2011 IPMU-YITP School and Workshop on Monte Carlo Tools for LHC
10 September 2011

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Recent results from LHC/ATLAS

LHC (Large Hadron Collider) at CERN

- For finding Higgs, understanding EW symmetry breaking mechanism and physics beyond the Standard Model
- Highest energy experiment

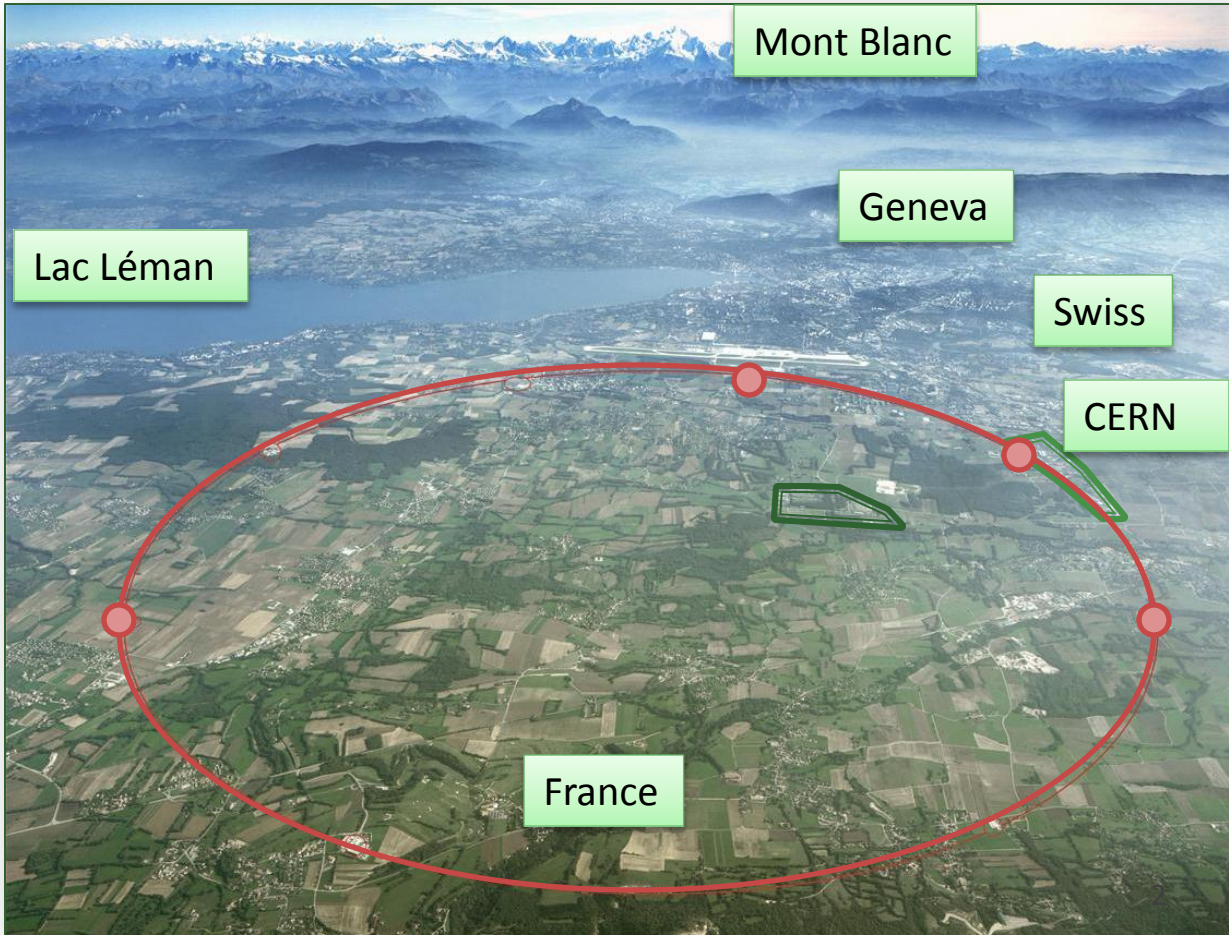
27km circumference

Design beam energy: 7TeV

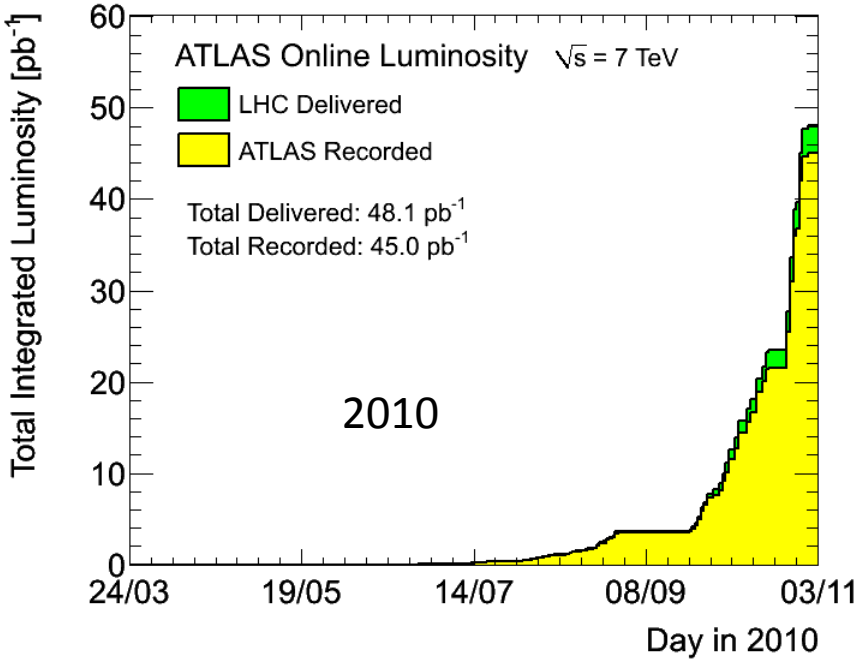
Currently 3.5 GeV
= 7 GeV CMS energy
(3.5 times design energy)

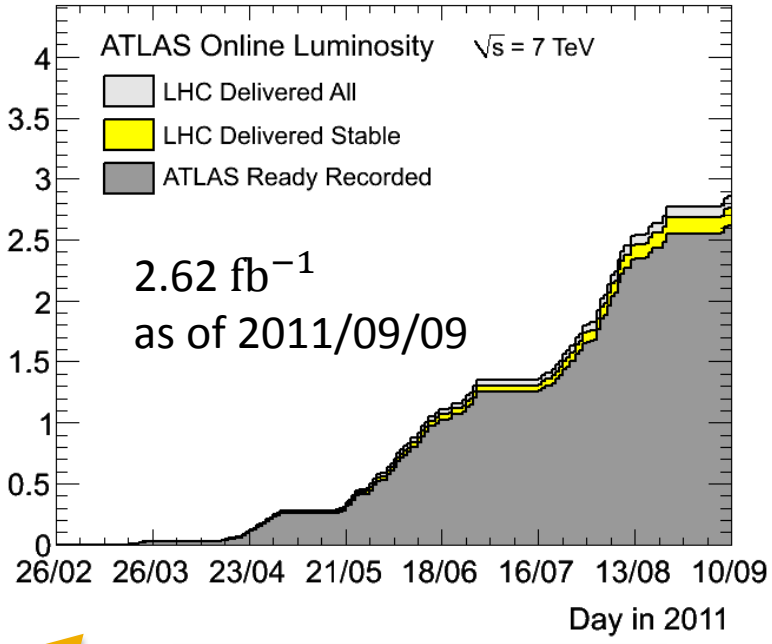
40MHz collision frequency

Design luminosity
$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



LHC accelerator operation





~ 2.6fb^{-1}, ×60 already

- 2011: $\gtrsim 4$ fb^{-1} ?
- 2012: continueing 7 TeV run, aiming for total 10 fb^{-1} for 7 TeV
- 2013-14 repairing super-conducting magnets for ~14 TeV run

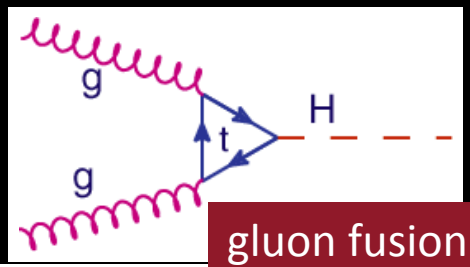
List of topics in this talk

- Higgs search result as of LP2011
- W and Z boson production
  - + jets
  - Diboson
- Top quark production
- SUSY and other searches
- QCD
  - Soft physics
  - jets

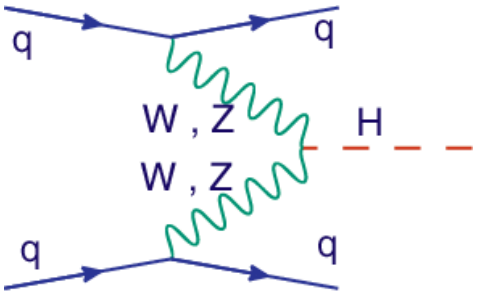
Subjects are chosen from ones something to do with
QCD part of Monte Carlo simulation / theoretical calculation

Higgs search

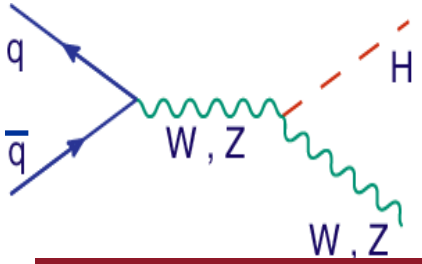
SM Higgs boson production @ LHC



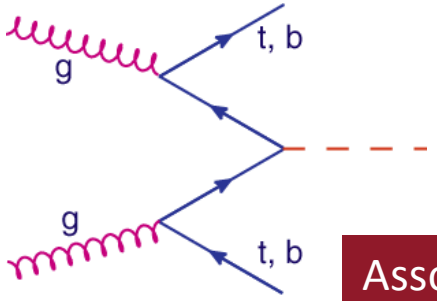
gluon fusion



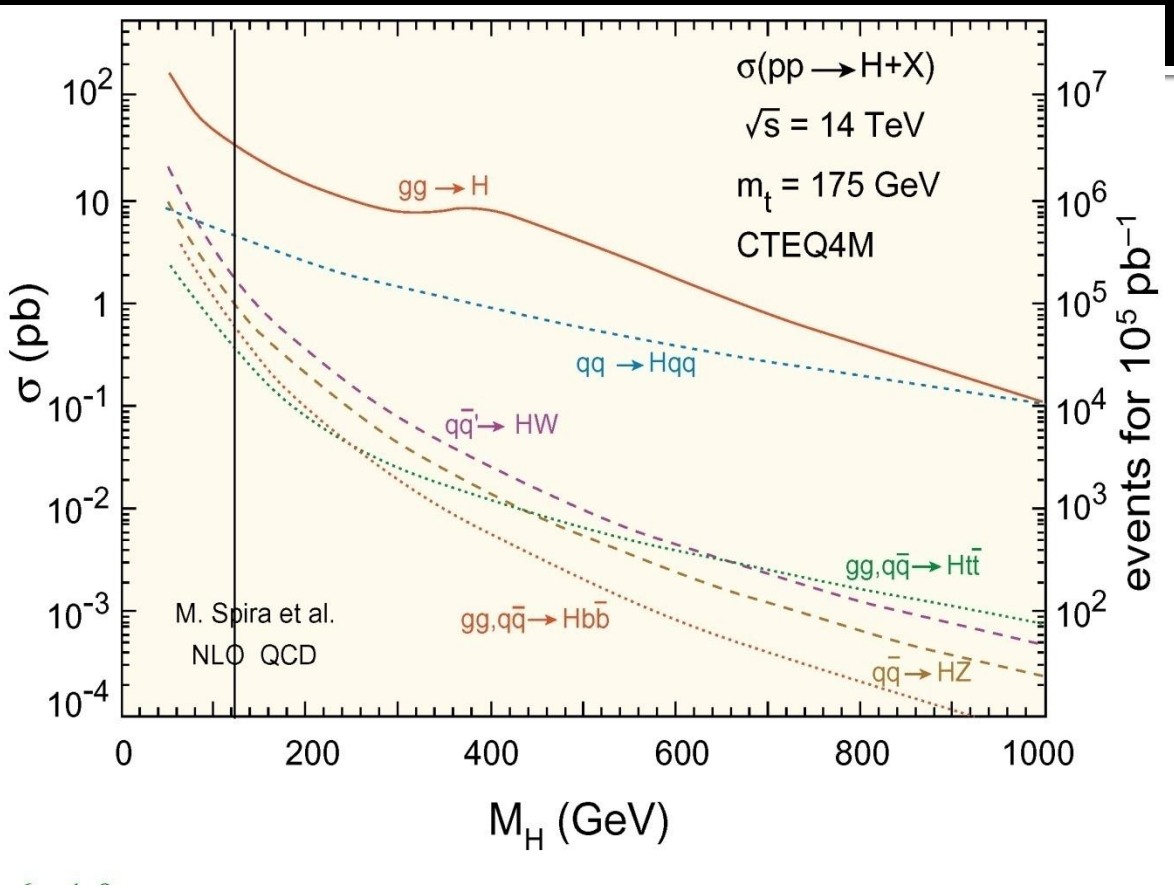
Vector-boson fusion (VBF)



Associated WH, ZH



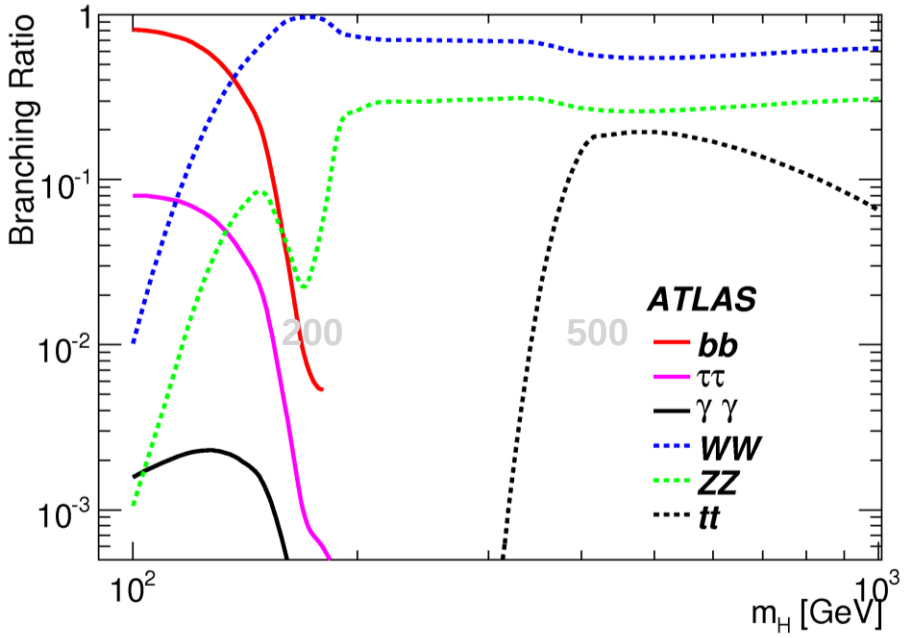
Associated ttH, bbH



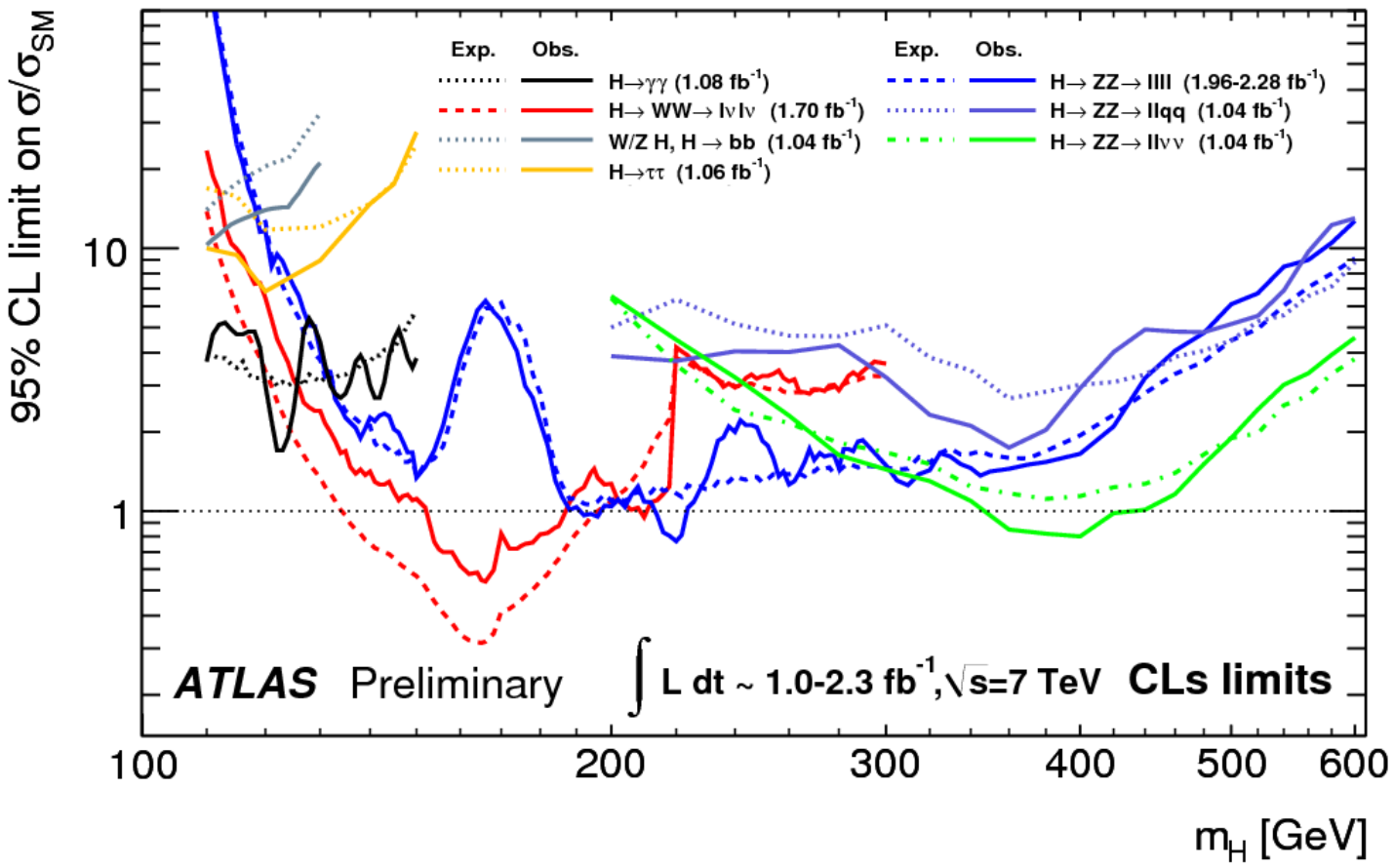
- Inclusive search
- VBF (+ 2 jets) just started
- WH, ZH only for $\rightarrow l(l,\nu)b\bar{b}$

SM Higgs decay

- $m_H > 2m_W$:
  $\rightarrow$ WW, ZZ (, tt)
- $m_H \approx 2m_W$:
  $\rightarrow$ $WW^{(*)}$ ~ 100%
- $m_H < 2m_W$
  $\rightarrow$ bb, WW*, ZZ*
  $\rightarrow$ ττ (< 10%)
  $\rightarrow$ γγ (2×10^{-3})
- Golden channel: ZZ$\rightarrow$4*l* , γγ
- Sensitivity at 1-2fb^{-1}:
  - $m_H \lesssim 2m_W : WW^{(*)},\ ZZ^{(*)}$
  - $m_H > 2m_W : ZZ \rightarrow llvv, llll$

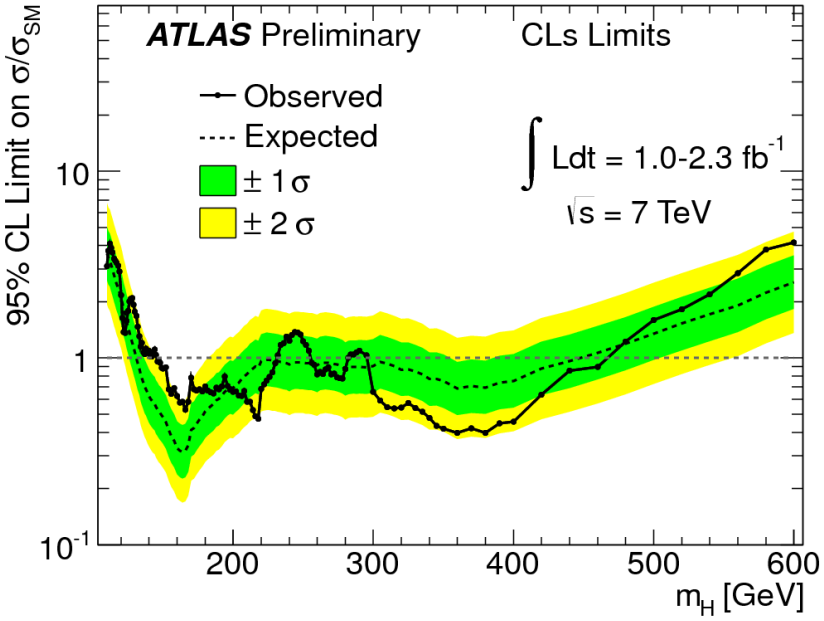


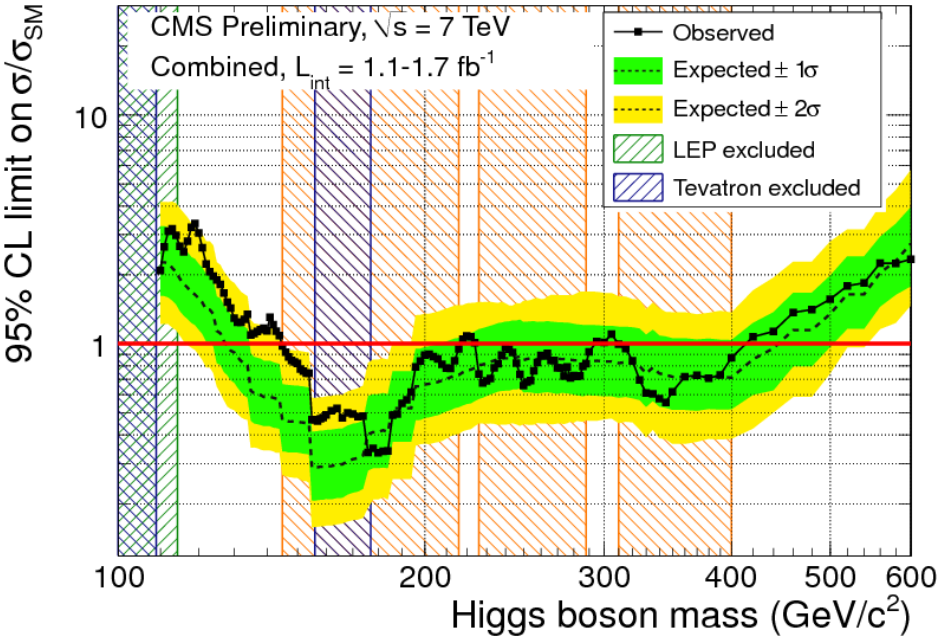
ATLAS result @ LP2011



- Individual channel upper limit already close to SM cross sections
- Insignificant excess in $H \rightarrow WW$ channel seen

