

# High $p_T$ Physics at the LHC

## Lecture 3: Introductory Topics and SM Physics

Warwick Week 2023

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## 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

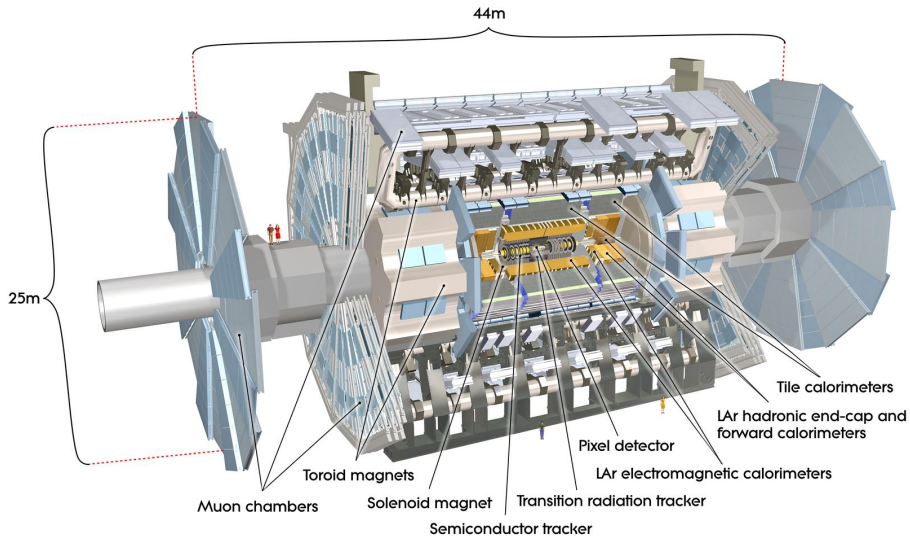
**The context of the lectures will focus on the ATLAS and CMS experiments, though LHCb and ALICE can and do study many of the processes discussed!**

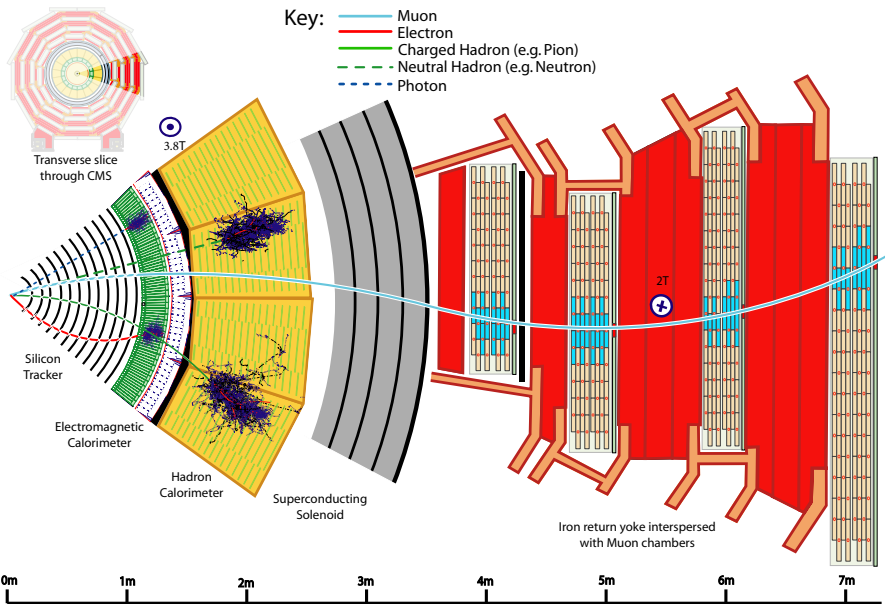
**Where differences between ATLAS/CMS measurements are irrelevant or minor, I will typically show ATLAS results as examples since I'm more familiar with this experiment!**

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

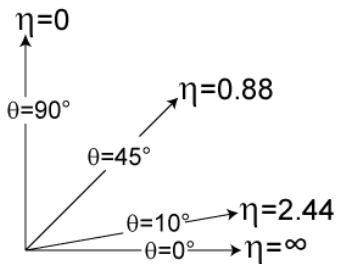
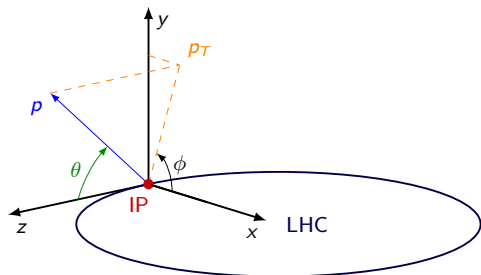
- **Tracking Detector + Solenoid Magnet:** Measure trajectory of charged particles to infer momentum and charge, used to reconstruct primary interaction point
- **Electromagnetic Calorimeter:** Measure the energy of high energy<sup>†</sup> electrons, positrons and photons
- **Hadronic Calorimeter:** Measure the energy of high energy<sup>†</sup> 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 ( $\mathcal{O}(10\text{MHz})$  at LHC) to a manageable rate ( $\mathcal{O}(100\text{Hz})$  at LHC) for permanent storage and offline analysis

