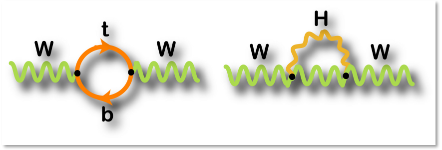
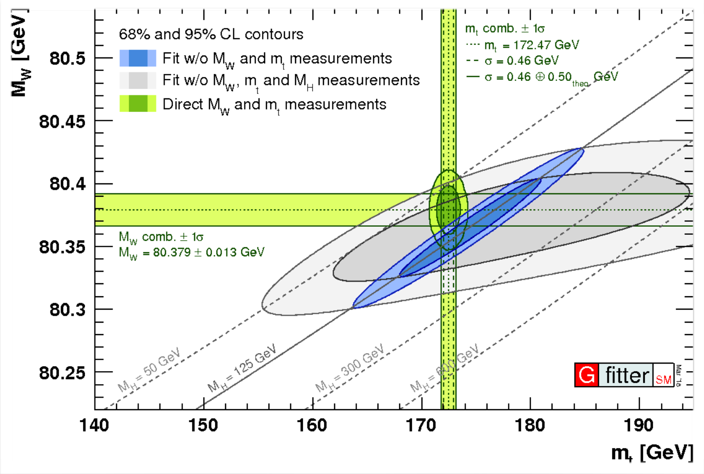
# Top Quark Mass Measurements

Prof Véronique Boisvert

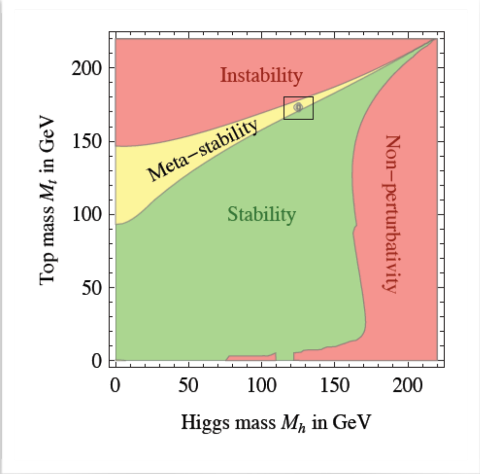
# Why measure the top quark mass?

- Top quark mass is one of the fundamental parameters of the SM that need to be measured
- Strong dependence of the top quark pair production cross section on top mass
  - tt production important background to Higgs and NP searches
- Consistency of SM looking at W, top and Higgs mass
  - Higgs enters into radiative corrections of EW boson
    - Only logarithmically
    - Top mass enters quadratically…
- Top mass enters into the Higgs potential



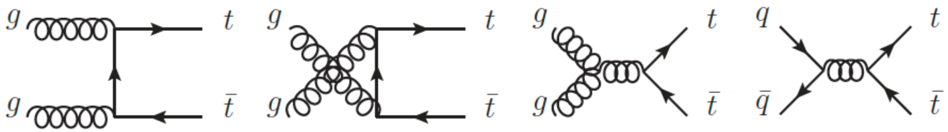


[G. Degrassi et. al. 2012]



# Top production and decay

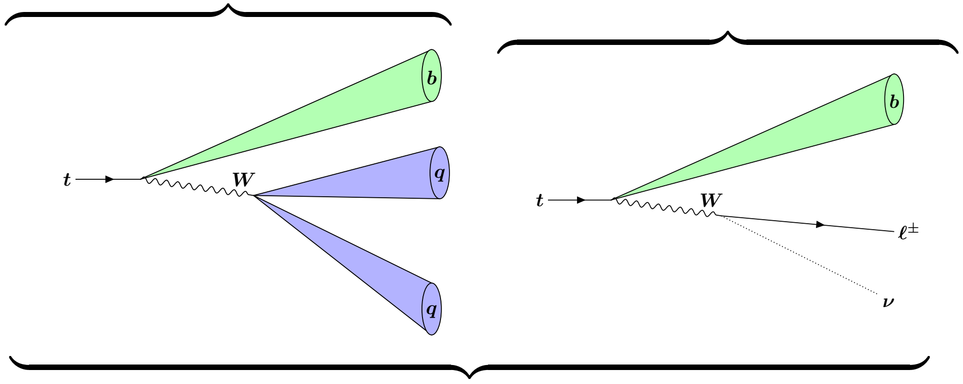
Production:



Decay:

**All-hadronic: 2 of these**

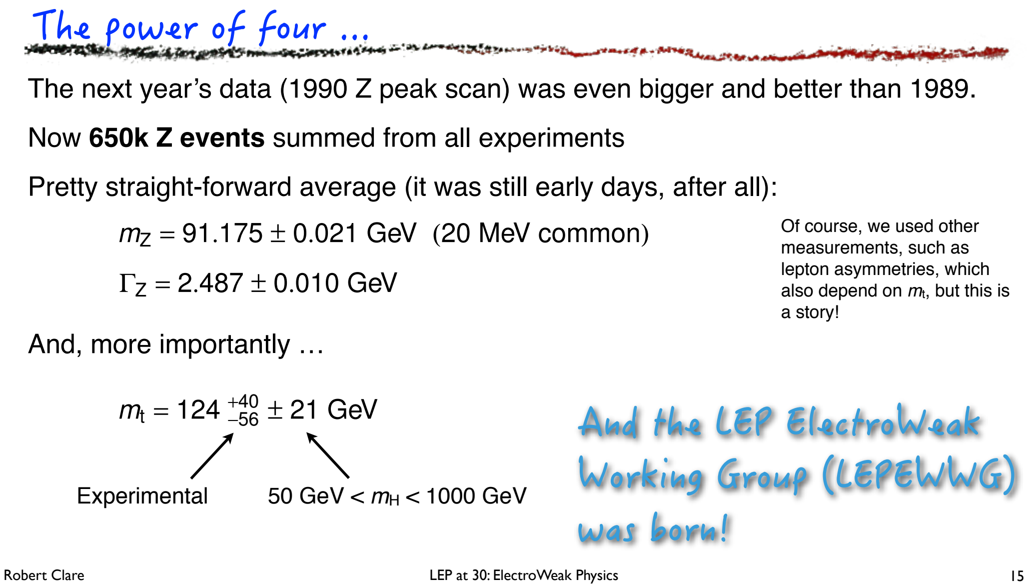
Dilepton: 2 of these



Lepton+Jets Resolved

# A Brief history of… top quark mass measurements

- First “measurement” of the top quark mass from LEP!



The power of four …

The next year’s data (1990 Z peak scan) was even bigger and better than 1989.

Now **650k Z events** summed from all experiments

Pretty straight-forward average (it was still early days, after all):

$$m_Z = 91.175 \pm 0.021 \text{ GeV} \quad (20 \text{ MeV common})$$

$$\Gamma_Z = 2.487 \pm 0.010 \text{ GeV}$$

Of course, we used other measurements, such as lepton asymmetries, which also depend on $m_t$, but this is a story!

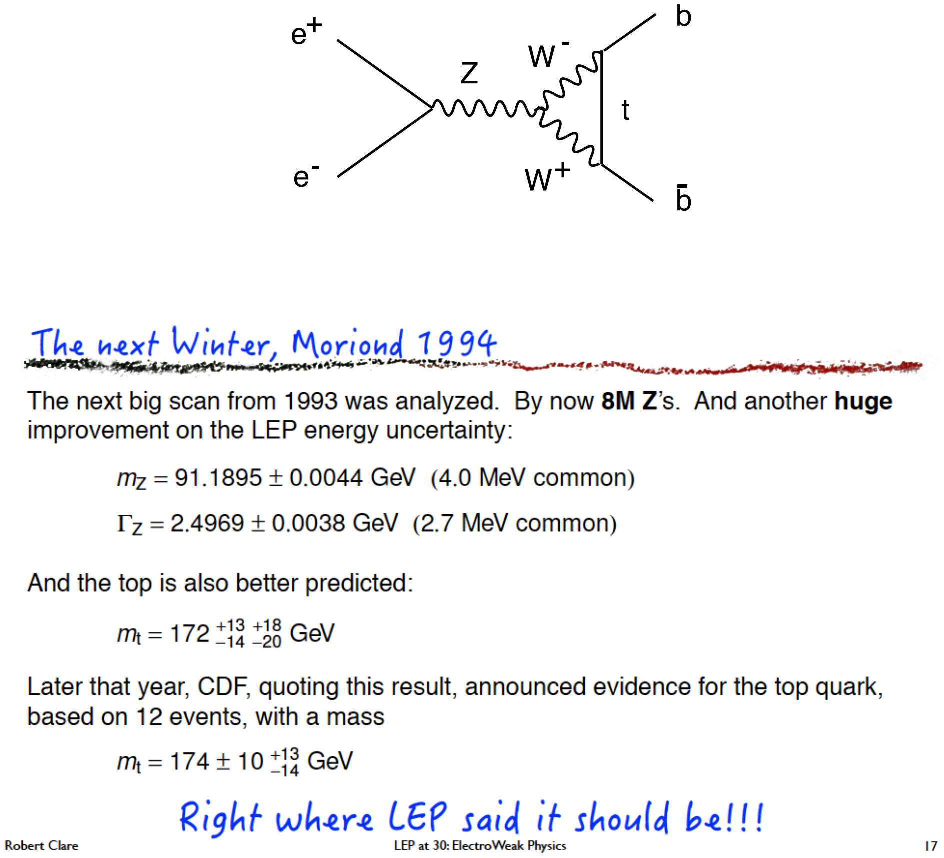
And, more importantly …

$$m_t = 124\,^{+40}_{-56} \pm 21 \text{ GeV}$$

Experimental

50 GeV < $m_H$ < 1000 GeV

And the LEP ElectroWeak Working Group (LEPEWWG) was born!