Upper limits combined

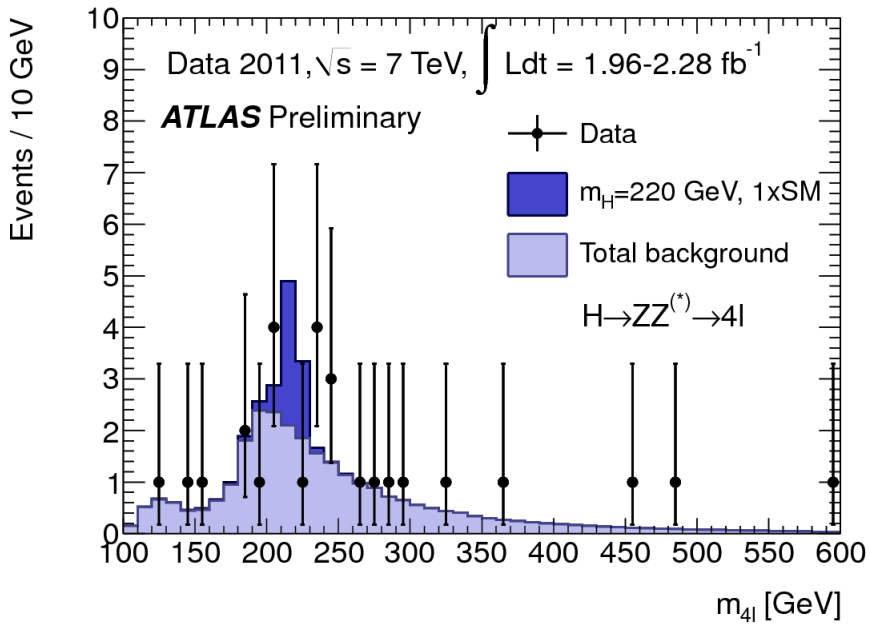


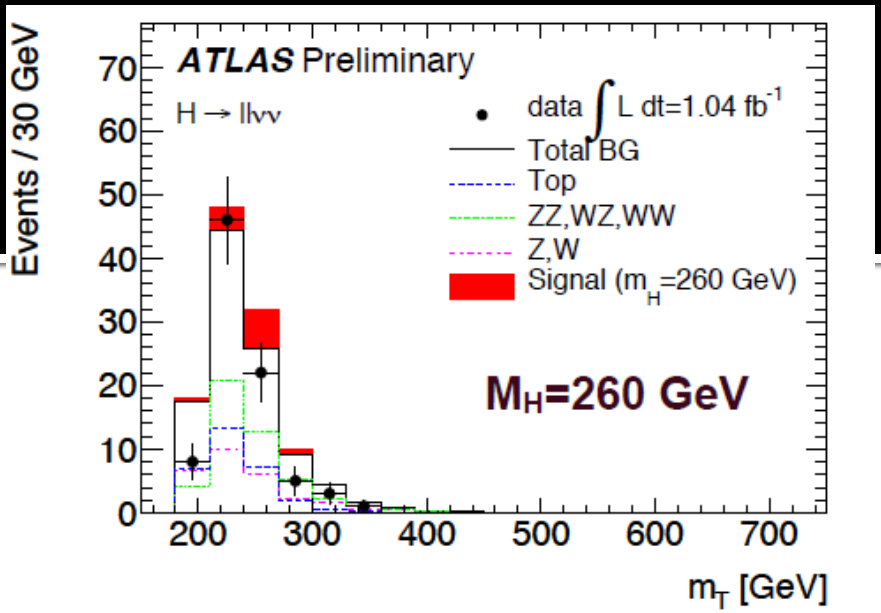


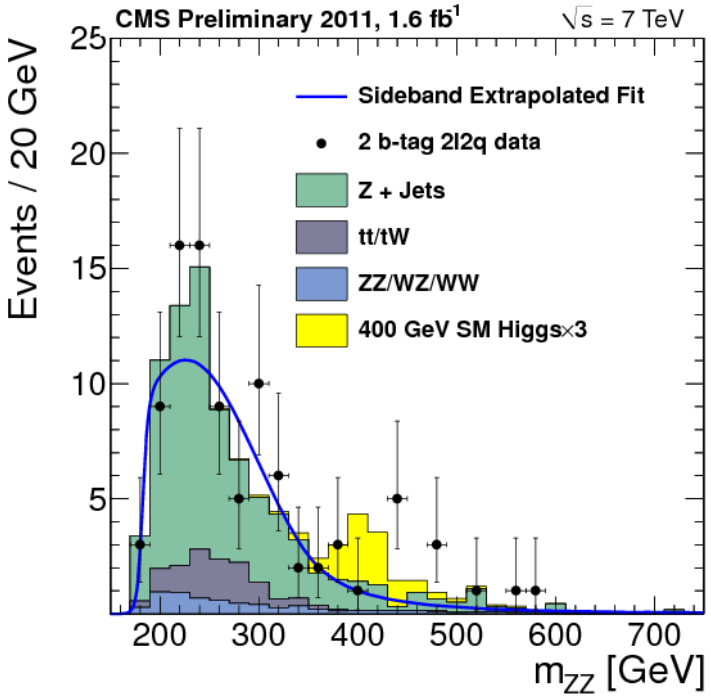
- Excess observed at around 130-150 GeV @ EPS2011 (July 2011): now with less significance
- $145 < m_H < 450$ GeV pretty much excluded

CMS results mostly with 1.6-1.7 fb^{-1}, ATLAS mostly 1.0 fb^{-1} but 4lepton and WW

High-mass Higgs



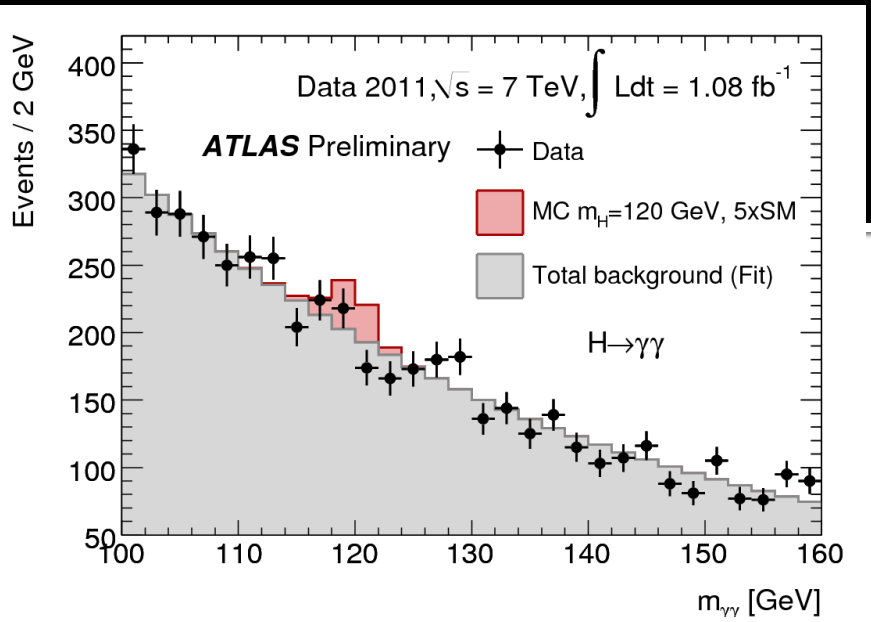


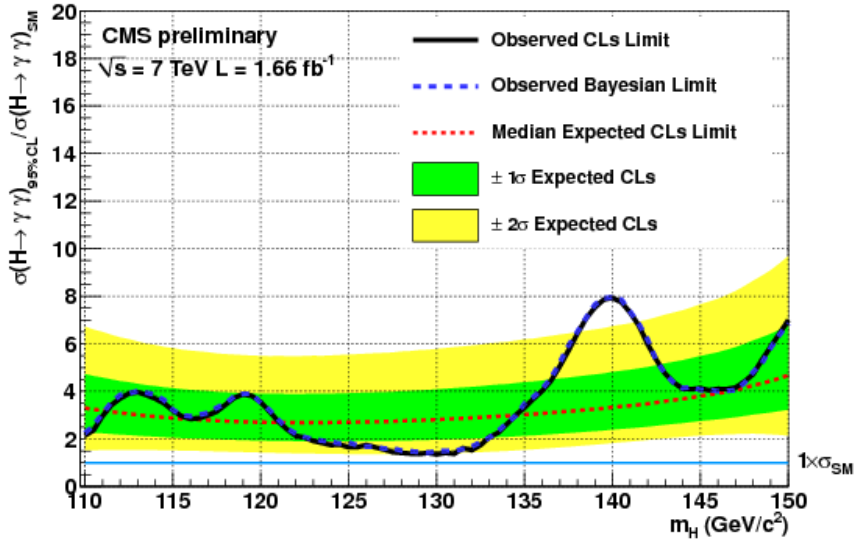


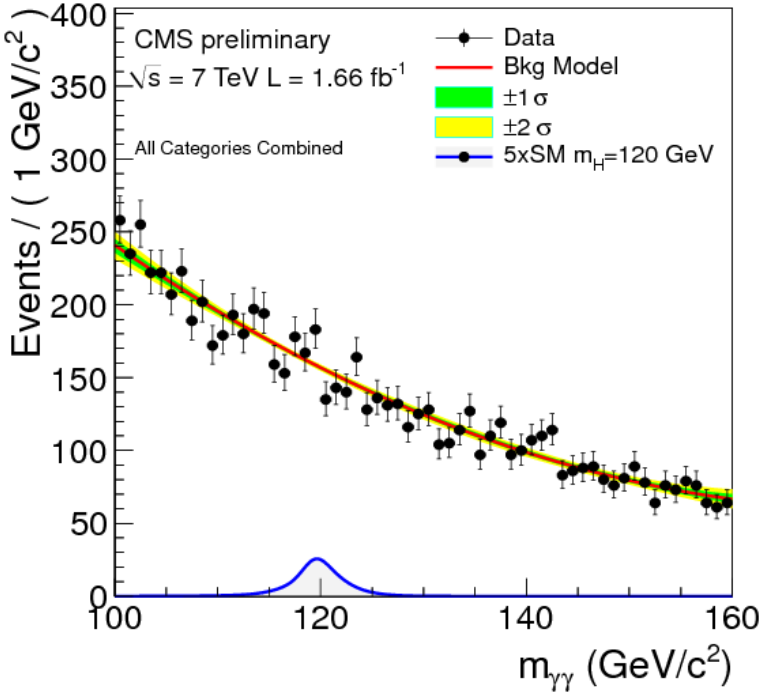
- Higgs decaying into 4leptons, $l\bar{l}\nu\bar{\nu}$ and $l\bar{l}q\bar{q}$
- $l\bar{l}\nu\bar{\nu}$: high-sensitivity at high mass
  - Small background

Low-mass Higgs (1) : $\gamma\gamma$

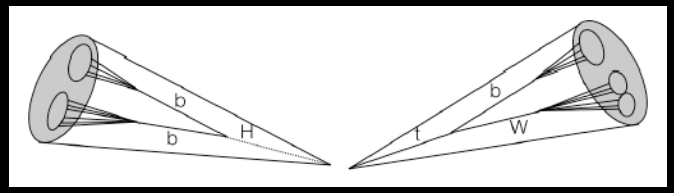
- The channel for low mass
  - Current limit: 2-4 times SM
  - some signal may be seen next year with 10 fb^{-1}





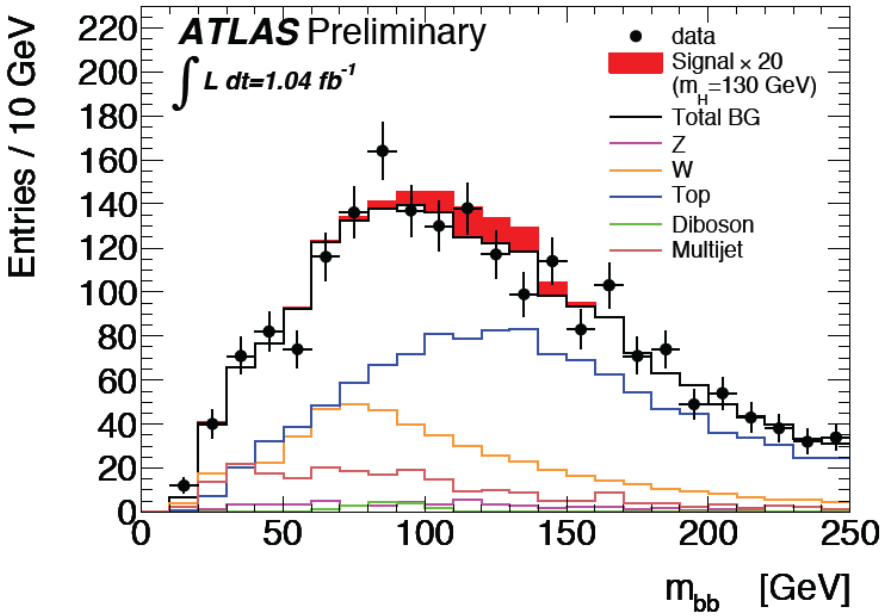


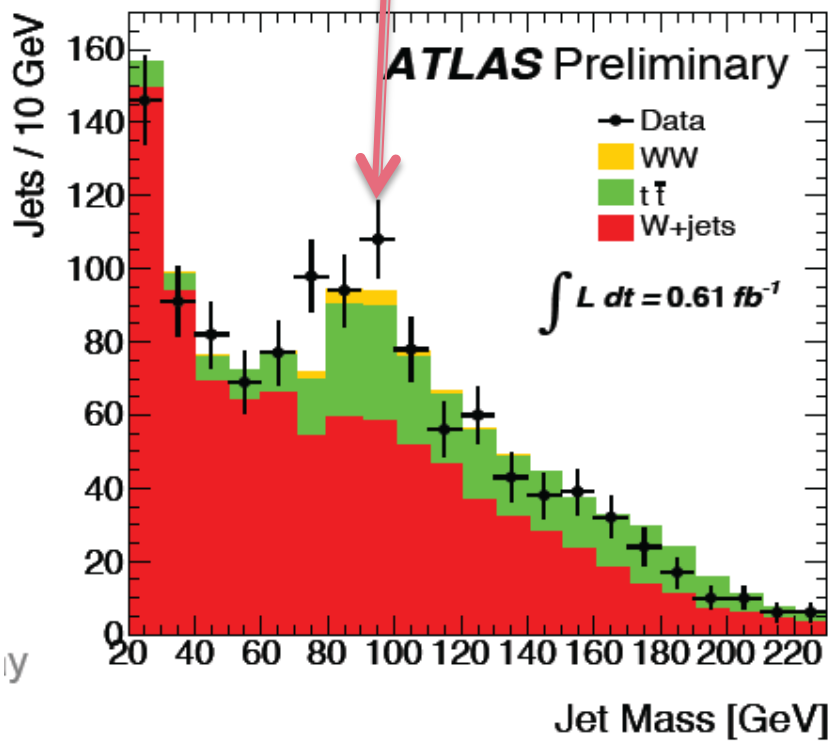
Low-mass Higgs
(2) $W(Z)H \rightarrow l(\nu, l)b\bar{b}$



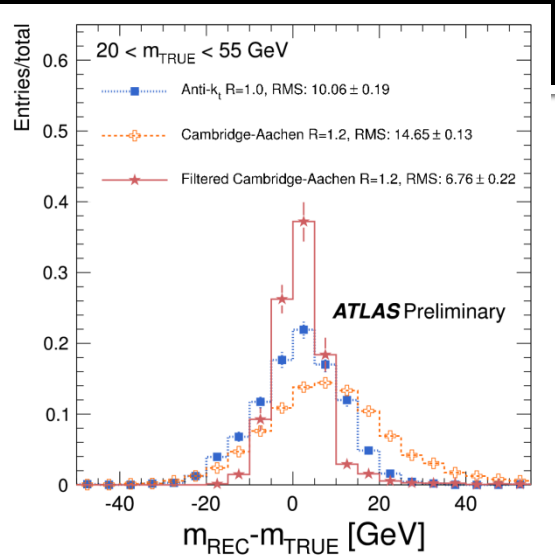
- W tagged by lepton + Etmiss, Z by dilepton
- Large cross section but huge background
- Key point: good resolution in mass reconstruction
  - using subjet technique

$W \rightarrow q\bar{q}$ mass reconstructed!v



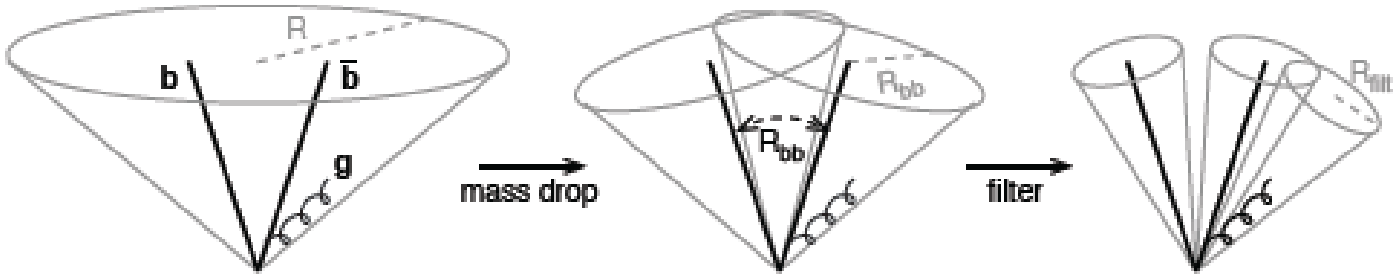


Reconstructing the mass of heavy objects from "fat jet"



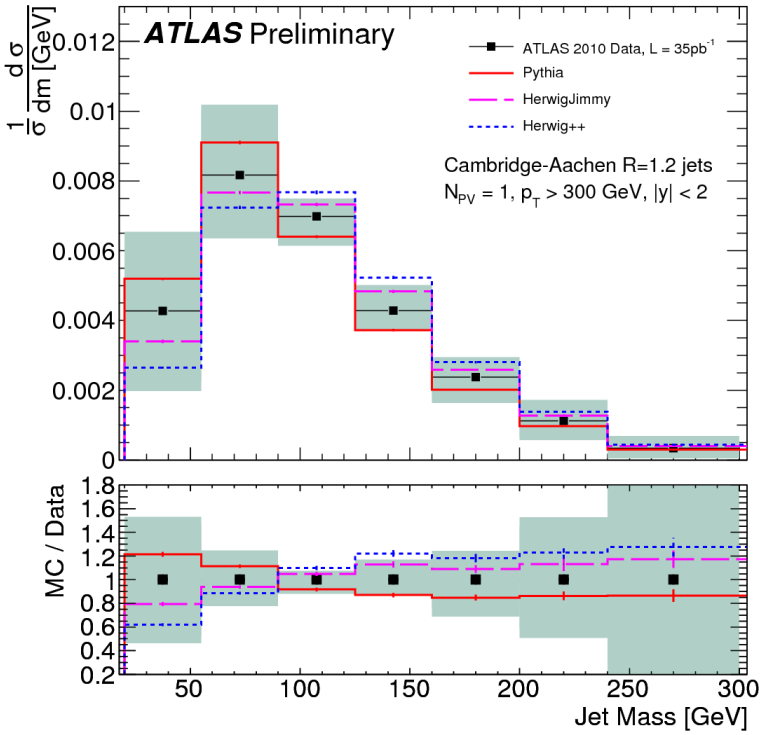
- Boosted heavy object may be reconstructed as a jet with large radius parameter (e.g. R = 1.2)
- Need to remove objects not from the decay
  - From QCD radiation not associated to the decay
  - Multi-parton interaction and pileup
- Procedure

