Measurement of the top-quark mass with the ATLAS experiment in 13 TeV pp collision data.

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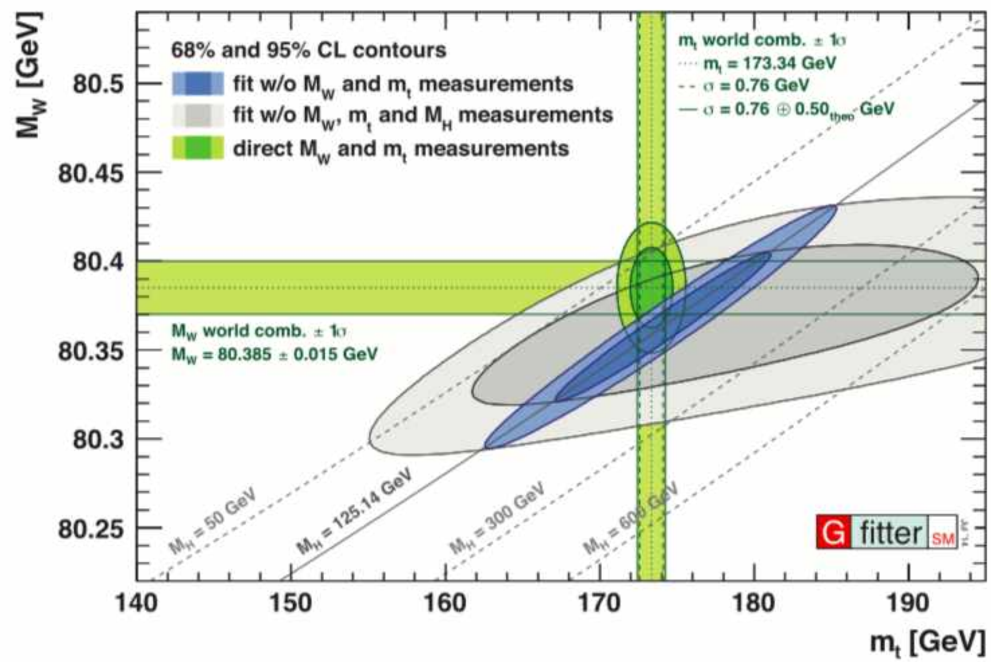
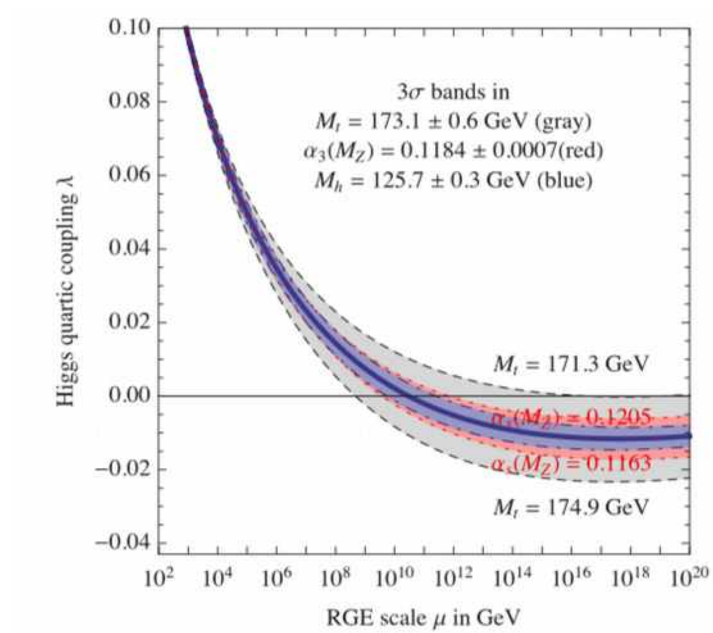
The top-quark mass

- The top quark is the heaviest known particle.
- Very short life time (τ_{top} = 0.5*10^{-24} s) and decays before hadronisation (τ^{had} ~10^{-23} s).
- Unique possibility to study "free-quark" properties: mass, width, spin, production asymmetries, entanglement...

The top-quark mass is a free parameter of the SM that need to be determined experimentally with important implications:

- Self consistency test of the SM together with Higgs and W bosons masses.
- Stability of the electroweak vacuum: top-quark radiative corrections may drive the Higgs self coupling to negative values.





Measurements of the top-quark mass

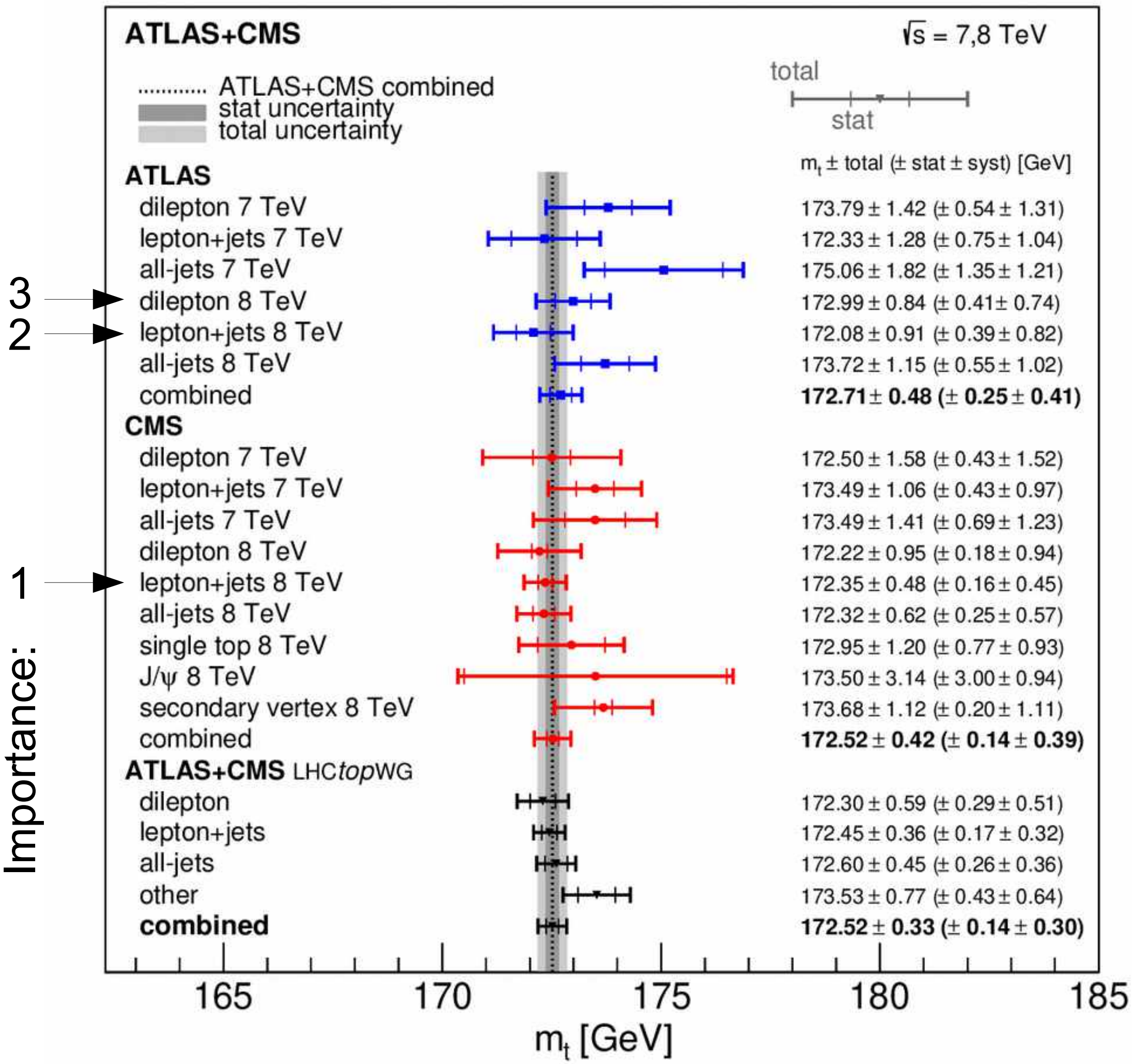
Direct measurements (focus of the talk)

- Target the MC top-quark mass, the parameter of the MC generator.
- Based on partial kinematic reconstruction of decay products from the top-quark.
- Manages to achieve great precision: Uncertainty below GeV in several measurements.
- Not directly comparable to the pole mass or other schemes.
- Recent measurement from CMS reaches a total uncertainty of 0.37 GeV: arXiv:2302.01967
- The latest combination of ATLAS and CMS measurements from Run-1 reaches a total uncertainty of 0.33 GeV: arXiv:2402.08713

Indirect measurements

- Target the a well defined mass scheme like the pole mass
- Based on inclusive or differential cross-section predictions (as a function of m_{top})
- Typically achieve worse precision than direct measurements, but improving.

