Recent LHC top mass results and prospects

LHC top WG meeting

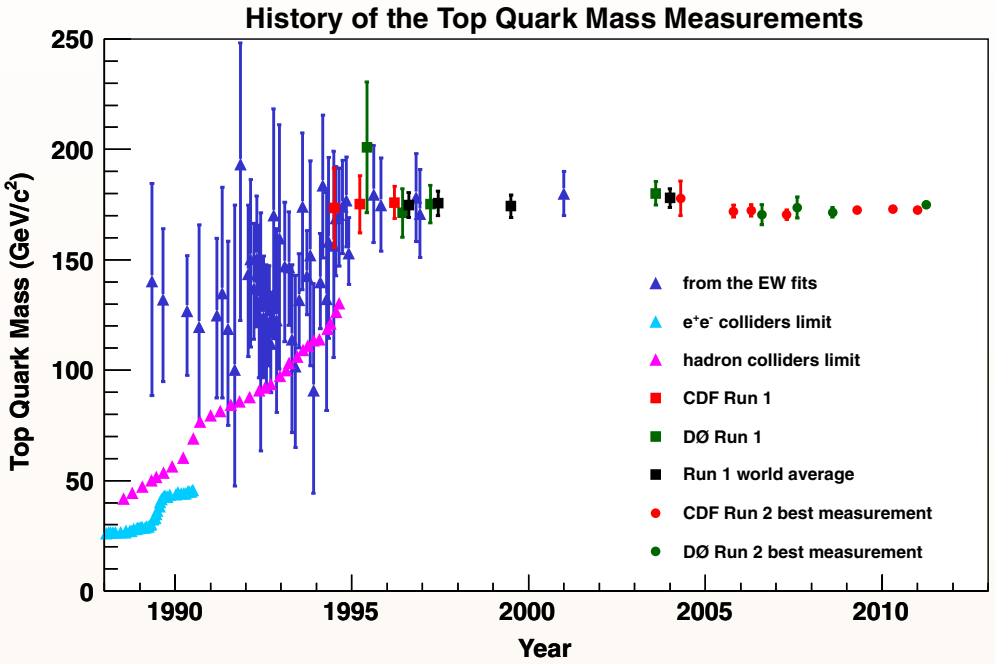
Elvire Bouvier,
UC Riverside

with the generous contribution of
Martin Mulders, Jan Kieseler, Pedro Silva, Rebeca Gonzalez
Martin zur Nedden, Reinhard Schwienhorst, Frédéric Déliot, Mark Owen

June 7, 2017

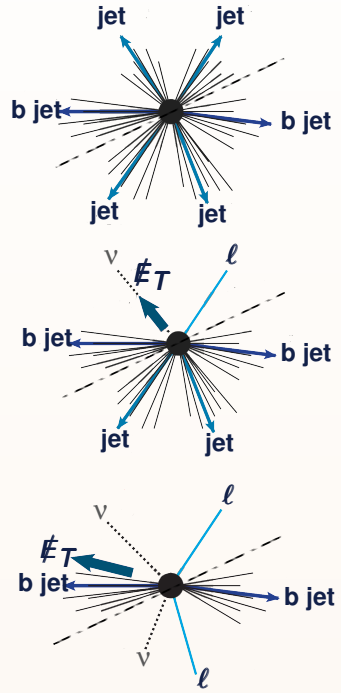
The heritage from the Tevatron

MC-calibrated measurements



all-jets, ℓ+jets:
template fit,
ideogram
method

dilepton:
template fit,
analytical matrix
weighting
technique



- sources of systematic uncertainty treated as external
- combination using the BLUE method

