Extracting Top-Yukawa Coupling from $t\bar{t}$ cross-section using ATLAS data

DESY Zeuthen Particle Physics Mini-Retreat

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Supriya Sinha

On the behalf of the top-Yukawa coupling analysis team

Klaus Mönig, Thorsten Kuhl, Evgeniya Cheremushkina, Oliver Majersky, (Sadia Marium, Lukas Roscher)

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

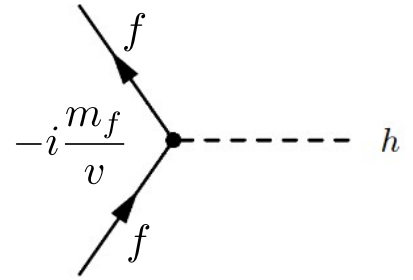
ATLAS EXPERIMENT

DESY.

Motivation

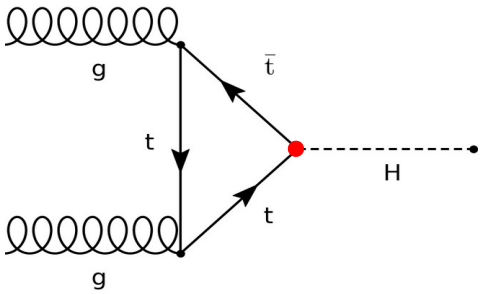
- Yukawa interaction: between the fundamental fermion fields and Higgs field
- Coupling strength α mass of fermions
  → top quark mass ~ 173 GeV => largest Yukawa coupling (Y_t)
- Deviation of measured top-Yukawa coupling from SM prediction
  → new phenomena beyond the SM

$$\mathcal{L}_{Yuk} = -\Sigma_f \left(m_f + \frac{m_f}{v} H \right) \bar{\psi}_f \psi_f + \ldots$$



Indirect:

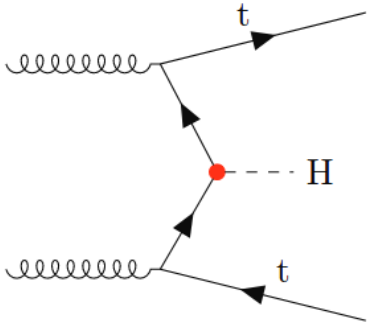
gluon-gluon fusion (loop diagram; H → γγ)



EPJ Web Conf. Volume 182, 2018

Direct:

ttH production



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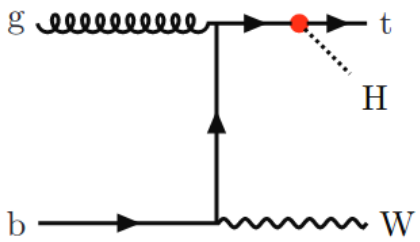
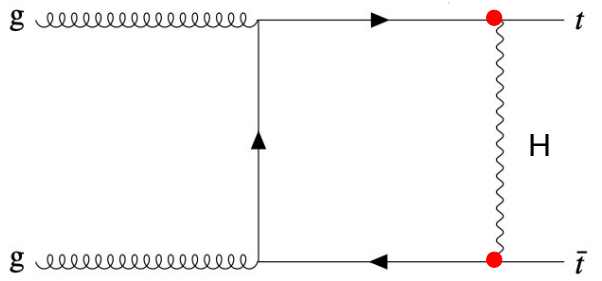
tH production



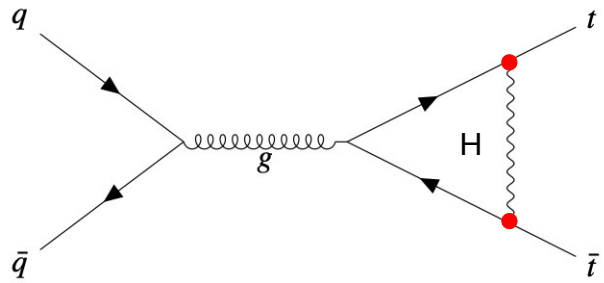
ATL-PHYS-PROC-2017-251

Threshold scan approach

- Measure Y_t mostly independent of Higgs coupling to other particles
- $t\bar{t}$ pair production: virtual Higgs exchange



Majority of events: gg

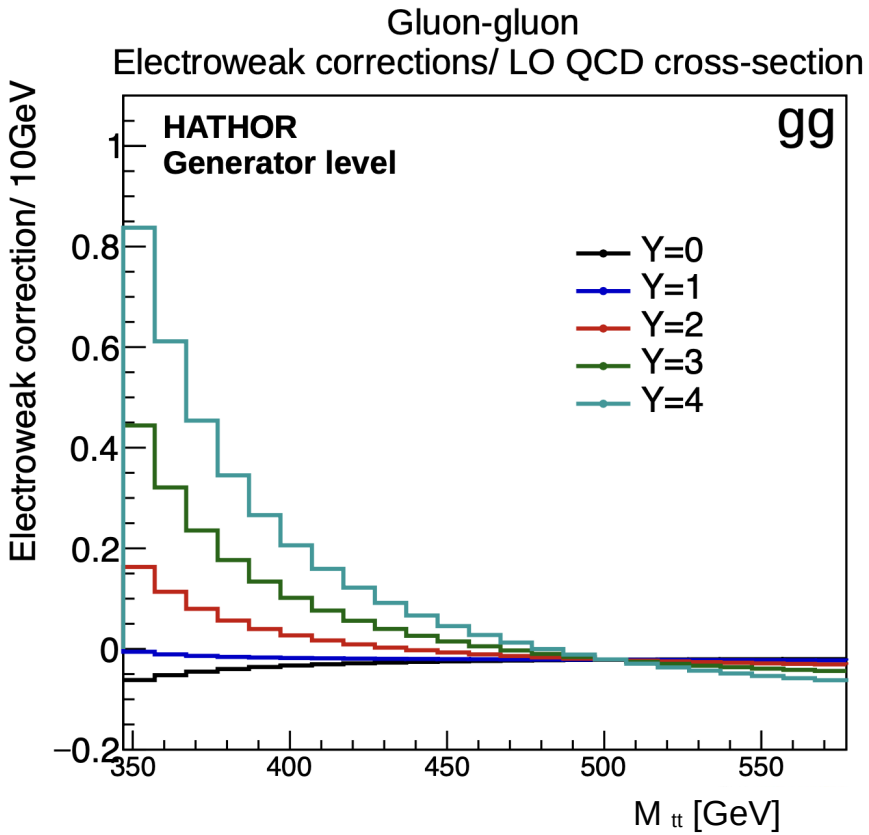


Electroweak force starts entering the cross-section at loop-induced order, α_{weak}, i.e., Y_t^2

(from Higgs contribution)

- At $t\bar{t}$ production threshold: $t\bar{t}$ cross-section sensitive to Y_t (through weak-force mediated corrections)
- How big are these Electroweak corrections? How much are the shapes of kinematic distributions affected?

Ratio of electroweak force corrections over the LO QCD production cross-section at generator level



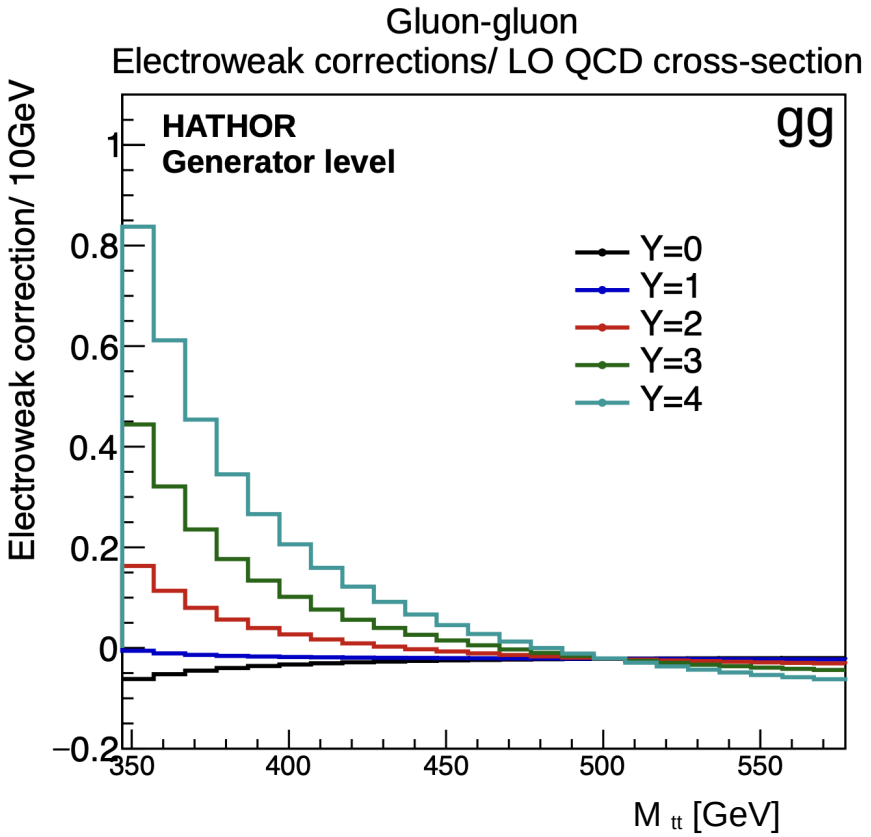
HATHOR

HAdronic Top & Heavy quarks crOss section calculatoR

- Program for the fast calculation of inclusive cross sections for the production of top quarks in hadron-hadron scattering
- Sub-package inside HATHOR 2.1-b3

  → calculates electroweak corrections corresponding to the Born level cross-section for different Y_t values

Webpage:https://www.physik.uni-hamburg.de/en/th2/ag-moch/hathor.html



Reweighting using HATHOR 2.1-b3

Performing fits to the corrections and analyzing Y_t sensitivity

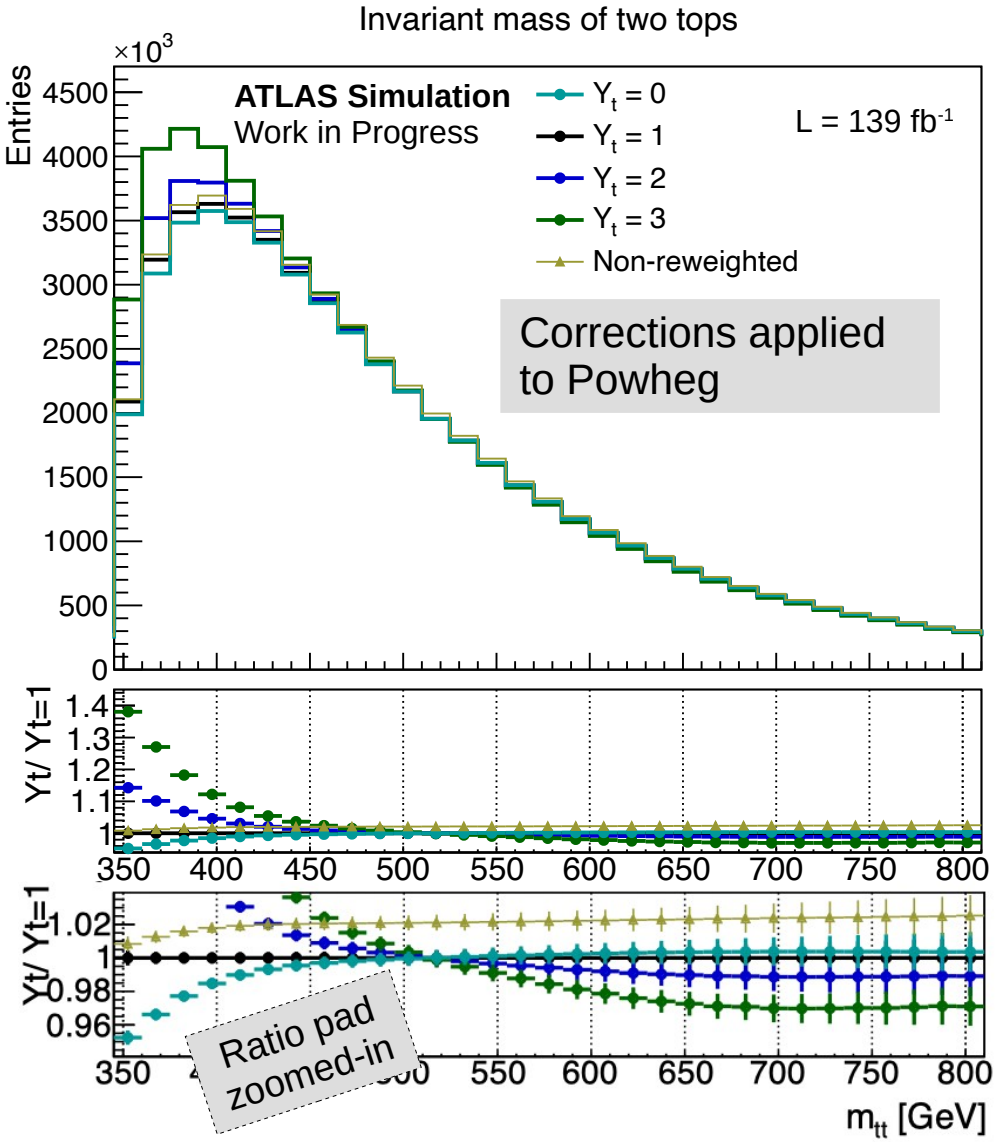
- Multiplicative approach in including electroweak corrections (considering differential cross-section):

$$\sigma_{\mathrm{POWHEG\times EW}} = (\mathrm{EW\ correction\ factor}) \times \sigma_{\mathrm{POWHEG}}$$

- Fit electroweak corrections as functions of cosθ*, Y_t, and m_{tt}
- The dependence on Y_t given as:

$$a(y_t), b(y_t), c(y_t) = a_y + c_y . y_t^2$$

  - The possible linear term comes out to be extremely small



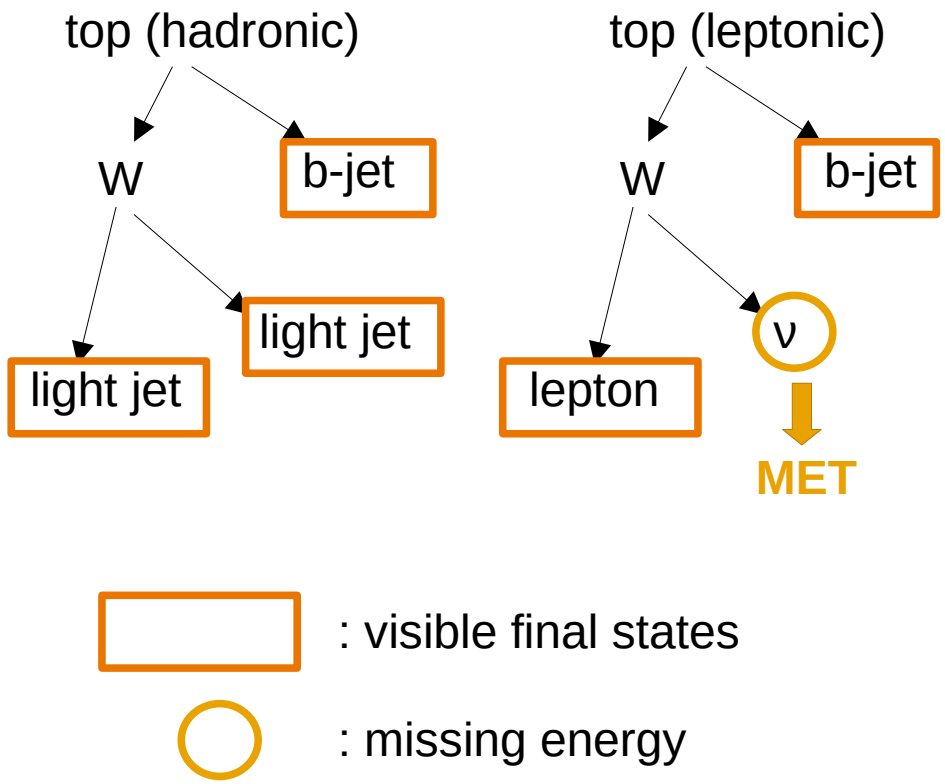
Selection criteria

Reconstruction level

- Number of jets ≥ 4: p_T > 25 GeV; |η| < 2.5
- Number of b-jets ≥ 2: DL1r 77% working point
- Leptons:
  - Electron: MET > 30 GeV; M_W^T > 30 GeV

    p_T > 27 GeV; |η| < 2.47 (excluding 1.37 ≤ |η| ≤ 1.52)
  - Muon: MET + M_W^T > 60 GeV

