Higgs & Jets

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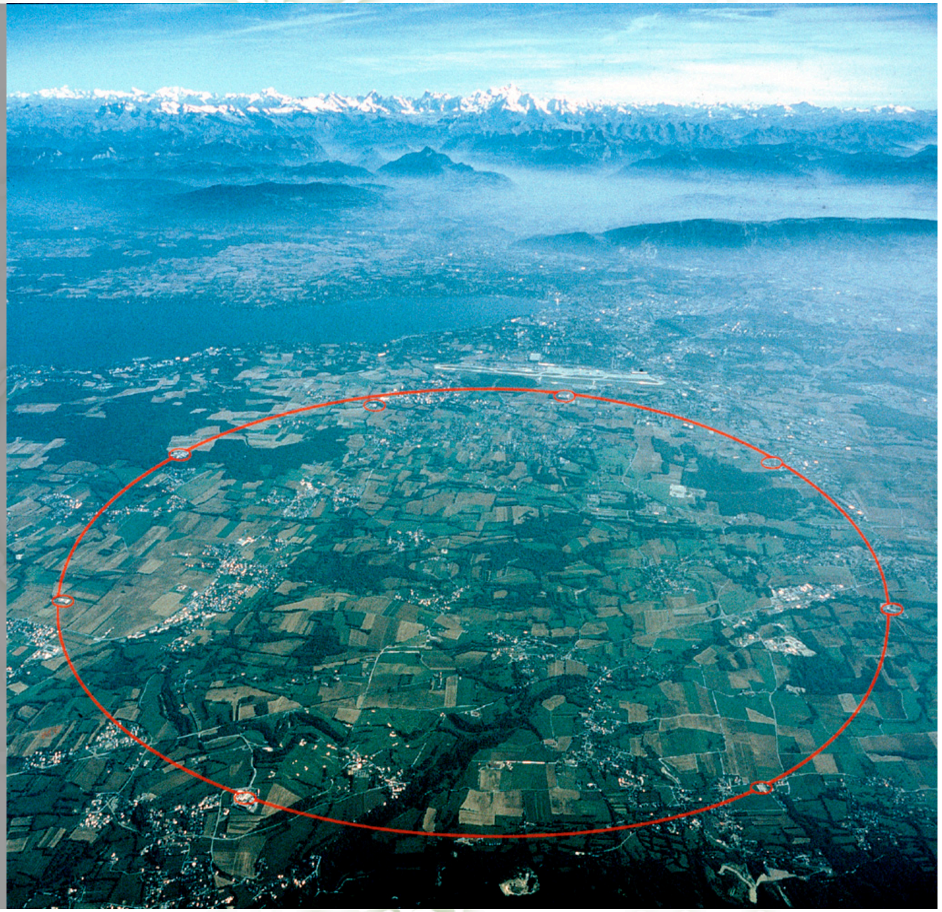
on behalf of the ATLAS Higgs Working Group
ATLAS Hadronic Calibration Workshop – SLAC 19-23 September 2011

Outline

- Recap and status of Higgs searches
- Jet/E_T^{miss} performance issues – channel by channel
- Jet energy scale/resolution and di-jet mass resolution
- Pileup and Jet Vertex Fraction
- Conclusions



Many thanks to: Marc Escalier, Taiki Yamamura, Andew Mehta, Paul Thompson Lianliang Ma, Bill Quayle, Martin Flechl, Liron Barak, Arnaud Ferrari, Daniel Pelikan, Alex Martyniuk, Konstantinos Nikolopoulos, Bill Murray, Eilam Gross

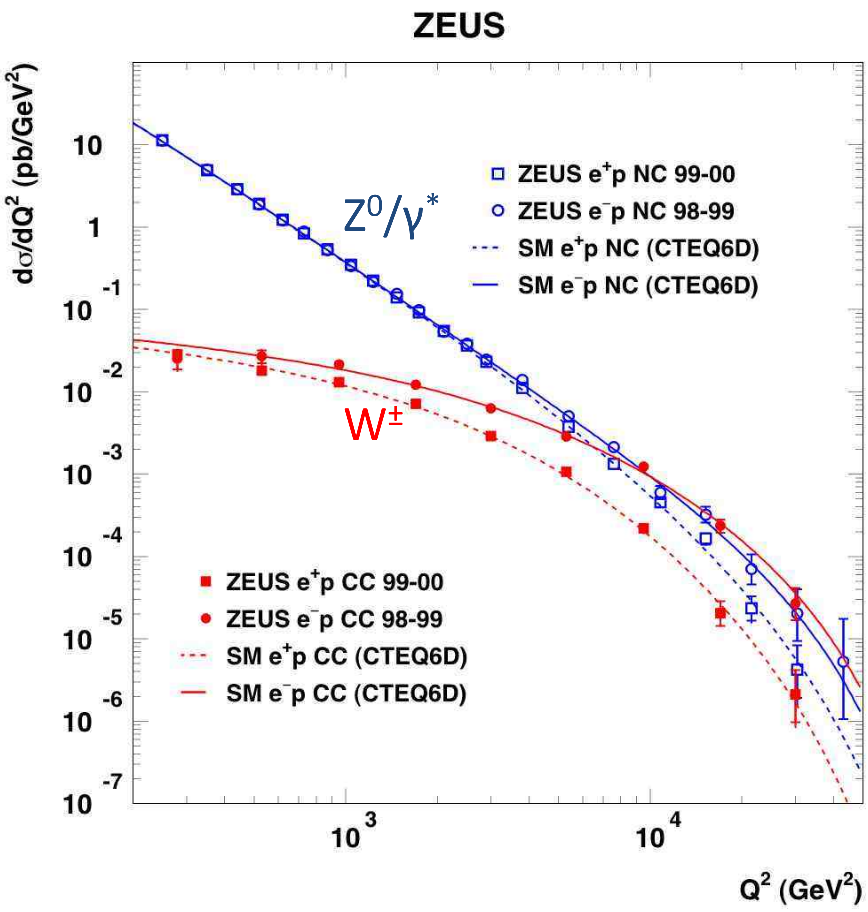
Disclaimer

- I may not be completely up to date on developments – I was offline for the last 2 weeks
- All I tried was to give an idea of where the jet and E_T^{miss} performance matters most for Higgs analyses
  - And so where improvements would be most beneficial

Of all things Higgsy

Why all the fuss?

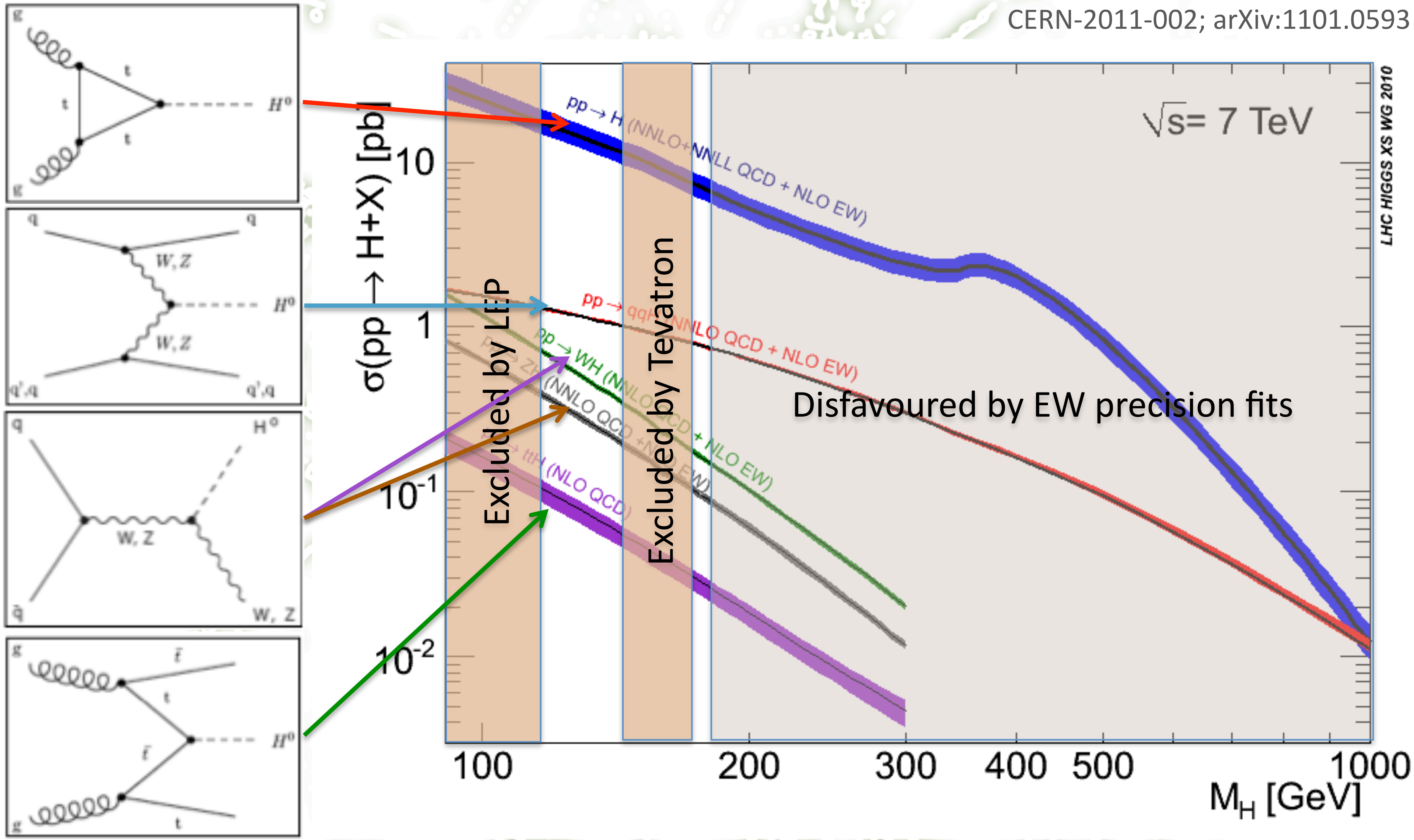
- Electroweak symmetry breaking/unification and the need to account for massive particles is clear from experimental data
- The **simplest model** of electroweak symmetry breaking predicts one **Higgs scalar** – the boson mass is the only free parameter in this model
- Without the Higgs boson, some cross section calculations would return wrong/un-physical results ($W_L W_L$ scattering)



