# ATLAS $t\bar{t}H$, $H\to b\bar{b}$ analysis towards Run-2

朱宏博
中科院高能物理研究所
邮箱：zhuhb@ihep.ac.cn

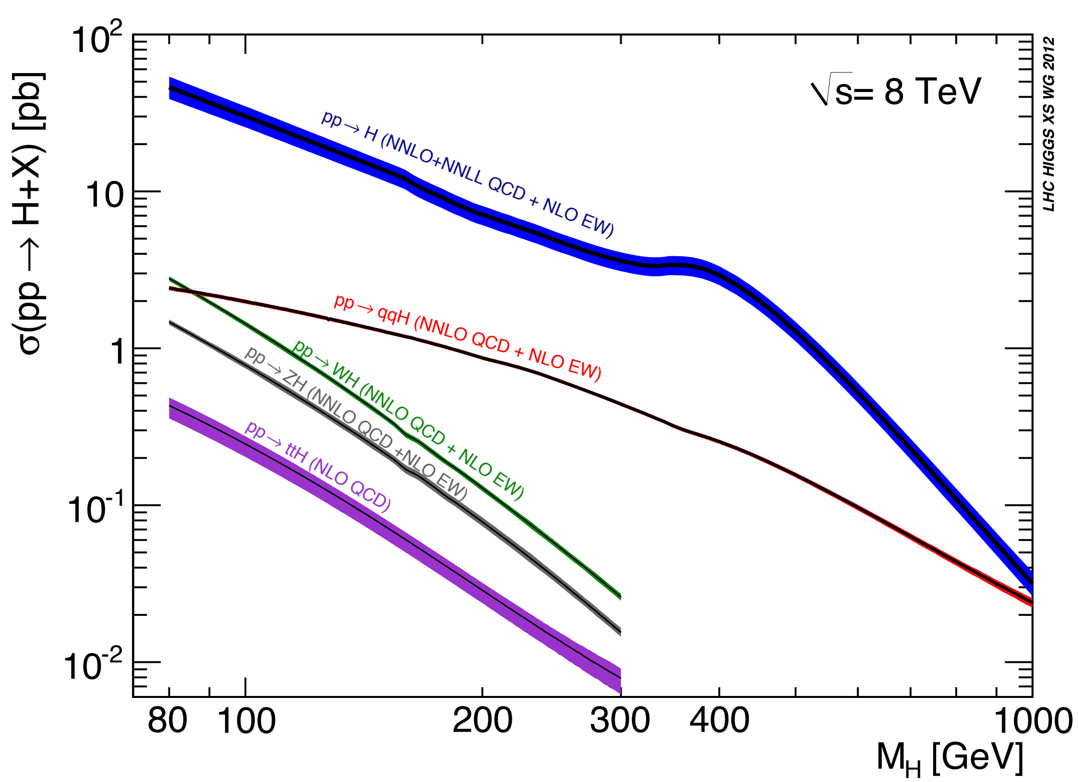
**2014年TeV工作组学术研讨会，5月15-18日，中山大学**

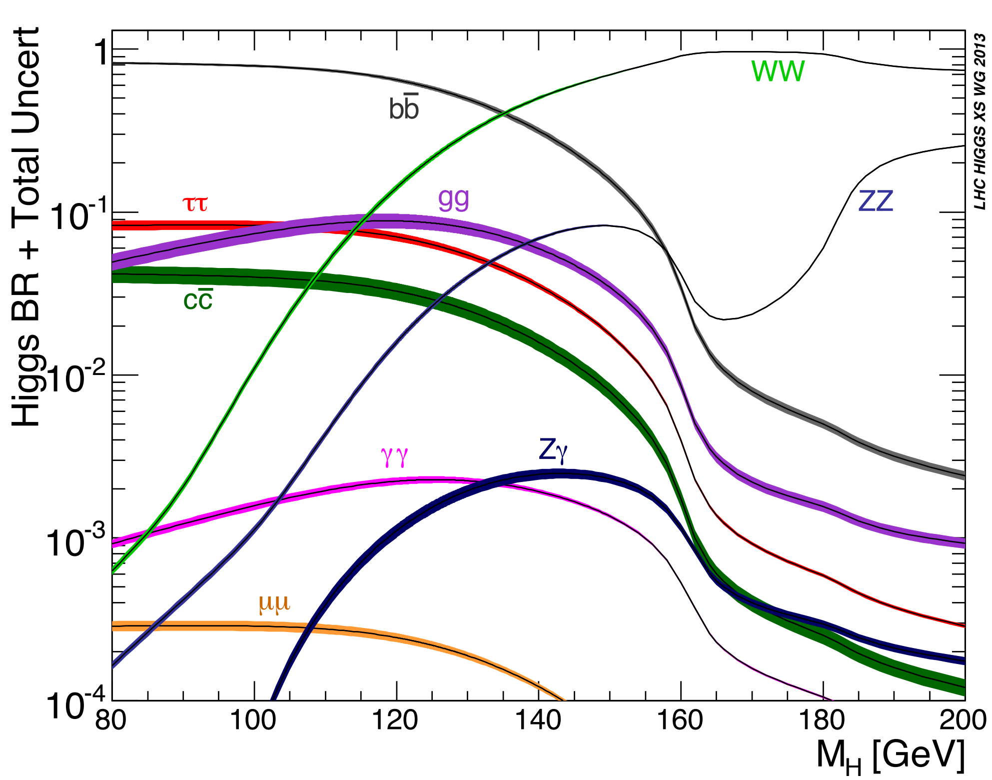
# Outline

- Physics motivation
- Review of current analysis
- Analysis strategy towards Run-2
- Summary

