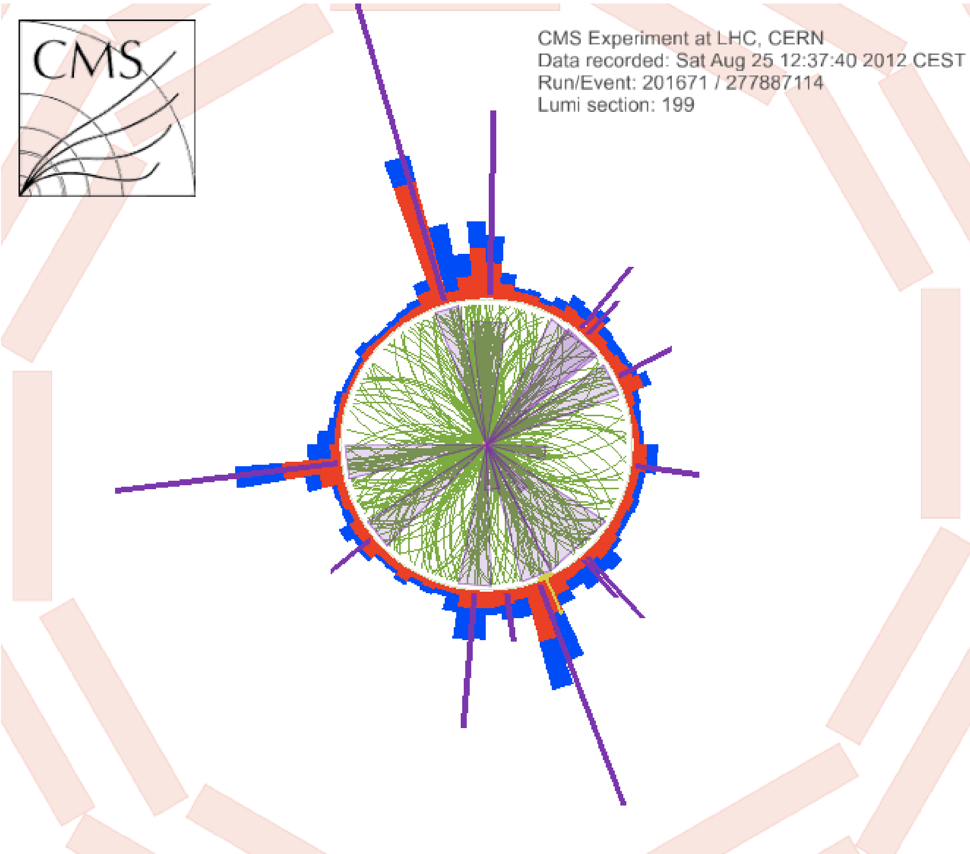
QCD@LHC in Higgs and BSM



ATLAS & CMS

Thorsten Kuhl

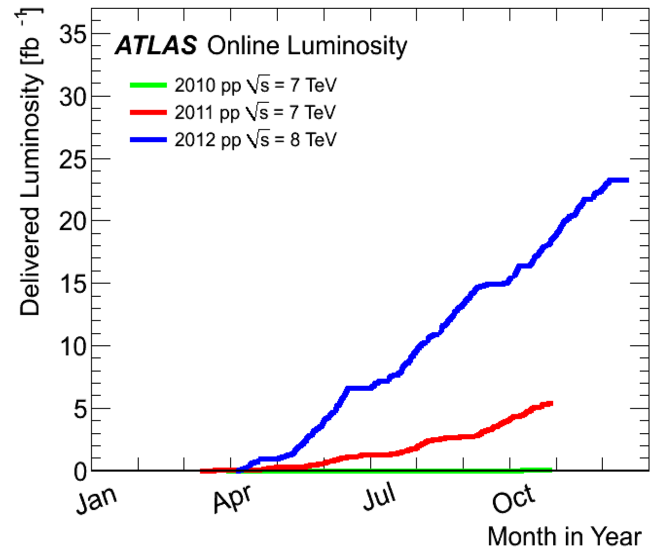
QCD@LHC2013, September, 2th-6th

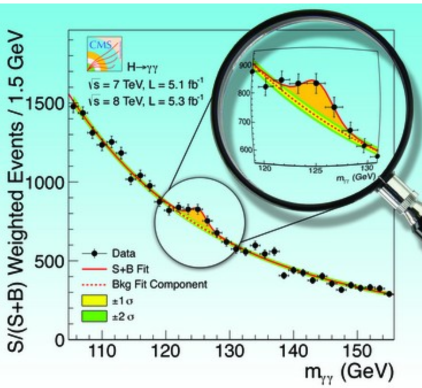
HELMHOLTZ GEMEINSCHAFT

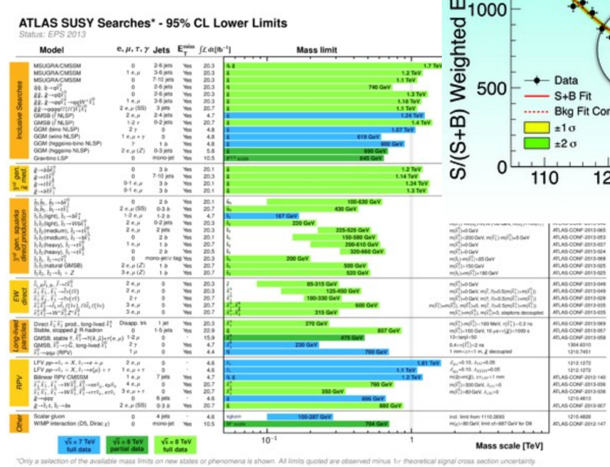
DESY

LHC excellent tool for searches

- 2010-12 Successful running of LHC
  - 5 fb^{-1} data at 7 TeV
  - 23 fb^{-1} data at 8 TeV
- Discovery machine
  - Discovery of a Higgs Boson
  - Wide range of SUSY searches
  - Test of many exotic models
- Experimental results in Searches
  - Depend on QCD
  - Experimental handle
  - The use of predictions

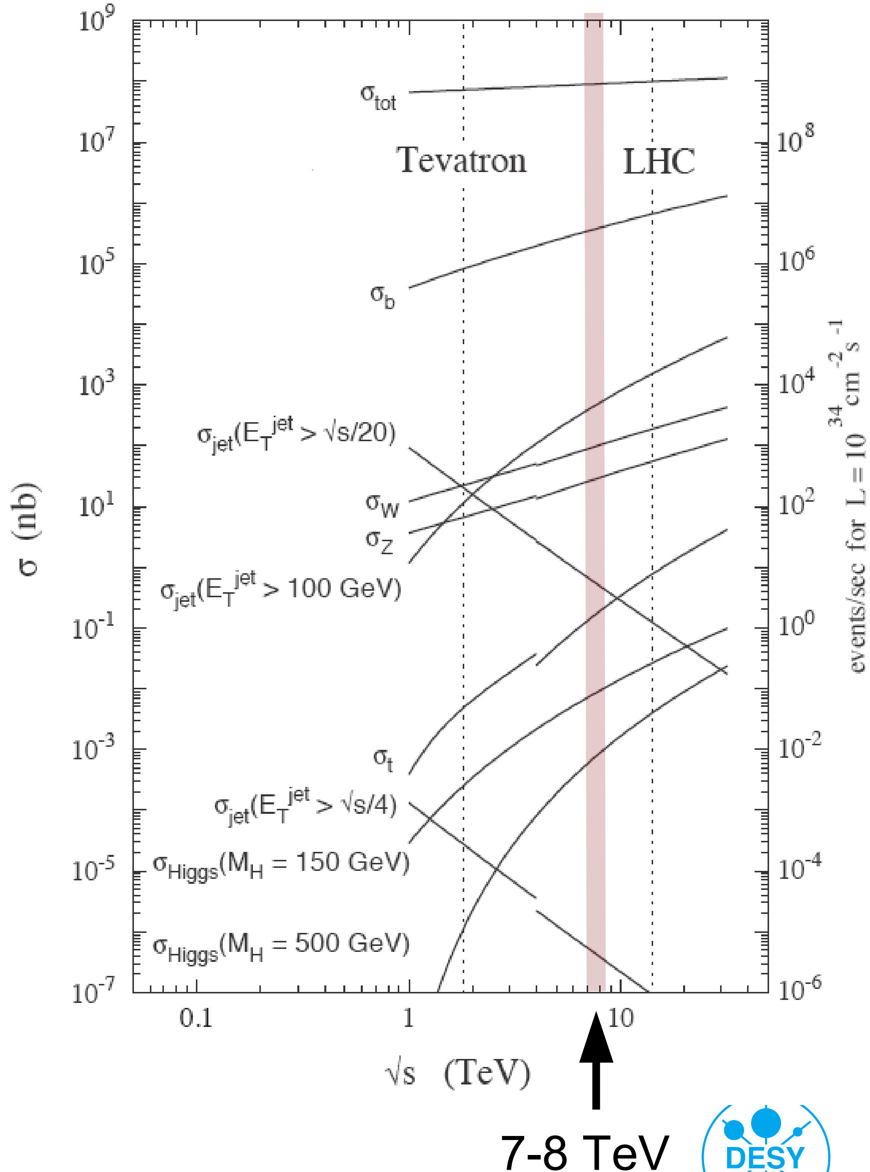






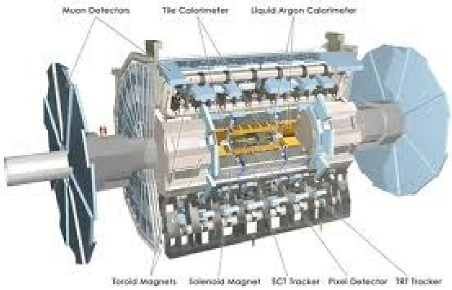
LHC Cross sections

- Total inelastic cross section is large
  - O(100mb)
  - 10^{7-9} higher then W/Z and top
  - 10^{10} times SM-Higgs
- Av. Pile-up 20.7 → max. 40 per bunch crossing
- Hard cross sections
  - Still orders of magnitudes bigger than other physics on the same scale
  - Need handle to reduce size and impact of QCD error on background prediction

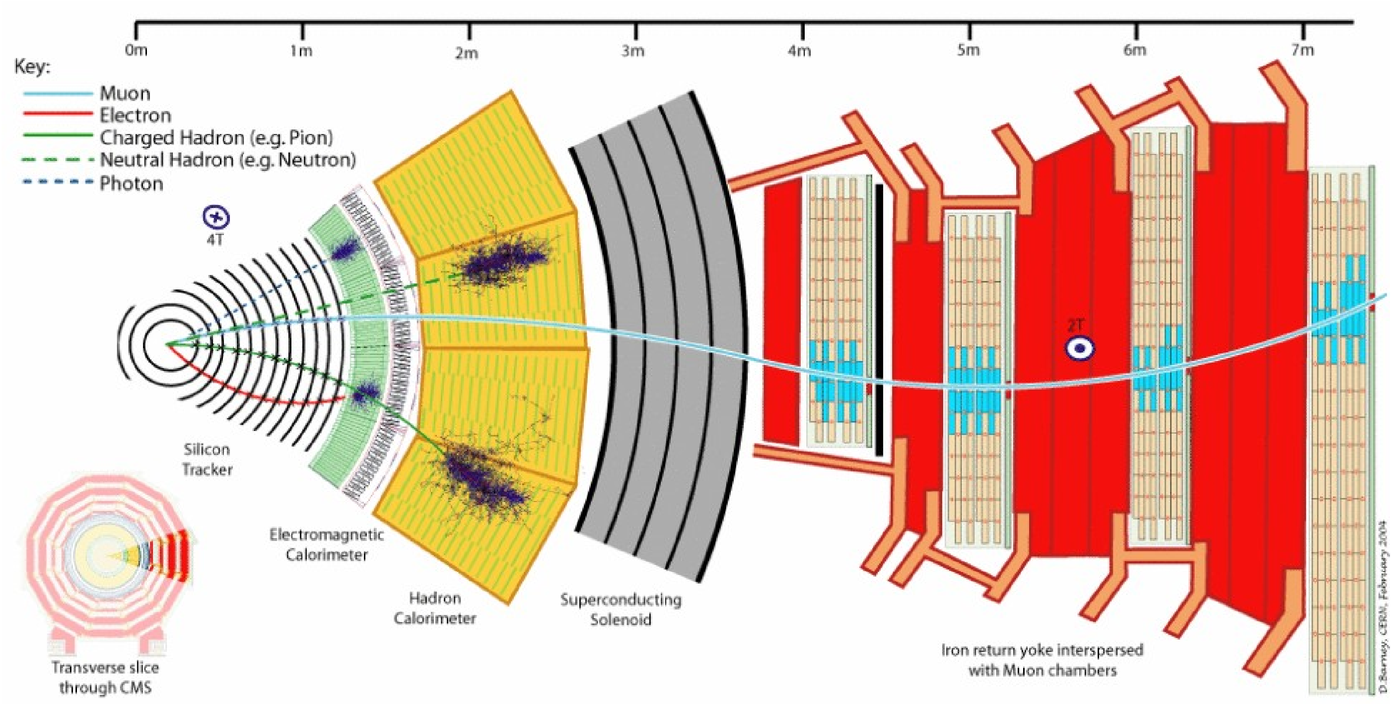


The Detectors

- Capability to separate signal from QCD:
  - Lepton identification
  - Fine granularity
  - B-tagging capability



