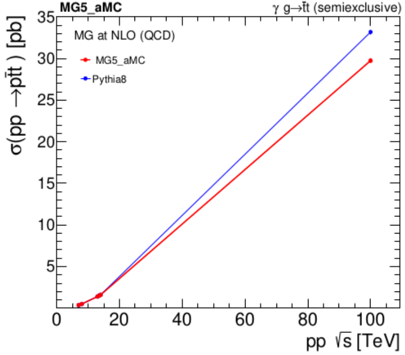


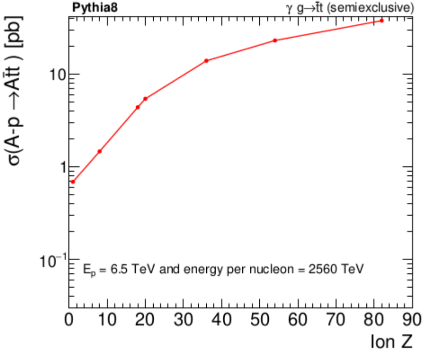

Generator level
Events/Normalized
b-quarks
Leptons
W bosons
top quarks
M$_{gen}$
Generator level
Positive - direction
Mean: 80.31
Std: 4.31
Negative - direction
Mean: 80.30
Std: 4.31
Pos/Neg
$M_{W^{\pm}}$ [GeV]
Generator level
Positive - direction
Mean: 172.68
Std: 3.13
Negative - direction
Mean: 172.68
Std: 3.15
$M_{t\bar{t}}$ [GeV]

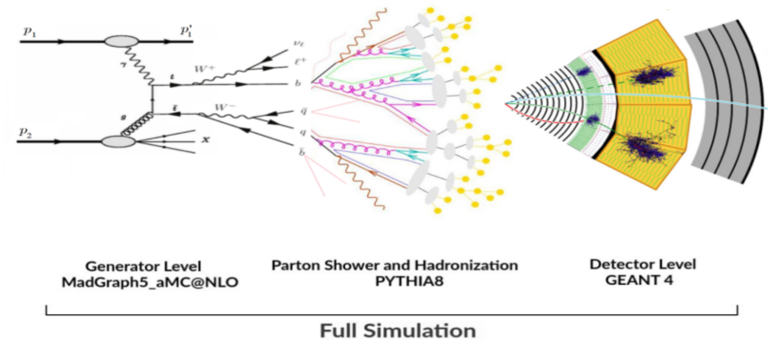
- The NLO cross section for $t\bar{t}$ photoproduction has been determined for both directions

Variable	Left	Right	Both directions
$\sigma_{\gamma p \to t\bar{t}}$	0.7079 ± 0.0054 pb	0.7002 ± 0.0079 pb	1.4081 ± 0.0096 pb
$N_{\gamma p \to t\bar{t}}$	1.0×10^6	1.0×10^6	2.0×10^6
$\sigma_{\gamma p \to tW}$	0.5143 ± 0.004 pb	0.5105 ± 0.0023 pb	1.0248 ± 0.0046 pb
$N_{\gamma p \to tW}$	1.0×10^6	1.0×10^6	2.0×10^6

- The theoretical cross section can be projected as a function of the center-of-mass energy, for example, for an FCC collider at 100 TeV.







Objects	Selection
$b, \bar{b}$	≥ 2 b-jets
$q, \bar{q}$	≥ 2 light-jets
$b, \bar{b}, q, \bar{q}$	≥ 4jets
Leptons	$= 1$
Neutrinos	= Lost Energy
Protons	$= 1$

Tabla **5-3.**: Object Selection

Objects	Selection
Electrons	$\lvert\eta\rvert < 2.1$
Electrons	$p_T > 30$ GeV
Muons	$\lvert\eta\rvert < 2.4$
Muons	$p_T > 30$ GeV
Jets	$\lvert\eta\rvert < 2.4$
Jets	$p_T > 25$ GeV
Jets	$\Delta R > 0.4$
Protons	$\xi \in [0.02, 0.13]$

Tabla 5-4.: Event Selection

Event reconstruction

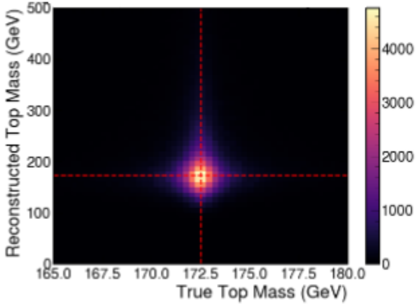
Event reconstruction

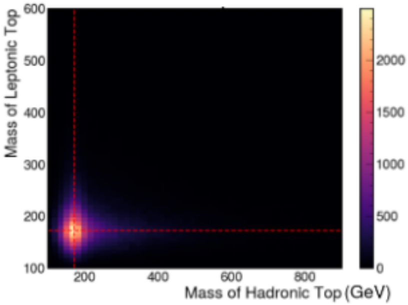
- **Particle Reconstruction:** Essential for deducing properties of undetectable particles, like the top quark.
- **Hadronic Top Quark Mass:** Calculated using a b-tagged jet and two light jets.

