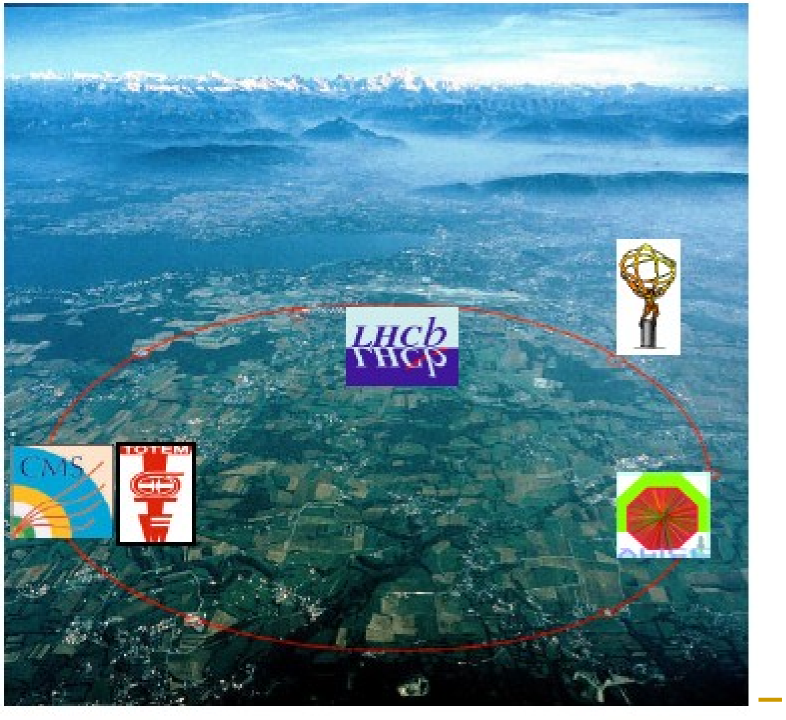
Physics Program

of the experiments at

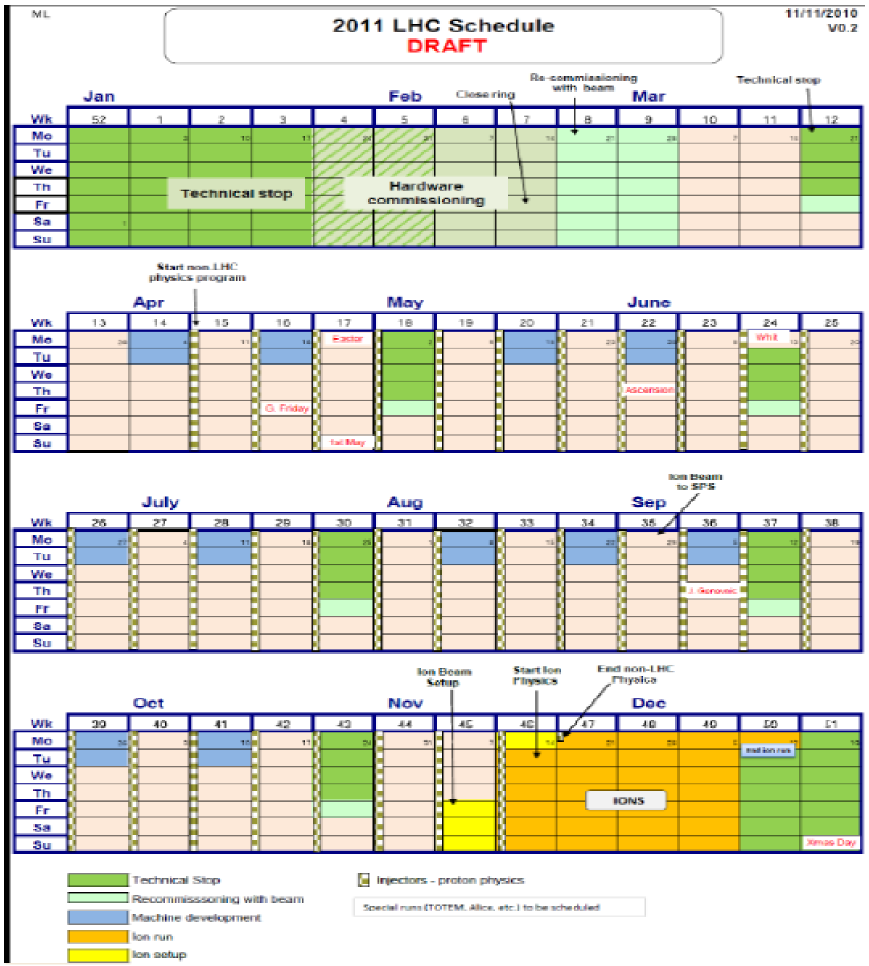
Large Hadron Collider



Lecture 8

Searches with $300nb^{-1}$ - $3pb^{-1}$

Plans for 2011



- **Beam back around 21st February**
- 2 weeks recommissioning with beam (at least)
- ~ 200 days of pp physics
- ~ 4 weeks of heavy-ion physics
- **"reasonable"** numbers

Peak luminosity	6.4×10^{32}
Integrated per day	11 pb^{-1}
200 days	2.2 fb^{-1}
Stored energy	72 MJ

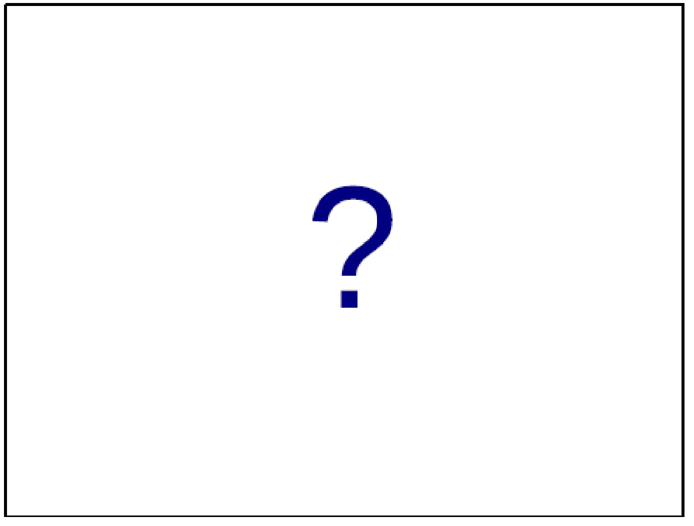
  - 2x4 TeV ?? (to be discussed)
  - 936 bunches, 1.2 10^{11} p/bunch
- **"optimistic"** numbers

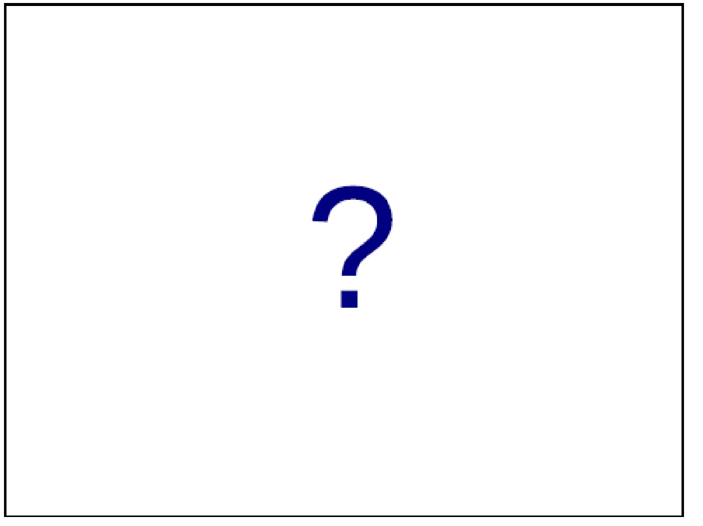
Peak luminosity	2.2×10^{33}
Integrated per day	38 pb^{-1}
200 days	7.6 fb^{-1}
Stored energy	134 MJ

Signature based searches

- **The idea:**
  - Choose a signature
  - Define a nominal selection, with variation
  - Compute SM backgrounds
  - Report event yields and kinematics
  - Investigate discrepancies
- **The why:**
  - There are many models, very few are obviously more likely than others
  - Model limits usually do provide critical insight
  - Save time
    - Cover more signatures
  - Experimental results are experimental

New physics searches



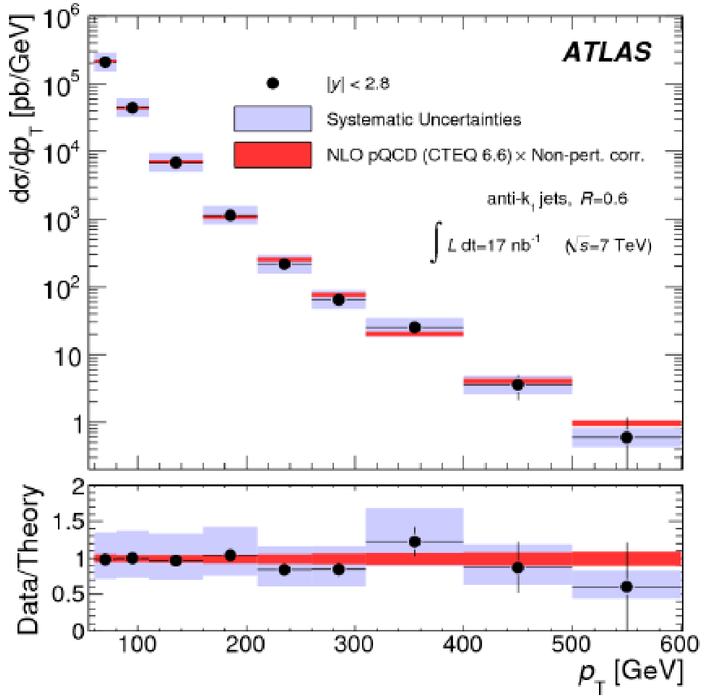


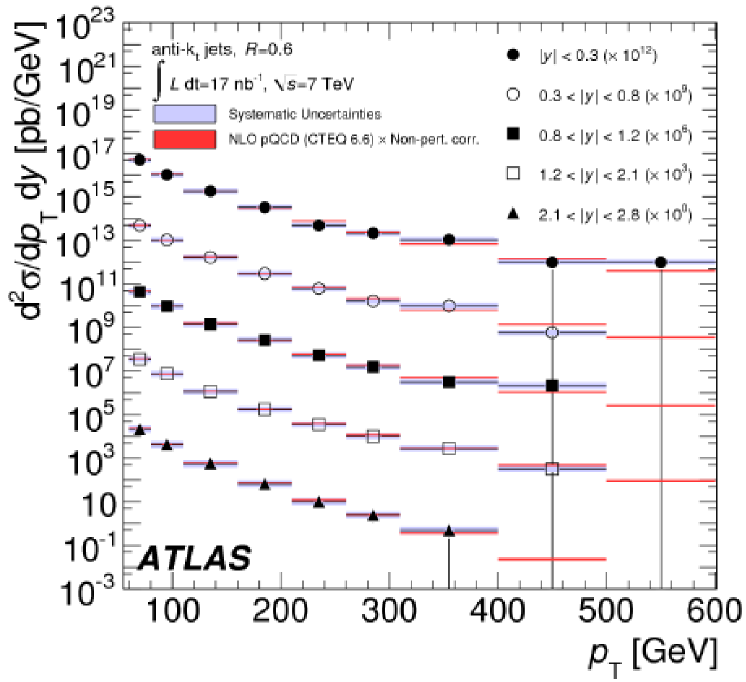
- Inclusive searches trying to be as model independent as possible
- Look for “anomalous” topologies
  - Unexpected mass peak in multi-body final states
  - Extremely massive particles
  - Large missing transverse energy