# Physics Motivation

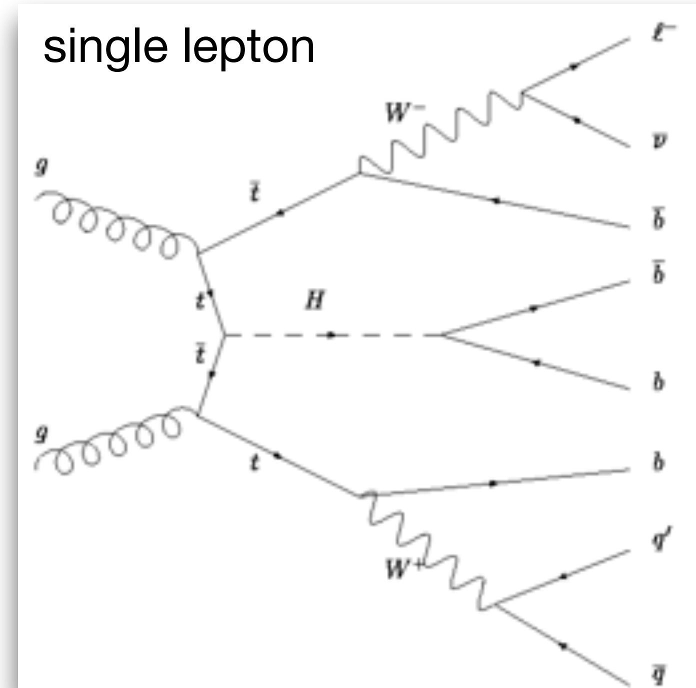
- To observe Higgs production and decay modes in various channels, including $t\bar{t}H$, $H \rightarrow b\bar{b}$ → SM Higgs ?
- Unique opportunity of direct measurement of the top-Higgs Yukawa coupling without making assumptions on possible BSM contributions
- Associated Higgs production ($t\bar{t}H$) to suppress overwhelming QCD multijet background, leaving $t\bar{t}$+jets the dominant background

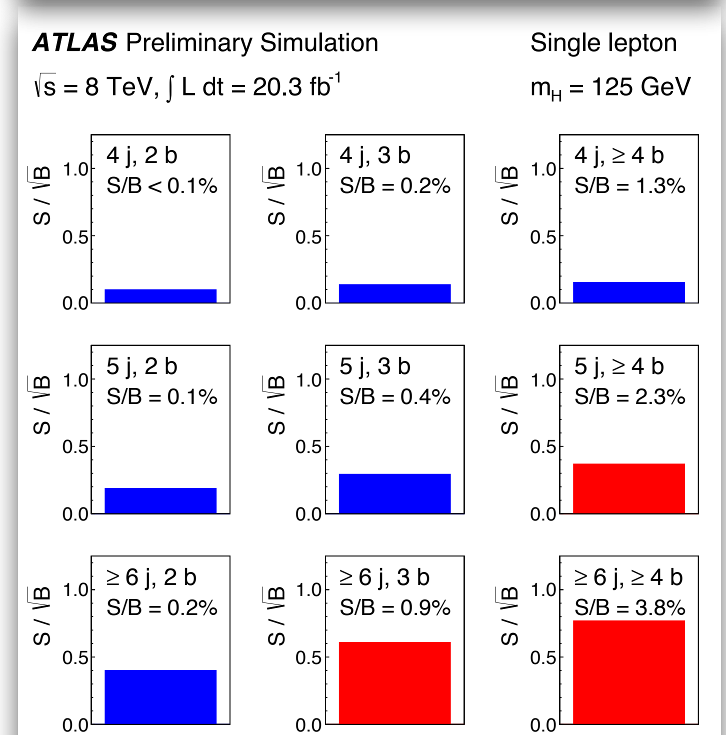


# ATLAS Moriond Analysis

- Signal signature — ATLAS-CONF-2014-011
  - single lepton: 1 lepton (*e*/*μ*), 6 jets (4 *b*-jets)
  - di-lepton: 2 leptons, 4 jets (4 *b*-jets)
- Analysis strategy with 20 $fb^{-1}$ 8 TeV data
  - categorise events in nJets and nBtags; signal-rich regions: (5j, ≥4b), (≥6j, 3b) and (≥6j, ≥6b)
  - simultaneous binned likelihood fit in multiple signal and background regions (Neural Network output and HT, respectively)
  - learn from background regions to limit or constraint effects of systematic uncertainties in the signal regions, e.g. $t\bar{t}$+jets related

