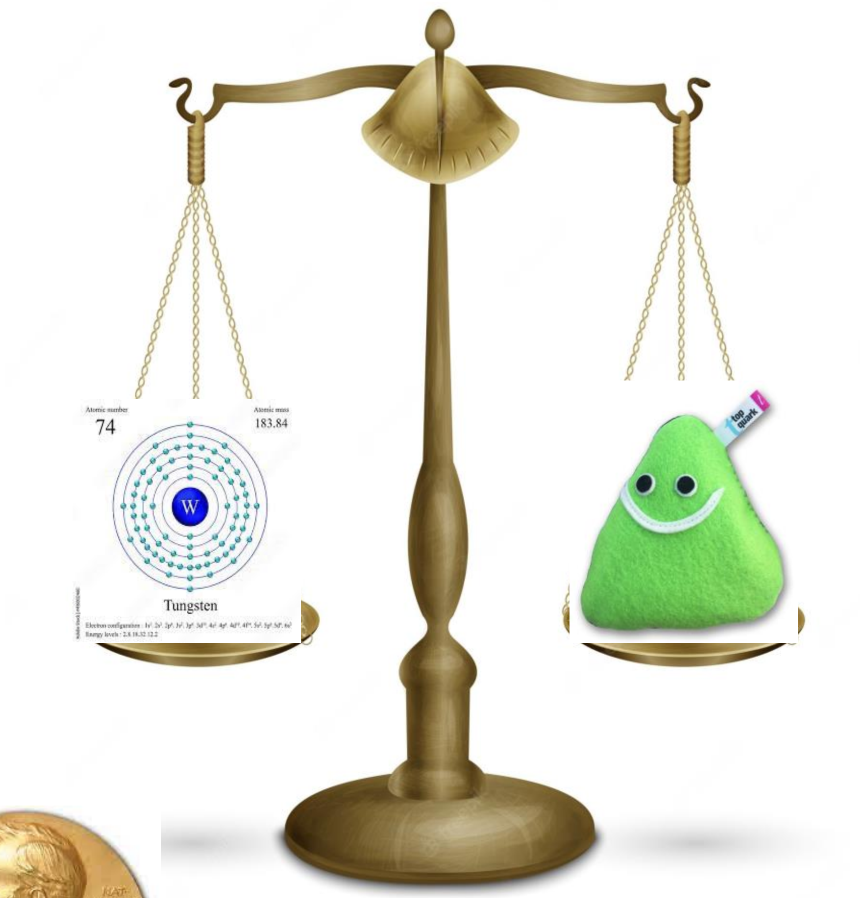
FINDING TOPS AT THE LHC

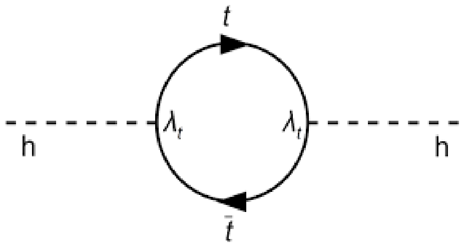
SAHIBJEET SINGH

BNL

THE TOP QUARK

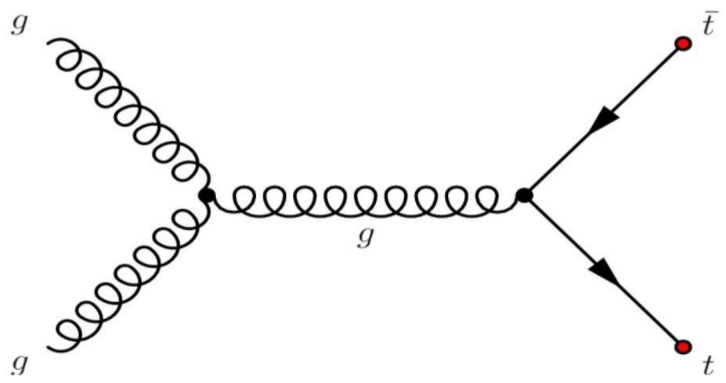
- Heaviest known particle at ~172 GeV or $3 * 10^{-25}$ kg
- ~40 times heavier than the 2nd heaviest quark
  - Almost equal to the mass of a Tungsten atom!
- Largest coupling to the Higgs field!
- Shortest lifetime of all particles
- Decays before any hadronization can occur
- Predicted alongside the b quark



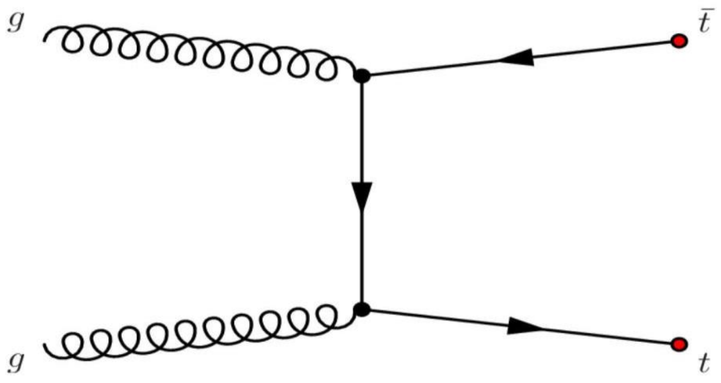


PRODUCING TOP QUARKS

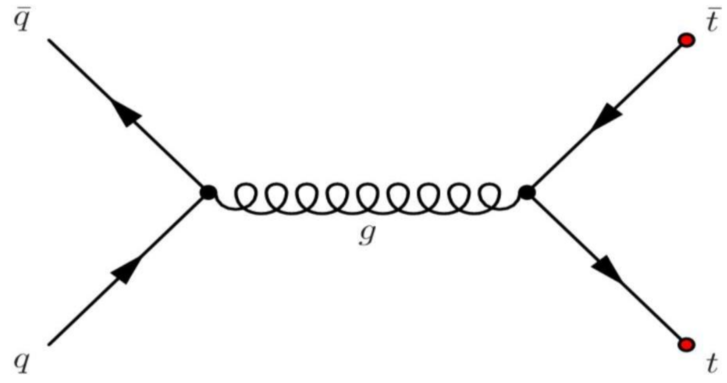
- Predominantly produced as top-antitop quark pairs via strong force interactions
- Need to collide gluons or quarks to produce top quarks