http://www-zeus.desy.de/physics/sfew/PUBLIC/sfew_results/preliminary/dis04/

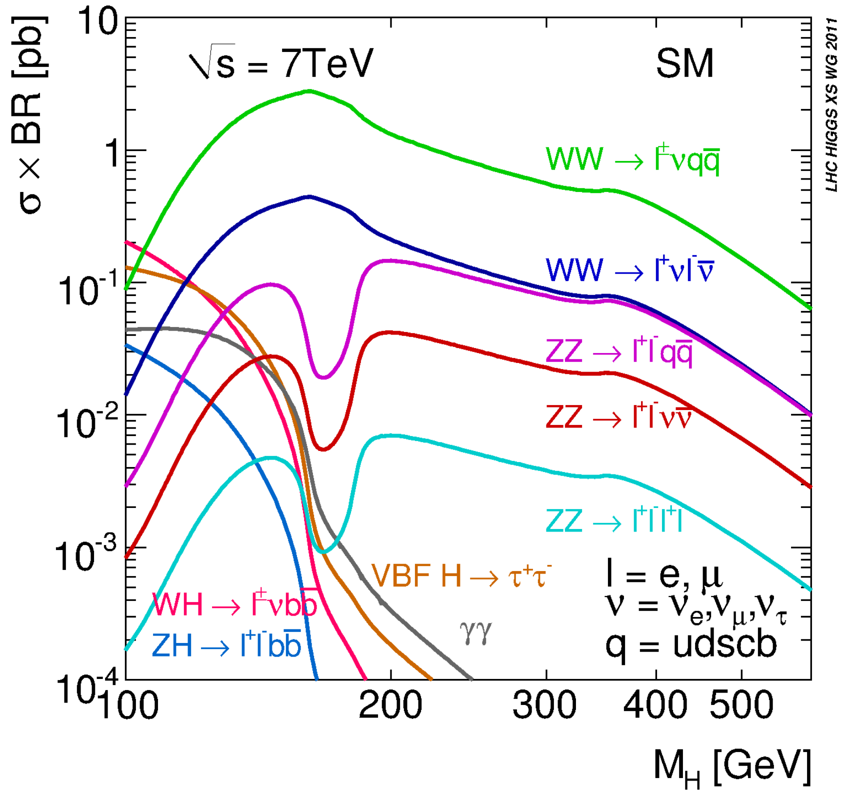
Higgs physics at the LHC: SM case

CERN-2011-002; arXiv:1101.0593



SM channels explored in ATLAS

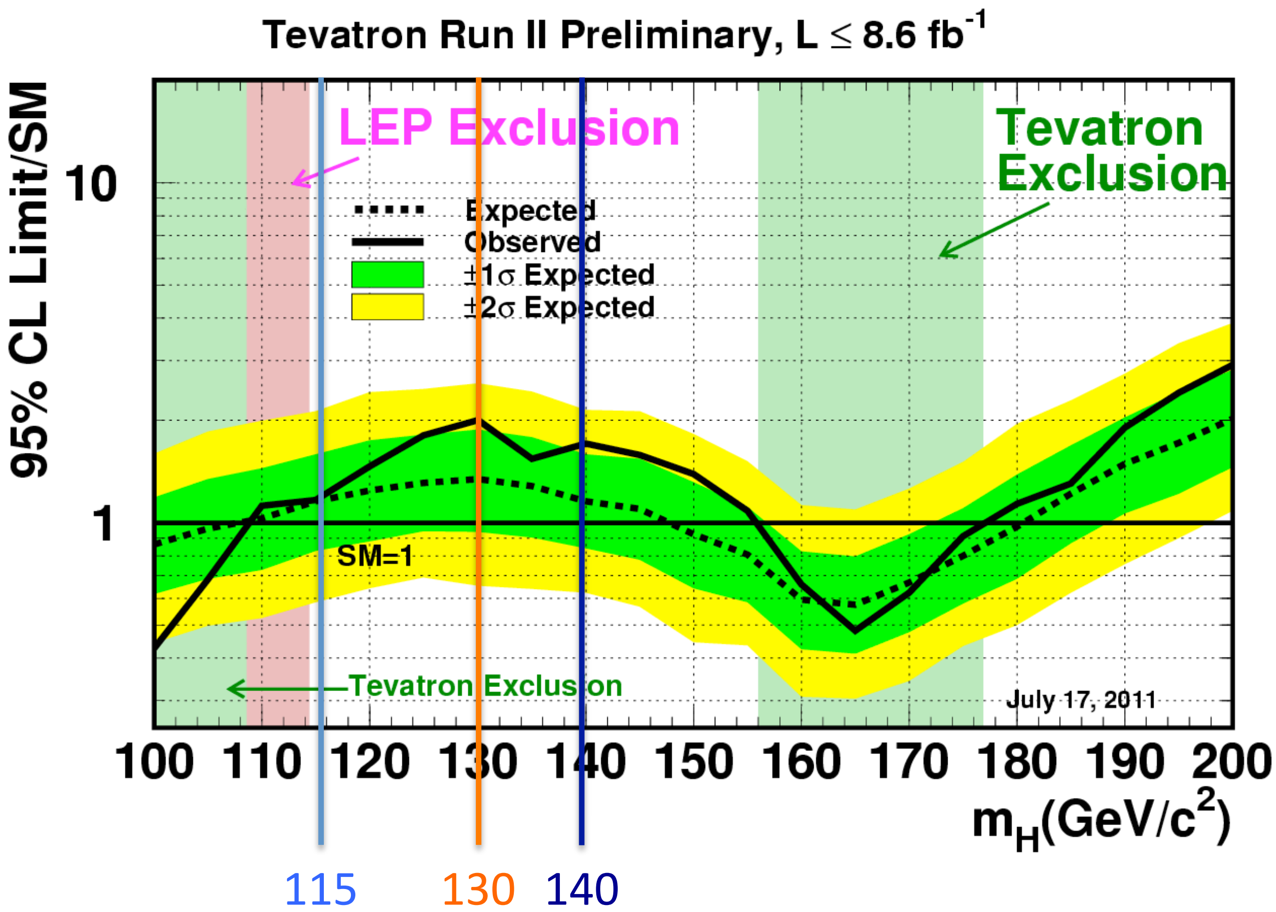
- **H→γγ**: rare channel, but the best for low mass
- **H→ττ**: good signal/background, important at low mass, rare
- Associated prod. **H→ bb-bar**
  - ttH, WH, ZH
  - Contributes to discovery
  - Very important for Higgs property studies if SM Higgs is discovered
- **H→WW$^{(*)}$**:
  - →lvlv: very important in the intermediate mass range
  - → lvqq: highest rate, important at high mass
- **H→ZZ$^{(*)}$**:
  - → 4l: golden channel
  - → llvv: good for high mass
  - → llbb: also high mass



Events expected with L=1 fb^{-1}:

m_H, GeV	WW→lvlv	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

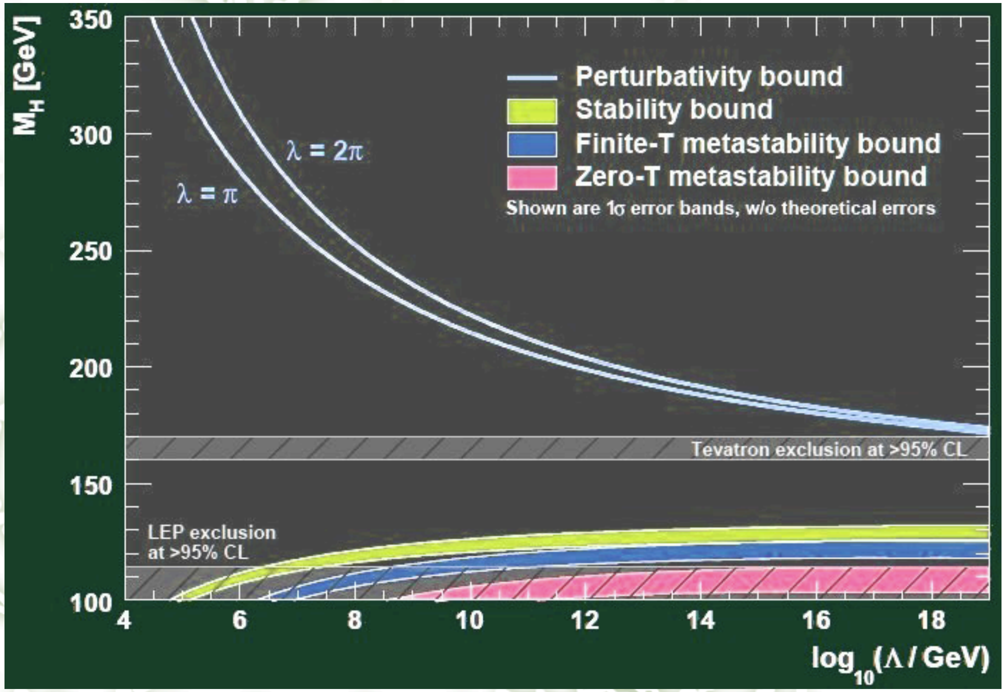
Where we are now…



- Expected exclusion: 130 GeV – 440 GeV
- Observed: 146 – 232, 256 – 282, 296 – 466 GeV
- Similar for CMS: 145 – 216, 226 – 288, 310 – 400 GeV

What next?

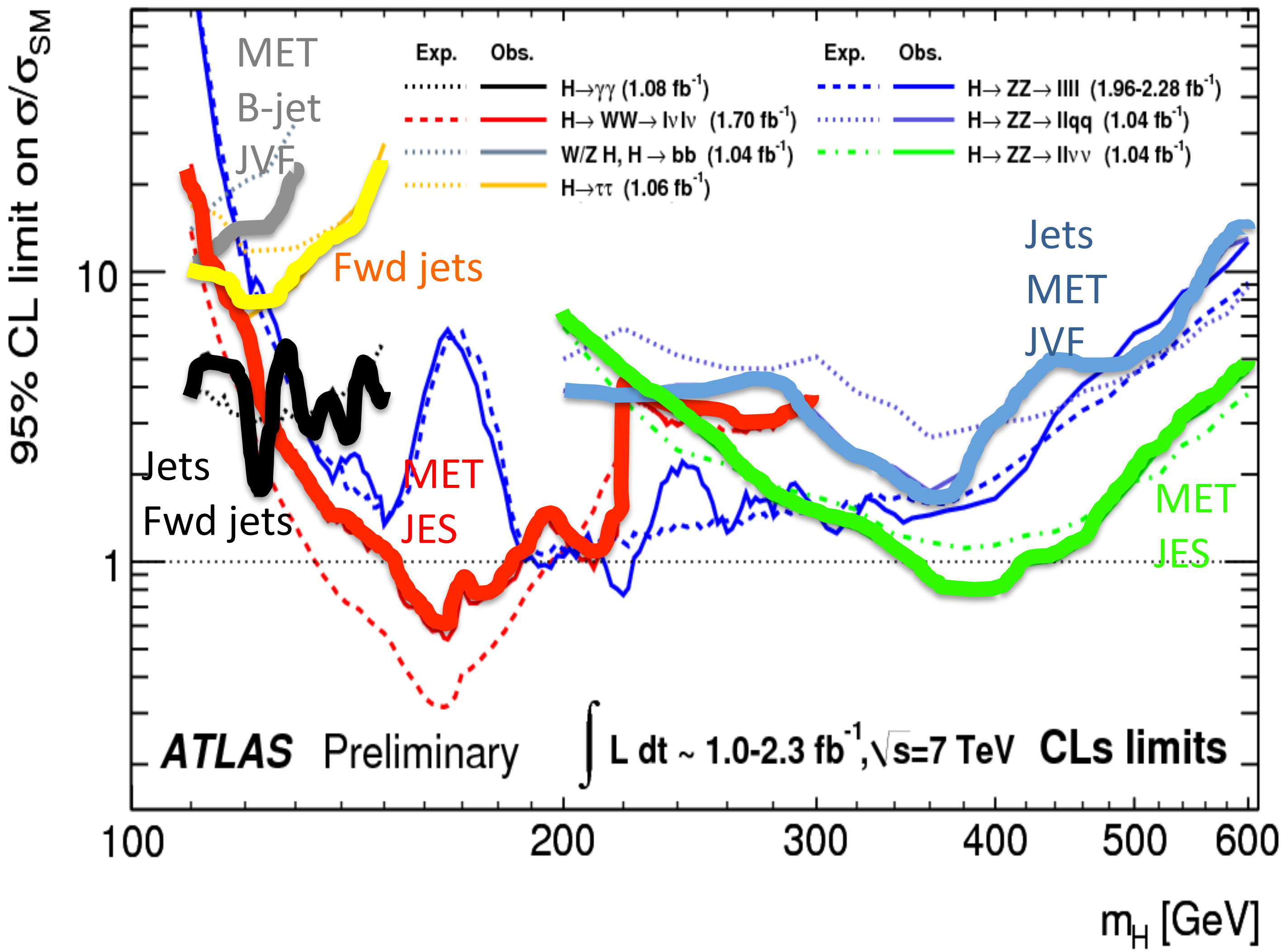
- Likely to have sensitivity to exclude ≈125 GeV – 500 GeV until end of year!
- End of Standard Model Higgs?
- Or will we find something at low mass around 140 GeV?
- Even if no SM Higgs, many scenarios of "beyond SM" Higgs mechanism – this was just the simplest case!