The next Winter, Moriond 1994

The next big scan from 1993 was analyzed. By now **8M Z**’s. And another **huge** improvement on the LEP energy uncertainty:

$$m_Z = 91.1895 \pm 0.0044 \text{ GeV} \quad (4.0 \text{ MeV common})$$

$$\Gamma_Z = 2.4969 \pm 0.0038 \text{ GeV} \quad (2.7 \text{ MeV common})$$

And the top is also better predicted:

$$m_t = 172\,^{+13}_{-14}\,^{+18}_{-20} \text{ GeV}$$

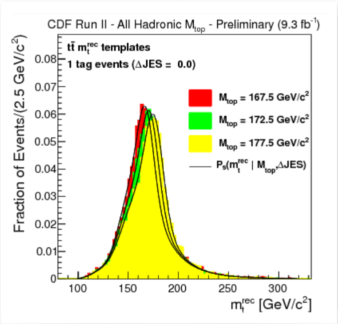
Later that year, CDF, quoting this result, announced evidence for the top quark, based on 12 events, with a mass

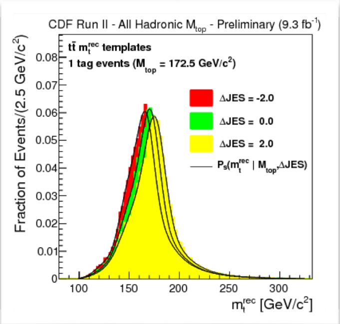
$$m_t = 174 \pm 10\,^{+13}_{-14} \text{ GeV}$$

Right where LEP said it should be!!!

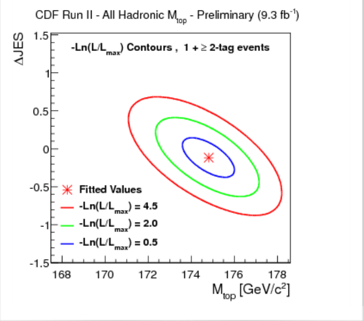
# A Brief history of… top quark mass measurements

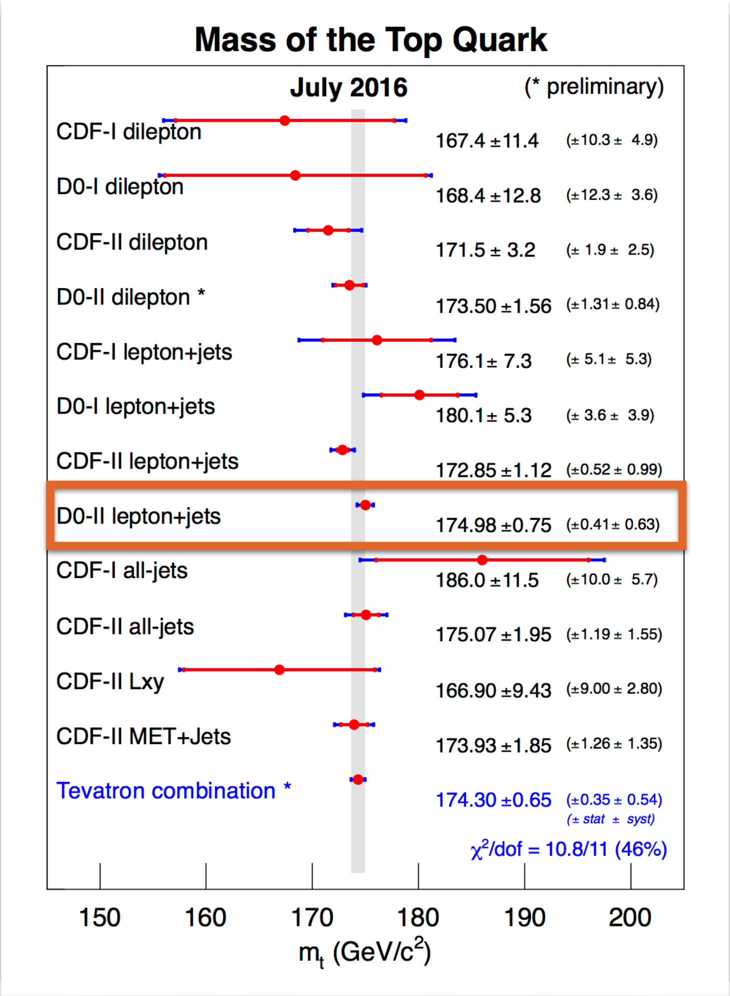
- Tevatron results
  - Introduction of in-situ JES measurement
  - Exploitation of powerful analysis methods like Matrix Element





PRD 90 091101 (2014)





0.43%

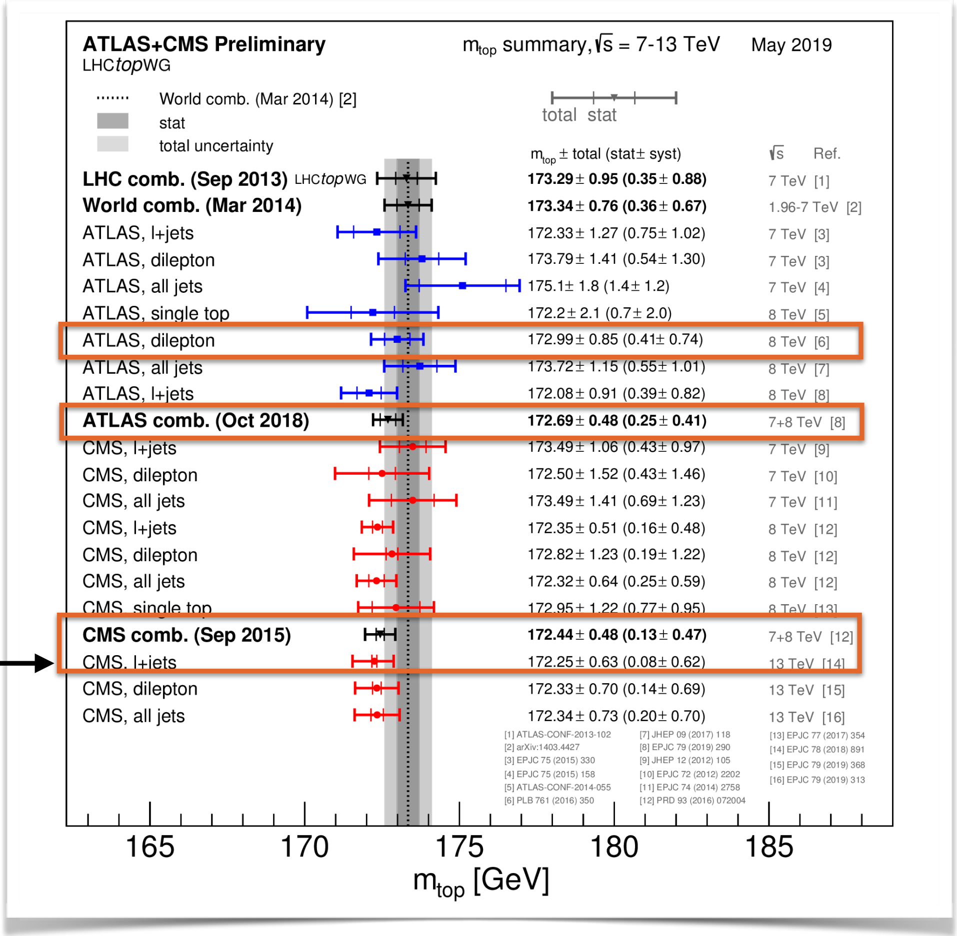
0.37%

# A Brief history of… top quark mass measurements

- LHC results: top quark factory!

This Presentation will focus on the most precise results to infer some (personal) projections

Next:



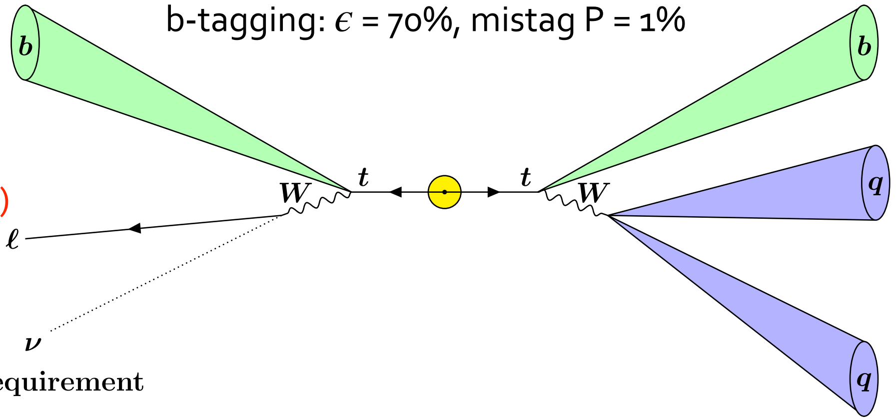
0.49%

0.28%

0.28%
0.37%

EPJC 78 (2018) 891

# CMS l+jets: Event Selection & Reconstruction



Leptonic top

Hadronic top

b-tagging: $\epsilon$ = 70%, mistag P = 1%

p$_T$>34 GeV (e) 26 GeV ($\mu$)

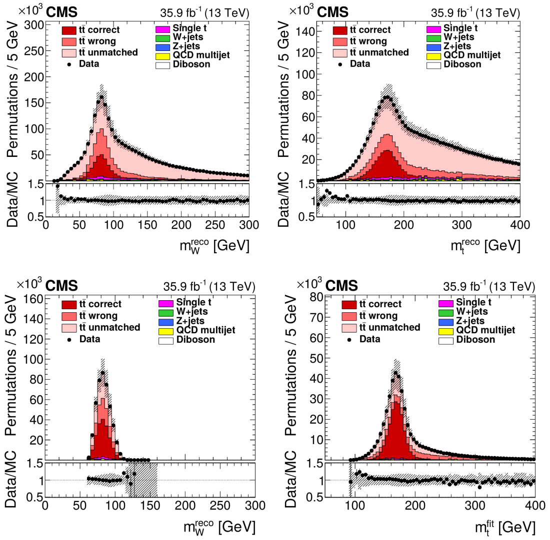
|η|<2.1 (e) 2.4 ($\mu$)