Gluon-gluon fusion



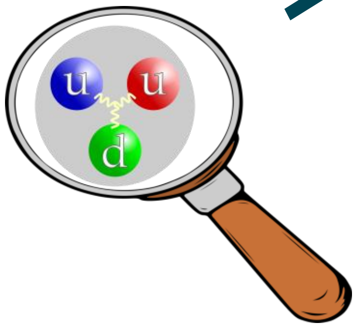
t-channel production

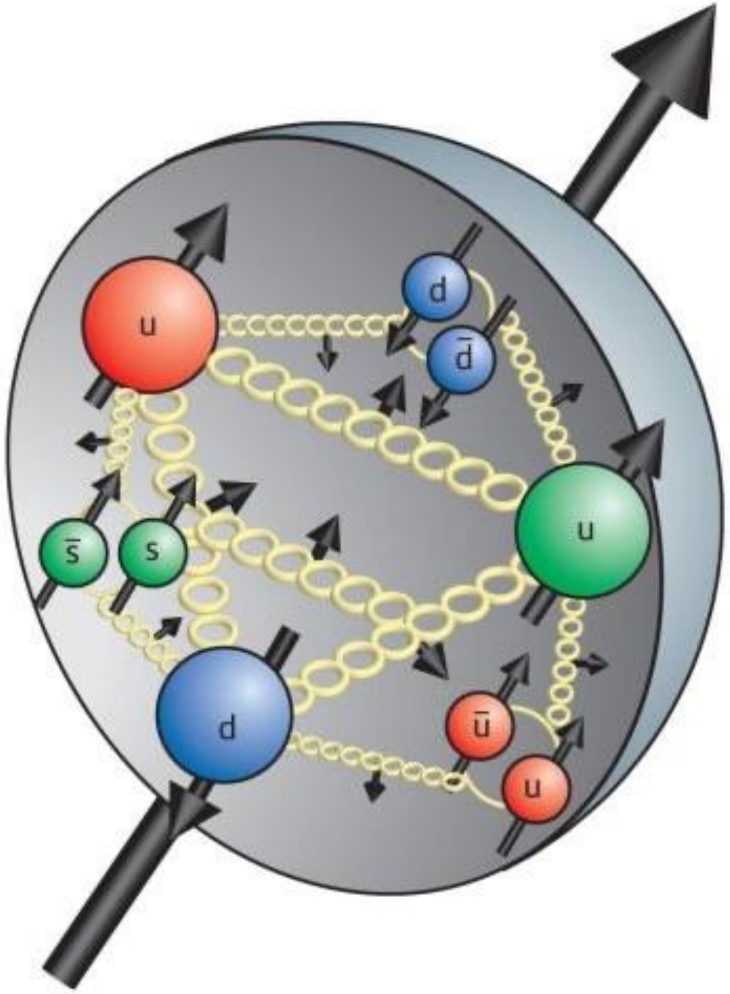


Quark annihilation

COLLIDING GLUONS AND QUARKS

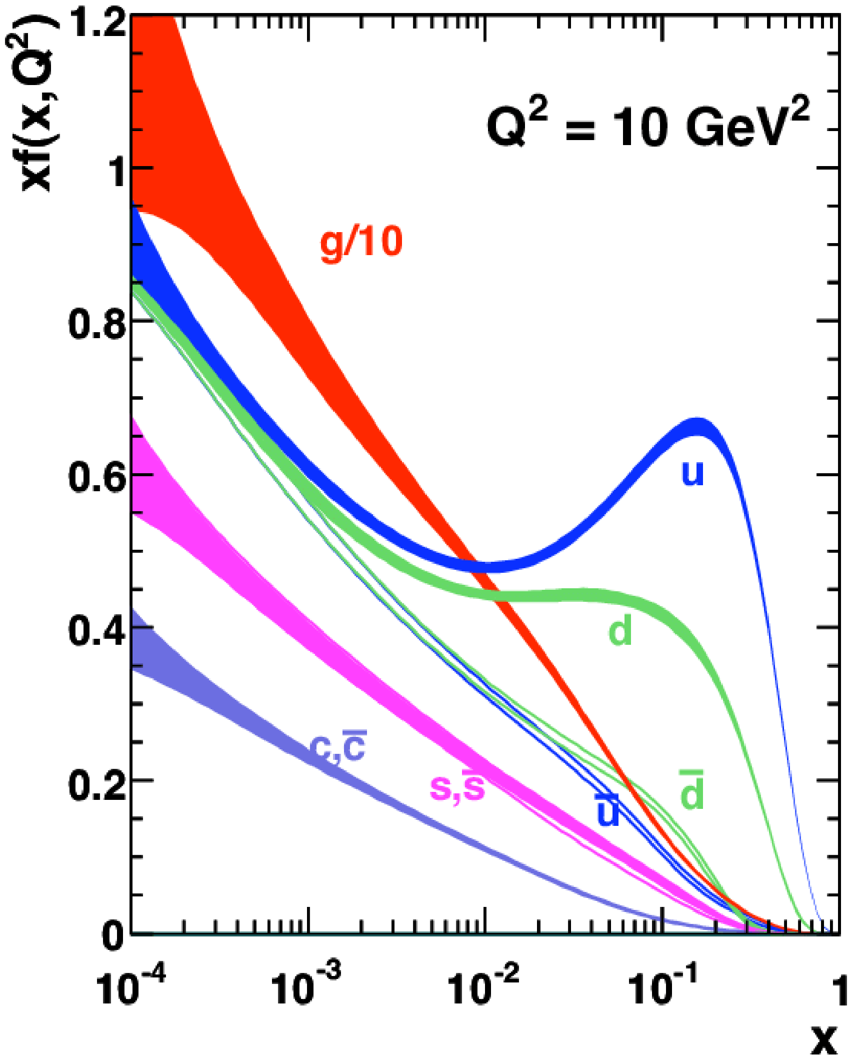
- Proton: “uud” (“valence quarks”) in a sea of quarks and gluons known as partons
- At high energy, collision of protons → **collisions** of quarks and gluons
- Increased popularity of hadron colliders
- Need to determine the momentum of the partons





PDF - PARTON DISTRIBUTION FUNCTION

- Probability of finding a certain fractional longitudinal momentum (x) of partons in the proton
  - Valence quarks, sea quarks, and gluons
  - Necessary for simulations in hadron colliders
- Typically presented at various energy scales (Q^2)
- Cannot be calculated from first principles yet*
  - Various groups perform fits to data and create their PDF sets



THE LHC

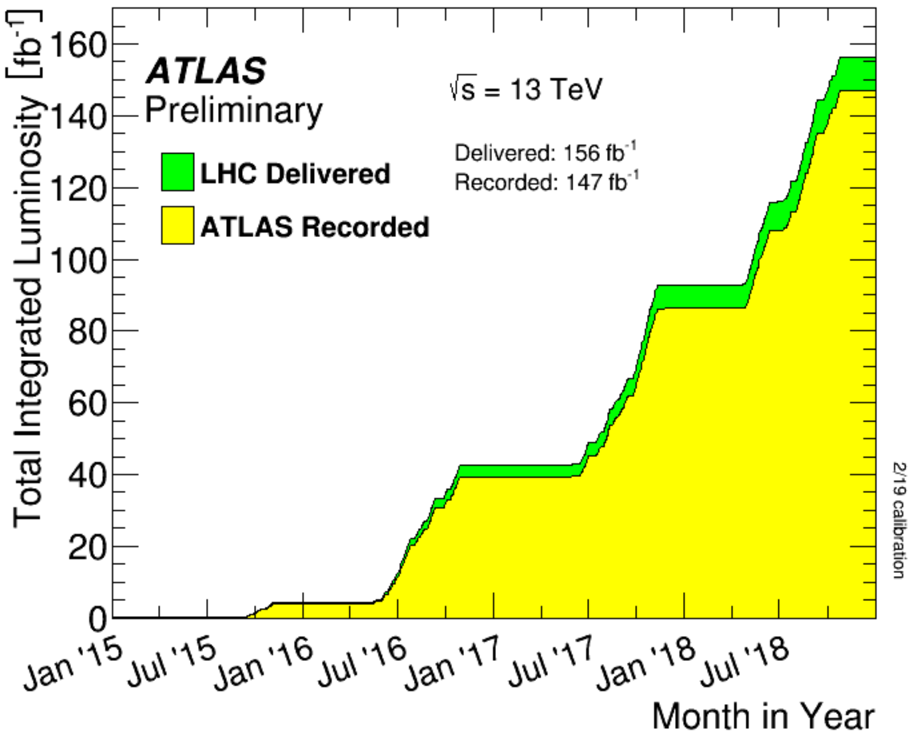
- 27 km long proton-proton collider at CERN
- Run 1 between 2009-2013 at 7 TeV and 8 TeV
  - Collected 20 fb^{-1} worth of data
- Run 2 between 2015-2018 at 13 TeV
  - 140 fb^{-1} worth of data
  - 5.02 TeV run in 2017
- Run 3 ongoing at 13.6 TeV
  - Expect to collect 300 fb^{-1} worth of data

ATLAS (A Torroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) are the two general purpose detectors

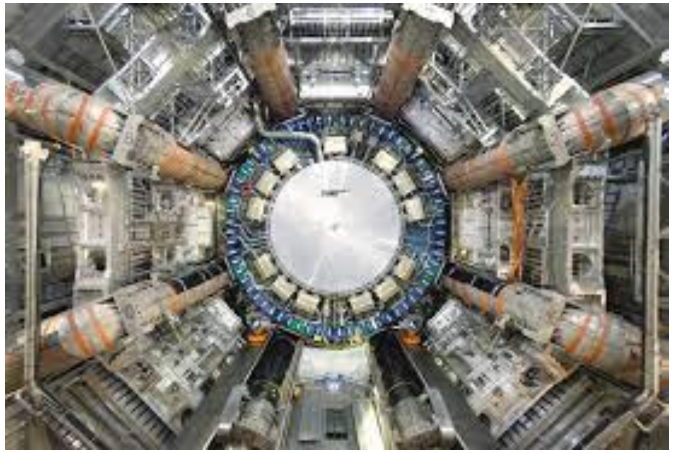
PHYSICS AT THE LHC

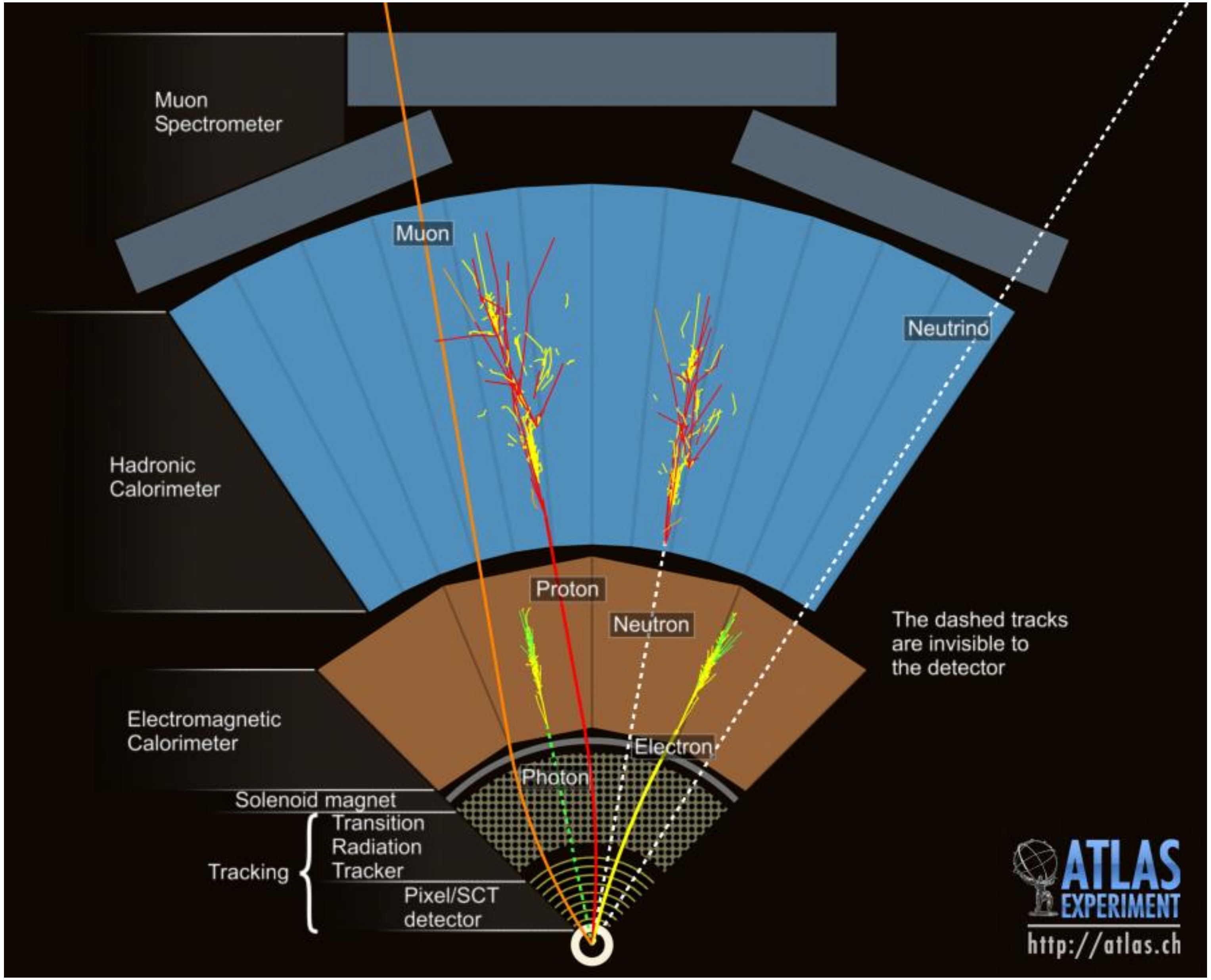
- Number of events seen by a detector depends on:
    - the cross section σ
    - the integrated luminosity $\mathcal{L}_{int}$
- Cross sections presented in barns [b]
- Integrated luminosity is units of inverse barns [1/b]
    - 1 barn = $10^{-28} m^2$
    - ATLAS collected $\sim 20 \text{ nb}^{-1}/s$
- Typically use transverse variables since they are well defined in the initial state
    - $p_T \equiv$ transverse momentum