- Electroweak symmetry breaking and particle masses will still be there – **WHY?**
- To find the answer we rely on an excellent performance of all parts of ATLAS – **Jet / ETmiss performance crucial!**

Of Higgs and Hadronic calibration

Where jet/E_t^{miss} really matters:



H->γγ

- H->γγ + MET starting to be studied – aiming at a confirmation channel if Higgs found at low mass
- H->γγ + N jets (N = 0, 1, 2) being developed (standard analysis is inclusive H->γγ)
- Ongoing mysteries:
  - Addition of H->γγ + 2 jets has very small impact – under study
  - Jet multiplicity not reproduced in background MC - using a reweighting procedure (below)

Status of H+2jets analysis

Event selection (example)

◆ **0jet-bin**

(A) Pt(γ1)>40GeV,
Pt(γ2)>25GeV

◆ **1jet-bin**

(A) Pt(γ1)>40GeV,
Pt(γ2)>25GeV

(B) Pt(j1)>25GeV,
|η(j1)|<4.5

(C) M(γγj) > 250GeV

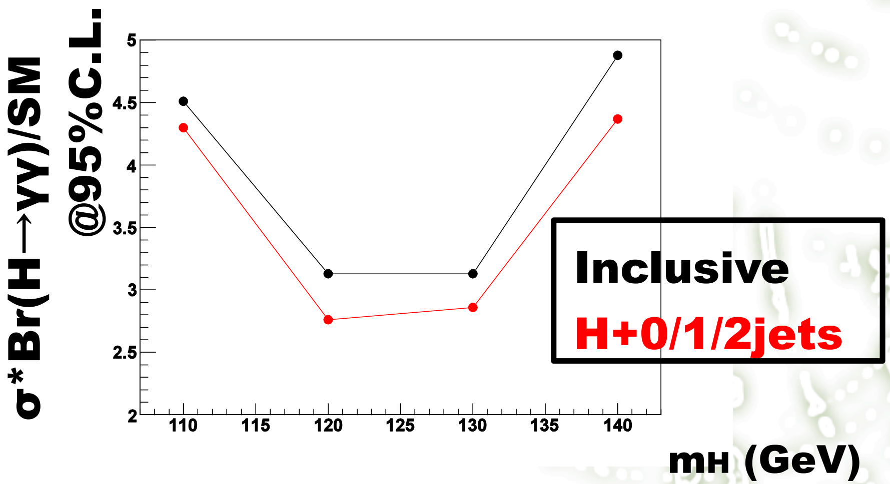
◆ **2jet-bin**

(A) Pt(γ1)>40GeV,
Pt(γ2)>25GeV

(B) Pt(j1)>40GeV,
Pt(j2)>25GeV
(|η(jet)|<4.5)

Expected limit (1.08fb^{-1})

Improved by ～10%.



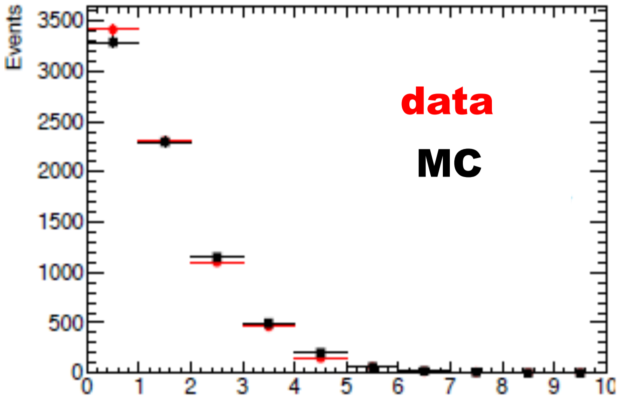
- Very loose selection for 2 jet-bin at present, in order to obtain sufficient statistics.
- Optimization is not yet finalized.

Jet distributions

(after inclusive selection, 1.6fb^{-1})

◆ data/MC comparison

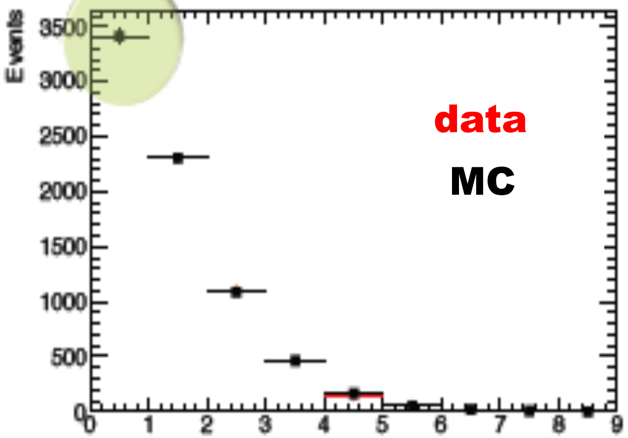
＜N(jet)＞



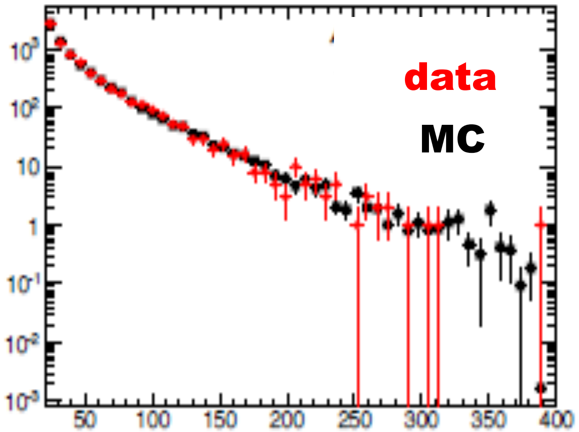
- By applying the reweighting w.r.t N(jet), basic distributions for jets are in good agreement between data and MC.
- Detailed studies are not yet done…
  (NLO effect, pileup effect etc.)

Apply reweighting to MC w.r.t. N(jet)

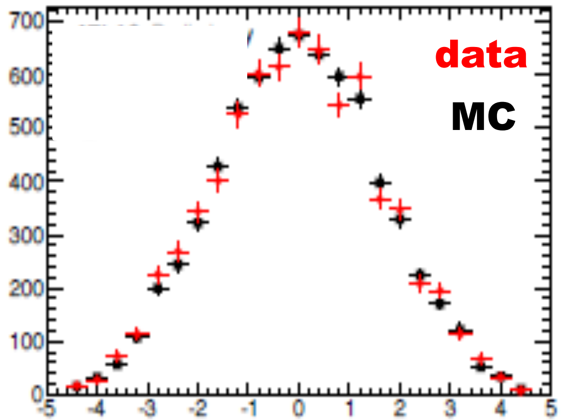
＜N(jet)＞



＜pT(jet)＞



＜η(jet)＞



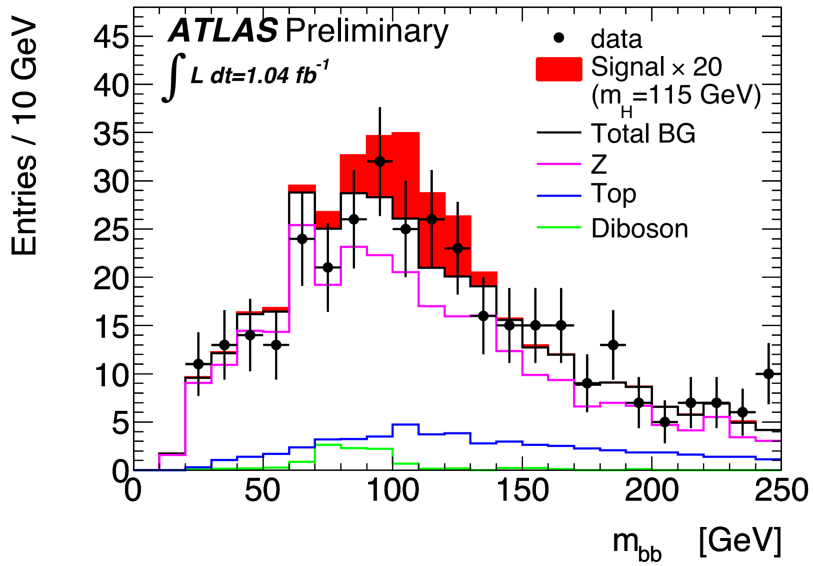
H -> bb

- Two channels: WH and ZH
  - Obviously very dependent on jet reconstruction performance
  - Both analyses use E_t^{miss} for cut or veto

- Analyses select good W or Z and then search for Higgs in m_{bb} spectrum
  - ZH relatively clean, but lower xsection
  - WH has twice higher xsection but also higher backgrounds
    - In particular, 3-jet bin dominated by **ttbar**
    - Need to cut on number of jets => **need JVF**

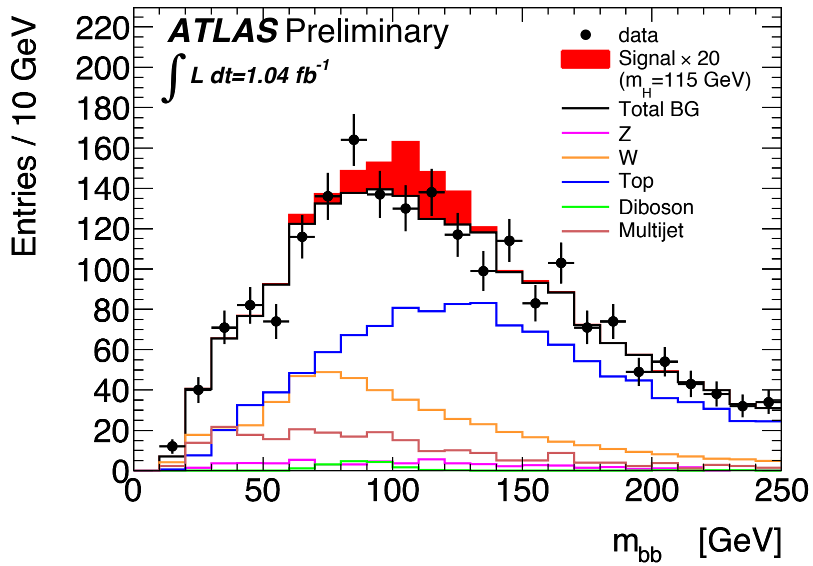
- CMS has published better H->bb results than us (although later ;-)
  - The difference mostly from better optimized analyses and the inclusion of ZH->ννbb
  - But there are hints of differences in performance:
    - Better di-jet mass resolution using energy-flow jets (and higher-p_T jets)
    - More agressive JES and b-tagging uncertainties
    - E.g.: similar systematics except **JES (1%)** and **b-tagging (10%)** **–** **9%** and **16%** for us, respectively (note this is partly due to higher jet p_T cut)

M(bb) spectra and systematics



Source of Uncertainty	Effect on the signal $m_H = 115$ GeV	Effect on the signal $m_H = 130$ GeV
Electron Energy Scale	< 1%	< 1%
Electron Energy Resolution	< 1%	< 1%
Muon Momentum Resolution	1%	3%
Jet Energy	9%	7%
Jet Energy Resolution	< 1%	< 1%
Missing Transverse Energy	2%	2%
b-tagging Efficiency	16%	17%
b-tagging Mis-tag Rate	< 1%	< 1%
Electron Efficiency	1%	1%
Muon Efficiency	1%	1%
Luminosity	4%	4%
Higgs Cross-section	5%	5%

ZH→llbb



Source of Uncertainty	Effect on the signal $m_H = 115$ GeV	Effect on the signal $m_H = 130$ GeV
Electron Energy Scale	1%	1%
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Muon Momentum Resolution	4%	1%
Jet Energy	1%	3%
Jet Energy Resolution	1%	1%
Missing Transverse Energy	2%	3%
b-tagging Efficiency	16%	17%
b-tagging Mis-tag Fraction	3%	3%
Electron Efficiency	1%	1%
Muon Efficiency	1%	1%
Luminosity	4%	4%
Higgs Cross-section	5%	5%

