Leptoquark and heavy quark searches in ATLAS

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On behalf of the ATLAS Collaboration

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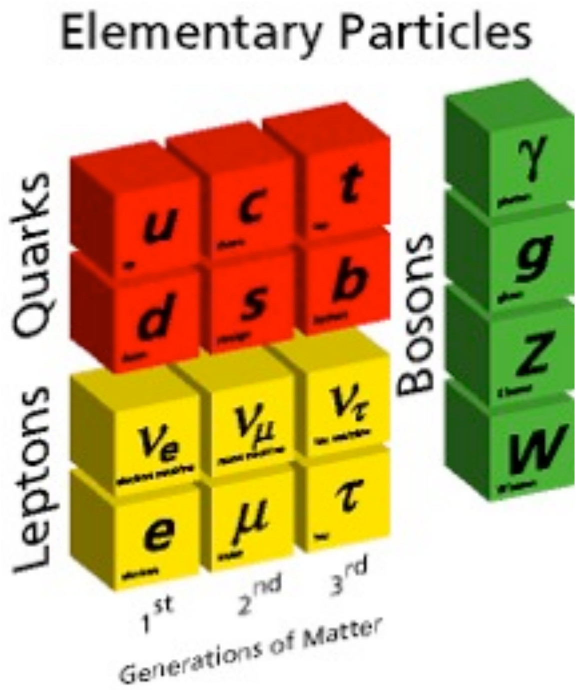
Trying to explain the SM generational structure

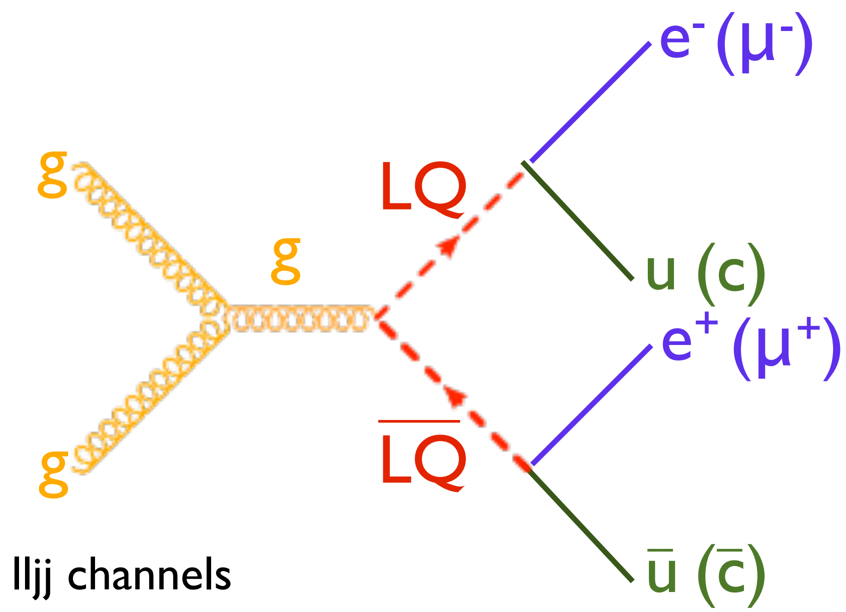


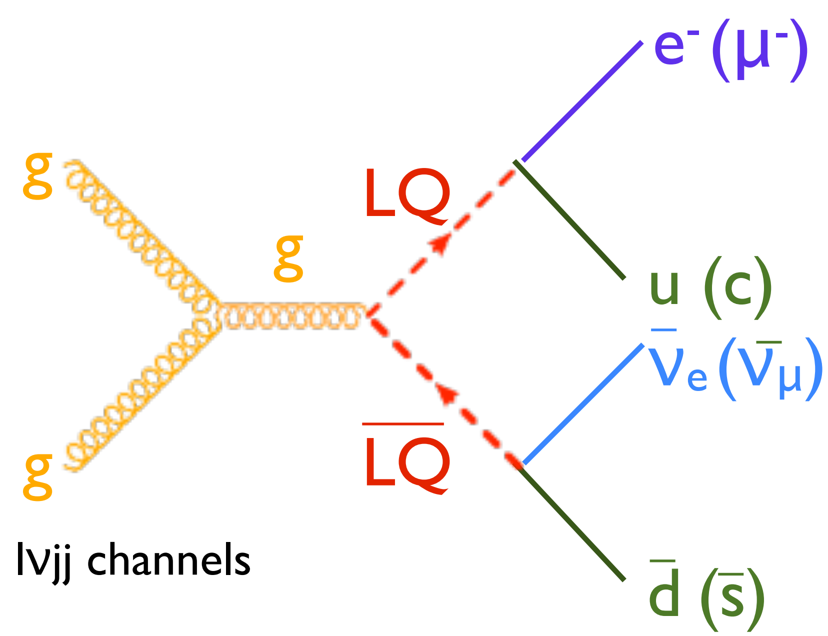
- The SM is a very successful model but leaves some questions unanswered
  - Where does the symmetry between quarks and leptons comes from?
  - Why exactly 3 generations? Do we have reasons to look for more?

- **Leptoquarks** (LQ) are gauge bosons that carry both lepton and baryon numbers and fractional electric charge
  - Introduced by many different extensions the SM (GUT theories, SUSY, Technicolor) (our searches are model independent)
  - Experimental limits on flavor-changing neutral currents and lepton-family number violation → LQ only couple to quarks and leptons of the same generation → 3 LQ generations
- Search for fourth generation quarks (**heavy quarks**)
  - The QCD asymptotic freedom limits the number of SM generations to be 9
  - Neutrino oscillations suggest the possibility of additional heavier neutrinos

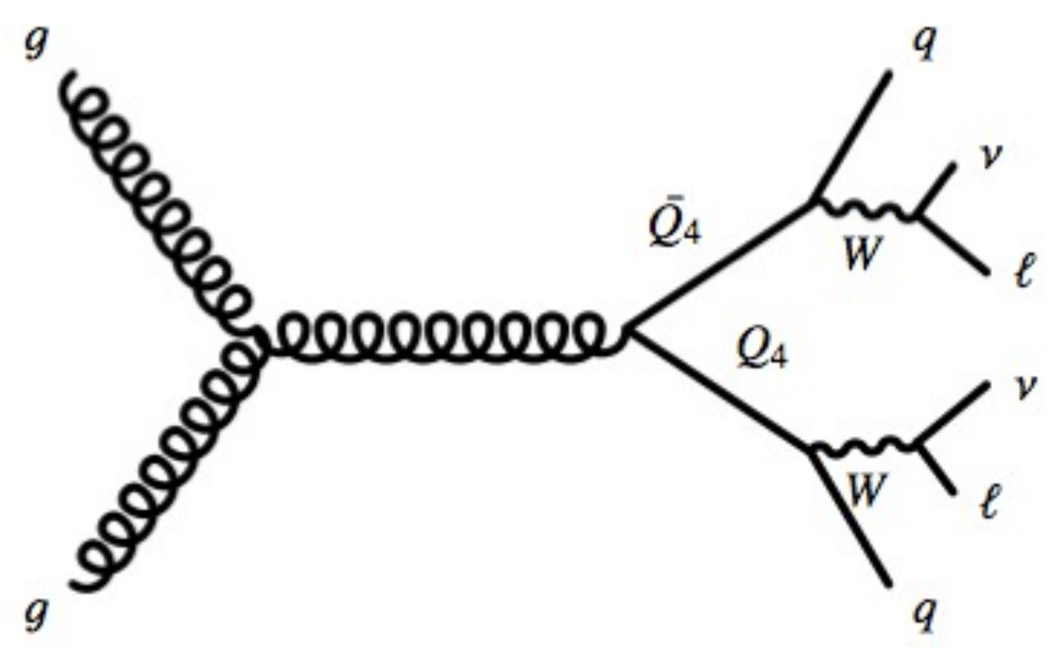
Experimental signatures

- **Leptoquark** searches for 1st and 2nd generations in the dilepton and single lepton channels





- **Heavy quark** searches in the dilepton channel



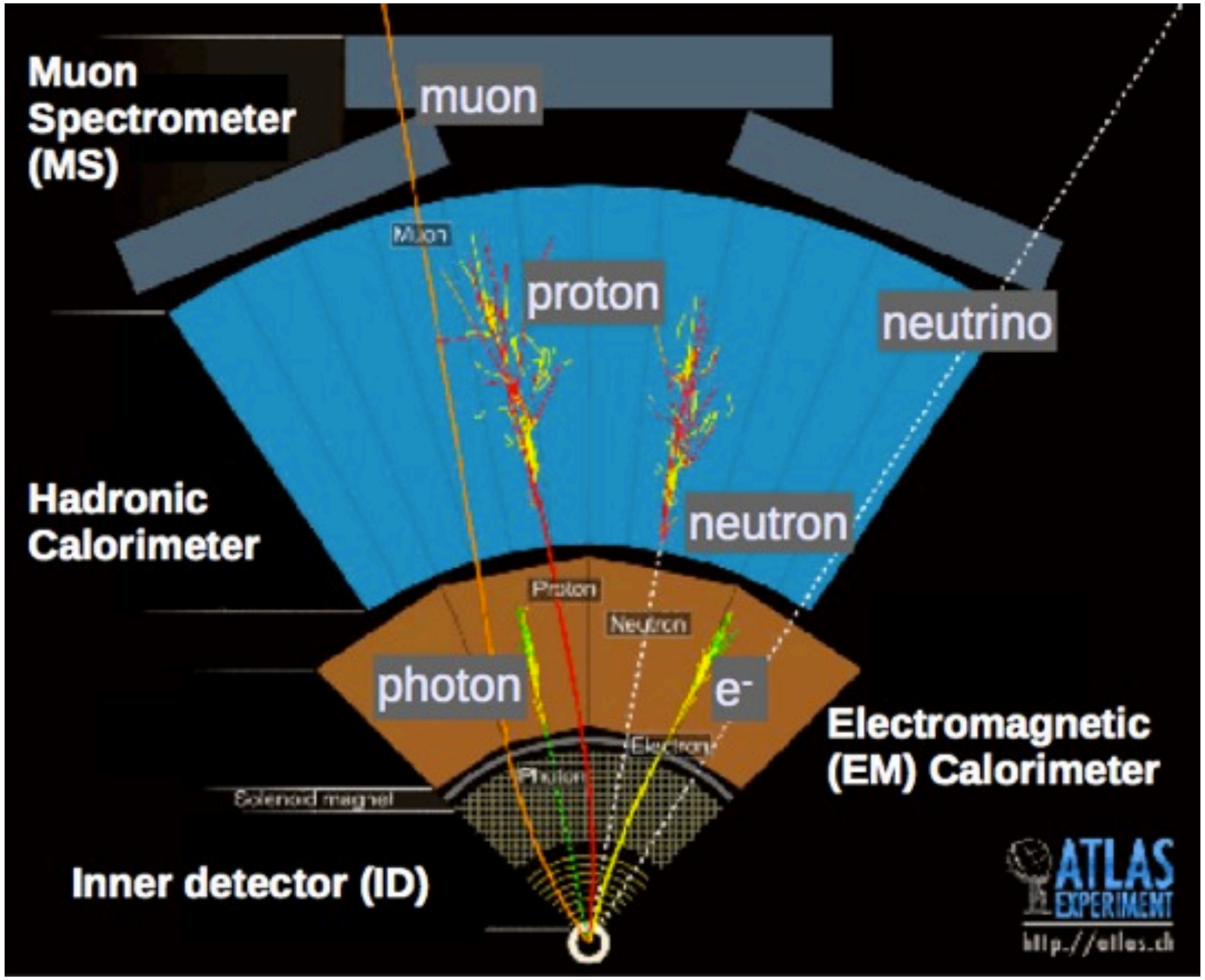
Key objects are
- Leptons
- Jets
- Missing E_T (MET)

Object selection

Electrons
Good EM shower
Track pointing to a EM cluster
$E_T > 20$ GeV, $\|\eta\| < 2.47$ (exclude crack region)
Isolated

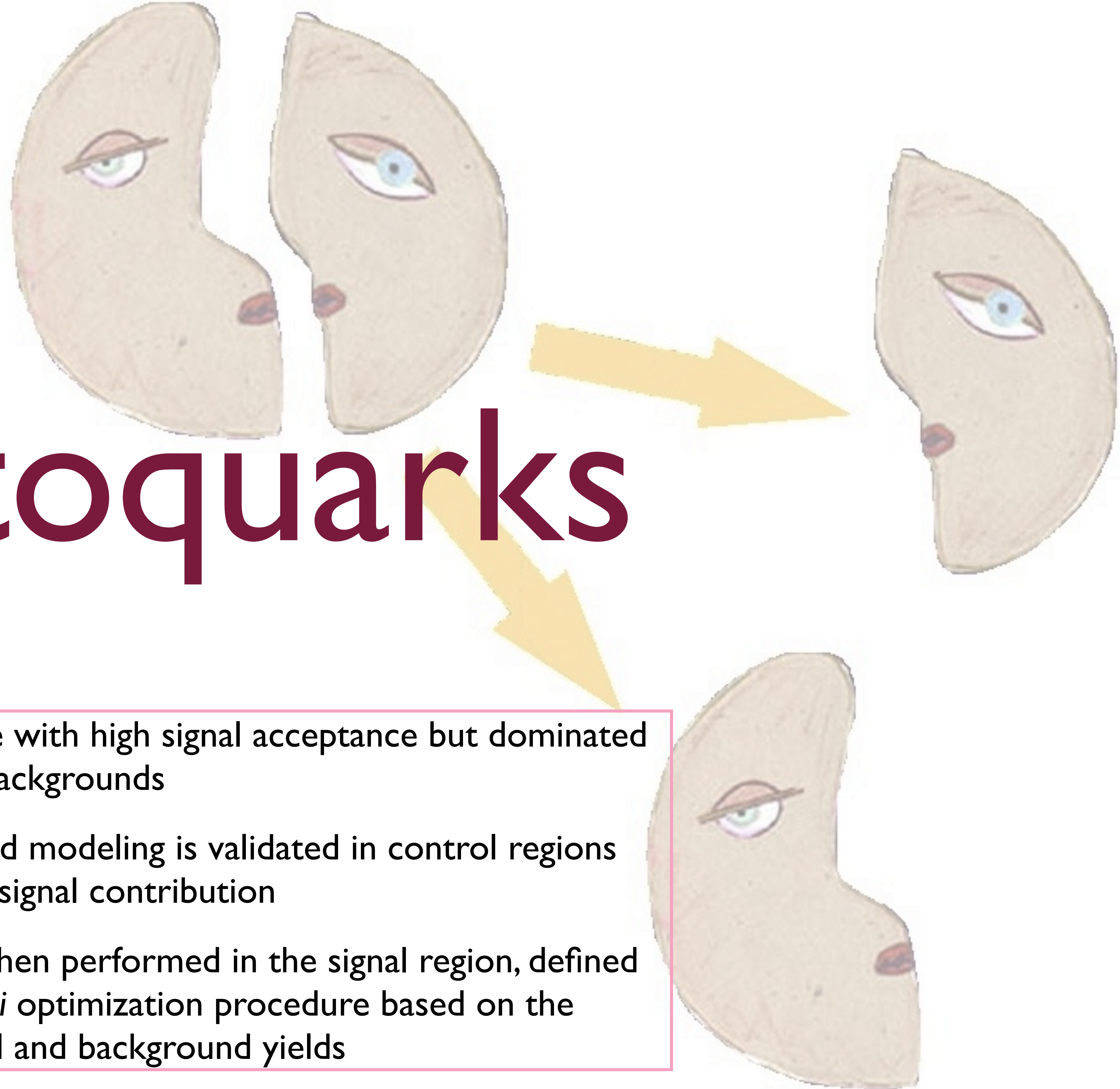
Muons
Reconstructed by matching independent tracks in the inner tracker and the muon spectrometer
$p_T > 20$ GeV, $\|\eta\| < 2.4$, Isolated

Jets
Anti-kt with R parameter of 0.4
$p_T > 20$ GeV, $\|\eta\| < 2.8$
Satisfy minimum dR(lepton, jet)
Pass quality criteria (timing, far from detector problematic regions, etc)



MET
Negative of the energy vector sum (corrected for muon p_T in the muon channels)
Pass quality criteria: no low quality jets in the event