    p_T > 27 GeV; |η| < 2.5
- Exactly one electron/muon in the final state

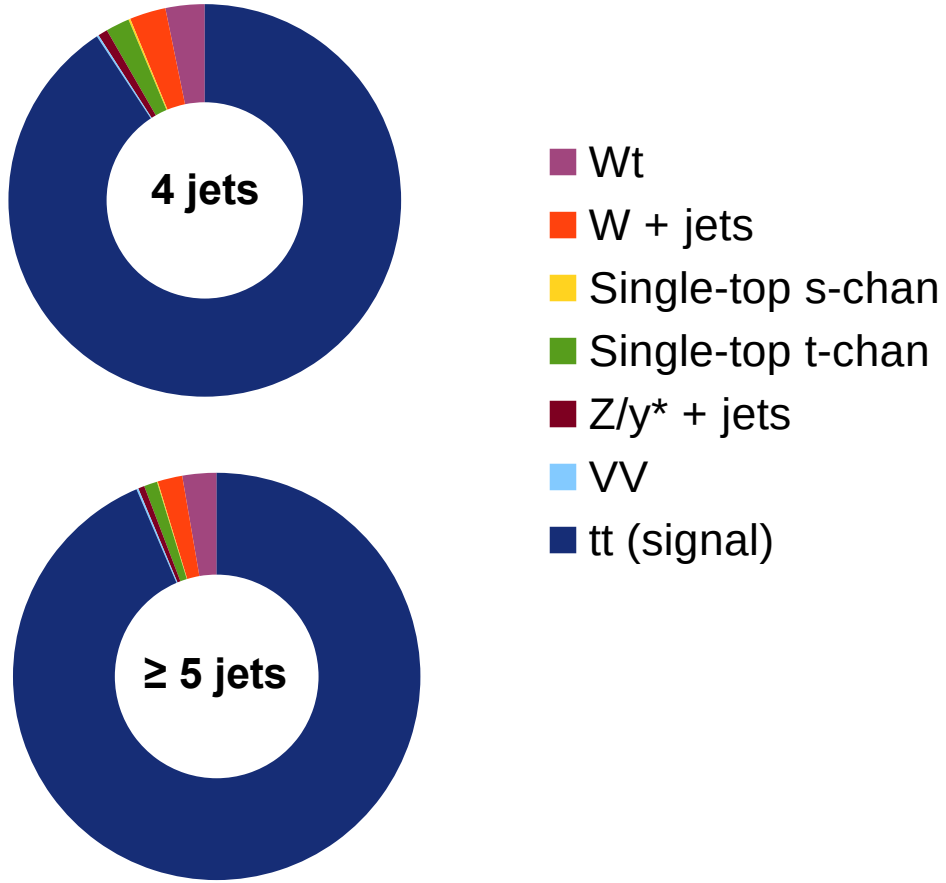


Data/ MC comparison

After general event selection (errors: statistical + systematic)

- The dominant background is : *Wt*, followed by *W* + jets and single-top s- and t- channel
- QCD background estimation in progress

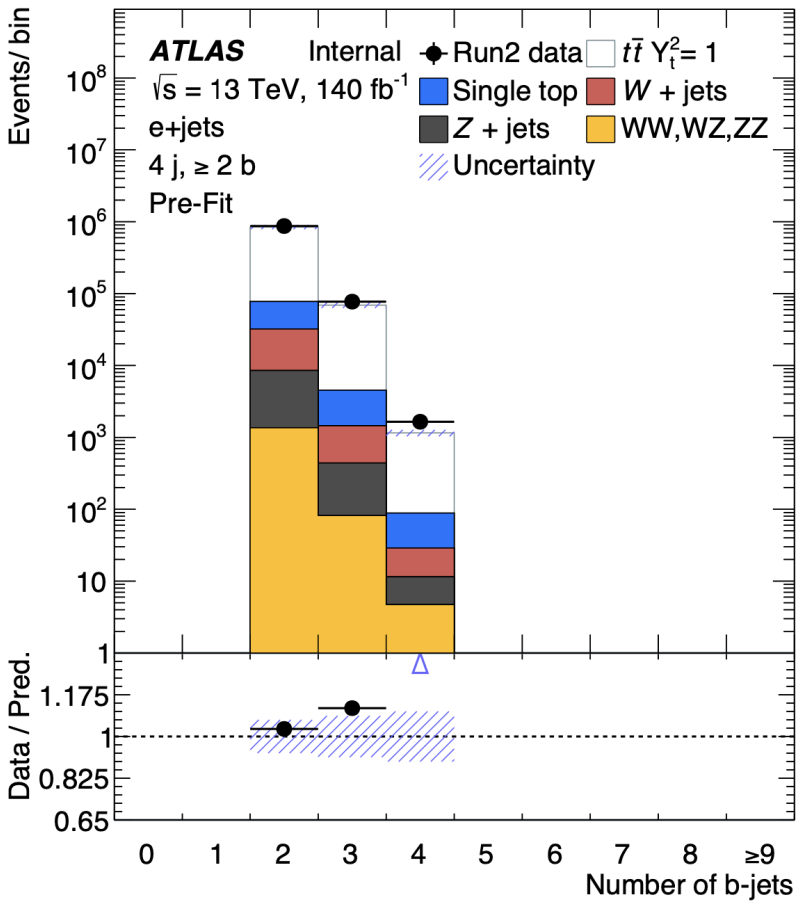
Process	All leptons (electron and muon both)	
Selection	**= 4j, ≥ 2b**	**≥ 5j, ≥ 2b**
Wt	65590 ± 5830	56440 ± 13060
W + jets	60730 ± 6220	40900 ± 5200
Single-top s-chan	3130 ± 220	1400 ± 160
Single-top t-chan	39780 ± 2980	21850 ± 2310
Z/y* + jets	16080 ± 1710	10380 ± 1430
VV	3330 ± 220	3160 ± 290
tt (signal)	**1848170 ± 133000**	**1947920 ± 182800**
total	**2036830 ± 139100**	**2082060 ± 194000**
data	**2175210**	**2234920**

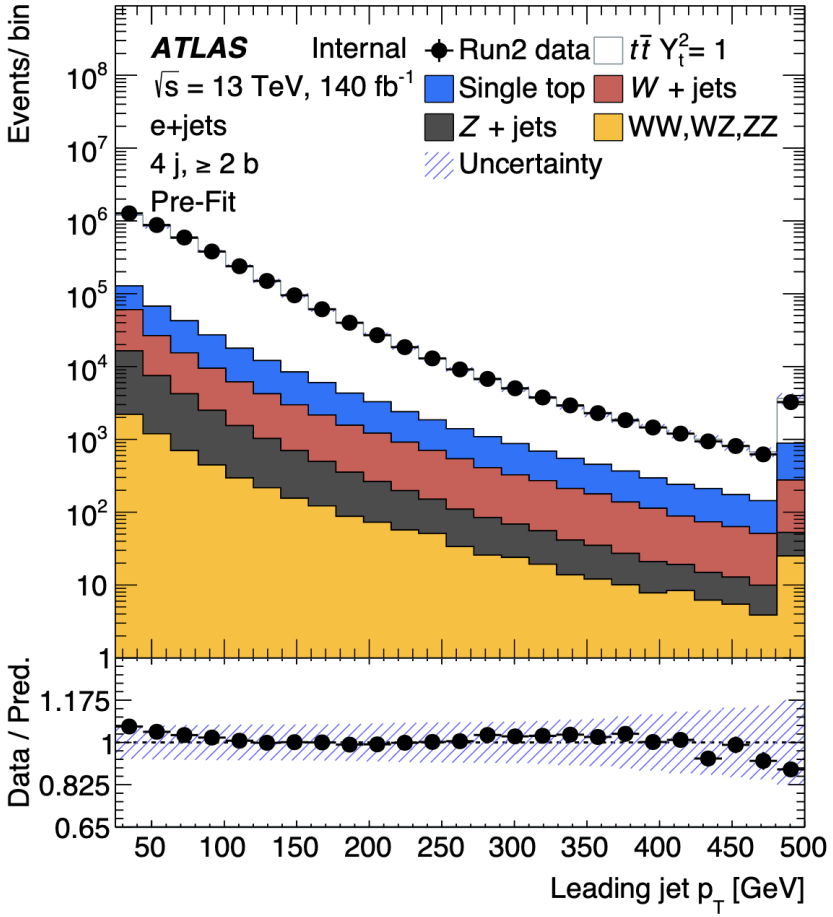


Data/ MC comparison

Pre-fit, electron channel, full Run-II data

Statistical & systematic uncertainties are taken into account





- Electrons 4j channel shown here as an example
- Plots before any fitting applied
- Reasonably good data-MC agreement obtained
- Very small backgrounds (log-y scale)
- QCD fake estimate work is in progress

Data/MC comparison

Pre-fit, electron channel, full Run-II data

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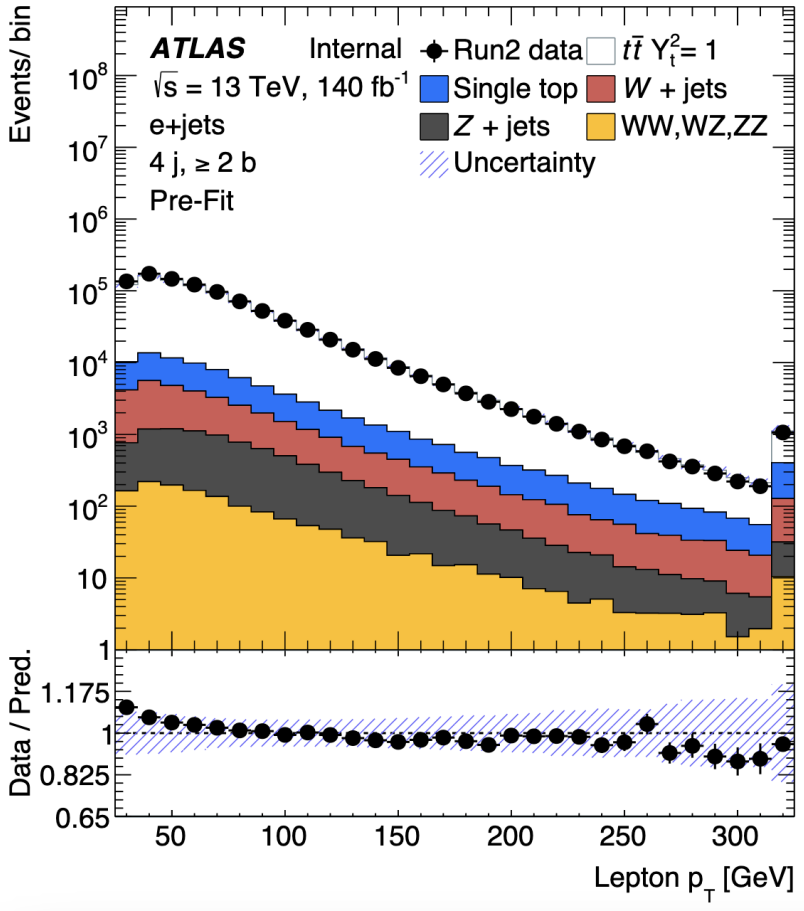
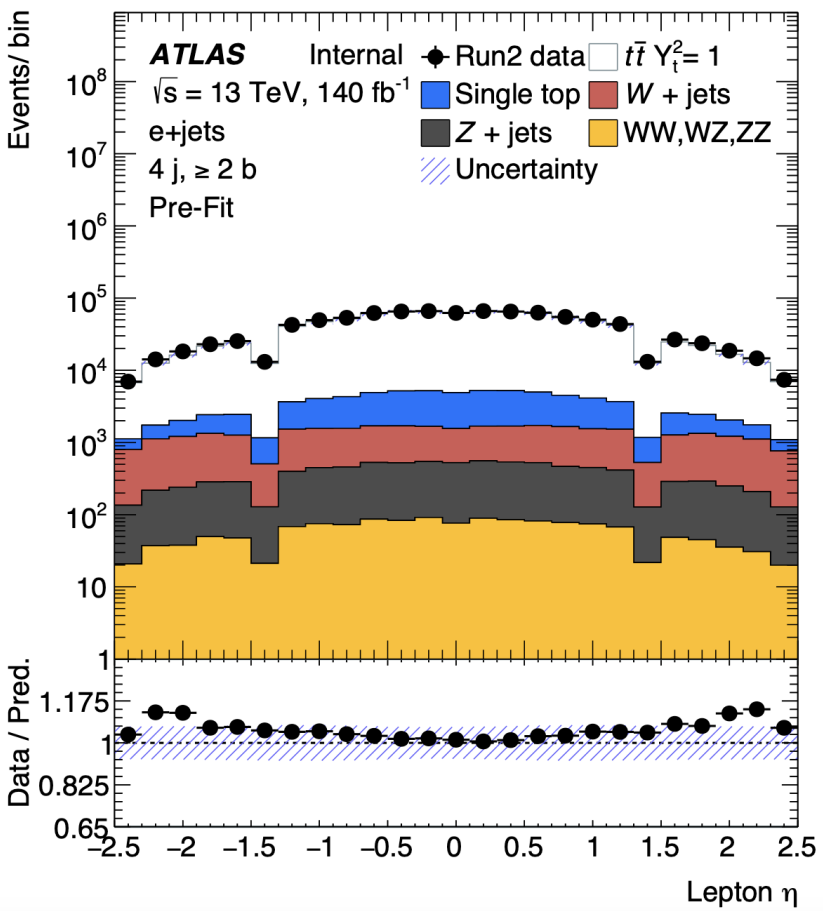
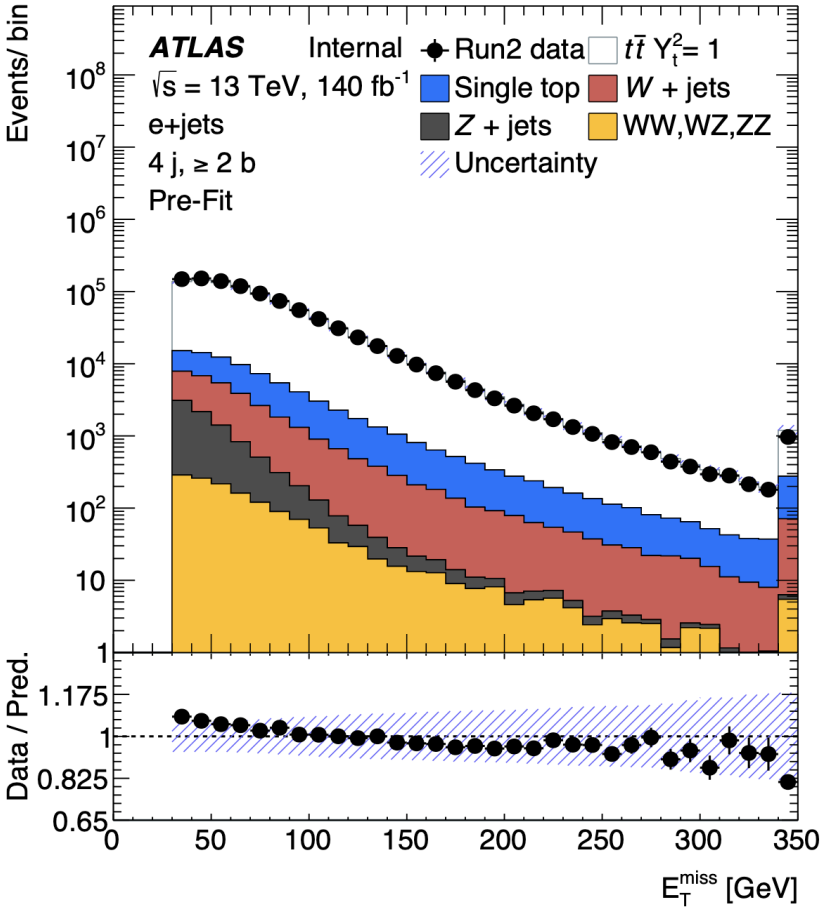






