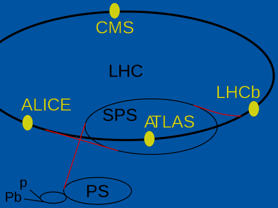


High p_T Physics at the LHC
Lecture 3: Introductory Topics and SM Physics

Warwick Week 2024

22^{nd} March 2024

Andy Chisholm (University of Birmingham)

Overview

Outline of Lecture

- Introduction to the ATLAS and CMS detectors
- Review of relevant definitions and conventions
- Low p_T processes
- Hadronic jets
- $W^{\pm}$ and Z boson physics
- Top quark physics

The context of the lectures will focus on the ATLAS and CMS experiments, though LHCb and ALICE can and do study many of the processes discussed!

Where differences between ATLAS/CMS measurements are irrelevant or minor, I will typically show ATLAS results as examples since I'm more familiar with this experiment!

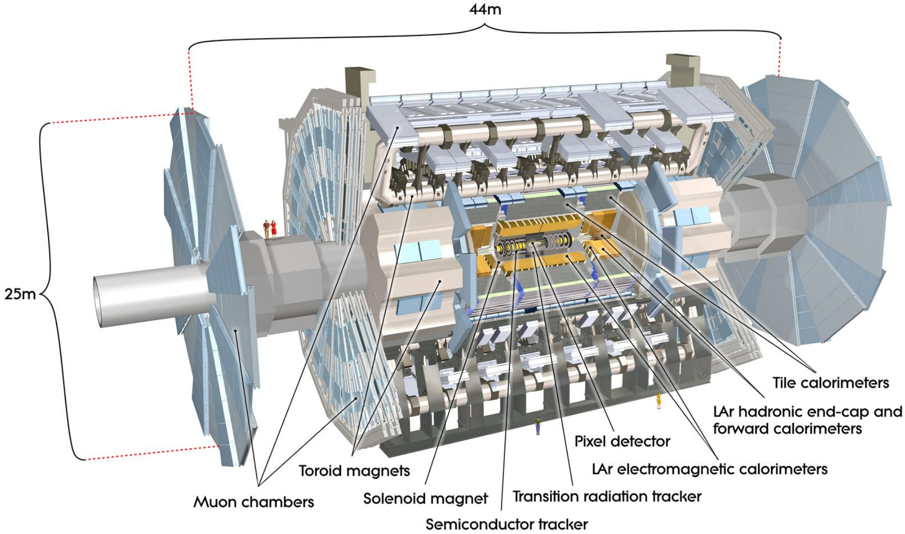
General Purpose Detector Overview

Most general purpose hadron collider detectors (GPDs) (e.g. ATLAS, CMS, CDF, DØ, UA1) share the same common components

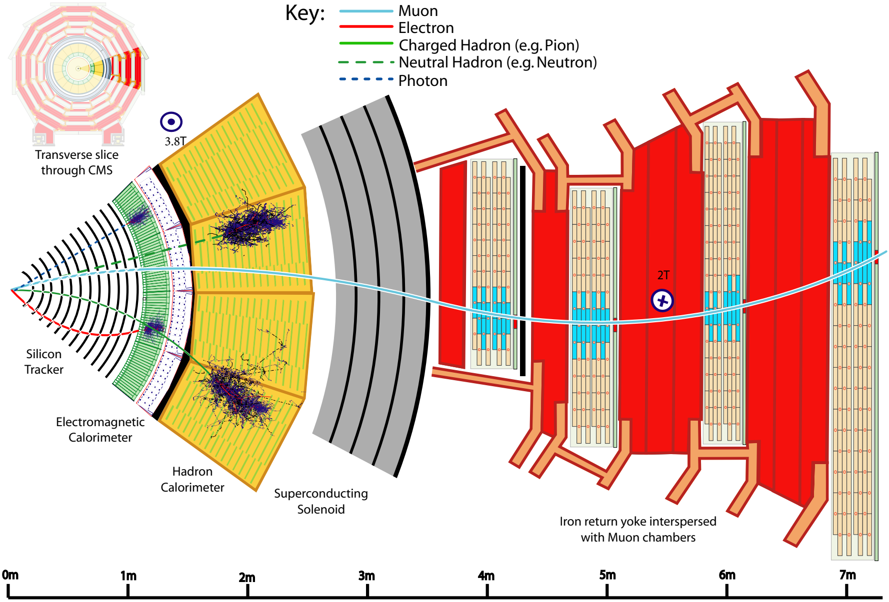
- **Tracking Detector + Solenoid Magnet:** Measure trajectory of charged particles to infer momentum and charge, used to reconstruct primary interaction point
- **Electromagnetic Calorimeter:** Measure the energy of high energy† electrons, positrons and photons
- **Hadronic Calorimeter:** Measure the energy of high energy† hadrons ($\pi^{\pm}, K^{\pm}, p/\bar{p}$), used (with EM calo.) to build "jets"
- **Muon Detector:** Detect muons with momentum sufficient to traverse calorimeters, sometimes a dedicated magnet system is present to measure momentum and charge
- **Trigger:** System to perform first coarse selection of "interesting" events to reduce raw collision data rate ($\mathcal{O}$(10MHz) at LHC) to a manageable rate ($\mathcal{O}$(100Hz) at LHC) for permanent storage and offline analysis

† **Typically $E_{\mathrm{T}} > 100$ MeV**

ATLAS Detector Overview

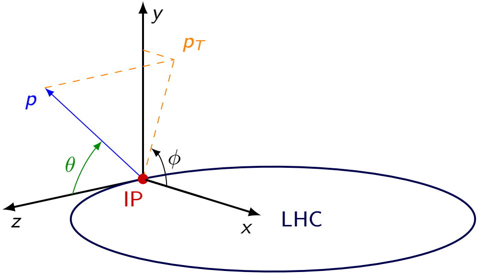


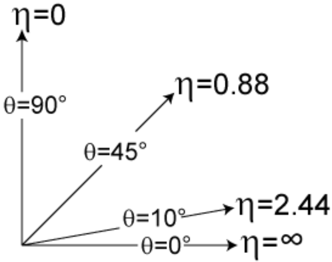
CMS Detector Overview



Definition of Kinematic Quantities

LHC proton beam design energy is 7 TeV, *pp* collisions with up to $\sqrt{s} = 14$ TeV occur at the interaction points (IP) (i.e. ATLAS/CMS detectors)





