High p_T physics at the LHC
Lecture III
Standard Model Physics

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1. LHC machine
2. High PT experiments – Atlas and CMS
3. Standard Model physics
4. Searches

Introduction

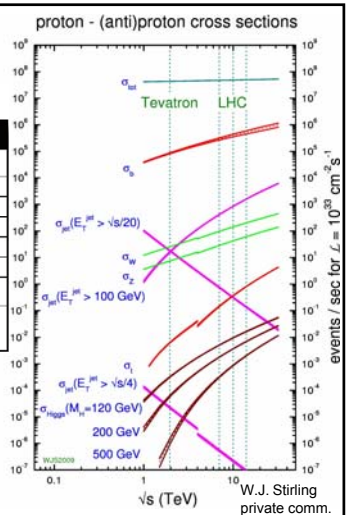
- Topics I will cover today:
  - Low p_T physics (briefly)
  - Jets
  - Vector bosons
  - Diboson channels
  - Top physics
- I will not cover
  - Heavy flavour physics
  - Particle spectroscopy
  - Heavy ion physics
- I will concentrate on ATLAS and CMS

Overview

Possible physics the first year(s)

Expected event rates at production in ATLAS at Luminosity = 10^{33} cm^{-2} s^{-1}

Process	Events/s	Events for 10fb^{-1}	Total statistics collected at previous machines by '07
Inelastic proton-proton reactions	10^8	10^{15}	
$W \to e\nu$	20	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	2	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{13}	10^2 Belle/BaBar
Higgs m = 120 GeV	0.04	10^6	--
Gluinos and Squarks m = 1 TeV	0.001	10^4	--
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	--



W.J. Stirling private comm.

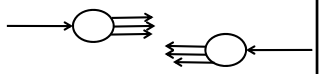
Total cross-section varies slowly with √s

'Interesting" physics processes are enhanced at high √s

But they can still be at the level of 1:10^8–10^{11}

Low p_T processes

- Total inelastic pp cross section ~ 70 mb
- High p_T processes (hard scattering) represent only a tiny fraction of the total cross section
- Most interactions are at large distance between incoming protons →small momentum transfer

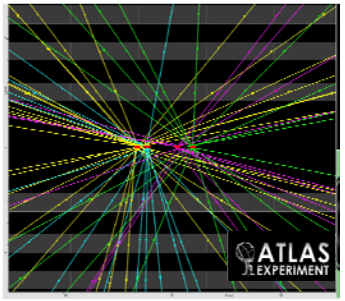


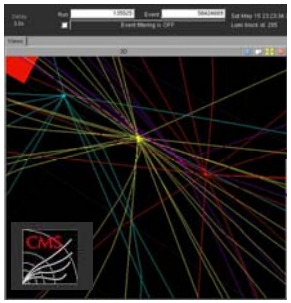
- Particles in the final state have small p_T
- These are SOFT interactions

- Minimum Bias events:
  → triggered INELASTIC collisions of two protons;
  → require minimal activity in the detector

Events with multiple interactions

- Many events per beam crossing at LHC (pileup), mostly low p_T → important to understand properties
- SOFT interactions are NOT easily calculable within QCD and rely on Monte Carlo models, which are tuned to data

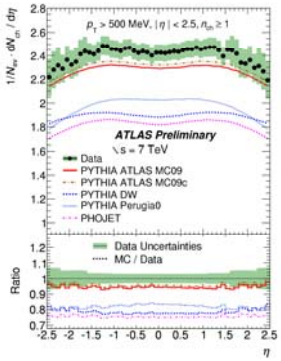




Particle flow in inelastic collisions

Charged particle multiplicities at 7 TeV for p_T>500 MeV, n_{ch}≥1

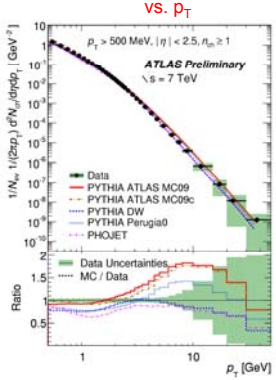
vs. pseudorapidity



Monte Carlo models are somewhat lower (5-20%) than data.

MC tuned to data from previous experiments →some refitting needed, but reasonable description of 7 TeV collision events.

vs. p_T



The "underlying event"

- The UE consists of the "beam remnants" and from particles arising from soft or semi-soft multiple parton interactions (MPI)
  - The underlying event is not the same as a minimum bias event

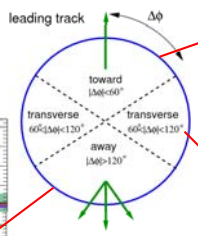
No hard scattering
"Min-Bias" event

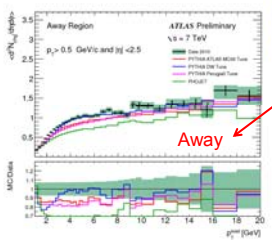
- Modeling of UE: important ingredient for jet physics and lepton isolation, energy flow, object tagging, etc

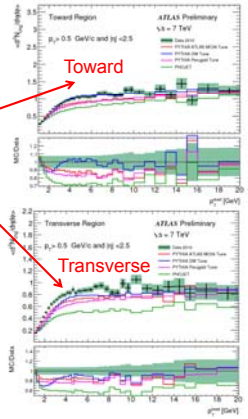
P. Sphicas
LHC 2010: summary and prospects

Underlying event

- Divide the azimuthal region with respect to the maximum p_T track.
- Charged particle density vs. leading track p_T
- Also: max. p_T, Σp_T, $\langle p_T \rangle$

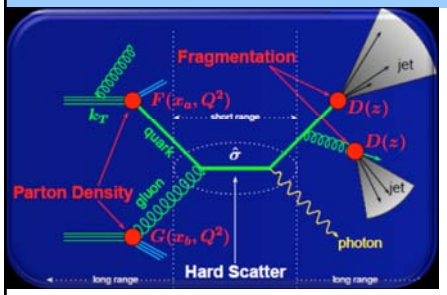






Determine best soft QCD "tune" for underlying event.