Top-quark pole mass measurements

- m_t^{pole} from $\sigma_{t\bar{t}}$

Recent use of these "standard" techniques

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 20.2\ \text{fb}^{-1}$

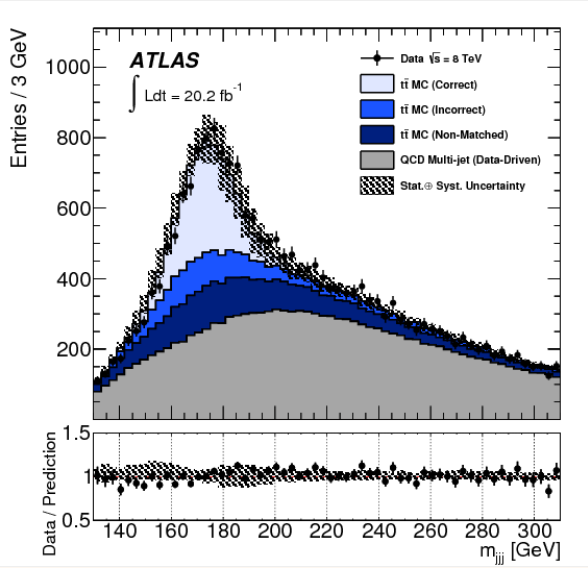
All-jets (Feb 2017)

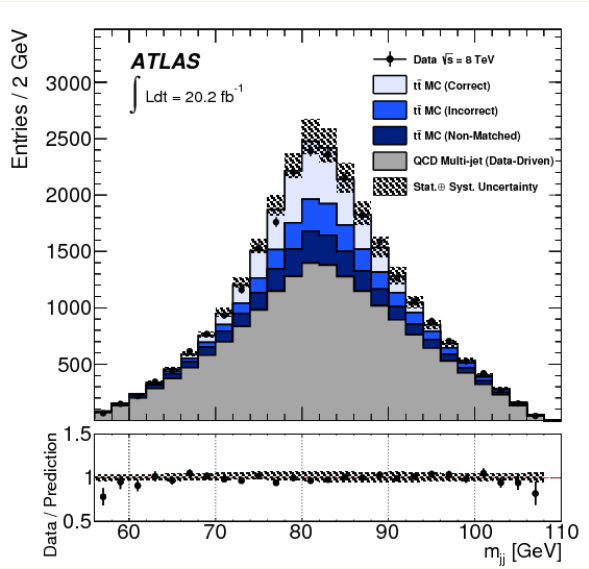
- Computing $R_{3/2} = m_{jjj}/m_{jj}$ in all-jets $t\bar{t}$ events
- Data-driven estimation of the multijet background
- Binned χ^2 fit for templates resulting in:

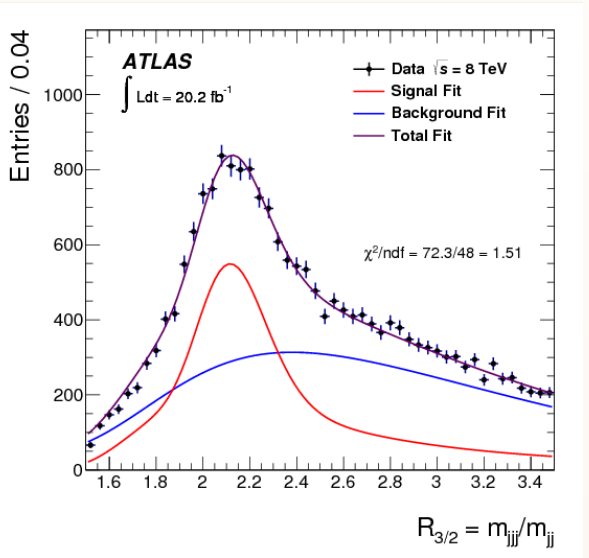
$$m_t = 173.72 \pm 0.55\,(\text{stat}) \pm 1.01\,(\text{syst})\ \text{GeV}$$