Neutrino p_z and top reconstruction

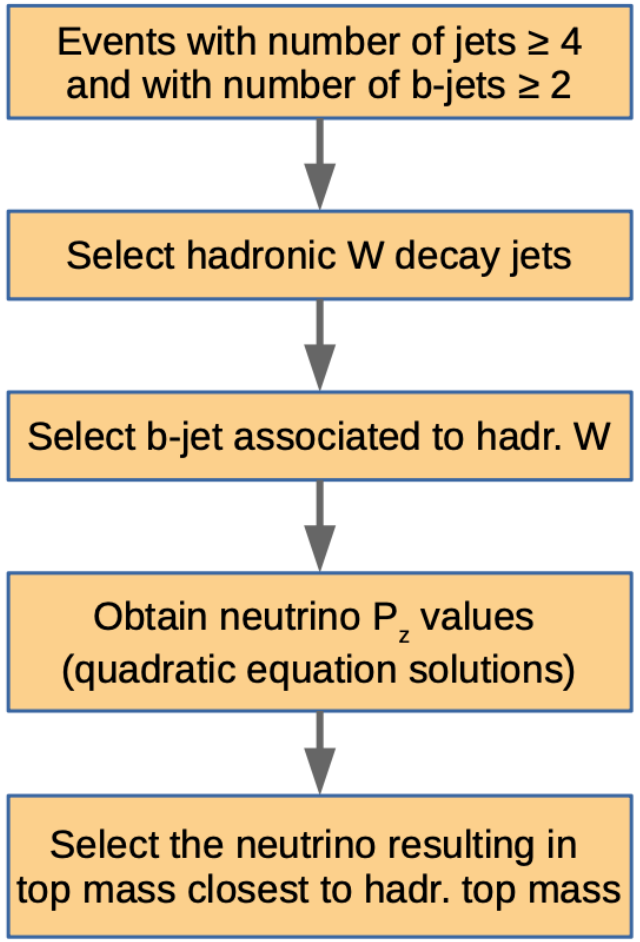
Reconstruction strategy

- Information in hand:

  transverse neutrino momentum (MET), neutrino phi
- To obtain: longitudinal component of neutrino momentum (p_z)
- Computed using an on-shell W mass constraint on:

  lepton + MET system
- Quadratic equation for p_z:
  - Real solutions: consider both solutions for top reconstruction

    (eventually taking the one giving the best top mass)
  - Imaginary solutions (possibly due to imperfect resolution on MET): take the real part of the root



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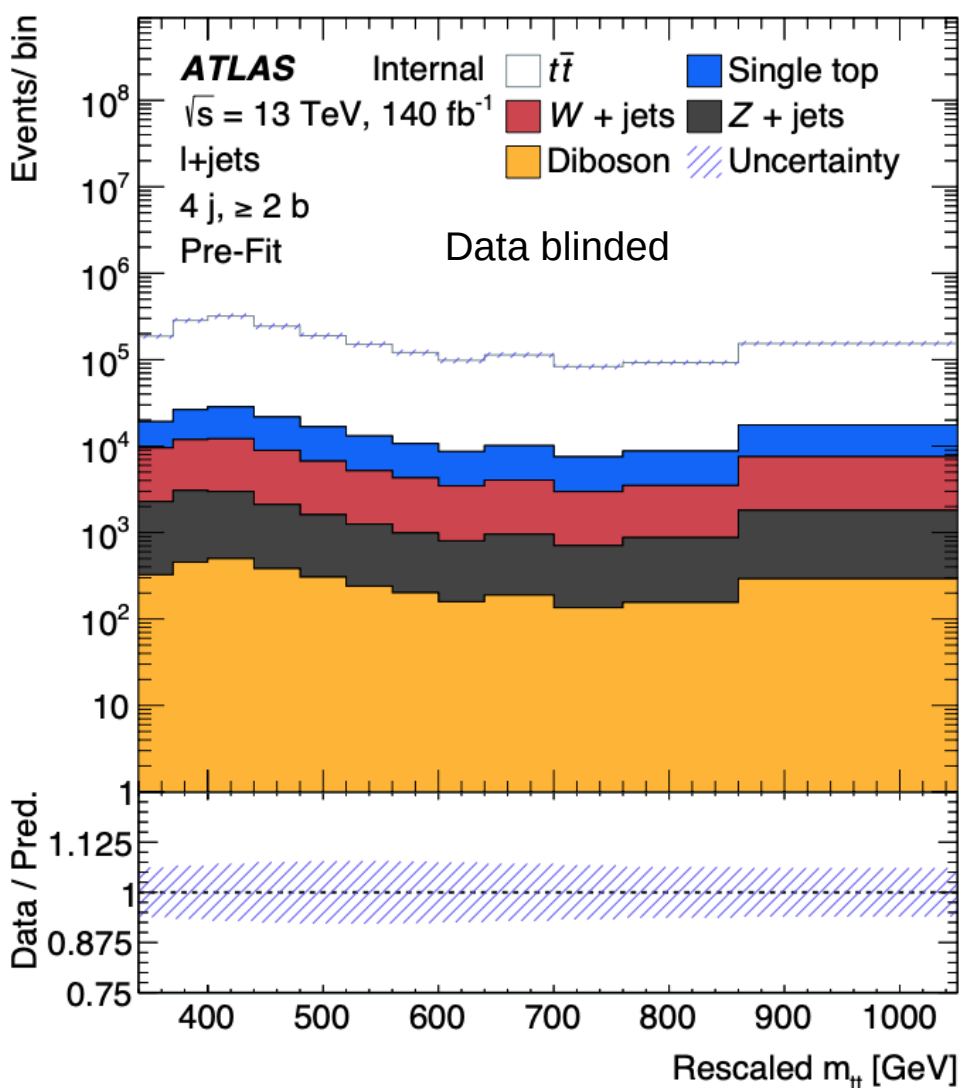


Events with number of jets ≥ 4
and with number of b-jets ≥ 2

↓

Select hadronic W decay jets

↓

elect b-jet associated to hadr. W

↓

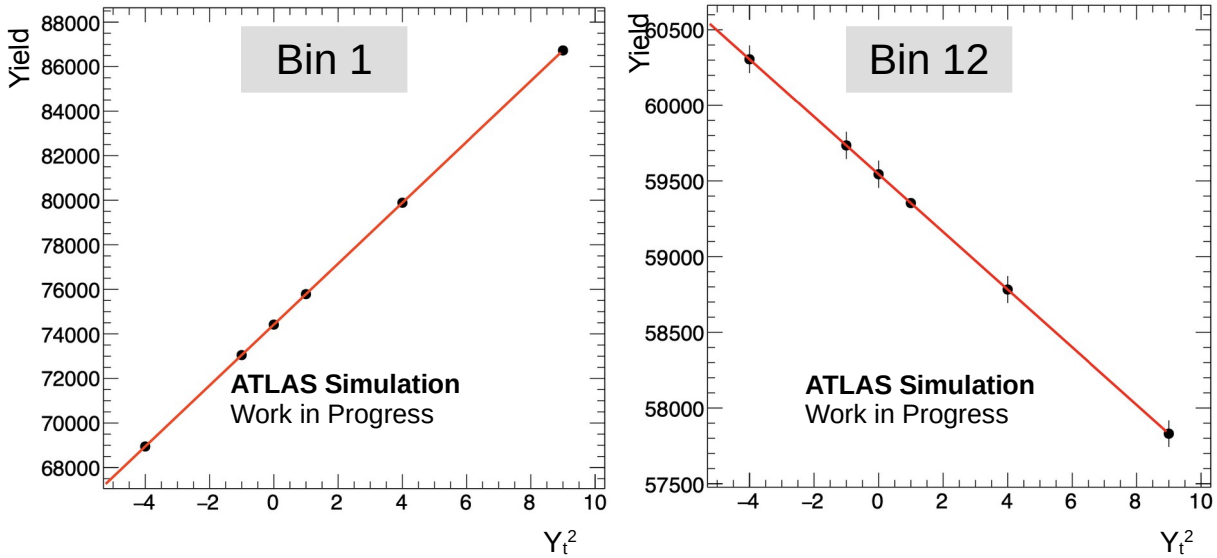
Obtain neutrino P_z values
(quadratic equation solutions)

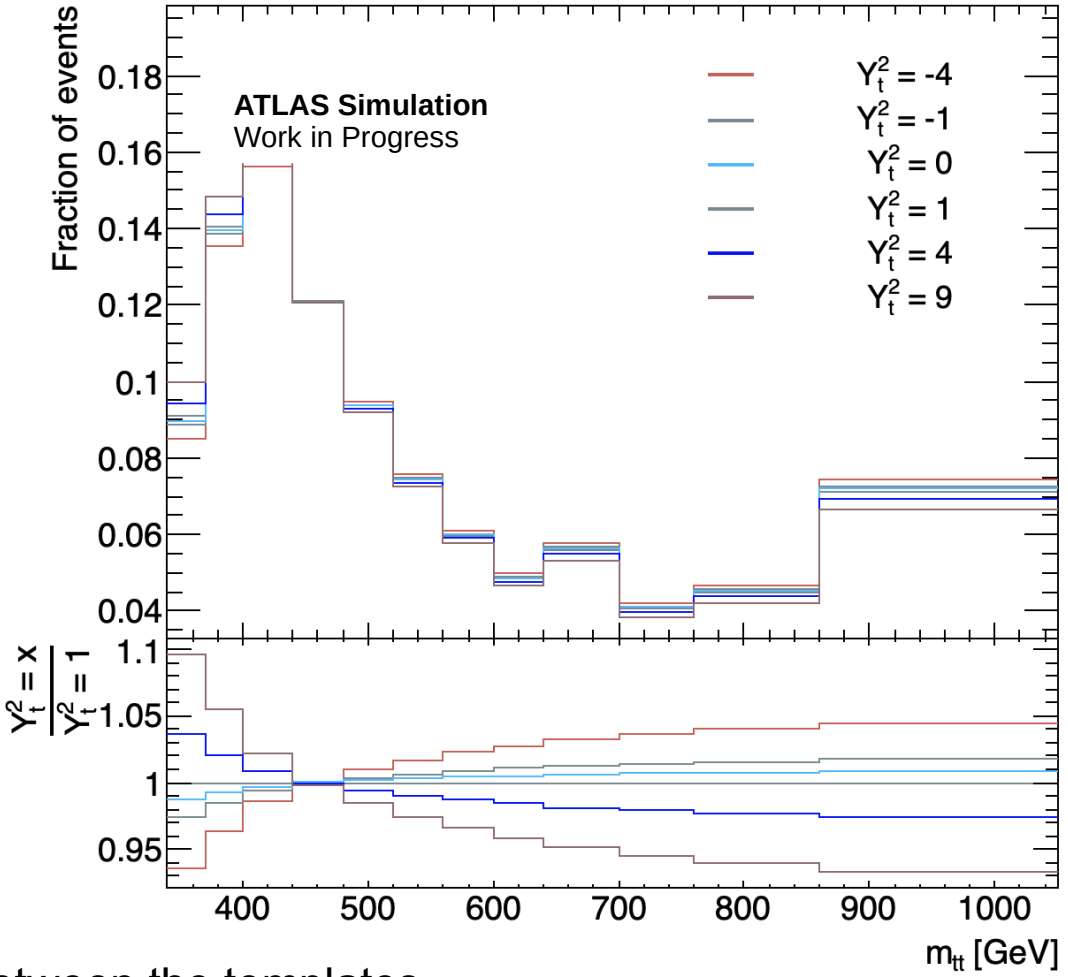
↓

Select the neutrino resulting in
o mass closest to hadr. top mass

Profile Likelihood Fit

Choice of POI: Linear dependence on Y_t^2

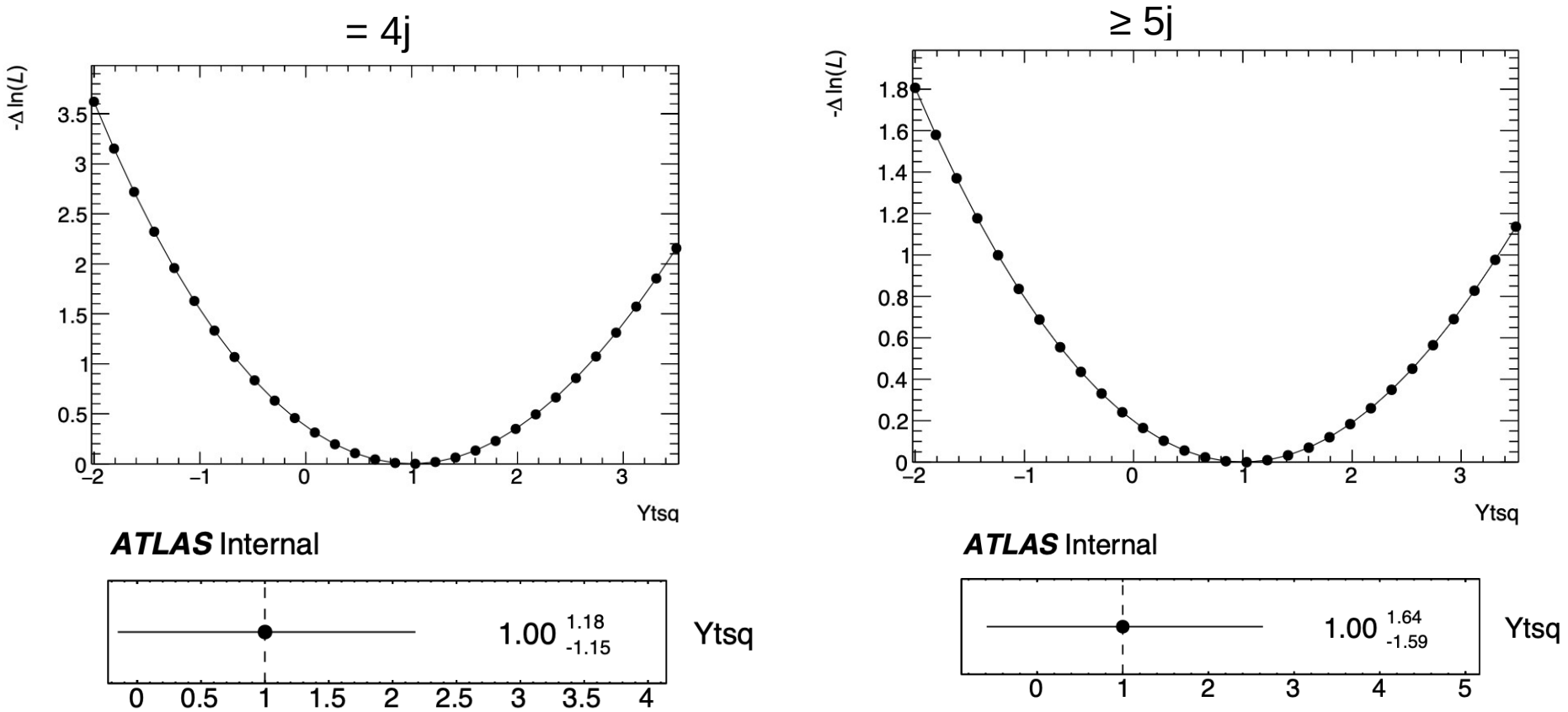




- Vary MC on top of data to get the best fit
- Taking statistical and systematic uncertainties into account
- A simple interpolation between the templates, where each template gets a normalisation
- Simplest interpolation uses a piece-wise linear interpolation between the templates
- Parameter of Interest: Y_t^2 instead of Y_t => linear dependence on yield

Fitting on Asimov

Lepton 4j and ≥ 5j channel: m_{tt}

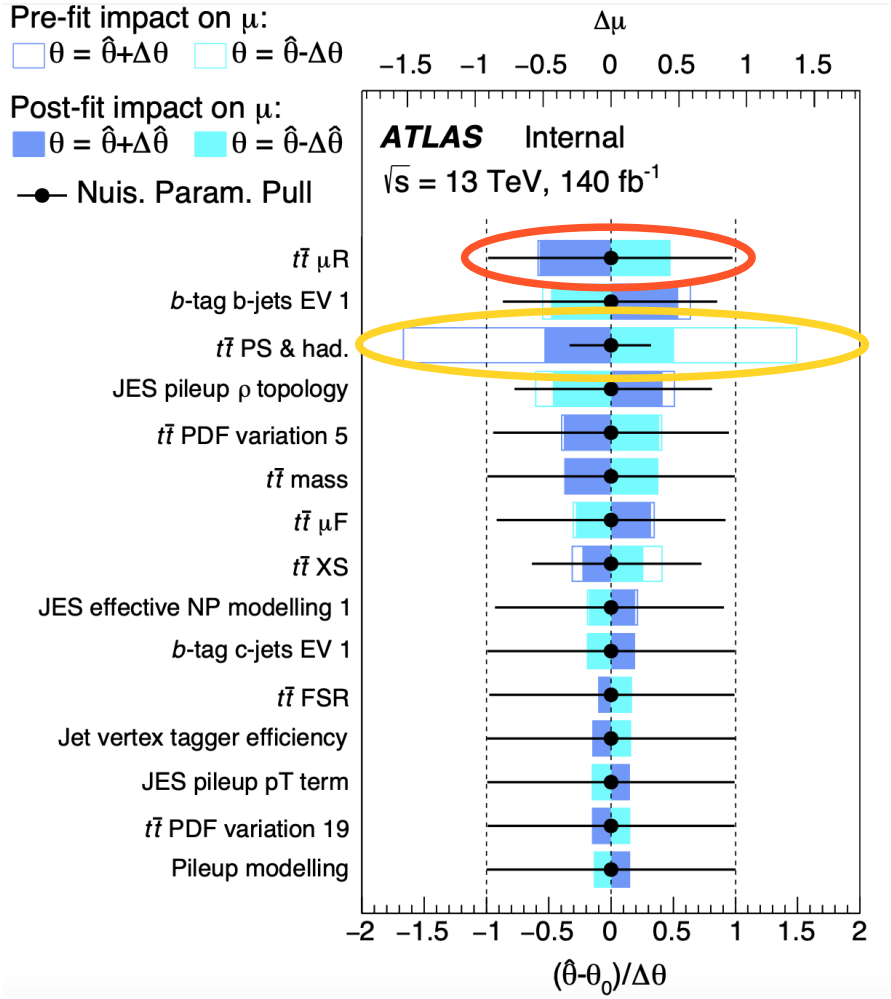


- The results from the two jet regions are not the same, 4j region being a bit better
- Some of their corresponding distributions for systematics behave very differently in these two regions

