Preparations for SUSY searches at the LHC

Alex Tapper

UK HEP Forum: LHC First Results and Outlook, September 20-21 2010.

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Outline

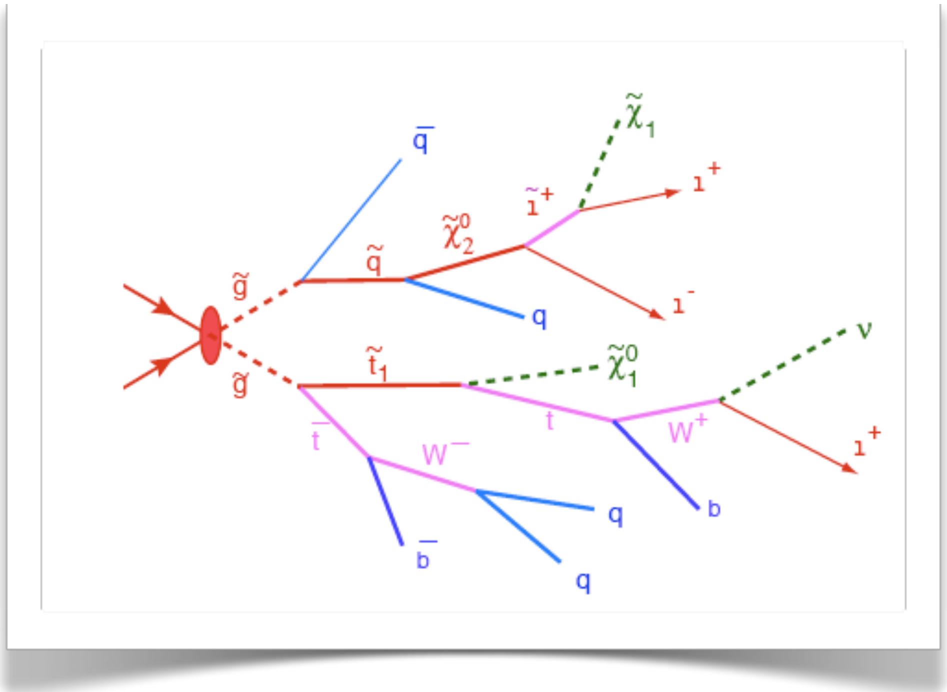
- Search strategy
- Examples with 70 nb^{-1}
  - Hadronic searches
  - Leptonic searches (single and di-lepton)
  - Photon searches (di-photon)
- Summary and outlook

Introduction/bibliography

- Documents for ICHEP on preparations for SUSY searches at LHC
  - ATLAS Collab., Early supersymmetry searches in channels with jets and missing transverse momentum with the ATLAS Detector (ATLAS-CONF-2010-065)
  - ATLAS Collab., Early supersymmetry searches with jets, missing transverse momentum and one or more leptons with the ATLAS Detector (ATLAS-CONF-2010-066)
  - CMS Collab., Performance of Methods for Data-Driven Background Estimation in SUSY Searches (CMS-SUS-10-001)

- Not planning to show
  - Early supersymmetry searches in events with missing transverse energy and b-jets with the ATLAS detector (ATLAS-CONF-2010-079)
  - Prospects for Supersymmetry discovery based on inclusive searches at a 7 TeV centre-of-mass energy with the ATLAS detector (ATL-PHYS-PUB-2010-010)
  - The CMS physics reach in searches at 7 TeV (CMS-NOTE-2010-008)

Search strategy (what and how?)



- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model

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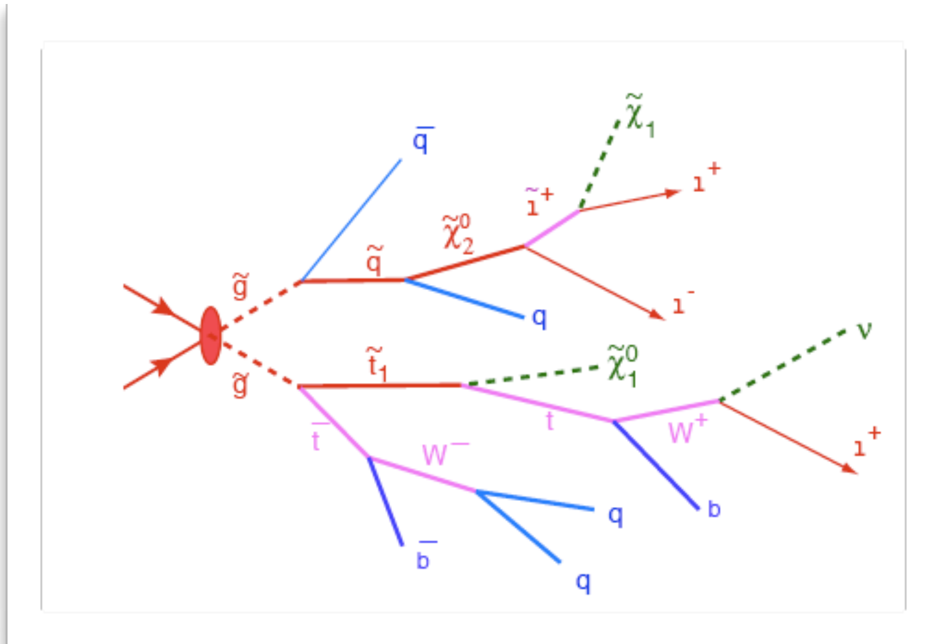
Search strategy (what and how?)



- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model
- Decay
  - Details of decay chain depend on SUSY model (mass spectra, branching ratios, etc.)
  - Assume R_P conserved ➔ decay to lightest SUSY particle (LSP)
  - Assume squarks and gluinos are heavy ➔ long decay chains
- Signatures
  - **MET** from LSPs, **high-E_T jets** and **leptons** from long decay chain
- Focus on robust and simple signatures
  - Common to wide variety of models
  - Let Standard Model background and detector performance define searches not models

Search strategy (MC example)

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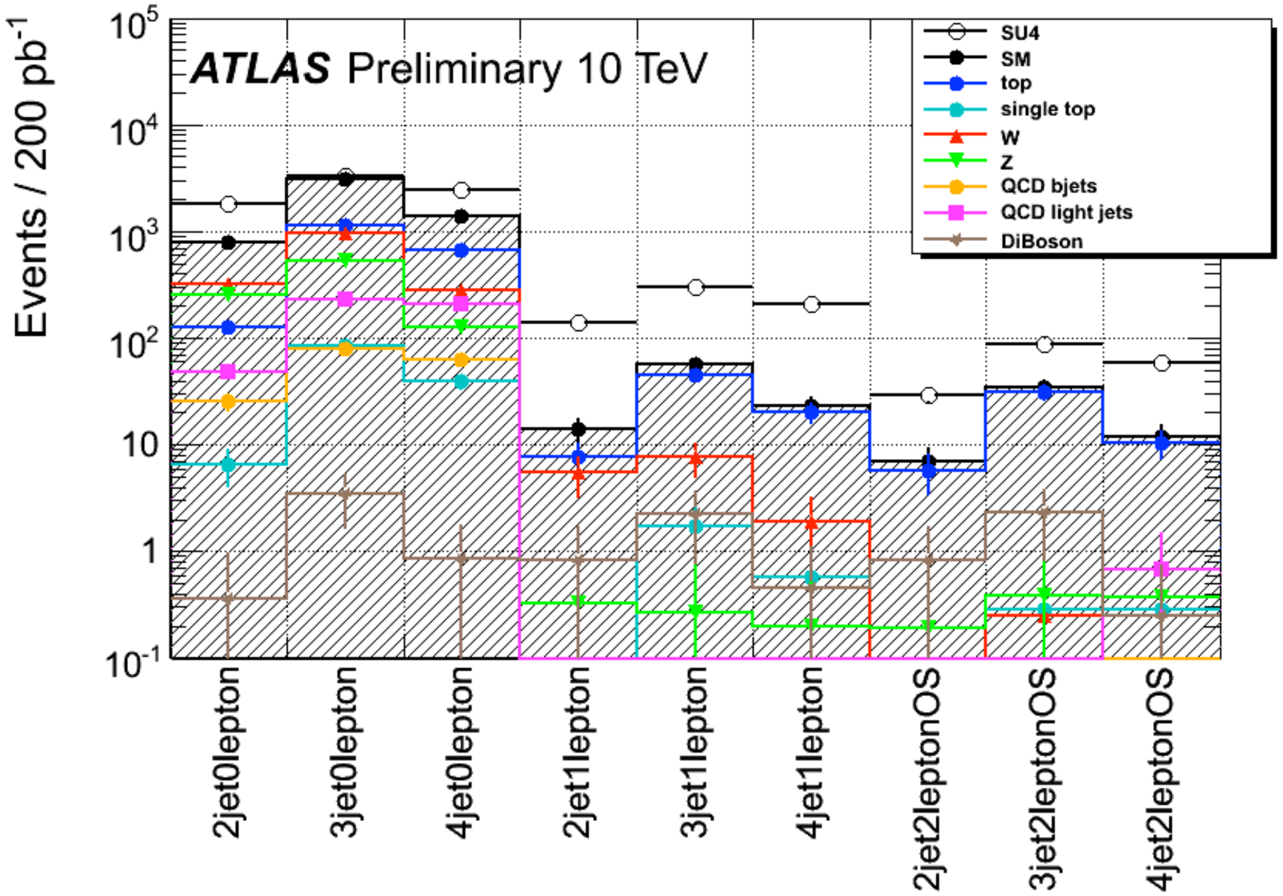
- How might such a generic search look?
  - Simple selection ➔ categorise events by numbers of leptons and jets



- Jet E_T > 100 (40) GeV
- $\Delta\Phi(\text{jet}_i,\text{MET})$ > 0.2 rad
- Lepton E_T > 20 (10) GeV
- MET > 80 GeV
- Meff = $\Sigma E_T^{jet} + \Sigma E_T^{lep}$ + MET
- MET > 0.2-0.3 x M_{eff}
- S_T>0.2
- M_T > 100 GeV

  - Good S/B for most channels (200 pb^{-1} @ 10 TeV centre-of-mass) but...
  - Backgrounds straight from Monte Carlo
- Measuring backgrounds is the key ➔

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Backgrounds

- Physics
  - Standard Model processes that give the same signatures as SUSY
  - Cannot rely on Monte Carlo predictions ➔ measure in data
- Detector effects
  - Detector noise, mis-measurements etc. that generate MET or extra jets
  - Commissioning and calibration ➔ results shown by Jon and Jim
- Beam related
  - Beam-halo muons (and cosmic-ray muons), beam-gas events
  - Data and simulation already ➔ measure in situ too

All-hadronic search (MC example)

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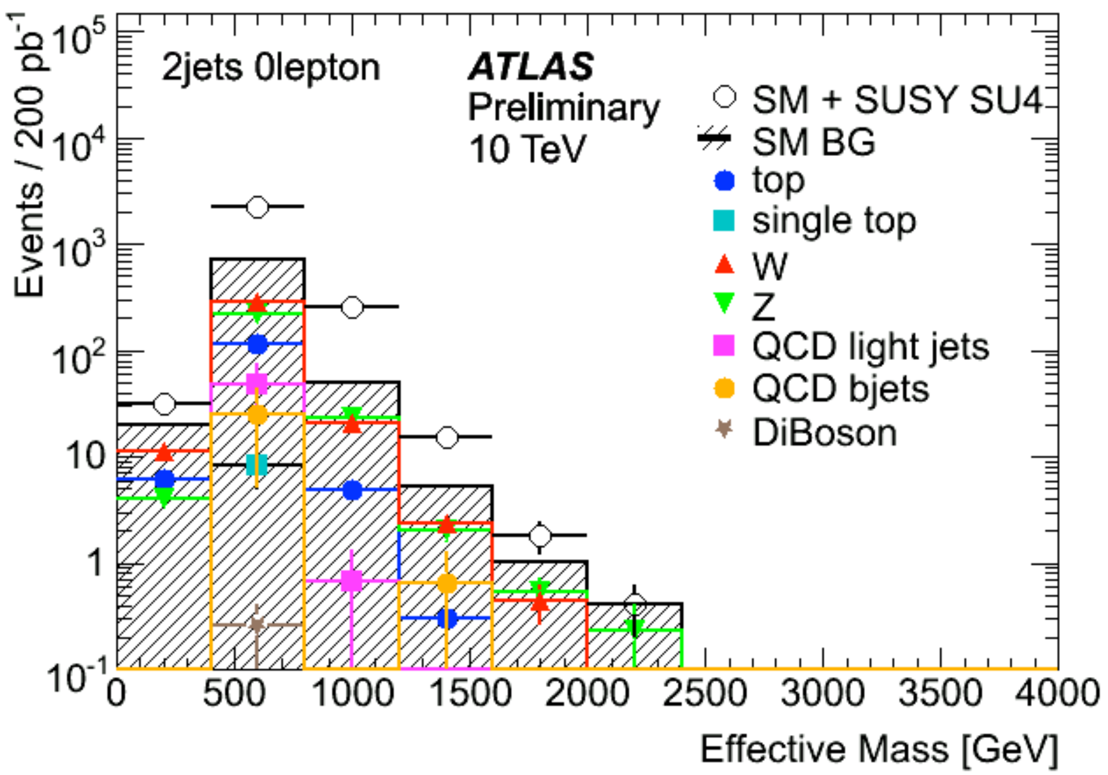
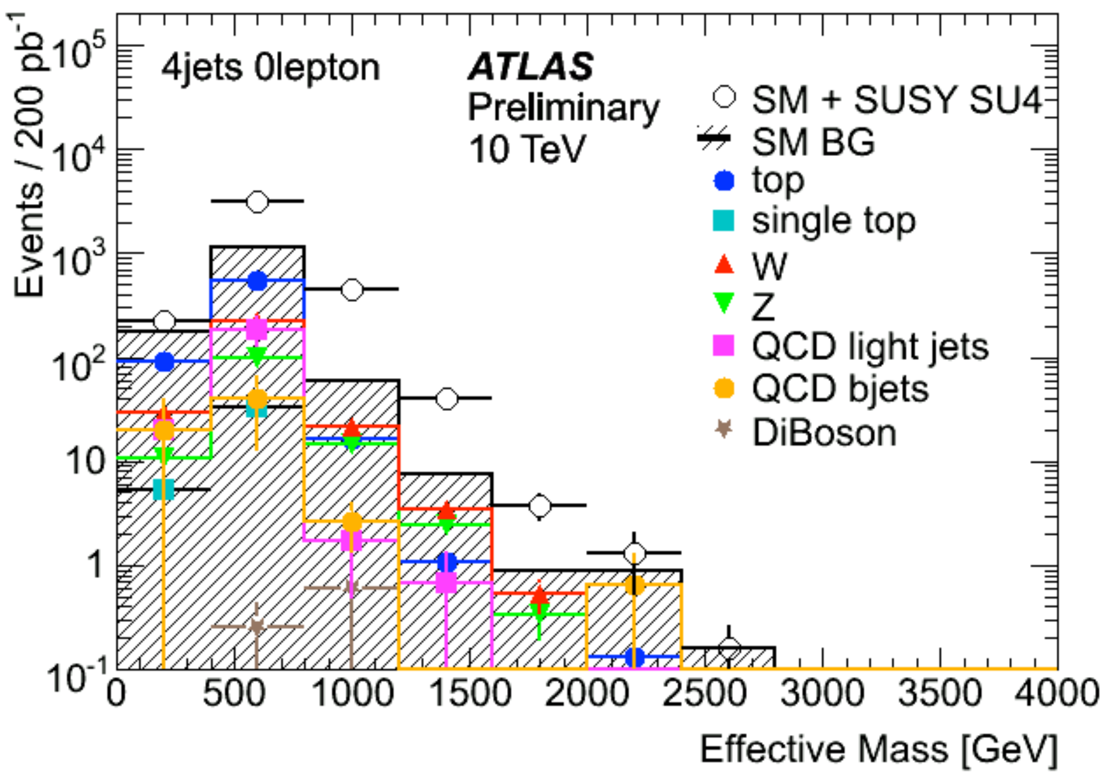
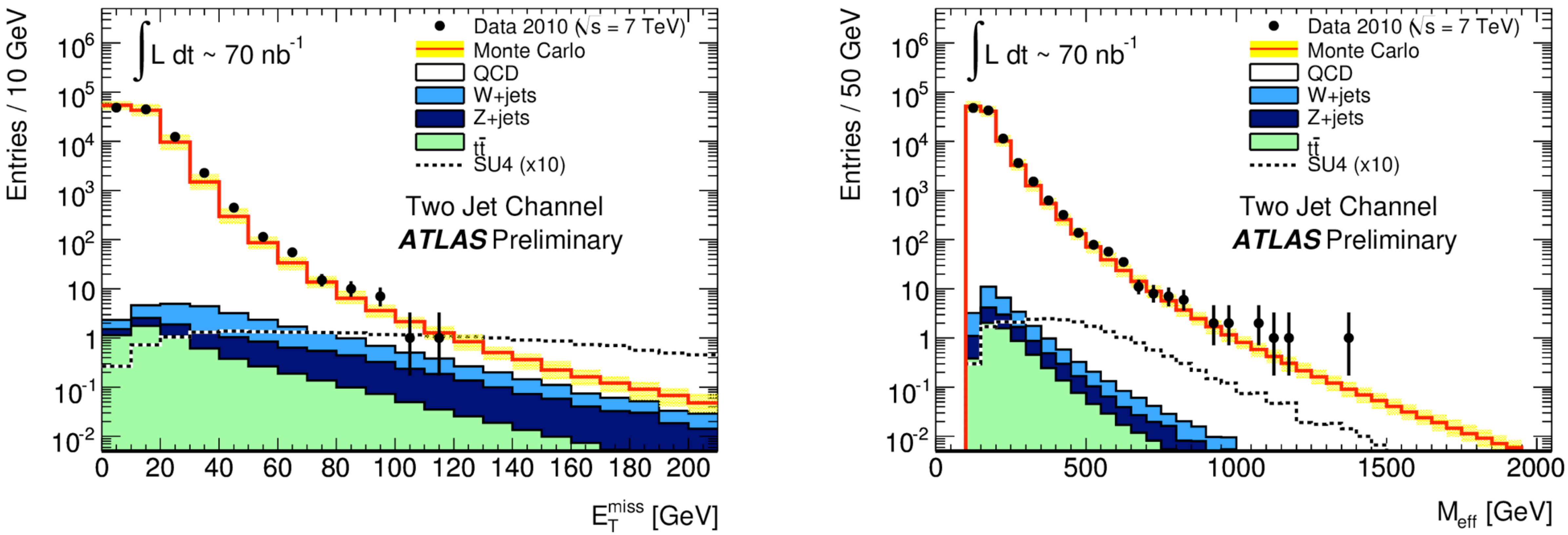




- All-hadronic search highly sensitive to SUSY, but suffers from many backgrounds

All-hadronic search (step I)



- Simple (ignoring trigger, cleaning….) jet cuts (anti-k_T R=0.4)
  - Leading jet E_T>70 GeV
  - Other jets E_T>30 GeV
- Veto isolated leptons (P_T>10 GeV)
- QCD MC normalised to data in two jet channel (uncertainty neglected)

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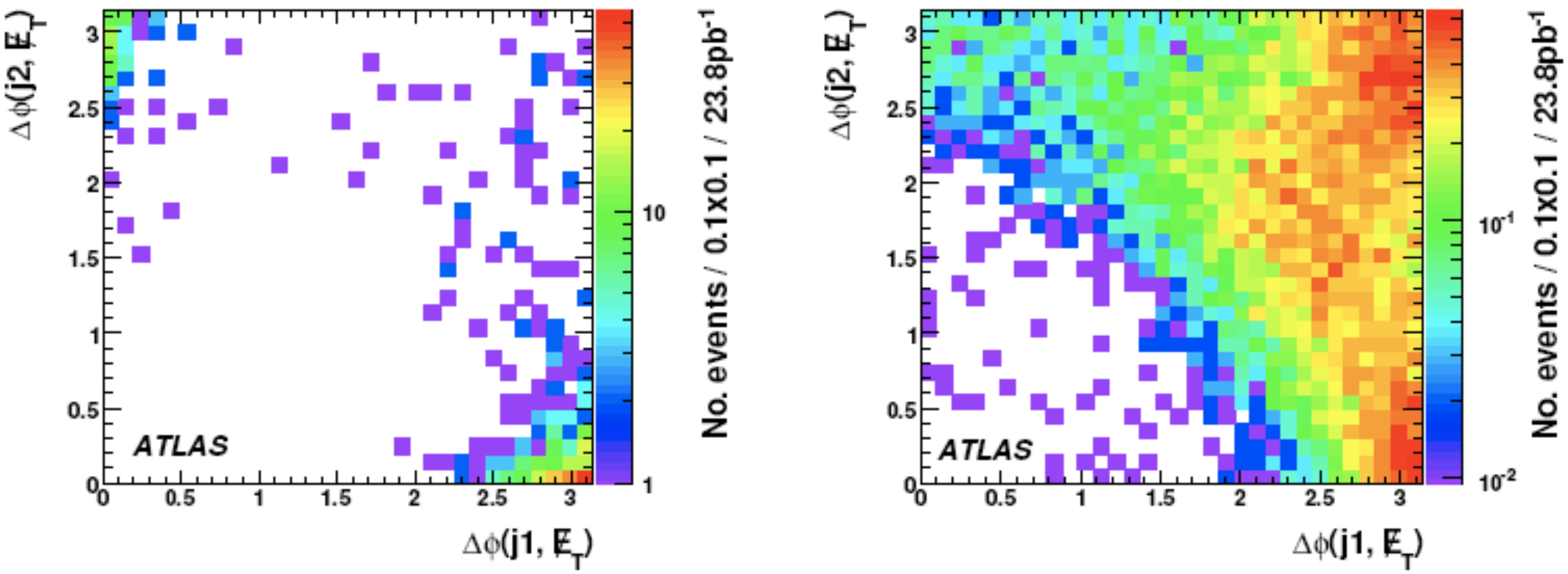
All-hadronic search (QCD)