$$m(t_{\text{had}}) = \sqrt{(E_b + E_{q1} + E_{q2})^2 - (\vec{p}_b + \vec{p}_{q1} + \vec{p}_{q2})^2}$$

- **Leptonic Top Quark Mass:** Determined from a b-tagged jet, a lepton, and a neutrino.

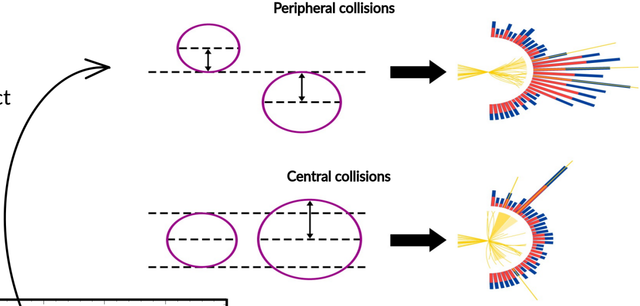
$$m(t_{\text{lep}}) = \sqrt{(E_b + E_l + E_\nu)^2 - (\vec{p}_b + \vec{p}_l + \vec{p}_\nu)^2}$$

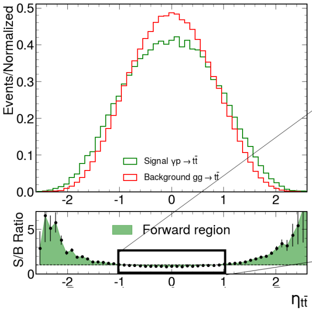


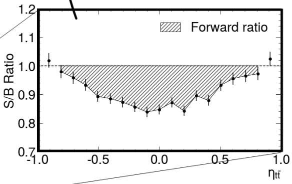


Event reconstruction

- There is more activity in the forward region (higher η) compared to central gluon-gluon collisions, indicating distinct kinematic properties and interaction dynamics.



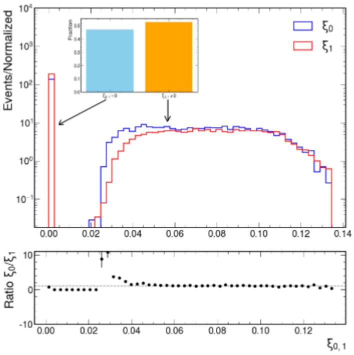




Event reconstruction

CT-PPS Proton reconstruction

- Momentum loss of the protons in range $\xi \in [0.02, 0.13]$.
    - First events case: ✓ $\longleftrightarrow$ × $\Longrightarrow$ $\xi_1 \neq 0$ and $\xi_2 = 0$
    - Second events case: × $\longleftrightarrow$ ✓ $\Longrightarrow$ $\xi_1 = 0$ and $\xi_2 \neq 0$
    - These events are the semi-exclusive nature of the signal process.

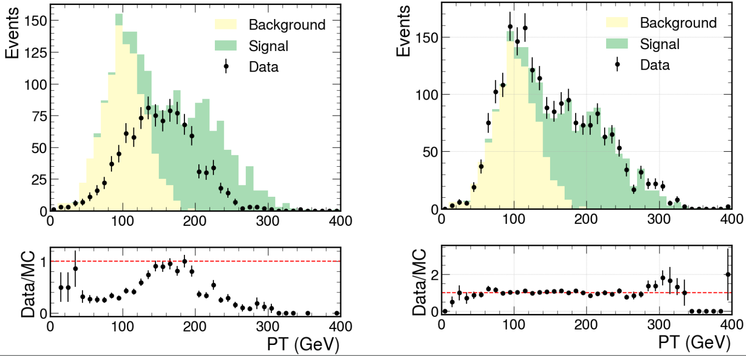


Event Reconstruction

- Reconstruct N kinematic variables from both simulation and data to compare their agreement, assessing how well our model simulates real-world data.
- Use the standard model equation for expected events

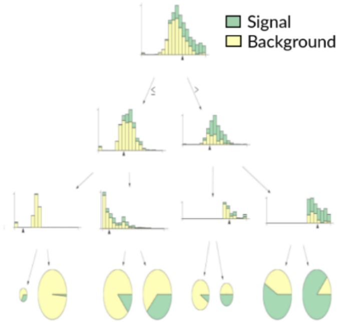
$$N_{exp} = L\sigma$$

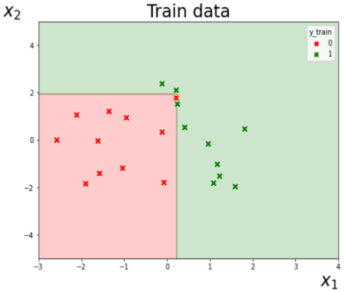
to scale MC according to cross sections and event counts.