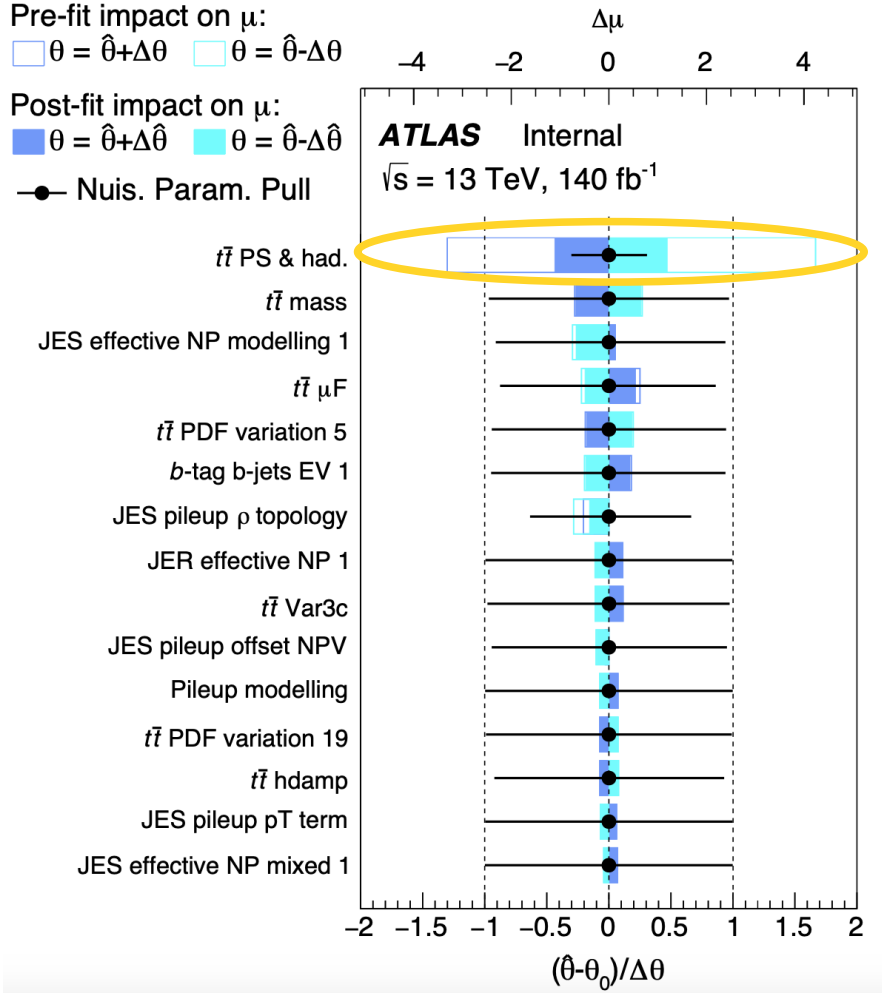
Fitting on Asimov

Lepton 4j and ≥ 5j channel: m_{tt}

= 4j

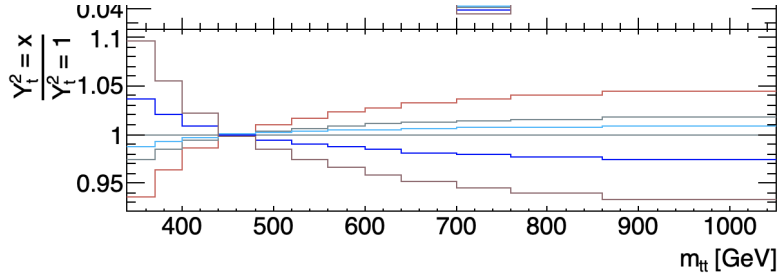


≥ 5j

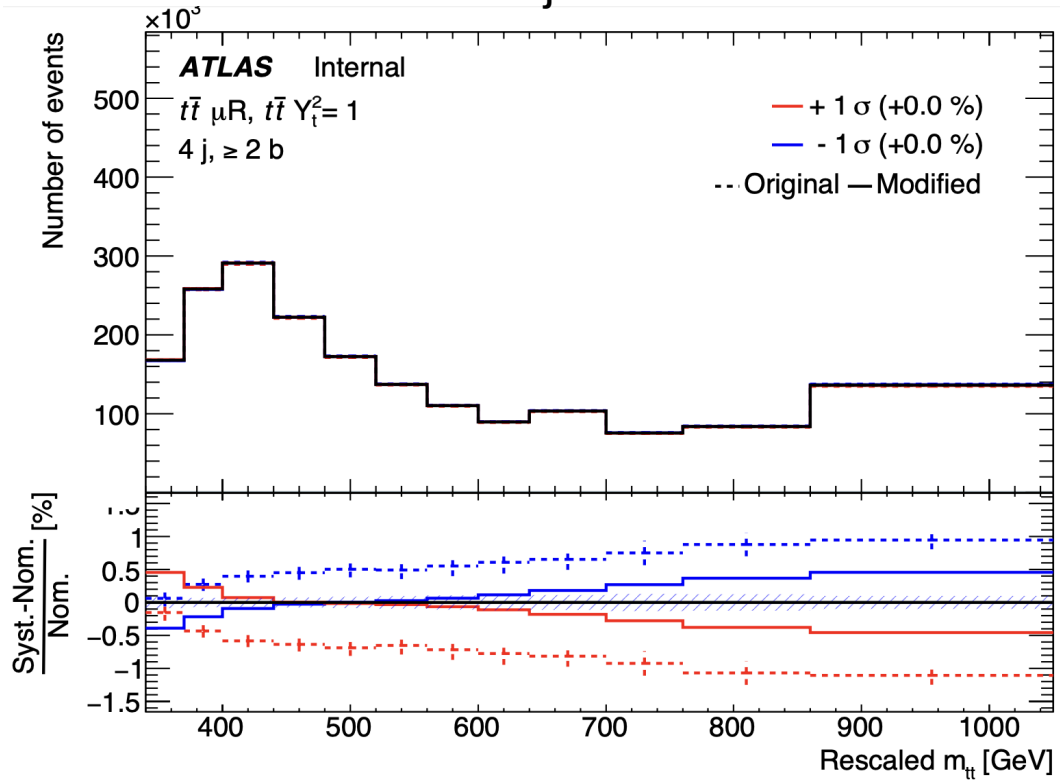


Uncertainties on tt μ_R

Renormalisation scale uncertainty for the two regions

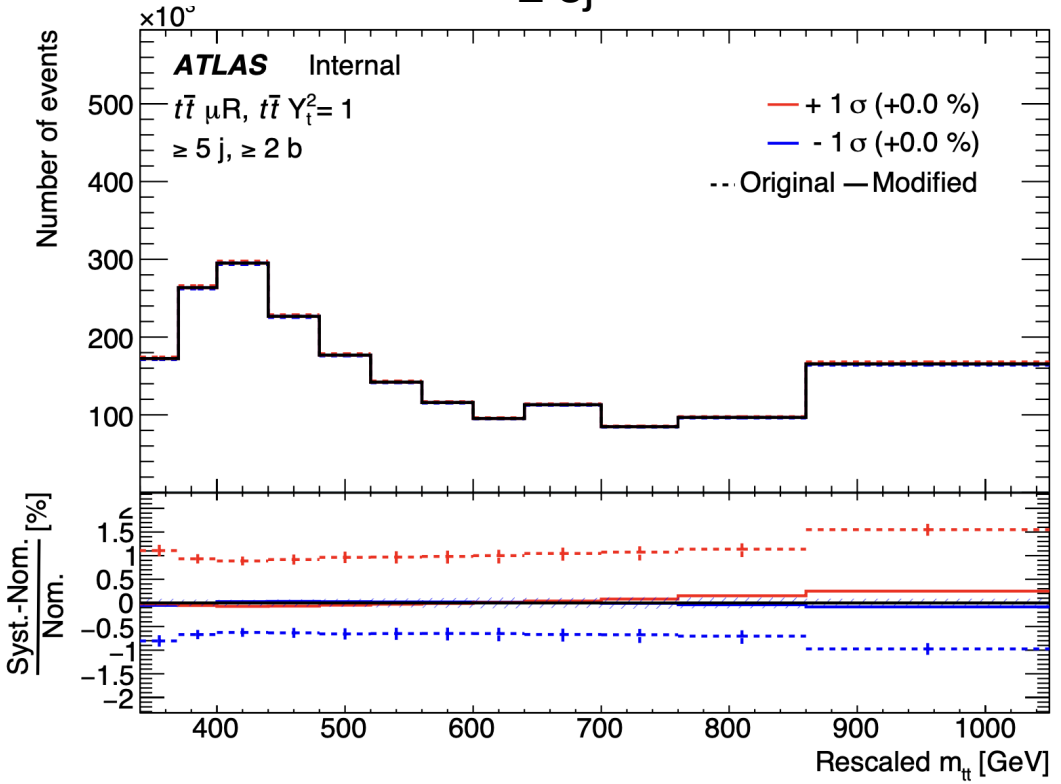


= 4j



- Shown here for shape only to understand the shape effects.
- Taken with shape as well as normalisation in the fit

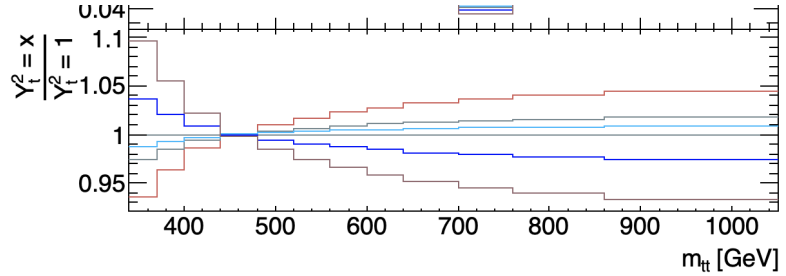
≥ 5j



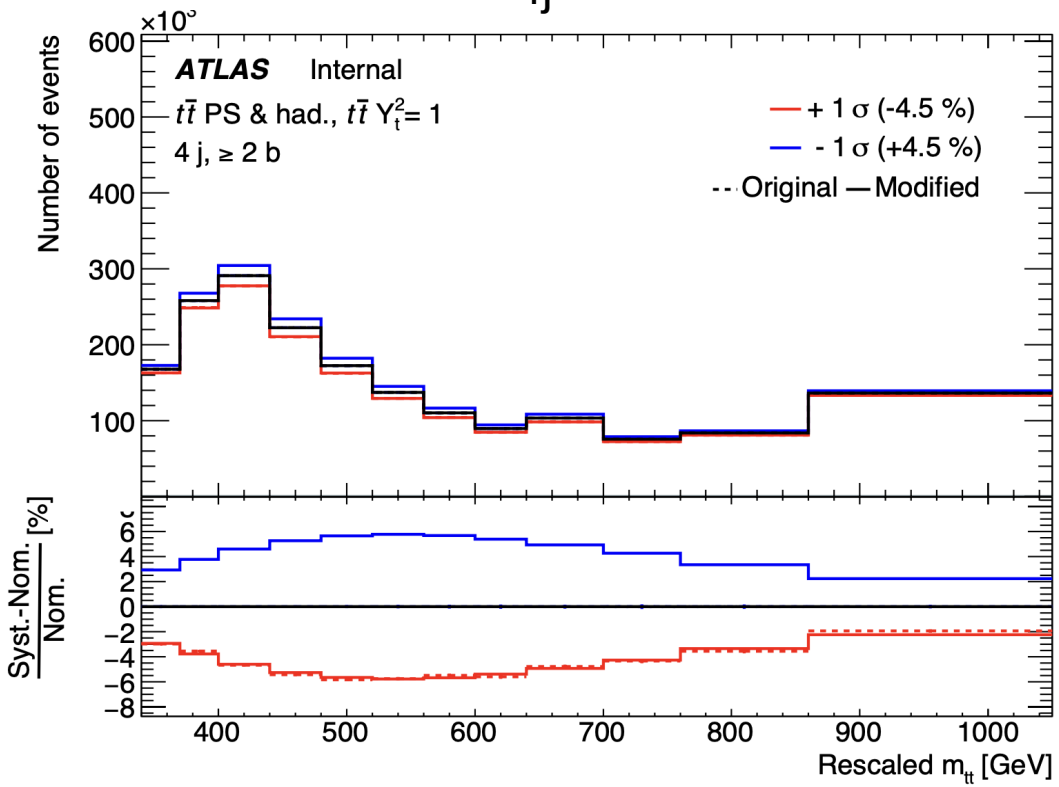
- 4j case: the shape resembles the Y_t variation (top)
- ≥ 5j case: the shape is mostly flat
  => this variation does not appear in the ranking plot for ≥ 5j case but appears for 4j case

Uncertainties on tt PS and had.