New physic searches

- **Final states with jets**
  - Dijet centrality ration, resonances in dijet mass distribution
  - Black Holes, Multi-jet Resonance, Mono-jet, High mass resonance
- **Long lived particles**
  - Stopped gluinos, Heavy Stable Charged Particles
  - GMSB SUSY decays to non-prompt photons
- **High mass dilepton and diphoton resonances**
  - Z' bosons, RS gravitons, excited leptons
- **High mass non-resonant signals**
  - W' bosons, extra dimensions, contact interactions
- **Leptoquarks, Fourth generation**
- **Supersymmetry**

Jets with 17nb^{-1}





- Measurement of inclusive jet and dijet cross-section
- Uncertainty dominated by jets energy scale (7%)

Dijet mass spectrum

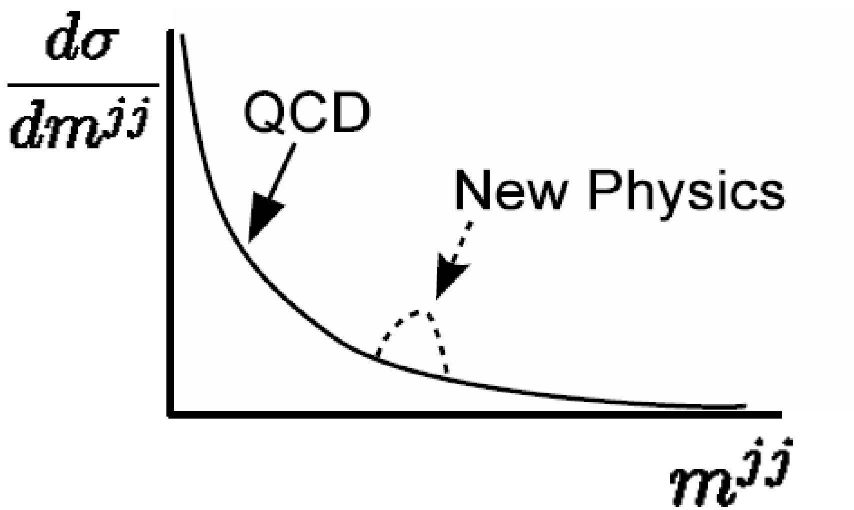
- Resonances decaying to jets are predicted by different models:
    - **String resonances**:Regge
        - excitations of quarks and gluons, models with largest cross-sections
    - Mass-degenerate **excited quarks**
    - **Axigluons**: axial vector particles
    - **Colorons**
    - **Scalar diquark**
    - **Randall-Sundrum (RS) gravitons**
    - **New gauge bosons (W', Z')**

Dijet mass spectrum

- Resonances decaying to jets are predicted by different models:

Model Name	X	Color	J^P	$\Gamma/(2M)$	Final-state Partons
String	S	mixed	mixed	0.003-0.037	qg, $q\bar{q}$, gg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Excited Quark	q*	Triplet	$1/2^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
RS Graviton	G	Singlet	2^+	0.01	$q\bar{q}$, gg
Heavy W	W'	Singlet	1^-	0.01	$q\bar{q}$
Heavy Z	Z'	Singlet	1^-	0.01	$q\bar{q}$

Dijet mass resonance search



$$m^{jj} = \sqrt{\left(E_1 + E_2\right)^2 + \left(\vec{p}_1 + \vec{p}_2\right)^2}$$

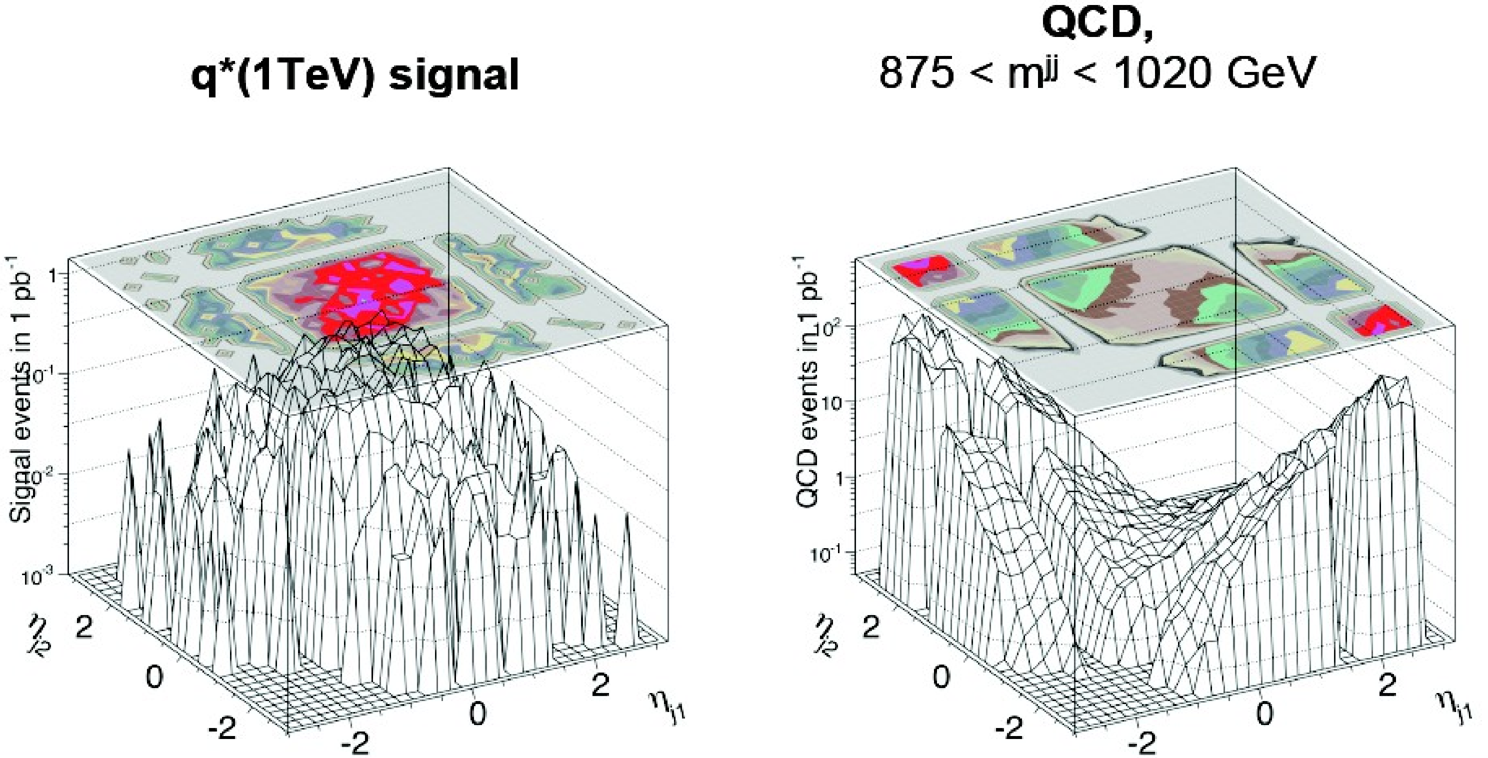
- Is there a bump in m_{jj}?
- If not, set limits on excited quark production. Excited quark is a representative example of narrow resonances (narrower than experimental resolution)

Event selection and analysis steps

- Standard event quality cuts
- Require the two leading jets:
  - to have $p_T^{j1} > 80$ GeV and $p_T^{j2} > 30$ GeV
  - to have $|\eta|<2.5$ and $|\Delta\eta|< 1.3$
- Compute m_{jj} without unfolding jets

  to hadrons or partons
- Fit mass spectrum with function $f(x) = p_0 \frac{(1-x)^{p_1}}{x^{(p_2 + p_3 \ln(x))}}$ $\quad x \equiv m^{jj}/\sqrt{s}$
- Perform statistical tests
- Set limits on σxA for several q* mass tested (in absence of new signal observed)