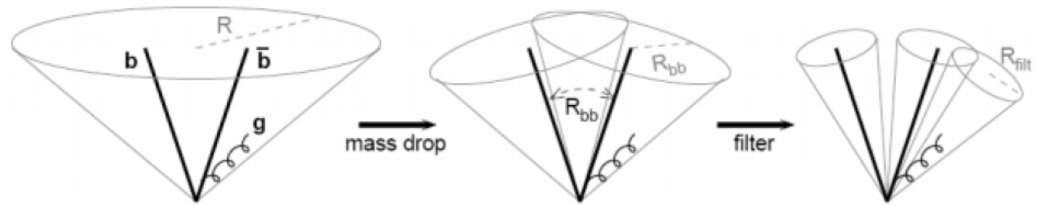
WH→lνbb

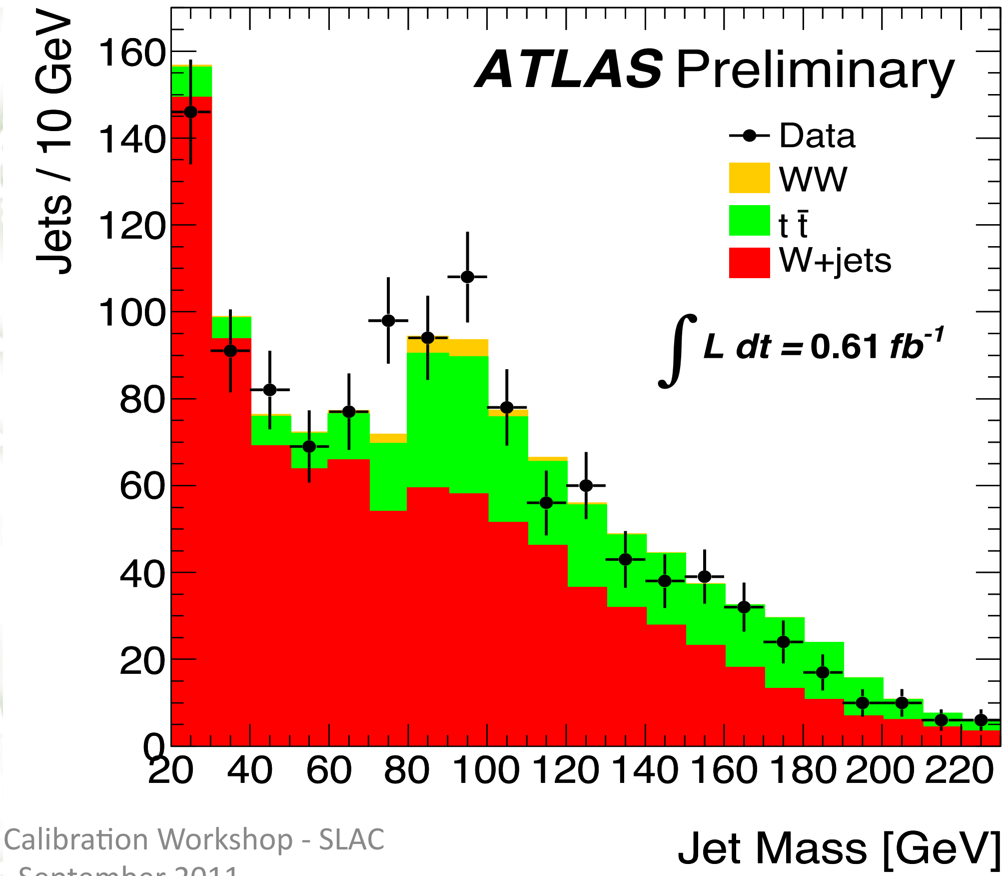
- Alternative to inclusive channels: search for high-pT Higgs to bb:
  - J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, Phys. Rev. Lett. 100 (2008) 242001, arXiv:0802.2470 [hep-ph]
- $p_T^H > 200$GeV ≈ 5% of inclusive cross section but improved significance

- Select W→lν events and search for a H→bb jet
  1. Search for high-p_T jet (Cambridge-Aachen algorithm, R=1.2)
  2. Search jet clustering history in reverse and look for large mass drop
  3. Re-cluster with small R parameter to find sub jets

- Peak consistent with W→jj in tt events
- Proof of principle for future jet substructure analysis

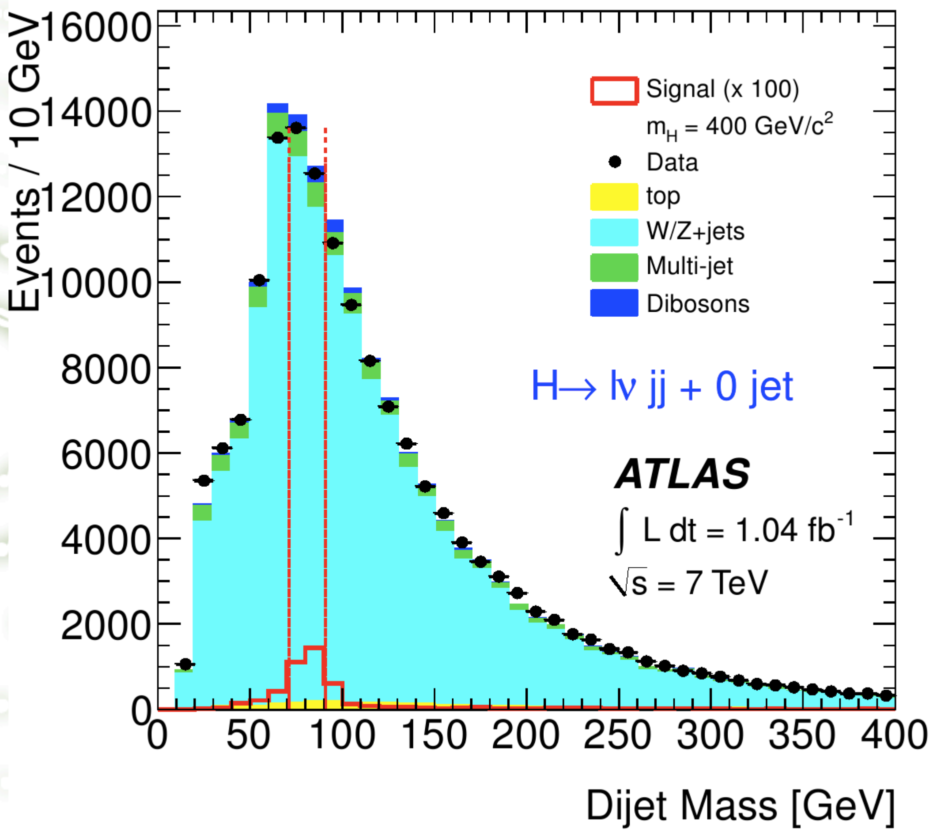
See talk by Adam Davison next





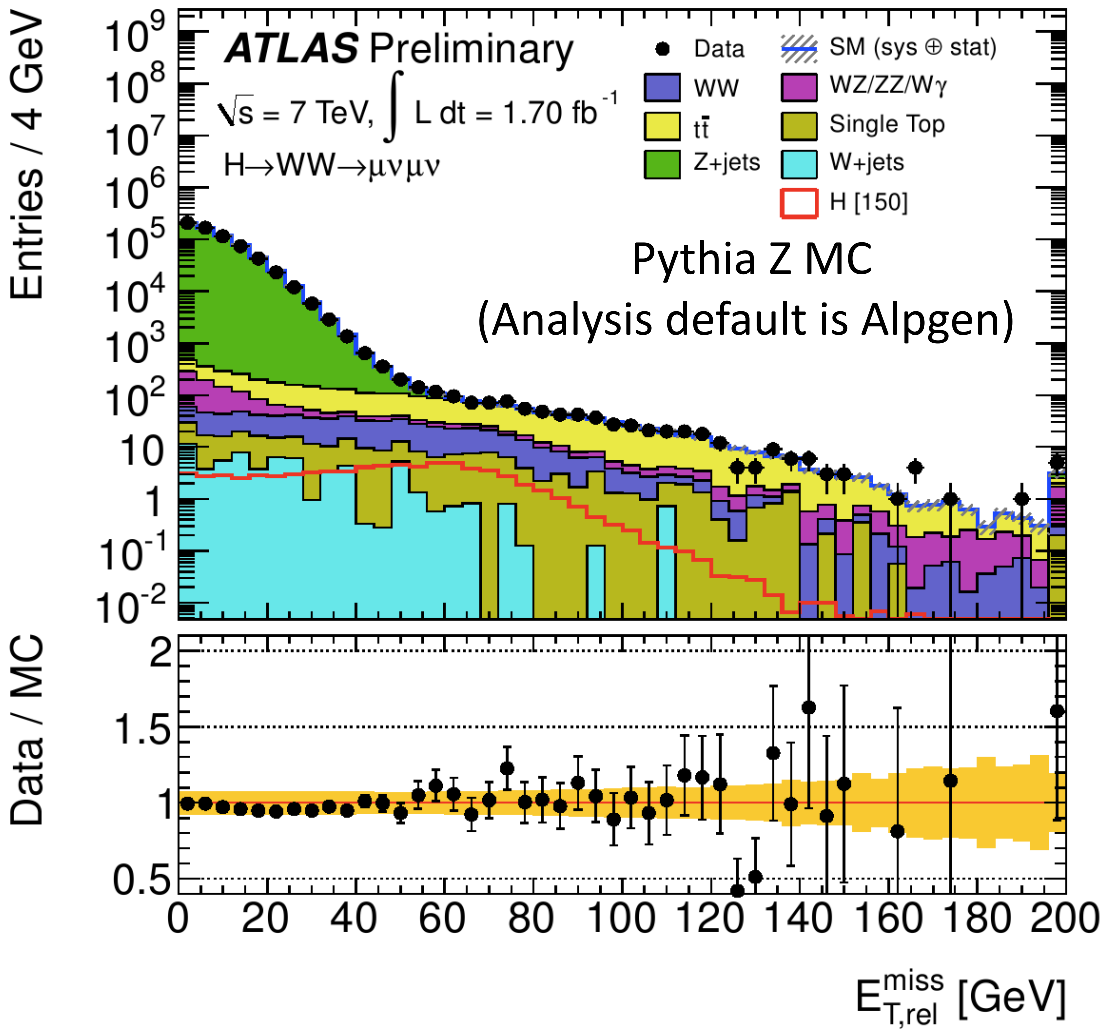
Jets in H→WW→lνqq

- JES uncertainty enters the signal efficiency systematic via
  - Tight cut on the invariant mass of the W→qq candidate (see plot)
  - Missing E_T measurement
- Large JES systematic uncertainty: ≈17%
- Note: the background uncertainty is not a big issue in this analysis, since the background comes from a fit



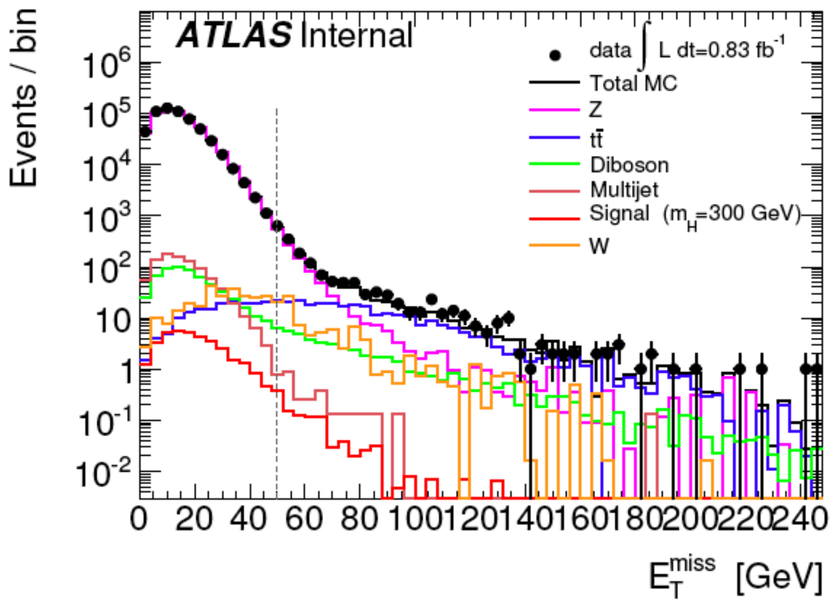
Jets in H→WW→lνlν

- Events are binned in jet multiplicity (H+0j and H+1j), but jets are not used for reconstruction of masses, etc
- Jet uncertainties affect migration between jet bins
- Control samples attempt to mitigate effect of jet systematics on the background estimates
- Jet calibration can affect the MET, and a cut on MET suppresses the Z background by a large factor in this analysis



H -> ZZ -> llqq/llνν

- Two relevant channels: H -> ZZ -> llqq and H -> ZZ -> llνν
- H -> ZZ -> llqq
  - Anti-k_T R=0.4 (EM+JES)
  - p_T^{jet} > 25 GeV
  - $|\eta_{jet}|$< 2.5
  - |JVF| > 0.75
  - E_T^{miss} < 50 GeV
  - Calculation uses **"signal" muons for MET muon term**
  - B-tagging used to create event categories