CMS



Impact of QCD for Searches

- Most analyses are designed to suppress QCD with non QCD signatures:
  - Use Leptons, Missing E_T, photons
  - QCD contribution described by cocktail of MC predictions plus data driven approach:
    - Experimental description of "Fakes"
- All hadronic searches use different methods:
  - Bump hunting
  - Data driven extrapolations from side band
  - Theoretical predictions (templates for shape, not normalization)
  - Top background from (N)NLO calculation

Examples of QCD@LHC

- **QCD in final states with leptons:**
  - "Lepton fakes"
- QCD in final states with MET
  - Pile up
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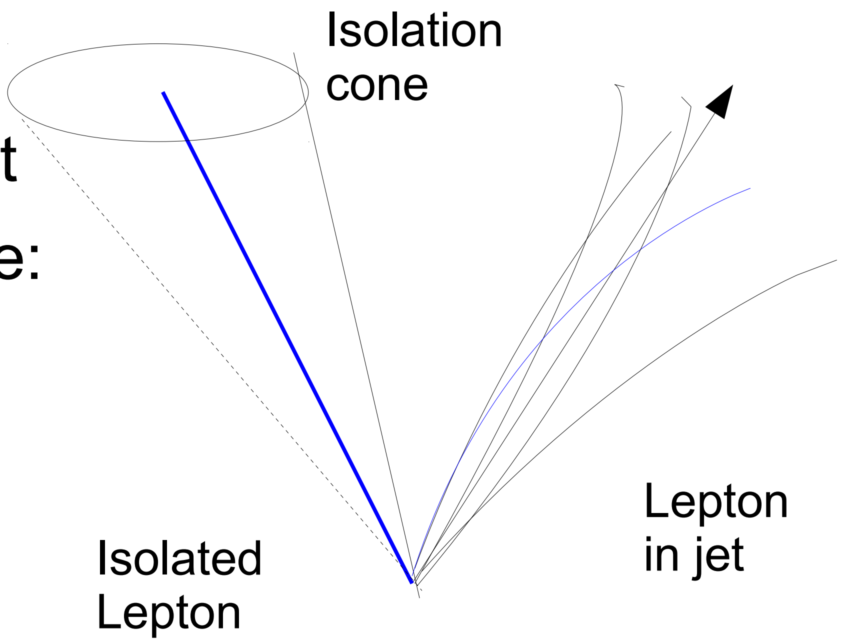
QCD suppression with Electrons and Muons

- Use leptons from EW processes (W and Z) to suppress QCD;
- remaining background are “fakes from QCD”:
  - Falsly reconstructed pions identified as electron
  - Decay muons from b/c-quark
- Suppression by Isolation:
  - W/Z leptons isolated/QCD not
  - Data driven fake rate estimate:

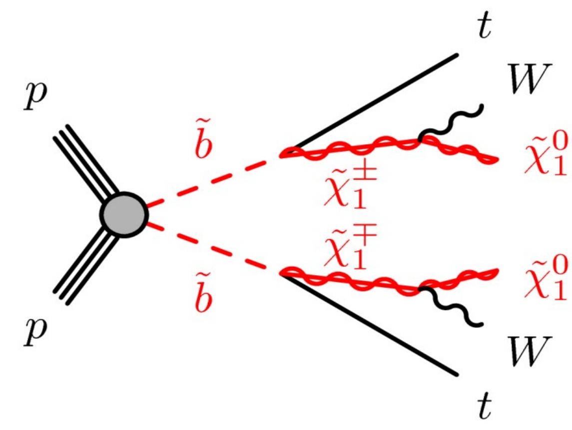
    Prob. (Jet → Lepton) from

    di-jets sample



QCD in same sign Lepton searches

- Search for two same sign Leptons + jets:
  - Many “W's” in final state
- Clean topology, very rare SM
- QCD Background: isolated heavy flavour leptons without hadronic activity



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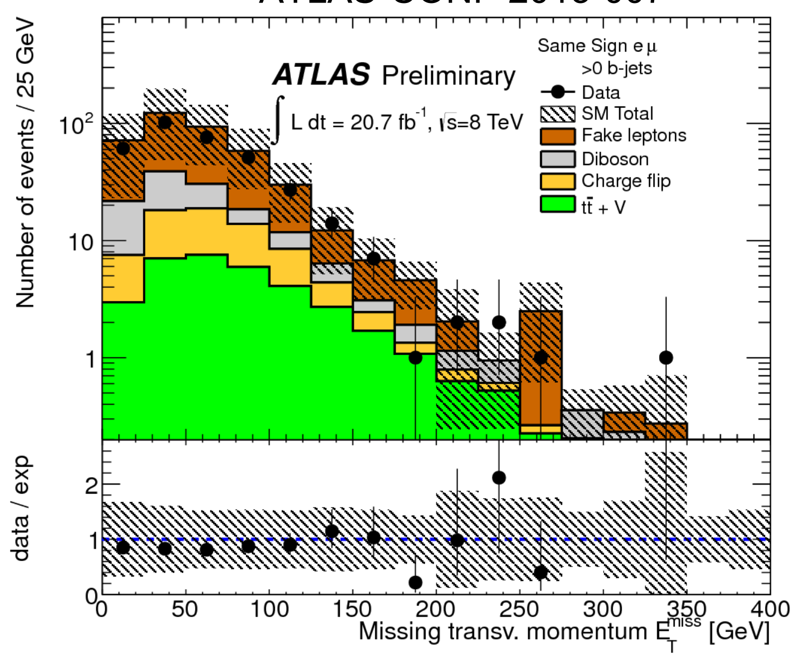

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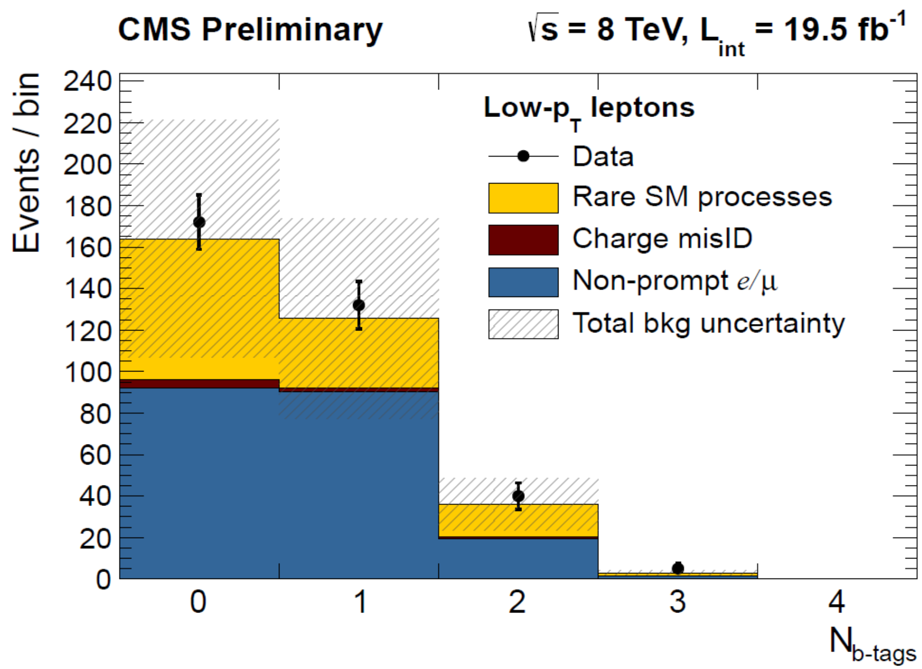

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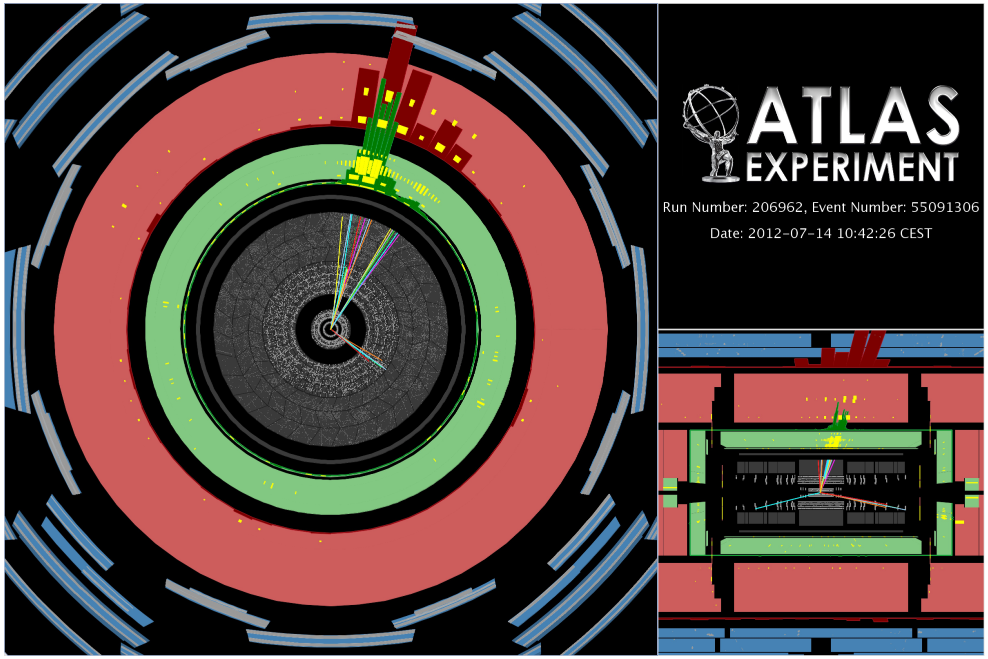
QCD suppression with ETmiss

- Monojet-searches in exotics
- QCD MET resolution proportional to square-root of visible hadronic energy
- MET in QCD: from decays or miss-reconstruction

