Recent measurements of the top-quark mass and other properties with the ATLAS detector

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Javier Jiménez Peña

Institut de Física d'Altes Energies
IFAE (Barcelona)

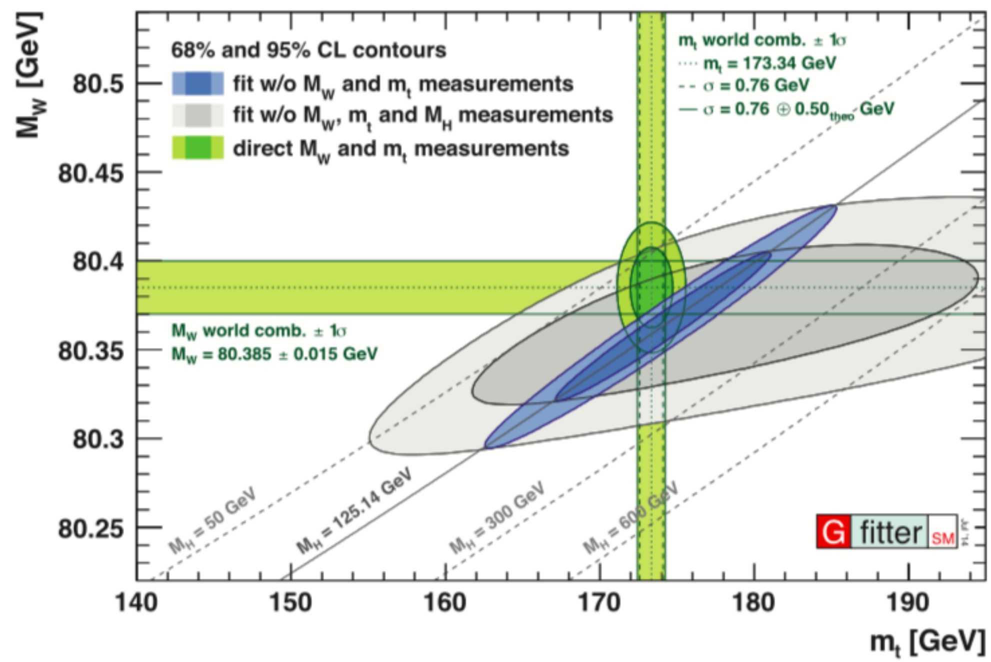
ATLAS collaboration

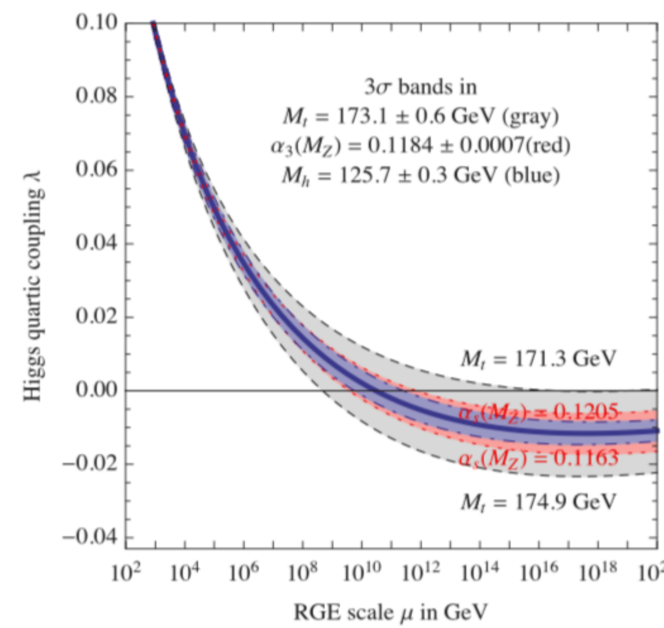
Introduction: the top-quark

- 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 and: mass, width, spin, production asymmetries...

- It´s **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.

- The **polarization of the top-quark** is accessible through the decay products. Allowing further tests of the SM.

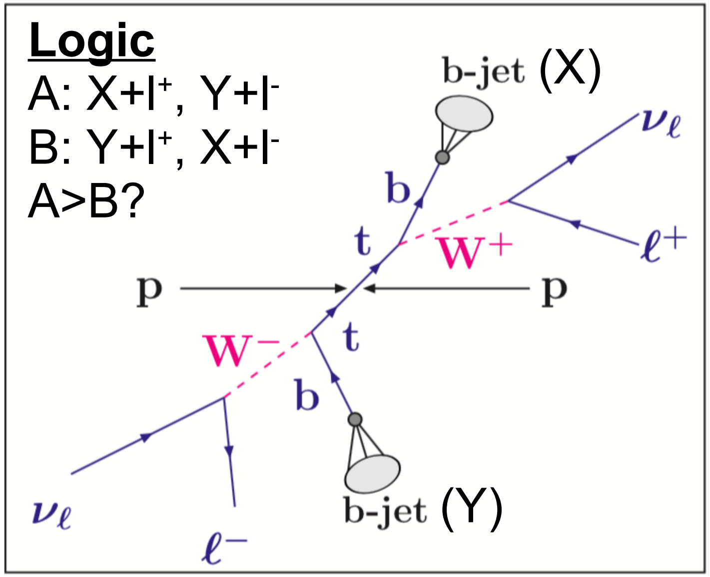


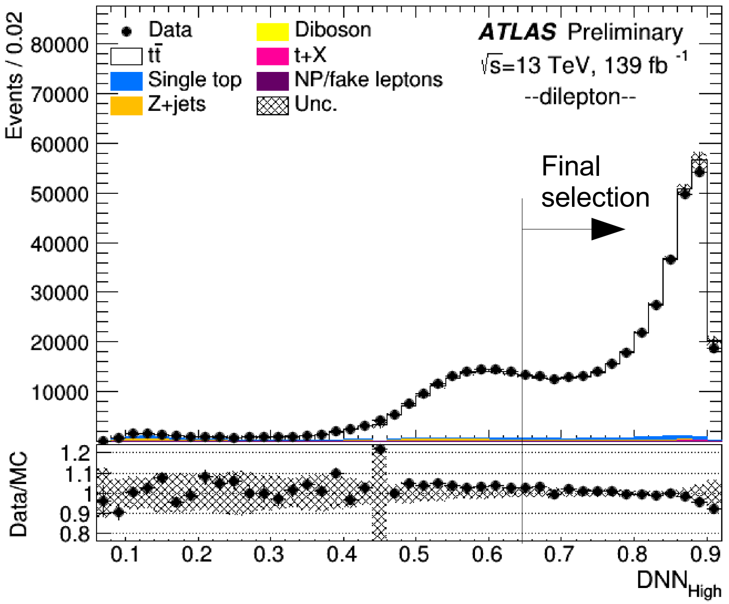


Top-quark mass template measurement

Preselection and event reconstruction DNN

- **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 cuts.