<sup>†</sup> Typically  $E_T > 100 \text{ MeV}$





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)

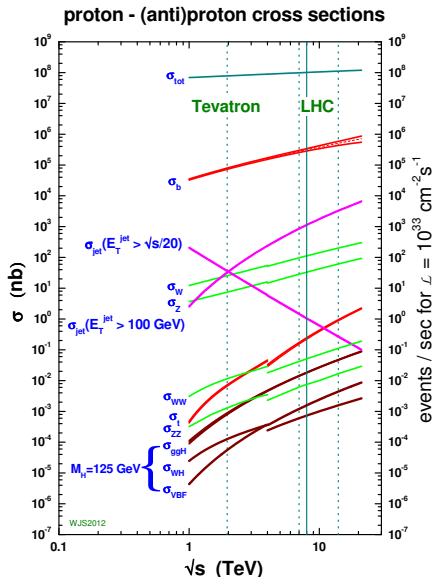


- Given the composite nature of the proton (i.e. quarks and gluons), **longitudinal momentum  $p_z$  and total energy  $E$  are typically not very useful**
- **Transverse momentum  $p_T = \sqrt{p_x^2 + p_y^2}$  is more helpful**, initial  $pp$  system has  $p_T \approx 0$  so one can assume  $\sum_i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

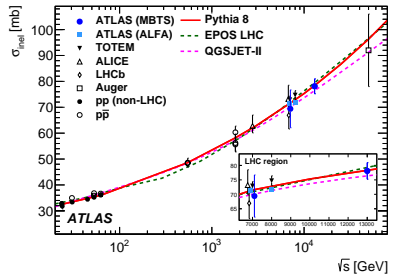
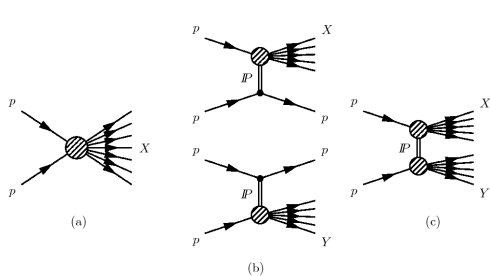
$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \quad \eta = \frac{1}{2} \ln \left( \frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z} \right) = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$$

$\eta = y$  for  
massless  
particles

- **Total** cross-section varies slowly with  $\sqrt{s}$ ,  $\sigma_{\text{Tot}} \approx 100 \text{ mb}$  (at  $\sqrt{s} \approx 10 \text{ TeV}$ )
- **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

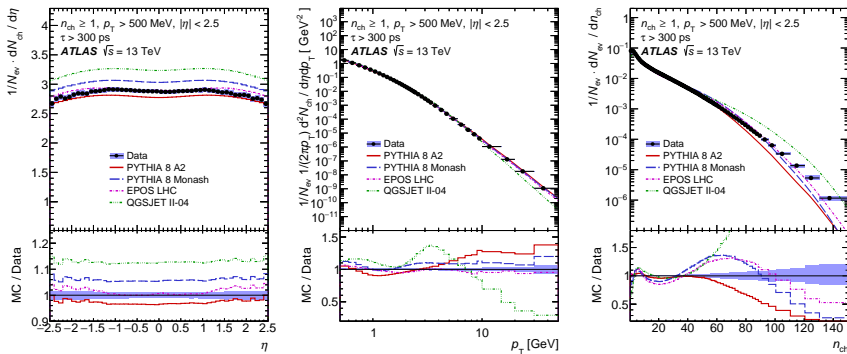


Left: Phys. Rev. D 92, (2015) 012003 (arXiv:1503.08689) Right: Phys. Rev. Lett. 117 (2016) 182002 (arXiv:1606.02625)

- (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



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



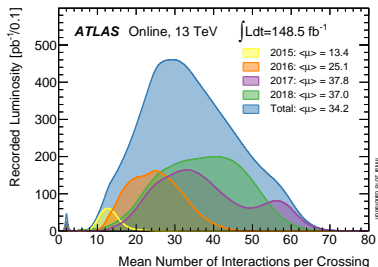
Figures: Phys. Lett. B 758 (2016) 67 (arXiv:1602.01633)

- 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

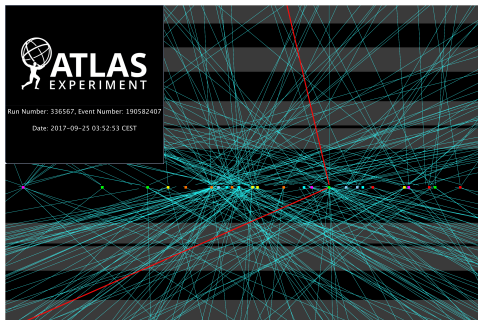
But why should you care, even if you’re only interested in “high  $p_T$ ” physics?