  → often in direction of one jet



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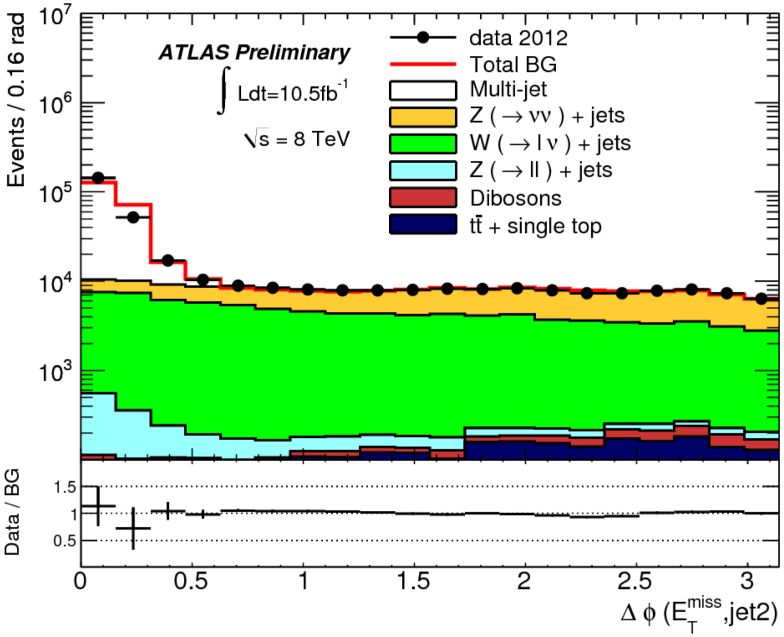

Impact of QCD pile up on MET

- Pile-up spoils MET
  - Experimental tails
- Clean control sample Z->μμ
- Decent description of MET
- Future: Pile up from data overlay (→ D0 Experiment)

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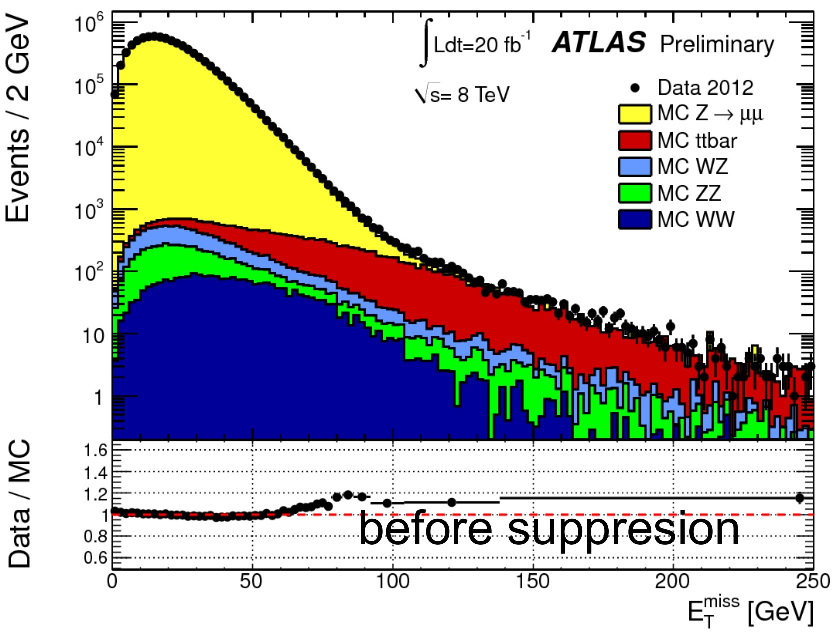

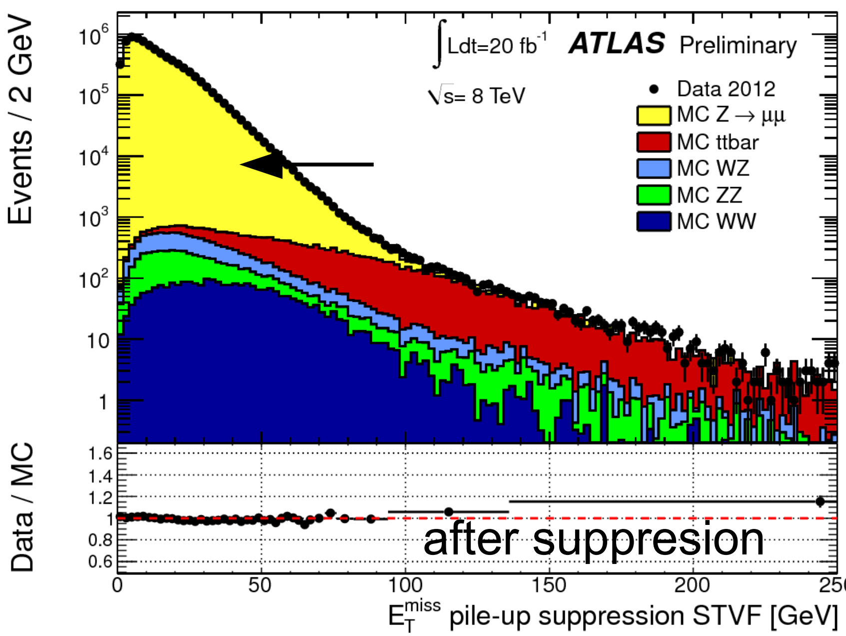

QCD background many jets plus MET

- CMS overview: Many Jets plus Missing ET CMS-SUS-13-012
- $\tilde{g}\tilde{g} \rightarrow q^n \chi^0 \chi^0$
- QCD important, if Missing-HT small vs HT

N_{jets}	Selection H_T	$\not{H}_T$	$Z \rightarrow \nu\bar{\nu}$ from γ+jets	$t\bar{t}$/W $\rightarrow$ e, μ+X	$t\bar{t}$/W $\rightarrow \tau_h$+X	QCD	Total background	Obs. data
3-5	500-800	200-300	1821.3±326.5	2210.7±447.8	1683.7±171.4	307.4±219.4	6023.1±620.2	6159
3-5	500-800	300-450	993.6±177.9	660.1±133.3	591.9± 62.5	34.5± 23.8	2280.0±232.1	2305
3-5	500-800	450-600	273.2± 51.1	77.3± 17.9	67.6± 9.5	1.3± 1.5	419.5± 55.0	454
3-5	500-800	> 600	42.0± 8.7	9.5± 4.0	6.0± 1.9	0.1± 0.3	57.6± 9.7	62
3-5	800-1000	200-300	215.8± 40.0	277.5± 62.4	191.6± 23.2	91.7± 65.5	776.7±101.6	808
3-5	800-1000	300-450	124.1± 23.7	112.8± 26.9	83.3± 11.2	9.9± 7.4	330.1± 38.3	305
3-5	800-1000	450-600	46.9± 9.8	36.1± 9.9	23.6± 3.9	0.8± 1.3	107.5± 14.5	124
3-5	800-1000	> 600	35.3± 7.5	9.0± 3.7	11.4± 3.2	0.1± 0.4	55.8± 9.0	52
3-5	1000-1250	200-300	76.3± 14.8	103.5± 25.9	66.8± 10.0	59.0± 24.7	305.6± 40.1	335
3-5	1000-1250	300-450	39.3± 8.2	52.4± 13.6	35.7± 6.2	5.1± 2.7	132.6± 17.3	129
3-5	1000-1250	450-600	18.1± 4.4	6.9± 3.2	6.6± 2.1	0.5± 0.7	32.1± 5.9	34
3-5	1000-1250	> 600	17.8± 4.3	2.4± 1.8	2.5± 1.0	0.1± 0.3	22.8± 4.7	32
3-5	1250-1500	200-300	25.3± 5.5	31.0± 9.5	22.2± 3.9	31.2± 13.1	109.7± 17.5	98
3-5	1250-1500	300-450	16.7± 4.0	10.1± 4.4	11.1± 3.6	2.3± 1.6	40.2± 7.1	38
3-5	1250-1500	> 450	12.3± 3.2	2.3± 1.7	2.8± 1.5	0.2± 0.5	17.6± 4.0	23
3-5	>1500	200-300	10.5± 2.8	16.7± 6.2	15.2± 3.4	35.1± 14.1	77.6± 16.1	94
3-5	>1500	> 300	10.9± 2.9	9.7± 4.3	6.5± 2.0	2.4± 2.0	29.6± 5.8	39
6-7	500-800	200-300	22.7± 6.1	132.5± 58.6	127.1± 21.5	18.2± 9.2	300.5± 63.4	266
6-7	500-800	300-450	9.9± 3.1	22.0± 10.8	18.6± 4.3	1.9± 1.7	52.3± 12.1	62
6-7	500-800	> 450	0.7± 0.6	0.0± 1.6	0.1± 0.3	0.0± 0.1	0.8± 1.7	9
6-7	800-1000	200-300	9.1± 2.8	55.8± 25.4	44.6± 8.2	13.1± 6.6	122.6± 27.7	111
6-7	800-1000	300-450	4.2± 1.6	10.4± 5.5	12.8± 3.1	1.9± 1.4	29.3± 6.6	35
6-7	800-1000	> 450	1.8± 1.0	2.9± 2.5	1.3± 0.5	0.1± 0.4	6.1± 2.7	4
6-7	1000-1250	200-300	4.4± 1.6	24.1± 12.0	24.0± 5.5	11.9± 6.0	64.4± 14.6	67
6-7	1000-1250	300-450	3.5± 1.4	8.0± 4.7	9.6± 2.5	1.5± 1.5	22.6± 5.7	20
6-7	1000-1250	> 450	1.4± 0.8	0.0± 1.8	0.8± 0.5	0.1± 0.3	2.3± 2.1	4
6-7	1250-1500	200-300	3.3± 1.3	11.5± 6.5	6.1± 2.5	6.8± 3.9	27.7± 8.1	24
6-7	1250-1500	300-450	1.4± 0.8	3.5± 2.6	2.9± 1.5	0.9± 1.3	8.8± 3.4	5
6-7	1250-1500	> 450	0.4± 0.4	0.0± 1.2	0.1± 0.2	0.1± 0.3	0.5± 1.3	2
6-7	>1500	200-300	1.3± 0.8	10.0± 6.9	2.3± 1.3	7.8± 4.0	21.5± 8.1	18
6-7	>1500	> 300	1.1± 0.7	3.2± 2.8	2.9± 1.2	0.8± 1.1	8.0± 3.3	3
≥8	500-800	> 200	0.0± 0.6	1.9± 1.5	2.8± 1.3	0.1± 0.4	4.8± 2.1	8
≥8	800-1000	> 200	0.6± 0.5	4.8± 2.9	2.7± 1.1	0.5± 0.9	8.7± 3.3	9
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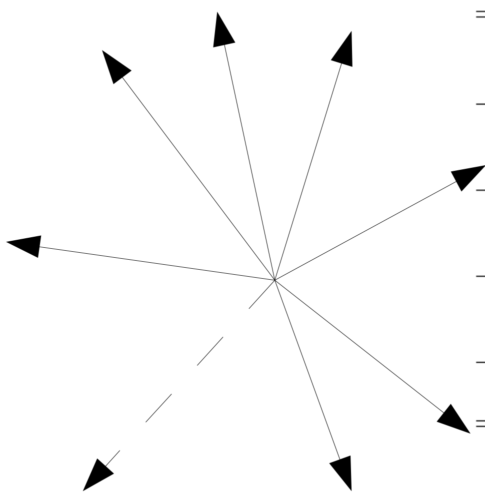
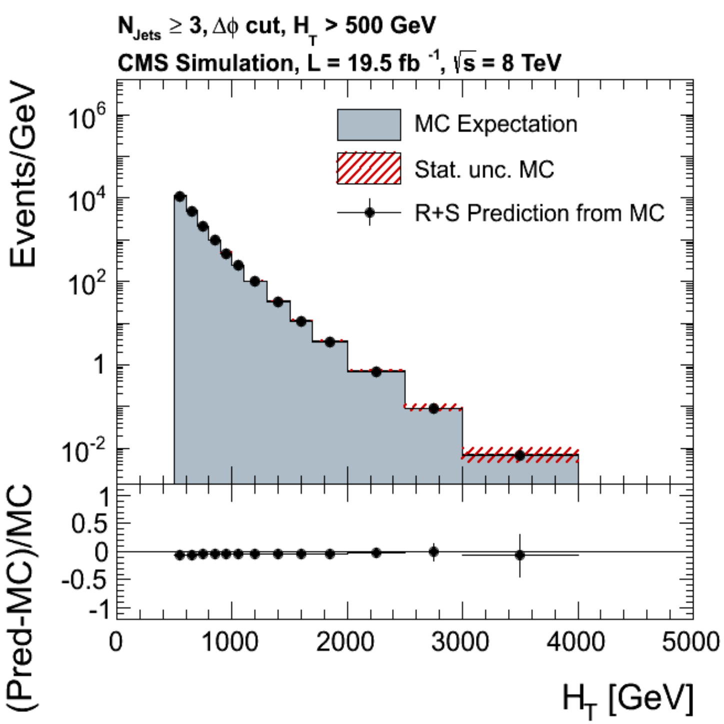
≥8	1500-	> 200	0.0± 0.6	0.0± 2.1	1.5± 1.0	0.9± 1.3	2.4± 2.8	2