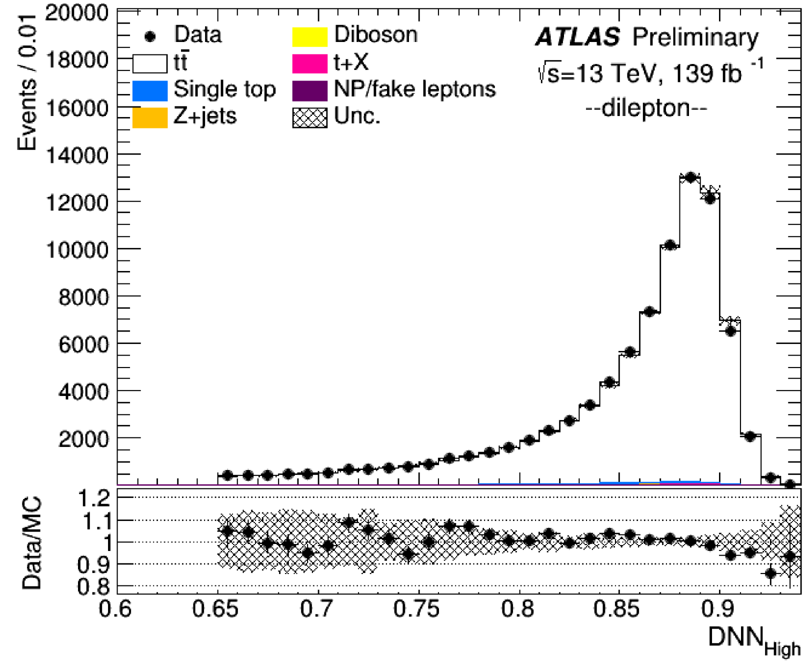


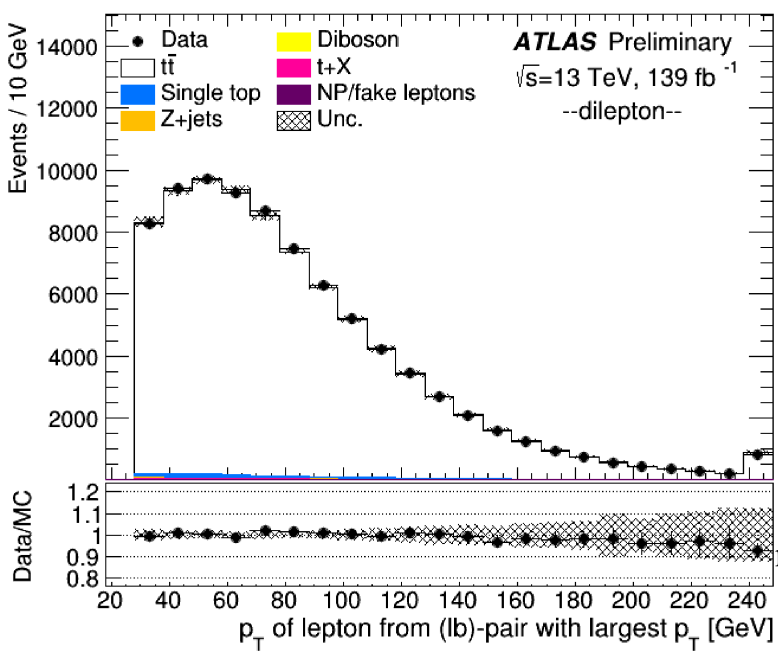


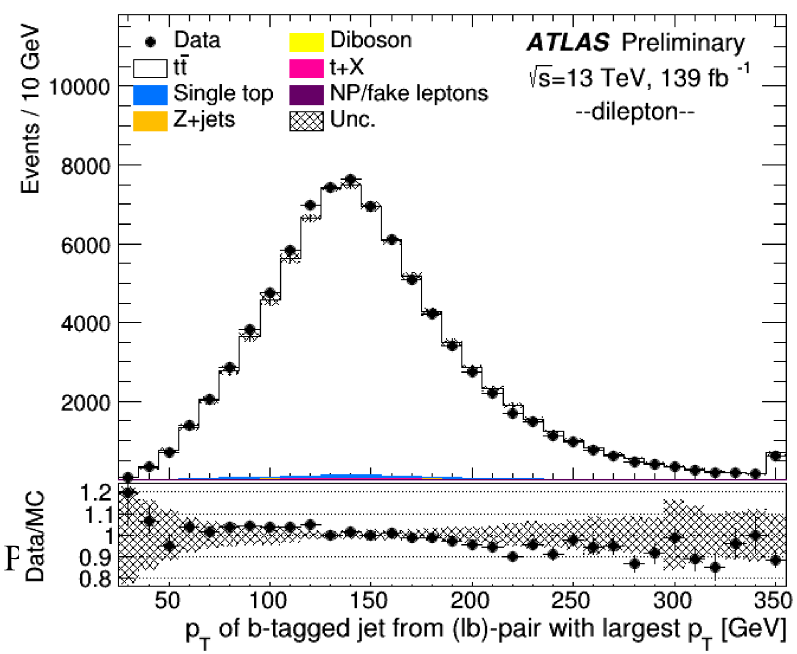
- For each event, both permutations are evaluated and the one obtaining the highest DNN score, DNN_{High}, is selected.
- Variables that depend on the permutation choice are needed: invariant masses and transverse momenta of the lb-pairs, lep/b-jet angular separation...

Event final selection

- Only the **lepton/b-jet pair with the largest transverse momentum is used** to measure the top quark mass.
- It has a **higher reconstruction efficiency** (~97%)
- **Reduces systematic uncertainties.**
- DNN_{High} > 0.65, p_T^{lb} > 160 GeV and selected b-jet has the largest p_T
- Good data/MC agreement in general.
- data/MC event yields agreement within 10±6%

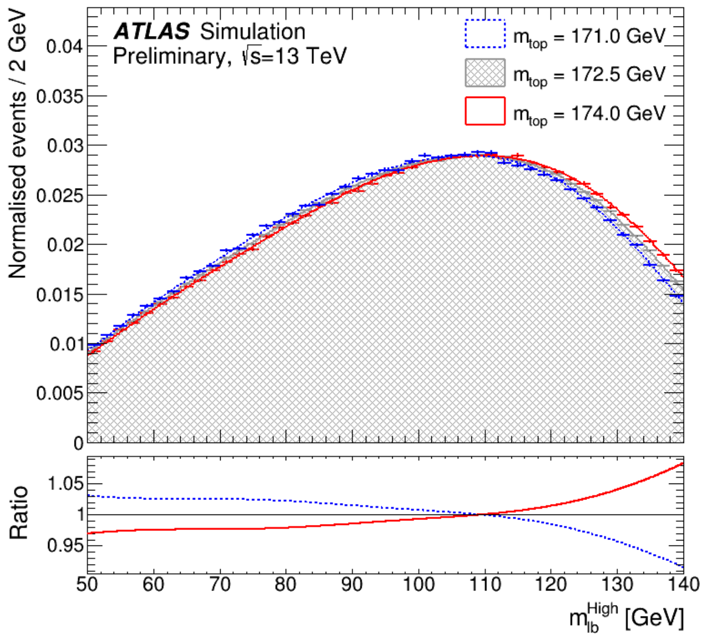


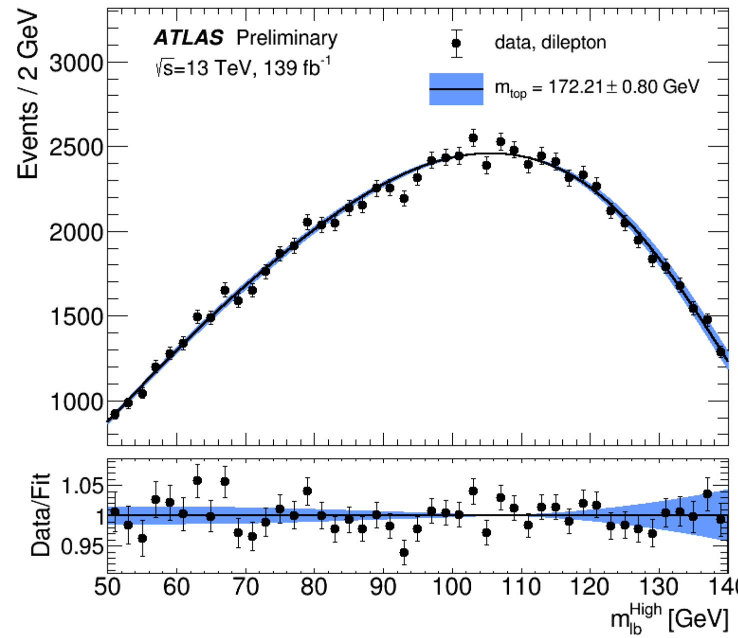




Final result and leading uncertainties

- Measured with **unbinned maximum likelihood** fit to data.
- **Invariant mass of the lepton/b-jet pair with the largest p_T, m_{lb}^{High}.**





Leading uncertainties:

- Matrix-element matching. (0.40 GeV)
- Recoil scheme (0.39 GeV) **New**
- Jet Energy Scale. (0.37 GeV)
- Colour reconnection. (0.27 GeV)

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

Current measurement limited by signal modelling (0.65 vs 0.43 GeV).

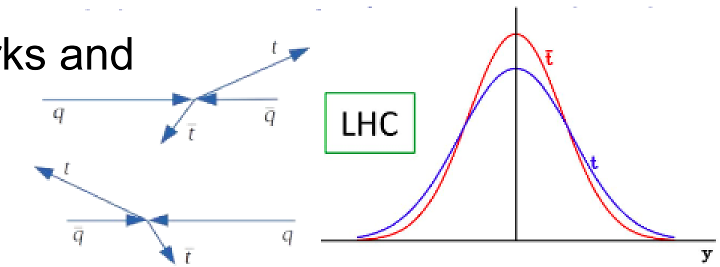
Charge asymmetry in ttbar production

Charge asymmetry in top pair production

JHEP 08 (2023) 077

- **Slight central-forward difference** in rapidity between top quarks and antiquarks in top pair production **at the LHC**, quantified as:

$$A_C = \frac{N(|y_t|>|y_{\bar{t}}|) - N(|y_t|<|y_{\bar{t}}|)}{N(|y_t|>|y_{\bar{t}}|) + N(|y_t|<|y_{\bar{t}}|)}$$



Arising from interference effects among **QCD diagrams at NLO**:

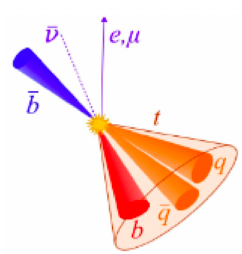
- Introduced by quark-antiquark initiated production, but **diluted by gluon-gluon** production.

Asymmetries exhibit kinematic dependence, **enhanced in BSM**:

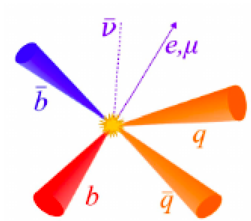
- Sensitivity of AC to EFT coefficients **complementary** to cross section measurements

ATLAS measurement with Full Run 2 data: Single and dilepton.

- **Single lepton:** split by b-jet multiplicity and boosted/resolved jet topologies. Use of a BDT for top reconstruction.



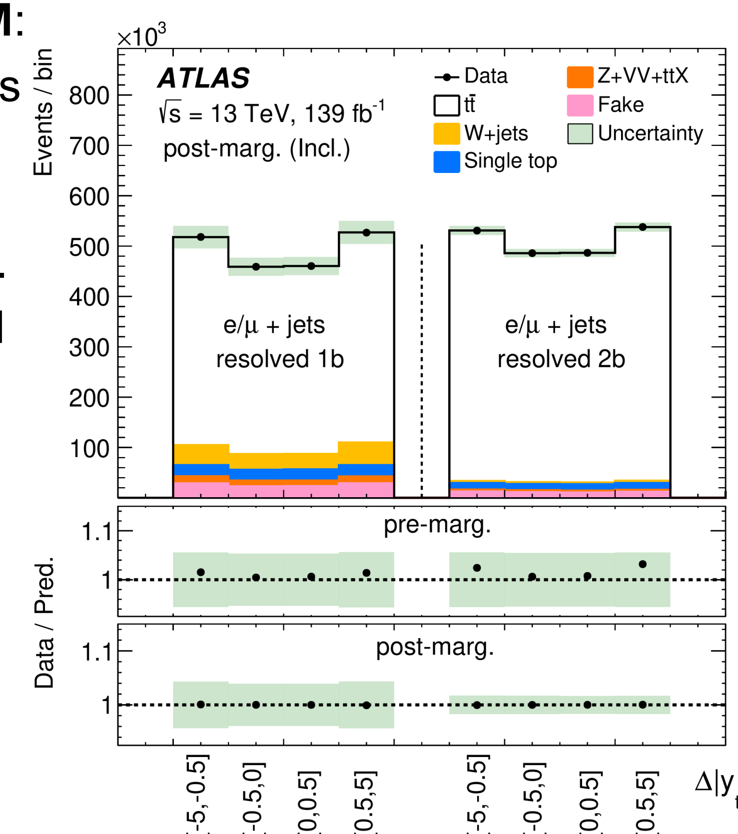
boosted



resolved

- **Dilepton:** split by lepton flavour and b-jet multiplicity. Also measure lepton charge asymmetry.

