Direct top quark mass measurements with the ATLAS and CMS detectors

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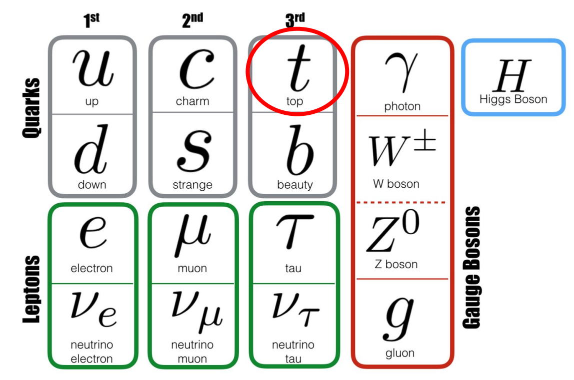
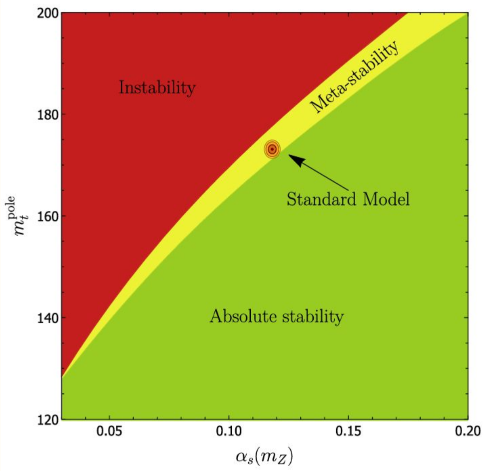
Marco Vanadia,
on behalf of the ATLAS and CMS collaborations
TOP 2022 5/9/2022 Durham

Introduction

- m_t~173 GeV → top quark has many unique features
  - decay quicker than hadronization and spin decorrelation
  - Yukawa coupling O(1)
  - top signatures for many BSM models
- Precise measurement of m_t crucial
  - EW precision tests
  - Higgs production, self-coupling, top-quark loops
  - Stability of SM ...
- LHC is a top factory
  - ~140/fb per experiment @ 13 TeV
    - ~830 pb (tt) + ~300 pb (t)
  - Expected ~250/fb per experiment @ 13.6 TeV
    - ~920 pb (tt) + ~330 pb (t)
- m_t measurements challenge for theory & experiments
  - control uncertainties at per-mill level
  - modelling uncertainties
  - interpretation of measurements: $m_t^{MC} \leftrightarrow m_t^{pole}$

see also ATL-PHYS-PUB-2021-034
and Miguel's talk on tuesday





PhysRevD.97.056006

Outline

CMS

- ttbar ℓ+jets CMS-PAS-TOP-20-008
- single-top t-channel JHEP 12 (2021) 161
- also: CMS-PAS-TOP-21-012 presents a m_t^{MC} measurement obtained from a cross-section
  - this was already covered in Matteo's talk!

ATLAS

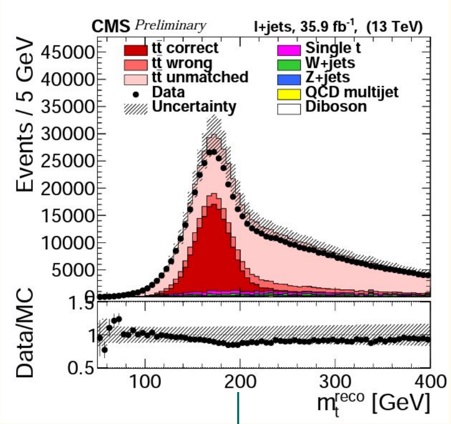
- ttbar soft muon tagging TOPQ-2017-17 arXiv:2209.00583
- ttbar ℓℓ ATLAS-CONF-2022-058

Top mass ℓ+jets

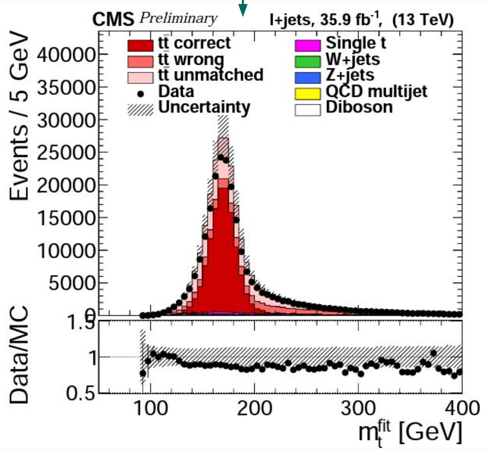
CMS-PAS-TOP-20-008

36/fb @ 13 TeV

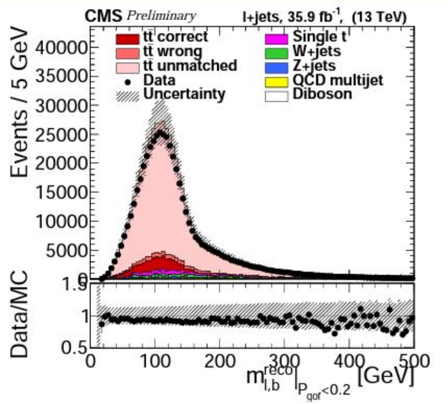
- 1 isolated e or μ
- $\geq$4 jets
- 2 b-jets (WP ε=78% with light-mistag rate 1%)
- kinematic fit: χ^2 minimization
  - 4 permutations: 2 b-jet ↔ b-quark **x** 2 $p_T^{neutrino}$
  - uses 4-mom. of lept., jets, $\mathbf{p_T^{miss}}$, resolutions
- Select permutation with max $P_{GOF}=\exp(-\chi^2/2)$
- Events classified as P_{GOF} < and > 0.2



before fit



after fit and $P_{GOF}>0.2$



Main observables:

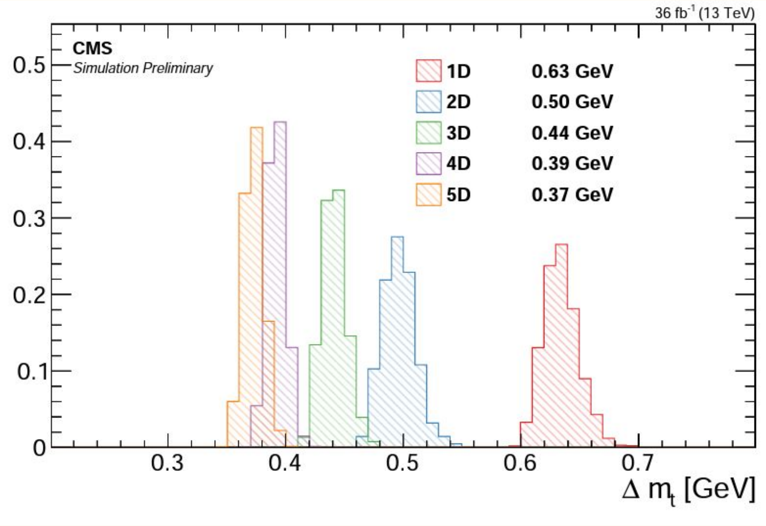
- m_t^{fit} for $P_{GOF}>0.2$
- m_{lb}^{reco} for $P_{GOF}<0.2$