No explicit requirement

≥4 jets

p$_T$>30 GeV |η|<2.4

- tt reconstruction:
  - Use highest 4 p$_T$ jets, among which 2 are b-tagged:
    - results in 2 parton-jets assignments and 2 $p_{z,\nu}$ each = 4 permutations
  - Kinematic fit minimizes a $\chi^2$ containing the measured and fitted 4-momenta, $P_{gof} = e^{-\frac{\chi^2}{2}} \geq 2$
    - Background reduced from 7.6% to 4.3% (mostly single top)
    - all 4 permutations used and weighted by $P_{gof}$



EPJC 78 (2018) 891

# CMS L+jets: Ideogram method

$$\mathcal{L}\left(\text{sample}|m_{\mathrm{t}},\text{JSF}\right)=\boxed{P(\text{JSF})}\prod_{\text{events}}\left(\sum_{\boxed{i=1}}^{n}P_{\text{gof}}\left(i\right)\left[\sum_{\boxed{j}}f_j\boxed{P_j}\left(m^{\text{fit}}_{\mathrm{t},i}|m_{\mathrm{t}},\text{JSF}\right)\boxed{P_j}\left(m^{\text{reco}}_{\mathrm{W},i}|m_{\mathrm{t}},\text{JSF}\right)\right]\right)^{\boxed{w_{\text{evt}}}}$$

$P_j$ = pdf from simulations of $m_t$ and $m_W$ (templates) for different values of top mass and JSF

j = correct, wrong, unmatched ($f_j$ their relative fractions)

i = different permutations (up to 4)

$w_{evt} = c\sum_i P_{gof}(i)$ —> reduces impact of events without correct permutations

P(JSF) = prior for JSF:

- fixed to 1: 1D analysis
- floating: 2D analysis
- Gaussian centered at 1: hybrid analysis

bias correction: 0.5 GeV at 172.5GeV with 3% slope
statistical unc corrections (from pulls): 5% for both the mass and JSF

EPJC 78 (2018) 891

# CMS l+jets: Systematic uncertainties

- Largest systematic uncertainties from jets:
    - Jet Energy Correction and JEC Flavor modeling (Pythia vs Herwig)
- Largest Modelling uncertainty from CR:
    - Color reconnection: Pythia with Early Resonance Decays vs “QCD inspired” and “gluon move”
    - ME generator: Powheg vs Madgraph5 with FxFx matching
    - FSR PS scale: up by $\sqrt{2}$ and down by $1/\sqrt{2}$, jet energy response of light quarks differ by 1.2% vs default sample —> scaled to default

| | 2D approach | | 1D approach | Hybrid | |
|---|---|---|---|---|---|
| | $\delta m_t^{2D}$ [GeV] | $\delta JSF^{2D}$ [%] | $\delta m_t^{1D}$ [GeV] | $\delta m_t^{hyb}$ [GeV] | $\delta JSF^{hyb}$ [%] |
| POWHEG P8 ERD on | $-0.22 \pm 0.09$ | $+0.8$ | $+0.42 \pm 0.05$ | $-0.03 \pm 0.07$ | $+0.5$ |
| POWHEG P8 QCD inspired | $-0.11 \pm 0.09$ | $-0.1$ | $-0.19 \pm 0.06$ | $-0.13 \pm 0.08$ | $-0.1$ |
| POWHEG P8 gluon move | $+0.34 \pm 0.09$ | $-0.1$ | $+0.23 \pm 0.06$ | $+0.31 \pm 0.08$ | $-0.1$ |

| | 2D approach | | 1D approach | Hybrid | |
|---|---|---|---|---|---|
| | $\delta m_t^{2D}$ [GeV] | $\delta JSF^{2D}$ [%] | $\delta m_t^{1D}$ [GeV] | $\delta m_t^{hyb}$ [GeV] | $\delta JSF^{hyb}$ [%] |
| MG5 P8 [FxFx] M2T4 | $+0.19 \pm 0.14$ | $+0.1$ | $+0.29 \pm 0.08$ | $+0.22 \pm 0.11$ | $+0.1$ |
| MG5 P8 [MLM] M1 | $+0.82 \pm 0.16$ | $<0.1$ | $+0.80 \pm 0.10$ | $+0.82 \pm 0.14$ | $<0.1$ |
| POWHEG H++ EE5C | $-4.39 \pm 0.09$ | $+1.4$ | $-3.26 \pm 0.06$ | $-4.06 \pm 0.08$ | $+1.0$ |

| | 2D approach | | 1D approach | Hybrid | |
|---|---|---|---|---|---|
| | $\delta m_t^{2D}$ [GeV] | $\delta JSF^{2D}$ [%] | $\delta m_t^{1D}$ [GeV] | $\delta m_t^{hyb}$ [GeV] | $\delta JSF^{hyb}$ [%] |
| *Experimental uncertainties* | | | | | |
| Method calibration | 0.05 | $<0.1$ | 0.05 | 0.05 | $<0.1$ |
| JEC (quad. sum) | 0.13 | 0.2 | 0.83 | 0.18 | 0.3 |
| – InterCalibration | $(-0.02)$ | $(<0.1)$ | $(+0.16)$ | $(+0.04)$ | $(<0.1)$ |
| – MPFInSitu | $(-0.01)$ | $(<0.1)$ | $(+0.23)$ | $(+0.07)$ | $(<0.1)$ |
| – Uncorrelated | $(-0.13)$ | $(+0.2)$ | $(+0.78)$ | $(+0.16)$ | $(+0.3)$ |
| Jet energy resolution | $-0.08$ | $+0.1$ | $+0.04$ | $-0.04$ | $+0.1$ |
| b tagging | $+0.03$ | $<0.1$ | $+0.01$ | $+0.03$ | $<0.1$ |
| Pileup | $-0.08$ | $+0.1$ | $+0.02$ | $-0.05$ | $+0.1$ |
| Non-$t\bar{t}$ background | $+0.04$ | $-0.1$ | $-0.02$ | $+0.02$ | $-0.1$ |
| *Modeling uncertainties* | | | | | |
| JEC Flavor (linear sum) | 0.42 | 0.1 | 0.31 | 0.39 | $<0.1$ |
| – light quarks (uds) | $(+0.10)$ | $(-0.1)$ | $(-0.01)$ | $(+0.06)$ | $(-0.1)$ |
| – charm | $(+0.02)$ | $(<0.1)$ | $(-0.01)$ | $(+0.01)$ | $(<0.1)$ |
| – bottom | $(-0.32)$ | $(<0.1)$ | $(-0.31)$ | $(-0.32)$ | $(<0.1)$ |
| – gluon | $(-0.22)$ | $(+0.3)$ | $(+0.02)$ | $(-0.15)$ | $(+0.2)$ |
| b jet modeling (quad. sum) | 0.13 | 0.1 | 0.09 | 0.12 | $<0.1$ |
| – b frag. Bowler–Lund | $(-0.07)$ | $(+0.1)$ | $(-0.01)$ | $(-0.05)$ | $(<0.1)$ |
| – b frag. Peterson | $(+0.04)$ | $(<0.1)$ | $(+0.05)$ | $(+0.04)$ | $(<0.1)$ |
| – semileptonic B decays | $(+0.11)$ | $(<0.1)$ | $(+0.08)$ | $(+0.10)$ | $(<0.1)$ |
| PDF | 0.02 | $<0.1$ | 0.02 | 0.02 | $<0.1$ |
| Ren. and fact. scales | 0.02 | 0.1 | 0.02 | 0.01 | $<0.1$ |
| ME/PS matching | $-0.08$ | $+0.1$ | $+0.03$ | $-0.05$ | $+0.1$ |
| ME generator | $+0.19 \pm 0.14$ | $+0.1$ | $+0.29 \pm 0.08$ | $+0.22 \pm 0.11$ | $+0.1$ |
| ISR PS scale | $+0.07 \pm 0.09$ | $+0.1$ | $+0.10 \pm 0.05$ | $+0.06 \pm 0.07$ | $<0.1$ |
| FSR PS scale | $+0.24 \pm 0.06$ | $-0.4$ | $-0.22 \pm 0.04$ | $+0.13 \pm 0.05$ | $-0.3$ |
| Top quark $p_T$ | $+0.02$ | $-0.1$ | $-0.06$ | $-0.01$ | $-0.1$ |
| Underlying event | $-0.10 \pm 0.08$ | $+0.1$ | $+0.01 \pm 0.05$ | $-0.07 \pm 0.07$ | $+0.1$ |
| Early resonance decays | $-0.22 \pm 0.09$ | $+0.8$ | $+0.42 \pm 0.05$ | $-0.03 \pm 0.07$ | $+0.5$ |
| Color reconnection | $+0.34 \pm 0.09$ | $-0.1$ | $+0.23 \pm 0.06$ | $+0.31 \pm 0.08$ | $-0.1$ |
| **Total systematic** | **0.72** | **1.0** | **1.09** | **0.62** | **0.8** |
| Statistical (expected) | 0.09 | 0.1 | 0.06 | 0.08 | 0.1 |
| **Total (expected)** | **0.72** | **1.0** | **1.09** | **0.62** | **0.8** |