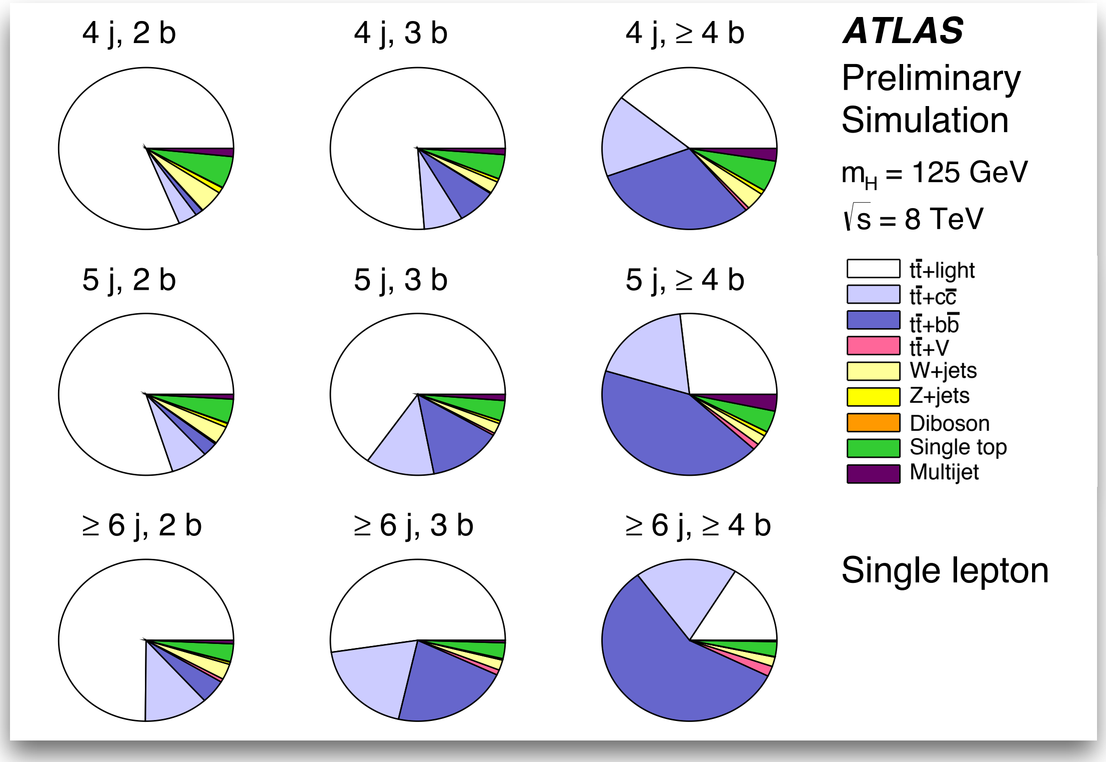


# Signal and Background Modelling

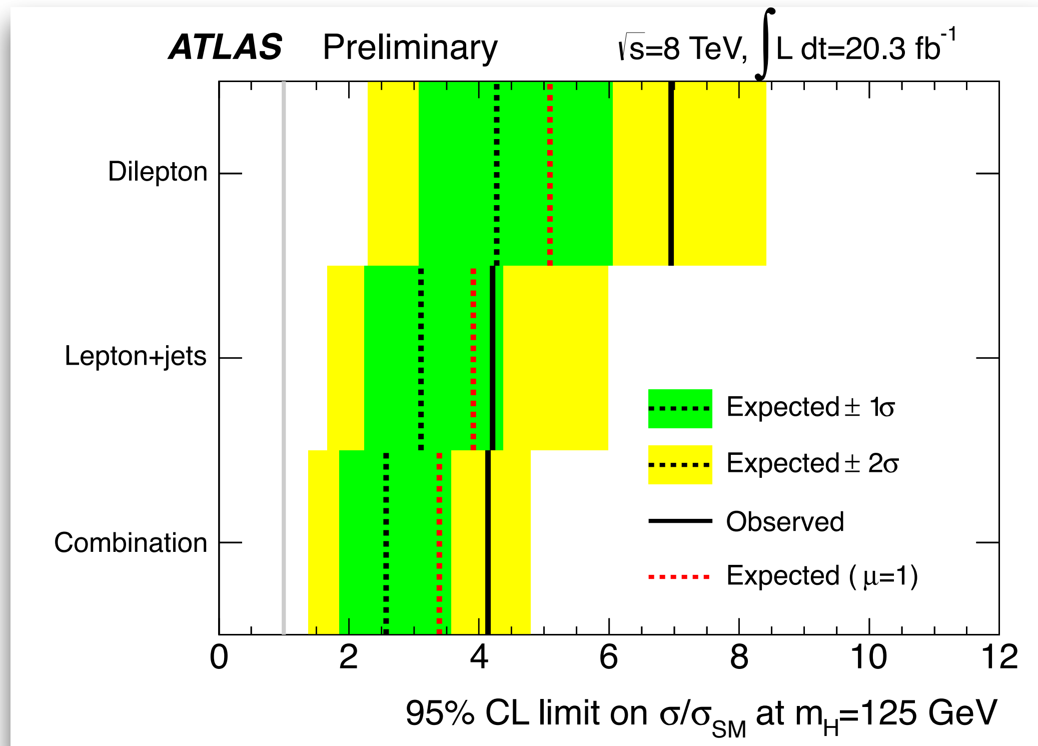
- Signal sample $t\bar{t}H$ generated with PowHel and showered with Pythia 8
- Dominant background sample $t\bar{t}$+jets generated with POWHEG NLO generator and showered with Pythia 6
  - inclusive samples split into $t\bar{t}+b\bar{b}$, $t\bar{t}+c\bar{c}$ and $t\bar{t}$+light jets
  - $t\bar{t}+b\bar{b}/c\bar{c}$ cross-checked with Madgraph 5 (à la CMS)
- Other background samples
  - W/Z+jets, WW/ZZ: Alpgen + Pythia 6
  - QCD multijet: data-driven