Top mass ℓ+jets

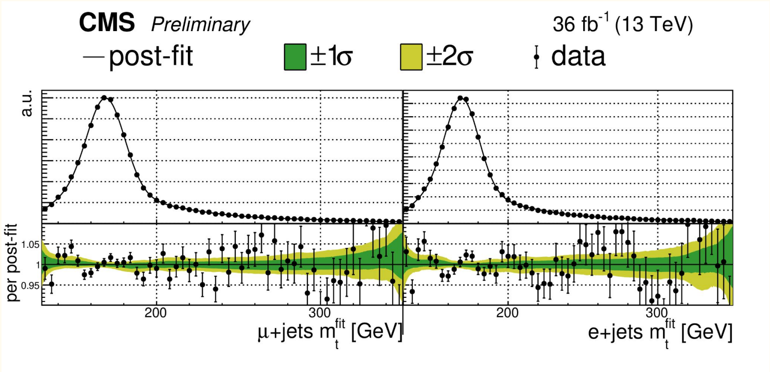
CMS-PAS-TOP-20-008

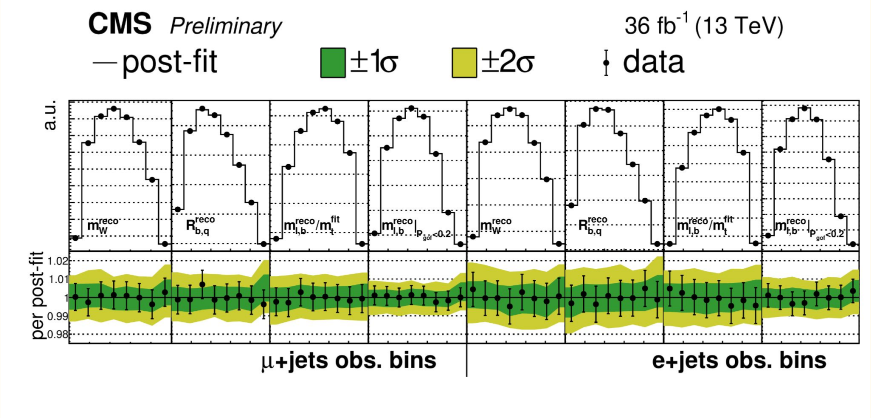
Additional observables included in the measurement to constraint syst. uncertainties:

histogram		set label				
observable	category	1D	2D	3D	4D	5D
$m_{\mathrm{t}}^{\mathrm{fit}}$	$P_{\mathrm{gof}} \geq 0.2$	x	x	x	x	x
$m_{\mathrm{W}}^{\mathrm{reco}}$	$P_{\mathrm{gof}} \geq 0.2$		x	x	x	x
$m_{\ell\mathrm{b}}^{\mathrm{reco}}$	$P_{\mathrm{gof}} < 0.2$			x	x	x
$m_{\ell\mathrm{b}}^{\mathrm{reco}} / m_{\mathrm{t}}^{\mathrm{fit}}$	$P_{\mathrm{gof}} \geq 0.2$				x	x
$R_{\mathrm{bq}}^{\mathrm{reco}}$	$P_{\mathrm{gof}} \geq 0.2$					x



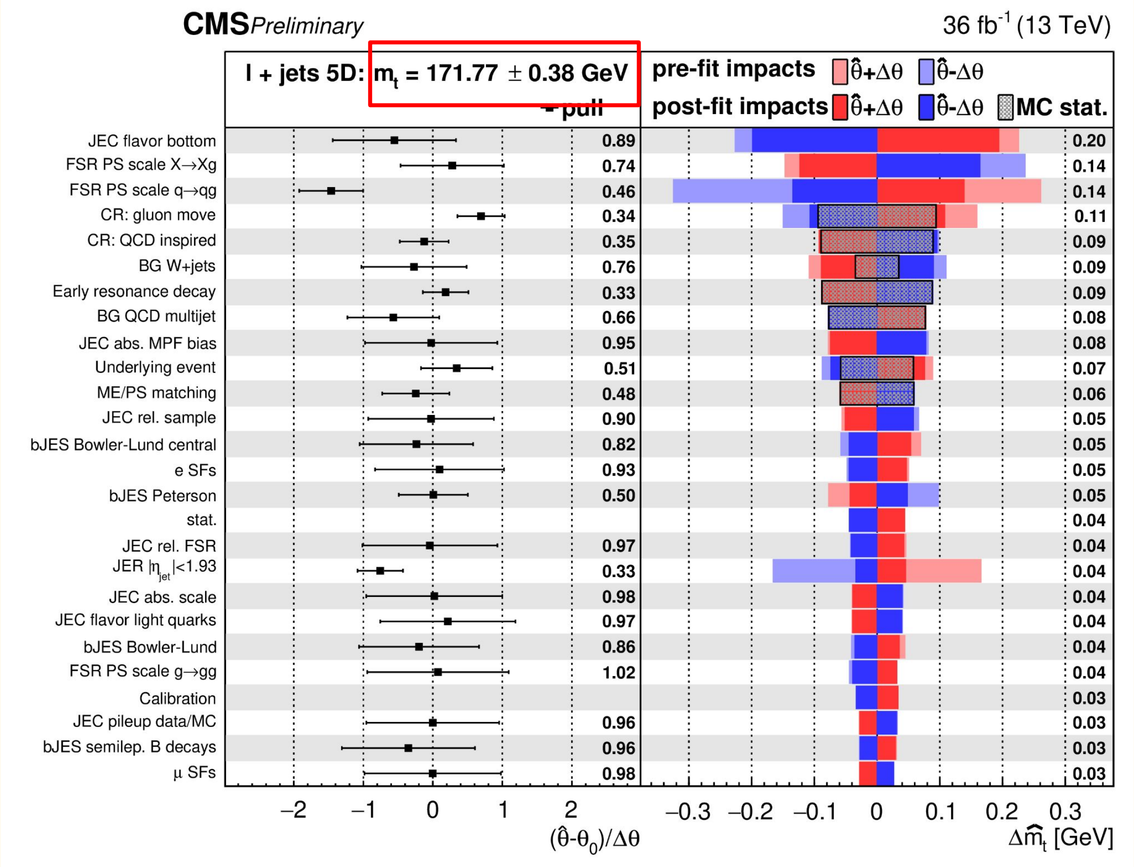
The mass is extracted from the observables with a profiled ML fit