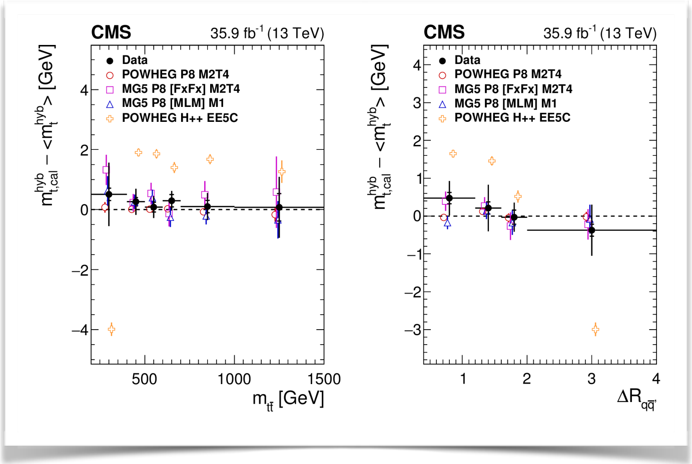
EPJC 78 (2018) 891

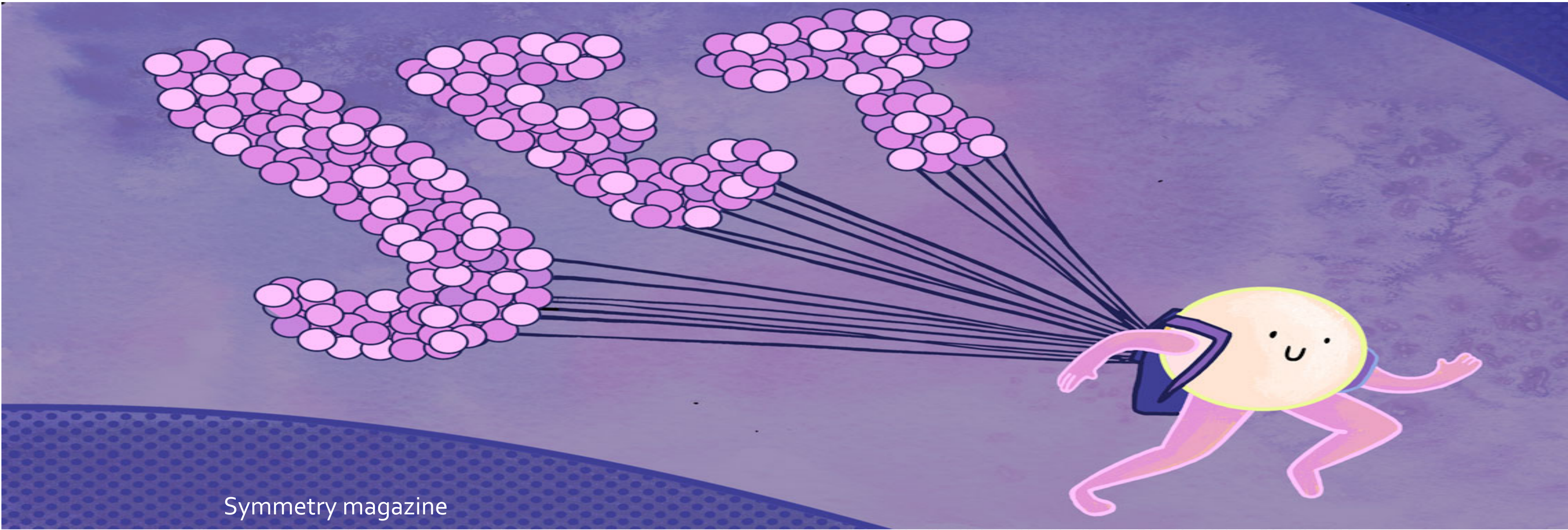
# CMS: l+jets: Results

$$m_t^{2D} = 172.40 \pm 0.09\,(\text{stat+JSF}) \pm 0.75\,(\text{syst})\,\text{GeV},$$
$$\text{JSF}^{2D} = 0.994 \pm 0.001\,(\text{stat}) \pm 0.011\,(\text{syst}).$$

$$m_t^{1D} = 171.93 \pm 0.06\,(\text{stat}) \pm 1.10\,(\text{syst})\,\text{GeV},$$
$$\boxed{m_t^{hyb} = 172.25 \pm 0.08\,(\text{stat+JSF}) \pm 0.62\,(\text{syst})\,\text{GeV}},$$
$$\text{JSF}^{hyb} = 0.996 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst}).$$

172.25 ±0.63 (0.37%)





Symmetry magazine

Since jets dominate uncertainties use alternative methods only relying on leptons

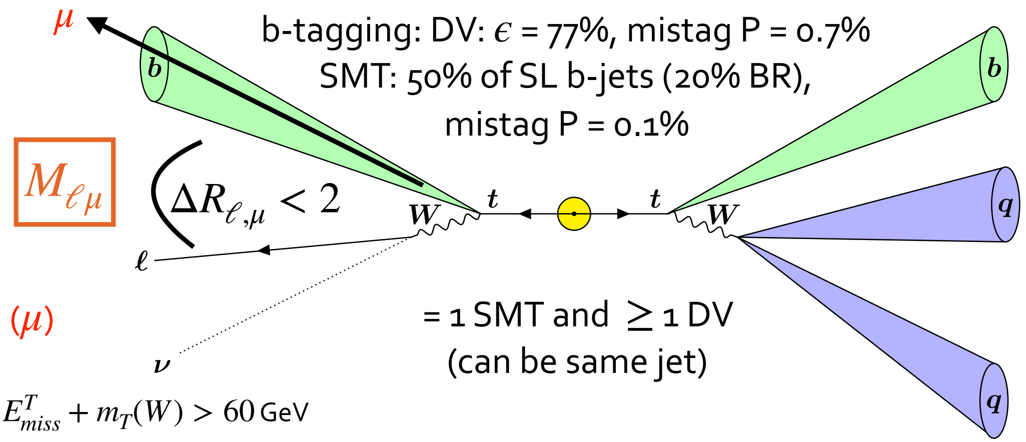
ATLAS-CONF-2019-046

# ATLAS l+jets: Event Selection & Reconstruction

**Leptonic top**

Same top

**Hadronic top**



$M_{\ell\mu}$

$\Delta R_{\ell,\mu} < 2$

b-tagging: DV: $\epsilon$ = 77%, mistag P = 0.7%
SMT: 50% of SL b-jets (20% BR),
mistag P = 0.1%

= 1 SMT and $\geq$ 1 DV
(can be same jet)

p$_T$>27 GeV

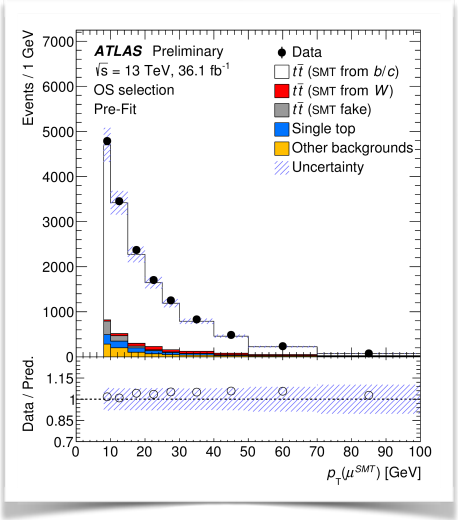
|η|<2.47 (e) 2.5 ($\mu$)

$E^T_{miss} > 30$ GeV and $E^T_{miss} + m_T(W) > 60$ GeV

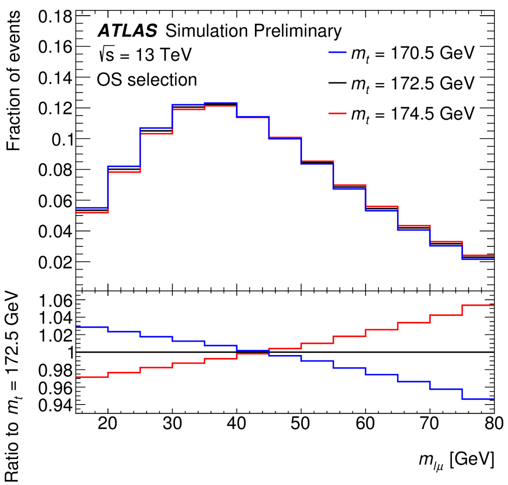
$\geq$4 jets
p$_T$>30 GeV |η|<2.5

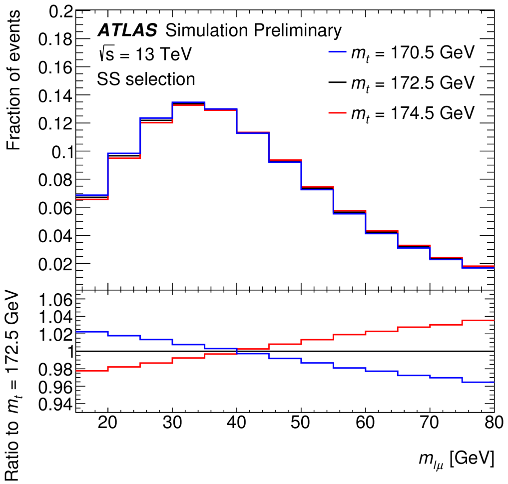
- Sample split into OS (mostly direct $b \to \mu X$ decays) vs SS (mostly sequential $b \to cX' \to \mu X''$)
  - OS: 83% same top, 10% different top, 7% unmatched to b from top (mostly from $t \to W \to cs$)
  - SS: 57% same top, 41% different top, 2% unmatched

| Process | Yield (OS) | Yield (SS) |
|---|---|---|
| $t\bar{t}$ (SMT from $b$- or $c$-hadron) | 56 000(4000) | 34 800(2800) |
| $t\bar{t}$ (SMT from $W \to \mu\nu$) | 2190(320) | 4.9(36) |
| $t\bar{t}$ (SMT fake) | 1490(210) | 1240(170) |
| Single top $t$-chan | 770(70) | 490(40) |
| Single top $s$-chan | 63(6) | 49(4) |
| Single top $Wt$ | 1840(140) | 1260(100) |
| $W$+jets | 1600(400) | 1080(240) |
| $Z$+light jets | 210(80) | 15(6) |
| $Z$+HF jets | 550(170) | 310(100) |
| Diboson | 17.2(29) | 6.3(14) |
| Multi-jet | 530(140) | 480(130) |
| Total Expected | 65 000(5000) | 39 800(3000) |
| Data | 66 891 | 42 087 |