Jets



P. Sphicas

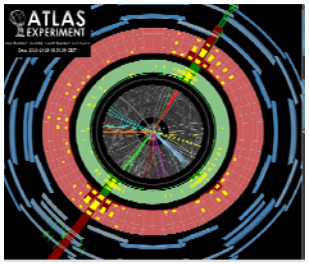
- Hard scattering processes are dominated by QCD jet production (from qq, qg, gg scattering)
- Fragmentation of quarks and gluons into final state hadrons → jets with large transverse momentum p_T in the detector
- Cross sections can be calculated in QCD (perturbation theory)
- Need to test the theory against experimental data

Jets at the LHC

- High p_T jets probe close to the kinematic limit of the LHC → test QCD in a new region
- Measurements of top, Higgs and SUSY all involve jets → jet energy scale, resolution and uncertainties must be understood

  Jet energy scale uncertainty dominates
- Search for deviations from the Standard Model as hints for new physics

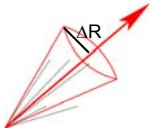
Highest p_T jet in ATLAS: p_T=1.5 TeV



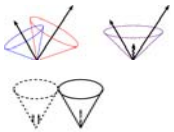
Jet definitions

- Cone algorithms:
  - Merge everything inside a cone

    $\Delta R = \sqrt{\Delta\eta^2+\Delta\phi^2}$
  - But an extra soft gluon can change the number of jets



- For pQCD to make sense, the (hard) jets should not change when
  - There is soft emission *i.e. add a very soft gluon*
  - There is a collinear splitting *i.e. one parton is replaced by two*



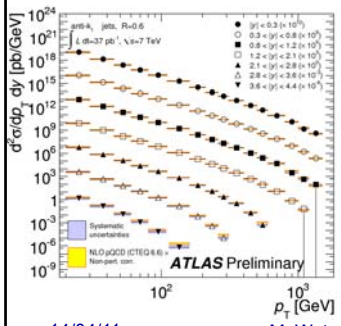
- Recombination algorithms:
  - Successively find the "closest" pair of particles and recombine them
  - stop at a distance R
  - p = −1: anti-k_t algorithm

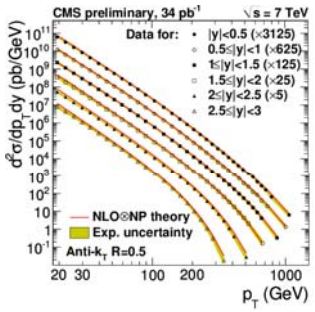
$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})\ (\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)$$

Soft particles will first cluster with hard particles
IR + Collinear safe

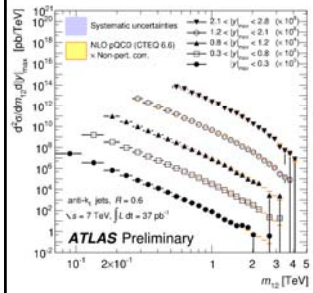
Inclusive single jet double differential cross-section

- Cross-section for different rapidity ranges as function of p_T
- Spans many orders of magnitude
- Total uncertainty on cross-section dominated by JES
- Good agreement with NLO perturbative QCD (pQCD) predictions within experimental and theoretical uncertainties

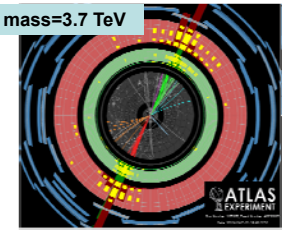




Inclusive double differential di-jet cross-section

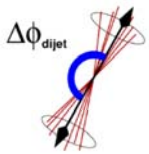


Di-jet mass=3.7 TeV

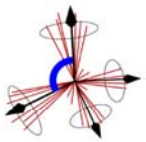


- Measured as a function of di-jet invariant mass up to 4 TeV!
- Additional test of pQCD
- Important distribution for new resonances

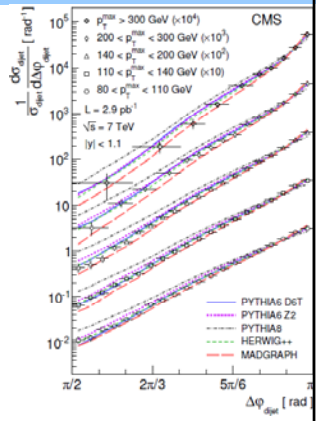
Di-jet azimuthal decorrelations



2-jet event
$\Delta\Phi = \pi$

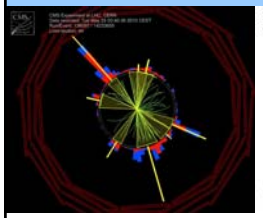


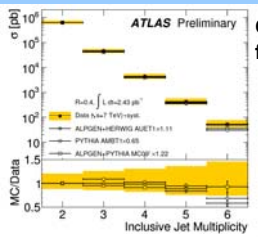
n-jet event
$\Delta\Phi < \pi$



- Sensitive to high-order QCD radiation
- Probes high jet multiplicities
- Important test of MC description of multiple parton radiation
- Compare with MC and NLO pQCD