Top mass ℓ+jets

CMS-PAS-TOP-20-008



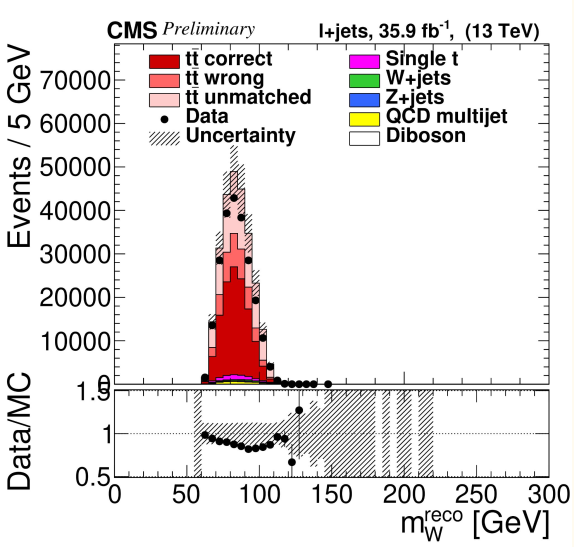
- Most precise result to date with 0.38 GeV uncertainty!
- Data stat 0.04 GeV
- Dominant uncertainty b-jet energy correction
- FSR description from PS is important and has a strong constraint (see next slide)

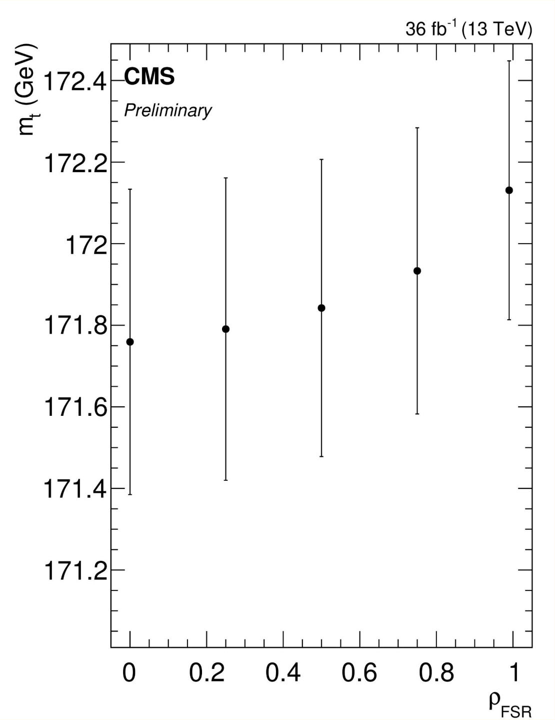
Top mass ℓ+jets

CMS-PAS-TOP-20-008

ISR/FSR PS uncertainty:

- 32 uncorrelated variations of a factor 2 on μ_R and non-singular terms cNS (see PRD.94.074005)
- cNS separately varied for branching type ($g\rightarrow gg, g\rightarrow qq, g\rightarrow qg, q\rightarrow qg$)





- pull due to m_W^{reco}
- result assuming full correlation m_t=172.14±0.31 GeV
  - more compatible with previous results (which assumed correlation)
- pulls to different NPs support choice to decorrelate

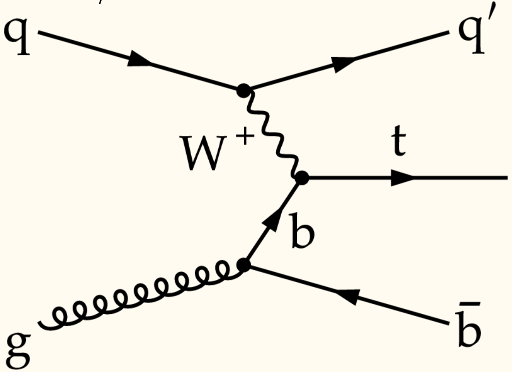
Previous result Eur. Phys. J. C 78, 891 (2018)
mt=172.25±0.63 GeV

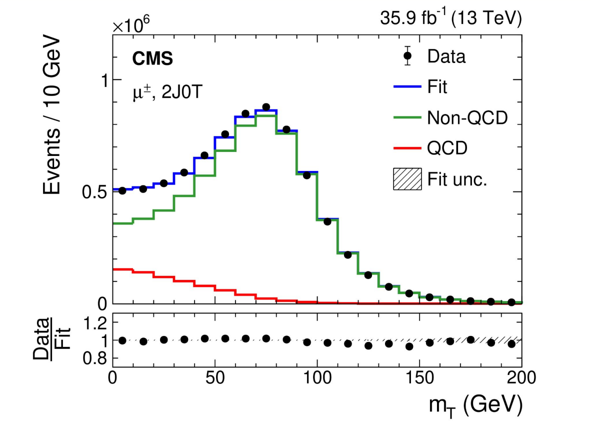
Top mass single-top

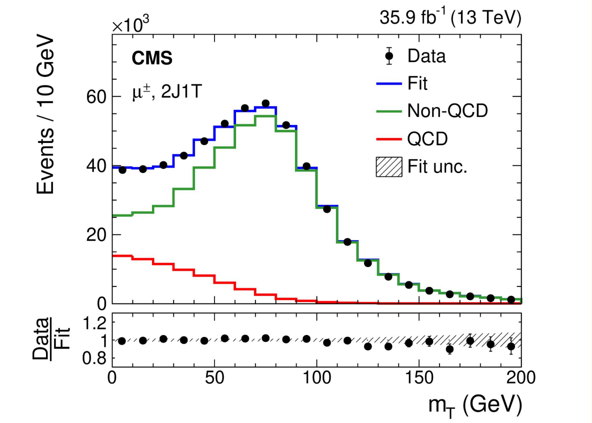
[JHEP 12 (2021) 161]

36/fb @ 13 TeV

- t-channel single-top events:
  - independent sample @ lower kin. threshold
  - different syst, less affected by Color Reconn.
- 1 isolated e or μ, 2 jets, 1 b-tagged
  - WP: ε=55%, mistag 0.1% light and 6% c
- top 4-momentum from decay products
  - m_W applied as constraint







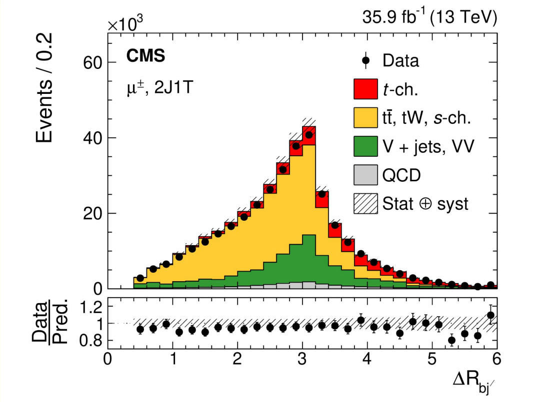
$$m_{\mathrm{T}} = \sqrt{(p_{\mathrm{T},l} + p_{\mathrm{T}}^{\mathrm{miss}})^2 - (p_{x,l} + p_x^{\mathrm{miss}})^2 - (p_{y,l} + p_y^{\mathrm{miss}})^2}$$