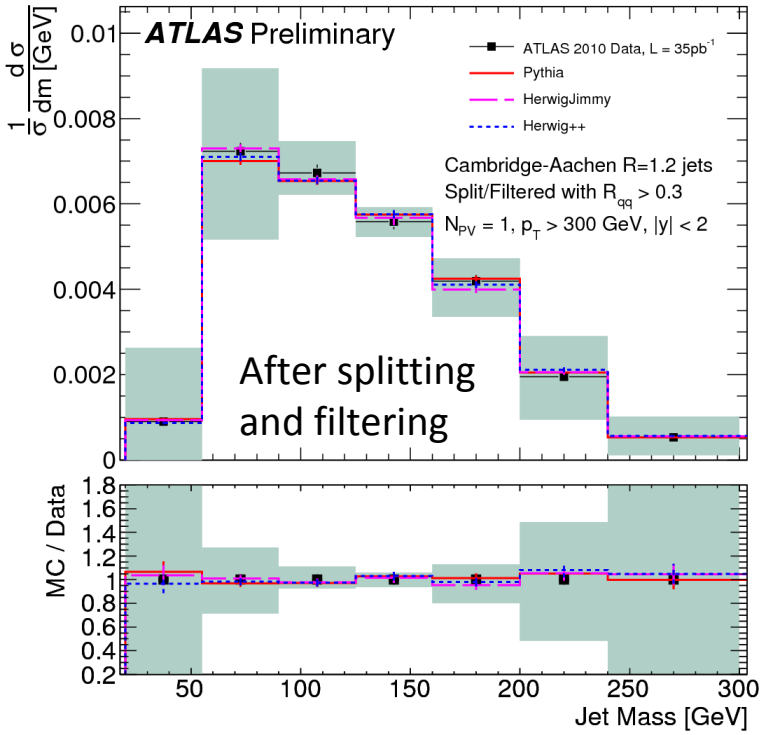
1. Splitting into two objects where mass after recombination becomes very large
2. Reclustering each of the small objects with small radius (e.g. R = 0.3)
3. Remove jets away from high-momentum partons (filtering)



Jet mass distribution before and after the treatment

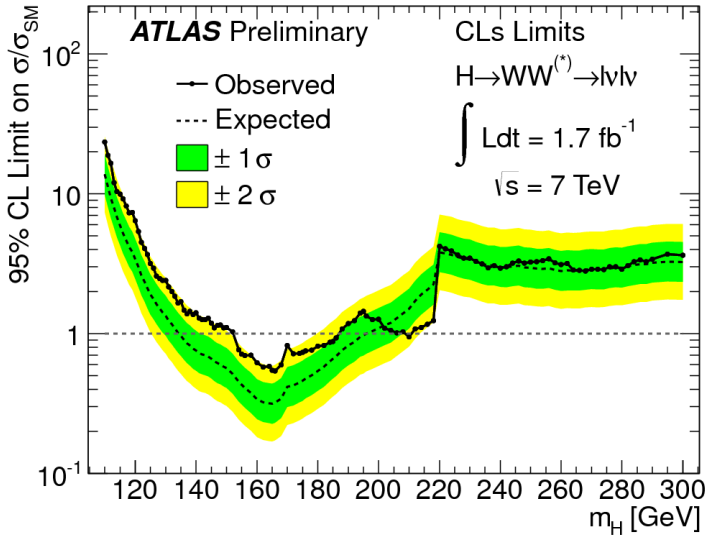
- Model dependence of mass distribution disappeared
- All models show good agreement to data
- Also much smaller dependence to pileup (not shown)

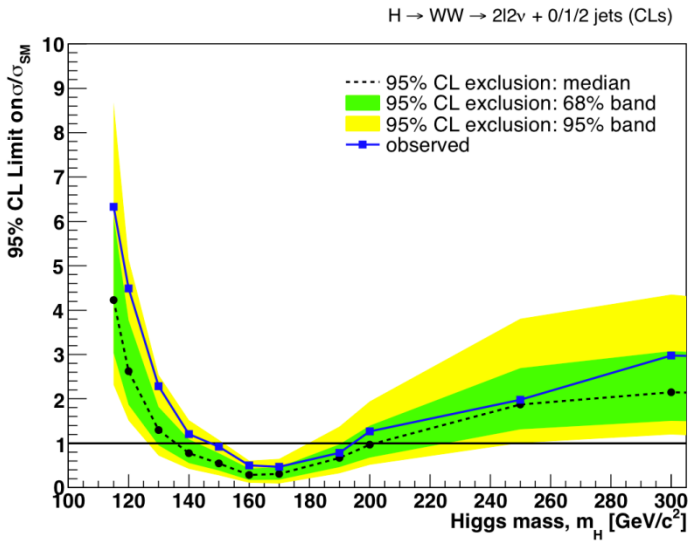




The $H \rightarrow WW \rightarrow l\nu l\nu$ channel

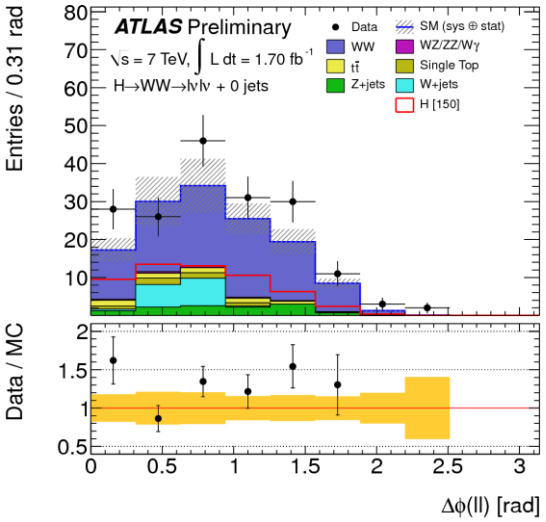
- Has lead excitement in July
  - Still cross section tend to be high
- No mass peak, counting experiment
- Events selection mainly by
  - 2 opposite sign lepton
  - Large missing Et
  - #of jets and b-tag to control bckgnd (mainly top)
  - Low m_{ll} and small $\Delta\phi(ll)$ assuming Higgs is scalar

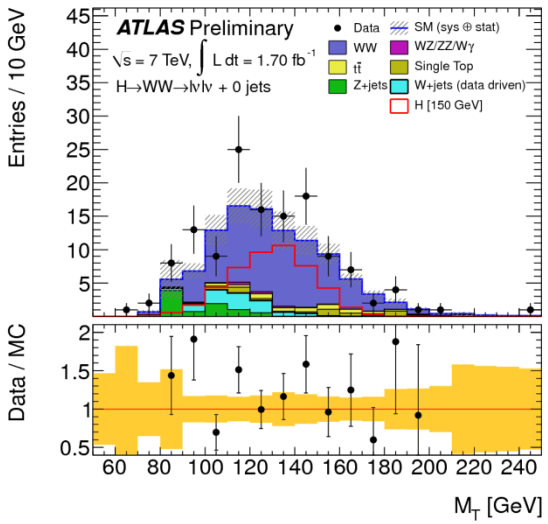


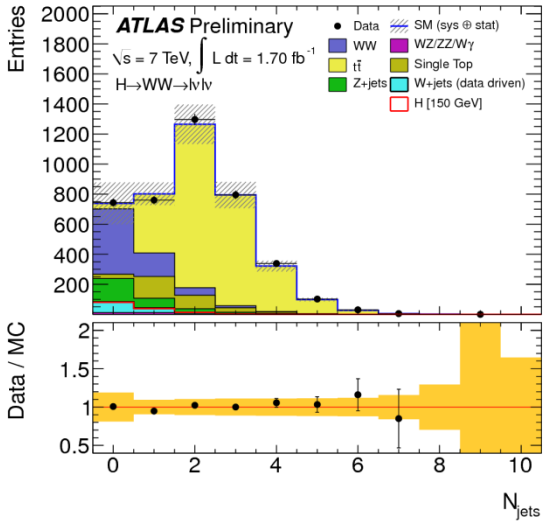


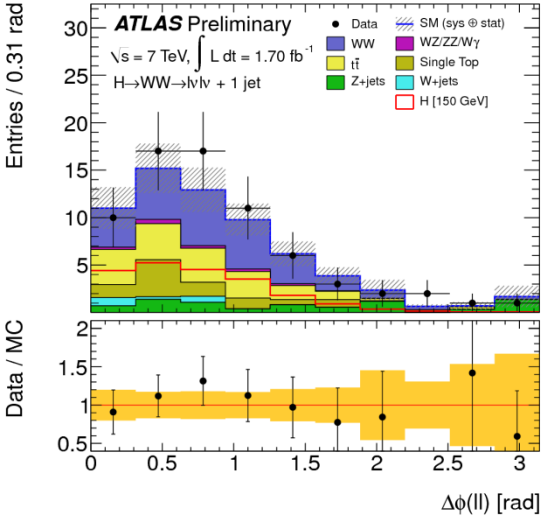
of jets, m_T and $\Delta\phi(ll)$

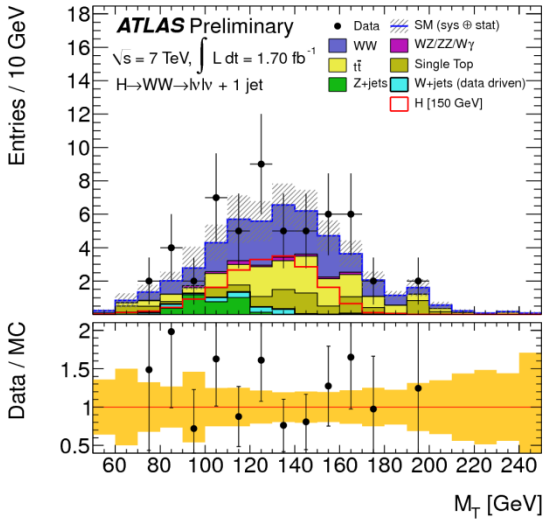
- Background from
  - 0-jet: WW
  - 1-jet: top, WW
- Insignificant excess in 0-jet sample





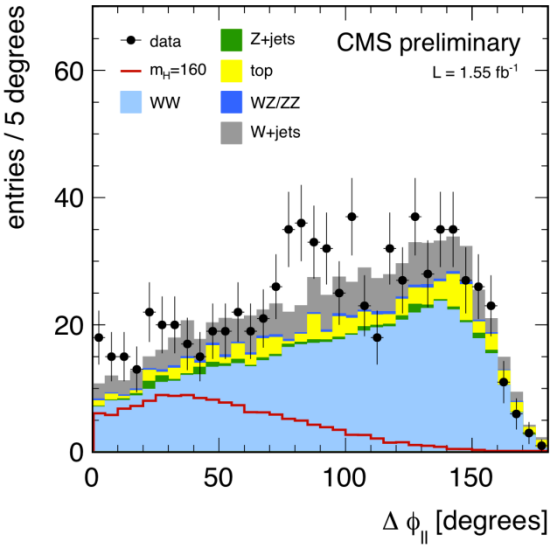


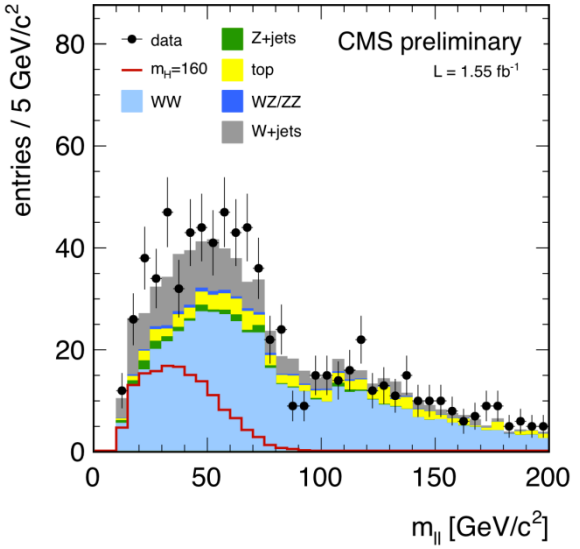


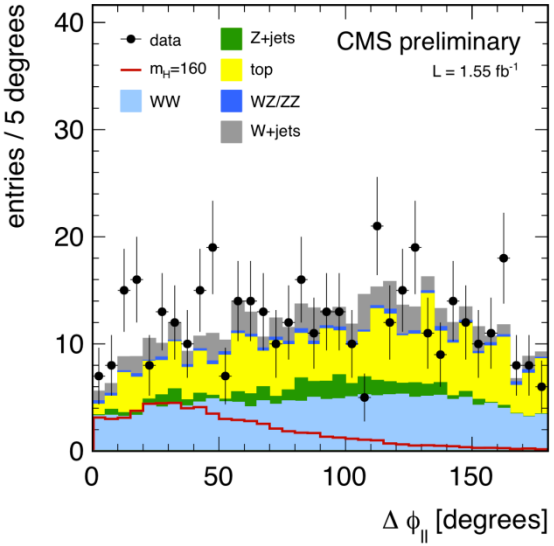


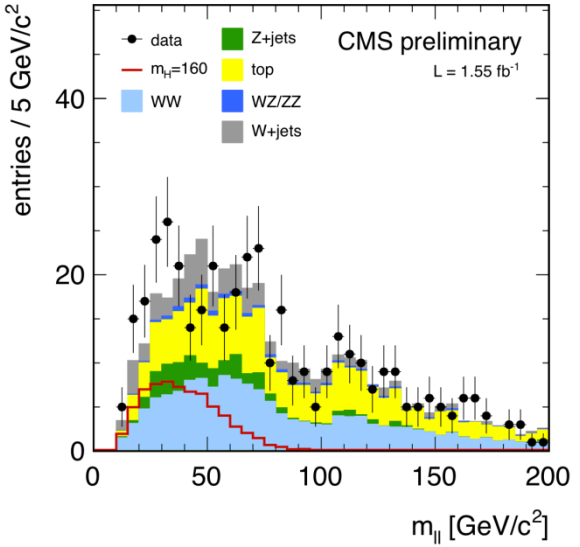
of jets, m_{ll} and $\Delta\phi(ll)$: CMS

- Similar degree of insignificant excess observed



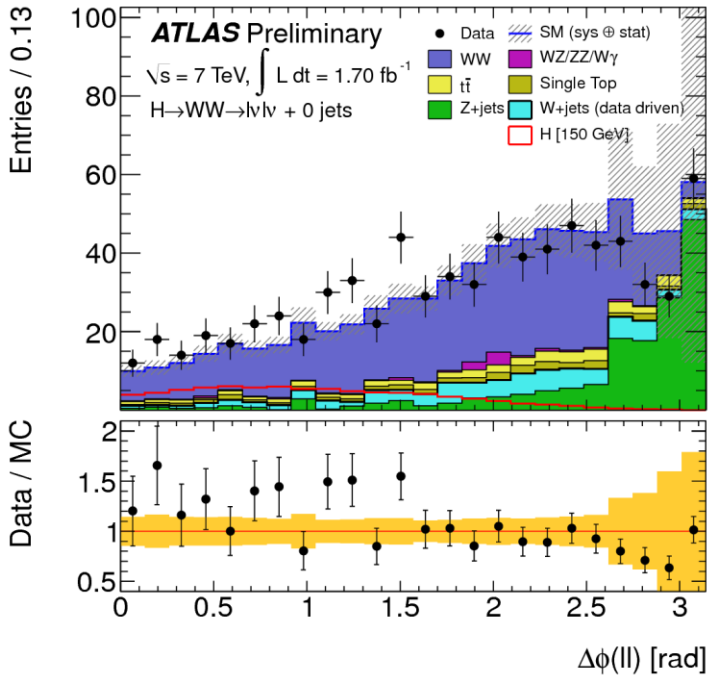






Background uncertainty

- Background estimated by control samples
- low mass region $m_H < 170$ GeV uses:
  - WW: $\Delta\phi(ll) < 1.3$ and $0.75m_H < m_T < m_H$ cuts removed
  - Z/γ^* + jets: Etmiss distribution from data used to estimate large fake Etmiss events
  - top: normalised by b-tag efficiency from data
  - W+jets: jet → lepton misID from data

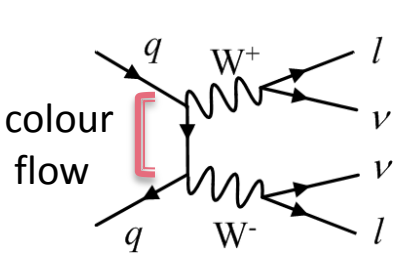


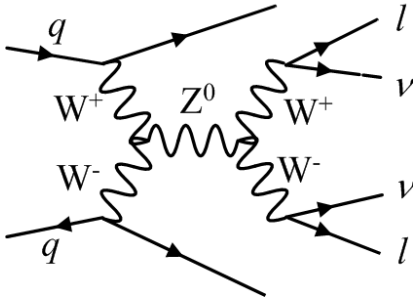
- MC samples used in ATLAS
  - WW: MC@NLO (syst: ALPGEN)
  - $t\bar{t}$: MC@NLO (syst: POWHEG)
- In CMS:
  - WW: MADGRAPH
  - $t\bar{t}$: MADGRAPH

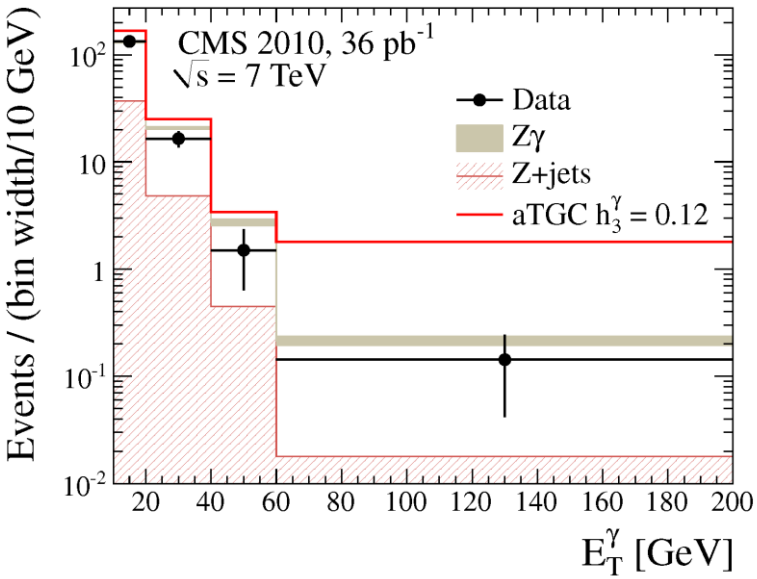
Diboson production

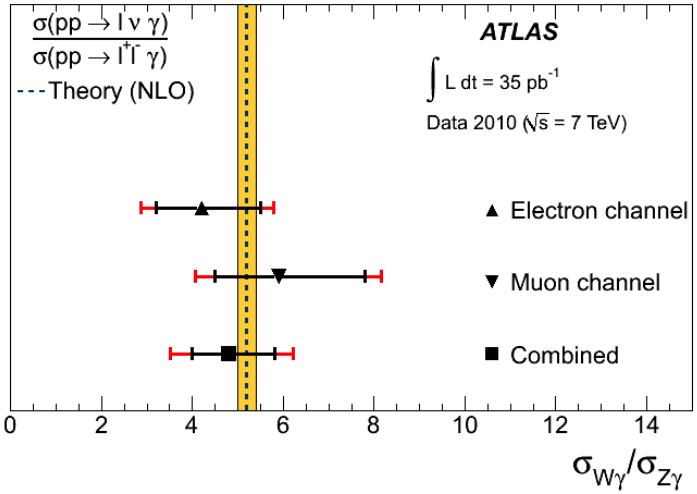
Diboson production at the LHC

- Motivation:
  - Sensitivity to (anomalous) triple gauge boson coupling (TGC) shown up as cross section enhancement at high E_T
  - Background to other searches
- Example from $W\gamma, Z\gamma$



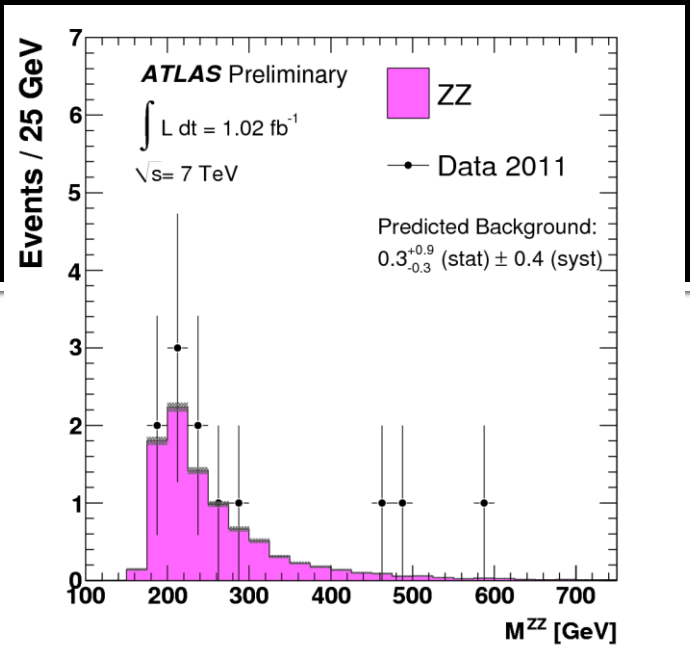


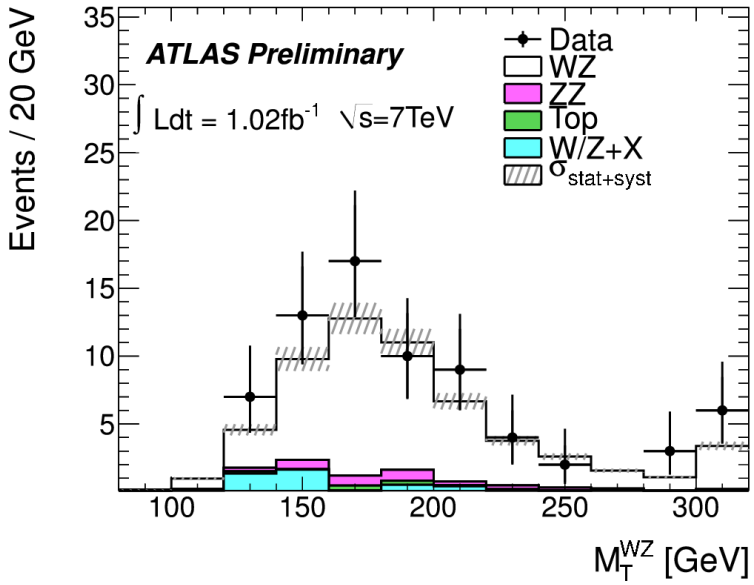


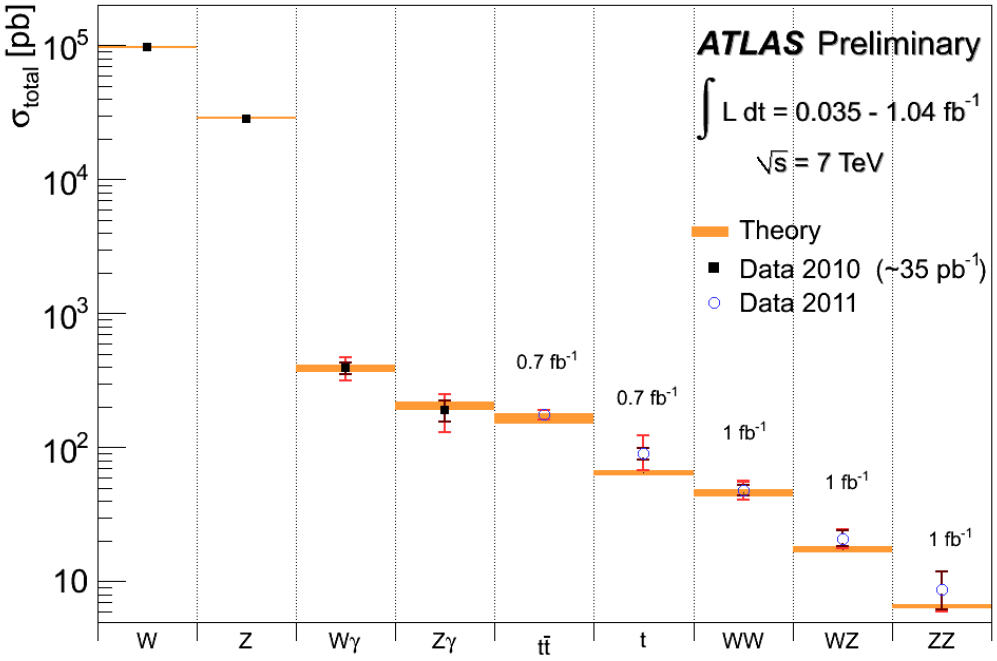


WW, WZ, ZZ cross sections

- Clear signal with 1fb^{-1} of data
  - Very small background
- Consistent with prediction

