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

Warwick Week 2020

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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
- Vector boson $W^{\pm}$ and Z 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!
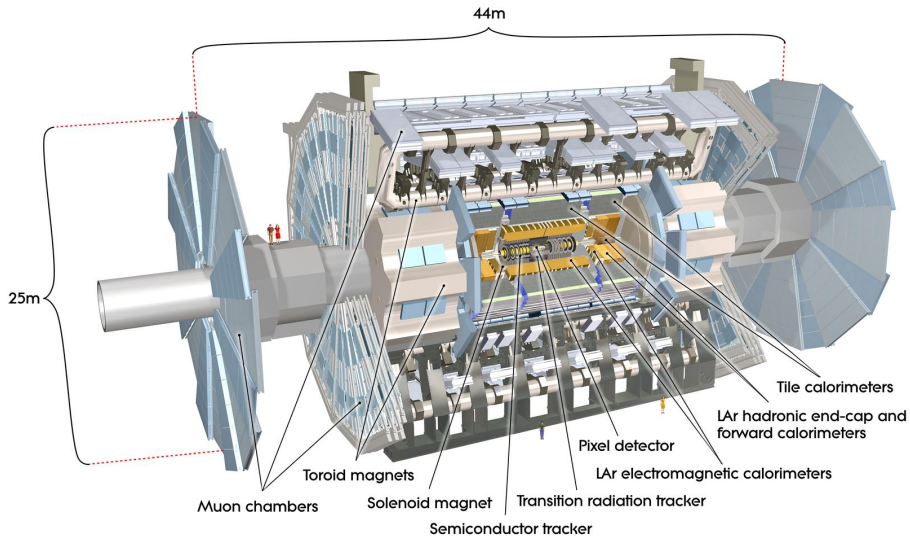
Where differences between ATLAS/CMS measurements are irrelevant or minor, I will typically show ATLAS results as examples since I'm more familiar with this experiment!
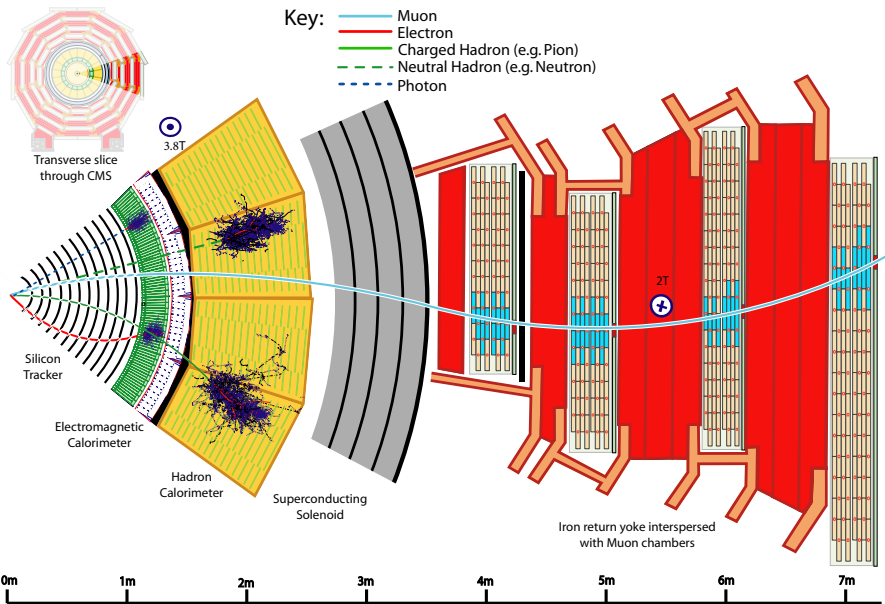
Credit to M. Watson (Birmingham) for material on top quarks!