- Mis-measurement of a jet leads to MET along the jet axis



- Remove with $\Delta\Phi(\text{jet}_i,\text{MET}) > 0.2$ rad

arXiv:0901.0512 (2009)

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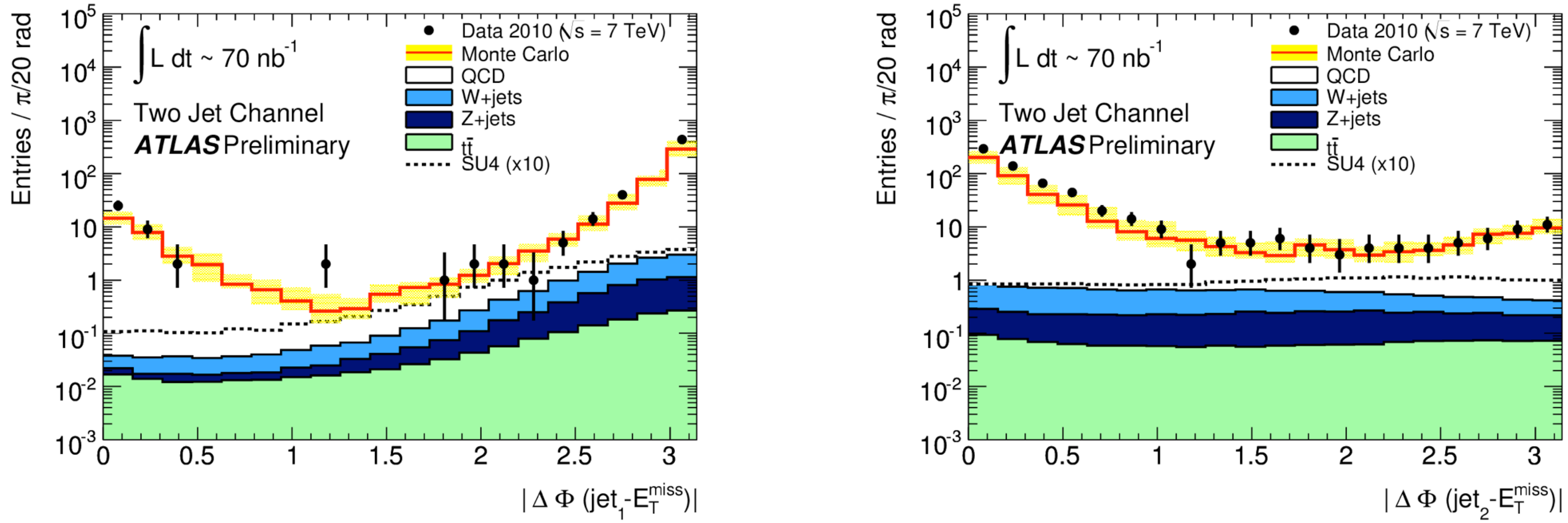
All-hadronic search (QCD)

- Mis-measurement of a jet leads to MET along the jet axis



- Remove with ΔΦ(jet$_i$,MET) > 0.2 rad

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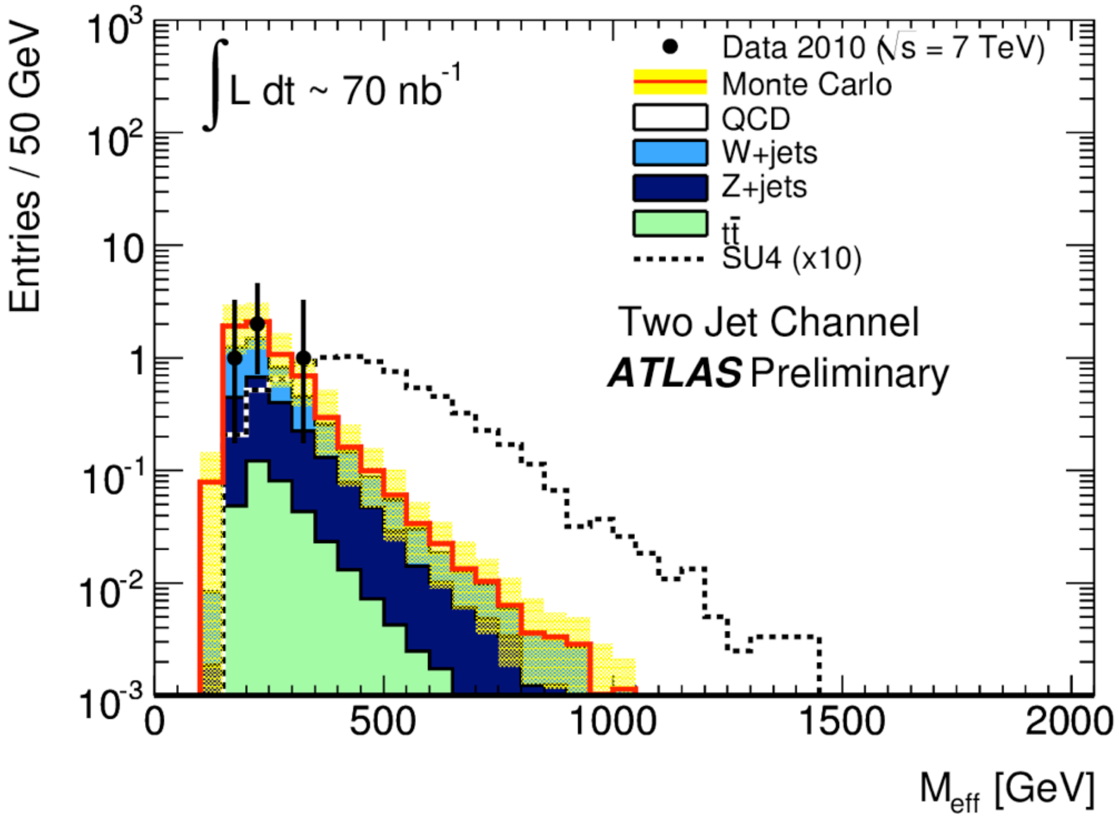
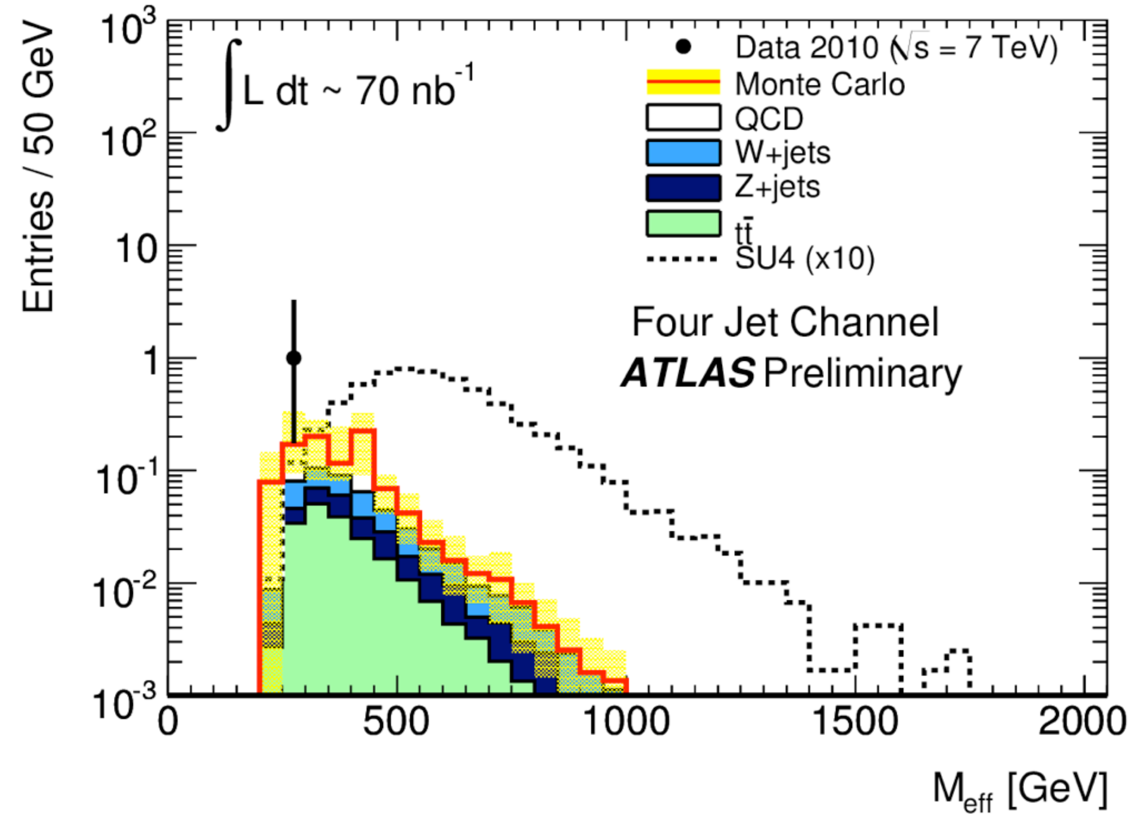
All-hadronic search (final)

- Further selection
  - MET>40 GeV
  - MET/M_{eff}>0.3(0.2)

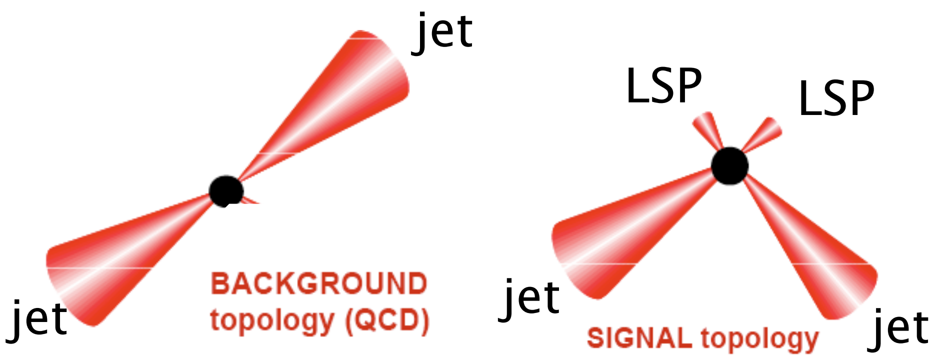
	Monojet		≥ 2 jets		≥ 3 jets		≥ 4 jets	
	Data	Monte Carlo	Data	Monte Carlo	Data	Monte Carlo	Data	Monte Carlo
After jet cuts	21 227	23000^{+7000}_{-6000}	108 239	108000^{+31000}_{-25000}	28 697	31000^{+10000}_{-8000}	5329	5600^{+2300}_{-1600}
$\cap\ E_T^{miss}$ cut	73	46^{+22}_{-14}	650	450^{+190}_{-120}	325	230^{+100}_{-70}	116	84^{+45}_{-30}
$\cap\ \Delta\phi$ and E_T^{miss} cuts	–	–	280	200^{+110}_{-65}	136	100^{+55}_{-30}	54	43^{+26}_{-16}
$\cap\ E_T^{miss}/M_{eff}$, $\Delta\phi$ and E_T^{miss} cuts	–	–	4	6.6 ± 3	0	1.9 ± 0.9	1	1.0 ± 0.6



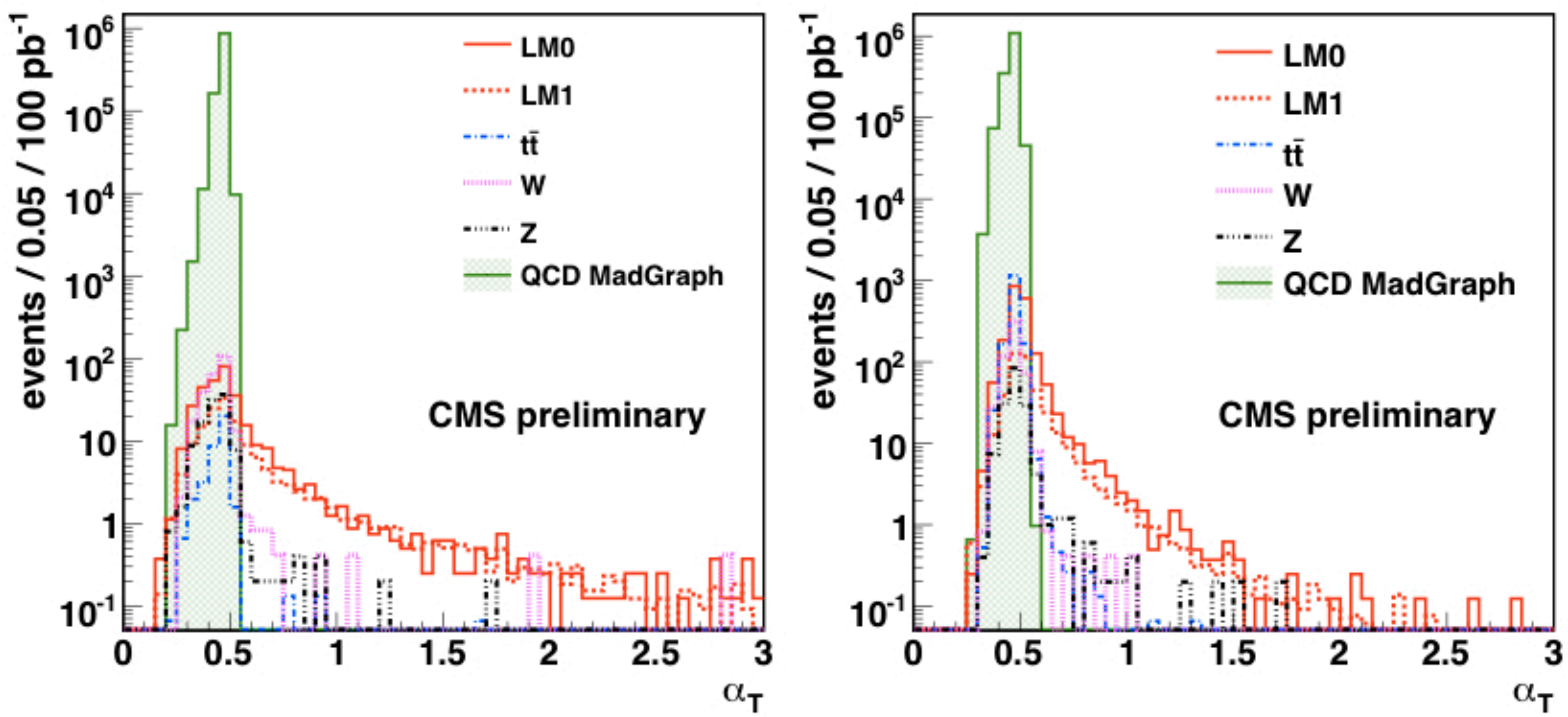


All-hadronic search (α_T)

PRL101:221803 (2008) & CMS-PAS-SUS-09-001



$$\alpha_T = \frac{E_{T\ j2}}{M_{T\ j1j2}} = \frac{\sqrt{E_{T\ j2}/E_{T\ j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$



- A novel approach combining angular and energy measurements
- No dependence on MET ➔ robust for early LHC running
- Originally proposed for di-jet events ➔ generalised up to 6 jets
- Perfectly balanced events have α_T=0.5 (cut at α_T>0.55)
- Mis-measurement of either jet leads to lower values

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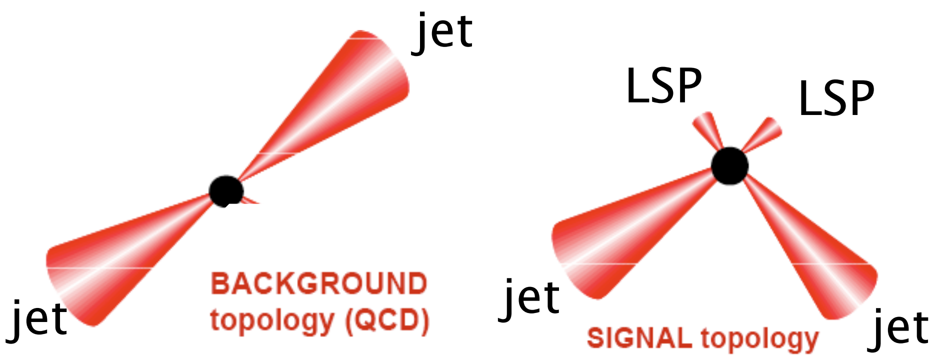

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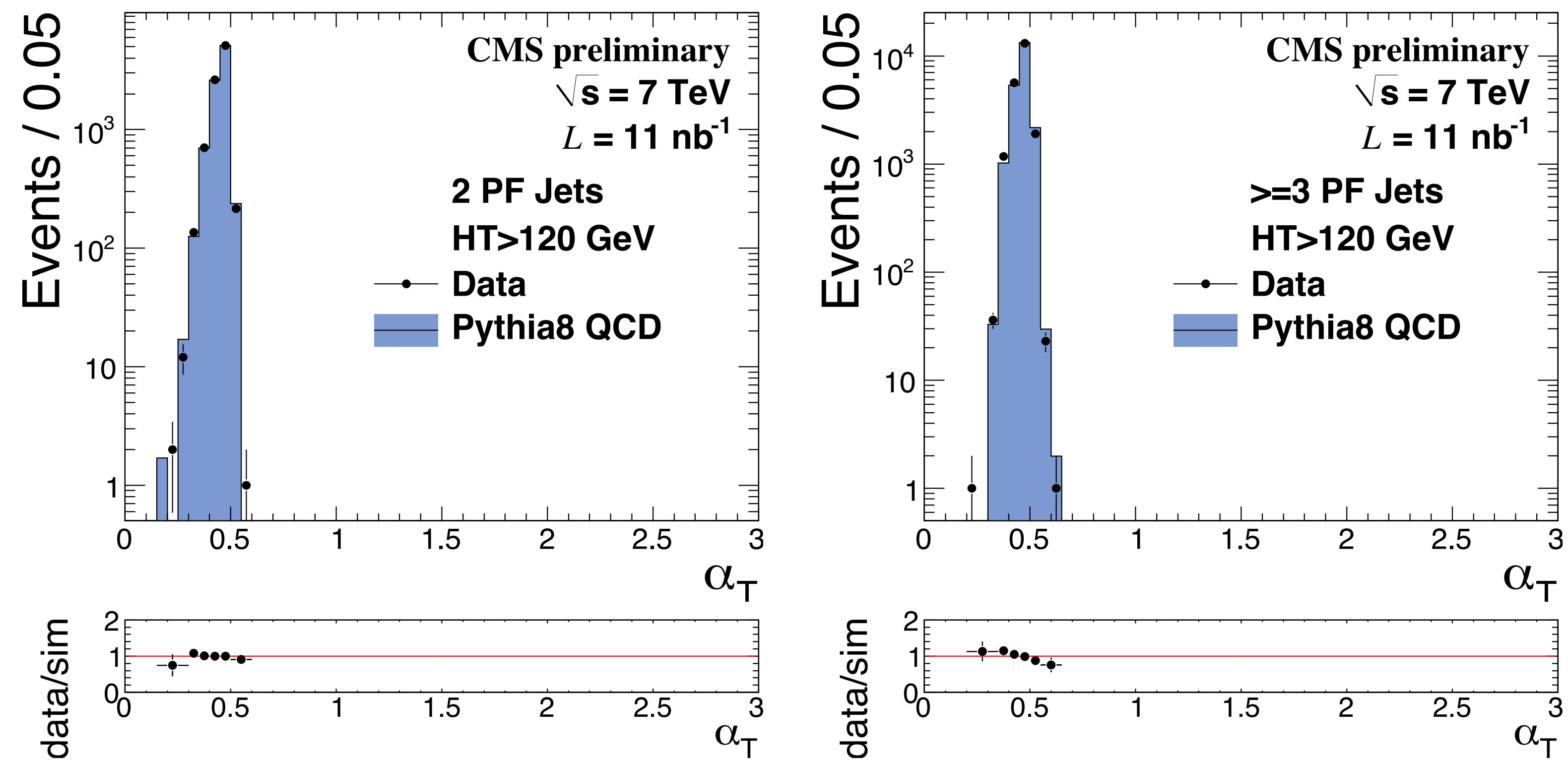