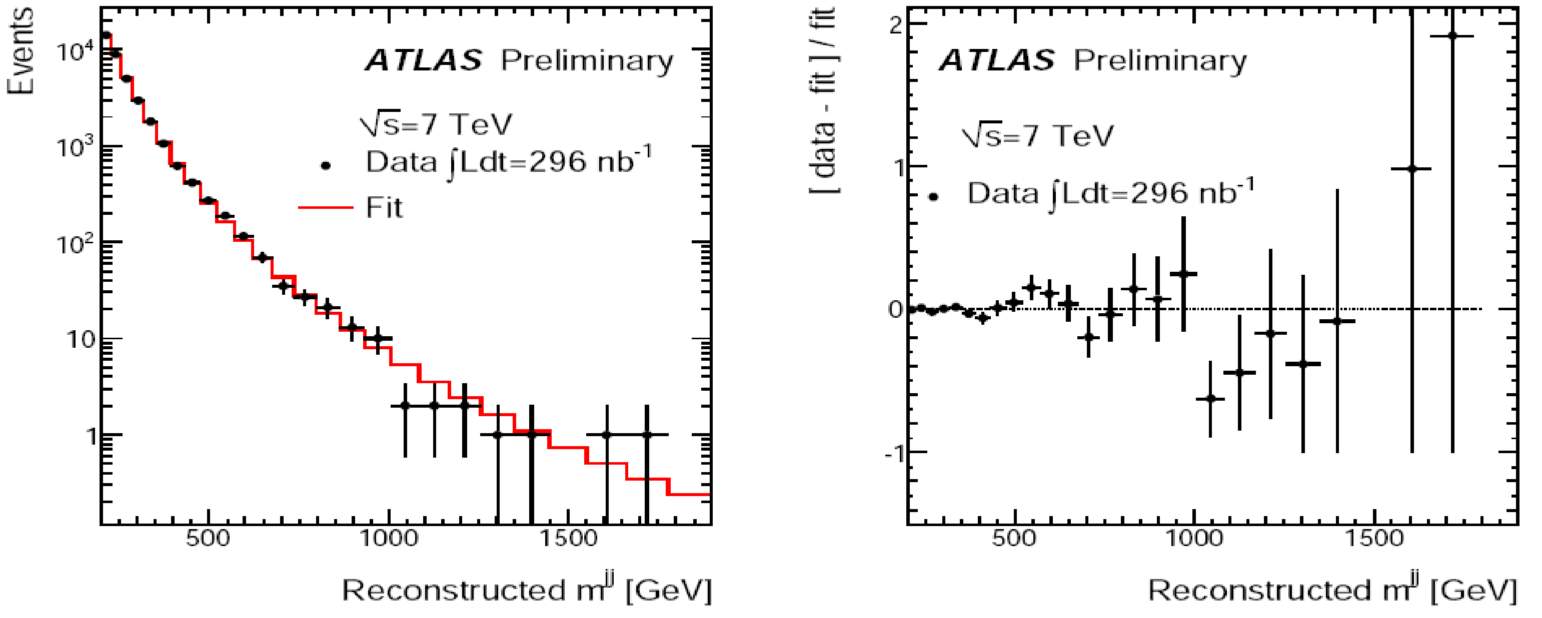
η optimisation



- QCD jets are forward, signal is central

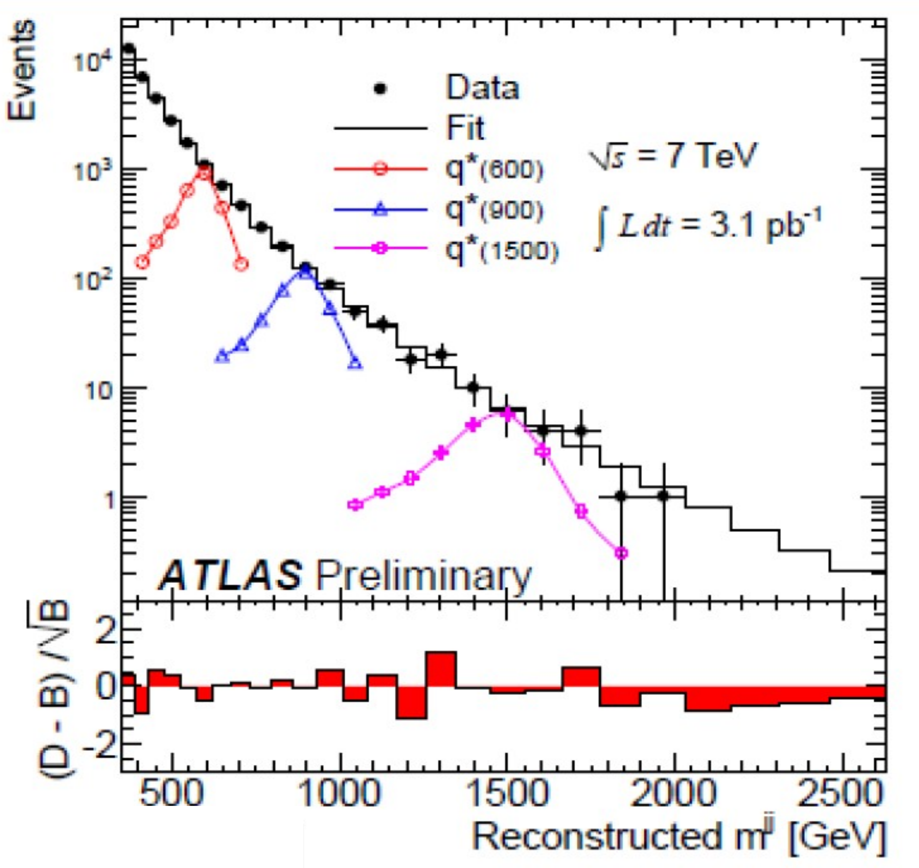
Are the data smooth, is there any bump?

$$f(x) = p_0 \frac{(1-x)^{p_1}}{x^{(p_2+p_3\ln(x))}} \qquad x \equiv m^{jj}/\sqrt{s}$$



- All tests: BumpHunter, Jeffrey divergences, Komlogorov-Smirnov, likelihood, Pearson χ^2, tailHunter, indicated no significant discrepancy

Signature of excited quarks



- Events expected after selection
- Signal acceptance ~ 50%
- Systematics:
  - Energy scale JES 5-10%
  - Luminosity 11%
  - Bgd fit 3% - 30%

Bayesian limit on q* production

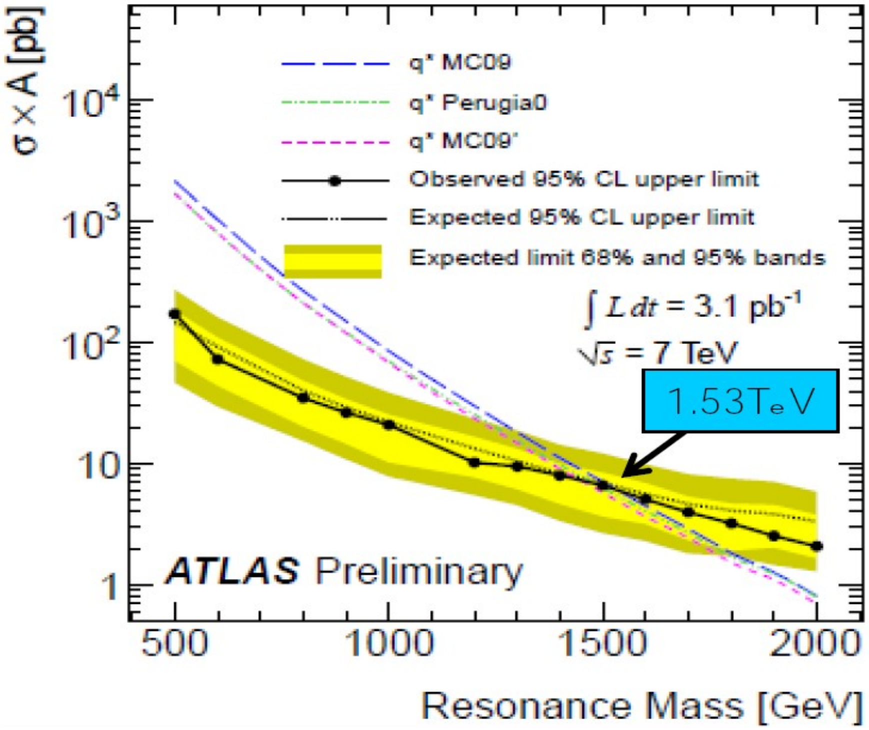
- For each test masses (indexed by ν) corresponding to excited-quark q* predictions, a likelihood function L_ν was defined as a product of Poisson factors computed for each bin (i) of the m_{jj} distribution

$$L_\nu(d|b_\nu, s) = \Pi_i \frac{[b_{\nu i} + s_i(\nu)]^{d_i}}{d_i!} e^{[-b_{\nu i} + s_i(\nu)]}$$

- Where d_i is the observed number of data events in bin i, $b_{\nu i}$ is the background in bin i, $s_i(\nu)$ is the predicted signal added in bin i with signal template, with normalisation $s = \sum_i s_i(\nu)$

Bayesian limit on q* production

Latest published limit:
870 GeV, with 1.1 fb^{-1}
CDF Collaboration,
Phys.Rev.D 79 (2009) 112002

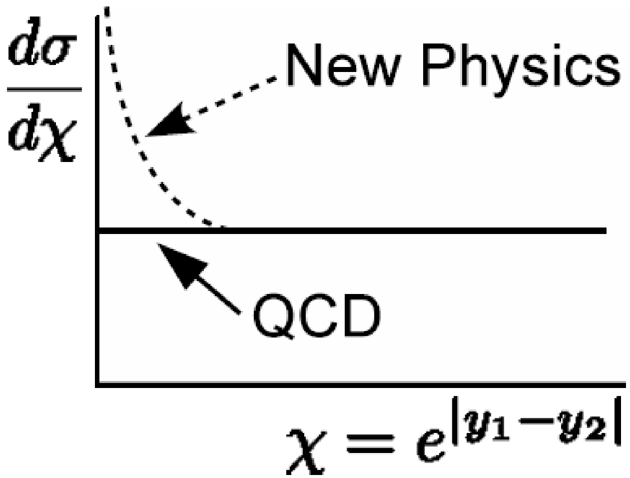


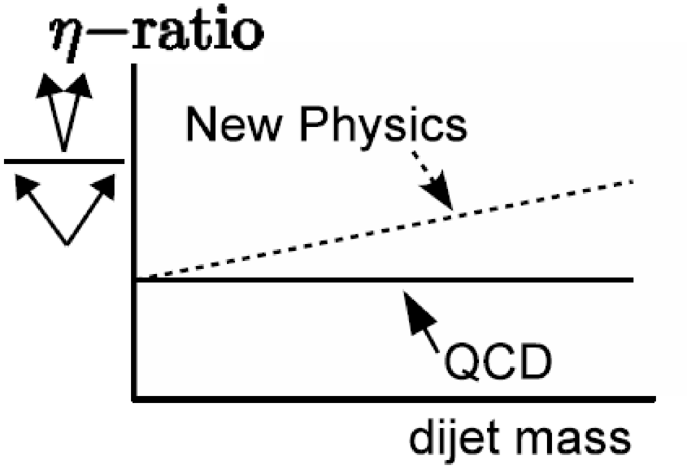
Simultaneous fit on bgd and signal

- Systematic uncertainty
  - Jet energy scale
  - Background fit parameters
  - Integrated luminosity
  - Jet energy resolution
- **0.5 < M(q*) < 1.53 TeV**
  - **excluded at 95% CL**

Dijet angular distribution

- Observables:





- Target: $\mathcal{L}_{qqqq}(\Lambda) = \frac{\eta g^2}{2\Lambda^2}\bar{\Psi}^L_q \gamma^\mu \Psi^L_q \bar{\Psi}^L_q \gamma_\mu \Psi^L_q$, where $g/4\pi = 1$ and $\eta = +1$.
  - Non-resonant production of new physics at high m_{jj}
    - Quark compositeness at high scale Λ

Searches for compositeness

- If quark have substructure it will appear at compositeness scale Λ

$$\chi = \exp(|y_1 - y_2|) = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