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 ($\mathcal{O}(10\text{MHz})$ at LHC) to a manageable rate ($\mathcal{O}(100\text{Hz})$ at LHC) for permanent storage and offline analysis

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

44m

25m

Tile calorimeters

LAr hadronic end-cap and forward calorimeters

Pixel detector

LAr electromagnetic calorimeters

Toroid magnets

Muon chambers

Solenoid magnet

Transition radiation tracker

Semiconductor tracker

Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

3.8T

2T

Transverse slice through CMS

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

0m   1m   2m   3m   4m   5m   6m   7m

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**)
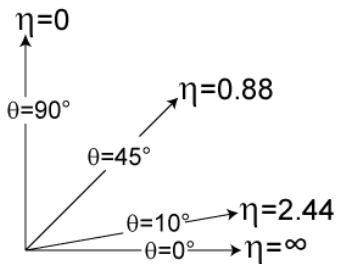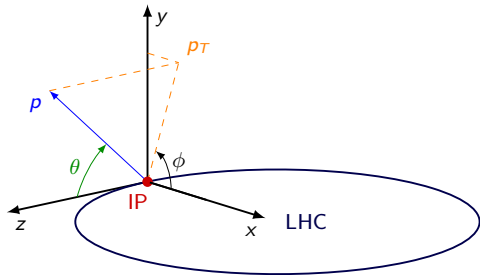
- Given the composite nature of the proton (i.e. quarks and gluons), **longitudinal momentum p_z and total energy E** are typically not very useful

- **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 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**

- **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 $\sqrt{s} \gg m_X$)

proton - (anti)proton cross sections
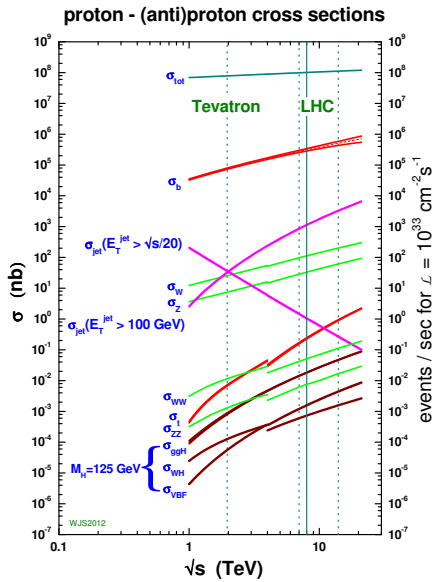
W.J. Stirling, private communication
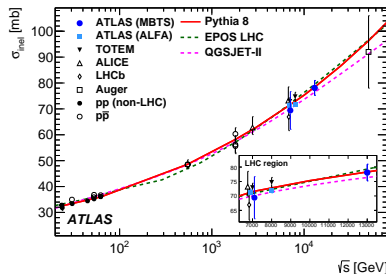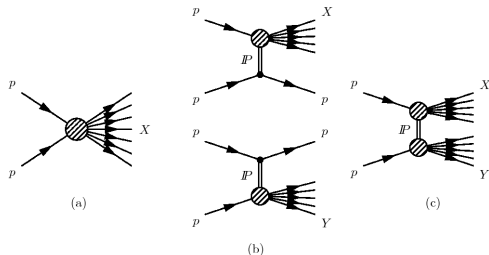
Left: Phys. Rev. D 92, (2015) 012003 (arXiv:1503.08689) Right: Phys. Rev. Lett. 117 (2016) 182002 (arXiv:1606.02625)

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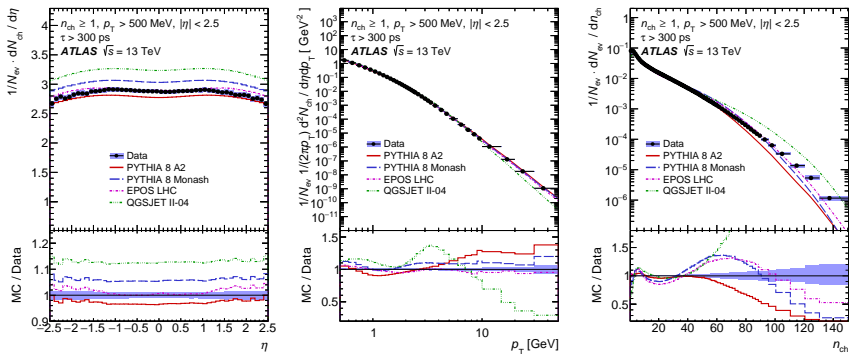
Figures: Phys. Lett. B 758 (2016) 67 (arXiv:1602.01633)