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 ( $2 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$ ), mean number of  $pp$  interactions was as high as 60!



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

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

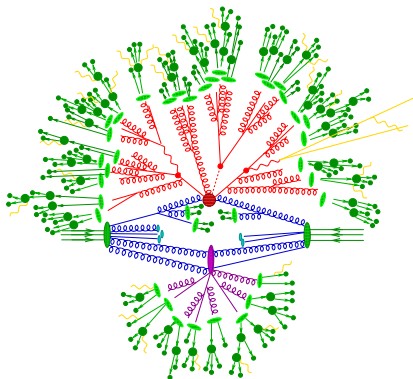


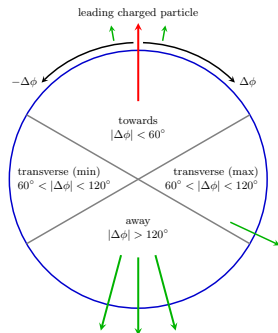
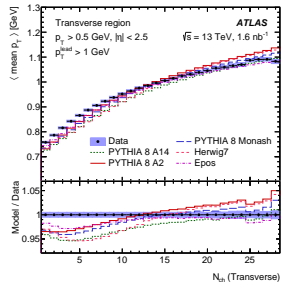
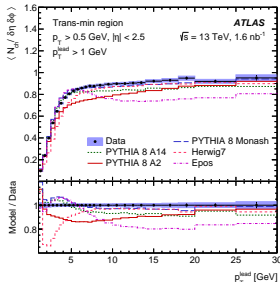
Figure: arXiv:hep-ph/0311270

- 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 disentangle the “hard process” from the underlying event in order to measure it?

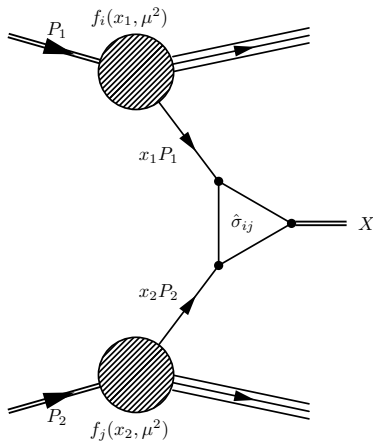
- Divide azimuthal plane w.r.t. direction of leading  $p_T$  track into four regions
- Towards and away regions sensitive to hard process
- Transverse region is more sensitive to the UE



Figures: JHEP 03 (2017) 157  
(arXiv:1701.05390)

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

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

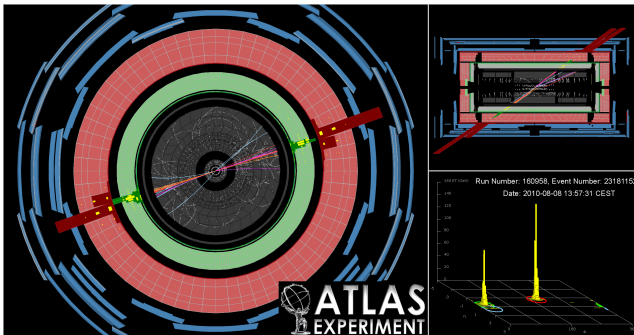


- The “hard scattering” **partonic cross-section**  $\hat{\sigma}$  for two *partons* (i.e. quarks and gluons)  $ij \rightarrow X$
- Calculable with perturbative QCD, often systematically improvable with higher order corrections to perturbative series
- Description of the probability (density)  $f$  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)

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

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.  $gg \rightarrow q\bar{q}$ ) are calculable in perturbative QCD
- The soft fragmentation/hadronisation process (i.e.  $q/g \rightarrow$  hadrons) is a non-perturbative, rely on physically motivated MC models (e.g. Lund string)



Jets are defined with an algorithm which clusters constituents 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  $g \rightarrow q\bar{q}$ )

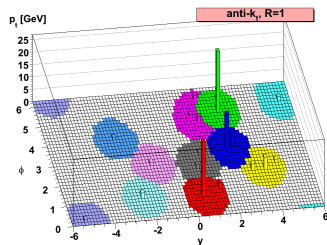
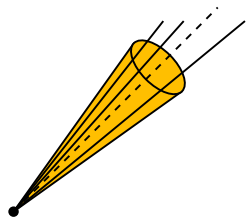
### Why should you care about the rules?