$y_{(2)1}$ (sub)leading jet rapidity
θ^* angle between two jets

- Coarse in m_{jj}, fine in θ^*

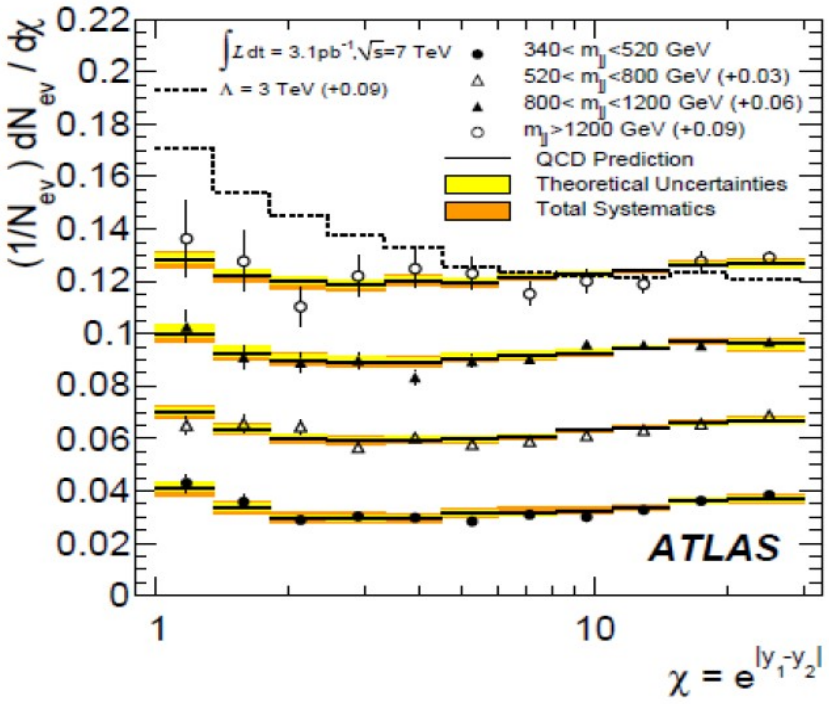
  where θ^* is an angle

  in CMS frame

- Data agrees with SM

  Exclude Λ below

  3.4 TeV@ 95%CL



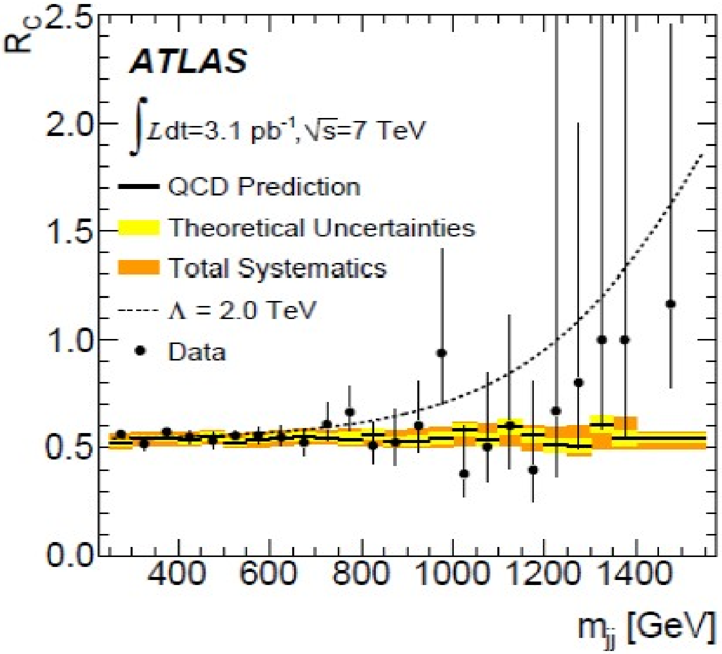
Searches for compositeness

- If quark have substructure it will appear at compositeness scale Λ
- Centrality ratio (two highest p_T jets)

$$R_C = \frac{N(|\eta_{1,2}|<0.7)}{N(0.7<|\eta_{1,2}|<1.3)}$$

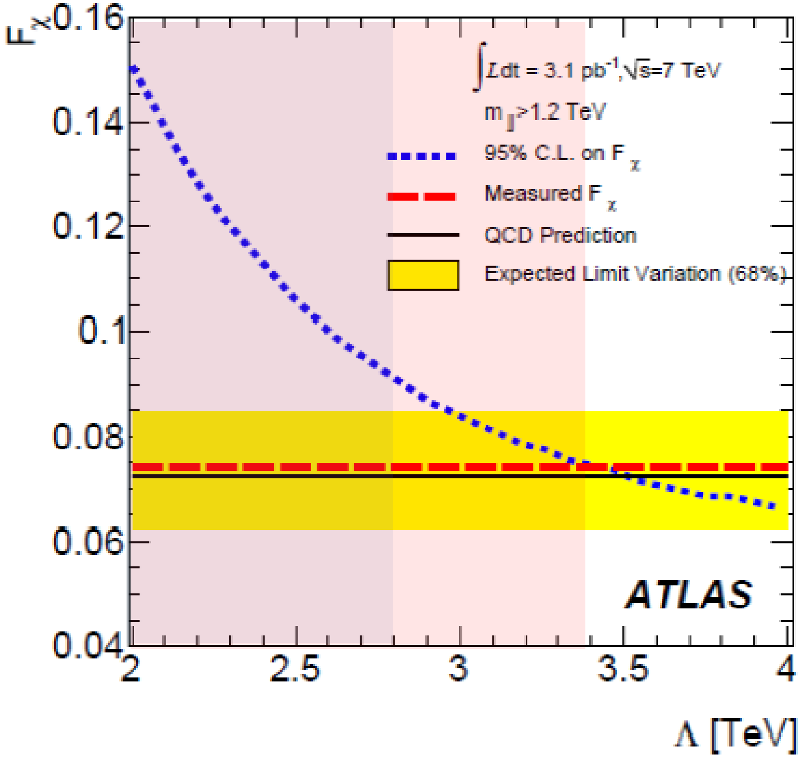
- Flat distribution for SM processes, excess at large R_c for signal.
- Coarse in θ^*, fine in m_{jj} better determines signal mass scale
- Data agrees with SM

Exclude Λ below 2 TeV@ 95%CL



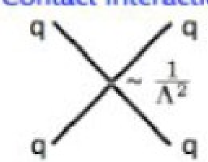
Searches for compositeness

- The compositeness scale is analysed on the χ distribution.
- $F\chi$ defined as ratio of number of events in the first four χ bins to the number in all χ bins
- Frequentist analysis is employed. The **observed limit is 3.4 TeV**, where the 95%CL countor crosses the measured $F\chi$ value.



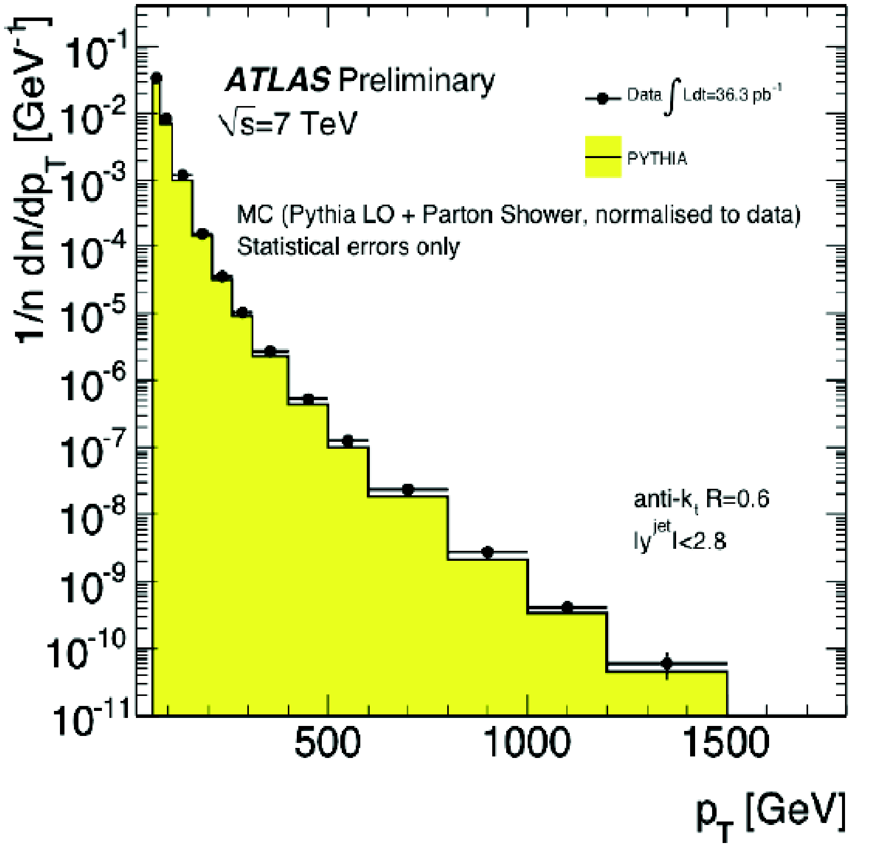
New physics searches with dijet events

- Provide both a test of QCD and sensitivity to physics beyond the Standard Model.

	Mass Spectrum	Centrality Ratio
QCD 	simple test of cross section vs dijet mass from QCD and PDFs	detailed measure of QCD dynamics from angular distribution
Dijet Resonance 	provide most sensitive "bump" hunt for new particles decaying to dijets	less sensitive to dijet resonances, but important confirmation that "bump" is not QCD fluctuation
Contact Interaction 	because of experimental uncertainties, less sensitive to quark compositeness	sensitive search for quark compositeness

Inclusive jets

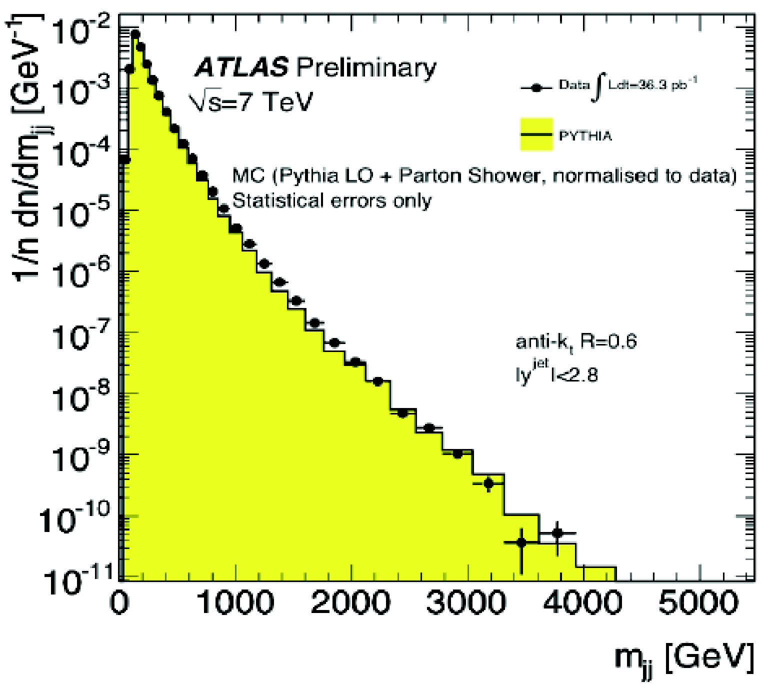
- Combine a range of triggers to cover full p_T spectrum
- Jets corrected to hadronic scale (JES uncertainty 7%)
- Jet p_T>60 GeV, highest p_T jet 1.3 TeV
- Shape comparison with MC PYTHIA (LO+parton shower)