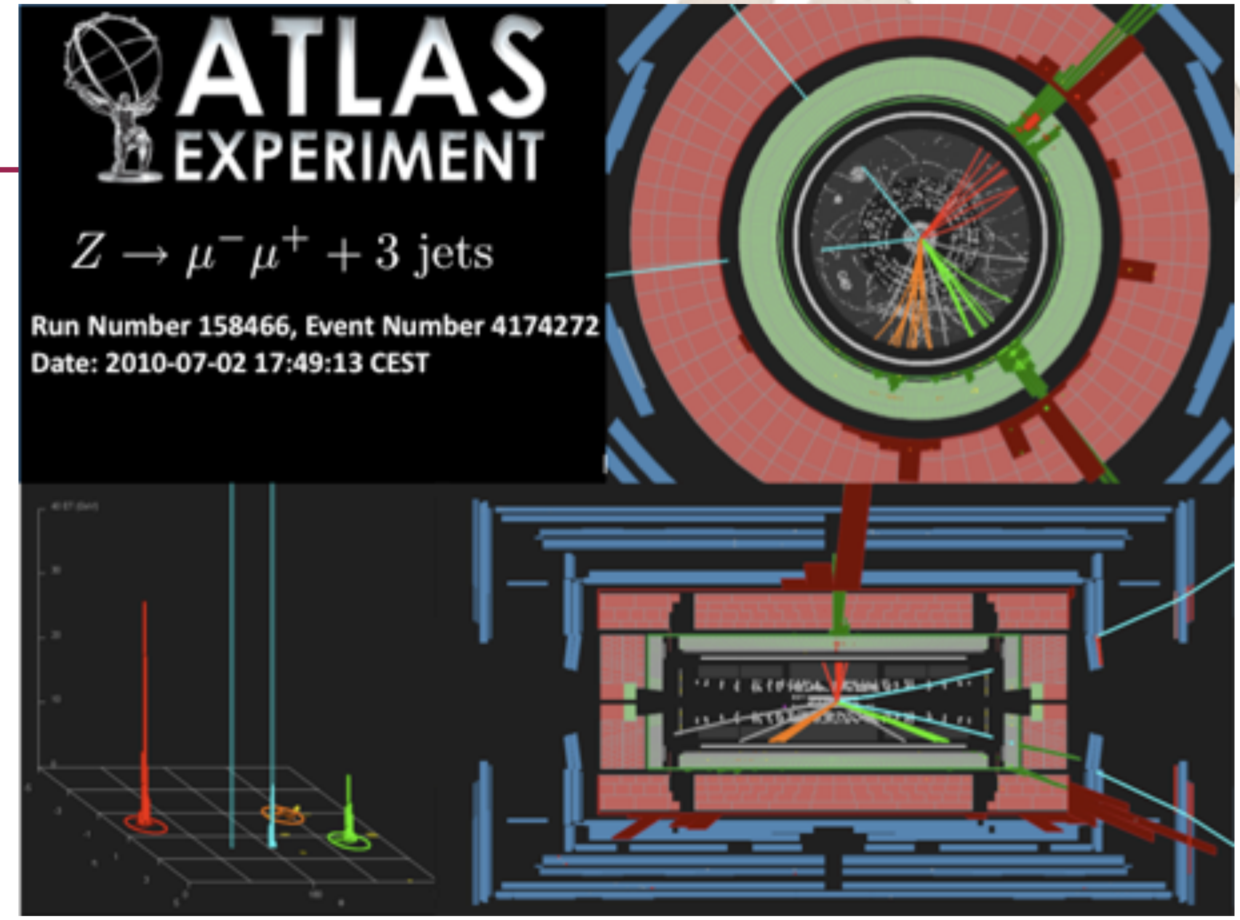
Leptoquarks

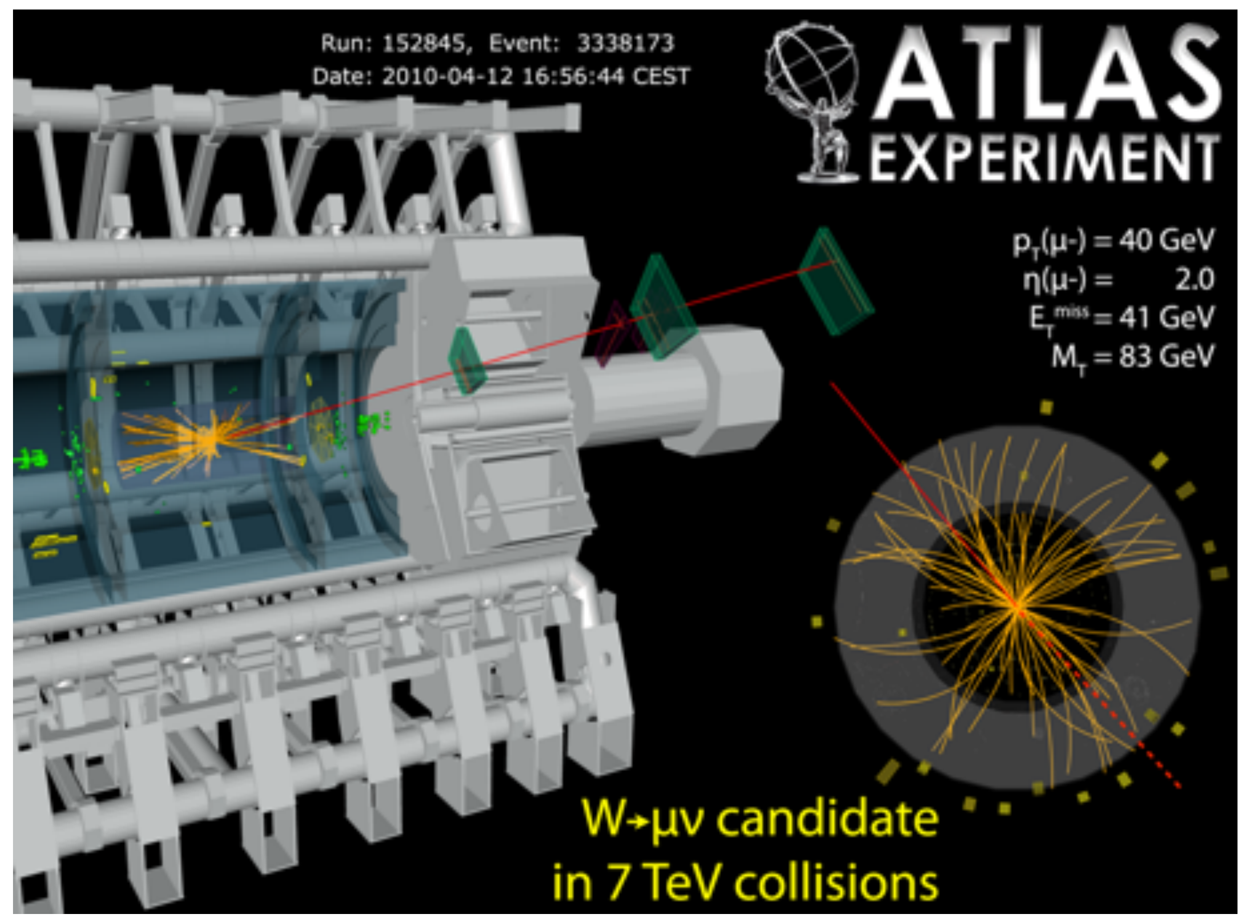


- Select a sample with high signal acceptance but dominated by the major backgrounds
- The background modeling is validated in control regions with negligible signal contribution
- The search is then performed in the signal region, defined using an *a priori* optimization procedure based on the expected signal and background yields

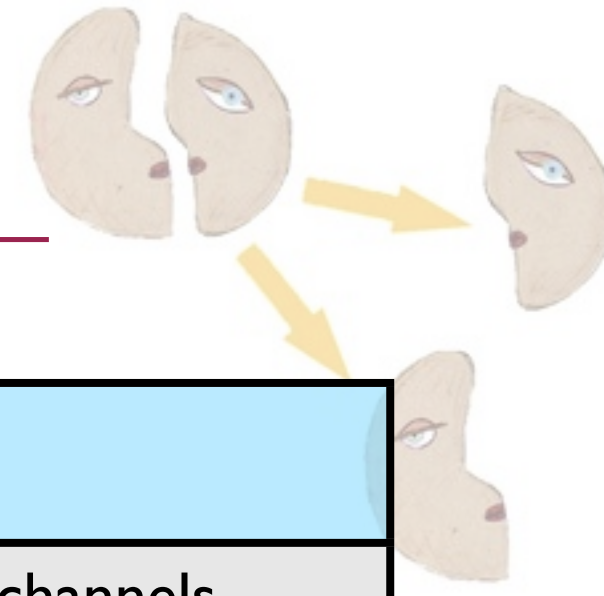
Event preselection

Only events collected with a fully operational detector
Events must fire a single lepton trigger
At least one primary vertex with at least 3 tracks pointing to it and $\|z\| < 15$ cm
Exactly one lepton for single lepton channels Exactly two leptons for dilepton channels
At least 2 jets
Single lepton channels: MET > 25 GeV
Single lepton channels: M_T (lepton,MET) > 40 GeV





Background estimation

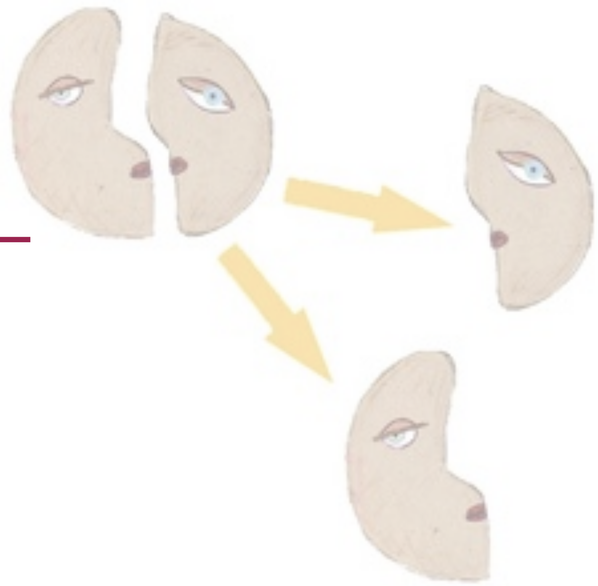


Source	Method
V+jets	ALPGEN Monte Carlo in single lepton channels Semi data-driven in dilepton channels Modeling validated in control regions
ttbar	Simulated samples using MC@NLO and POWHEG Modeling validated in control regions
single top	Simulated MC@NLO samples
Diboson	Simulated Herwig samples
Multijet*	Data-driven, different methods depending on the channel

major backgrounds

* = includes fakes from W+jets events in dilepton channels

Data-driven backgrounds



Multijet in the single muon channel

- ABCD method with MET and the muon transverse impact parameter (d_0) for the single muon channel
  - Uncorrelated variables (less than 10% in the data)
  - The (MET, d_0) space is divided into four statistically independent regions
  - One of these regions is the signal region, and the others are used to obtain the background yield and normalization

$$N_{QCD} = \frac{N_A N_C}{N_B}$$

QCD in dilepton channels

- Fit isolation distribution to templates
- Signal templates obtained from Zs, background templates from a QCD enriched sample

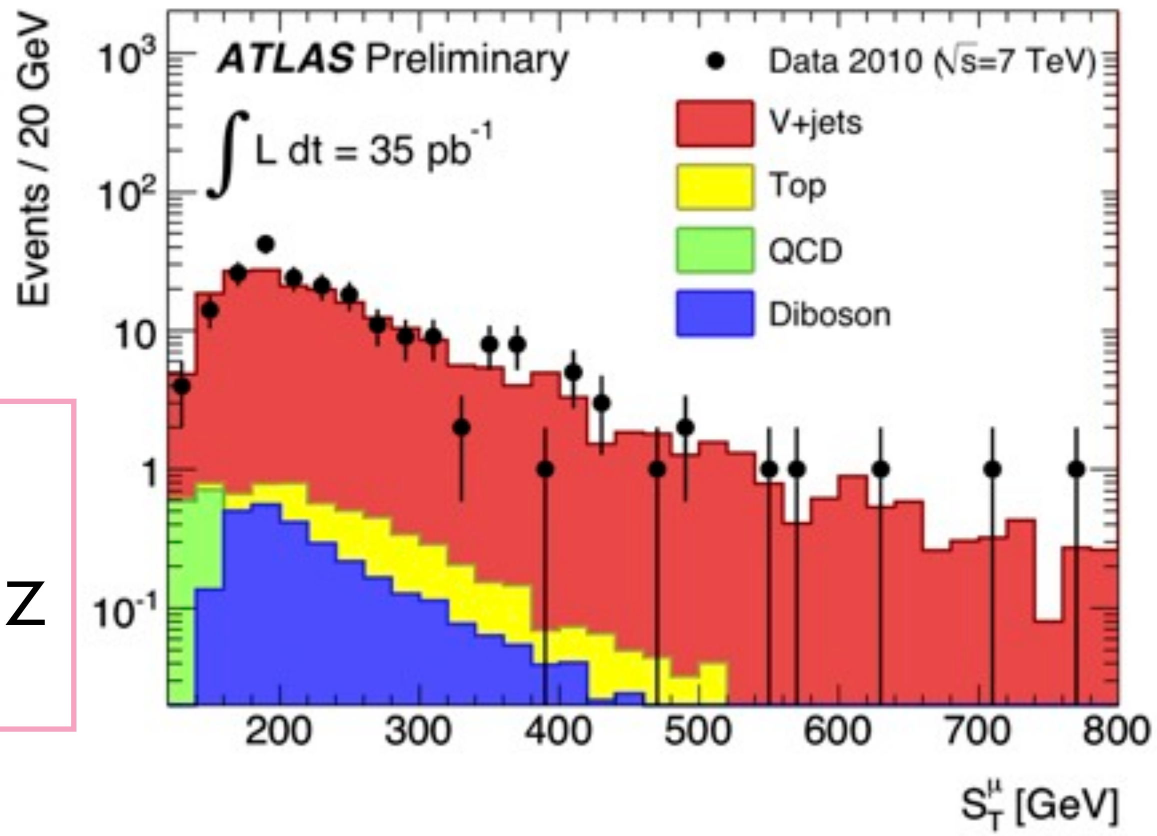
Multijet in the single electron channel

- Fit the M_T distributions to the total simulated background and a QCD enriched sample
- The QCD enriched sample is formed with the electrons that pass the trigger selection but not the offline selection
- A matrix method is used to remove the shape of the residual real electron contamination

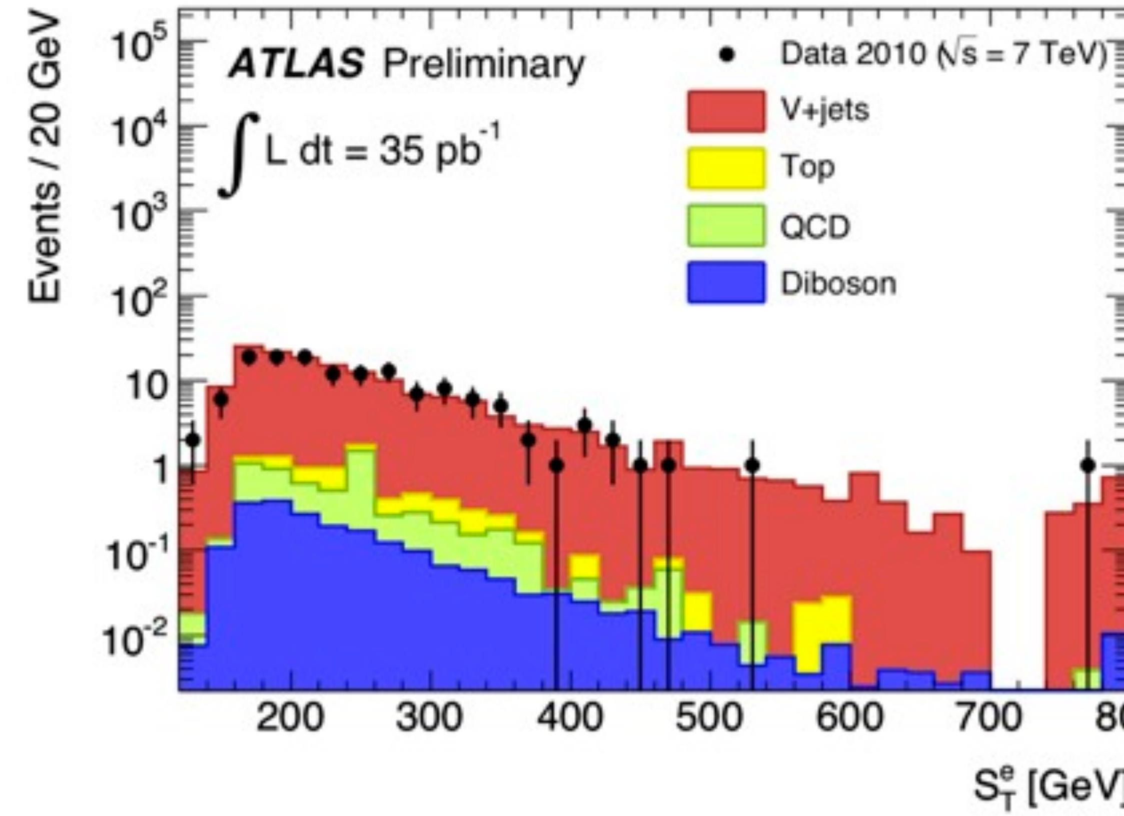
Z+jets in dilepton channels

- The Monte Carlo Z+jets events in the signal region are scaled using the yields obtained from the data under the Z peak mass
- Different mass windows, generators, and jet multiplicity requirements