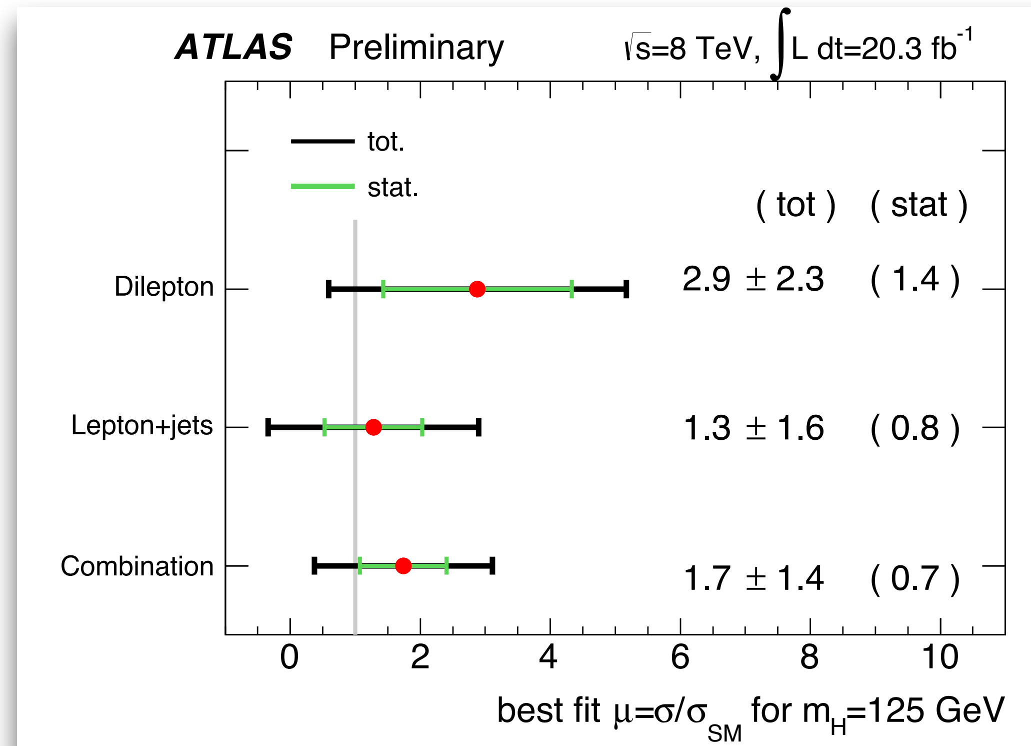
pT re-weighting applied to W+jets and $t\bar{t}$+jets to improve data/MC agreement (motivated by 7 TeV top and W/Z analyses)



# Preliminary Result

ATLAS-CONF-2014-011




- No significant excess; combined upper limits set ($m_H$ = 125 GeV):
  - 4.1 (2.6) × $\sigma/\sigma_{SM}$ for observed (expected), best fit $\mu = 1.7 \pm 1.4$
  - syst. uncert.: $t\bar{t}+b\bar{b}$ modelling, light jet mis-tagging, pT reweighing
- Future improvements towards publication, e.g.
  - new discrimination variables from the Matrix Element calculation

PRL 111, 091802 (2013)