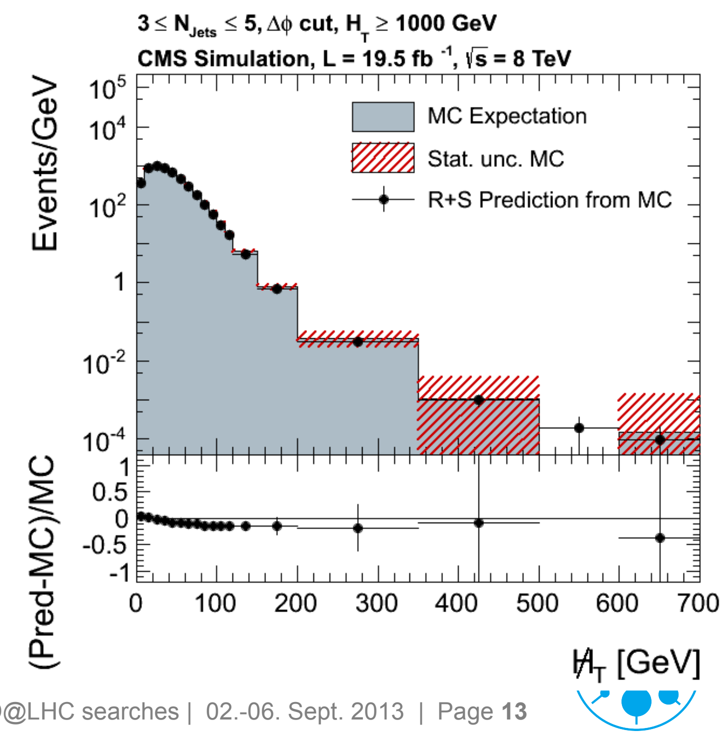
MET

QCD background many jets plus MET

- CMS analyses: smearing approach
  - Veto events with MET aligned to jets
  - Rebalance events by kinematic fit
  - Smear with jet response functions from simulation
  - Comparison of MC with this prediction

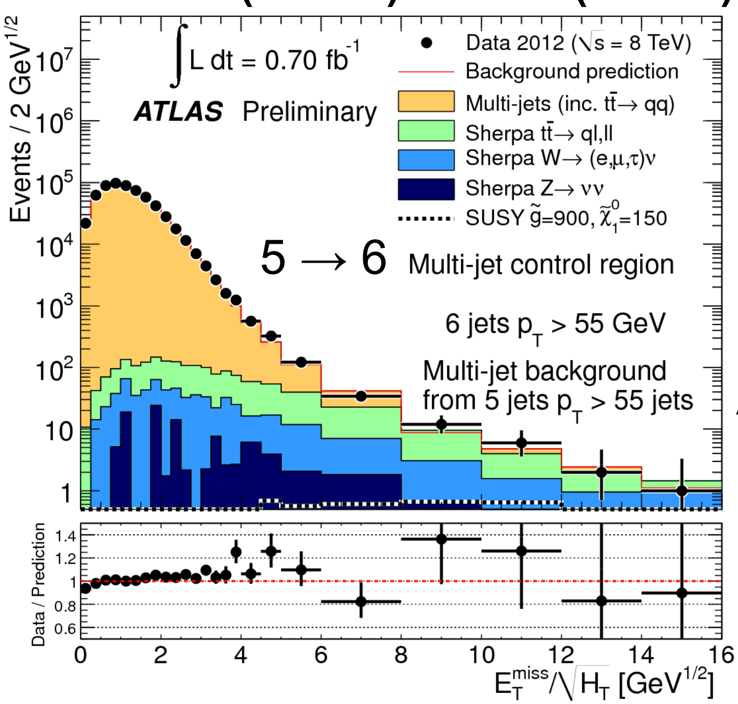


CMS-SUS-13-012



QCD background many jets plus MET

- Atlas analysis: scaling
  - Missing-E_T proportional to $\sqrt{(\Sigma E_T)}$
  - Estimate QCD-shape (jet-p_T) in low jet bin data driven
  - Then scale to higher jet bins with help of prediction:
  - $N^{n\text{-jet}}(\text{data})=N^{m\text{-jet}}(\text{data})*N^{n\text{-jet}}(\text{MC})/N^{m\text{-jet}}(\text{MC})$ n > m



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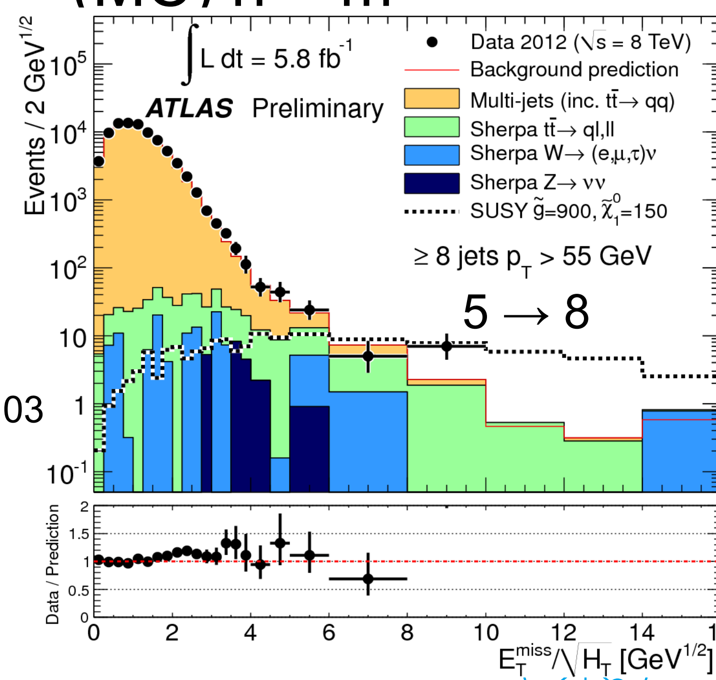

Examples of QCD@LHC

- QCD in final states with leptons
  - "Lepton fakes"
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- **QCD in all hadronic final states**
  - Many Jets
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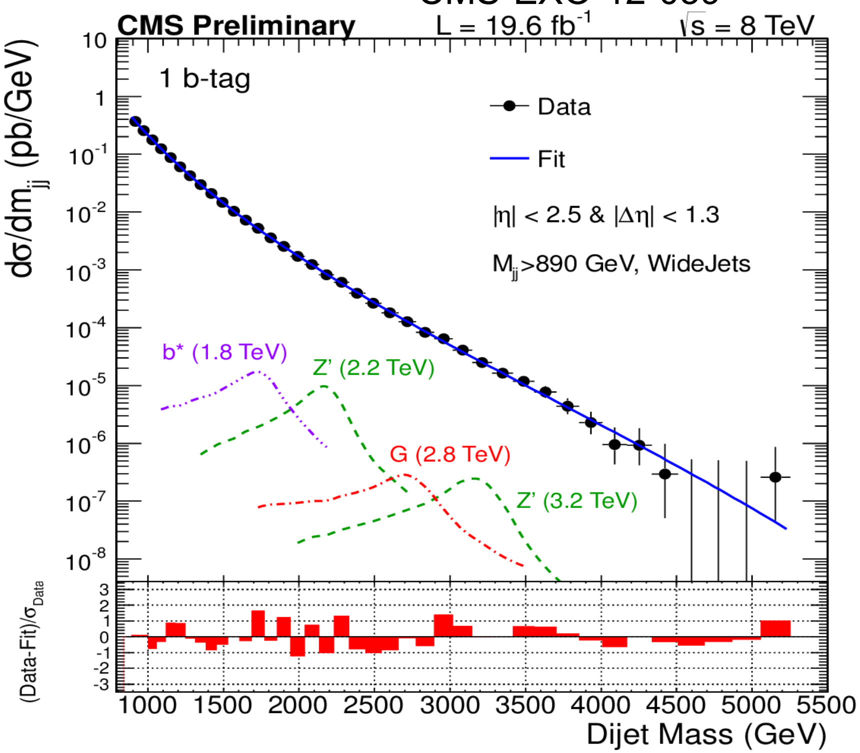
QCD in hadronic final states

- Most difficult case of QCD background:
  - All hadronic decaying resonances (di-jet and ttbar)
  - SUSY particles decaying into many jets
  - Black hole searches
- Dedicated search approaches:
  - Bump hunting
  - Use of Monte Carlo with data driven normalisation
  - Extrapolation of data driven estimate using theory input
  - Top-pair and single-Top from Monte Carlo with/wo data normalisation

Bump hunting

- Data only method
- Fit data distribution and try to find a bump above the QCD fit
- Used for di-jet resonances in both experiments
- Other famous example: $H \rightarrow \gamma\gamma$