Multi-jet properties



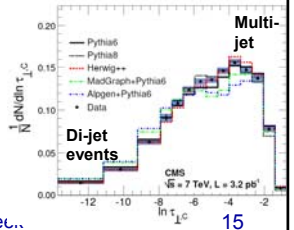


Cross section as a function of no. of jets

Important test of QCD and must be understood for searches for new physics

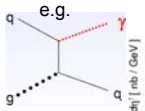
Central transverse thrust

$$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}$$

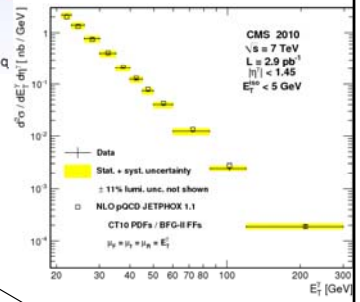


Prompt photon production

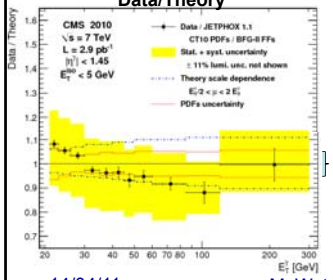
- Isolated prompt photon production:
  - Complementary test of pQCD
  - Can constrain proton PDF



Cross section vs. $E_T(\gamma)$



Data/Theory



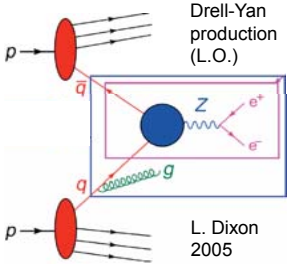
Scale uncertainty

PDF uncertainty

W and Z physics

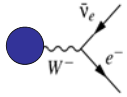
- Final state contains
  - Jets
  - Leptons
  - Missing E_T (in the W channel)

  => major background to new physics
- Main source of isolated high p_T leptons
- Benchmark for lepton performance (efficiency, scale, resolution,…)
- Search for leptonic decays:
  - Lepton trigger
  - $Z \rightarrow \ell\,\ell$ large p_T (ℓ)
  - $W \rightarrow \ell\,\nu$ +large missing E_T

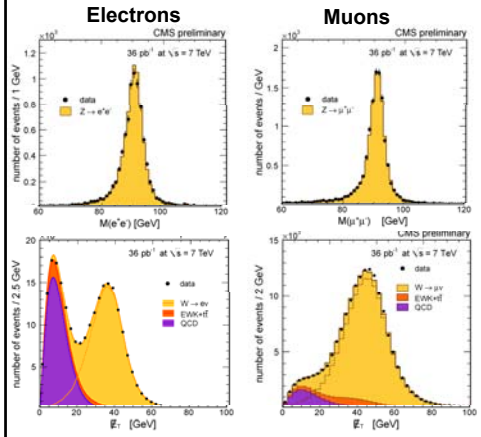


Drell-Yan production (L.O.)

L. Dixon 2005



W and Z mass distributions



Z candidates:

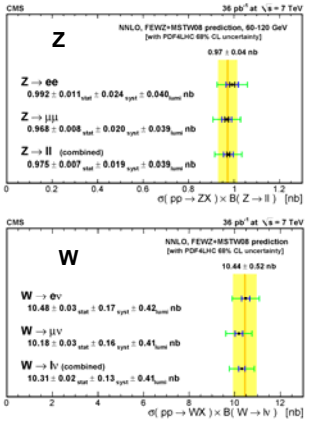
Reconstruct $M(\ell^+\ell^-)$, consistent with Z peak

W candidates:

Associate E_T^{miss} with the neutrino. Do not have information on z component → use Transverse Mass:

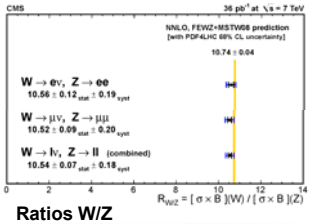
$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss})}$$

W and Z inclusive cross-sections

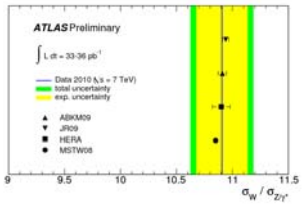


Consistent with predictions

NNLO calculation +PDFs

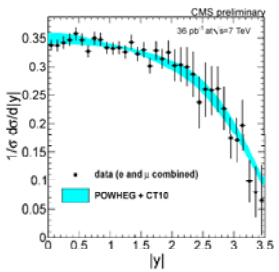


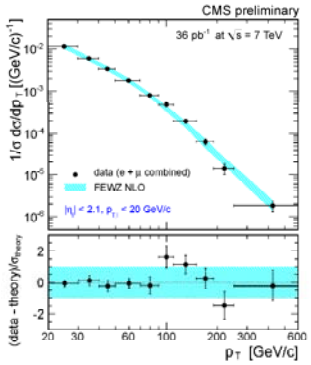
Ratios W/Z



Z differential cross-sections

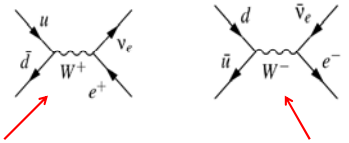
- Form cross-section as a fn. of Z rapidity and p_T
- Agreement with NLO at 1-2 σ level