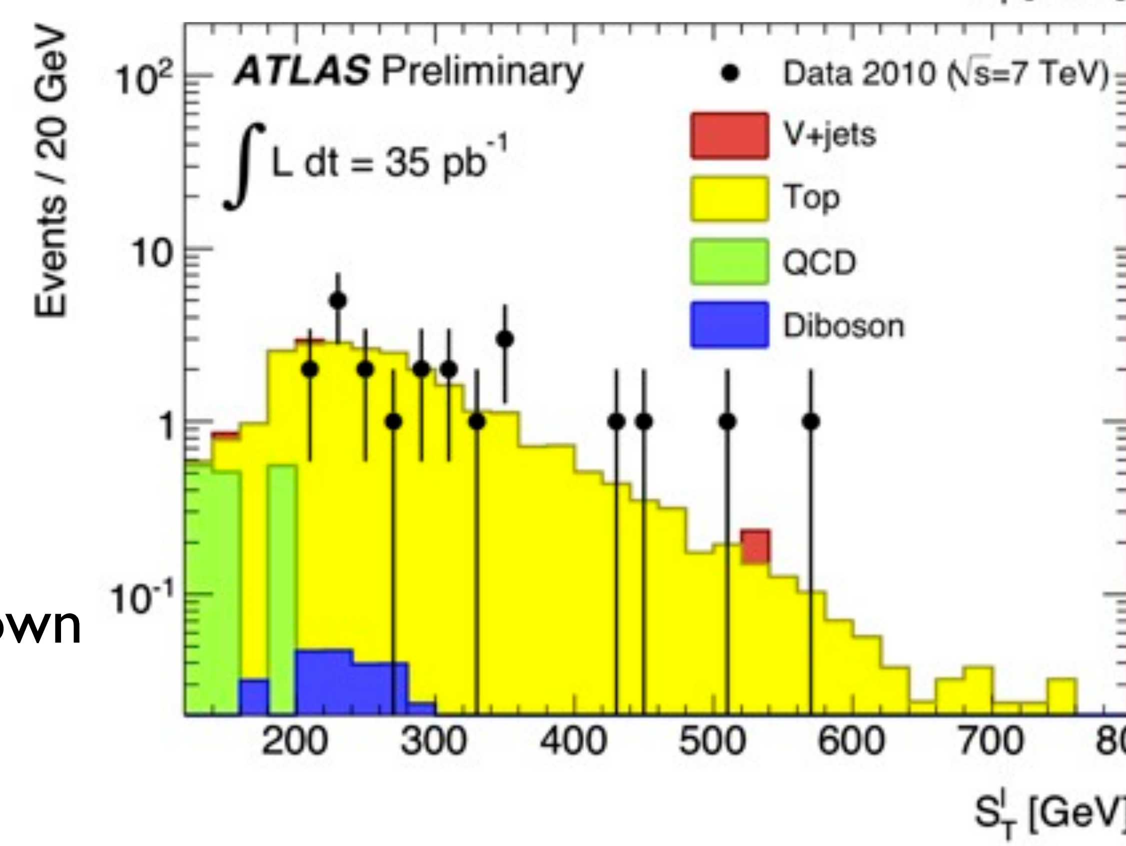
Dilepton control regions



Z+jets: Events under the Z mass peak



ttbar: Events with one electron and one muon

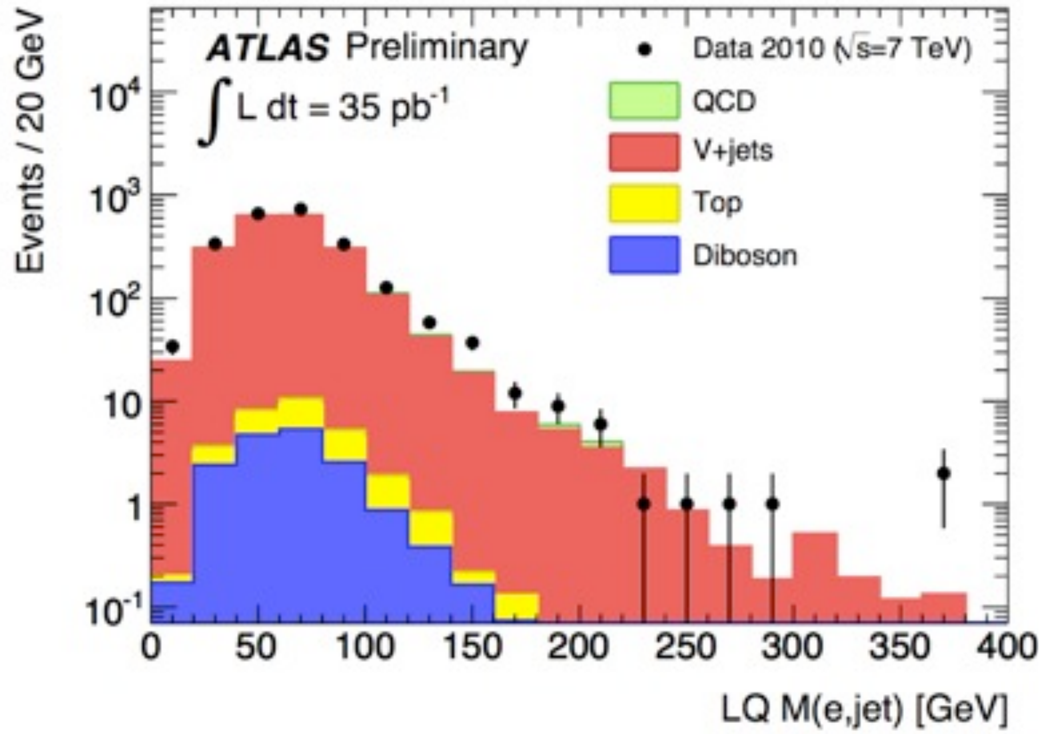


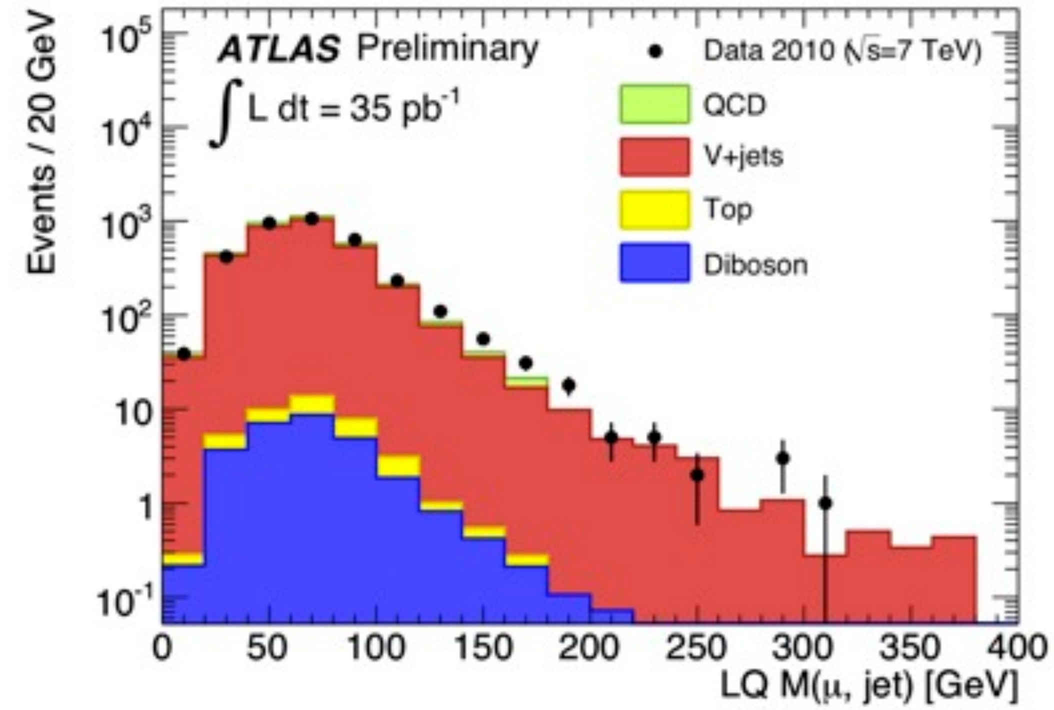
$$S_T = p_T^{lepton1} + p_T^{lepton2} + p_T^{jet1} + p_T^{jet2}$$

- Systematic uncertainties of the order of 20% not shown
- Good agreement between data and SM predictions

Single lepton control regions

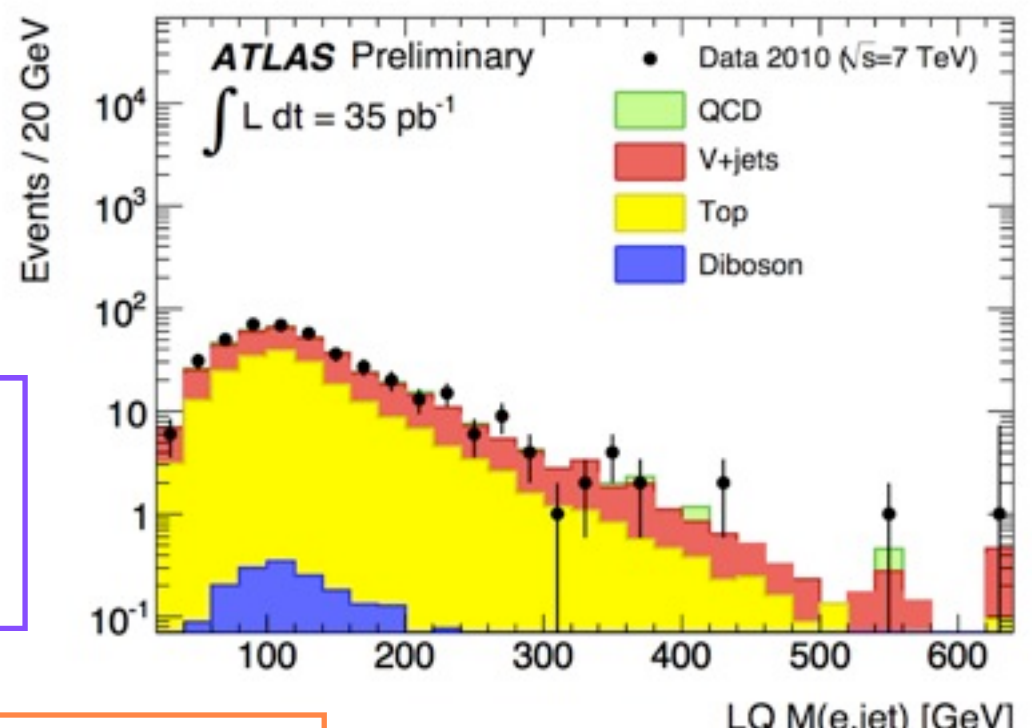
W+jets: Events under the W mass peak and exactly 2 jets (also an inclusive 3 jets CR)

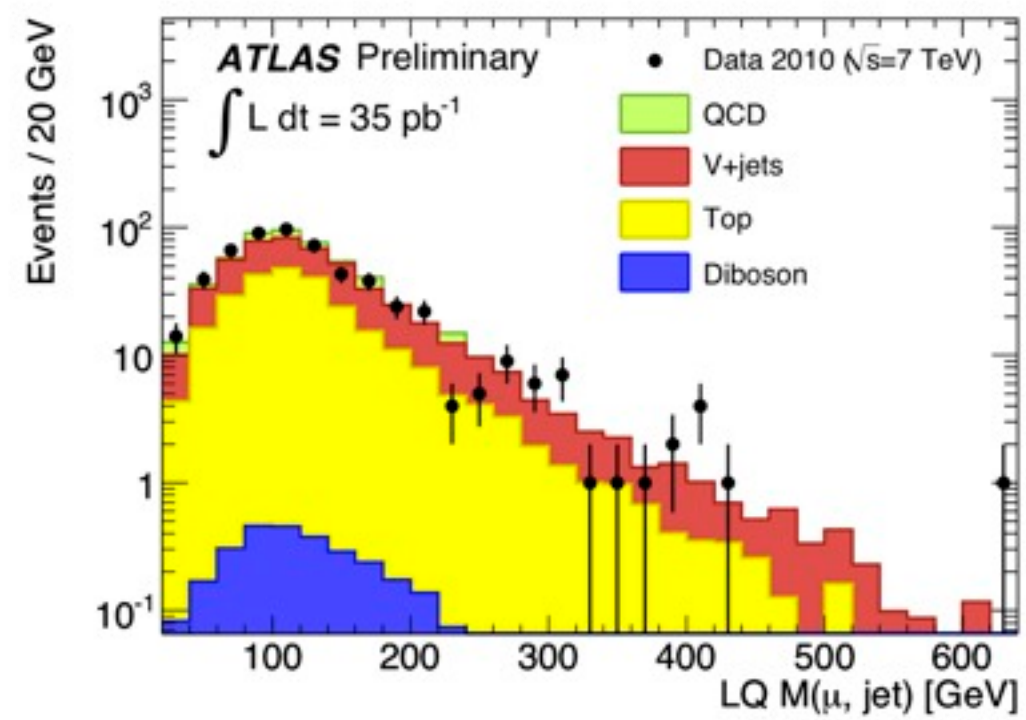




ttbar: Events with more than 4 jets

Signal contamination is reduced by requiring small S_T



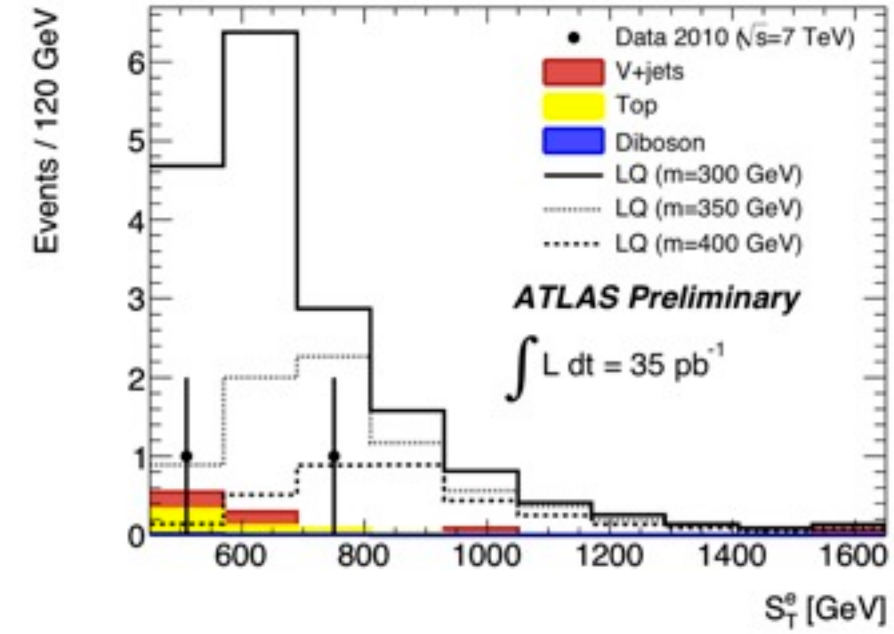


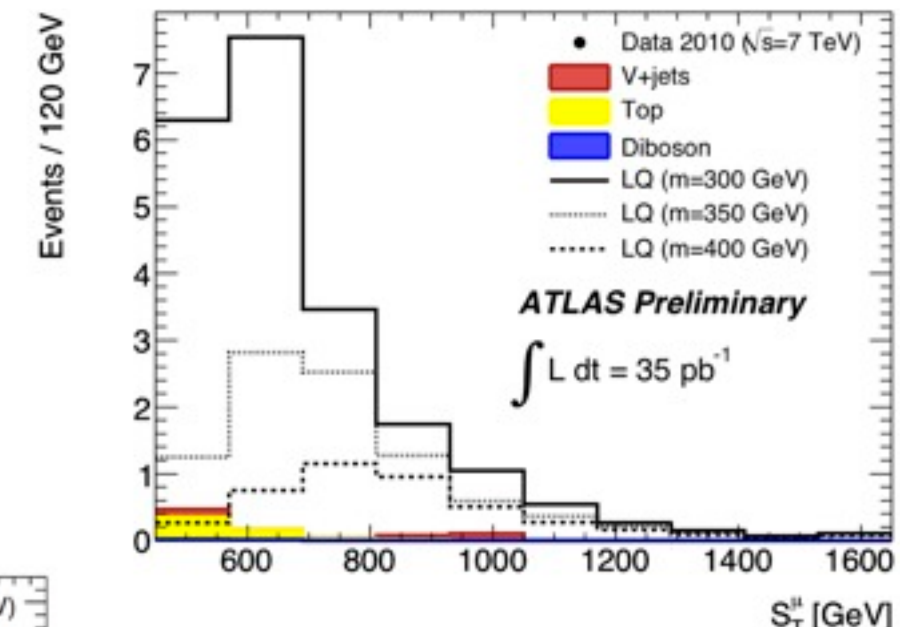
LQ mass is reconstructed from the minimum ΔM between all the possible (lepton,jet) pairings

- Systematic uncertainties of the order of 30% not shown
- Good agreement between data and SM predictions

Optimization and signal region

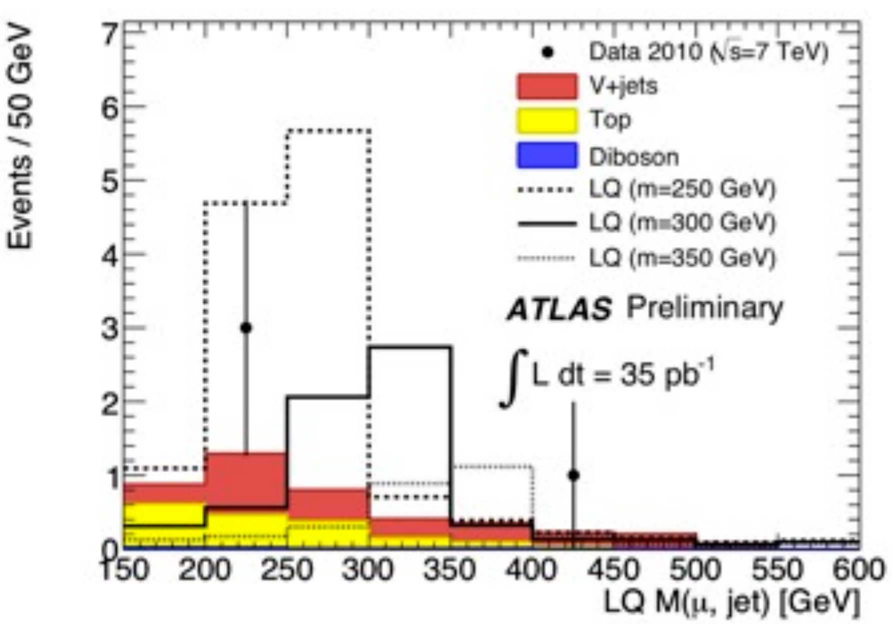
- Obtain the cut combination that results in the highest signal significance combining as few variables as possible
- We use a Random Grid Search where the grid points are all the signal events, and the signal significance is calculated as the Poisson probability that the predicted bkg fluctuates to at least the signal + bkg yields (no shapes taken into account)

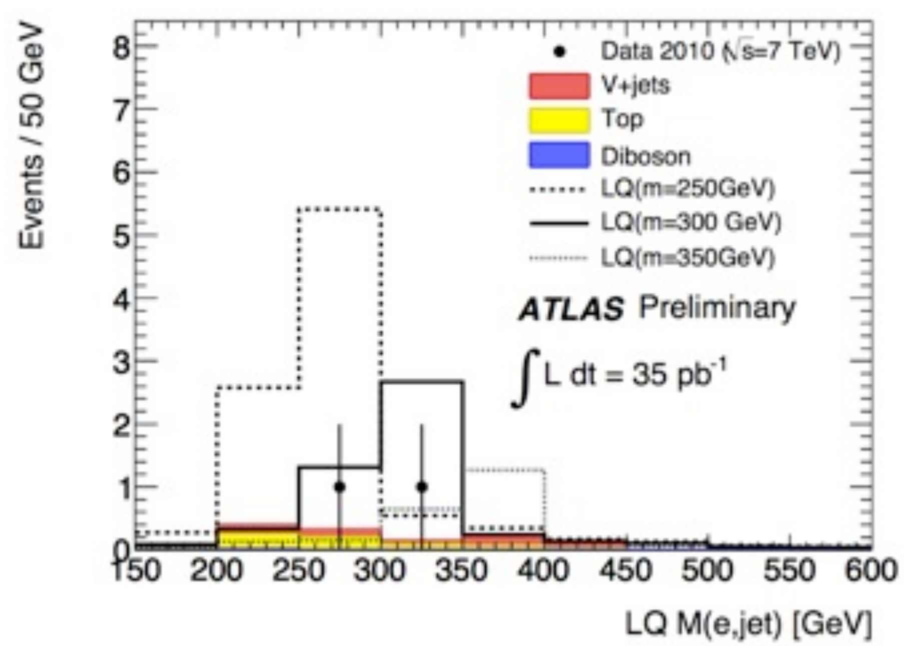




Use reconstructed boson and LQ masses and ST to distinguish signal from bkg

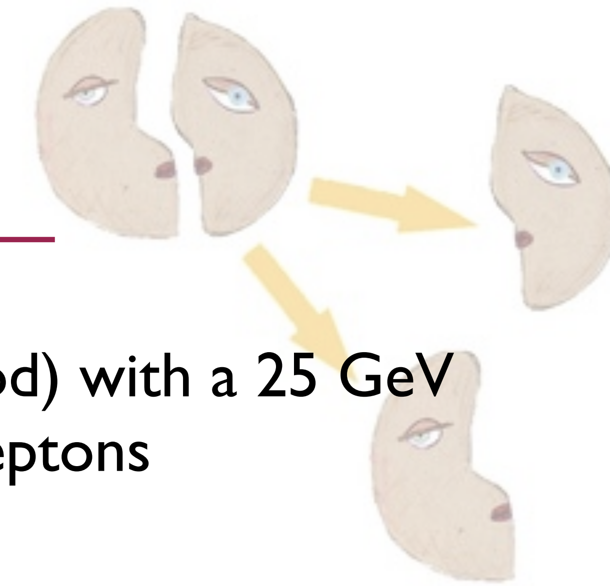
$eejj$ and $\mu\mu jj$	$e\nu jj$	$\mu\nu jj$
$M_{ll} > 120$ GeV	$M_{\mathrm{T}} > 200$ GeV	$M_{\mathrm{T}} > 160$ GeV
$M_{\mathrm{LQ}} > 150$ GeV	$M_{\mathrm{LQ}} > 180$ GeV	$M_{\mathrm{LQ}} > 150$ GeV
$p_{\mathrm{T}}^{\mathrm{all}} > 30$ GeV	$M_{\mathrm{LQ}}^{\mathrm{T}} > 180$ GeV	$M_{\mathrm{LQ}}^{\mathrm{T}} > 150$ GeV
$S_{\mathrm{T}}^{\ell} > 450$ GeV	$S_{\mathrm{T}}^{\nu} > 410$ GeV	$S_{\mathrm{T}}^{\nu} > 400$ GeV