Combination of Run-1 ATLAS/CMS measurements



- A combination of **fifteen** top quark mass measurements performed by the ATLAS and CMS experiments in **Run-1**.
- Using proton-proton collision data at COM of **7** & **8 TeV**.
- The combination carefully accounts for the **correlations** between measurements.
- The combination improves total uncertainty by 31% relative to the most precise input measurement.

m_t = 172.52 ± 0.14 (stat) ± 0.30 (syst) GeV = **172.52 ± 0.33 GeV**

Measurement of the top-quark mass in $t\bar{t} \rightarrow$ dilepton events with the ATLAS experiment using the template method in 13 TeV *pp* collision data

Template method: Basic idea

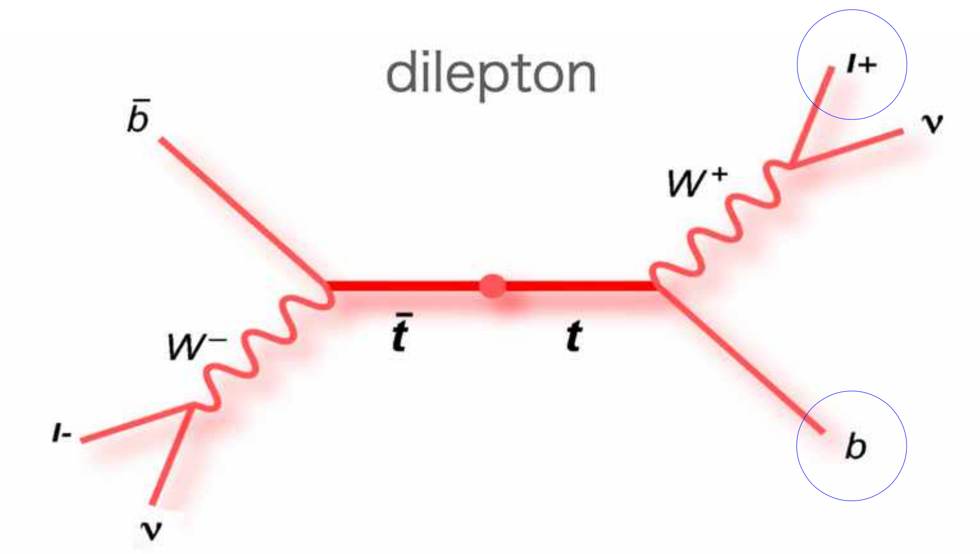
1) Build an **observable with sensitivity to the top-quark mass**.

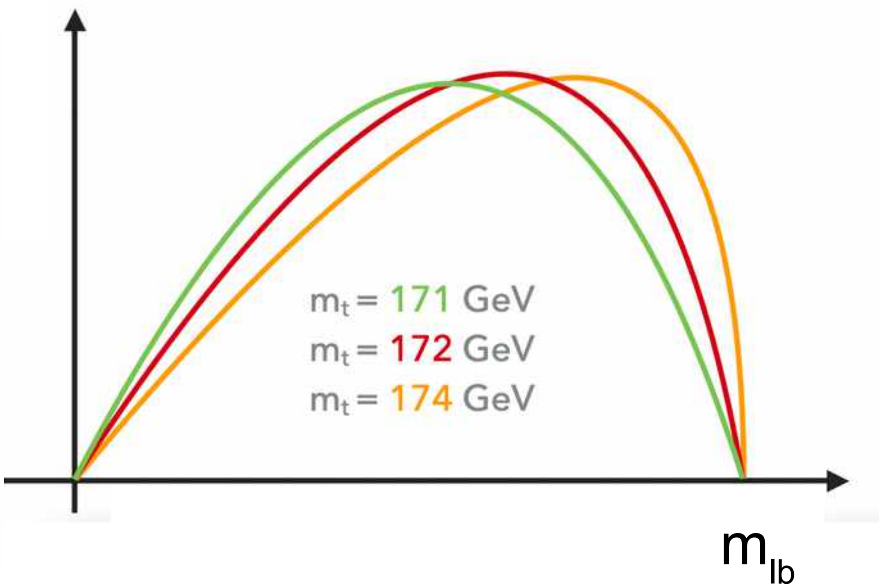
- Example: reconstructed lepton/b-jet pair invariant mass

2) Simulate multiple signal samples with varied values of the top-quark mass.

3) Produce templates parametrizing the observable shape as a function of m_{top}.

4) Perform an unbinned maximum-likelihood fit to data to extract the top-quark mass.



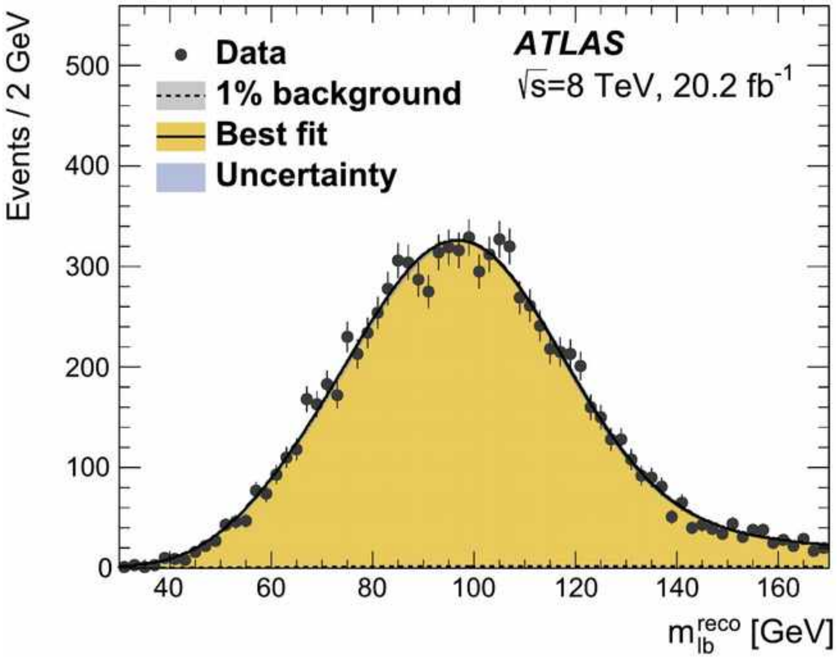


Extra steps:

- Systematic uncertainties are calculated by fitting systematically varied samples with the nominal templates and measuring the shift in the extracted value of m_{top}
- Additional templates are derived for background sources.

Dilepton template method

- ATLAS Run-1 most precise single measurement :
  m_{top} = 172.99 ± 0.41 (stat) ± 0.74 (sys) GeV
- Main systematics: JES, bJES and data statistics.
- Events reconstructed with MinAvg algorithm.
- Uses **average m_{lb}^{reco}** to extract top-quark mass.
- Reduced total uncertainty by cut in p_T^{lb} > 120 GeV.



New measurement at 13 TeV:

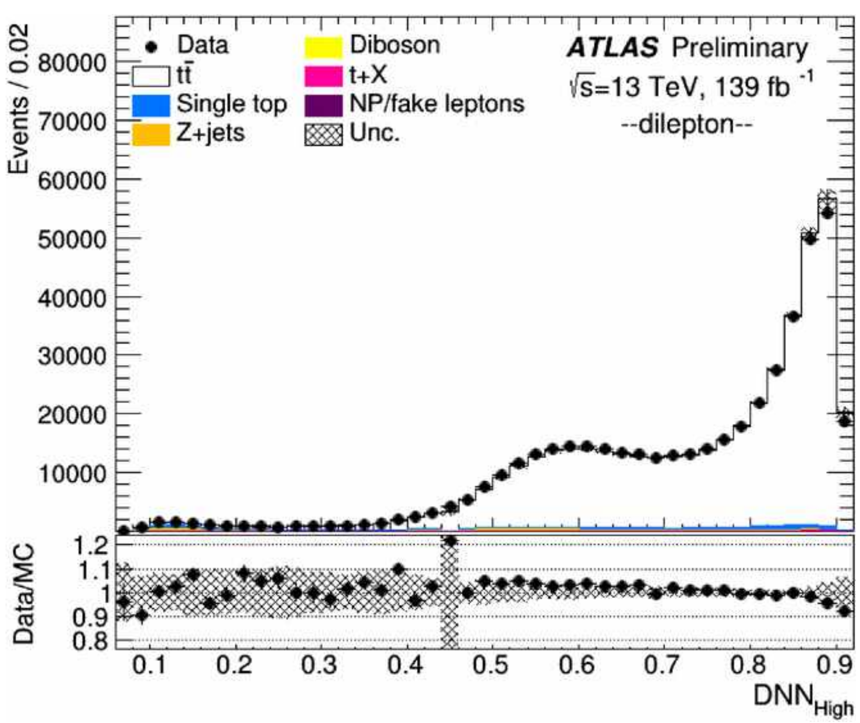
- Larger dataset (7x luminosity, XS++)
- Reconstruction of events improved by the use of a Deep Neural Network (DNN).
- Only the best reconstructed lepton/b-jet pair is used in the measurement: m_{lb}^{High}.
- Cut harder on the transverse momenta of lepton/b-jet pair: from 120 to 160 GeV.

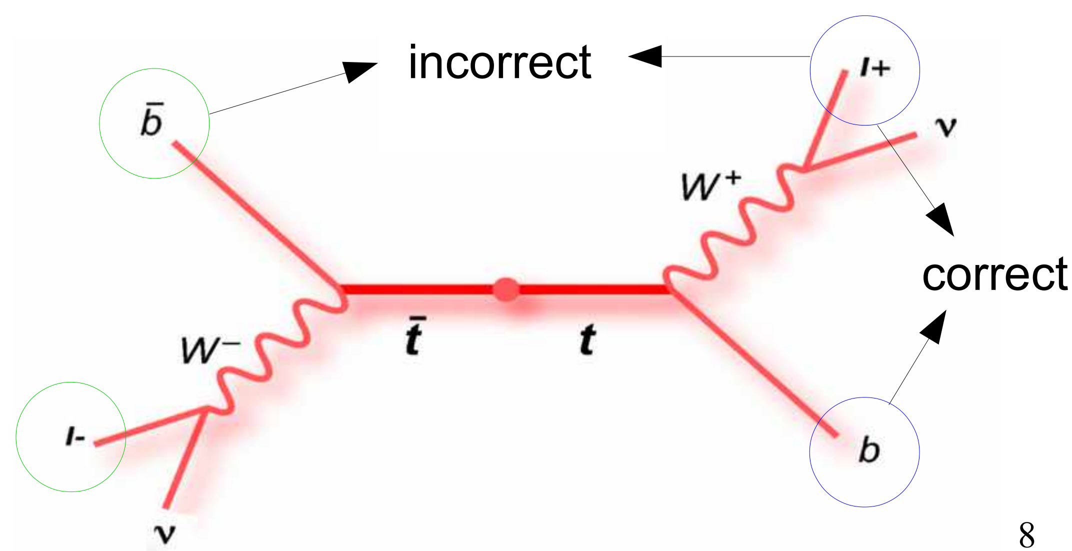
Selection in a nutshell:

- **Single-electron or a single-muon trigger.** Exactly two OS leptons of p_T > 28 GeV
- **Exactly two b-tagged jets** of p_T > 25 GeV. Avoid Z and DY with m_{ll}. No MET.