# ATLAS l+jets: binned-template profile likelihood





- 3 free parameters: $m_t$, normalisation for OS and SS
- To improve stability of fit: templates are smoothed
- Stat unc of MC samples and background estimates: bin by bin uncertainty
- Fit found to be linear and unbiased
- Fit method and event selection optimised to minimise total top mass uncertainty blinded

ATLAS-CONF-2019-046

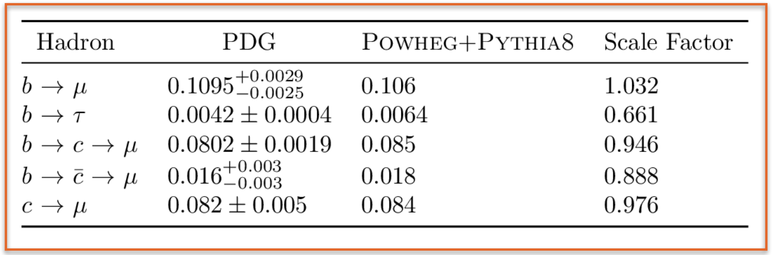
# ATLAS l+jets: systematic uncertainties

Physics

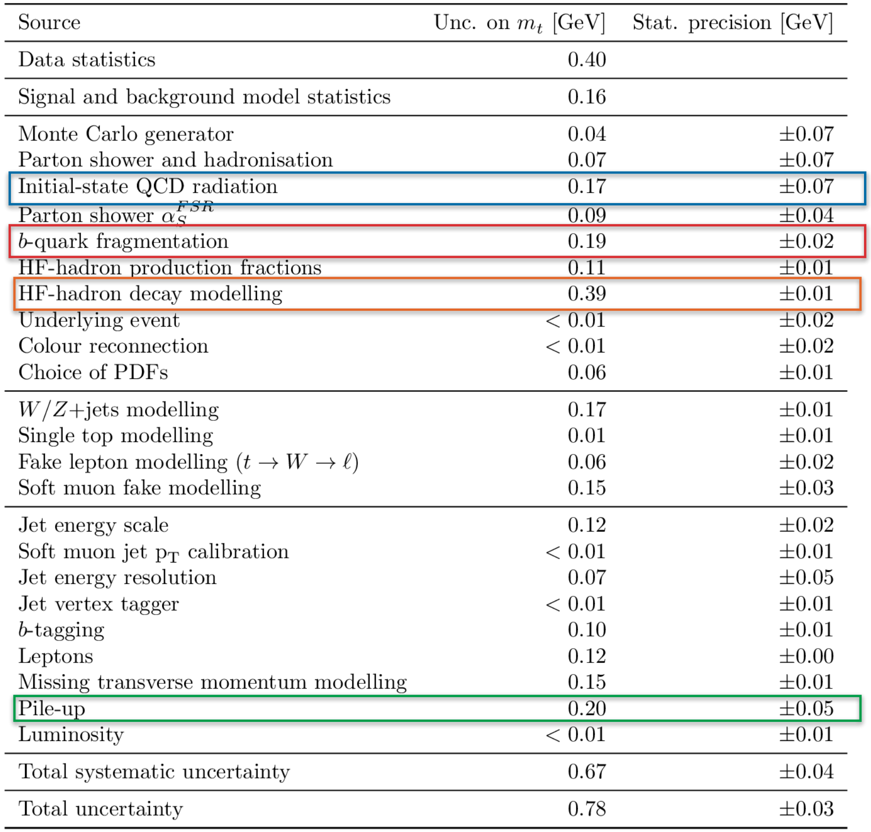
- tt simulation used: Powheg+Pythia+EvtGen with A14 tune and fragmentation $r_b$ fit to ALEPH, DELPHI, OPAL, SLD data ($r_b$ = 1.05 ± 0.02)

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_{\mathrm{T}}^2/z),$$

- Dominant uncertainties from modelling:
  - HF-hadron decays
  - b-quark frag: $r_b$ unc.
  - ISR:
    - rad up = 1/2 x (renorm. and fact. scales), 2 x $h_{\mathrm{damp}}$, Var3cUp $\alpha_S^{ISR}$ value
    - rad down = 2 x (renorm. and fact. scales), Var3cDw $\alpha_S^{ISR}$ value
- Pile-up: dilepton and Z+jets where prompt muons overlap a jet, affects tail of $M_{\ell\mu}$



| Hadron | PDG | Powheg+Pythia8 | Scale Factor |
|---|---|---|---|
| $b \to \mu$ | $0.1095^{+0.0029}_{-0.0025}$ | 0.106 | 1.032 |
| $b \to \tau$ | $0.0042 \pm 0.0004$ | 0.0064 | 0.661 |
| $b \to c \to \mu$ | $0.0802 \pm 0.0019$ | 0.085 | 0.946 |
| $b \to \bar{c} \to \mu$ | $0.016^{+0.003}_{-0.003}$ | 0.018 | 0.888 |
| $c \to \mu$ | $0.082 \pm 0.005$ | 0.084 | 0.976 |

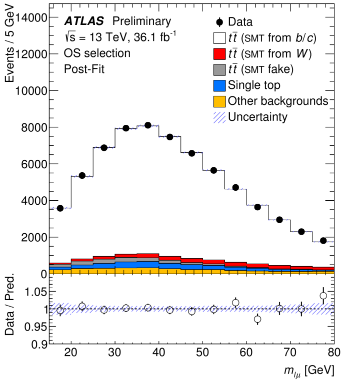


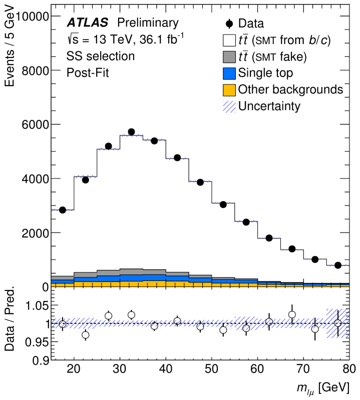
| Source | Unc. on $m_t$ [GeV] | Stat. precision [GeV] |
|---|---|---|
| Data statistics | 0.40 | |
| Signal and background model statistics | 0.16 | |
| Monte Carlo generator | 0.04 | ±0.07 |
| Parton shower and hadronisation | 0.07 | ±0.07 |
| Initial-state QCD radiation | 0.17 | ±0.07 |
| Parton shower $\alpha_S^{FSR}$ | 0.09 | ±0.04 |
| $b$-quark fragmentation | 0.19 | ±0.02 |
| HF-hadron production fractions | 0.11 | ±0.01 |
| HF-hadron decay modelling | 0.39 | ±0.01 |
| Underlying event | $< 0.01$ | ±0.02 |
| Colour reconnection | $< 0.01$ | ±0.02 |
| Choice of PDFs | 0.06 | ±0.01 |
| $W/Z$+jets modelling | 0.17 | ±0.01 |
| Single top modelling | 0.01 | ±0.01 |
| Fake lepton modelling ($t \to W \to \ell$) | 0.06 | ±0.02 |
| Soft muon fake modelling | 0.15 | ±0.03 |
| Jet energy scale | 0.12 | ±0.02 |
| Soft muon jet $p_{\mathrm{T}}$ calibration | $< 0.01$ | ±0.01 |
| Jet energy resolution | 0.07 | ±0.05 |
| Jet vertex tagger | $< 0.01$ | ±0.01 |
| $b$-tagging | 0.10 | ±0.01 |
| Leptons | 0.12 | ±0.00 |
| Missing transverse momentum modelling | 0.15 | ±0.01 |
| Pile-up | 0.20 | ±0.05 |
| Luminosity | $< 0.01$ | ±0.01 |
| Total systematic uncertainty | 0.67 | ±0.04 |
| Total uncertainty | 0.78 | ±0.03 |

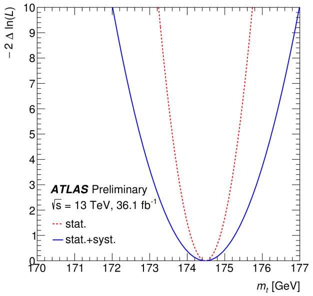
ATLAS-CONF-2019-046

# ATLAS L+Jets: fit results

- Nuisance parameters: no significant pulls or constraints
- Numerous checks performed showing fit stability