“Infrared unsafety is a serious issue, not just because it makes impossible to carry out meaningful (finite) perturbative calculations, 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 precisely 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)

## Cone Algorithms:

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



JHEP 0804:063,2008 (arXiv:0802.1189)

## Sequential Recombination Algorithms:

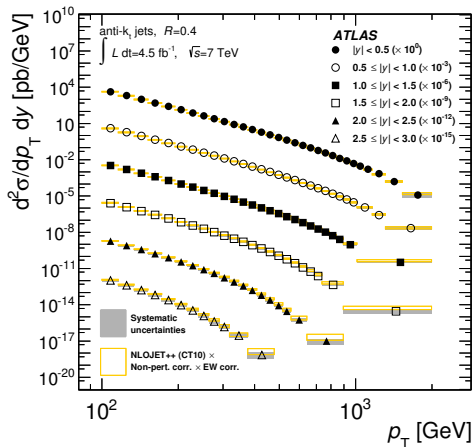
- Successively combine the “closest” pair of particles according to distance measure  $d_{ij}$
- Stop at a cut-off scale  $R$ , final clustering of particles defines the jet
- ✓ Features:** IR + Collinear safe
- Version with  $p = -1$  known as “anti- $k_T$ ”, widely used at ATLAS/CMS

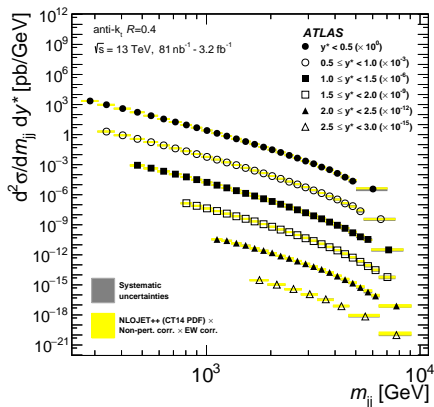
$$d_{ij} = \min \left( k_{T,i}^{2p}, k_{T,j}^{2p} \right) \frac{(\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)}{R^2}$$



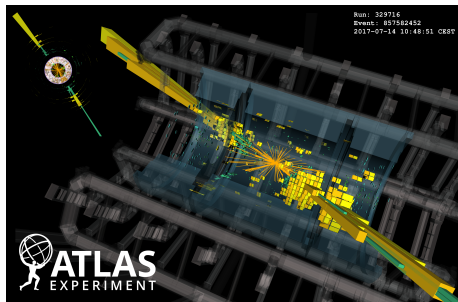
Jets are everywhere at the LHC, note  $y$ -axis units,  $\approx 10^4$  pb / GeV at  $p_T = 100$  GeV, very high rate! (c.f. total Higgs cross-section  $\approx 20$ pb at  $\sqrt{s} = 7$  TeV)

- 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



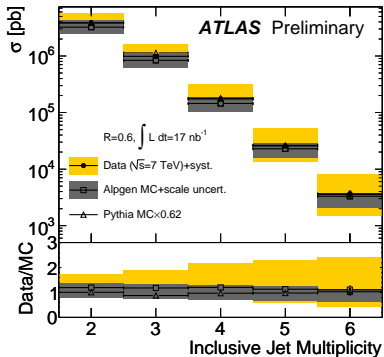


← JHEP 05 (2018) 195 (arXiv:1711.02692)

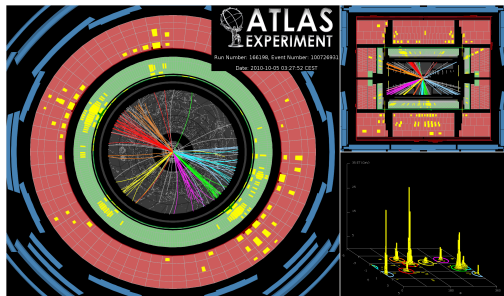


Di-jet event with  $m_{jj} = 9.3 \text{ TeV}$  reconstructed in ATLAS

- 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 ( $\sqrt{s} = 13 \text{ TeV}$ )



← ATLAS-CONF-2010-084

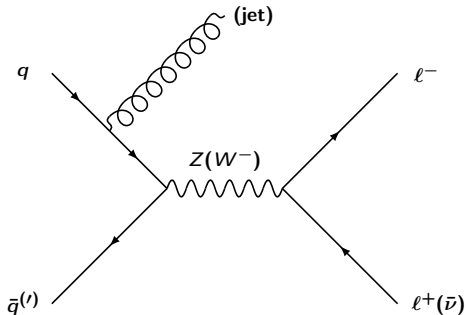


Event with 8 jets reconstructed in ATLAS

- 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 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
- $\mathcal{B}(Z \rightarrow \ell\ell) \approx 3\%$   $\mathcal{B}(W \rightarrow \ell\nu) \approx 11\%$
- 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:

**$Z \rightarrow \ell^+\ell^-$ : Pair of isolated high  $p_T$  oppositely charged leptons**

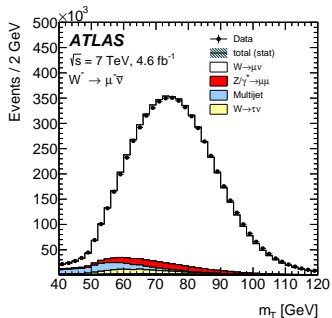
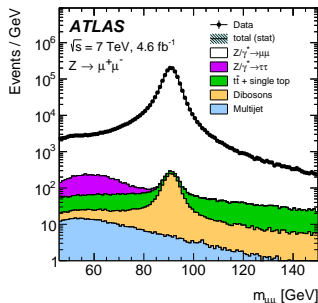
**$W^\pm \rightarrow \ell^\pm\nu$ : Single isolated high  $p_T$  lepton and large missing transverse energy**

## $Z \rightarrow \ell^+ \ell^-$ 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)

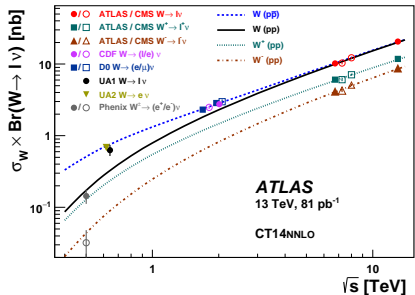
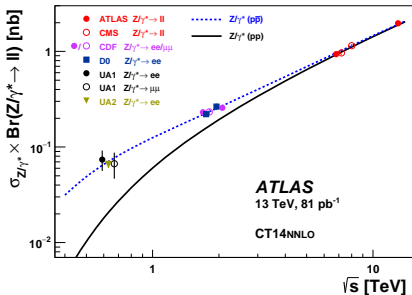
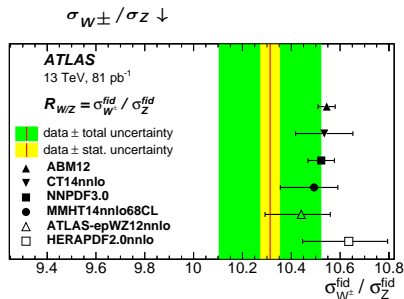
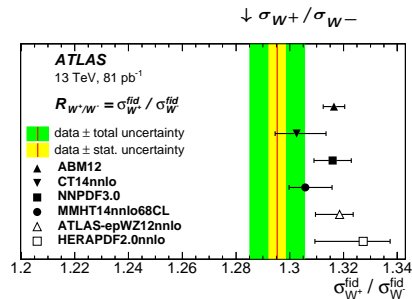
Reminder:  $m_Z = 91.2$  GeV and  $m_W = 80.4$  GeV



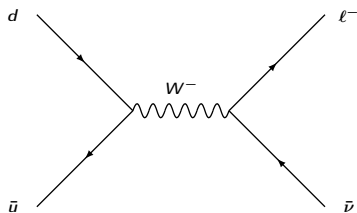
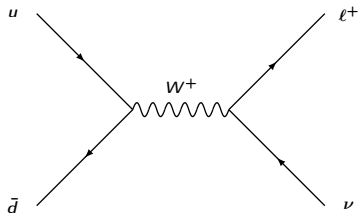
## $W^\pm \rightarrow \ell^\pm \nu$ candidates

- Neutrino not detected, only its transverse momentum can be inferred from  $E_T^{\text{miss}}$
- 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

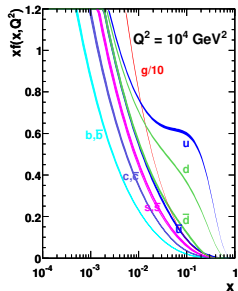
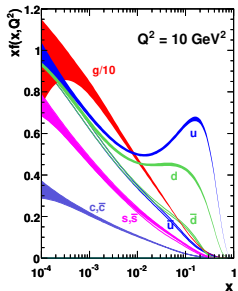
$$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}} (1 - \Delta\phi_{\ell,\nu})}$$