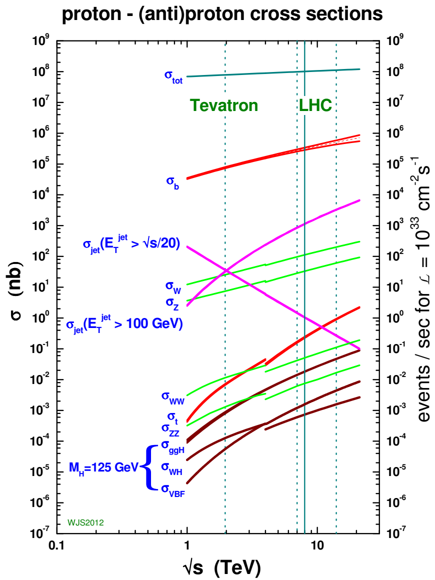
- Given the composite nature of the proton (i.e. quarks and gluons), **longitudinal momentum p_z and total energy E are typically not very useful**
- **Transvere momentum $p_T = \sqrt{p_x^2 + p_y^2}$ is more helpful**, initial *pp* system has $p_T \approx 0$ so one can assume $\sum_i p_T^i = 0$ for the system of particles produced
- Polar angle **θ is not Lorentz invariant, so rapidity y and pseudo-rapidity η are typically used** (*differences* in y and η are Lorentz invariant)

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right) \qquad \eta = \frac{1}{2}\ln\left(\frac{|p| + p_z}{|p| - p_z}\right) = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$\eta = y$ for massless particles

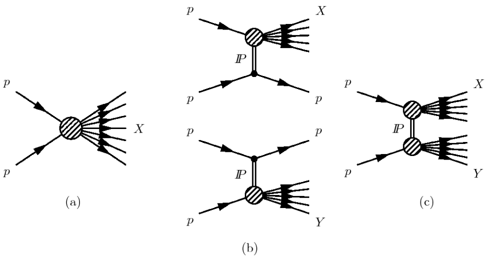
Event rates in *pp* collisions

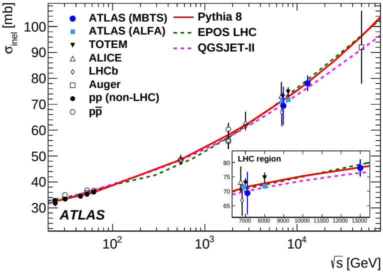
- **Total** cross-section varies slowly with $\sqrt{s}$, $\sigma_{\text{Tot}} \approx 100$ mb (at $\sqrt{s} \approx 10$ TeV)
- **Elastic** *pp* collisions ($\sigma_{\text{El}} \approx 0.25 \times \sigma_{\text{Tot}}$) result in no new particles, protons simply exchange momentum
- **Inelastic** *pp* collisions ($\sigma_{\text{El}} \approx 0.75 \times \sigma_{\text{Tot}}$) can produce new particles, one or both protons break up
- Cross-sections for "interesting" physics events (e.g. $X = H, W, Z, \gamma$) many orders of magnitude lower, but tend to rise rapidly with $\sqrt{s}$ (as $\sqrt{s} \gg m_X$)



W.J. Stirling, private communication

Inelastic *pp* collisions



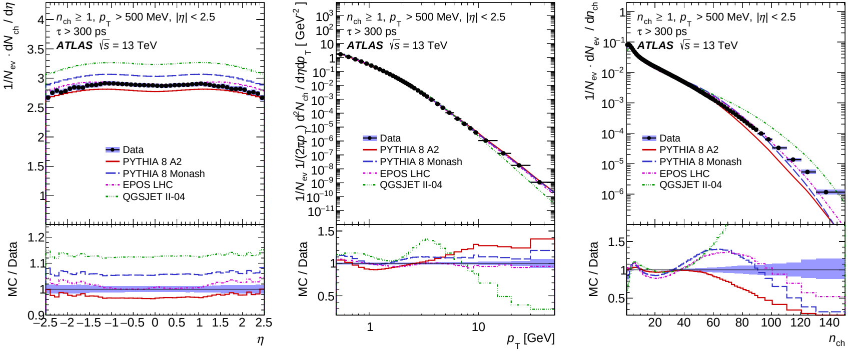


Left: Phys. Rev. D 92, (2015) 012003 (arXiv:1503.08689) Right: Phys. Rev. Lett. 117 (2016) 182002 (arXiv:1606.02625)

- **(a) Non-diffractive ($pp \rightarrow X$) - Around 55% of total *pp* cross-section**
- Non-diffractive events involve colour exchange, more uniform production of particles in y
- **(b) Single-diffractive ($pp \rightarrow Xp/pY$) - Around 12% of total *pp* cross-section**
- **(c) Double-diffractive ($pp \rightarrow XY$) - Around 8% of total *pp* cross-section**
- Diffractive events involve excitation of one or both protons into a high mass colour singlet state which decays to system X/Y, no colour is exchanged, localised (in y) production of new particles

Soft *pp* interactions

The majority of *pp* events at LHC energies involve soft non-diffractive processes, characterised by a low particle multiplicity with low p_T hadronic activity



Figures: Phys. Lett. B 758 (2016) 67 (arXiv:1602.01633)

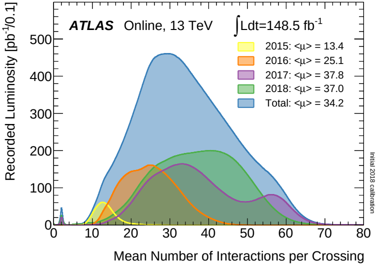
- Generally referred to as "minimum bias" events (i.e. trigger requires minimal activity in the detector, such as a single low p_T track / calo. deposit)
- Modelled semi-empirically with MC generators which are "tuned" to data, predictions can vary quite a bit among generators / data used for tunes

But why should you care, even if you're only interested in "high p_T" physics?