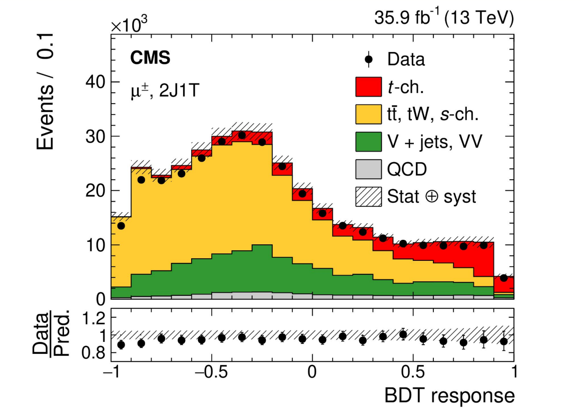
QCD bkg from m_T fit

- template from non-isolated lepton events
- method validated in events with no b-jets
- 50% uncertainty assigned to yield and shape
- events with m_T>50 GeV are used afterwards

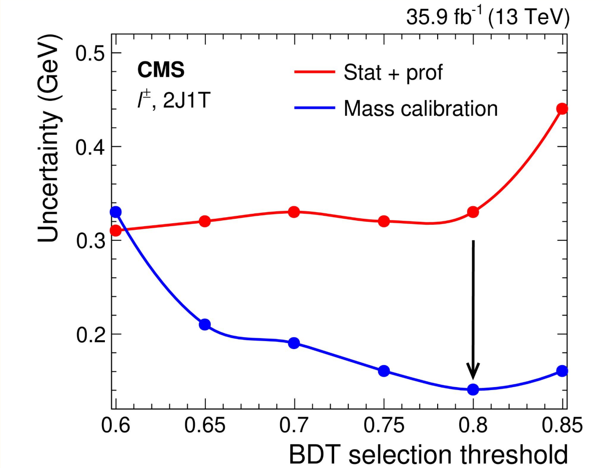
Top mass single-top

JHEP 12 (2021) 161





MVA discriminant built to enhance single-top t-channel contribution



Variable	Rank Muon	Rank Electron	Description
$\Delta R_{\mathrm{bj'}}$	1	1	Angular separation in $(\eta,\ \phi)$ space between the b-tagged and untagged jets
Untagged jet $\lvert\eta\rvert$ ($\lvert\eta_{\mathrm{j'}}\rvert$)	2	2	Absolute pseudorapidity of the untagged jet
$m_{\mathrm{bj'}}$	3	3	Invariant mass of the system comprising the b-tagged and untagged jets
$\cos\theta^*$	4	4	Cosine of the angle between the lepton and untagged jet in the rest frame of the top quark
m_{T}	5	5	Transverse mass as defined in eq. (4.1)
FW1	—	6	First-order Fox-Wolfram moment [65, 66] (electron final state)
$\lvert\Delta\eta_{l\mathrm{b}}\rvert$	6	7	Absolute pseudorapidity difference between the lepton and b-tagged jet
$p_{\mathrm{T}}^{\mathrm{b}}+p_{\mathrm{T}}^{\mathrm{j'}}$	7	8	Scalar sum of the p_{T} of the b-tagged and untagged jets
$\lvert\eta_l\rvert$	8	—	Absolute pseudorapidity of the lepton (muon final state)

ε_{sig} ~ 65% (muons), 60% (electrons)

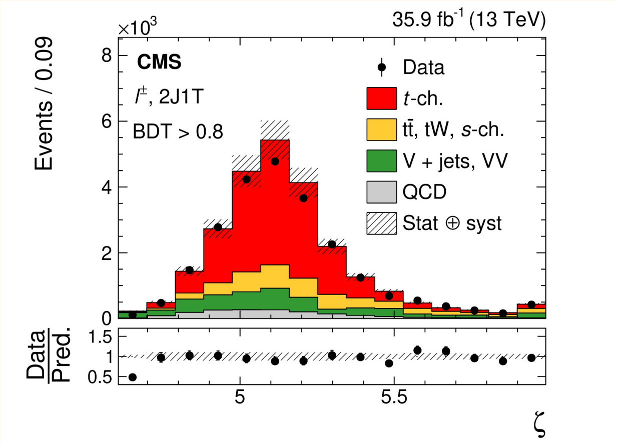
Low correlation between BDT score and m_t (-13%)

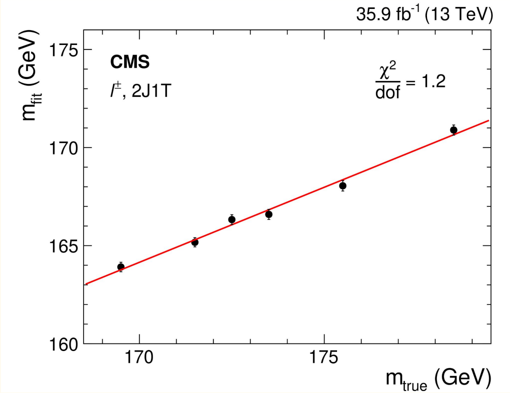
Top mass single-top

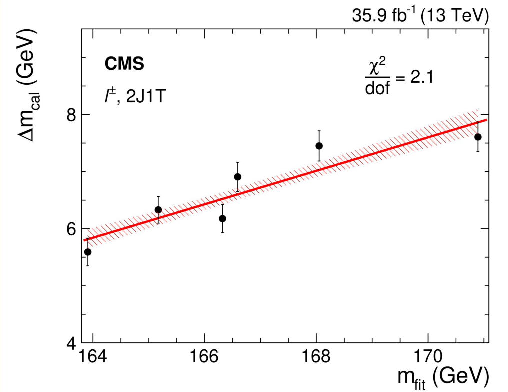
JHEP 12 (2021) 161

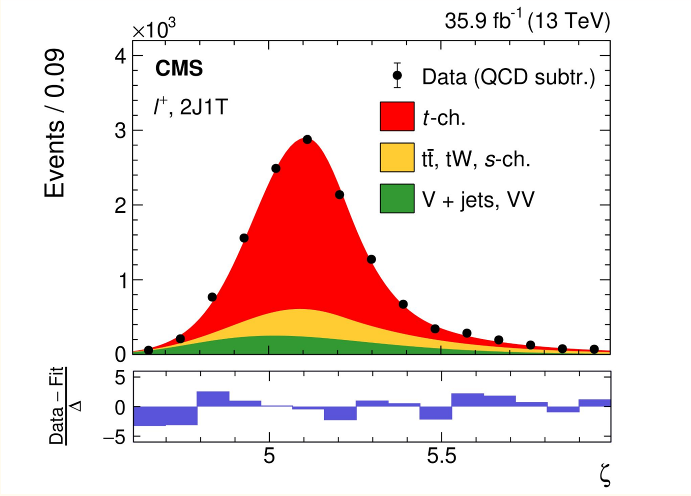
ML fit to $\zeta = \ln(m_t/1\ \text{GeV})$