- 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...
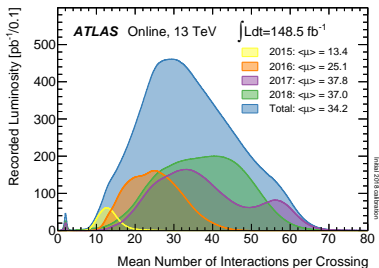
↑ **For peak Run 2 luminosities ($2 \times 10^{34} \text{cm}^2 \text{s}^{-1}$), mean number of *pp* interactions was as high as 60!**
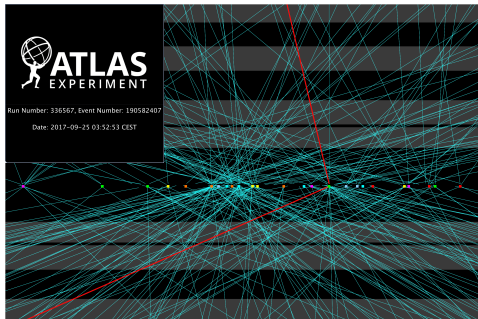
↑ **Candidate $Z \to \mu^+ \mu^-$ event reconstructed among 25 "pileup" *pp* interaction vertices**

In hard *pp* scattering events, the underlying event (UE) consists of the "beam remnant" and particles produced in multiple parton interactions (MPI) and inital/final state radiation
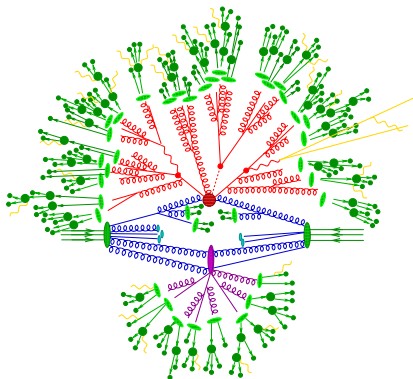
Figure: arXiv:hep-ph/0311270

- 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

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
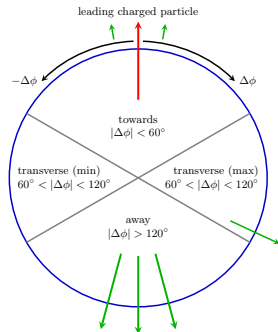
Figures: JHEP 03 (2017) 157
(arXiv:1701.05390)
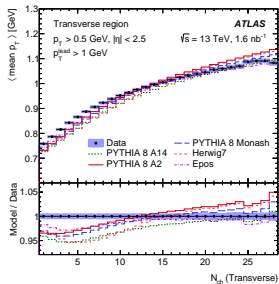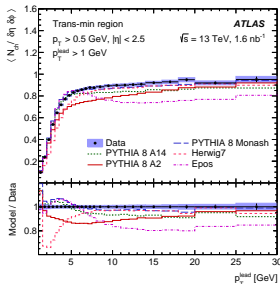
Use observables such as mean charged-particle p_T and multiplicity in Transvere region to "tune" predictions of UE models in MC generators

The "QCD Collinear Factorisation" method is the basis of all *pp* scattering calculations and MC simulations, cross-section calculation separated into two parts:
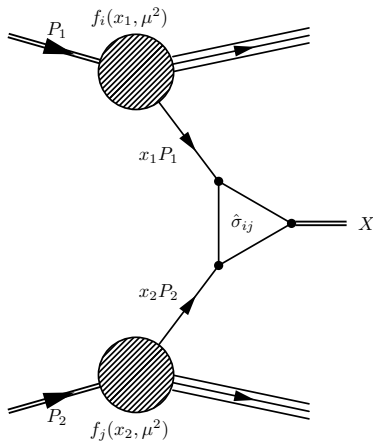
- The "hard scattering" **partonic cross-section** $\hat{\sigma}$ for two *partons* (i.e. quarks and gluons) $ij \to X$
- Calculable with perturbative QCD, often systematically improvable with higher order corrections to perturbative series
- Description of the probability (density) f to find a parton 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)