CMS-EXO-12-059



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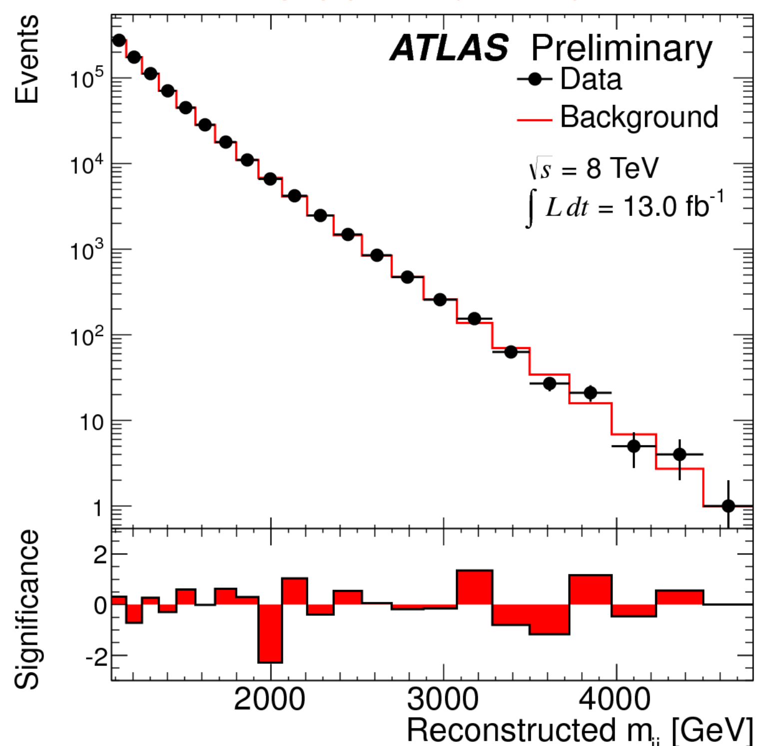
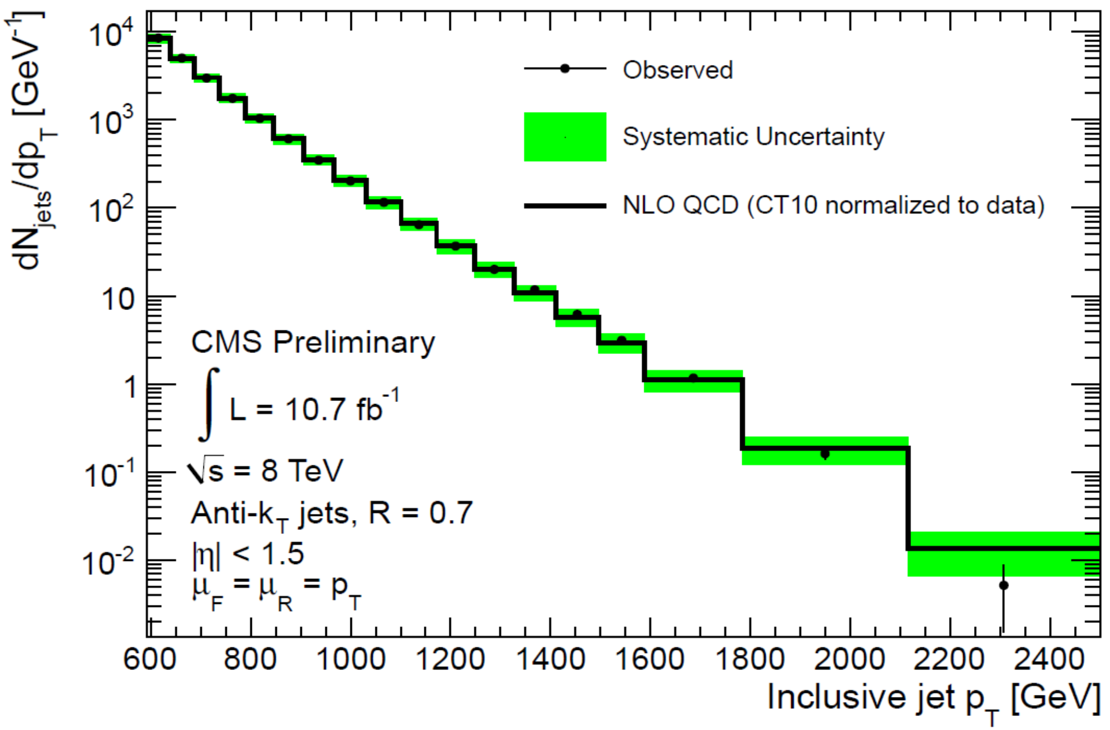


Anomalous shape of QCD jet pt spectrum

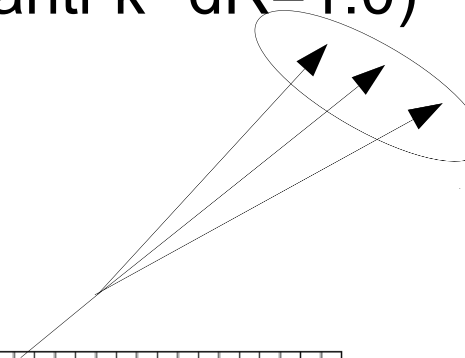
- Have to rely on predictions for inclusive jet pt spectrum
- Inclusive QCD jet-p_T spectrum from NLO-calculation:
  - Using data driven normalisation at low p_T
  - Good agreement but big systematic errors O (50%)

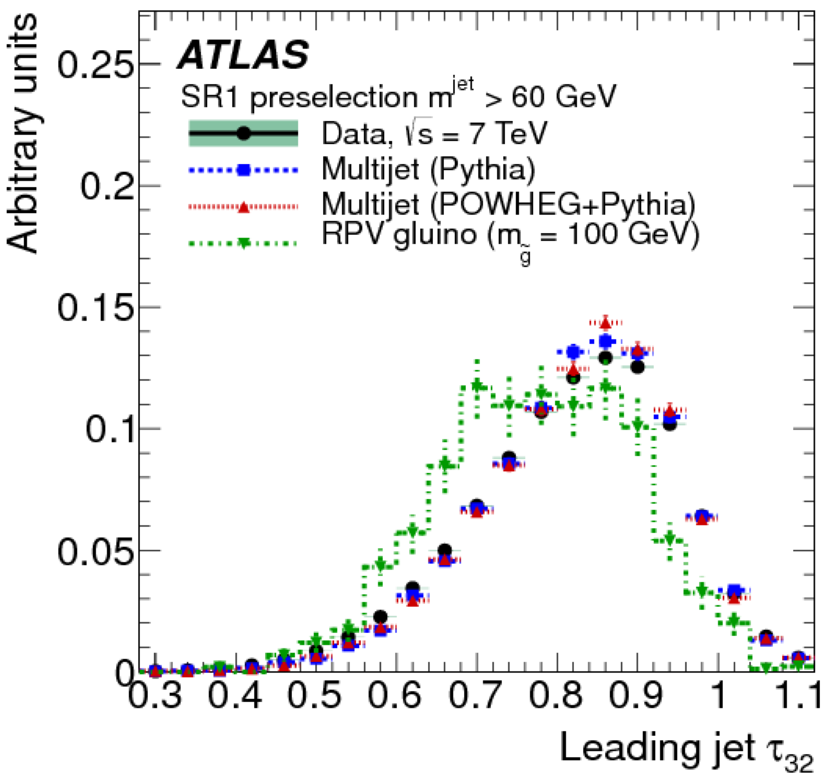


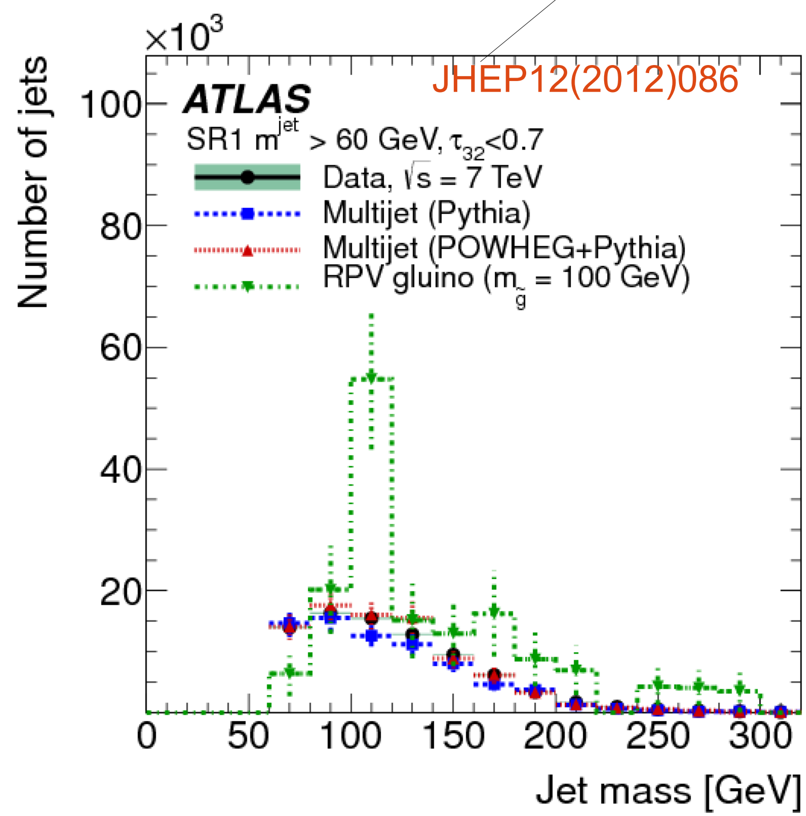
CMS-EXO-12-051

Boosted objects and QCD

- Small gluino mass: partons merge into big jet (anti-k_T dR=1.0)
  - MC comparisons for large jet properties
  - Very sensitive to final state modelling





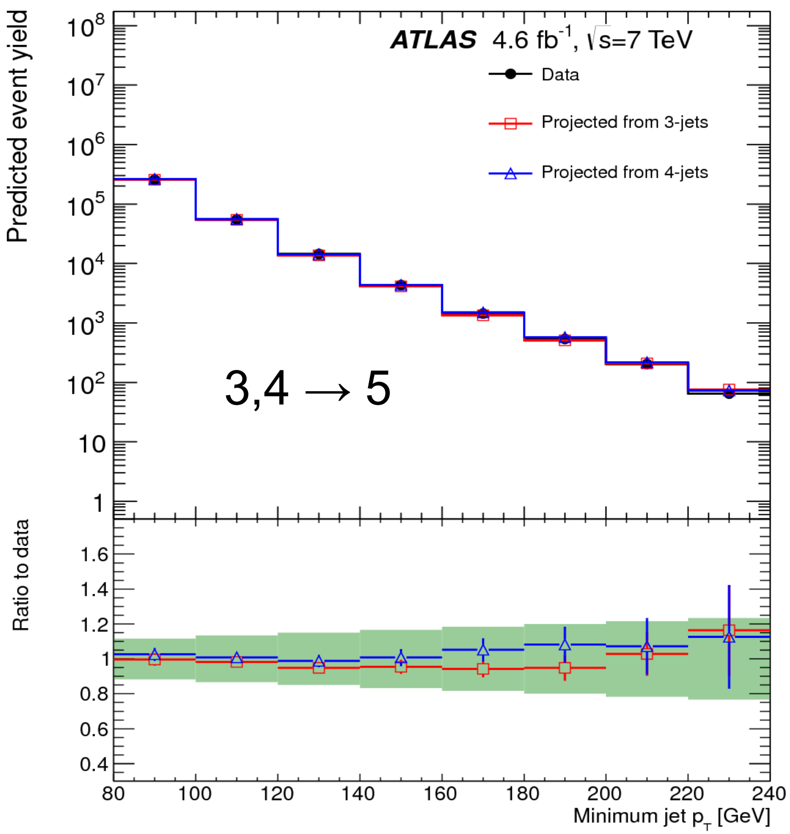


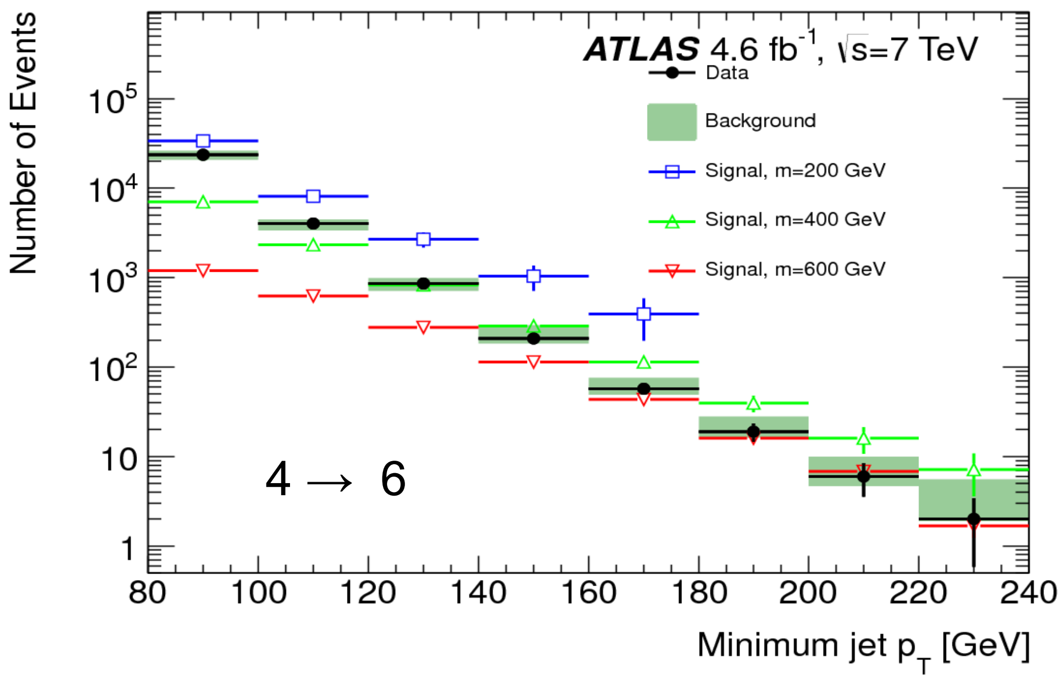
τ_{23}: jet Splitting 2 → 3

All hadronic with many jets

- Atlas: Search for gluinos decaying into three jets
- Scaling to higher number of jets using prediction :
  - $N^{n\text{-jet}}(data)=N^{m\text{-jet}}(data)*N^{n\text{-jet}}(MC)/N^{m\text{-jet}}(MC);\ n>m$