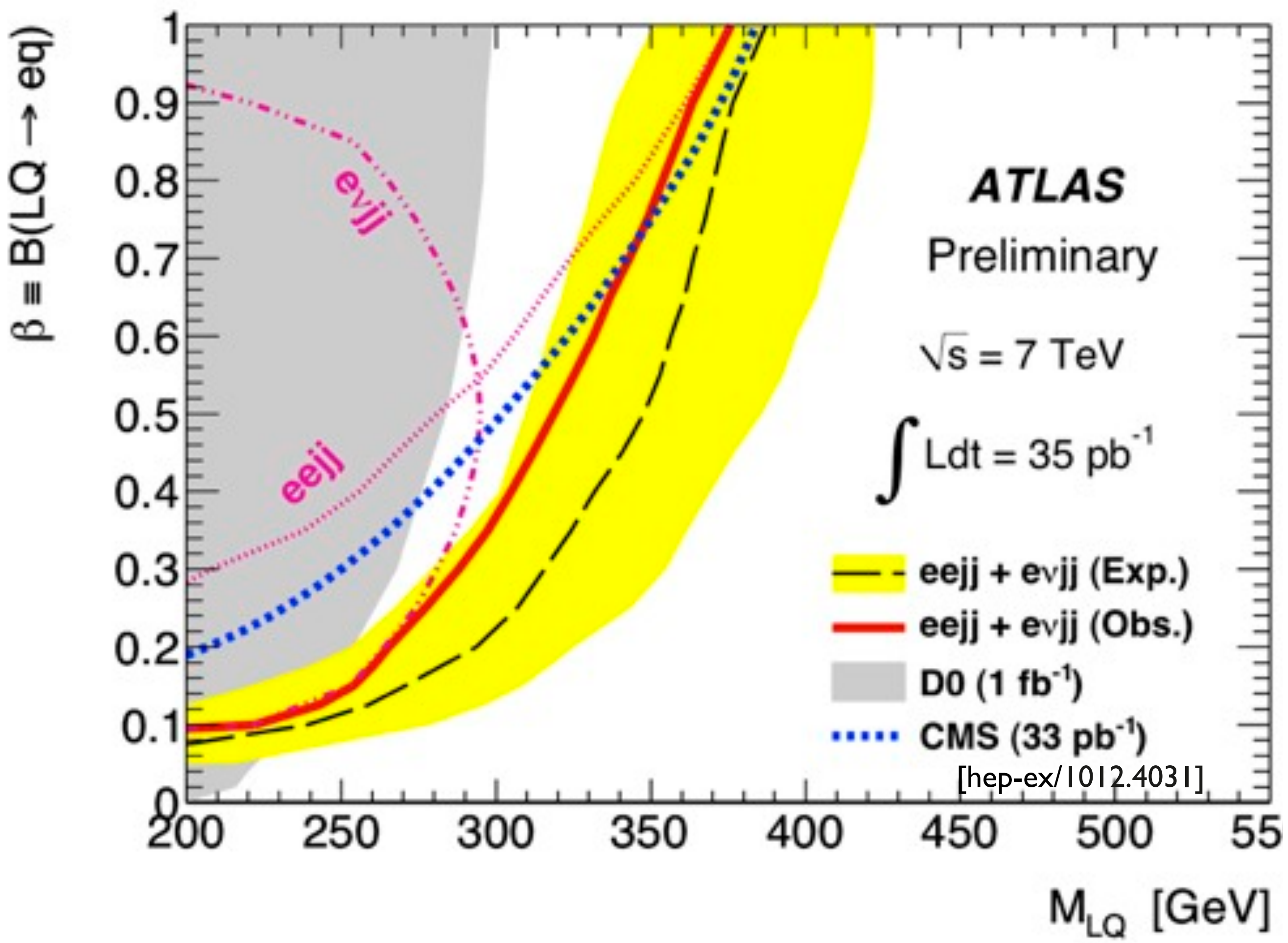


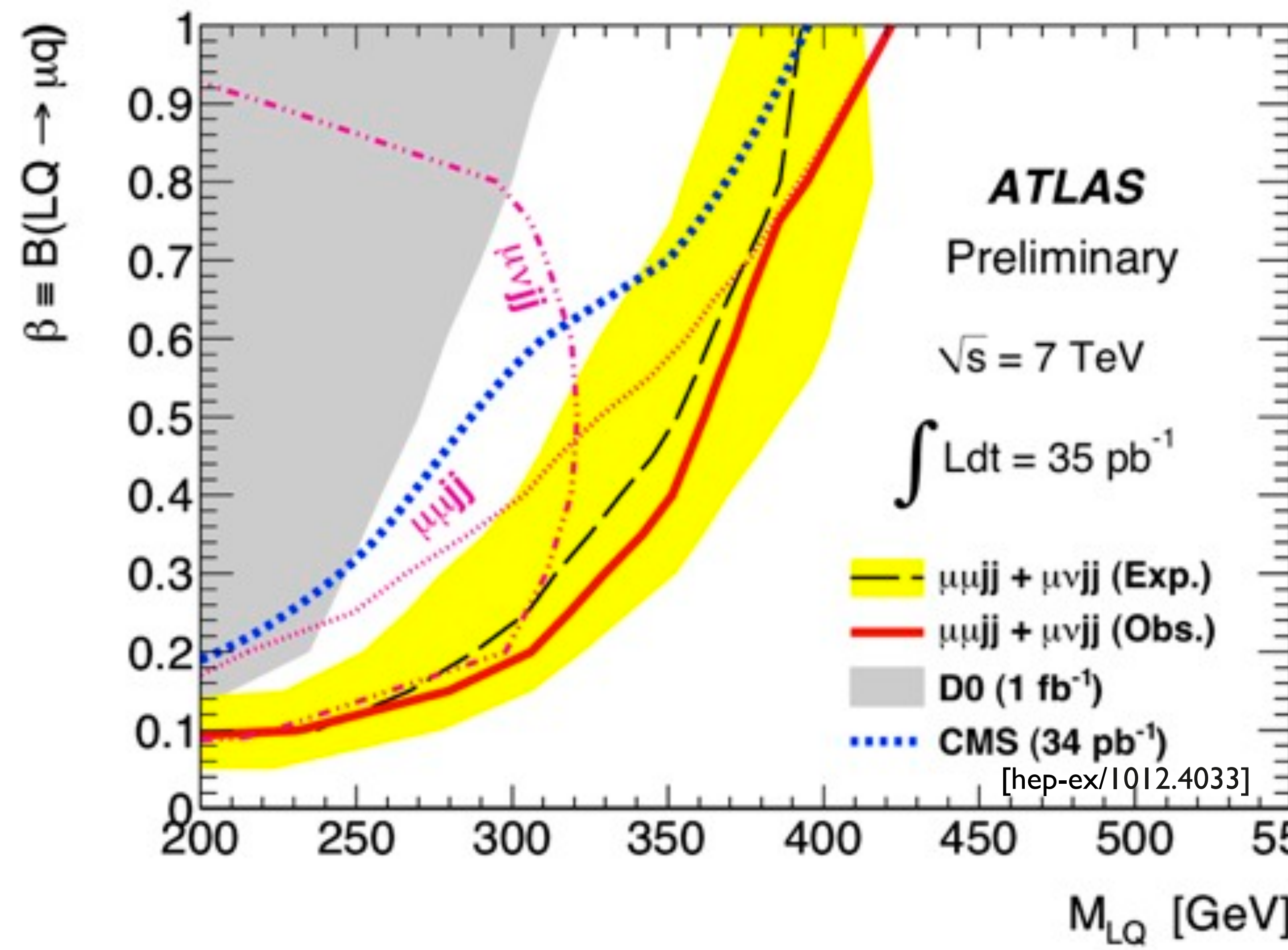
No hint of LQs: Good agreement between data and SM expectation

Results



- Limits are calculated using a modified Frequentist approach (CLs method) with a 25 GeV binning and using the S_T for the dileptons, and the mLQ for the single leptons





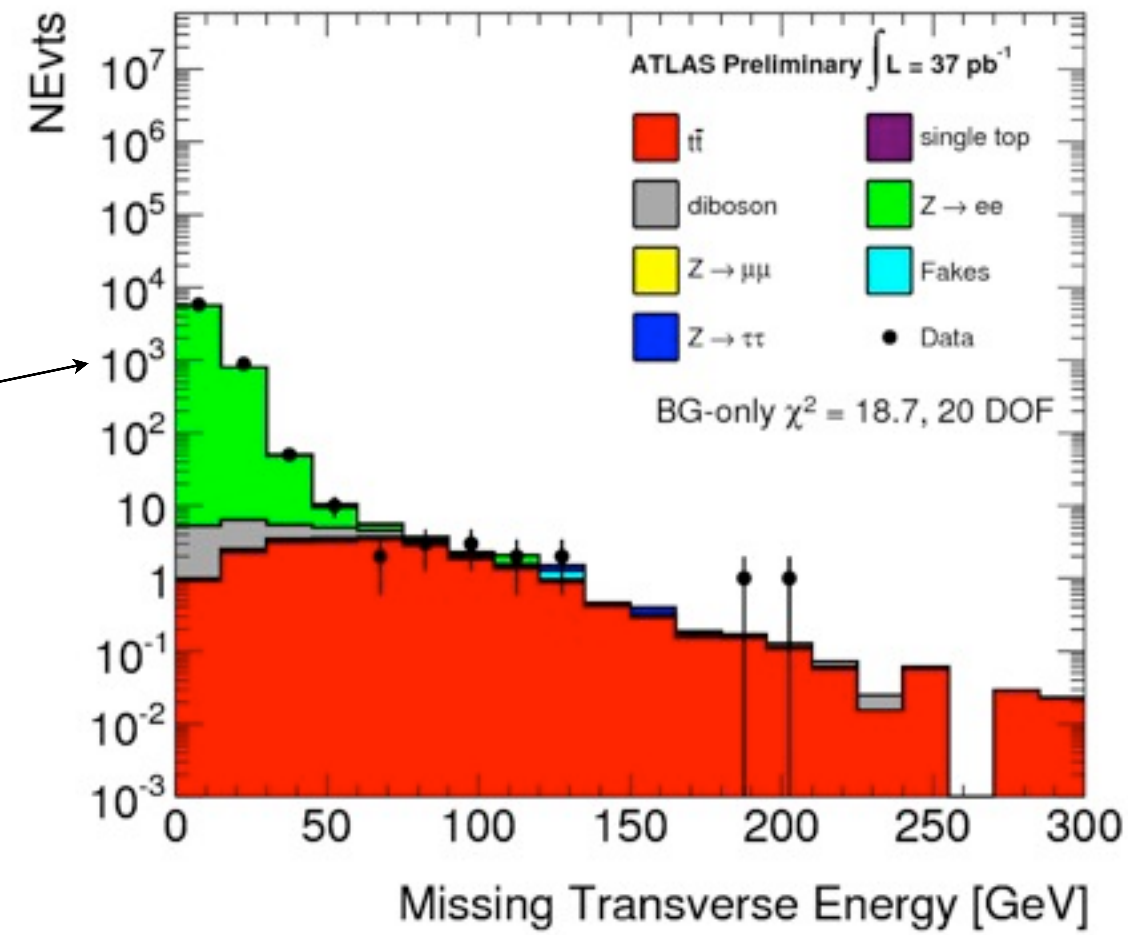
Exclude 376 (319) GeV 1st generation LQ at $\beta = 1$ ($\beta = 0.5$)	Exclude 422 (362) GeV 2nd generation LQ at $\beta = 1$ ($\beta = 0.5$)

Heavy quarks

- Initial selection and control regions to validate backgrounds
- Use of the H_T and reconstructed mass to reject background and define the signal region
- Search for heavy quarks in the signal region

Event selection and background estimation

Only events collected with a fully operational detector
Events must fire a single lepton trigger
At least one primary vertex with at least 5 tracks pointing to it
Exactly two opposite charged leptons
At least 2 jets
Same flavor leptons must fall outside a Z mass window of 20 GeV
MET > 40 GeV for same flavor leptons
$H_T = p_T^{lepton1} + p_T^{lepton2} + p_T^{all\ jets} + MET > 130$ GeV

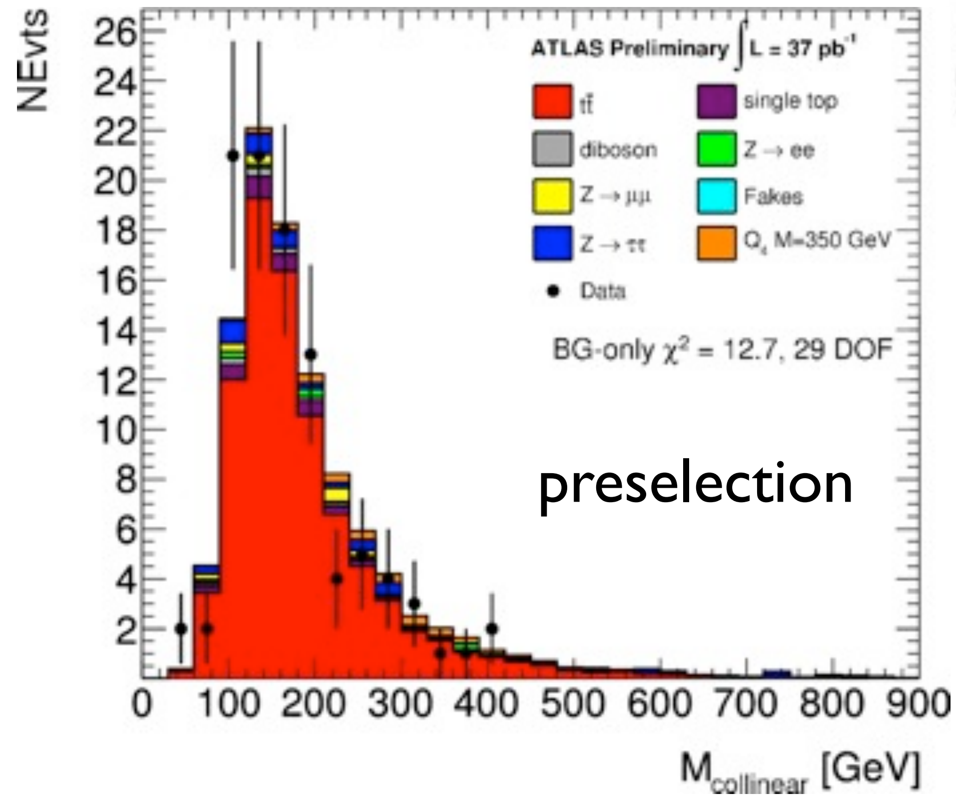


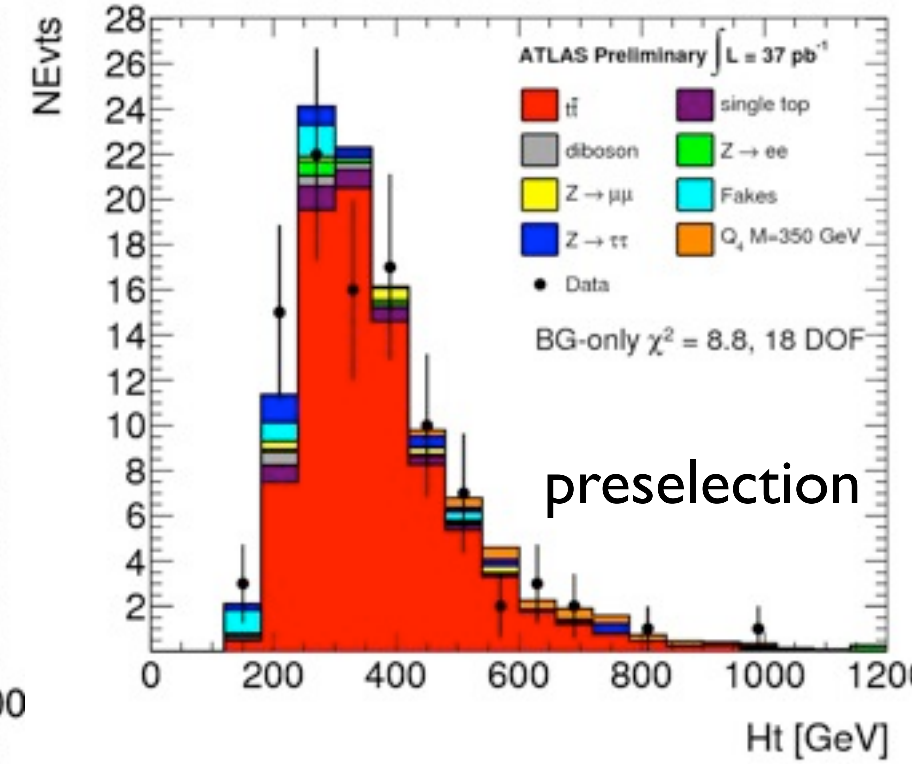
Used to validate the backgrounds and to reduce the Z/γ* + jets background

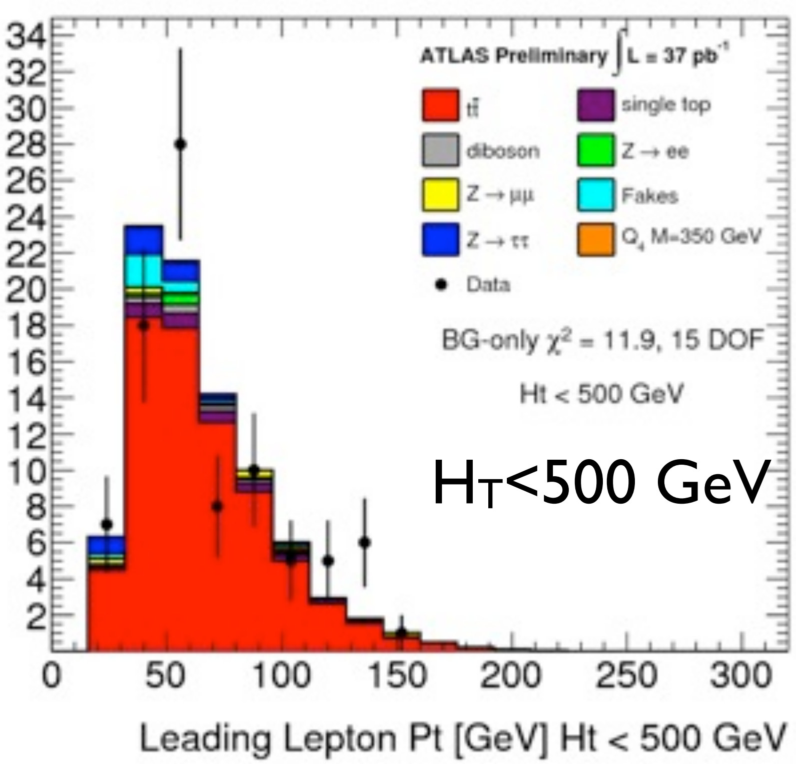
- ttbar (dominant), single top, Z + jets and diboson backgrounds are estimated with Monte Carlo
- Background from jets mis-identified as a leptons coming primarily from W+jets and single lepton ttbar events is estimated using a data-driven matrix method