Event reconstruction

- A DNN has been trained to select the **correct pairing** of lepton/b-jets.
- Permutation choice dependent variables are used: ΔR_{lb}, m_{lb}, p_T^{lb}
- The permutation with the highest DNN score, DNN_{High}, is selected.
- High reconstruction efficiency (88%) and improved resolution in m_{lb}
- DNN_{High}: discriminant between well reconstructed events and background.

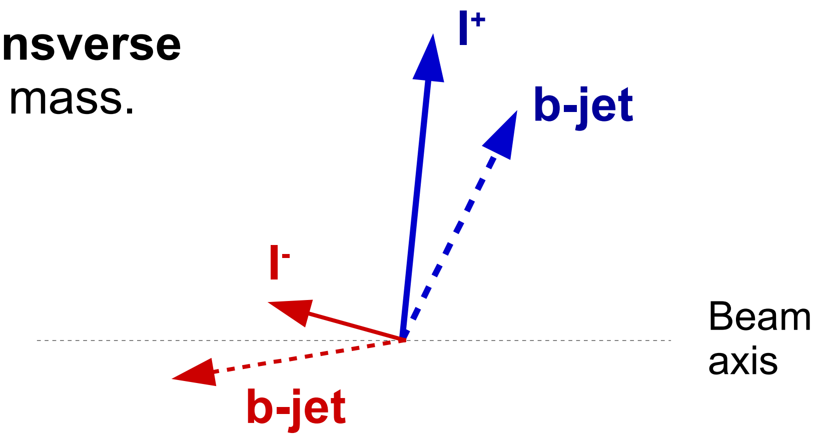


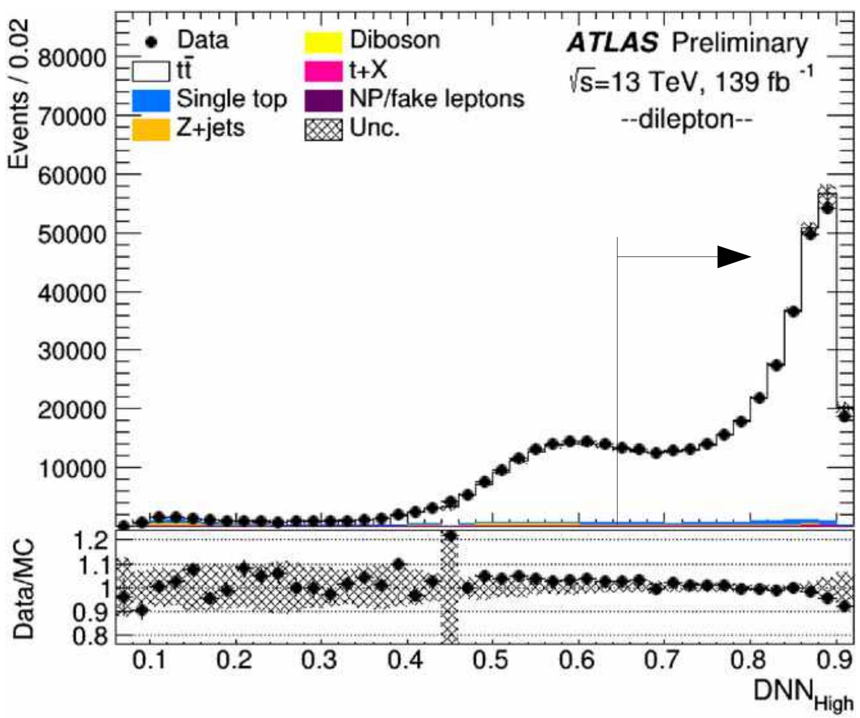


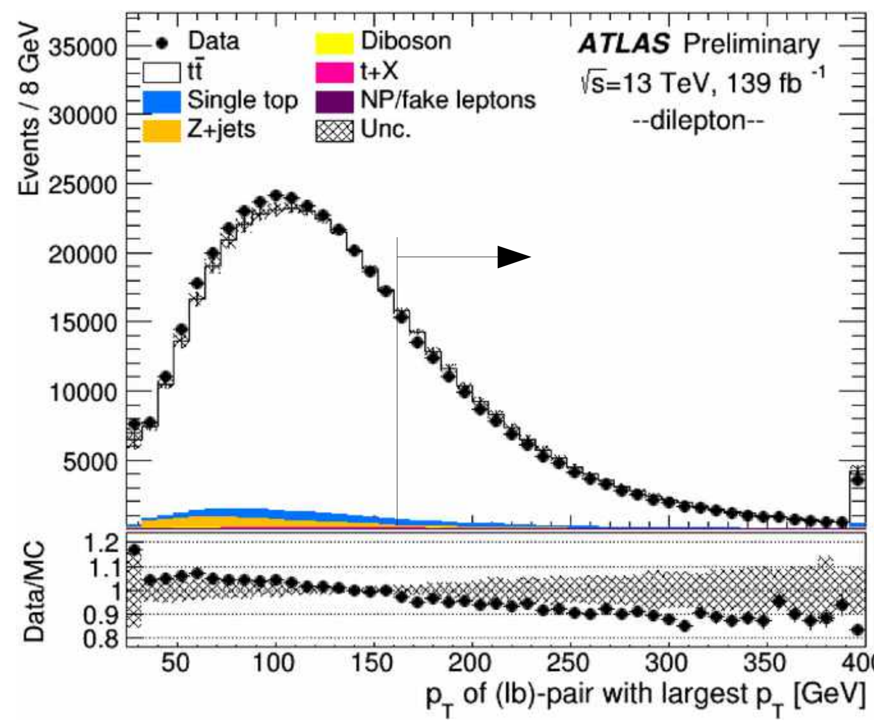
Selection optimization

Only the **lepton/b-jet pair** with the **largest transverse momentum** is used to measure the top quark mass.

- Higher reconstruction efficiency (~97%)
- Reduced systematic uncertainties.
- $DNN_{High} > 0.65$, $p_T^{lb} > 160$ GeV
- Selected b-jet has the largest p_T