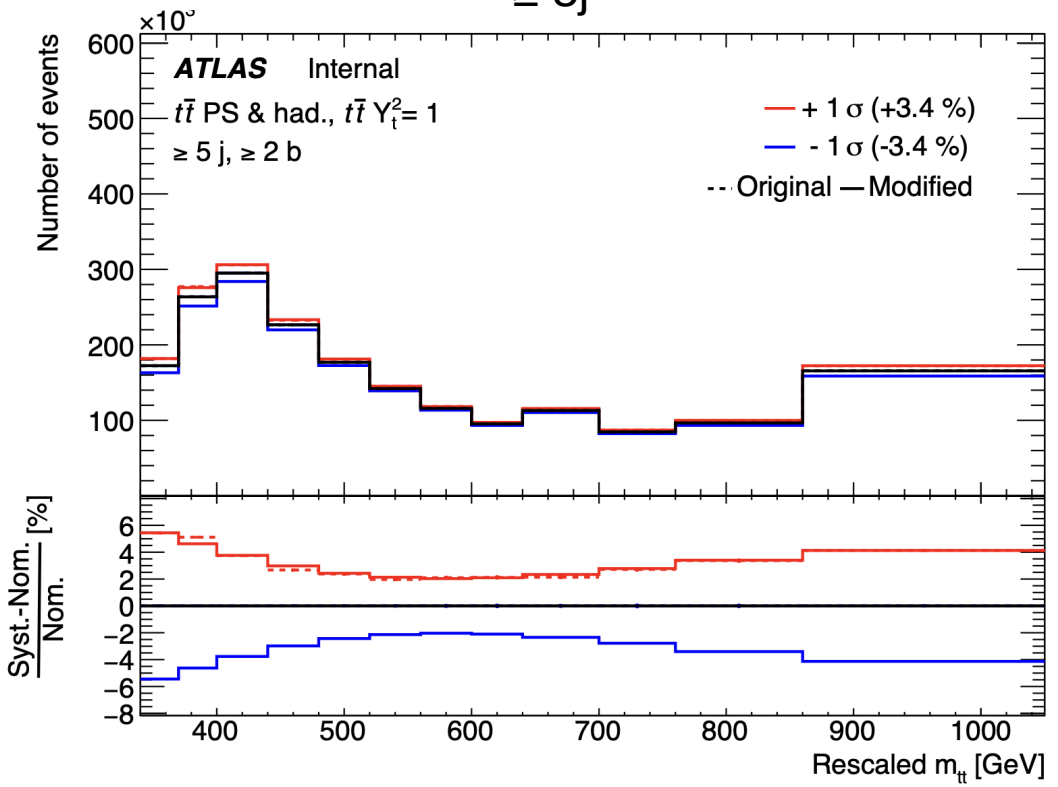
PS and hadronisation uncertainty for the two regions



= 4j



≥ 5j

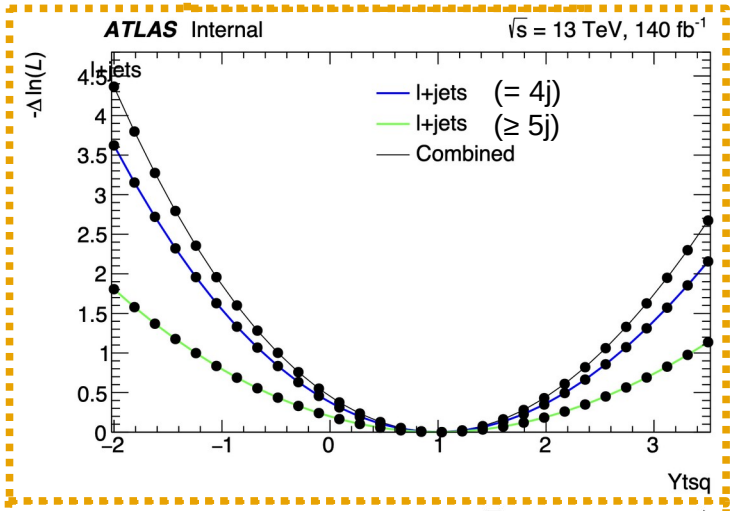


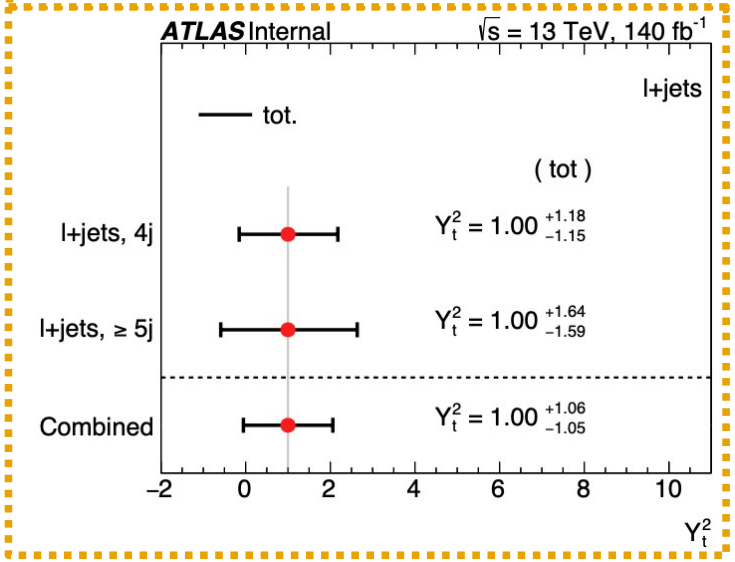
- tt PowHeg+Herwig7 sample varied on top of PowHeg+Pythia8 sample
- Big variations can be seen for both the signal regions, which should partially cancel-out when the two jet regions are combined

Fitting on Asimov

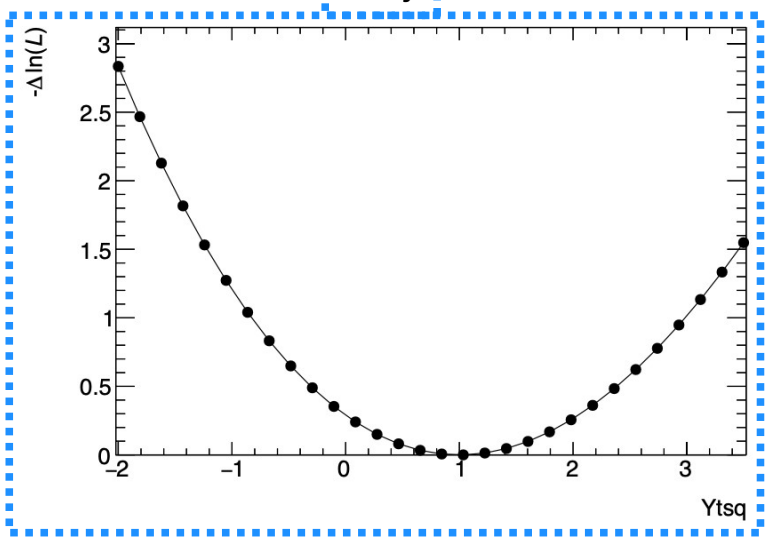
Comparing Lepton: ≥ 4j with Lepton with a multifit from 4j and ≥ 5j

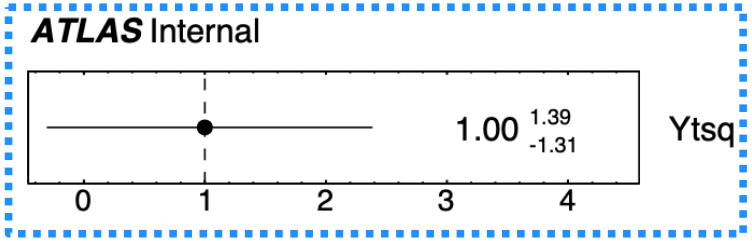
4j and ≥ 5j multifit





≥ 4j

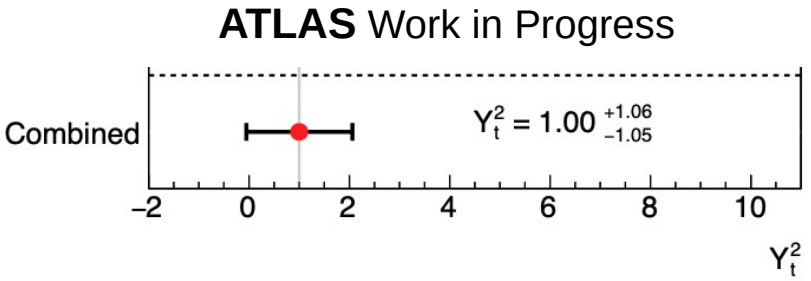




- ~30% difference between the two results (combined 4j and ≥ 5j regions, vs only one region for ≥ 4j)
- Better sensitivity obtained when the two jet regions are combined, compared to all jet inclusive region

Summary and next steps

- Using full Run-II data at 140 fb^{-1} to extract the Y_t value
- Different templates for Y_t values obtained using HATHOR tool
- Neutrino and top reconstruction strategy set up
- Fit results obtained:
  - fit results translated from Y_t^2 to Y_t gives a result similar to the CMS results (https://arxiv.org/abs/1907.01590)
  - need to understand a few systematics better:
    - Eg: constraints on PS and had. systematic



- Work on the QCD background estimate in progress
- Improvement in neutrino reconstruction strategy: attempt to reduce the imaginary part of the neutrino p_z solution
- Beginning to work on the sister analysis: top-Yukawa coupling in the di-leptonic channel

Thank you for your attention.

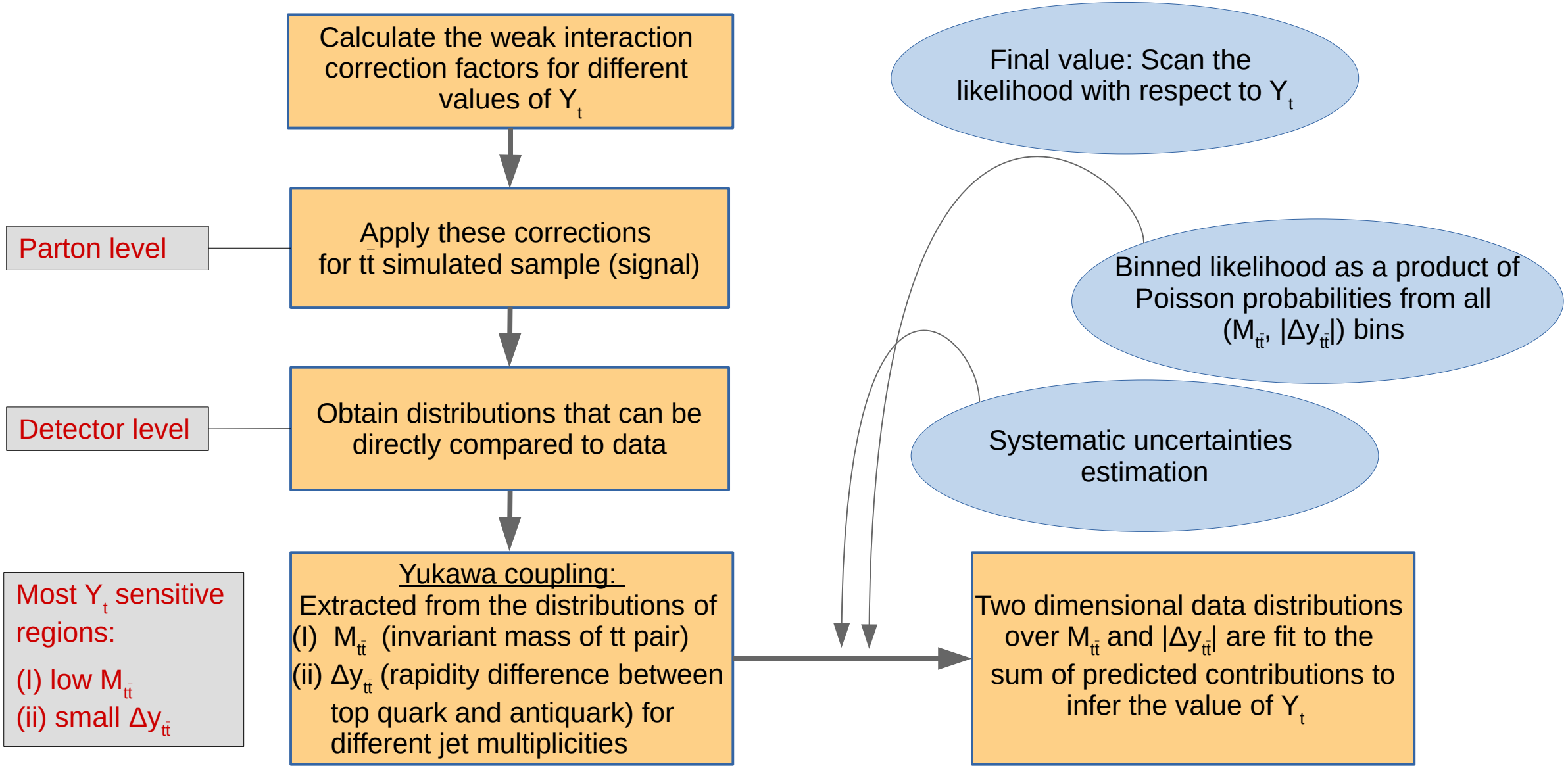
Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

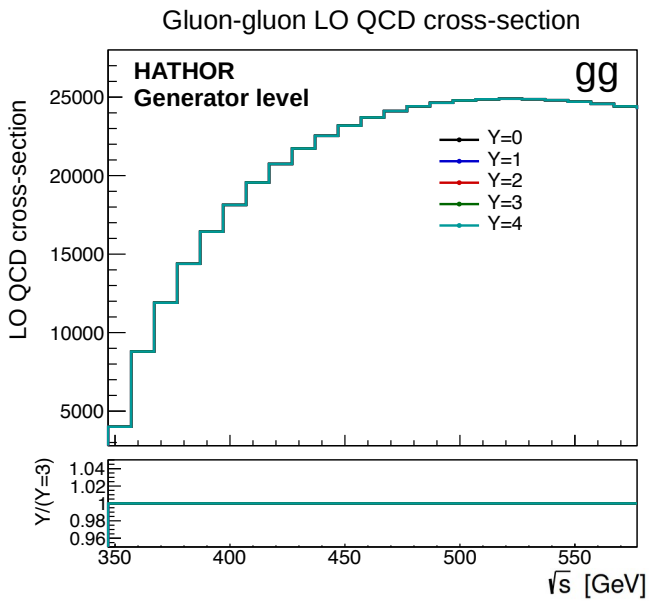
Supriya Sinha
ATLAS_Z
E-mail : supriya.sinha@desy.de
Telefon: +49 408998 7645

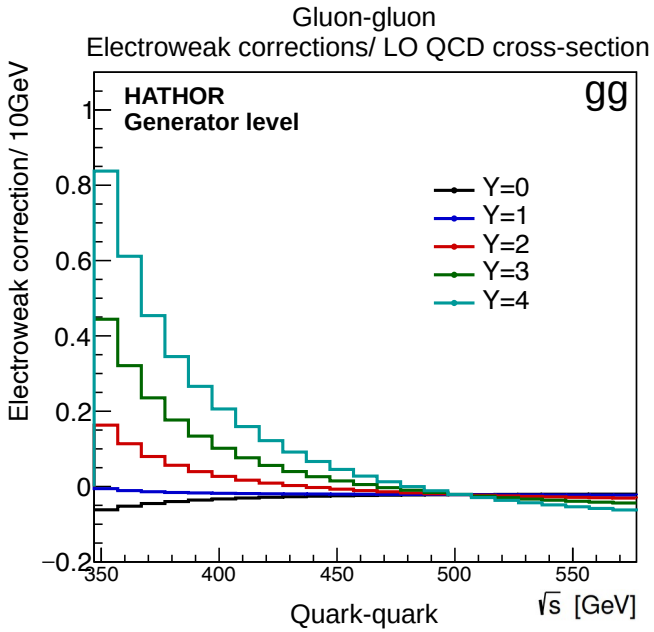
Analysis strategy

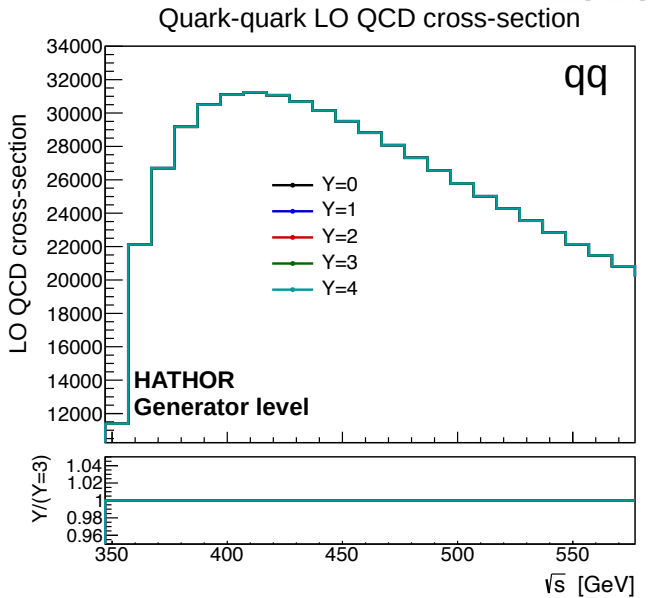


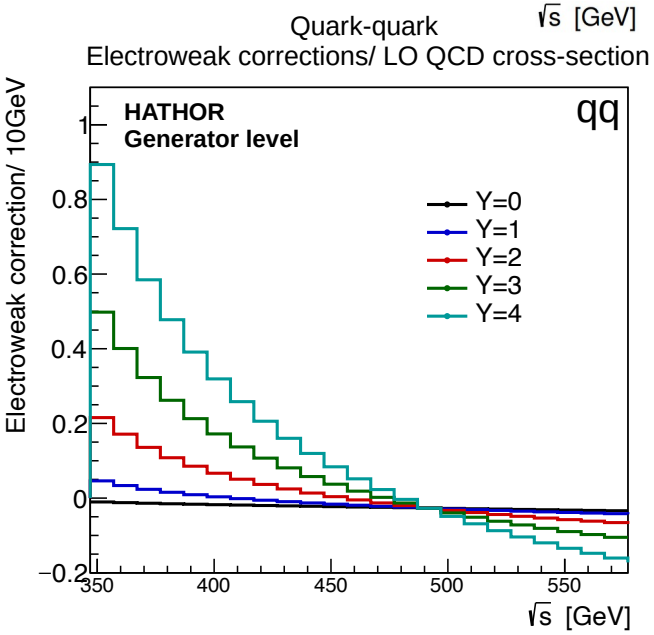
LO QCD cross-section and Electroweak corrections

Versus √s









Using HATHOR 2.1-b3

- Events are separated into gg or qq, and their plots are obtained separately
- Left: An overlay of pure QCD cross-sections versus √s for different Y_t values
- Right: Ratio of weak force corrections over the LO QCD production cross-section, versus √s for different Y_t values