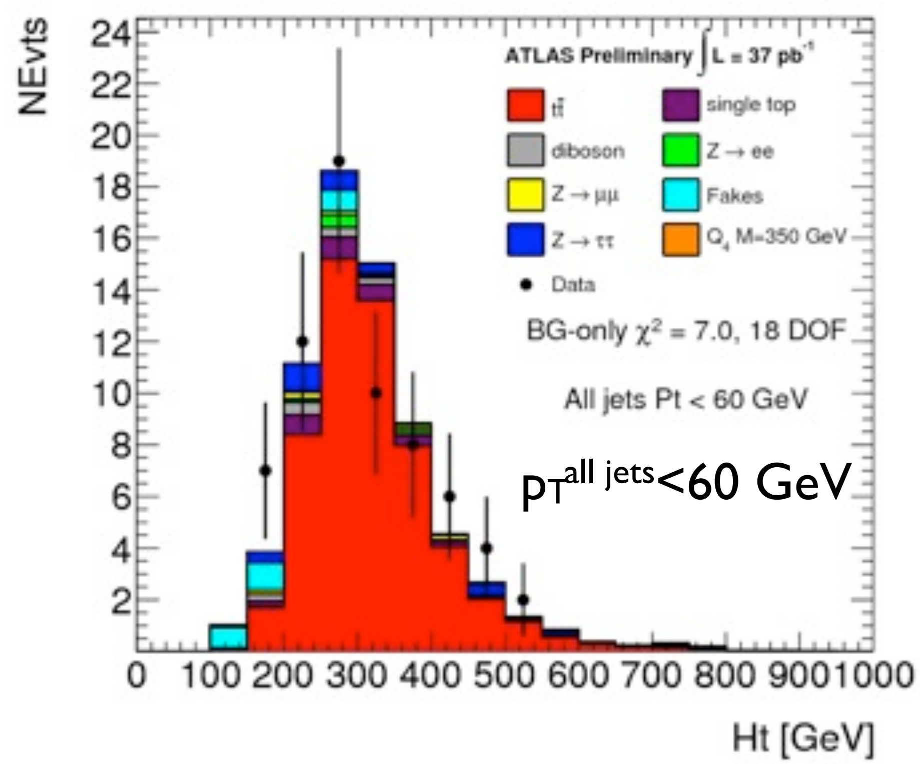
Background validation

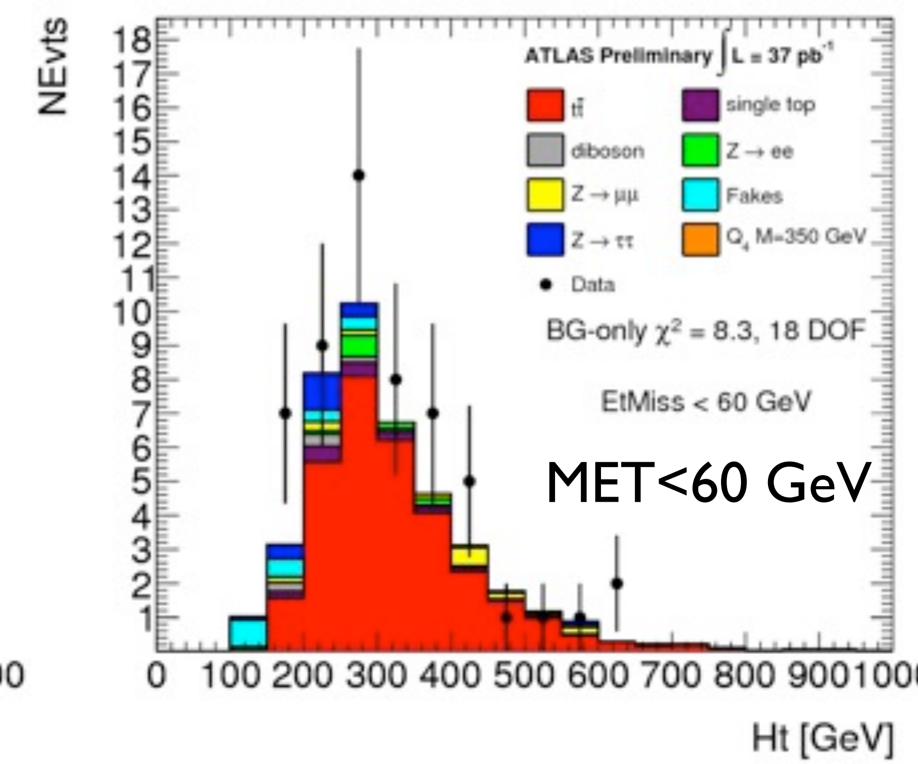
- Small H_T is used to reduce possible signal contamination and validate the background modeling
- Good agreement within limited statistics







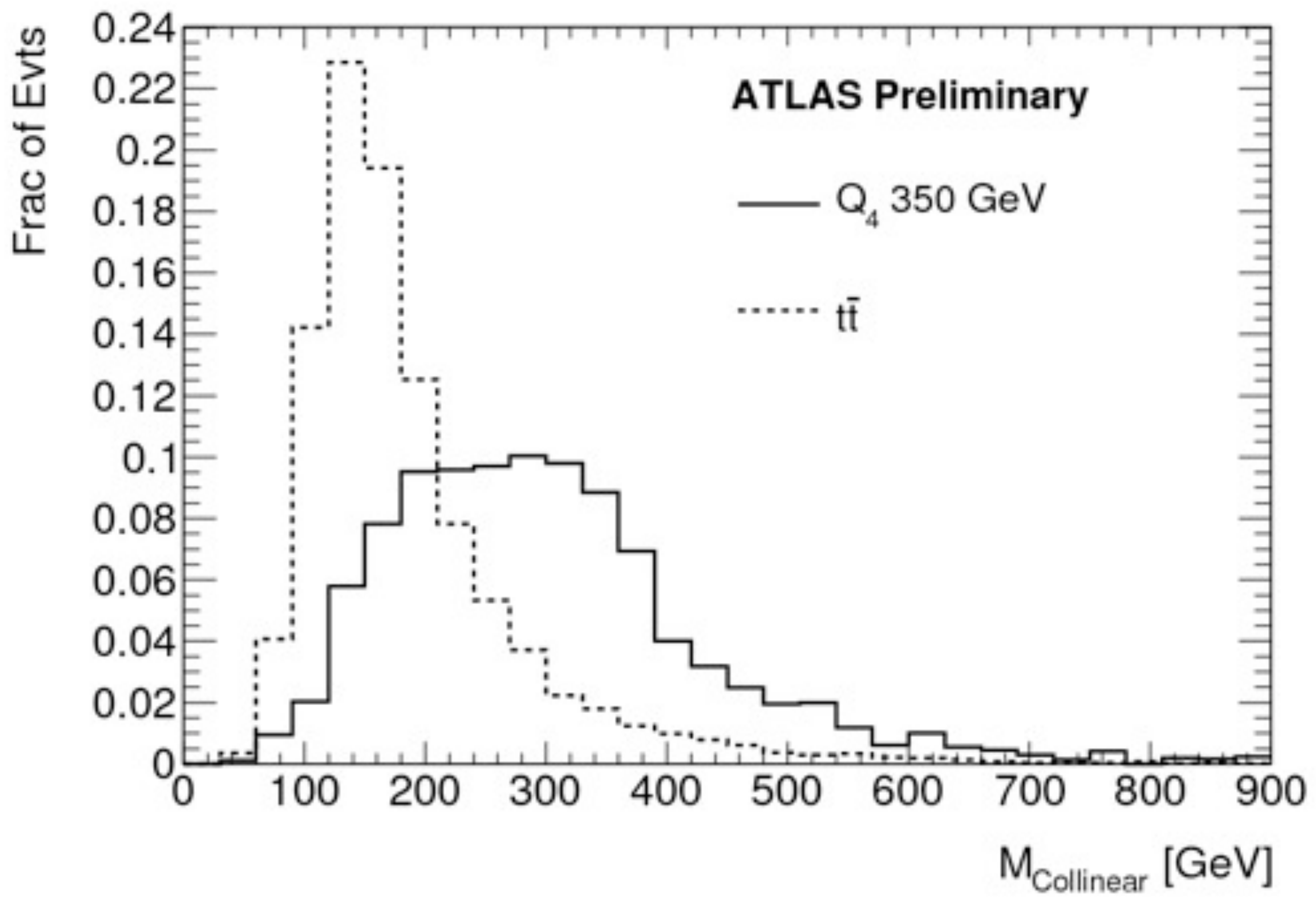


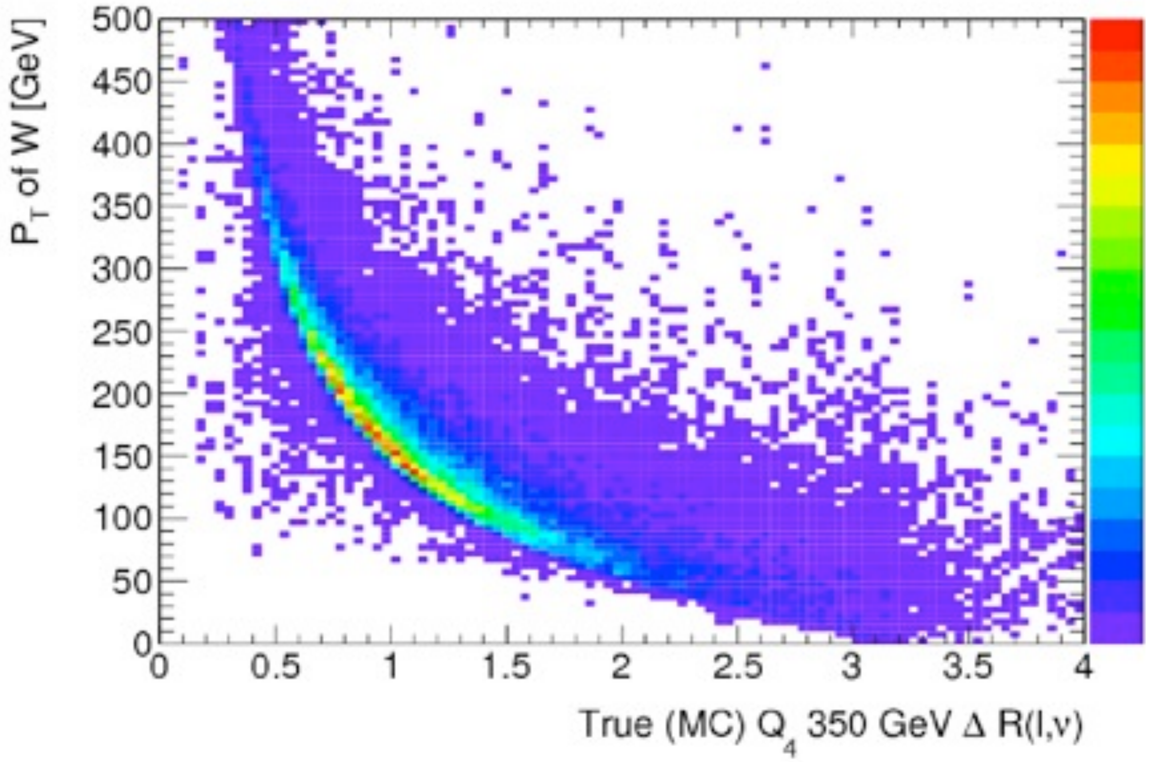


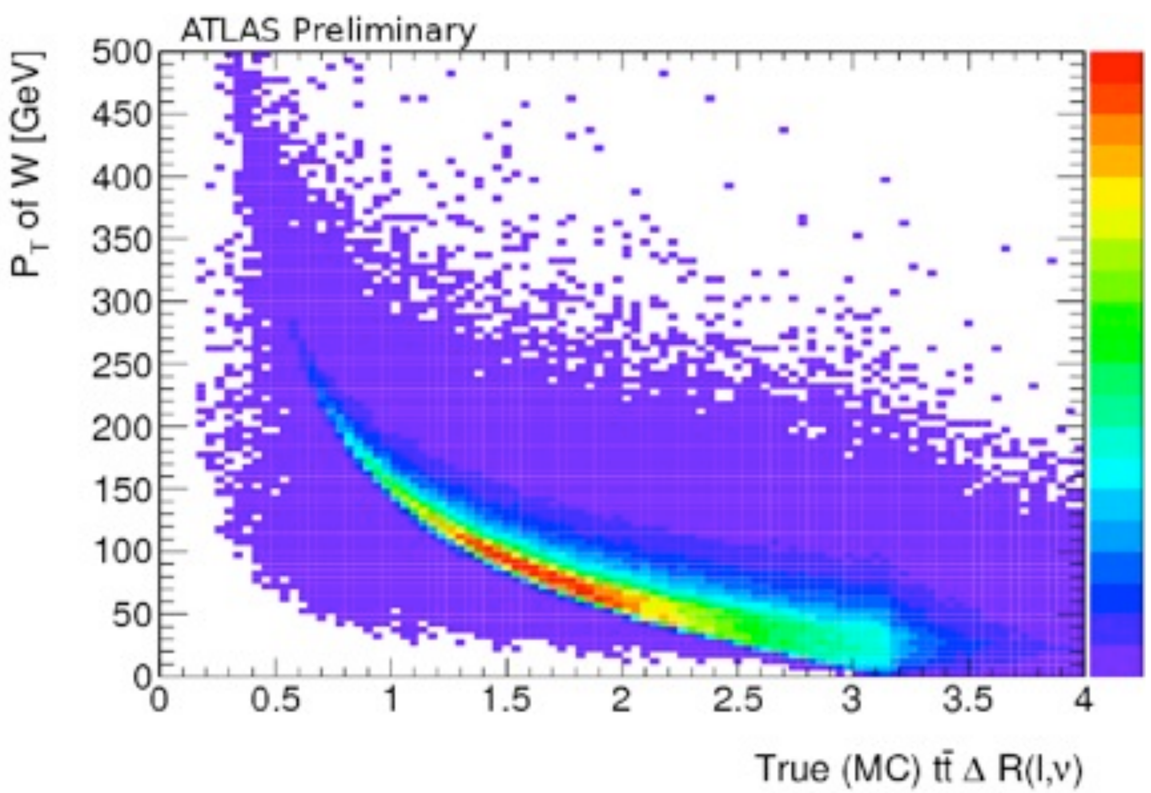
All the distributions show the sum of the ee, μμ and eμ channels

Mass reconstruction

- Used to separate the signal from the ttbar decays
- The mass cannot be fully reconstructed, as the neutrinos escape the detector, but the largely boosted decay products allows the assumption that the neutrinos will be approximately collinear with the charged leptons

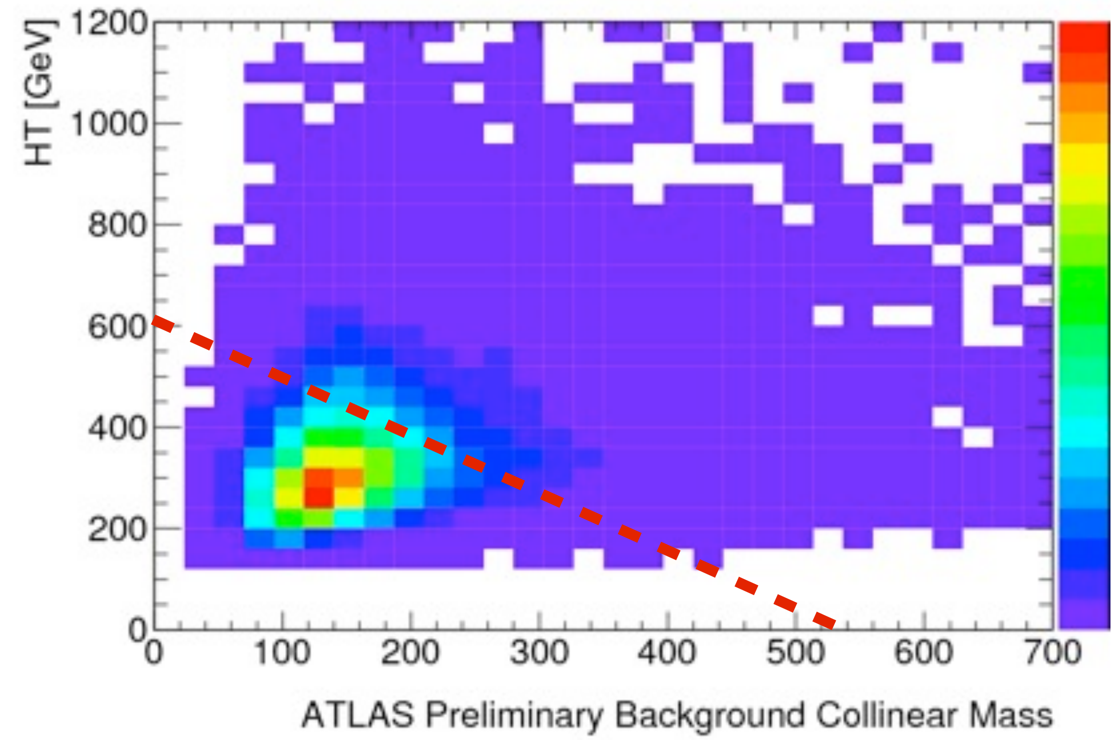




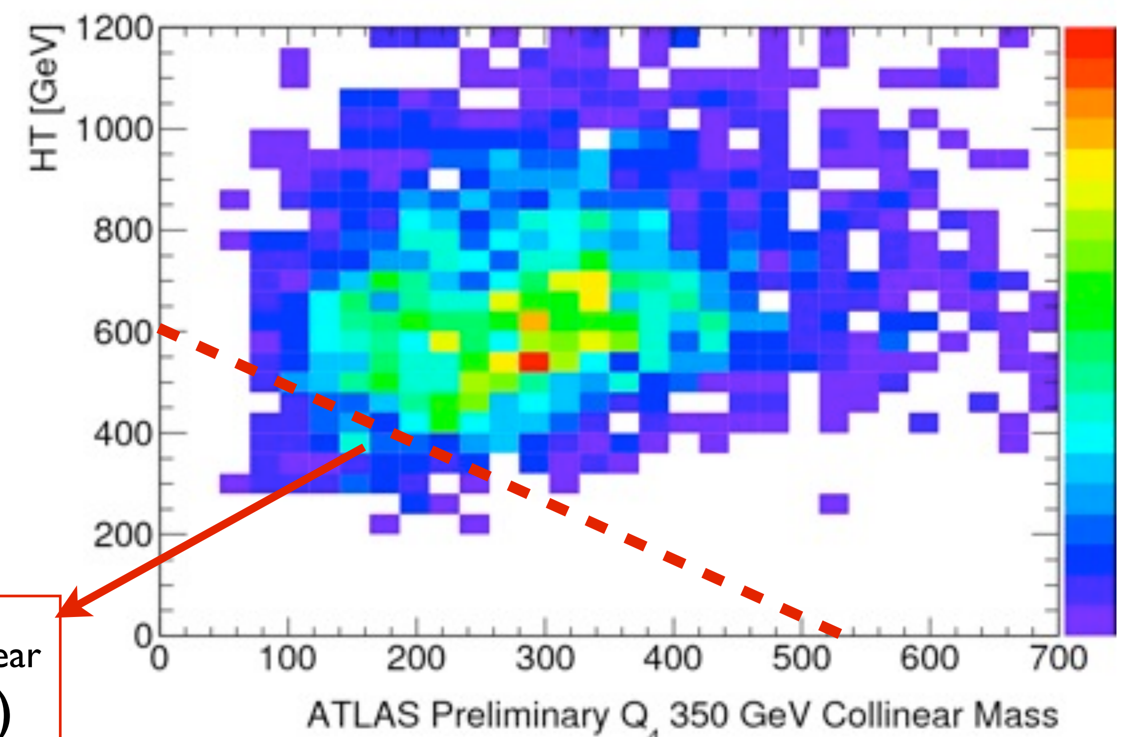


Optimization

- Use the reconstructed mass and the H_T observables to increase the signal significance
- The cut is chosen by doing a significance scan on a triangle cut on the H_T and the reconstructed mass
- Significance defined as $S/(S+B)^{1/2}$