- Main systematic sources:
  - hadronization modeling ~ 0.6 GeV
  - JES ~ 0.6 GeV
  - b-JES ~ 0.35 GeV

arXiv:1702.07546



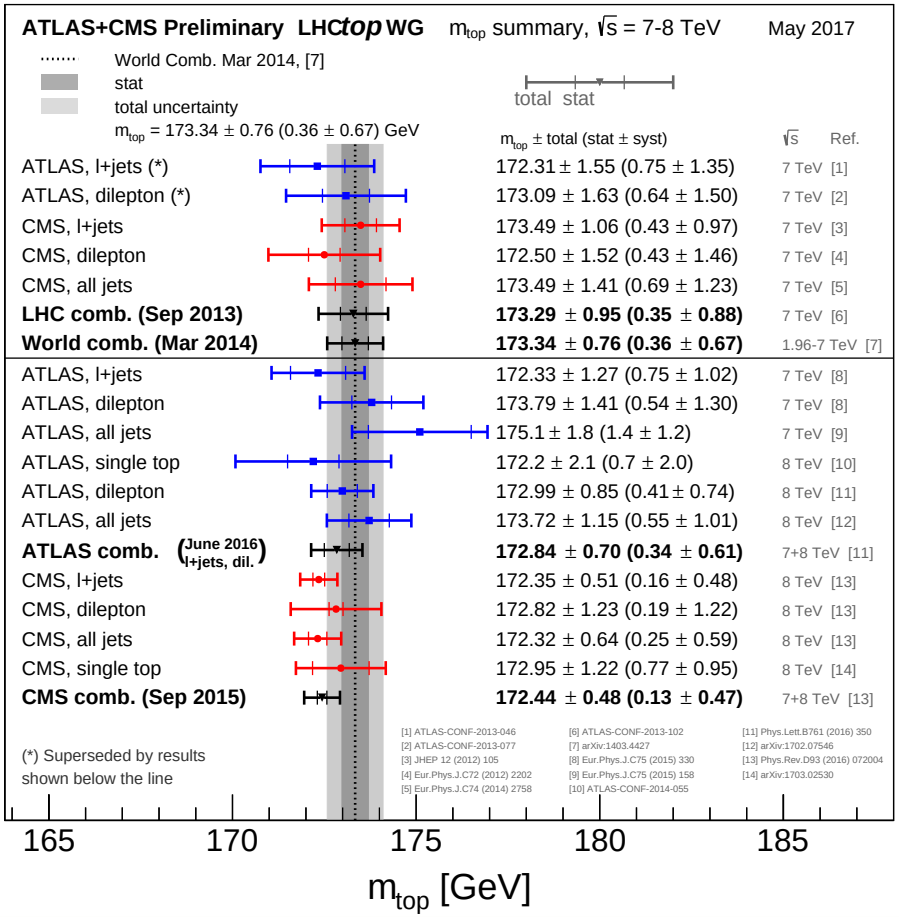




LHC Run-1 measurements

with standard decay channels

$\sqrt{s} = 7$ and 8 TeV



- Using the Best Linear Unbiased Estimate (BLUE) method to combine LHC Run-1 "standard" measurements
- Main systematic uncertainties
  - hadronization ~ 0.35 GeV
  - jet energy corrections ~ 0.15 GeV
  - hard-process scattering ~ 0.15 GeV

$\hookrightarrow$ correlated between channels, methods, and experiments

$\hookrightarrow$ total uncertainty $< 0.3\%$

Some innovations already integrated in these measurements, more to come, taking advantage of the increasing statistics

Approaches to reduce systematic uncertainties

Phase space restriction

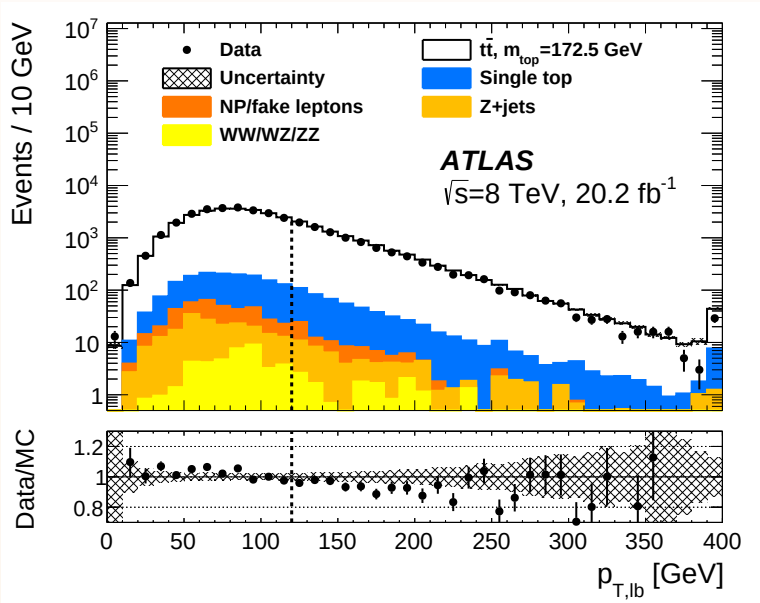
$\sqrt{s} = 8$ TeV,
$\mathcal{L} = 20.2\ \text{fb}^{-1}$