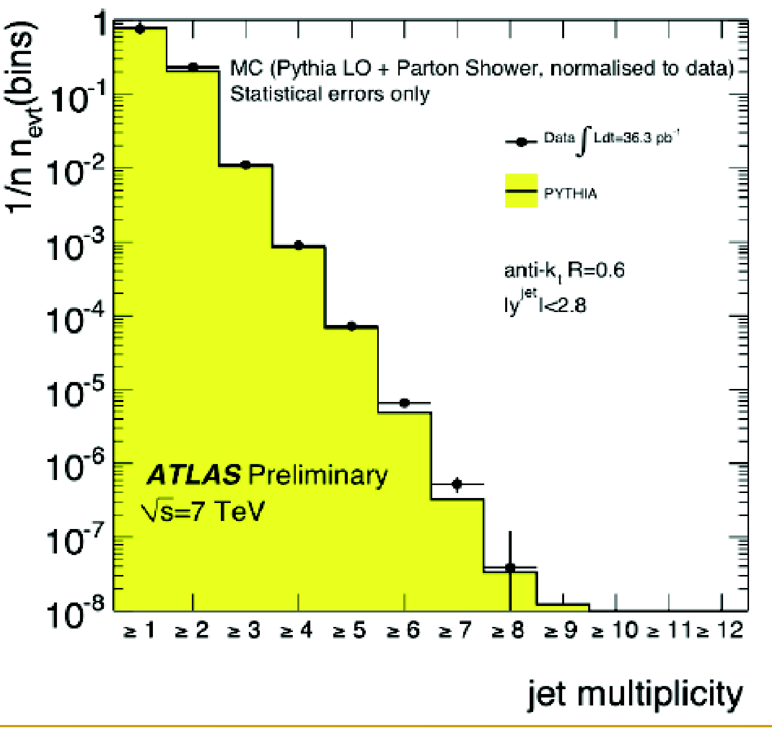


Dijets and multi-jets

- Jets p_T>60 GeV (30 GeV),
- Highest dijet mass 3.7 TeV

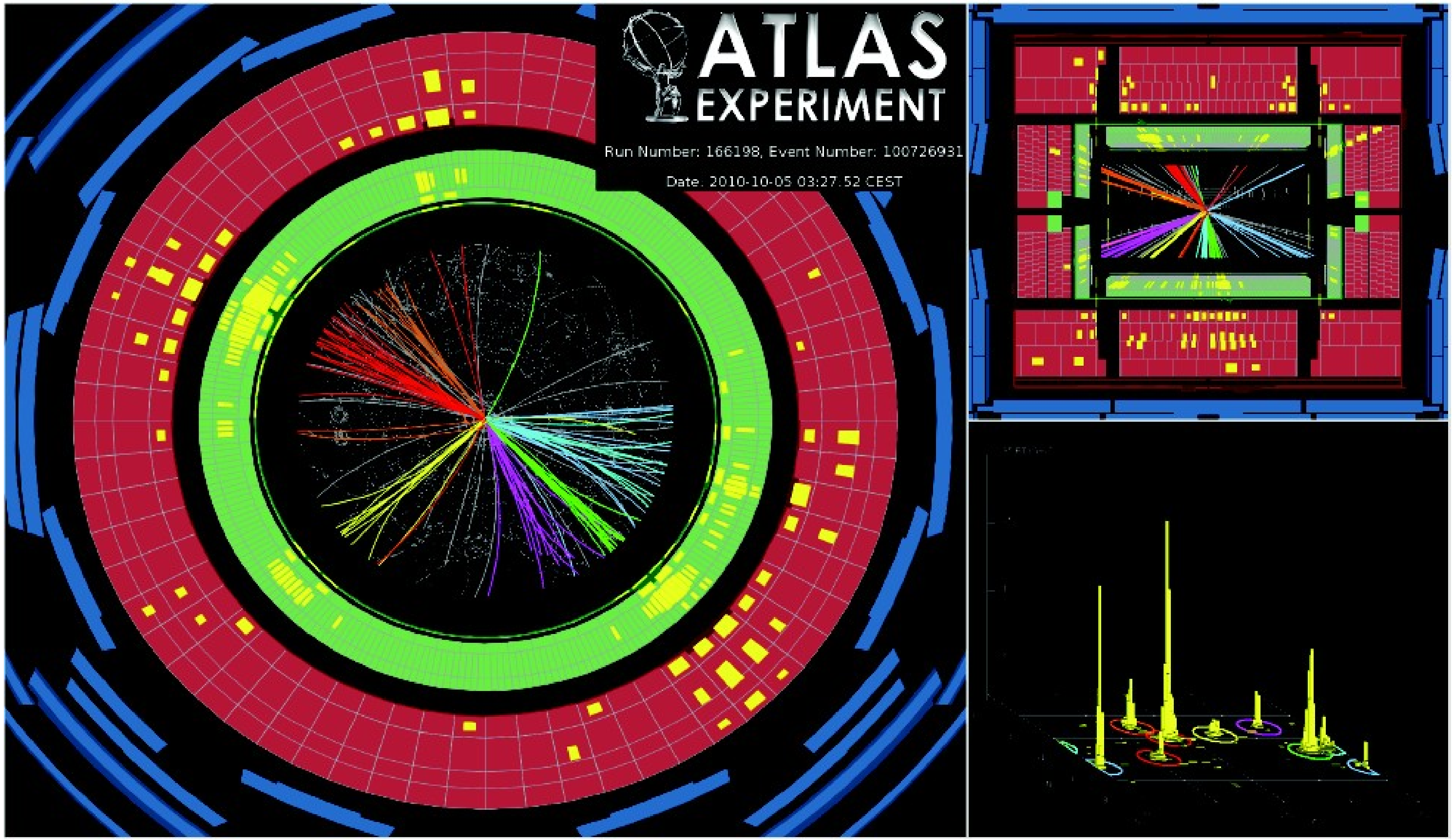
- Count events with p_T>60 GeV jets
- 1 events with 8 jets





ATLAS multi-jet event

8 jets with p_T > 60 GeV



ATLAS analysis: multi-body final state

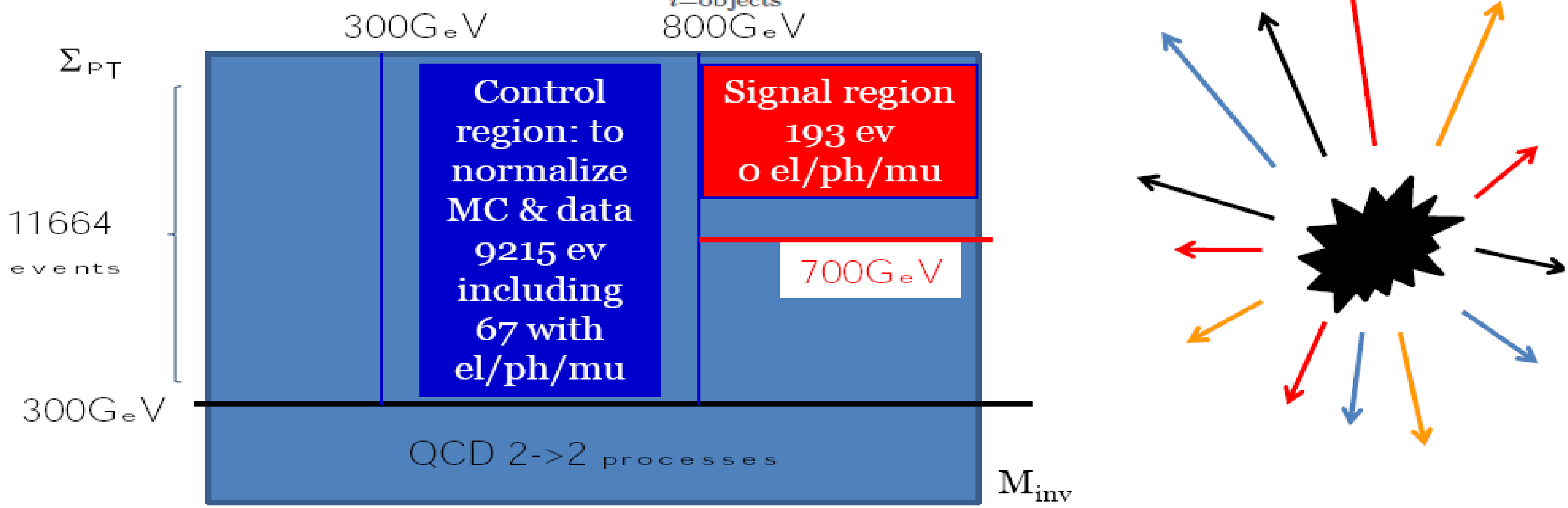
- The fundamental scale of gravity M_D
  - **in TeV range in extra dimensions model**
- Low-scale gravity models predict gravitational states
  - **decay to all degrees of freedom in SM democratically**
  - **several high p_T objets**
  - **deviation from SM in the high invariant mass**
- Benchmark: TeV Gravity models (e.g. Black holes, string balls)

ATLAS analysis: high invariant mass, multi-object search

Benchmark model: TeV Scale Gravity (continuum spectrum black holes)

- The fundamental scale of gravity M_D is ~TeV, as gravity is operating in higher-dimentional space than SM fields
- Search for deviations from the SM spectrum due to gravitational state decays
- Democratic production of electrons/photons/muons/jets with any number (>2)

$$M_{\rm inv} = \sqrt{p^2} \quad \text{and} \quad p = \sum_{i=\text{objects}} p_i + (E_{\rm T}^{\rm miss}, E_{{\rm T}x}^{\rm miss}, E_{{\rm T}y}^{\rm miss}, 0)\,,$$



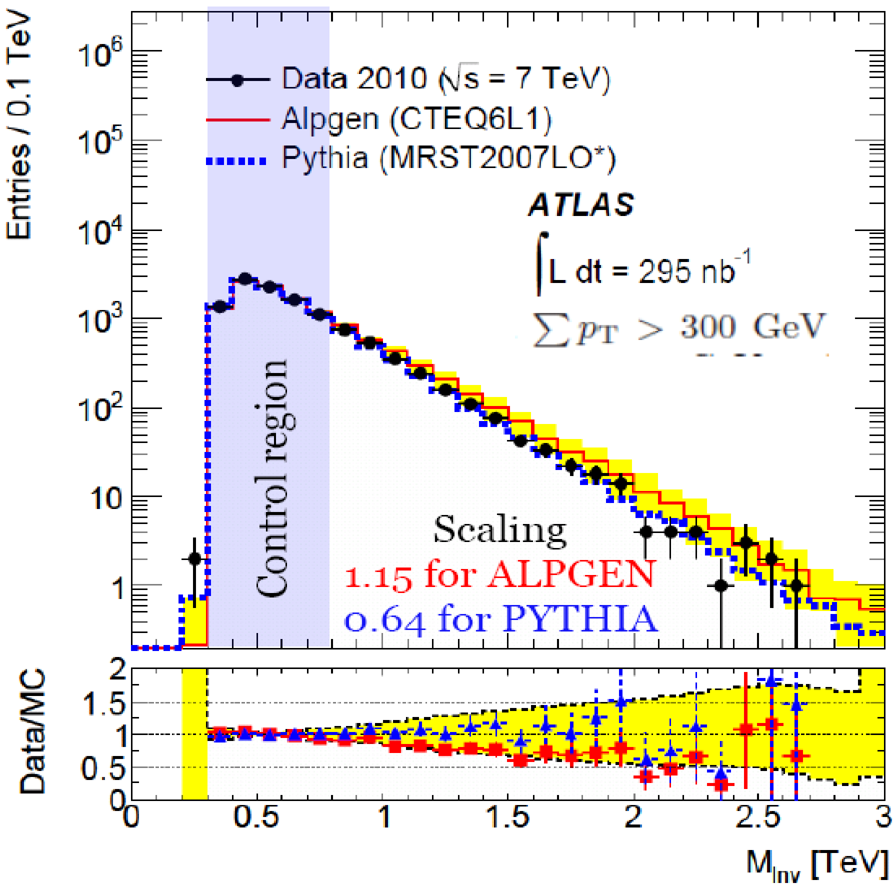
- Previous Limits on M_D>800GeV for extra dimentions (ED)>6,
- Main selection variables (strongly correlated): scalar sum of p_T (Σp_T) and