# Analysis towards Run-2

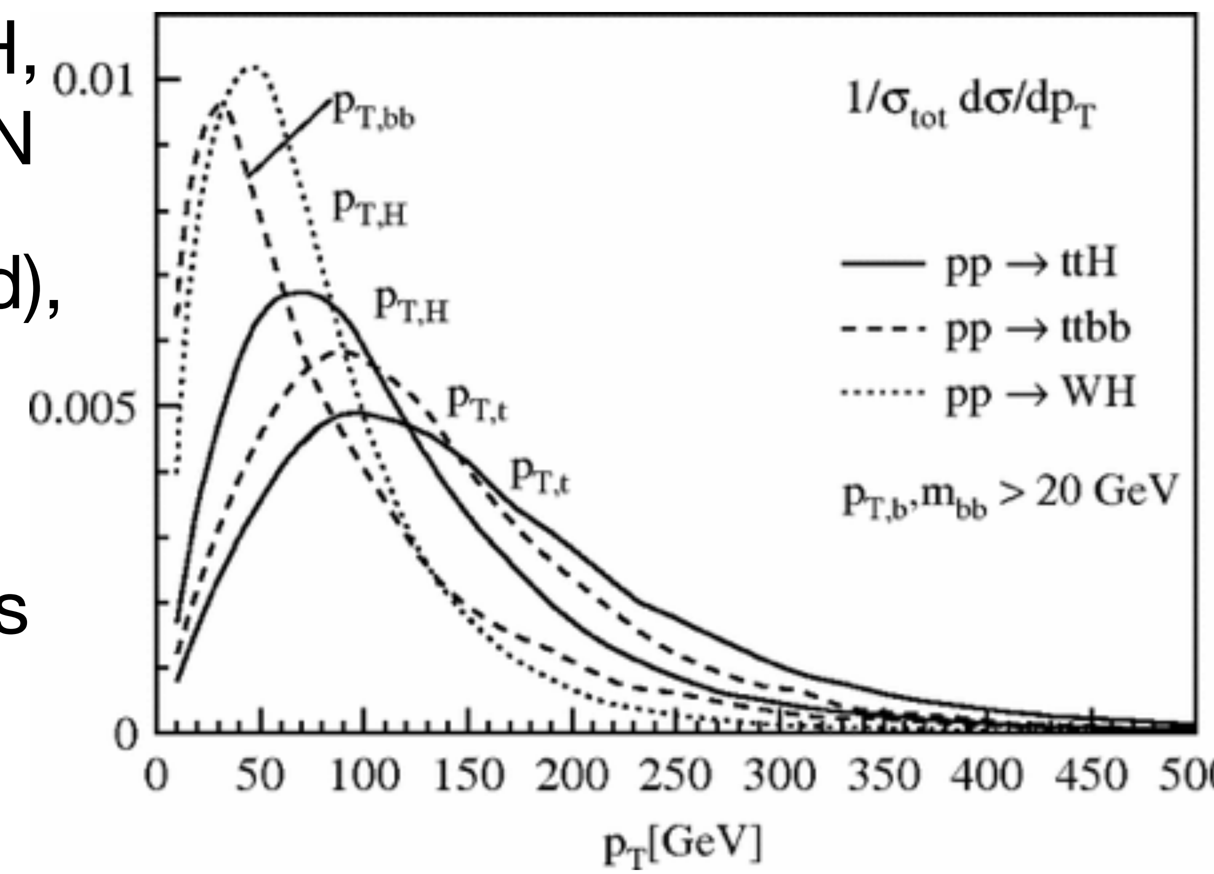
- Raised center-of-mass energy to the design parameter 13/14 TeV
  - $t\bar{t}H$ cross-section increases faster than $t\bar{t}$ + jets → better S/B
  - More boosted objects → challenging but also more handles on reconstruction of final state objects
- Increased integrated luminosity to ~250 $fb^{-1}$
  - to probe rare processes, including $t\bar{t}H$, $H \to b\bar{b}$
- Improved detector performance, in particular the Insertable B-layer (IBL) ← $4^{th}$ pixel detector layer mounted on the beam pipe
  - Enhanced track and vertex reconstruction capability → improved rejection of pileup tracks/vertices; improved b-tagging efficiency for the same light and c-jet rejection rate

↓

**boosted** $t\bar{t}H, H \to bb$

# Boosted $t\bar{t}H$, $H\to b\bar{b}$ Analysis

*Phys. Rev. Lett. 104, 111801*



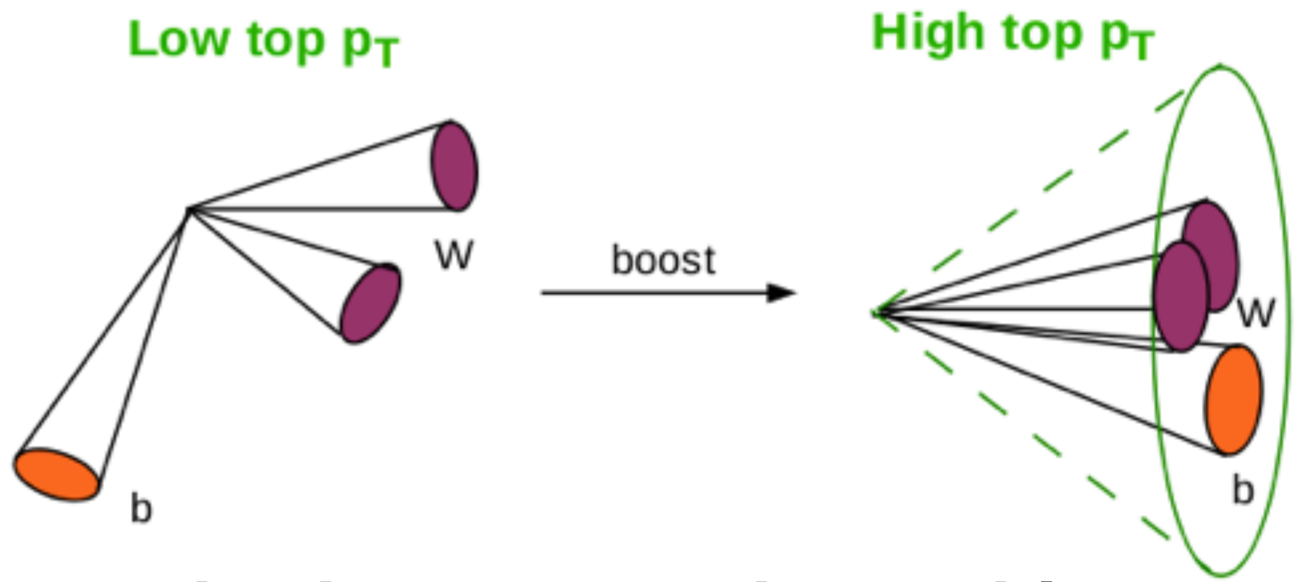

- Harder Higgs and top pT spectra in $t\bar{t}H$, compared to that in $t\bar{t}+b\bar{b}$ → better S/N
- At high enough pT (sufficiently boosted), decay products appear as heavy and collimated jets
- Conventional reconstruction algorithms fail to resolve the individual objects