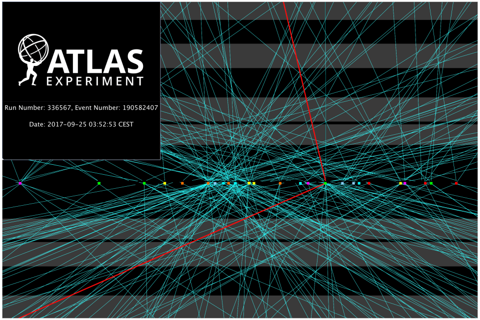
Events with multiple *pp* collisions

Given the high density of nominal LHC bunches (10^{11} protons/bunch), multiple independent *pp* interactions in a single bunch crossing ("pileup") are common

- Most of these interactions are soft non-diffractive collision events, **critical to understand their behaviour!**
- This phenomenon presents a wide variety of challenges for triggering, event reconstruction and physics analysis...



↑ **For peak Run 2 luminosities (2×10^{34}cm^{2}s^{-1}), mean number of *pp* interactions was as high as 60!**



↑ **Candidate $Z \rightarrow \mu^+\mu^-$ event reconstructed among 25 "pileup" *pp* interaction vertices**

The “Underlying Event”

In hard *pp* scattering events, the underlying event (UE) consists of the “beam remnant” and particles produced in multiple parton interactions (MPI) and inital/final state radiation

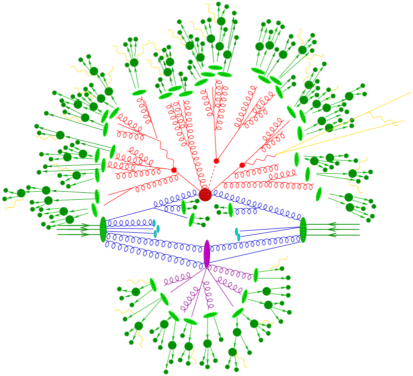


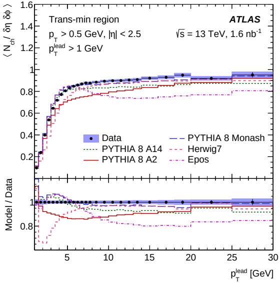
Figure: arXiv:hep-ph/0311270

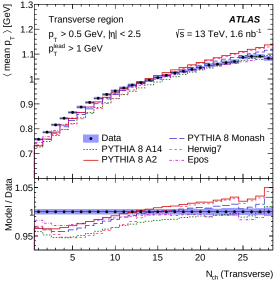
- Not simply a “minimum bias” event overlaid on the hard scattering, activity is correlated with hard process due to colour and momentum conservation
- As with soft non-diffractive events, modelled with effective descriptions within MC generators tuned to data

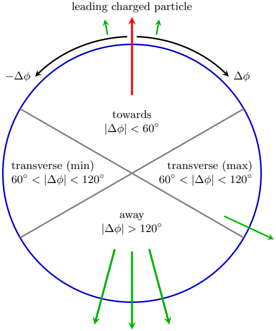
How to measure the “Underlying Event”?

Since it accompanies every “interesting” *pp* event, we need to understand the UE, but how can one disentagle the “hard process” from the underlying event in order to measure it?

- Divide azimuthal plane w.r.t. direction of leading p_T track into four regions
- Towards and away regions sensitive to hard process
- Transverse region is more sensitive to the UE







leading charged particle

$-\Delta\phi$

$\Delta\phi$

towards
$|\Delta\phi| < 60^\circ$

transverse (min)
$60^\circ < |\Delta\phi| < 120^\circ$

transverse (max)
$60^\circ < |\Delta\phi| < 120^\circ$

away
$|\Delta\phi| > 120^\circ$

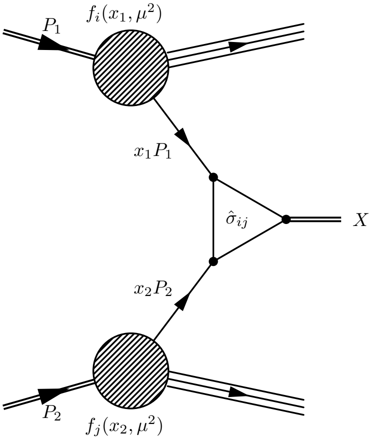
Figures: JHEP 03 (2017) 157

(arXiv:1701.05390)

Use observables such as mean charged-particle p_T and multiplicity in Transvere region to “tune” predictions of UE models in MC generators

Hard parton – parton scattering in QCD

The "QCD Collinear Factorisation" method is the basis of all *pp* scattering calculations and MC simulations, cross-section calculation separated into two parts:



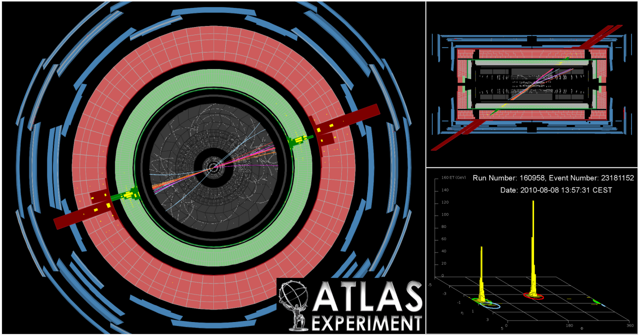
- The "hard scattering" **partonic cross-section $\hat{\sigma}$** for two *partons* (i.e. quarks and gluons) $ij \to X$
- Calculable with perturbative QCD, often systematically improvable with higher order corrections to perturbative series
- Description of the probability (density) f to find a parton with (longitudinal) momentum fraction x within a proton, known as a **parton density function**
- Non-perturbative quantity, obtained by fitting to data (typically *ep* DIS measurements)

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) \cdot f_j(x_2, \mu^2) \cdot \hat{\sigma}_{ij}(p_1, p_2, \alpha_\mathrm{S}(\mu^2), Q^2/\mu^2)$$

Jets

The fragmentation of a high energy quark/gluons into a collimated hadronic final state is known as a "jet"

- Hard pp interactions are dominated by jet production initiated hard qq, gg, qg scattering, jets are ubiquitous at the LHC!
- The hard scattering processes (e.g. $gg \to q\bar{q}$) are calculable in perturbative QCD
- The soft fragmentation/hadronisation process (i.e. $q/g \to$ hadrons) is a non-perturbative, rely on physically motivated MC models (e.g. Lund string)



Jet Definitions I

Jets are defined with an algorithm which clusters constituants within an event (usually calorimeter energy deposits, occasionally tracks) into a single entity

The Rules

- For jets to make sense in the context of perturbative QCD to make sense, the (hard) jets should not change when:
- **IR Safety:** There is soft emission (i.e. add a very soft gluon)
- **Collinear Safety:** There is a collinear splitting (i.e. one parton is replaced by two such as $g \rightarrow q\bar{q}$)

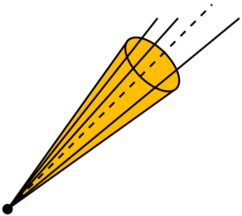
Why should you care about the rules?