ATLAS analysis: high invariant mass, multi-object search

- Objets: $N_{obj} \geq 3$
  - Central jets (p_T > 40 GeV)
  - e/γ (p_T > 20 GeV)
  - μ (p_T > 20 GeV)

$$M_{inv} = \sqrt{\sum E_i^2 - \sum \vec{P}_i^2}$$

sumPt = $\sum P_{Ti}$



- Control region

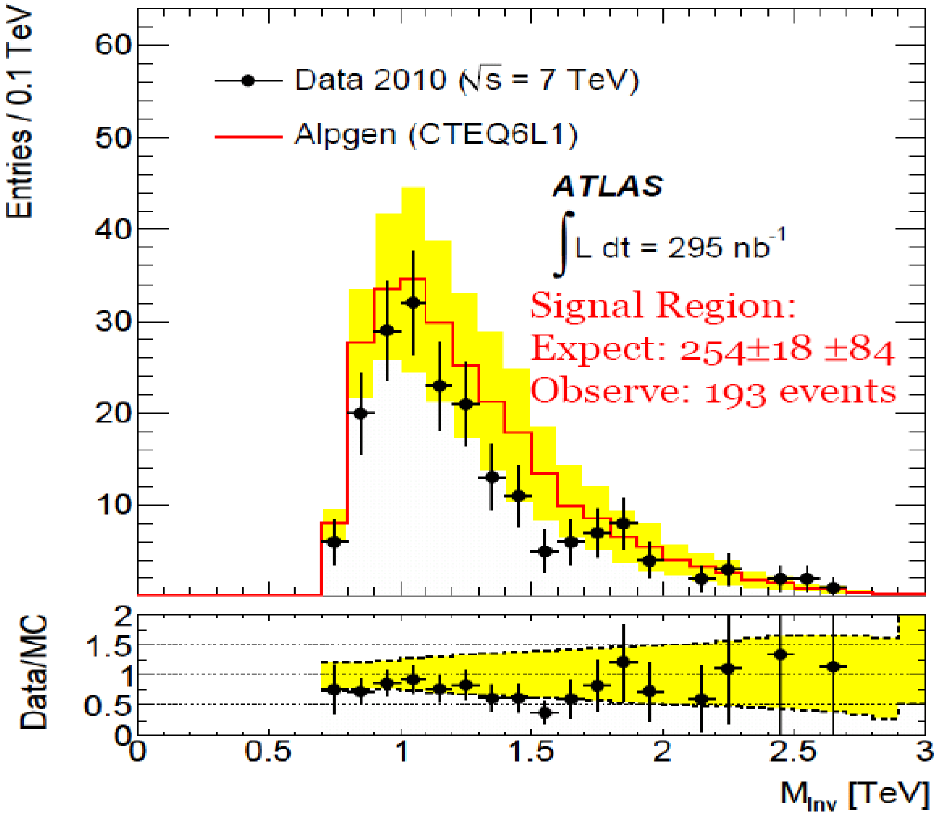
sumPt>300GeV

300GeV<M_{inv} <700GeV

ATLAS analysis: high invariant mass, multi-object search

$$\sum p_T > 700GeV$$

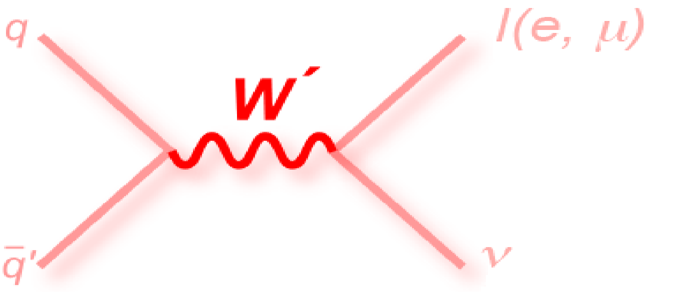
- Production cross-section times acceptance upper limit at 95% CL is 0.32nb
- Black hole acceptance of 58% gives upper limit of 0.6nb for masses above 800 GeV
- Rules out models with large order of 100nb cross-section



Search for New Physics in lepton + MET

Benchmark signal: W' Boson decaying into $l\nu$

- High-pT lepton + $E_T$miss
- $p_T \sim m(W')/2$
- $E_T$miss ~ $m(W')/2$



If data are consistent with SM predictions, set a limit on W' mass

Current limit: $m_{W'}$>1.0TeV at 95% CL

- D0 Collaboration, Phys. Rev. Lett. **100** (2008) 031804

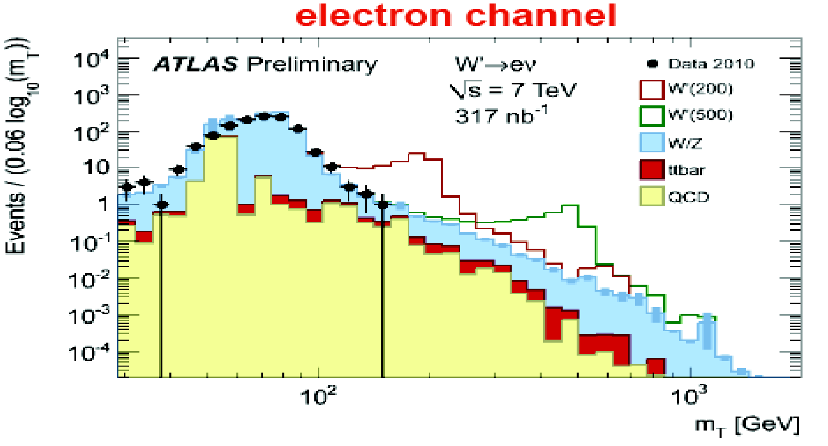
Search for New Physics in lepton + MET

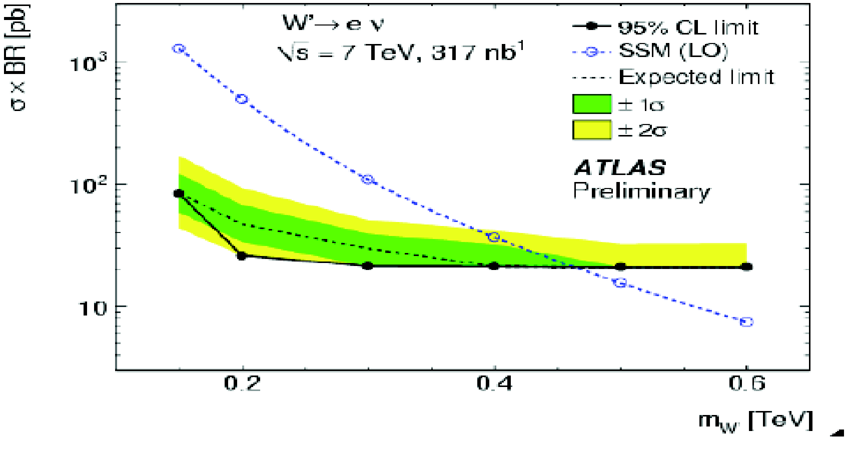
Analysis exercised with 317 nb-1 of data

Data consistent with SM predictions

Current limit that can be set (electrons): 465 GeV

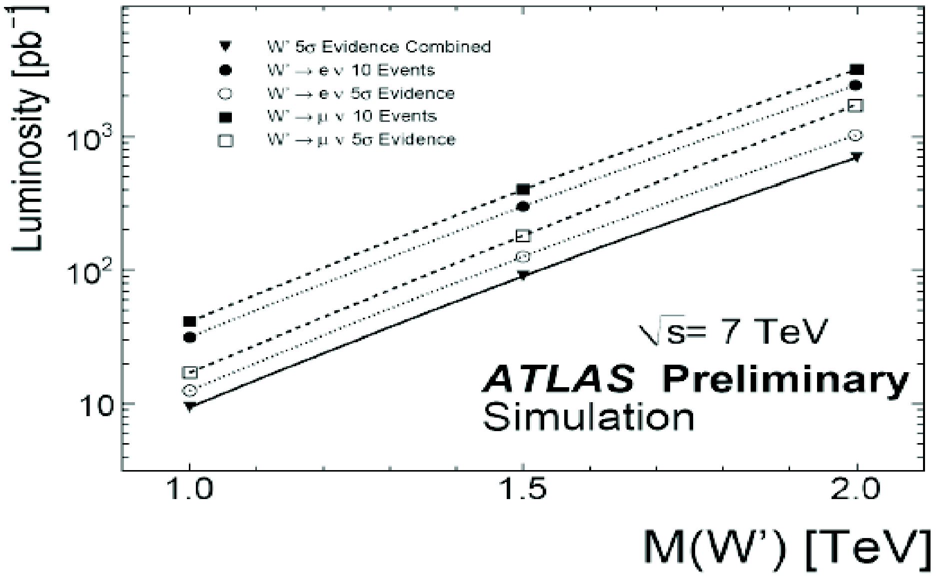
Current results support estimates from previous MC sensitivity studies





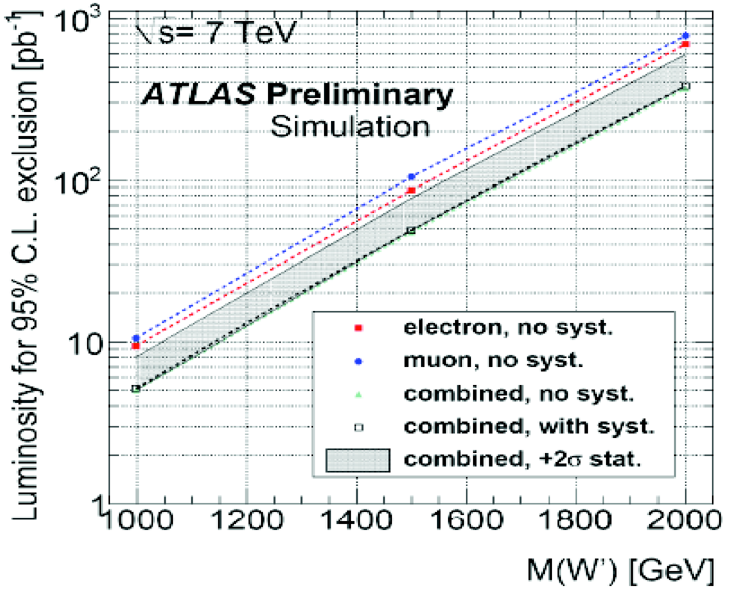
W' prospect at 7 TeV

Discovery



Discovery potential with ~10-20 pb^{-1} (fall)