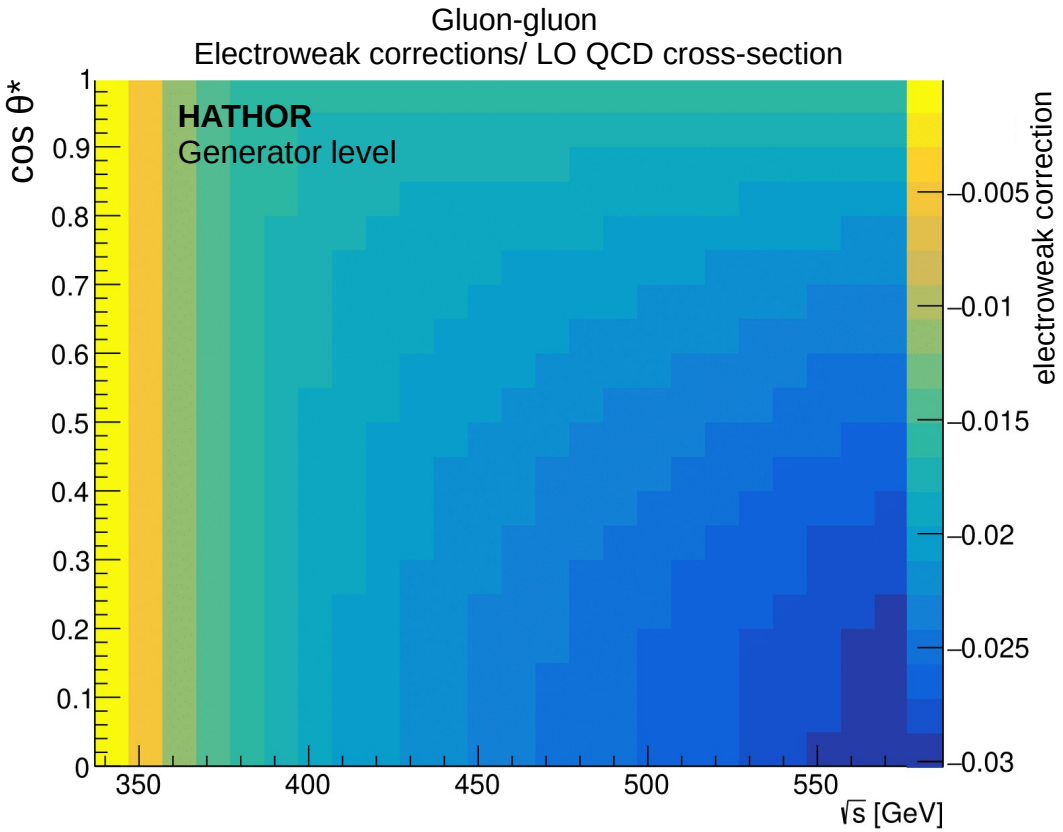
- As expected, no difference in total cross-section versus √s for different Y_t values is seen

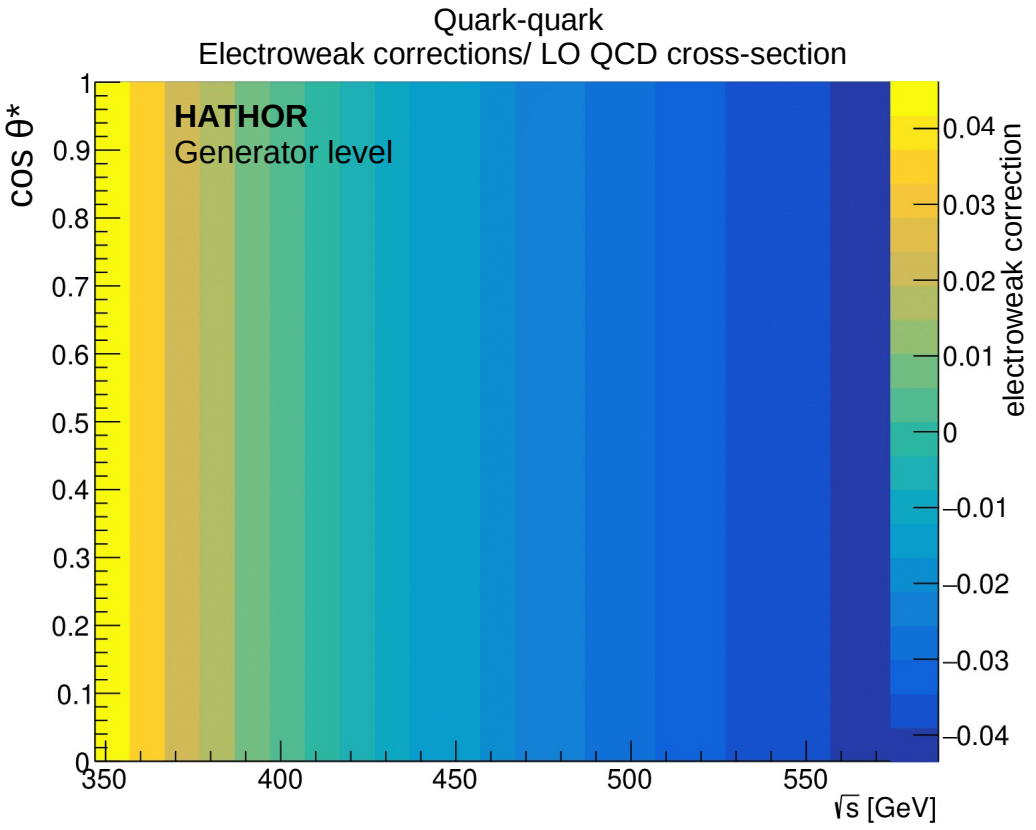
- For gg as well as qq events, a very strong sensitivity with respect to Y_t is seen at √s near threshold

Electroweak correction relative to LO QCD cross-section

For Y_t=1; 2D: versus √s, cosθ*

θ*: Scattering angle of top quark in $t\bar{t}$ rest frame



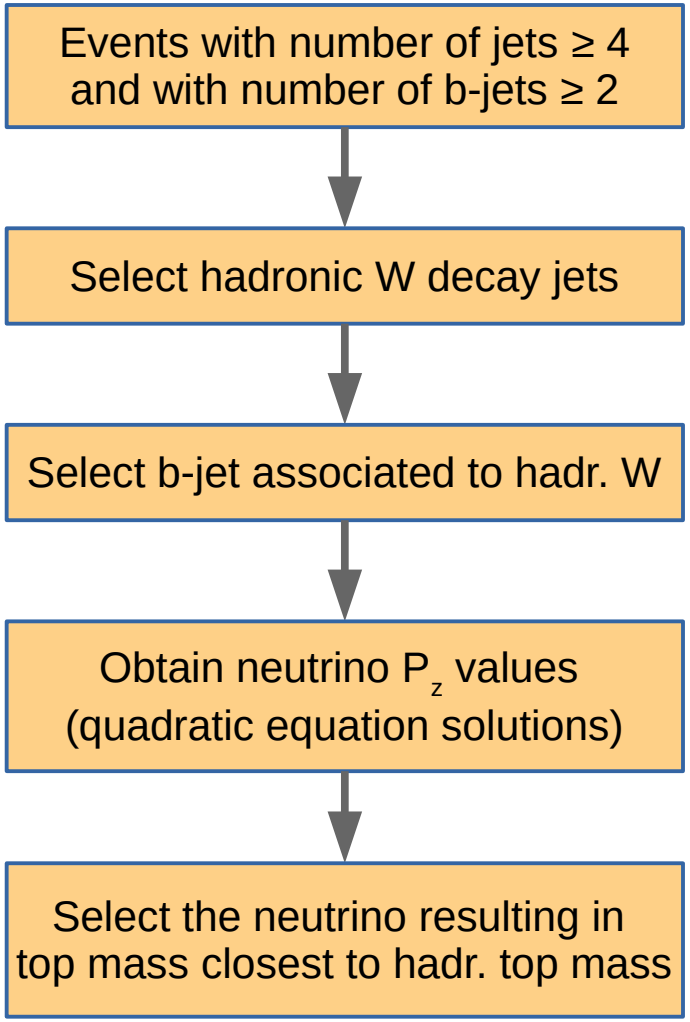


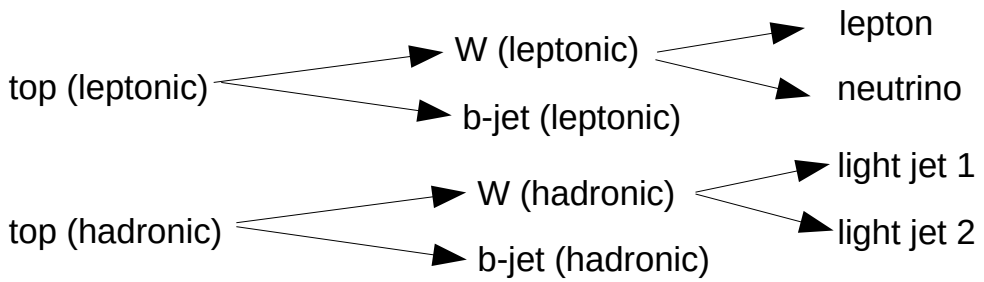
For gg, there is a high cosθ* dependence for higher √s values

For uu, not much cosθ* dependence seen for each individual √s range

Reconstructing $t\bar{t}$

Best combination





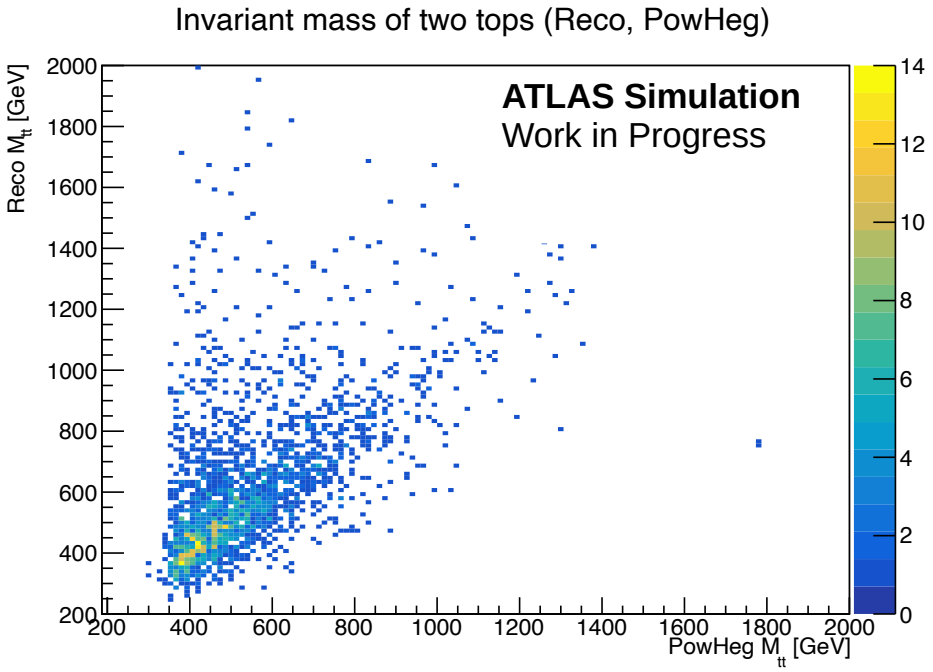
- Test the combination of non-b-tagged jets j1, j2, j3
- Possible combinations: j1+j2, j1+j3, j2+j3
- The combination with the smallest mass difference $|m_{(j1+j2)} - m_W|$ is taken

- One of the two leading p_T b-jets is associated with the jets selected above
- Possible combinations: jet1+jet2+b1, jet1+jet2+b2
- The combination with the smallest mass difference $|m_{(jet1+jet2+b1)} - m_{top}|$ is taken as the hadronic b-jet

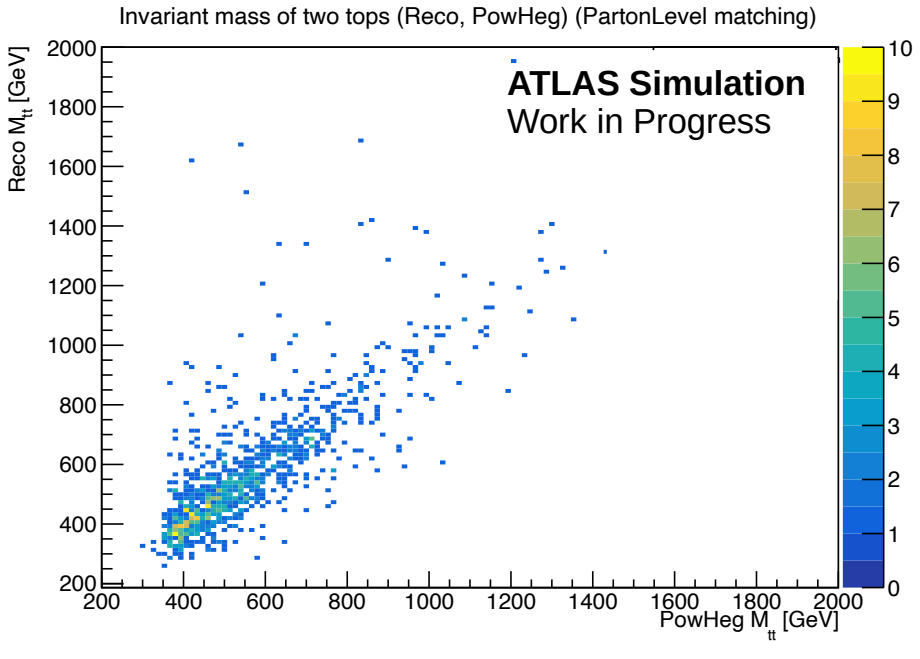
- Neutrino p_z is obtained using the quadratic equation from four momentum conservation
- Possible solutions: nu1, nu2 (two roots of the quadratic equation)
  - Imaginary roots: Only real part is taken as the solution
  - Real roots: The neutrino with the smallest mass difference $|m_{(lep+nu+b2)} - m_{top\ (hadronic)}|$ is taken as the solution

Reconstructing $t\bar{t}$

Best combination: comparison with generator level value



Parton matched to ΔR< 0.4 with generator level

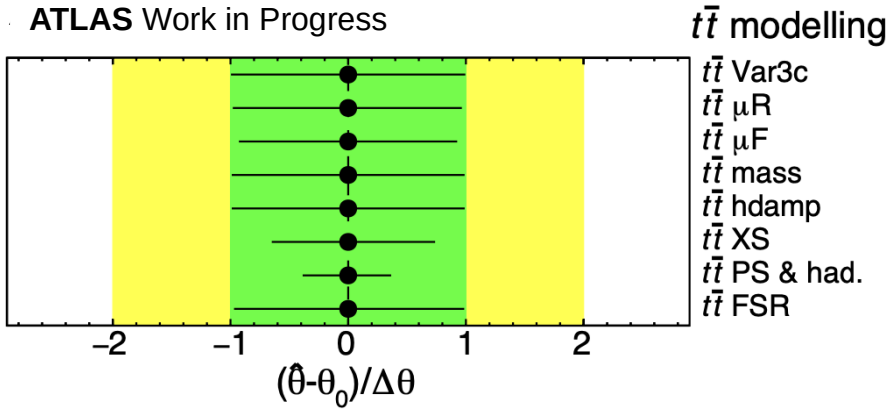


- Invariant mass of two top quarks (reconstructed) shows a good correlation with the generator level mass value
- The events which are matched at parton level confirms a very good resolution

Fitting on Asimov

Electron 4j channel: m_{tt}

Move to Backup!!