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

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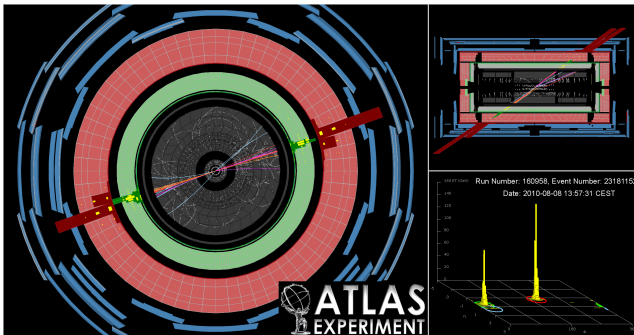
Jets are defined with an algorithm which clusters constituents within an event (usually calorimeter energy deposits, occasionally tracks) into a single entity

The Rules

- For jets to make sense in the context pf 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 $g \to q\bar{q}$)

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)

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`)

anti-k_t, R=1

P$_t$ [GeV]
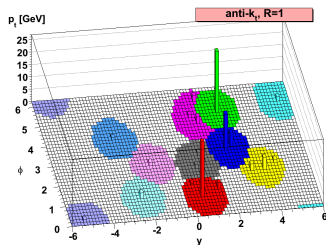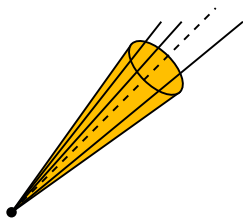
JHEP 0804:063,2008 (arXiv:0802.1189)

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 ≈ 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)
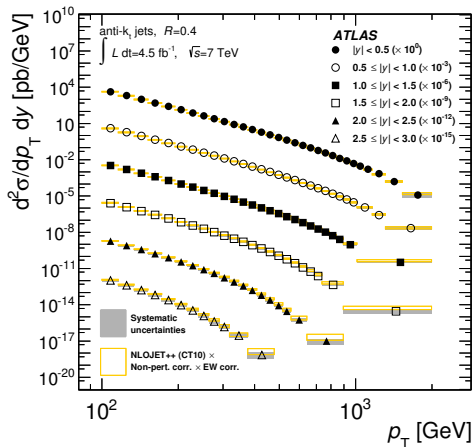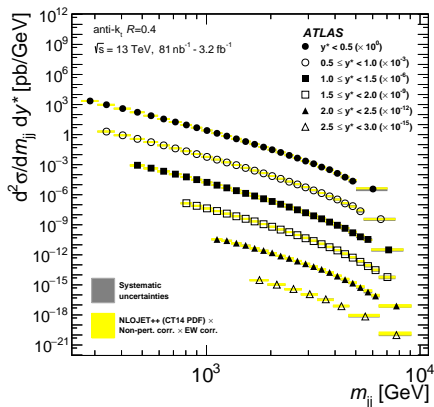
← **JHEP 05 (2018) 195 (arXiv:1711.02692)**
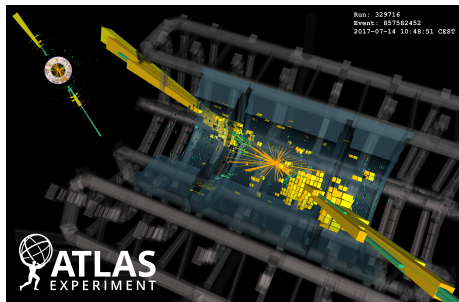
Di-jet event with $m_{jj} = 9.3$ TeV reconstructed in ATLAS