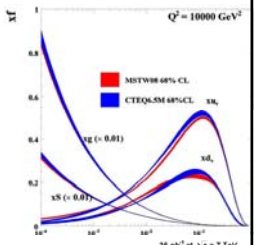


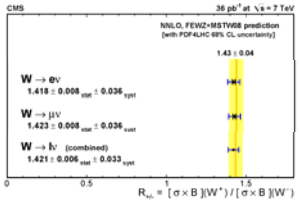
W^+ and W^- cross-sections

- Proton-proton collisions ⇒ $\sigma_{W+} \neq \sigma_{W-}$



- This process occurs more than this ⇒ $\sigma_{W+} > \sigma_{W-}$
- Measurements give $\sigma_{W+} \approx 1.4\ \sigma_{W-}$ in good agreement with NNLO QCD



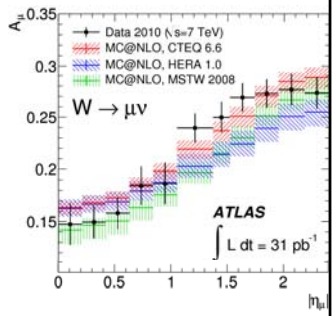


W charge asymmetry

- Cross-section asymmetry depends on the momentum fraction *x* of the partons
  ⇒ dependence on rapidity y of W
- Difficult to reconstruct W rapidity,
  ⇒ use **lepton charge asymmetry** (fn. of muon pseudorapidity, η_μ):

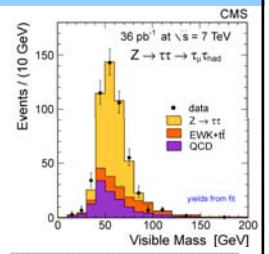
$$A_\mu = \frac{d\sigma_{W\mu^+}/d\eta_\mu - d\sigma_{W\mu^-}/d\eta_\mu}{d\sigma_{W\mu^+}/d\eta_\mu + d\sigma_{W\mu^-}/d\eta_\mu}$$

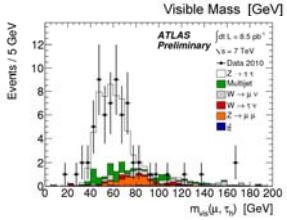
- Measurement can be used to constrain PDFs



Z→ττ

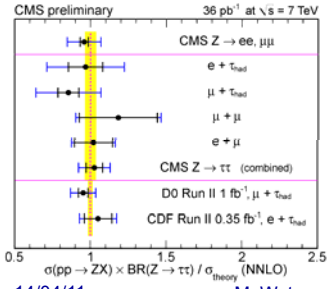
- Z → ττ and W → τν are important background processes in searches
- Production cross-sections need to be well measured
- Study Z→ττ with one τ→ e or μ; other τ→hadrons (or e,μ)
- Identify with e.g.
  - an e or μ (trigger)
  - a hadronic τ candidate
  - missing E_T
- Significant backgrounds from
  - Z→ℓℓ
  - QCD

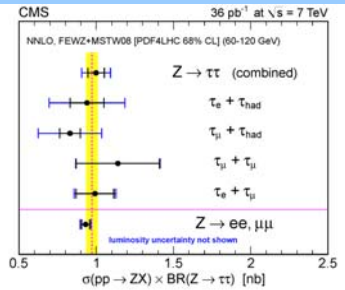




Z→ττ cross-sections

- Measurements consistent with SM expectations (NNLO)
- Will improve with more data

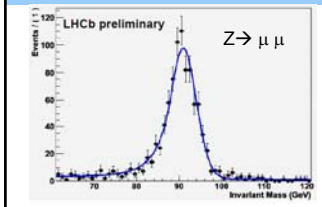


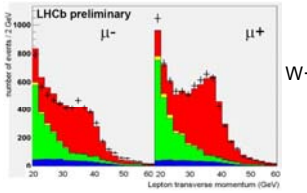


Measured cross-section

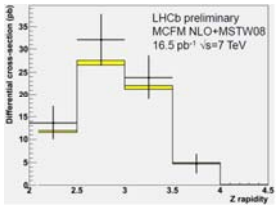
Data/NNLO (incl. Tevatron)

W and Z production in the forward region

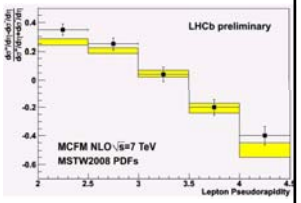




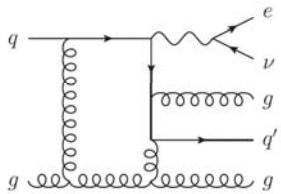
W→ μ ν



Differential Z and W cross-sections cover a complementary region to ATLAS & CMS



W+jets and Z+jets



V. Ciulli, Moriond QCD

Diagram: ordinary QCD+EWK

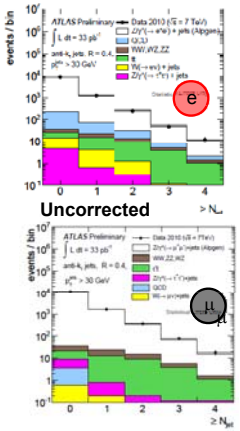
But very challenging for NLO with many jets