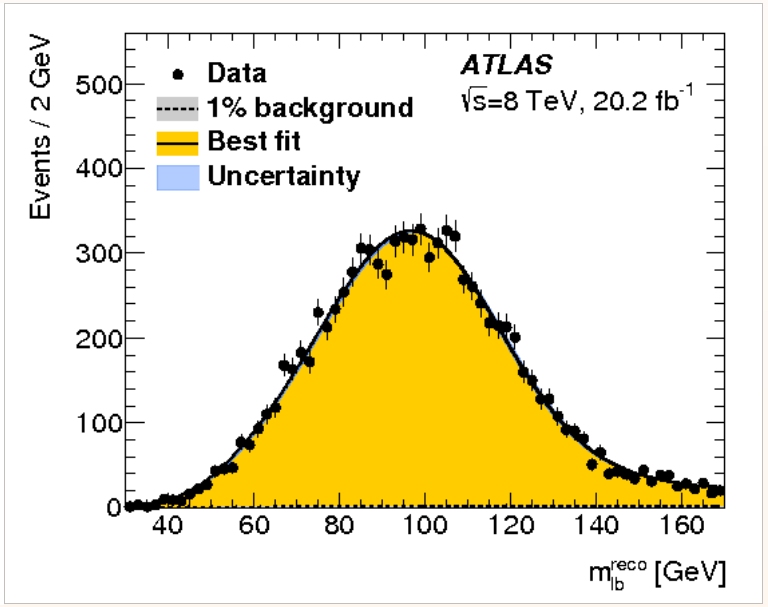
- Computing $m_{\ell b}$ in dilepton $t\bar{t}$ events ($\ell = \mu$ or e)
- Phase-space restriction ($p_{T,\,\ell b} > 120$ GeV) to minimize the uncertainty on m_t
- Likelihood fit resulting in:

$$m_t = 172.99 \pm 0.41\,(\text{stat}) \pm 0.74\,(\text{syst})\ \text{GeV}$$

- Main systematic sources:
  - JES ~ 0.55 GeV
  - b-JES ~ 0.3 GeV
  - ISR/FSR ~ 0.25 GeV

PLB 761 (2016) 350





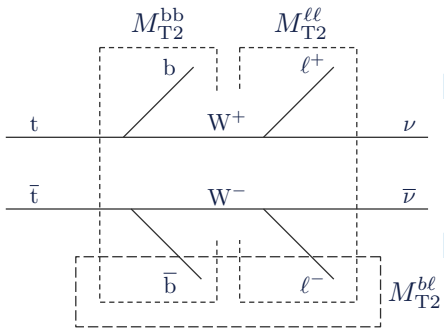
Approaches to reduce systematic uncertainties

In-situ constraints in simultaneous measurements (1)

m_t and JSF (Apr 2017)

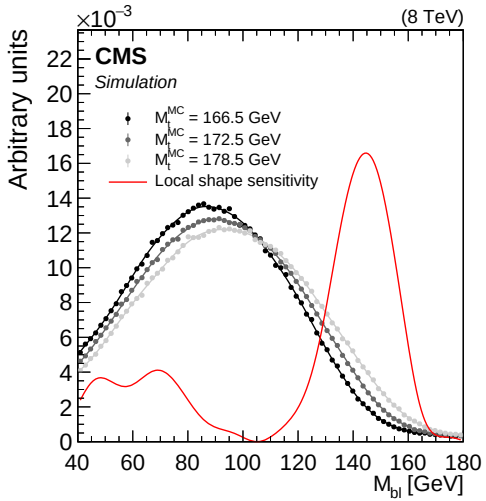
- Computing $m_{\ell b}$ and m_{T2}^{bb} in dilepton $t\bar{t}$ events