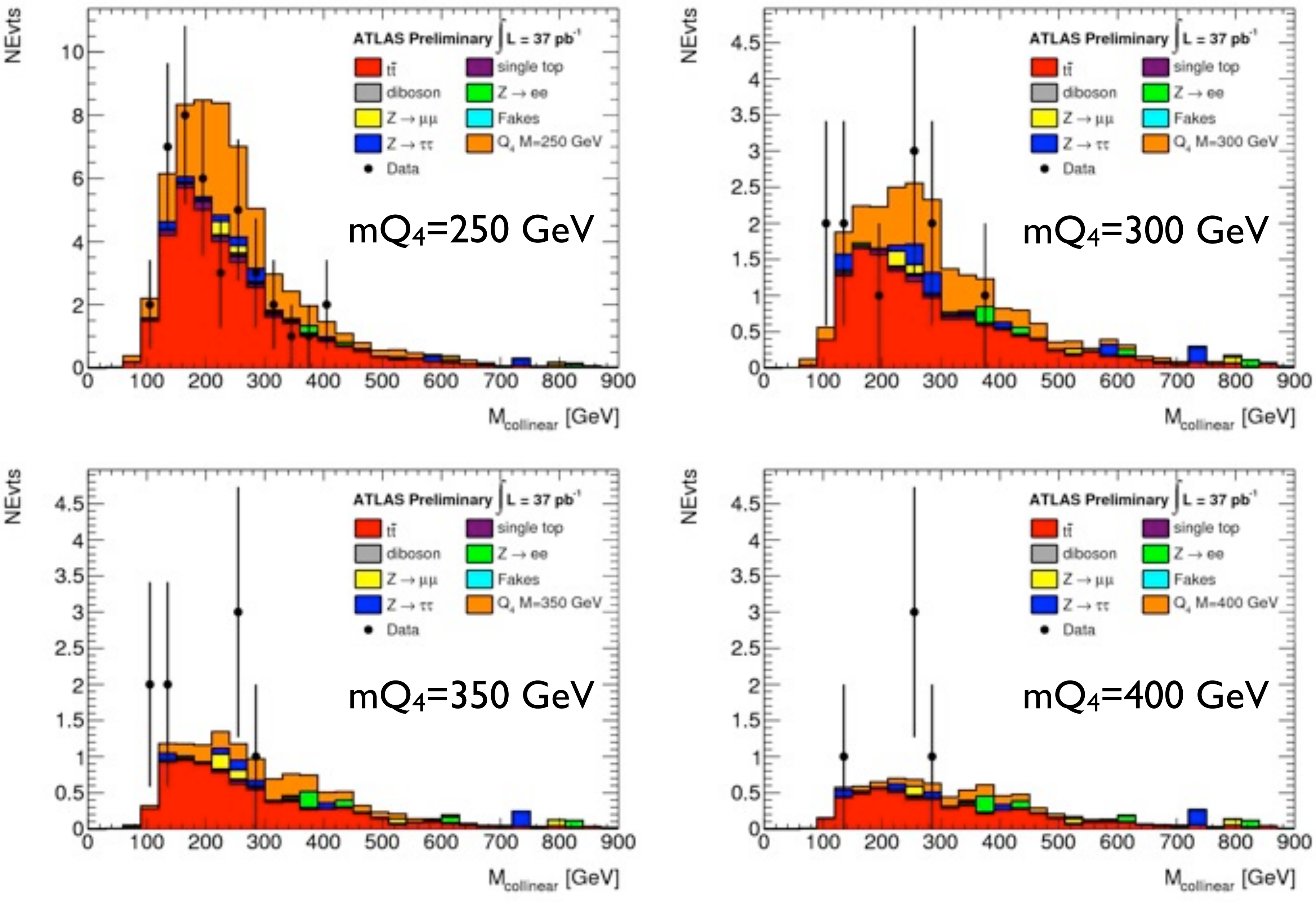


Q_4 Mass (GeV)	Final selection
250	$H_T > 500 - 0.7 \times M_{collinear}$
300	$H_T > 600 - 0.5 \times M_{collinear}$
350	$H_T > 600 - 0.2 \times M_{collinear}$
400	$H_T > 700 - 0.3 \times M_{collinear}$



$H_T > 600 - 0.2M_{collinear}$
($M_{collinear}$=350 GeV)

Signal region



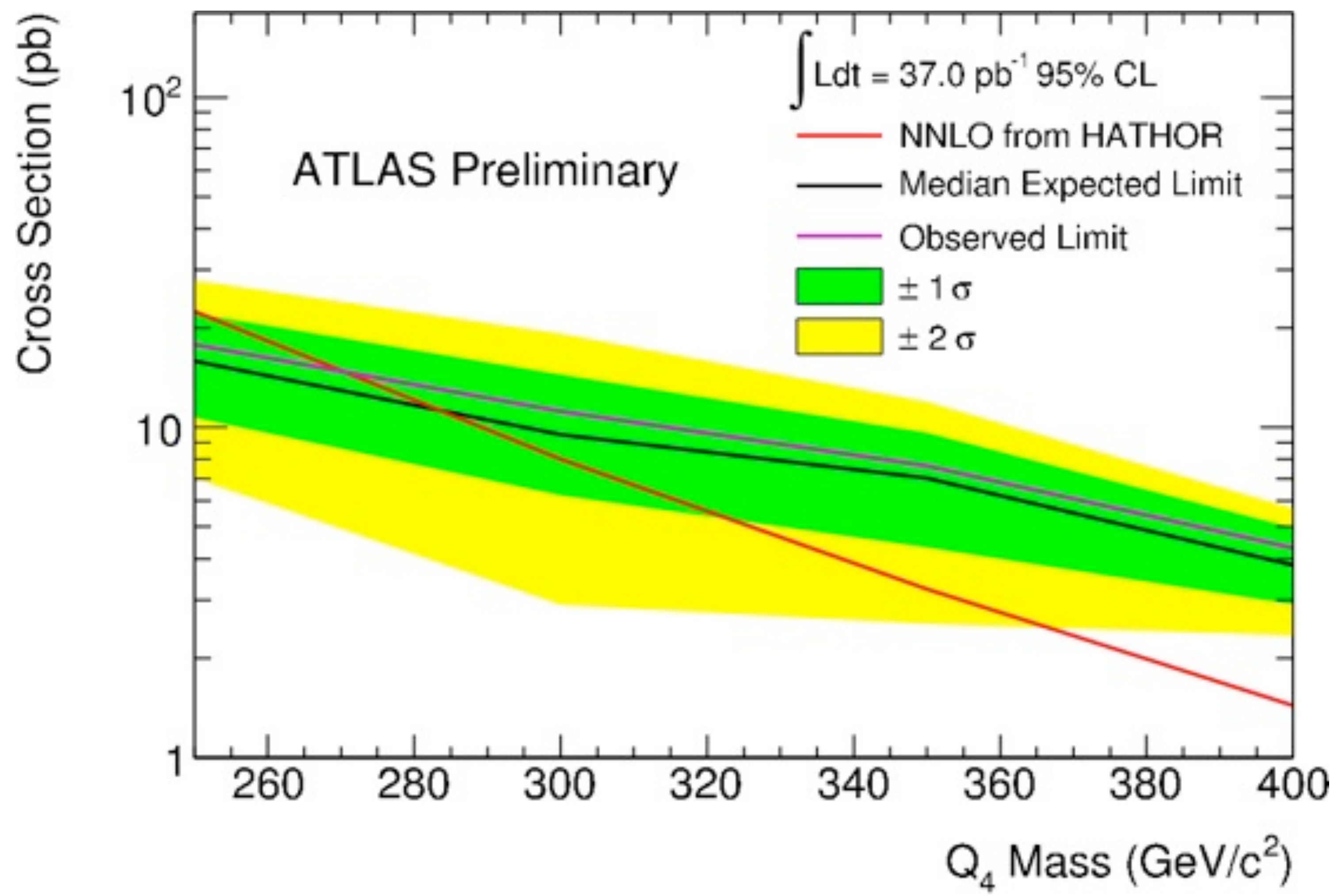
No hint of Q_4: Good agreement between data and SM predictions

Q_4 Mass [GeV/c^2]	250	300	350	400
Total BG	40.4 ± 0.7 ± 3.9	16.8 ± 0.5 ± 1.7	10.1 ± 0.4 ± 1.0	6.3 ± 0.4 ± 0.8
Signal	20.7 ± 0.5 ± 1.9	7.1 ± 0.2 ± 0.3	3.0 ± 0.1 ± 0.2	1.4 ± 0.1 ± 0.1
Observed	40	11	8	5

Results

- Expected limits are calculated by finding the maximum theoretical cross section for a hypothetical measured cross section of 0 pb by using the Neyman 95% Confidence band

- Observed limits are calculated by measuring the cross section in data, replacing the hypothetical signal + bkg shapes with the data shape. If the measured cross section is consistent with 0, upper limit are set using the Neyman 95% Confidence band



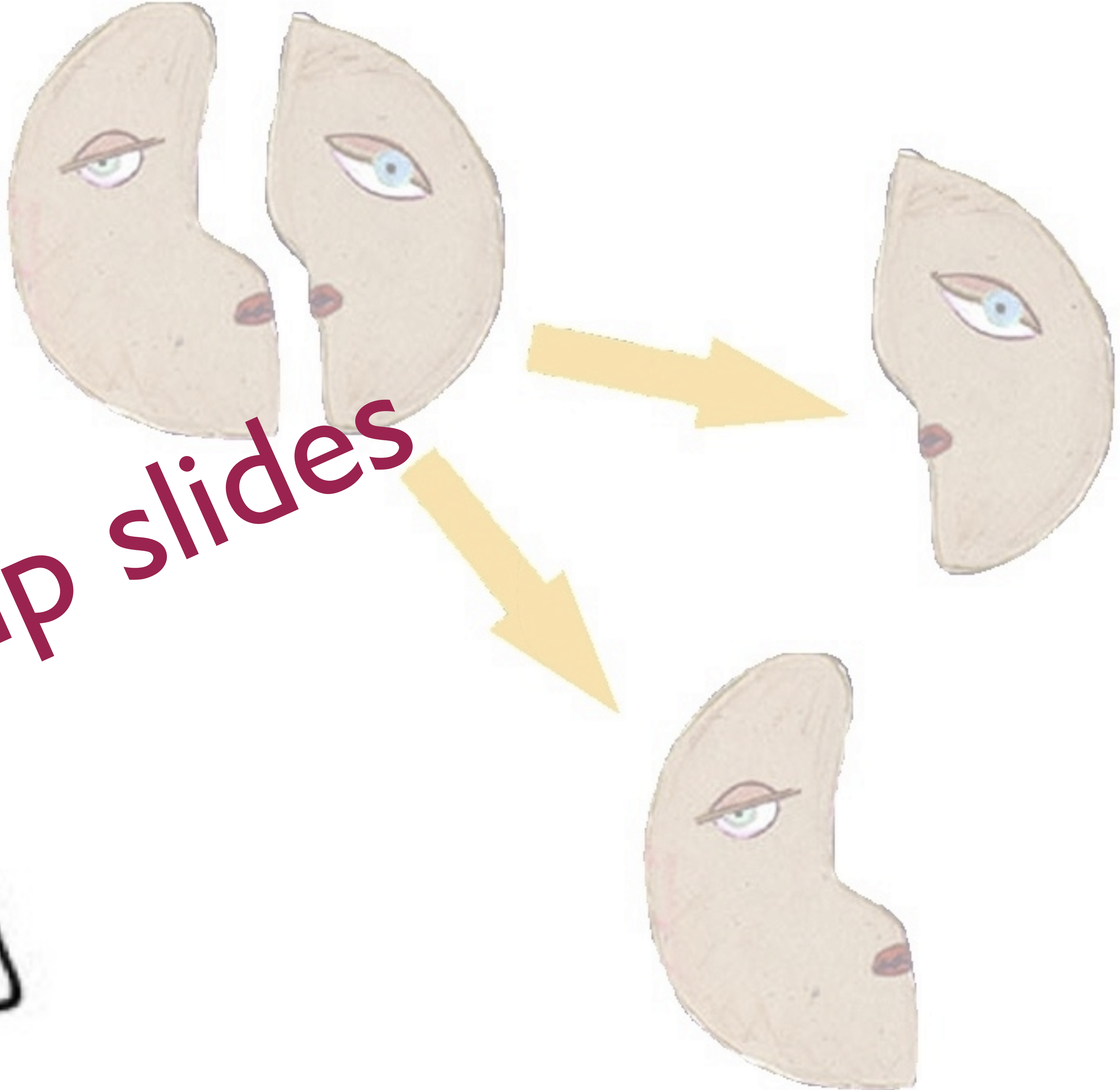
Excluded a $mQ_4 < 270$ GeV

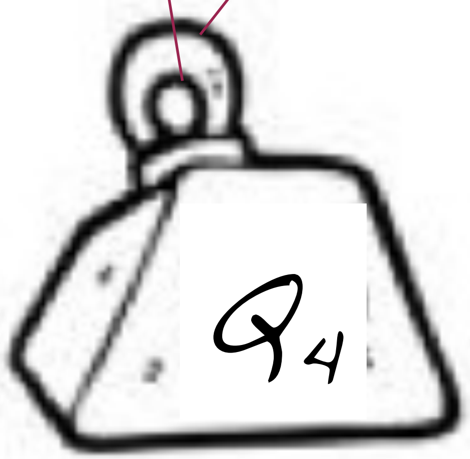
These limits are directly applicable to u_4 quarks as well as other exotic quark models of quarks with charges −1/3, −4/3 decaying to light quarks, $Q_4 \rightarrow Wq$, including $d_4 \rightarrow Wq$

Summary and conclusions

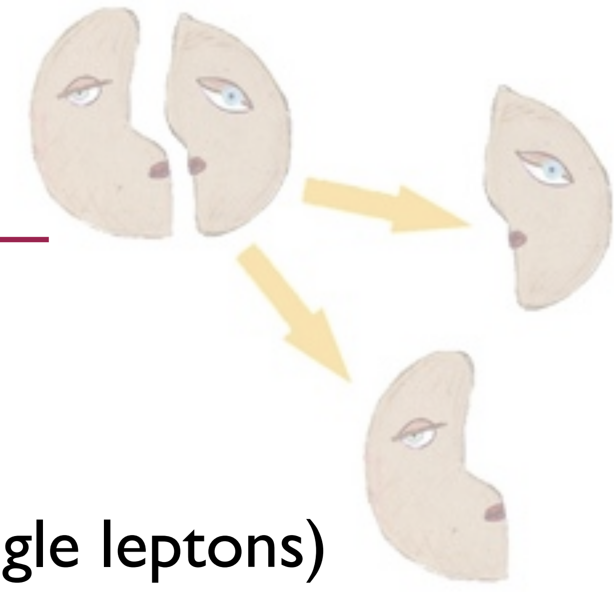
- Presented LQ and Q_4 searches in ATLAS using the 2010 dataset
  - Good control of the backgrounds evidences an excellent detector performance, from data-taking to the last step in the reconstruction chain
- LHC sensitivity to LQ already surpassed that of the Tevatron with the 2010 dataset
  - New possibilities opening up for this coming year !
    - The 10x statistics will allow to perform more ambitious searches → Targeting ~800 GeV LQ for 1 fb^{-1} of data!
    - Extend searches to MET+jet channels and 3rd generation LQs
- First searches of heavy quarks at the LHC using dilepton channel (not available from Tevatron)
  - The approach presented in this talk will be combined with searches in other decay channels
  - With additional data from the LHC, this analysis method will provide excellent sensitivity to new quarks in a wide mass range
- In conclusion: very exciting times are quickly approaching for searches at the LHC !