- QCD bkg subtracted before the fit
- signal, tt, EW component modelled with analytical functions
- peak position ζ_0 is the POI
- validated in region with inverted BDT cut
- sig and bkg normalization profiled in the fit
- all other uncertainties externalized









Top mass single-top

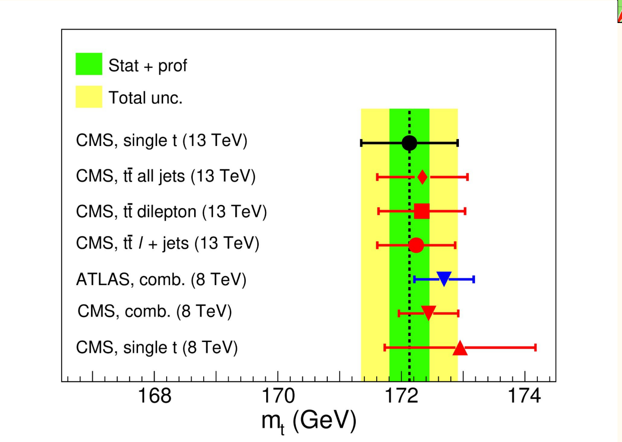
JHEP 12 (2021) 161

improves by 30% wrt previous result!

$$m_t = 172.13 \pm 0.32\,(\text{stat+prof})^{+0.69}_{-0.71}\,(\text{ext})\,\text{GeV} = 172.13^{+0.76}_{-0.77}\,\text{GeV}$$

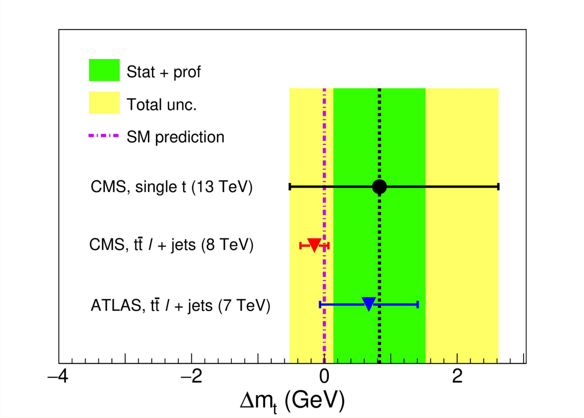
$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.9952 \pm 0.0040\,(\text{stat+prof})^{+0.0068}_{-0.0096}\,(\text{ext}) = 0.9952^{+0.0079}_{-0.0104}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83 \pm 0.69\,(\text{stat+prof})^{+1.65}_{-1.16}\,(\text{ext})\,\text{GeV} = 0.83^{+1.79}_{-1.35}\,\text{GeV}$$



Dominant uncertainties:

- Stat 0.19 GeV, Stat+profiled 0.32 GeV
- JES 0.4 GeV, b-tagging 0.20 GeV
- Color reconnection, Early res. decay 0.24 GeV
- b-quark hadronization 0.23 GeV
- FSR PS 0.28 GeV

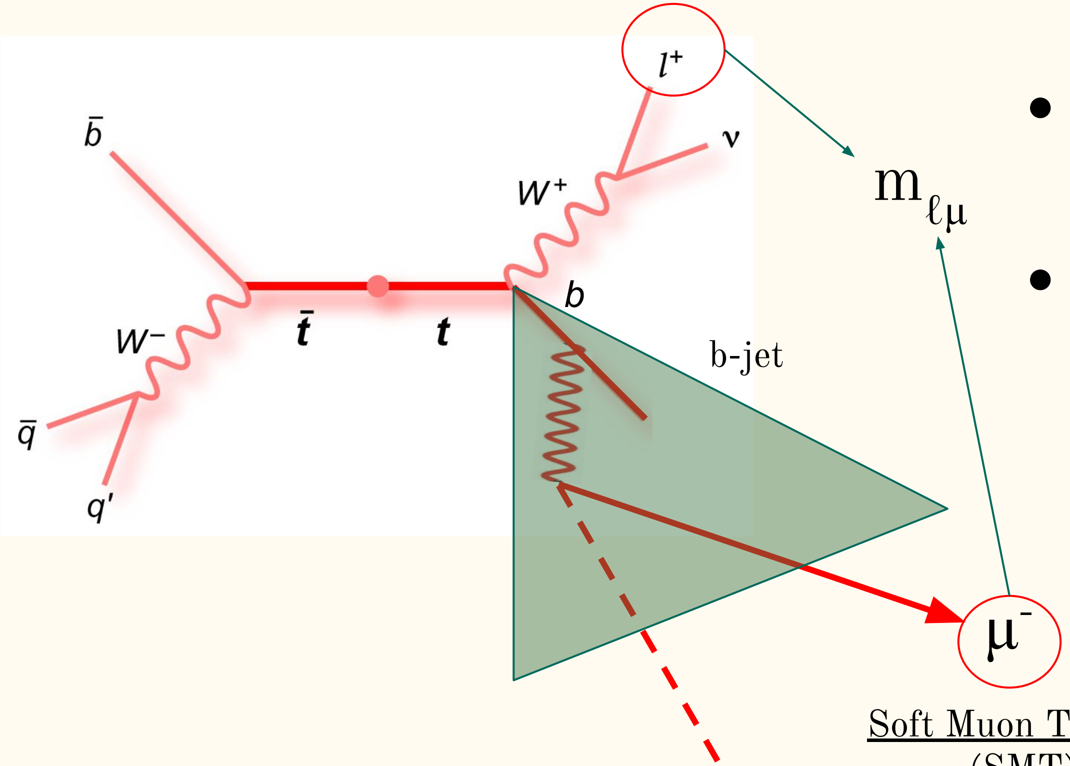


difference between top and anti-top

Top mass SMT

TOPQ-2017-17 arXiv:2209.00583

36/fb @ 13 TeV



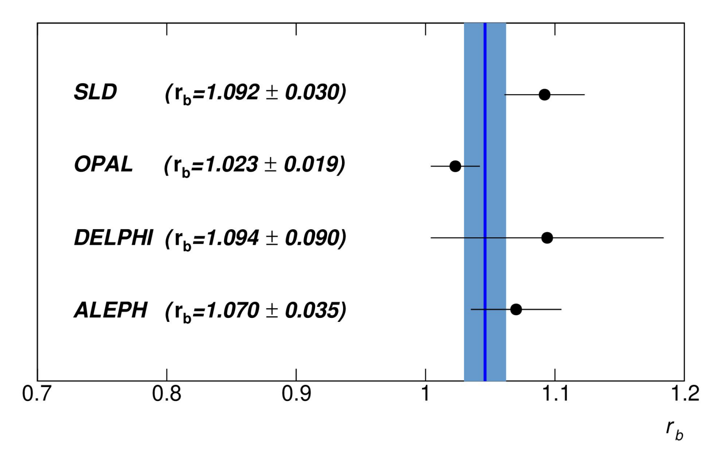
Soft Muon Tagging
(SMT)