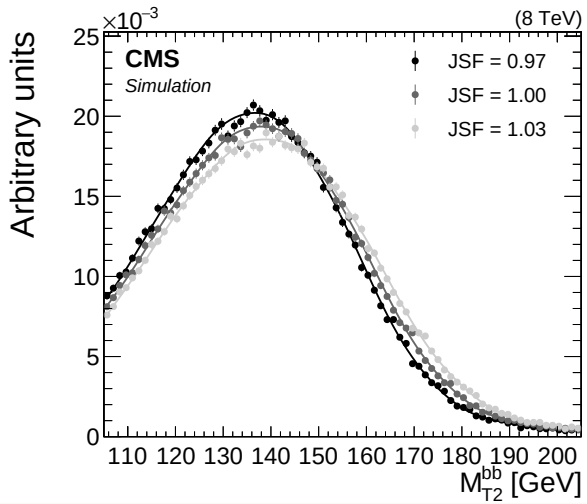
  $m_{T2} = \min_{\vec{p}_T^a + \vec{p}_T^b = \vec{p}_T^{miss}} [\max(M_T^a, M_T^b)]$, with W bosons as "child" particles



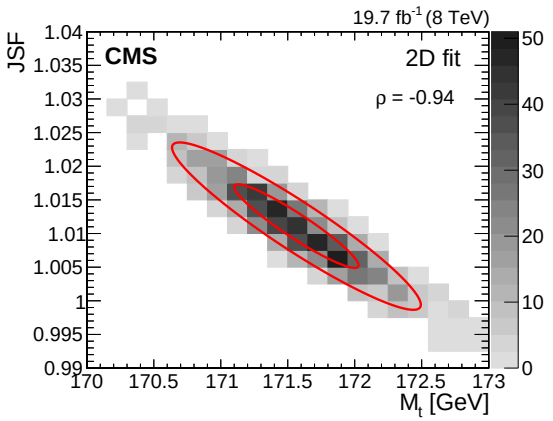
branch a

branch b





$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}



arXiv:1704.06142

- Shape estimation from MC templates:

  $m_t = 172.22 \pm 0.18\,(\text{stat})^{+0.89}_{-0.93}\,(\text{syst})$ GeV

- Main systematic sources: $p_T(t)$, ren. and fact. scales, JES

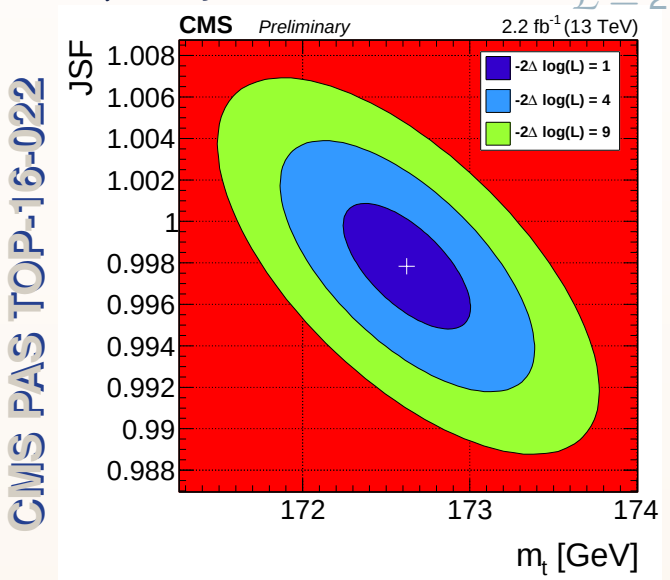
  ~ 0.5 GeV ~ 0.45 GeV ~ 0.45 GeV

Approaches to reduce systematic uncertainties

In-situ constraints in simultaneous measurements (2)

m_t and JSF (Mar 2017)