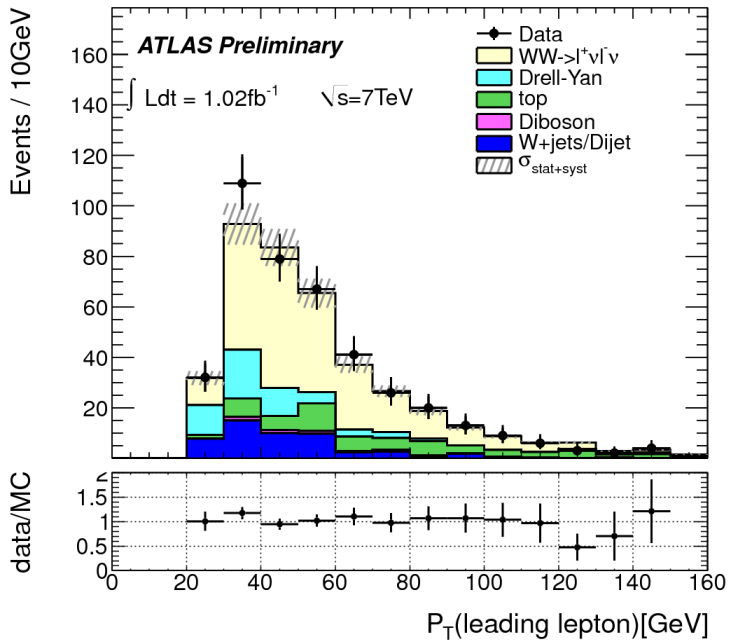


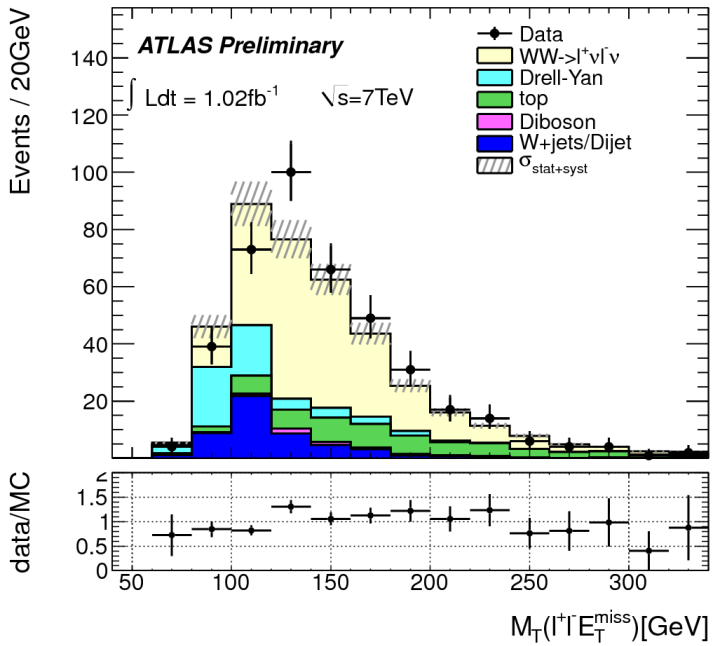




WW distribution in detail

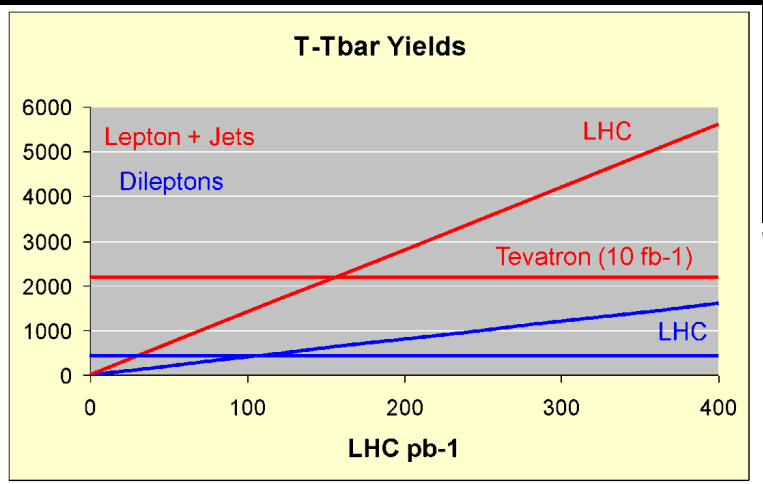
- Plots with jet-veto (no jet with $E_T > 30$ GeV, $|\eta| < 4.5$)
- Overall agreement OK, some shift in some distribution
  - More events in small $\Delta\phi(ll)$ as in the Higgs search (not shown)
  - $p_T(lepton)$ OK; transverse mass of 2leptons + Etmiss some shift



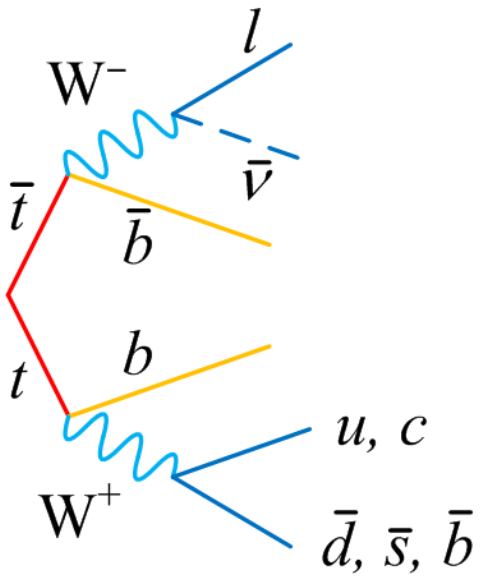


Top quark physics

LHC: top factory



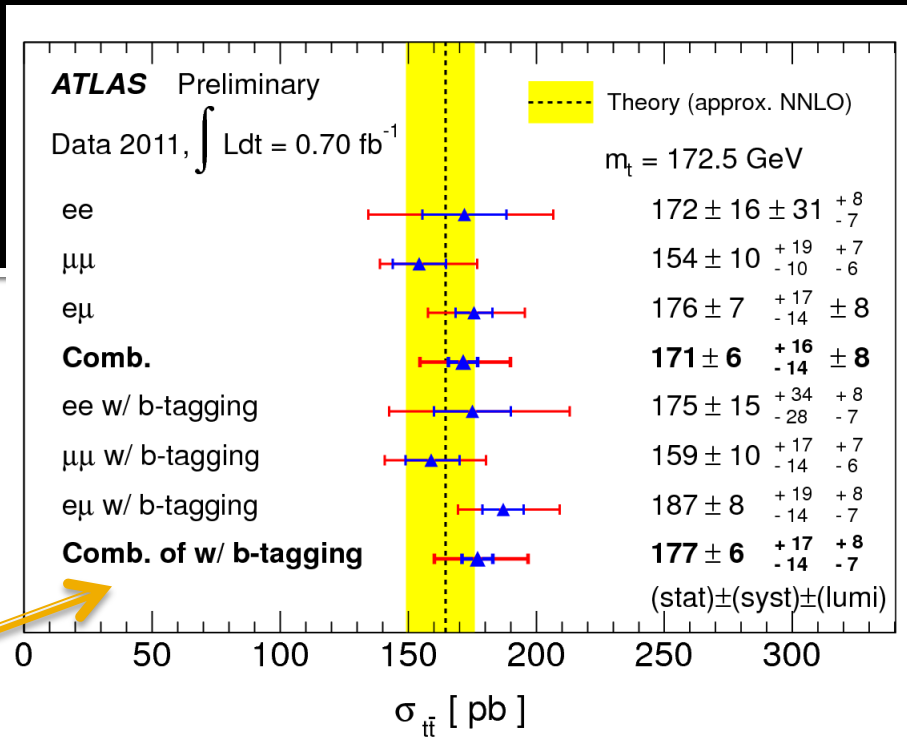
- Already $O(10^4)$ events with 1fb^{-1}
  - More statistics than in Tevatron
  - Sensitivity to new physics
- Single top cross section is also much larger
- Mass of top quarks: still better measured at Tevatron (hence not shown today)
- How to find
  - $t \to Wb$ ~100%
    b-quark tagging for most of analysis
  - $W \to e$ or μ (leptonic) or
    $W \to q\bar{q}$ (hadronic)

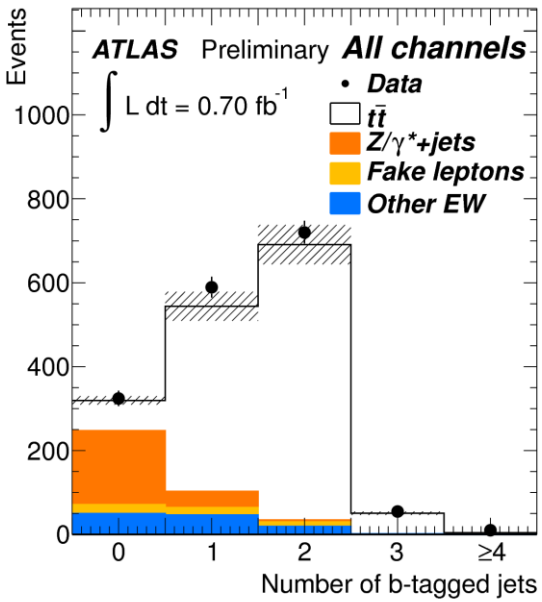


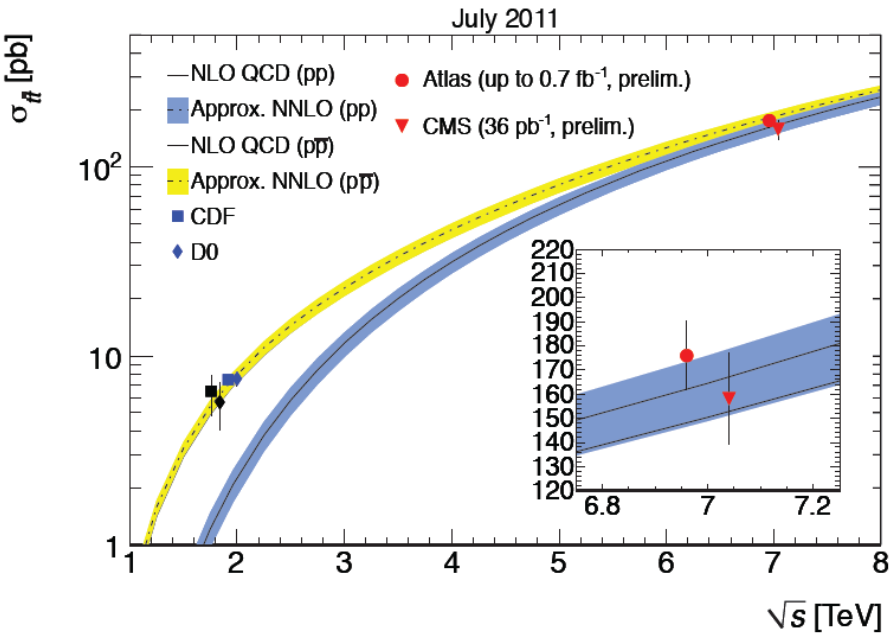
Top quark cross sections

- Good agreement with NNLO
  - More precision: stringent test of pQCD in top sector

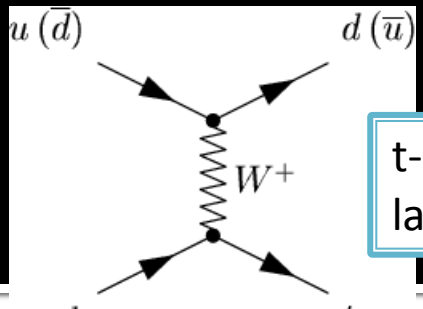
NEW: L+jets w/o b-tagging ($\int Ldt = 0.7 fb^{-1}$ 2011):
$\sigma = 179 \pm 3.9 \pm 9.0 \pm 6.6$ pb





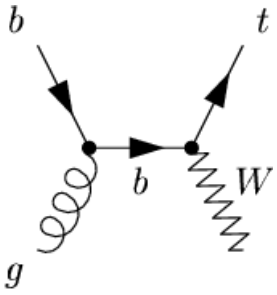


Single top production

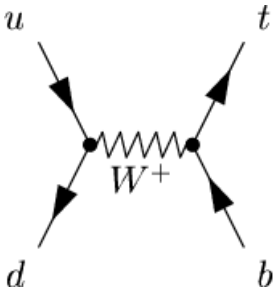


t-channel:
large σ 64pb

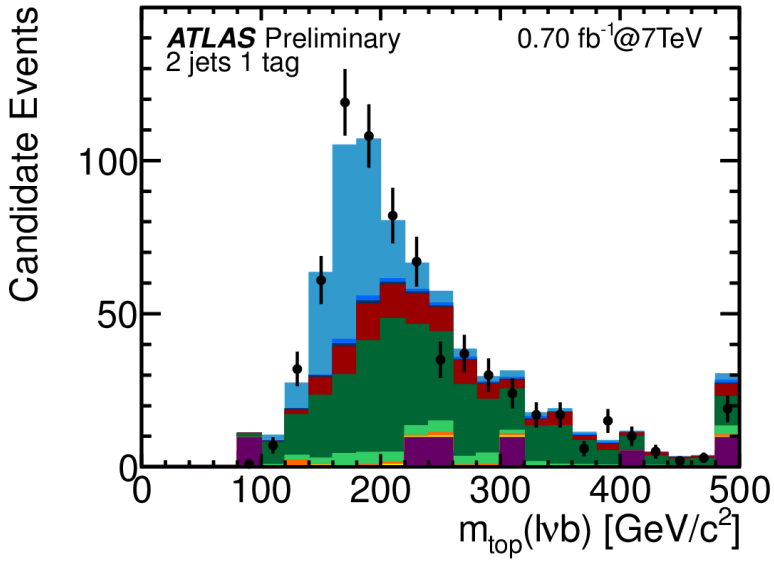
- Sensitive to $|V_{tb}|$ and new physics
- Cross section @ LHC almost two order of magnitude larger than at the Tevatron
  - Clear signal by cut-based analysis

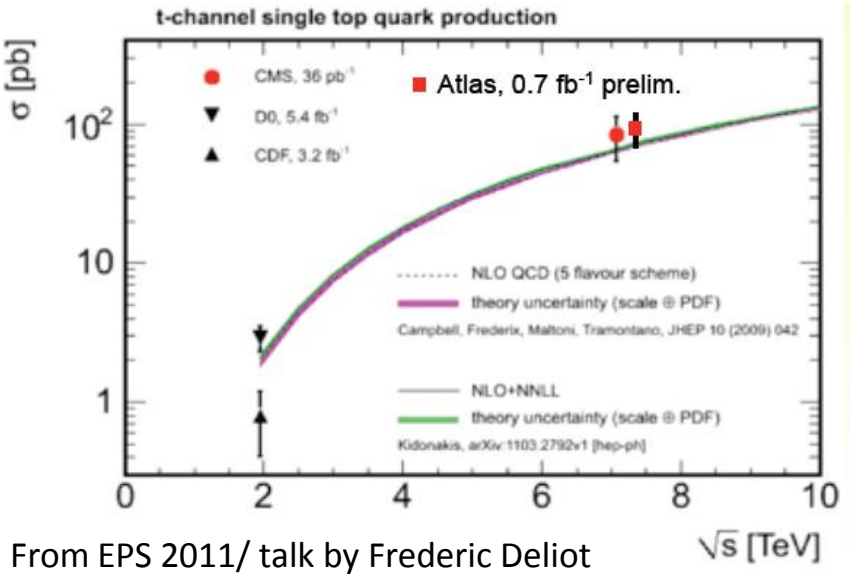


tW production
moderate σ 17pb



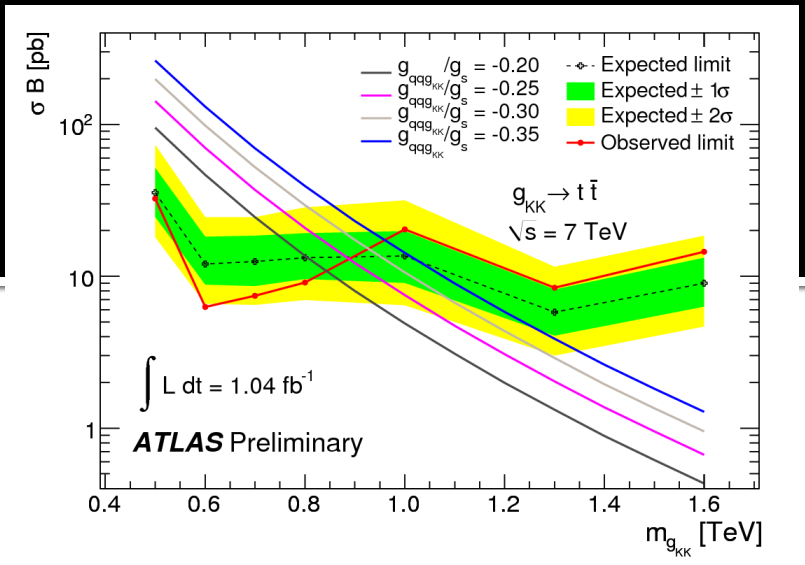
s-channel:
large σ 4.6pb



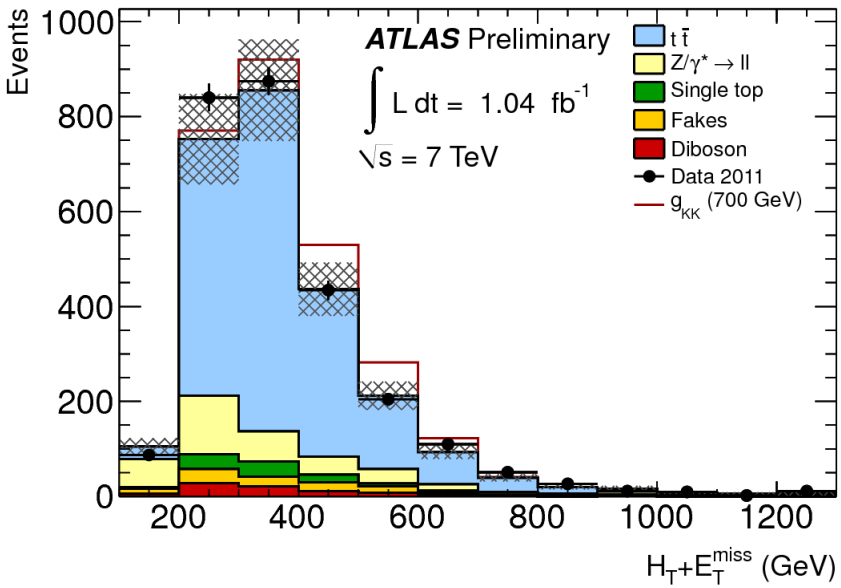


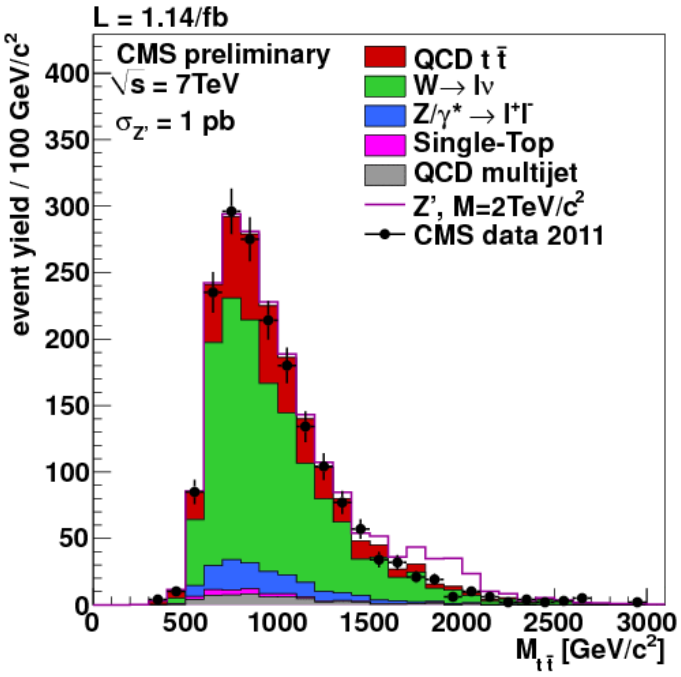
From EPS 2011/ talk by Frederic Deliot

High-pt top pairs: resonance search



- Many models have enhanced coupling to top quark
  - e.g. KK excitation of graviton/gluon
- Using dilepton channel for high purity (ATLAS) muon + jet from boosted top (CMS)