↓

## Fat jet & jet substructure

- In Higgs searches, first proposed for the search for $VH, H\to b\bar{b}$ [Phys. Rev. Lett. 100, 242001 ], and later $t\bar{t}H$, $H\to b\bar{b}$ [Phys. Rev. Lett. 104, 111801]
- To tag both top and Higgs Fat jets in the $t\bar{t}H$, $H\to b\bar{b}$ analysis

# Jet Substructure



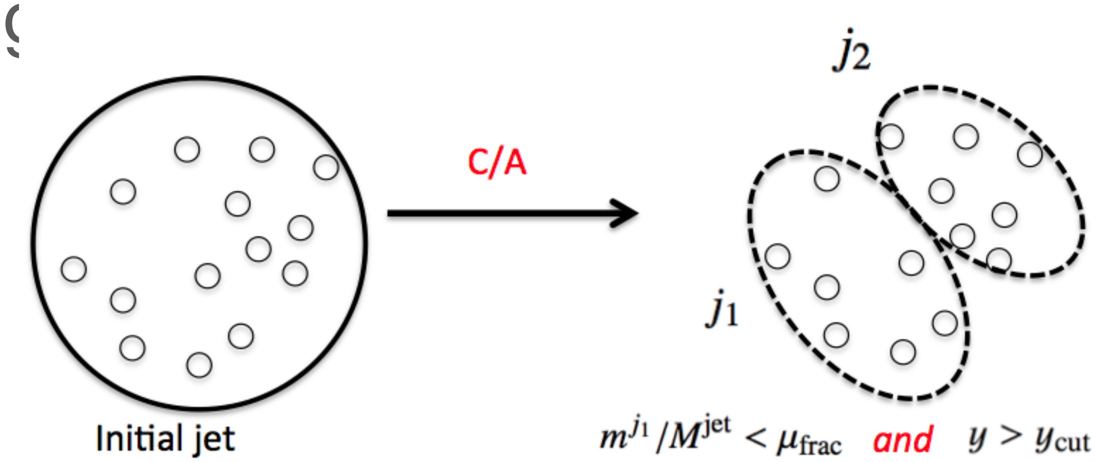

- **Jet properties and substructure observables**, to distinguish fat jets formed by products from boosted heavy particles from those originating from QCD light quarks
  - Jet mass, kt splitting scales, N-subjettiness …
- **Jet grooming algorithms**, to minimise impact of pileup and underlying events
  - mass-drop filtering, trimming and pruning
- Systematic studies with 7 TeV data published in JHEP09(2013)076

# Mass Drop Filtering

- Designed to identify relatively symmetric subjects, each with significantly smaller mass, e.g. $H \to b\bar{b}$.
  - Mass-drop and symmetry: split the C/A jet into two subjets (reverse the jet clustering algorithm), requiring

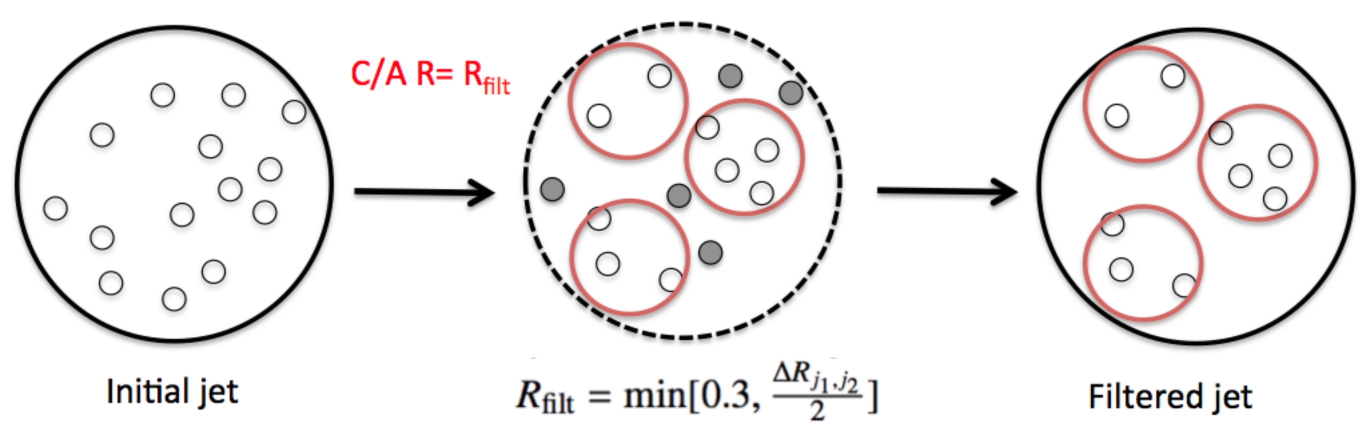
$$\max[m^{j1}, m^{j2}]/m^{\mathrm{jet}} < \mu_{\mathrm{frac}}$$

$$\frac{\min[(p_T^{j1})^2, (p_T^{j2})^2]}{(m^{\mathrm{jet}})^2} \times \Delta R^2_{j1,j2} > y_{\mathrm{cut}}$$