- H -> ZZ -> llνν
  - Anti-k_T R=0.4 (EM+JES)
  - B-jet event veto
  - p_T^{jet} > 20 GeV (25 GeV for b-tagged jet veto)
  - $|\eta_{jet}|$< 4.5 (2.5 for b-tagged jet veto)
  - E_T^{miss} calculation using only **"signal" muons for MET muon term**
    - Cut threshold depends on Higgs mass hypothesis

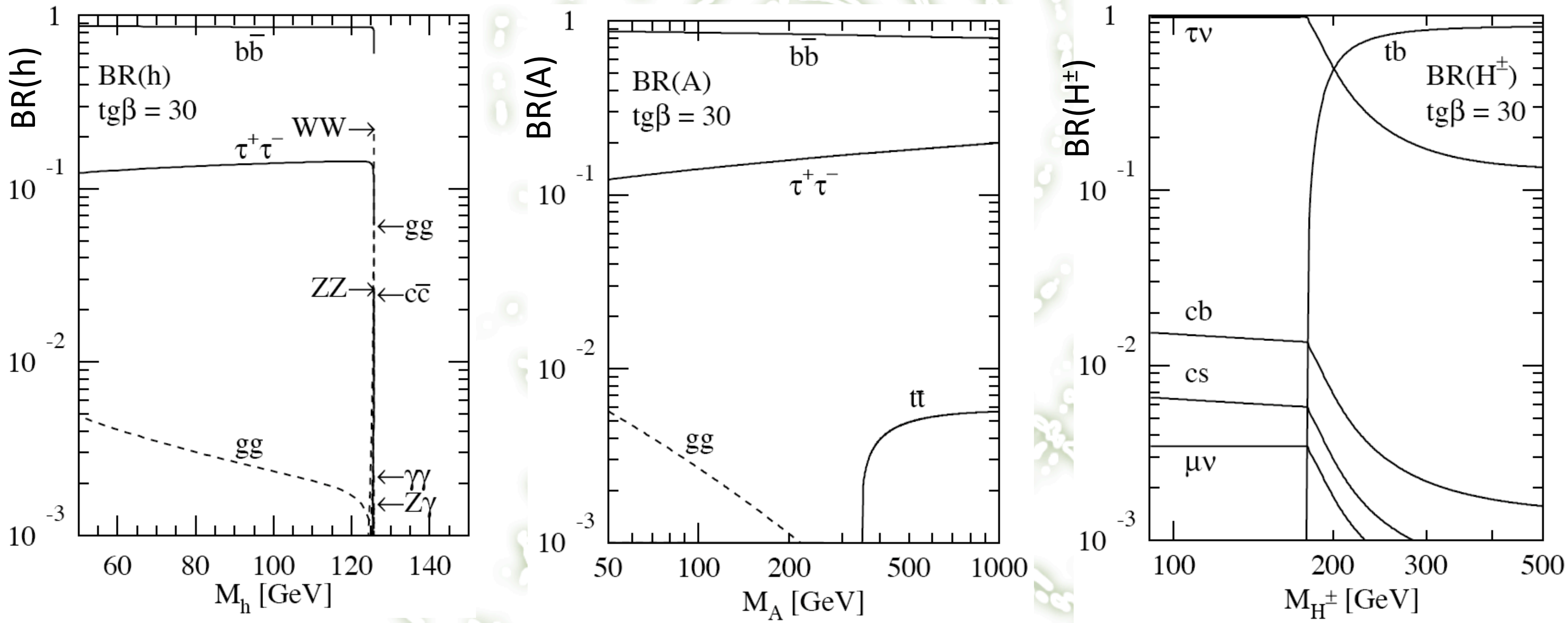
H -> ZZ -> llνν/llqq

Impressions:

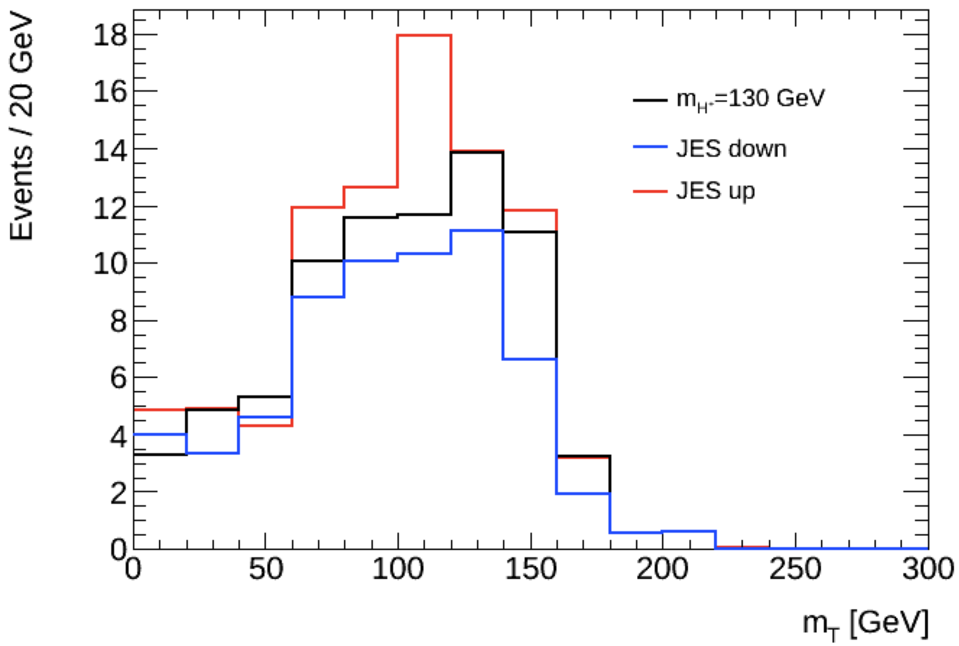
- Pileup:
  - Suppressing pileup is essential
    - See e.g. joint jet-tracking meeting contribution on JVF: ttps://indico.cern.ch/getFile.py/access?subContId=3&contribId=1&resId=0&materialId=slides&confId=147426
- E_T^{miss} reconstruction:
  - Systematic uncertainty recipe seems to overestimate true uncertainty – MC/data agreement much better than estimated uncertainty
  - Moving towards using METRefFinal in this analyses would be welcome (status?)

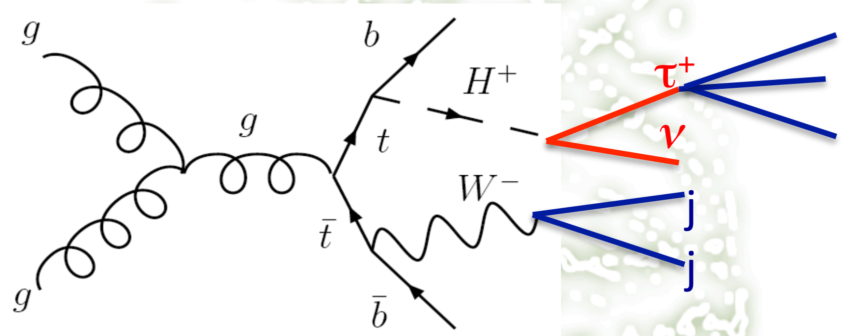
Going beyond the SM Higgs

- In the MSSM, 2 Higgs doublets give 5 physical particles
  - Three neutral: h, H (CP-even), A (CP-odd); two charged: $H^{\pm}$
- Important parameters: m_A, tan β = v1/v2
- As tan β increases, Higgs decays to b quarks and tau leptons enhanced over vector bosons
- Analyses below looking for charged Higgs – clear sign of new physics…



$H^+ \rightarrow \tau_{had}\nu$

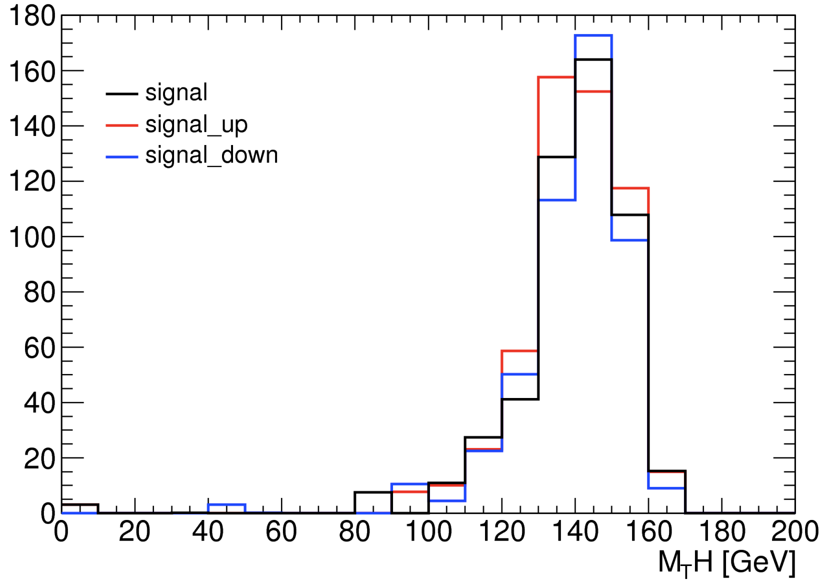


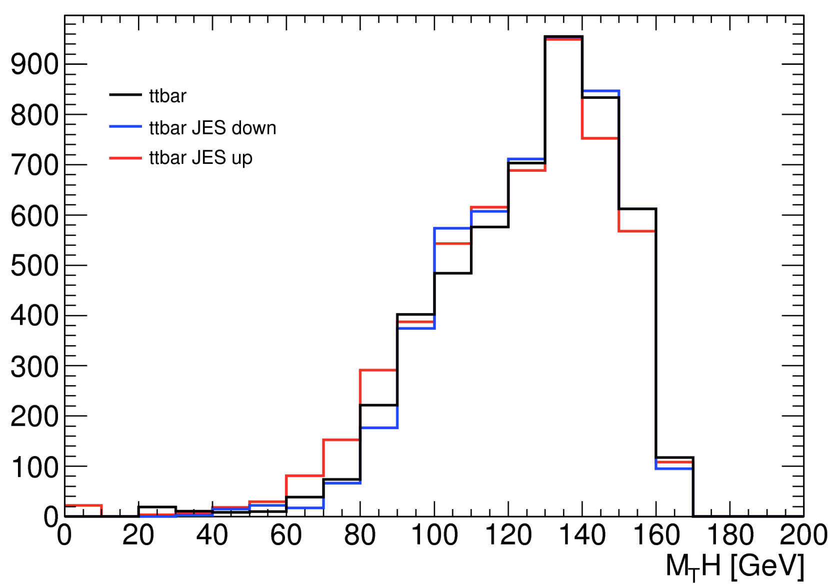


- Production channel: $t\bar{t} \rightarrow bWbH^+ \rightarrow bqq\ b\tau_{had}\nu$
- Final discriminant: transverse mass $m_T(\tau$+MET)
- Jet Energy Scale systematic uncertainty up/down variation
- Shows strong dependence

$H^+ \to \tau_{lep}\nu$ hadronic top channel

- Production channel: $t\bar{t} \to bWbH^+ \to bqq\ b\tau_{lep}\nu$
- Jet Energy Scale systematic uncertainty up/down variation
- Left: **signal** 130 GeV, right: dominant background **ttbar**
- Final discriminant: generalized $m_T(H^+)$