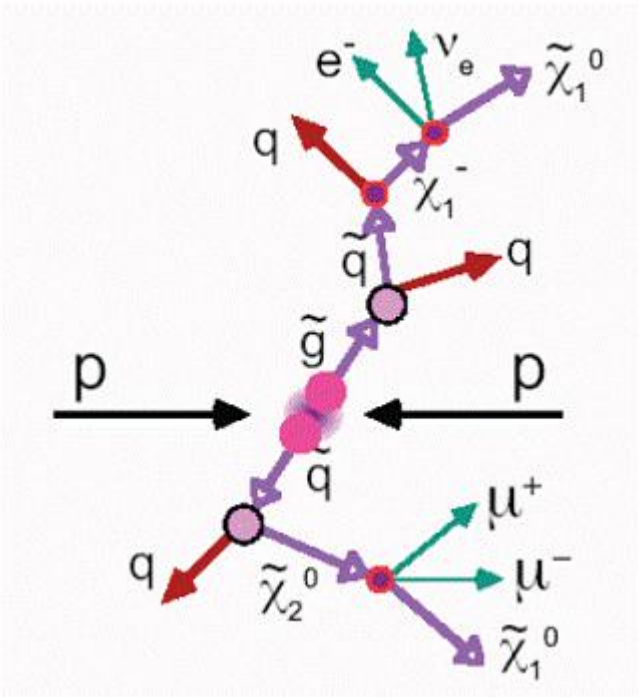




Search for SUSY and other BSM models

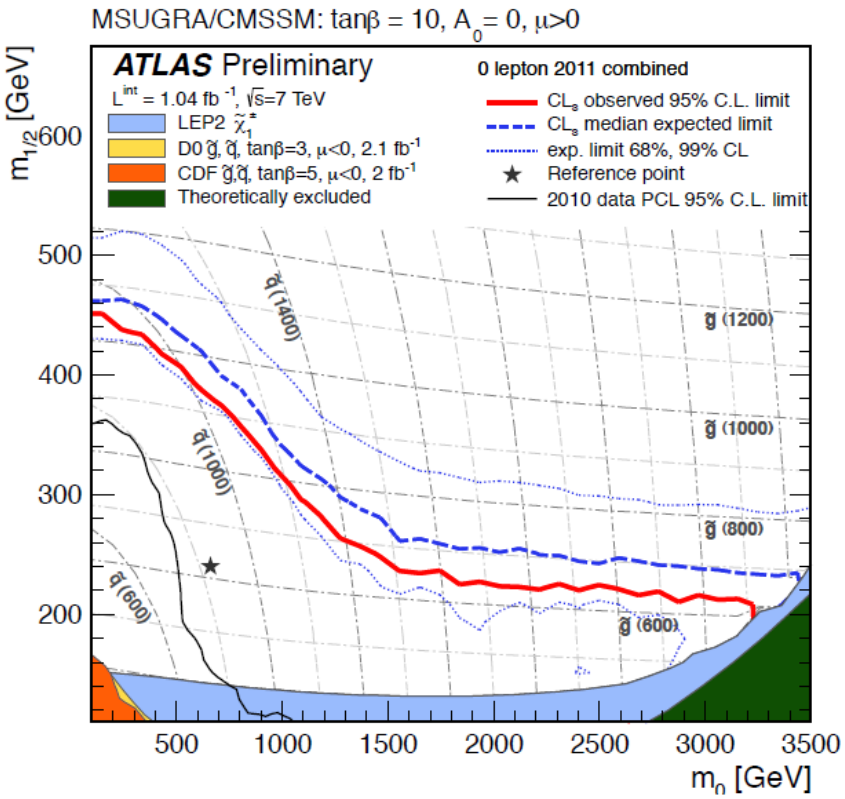
SUSY search strategy

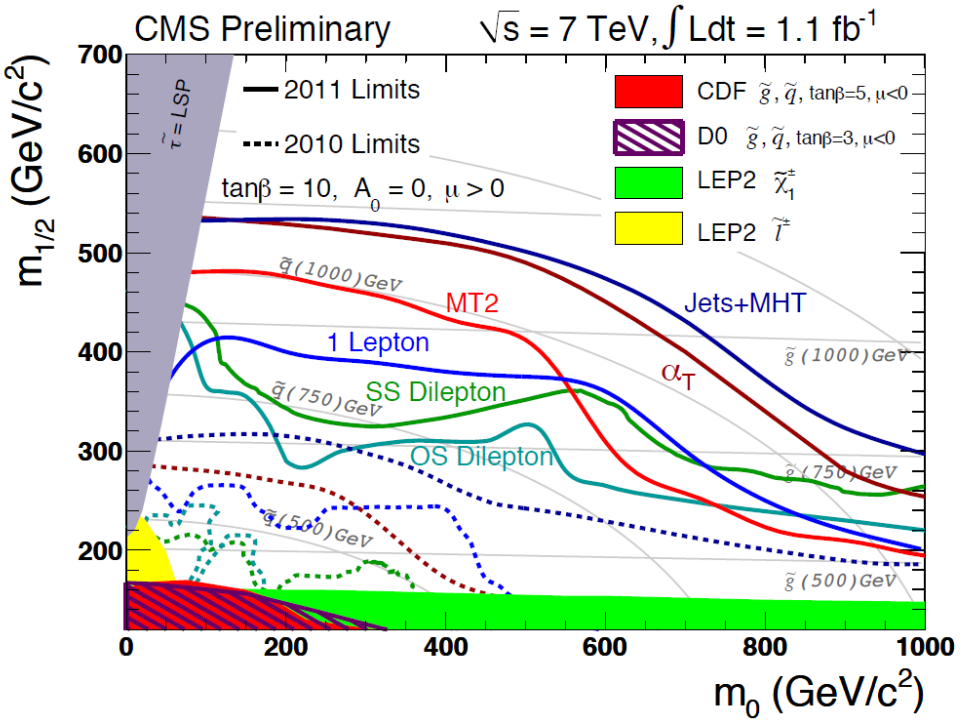
- Detailed mass spectrum depends on models
- Common strategy:
  - Coloured $\tilde{q}, \tilde{g}$ produced
  - Cascade decay:
    e.g. $\tilde{g} \rightarrow qq'\tilde{\chi}^{\pm} \rightarrow qq'l\nu\tilde{\chi}^{0}$
  - Many models give leptons
  - Most models give many jets
- Neutralino is LSP: R-parity conserved
  - Missing E_T



Events with Multi-Jet(≥ 4) + MissingEt (+ lepton(s))

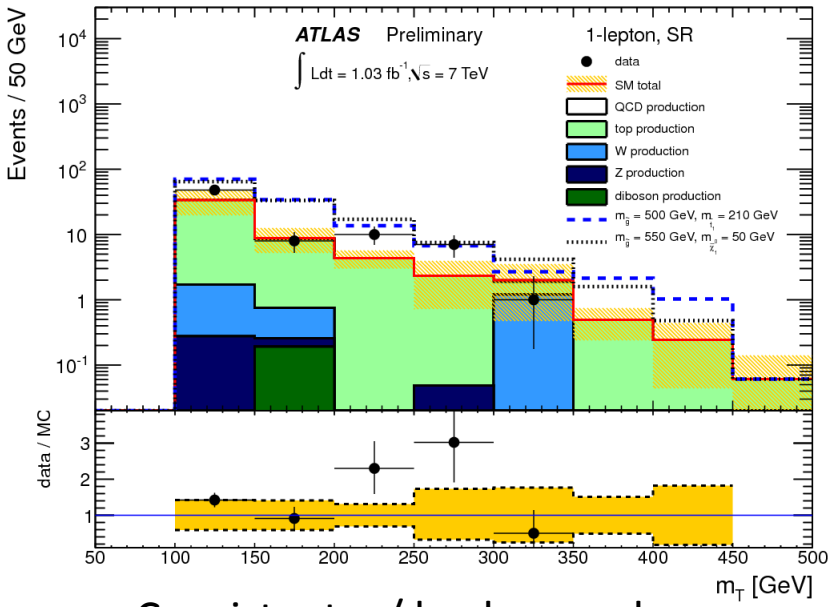
Result 0/1-lepton: ATLAS and CMS



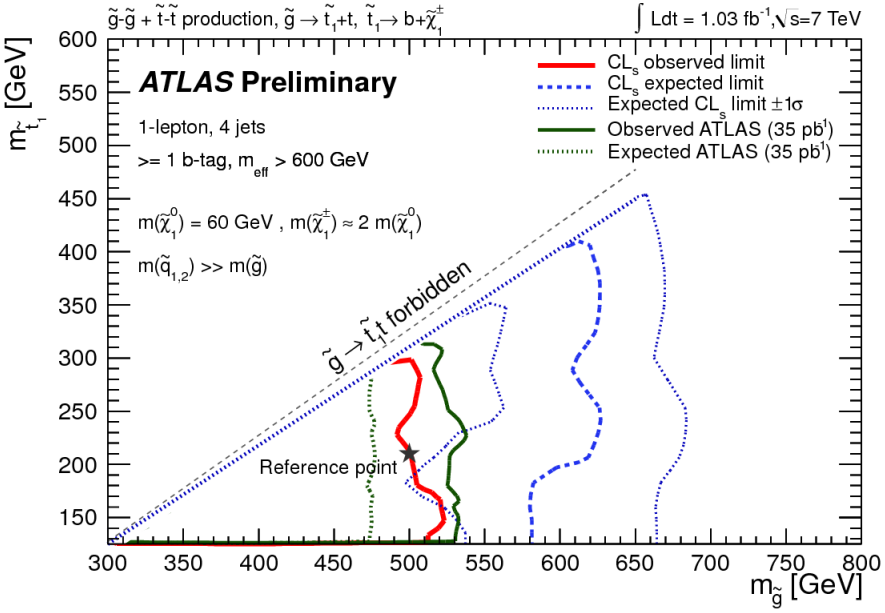


- No excess – giving limits
- Already exhausting sensitivity with 7 TeV beam for simple scenario

More exclusively: 1-lepton+btag



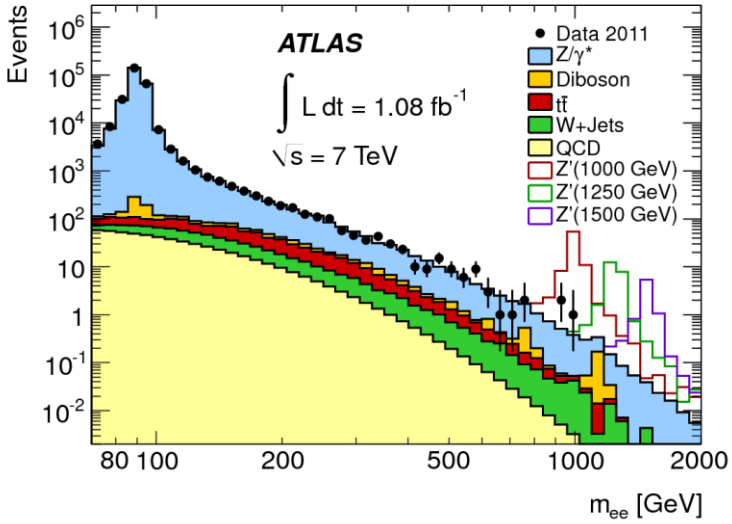
Consistent w/ background, with (unfortunate) excess

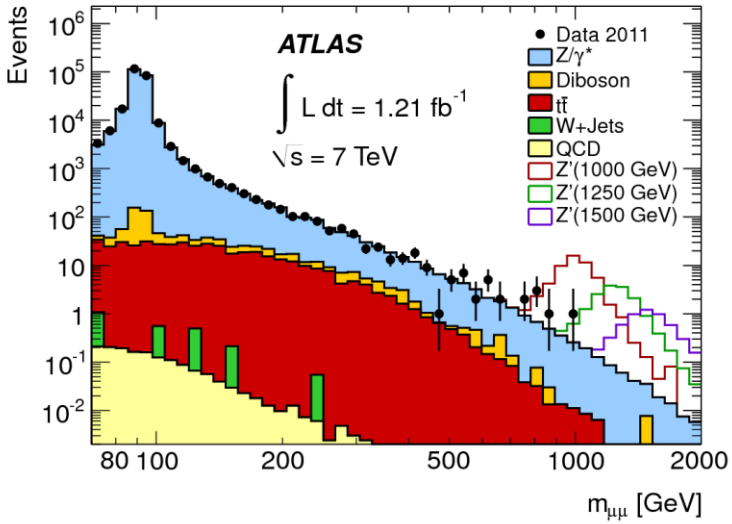


Limit from 35pb^{-1} to 1fb^{-1}

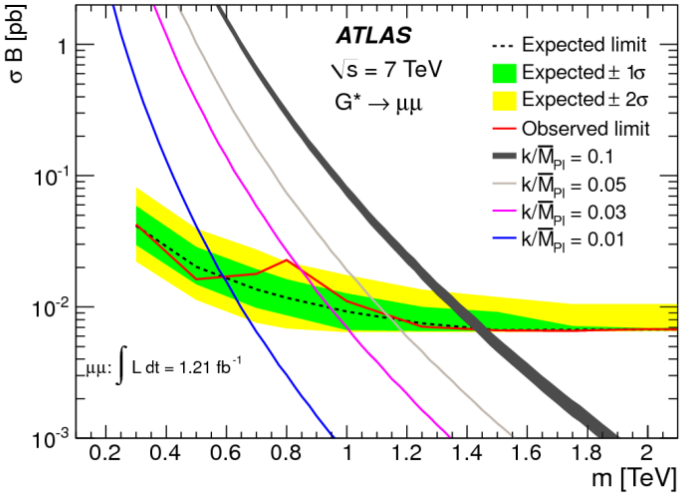
- Other exclusive search for investigating scenarios such as
  - LSP not escaping detector (either long-lived NLSP or R-parity violation)
  - Many leptons

Generic resonance search (1) dilepton



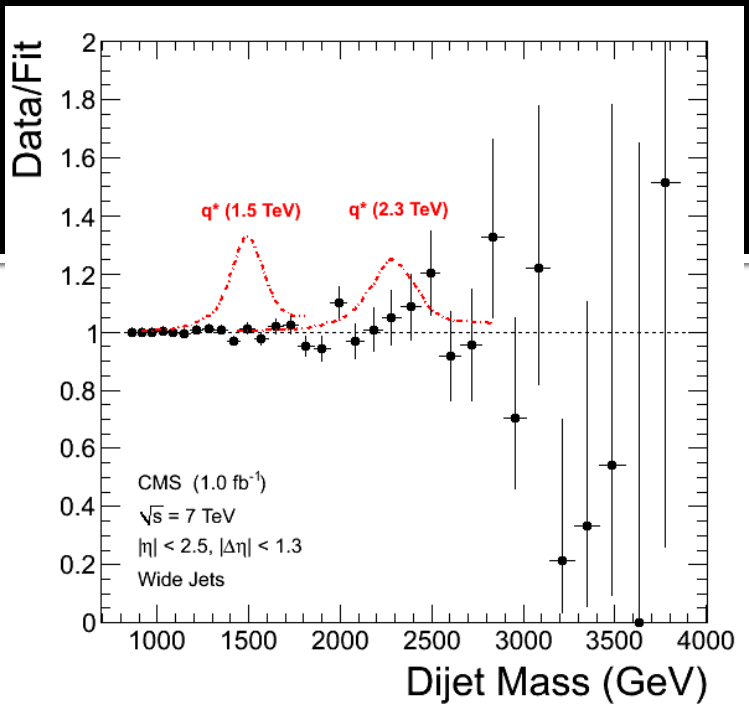


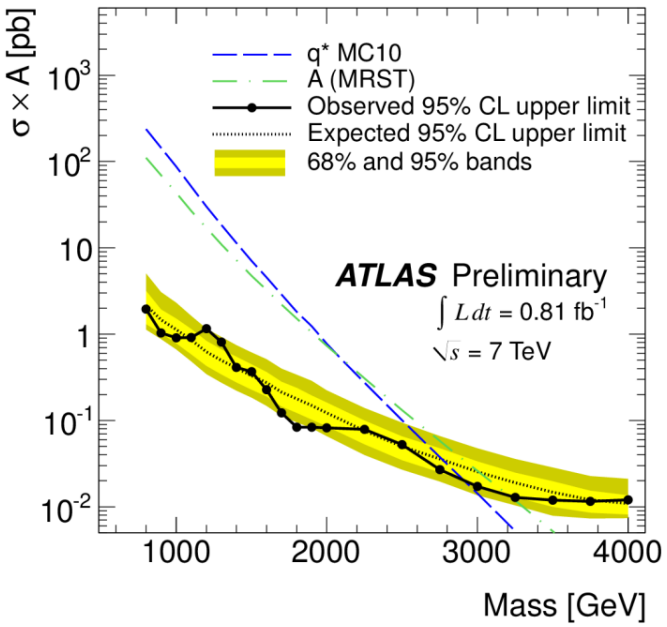
- Z', G_{KK} etc.
- Limit up to 1-1.5 TeV

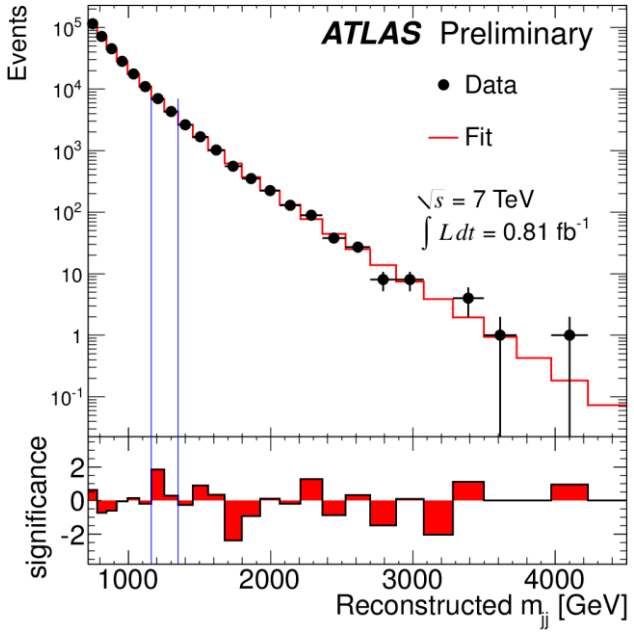


Dijet resonance

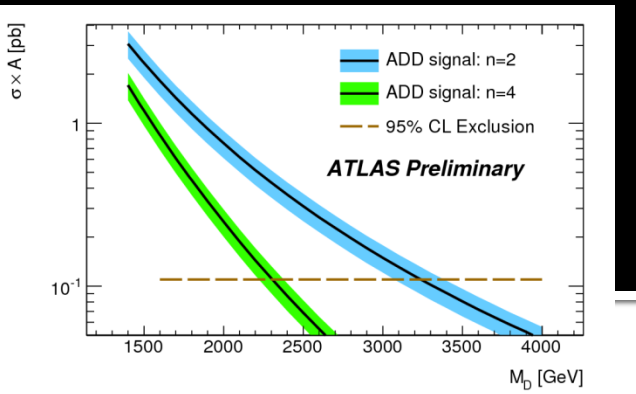
- Various models:
  excited quarks (q*), heavy W/Z,
  RS graviton, axigluon, E6 diquark…
- Limit: 1.5-4 GeV



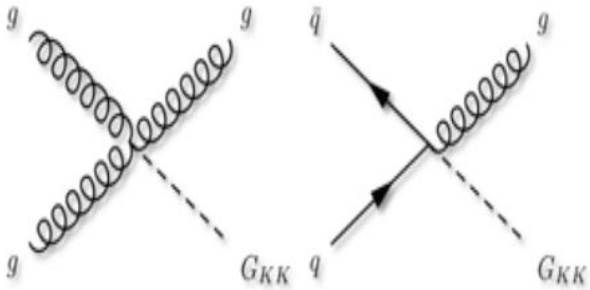


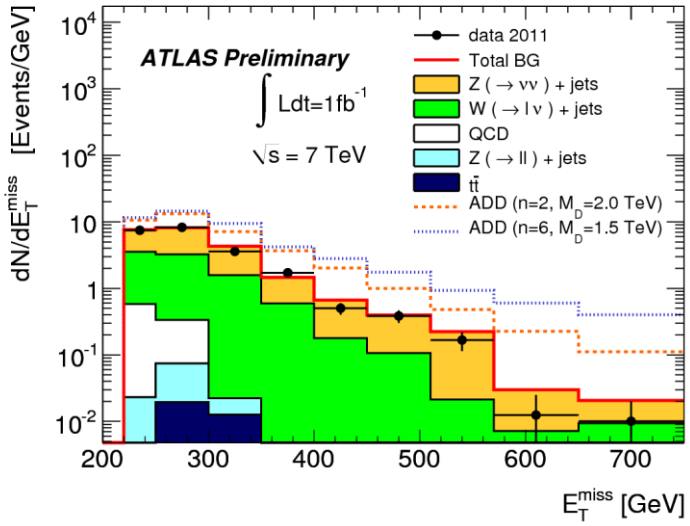


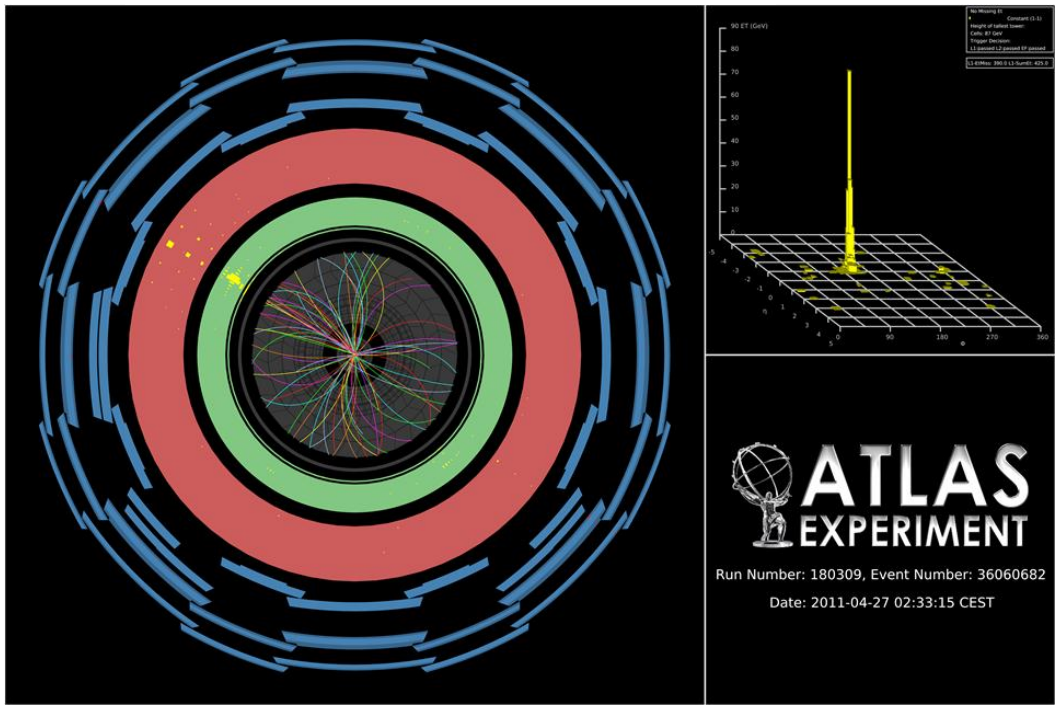
Monojet + missing E_T



- Graviton goes away from brane to bulk (into extra-dimension)
- M_D > 3.39 TeV (n = 2) ADD model
  - M_D: planck scale in 4+n dimension