$$N \propto \mathcal{L}_{int} \sigma$$



ATLAS

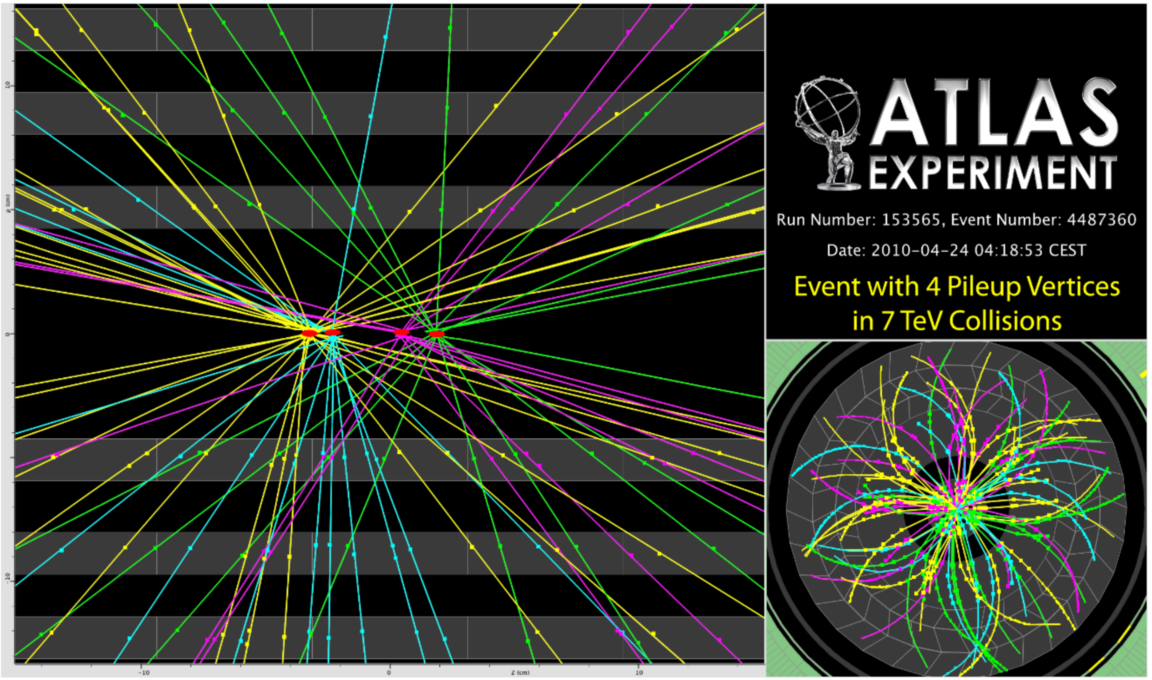


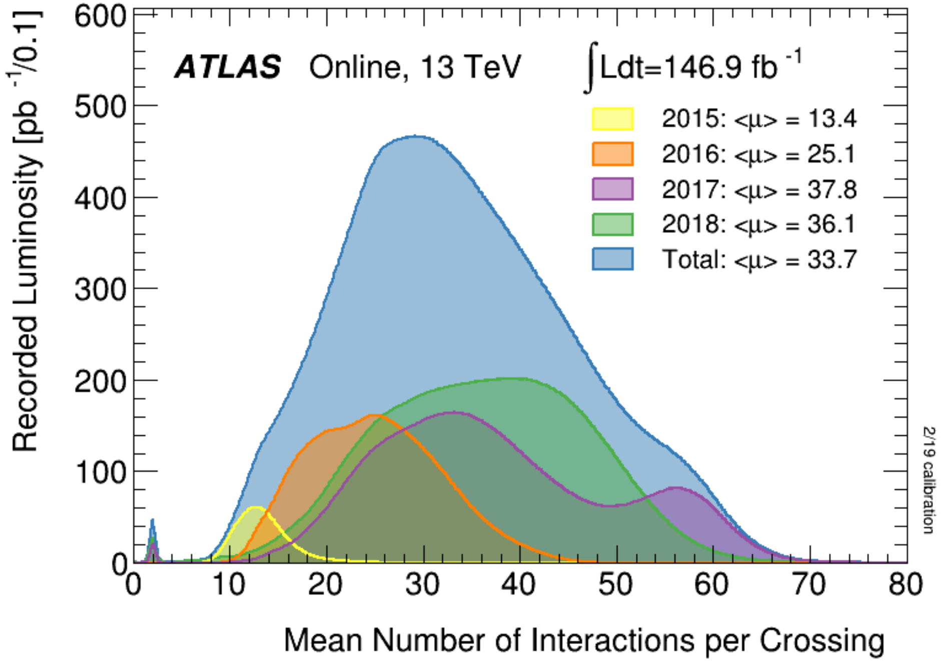


Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

PILEUP

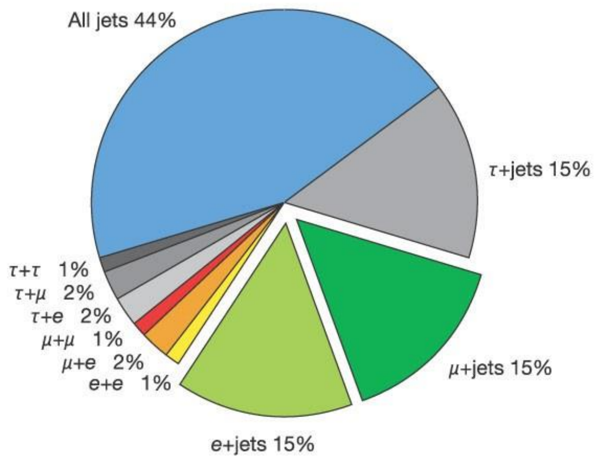
- More than 1 pp collision at any given time
- Average number of pp collisions $\langle \mu \rangle$ is proportional to $\mathcal{L}_{int}$
- Need to select events coming from the “hard scatter”