Jet Energy Scale and Jet Resolution

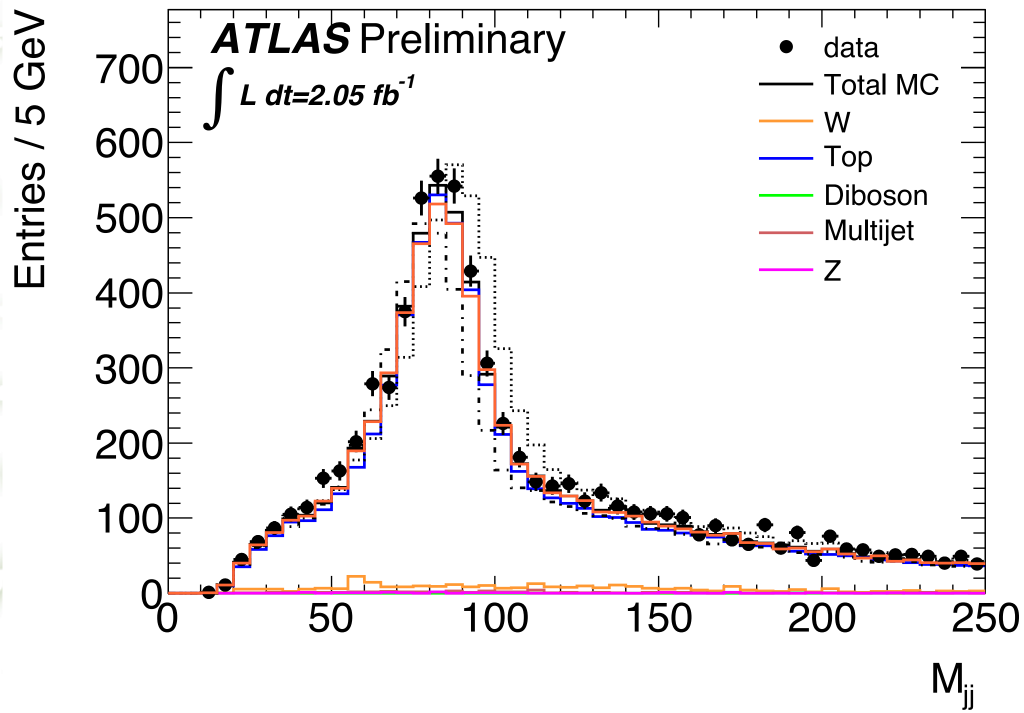
Jet energy scale

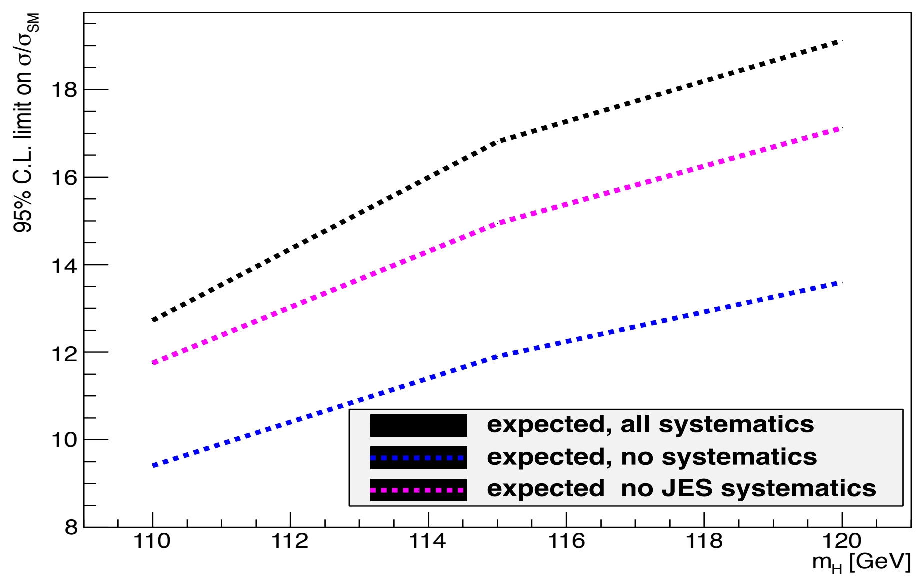
Top:

- mjj for W->jj in top events
- Cuts used: pTjet > 25 GeV, η < 2.5
- The JES uncertainty seems overestimated

Bottom:

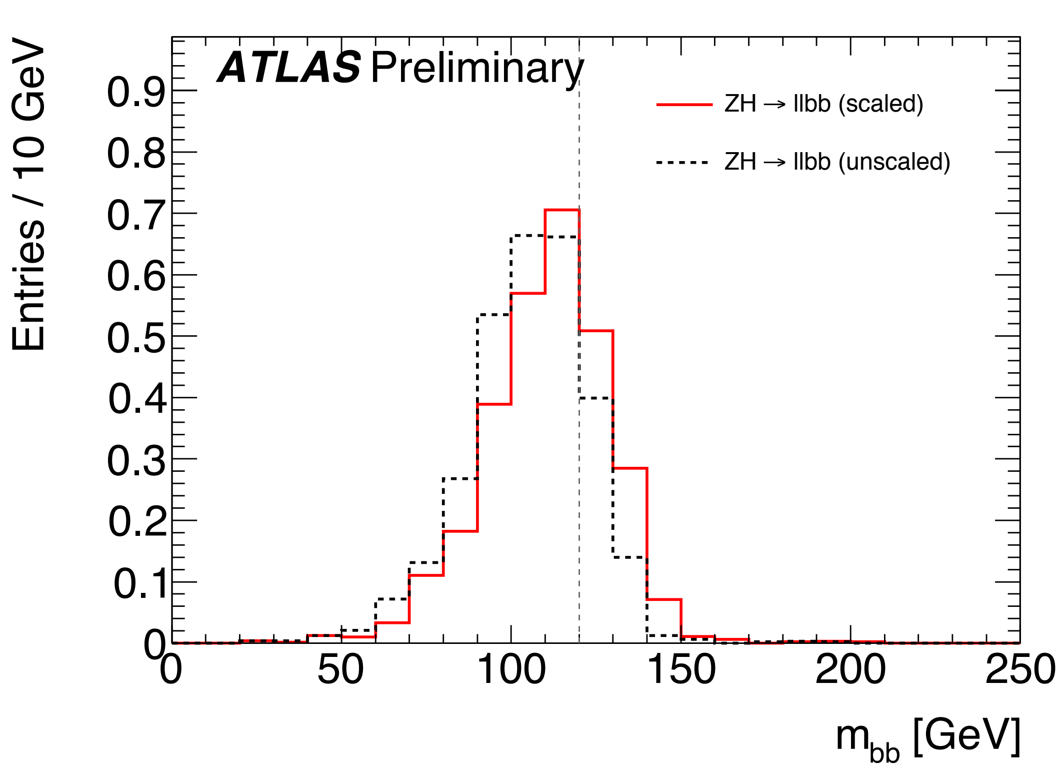
- Effect of JES uncertainty on WH->lvbb analysis expected limit (1fb-1)
- Note CMS quote 1% rather than our ≈7%
- B-tag efficiency systematic is still dominant (≈16%) – can we improve on it?





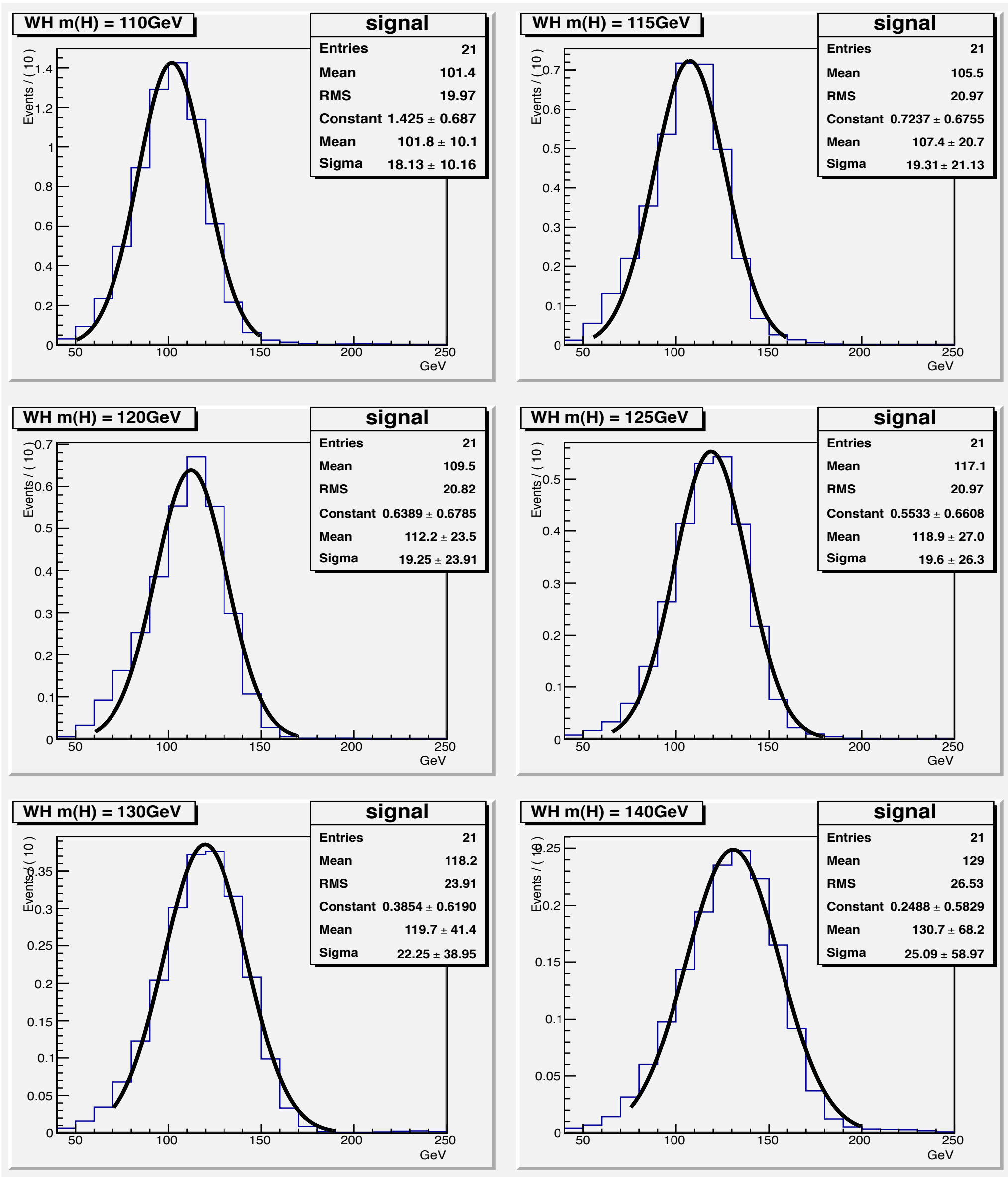
B-jet energy scale

- H->bb Monte Carlo
- Dashed line shows JES-corrected m_{bb} peak
- B-jet energy scale set through p_T-dependent scale factor
- Used in WH/ZH->bb and H->ZZ->llqq analyses
- Not perfect, can still be improved!...



Jet resolution effect on di-jet mass

- Focusing on the WH -> lvbb example
- Very large di-jet mass resolution (≈20GeV)
- Any improvement would lead to better significance



Attempt at conclusions

Missing Energy

- Feeling is it would be good to use METRefFinal
- Major drawback is that it depends on definitions of many objects – muons, electrons, jets
- Not clear How to deal with analysis-dependent object selections
- There's a feeling that the systematic uncertainty is overestimated

Jet reconstruction

- JES systematic uncertainty also seems to be over-estimated
- Can we optimize jets for kinematic region of interest? How?
- CMS uses energy-flow jets – could we benefit from something similar?