- 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. $Z' \to q\bar{q}$)
- Di-jet events with m_{jj} up to 9 TeV measured at the LHC ($\sqrt{s} = 13$ TeV)
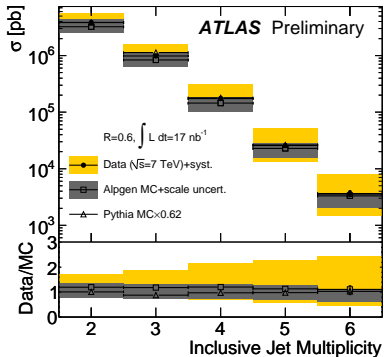
← **ATLAS**-CONF-2010-084
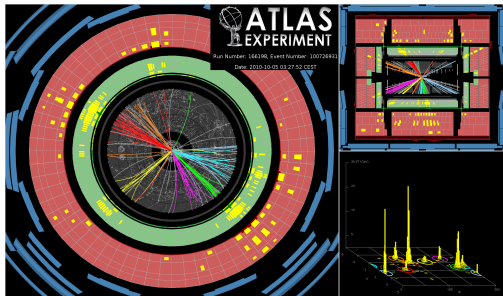
Event with 8 jets reconstructed in ATLAS

- 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

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

- 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)
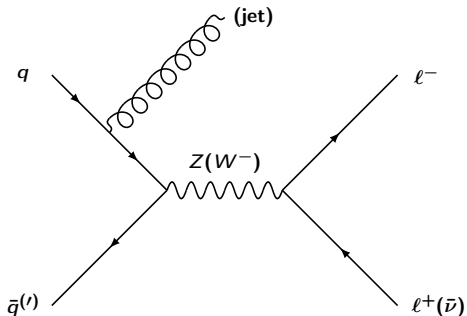
Experimental Signature:

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

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

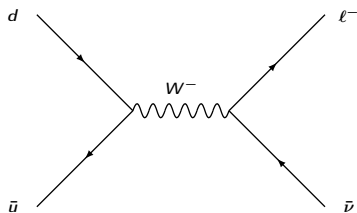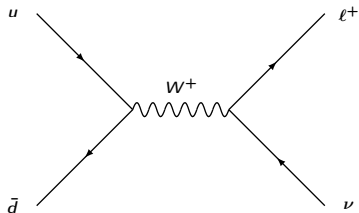**Figures: Eur. Phys. J. C 77 (2017) 367 (arXiv:1612.03016)**

Reminder: $m_Z = 91.2$ GeV and $m_W = 80.4$ GeV
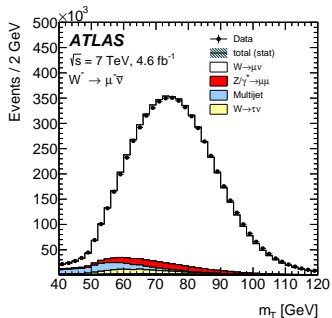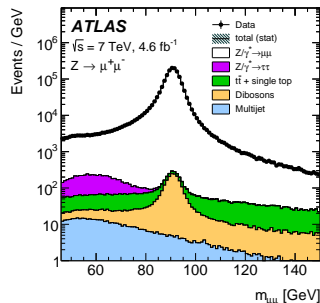
$W^\pm \to \ell^\pm\nu$ candidates