- Applying the ideogram method to the reconstructed m_t and m_W distributions from $\mu^{\pm}$+jets $t\bar{t}$ events $\sqrt{s} = 13$ TeV, $\mathcal{L} = 2.2$ fb^{-1}



$m_t = 172.62 \pm 0.38\,(\text{stat}) \pm 0.70\,(\text{syst})$ GeV

- Main systematic sources:
  flavor-dep. JES, JES, PS scale
  ~ 0.4 GeV ~ 0.3 GeV ~ 0.25 GeV

m_t, JSF, and b-JSF (May 2013)

- Applying a 3D template fit to the reconstructed m_t, m_W, and $R_{\ell b}$ distributions from ℓ+jets $t\bar{t}$ events

$$R_{\ell b}^{2b} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet1}} + p_T^{W_{jet2}}}$$

$$R_{\ell b}^{1b} = \frac{2 \cdot p_T^{b}}{p_T^{W_{jet1}} + p_T^{W_{jet2}}}$$

$\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7$ fb^{-1} EPJC 75 (2015) 330 (ATLAS)

$m_t = 172.31 \pm 0.75\,(\text{stat}) \pm 1.35\,(\text{syst})$ GeV

(8 TeV analysis targeting TOP2017)

- Main systematic sources:
  b-tagging eff. ~ 0.8 GeV, JES ~ 0.8 GeV

The cost in term of statistical uncertainty will become more and more affordable with the increasing luminosity

Approaches to reduce systematic uncertainties

In individual measurements

- phase-space restriction to minimize the uncertainty
- more in-situ constraints in simultaneous measurement and/or treating systematic sources as nuisance parameters
- correcting top-quark p_T mismodeling instead of treating the full data-to-MC discrepancy as uncertainty ?
- new effects becoming relevant ?
  $\hookrightarrow$ off-shell effects, other ME/PS possible variations...
- ...

In combinations

- improvement of combination methods ?

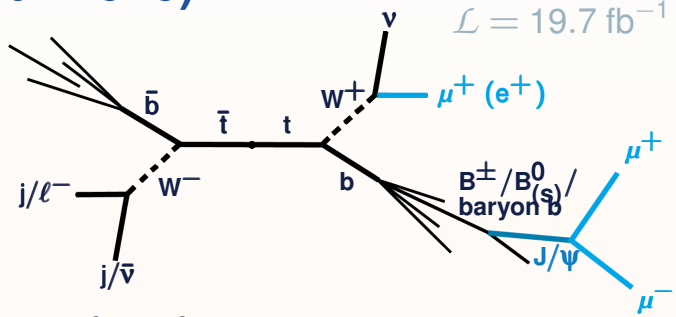
Alternative measurements

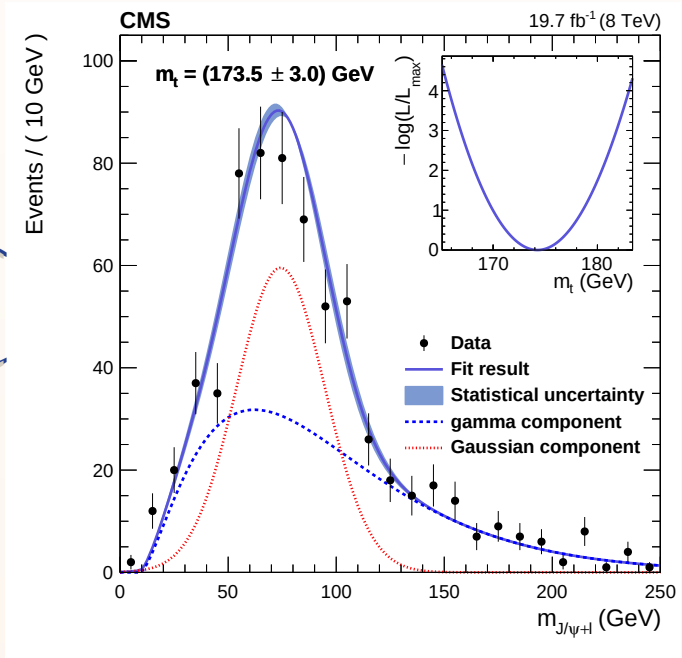
Alternative methods (1)