> "Infrared unsafety is a serious issue, not just because it makes impossible to carry out meaningful (finite) perturbative calcuations, but also because it breaks the whole relation between the (Born or low-order) partonic structure of the event and the jets that one observes, and it is precisly this relation that a jet algorithm is supposed to codify: it makes no sense for the structure of multi-hundred GeV jets to change radically just because hadronisation, the underlying event or pileup threw a 1 GeV particle in between them."
>
> **(arXiv:0704.0292)**

Jet Definitions II

Cone Algorithms:

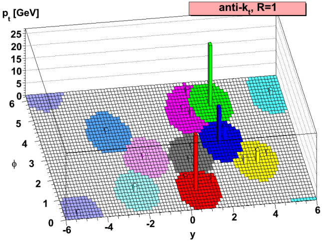
- Cluster all constituants within a given geometric cone, defined by $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- ✗ **Features**: behaviour very susceptible to additional soft gluon radiation (e.g. number of jets in event)
- Generally considered obsolete (exception of `SISCone`)



Sequential Recombination Algorithms:

- Successively combine the "closest" pair of particles according to distance measure d_{ij}
- Stop at a cut-off scale R, final clustering of particles defines the jet
- ✓ **Features:** IR + Collinear safe
- Version with $p = -1$ known as "anti-k_T", widely used at ATLAS/CMS

$$d_{ij} = \min\left(k_{\mathrm{T},i}^{2p}, k_{\mathrm{T},j}^{2p}\right) \frac{(\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)}{R^2}$$

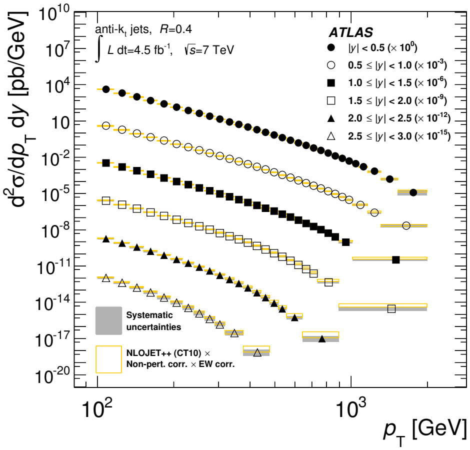


JHEP 0804:063,2008 (arXiv:0802.1189)

Inclusive Jet Cross-sections

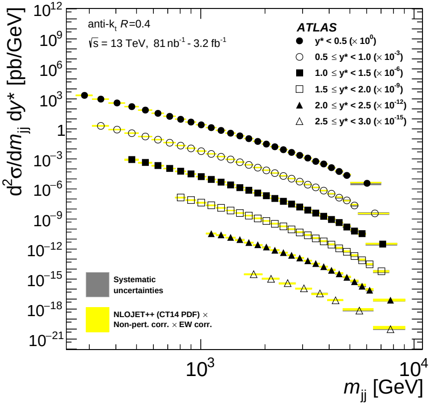
Jets are everywhere at the LHC, note y-axis units, $\approx 10^4$ pb / GeV at $p_T = 100$ GeV, very high rate! (c.f. total Higgs cross-section $\approx$ 20pb at $\sqrt{s} = 7$ TeV)

- Cross-section for anti-k_T $R = 0.4$ jet production as a function of jet p_T, for different rapidity (y) ranges (note y-axis scaling on plot)
- Jet p_T distribution spans many orders of magnitude, drops towards maximum $\sqrt{\hat{s}}$ kinematically allowed (few TeV here)
- Good agreement with NLO perturbative QCD predictions within experimental and theoretical uncertainties

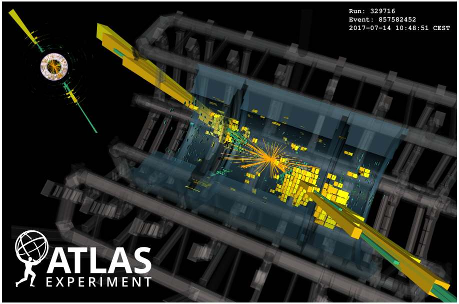


JHEP 02 (2015) 153 (arXiv:1410.8857)

Di-jet Cross-sections



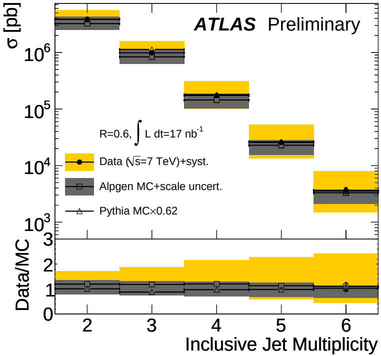
← **JHEP 05 (2018) 195 (arXiv:1711.02692)**



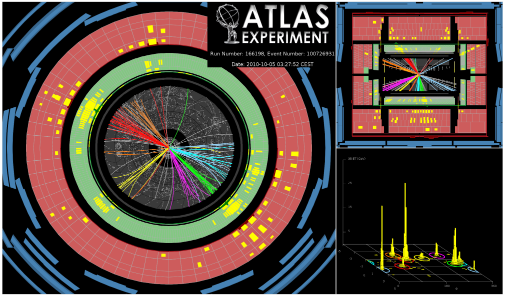
Di-jet event with $m_{jj} = 9.3$ TeV reconstructed in ATLAS

- Di-jet production is another critical test of perturbative QCD
- Good agreement with NLO perturbative QCD predictions within experimental and theoretical uncertainties
- Also important as a search channel for new resonances (e.g. $Z' \rightarrow q\bar{q}$)
- Di-jet events with m_{jj} up to 9 TeV measured at the LHC ($\sqrt{s} = 13$ TeV)