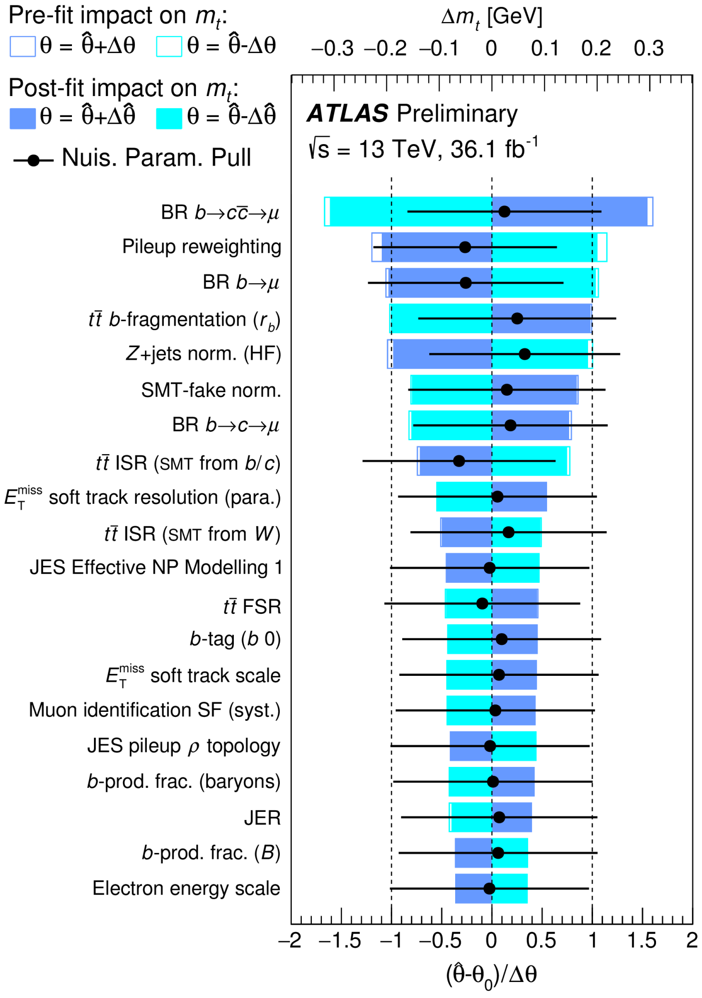




$$m_t = 174.48 \pm 0.40\,(\text{stat}) \pm 0.67\,(\text{syst})\ \text{GeV}$$

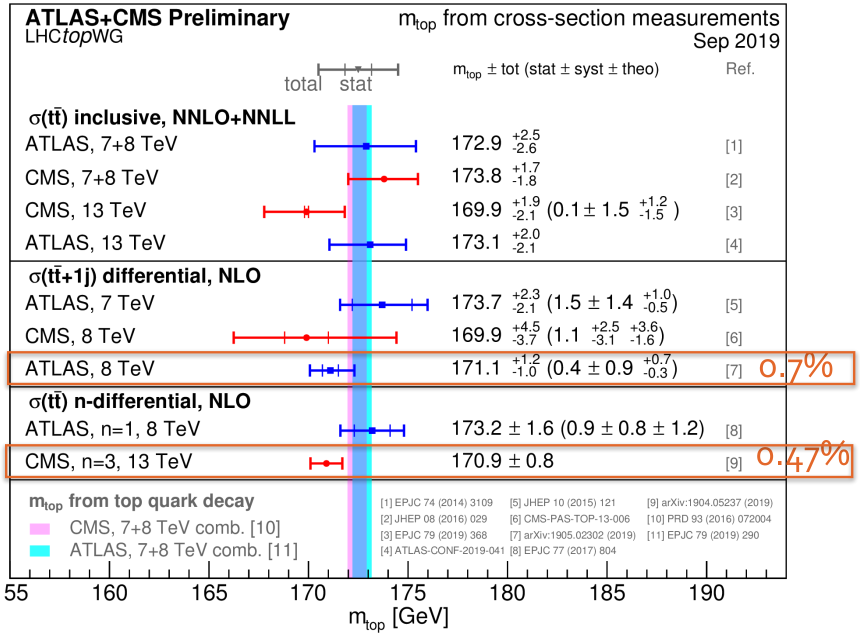
174.48 ±0.78 (0.45%)

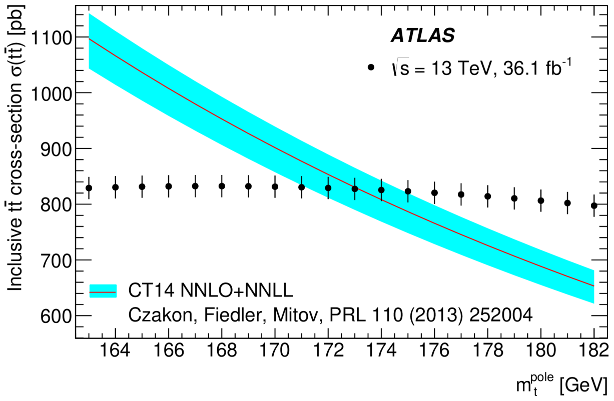
Compatible with ATLAS combination at 2.2$\sigma$



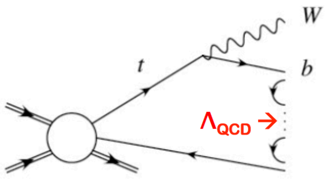
# But which mass are we measuring?

- “Direct” methods measure the “MC” top quark mass, not necessarily the mass parameter in the cross-section
  - Difference could be of order $\Lambda_{QCD} \sim$ 500 MeV- 1 GeV
- “Indirect” methods use the theoretical cross-section dependence on mass





1910.08819, submitted to EPJC

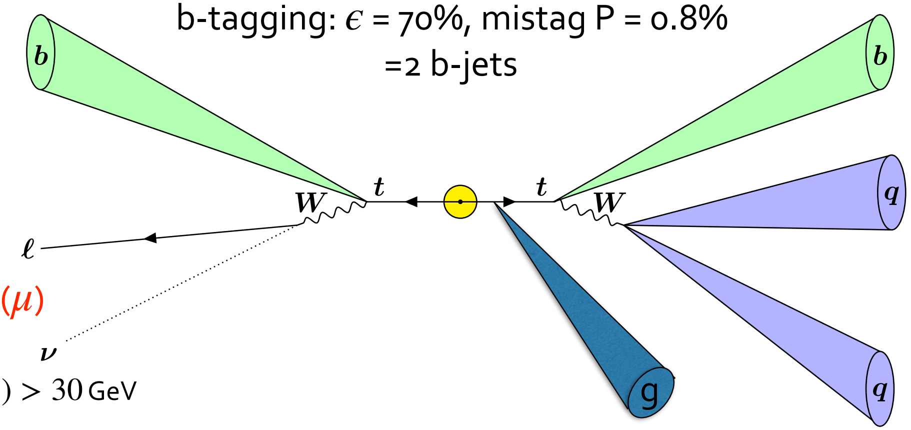


JHEP 11 (2019) 150

# ATLAS l+jets pole mass: Event Selection & Reconstruction

**Leptonic top**

**Hadronic top**



b-tagging: $\epsilon$ = 70%, mistag P = 0.8%
=2 b-jets

$\geq$5 jets
$p_T$>25 GeV |η|<2.5

hadronic W:

$$0.9 < \frac{m_W}{m_{ij}} < 1.25$$

$\min(p_T^i, p_T^j) \times \Delta R_{ij} < 90$ GeV

$p_T$>25 GeV

|η|<2.47 (e) 2.5 ($\mu$)

$E^T_{miss} > 30$ GeV and $m_T(W) > 30$ GeV

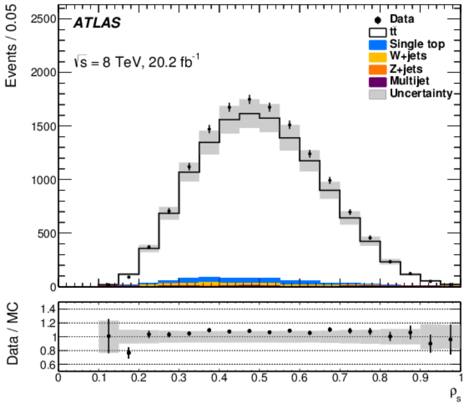
leptonic W:
lepton+up to 2 $\nu$ solutions

extra jet not used in top candidates:
$p_T$>50 GeV

- Pairs of leptonic and hadronic top quarks chosen based on min: $\frac{|m_{t,lep} - m_{t,had}|}{m_{t,lep} + m_{t,had}}$
- and require $\frac{m_{t,lep}}{m_{t,had}} < 0.9$
- $m_0 = 170$ GeV

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}$$

$$\rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}}$$



sensitivity to top mass near prod. threshold $\rho_s > 0.775$

JHEP 11 (2019) 150

# ATLAS l+jets pole mass: Differential distribution

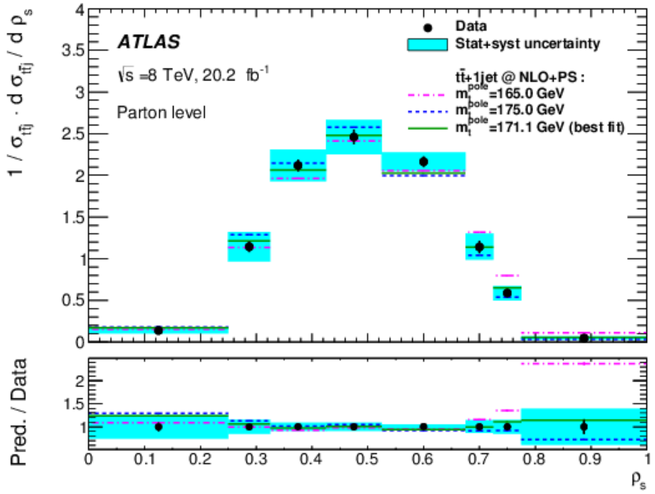
Physics

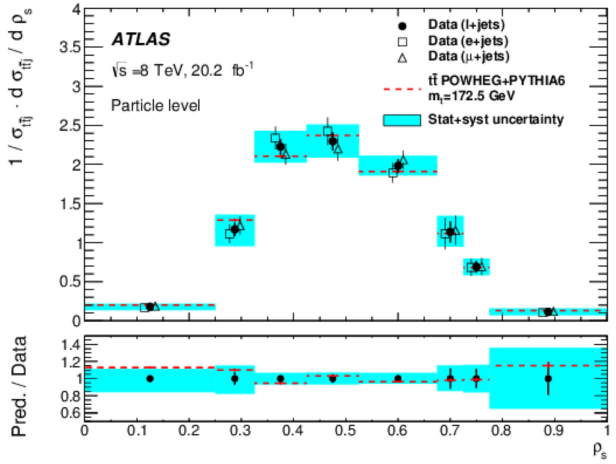
- R is unfolded at:
  - parton level (to compare with fixed-order calculations and extract pole mass)
  - particle level (for future calculations which may include top decay and hadronisation)
- iterative Bayesian unfolding

$$\mathcal{R}^{t\bar{t}+1\text{-jet}}(\rho_s) = \left[\mathcal{M}^{-1} \otimes \mathcal{R}^{\text{det}}(\rho_s)\right] \cdot f(\rho_s) \cdot f^{\text{ph.sp.}}\left(\rho_s, \mathcal{R}^{t\bar{t}+1\text{ jet}}_{\text{ACC}}\right)$$