Machine learning for signal/background discrmination

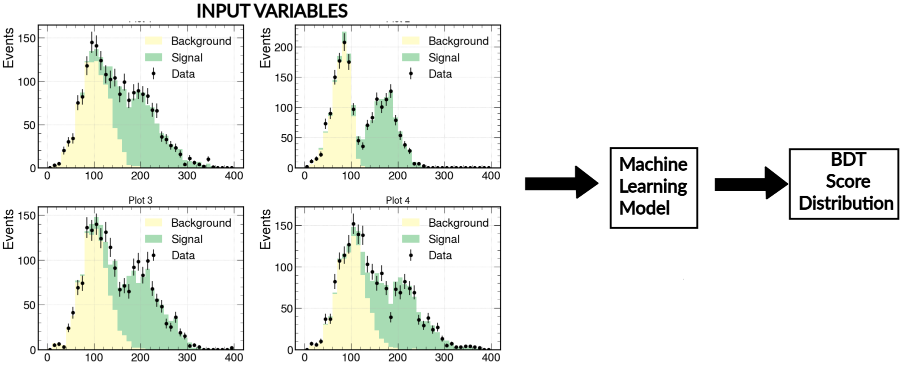
- Machine learning can model complex non-linear relationships between variables, which is often required for accurate signal-background discrimination.
- Boosted decision trees are a type of ensemble learning method that combines multiple weak classifiers to form a strong classifier, improving prediction accuracy.





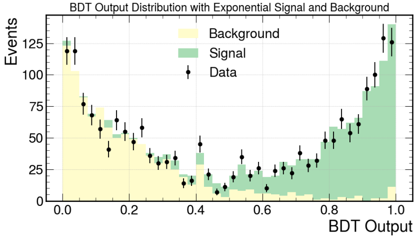
Machine learning for signal/background discrmination

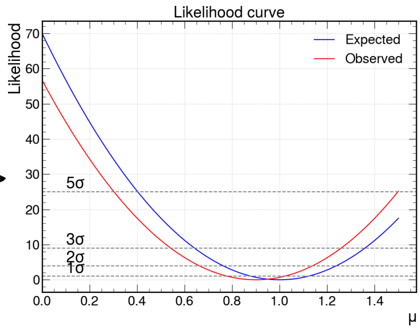
- Use statistical tests like the Kolmogorov-Smirnov test or the Chi-squared test to evaluate the discrimination power of kinematic variables.
- Use the BDT score distribution as an input to further statistical methods or likelihood fits to extract the cross-section



Likelihood statistics

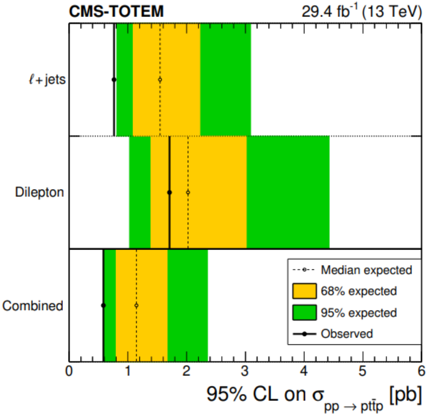
- We then utilize this BDT output to perform a profile likelihood fit. The key parameter here is the signal strength, denoted as μ, which is the ratio of the observed cross-section to the expected cross-section ($\mu = \frac{\sigma_{obs}}{\sigma_{exp}}$).
- A signal strength of $\mu = 1$ indicates that the observed data matches the expected number of events from the new phenomenon based on the theory.





Likelihood statistics

- In cases where the observed data lacks enough events to reach a statistically significant discovery (low sigma), a likelihood fit can still be informative.
- By analyzing the likelihood function, we can establish an upper limit for the possible cross section of a theorized process. This provides valuable constraints on the theory, even without a definitive discovery.



Conclusions

- Measuring the cross section reveals details about particle production, like top quark photoproduction.
- Top quark photoproduction is an interesting process because its peripheral nature leads to a rich particle signature.
- Good agreement between data and simulation indicates a good modelling of the signal and background processes.
- Discovery or Upper Limit: Analysis can lead to a discovery (5 σ), evidence (3 σ), or an upper limit.