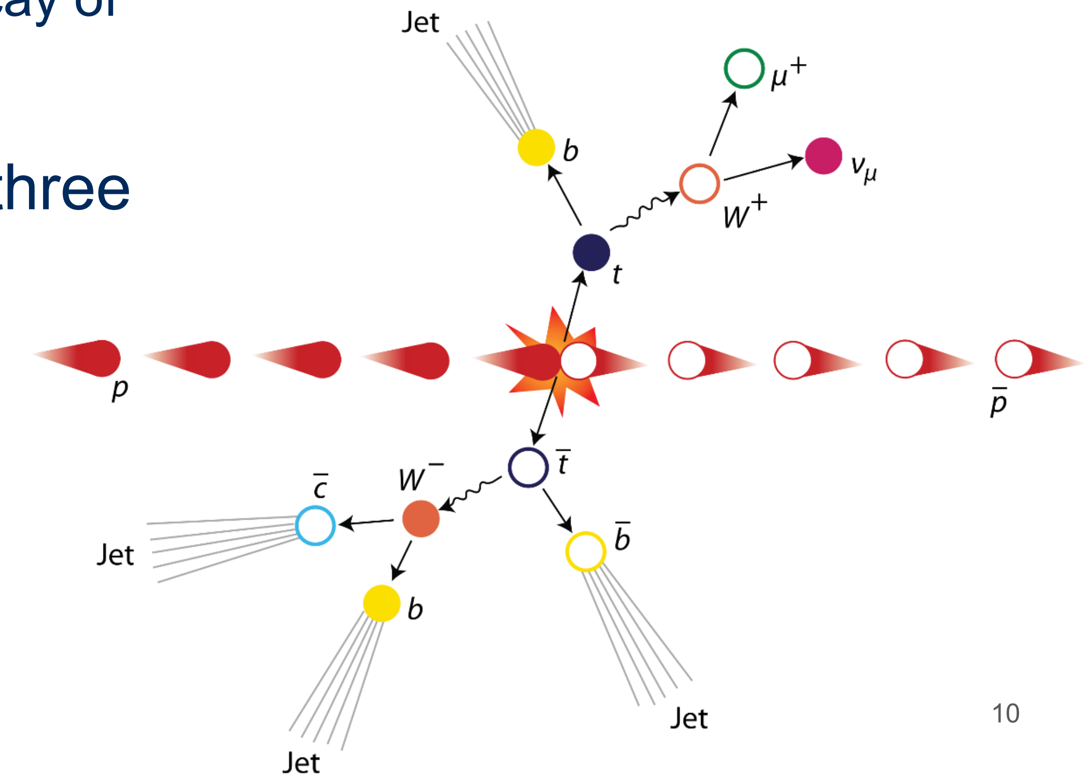




TOP QUARK DECAYS

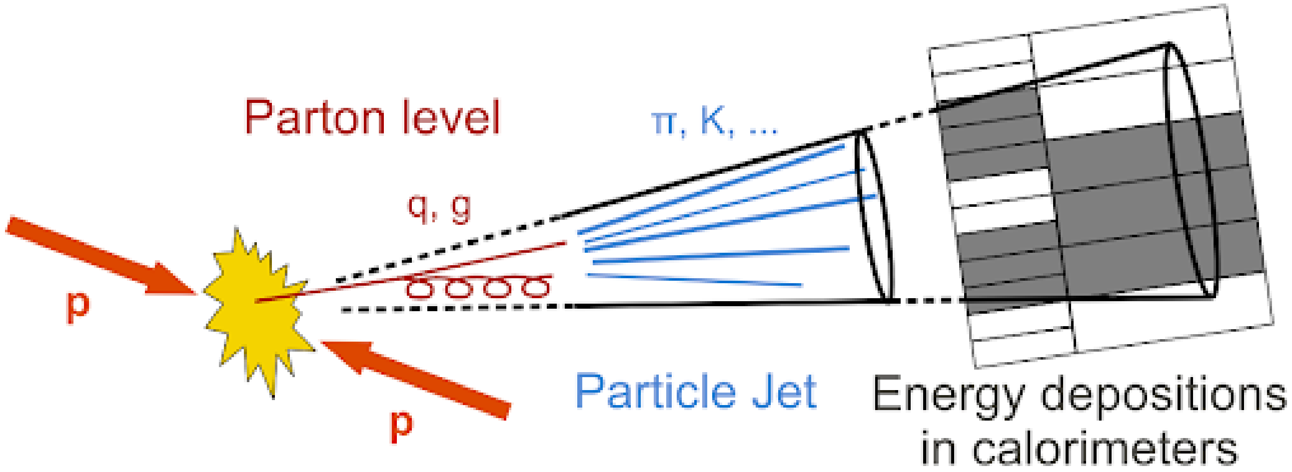
- Top quark always has an associated b quark – easy to ID a top quark using b-tagging algorithms!
- Top quark decays characterized by the decay of the W boson
  - Due to a factor from the CKM matrix
  - Leptonic decay of W boson → semi-leptonic decay of the top quark
  - Hadronic decay
- Top quark pair production categorized into three categories
  - All-hadronic: ~45%
  - Lepton+jets: ~45%
  - Dilepton: ~10%
- Can use number of jets to discriminate





JETS AT ATLAS

- Quarks cannot exist as free particles → hadronize and form bound states
  - This is non-perturbative QCD and not well understood
  - Various models exist and are tuned to data
- Additional final state radiation and hadronization leads to jets
- Depending on the lifetime of the bound states, they can be detected
  - Pions, Kaons, protons, neutrons…
- Can reconstruct clusters of energy deposits as jets of particles

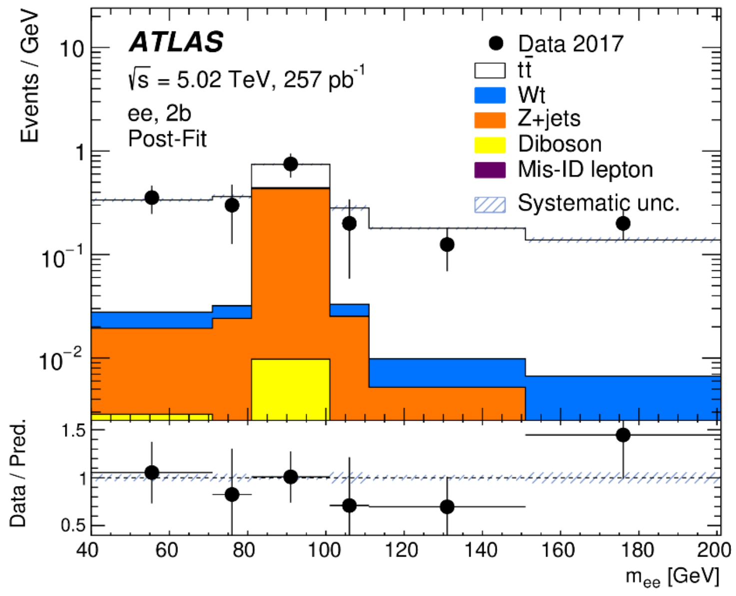


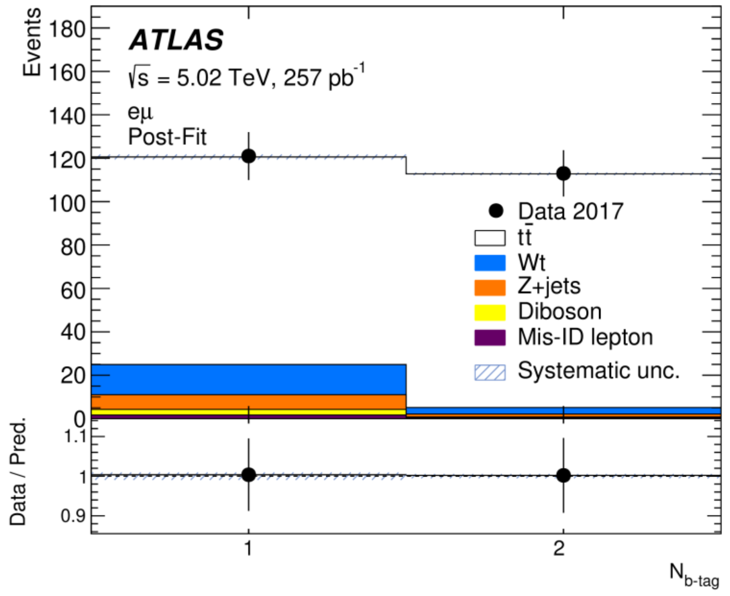
TOP QUARKS AT 5.02 TEV

- 257 pb^{-1} worth of pp collision data taken in 2017 at $\sqrt{s} = 5.02$ TeV
- Low pileup environment with respect to 13 TeV collisions
- $\sigma_{t\bar{t}}$ is an order of magnitude smaller at 5.02 TeV but still possible to measure
- Needed a dedicated calibration for the jet energy scale at 5.02 TeV
- Gluon PDF sensitive to $\sigma_{t\bar{t}}$ measurements at low $\sqrt{s}$
- Effort to measure $\sigma_{t\bar{t}}$ in both the dilepton and lepton+jets channels to a better accuracy than CMS

THE DILEPTON CHANNEL

- First time using both same flavour ($ee, \mu\mu$) and opposite flavour ($e\mu$) dilepton events
- Good purity but low statistics
- Single lepton trigger
  - Require 2 opposite sign leptons to be reconstructed
- Lepton $p_T > 18$ GeV and $|\eta| < 2.5$
  - Trigger is fully efficient
- Jet $p_T > 25$ GeV, $|\eta| < 2.5$, and one or two b-tagged jets
- $\eta \equiv -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$