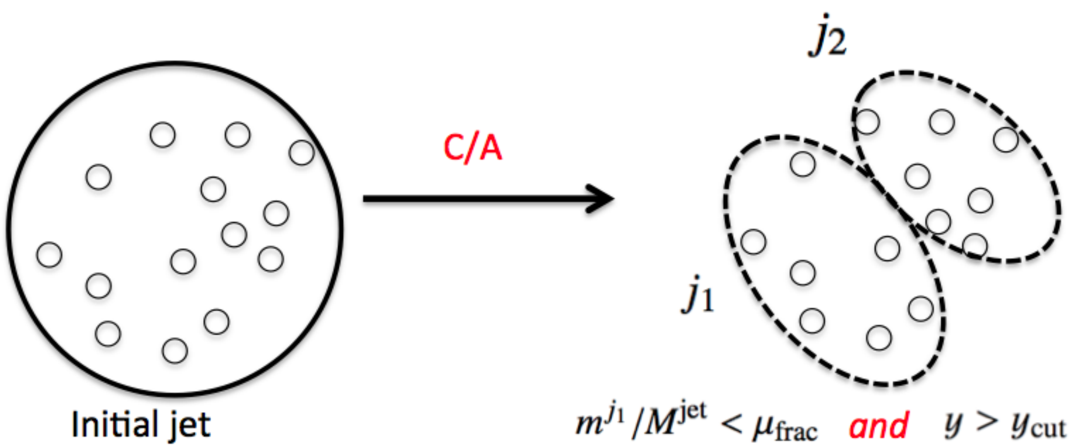

  - Filtering: recluster three hardes

$$R_{\mathrm{filt}} = \min[0.3, \Delta R_{j1,j2}/2]$$



# Mass-drop Filtering

- Designed to identify relatively symmetric subjects, each with significantly smaller mass, e.g. $H \rightarrow b\bar{b}$.




**Mass-drop and symmetry:** split the large-*R* C/A jet into two subjets (reverse the jet clustering algorithm), requiring

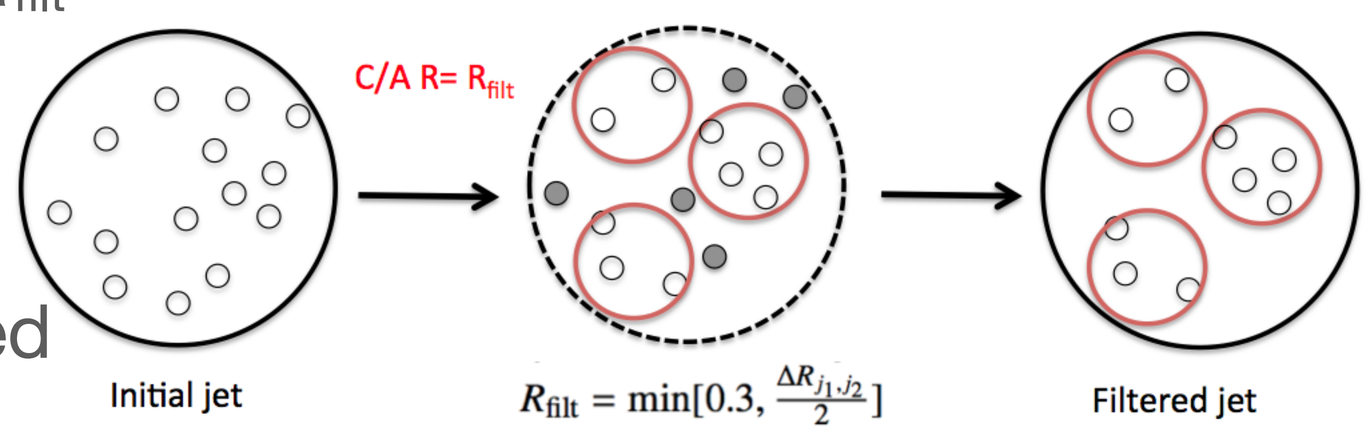
$$\max[m^{j1}, m^{j2}]/m^{\rm jet} < \mu_{\rm frac}$$

$$\frac{\min[(p_T^{j1})^2, (p_T^{j2})^2]}{(m^{\rm jet})^2} \times \Delta R^2_{j1,j2} > y_{\rm cut}$$

**Filtering:** reconstruct three hardest subjets using the radius parameter $R_{\rm filt}$

$$R_{\rm filt} = \min[0.3, \Delta R_{j1,j2}/2]$$

soft constituents (pileup …) discarded



# Other Tagging Techniques

- Shower deconstruction
  - construct likelihood based on subjets variables in shower history
  - Phys. Rev. D 84, 074002, Phys. Rev. D 87, 054012, ATLAS-CONF-2014-003
- Buckets (JHEP02(2014)130) and Template Overlap method (Phys. Rev. D 85, 114046, JHEP07(2013)114)
  - new ideas, not yet fully explored with data

Explore the proposed techniques and find out the most suitable for top and Higgs tagging

# Other Ingredients

- Subjet *b*-tagging
  - b-tagging of the subjects provide extra information but non-trivial
  - to utilise the full power of the tracking system (IBL!) and improve reconstruction algorithms to achieve the best performance
- Lepton isolation
  - lepton isolation critical in such busy environment
  - mini-isolation with variable cone size ΔR=KT/pT (already adopted for several 7/8 TeV analyses)
- Top background
  - Important to advance our understanding the top related background, in particular $t\bar{t}+b\bar{b}/t\bar{t}+c\bar{c}$
  - Better to measure them directly

# Summary

- Reviewed the ATLAS $t\bar{t}H$, $H\rightarrow b\bar{b}$ analysis with 8 TeV data
- Presented the analysis strategy of boosted $t\bar{t}H$, $H\rightarrow b\bar{b}$ towards Run-2 and selected jet substructure techniques
- The result from the boosted $t\bar{t}H$, $H\rightarrow b\bar{b}$ will be eventually combined with that from the resolved analysis, not mentioned though, to achieve higher sensitivity.
- Joint efforts, among both home and overseas participants (e.g. IHEP & SJTU), on certain topics are being pursued. **JOIN US** if you are interested.