$$A_C^{\ell\bar{\ell}} = \frac{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) - N(\Delta|\eta_{\ell\bar{\ell}}| < 0)}{N(\Delta|\eta_{\ell\bar{\ell}}| > 0) + N(\Delta|\eta_{\ell\bar{\ell}}| < 0)} \qquad \Delta|\eta_{\ell\bar{\ell}}| = |\eta_{\bar{\ell}}| - |\eta_{\ell}|$$



Charge asymmetry in top production

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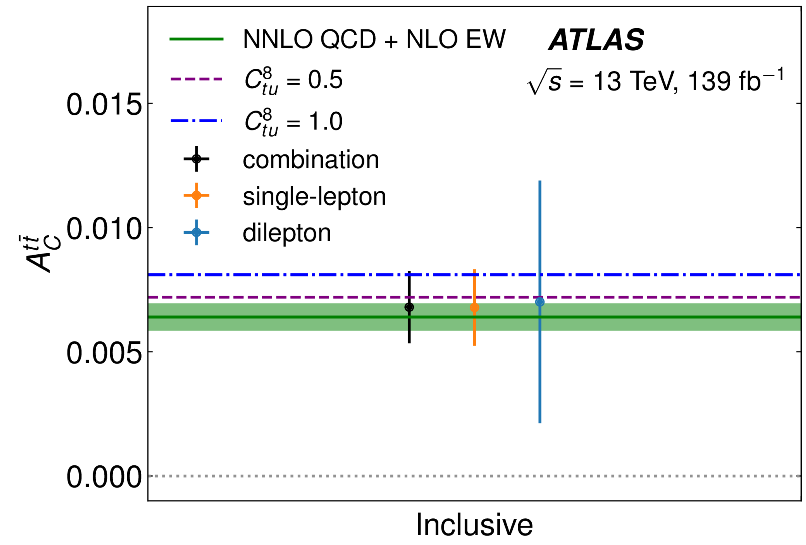
Δ|y| (Δ|η|) distributions corrected to parton level using Fully Bayesian Unfolding approach

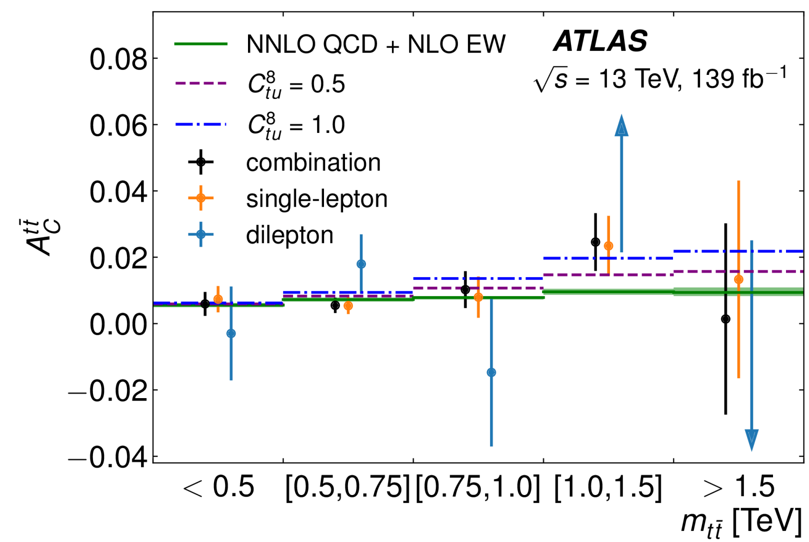
A_C measured inclusively and **differentially** as a function of m_{tt}, $p_{T,tt}$, $\beta_{z,tt}$ in the dilepton, lepton+jets channel and simultaneously.

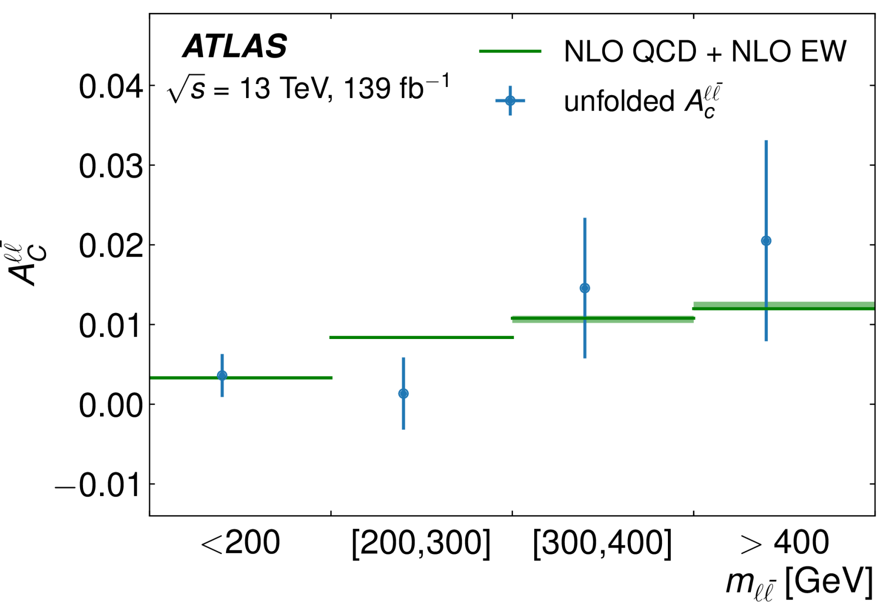
$$A_C = 0.0068 \pm 0.0015 \text{ (4.7 } \sigma \text{ from } A_C = 0)$$

$A^{\ell\ell}_C$ measured inclusively and differentially as a function of $m_{\ell\ell}$, $p_{T,\ell\ell}$, $\beta_{z,\ell\ell}$.

All results are compatible with SM predictions.







Charge asymmetry also in:

tt+gamma: Phys. Lett. B 843 (2023) 137848

ttW: ATLAS-CONF-2023-019

Charge asymmetry in top production

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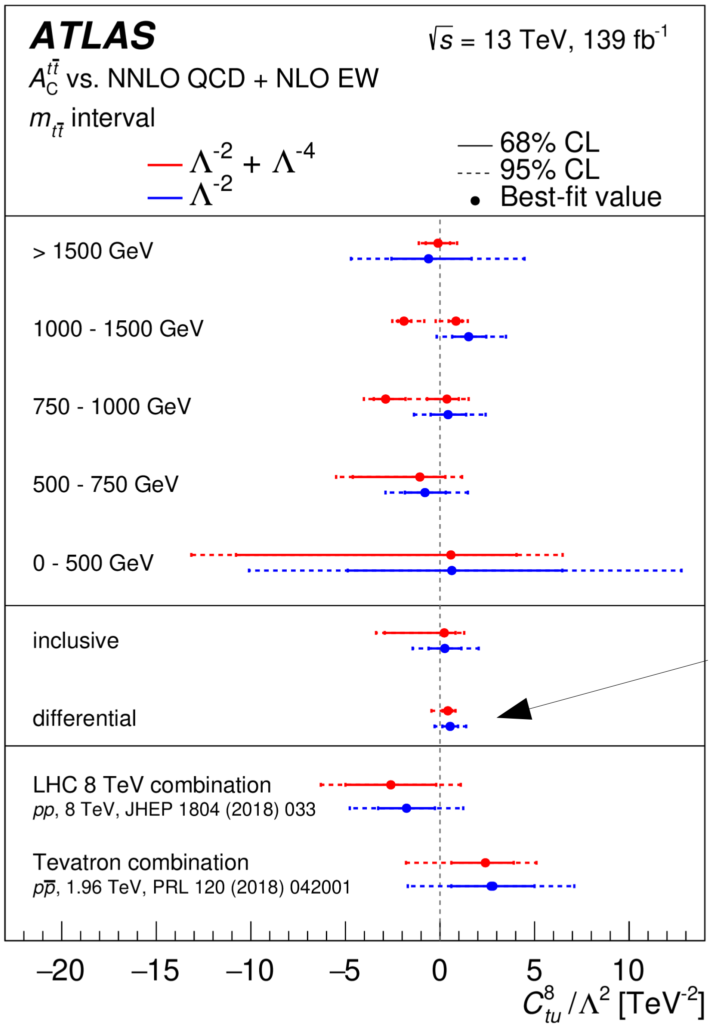
Combined results interpreted in the SMEFT framework:

- Constraint from the **differential measurement: factor >2 stronger** than the one from inclusive measurement (sensitivity increases with m_{tt})

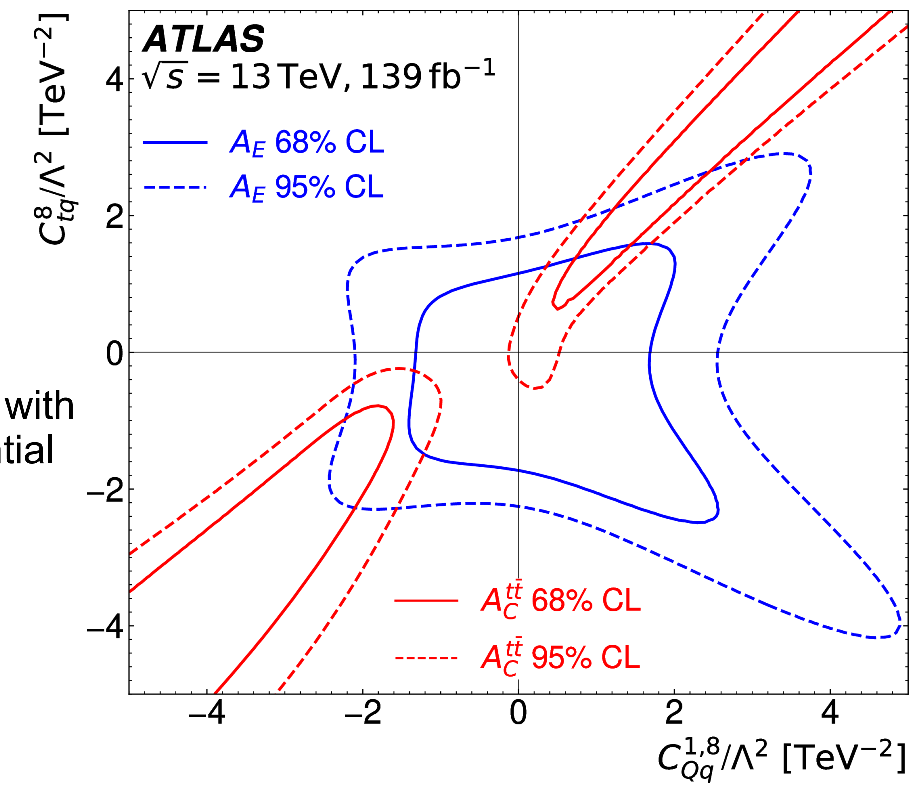


Big gain with differential

Energy asymmetry, A_E

Eur. Phys. J. C 82 (2022) 374

- Complementary measurement.
- Probe blind directions of A_C .