JHEP12(2012)086





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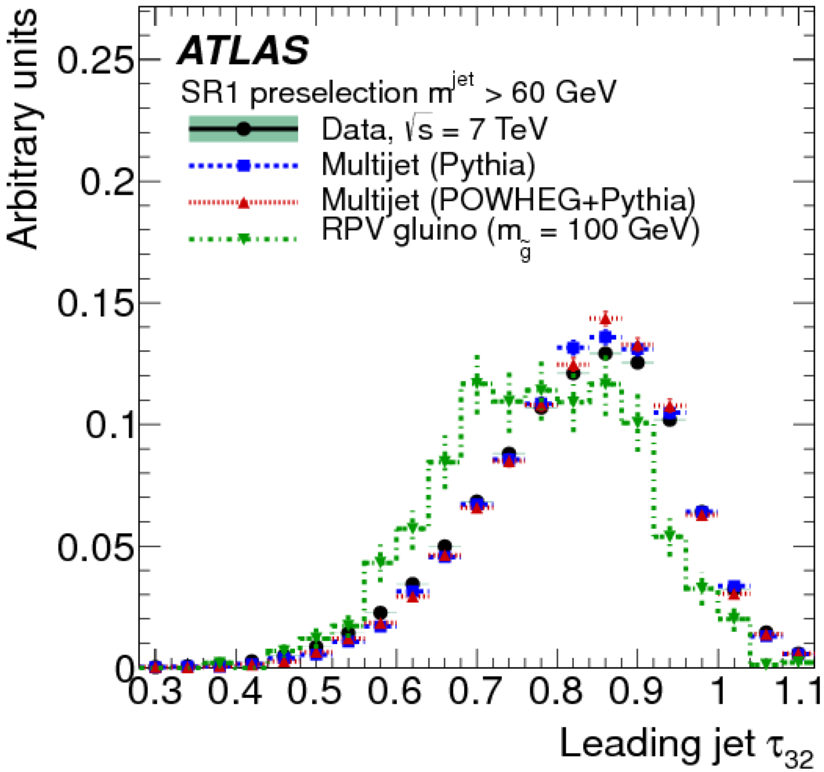

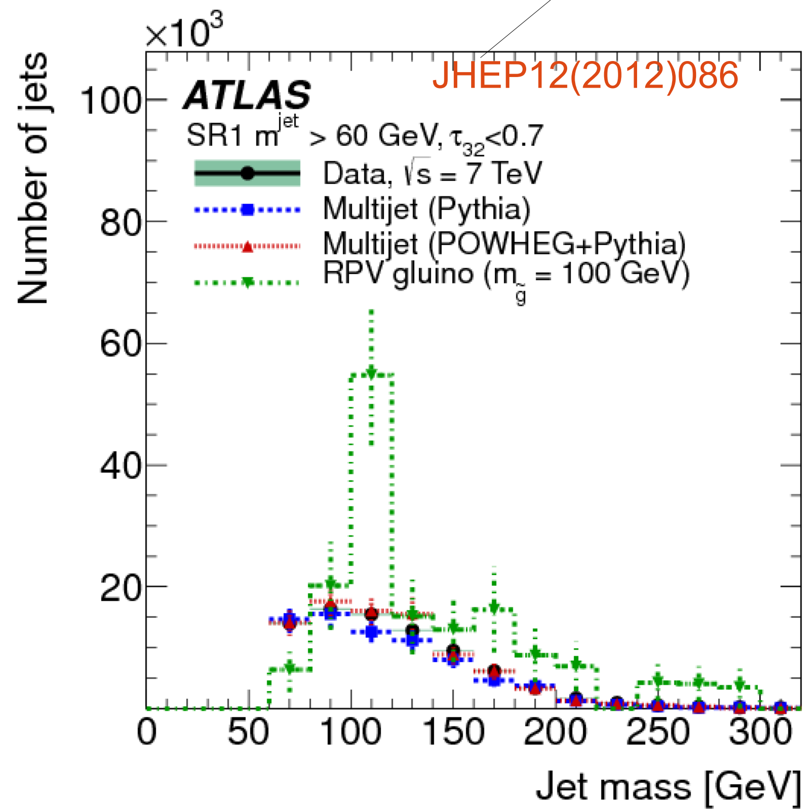

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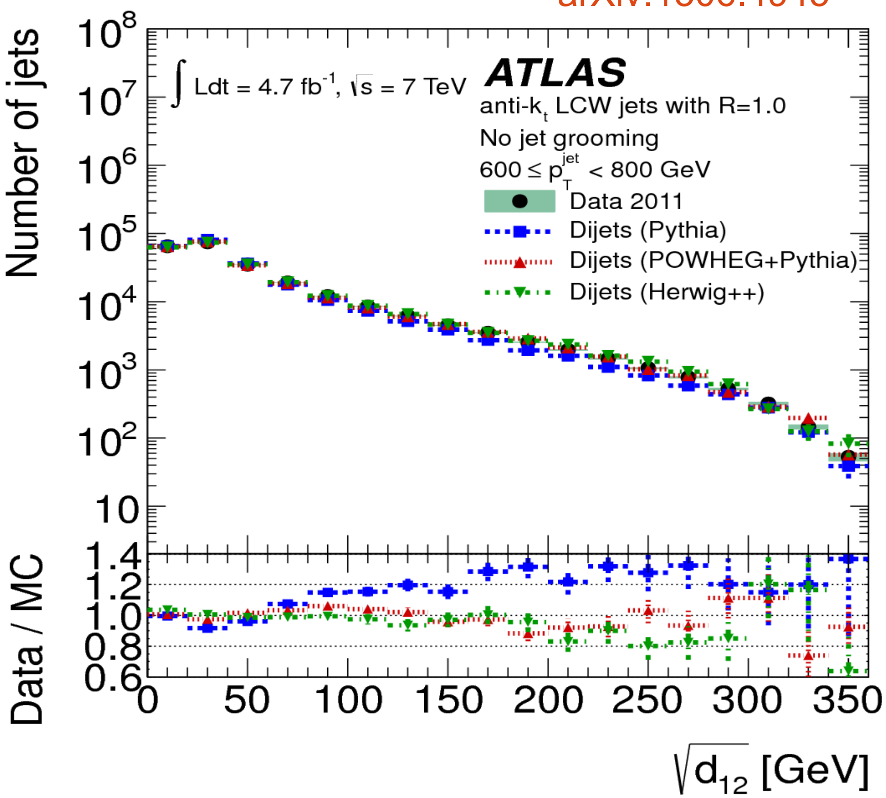
All hadronic Top-Pair resonances

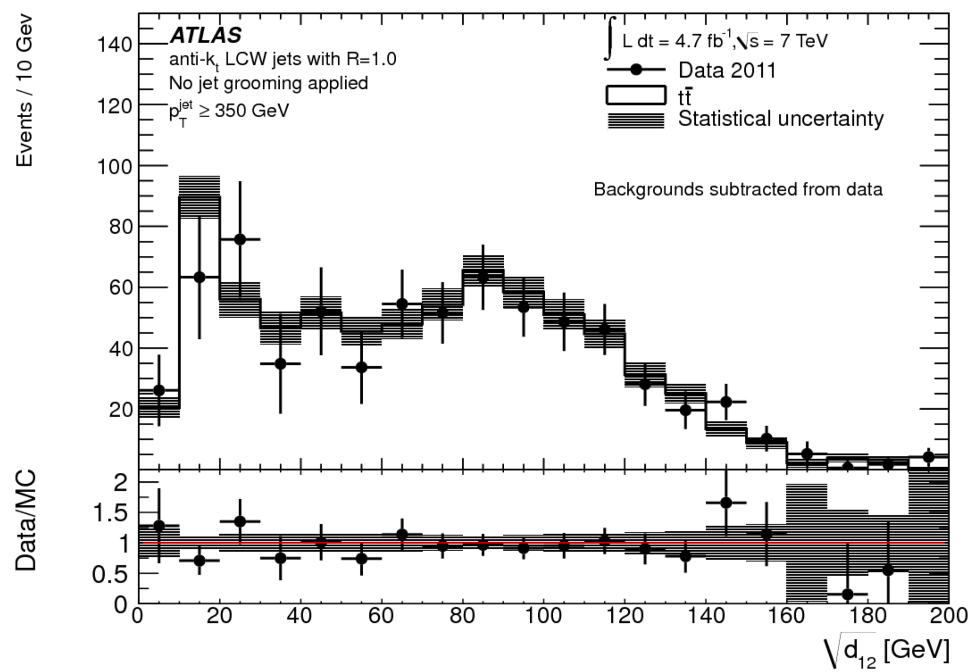
- Boosted tops: all decay products are in one fat jet
- Test of top-performance: lepton+jet events
- QCD Background by cut inversions