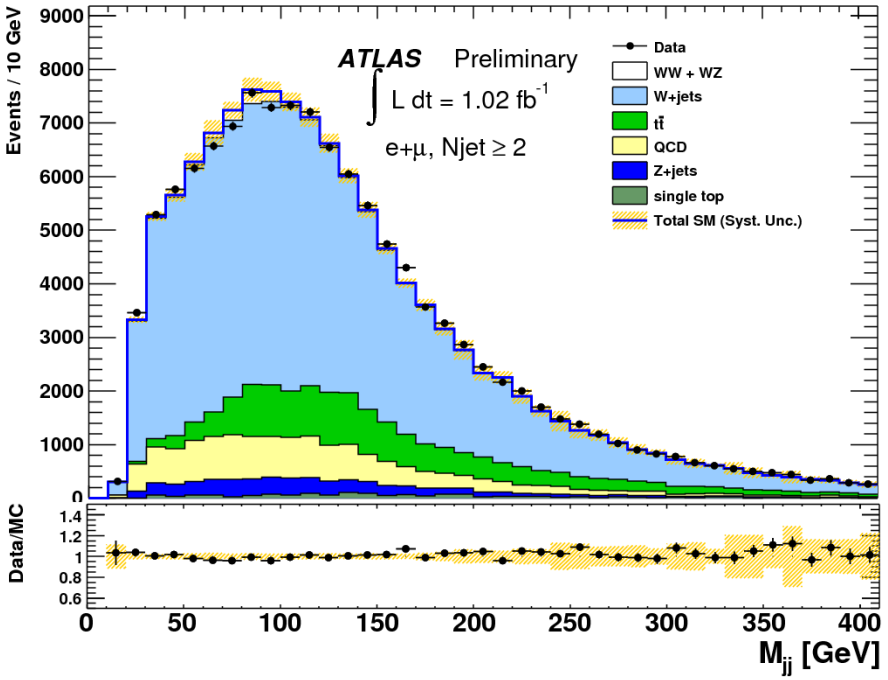


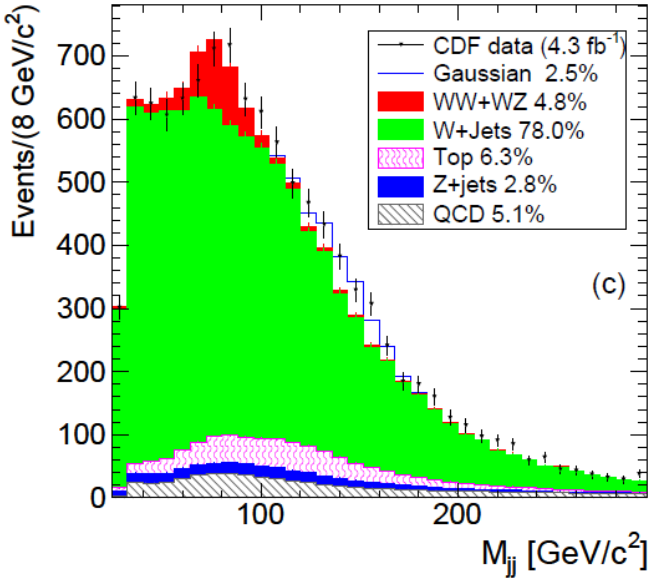


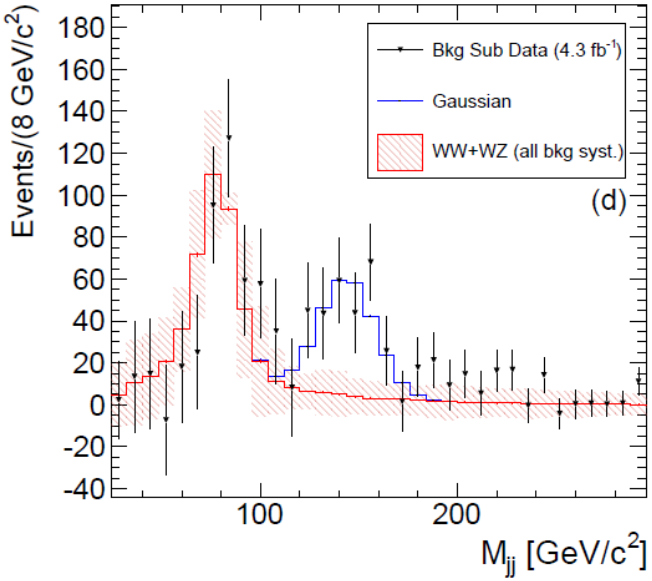


W + dijet excess @ CDF

- Not observed in LHC
- Large W+jets background with this cut

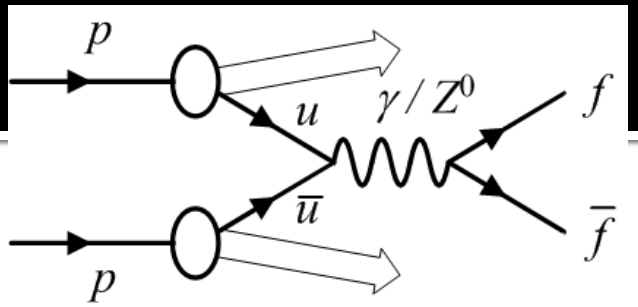




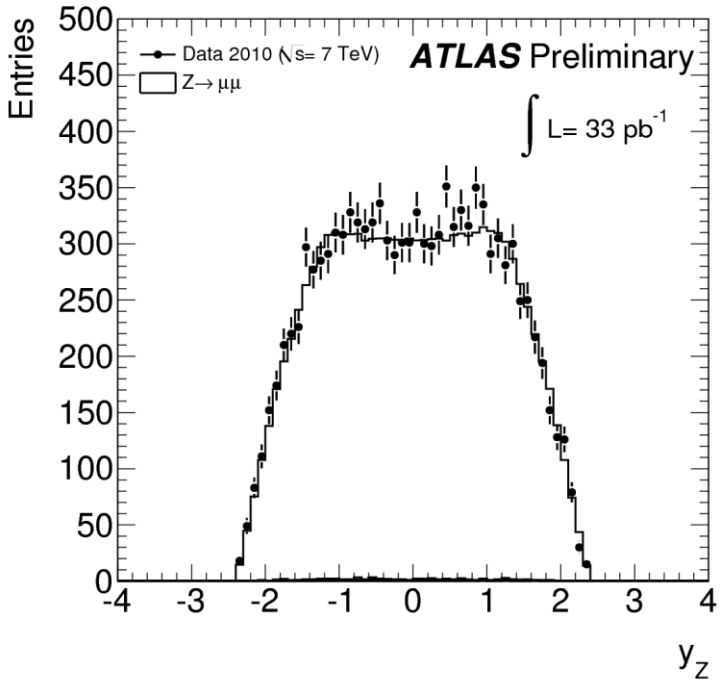


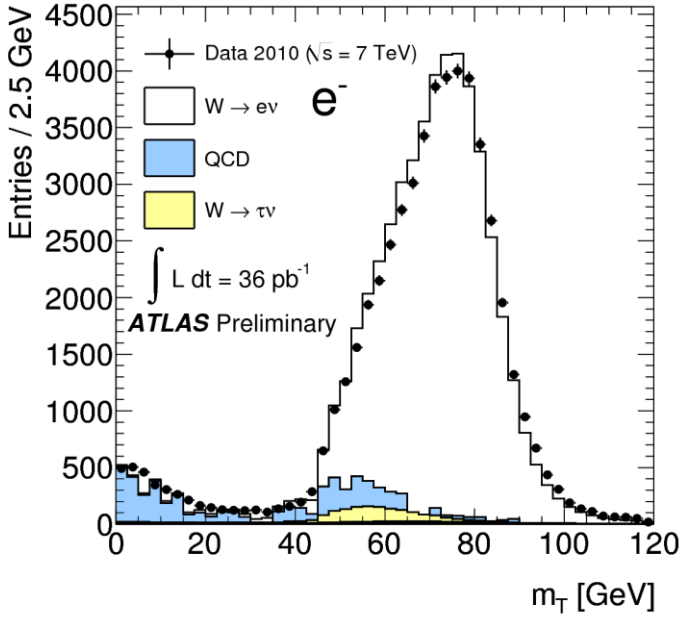
W, Z production and QCD

Drell-Yan process



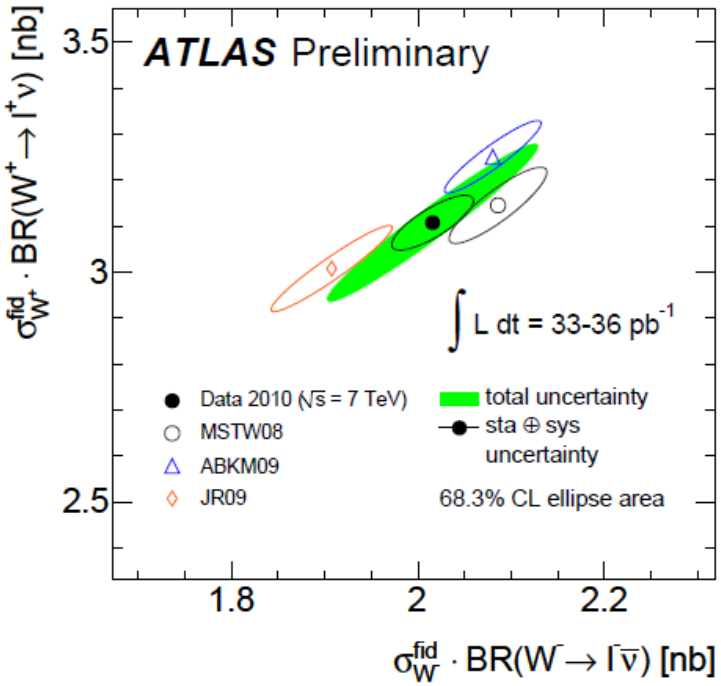
- Electroweak process
  - Precise prediction
  - Standard candle for detector understandings

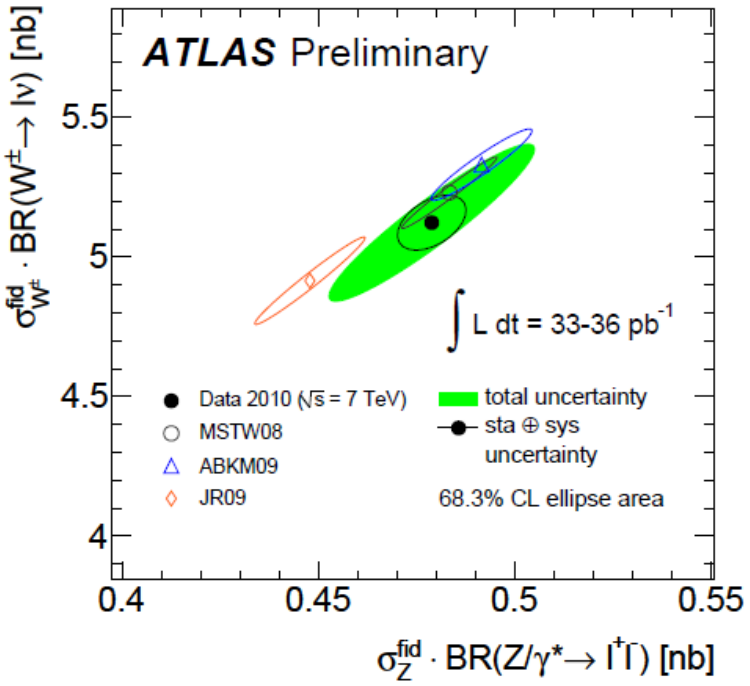




m_T: invariant mass with only component of momentum

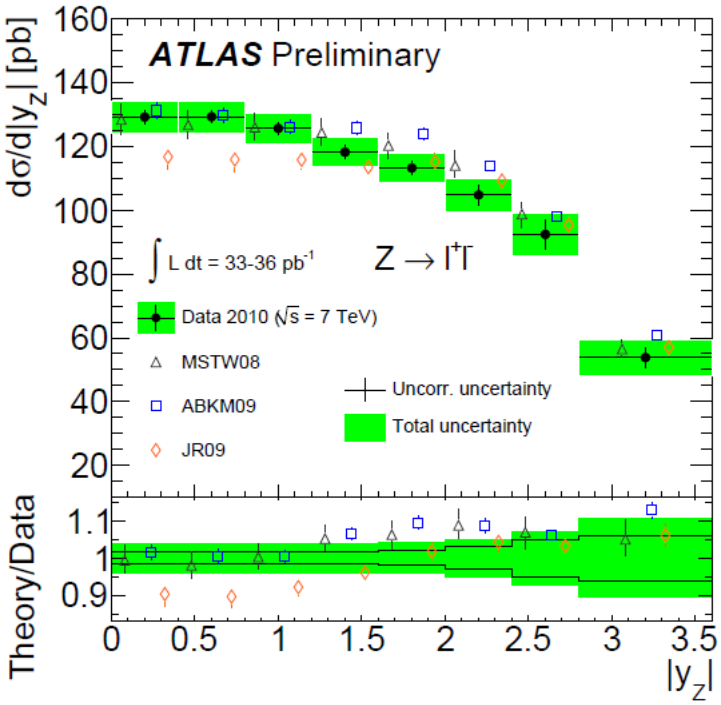
W/Z "visible" cross section



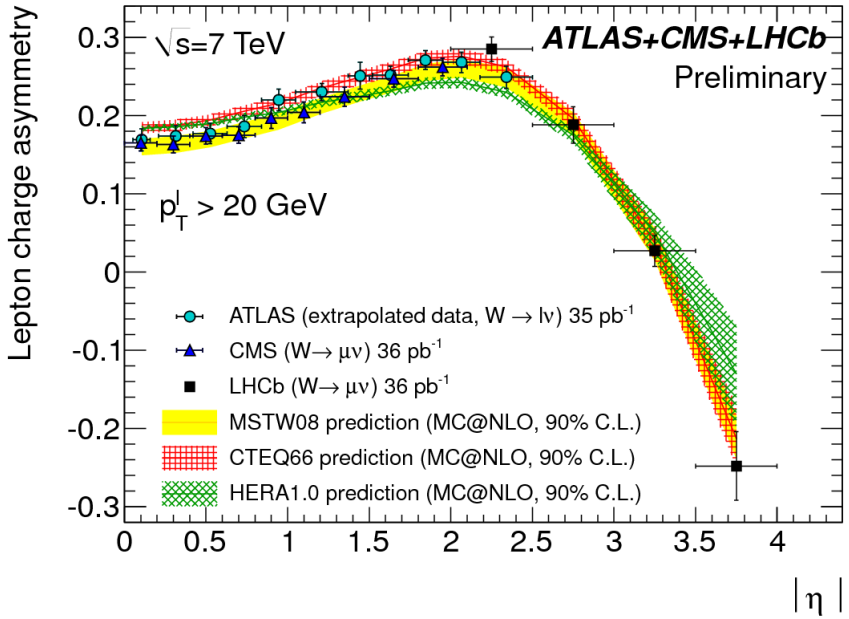


- No extrapolation to total cross section – smaller uncertainty
- Comparison to calculations with various pdfs
  - LHC data will be sensitive to PDFs with improved precision

Z and W: rapidity dependence

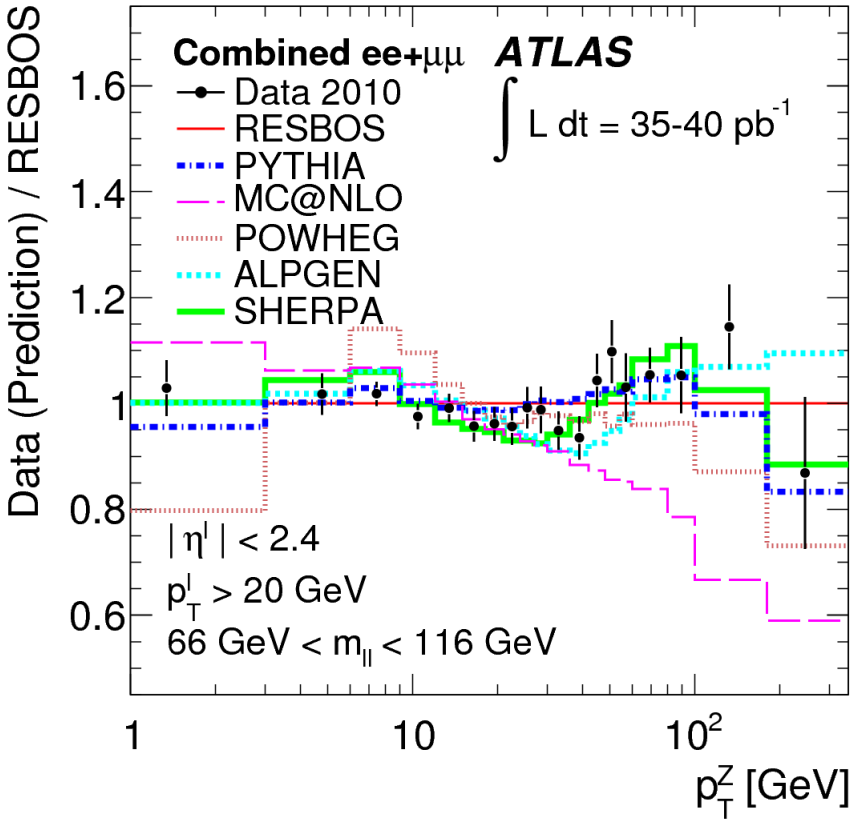


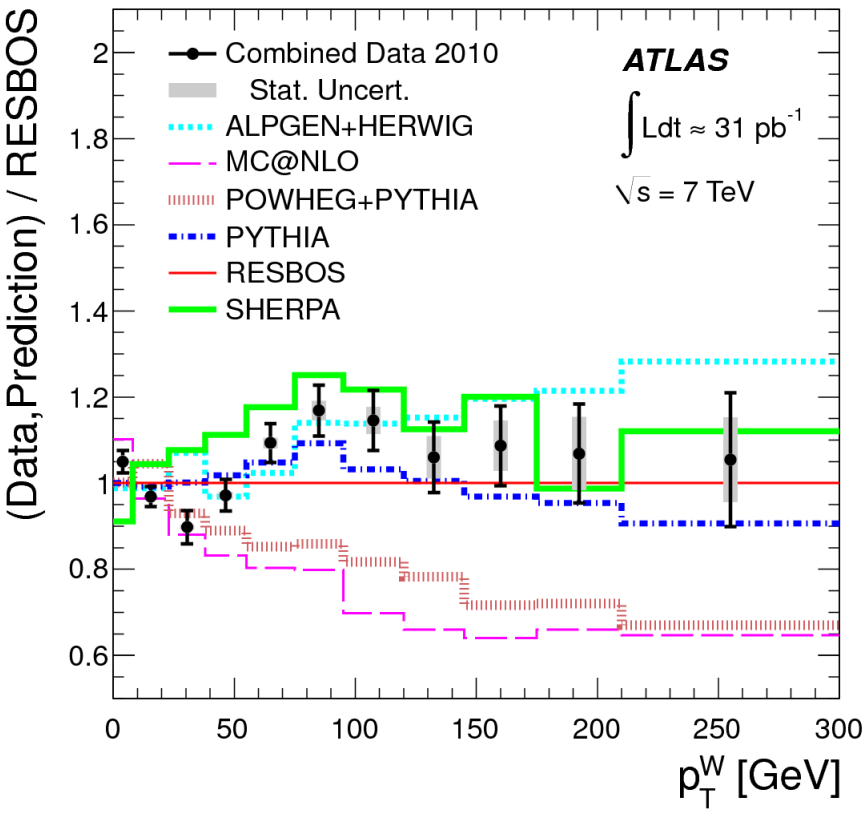
- Rapidity dependence of Z^0 cross sections
- Sensitivity to pdf