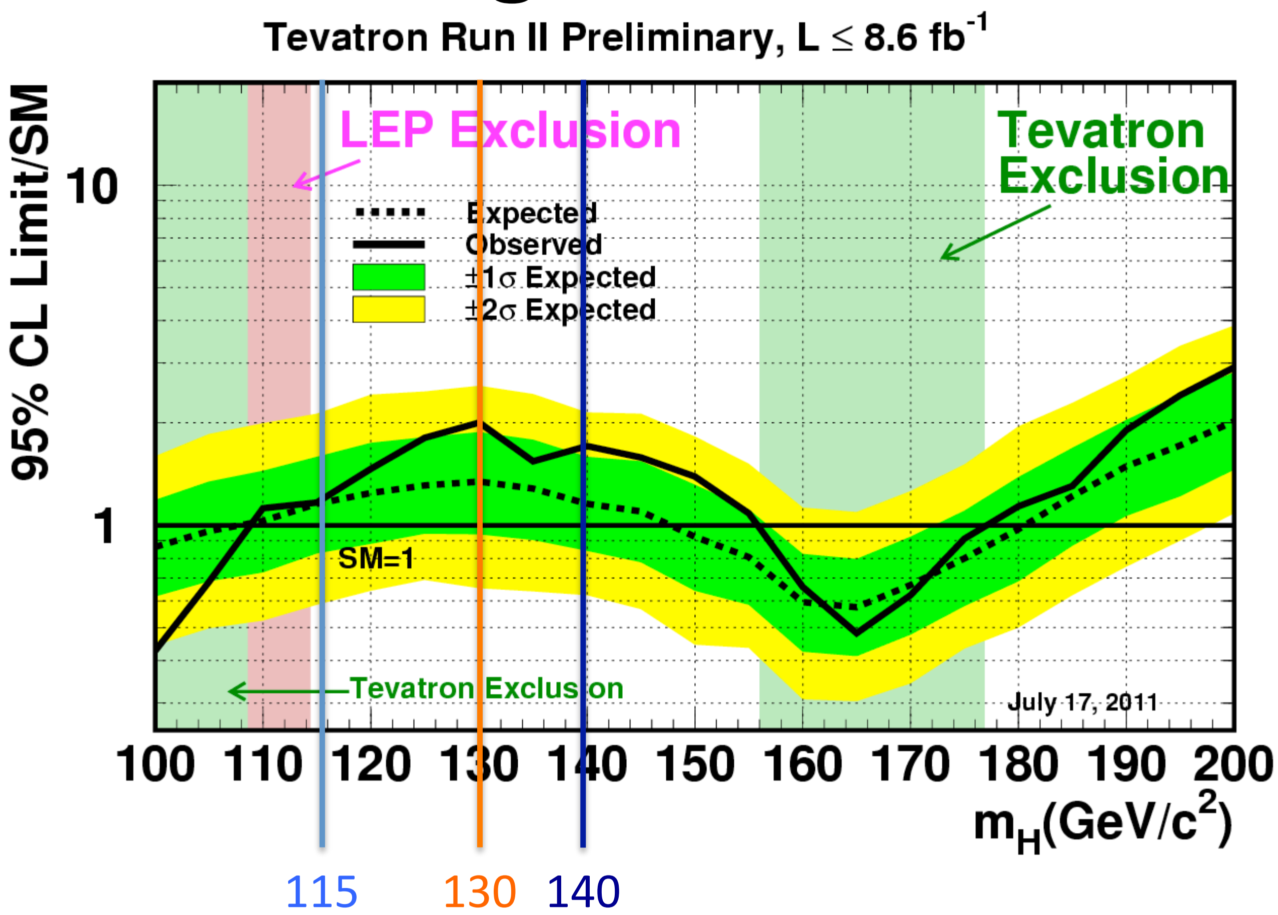
Finally…

- What is clear is that good ATLAS physics can only come from good reconstruction performance! We're all in the same boat!

- … as I said in the beginning, this is not the end of the discussion, just the beginning (the end of the beginning?)

Backup slides

Including the Tevatron…



- ≈115 GeV: CMS and ATLAS see small excess – inconsistent w. Tevatron
- ≈130 GeV: Tevatron and ATLAS see some excess
- ≈140 GeV: Tevatron, CMS and ATLAS see some excess
- Though CMS, ATLAS prefer very small signal (CMS best fit is 0.6*SM)

Backup info for H->γγ

- H->γγ + N jets:
  - See e.g. talk by Taiki Yamamura here: https://indico.cern.ch/conferenceDisplay.py?confId=152120
  - Jet selection:
    - $|\eta_{jet}|<4.5$
    - jet variables (D3PD):
    - AntiKt4TopoEM
    - jet_AntiKt4TopoEM_pt [E,eta,phi]
  - Njet reweighting:
    - MC used is γγ and γj from Alpgen and Pythia
    - See e.g. talk by Olivier Davignon here: https://indico.cern.ch/conferenceDisplay.py?confId=152120

- Initial H->γγ + MET study: https://indico.cern.ch/conferenceDisplay.py?confId=143672

Backup info for H->bb

ZH:

- Trigger:
  - e (p_T^e>20GeV) or μ (p_T^μ>18GeV)
  - 2e/2μ trigger (p_T>12GeV)
- Exactly 2 leptons p_T > 20GeV
  - Opposite charge for μ
- Z mass cut: $76 < m_{ll} < 106$ GeV
- E_T^{miss} < 50GeV
- Two leading jets b tagged

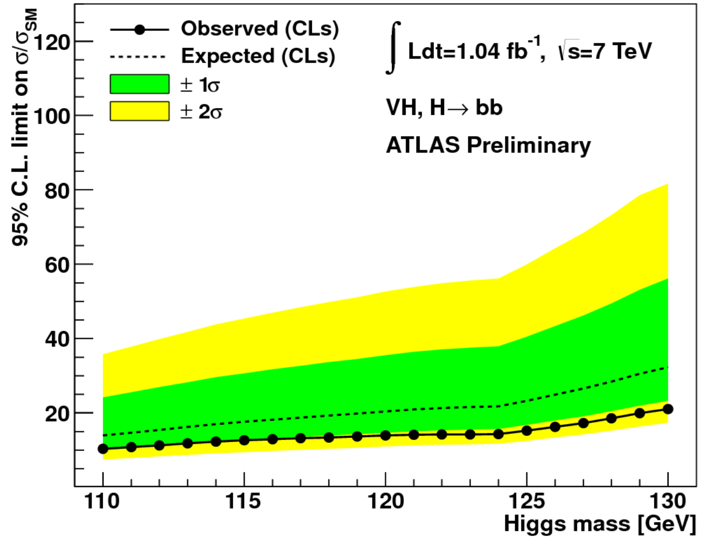
WH:

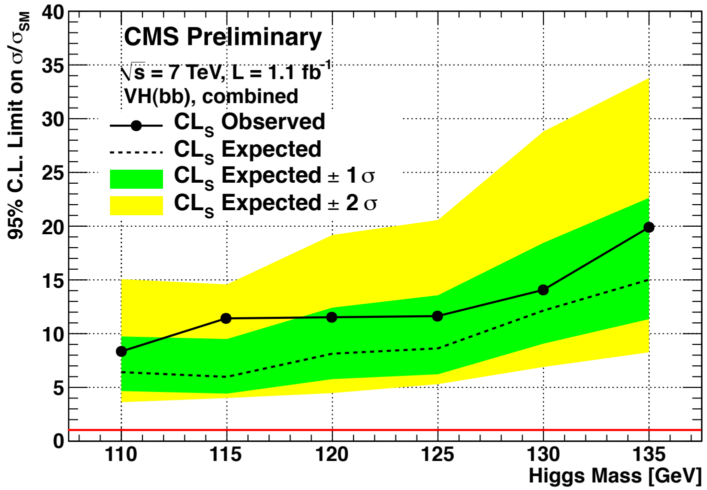
- Trigger: e (p_T^e>20GeV) or μ (p_T^μ>18GeV)
- Exactly 1 lepton – p_T > 25GeV
- $M_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos \Delta\phi_{l\nu})} > 40$ GeV
- E_T^{miss} > 25GeV
- Exactly 2 jets (anti-k_T 0.4; E_T > 25GeV) to reduce top background
- Both jets b tagged

Comparison with CMS H->bb Note

CDS record: http://cdsweb.cern.ch/record/1376636?ln=en

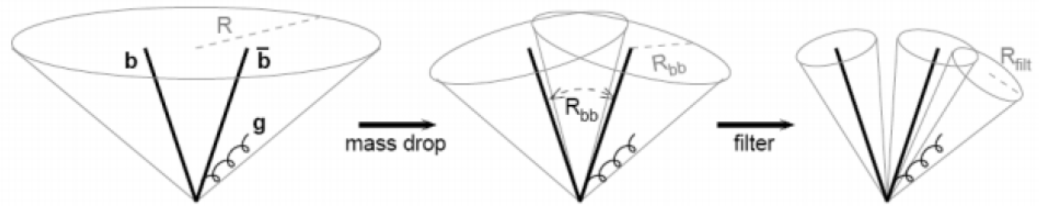
- Subjective impression:
  - Looks as clever as our own analysis but better optimized
- Some different strategic choices:
  - Included ZH->ννbb – best significance channel (S/√(S+B) = 0.25 @ m_H=115GeV)
  - B-jet selection:
    - 1 tight b-jet & 1 loose b-jet
    - Used sum of b-tag weights to select H->bb jet pair (Σp_T^{jet} for WH)
  - Selected a more boosted topology (but no jet substructure analysis):
    - Cut on vector boson and Higgs p_T allows cut on Δϕ(V,H)
  - Used m(H)-dependent m(bb) cuts
  - Used BDT: 10-20% improvement in each channel wrt cut-based
- According to note some significant differences in performance:
  - Better di-jet mass resolution
  - Better JES and b-tagging uncertainties



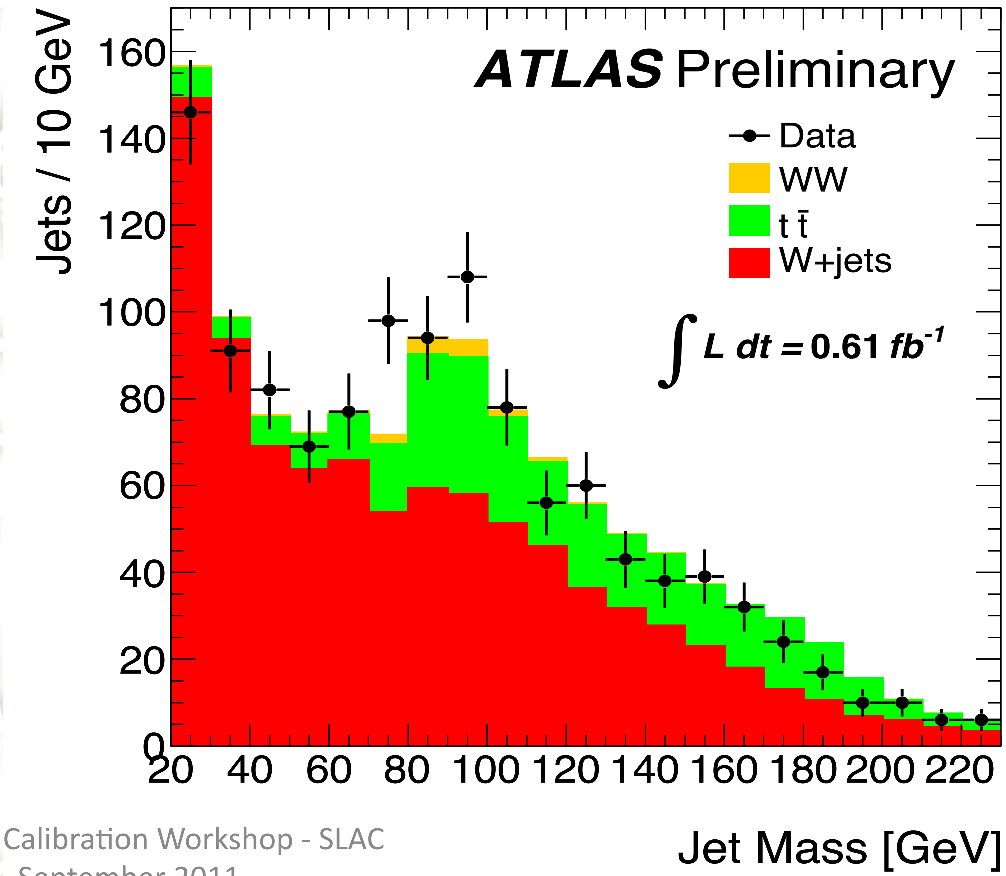


Comparison between CMS' LP2011 results and our EPS2011 CONF note	
Channels	Included ZH->ννbb channel (best significance)
Multivariate	Boosted Decision Tree: ≈ 10 – 20% improvement in each channel
Monte Carlo	Hwg++/Powheg (NLO) for signal; Madgraph for some backgr
Trigger: some work spent optimizing this, esp. e triggers	Used particle flow for MET triggers & ≠ triggers for ≠ run periods WH: mu17, e22_2j30_j25_xe15 Z(ll)H: mu17, e17i_e8i Z(νν)H: j20 OR xe150
Missing energy	Particle-flow based MET and MET significance
Jets	Particle-flow jets: $p_T > 30$ GeV (WH), 20 GeV (llbb), 80/30 GeV (ννbb)
Pileup rejection	JVF-like algorithm plus calo-based algorithm
Leptons	$p_T^{\mu} > 20$GeV, p_T^{e}>20(ZH)/30(WH)
B-tagging	Similar to IP3D+SV1; 1 tight (ε=50%) b-jet & 1 loose (ε=72%) b-jet Used sum of b-tag weights to select H->bb jet pair (Σp_T^{jet} for WH)
Other cuts	Cut on Δφ(V,H) in conjunction with p_T^V and p_T^{bb} (≈ 100-160 GeV) m(bb) window cuts: $m_H \pm 15$ GeV
m(H) reconstruction	Efficiency of m_H window cut (m_H±15GeV) ≈75-80% If normal distr. => 1.2×σ(bb), i.e. σ(bb)≈13 GeV (20GeV for us)
Systematics	Similar except: JES (1%) & of b-tagging (10%) – (9% & 16% for us)