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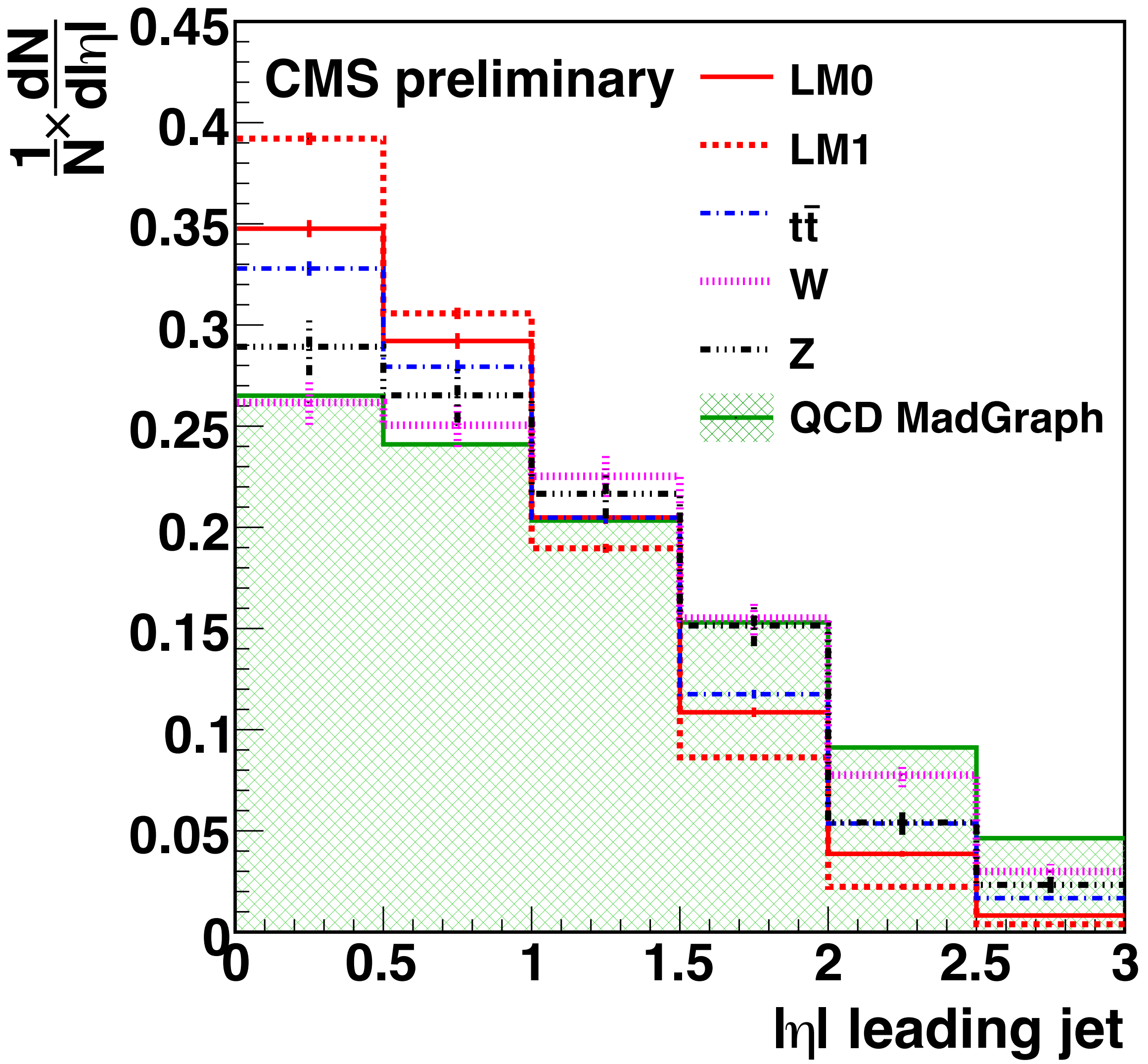
All-hadronic search (centrality)

- Heavy particles preferentially produced centrally
- Use forward regions as background control region



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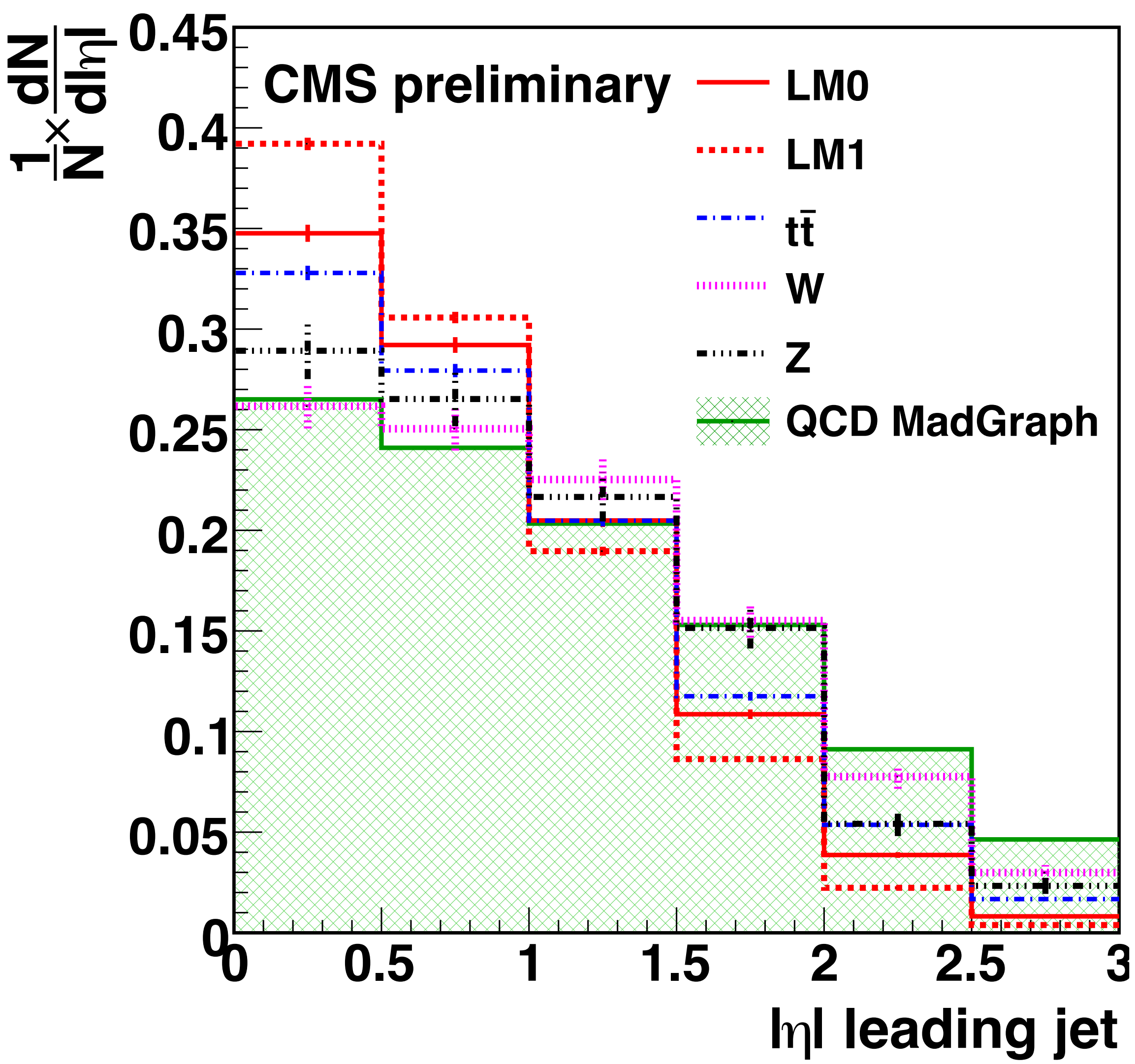

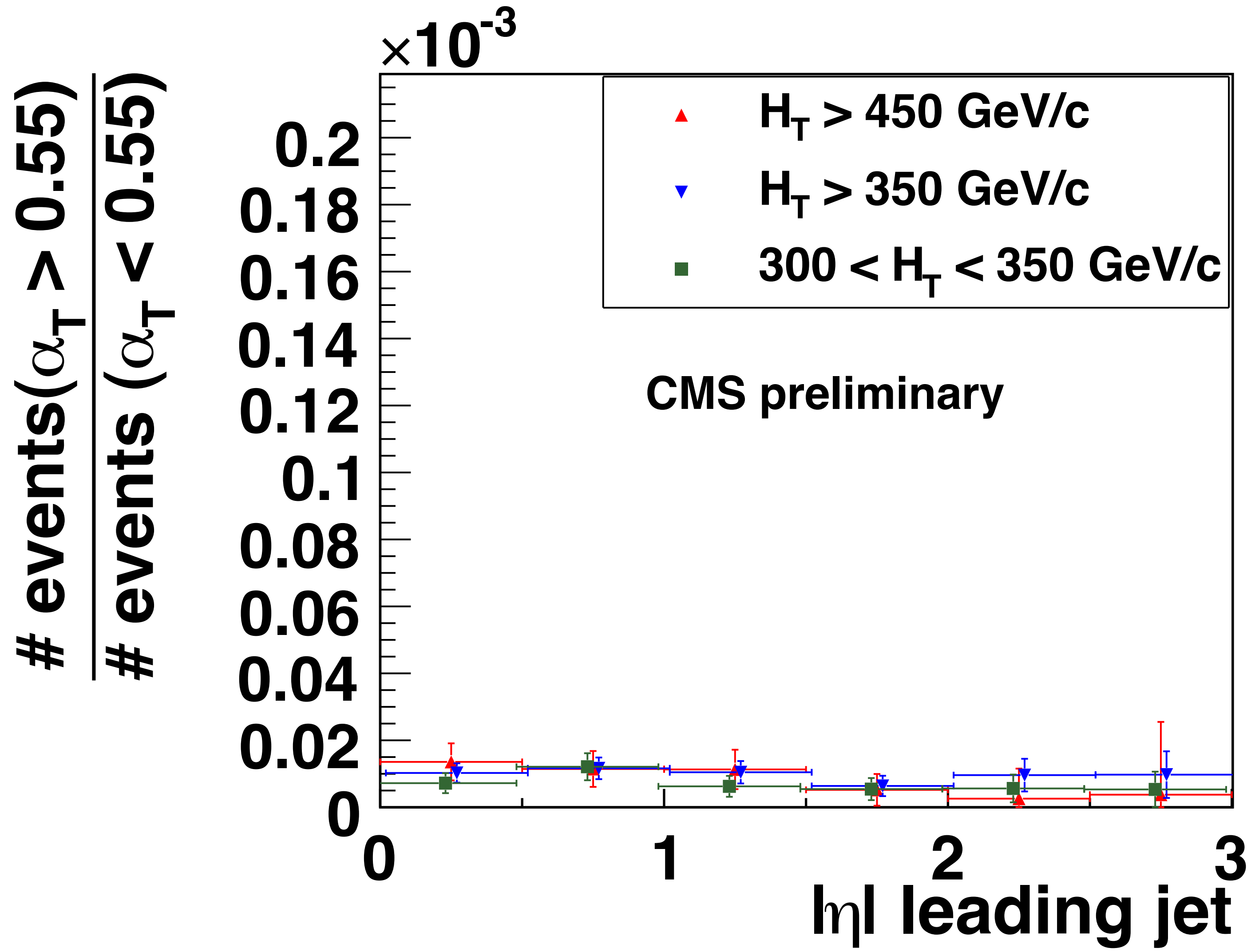

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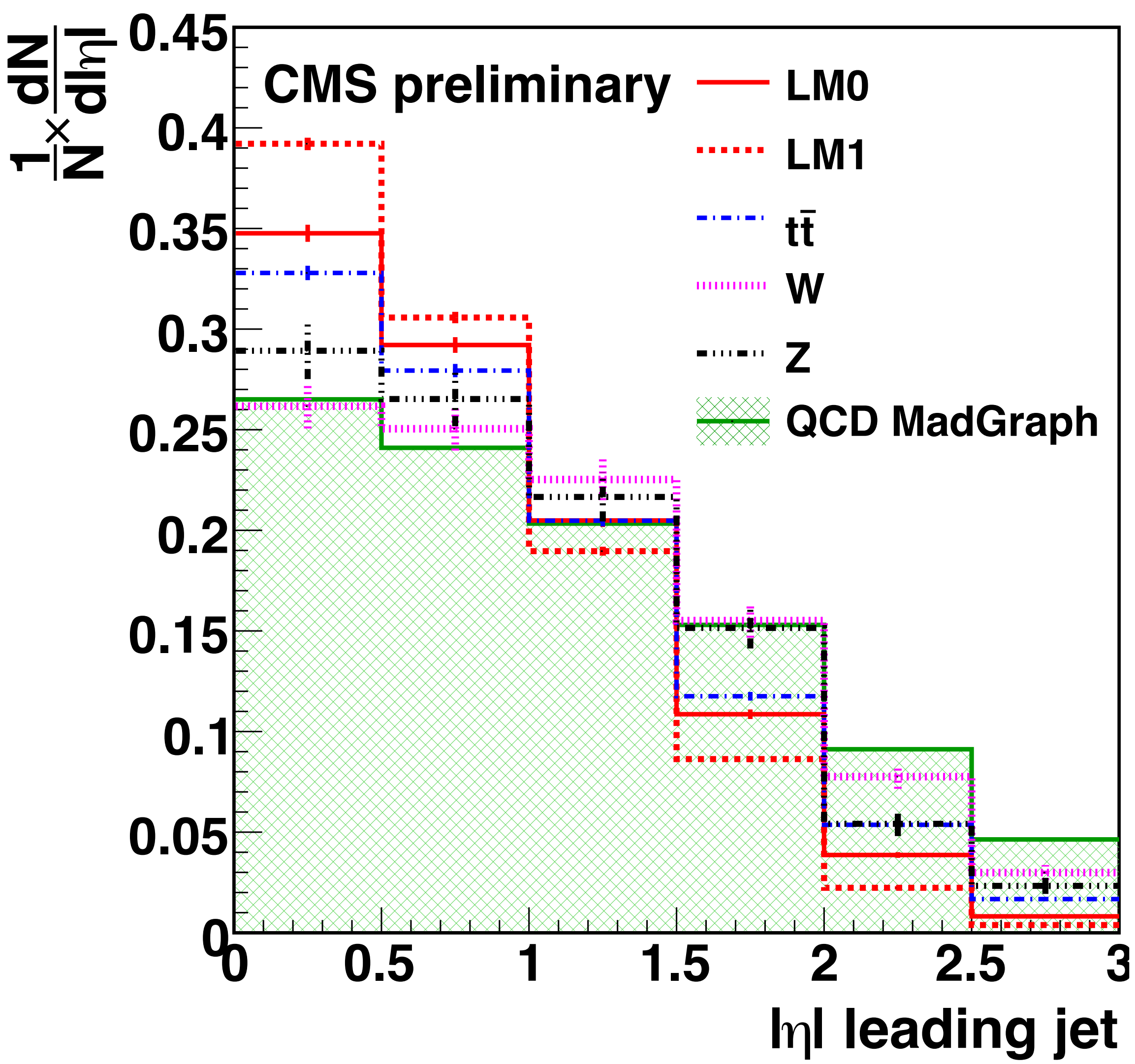

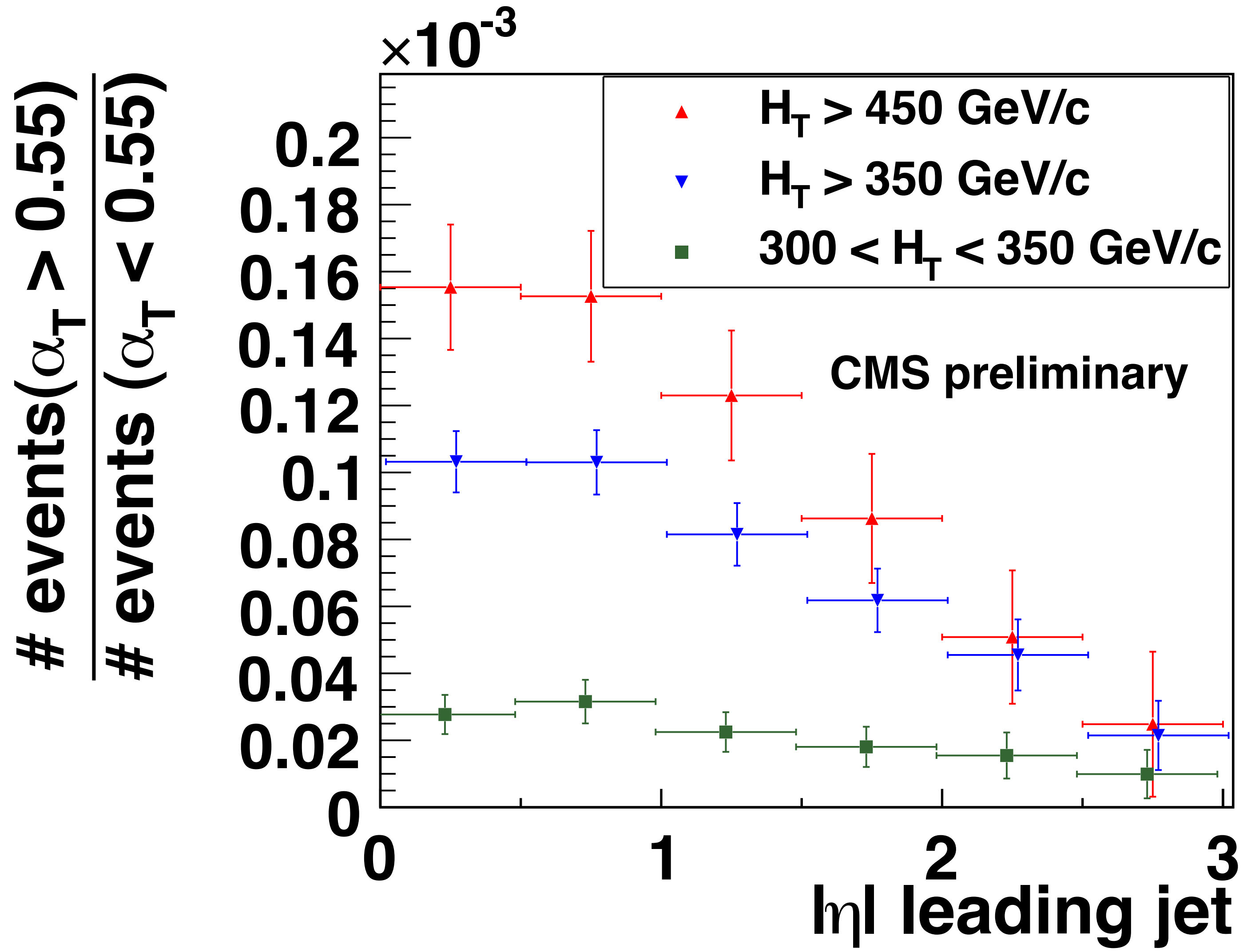

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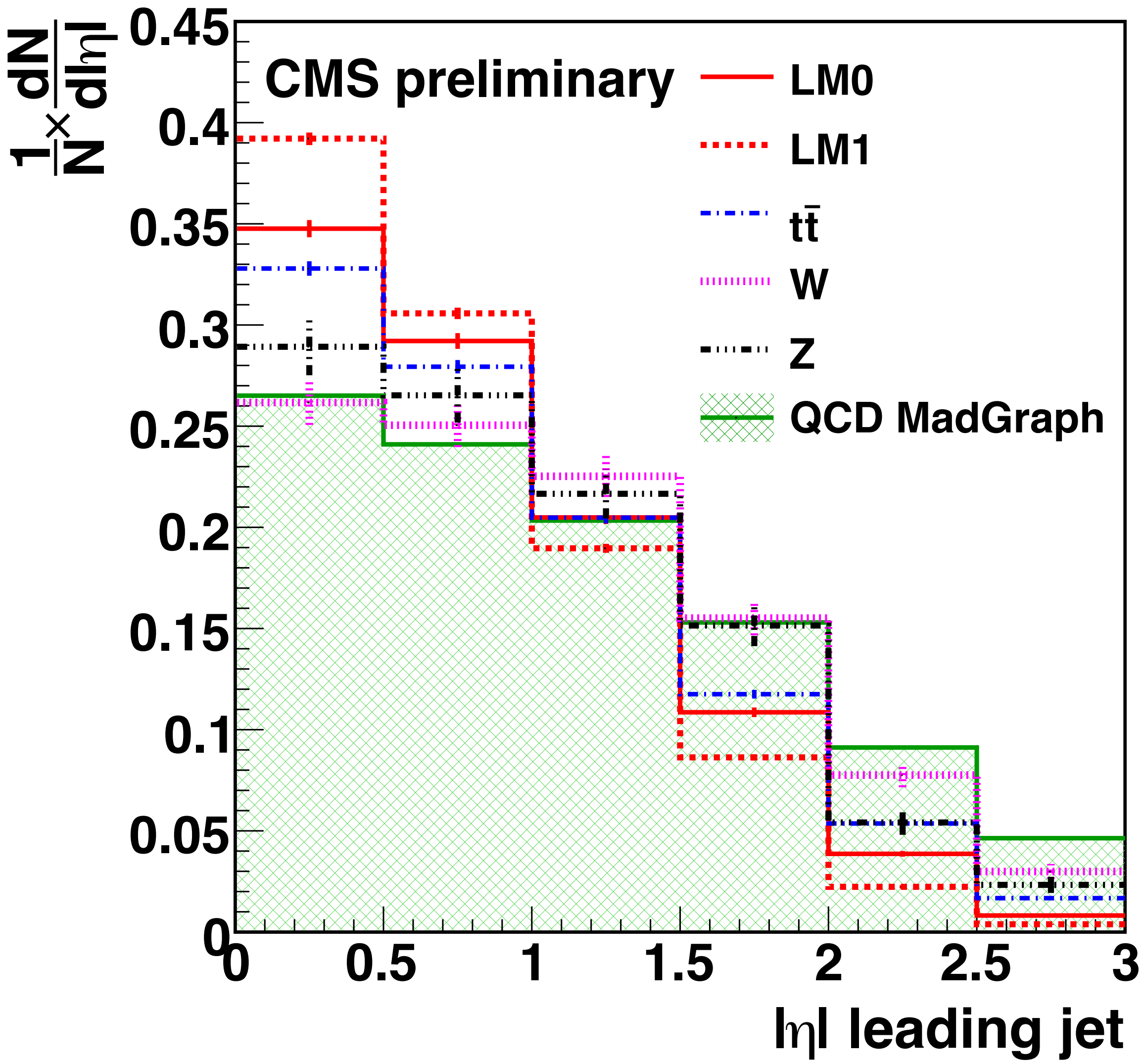