The most relevant systematics in the fit are the modelling systematics, imposing the most constraints

	Systematic	Components
1	Luminosity	1
2	Pileup modelling	1
Physics objects		
3	Electrons	6
4	Muons	12
5	Jet energy scale	36
6	Jet energy resolution	14
7	Jet vertex tagger	1
8	ETMiss	3
b-tagging		
9	Efficiency	9
10	Mis-tag rate (c-jets)	4
11	Mis-tag rate (light jets)	4
12	Extrapolation	2
tt XS		
13	Overall tt XS uncertainty	1

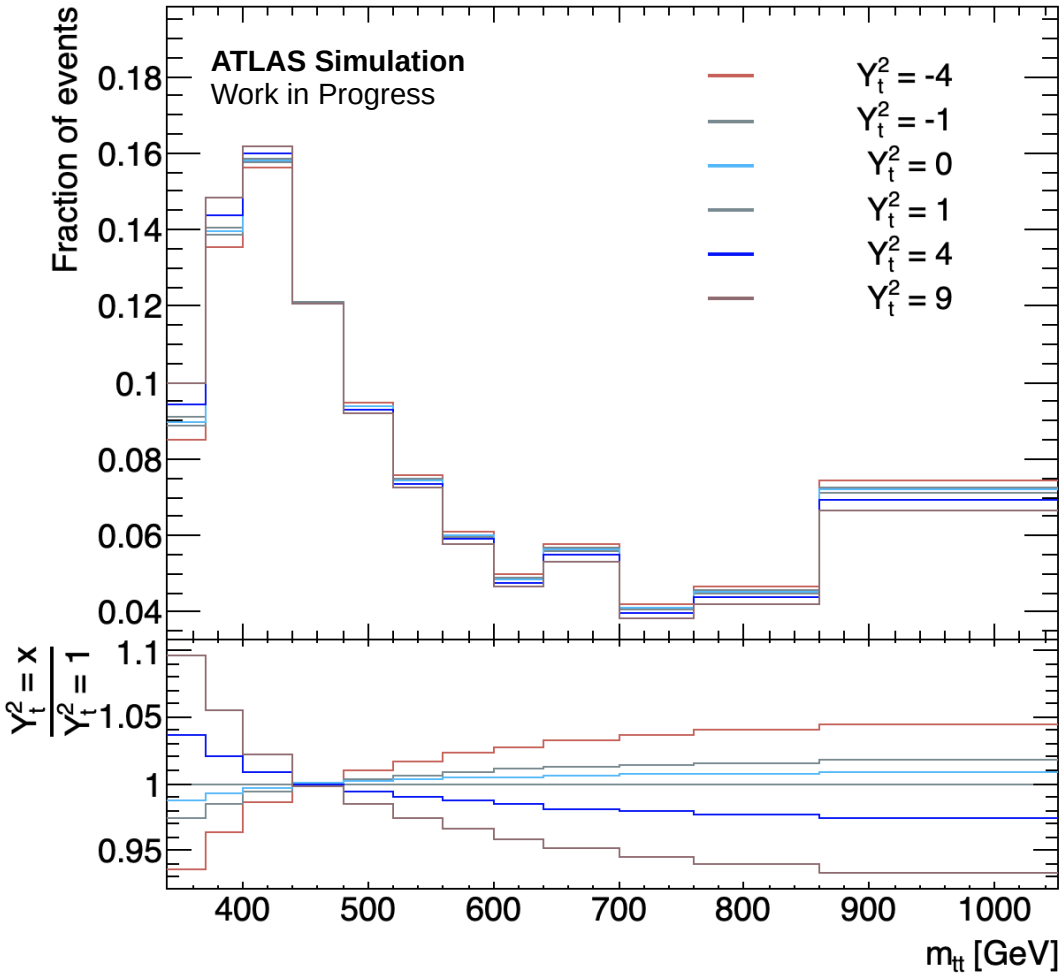
	Systematic	Components
tt̄ modelling Luminosity 1		
1	PDF variations	30
2	Parton shower & hadr.	1
3	Mass variation	1
4	hdamp	1
5	ISR	3
6	FSR	1
Wt modelling		
1	ISR	3
2	FSR	1
3	DS scheme	1
single-top		
1	ISR	3
2	FSR	1

Profile Likelihood fit

Fitting method used to obtain Y_t

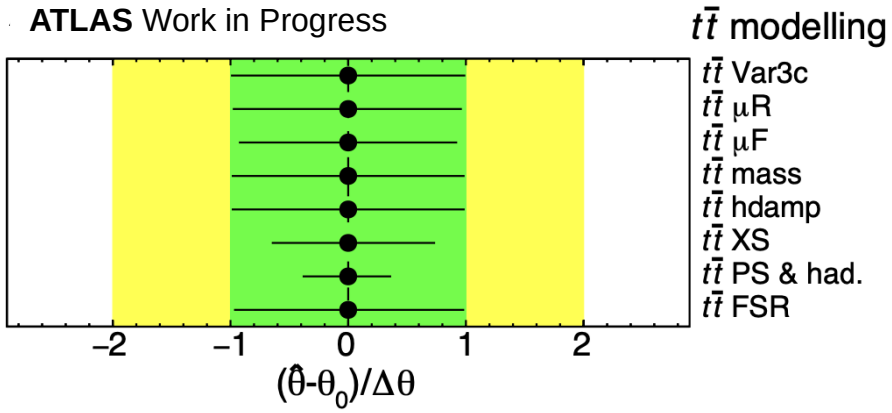
- A simple morphing interpolates between the templates, where each template gets a normalisation w(POI)
- Simplest interpolation uses a piece-wise linear interpolation between the templates
- T_i^t: number of events in bin i for template t, and S_i: total number of events in bin i, then

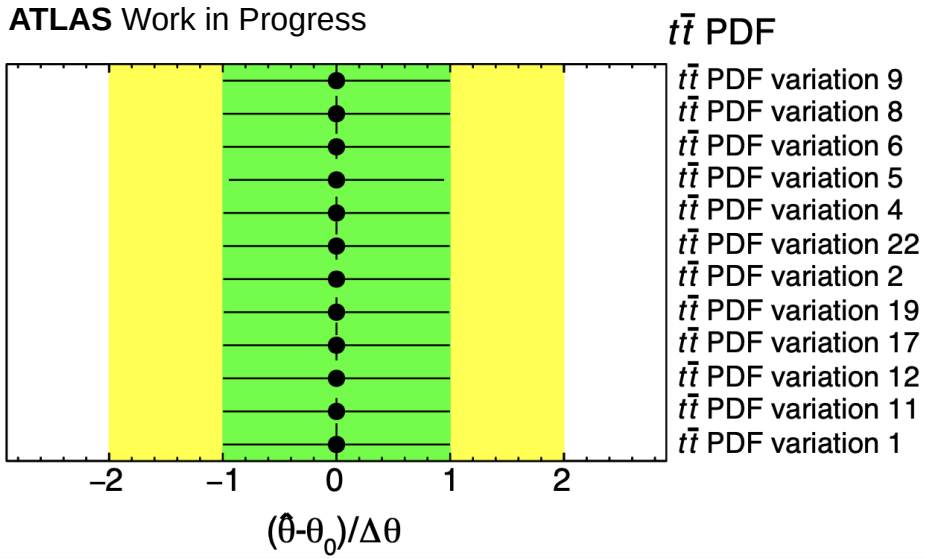
$$S_i = \sum_t w_i^t(POI) \cdot T_i^t,$$