Recently done with up to 4(3) jets for W(Z)

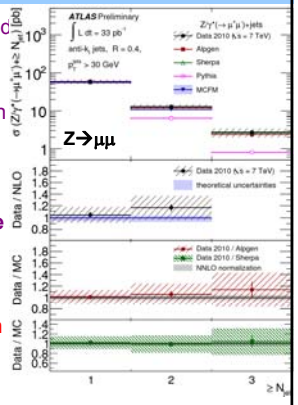
Phys. Rev. Lett. 106 (Mar, 2011) 092001
Phys. Rev. D 82 (Oct, 2010) 074002

- Vector Boson+jets cross section is a stringent test of pQCD
  - choice of scales, parton showering,…
- Significant background for SM and beyond SM processes

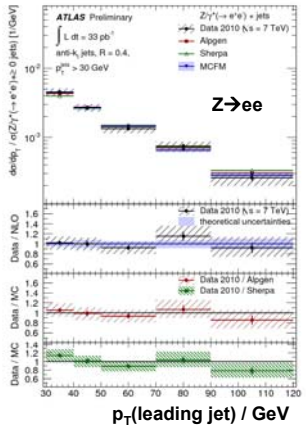
Z+jets



- Estimate background
- Unfold detector effects
- Obtain cross-section vs. N_{jet}
- **NLO predictions and generators are in agreement with measured cross sections**
- Except Pythia which does not reproduce the data at high jet multiplicity



Z+jets as a function of p_T



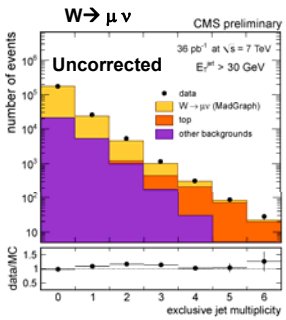
Tails in p_T(Z/W) enter in many searches e.g.SUSY

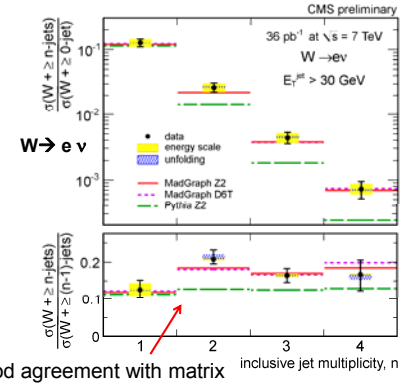
Important to understand them

Data are well described by NLO pQCD predictions and MC models

W+jets

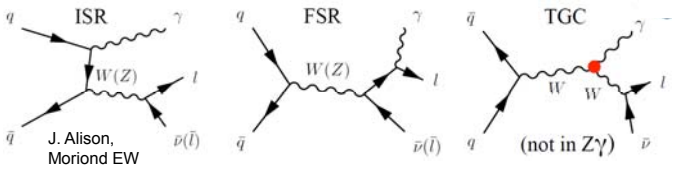
- Similar analyses to Z+jets





Good agreement with matrix element + parton shower, while PS alone fails for $n_{jet} \geq 2$

Di-boson: W γ and Z γ

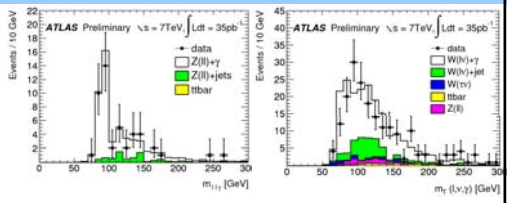


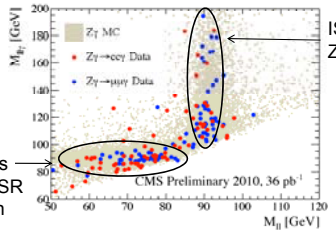
J. Alison, Moriond EW

- Motivation:
  - First Wγ, Zγ cross section measurements at 7 TeV
  - Test Electroweak model
  - Sensitive to Triple Gauge Couplings
  - Will constrain new physics in Anomalous TGCs
- Selection:
  - W or Z candidate in e or μ channel
- Isolated photon candidate *e.g.* $E_T > 15$ GeV, not near lepton(s)

W γ and Z γ analysis

- Dominant source of background is W(Z)+jets events with photons present in the jet hadronization





ISR photon and Z to leptons

Z to leptons with FSR photon

- FSR and ISR photons fall in different regions of the M(ℓℓγ) – M(ℓℓ) plane

W γ and Z γ results

- First cross-sections and limits at 7 TeV
- In agreement with SM expectations, within large uncertainties

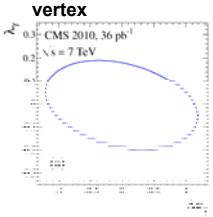
ATLAS cross-sections

W+γ+X	Measured cross section (pb)
e-channel	73.9 ± 10.5 (stat) ± 15.9 (sys) ± 8.1 (lumi)
μ-channel	58.6 ± 8.2 (stat) ± 11.7 (sys) ± 6.4 (lumi)
SM NLO Prediction: 69.0 ± 4.6 (sys)	

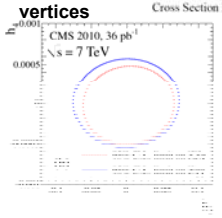
Z+γ+X	Measured cross section (pb)
e-channel	16.4 ± 4.5 (stat) ± 4.3 (sys) ± 1.8 (lumi)
μ-channel	10.6 ± 2.6 (stat) ± 2.5 (sys) ± 1.2 (lumi)
SM NLO Prediction: 13.8 ± 0.9 (sys)	