QCD enrich

arXiv:1306.4945



Top enrich

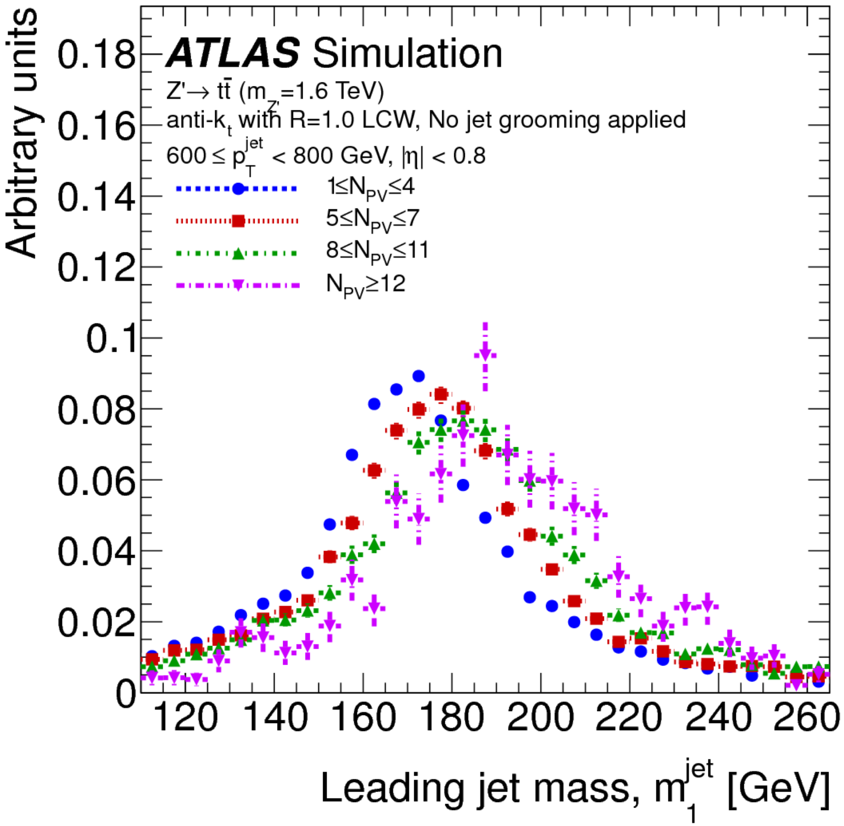


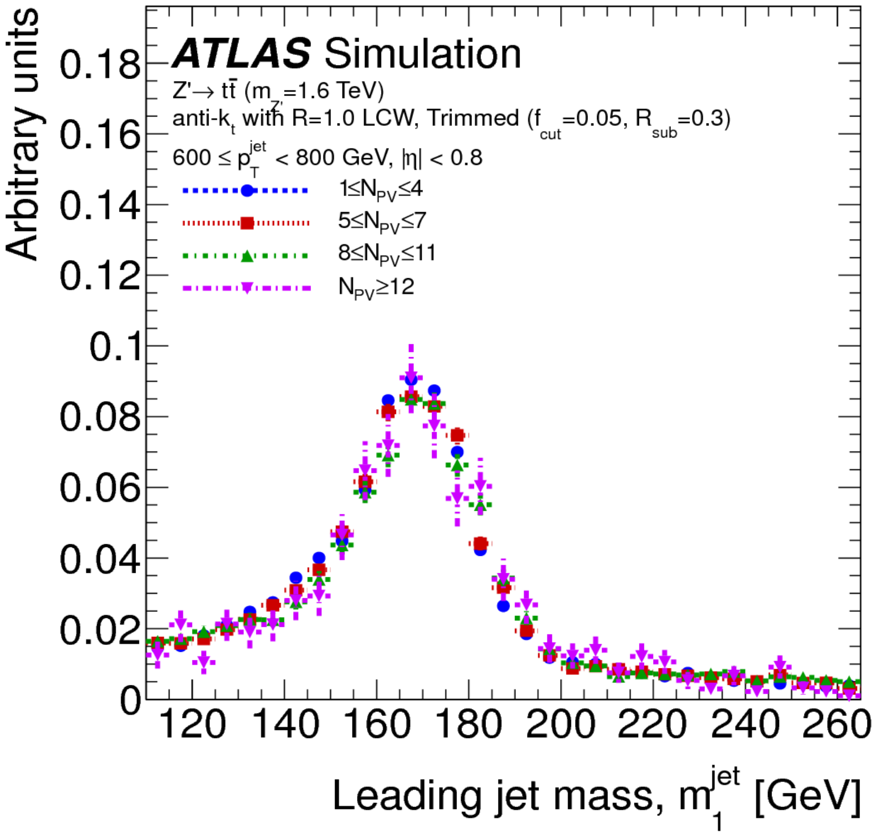
kT → 1 to 2 jets

All hadronic Top-Pair resonances

- Large jet area → large pile up influence
- Pile-up removal via trimming (removal of soft subjets)
- Top mass for different number of pile up (vertices): N_{PV}

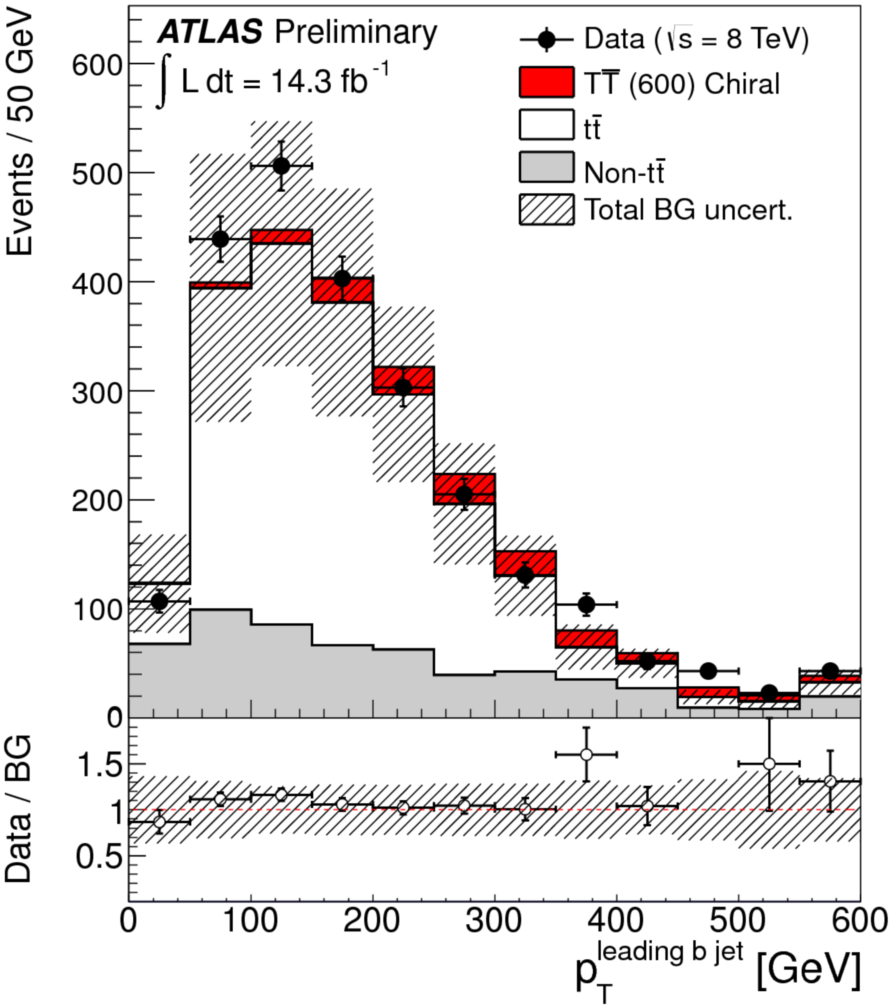
arXiv:1306.4945





Top as QCD-background

- Top-pair and single top cross section often taken from NNLO calculation
  - Full uncertainty from scale, fragmentation/ hadronisation/PDF
- Try to constrain top modelling from data:
  - Rapidity gap fraction (ISR/FSR)
  - Jet shapes
  - N-Jet spectrum
- Possible handling: comparing data with one and two b-tags

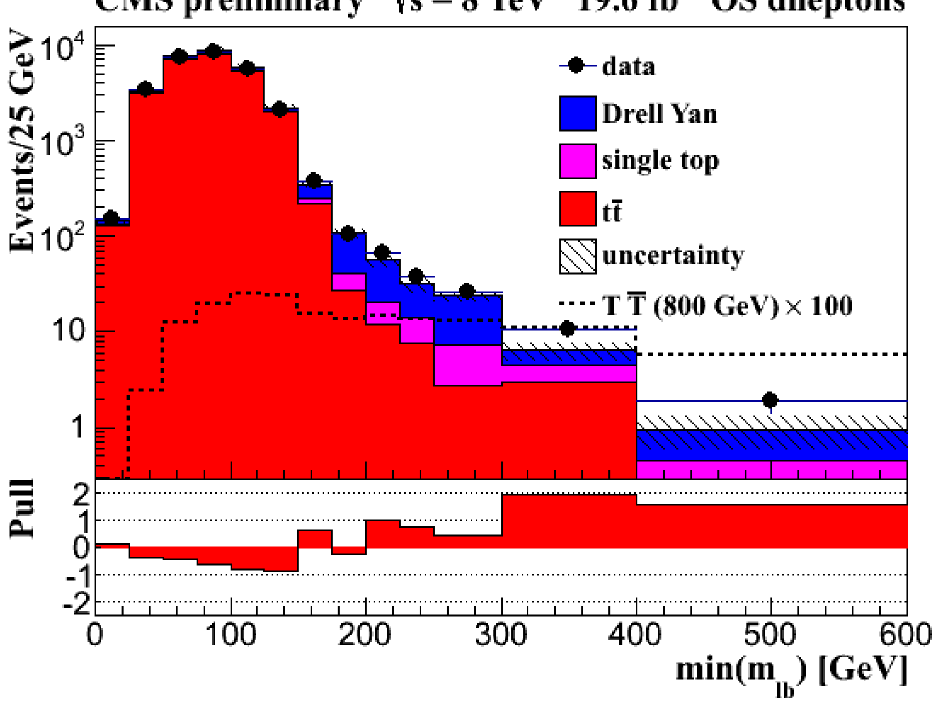


Top as QCD-background

- Searches are very often sensitive to tails of ttbar Monte Carlo:
  - High mass tails
  - HT tails
  - Large MET tails
- Often new developments on NLO:
  - Off-shell tops (single-top Wt has only one "off-shell")
  - ttZ, ttW
  - ttbb, ttcc (see also ttH)

Heavy top like production:
TT → WbWb

CMS-B2G-12-015



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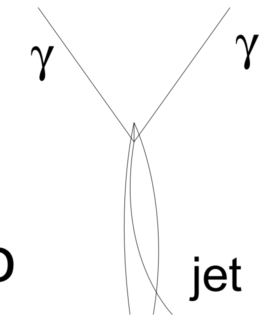
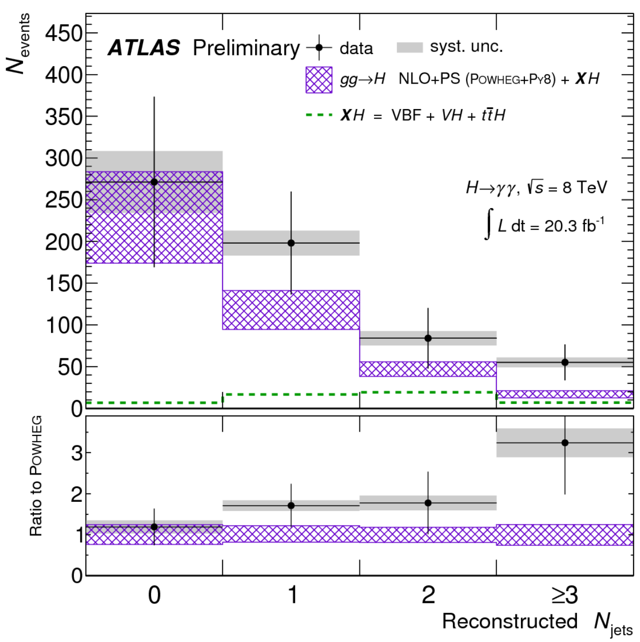
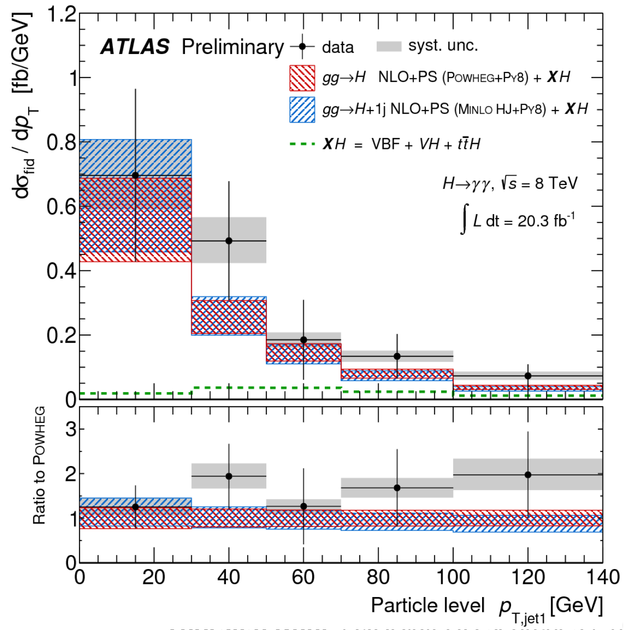
  - Real Missing ET
- QCD in all hadronic final states
  - Many Jets
  - Boosted objects
- Top Background
- **QCD and signal acceptance times efficiency**
  - ISR/FSR and Scale uncertainties

QCD effects and signal acceptance

- Higgs area of precision measurement started:
  - Most analyses in fixed number of jets bin
  - Many analyses using multivariate methods, need to describe distribution in exclusive jet bins good
  - Need calculations of of H+0,1,2 jets plus VBF
  - Start to constrain by measurements:







ATLAS-CONF-2013-072

H → γγ+jets: Frank Tackmann talk

QCD effects and signal acceptance

- Signal efficiency/acceptance: Monte Carlo prediction
- ISR very important for efficiency and acceptance correction
- Test of NLO generators with SM processes
- Powheg: Z and ttbar p_T of add. radiation including all theory and simulation uncertainties