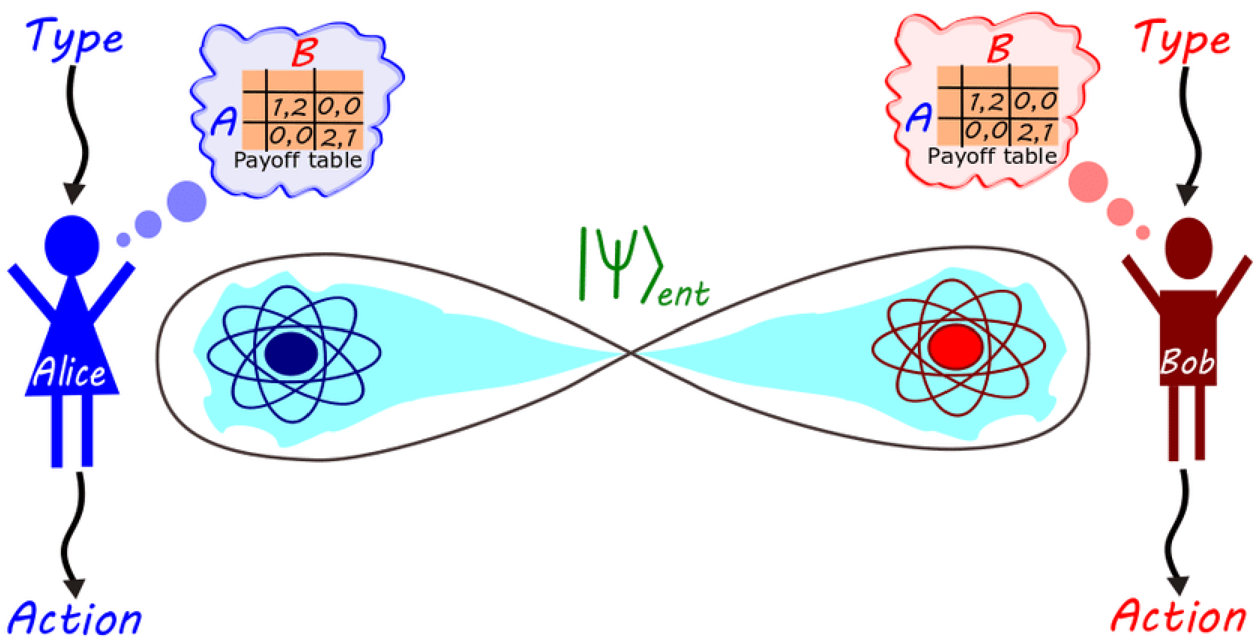


Quantum entanglement of top-quark pairs

Quantum entanglement

- **The SM is a quantum field theory:** special relativity + quantum mechanics.
- Entanglement is one of the most striking features of quantum mechanics:
  - Two entangled particles can't be described by individual quantum states, but only by a single state considering the state as whole
  - Correlated properties: The measurement of one of the particle “affects” the other.

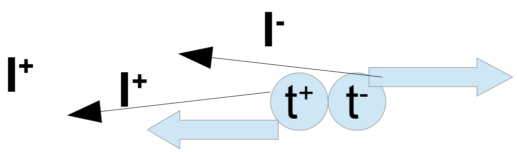
- Quantum entanglement have been proven in photons, atoms, superconductors, mesons and even macroscopic diamonds.



ATLAS-CONF-2023-069

Entangled top-quark pairs at the LHC

- Recent publications proposed using the LHC as a lab to test quantum mechanics at the highest energies ever.
- Close to production threshold (low top-antitop invariant mass), top-quarks are predicted to be produced in an entangled state: The correlation of top and antitop-quark spins is larger than the classical limit.



- The top quark spin can be analyzed through the lepton direction in top rest frame.
- A top quark pair forms a two-qubit system, with a spin density matrix given by:

$$\rho = \frac{I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

- The trace of the correlation matrix C is a good entanglement witness.
- Sufficient condition for entanglement: tr[C] + 1 < 0 (or D = tr[C]/3 < -1/3):

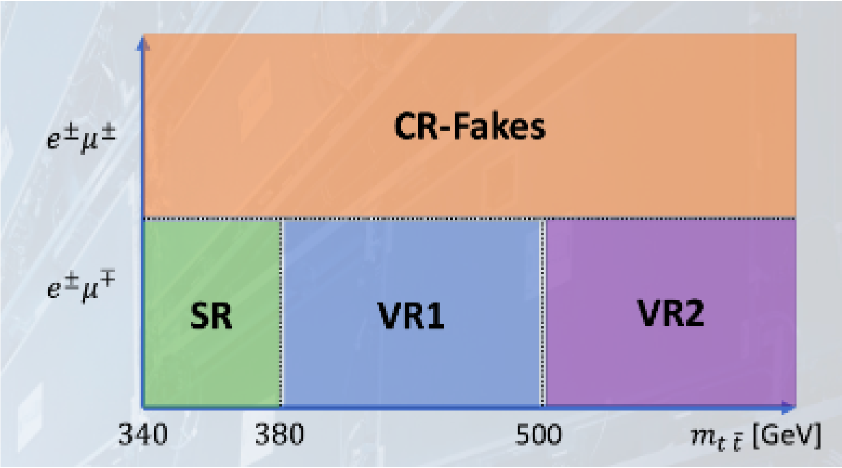
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}\left(1 - D\cos\varphi\right) \qquad D = \frac{\mathrm{tr}[\mathbf{C}]}{3} = -3 \cdot \langle \cos\varphi \rangle$$

Analysis strategy

- **Selection:** 1 electron and 1 muon of OS.
- Single lepton trigger. At least 1 b-jet (85%).

- **Backgrounds:** tW, tt+X, fakes, VV and Z→ ττ

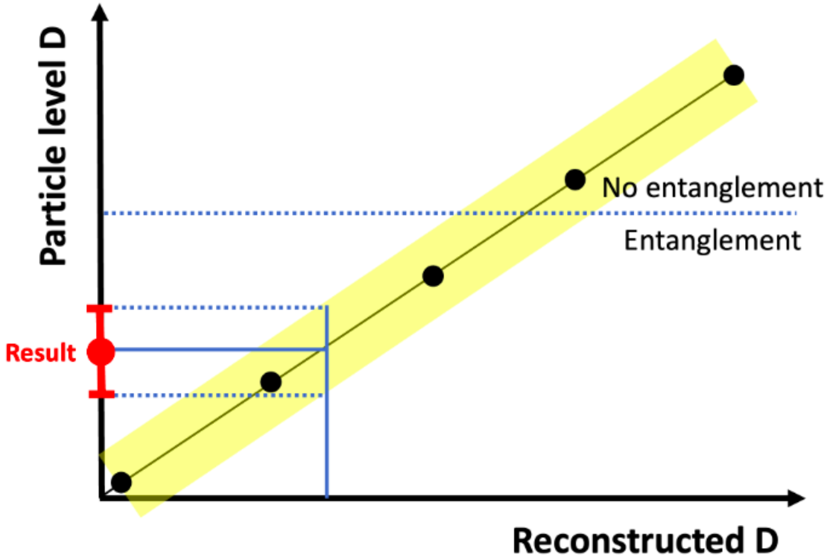
- Events categorized by m(ttbar): One signal region with expected entanglement and two validation regions without entanglement.



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

$$D = \frac{\mathrm{tr}[\mathbf{C}]}{3} = -3 \cdot \langle\cos\varphi\rangle$$

- Particle level fiducial regions with similar selections are defined.
- A calibration curve is used to correct the reconstructed value of D to particle level.
- A reweighting method is used to generate samples with varied values of D (entanglement)

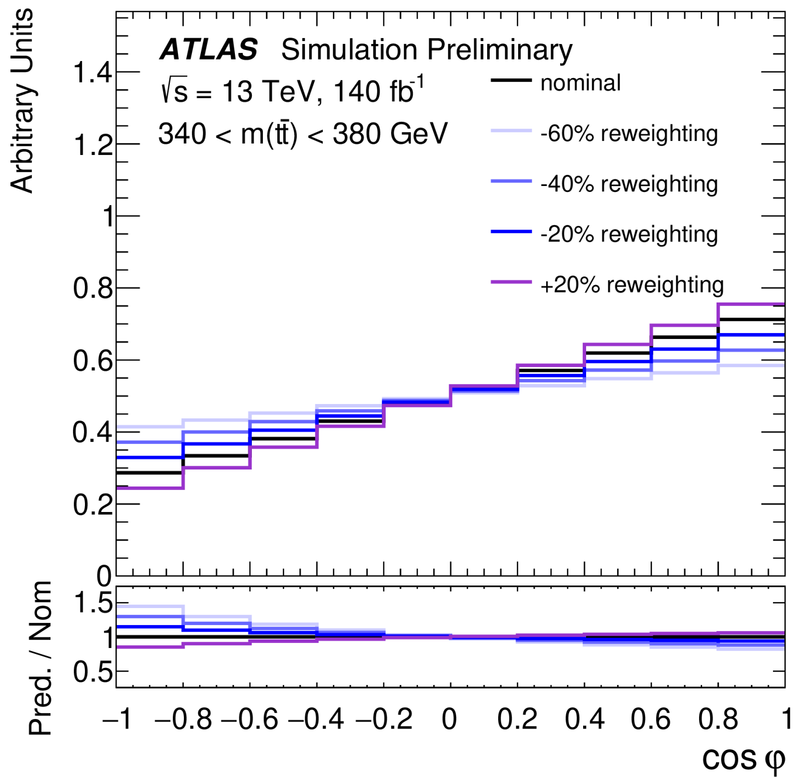


Reweighting method and calibration curve

- The amount of entanglement is not a parameter of the MC generators that can be changed (Inherent in particle generators).
- Alternative test hypotheses with varied values of D are needed.
- Each event is reweighted at parton level to modify D, taking into account m_ttbar to preserve the linearity of the cos φ distribution.