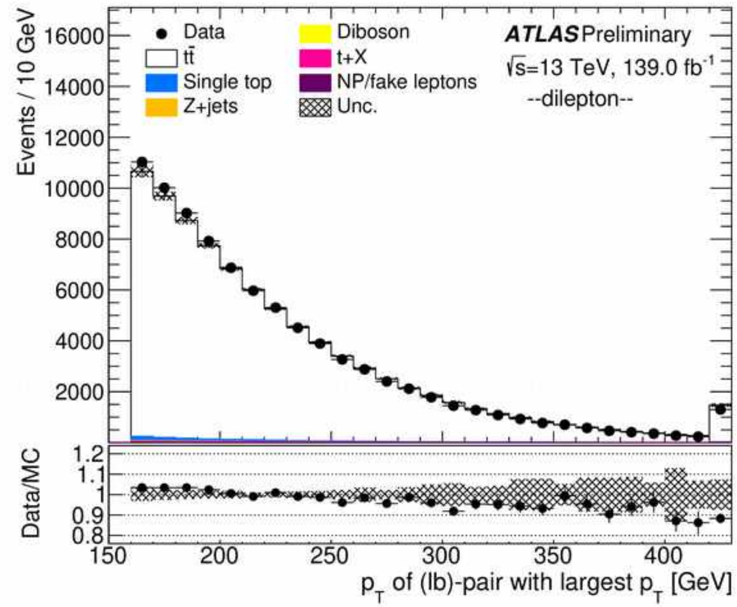


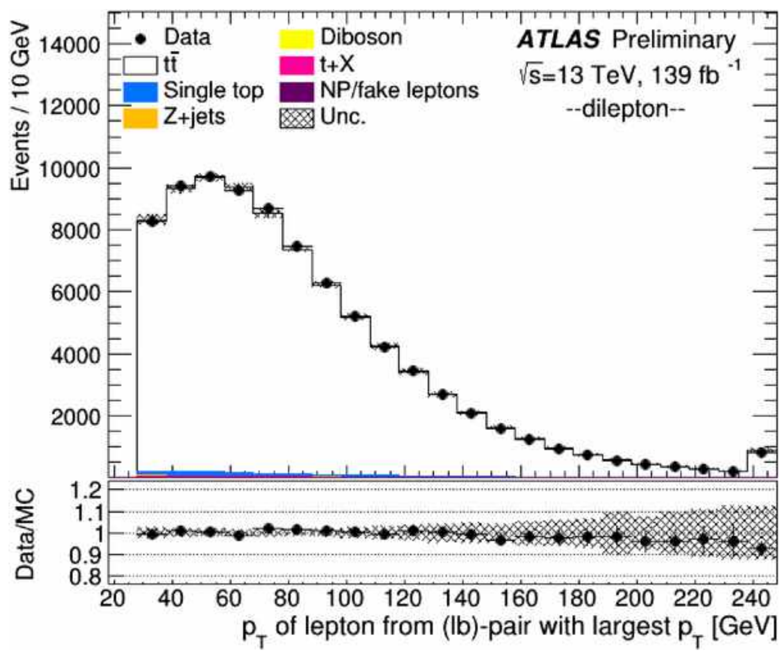


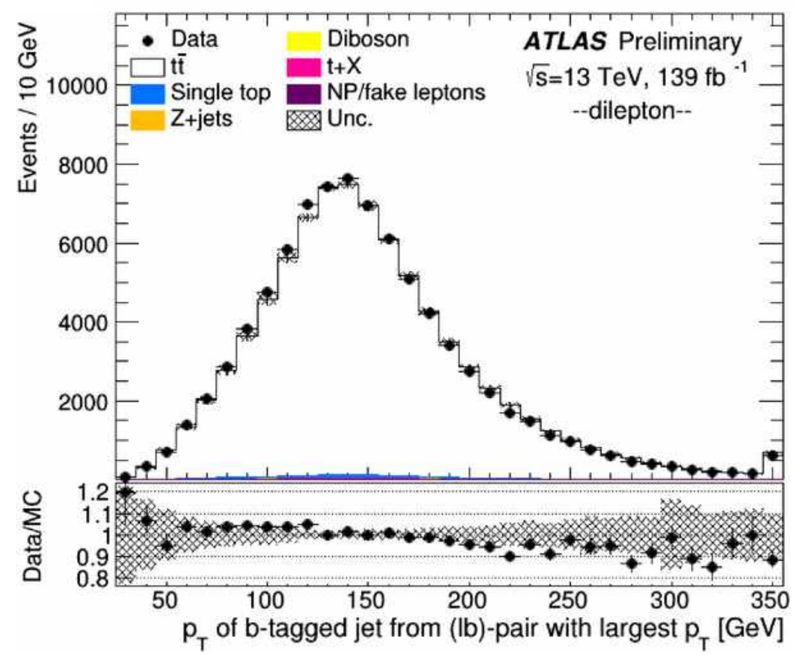


Event final selection

Data	86811
$t\bar{t}$ signal	94000 ± 5800
Single-top-quark signal	1167 ± 75
Z+jets	131 ± 52
Diboson	4.7 ± 2.4
$t\bar{t}+V$, tWZ, tZq	301 ± 46
$t\bar{t}+H$	97.0 ± 9.8
NP/fake leptons	110 ± 110
Signal+background	95800 ± 5800
Expected background fraction	0.006 ± 0.001
Data/(Signal + background)	0.906 ± 0.058



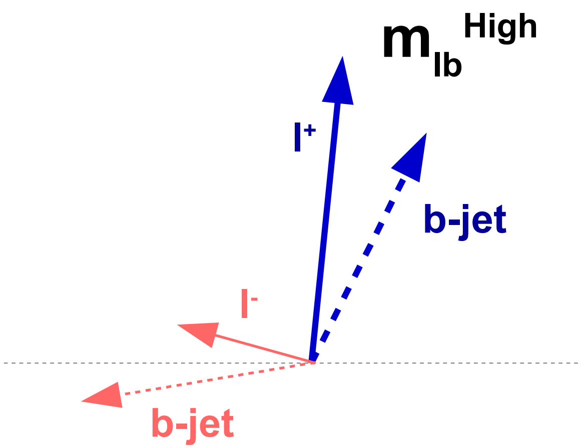


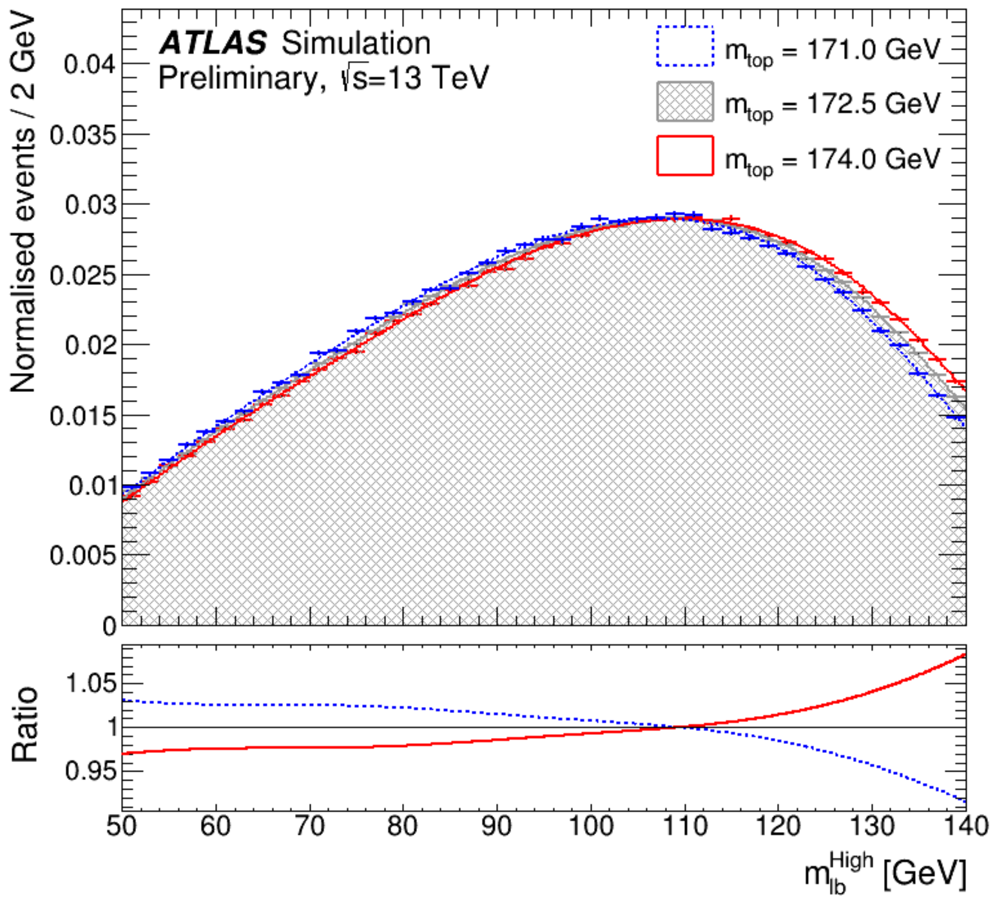


Good data/MC before and after final selection: Data/MC event yields within 10±6%

Extraction of top quark mass

- Measurement observable is $\mathbf{m_{lb}^{High}}$: invariant mass of the lb-pair with the largest p_T^{lb}.
- $\mathbf{m_{lb}^{High}}$ fitted in the range between 50 and 140 GeV: reduced systematic sensitivity.
- Templates are derived from **ttbar and single top** samples simulated with different values of m_{top} and parametrized: The final template fit only depends on m_{top}.
- Systematic uncertainties are evaluated by fitting each varied sample.



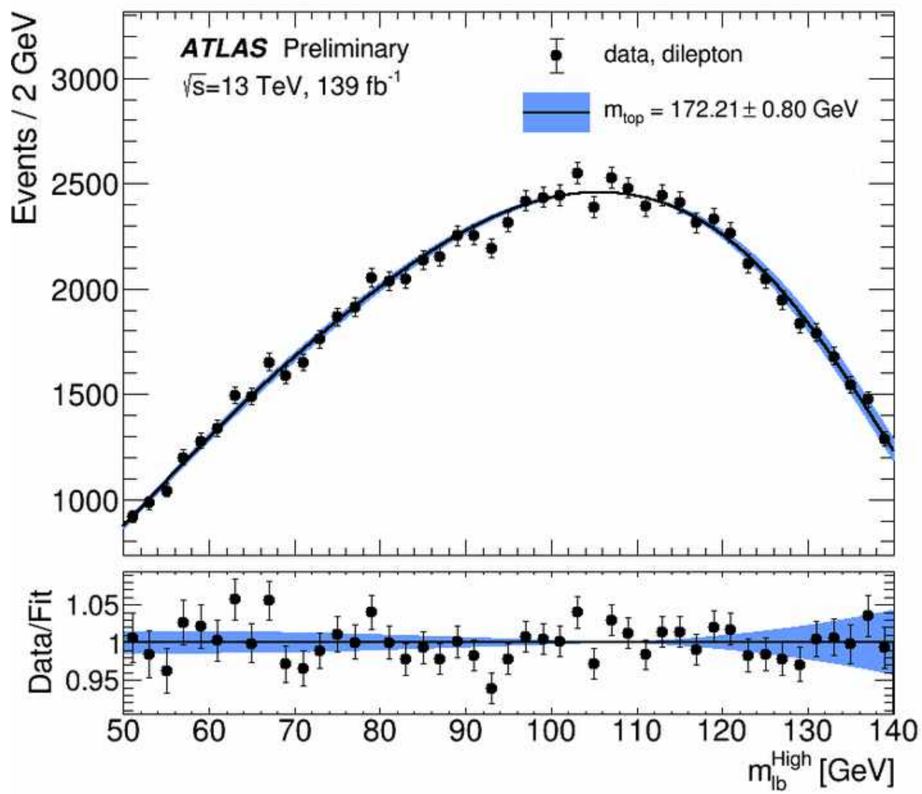


Final result and leading uncertainties

The top quark mass is measured in the dilepton channel using the lepton/b-jet invariant mass with a total **uncertainty of 0.80 GeV**.