- 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

$$m_T = \sqrt{2p_T^\ell E_T^{\mathrm{miss}}\left(1 - \Delta\phi_{\ell,\nu}\right)}$$
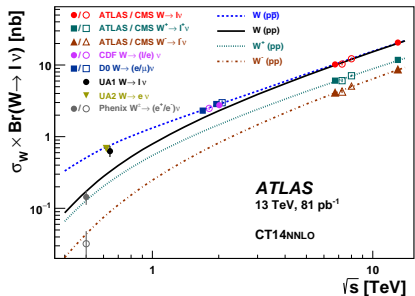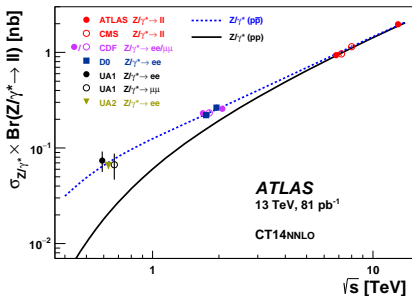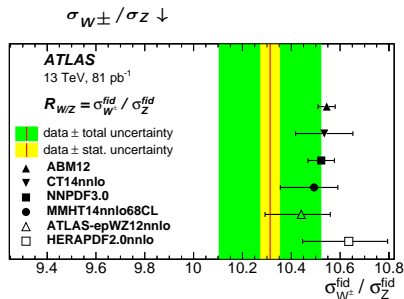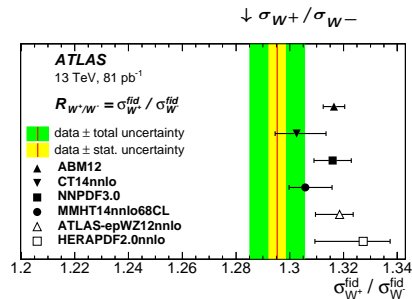
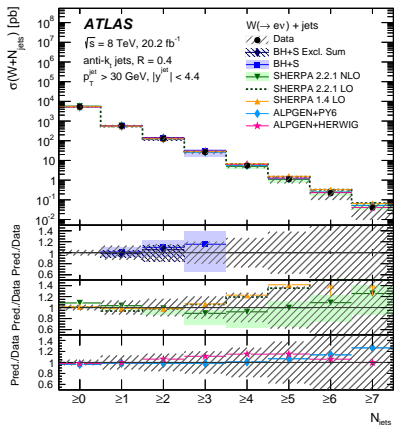Figures: Phys. Lett. B 759 (2016) 601 (arXiv:1603.09222)

MSTW 2008 NNLO PDFs (68% C.L.)
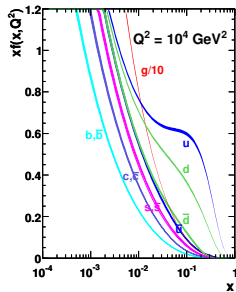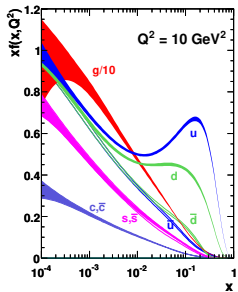
**In pp collisions, $\sigma_{W^+} > \sigma_{W^-}$, why?**

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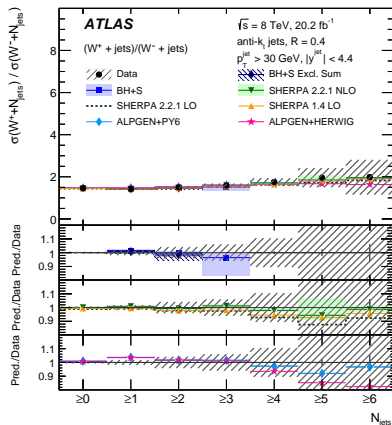
- Important test of perturbative QCD and common background for many searches
- MC generators tend to struggle to describe multiplicity beyond 3 additional jets
- Relative jet multiplicity very similar for W^+ and W^- until around 4 additional jets where PDF affects become more important

Figures: Eur. Phys. J. C77 (2017) 361 (arXiv:1702.05725)
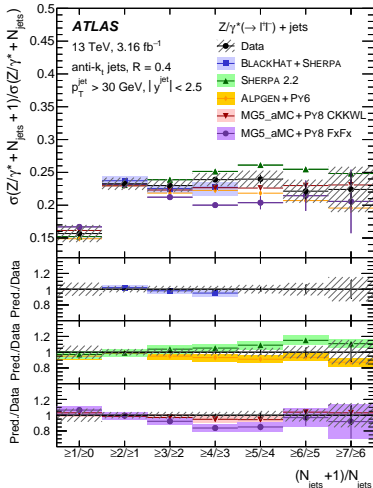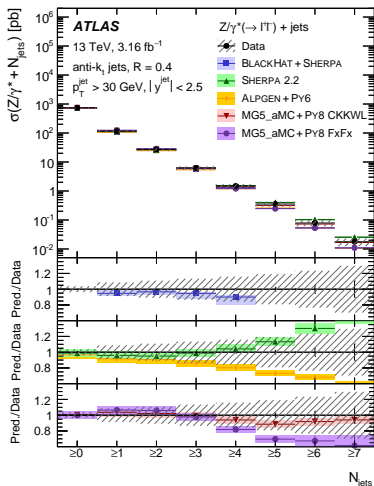
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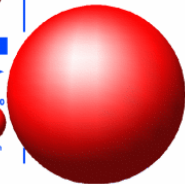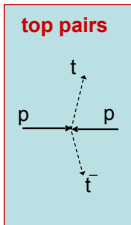- Discovered by CDF and DØ collaborations at the Tevatron in 1995