- W charge asymmetry vs rapidity for ATLAS/CMS/LHCb data
  - Wide range of coverage
- Strong discrimination power for pdfs

p_T of Z^0: higher order in QCD

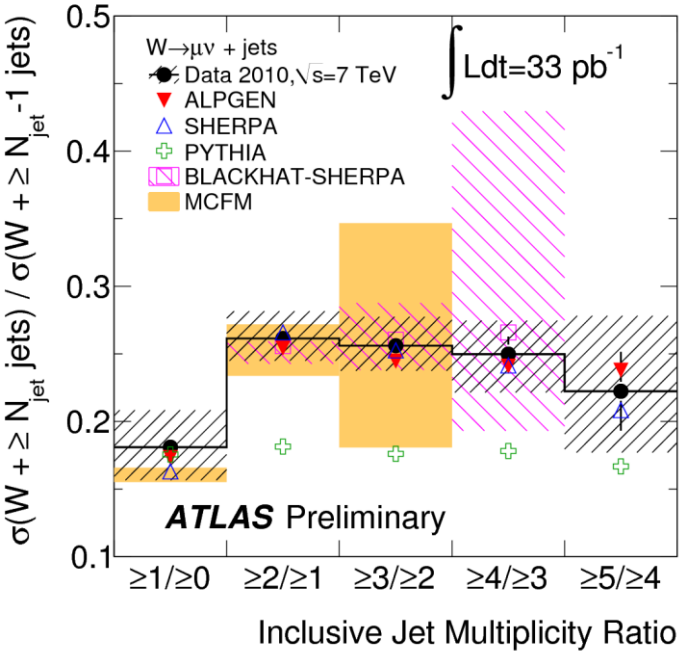


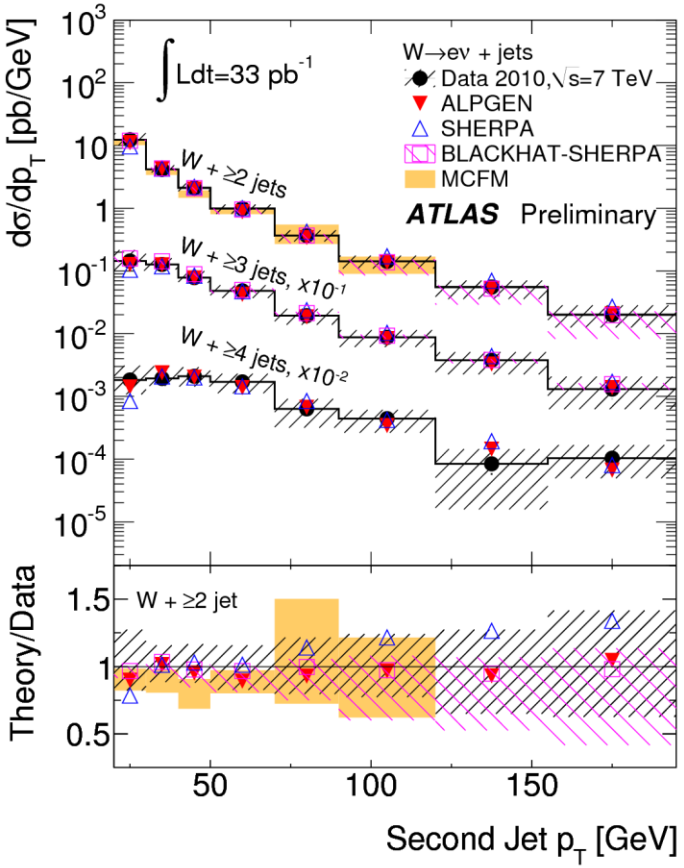


- Sherpa, ALPGEN, Pythia: good
- $O(\alpha_S)$ cannot explain: need $O(\alpha_S^2)$

- Fixed order+parton shower models show large deviation

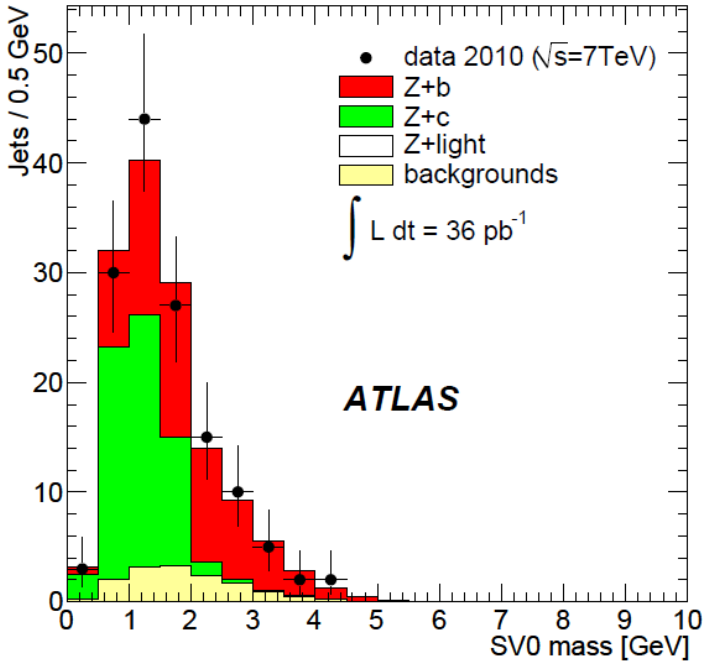
W + jets



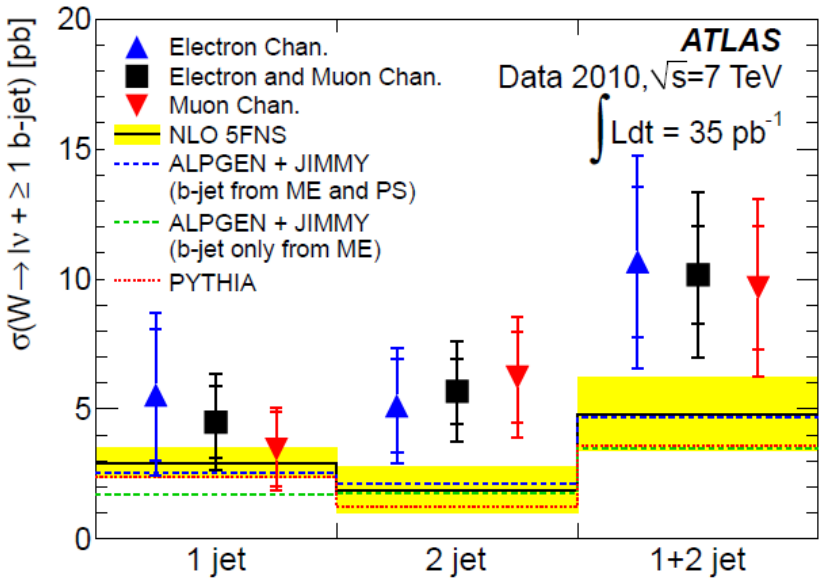


- Often the background for searches
- LO+PS cannot reproduce jet multiplicity ratio
- ALPGEN/Sherpa, fixed order calculation show good agreement

Z, W + b-jets



Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58 pb
ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

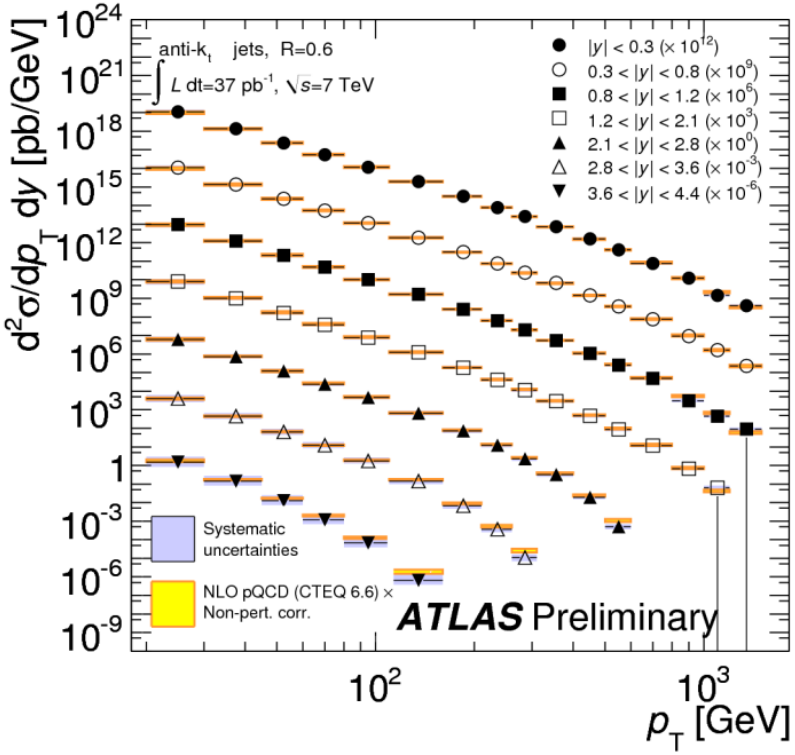


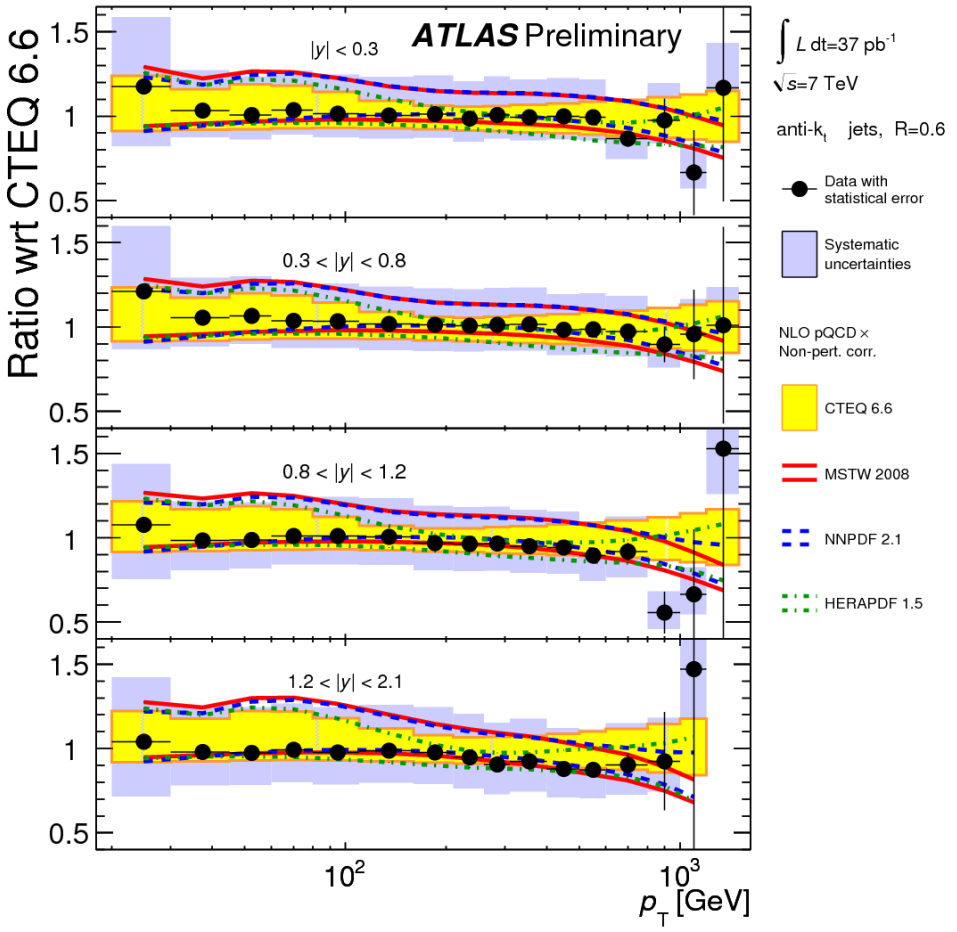
- W + bjets show good agreement, with slight tendnecy of cross section being higher
- High statistics study awaited

Jets and QCD

Jet production

- Inclusive jet double-differential cross sections
- Comparison to NLO calculations

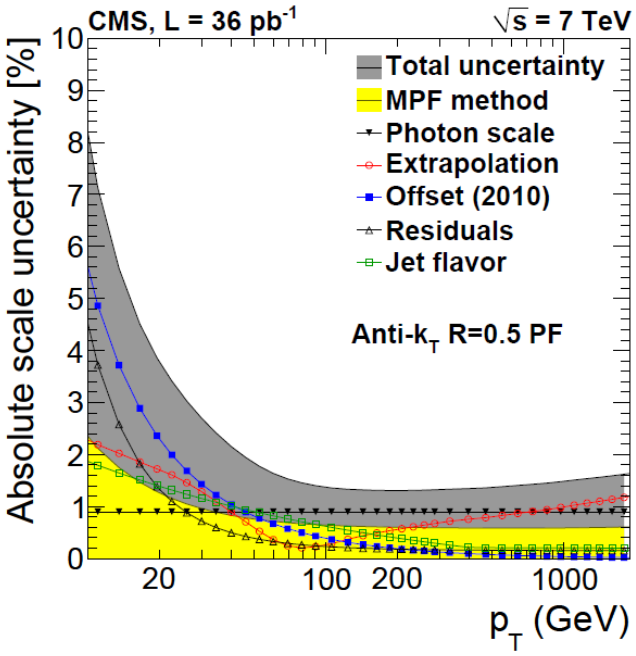


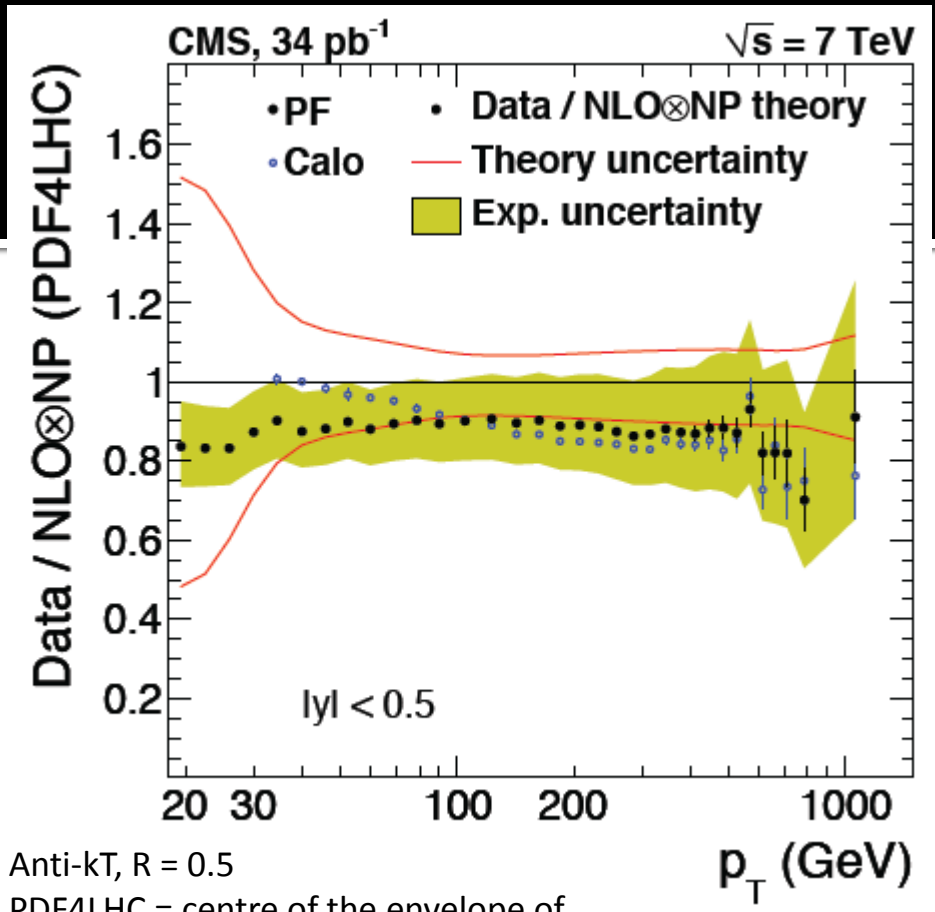


Good agreement in central rapidity

CMS result

- Good agreement
  - With slight tendency of being low (also for ATLAS)





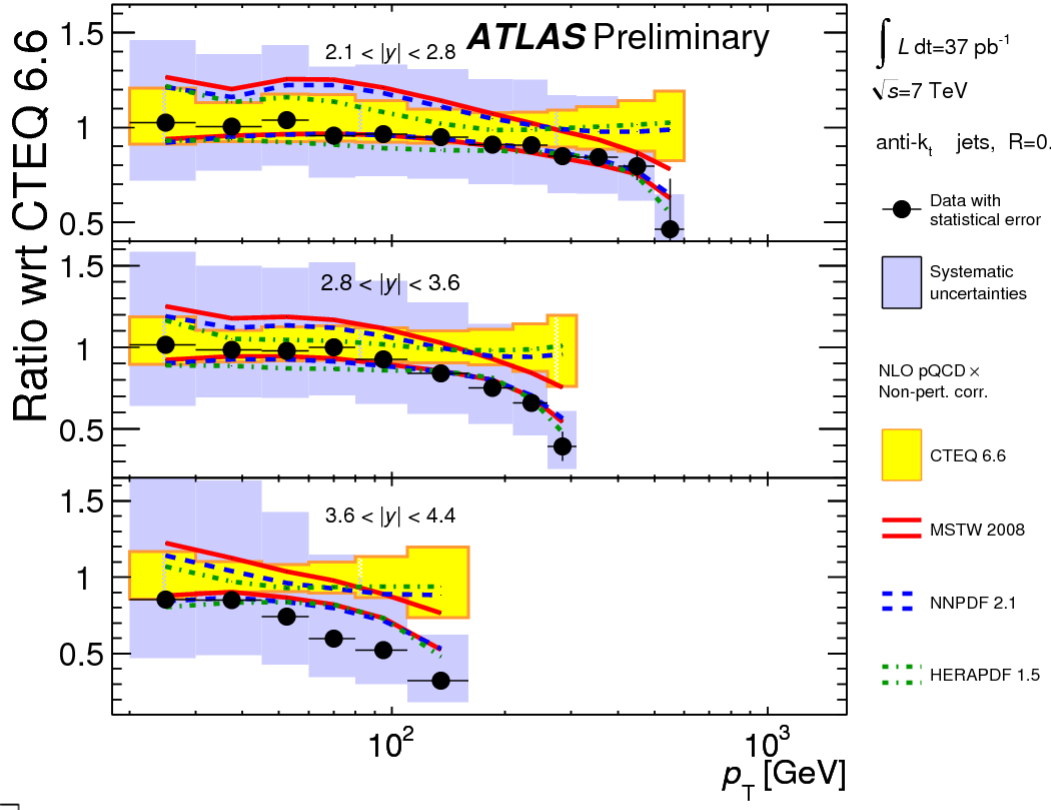
Anti-kT, R = 0.5
PDF4LHC = centre of the envelope of MSTW08, CTEQ6.6, NNPDF2.0

- Jet energy scale (JES) key for precision

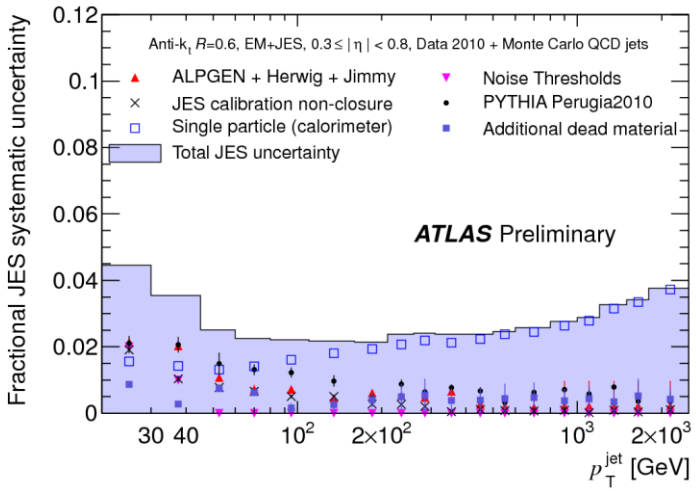
JES (particle flow)
2.5 – 4% uncertainty