- Alternative to inclusive channels: search for high-pT Higgs to bb:
  - J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, Phys. Rev. Lett. 100 (2008) 242001, arXiv:0802.2470 [hep-ph]
- $p_T^H > 200\text{GeV} \approx 5\%$ of inclusive cross section but improved significance



- Select $W \rightarrow l\nu$ events and search for a $H \rightarrow bb$ jet
  1. Search for high-p_T jet (Cambridge-Aachen algorithm, R=1.2)
  2. Search jet clustering history in reverse and look for large mass drop
  3. Re-cluster with small R parameter to find sub jets



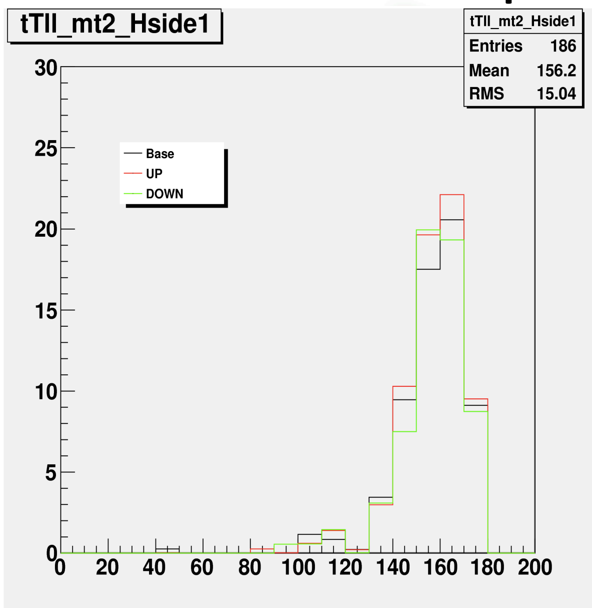
- Peak consistent with $W \rightarrow jj$ in $t\bar{t}$ events
- Proof of principle for future analysis

See talk by Adam Davison next

H->WW backup info

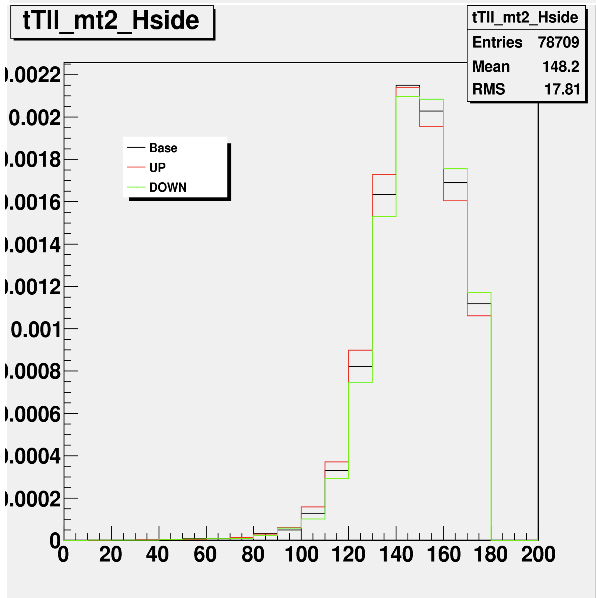
- H->WW->lνqq cuts:
- Leptons:
  - p_T^{lep} > 20 GeV (isolated)
  - $|\eta_{lep}|$< 2.47 (e, excl. crack) / 2.4 (μ)
- Jets & MET:
  - Anti-k_T R=0.4 (calibrated topoclusters, EM+JES)
  - p_T^{jet} > 25 GeV
  - $|\eta_{jet}|$< 4.5
  - E_T^{miss} > 30 GeV
- H→WW→lνqq
  - JES systematic uncertainty important
- H -> WW -> lνlν
  - Jets & E_T^{miss}:
  - Anti-k_T R=0.4 (calibrated topoclusters, EM+JES)
  - Uses B-jet veto
  - Does not use JVF cut in current results – but will use soon)(see Haifeng Li's contribution to JVF session)
  - Uses E_T^{miss} projection ($E_{T,rel}^{miss}$)

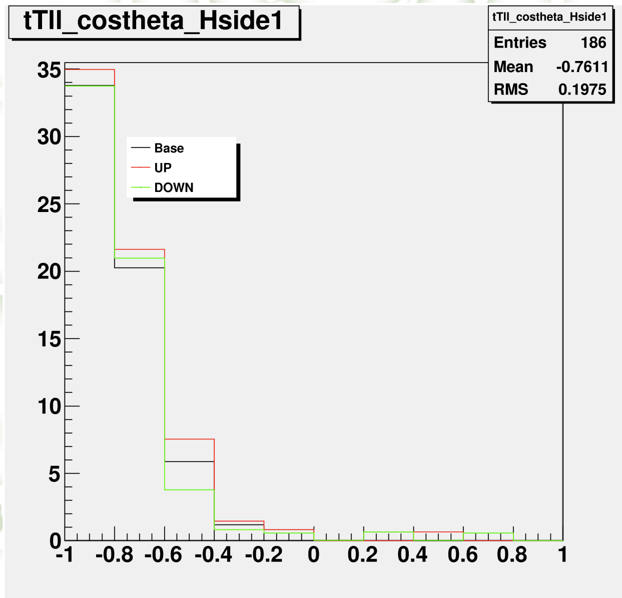
$H^+ \to \tau_{lep}\nu$ semi-leptonic top channel

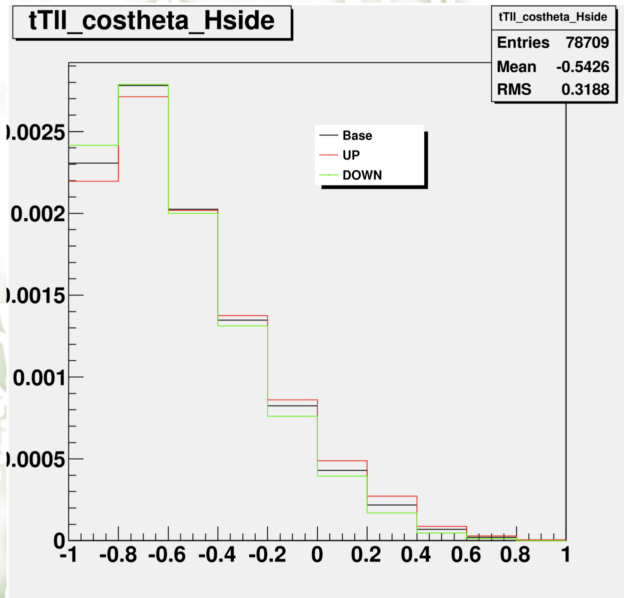


- Production channel: $tt \to bWbH^+ \to bl\nu\ b\tau_{lep}\nu$
- Jet Energy Scale systematic up/down variations
- Left: Final discriminant: generalized mT2(H+)
  - Top: signal 140 GeV; bottom: dominant background ttbar
- Bottom: cos*θ Important discriminating variable, also used for background normalization
  - Center: signal 140 GeV; right: dominant background ttbar

$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{top}^2 - m_W^2} - 1 \simeq \frac{4\, p^b \cdot p^l}{m_{top}^2 - m_W^2} - 1$$





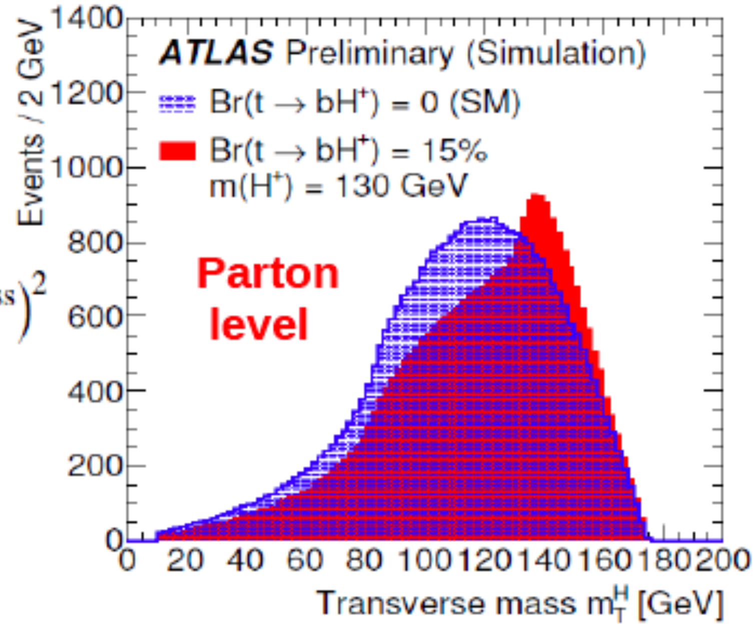


$m_T(H)$

- Novel method for the 3-neutrino-case:
  H+ -> τν with τ->lνν
- Maximize (1 constraint, 2 variables) $(m_T^H)^2 = \max_{\left\{ \substack{p_z^{miss}, E^{miss} \\ (p^{miss}+p^l+p^b)^2 = m_{top}^2} \right\}} [(p^l + p^{miss})^2]$
- Solution:

$$(m_T^H)^2 = \left(\sqrt{m_{top}^2 + (\vec{p}_T^{\,l} + \vec{p}_T^{\,b} + \vec{p}_T^{\,miss})^2} - p_T^b \right)^2 - \left(\vec{p}_T^{\,l} + \vec{p}_T^{\,miss} \right)^2$$

- By construction:
  m(W) <m_T(H)<m(top) [background],
  m(H+)<m_T(H)<m(top) [signal]



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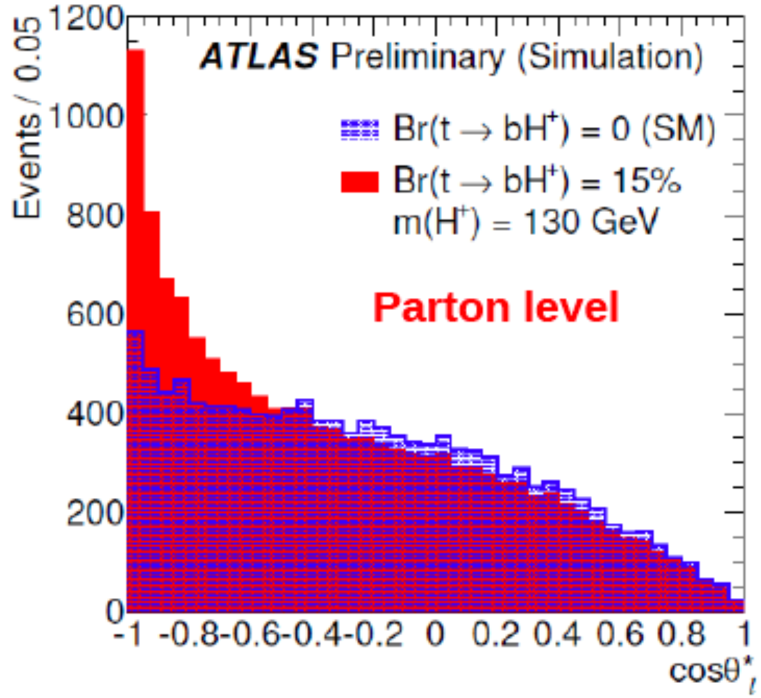
cos θ*

- For W → lν, angle of lepton momentum wrt the helicity axis in the W rest frame:

$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{top}^2 - m_W^2} - 1 \simeq \frac{4\, p^b \cdot p^l}{m_{top}^2 - m_W^2} - 1$$

  - Here, discriminatory power is mostly a mass (H+ vs W) effect
  - Also suppresses direct lepton wrt τ → lνν



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