- A unique quark:
  - lifetime ~5x10^{-25} s
  - decays before it hadronises
  - no bound states (mesons)

- We want to know more about its properties:
  - Mass (why so large?)
  - Spin
  - Charge
  - Lifetime
  - Decay properties (rare decays)
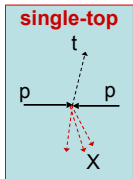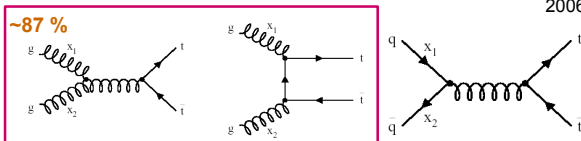 - Gauge couplings
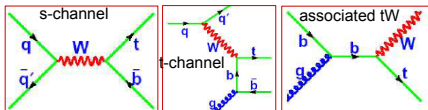 - Yukawa coupling to Higgs (why ~1?)
  - ...

top pairs
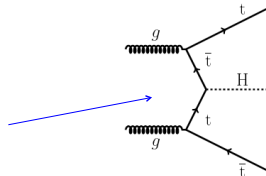
Pair production: q$\bar{q}$ and gg-fusion (QCD)

Figures
J.D'Hondt
2006

~87 %

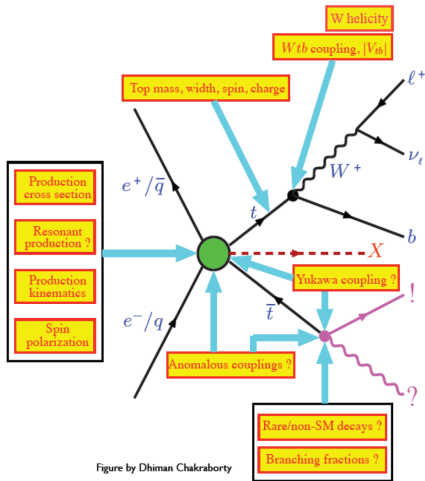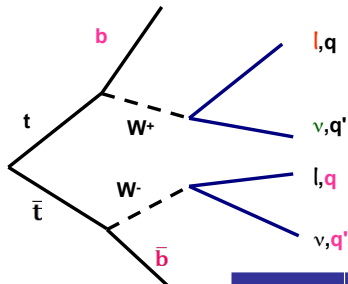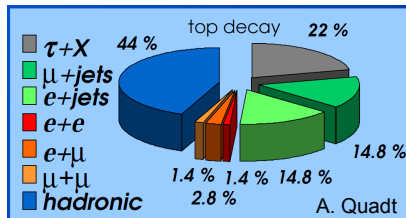**EW production of single top-quarks
(Drell-Yan and Wg-fusion)**

single-top

s-channel

t-channel

associated tW

Dominant

Figure by Dhiman Chakraborty

$t\bar{t}$

A. Quadt

Most common channel for XS/Mass analyses Lepton = e/μ

	BR	Bkd.	b jets	Light jets	Leptons	ν
Fully hadronic	High	Very high	2	4	0	0
Semi-leptonic	High	Fairly high	2	2	1	1
Dileptonic	Low	Low	2	0	2	2

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
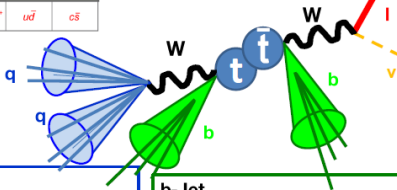- Corrected for identified objects