Back up slides



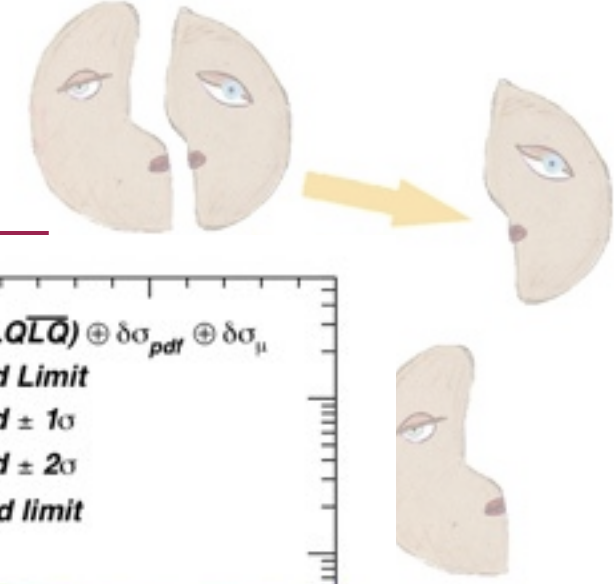


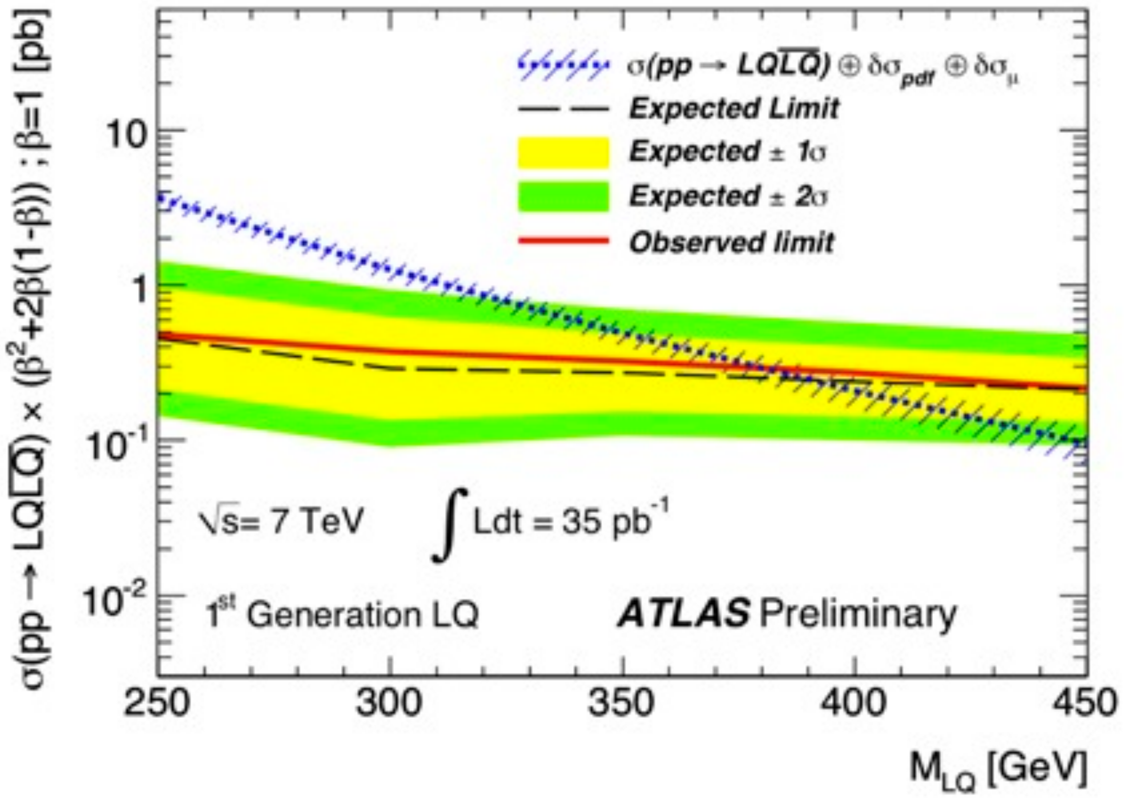
Systematic uncertainties

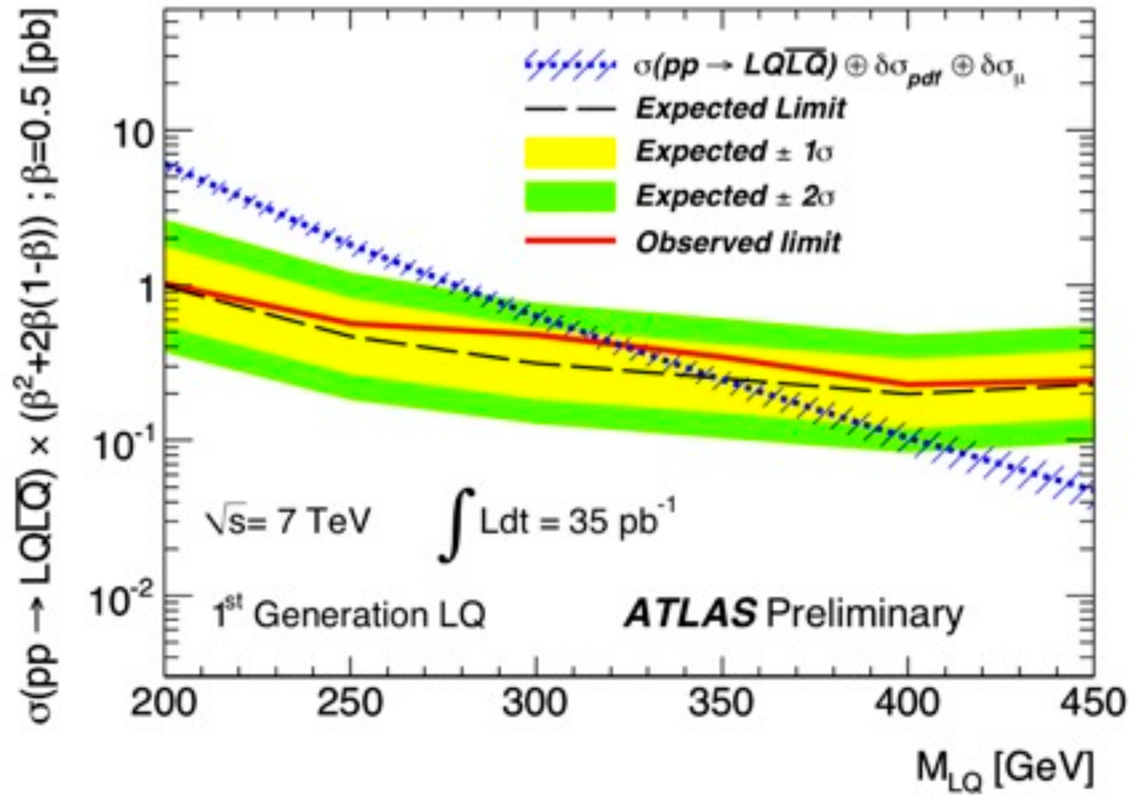


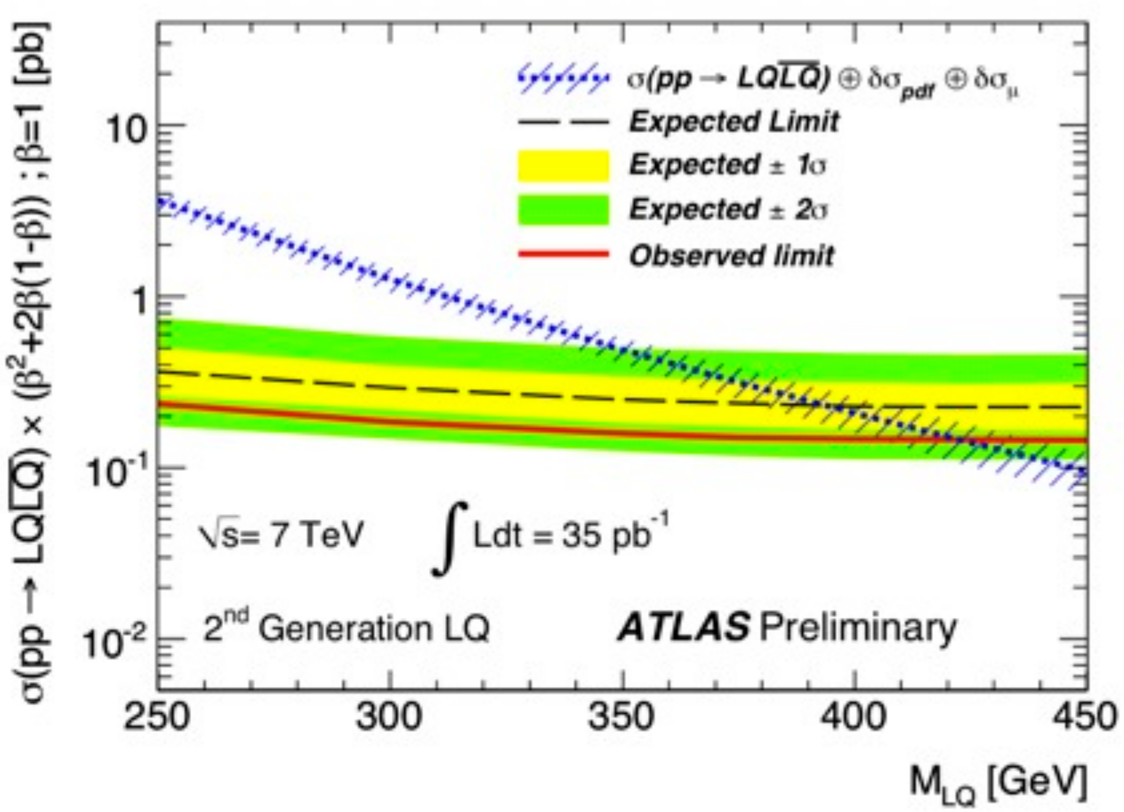
- Dominant sources of systematic uncertainties come from:
  - Jet energy scale and resolution: ~ 20% (dileptons) and 30% (single leptons)
  - V+jets modeling: ~ 40%
  - ttbar modeling: ~ 35%
- Others
  - Lepton-related (energy/momentum scale and resolution, reconstruction and ID) are < 10% for single lepton channels and < 20% for dilepton channels
  - Pileup < 5% for single leptons, negligible for dileptons
  - Luminosity: 11%
- Total systematics is of the order of 50% for the major backgrounds ttbar and V+jets, while it is of around 20% for dibosons and the signal (major contributor for the signal is the production cross-section with 18%)
- Impact on the limits is between 5 and 10 GeV at maximum sensitivity

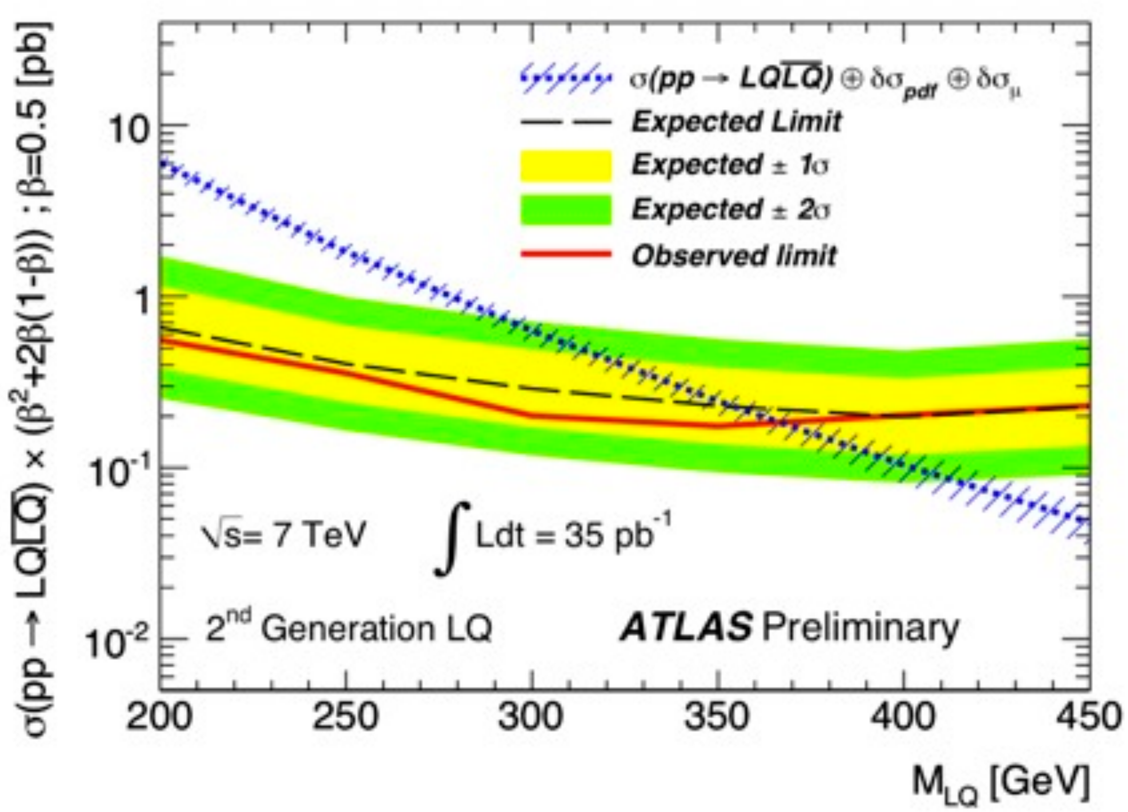
Cross section limits



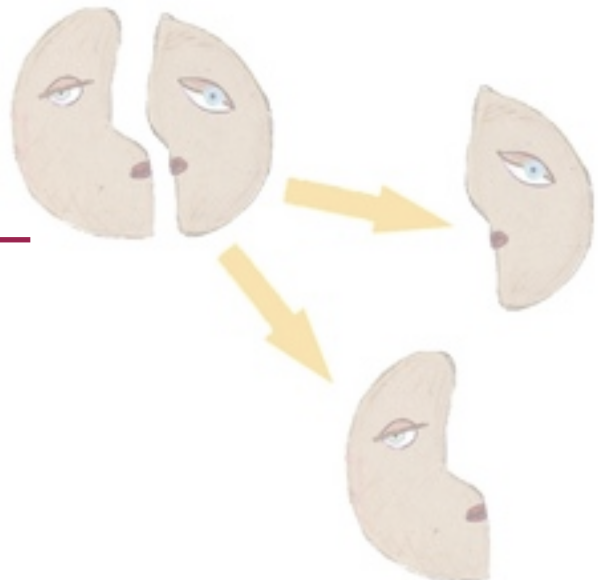




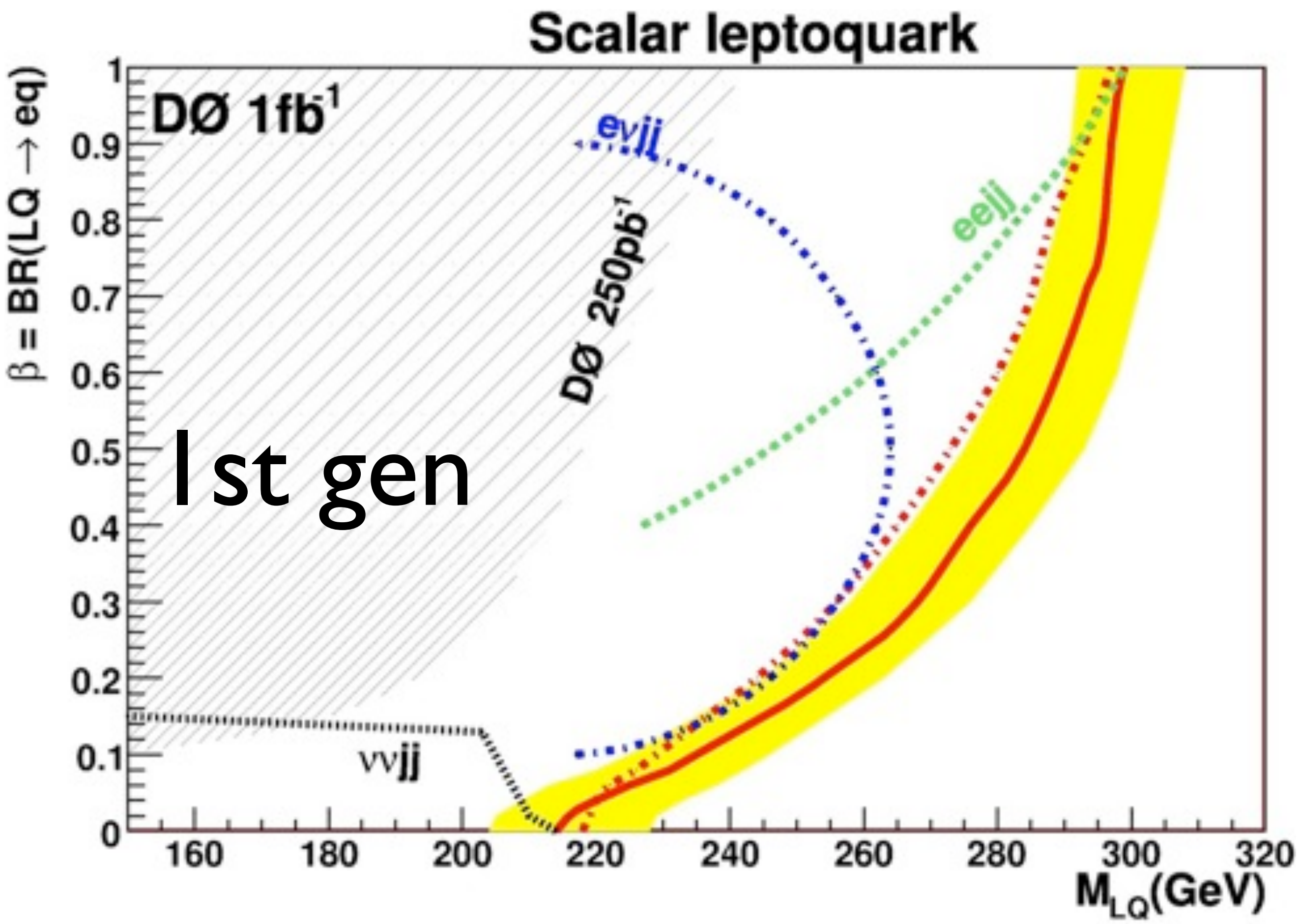


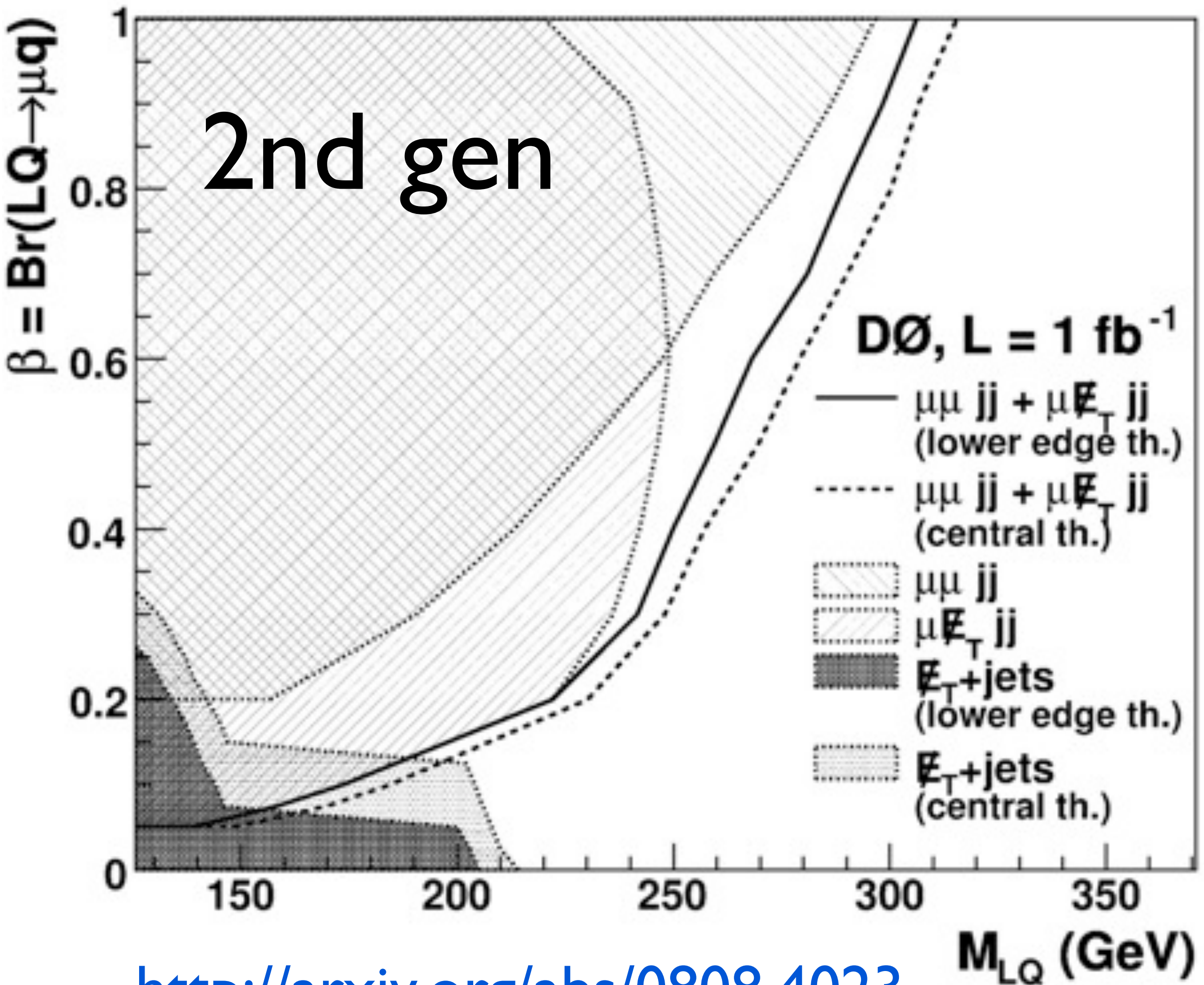


Tevatron limits



- Latest results from Tevatron:
  - Nothing was found, so limits were set
  - Scalar LQ pair production for both generations set limits ~ 300 GeV for a branching fraction of ~1/2 (similar acceptance for muons and electrons)