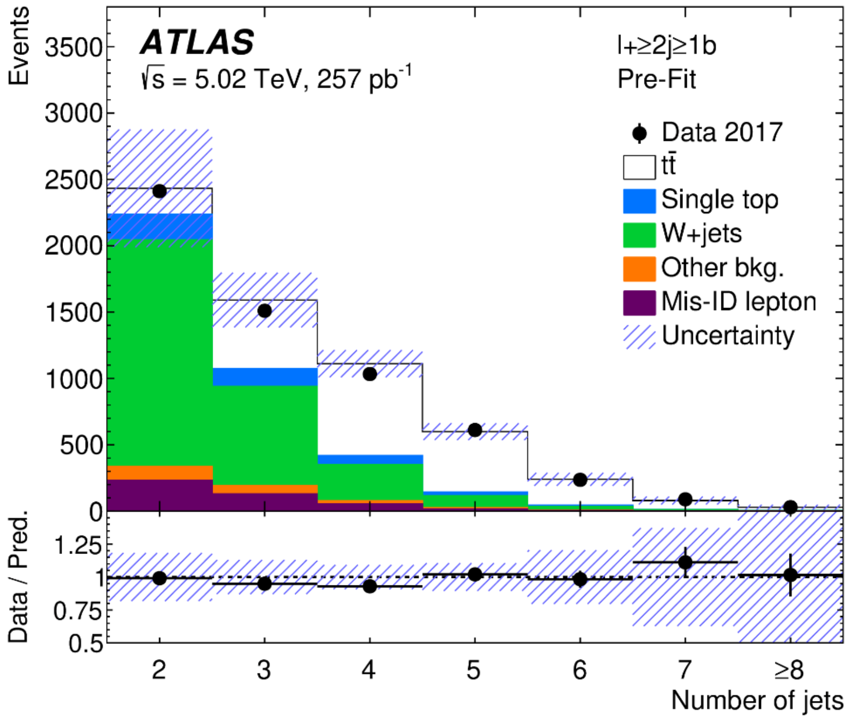




LEPTON+JETS CHANNEL

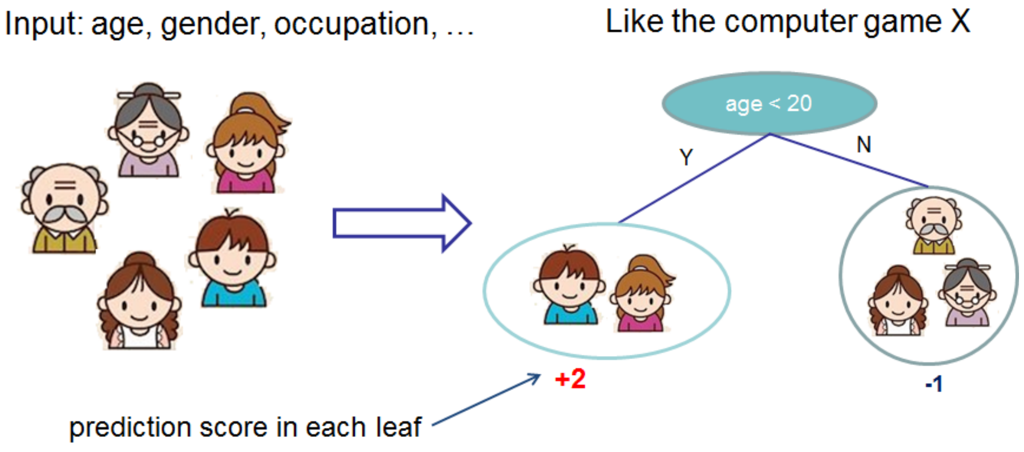
- More statistics but more background
- Exactly one electron or muon candidate that was triggered on
- Lepton $p_T > 25$ GeV
  - Reject "soft" mis-identified leptons
- Two or more jets with $p_T > 25$ GeV and $|\eta| < 2.5$
- Events classified into 6 regions based on number of jets and b-tagged jets
- Boosted Decision Tree (BDT) trained to separate signal from background

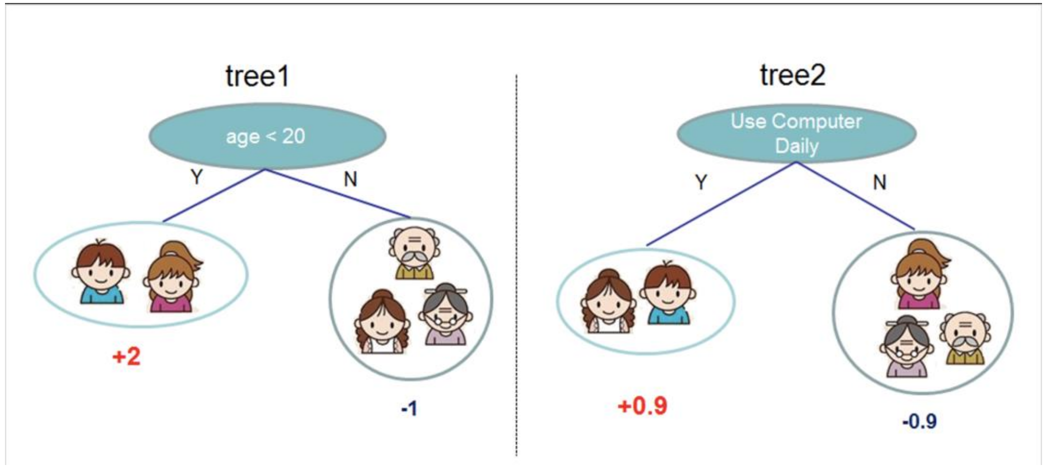
Region name	Jet multiplicity	b-jet multiplicity
ℓ+2j≥1b	2	≥ 1
ℓ+3j 1b	3	1
ℓ+3j 2b	3	2
ℓ+≥4j 1b	≥ 4	1
ℓ+4j 2b	4	2
ℓ+≥5j 2b	≥ 5	2



BDTS 101

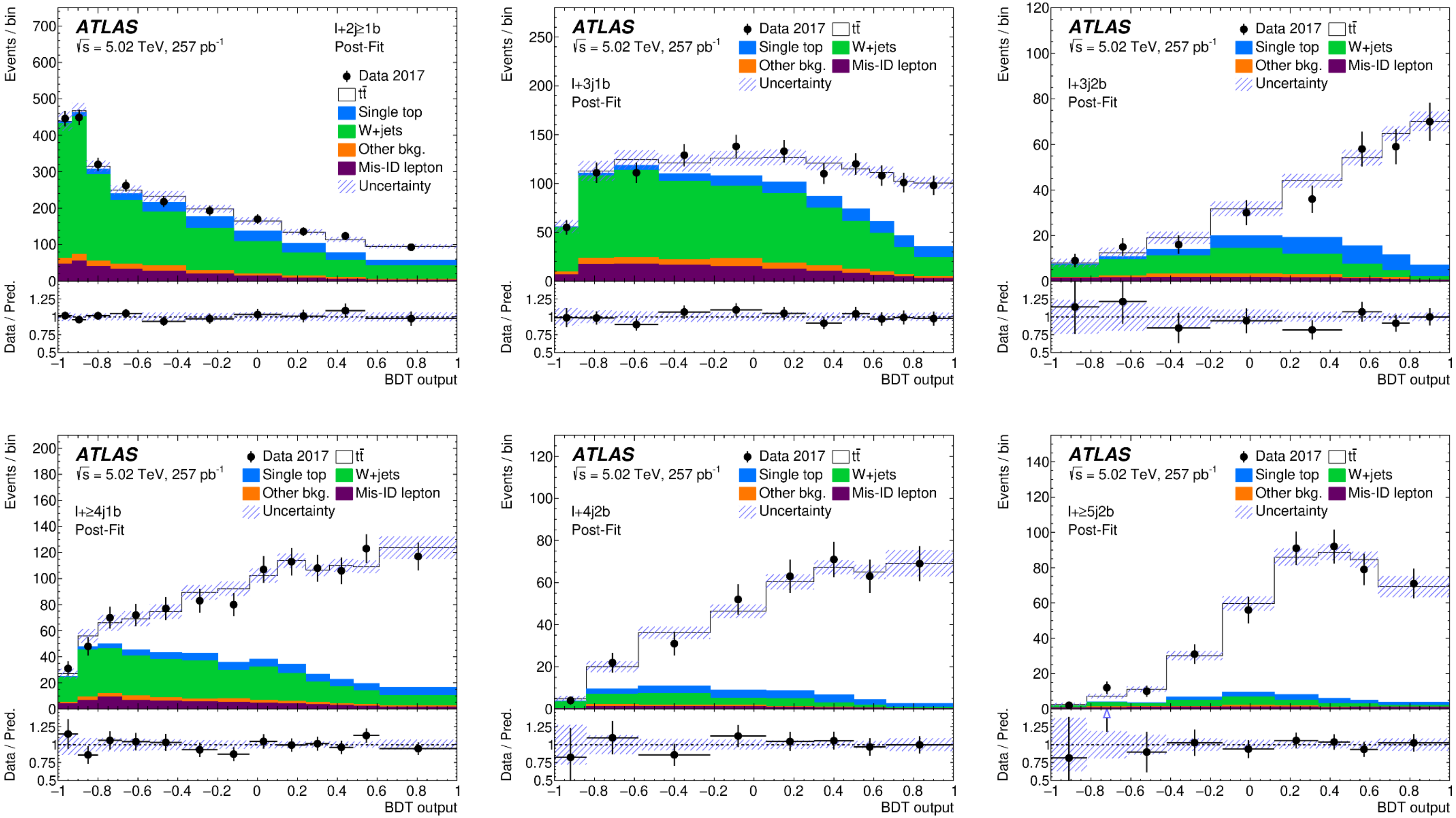
- Multivariate analysis technique similar to neural networks
  - Train a model by minimizing the loss function
- Can be used to solve classification or regression problems
- Create trees denoted by j based on a set of input parameters $(x_i)$and extract a score for each tree $(S_j = f(x_i))$
- Final BDT score is $\sum_j S_j$