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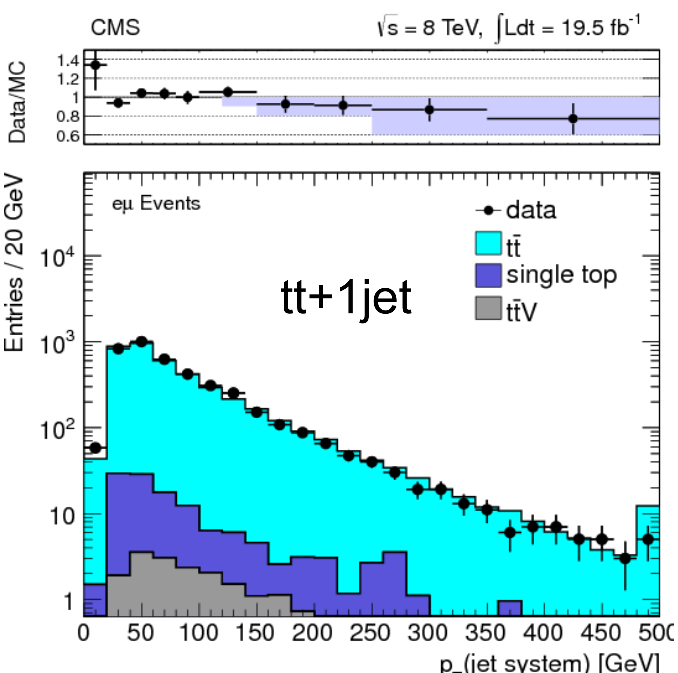
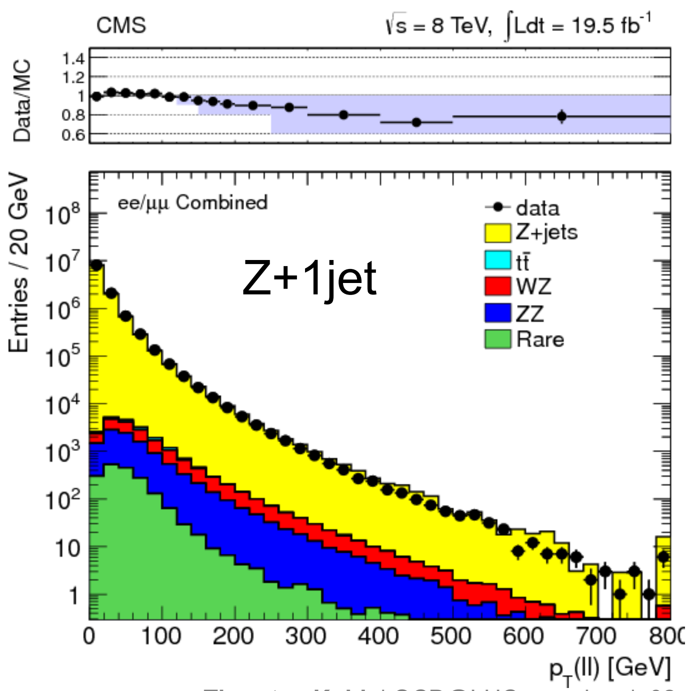


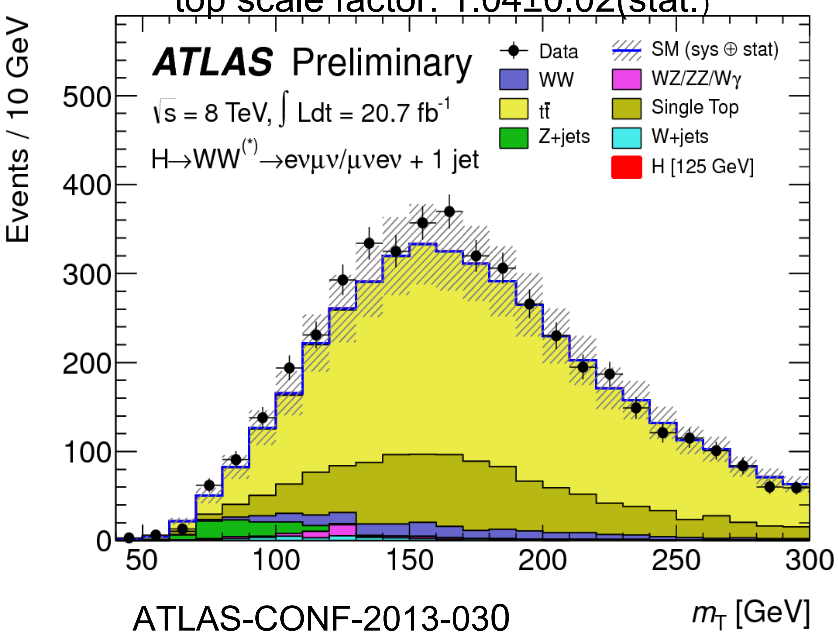


Theoretical uncertainties are much bigger then stat. Error of data.

Top as QCD-background for H → WW

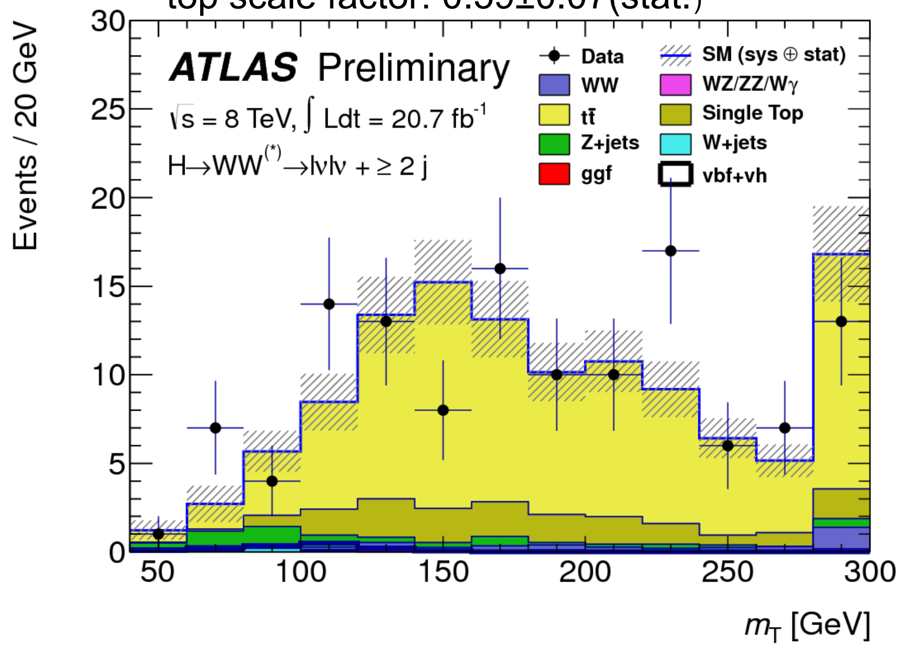
- H → WW+1jet: signal with hard ISR
- 2jets: VBF, rapidity gap $|Y_{jj}|$> 2.8
- Control region using b-tag
- NLO-ttbar Monte Carlo does not describe VBF-like events well (system variation between generators ~15%)

top scale factor: 1.04±0.02(stat.)



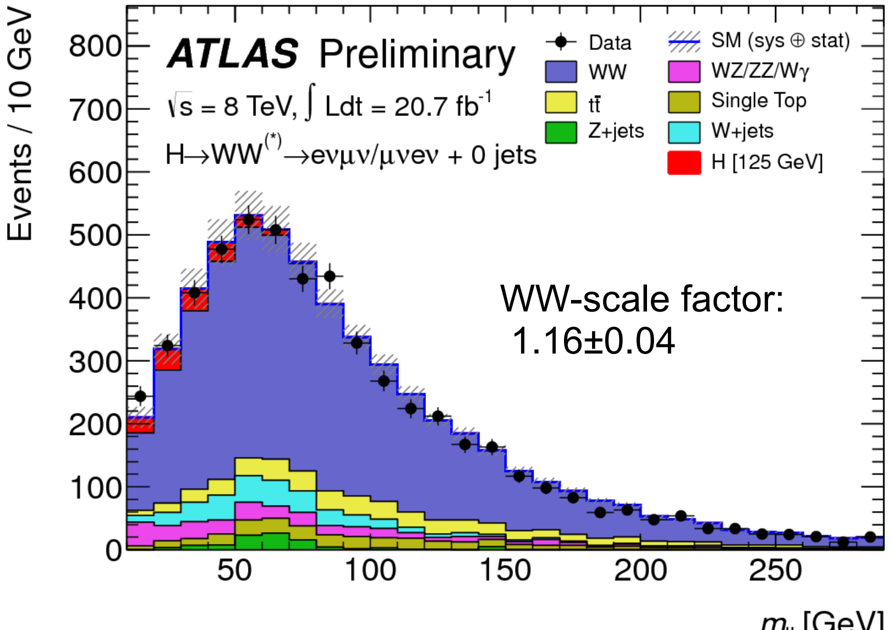
ATLAS-CONF-2013-030

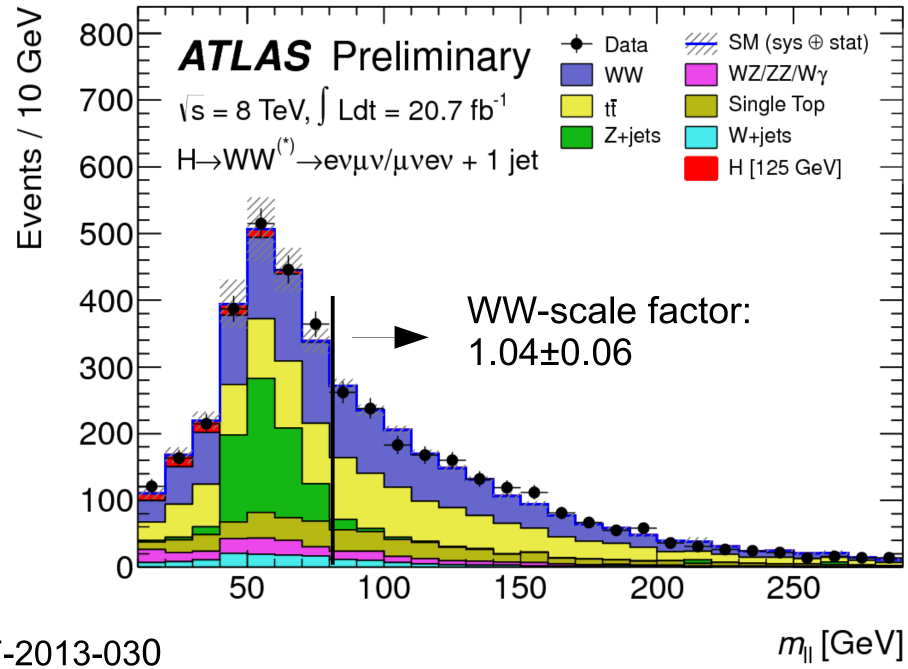
top scale factor: 0.59±0.07(stat.)



QCD radiation in EW-background H → WW

- Background composition depends on QCD radiation (ISR)
  - H → WW+0jet: WW 70% of background
  - H → WW+1jet: WW 40% of background
- Rate off WW depends on rate of ISR radiation, data driven normalization





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Summary

- QCD effects and background are a topic with large diversity in Searches for Higgs Bosons and BSM at the LHC
- Most analyses use data driven approach for QCD estimate
  - Side bands
  - Templates from Monte Carlo plus data driven normalisation
- Predictions are used for shapes, normalization from data
  - Shapes well described by predictions
- Many searches rely on precise descriptions of tails
- QCD uncertainties for Higgs and BSM signal processes:
  - QCD predictions are important for signal acceptance/cross sections
  - Migration between different jet bins via ISR