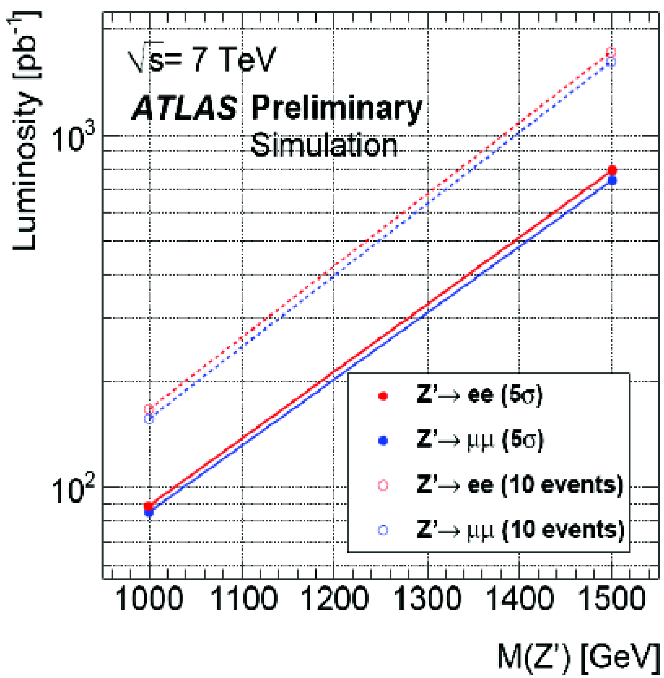
95% CL Mass Limit



Improve current limits with ~5pb^{-1}

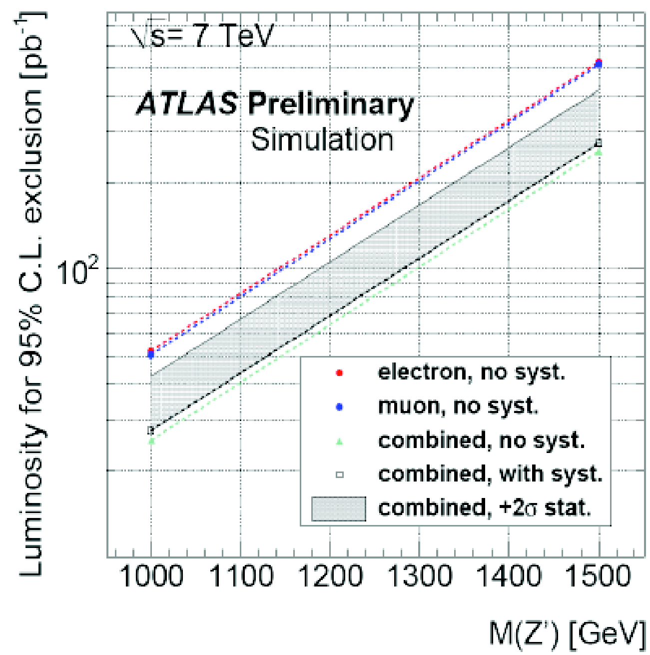
Z' prospects at 7 TeV

Discovery



Discovery potential with ~100 pb^{-1} (2011)

95% CL Mass Limit



Improve current limits with ~30 pb^{-1}

Dilepton resonance search

Benchmark signal: Z' Boson

- Current limit from CDF: $M_{Z'}>1$ TeV

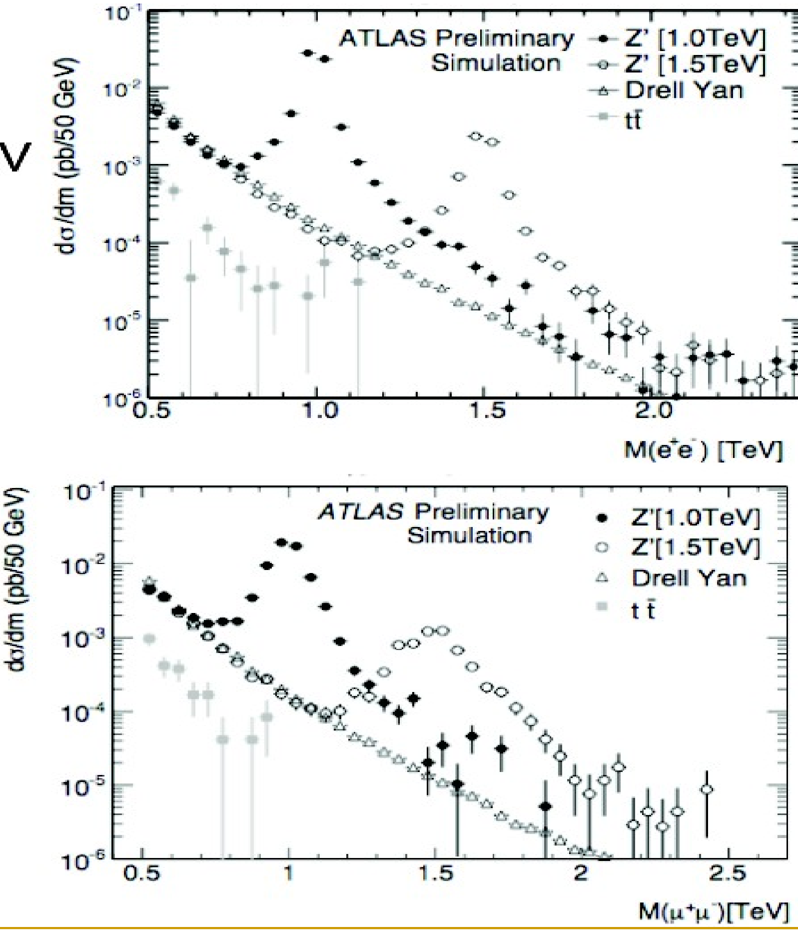
Observable: Invariant mass

Event Selections

- Two high-pt isolated leptons
  - Pt >20 GeV
- Lepton $|\eta| < 2.5$

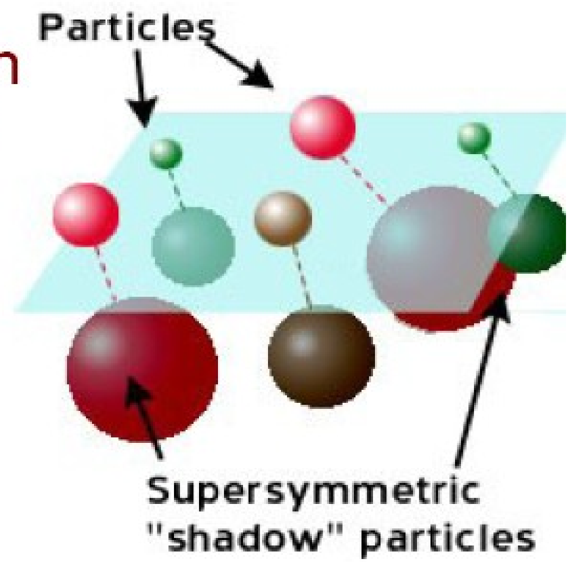
Main background:

High-mass Drell-Yan



Supersymmetry

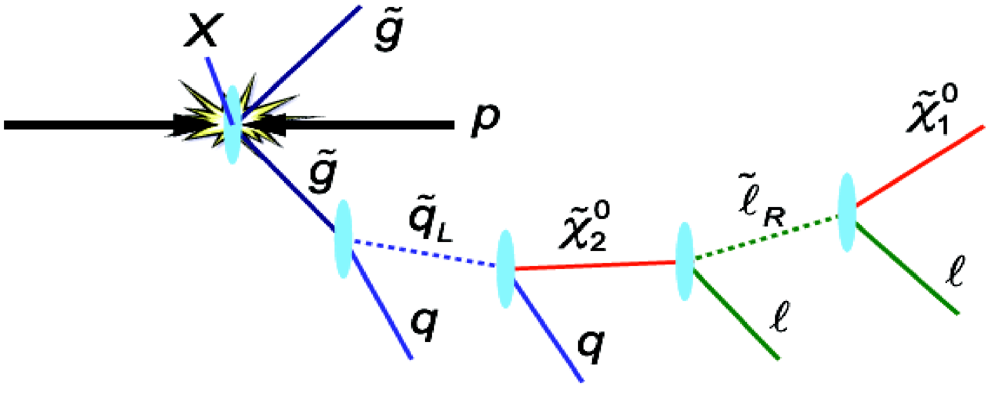
- Supersymmetry (SUSY) predicts that each standard model particle will have a SUSY partner (differing by ½ unit of spin)
  - Must be a broken symmetry, or the “sparticles” would have the ~same mass as the SM particles (and we would have seen them by now)
- SUSY phenomenology is driven by how SUSY is broken
  - Most generic has ~100 free parameters
  - Much easier to work with mSUGRA (gravity-mediated), GMSB (gauge-mediated), or other SUSY breaking models with O(5) free parameters
- R-parity



Leptons → sleptons
Neutrinos → sneutrinos
Quarks → squarks
Gauge bosons → gauginos
Higgs bosons → higgsinos
These mix to form neutralinos *and* charginos.

Searches for SUSY

SUSY provides benchmark signals for final states with high-pt jets, leptons, and $E_t$miss



Strongly produced particles

- Relatively large cross-sections

$$gg, q\bar{q}, qq, qg \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$$

Focus on inclusive searches

- First step: background studies

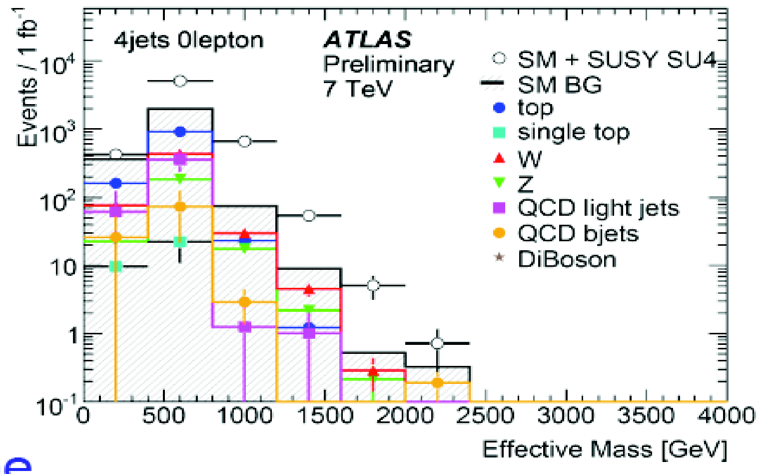
Early SUSY searches

Benchmark SUSY scenario:

- "SU4" $\sigma \sim 60$ pb
- m_0=200 GeV, $m_{1/2}$=160 GeV, A_0=-400 GeV, $\tan\beta$=10 and $\mu>0$
- Low mass point above Tevatron limits: m(squarks, gluinos) ~410-420 GeV
- current best limits from Tevatron:
  - m(squark) > 280 GeV
  - m(gluino)> 340 GeV