Leading uncertainties are:

- The **Matrix-element matching**. (0.40 GeV)
- The **recoil scheme** (0.39 GeV) **New**
- The Jet Energy Scale. (0.37 GeV)
- The colour reconnection. (0.27 GeV)
- Data statistics (0.20 GeV)
- Initial and final state radiation (0.20 GeV)



$$m_{\text{top}}^{\text{dilepton}} = 172.21 \pm 0.20\,(\text{stat}) \pm 0.67\,(\text{syst}) \pm 0.39\,(\text{recoil})\ \text{GeV}.$$

Modelling = 0.65 GeV, detector = 0.43 GeV

Current measurement limited by signal modelling.

Signal modelling uncertainties:

Recent developments

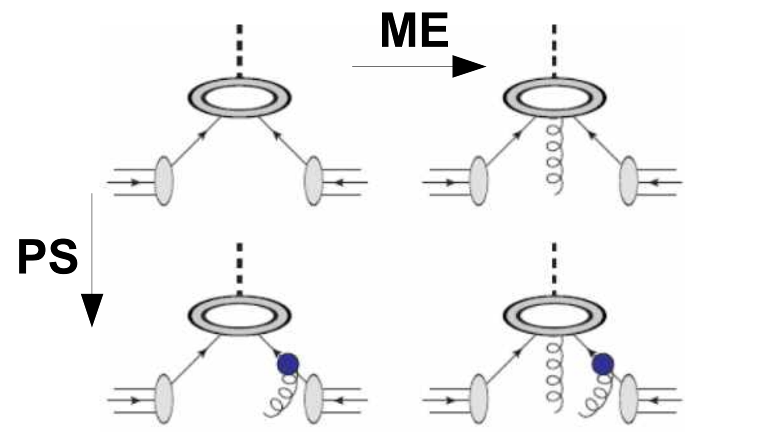
Improving matching uncertainty

Top-quark processes modeled in ATLAS by matching:

- Hard-scatter matrix element (ME) calculations of NLO MC generators
- Parton shower generator (PS).
- Ex: Powheg+Pythia

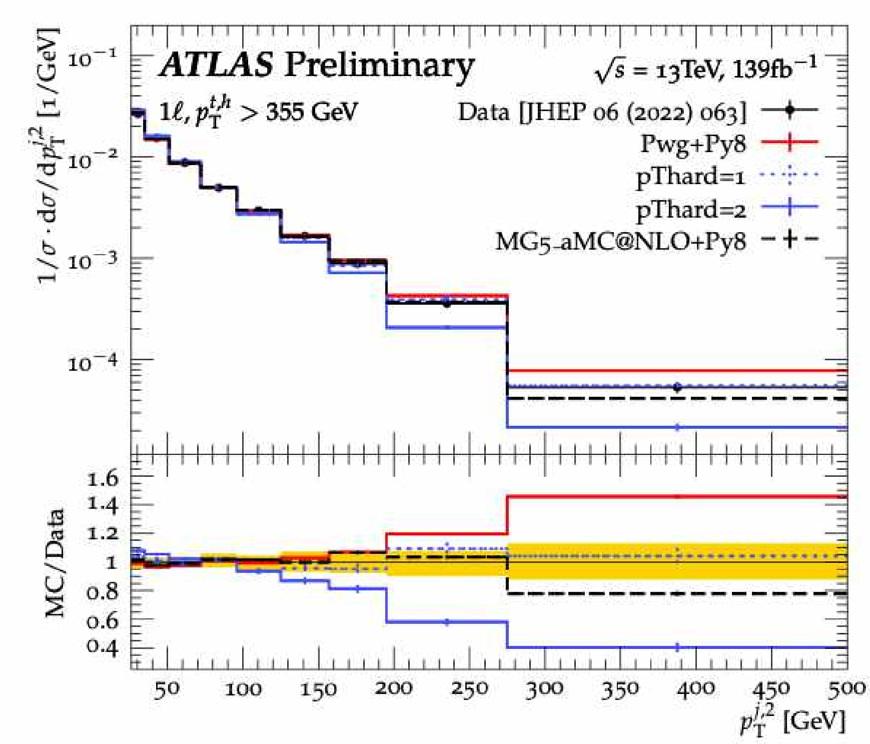
Uncertainty traditional comparing two generator setups.

- Ex: Powheg+Pythia Vs aMC@NLO+Pythia.



Powheg and Pythia: order of emissions is handled by a variable related to p_T of the emissions called "hardness" or pThard.

- Double counting avoided by vetoing PS emissions in the phase space covered by Powheg.
- Differences in the "hardness" definition can introduce double counting or not covered regions.



New uncertainty treatment: comparison of two pThard definitions:

--- pThard-0: The Powheg definition value.

- - pThard-1: The p_T of the Powheg emission.

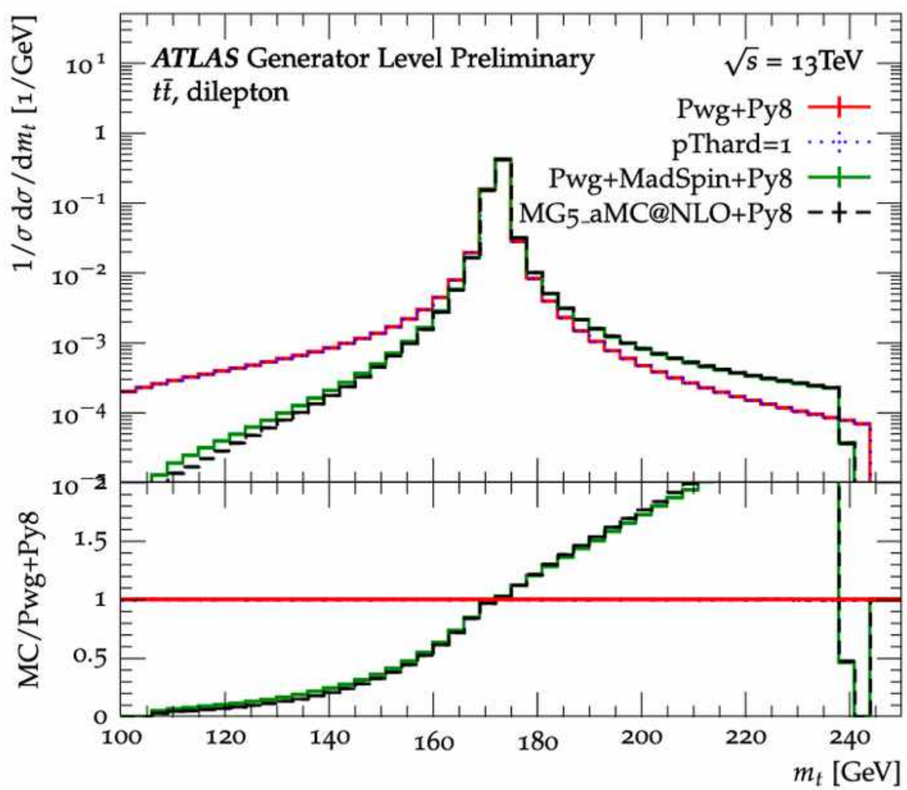
Improving matching uncertainty

Two additional effects considered as an uncertainty:

Top quark lineshape

Decay of the top-quark is based on the narrow width approximation with a smearing of a Breit-Wigner followed by momentum reshuffling.

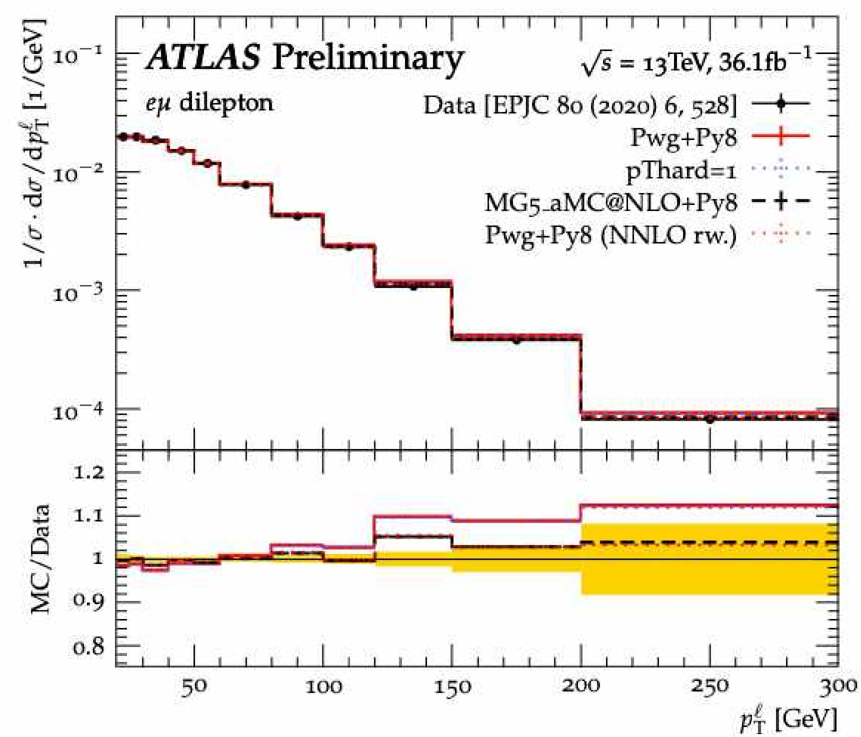
Two different ways of doing this are implemented in PowhegBox and MadSpin



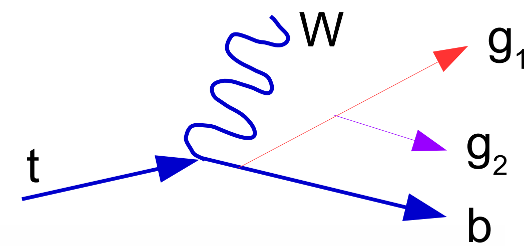
Top-quark p_T mis-modelling

Observed mis-modelling due to absence of higher-order corrections that would soften the top-quark p_T spectrum.