LEPTON+JETS CHANNEL BDT

- BDT response distributions in the six regions



MEASURED CROSS SECTION

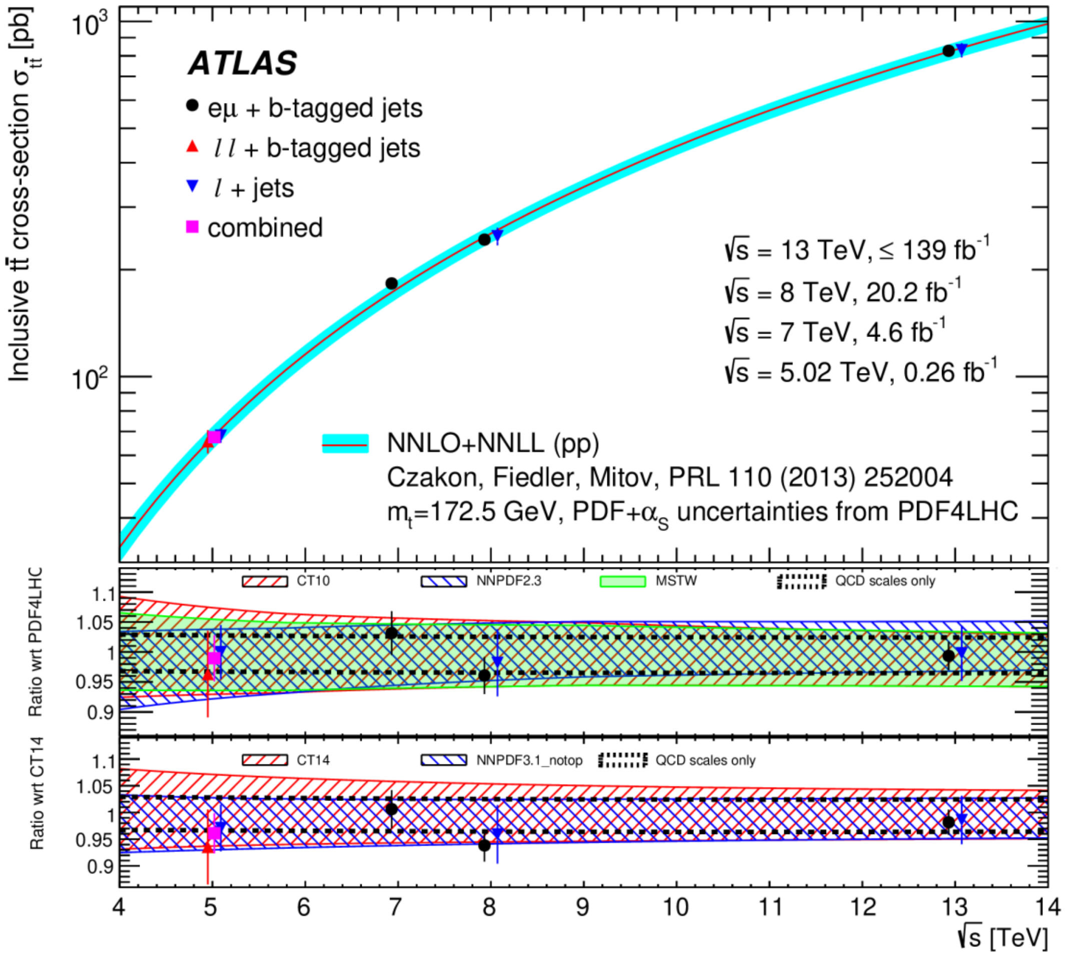
- SM predicts $\sigma_{t\bar{t}} = 68.2$ pb

SL: $68.2 \pm 0.9(\text{stat.}) \pm 2.9(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})$ pb

DL: $65.7 \pm 4.5(\text{stat.}) \pm 1.6(\text{syst.}) \pm 1.2(\text{lumi.}) \pm 0.2(\text{beam})$ pb

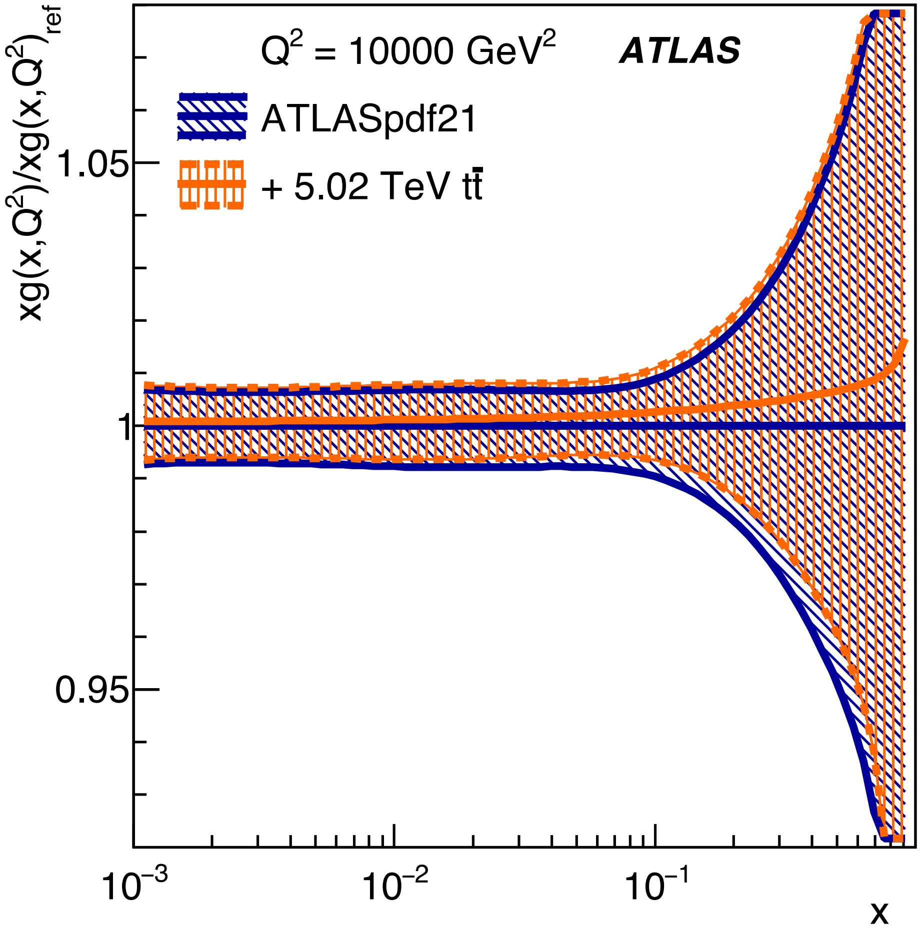
Comb: $67.5 \pm 0.9(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})$ pb

- 4.5% relative uncertainty in lepton+jets
- Most precise $\sigma_{t\bar{t}}$ measurement in the lepton+jets channel by ATLAS!
- 3.9% overall uncertainty in the combined result of the two channels



EFFECT ON THE GLUON PDF

- Including the combined $\sigma_{t\bar{t}}$ measurement to the ATLASPDF21 fit
- ~1% increase in the gluon PDF at high x
- ATLASPDF21 also contains multiple top quark measurements from and 8 and 13 TeV
  - The effect of these measurements at high x is O(1%) as well
  - One measurement at 5.02 TeV gives a 1% change in a fit with ~1500 DOFs

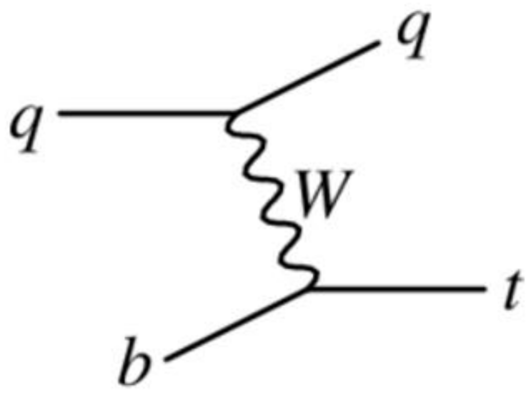


THE NEXT STEP

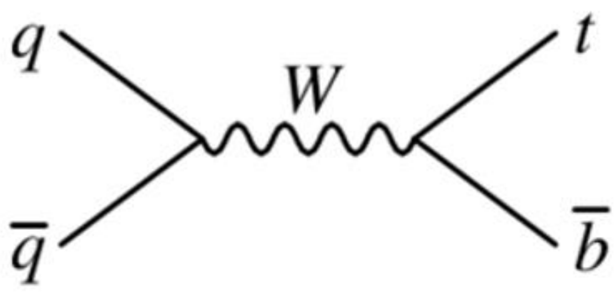
- 5 TeV $\sigma_{t\bar{t}}$ measurement uploaded to Arxiv on July 4th 2022
  - JHEP06(2023)138
- Analysis team met for the first time in person at the 2022 ATLAS top workshop in Valencia
- Discussed the possibility of observing single top quark production at 5.02 TeV
  - Additional test of the SM
  - Could be used to further constrain PDFs
- Summer student from Toronto was available and we got to work!

OVERVIEW OF SINGLE TOP QUARK PRODUCTION

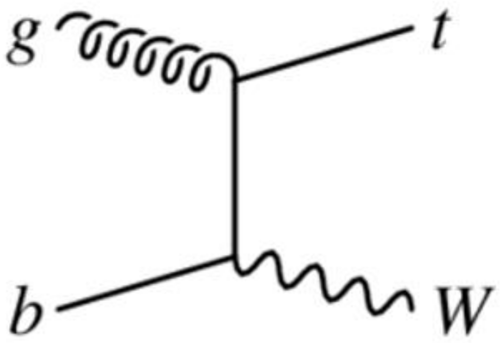
- Single top quarks produced through three mechanisms
- t-channel has the largest cross-section of the three
  - $\sigma(tq + t\bar{q}) \propto V_{tb}$ term of the CKM matrix
- At 5.02 TeV the t-channel cross section is predicted to be 30.3 pb