Multi-jet Cross-sections



← **ATLAS-CONF-2010-084**



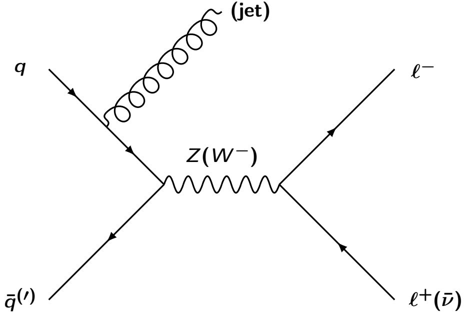
Event with 8 jets reconstructed in ATLAS

- Multi-TeV *pp* collisions provide a huge phase space for multi-jet production
- Another important test for QCD and MC generator predictions, critical background for general searches for new physics

W and Z bosons

W and Z boson production in pp collisions proceeds primarily through $q\bar{q}$ annihilation (Drell-Yan), inclusive production often involves additional high p_T jets

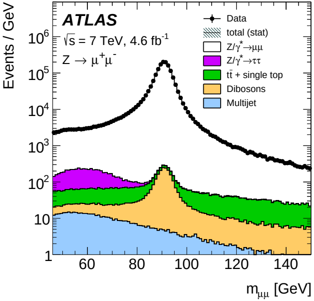
- Leptonic W and Z boson decays are the primary source of isolated high p_T leptons at the LHC
- $\mathcal{B}(Z \to \ell\ell) \approx 3\%$ $\mathcal{B}(W \to \ell\nu) \approx 11\%$
- Useful as probes of parton densities and for precise tests of the SM
- Present in decays of H, top quark and particles beyond the SM
- Very useful as a calibration source for lepton efficiency, energy scale / resolution measurements
- Important background for many search channels (e.g. SUSY)



Experimental Signature:

$Z \to \ell^+\ell^-$: Pair of isolated high p_T oppositely charged leptons
$W^\pm \to \ell^\pm\nu$: Single isolated high p_T lepton and large missing transverse energy

W and Z boson mass distributions

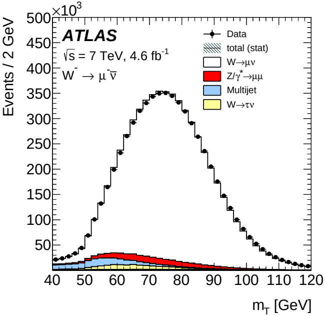


$Z \to \ell^+\ell^-$ candidates

- Di-lepton invariant mass distribution is the primary means by which Z boson candidates can be identified
- Mass resolution (at ATLAS/CMS) is typically smaller than $\Gamma_Z \approx 2.5$ GeV

Figures: Eur. Phys. J. C 77 (2017) 367 (arXiv:1612.03016)

Reminder: $m_Z = 91.2$ GeV and $m_W = 80.4$ GeV



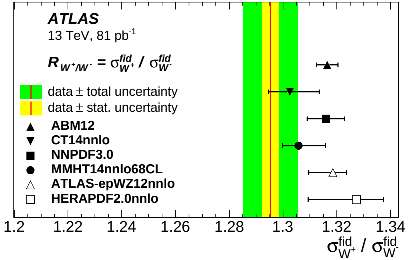
$W^\pm \to \ell^\pm\nu$ candidates

- Neutrino not detected, only its transverse momentum can be inferred from E_T^{miss}
- Can only reconstruct "transverse mass" m_T
- Peaking structure observed, though peak below m_W and much broader than $\Gamma_W \approx 2.1$ GeV

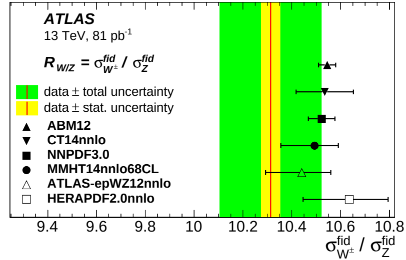
$$m_T = \sqrt{2 p_T^\ell E_T^{\text{miss}} (1 - \Delta\phi_{\ell,\nu})}$$

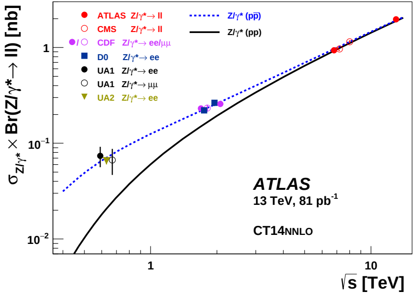
W and Z inclusive cross-sections

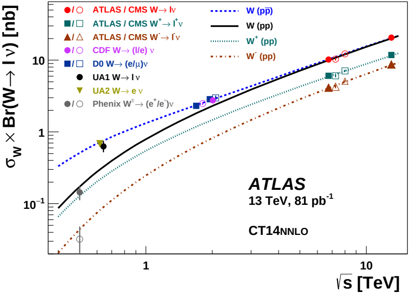
$\downarrow \sigma_{W+}/\sigma_{W-}$



$\sigma_{W\pm}/\sigma_{Z} \downarrow$

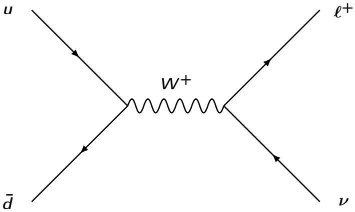


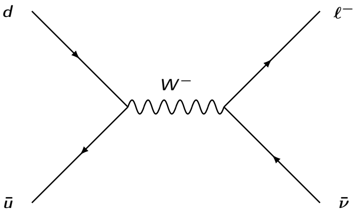


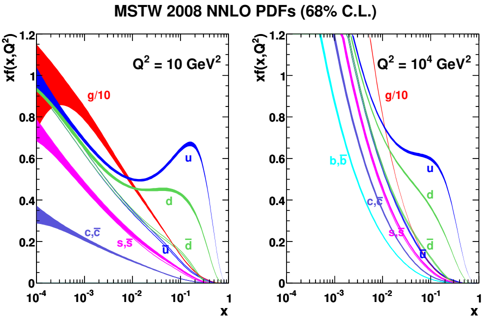


Figures: Phys. Lett. B 759 (2016) 601 (arXiv:1603.09222)