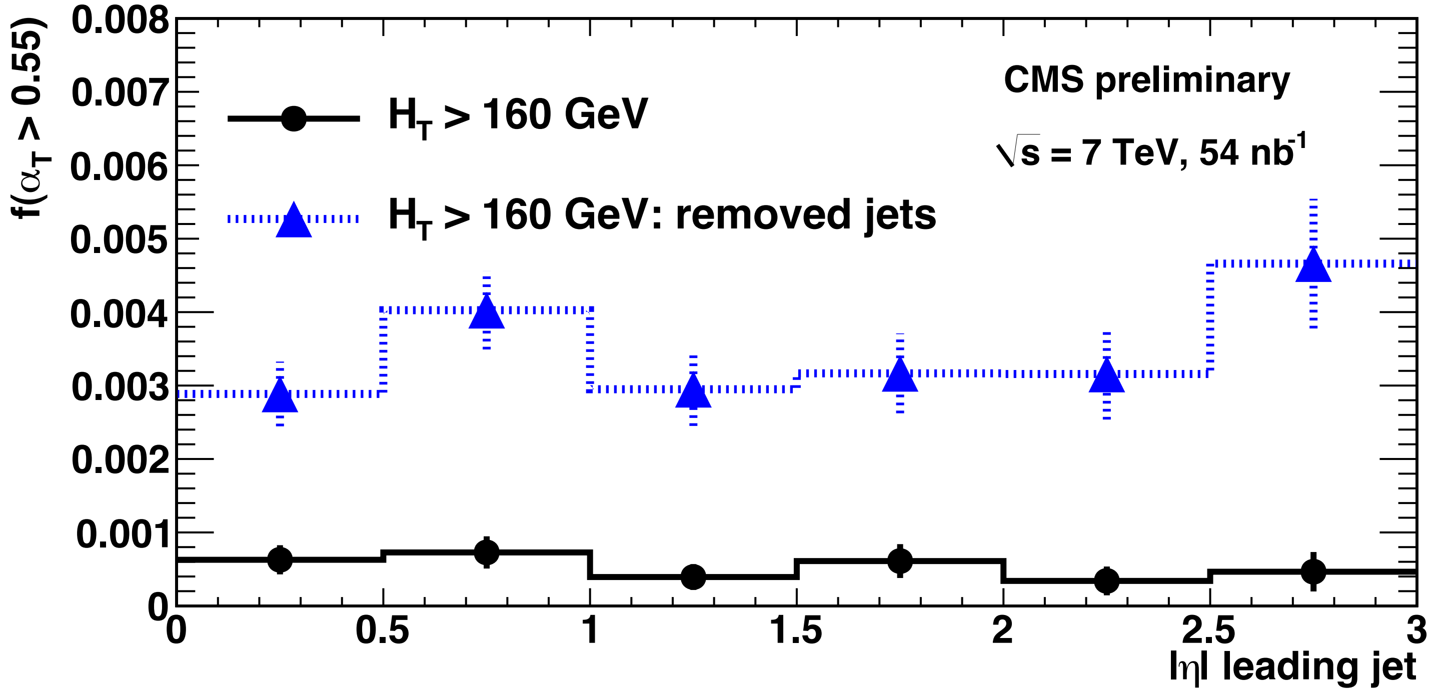

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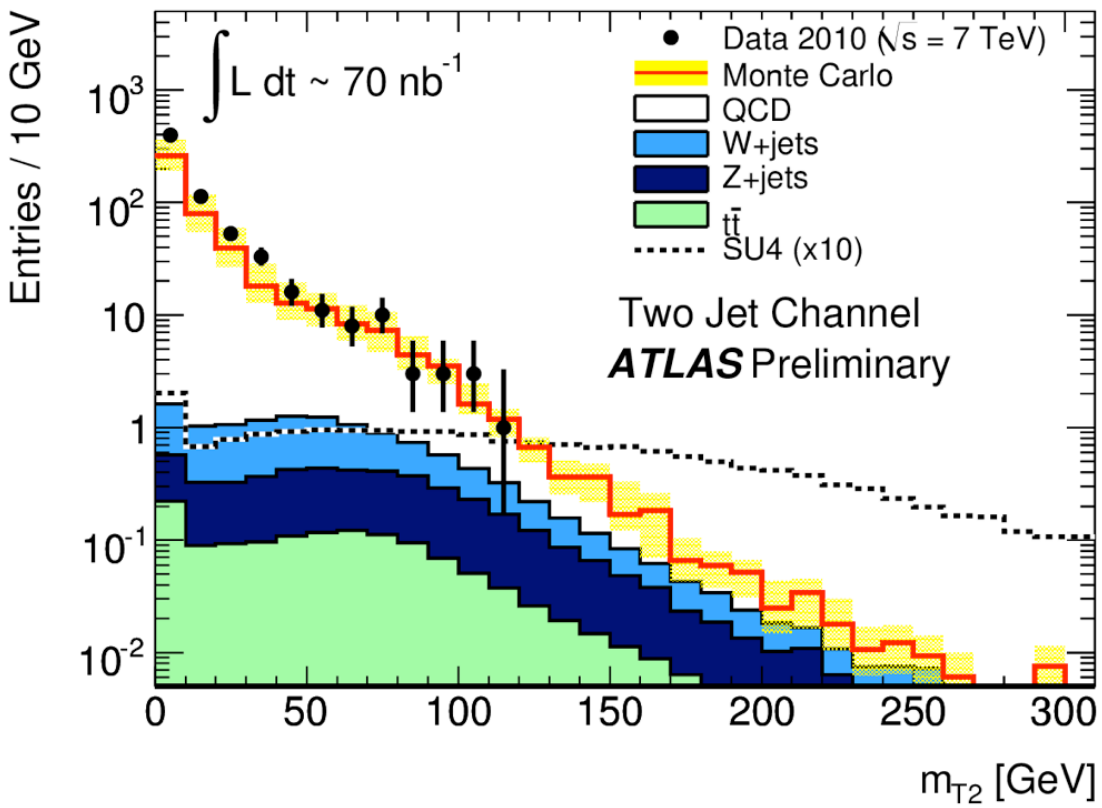
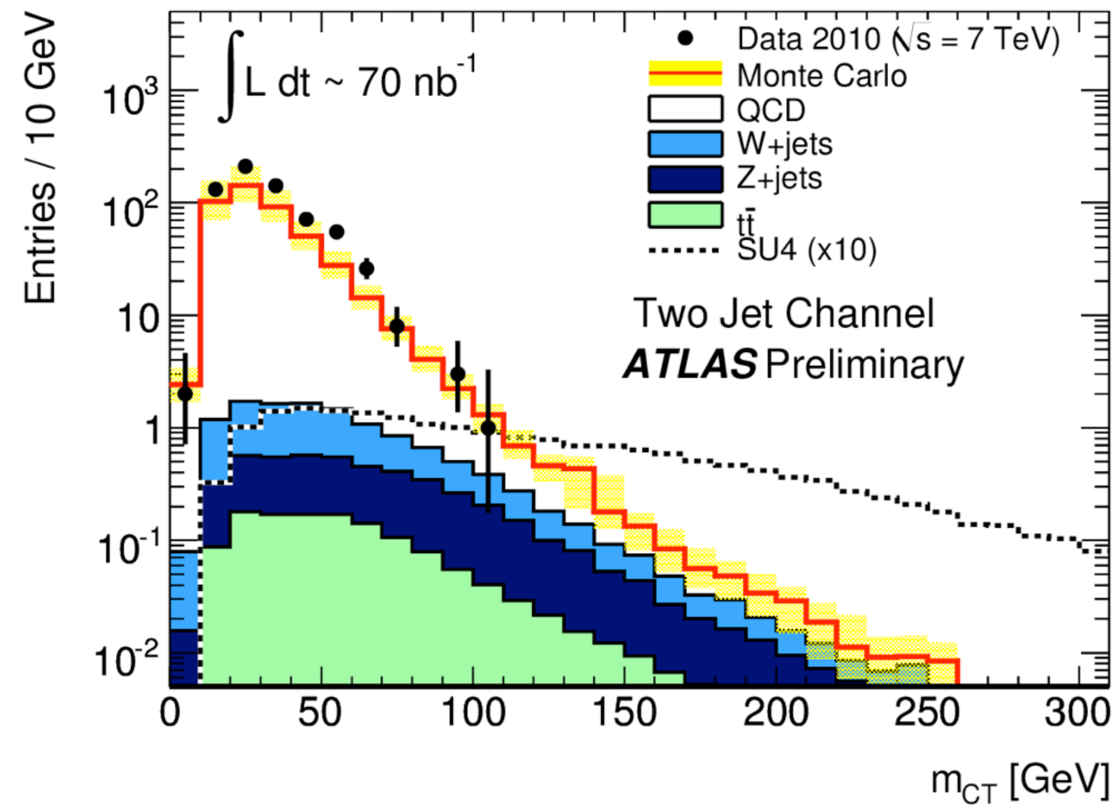
Search (and discovery) variables





Stransverse mass The m_{T2} variable is the generalization of the transverse mass to pair decays [32]. For a final state consisting of two visible objects with transverse momenta $\mathbf{p}_T^{(1)}$ and $\mathbf{p}_T^{(2)}$ respectively, and with missing transverse momentum $\not{\mathbf{p}}_T$, it is defined by

$$m_{T2}\left(\mathbf{p}_T^{(1)}, \mathbf{p}_T^{(2)}, \not{\mathbf{p}}_T\right) \equiv \min_{\not{\mathbf{q}}_T^{(1)}+\not{\mathbf{q}}_T^{(2)}=\vec{E}_T^{\mathrm{miss}}} \left\{\max\left(m_T\left(\mathbf{p}_T^{(1)}, \not{\mathbf{q}}_T^{(1)}\right), m_T\left(\mathbf{p}_T^{(2)}, \not{\mathbf{q}}_T^{(2)}\right)\right)\right\} \tag{4}$$

where m_T is the transverse mass [5)]

$$m_T^2\left(\mathbf{p}_T^{(i)}, \not{\mathbf{q}}_T^{(i)}\right) \equiv 2|\mathbf{p}_T^{(i)}||\not{\mathbf{q}}_T^{(i)}| - 2\mathbf{p}_T^{(i)} \cdot \not{\mathbf{q}}_T^{(i)}, \tag{5}$$

and the minimization is over all values of the two undetectable particles' possible missing transverse momenta $\not{\mathbf{q}}_T^{(1,2)}$ consistent with the $\vec{E}_T^{\mathrm{miss}}$ constraint. This variable represents an event-by-event lower bound on the mass of any pair-produced semi-invisibly decaying particle which could have resulted in the observed state [34] .

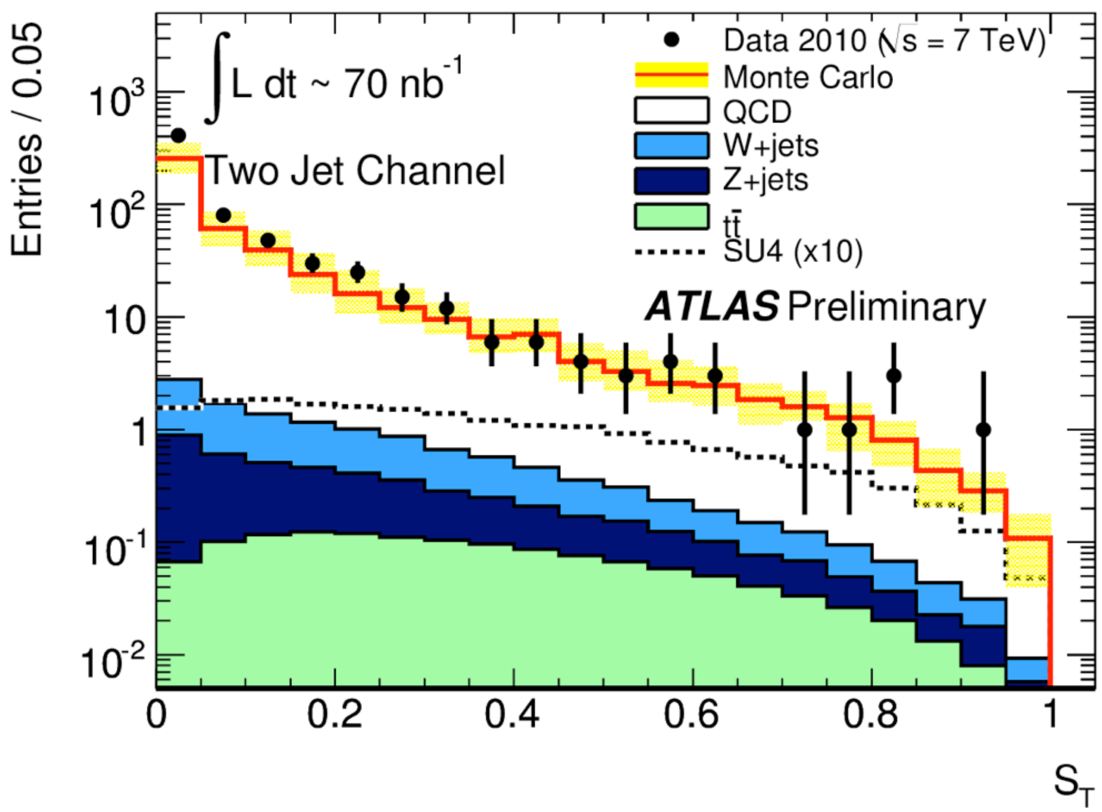
Contransverse mass This variable is useful in events in which a pair of identical parent particles has decayed semi-invisibly producing visible daughters (with momenta $j^{(1,2)}$). The contransverse mass is defined by [35]

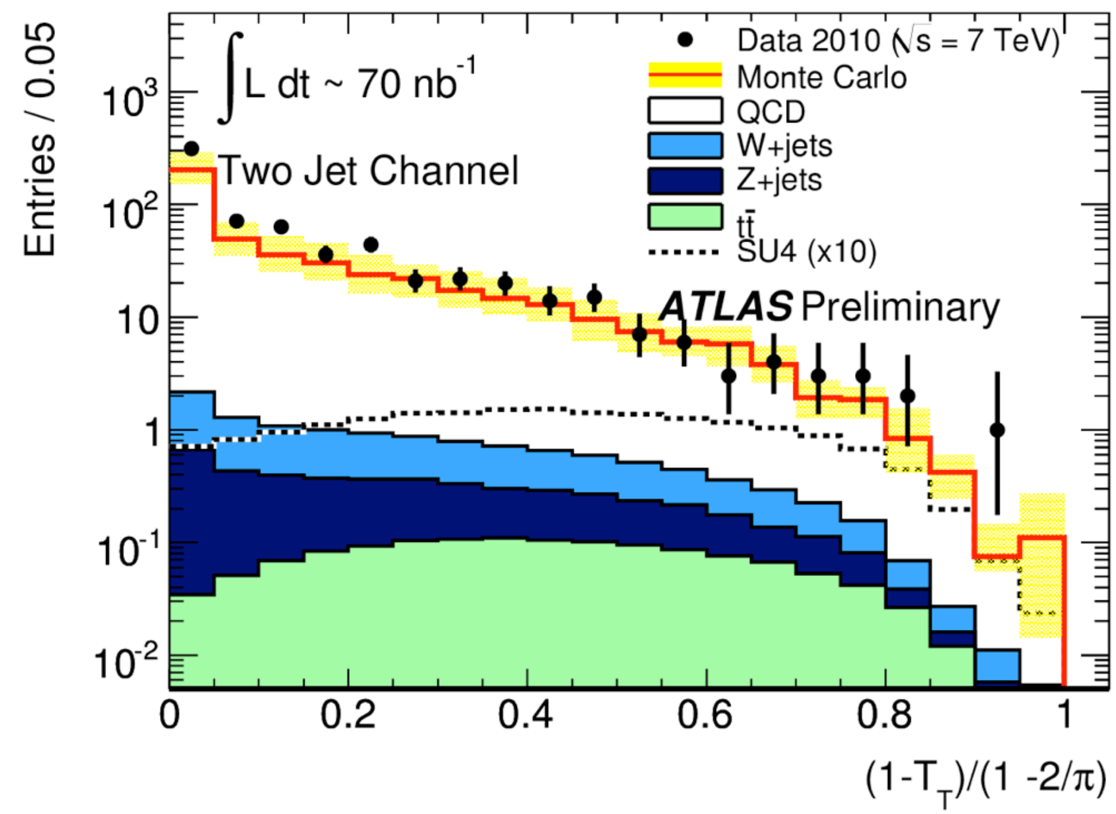
$$m_{CT}^2\left(j^{(1)}, j^{(2)}\right) \equiv 2E_T^{(1)}E_T^{(2)} + 2\mathbf{p}_T^{(1)} \cdot \mathbf{p}_T^{(2)}. \tag{6}$$

It is invariant under back-to-back boosts of the parent particles, and provides a lower bound on a combination of the masses of the parent and undetectable daughter particles. The contransverse mass is sensitive to the boost of the centre-of-momentum frame of the parent particles in the laboratory transverse plane and must therefore be corrected using the procedure described in [36].

Barr and Gwenlan PRD80:074007,2009.