A reweighted (using weights from a NNLO calculation) nominal sample can be used to access a system uncertainty and/or to get the prediction in agreement with the data.



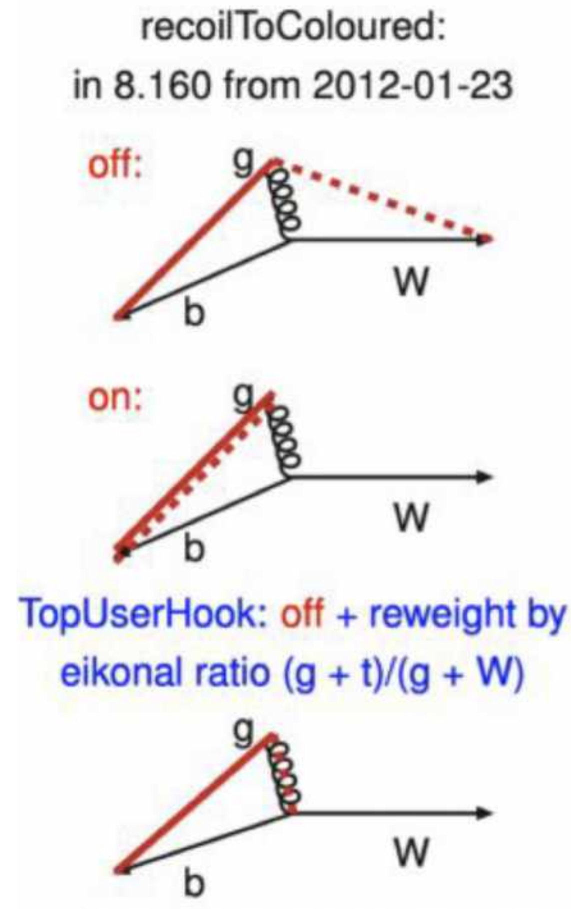
Radiation and recoil effects



First emission of a gluon (g_1) in the final state is controlled with NLO matrix element corrections (MEC).

Second emission (g_2) is not: ambiguity in the treatment.

- Recoil-to-Colour=ON: Any gluon radiation after the FE recoils against the b-quark.
- Recoil-to-Colour=OFF : W boson is the recoiler. Too much radiation along W direction.
- Recoil-to-Top. New scheme allows the top to be the recoiler. Suppresses radiation in W hemisphere.



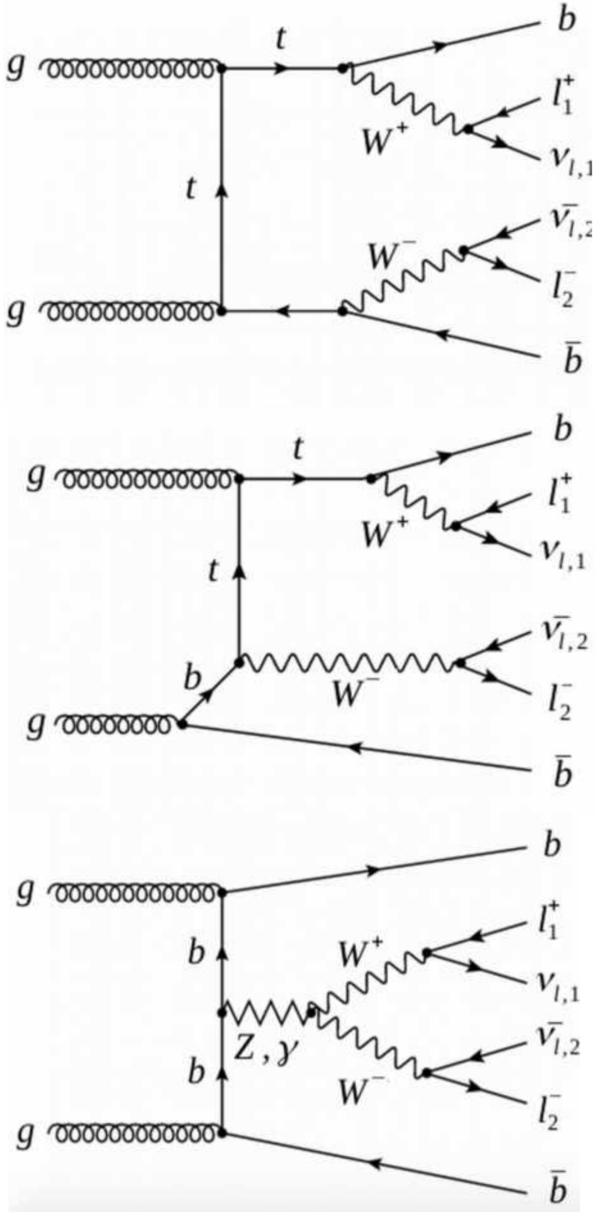
(Sketch by T. Sjostrand)

All these schemes vary the amount of out-of-cone radiation, and the W/b momentum fraction, what translates into a shift of the inferred m_{top}.

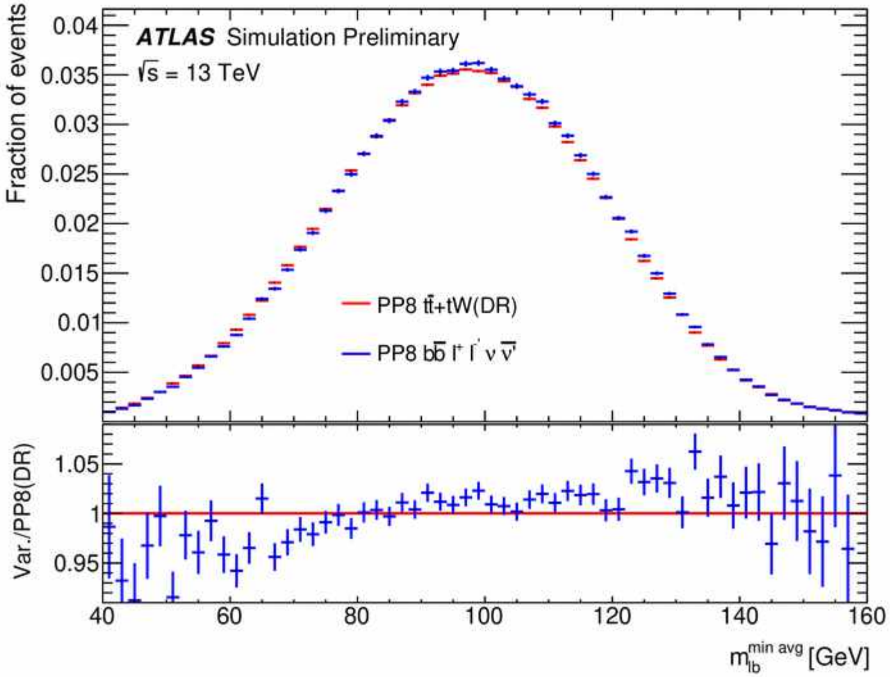
- ATLAS has added recoil-to-top vs recoil-to-colour=ON as an additional uncertainty.
- **No dedicated tuning of the recoil-to-top** has been performed yet. Current uncertainties probably overestimate the effect.

- **Next steps:** Implement Vincia in ATLAS. Better description of shower model.

Non-resonant and off-shell effects: bb4l



- Final states of **ttbar and Wt+b** production are **identical**.
- Traditionally, they are produced individually and the interference is handled through diagram removal.
- A new bb4l NLO generator targets the bb4l final state, better describing the ttbar/Wt interference.
- Also off-shell effects and non-resonant production.
- Plans to use bb4l as nominal generator in the future.



- In the most recent dilepton template method:

$$\Delta m_{top} = m_{top}^{bb4l} - m_{top}^{nom} = 0.23 \pm 0.14 \text{ GeV}$$

Summary and conclusions

Summary and conclusions

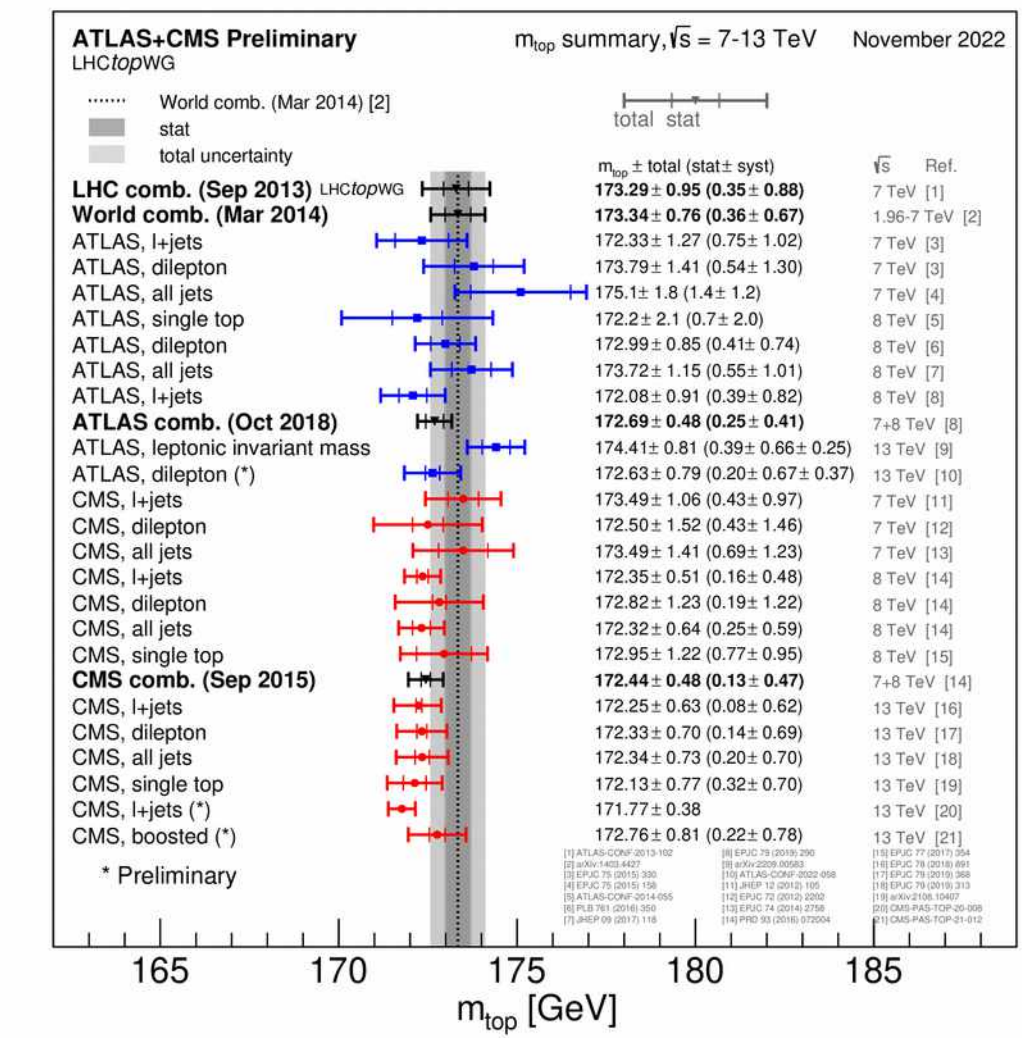
- The most recent direct measurement of the top-quark mass from ATLAS have been presented: **A precision of 0.80 GeV is achieved**
- The **event reconstruction** method has been **improved with a DNN**.
- Only the **lepton/b-jet pair with largest p_T** is used to reduce systematics.
- The **detector related uncertainties start to be subdominant** compared to modelling uncertainties: Excellent performance of ATLAS detector in Run-2.
- ATLAS actively working in the improvement of modelling uncertainties.
- The latest studies about the Matching uncertainty have been presented, replacing comparisons of different generators by dedicated variations.
- The measurement show that **the choice of the recoil scheme can lead to significant shifts in the top quark mass** and that more studies are needed to provide a sensible recipe to take this effect into account.

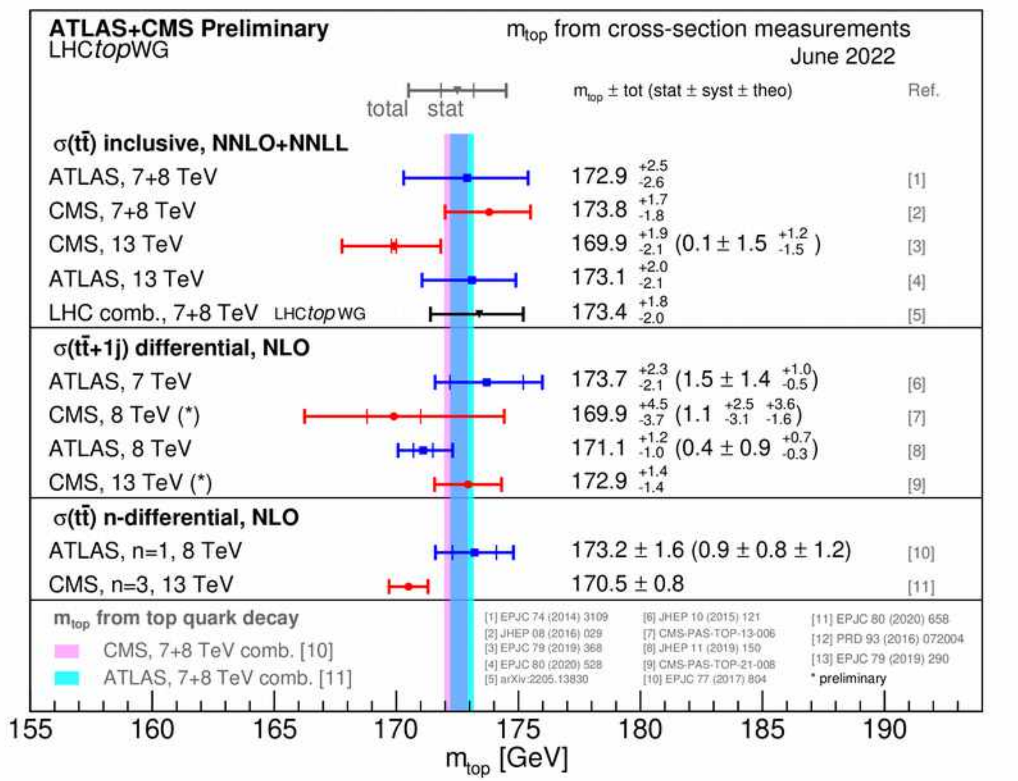
- New measurement with improved modelling systematics and extended also to lepton+jets channel expected to finalize soon. Stay tuned.

Thanks for your attention

Backup

Direct (MC) and indirect (pole) top mass





Event yields & full systematic breakdown

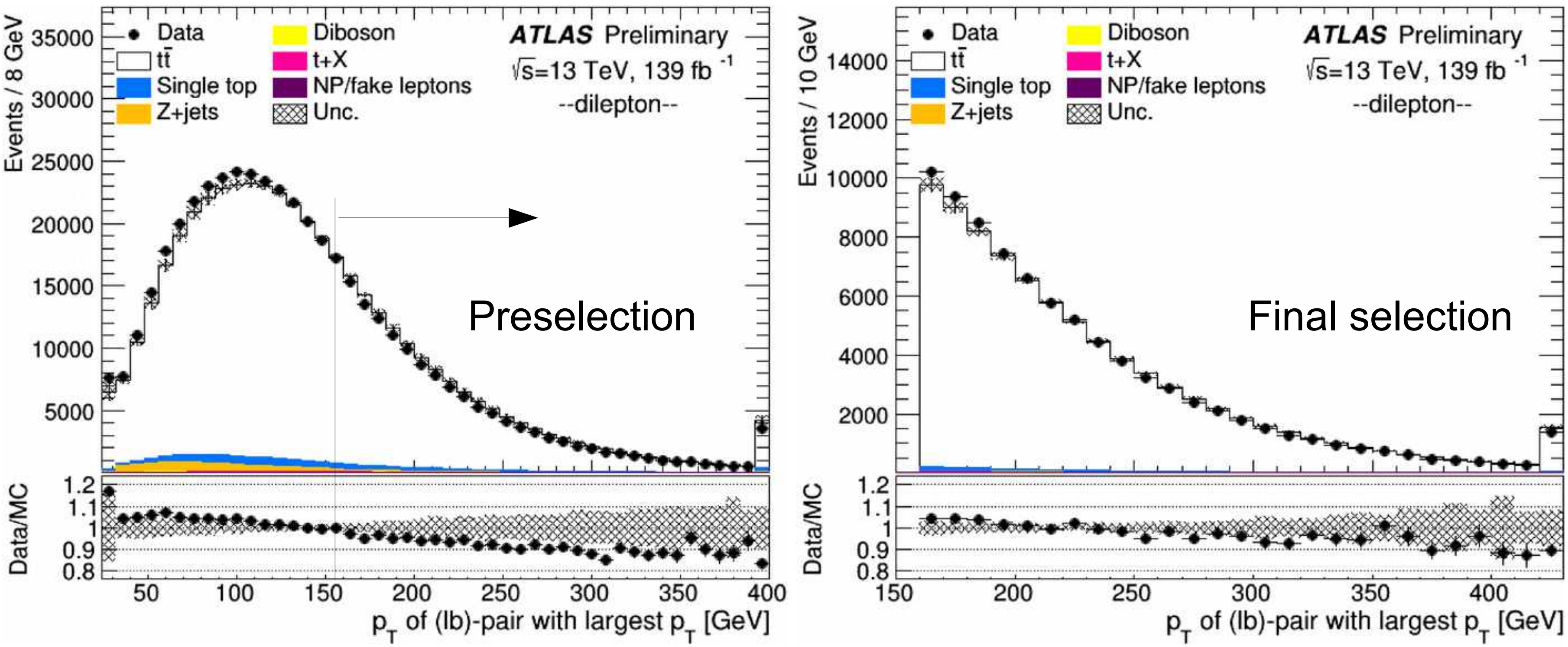
Data	454960
$t\bar{t}$ signal	445000 ± 28000
Single-top-quark signal	14320 ± 890
Z+jets	10200 ± 4400
Diboson	420 ± 210
$t\bar{t}+V$, tWZ, tZq	1320 ± 200
$t\bar{t}+H$	440 ± 45
NP/fake leptons	760 ± 760
Signal+background	472000 ± 29000
Expected background fraction	0.028 ± 0.010
Data/(Signal + background)	0.963 ± 0.059

Data	83785
$t\bar{t}$ signal	90800 ± 5800
Single-top-quark signal	1144 ± 74
Z+jets	122 ± 49
Diboson	4.1 ± 2.2
$t\bar{t}+V$, tWZ, tZq	270 ± 41
$t\bar{t}+H$	86.9 ± 8.8
NP/fake leptons	100 ± 100
Signal+background	92500 ± 5800
Expected background fraction	0.006 ± 0.001
Data/(Signal + background)	0.905 ± 0.058

	m_{top} [GeV]
Result	172.63
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.35 ± 0.07
Parton shower and hadronisation	0.08 ± 0.05
Initial- and final-state QCD radiation	0.20 ± 0.02
Underlying event	0.06 ± 0.10
Colour reconnection	0.29 ± 0.07
Parton distribution function	0.02 ± 0.00
Single top modelling	0.03 ± 0.01
Background normalisation	0.01 ± 0.02
Jet energy scale	0.38 ± 0.02
b-jet energy scale	0.14 ± 0.02
Jet energy resolution	0.05 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.12 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.37 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.79 ± 0.06

Impact of the transverse momentum cut

- 10±6% more events are predicted by the simulation than are observed in data.
- Caused by the p_T^{lb} > 160 GeV requirement: softer data p_T spectrum than in MC.
- Caused by a softer top-p_T as observed in previous analyses. 8 TeV: ΔEY = 7±7%.