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



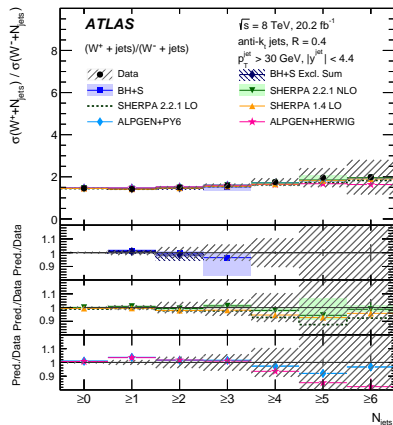
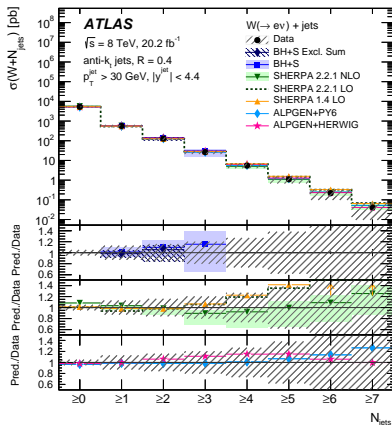
MSTW 2008 NNLO PDFs (68% C.L.)



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

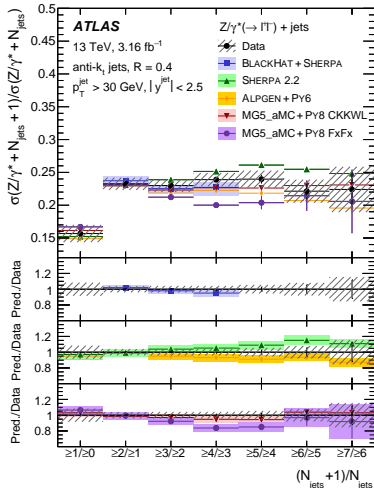
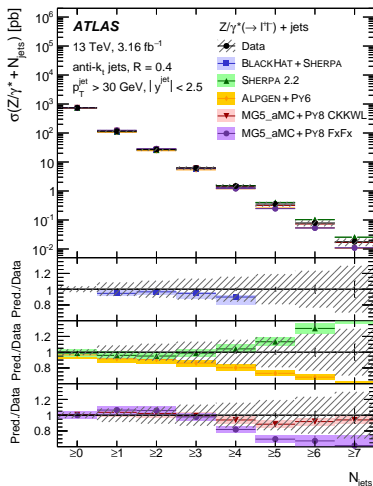
Figures: JHEP 05 (2018) 077 (arXiv:1711.03296)



- 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



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

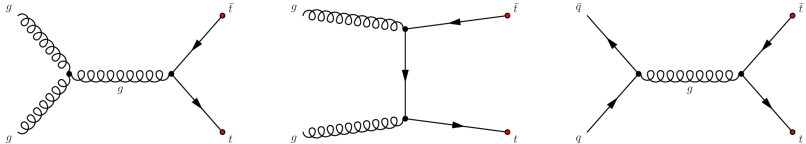
**The top quark was discovered by the CDF and DØ experiments at the Fermilab Tevatron in 1995 and is unique among the other known quarks:**

- 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

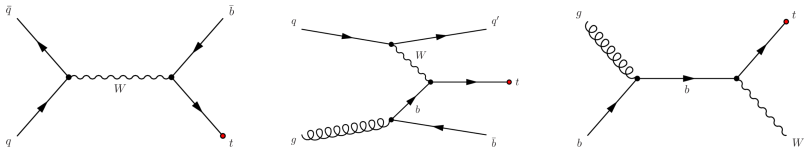
**Many interesting properties to study:**

- 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  $\sim 1$  (i.e. very large!)

- **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

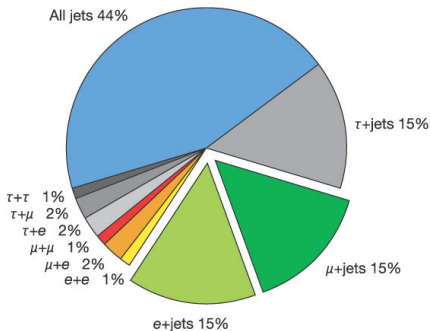


All diagrams from [Wikipedia](#)