Cross Section Reported for: $E_T^\gamma > 10$ GeV / $\Delta R(l,\gamma) > 0.5$ / $f_{iso}^\gamma < 0.5$

WWγ vertex



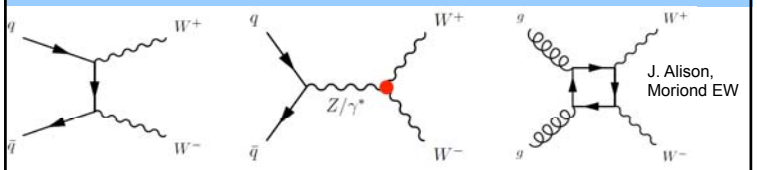
ZZγ and Zγγ vertices



CMS limits on anomalous couplings

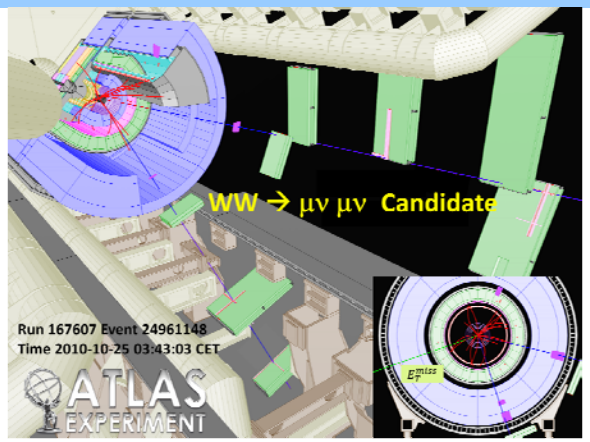
SM values are zero

Di-boson: WW

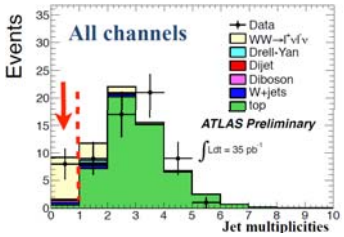


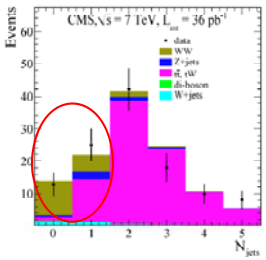
- Motivation:
  - Test electroweak model
  - Sensitive to Triple Gauge Couplings
  - Will constrain new physics in Anomalous TGCs
  - Dominant background to H→WW search
- Selection:
  - W→lν decays
  - Opposite sign e, μ candidates
  - Large missing E_T

WW candidate



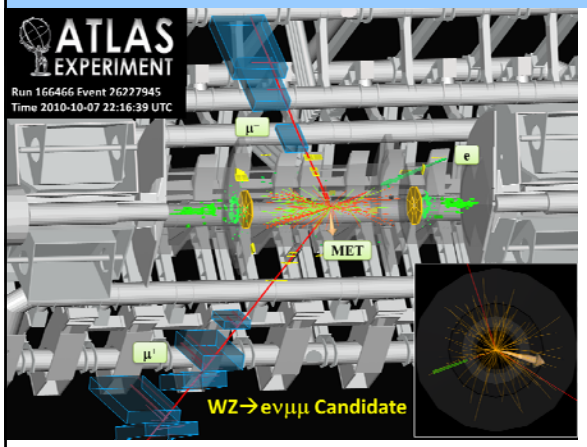
WW distributions and results





- First cross-sections and TGC limits at 7 TeV
- Consistent with expected WW production
  (e.g. ATLAS signal significance of 3.0 s.d. → inconsistent with bkd. only)
- Large statistical uncertainties – more data will help

Di-boson: WZ candidate



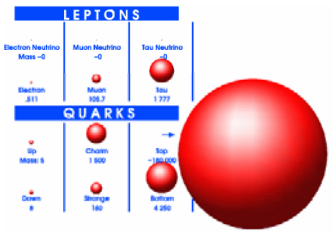
Cross-sections and other measurements will follow

Additional topics in W and Z phyics

- Boosted W polarisation
  - "Polarisation has been measured to be predominantly left-handed"
- Observation of Z+b events
  - "Compatible with NLO calculations"
- Drell-Yan cross-section in $Z/\gamma \rightarrow \mu^+\mu^-$
  - "Agreement with NNLO prediction"
- $Z \rightarrow \ell^+\ell^-$ polarization
  - "Forward-backward asymmetry is in good agreement with the SM"

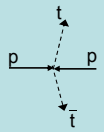
Introduction to top physics

- Discovered by CDF and DØ collaborations at the Tevatron in 1995
- A unique quark:
  - lifetime ~10^{-24} 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 (why ~1?)
  - ...