- pole mass extracted from minimizing:

$$\chi^2 = \sum_{i,j} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_i \left[V^{-1}\right]_{ij} \left[\mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{data}} - \mathcal{R}^{t\bar{t}+1\text{-jet}}_{\text{NLO+PS}}(m_t^{\text{pole}})\right]_j$$

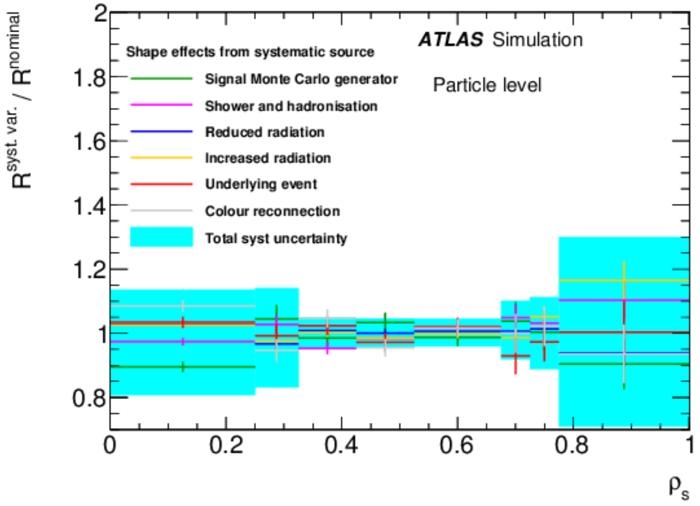




JHEP 11 (2019) 150

# ATLAS l+jets pole mass: Systematic uncertainties

- Dominant uncertainties:
  - theory ones
    - usual scales ($\overline{\text{MS}}$ sensitive to this near prod. threshold)
    - PDF+$\alpha_S$:half the envelope of: CT10nlo+$\alpha_S$=0.118, MSTW2008nlo90cl+$\alpha_S$=0.120, NNPDF23+ $\alpha_S$=0.119
  - Shower and hadronisation: Pythia vs Herwig
  - Colour reconnection: Pythia Perugia tunes
  - Jet Energy scale



| Mass scheme | $m_t^{\text{pole}}$ [GeV] | $m_t(m_t)$ [GeV] |
|---|---|---|
| **Value** | **171.1** | **162.9** |
| **Statistical uncertainty** | **0.4** | **0.5** |
| *Simulation uncertainties* | | |
| Shower and hadronisation | 0.4 | 0.3 |
| Colour reconnection | 0.4 | 0.4 |
| Underlying event | 0.3 | 0.2 |
| Signal Monte Carlo generator | 0.2 | 0.2 |
| Proton PDF | 0.2 | 0.2 |
| Initial- and final-state radiation | 0.2 | 0.2 |
| Monte Carlo statistics | 0.2 | 0.2 |
| Background | <0.1 | <0.1 |
| *Detector response uncertainties* | | |
| Jet energy scale (including *b*-jets) | 0.4 | 0.4 |
| Jet energy resolution | 0.2 | 0.2 |
| Missing transverse momentum | 0.1 | 0.1 |
| *b*-tagging efficiency and mistag | 0.1 | 0.1 |
| Jet reconstruction efficiency | <0.1 | <0.1 |
| Lepton | <0.1 | <0.1 |
| *Method uncertainties* | | |
| Unfolding modelling | 0.2 | 0.2 |
| Fit parameterisation | 0.2 | 0.2 |
| **Total experimental systematic** | **0.9** | **1.0** |
| Scale variations | (+0.6, −0.2) | (+2.1, −1.2) |
| Theory PDF$\oplus\alpha_s$ | 0.2 | 0.4 |
| **Total theory uncertainty** | **(+0.7, −0.3)** | **(+2.1, −1.2)** |
| **Total uncertainty** | **(+1.2, −1.1)** | **(+2.3, −1.6)** |

JHEP 11 (2019) 150

# ATLAS l+jets pole mass: results

$$m_t^{\text{pole}} = 171.1 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst})\,{}^{+0.7}_{-0.3}\,(\text{theo})\ \text{GeV}$$

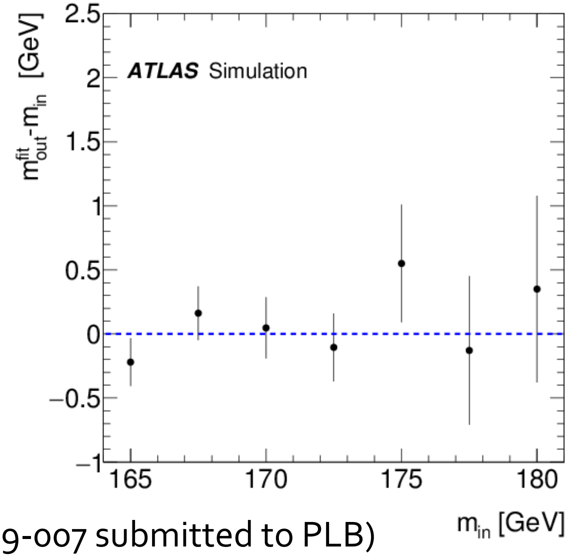
171.1 +1.2 - 1.0 (0.7%)

$$m_t(m_t) = 162.9 \pm 0.5(\text{stat}) \pm 1.0(\text{syst})\,{}^{+2.1}_{-1.2}\,(\text{theo})\ \text{GeV}$$

162.9 +2.4 - 1.6 (1.5%)

- Several checks performed for stability of fit (eg top mass in MC samples, unfolding ingredients from MC with 172.5 GeV)
- Get pole mass value of 170.9 if use $\overline{\text{MS}}$ mass using ($\alpha_S$(163 GeV) = 0.116):

$$m_t^{\text{pole}} = m_t(m_t)\left(1 + \frac{4}{3}\,\frac{\alpha_s\,(\mu = m_t)}{\pi}\right) + O(\alpha_s^2)$$

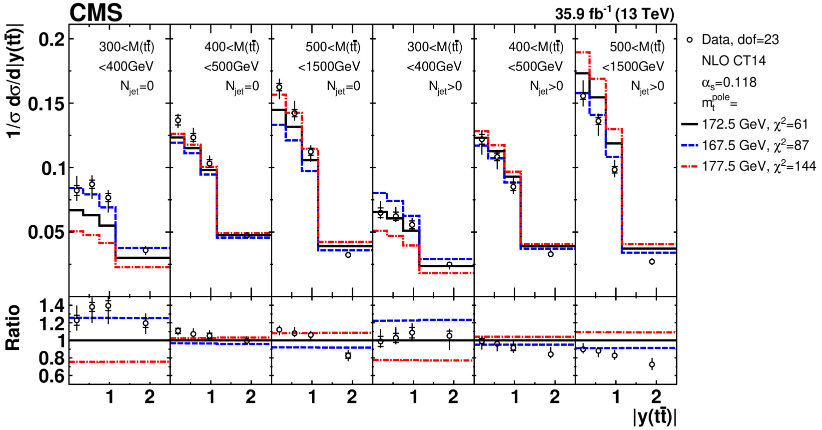


(For a measurement of the running of the $\overline{\text{MS}}$ mass, see CMS recent 13 TeV paper: CMS-TOP-19-007 submitted to PLB)

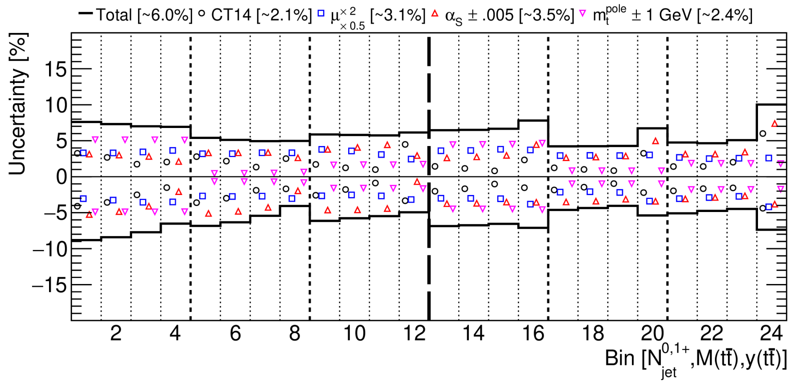
CMS-TOP-18-004

# CMS DIL pole mass: Results

- Use 3D differential distributions: $\left[N_{\text{jet}}^{0,1+}, m^{t\bar{t}}, y^{t\bar{t}}\right]$
- Dominant uncertainties: JES and signal modelling