Other search variables





Transverse sphericity The transverse sphericity is defined by

$$S_{\mathrm{T}} \equiv \frac{2\lambda_2}{(\lambda_1+\lambda_2)} \tag{7}$$

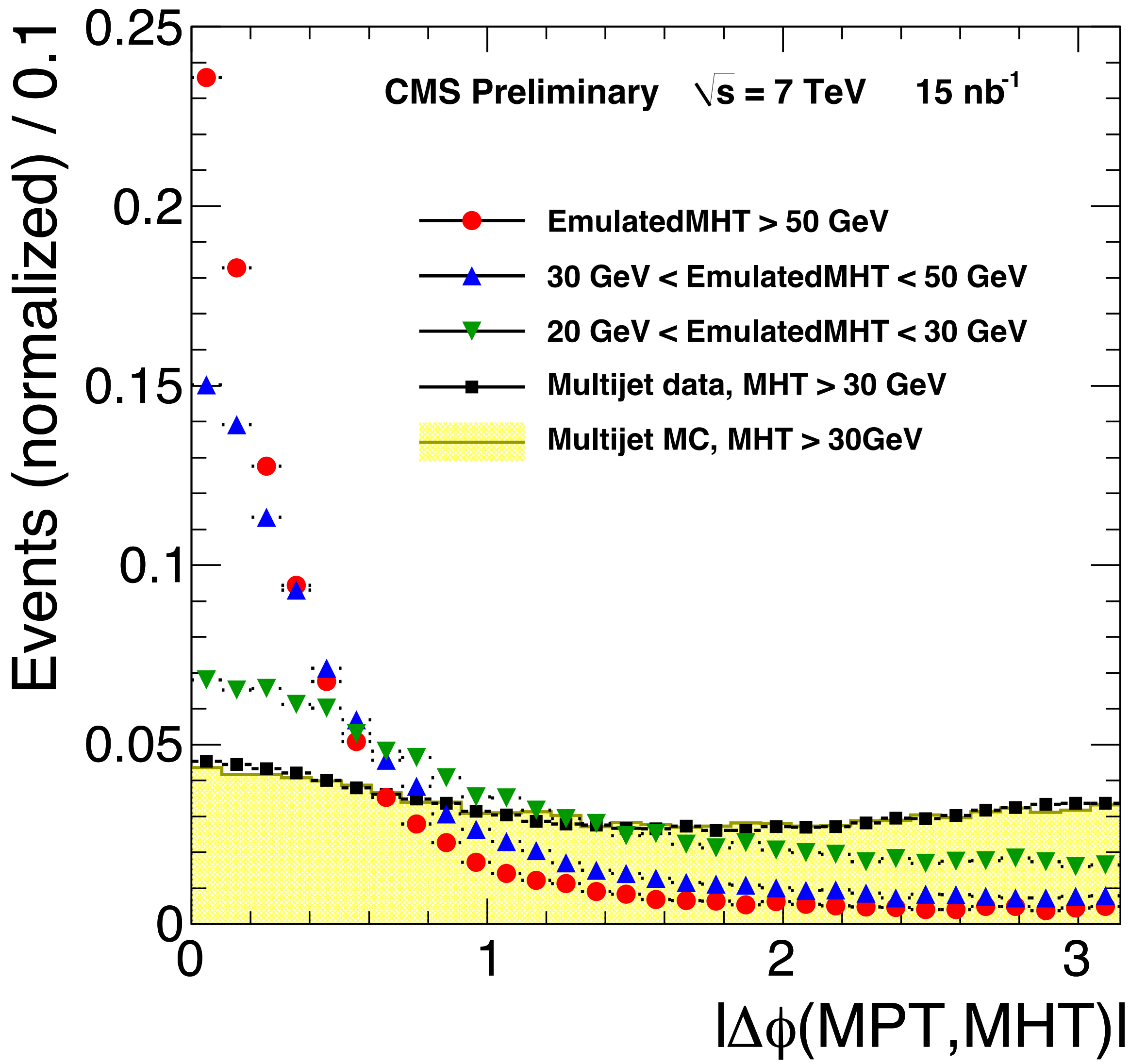
where λ_1 and λ_2 are the eigenvalues of the 2×2 sphericity tensor $S_{ij} = \sum_k p_{ki} p^{kj}$ computed from all jets selected. The variable is useful because QCD events tend to be found at lower S_{T} than SUSY events.

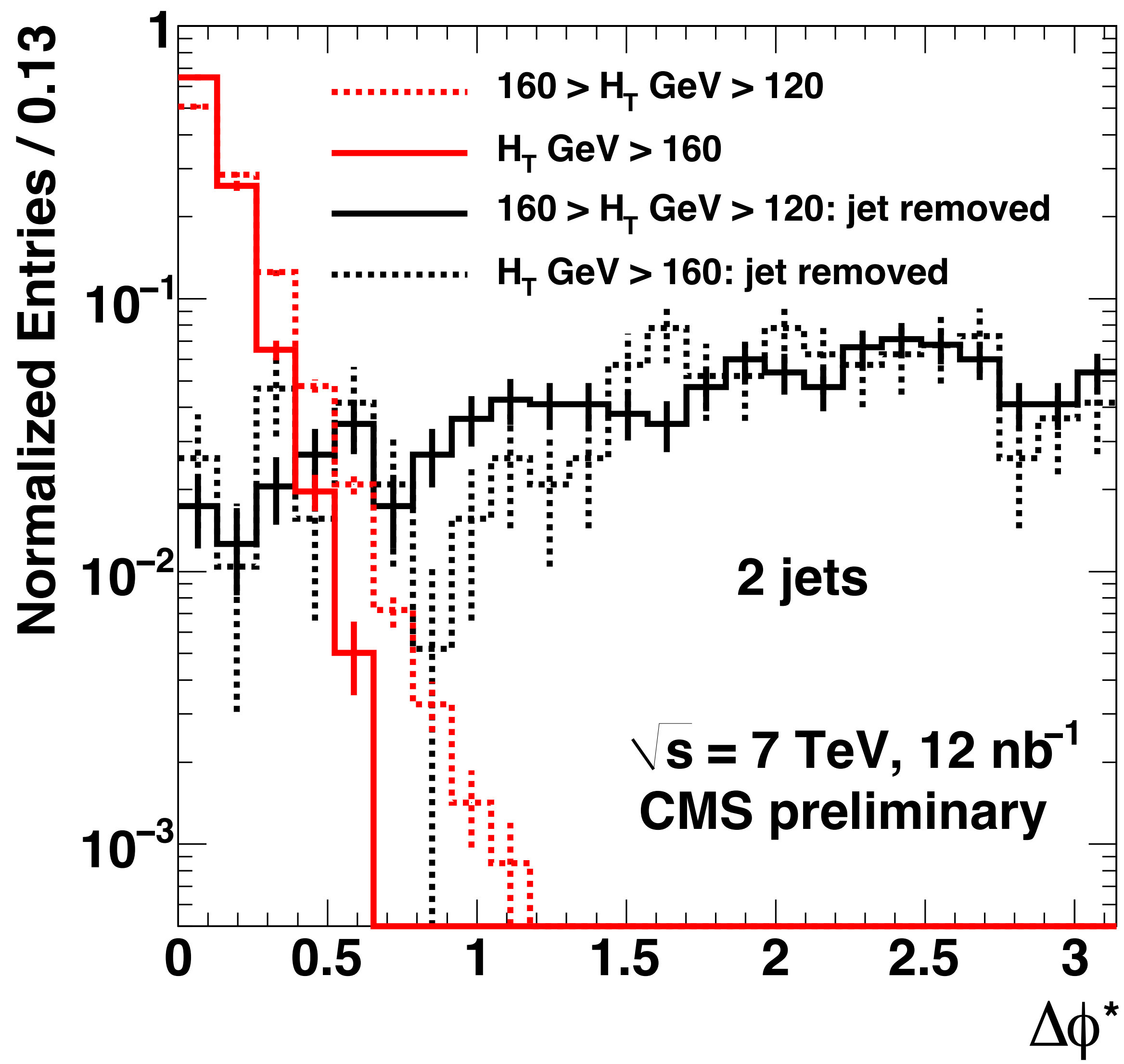
Transverse thrust The thrust axis is found in the $x-y$ plane via an iterative procedure, where the particle two-momenta p_i are projected to the thrust axis n and then the total sum is maximized. The value of thrust is defined as

$$T_{\mathrm{T}} = \frac{\max(\sum_i |p_i \cdot n|)}{(\sum_i |p_i|)} \tag{8}$$

The quantity plotted is $(1-T_{\mathrm{T}})/(1-\frac{2}{\pi})$.

QCD control variables





Play independent detectors off against each other

$$\Delta\phi^* \equiv \min_{\text{jets } k}\left(\left|\Delta\phi(\vec{p}_k, -\sum_{\text{jets } i\neq k}\vec{p}_i)\right|\right)$$

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Single-lepton search (MC example)

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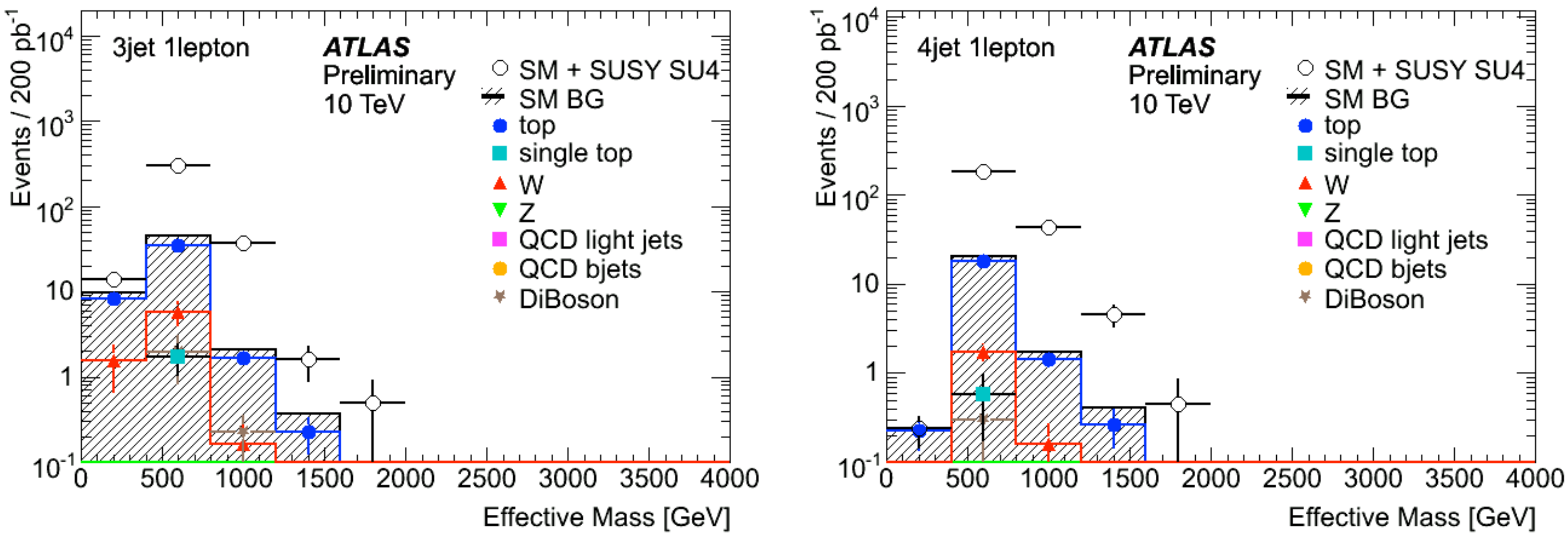
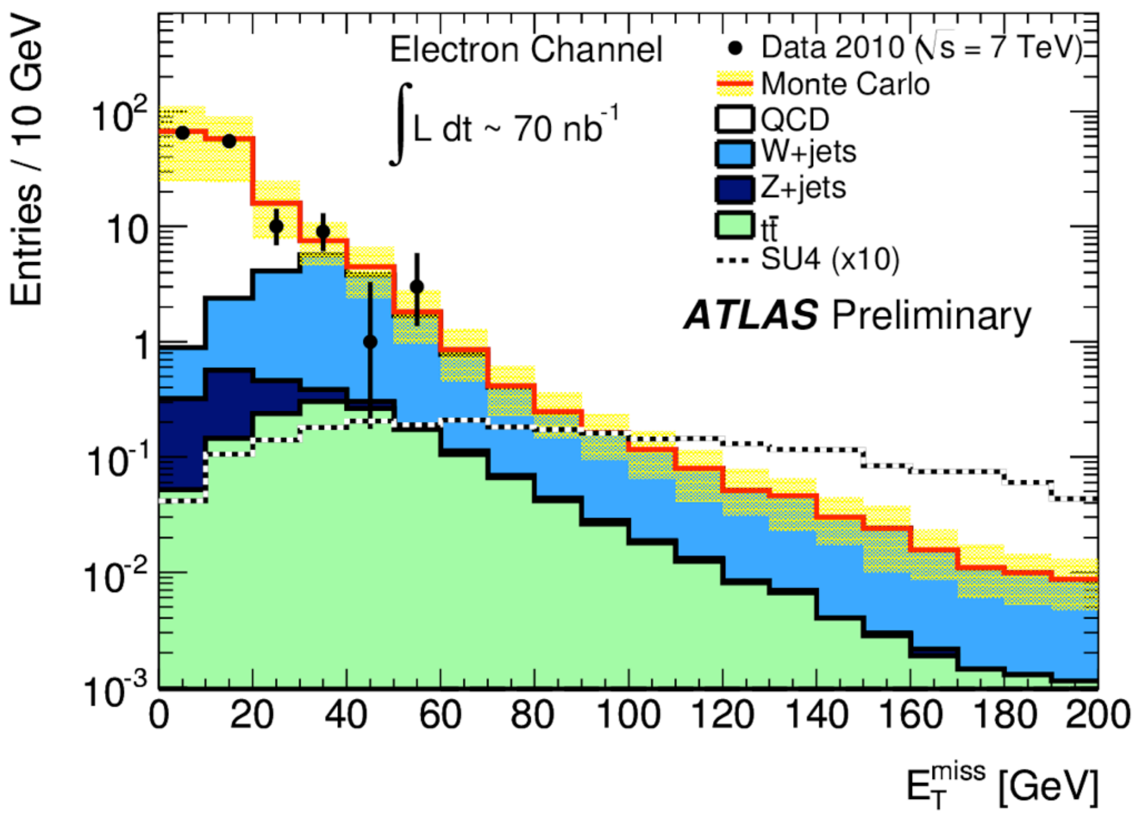
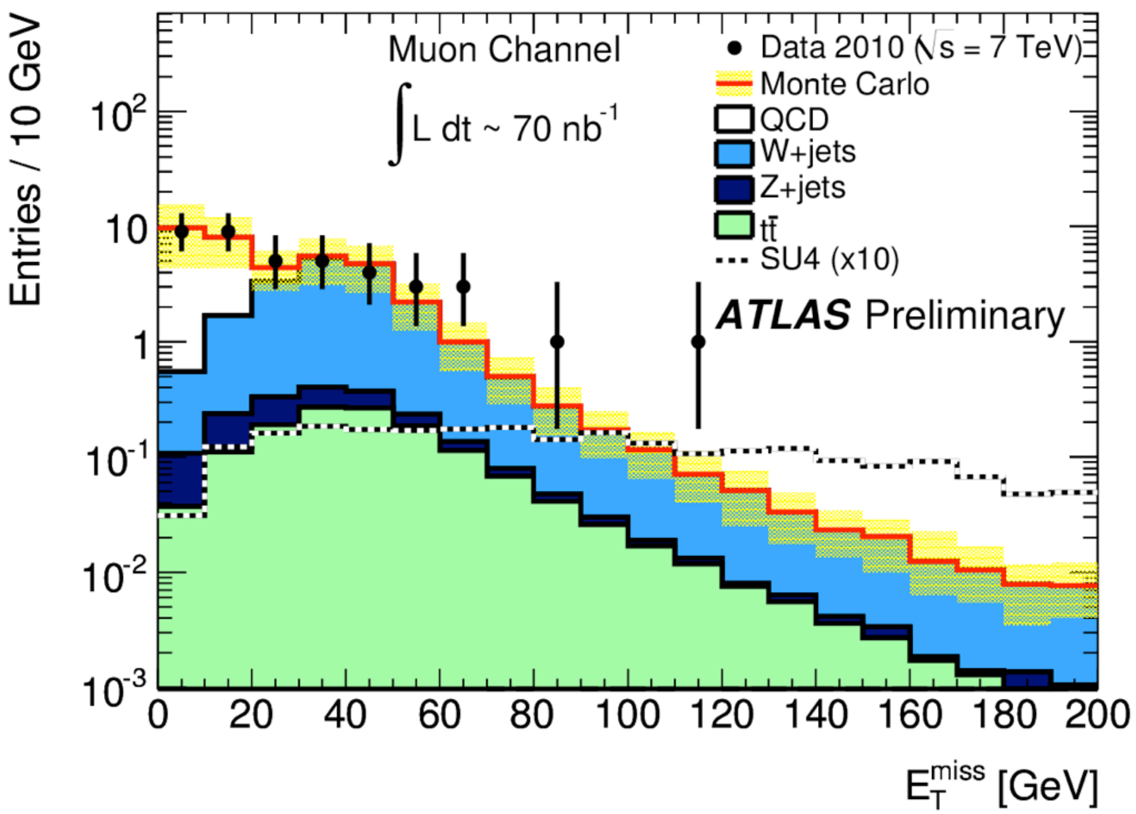


- Requiring one lepton (e or μ) suppresses QCD background powerfully
- Highly sensitive to SUSY
- Backgrounds come from Standard Model processes with neutrinos ➔ real MET
- In particular top and W decays

Single-lepton search (part I)





- Simple cuts (once again too lazy to list cleaning, triggers...)
  - One isolated lepton with P_T>20 GeV
  - At least two jets E_T>30 GeV
- QCD MC normalised to data at MET < 40 GeV and M_T < 40 GeV
- Uncertainty 50% from fake rate study comparison with data

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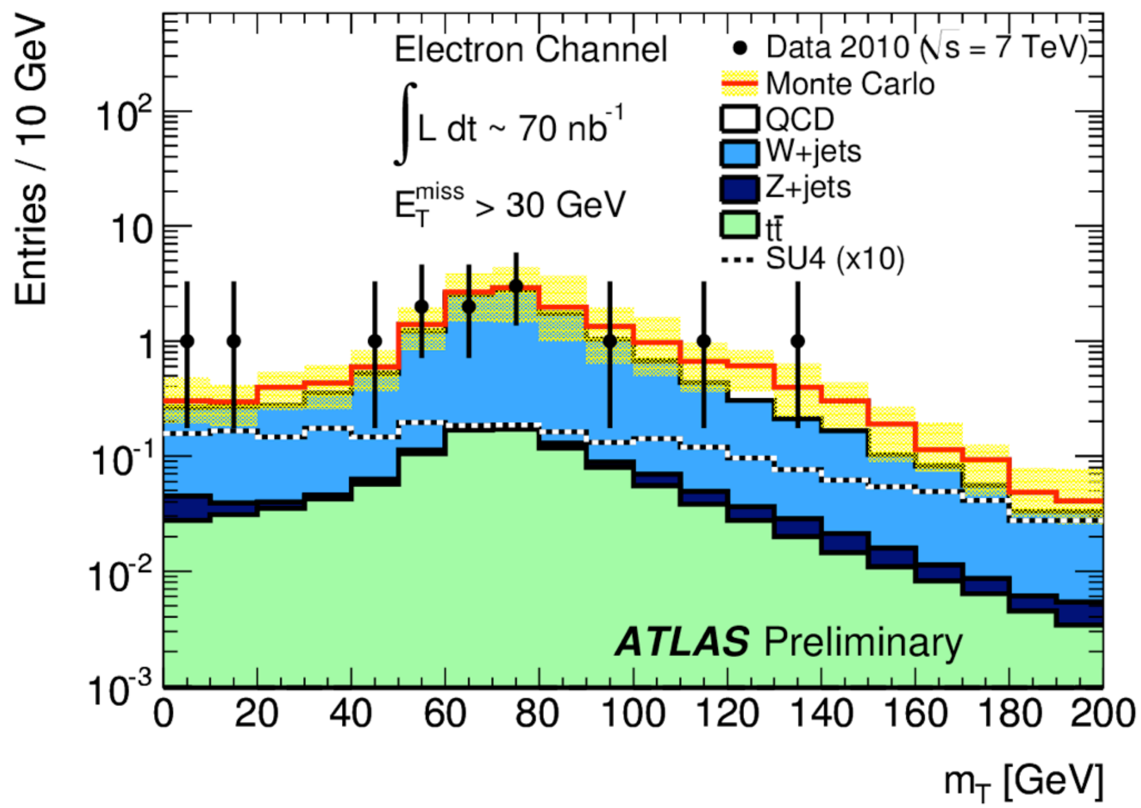
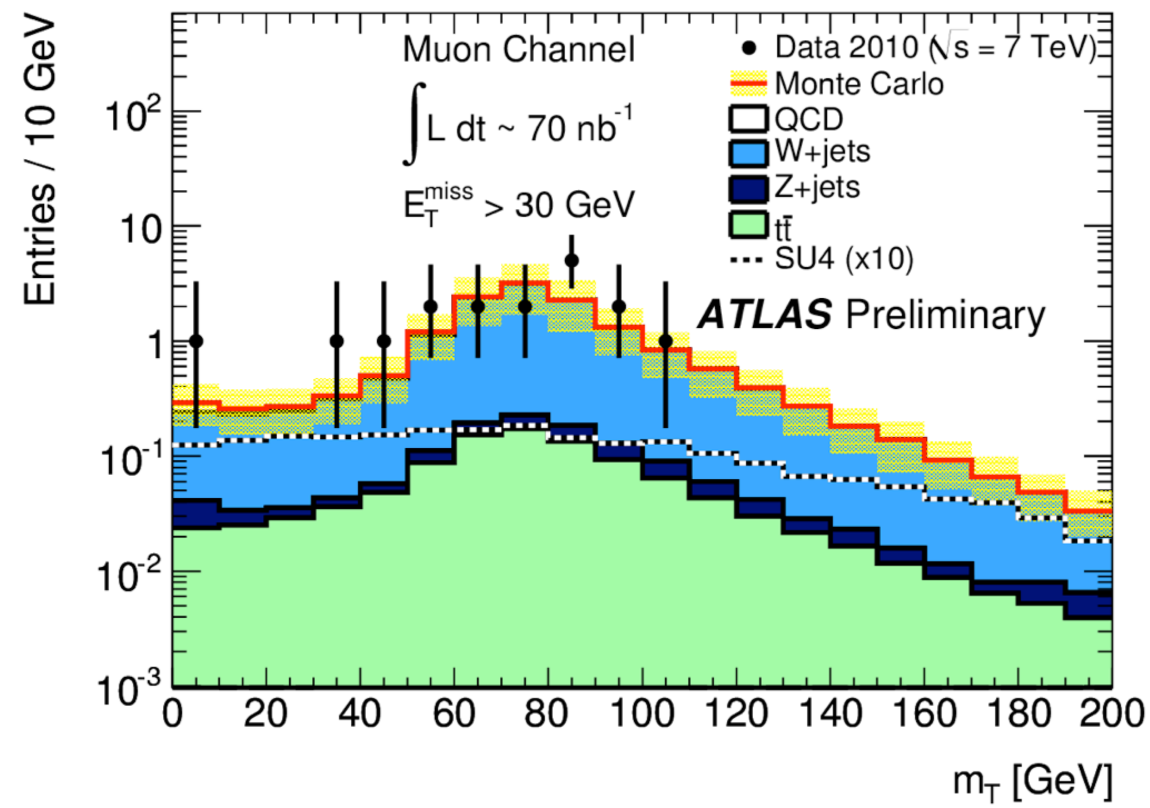
Single-lepton search (W bkgd)