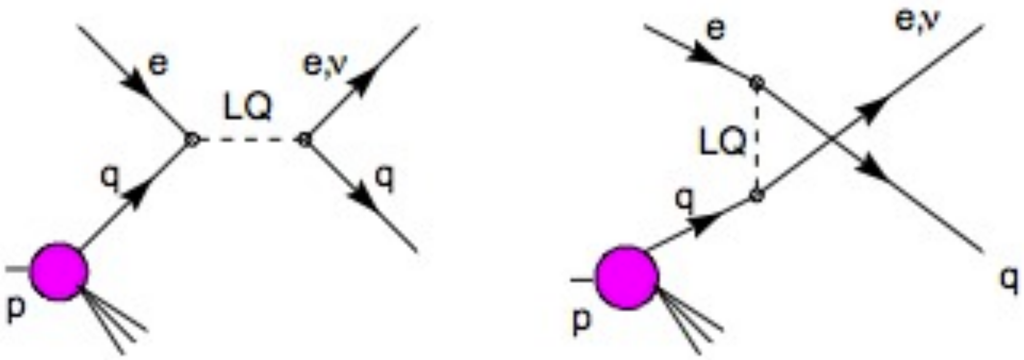




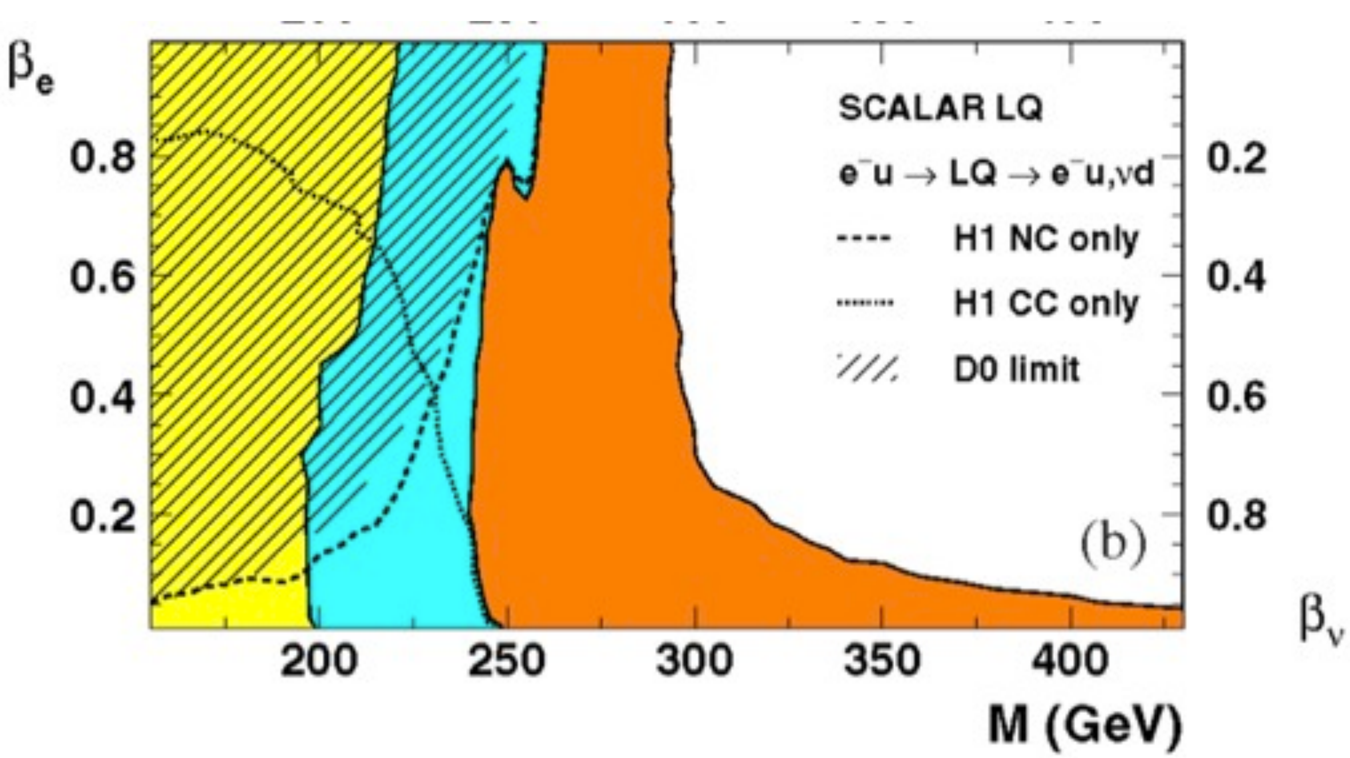
http://arxiv.org/pdf/0907.1048v2

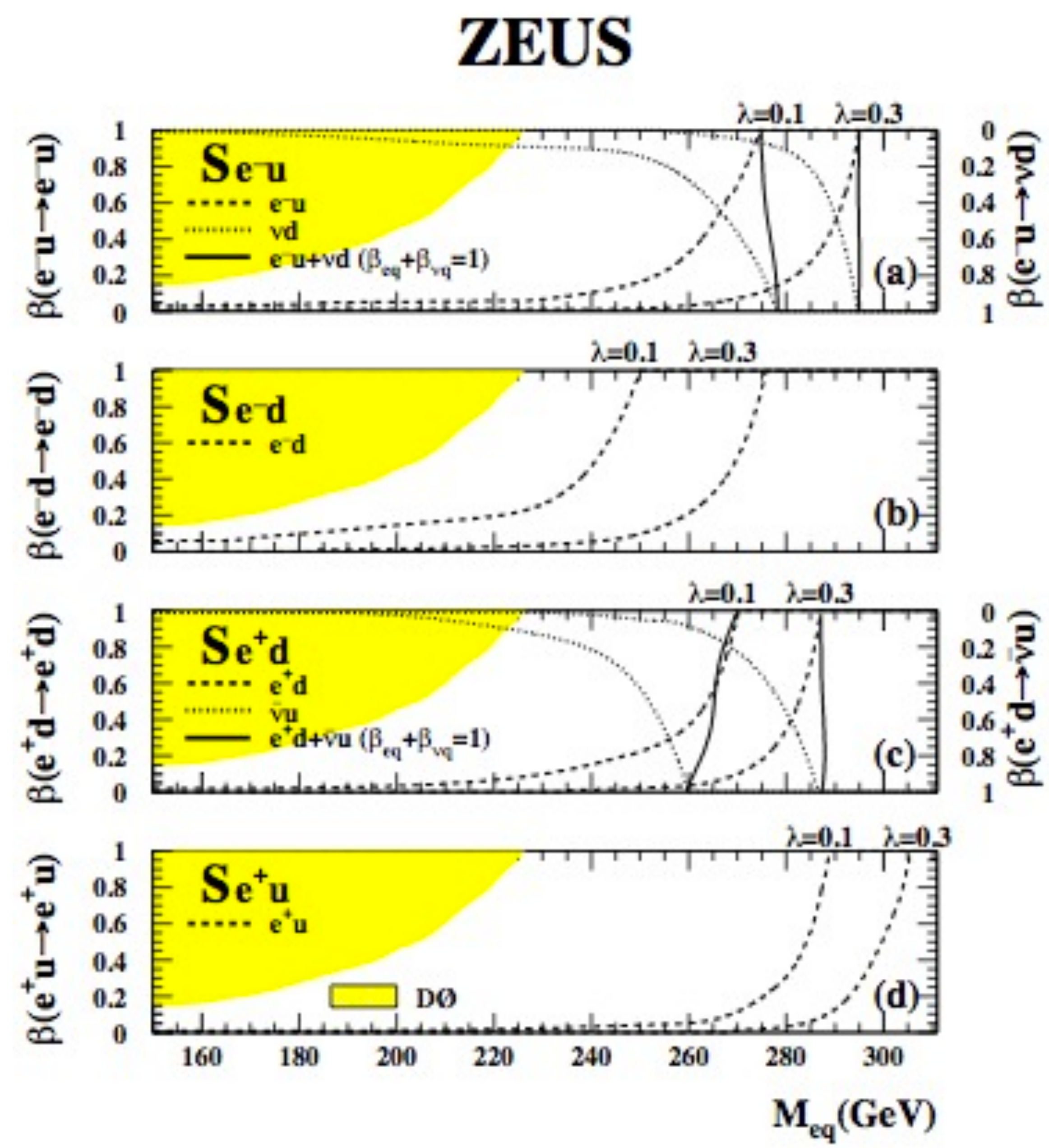
http://arxiv.org/abs/0808.4023

Hera limits



- Single LQ searches → The LQ production cross section largely depends on the Yukawa coupling λ
- ep collisions → only sensible to direct searches of 1st generation LQ (if search for LVF can look for other generations)





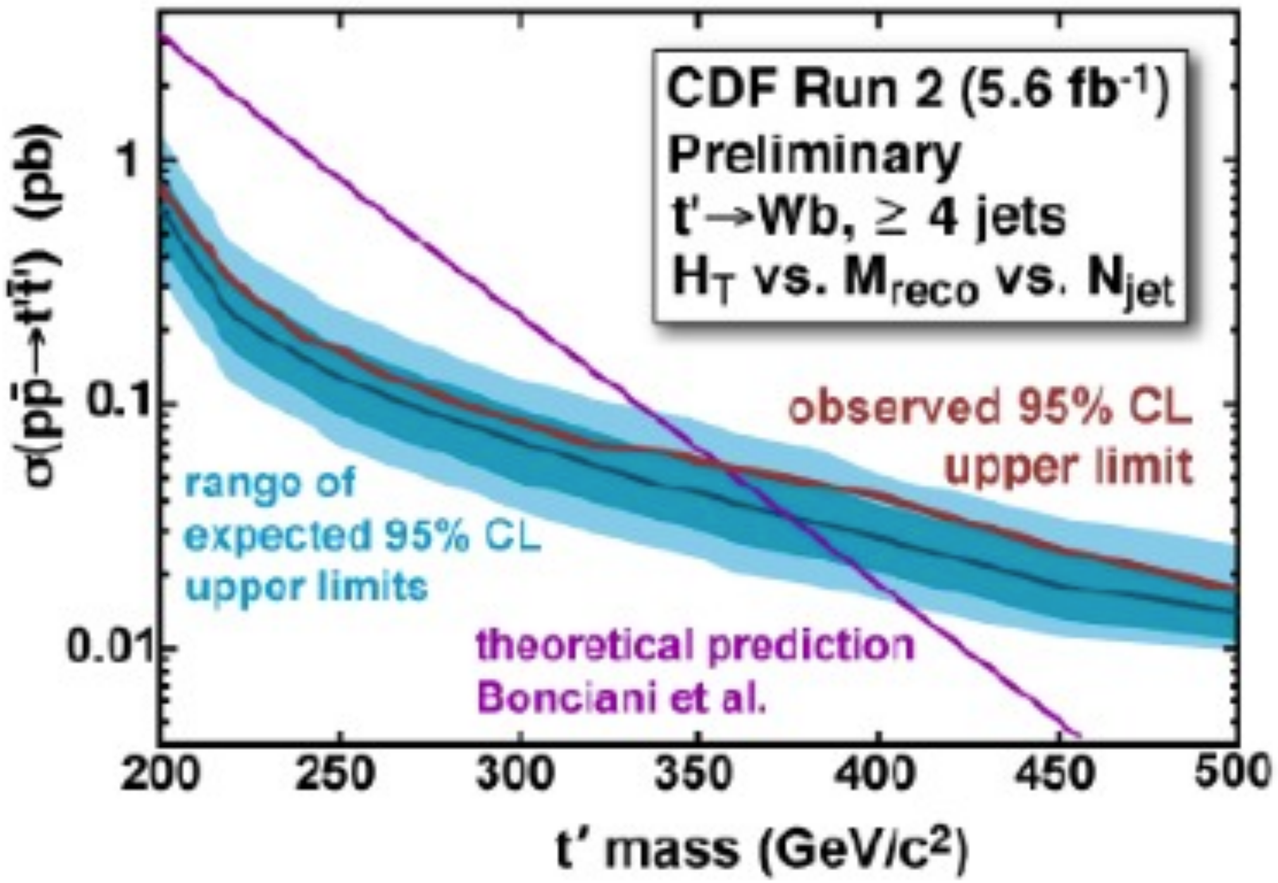
Exclude LQs up to masses of ~275 to 325 GeV for $\lambda \sim \alpha_{em}$

Systematic uncertainties

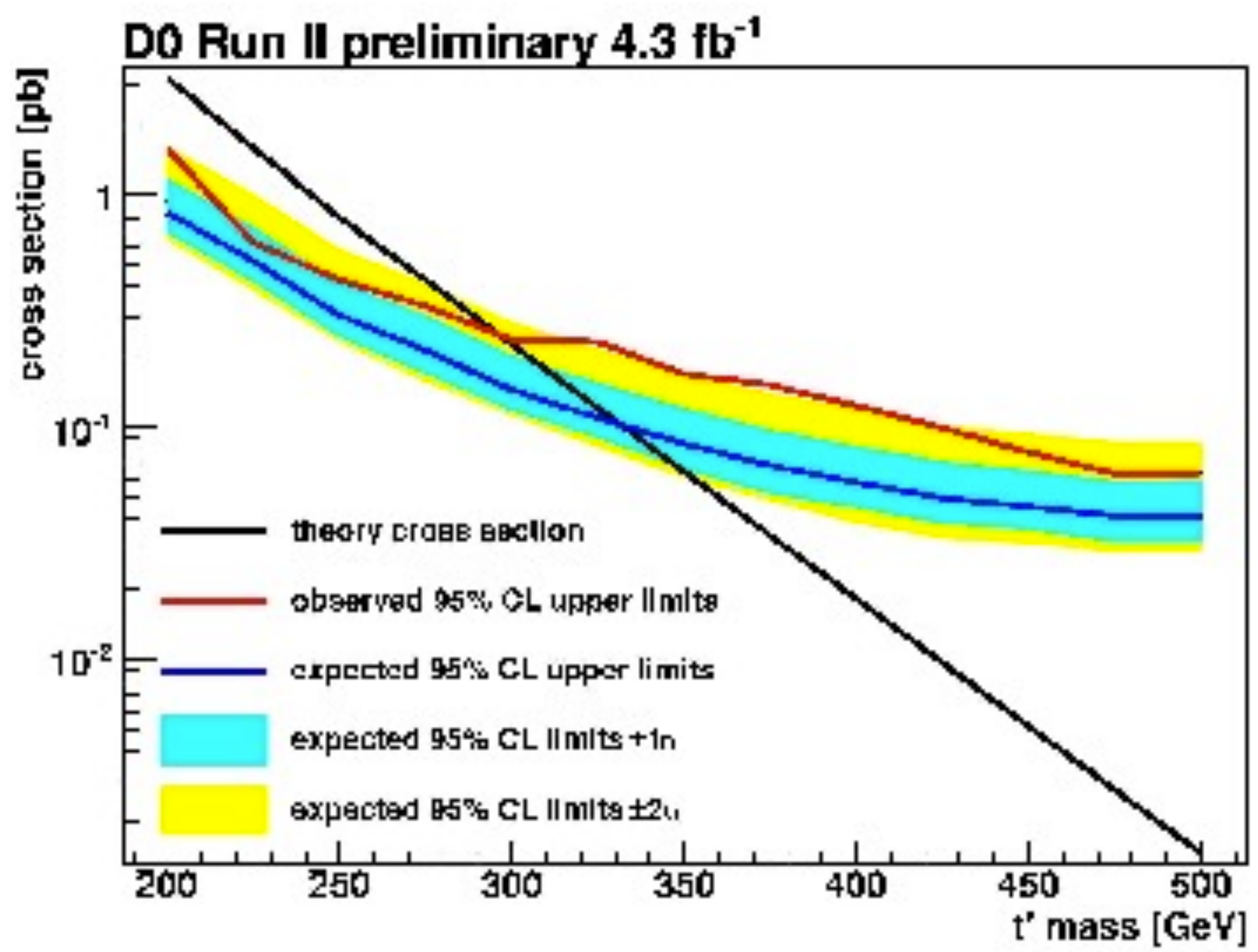
Table 6: Summary of systematic uncertainties for backgrounds and 350 GeV signal. The percentages quoted are the effect on the yield; where the uncertainty varies (eg as a function of η), a minimum and maximum are quoted.

Source	Effect	Size [%]
Electron trigger and reconstruction	Yield	1.6%
Electron ID	Yield	2-9%
Muon ID and reconstruction	Yield	0.3%
Muon trigger	Yield	0.1-1.3%
Electron energy scale	Shape	0.6%
Muon momentum scale	Shape	0.1%
Jet energy scale	Shape and Yield	12%
Gluon radiation	Shape and Yield	15%
Signal cross-section	Yield	14%
Background cross-sections	Yield	5-30%
Fake lepton background	Shape and Yield	50%
Luminosity	Yield	11%

Tevatron limits



- Most recent CDF limit is M_u4 > 356 GeV
  - l+jets channel with 5.6 fb^{-1} of integrated luminosity at Tevatron



- Most recent D0 limit is M_u4 > 296 GeV
  - l+jets channel with 4.3 fb^{-1} of integrated luminosity at Tevatron