$$w = \frac{1 - D(m_{t\bar{t}}) \cdot \chi \cdot \cos\varphi}{1 - D(m_{t\bar{t}}) \cdot \cos\varphi}$$

$$\chi = 0.4, 0.6, 0.8, 1.2.$$



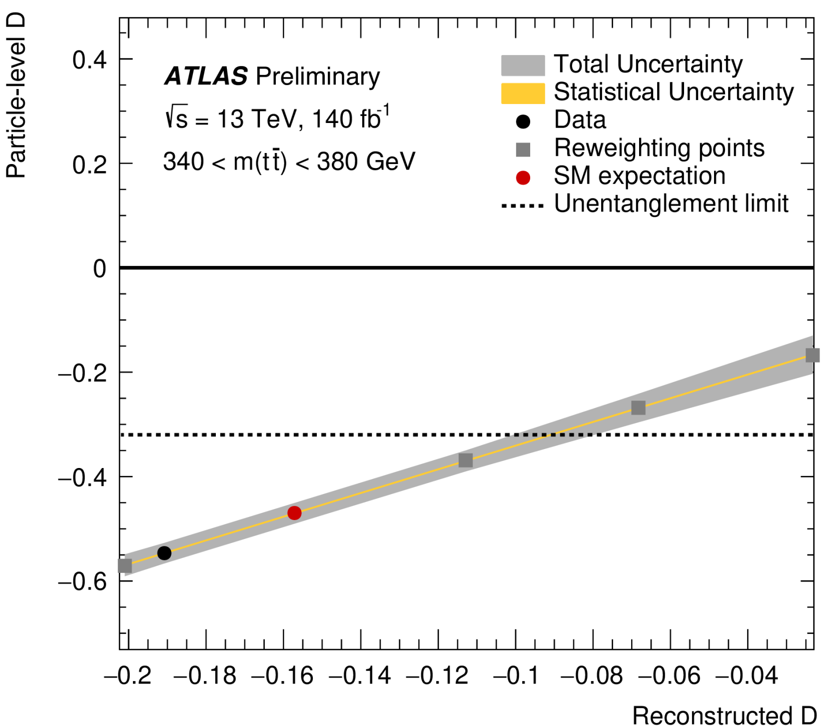
- D(m_ttbar) is calculated for every modelling uncertainty (different at parton level)
- The reweighting is done for every systematic uncertainty, obtaining a dedicated calibration curve for each uncertainty.

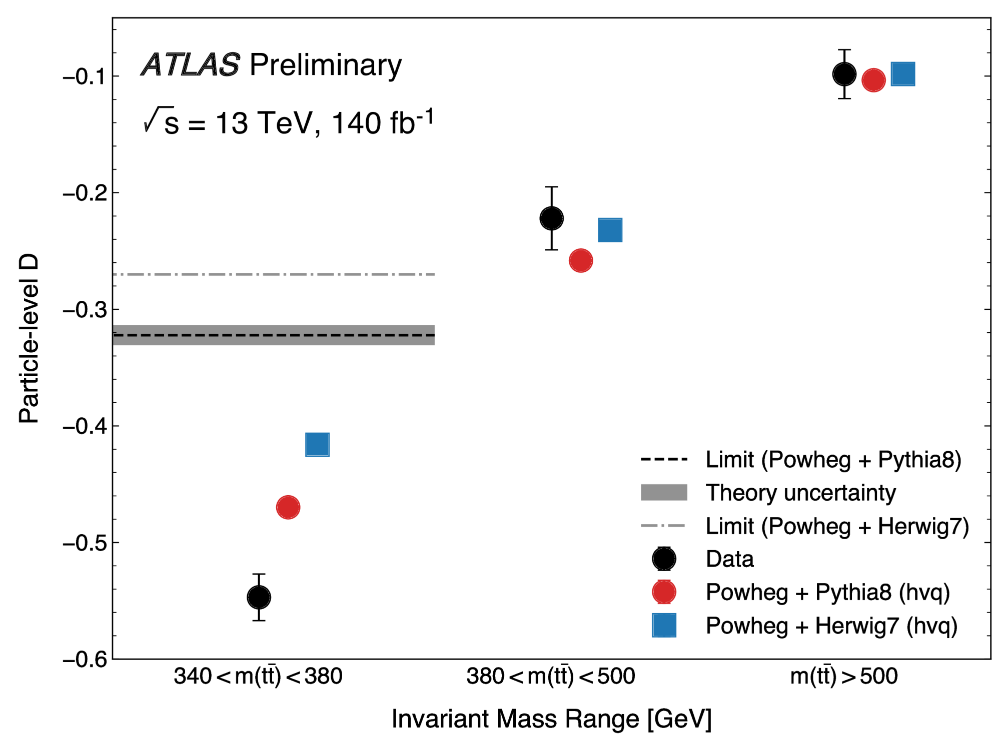
Observation of entangled top-quark pairs

ATLAS-CONF-2023-069

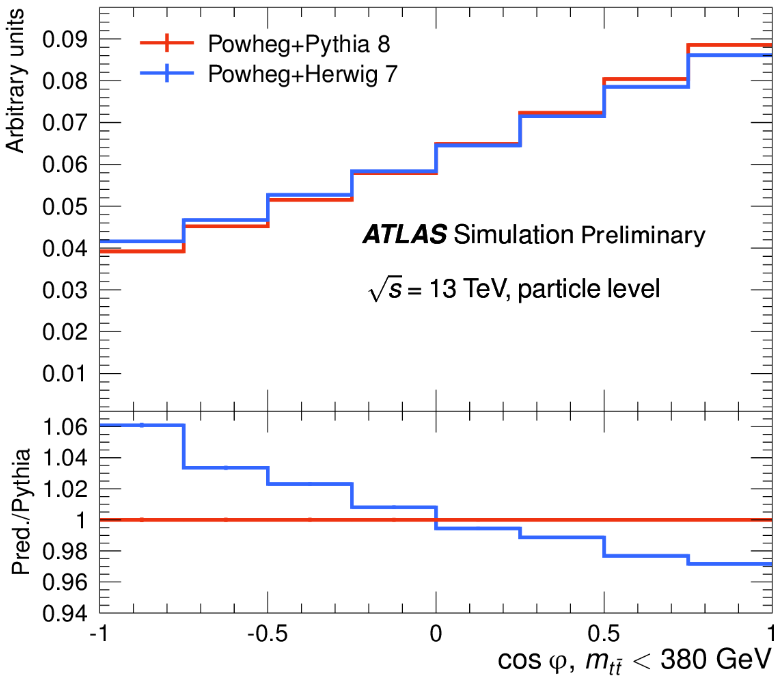
- Entanglement in top-quark pairs **observed for the first time** with more than 5 sigmas.
- Main uncertainties: signal modeling and Z→ τ τ
- Large difference in predicted value of D in SR between Powheg+Pythia and Powheg+Herwig
- Main origin: ordering of the parton shower.
- Not a large uncertainty at particle level: Entanglement observed with both models.

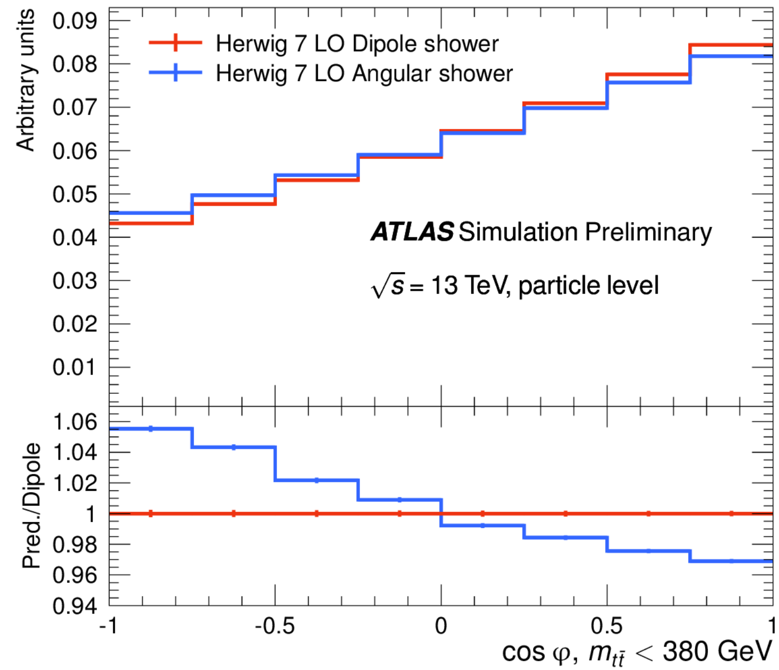
Systematic source	$\Delta D_{\text{observed}}(D = -0.547)$	ΔD (%)
Signal Modelling	0.017	3.2
Electrons	0.002	0.4
Muons	0.001	0.1
Jets	0.004	0.7
b-tagging	0.002	0.4
Pile-up	< 0.001	< 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.002	0.3
Backgrounds	0.010	1.8
Total Statistical Uncertainty	0.002	0.3
Total Systematic Uncertainty	0.021	3.8
Total Uncertainty	0.021	3.8