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

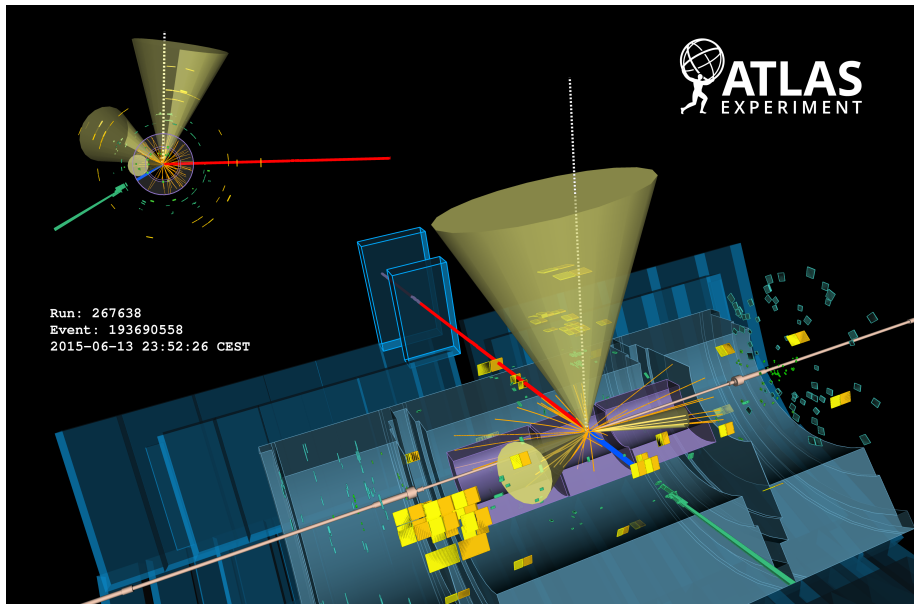
- Other decays  $t \rightarrow W\{s, d\}$  are suppressed by very small CKM elements and have not been observed directly
- Decays involving flavour changing neutral currents (e.g.  $t \rightarrow q\{\gamma, H\}$ ) are very rare in the SM (loop suppressed) and highly susceptible to potential BSM contributions

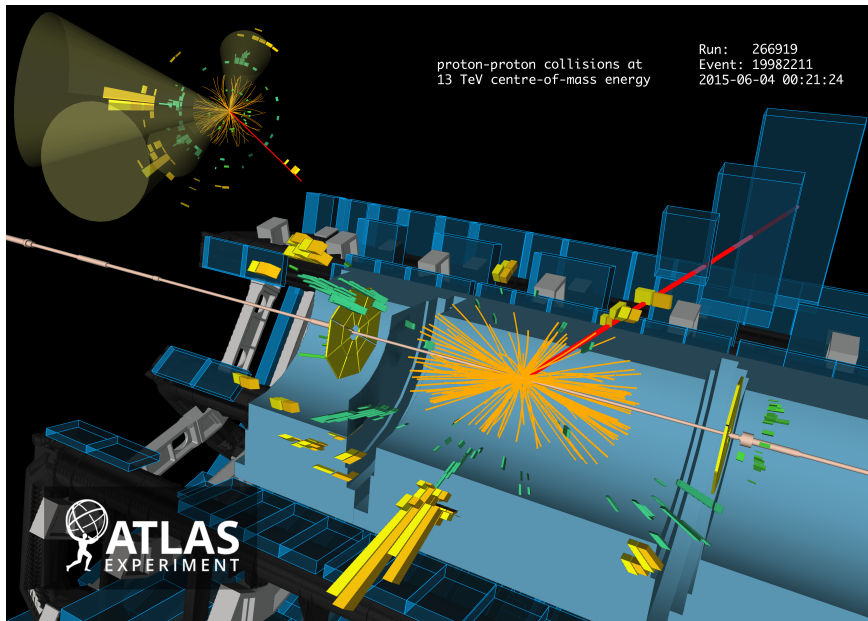
Figure: Nature 429, 638–642 (2004)



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





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

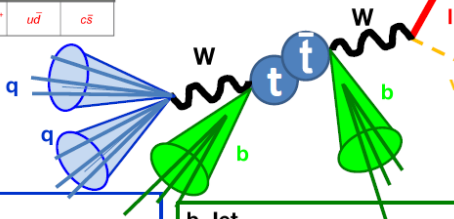
$c\bar{s}$	electron+jets	muon+jets	tau+jets	all-hadronic
$u\bar{d}$	electron+jets	muon+jets	tau+jets	all-hadronic
$\tau^+\tau^-$	electron+jets	muon+jets	tau+jets	all-hadronic
$\mu^+\mu^-$	electron+jets	muon+jets	tau+jets	all-hadronic
$e^+e^-$	electron+jets	muon+jets	tau+jets	all-hadronic
$W$ decay	$e^+$	$\mu^+$	$\tau^+$	$u\bar{d}$ $c\bar{s}$