- Identify semi-lept. decay of B-had.
  - BR=20% for B→...→μ+X
- Invariant mass $m_{\ell\mu} \rightarrow m_t$
  - purely leptonic,
    less sensitive to jets unc.
  - more direct impact from b→B
    fragmentation modelling

1st proof of principle: CDF Phys. Rev. D80 (2009) 051104, m_t=180.5 ± 12.5 GeV
Similar idea: with J/Ψ→μμ from CMS JHEP 12 (2016) 123, m_t=173.5 ± 3.1 GeV

Top mass SMT: signal modelling

TOPQ-2017-17 arXiv:2209.00583



Hadron	PDG	Powheg+Pythia8	Scale Factor
B^0	0.404 ± 0.006	0.429	0.941 ± 0.014
B^+	0.404 ± 0.006	0.429	0.942 ± 0.014
B^0_s	0.103 ± 0.005	0.095	1.088 ± 0.052
b-baryon	0.088 ± 0.012	0.047	1.87 ± 0.26
D^+	0.226 ± 0.008	0.290	0.780 ± 0.027
D^0	0.564 ± 0.015	0.553	1.020 ± 0.027
D^0_s	0.080 ± 0.005	0.093	0.857 ± 0.054
c-baryon	0.109 ± 0.009	0.038	2.90 ± 0.24

b-frag. universality for ee/pp assumed

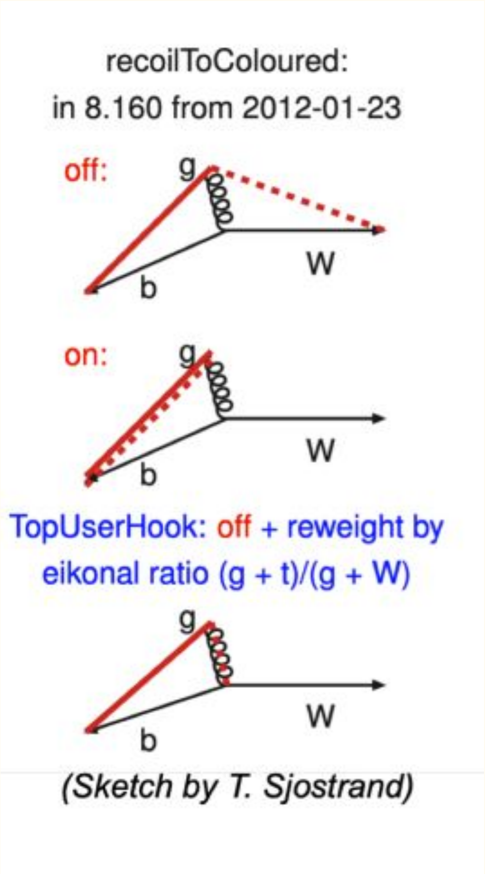
- recent results: deviations for frag. fractions, but significant only at low-p_T
- for frag. function, supported by recent CMS studies CMS-PAS-TOP-18-012

Thus:

- r_b (frag. func. parameter in Pythia8) fitted on LEP+SLD data (now with bin-by-bin correlation)
- fragmentation fractions and BRs reweighted to world averages

Top mass SMT: recoil in PS

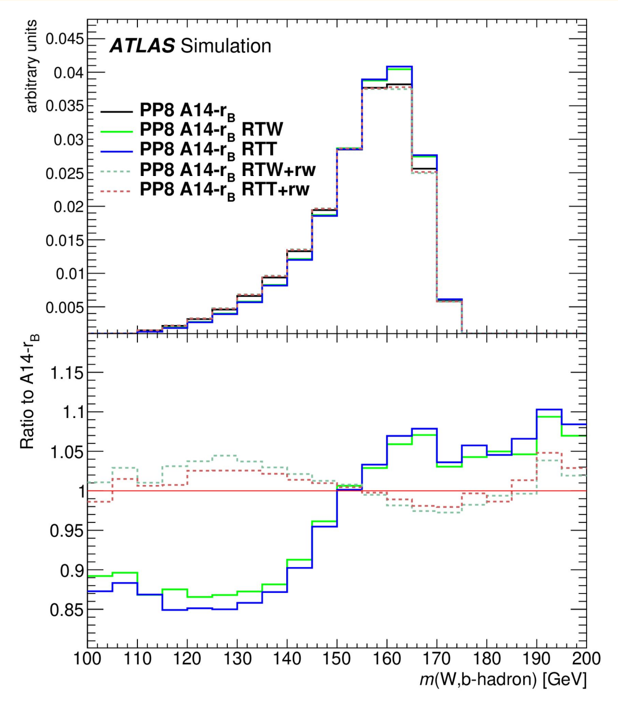
TOPQ-2017-17 arXiv:2209.00583



see slides from P. Skands

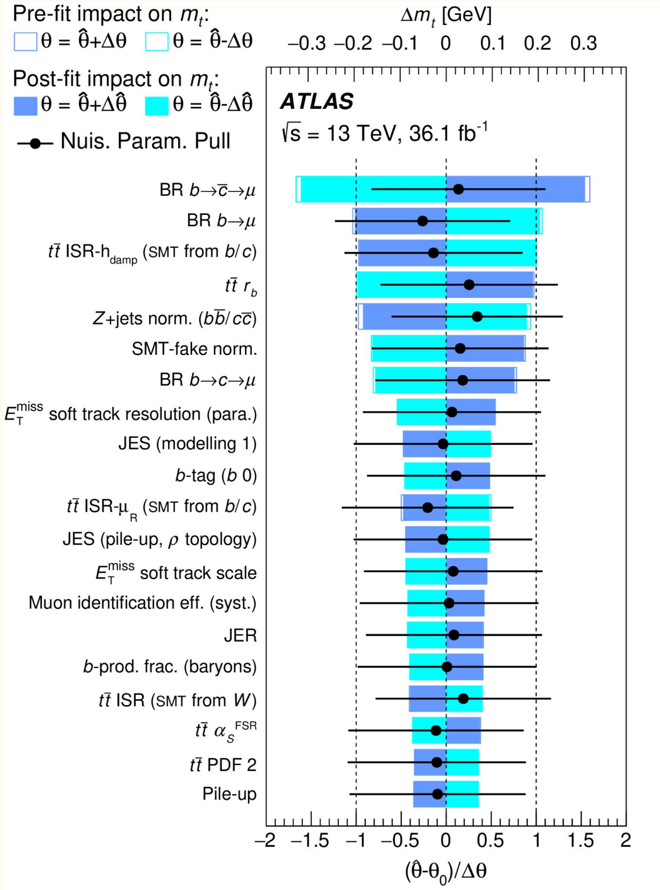
For the first time used uncertainty on gluon emission in t→Wb

- impacts PS modelling of gluons from b→gb
- changes energy distribution within jet
- changes jet p_T due to out-of-cone radiation → impacts jet-based measurement
- b-frag. func. changed as a side effect.
  Nominal in better agreement with NLL resummations → reweighted to that
- No dedicated tune yet!