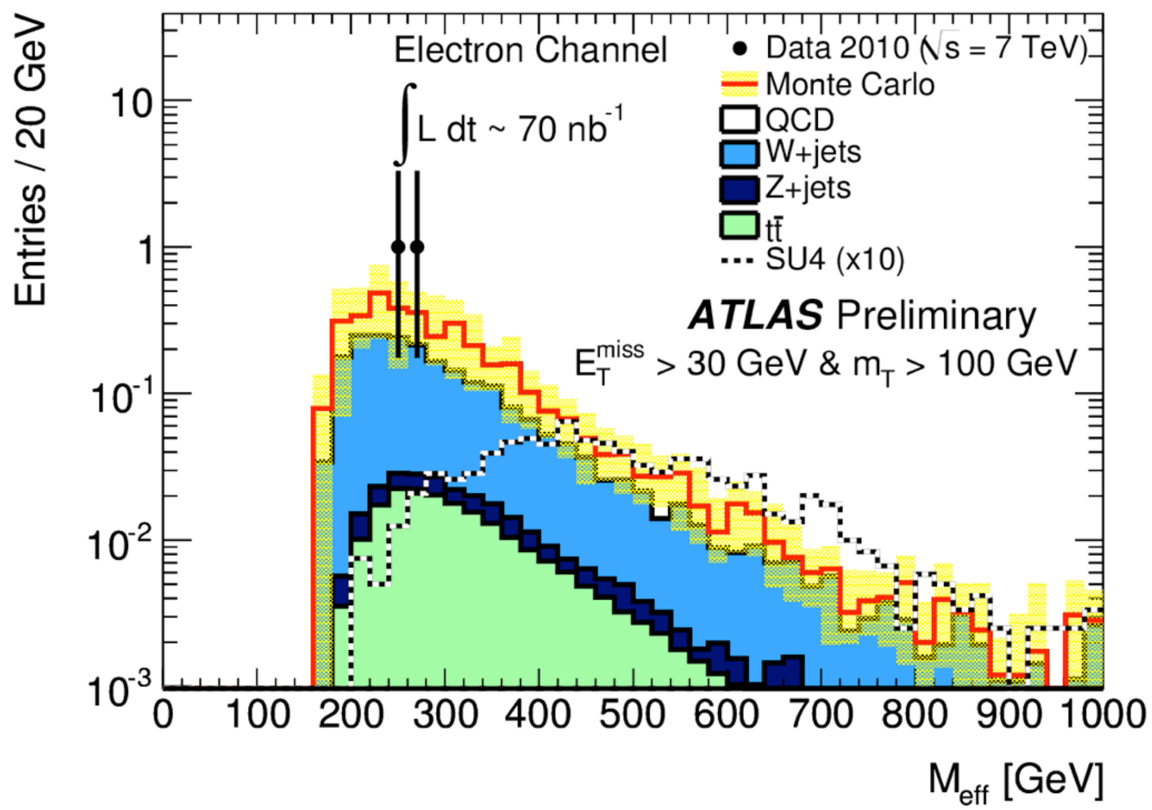


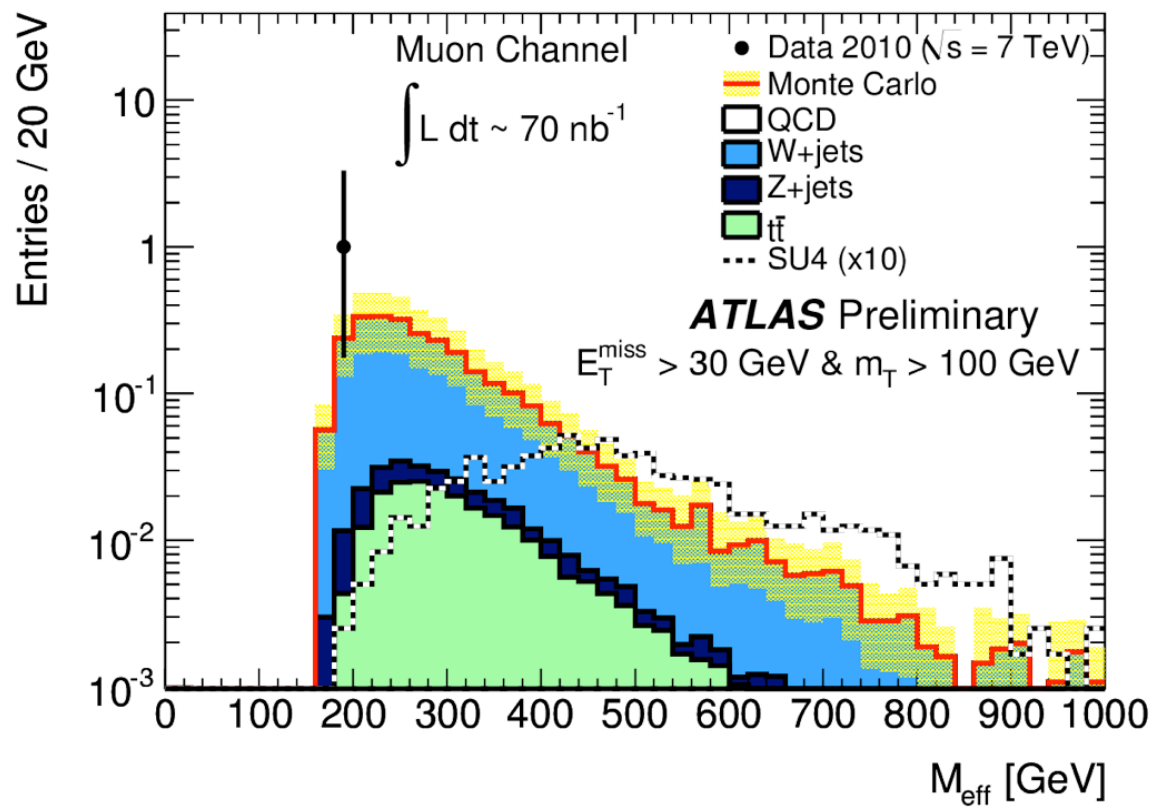
- Require MET>30 GeV ➔ remove QCD background
- Dominated by W+jets (no ttbar yet in this dataset)
- Normalise W+jets in 40 < M_T < 80 GeV and 30 < MET < 50 GeV
- 50% uncertainty assumed and propagated to high M_T and MET
- 60% uncertainty assume for Z+jets

Single-lepton search (final)

- Further selection
  - MET>30 GeV
  - M_T>100 GeV

Selection	Electron channel Data	Electron channel Monte Carlo	Muon channel Data	Muon channel Monte Carlo
$p_T(\ell) > 20$ GeV $\cap$ ≥ 2 jets with $p_T > 30$ GeV	143	157 ± 85	40	37 ± 14
$\cap\ E_T^{miss} > 30$ GeV	13	16 ± 7	17	15 ± 7
$\cap\ m_T > 100$ GeV	2	3.6 ± 1.6	1	2.8 ± 1.2





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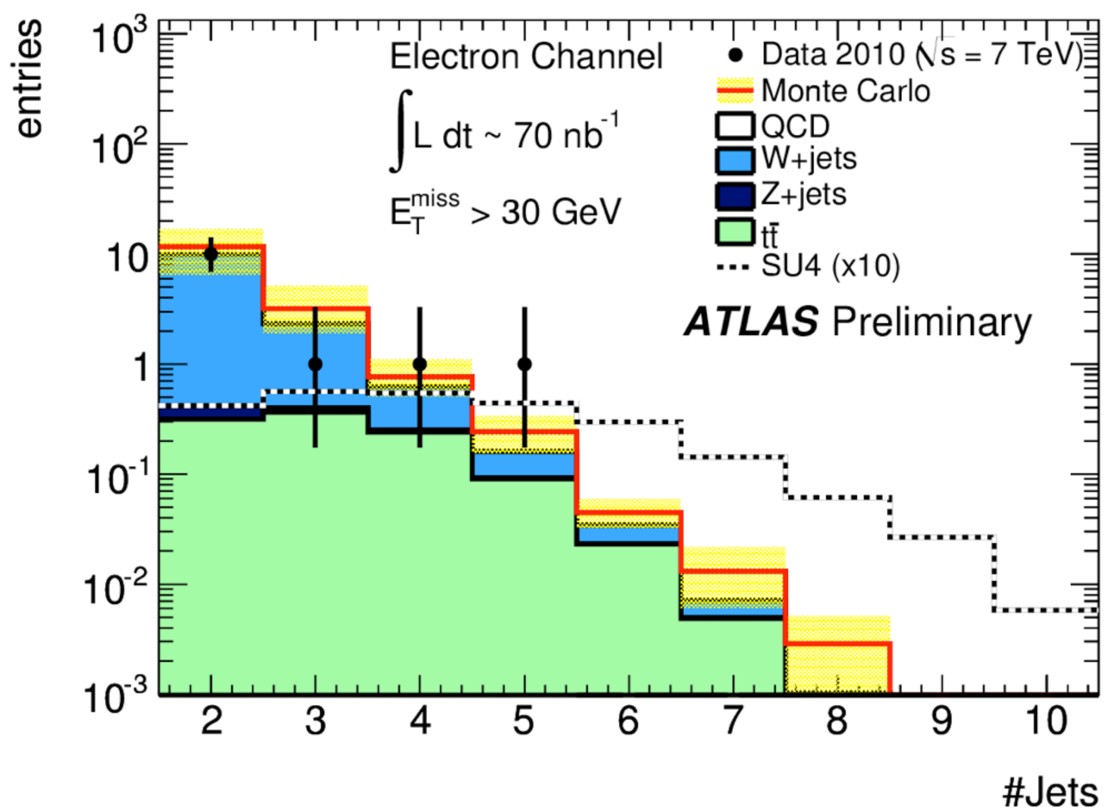
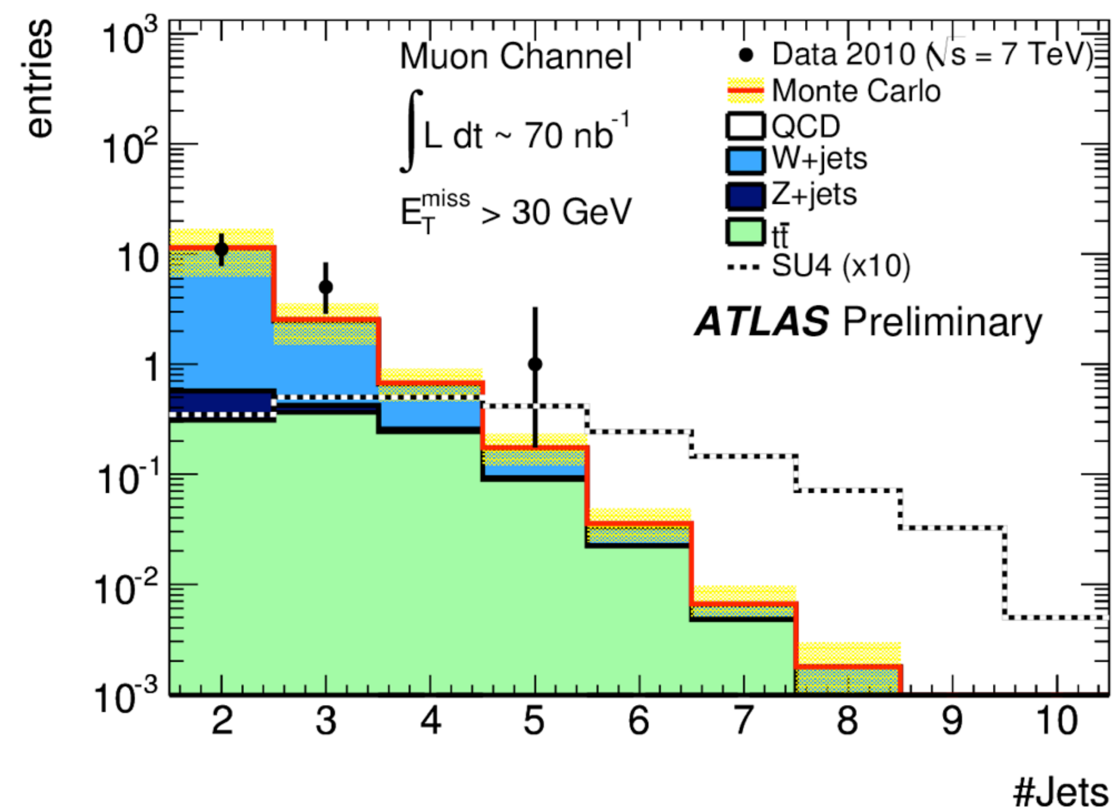
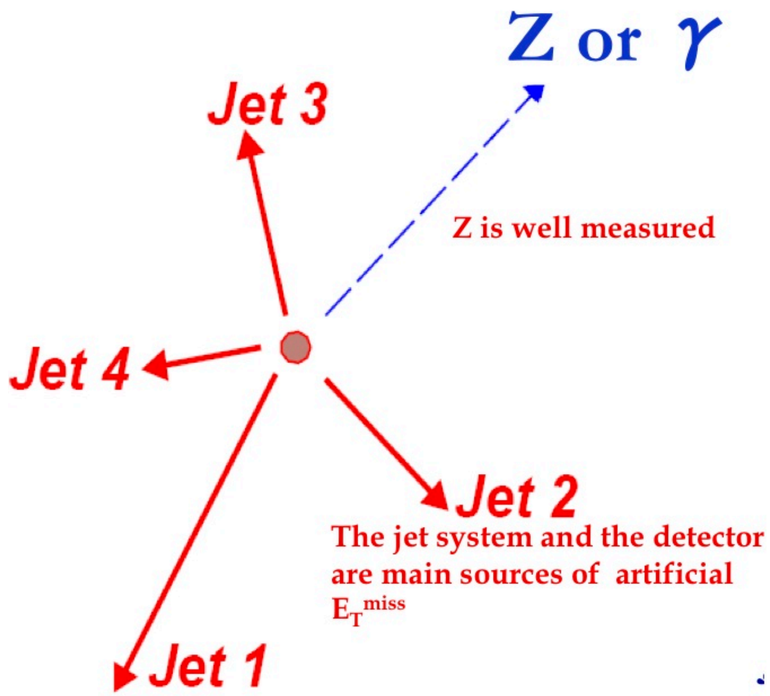
Single-lepton searches (future)

- So far not categorised by number of jets, for the future

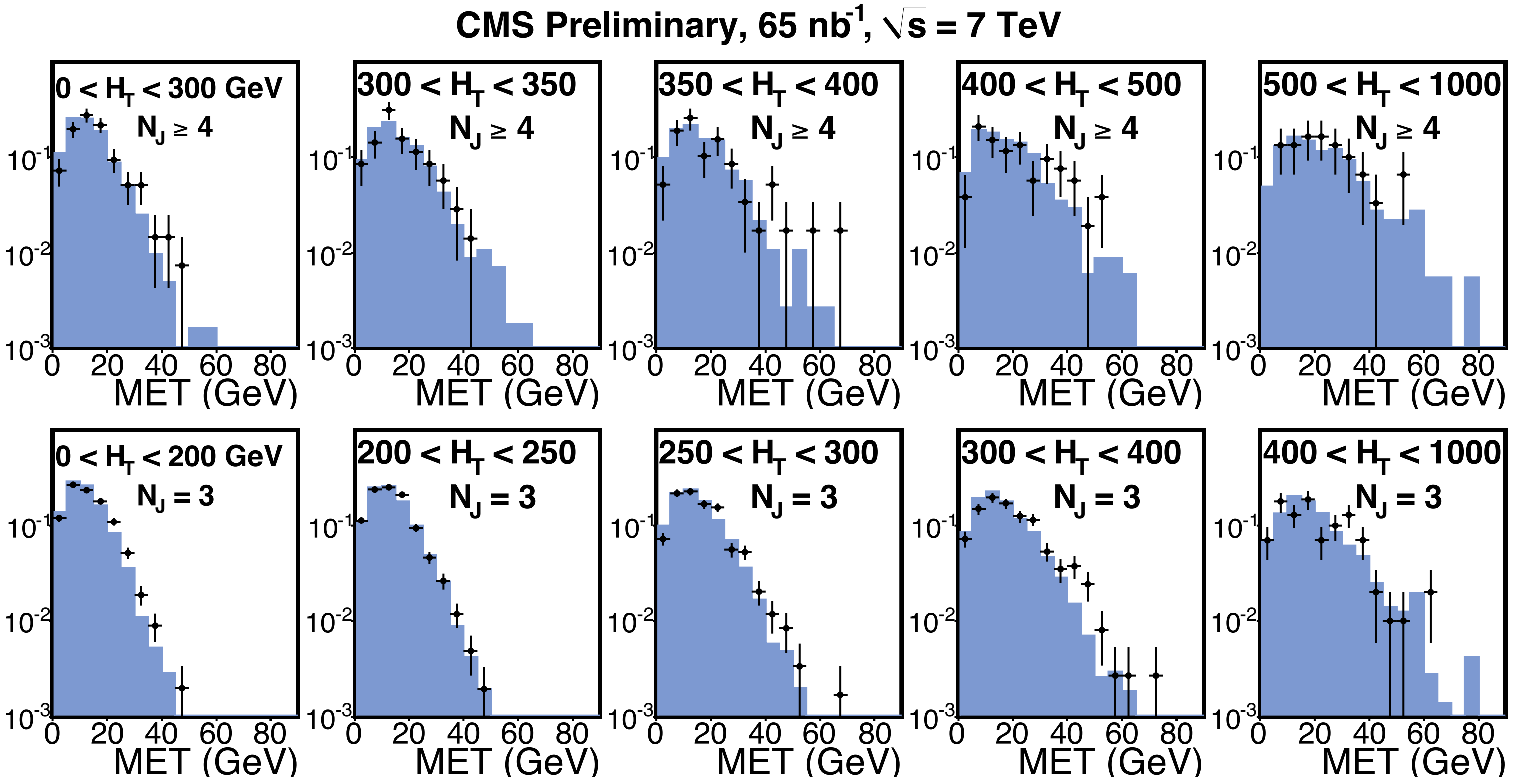




Modelling MET resolution



- Aim to measure fake MET tail for single-lepton + jets + MET search
- Measure MET templates in multi-jet QCD events and categorise them in N_{jets} and H_T
- For each γ/Z event look for the corresponding template
- Separate procedure for real MET