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
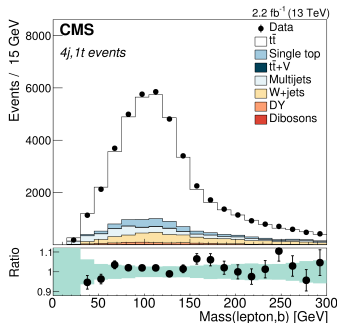- JetProb: track/jet compatibility with primary vertex

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

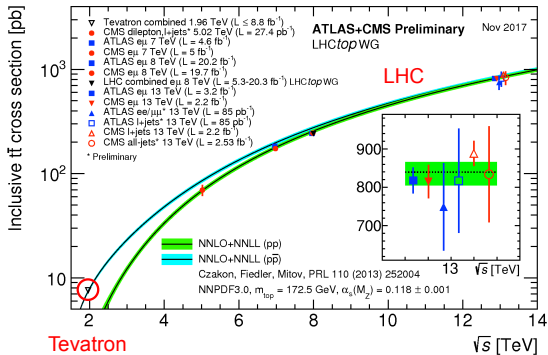- Use binned likelihood fit to kinematic distributions

- Selection:
  - Lepton trigger
  - Lepton(s)
  - Jets
  - Missing E_T
  - (b-tagging)

- b-tagging reduces background, introduces additional uncertainties
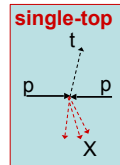
- Cross-section measurements also for
  - $\tau(\rightarrow$ had.)+jets
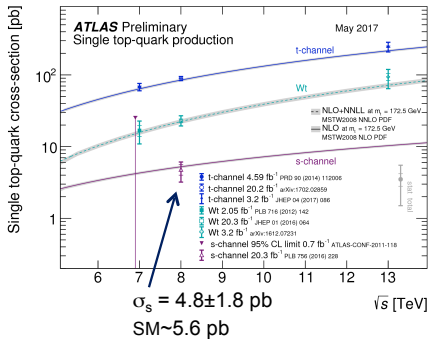 - Fully hadronic
  - Lepton + τ
  - etc.

σ agrees with NNLO QCD
δσ/σ ~4% (7,8,13 TeV)

σ(7 TeV) ~ 170 pb
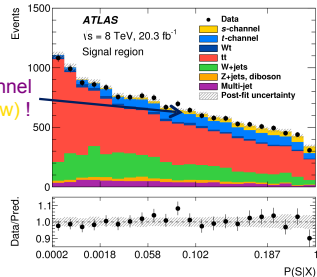σ(8 TeV) ~ 250 pb
σ(13 TeV) ~ 820 pb

- Motivation:
  - Single top is a direct probe of CKM element V_{tb}
  - 3 modes with distinct signatures
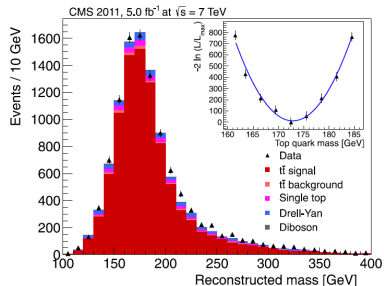 - Sensitive to many models of new physics

single-top

Single top will improve with more data

ATLAS Preliminary
Single top-quark production
May 2017

s-channel (yellow) !

$\sigma_s = 4.8 \pm 1.8$ pb
SM~5.6 pb

- Top mass is an important parameter of the SM
- Provides constraints on the properties of new particles, including the Higgs boson

- General method:
  - set of templates constructed from simulated samples with various m_t
  - likelihood fit is performed to derive the mass

CMS 2011, 5.0 fb^{-1} at $\sqrt{s}$ = 7 TeV

Events / 10 GeV

Reconstructed mass [GeV]

-2 ln (L/L$_{max}$)

Top quark mass [GeV]

- Data
- t$\bar{t}$ signal
- t$\bar{t}$ background
- Single top
- Drell-Yan
- Diboson

First ever combined measurement from LHC and Tevatron:
m_t = 173.34 ± 0.76 GeV

…but Tevatron only (Summer 2016):
174.30 ± 0.65 GeV !

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

- Soft interactions can never be ignored, 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