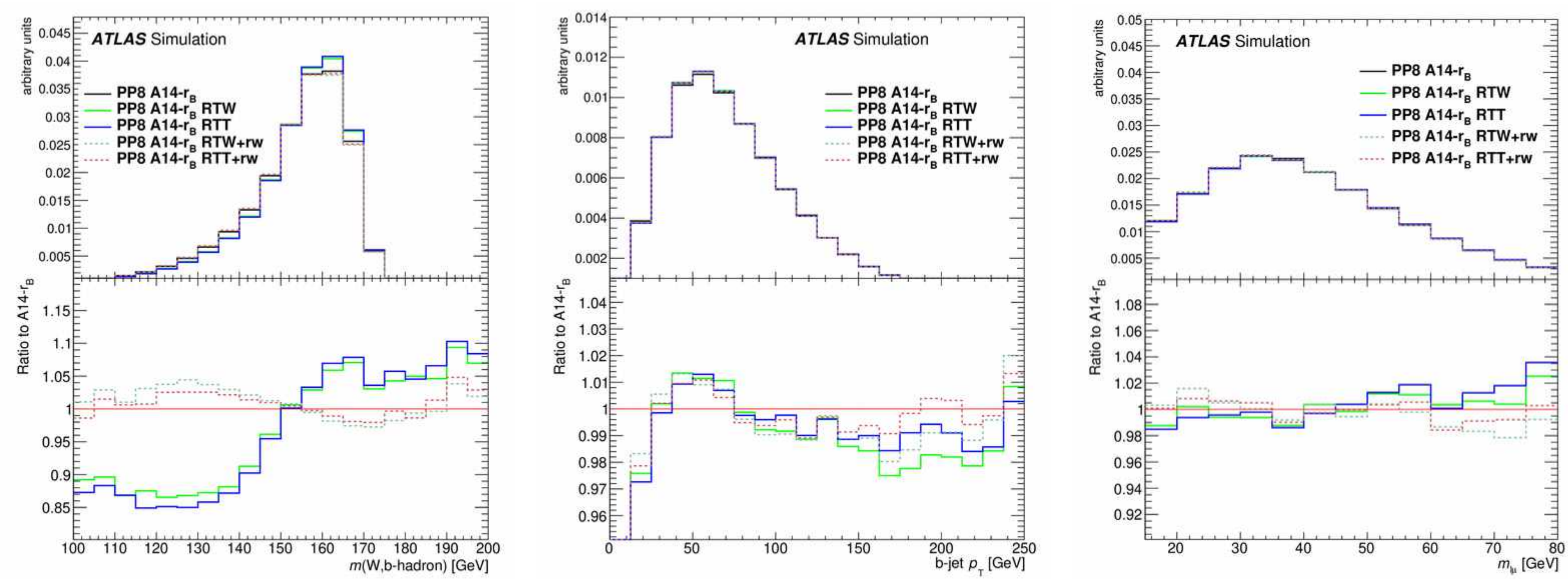


- A parton-level reweighting to the NNLO calculation as a function of p_T^{top}, p_T^{tt}, m_{tt} has been tested: Δm_{top} = 0.10 ± 0.01 GeV, smaller than scale variations uncer.

ATLAS-CONF-2022-058
arXiv.2209.00583
TOPQ-2017-17

Radiation and recoil effects

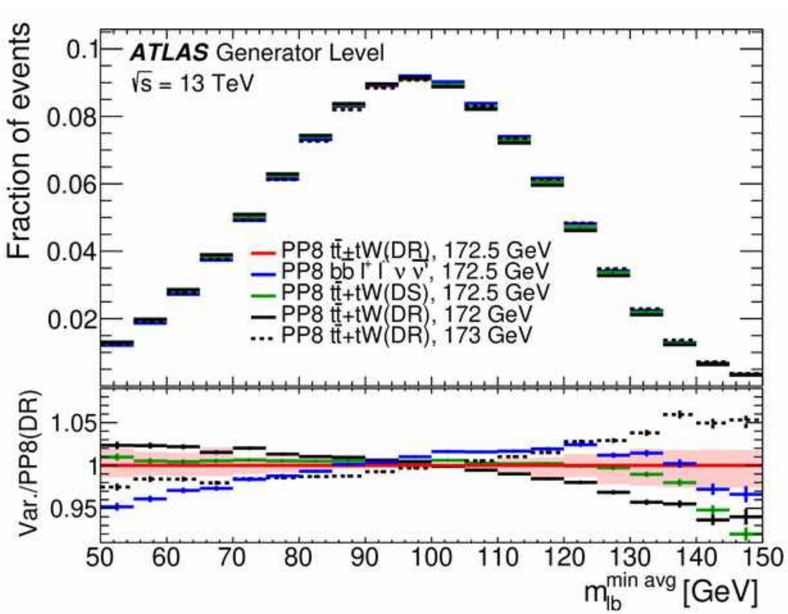
As the recoil scheme modifies the distribution of the b-hadron momentum fraction, for the SMT analysis, a rederivation of the best rb value has been performed for RTT.

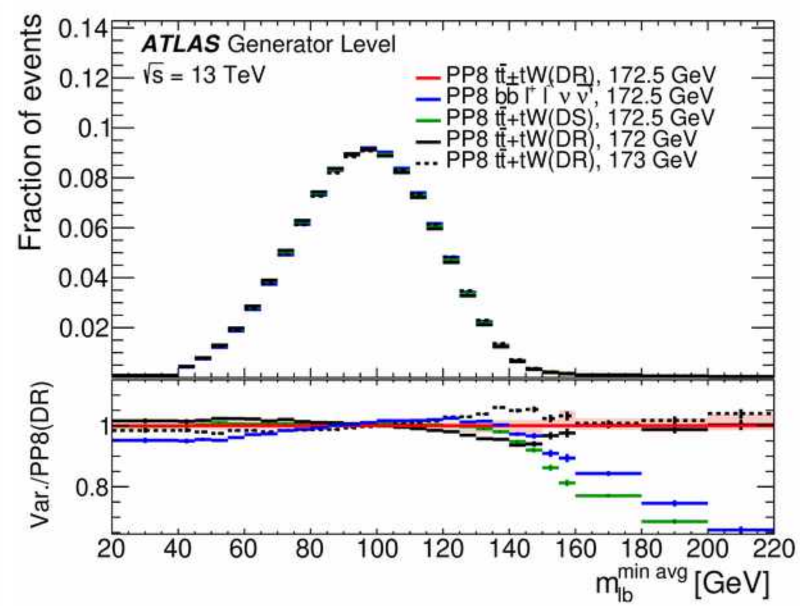


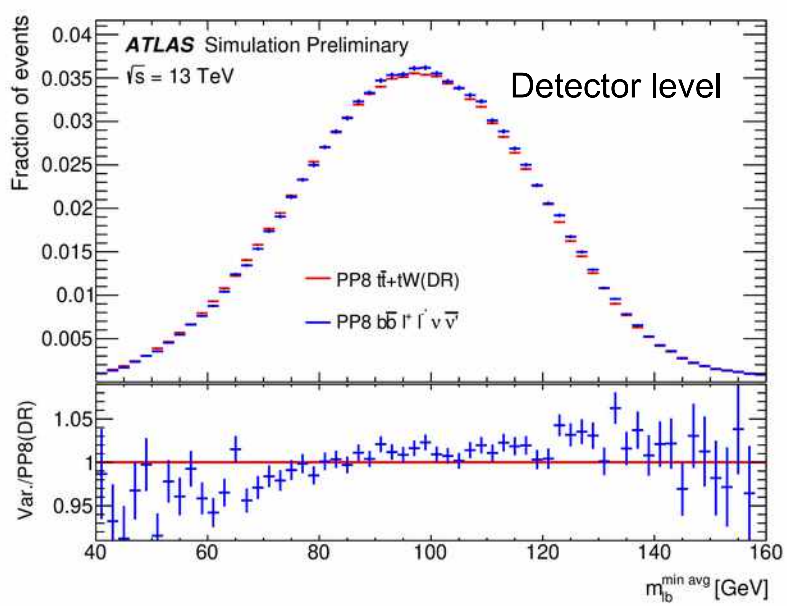
Δm_{top}(recoil-to-Top – recoil-to-colour=ON) [SMT] = 250 MeV

Δm_{top}(recoil-to-Top – recoil-to-colour=ON) [dilep] = -370 ± 90 MeV

Non-resonant and off-shell effects: bb4l







- Larger effects in the tails of the m_{lb} distribution: Where actually Off-shell effects are expected to be more important.
- At detector level, the differences seem to be slightly reduced, but low stats.
- Working in a hacked sample to include SF lepton production.