t-channel



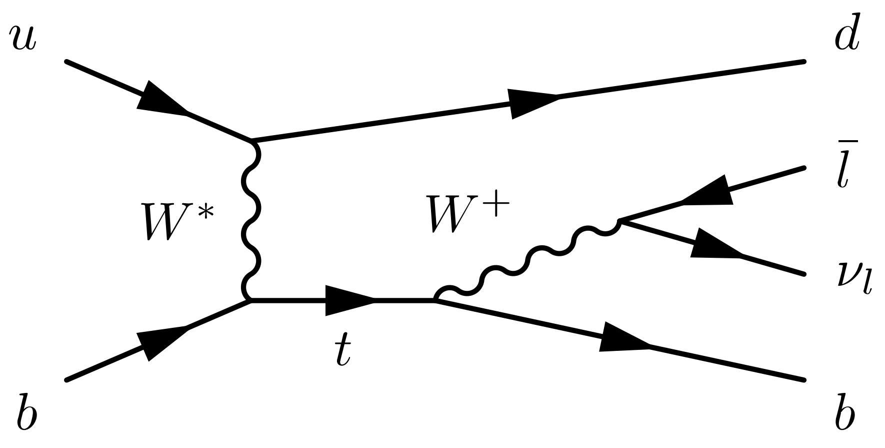
s-channel

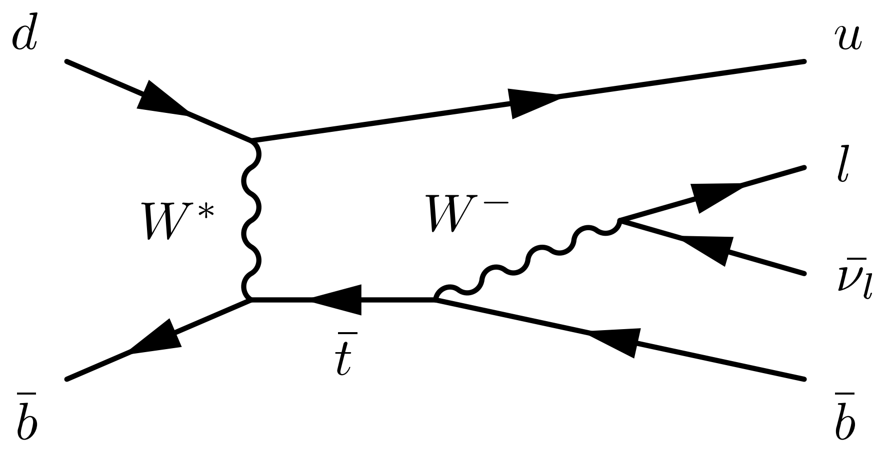


tW associated production

PROPERTIES OF T-CHANNEL PRODUCTION

- There is an additional spectator jet produced with the top quark
  - This forward jet is typically produced in the high $|\eta|$ region
- Use the leptonic decay of the top quark to trigger on events
- Require one b-tagged jet with $|\eta| < 2.5$ and one "untagged" jet with $|\eta| < 4.0$
  - Needed to calibrate the forward jets!

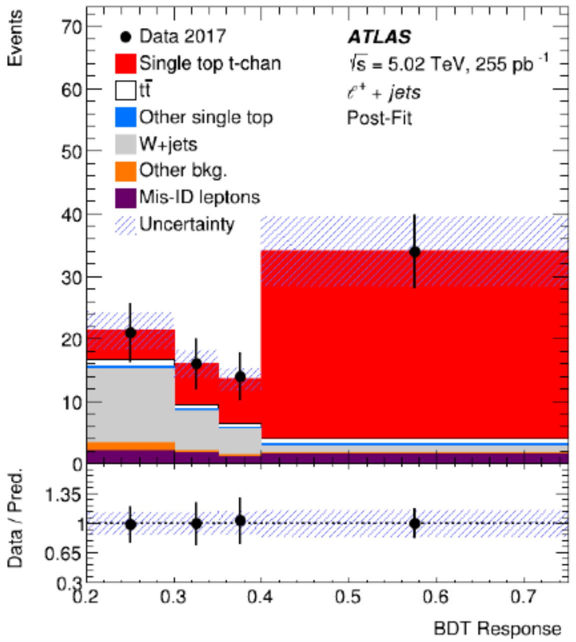


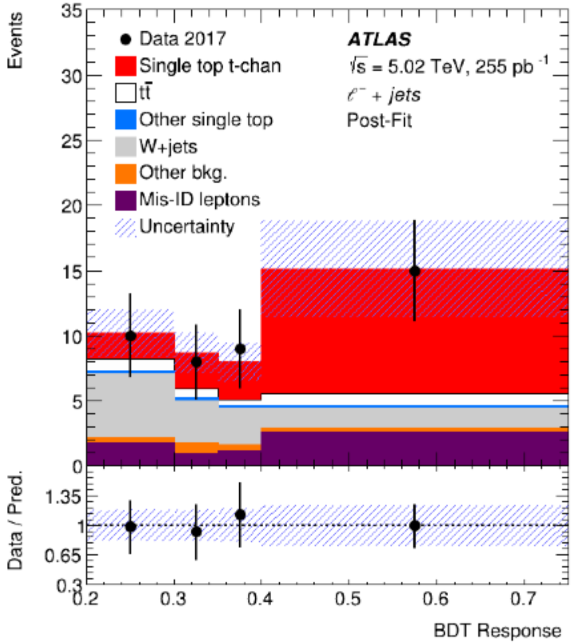


BDT IMPLEMENTATION AND RESULTS

- Train a BDT to separate signal from background
- Apply it to a positive lepton and negative lepton regions
  - Used to select for top quark or antitop quark production
- Extract $\sigma(tq + t\bar{q})$ and R_t (ratio of individual cross sections) from a fit to data
- Calculate $\sigma(tq), \sigma(t\bar{q})$, and $|f_{LV} \cdot V_{tb}|$

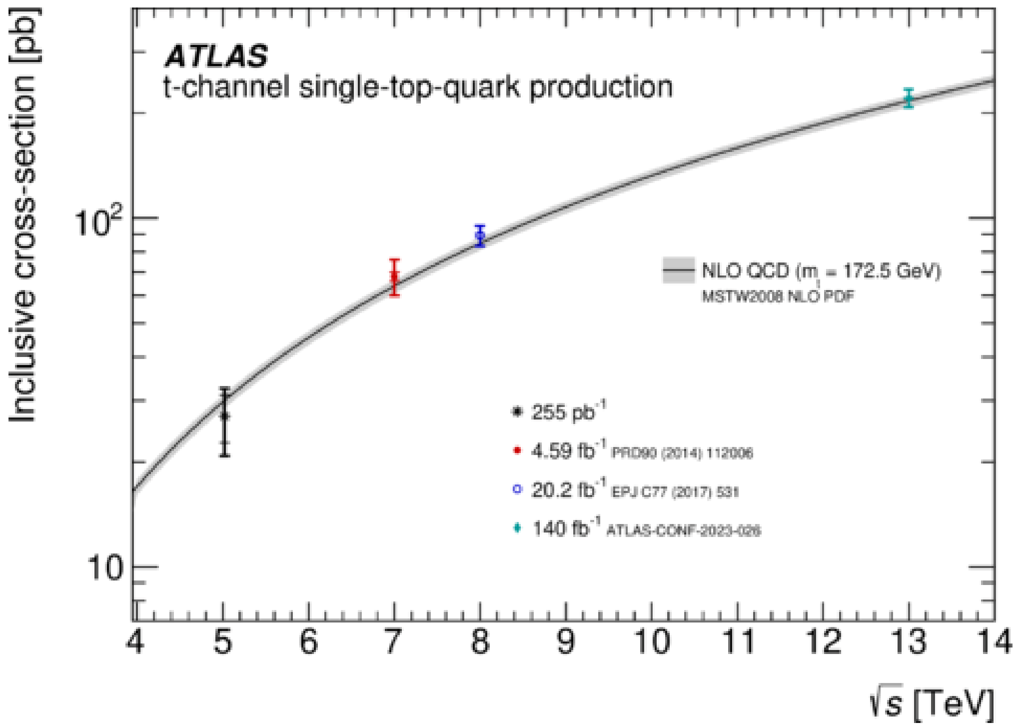
Variable	Predicted	Measured
$\sigma(tq + \bar{t}q)$	$30.3^{+0.7}_{-0.5}$ pb	$27.1^{+4.4}_{-4.1}$ (Stat.) $^{+4.4}_{-3.7}$ (Syst.) pb
R_t	$2.03^{+0.06}_{-0.07}$	$2.73^{+1.43}_{-0.82}$ (Stat.) $^{+1.01}_{-0.29}$ (Syst.)
$\sigma(tq)$	$20.3^{+0.5}_{-0.4}$ pb	$19.8^{+3.9}_{-3.1}$ (Stat.) $^{+2.9}_{-2.2}$ (Syst.) pb
$\sigma(\bar{t}q)$	$10.0^{+0.2}_{-0.3}$ pb	$7.3^{+3.2}_{-2.1}$ (Stat.) $^{+2.8}_{-1.5}$ (Syst.) pb
$\|f_{LV} \cdot V_{tb}\|$	–	$0.94^{+0.11}_{-0.10}$ (Stat. $\oplus$ Syst. $\oplus$ Theory)

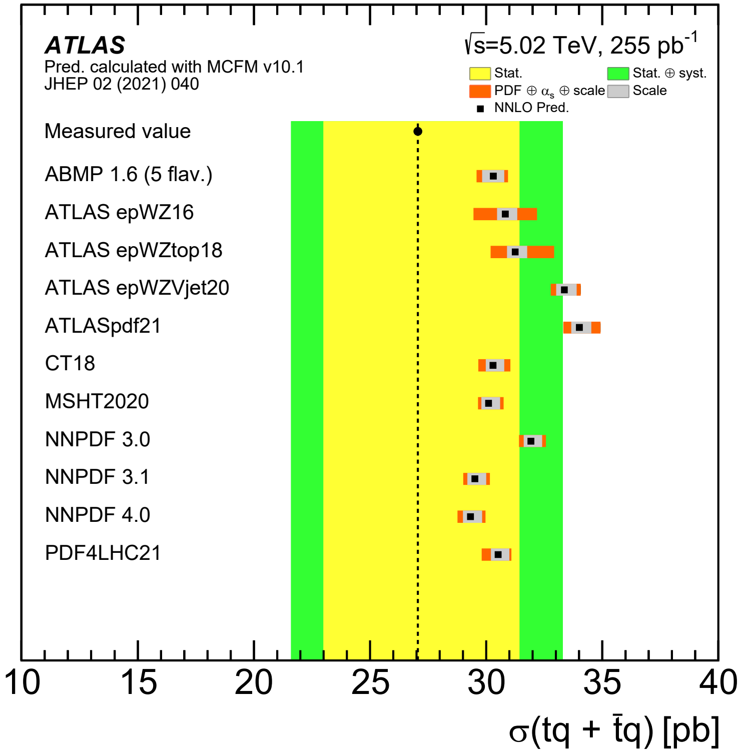




SINGLE TOP QUARK PRODUCTION AT 5.02 TEV

- Observed single top t-channel production with a significance of 6.1σ
- Statistics limited due to small dataset
- Published in PLB in 2024!