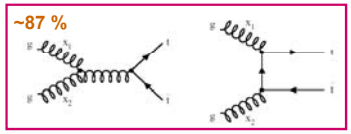
Top production

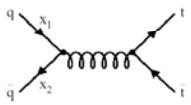
top pairs



Pair production: qq and gg-fusion (QCD)

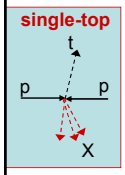
Figures J.D'Hondt 2006

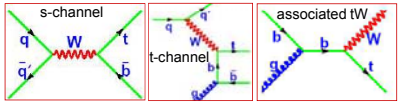




EW production of single top-quarks (Drell-Yan and Wg-fusion)

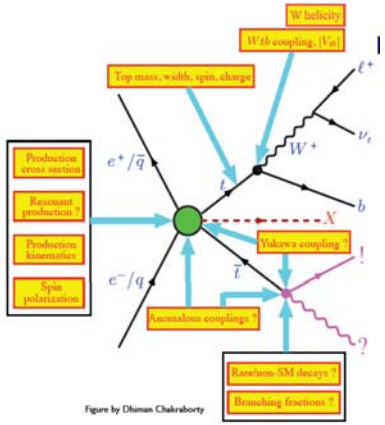
single-top



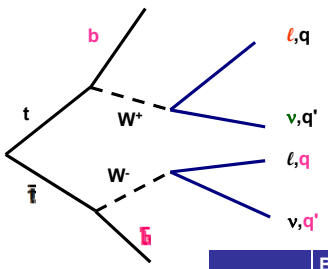


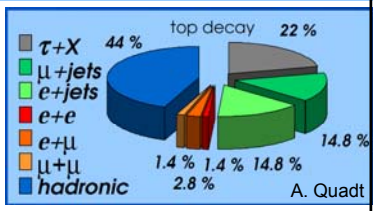
Dominant

What we would like to know about top



Overview of $t\bar{t}$ decays

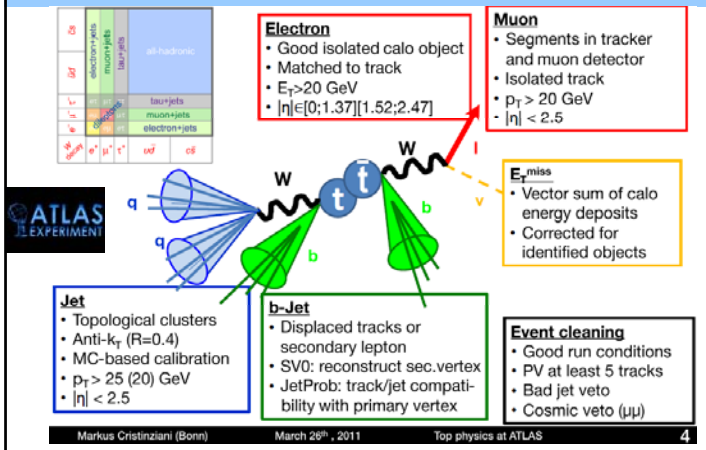




Most common channel for XS/Mass analyses Lepton = e/μ

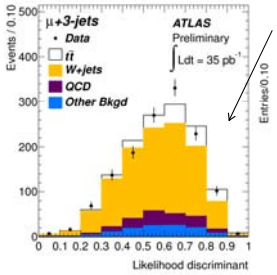
	BR	Bkd.	b jets	Light jets	Leptons	ν
Fully hadronic	High	Very high	2	4	0	0
Semi-leptonic	High	Fairly high	2	2	1	1
Dileptonic	Low	Low	2	0	2	2

Selection of top events

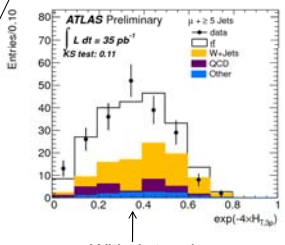


Top pair cross-section (lepton+jets)

- Use binned likelihood fit to kinematic distributions
- Selection:
  - Lepton trigger
  - Lepton
  - Jets
  - Missing E_T



No b-tagging



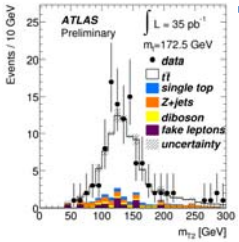
With b-tagging

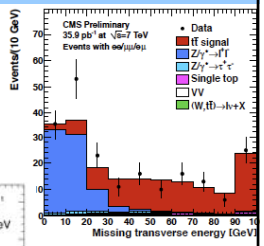
- Jet energy scale and reconstruction uncertainties dominate
- Most backgrounds determined from data
- Larger background w/o b-tagging, but no tagging uncertainties

Top pair cross-section (dilepton)

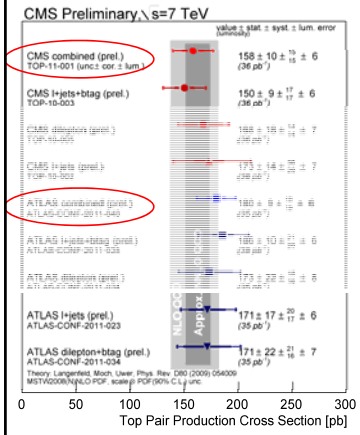
- Cut-based methods
  - 2 leptons (opp.sign)
  - 2 jets
  - Missing E_T, total E_T
- Main systematics
  - JES
  - Parton shower
  - Fakes

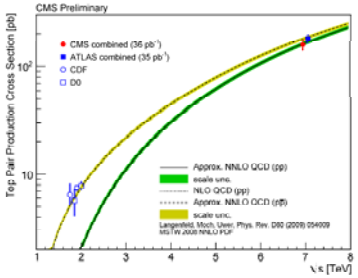
ee, μμ, eμ channels





Cross-section combination



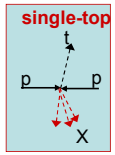


σ agrees with NNLO QCD

δσ/σ ~ 10% (each expt.)