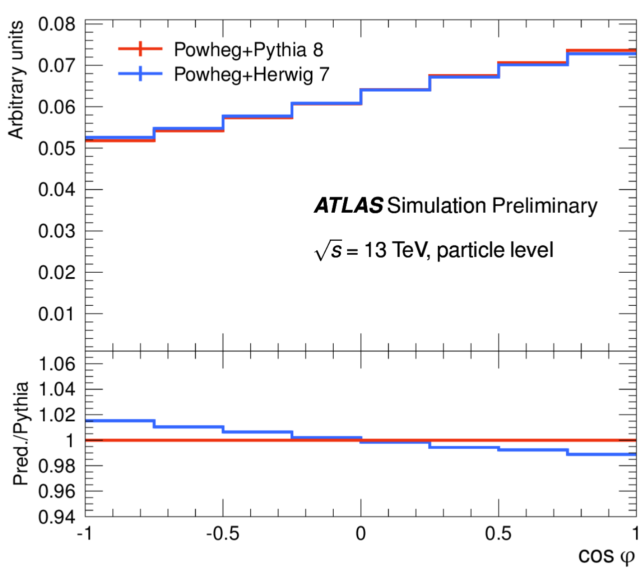




Parton shower and top quark spin correlation







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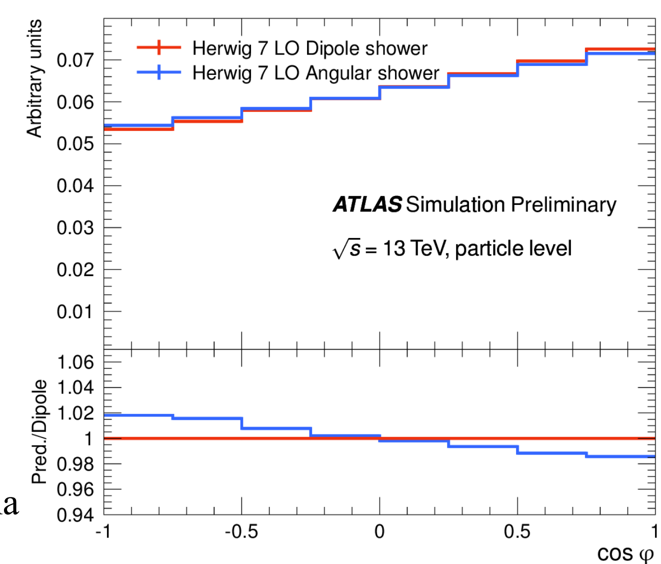


Summary and conclusions

ATLAS EXPERIMENT

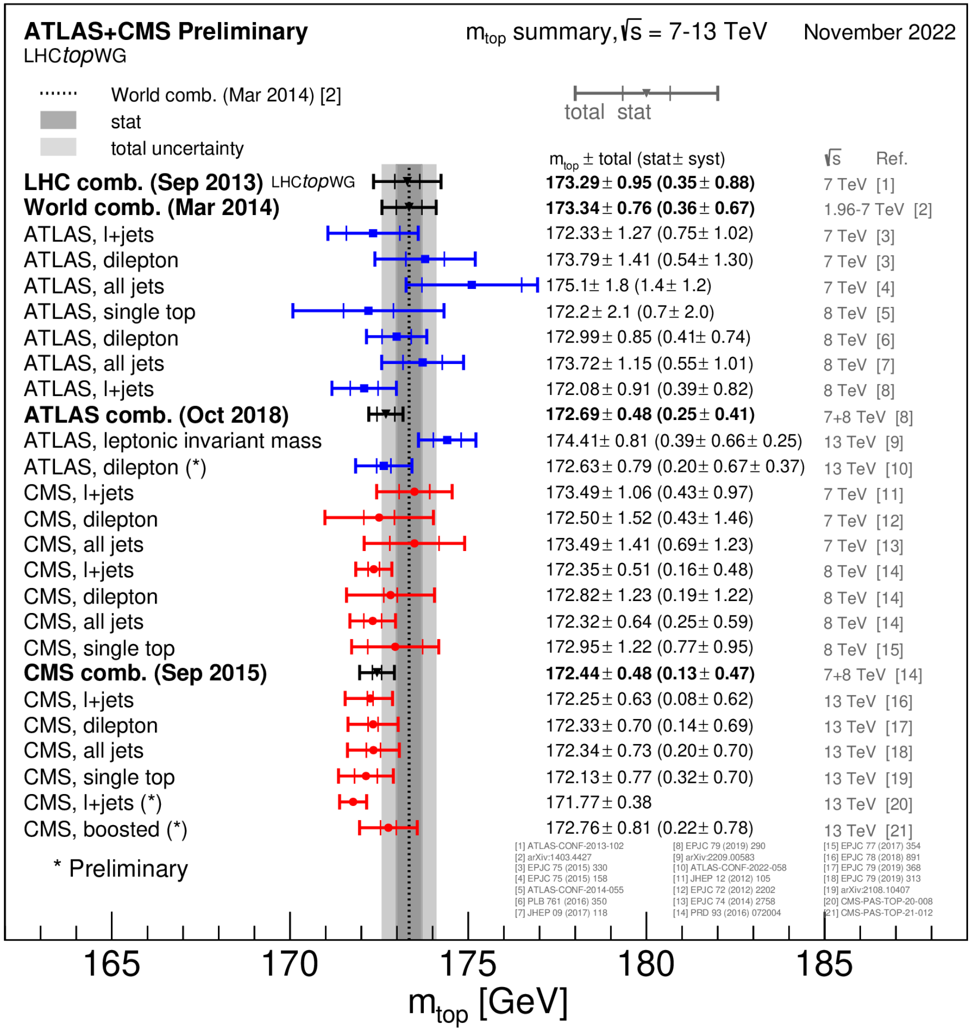
Summary and conclusions

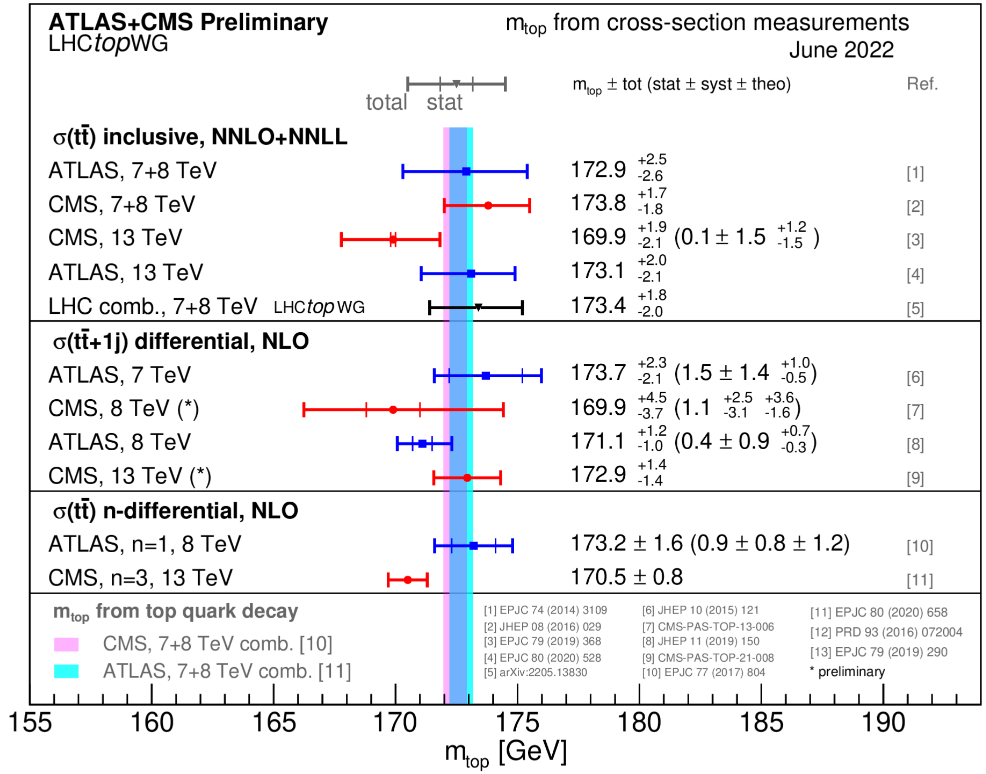
- The top-quark is the heaviest known elementary particle and the only case where a “free quark” can be studied in nature.
- ATLAS has a rich program of measurements of the top-quark properties: mass, spin correlation, production asymmetries, LFU tests...
- Only a few results covered in this talk, but many more here: TopPublicPage
- First Run-2 measurements of the top-quark mass recently published: dominated by modeling uncertainties and no longer by detector ones.
- Strong evidence of charge energy asymmetry in ttbar production in Run-2.
- Asymmetries in top-quark production exploited to test EFT SM.
- First measurement of entanglement of top-quark pairs at LHC just presented last week: New possibilities of measurements at the LHC