**DATA** will tell us more …

# Backup

# Discrimination Variables

| Variable | Definition |
|---|---|
| Centrality | Sum of the $p_{\mathrm{T}}$ divided by sum of the $E$ for all jets and the lepton |
| H1 | Second Fox-Wolfram moment computed using all jets and the lepton |
| $m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$ | Mass of the combination of two $b$-tagged jets with the smallest $\Delta R$ |
| $N_{40}^{\mathrm{jet}}$ | Number of jets with $p_{\mathrm{T}} \geq 40$ GeV |
| $\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$ | Average $\Delta R$ for all $b$-tagged jet pairs |
| $m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$ | Mass of the combination of any two jets with the largest vector sum $p_{\mathrm{T}}$ |
| $\mathrm{Aplanarity}_{\mathrm{b-jet}}$ | $1.5\lambda_2$, where $\lambda_2$ is the second eigenvalue of the momentum tensor built with only $b$-tagged jets |
| $H_{\mathrm{T}}^{\mathrm{had}}$ | Scalar sum of jet $p_{\mathrm{T}}$ |
| $m_{\mathrm{jj}}^{\mathrm{min}\ \Delta\mathrm{R}}$ | Mass of the combination of any two jets with the smallest $\Delta R$ |
| $\Delta R_{\mathrm{lep-bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$ | $\Delta R$ between the lepton and the combination of two $b$-tagged jets with the smallest $\Delta R$ |
| $m_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$ | Mass of the combination of a $b$-tagged jet and any jet with the smallest $\Delta R$ |
| $m_{\mathrm{bj}}^{\mathrm{max}\ p_{\mathrm{T}}}$ | Mass of the combination of a $b$-tagged jet and any jet with the largest vector sum $p_{\mathrm{T}}$ |
| $m_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$ | Mass of the combination of two untagged jets with the smallest $\Delta R$ |
| $p_{\mathrm{T}}^{\mathrm{jet5}}$ | Fifth leading jet $p_{\mathrm{T}}$ |
| $\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$ | $\Delta R$ between two $b$-tagged jets with the largest vector sum $p_{\mathrm{T}}$ |
| $m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$ | Mass of the combination of two $b$-tagged jets with the largest invariant mass |
| $p_{T,\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$ | Scalar sum of the $p_{\mathrm{T}}$'s of the pair of untagged jets with the smallest $\Delta R$ |
| $m_{\mathrm{jjj}}$ | Mass of the jet triplet with the largest vector sum $p_{\mathrm{T}}$ |
| $\Delta R_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$ | Minimum $\Delta R$ between two untagged jets |
| $m_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$ | Mass of the combination of two $b$-tagged jets with the largest vector sum $p_{\mathrm{T}}$ |

Table 4: List of variables used in the NN in the single lepton channel in at least one region. From the list, 10 variables are chosen in each region.

# Ranking of the Variables

| Variable | ($\geq$ 6j, $\geq$ 4b) | ($\geq$ 6j, 3b) | (5j, $\geq$ 4b) | (5j, 3b) |
|---|---|---|---|---|
| $\Delta R_{bb}^{avg}$ | 1 | 5 | 5 | - |
| $m_{bb}^{min\ \Delta R}$ | 2 | 9 | 3 | 1 |
| Centrality | 3 | 2 | 1 | - |
| H1 | 4 | 3 | 2 | - |
| $p_T^{jet5}$ | 5 | 8 | - | - |
| $\text{Aplanarity}_{b-jet}$ | 6 | - | 7 | - |
| $m_{uu}^{min\ \Delta R}$ | 7 | 7 | - | 2 |
| $\Delta R_{bb}^{max\ p_T}$ | 8 | - | - | - |
| $\Delta R_{lep-bb}^{min\ \Delta R}$ | 9 | 10 | 10 | - |
| $m_{bj}^{max\ p_T}$ | 10 | 6 | - | - |
| $N_{40}^{jet}$ | - | 1 | 4 | - |
| $m_{bj}^{min\ \Delta R}$ | - | 4 | - | - |
| $m_{jj}^{max\ p_T}$ | - | - | 6 | - |
| $H_T^{had}$ | - | - | 8 | - |
| $m_{jj}^{min\ \Delta R}$ | - | - | 9 | - |
| $m_{bb}^{max\ m}$ | - | - | - | 3 |
| $p_{T,uu}^{min\ \Delta R}$ | - | - | - | 4 |
| $m_{jjj}$ | - | - | - | 5 |
| $\Delta R_{uu}^{min\ \Delta R}$ | - | - | - | 6 |
| $m_{bb}^{max\ p_T}$ | - | - | - | 7 |