W^+ and W^- cross-sections





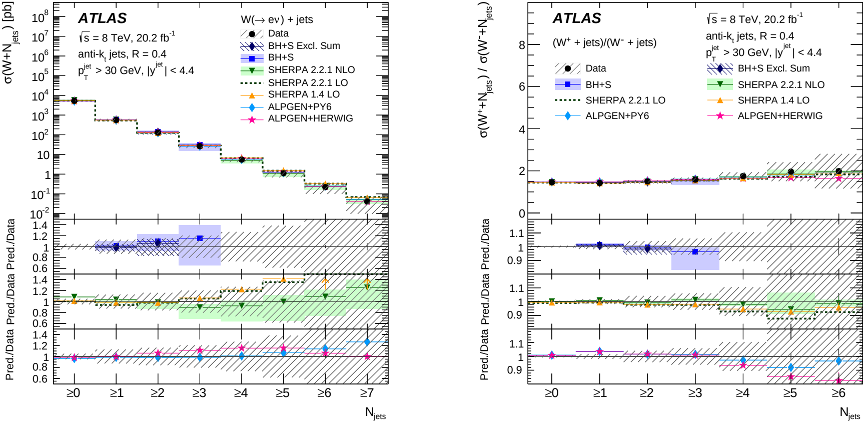


In *pp* collisions, $\sigma_{W^+} > \sigma_{W^-}$, why?

- Primarily due to larger valance u quark proton parton density
- The cross-section ratio is thus a useful input to PDF fits

W boson production in association with jet(s)

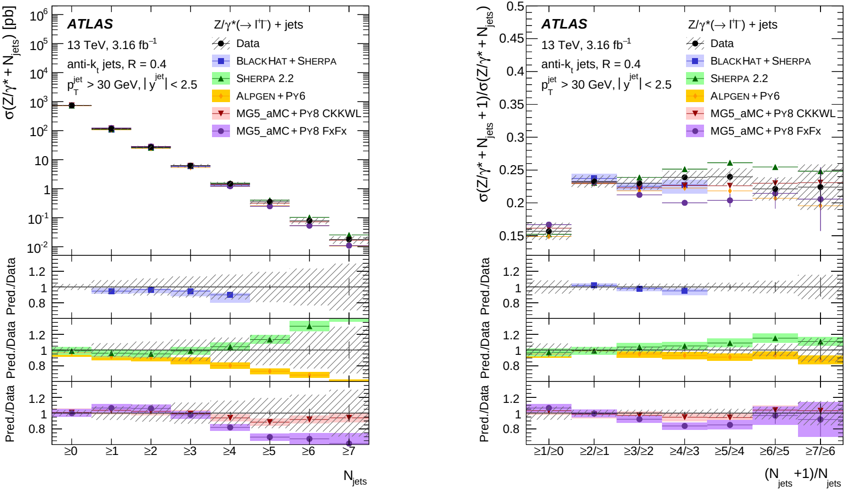
Figures: JHEP 05 (2018) 077 (arXiv:1711.03296)



- Important test of perturbative QCD and common background for many searches
- MC generators tend to struggle to describe multiplicity beyond 3 additional jets
- Relative jet multiplicity very similar for W^+ and W^- until around 4 additional jets where PDF effects become more important

Z boson production in association with jet(s)

Figures: Eur. Phys. J. C77 (2017) 361 (arXiv:1702.05725)



- Important test of perturbative QCD and common background for many searches
- MC generators tend to struggle to describe multiplicity beyond 3 additional jets

Introduction to Top Quark Physics

The top quark was discovered by the CDF and DØ experiments at the Fermilab Tevatron in 1995 and is unique among the other known quarks:

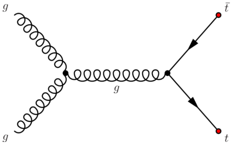
- Lifetime of $\approx 5 \times 10^{-25}$ s ($\Gamma_t \approx 1.3$ GeV), shorter than timescale associated with hadronisation
- Top quarks decay before they form bound states (i.e. no "toponium")
- Provides a unique opportunity to study the properties of a "bare" quark

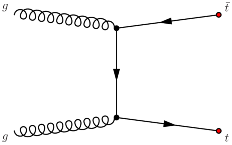
Many interesting properties to study:

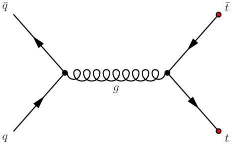
- Mass - why is it so much larger than the other quarks?
- Spin - is it consistent with the SM hypothesis of spin $\frac{1}{2}$ (fermion)?
- Width and decays - very large phase space open for decay products (e.g. BSM particles?)
- Couplings - in addition to gauge couplings, the top quark Yukawa coupling ($t\bar{t}H$) is expected to be ~ 1 (i.e. very large!)

Top Quark Production

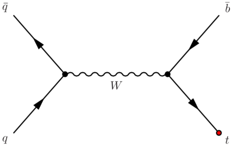
- **Top Pair Production:** this is the dominant source of top quarks at the LHC, proceeds entirely via strong interactions
- At the LHC, this process proceeds mainly via gluon-fusion ($\approx 90\%$, left two diagrams) and $q\bar{q}$ annihilation ($\approx 10\%$, right diagram)

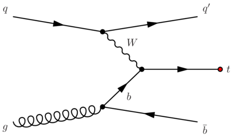


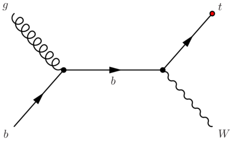




- **Single top quark production:** top quarks are also produced alone, in an electroweak process, in association with other quarks and W bosons
- At the LHC, the t-channel (centre diagram) process is the dominant source of single top quark production







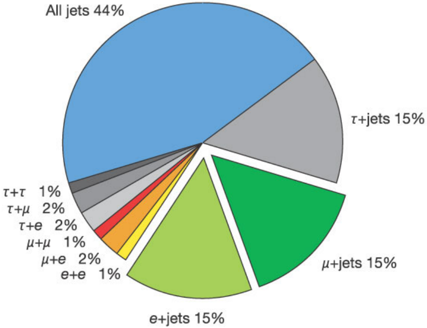
All diagrams from Wikipedia

Top quark decays and $t\bar{t}$ final states

The decay $t \to Wb$ accounts almost the entire top quark decay width

- Other decays $t \to W\{s, d\}$ are suppressed by very small CKM elements and how not been observed directly
- Decays involving flavour changing neutral currents (e.g. $t \to q\{\gamma, H\}$) are *very* rare in the SM (loop suppressed) and highly susceptible to potential BSM contributions