Thanks for your attention

Backup

Direct (MC) and indirect (pole) top mass





ATL-PHYS-PUB-2021-042

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

ATLAS-CONF-2022-058

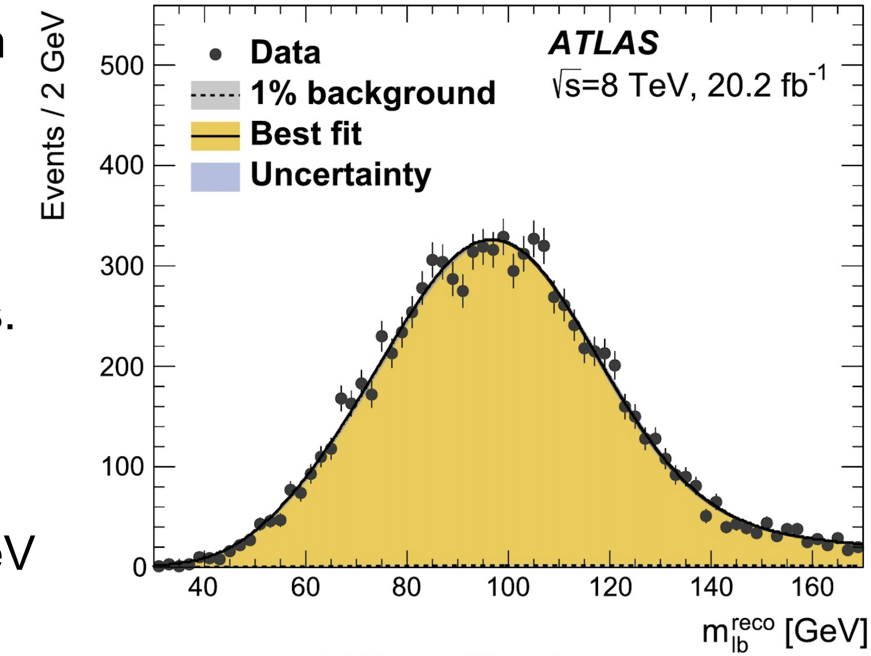
Phys. Lett. B 761 (2016) 350

Comparison to 8 TeV

- The template method top quark measurement in the dilepton channel is the ATLAS most precise single direct measurement of Run-1:

$$m_{top} = 172.99 \pm 0.41 \text{ (stat)} \pm 0.74 \text{ (sys) GeV}$$

- 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



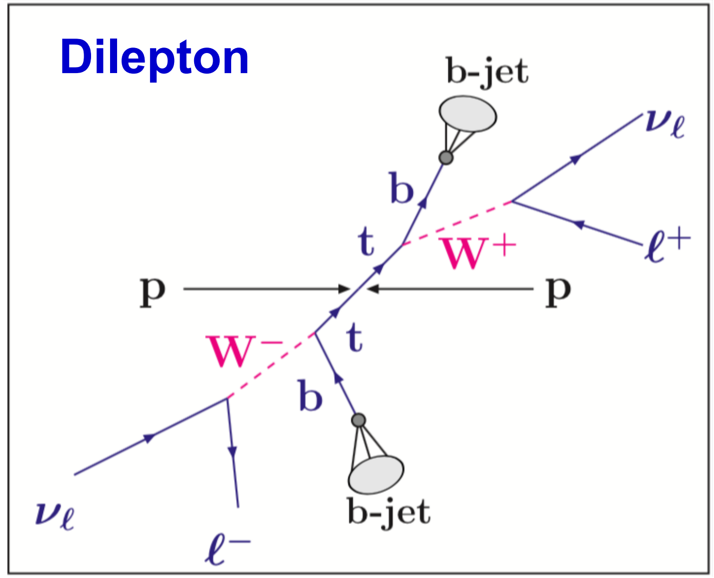
New measurement at 13 TeV:

- Larger dataset (7x luminosity, XS++): require exactly two b-tagged jets.
- 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.

Top quark pair event reconstruction



No attempt of reconstructing the neutrino's kinematics is performed.

Signal events can be classified into 3 categories:

Unmatchable: Either a reconstructed lepton or jet is not matched to its correct parton level partner. Requirements are $\Delta R = 0.1$ for leptons and $\Delta R = 0.3$ for jets.

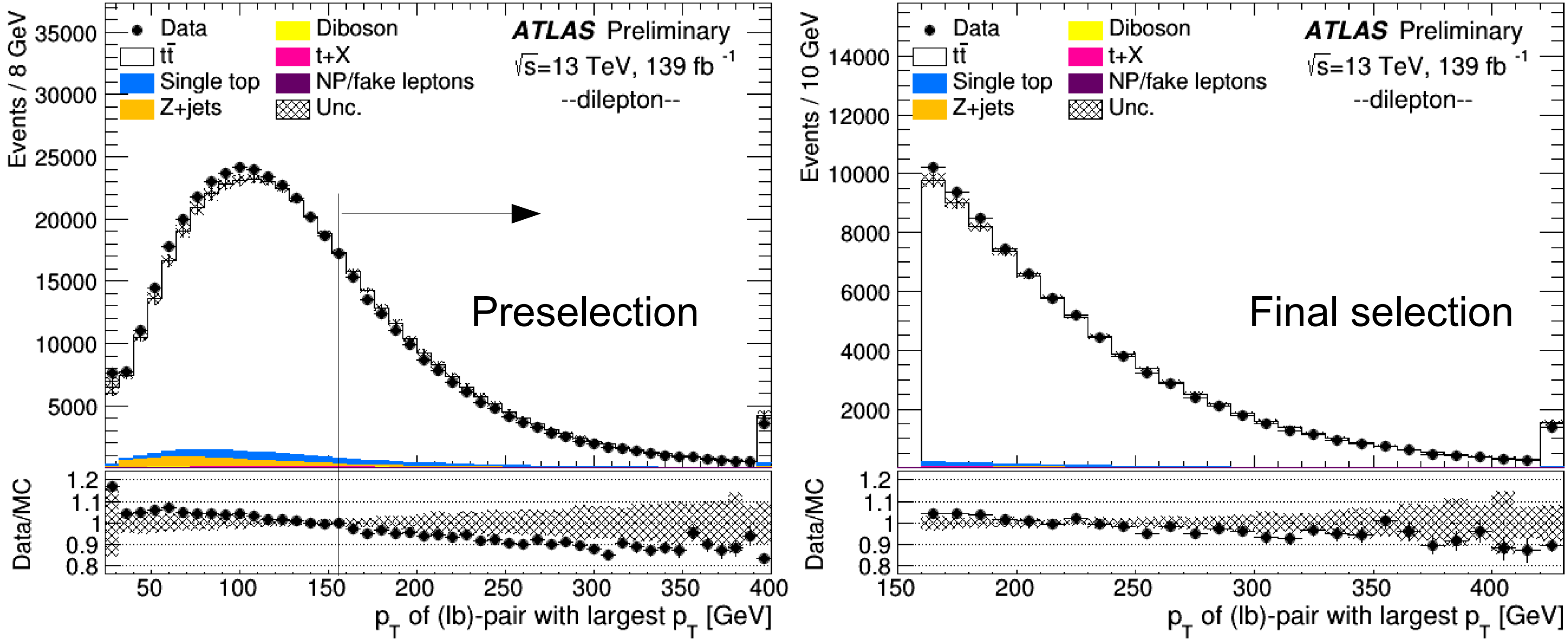
Correctly matched: Each lepton is assigned to its corresponding b-tagged jet.

Incorrectly matched: At least one reconstructed object is not correctly assigned.

Reconstruction efficiency ≡ C/(C+I) Signal purity ≡ C/(C+I+U)

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%.

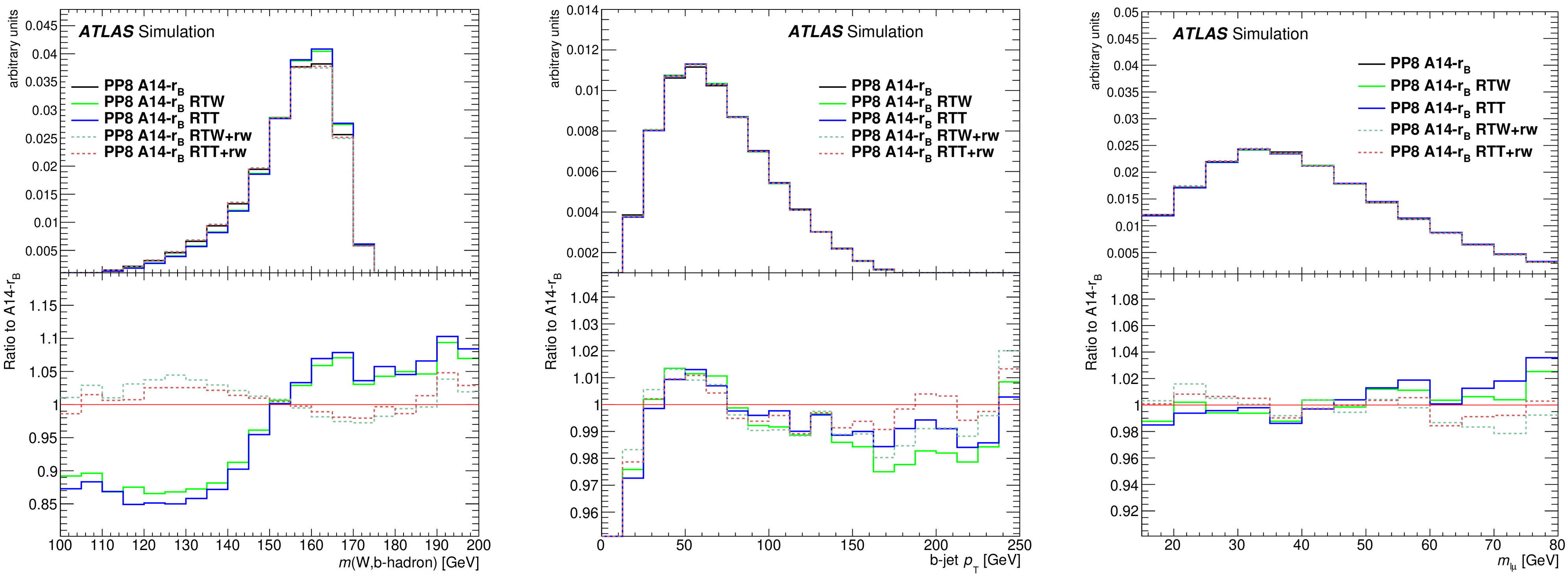


- A parton-level reweighting to the NNLO calculation as a function of p_T^{top}, p_T^{tt}, m_{tt} has been tested: Δm_{top} = 0.10 ± 0.01 GeV, smaller than scale variations uncer.