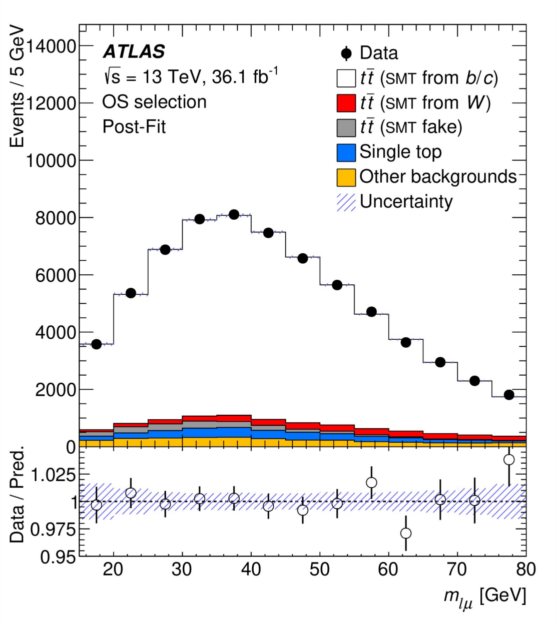


Top mass SMT: results

TOPQ-2017-17 arXiv:2209.00583



$$174.41 \pm 0.39\ (\text{stat.}) \pm 0.66\ (\text{syst.}) \pm 0.25\ (\text{recoil})\ \text{GeV}$$



- Final result from ML profiled fit on $m_{\ell\mu}$
- Recoil uncertainty not profiled
- Result stable vs changes of selection or tune (i.e. Monash vs A14-r_b)
- Compatible at 2σ level with previous ATLAS/CMS results

Top mass $\ell\ell$

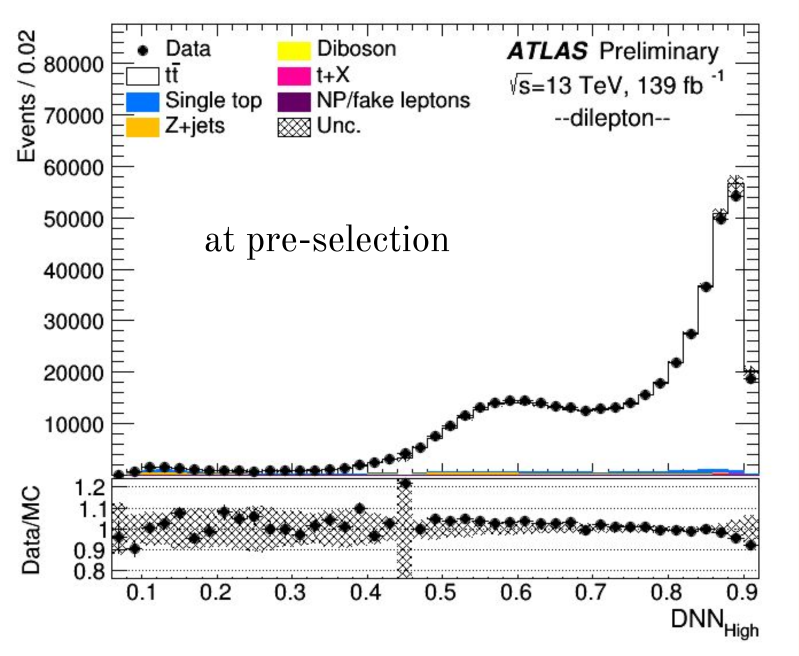
see also Dimbiniaina's poster!

ATLAS-CONF-2022-058

139/fb @ 13 TeV

Updated dataset and new Machine Learning method for event topology reconstruction

- 2 isolated e or μ with opposite charge
- $\geq$2 jets, 2 b-jets
  - WP ε=70% with light/c mistag rate 0.2%/10%
- $m_{\ell\ell} < 15$ GeV or within 80-100 GeV vetoed for $ee/\mu\mu$ events
- DNN to identify b-jet/ℓ pairing using
  - ΔR and inv. mass of ℓb-pairs
  - p_T and η of ℓb-pairs
  - p_T and η of leptons, b-jets
  - m_{bb}
- Select permutation (out of 2) with highest DNN score
  - good data/MC agreement!



classifier performance doesn't depend on m_t

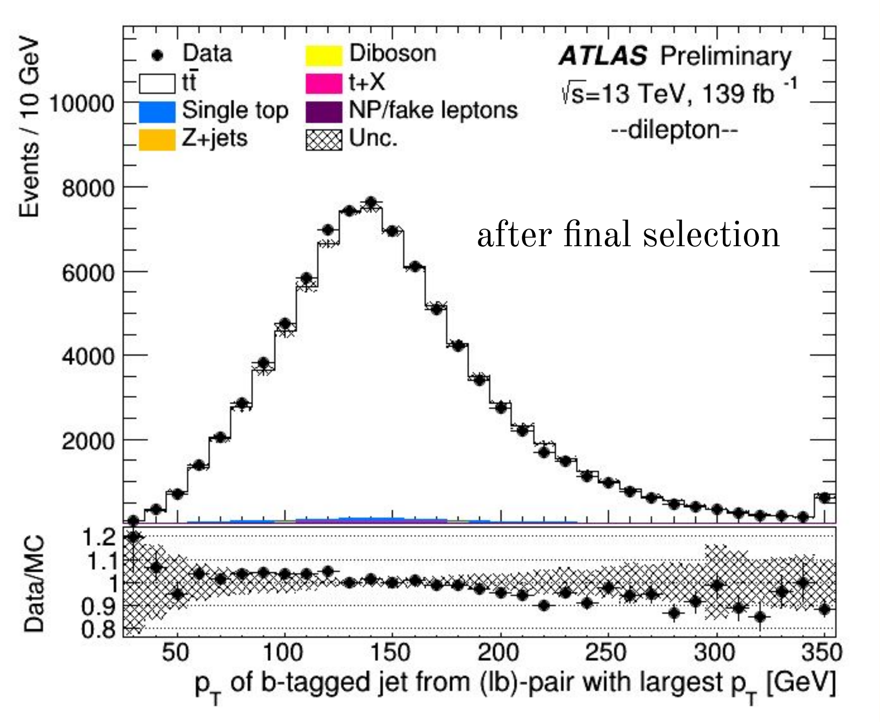
Top mass $\ell\ell$

ATLAS-CONF-2022-058

Optimised selection:

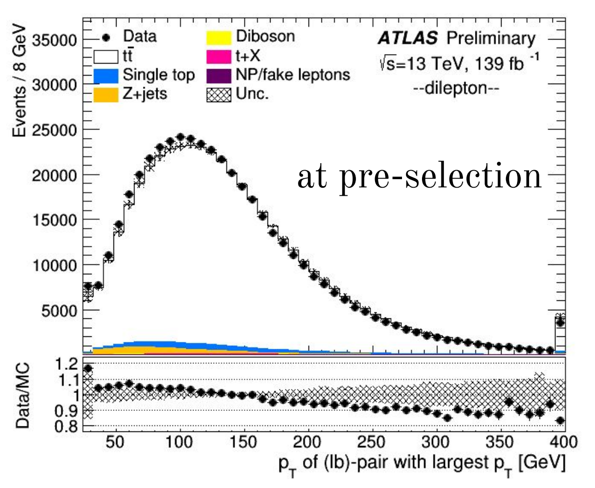
- $\mathrm{DNN_{High}} > 0.65$
- Select the ℓb-pair with largest p_T
- For that pair, $p_T > 160$ GeV
- b-jet in that pair must be leading b-jet

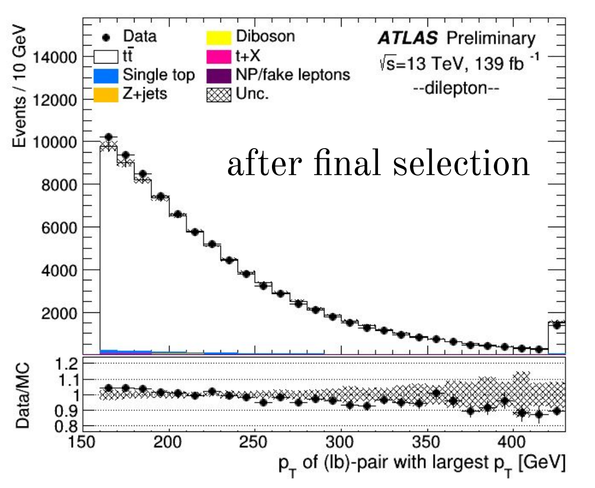
The **invariant mass** of the selected ℓb-pair, $\mathbf{m_{\ell b}^{High}}$, is used as observable.
Fit performed in the range:
$50 \leq m_{\ell b}^{High} \leq 140$ GeV



Top mass ℓℓ

ATLAS-CONF-2022-058





10% less events in data than MC, due to known mismodelling of ℓb p_T

- partially coming from missing NNLO corrections to top p_T

But:

- measurement is shape-only
- reweighting top p_T, ttbar p_T and invariant mass to NNLO predictions covered by scale uncertainties

no bias is expected by the normalisation disagreement

Top mass $\ell\ell$

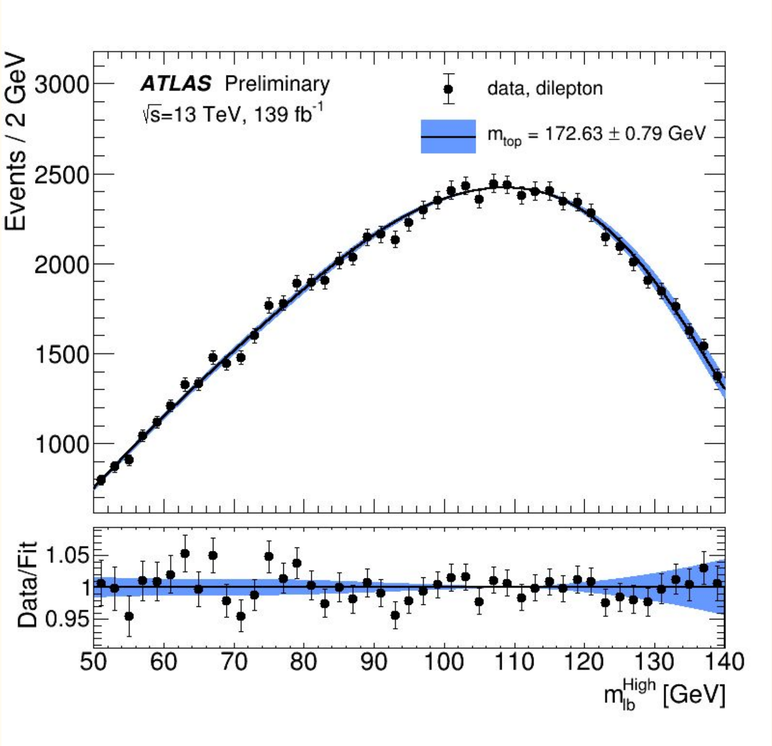
ATLAS-CONF-2022-058

ATLAS EXPERIMENT

$$m_{\text{top}}^{\text{dilepton}} = 172.63 \pm 0.20\,(\text{stat}) \pm 0.67\,(\text{syst}) \pm 0.37\,(\text{recoil})\ \text{GeV}$$

Final result from unbinned ML fit $m_{\ell b}^{\text{High}}$

- Dominant uncertainties are modelling (ME algorithm, ISR/FSR, color reconnections) and JES
- New recoil uncertainty also dominant
    - no dedicated tune though, likely overestimated
- Crosscheck for off-shell and non-resonant effects using bb4l has been performed. The difference in m_t is smaller than modelling uncertainties
- Without recoil uncertainty, improves by ~17% the 8 TeV precision



Top mass $\ell\ell$

ATLAS-CONF-2022-058

$$m_{top}^{dilepton} = 172.63 \pm 0.20\,(\text{stat}) \pm 0.67\,(\text{syst}) \pm 0.37\,(\text{recoil})\ \text{GeV}$$

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	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

Conclusion and final remarks

- CMS l+jets CMS-PAS-TOP-20-008

$$171.77 \pm 0.38\ \text{GeV}$$

- CMS single-top JHEP 12 (2021) 161

$$m_t = 172.13 \pm 0.32\,(\text{stat+prof})^{+0.69}_{-0.71}\,(\text{ext})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

- ATLAS Soft muon tagging TOPQ-2017-17 arXiv:2209.00583

$$174.41 \pm 0.39\ (\text{stat.}) \pm 0.66\ (\text{syst.}) \pm 0.25\ (\text{recoil})\ \text{GeV}$$

- ATLAS Dilepton template mass ATLAS-CONF-2022-058

$$172.63\ \pm\ 0.20\,(\text{stat})\ \pm\ 0.67\,(\text{syst})\ \pm\ 0.37\,(\text{recoil})\ \text{GeV}$$

- Just started to use full power of run-2 data(and run-3 ongoing...)
- More optimised and alternative experimental techniques being developed
- ttbar modelling biggest challenge, need inputs from exp. and theory