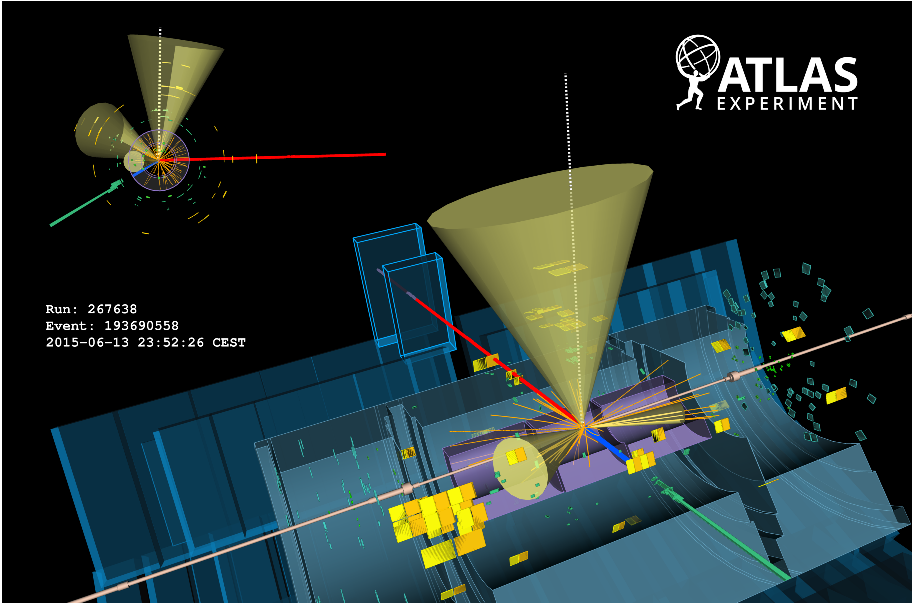
Figure: Nature 429, 638–642 (2004)



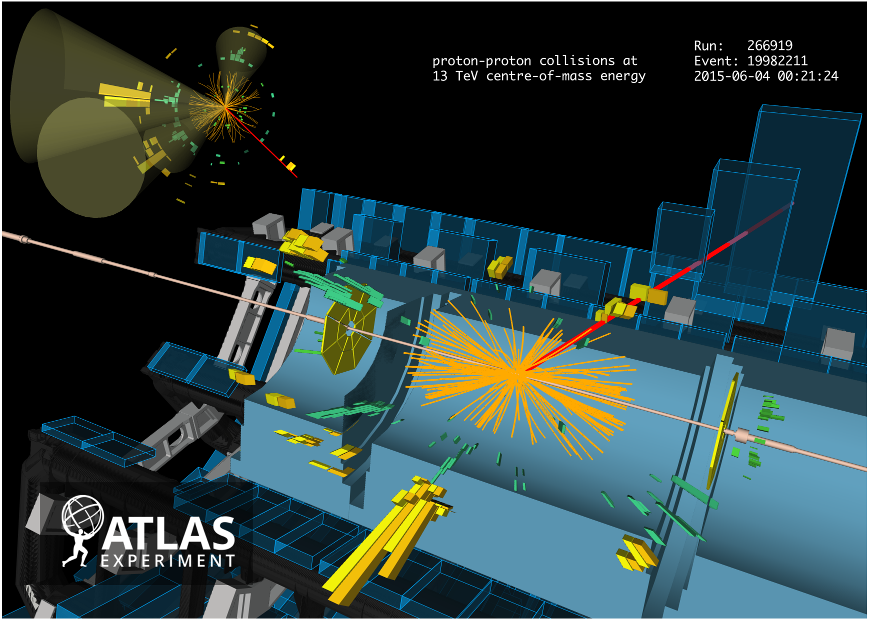
From an experimental perspective, $t\bar{t}$ decays are often categorised in three classes, determined by the W boson decays (all involve two b-jets):

- **All-hadronic:** Two hadronic ($W \to q\bar{q}'$) → up to six jets **(44% of total)**
- **Semi-leptonic:** One hadronic ($W \to q\bar{q}'$) and one leptonic ($W \to \ell\nu$) → up to four jets, one lepton and neutrino **(45% of total)**
- **Di-leptonic:** Two ($W \to q\bar{q}'$) → two jets, two leptons and two neutrinos **(11% of total)**

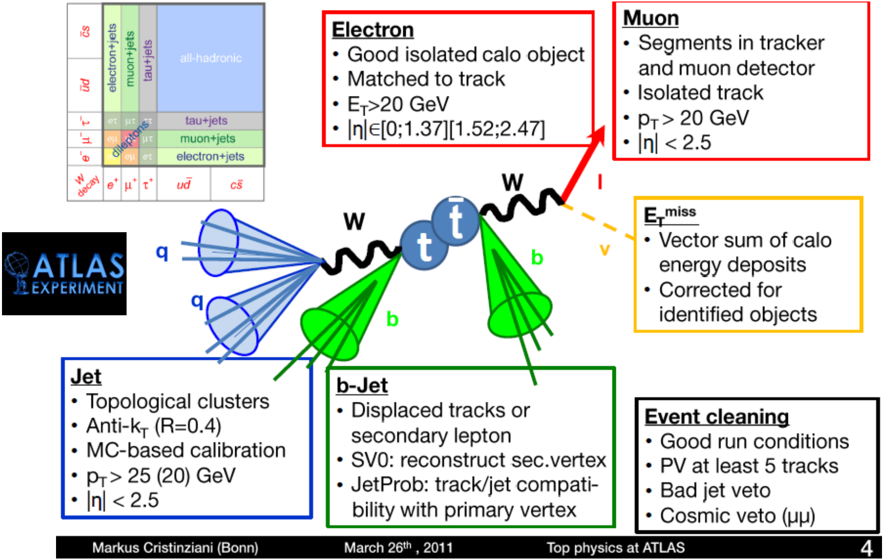
Example of di-leptonic $t\bar{t}$ event candidate



Example of semi-leptonic $t\bar{t}$ event candidate



Principles of semi-leptonic $t\bar{t}$ event selection



Electron
- Good isolated calo object
- Matched to track
- E_T>20 GeV
- $|\eta|\in[0;1.37][1.52;2.47]$

Muon
- Segments in tracker and muon detector
- Isolated track
- $p_T > 20$ GeV
- $|\eta| < 2.5$