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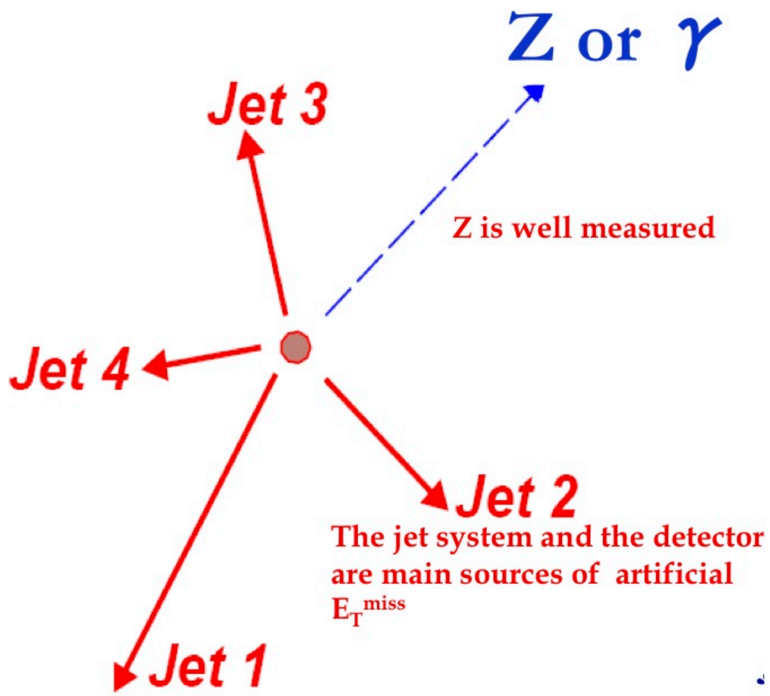
Modelling MET resolution



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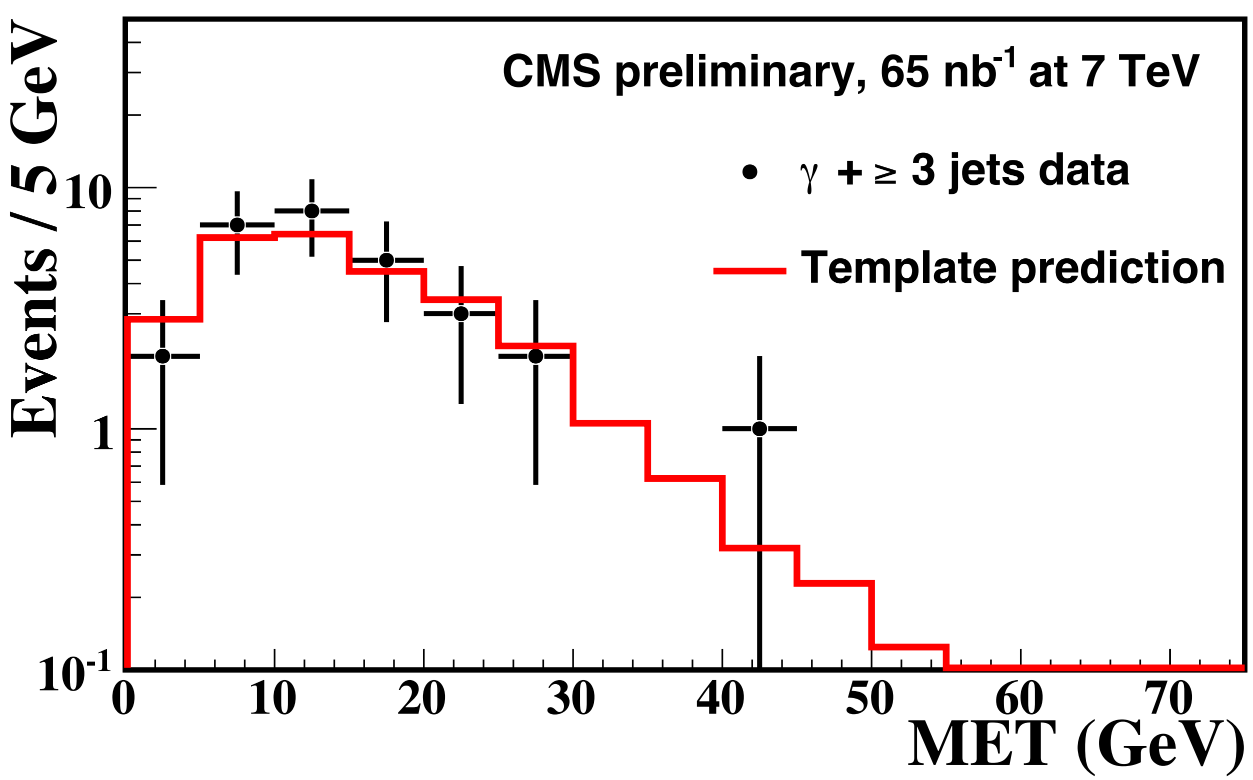

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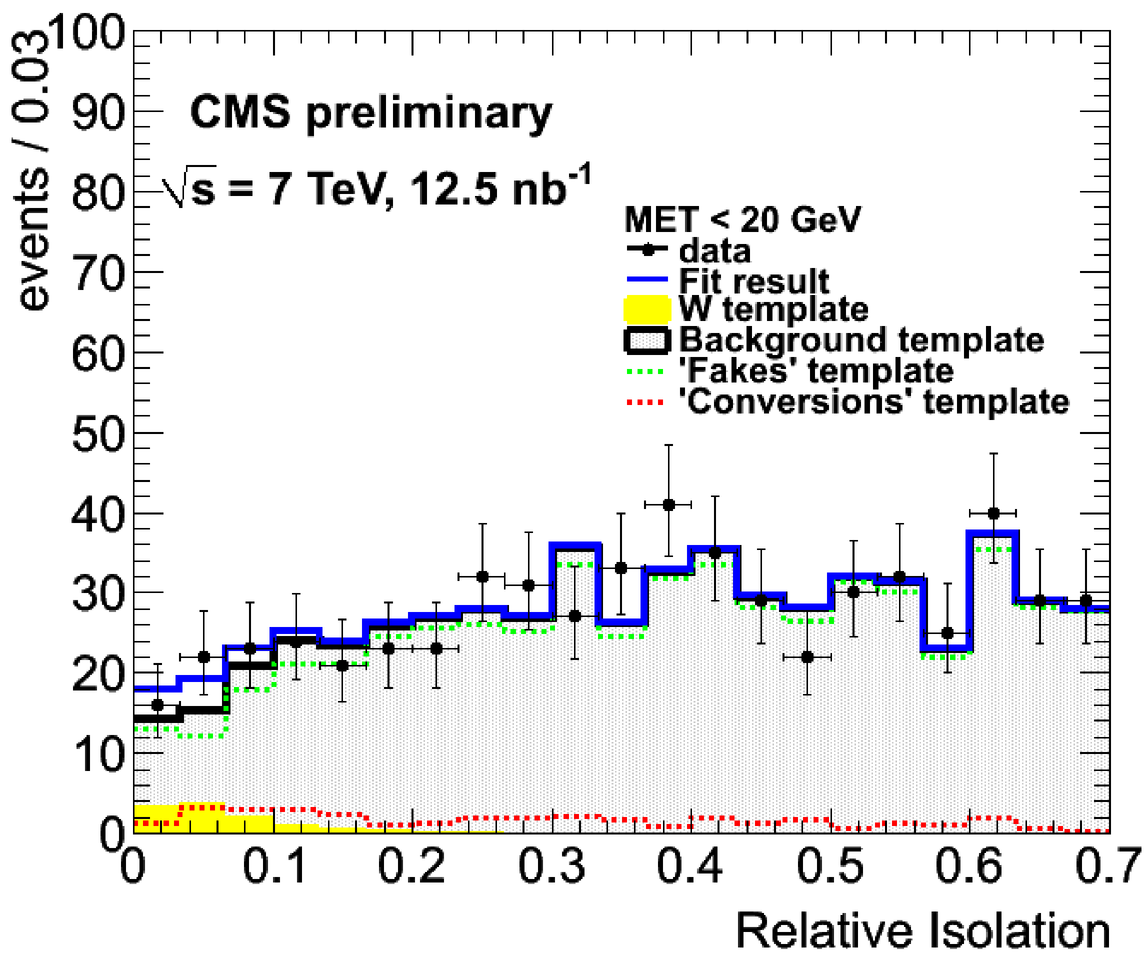
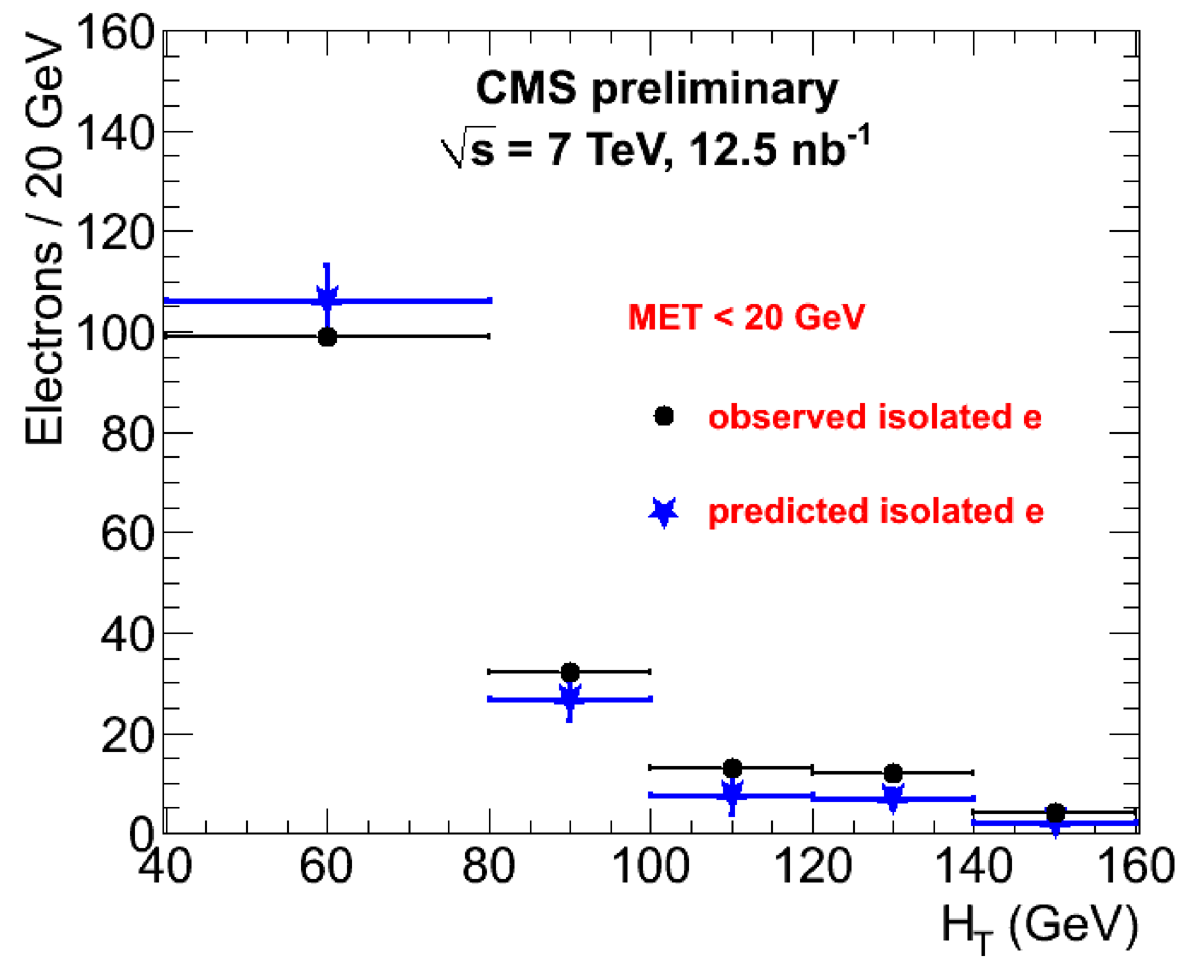
Determining QCD background





- QCD small background (even smaller for μ) but with large uncertainty
- Example of data-driven template fit to relative isolation distribution
- Good closure in data ➔ method works

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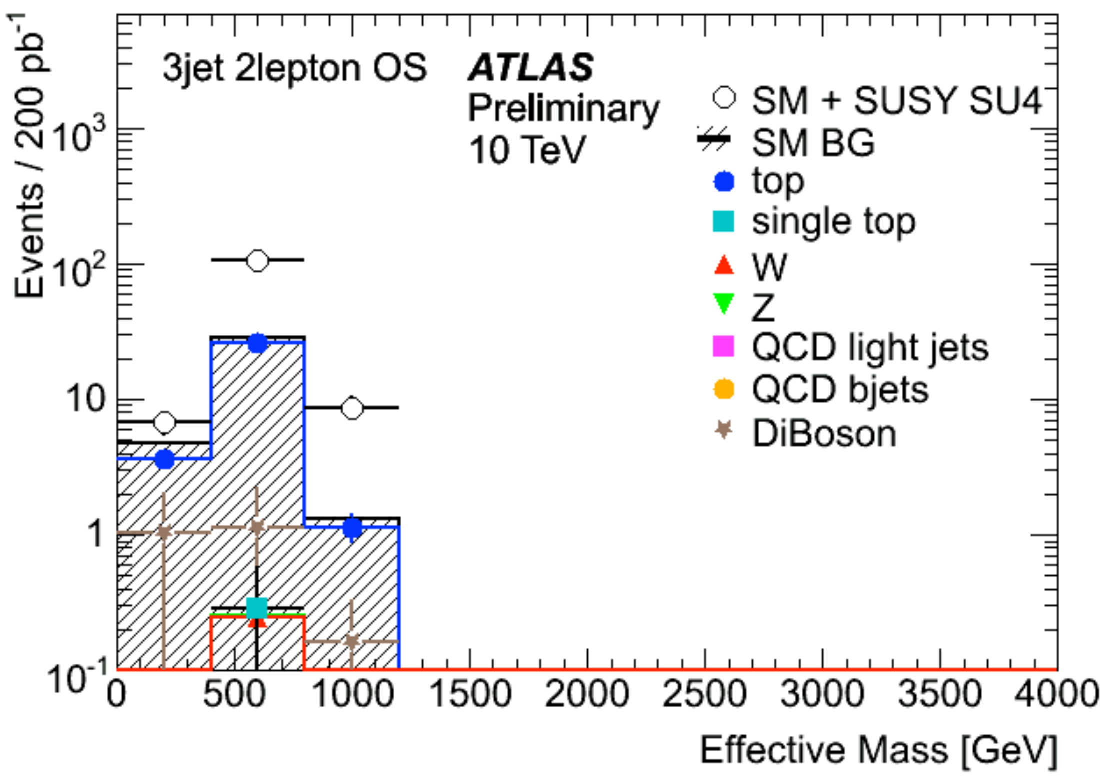
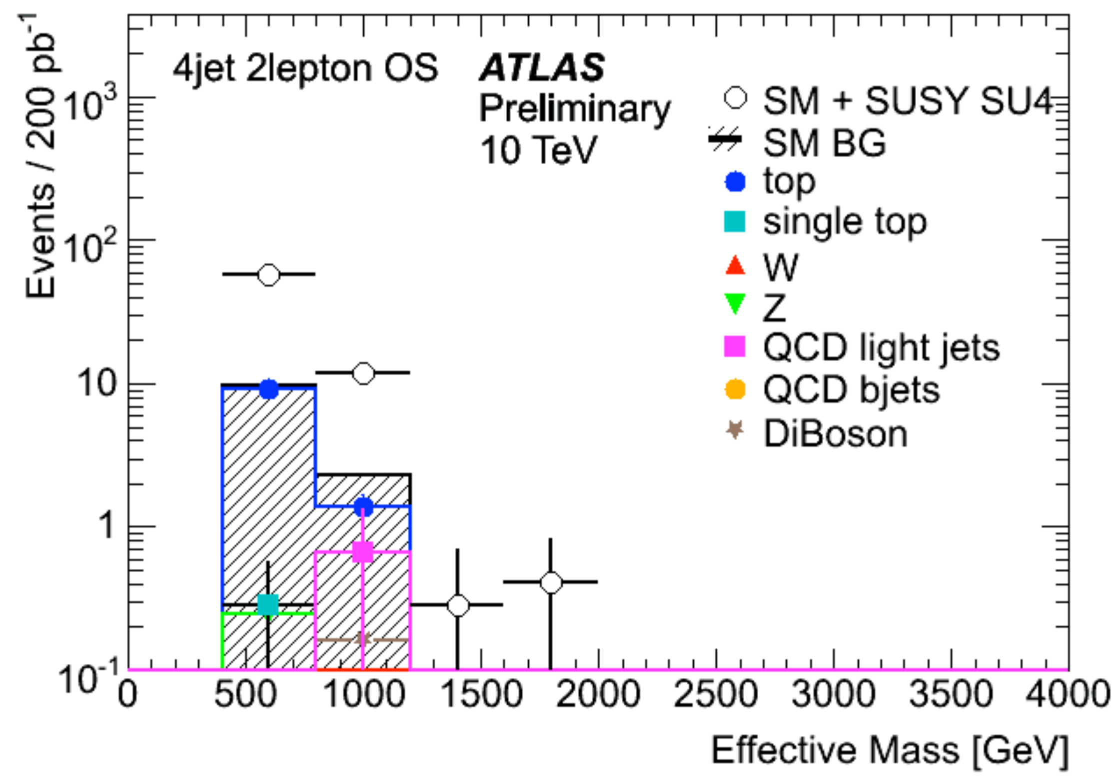
Di-lepton searches (MC example)

ATL-PHYS-PUB-2009-084





- Low yields but very interesting properties
- Same sign searches
  - Very low Standard Model background rate
  - Backgrounds from charge mis-identified top events (QCD in τ channel)
- Opposite sign
  - Use opposite-sign, opposite-flavour sample to subtract SM background

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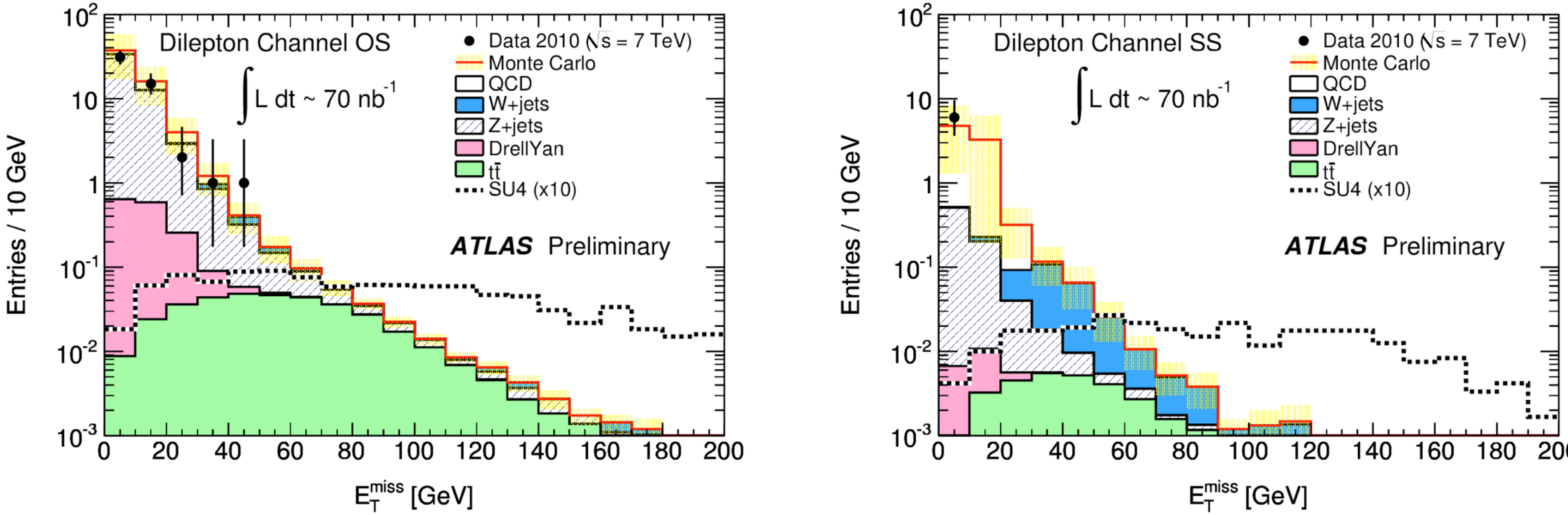
Di-lepton searches