Single top cross-sections

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



- **t-channel cross-section:**

$\sigma_t = 53^{+27}_{-24}(\text{stat})^{+38}_{-27}(\text{syst}) = 53^{+46}_{-36}$ pb ATLAS

$\sigma_t = 83.6 \pm 29.8$ (stat+syst) ± 3.3 (lumi) pb CMS

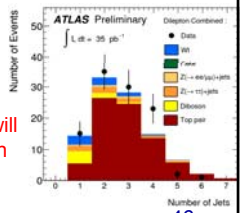
σ_t(SM) ~ 59 - 66 pb

- **Wt production:**

$\sigma_t < 158$ pb at 95% c.l. ATLAS

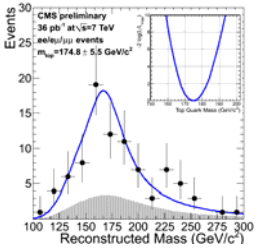
σ_t(SM) ~ 15 pb

Single top will improve with more data

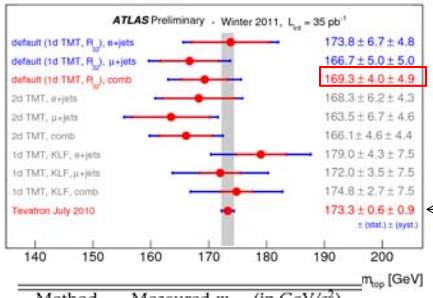


Top quark mass

- Top mass is an important parameter of the SM
- Provides constraints on the properties of new particles, including the Higgs boson
- General method: a set of templates is constructed from simulated samples with various m_t and a likelihood fit is performed to derive the mass
- CMS dilepton channel:
  - Two methods of solving kinematic equations describing the tt system, with different assumptions on p_z, JES, E_ℓ
- ATLAS lepton+jets:
  - Construct event-by-event ratio of the reconstructed top and W masses associated to the hadronically decaying top-quark candidate
  - Reduces dependence on jet energy scale



Top quark mass results



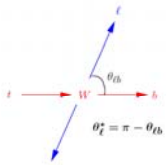
Tevatron

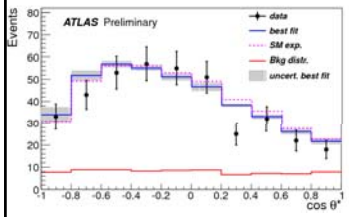
LHC has some way to go to reach this precision and level of understanding of data

	Method	Measured m_{top} (in GeV/c^2)
	AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$
	KINb	$174.8 \pm 5.5(stat)^{+4.5}_{-5.0}(syst)$
CMS	combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$

W boson polarisation in top decays

- Standard Model predicts helicity fractions of W from top
- F_L = 0.301, F_0 = 0.698, F_R=4.1x10^{-4} (LH, longitudinal, RH)
- Probe Wtb structure; set limits on new physics
- Extract directly from cos θ* or unfold and calculate asymmetry
- Use e+jets, μ+jets channels



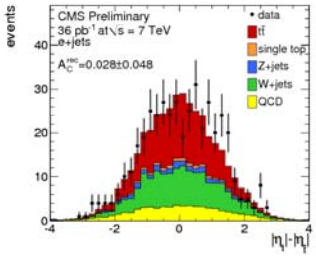


	Template method	Asymmetry method
F_L	0.41 ± 0.12	0.36 ± 0.10
F_0	0.59 ± 0.12	0.65 ± 0.15
F_R	Fixed 0	-0.01 ± 0.07

→ **consistent with SM, large uncertainties**

Charge asymmetry

- At the Tevatron: deviation > 3σ from SM predicted A_{FB} ~5%
- At the LHC: pp state symmetric
  →charge asymmetry visible in $|\eta_t|-|\eta_{\bar{t}}|$
- Expected asymmetry is small: $A_C \approx 0.0130$
- A deviation could indicate new physics, e.g. Z'



A_C = 0.060±0.134(stat.) ±0.026(syst.)

Top quark charge asymmetry will reach comparable sensitivity to the Tevatron results with ~1 fb^{-1}

Concentrate on high mass region to improve sensitivity to new resonances

Summary

- A huge number of Standard Model studies have been performed with the first LHC data
- Can probe higher mass and p_T regions than before, and find that everything looks pretty much as predicted (within uncertainties)
- Most measurements would benefit from more data, especially
  - Top physics
  - Diboson measurements
- Understanding the detectors is extremely important, because
  - The tails of "standard" distributions are the most relevant to searches for physics beyond the Standard Model
- We will cover new physics tomorrow

Additional material (and acknowledgements)

- Last year's lectures:
  - http://www2.warwick.ac.uk/fac/sci/physics/staff/academic/gershon/gradteaching/warwickweek/material/lhcphysics
- CERN Academic Training lectures (Sphicas and Jakobs):
  - http://indico.cern.ch/conferenceDisplay.py?confId=124047
  - http://indico.cern.ch/conferenceDisplay.py?confId=77835
- London lectures (de Santo et al.):
  - http://www.hep.ucl.ac.uk/~mw/Post_Grads/2007-8/Welcome.html
- ATLAS and CMS public results:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome
- Moriond Electroweak and QCD:
  - http://indico.in2p3.fr/conferenceOtherViews.py?view=standard&confId=4403
  - http://moriond.in2p3.fr/QCD/2011/MorQCD11Prog.html