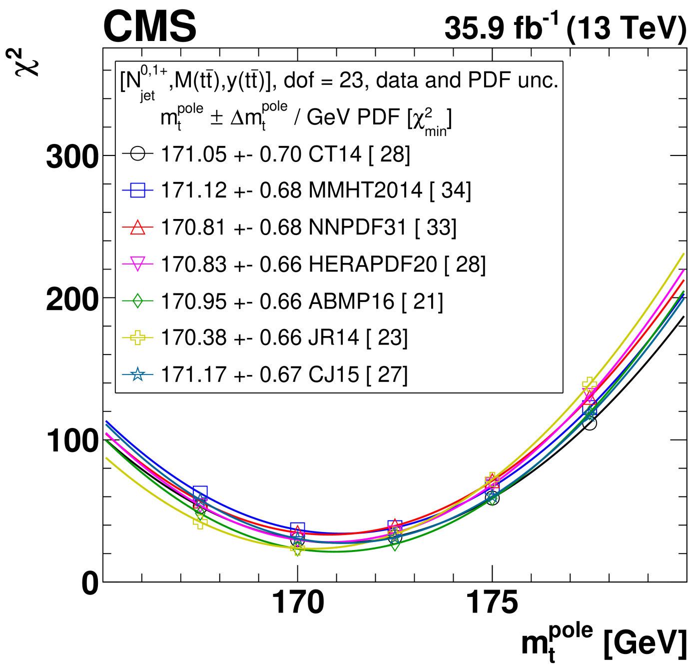


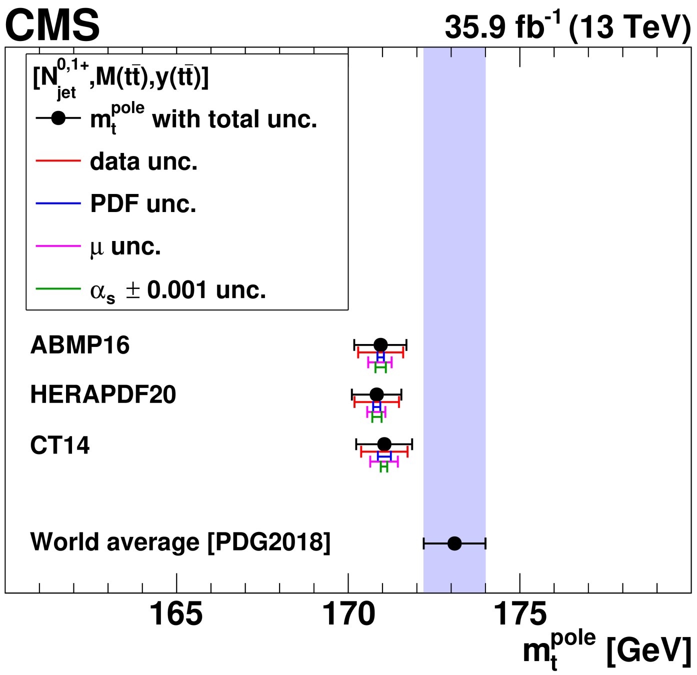
Theoretical uncertainties



# CMS DIL pole mass: Results

- Appendix contains lots of $\chi^2$ plots for mass under different parameters

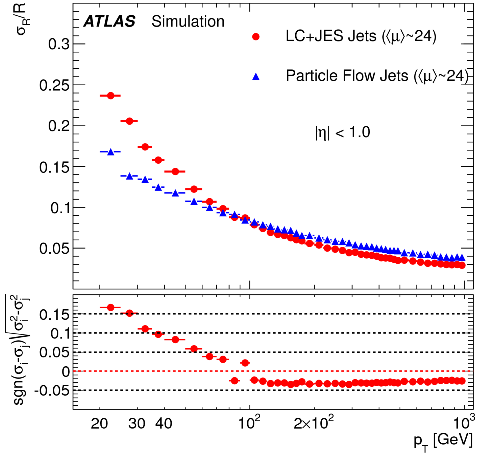




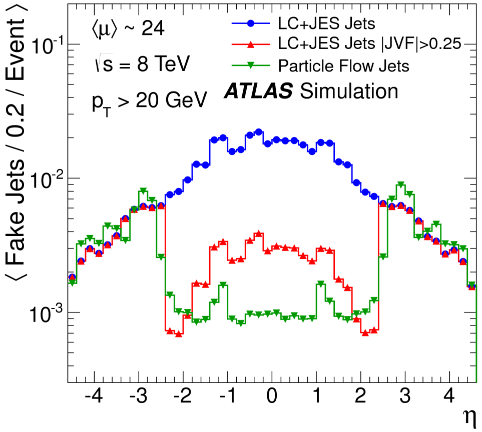
170.9 ±0.8 (0.47%)

# How to improve the uncertainty on top mass?

- Most analyses are dominated by:
- Jet uncertainties
    - Improve jets (ATLAS track jets, very large calibration samples, etc.)
    - Choose methods that don’t rely on jets (eg SMT analysis), helps in combinations as well
- Signal modelling uncertainties
    - Go beyond two-point comparison
    - NLO in decay and off-shell effects
    - Better Multileg MC
    - MC tuning using precision data
    - Cooperation with theorists!

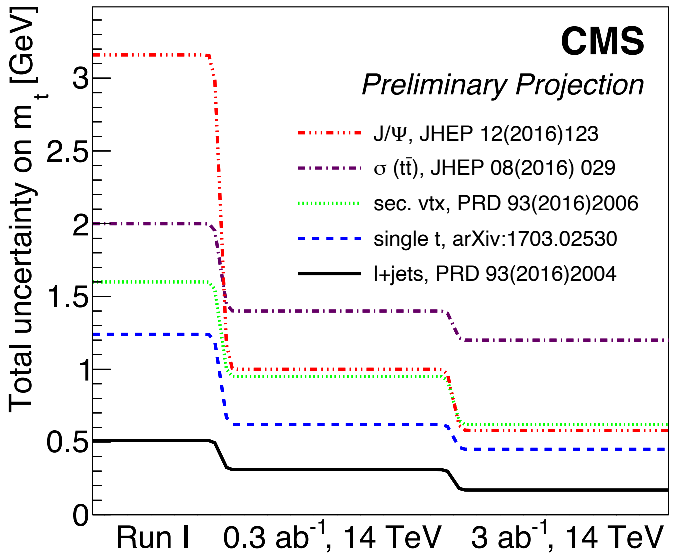


EPJC 77 (2017) 466

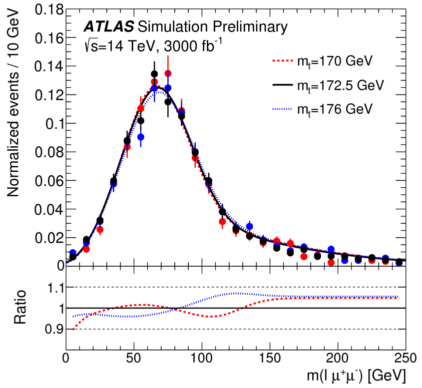


# Medium term projections

- HL-LHC projections done by ATLAS and CMS for the Yellow Reports
- ATLAS: use J/$\Psi$ method —> reach 0.5 GeV
- CMS: various methods studied



CMS-PAS-FTR-16-006

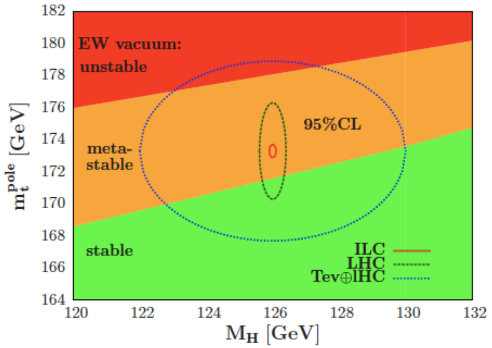


ATL-PHYS-PUB-2018-042

| Source of uncertainty | $\sigma(m_{\text{top}})$ [GeV] |
|---|---|
| Statistical uncertainty | 0.14 |
| Method uncertainty | 0.11 |
| **Signal modelling uncertainties** | |
| $t\bar{t}$ NLO modelling | 0.06 |
| $t\bar{t}$ PS and hadronisation | 0.05 |
| $t\bar{t}$ $b$-production | 0.24 |
| $t\bar{t}$ $b$-fragmentation | 0.11 |
| Initial- and final-state radiation | 0.04 |
| Underlying event | 0.02 |
| Colour reconnection | 0.02 |
| Background modelling uncertainties | 0.10 |
| **Experimental uncertainties** | |
| Jet energy scale (JES) | 0.31 |
| $b$-jet energy scale ($b$-JES) | 0.06 |
| Jet energy resolution (JER) | 0.13 |
| Jet vertex fraction | 0.02 |
| Electrons | 0.03 |
| Muons | 0.09 |
| Pile-up | 0.04 |
| Total Systematic uncertainty | 0.48 |
| Total | 0.50 |

# Conclusions

- Best single analyses able to reach 0.4% precision while combinations reach 0.3%!
- Even pole mass now reach about same level of precision
- Improvements mainly due to increased statistics which allow for differential measurements and regions of phase space sensitive to top mass
- If I do a naive combination of ATLAS SMT with ATLAS comb assuming completely uncorrelated, get: 173.18 ±0.41 (0.24%) very close to world comb.
- Best long term precision will come from a lepton collider
- For Higgs Mass of 125 GeV, need top pole mass > 175 GeV to be in unstable region… seems unlikely…



[S. Alekhin et. al. 2012]

“MC” mass

CMS l+jets: 172.25 ±0.63 (0.37%)

ATLAS SMT: 174.48 ±0.78 (0.45%)

ATLAS Comb.: 172.69 ±0.48 (0.28%)

CMS Comb.: 172.44 ±0.48 (0.28%)

Tevatron Comb.: 174.30 ±0.65 (0.37%)

World Comb.: 173.34 ±0.76 (0.44%)

Pole mass

ATLAS tt+1 jet: 171.1 +1.2 - 1.0 (0.7%)

CMS 3D diff: 170.9 ±0.8 (0.47%)