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

Radiation and recoil effects

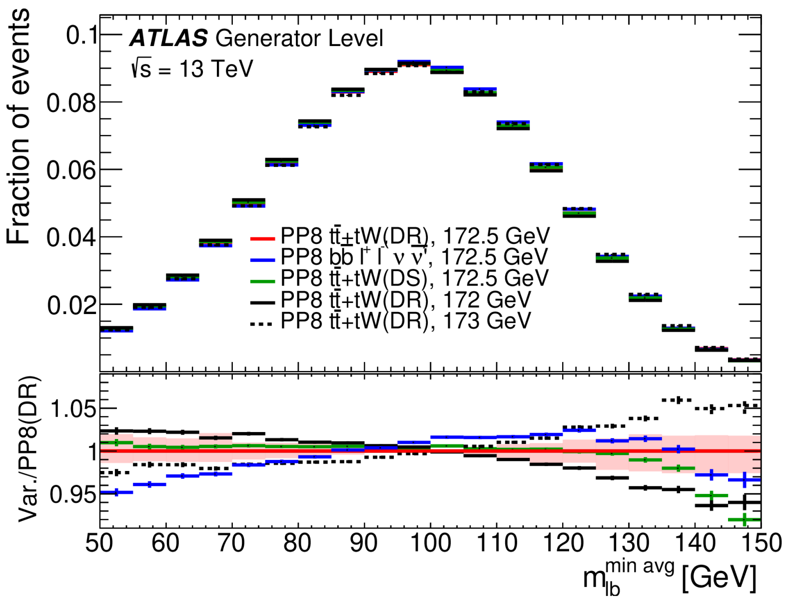
As the recoil scheme modifies the distribution of the b-hadron momentum fraction, for the SMT analysis, a rederivation of the best rb value has been performed for RTT.

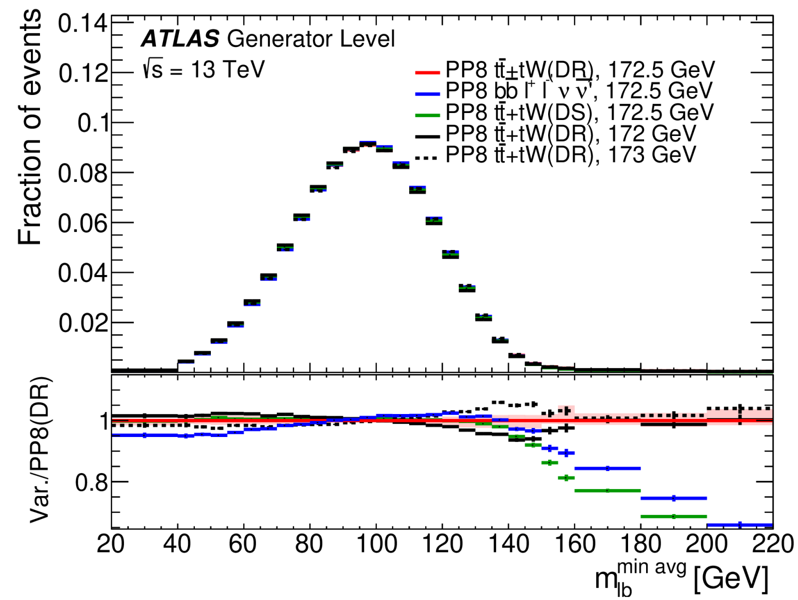


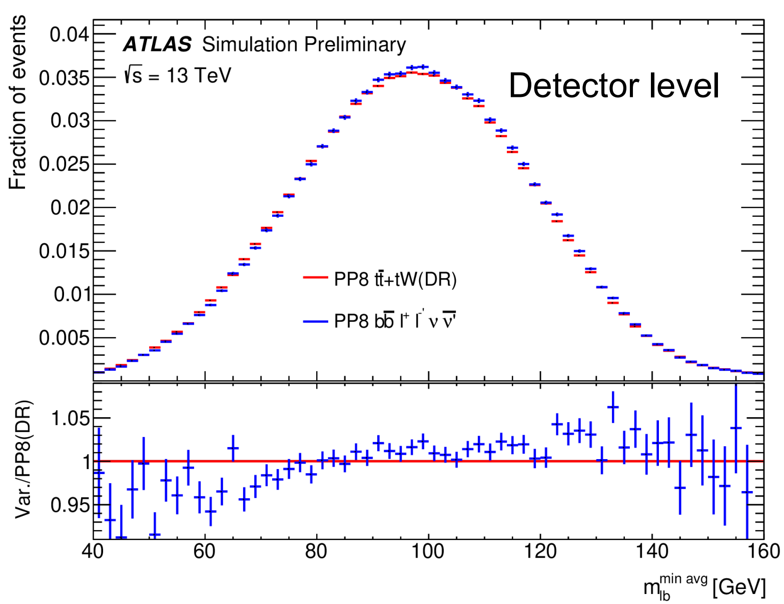
Δm_{top}(recoil-to-Top – recoil-to-colour=ON) [SMT] = 250 MeV

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.

Radiation and recoil effects

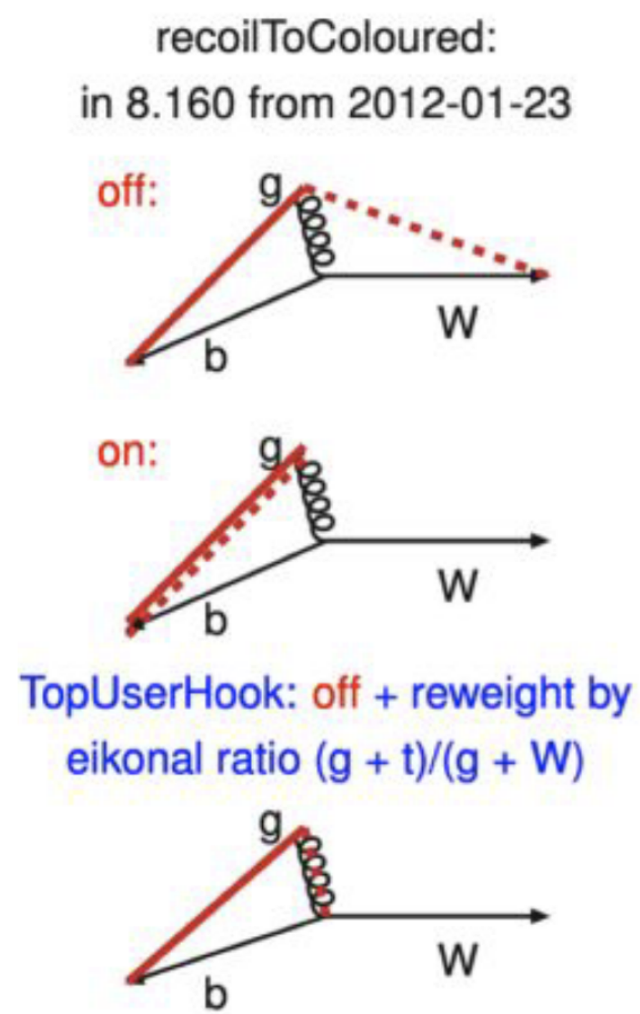
First emission (FE) of a gluon in the final state is controlled with matrix element corrections (MEC).

Second emission is not: ambiguity in the treatment.

- Recoil-to-colour=ON (Powheg+Pythia8): Any gluon radiation after the FE recoils against the b-quark.
- Recoil-to-colour=OFF (Pythia6 (Run-1)): 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.

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}.

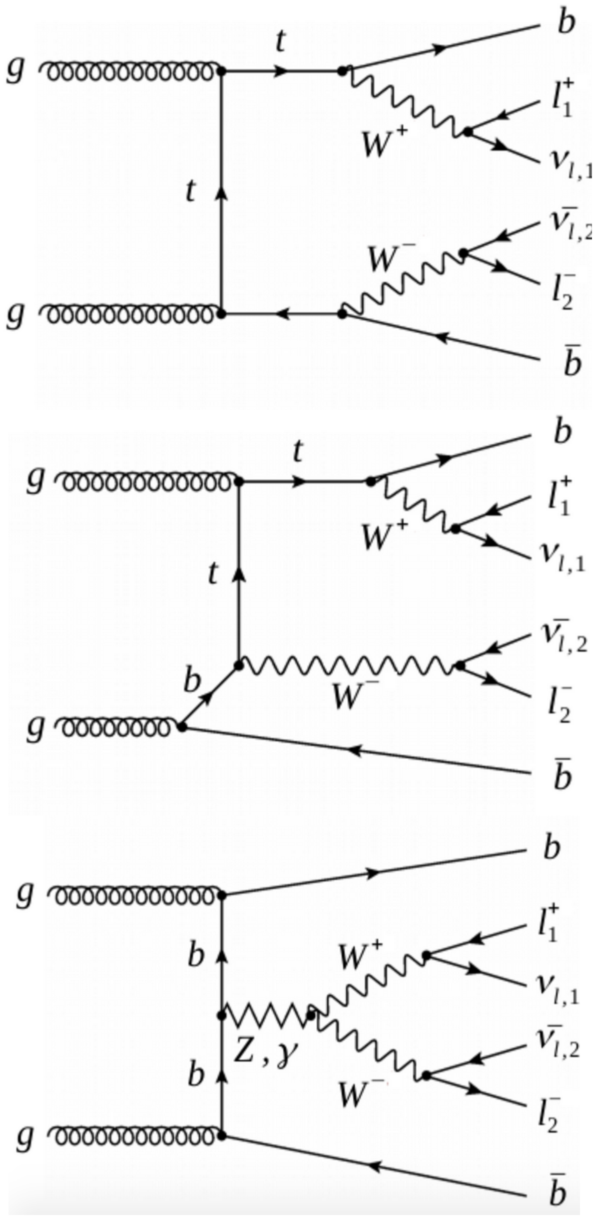
- Following previous recommendations, **ATLAS has added recoil-to-top vs recoil-to-colour=ON as an additional uncertainty.**
- **No dedicated tuning of the recoil-to-top** has been performed yet. Current uncertainties probably overestimate the effect.



(Sketch by T. Sjostrand)

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

Non-resonant and off-shell effects: bb4l



The impact of the bb4l sample in a 8-TeV-like m_{top} measurement was studied:

$$\Delta m_{top} = m_{top}^{bb4l} - m_{top}^{nom} = 0.36 \pm 0.08 \text{ GeV}$$

Of a similar order than the modelling uncertainties.

In the most recent dilepton template method:

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