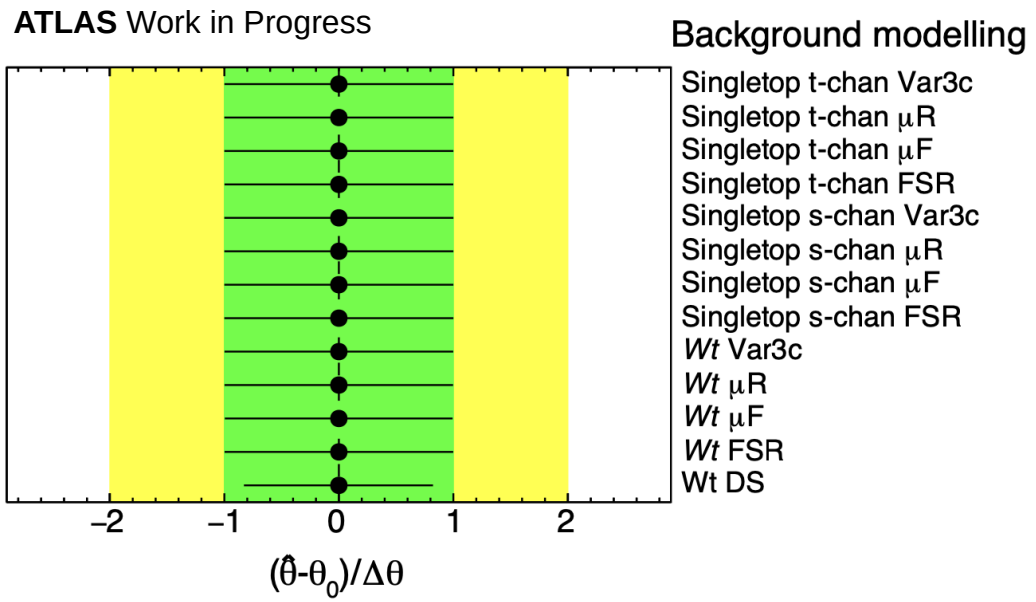


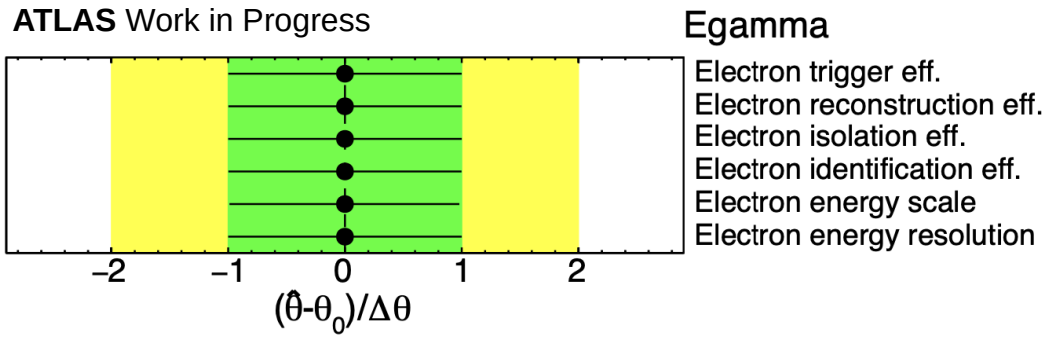
Fitting on Asimov

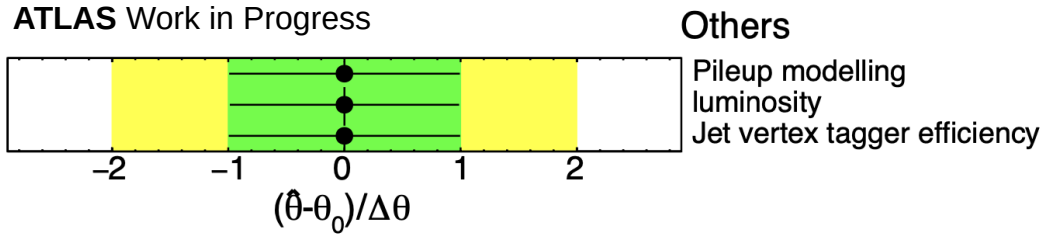
Electron 4j channel: m_{tt}





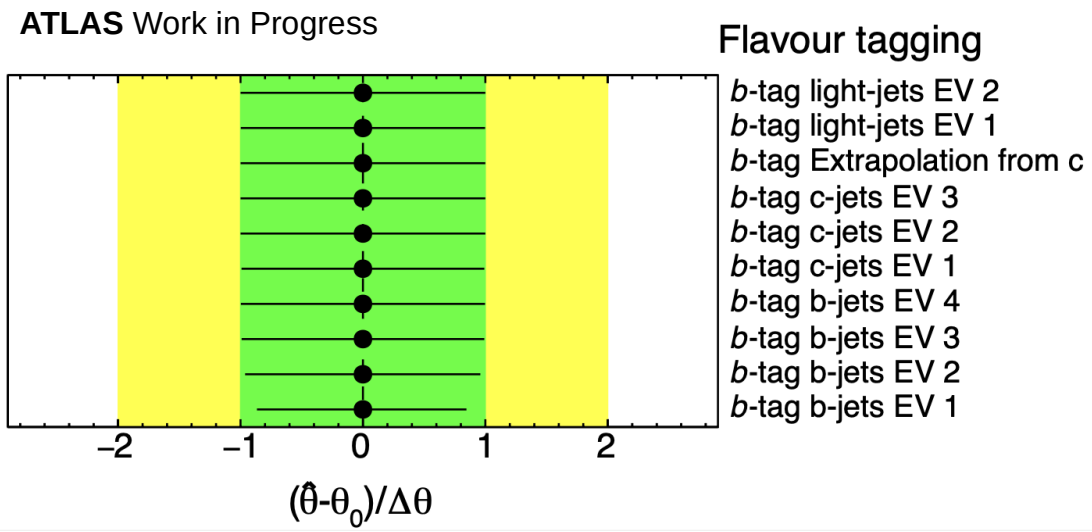


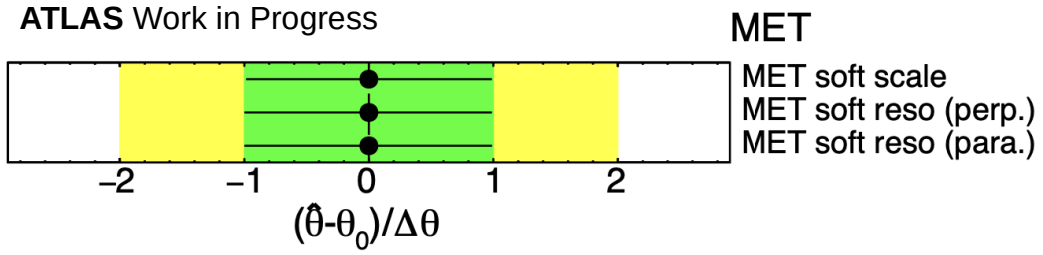


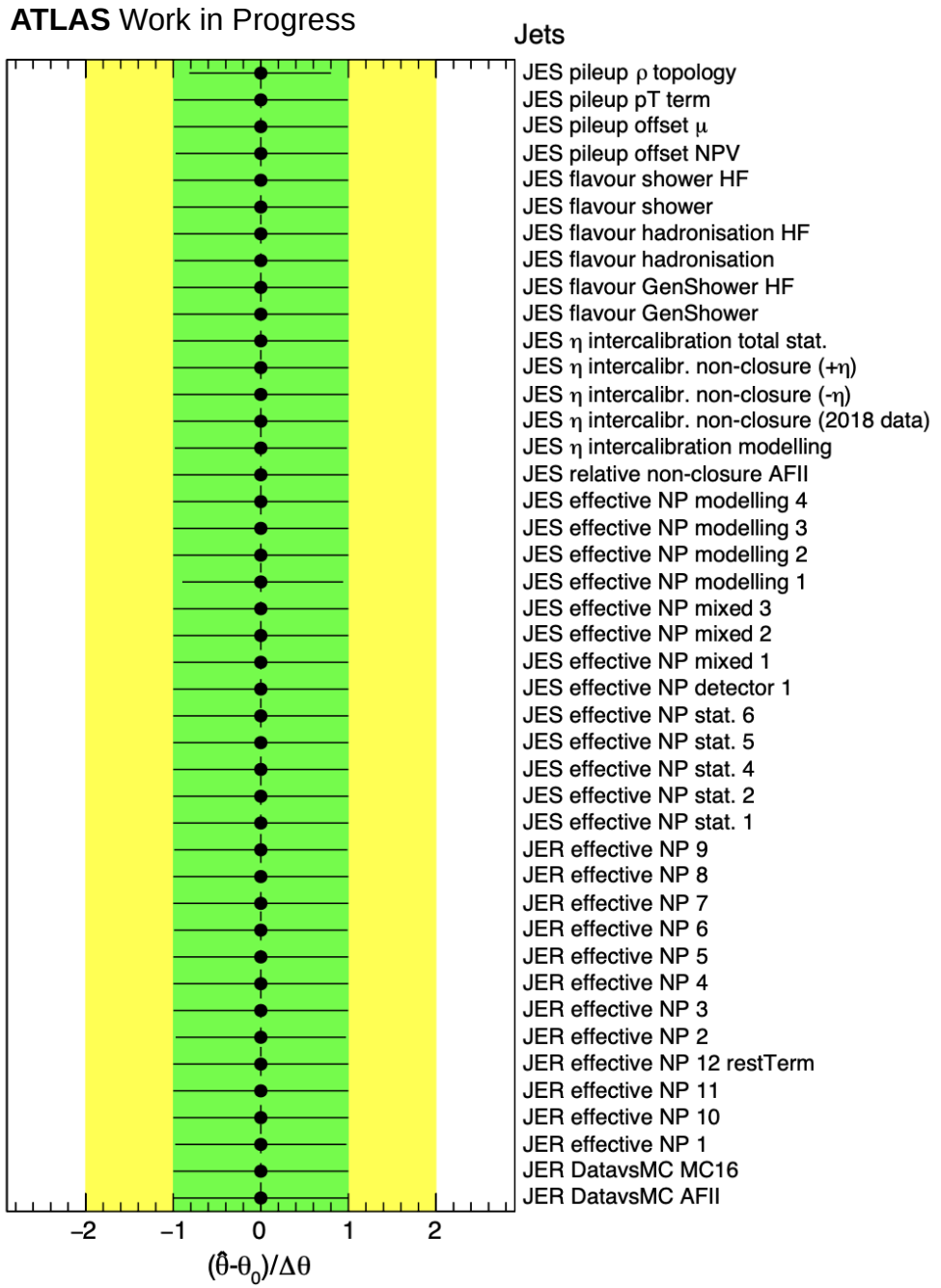


Fitting on Asimov

Electron 4j channel: m_{tt}

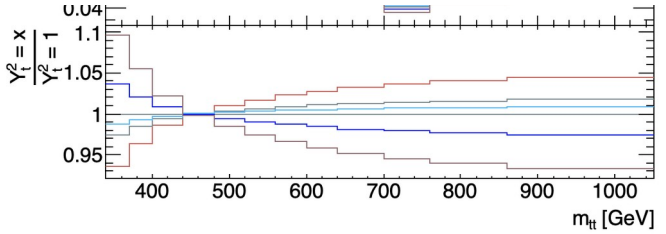


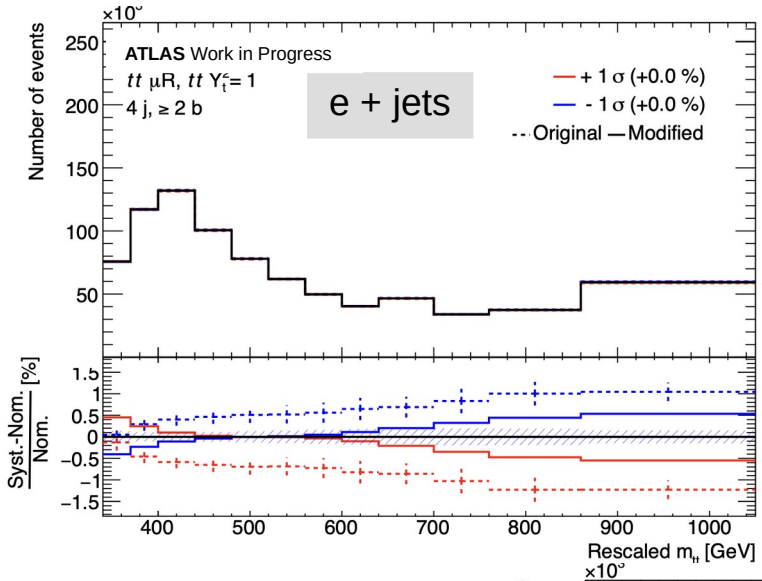


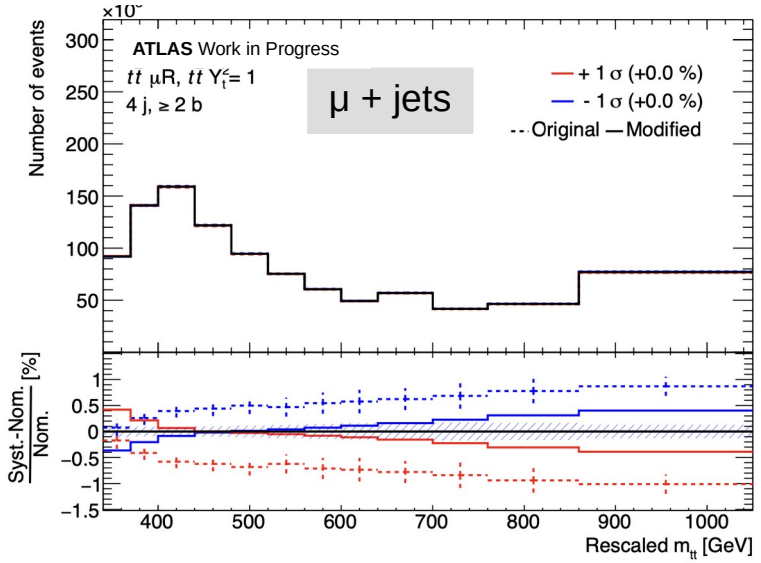


Systematics

Comparison for different channels: $t\bar{t}$ μR

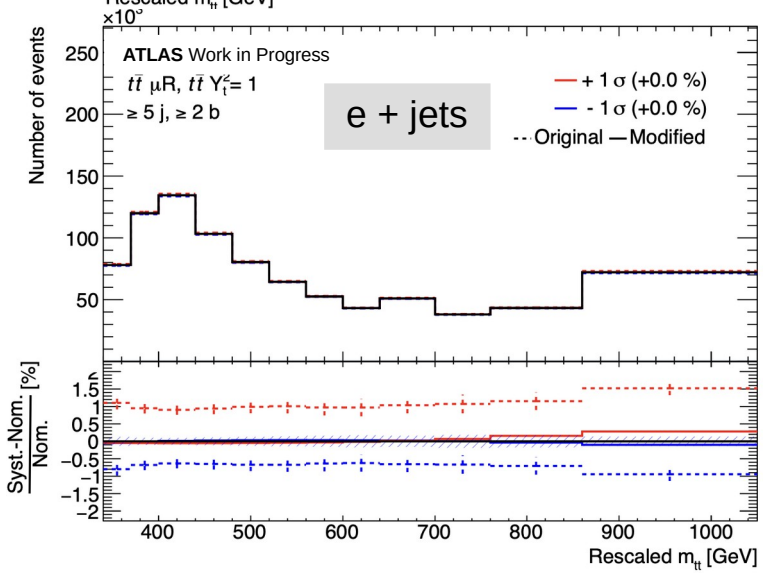


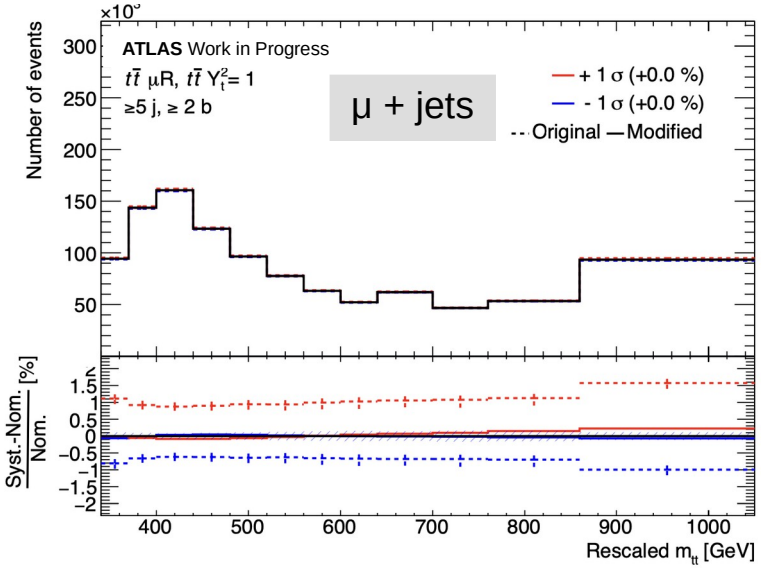




This systematic becomes important for (lep, 4j) channel, due to the shape resembling the Y_t templates

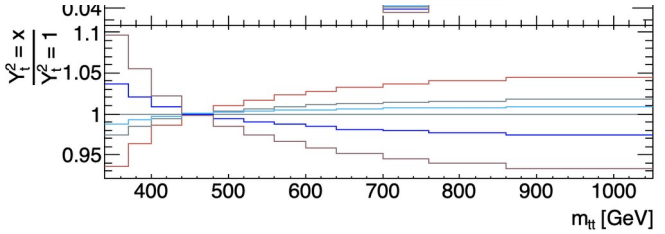
This systematic becomes less relevant for (lep, ≥ 5j) channel, hence does not appear in the ranking plot for (lep, ≥ 5j) case

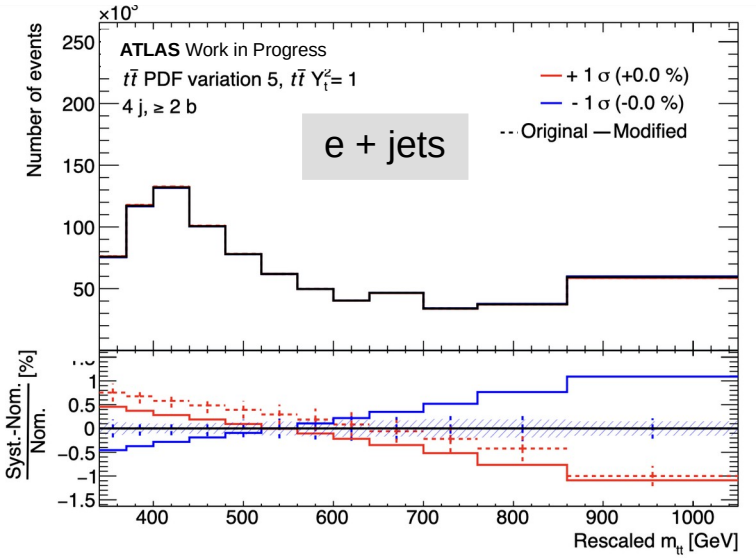


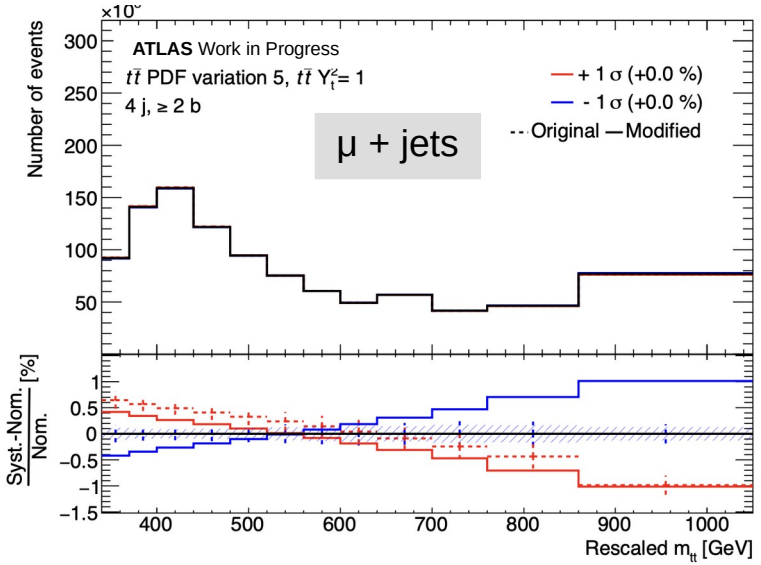


Systematic with strong shape effect

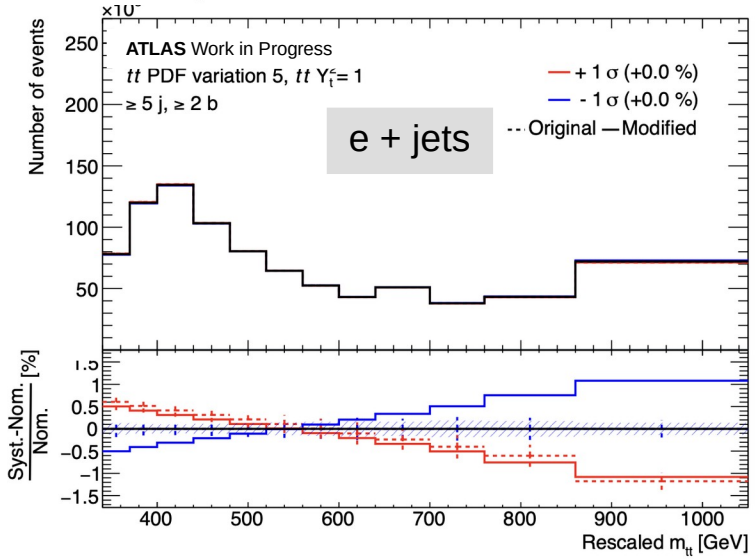
Comparison for different channels: $t\bar{t}$ PDF variation 5

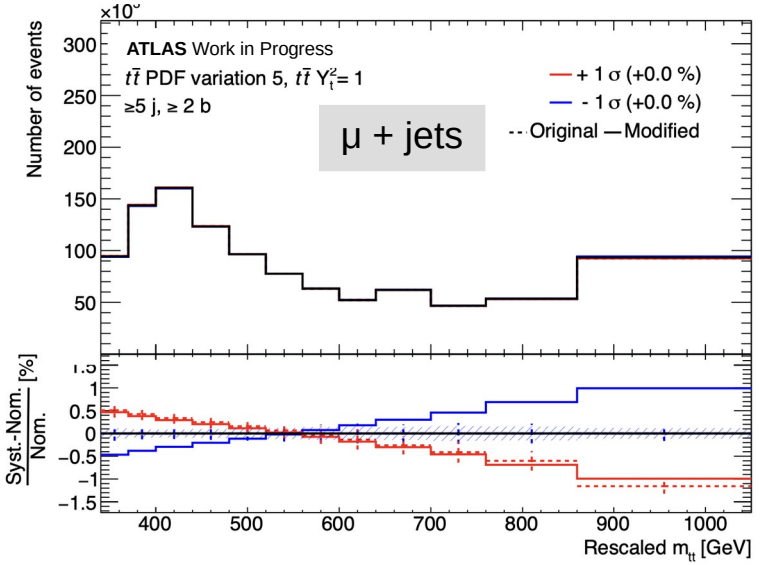






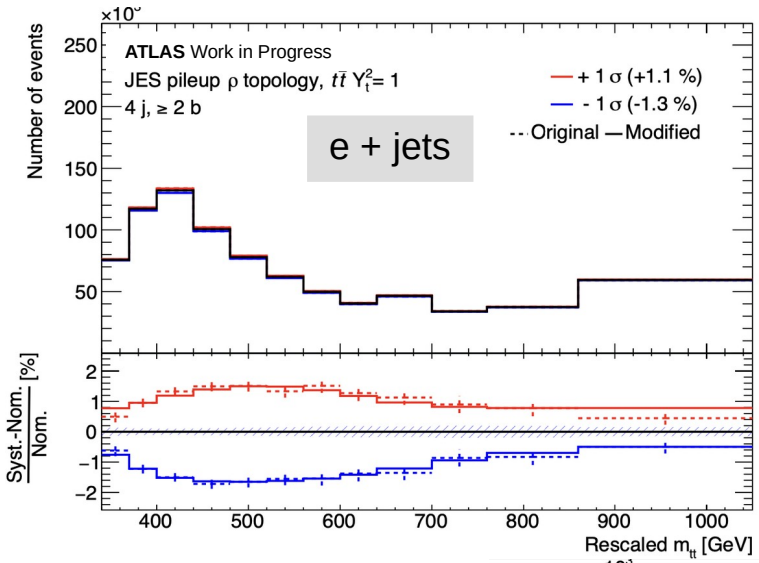
This systematic becomes important, due to the shape resembling the Y_t templates

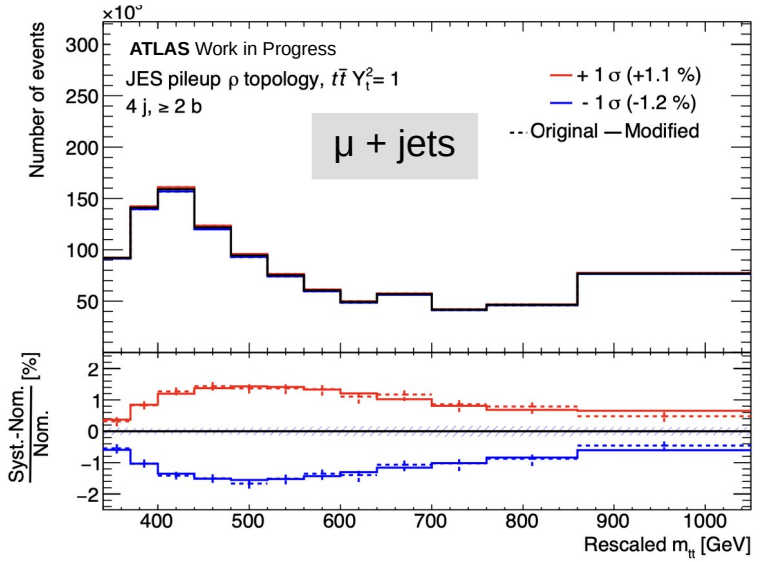




Systematic with strong effect

Comparison for different channels: Jet pileup ρ topology





Need to undertand the effect of this systematic better.