Many alternative methods have been investigated at Run 1, most were statistically limited but some are very promising

Using J/ψ (Mar 2016)

- Reconstructing $J/\psi \to \mu^+\mu^-$ in dilepton and ℓ+jets $t\bar{t}$ and t events
  $\hookrightarrow$ very clean experimental signature
  but very small branching fraction





- Extraction of m_t from $m_{J/\psi+\ell}$:
  $m_t = 173.5 \pm 3.0\,(stat) \pm 0.9\,(syst)$ GeV
- Main systematic sources:
  $p_T(t)$, ME/PS matching, ren. and fact. scales
  ~ 0.65 GeV ~ 0.55 GeV ~ 0.45 GeV
- b-fragmentation uncertainty of ± 0.30 GeV,
  JES uncertainty < 0.01 GeV
- Relevant exp. uncertainty < 0.10 GeV

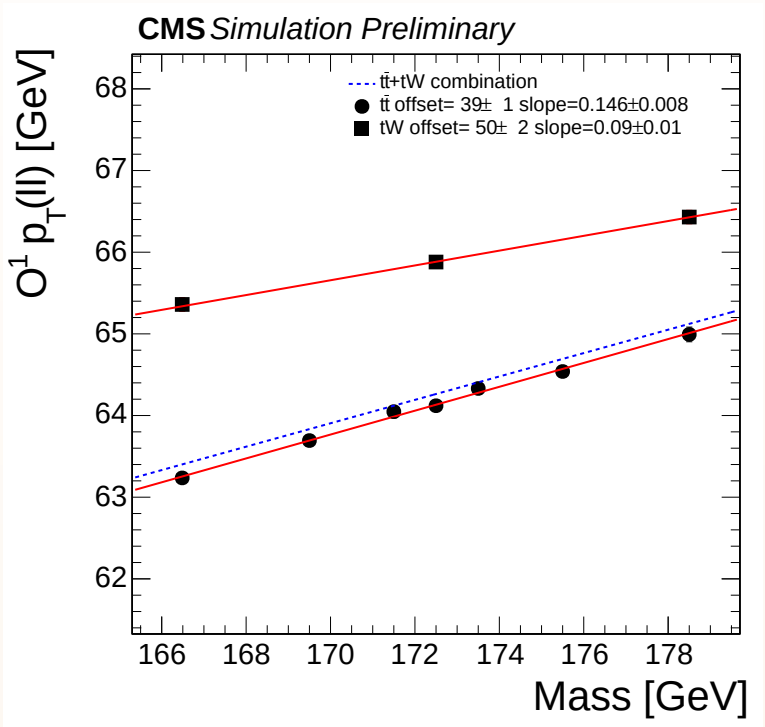
Alternative measurements

Alternative methods (2)

Using isolated leptons (Mar 2016)

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7\ \text{fb}^{-1}$

- Inferring m_t from $p_T(e^{\pm}\mu^{\mp})$ in dilepton $e^{\pm}\mu^{\mp}$ $t\bar{t}$ and tW events:
  $$m_t = 171.7 \pm 1.1\,(\text{stat}) \pm 0.5\,(\text{exp}) \, {}^{+2.5}_{-3.1}(\text{th}) \, {}^{+0.8}_{-0.0}(p_T(t))\ \text{GeV}$$
  ↪ Would benefit from a common $t\bar{t} + tW$ description at NLO
- Main systematic sources:
  - ren. and fact. scales ~ 2.5 GeV
  - ME/PS matching ~ 1.0 GeV
  - $p_T(t)$ ~ 0.85 GeV
- JES uncertainty of ± 0.05 GeV
- With higher statistics, m_t^{pole} could be extracted from the differential $p_T(e^{\pm}\mu^{\mp})$ distribution