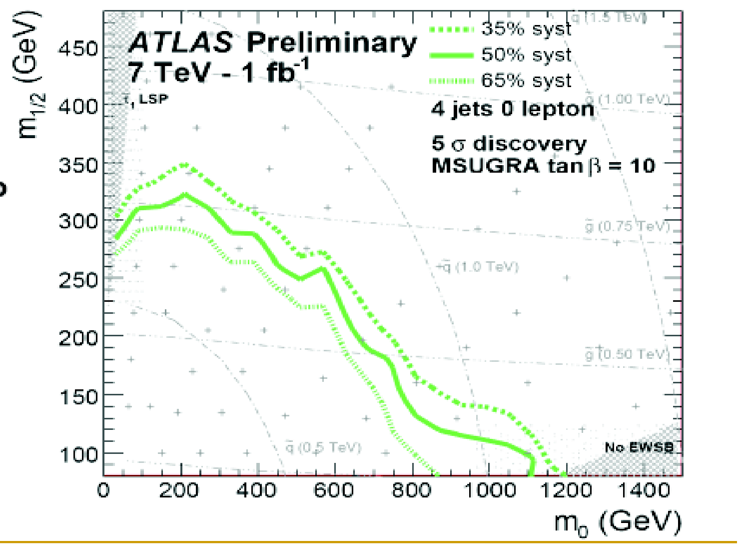
Prospects for SUSY at 7 TeV

- $E_T$miss + 4 jets + 0 lept”
  - best discovery potential
  - dominant backgrounds:
    - Top production (pair, single)
    - Vector Bosons + jets



Discovery potential in mSUGRA plane

- $\int Ldt = 1fb^{-1}$
- optimized M_{eff} cut at each point
- Expected uncertainty from data ~50 %



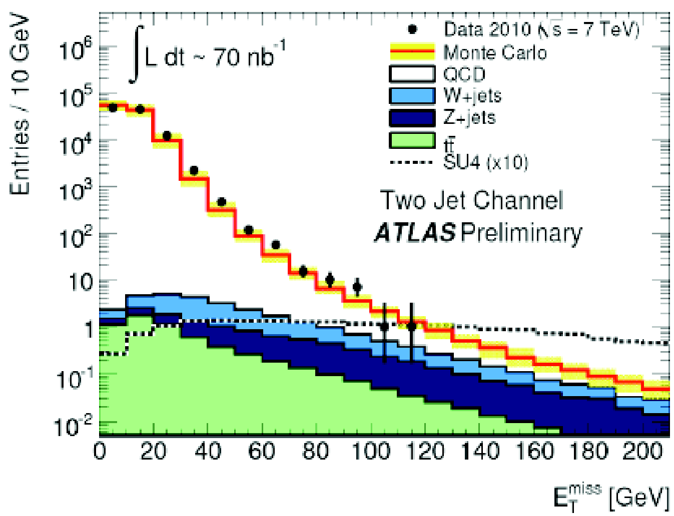
- 5σ discovery potential for squarks and gluinos up to ~700 GeV

Searches in jets + E_T^{Miss} channel

- >= 2 jets+ $E_T$miss channel

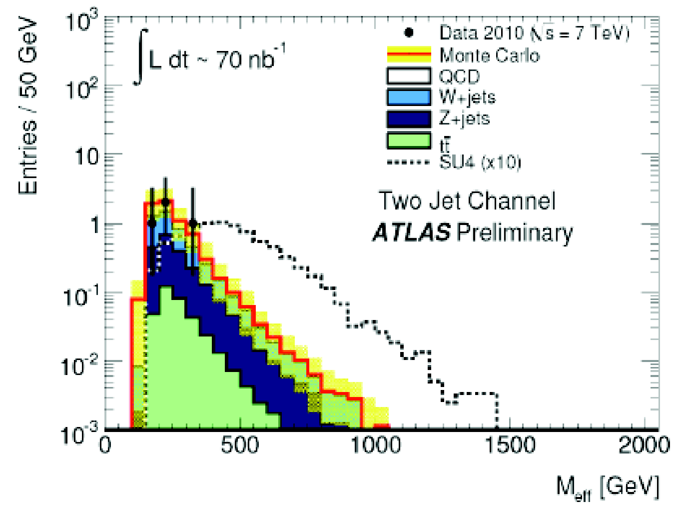
Preselection: (70nb^{-1})

- ≥2 jets with p_T>70 (30) GeV



Final selection:

- E_{Tmiss}>40GeV, ΔΦ(j_i, E_{Tmiss})>0.2
- E_{Tmiss}/M_{eff}> 0.3



LO Pythia MC normalized to data after preselection

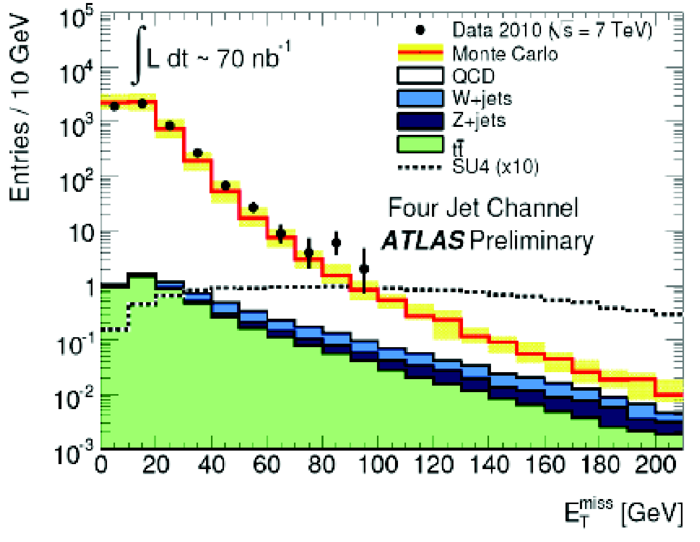
- Good description of $E_T$miss and M_{eff} shapes by MC (QCD)
- signal region: 4 events, expected: 6.6±3 (main bkg. VB +jets)

Searches in jets + E_T^{Miss} channel

- **>4 Jets +$E_T$miss channel**

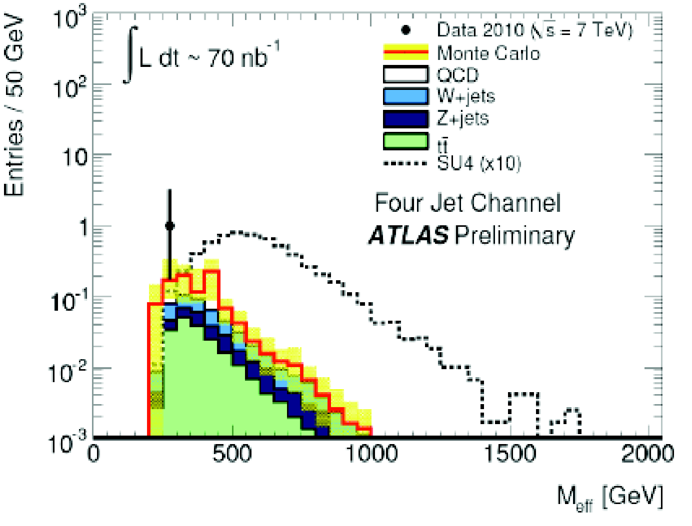
Preselection: (70nb^{-1})

- ≥4 jets with p_T>70 (30) GeV



Final selection:

- E_{Tmiss}>40GeV, $\Delta\Phi(j_i, E_{Tmiss})$>0.2
- E_{Tmiss}/M_{eff}> 0.25

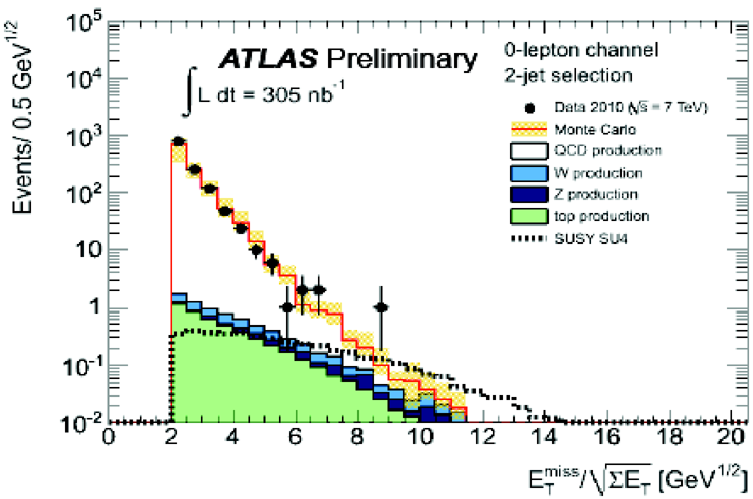


- Preselection: QCD shape well-described described by MC
- Final selection: 1 event in data; expected: 1.0±0.6

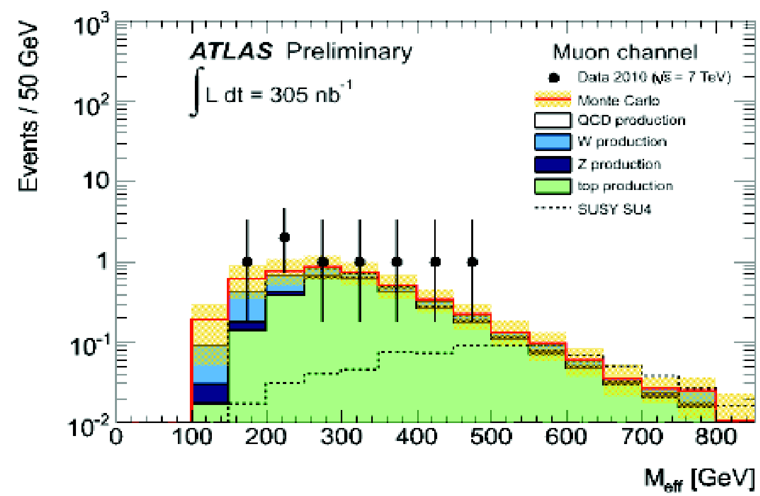
Searches in b-jets + E_T^{miss} channel

- Secondary vertex b-tagging algorithm:
  - decay length significance: $L/\sigma > 6$
  - $\varepsilon_{b\text{-tagging}} \sim 50\%$
- event selection (305 nb^{-1}):
  - channels: "≥2-j (70,30)", "≥1 lep (20) + 2 j (30,30)"
  - $E_{Tmiss}/\sqrt{\Sigma E_T} > 2\ \sqrt{GeV}$, at least one b-jet

dijet channel



1μ+2jets



ATLAS analyses: end of September

- Preliminary results show that data is consistent with SM predictions.
- SUSY search with loose threshold :
  - The good level of understanding of the ATLAS performance
- Dijet resonance search :
  - Exclude **0.4TeV**$<$**m**$_q^*$ $<$**1.26TeV**
  - Surpassed world's best limit, paper accepted by PRL.
- Dijet angle distribution search :
  - Limit on **compositeness scale** Λ **3.4TeV**
  - Surpass the current best limit
- Multi-object search :
  - **The upper limit of 0.34nb** with $M_{inv} > 800 GeV$, sumPt>700GeV
  - First time!, sensitive to black hole, string ball search
- Electron + E_T^{miss} search :
  - Limit on **SSM W' 465GeV**
  - Expect $10pb^{-1}$ to surpass the current best limit

Next topics

- 1.12 – di-bosons and anomalous couplings
- 8.12, 15.12 – Higgs (SM)
- 5.01 - Searches: new exclusion limits
- 12.01 - Higgs (MSSM)
- 19.01, 26.01 - SUSY