E_T^{miss}
- Vector sum of calo energy deposits
- Corrected for identified objects

Jet
- Topological clusters
- Anti-k_T (R=0.4)
- MC-based calibration
- $p_T > 25$ (20) GeV
- $|\eta| < 2.5$

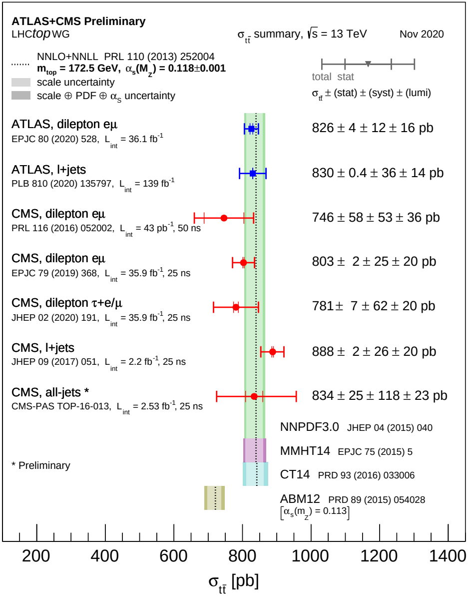
b-Jet
- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with primary vertex

Event cleaning
- Good run conditions
- PV at least 5 tracks
- Bad jet veto
- Cosmic veto (μμ)

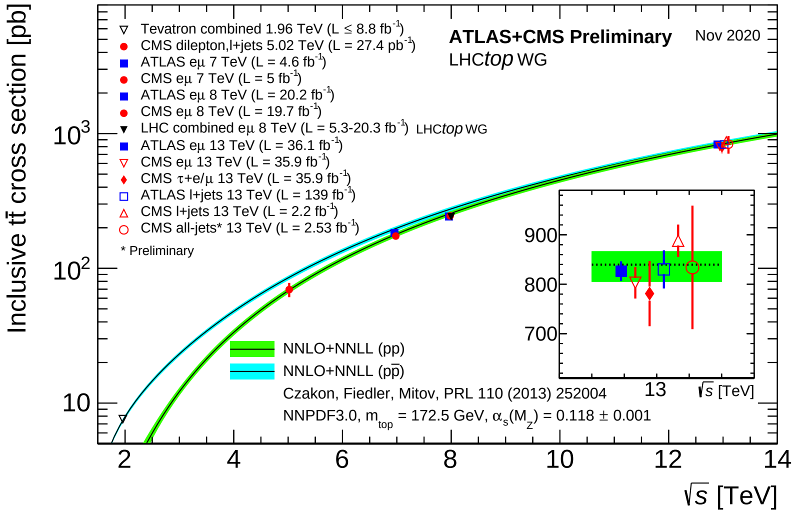
Markus Cristinziani (Bonn) March 26th , 2011 Top physics at ATLAS 4

Measurements of $t\bar{t}$ production I

- **Most precise measurements made in the di-leptonic channel** due to higher S/B ratio, lower susceptiblity to experimental systematic uncertainties
- Precision of LHC Run 2 measurements typically limited by systematic and luminosity uncertainties
- $t\bar{t}$ cross-sections sensitive to different PDFs

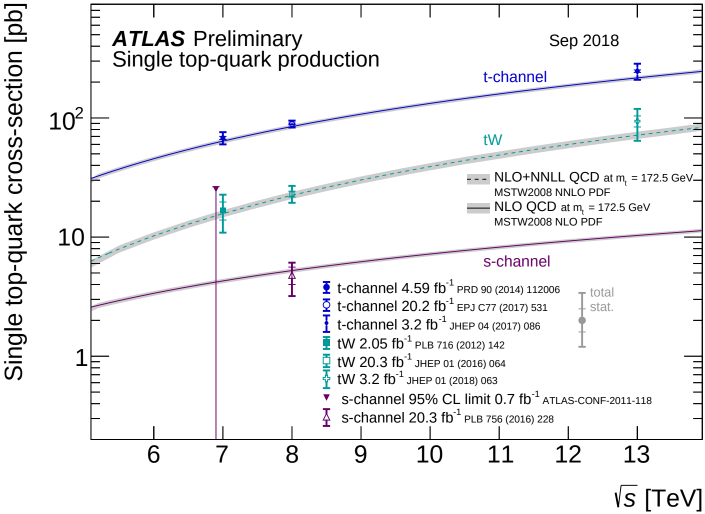


Measurements of $t\bar{t}$ production II



NNLO+NNLL QCD theoretical predictions for $t\bar{t}$ production in agreement with LHC and Tevatron measurements spanning order of magnitude in $\sqrt{s}$

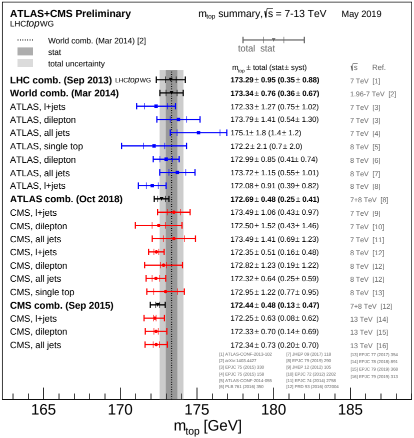
Measurements of single top quark production



The cross-sections for single top quark production are at least an order of magnitude lower than $t\bar{t}$, but now firmly estblished by LHC measurements

- Direct probe of $|V_{tb}|$ and sensitive to a variety of BSM models

Measurements of the top quark mass



The top quark mass is an important parameter of the SM and also has implications for our understanding of SSB and the Higgs sector

- Most precise measurements from the LHC offer $\mathcal{O}(100\,\mathrm{MeV})$ precision, now more precise than the Tevatron combination (174.30 ± 0.65 GeV)
- “Which top mass is being measured?” becomes a relevant question (i.e. soft QCD effects relevant at 100 MeV scale)

Summary

The physics available to study at the LHC is broad and very rich, spanning orders of magnitude in terms of energy and coupling strength!

- Soft interactions at a hadron collider can never be ignored, it's essential that they are well understood
- Jets are everywhere at the LHC, important background to any measurement or search
- W and Z bosons are the primary source of isolated leptons
- The LHC produces a huge number of top quarks, now a major background to many Higgs / BSM searches