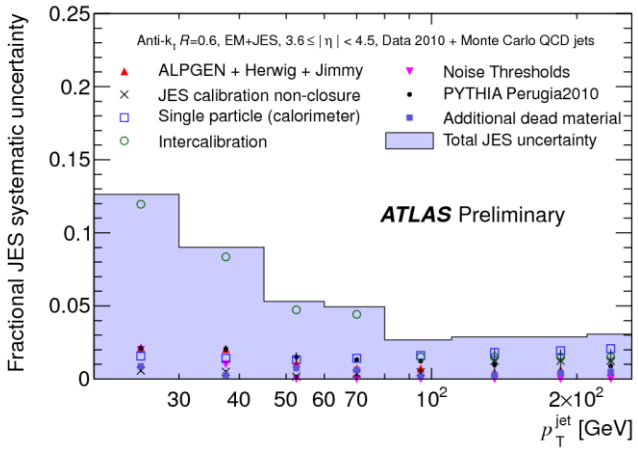
Forward jets

- Need to understand and reduce systematic error
- Interesting tendency



ATLAS JES central rapidity:
similar to CMS

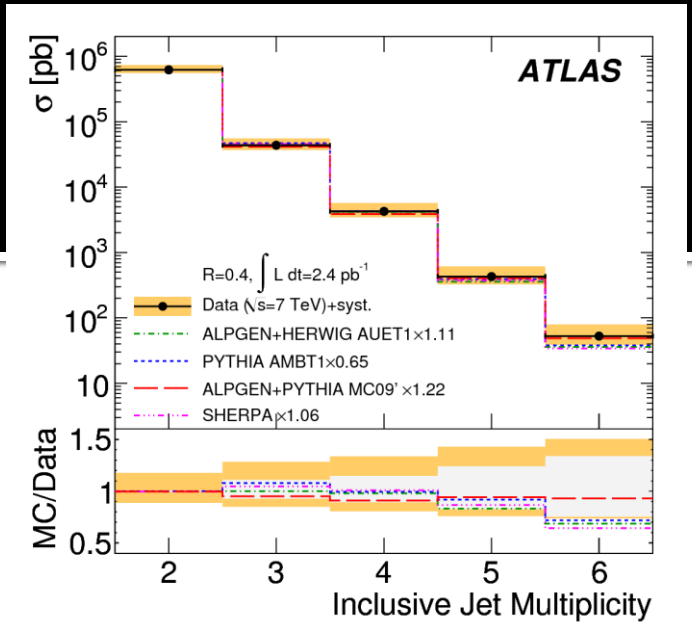


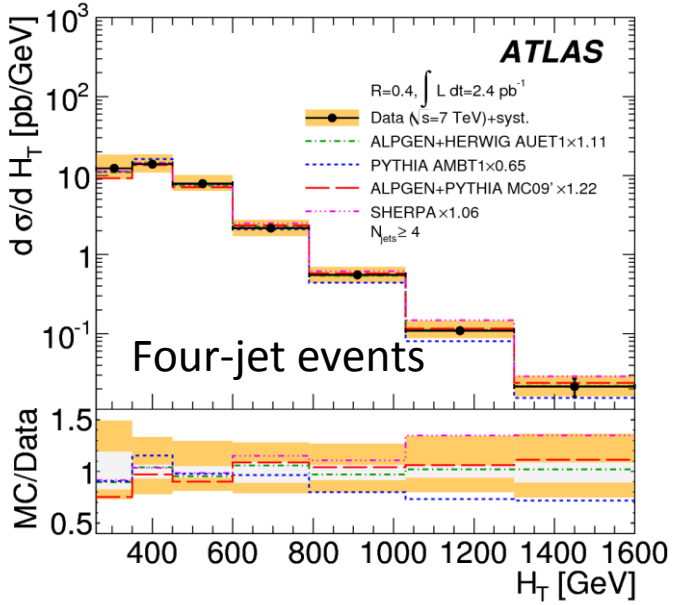


JES in forward rapdity:
large uncertainty
at low p_T
good at high-p_T : 3%

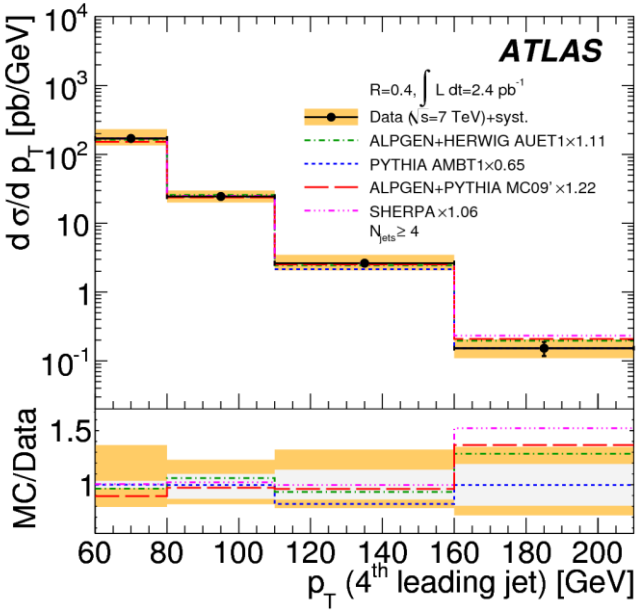
Multi-jet events

- Providing good test on MC simulation / QCD calculation
- Good description of models within experimental uncertainties



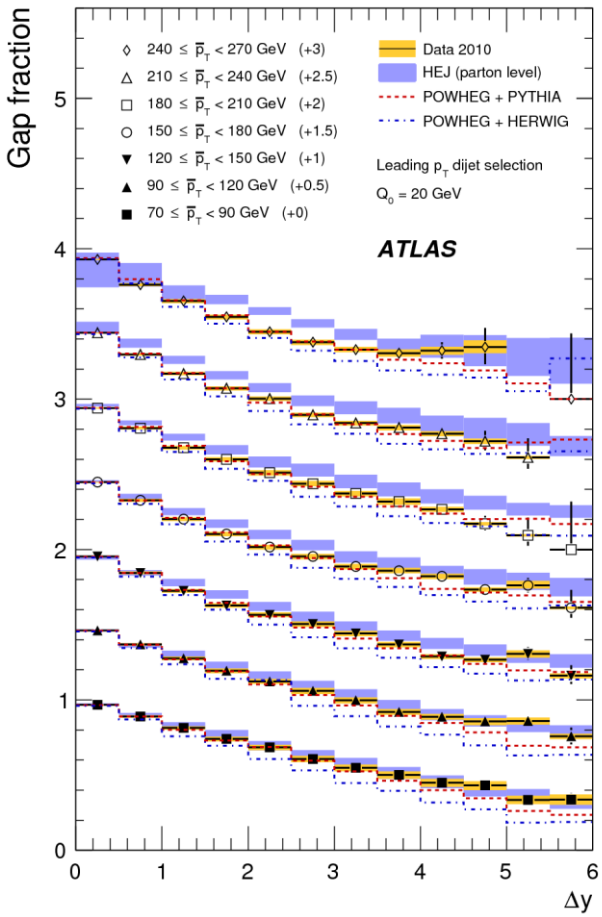


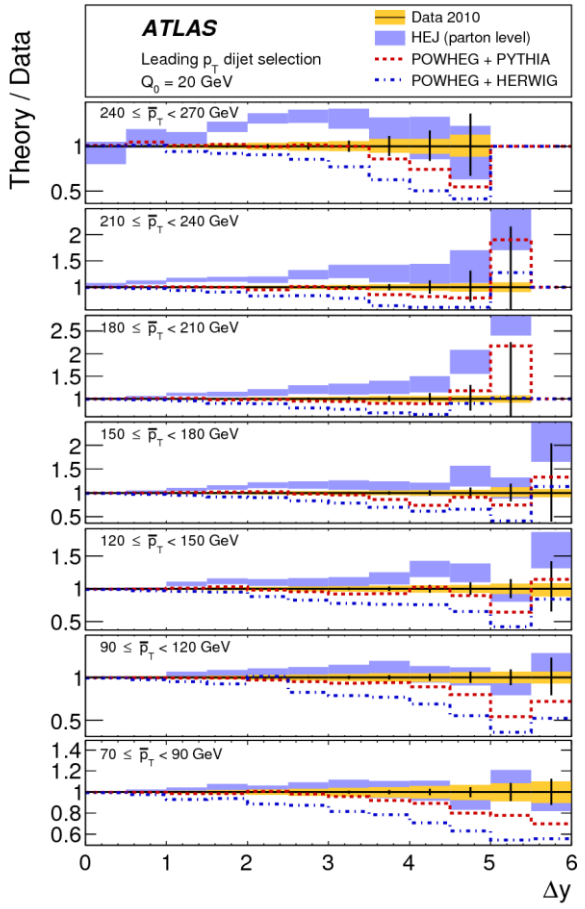
Scalar sum of jet E_T



Gap between jets

- See if there is any jet (> 20 GeV) between two leading jets separated in rapidity by Δy
- Sensitive to non-p_T ordered QCD radiation
- POWHEG tend to give more radiation if gap rapidity is large
- HEJ too few radiation
  – parton shower may improve the situation

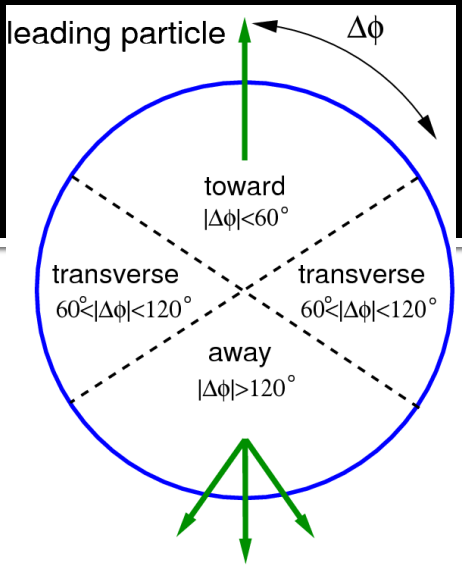




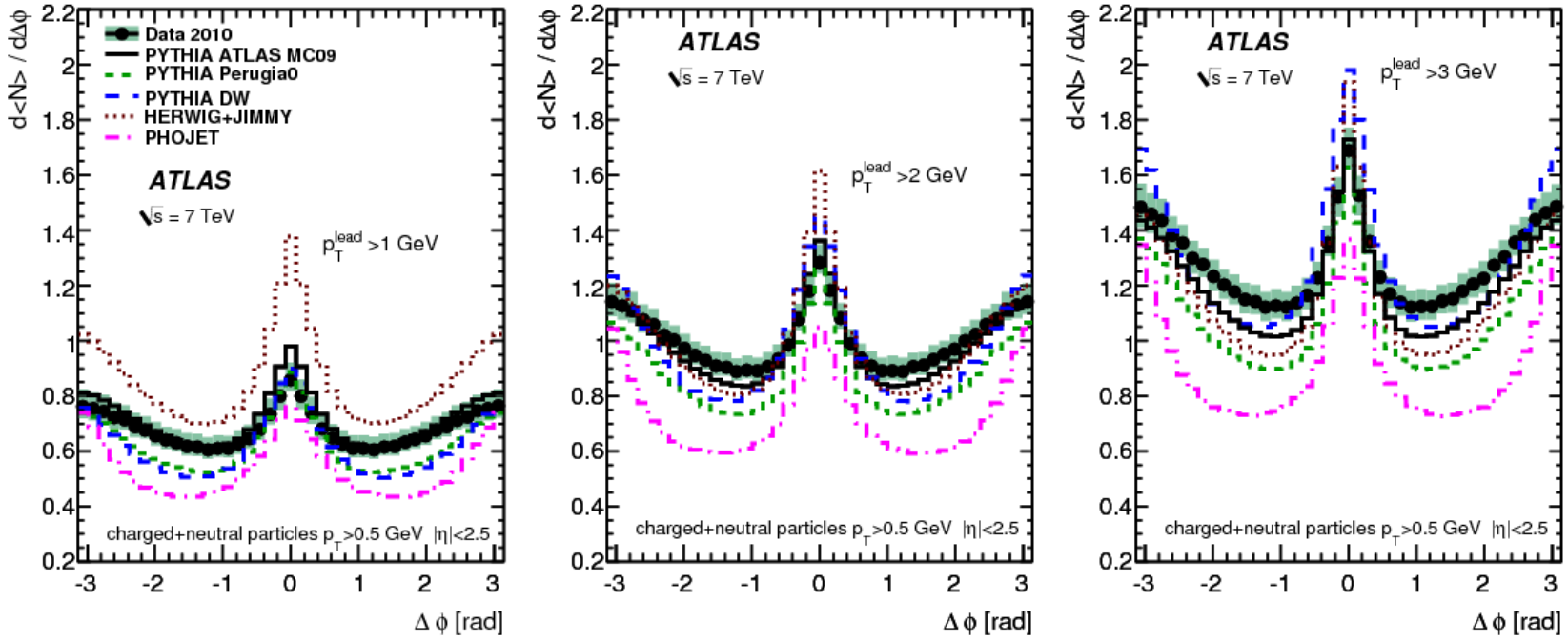
Soft QCD

Very selected example

Underlying event studies

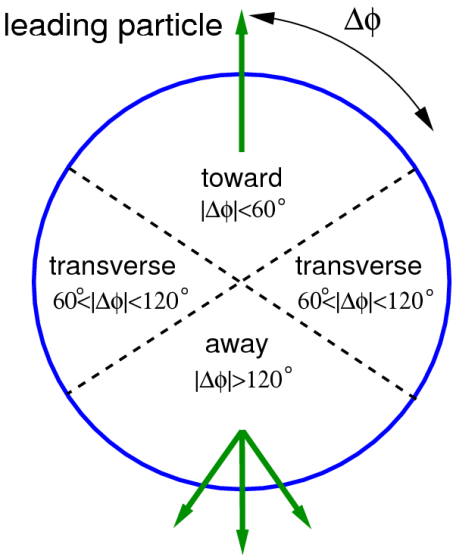


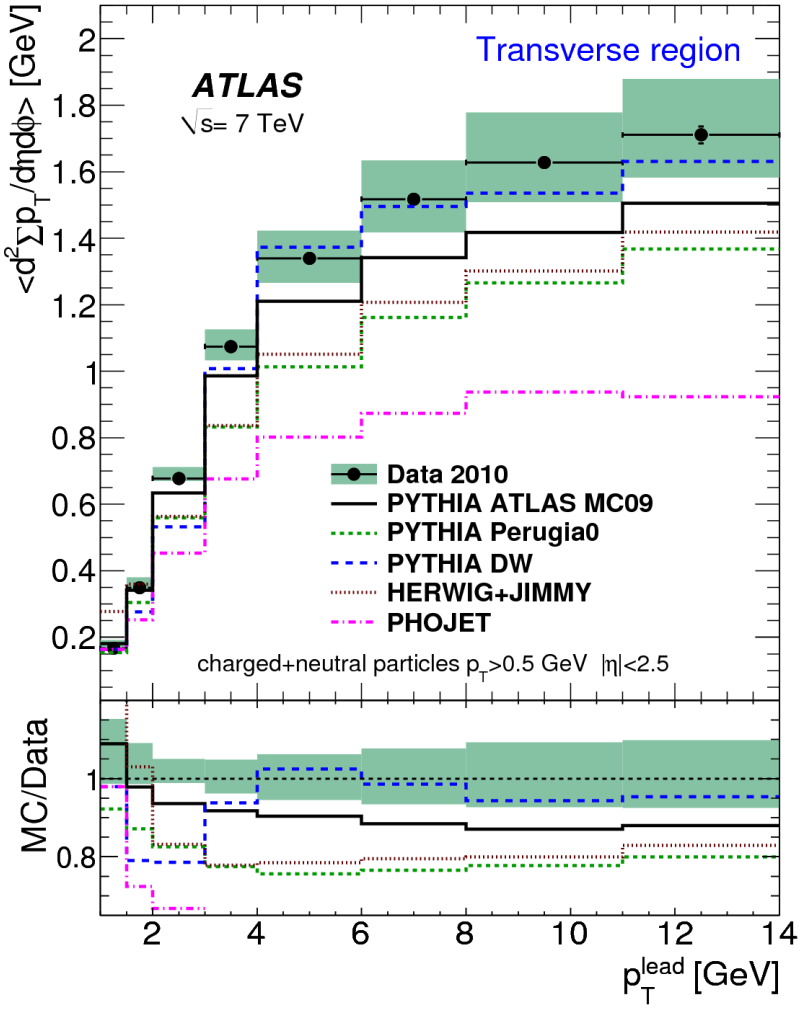
- Energy/particle flow measured w.r.t. the leading particle
- Azimuthal profile quite flat
  - Pythia with MC09 or Perugia0 tune ~ OK



Energy flow in transverse region

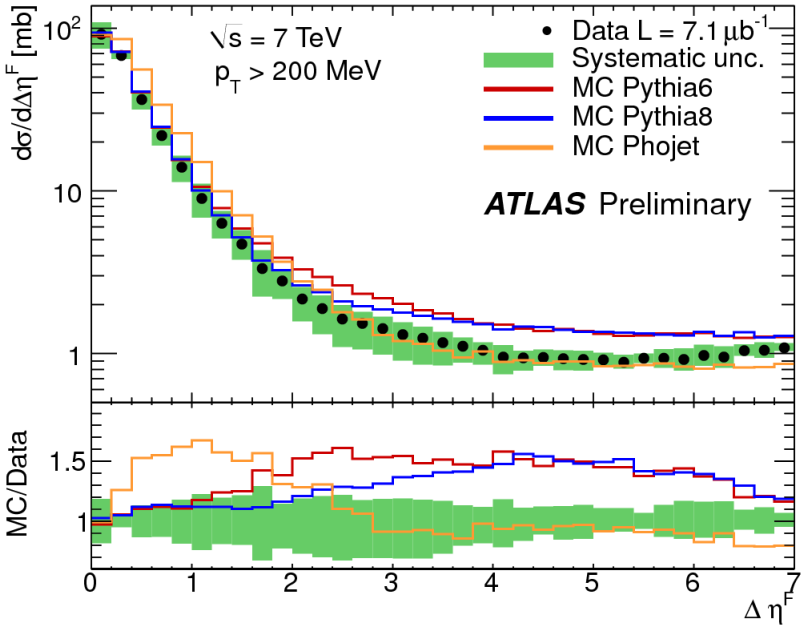
- Insufficient flow for most models
- Perugia0 OK, MC09 fair
- Important to tune the MC further for precise jet and Etmiss reconstruction

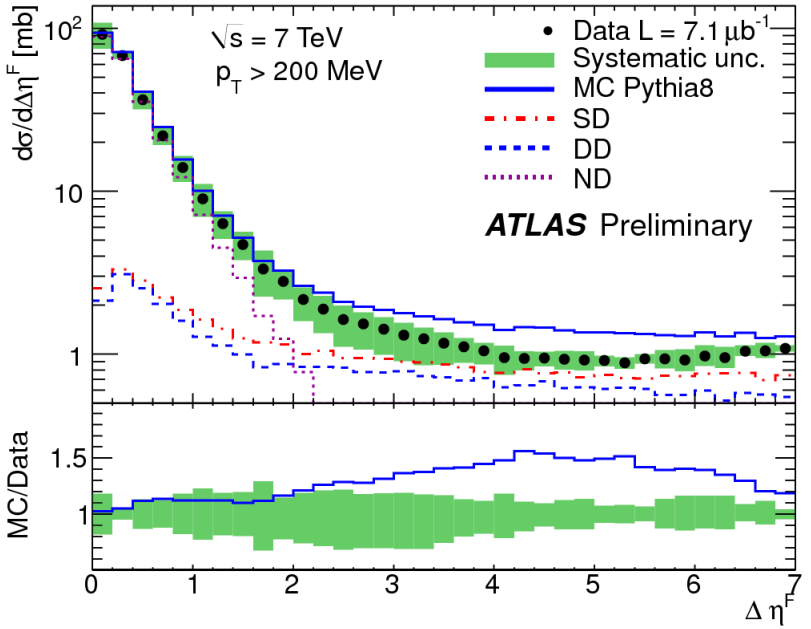




Events with and without rapidity gap

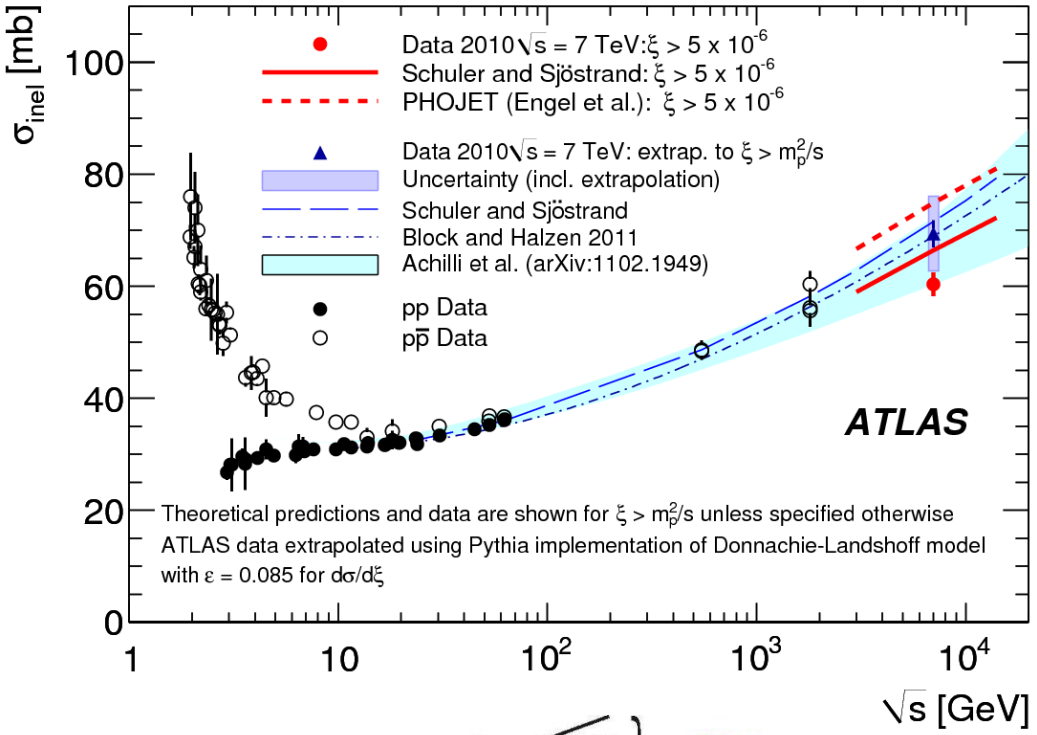
- Diffraction may be suppressed by multi-parton interactions
  - Tevatron has observed O(10) suppression for hard-jet events
- Minimum-buias event cross section as a function of rapidity gap
  - No big overestimation of diffractive contribution by Pythia and Phojet

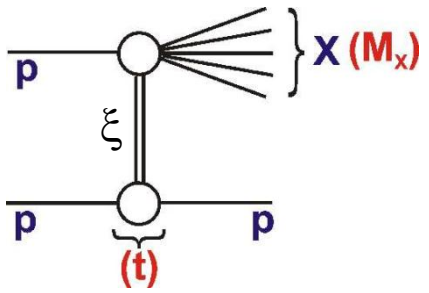




Inelastic pp cross section

- Visible inelastic cross section measured
  - dissociated mass $M_X > 17.5$ GeV can be triggered by ATLAS
  - Corresponding to $\xi > 5 \times 10^{-6}$ (ξ: fraction of longitudinal momentum of exhcanged particle)
- Slow rise of inelastic cross sections confirmed





Summary

- LHC performance is spectacular, experimentalists are super busy
- (unfortunately) no hint of new physics yet
  But they may be just behind
- QCD calculations and MCs are surprisingly good
  - Items on our wish list were delivered, in time
- Detailed check is still important for precision and higher sensitivity to new physics
  - Scene is quite dominated by Higgs search and related QCD subjects
  - But also important to have more studies for testing QCD itself
    we should keep in touch