- First look at the MET distributions for di-leptons
- At least two muons P_{T1}>20 GeV P_{T2}>10 GeV M_{ll}>5 GeV
- Normalise QCD MC to data in 5 < M_{ll} < 15 GeV and MET < 15 GeV
- 100% uncertainty assumed on W and QCD backgrounds and 60% for Z
- Good description by Monte Carlo (so far as one can tell…)

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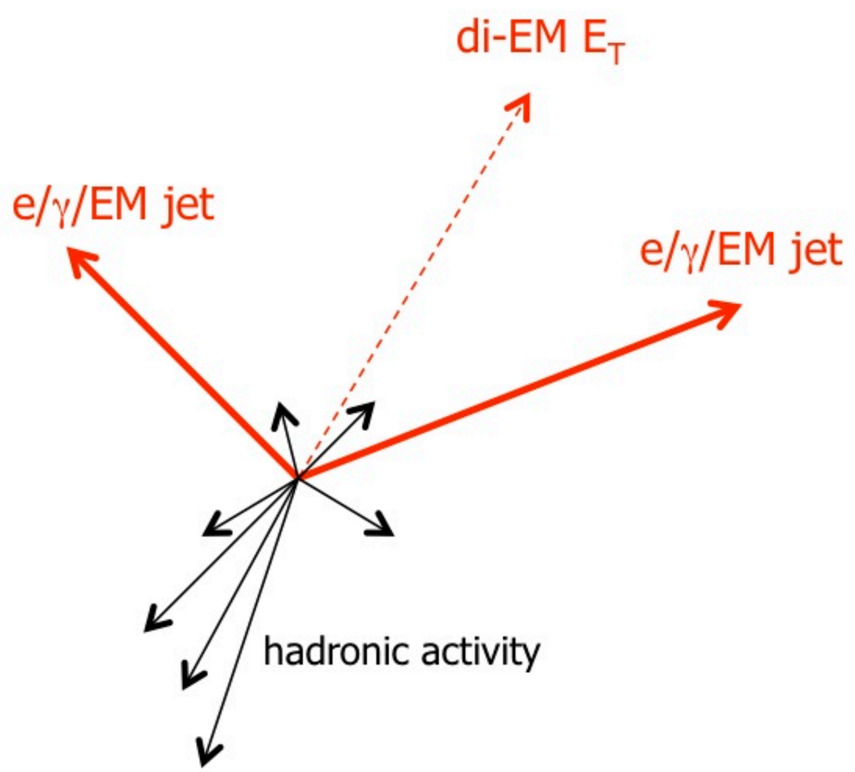
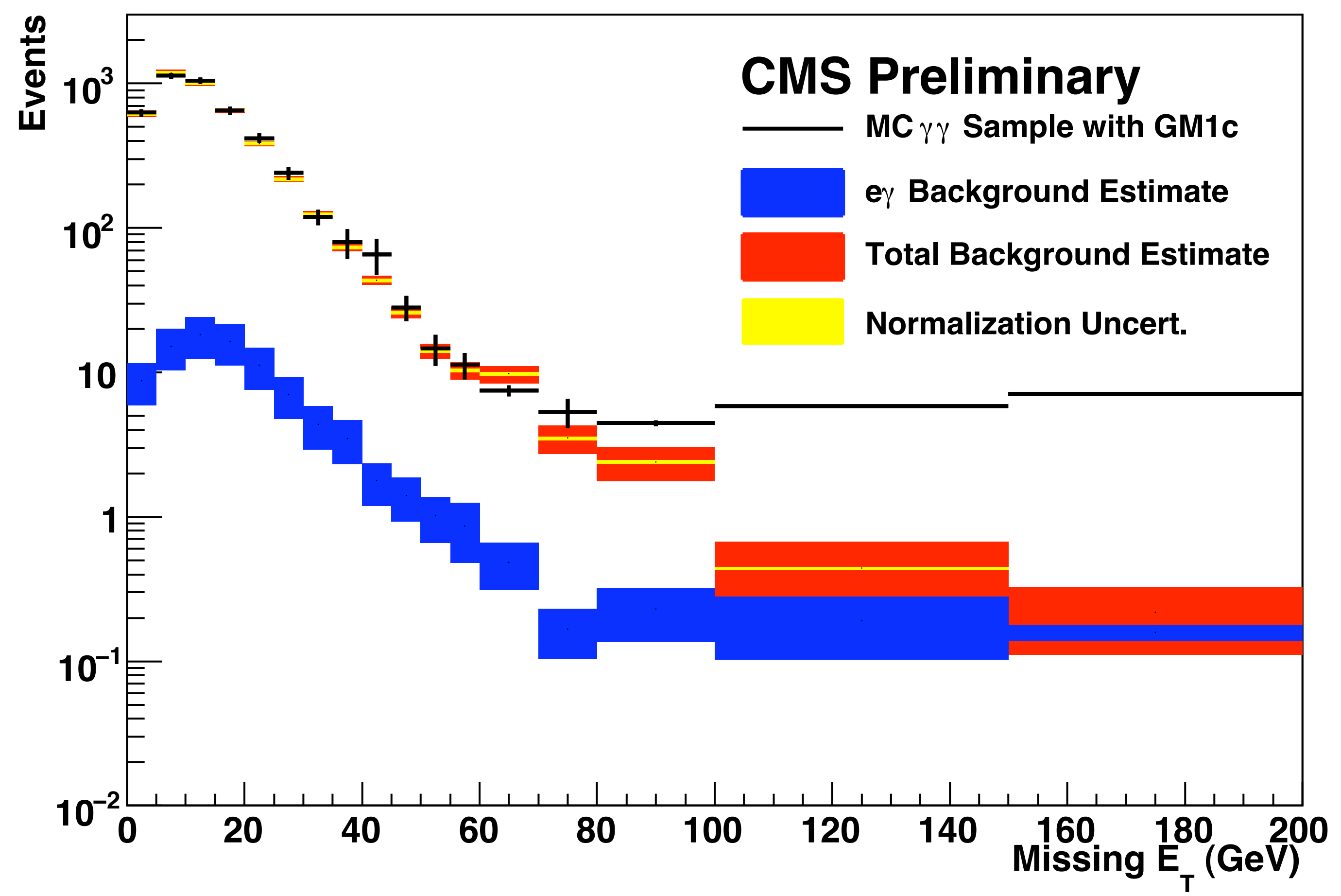
Search with di-photon events





- Di-photons + MET search
  - Background is dominated by mis-measured QCD ➔ fake MET
  - MET resolution determined by hadronic recoil
  - Predict using control samples (now fake-fake later $Z \rightarrow e^+e^-$)

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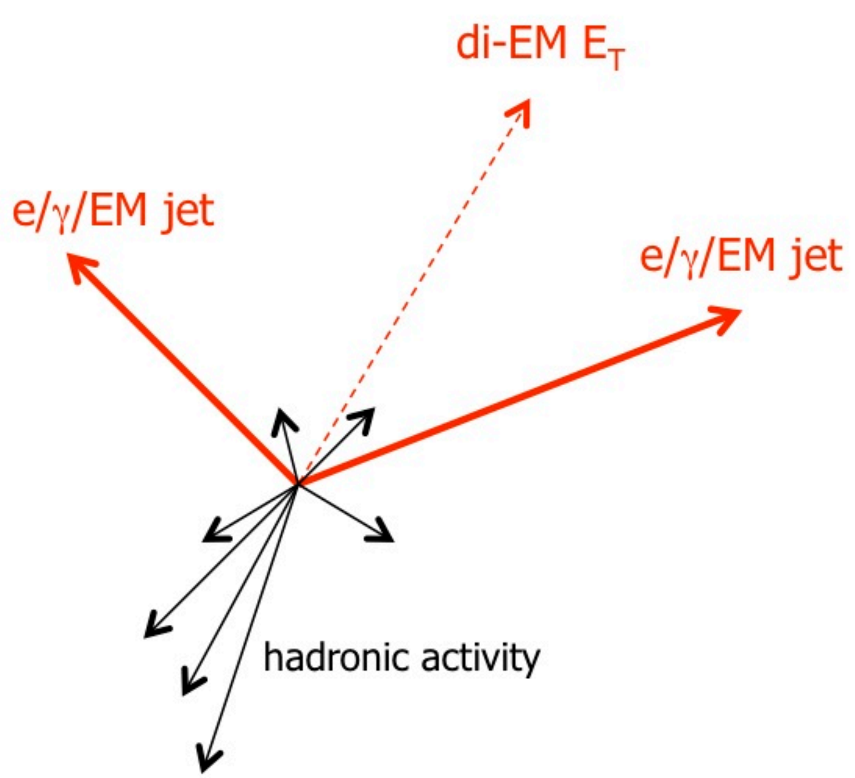
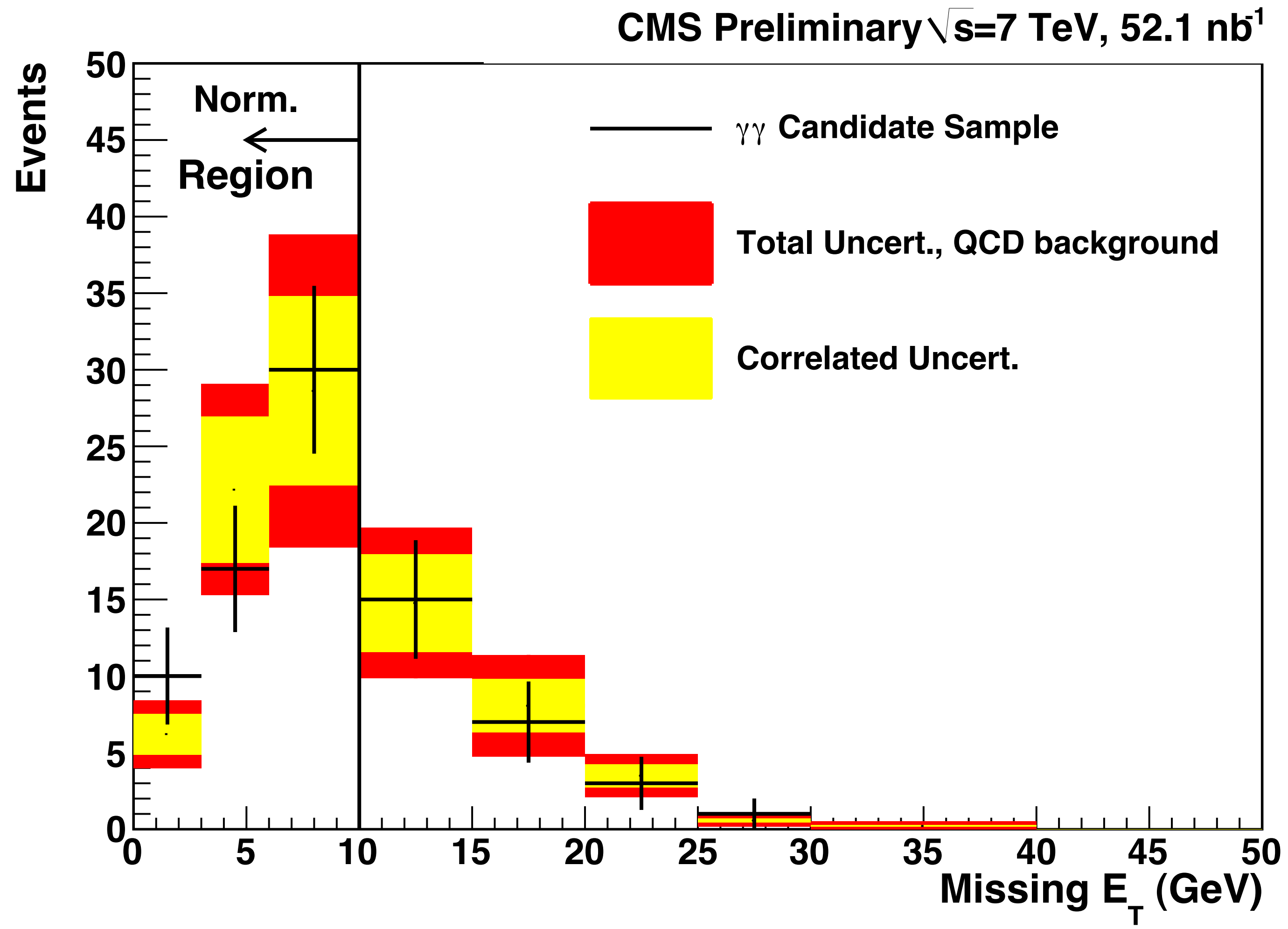
Search with di-photon events



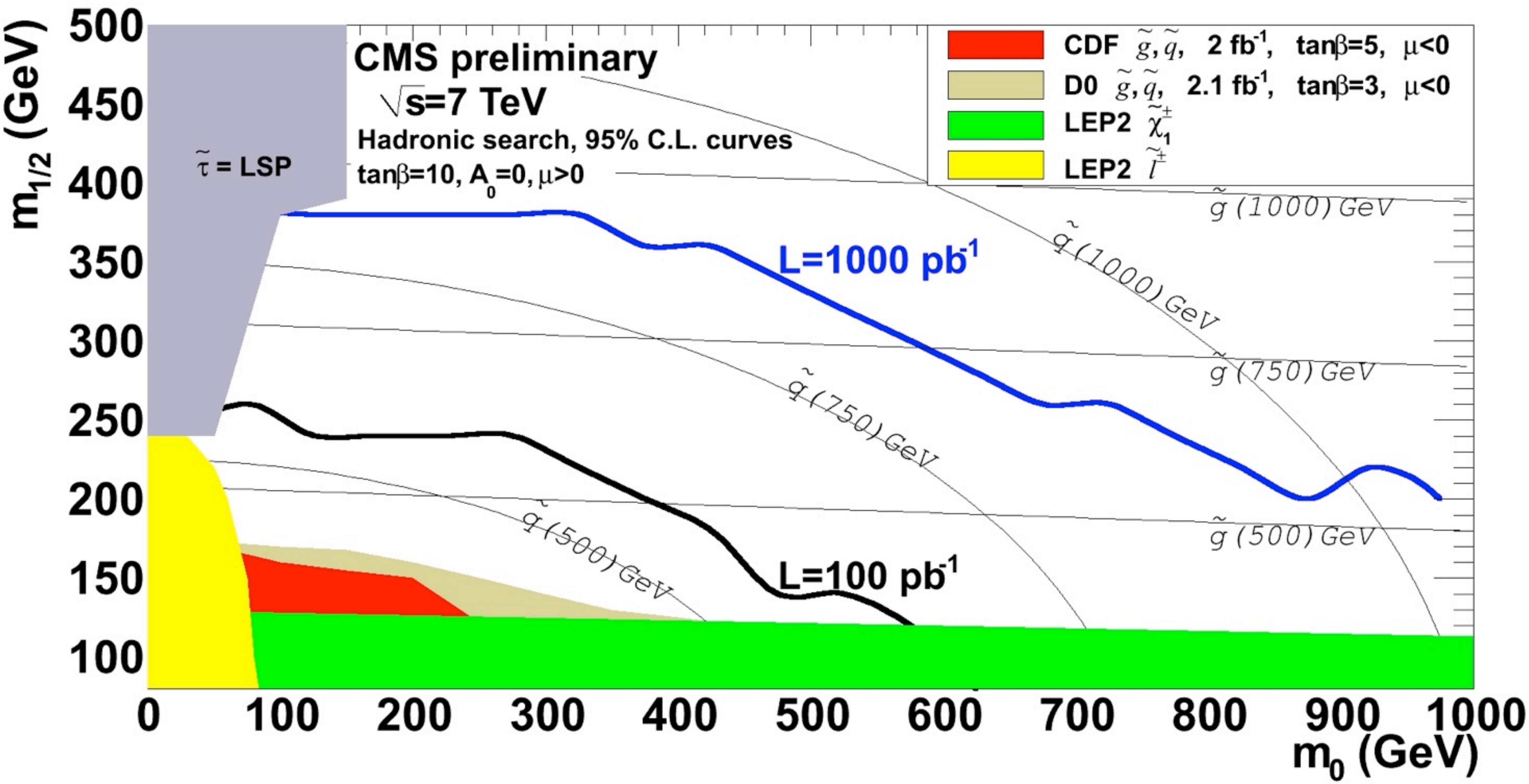


- Di-photons + MET search
  - Background is dominated by mis-measured QCD ➔ fake MET
  - MET resolution determined by hadronic recoil
  - Predict using control samples (now fake-fake later $Z \rightarrow e^+e^-$)
  - 4 observed (MET>20 GeV) 4.2 ± 1.5 events predicted.

Summary and outlook

- Early searches based on robust generic signatures
  - Sensitive as possible to a variety of new physics models
- Detectors in great shape already and ready for searches
  - Electrons, muons, jets, MET, taus and b-tagging all available to us
- A wide range of data-driven techniques developed to measure efficiencies and backgrounds
- Will have something to say with 2010 data in many channels
- $1fb^{-1}$ 2011 dataset will give us huge discovery potential!

Backup (if you really want it…)



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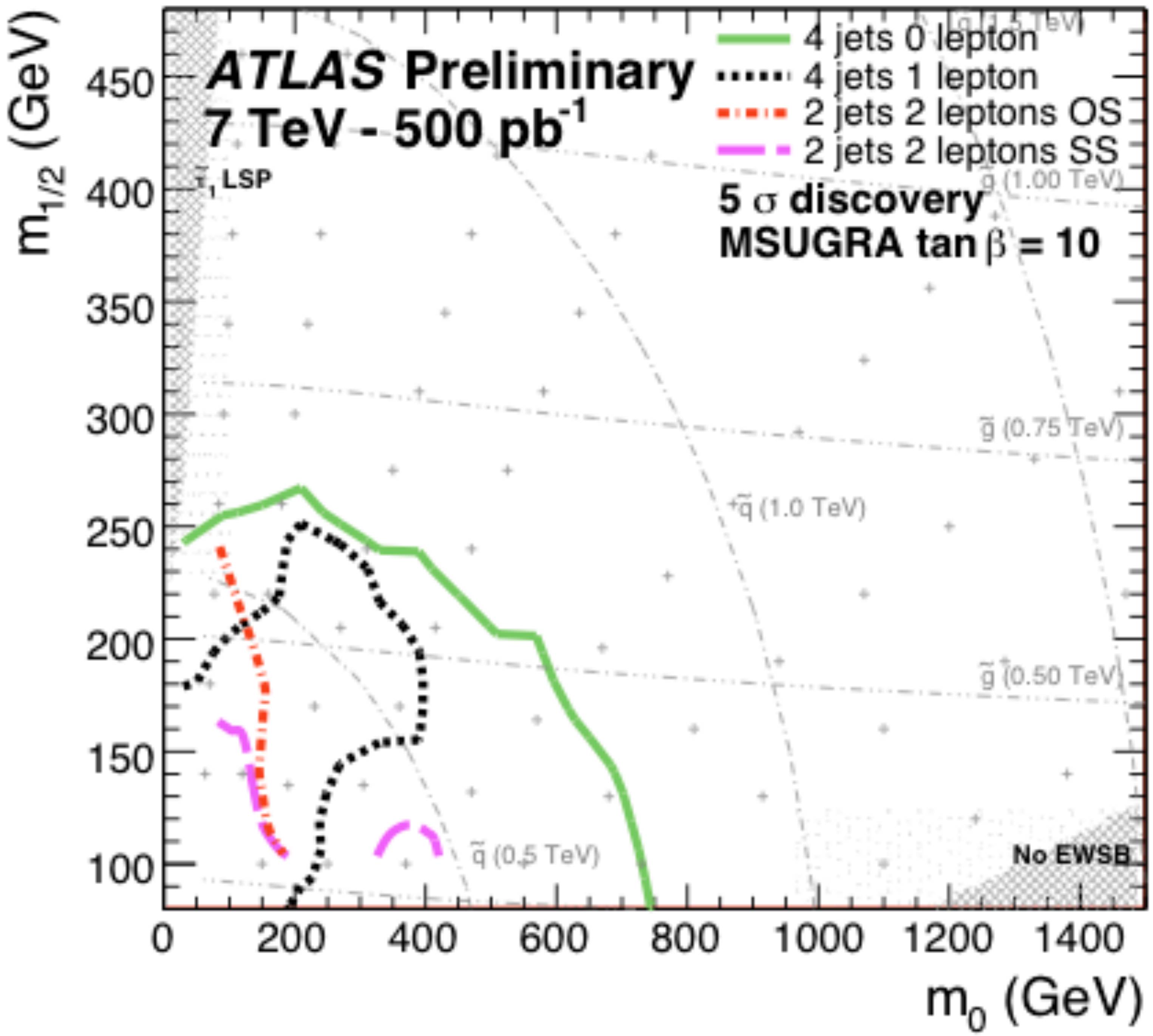
Backup (if you really want it...)



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Backup (if you really want it…)

Alves et al. arXiv:1008.0407