**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
- $|\eta| < 2.5$

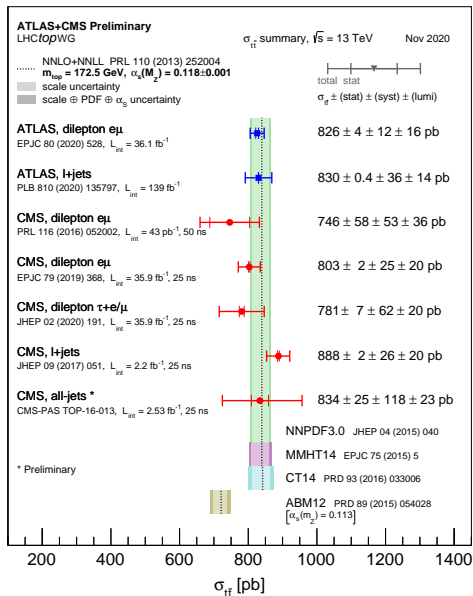
**b-Jet**

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

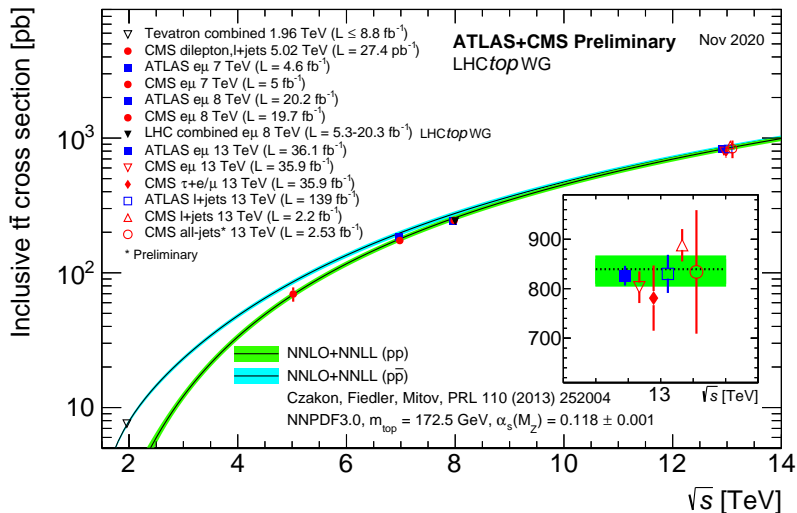
**Event cleaning**

- Good run conditions
- PV at least 5 tracks
- Bad jet veto
- Cosmic veto ( $\mu\mu$ )

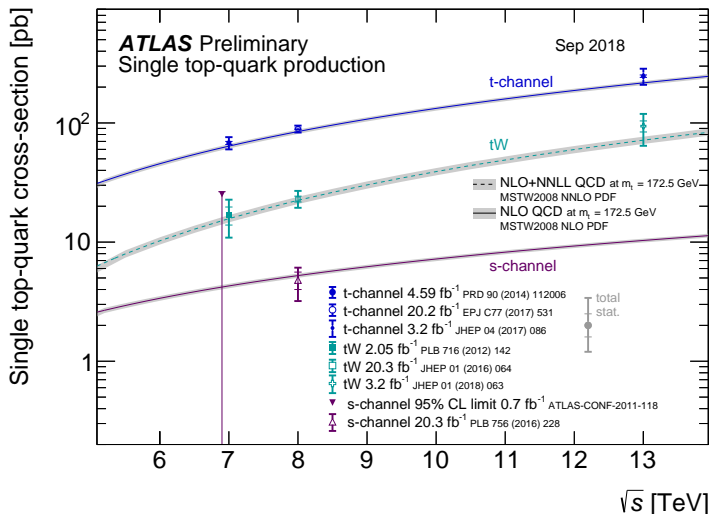
- Most precise measurements made in the di-leptonic channel due to higher S/B ratio, lower susceptibility to experimental systematic uncertainties
- Precision of LHC Run 2 measurements typically limited by systematic and luminosity uncertainties
- $t\bar{t}$  cross-sections sensitive to different PDFs







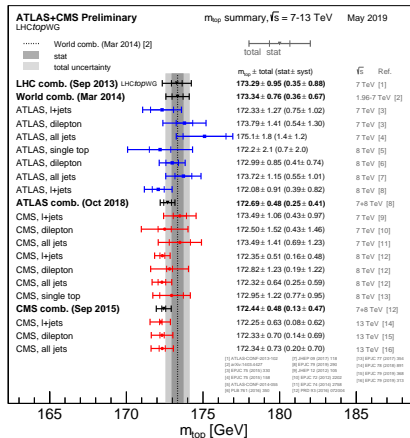
NNLO+NNLL QCD theoretical predictions for  $t\bar{t}$  production in agreement with  
 LHC and Tevatron measurements spanning order of magnitude in  $\sqrt{s}$



The cross-sections for single top quark production are at least an order of magnitude lower than  $t\bar{t}$ , but now firmly established 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  $\mathcal{O}(100\text{ MeV})$  precision, now more precise than the Tevatron combination ( $174.30 \pm 0.65\text{ GeV}$ )
- “Which top mass is being measured?” becomes a relevant question (i.e. soft QCD effects relevant at 100 MeV scale)

**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