SUMMARY

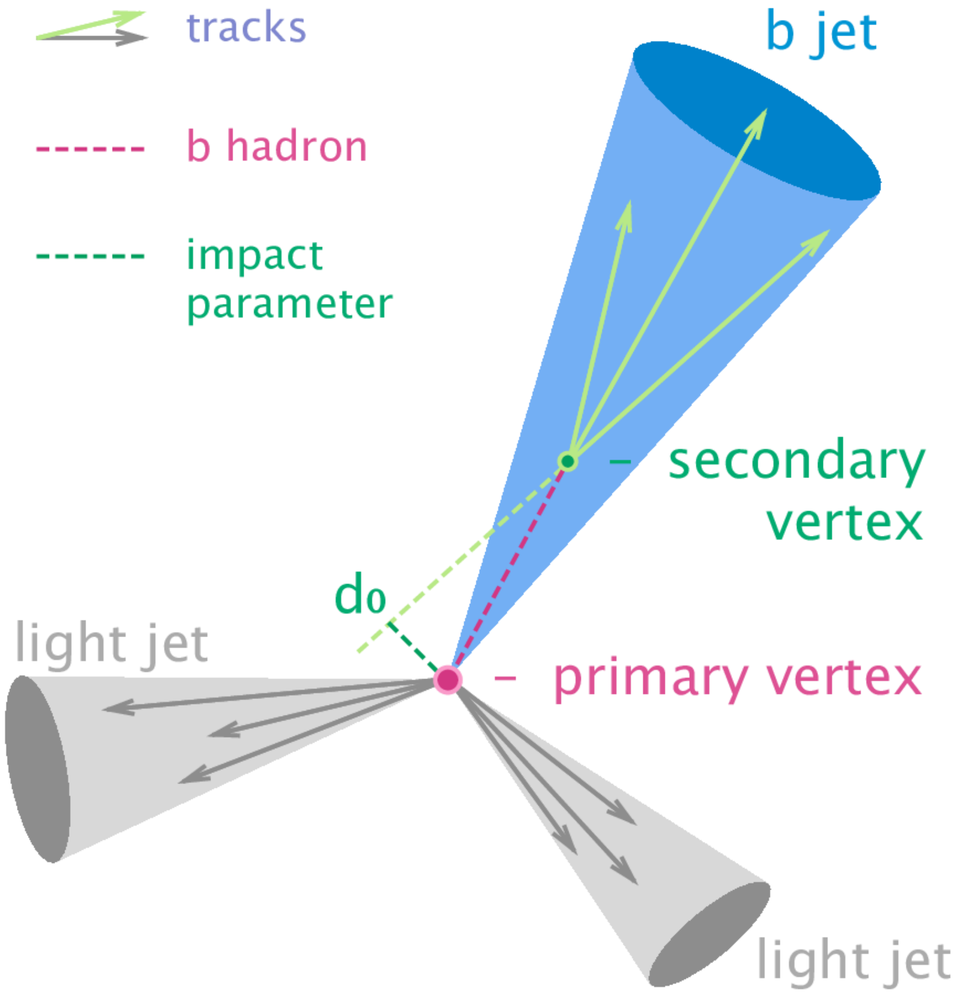
- The LHC has provided an abundance of interesting data to study
  - Discovered the Higgs in 2012
- Can continue to learn more about top quarks with LHC data
- LHC started off as a search machine but has transitioned to a precision measurement machine
- Unique LHC runs such as the 5.02 TeV run can give interesting physics results!

More LHC data is on its way

BACKUP

B-TAGGING IN ATLAS

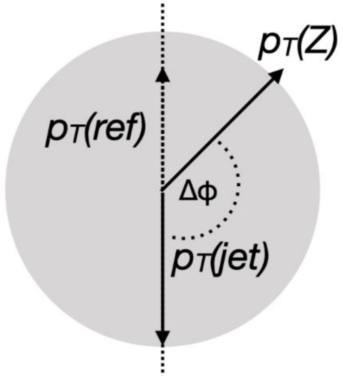
- b quarks hadronize into B hadrons
  - Large B hadron mass
  - Displaced secondary vertex due to long life of the b quark (~1.5 ps)
  - Large impact parameter (d0)
  - Soft semi-leptonic decay (e/μ) of B hadrons (~40%)
- High level variables exploiting B hadron properties fed into a Deep Neural Network (DNN)



JET CALIBRATIONS

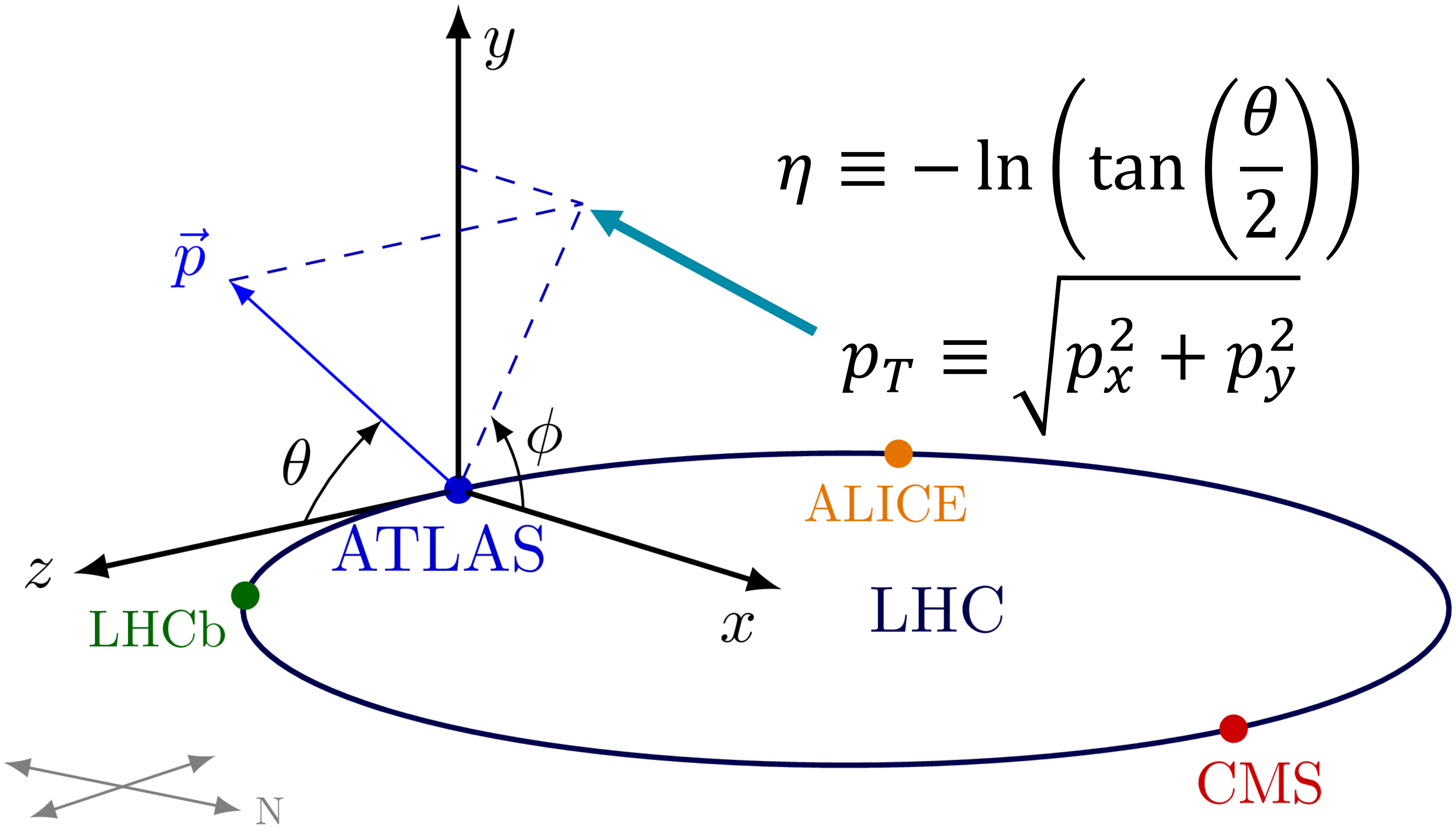
- Need to calibrate the jets that were detected
- Use simulation after corrections as a reference and calibrate using a well defined system like the Z+jet balance
  - Look for Z boson and one jet back-to-back

$$\langle r \rangle \equiv \left\langle \frac{p_T^{ref}}{p_T^{jet}} \right\rangle$$



- Correct the jet p_T in data such that $\langle r \rangle$ is the same in data and simulation

THE ATLAS COORDINATE SYSTEM



$$\eta \equiv -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

$$p_T \equiv \sqrt{p_x^2 + p_y^2}$$