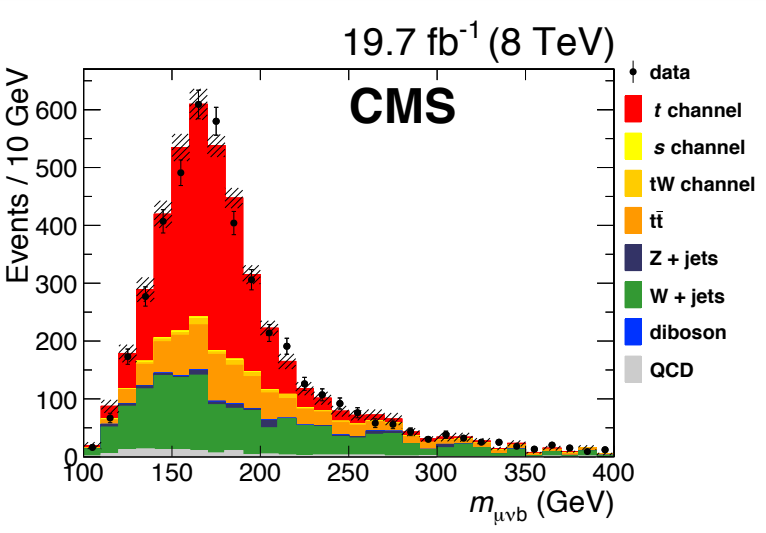
Though these techniques do not use jet kinematics to infer m_t,
JES uncertainty impacts the acceptance and thus the measurement

Alternative measurements

Alternative topologies, i.e. in single-top events $\sqrt{s} = 8$ TeV

Electroweak process $\Rightarrow$ different CR, hard scattering, PDFs

arXiv:1703.02530



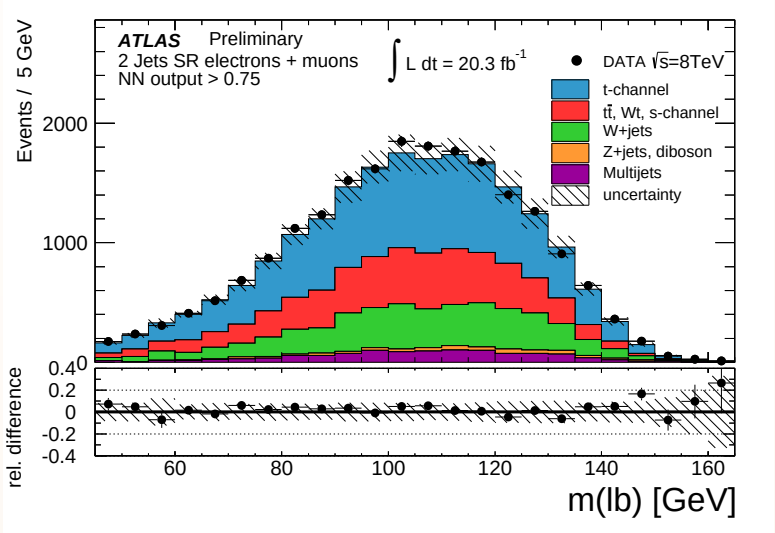
- Proportion of the t-channel increased to 71% by requiring $|\eta(\text{light jet})| > 2.5$
- Extraction of m_t from $m_{\ell\nu b}$

  $\mathbf{m_t = 172.60 \pm 0.77\ (stat)^{+0.97}_{-0.93}\ (syst)\ GeV}$
- Main sources of systematic uncertainties:

  JES, background calculations, fit calibration

  ~ 0.65 GeV ~ 0.40 GeV ~ 0.40 GeV

ATLAS-CONF-2014-055



- Proportion of the t-channel increased to 47% with a 3-layer NN
- Extraction of m_t from $m_{\ell b}$

  $\mathbf{m_t = 172.2 \pm 0.7\ (stat) \pm 2.0\ (syst)\ GeV}$
- Main sources of systematic uncertainties:

  JES, hadronization, background calculations

  ~ 1.5 GeV ~ 0.7 GeV ~ 0.7 GeV

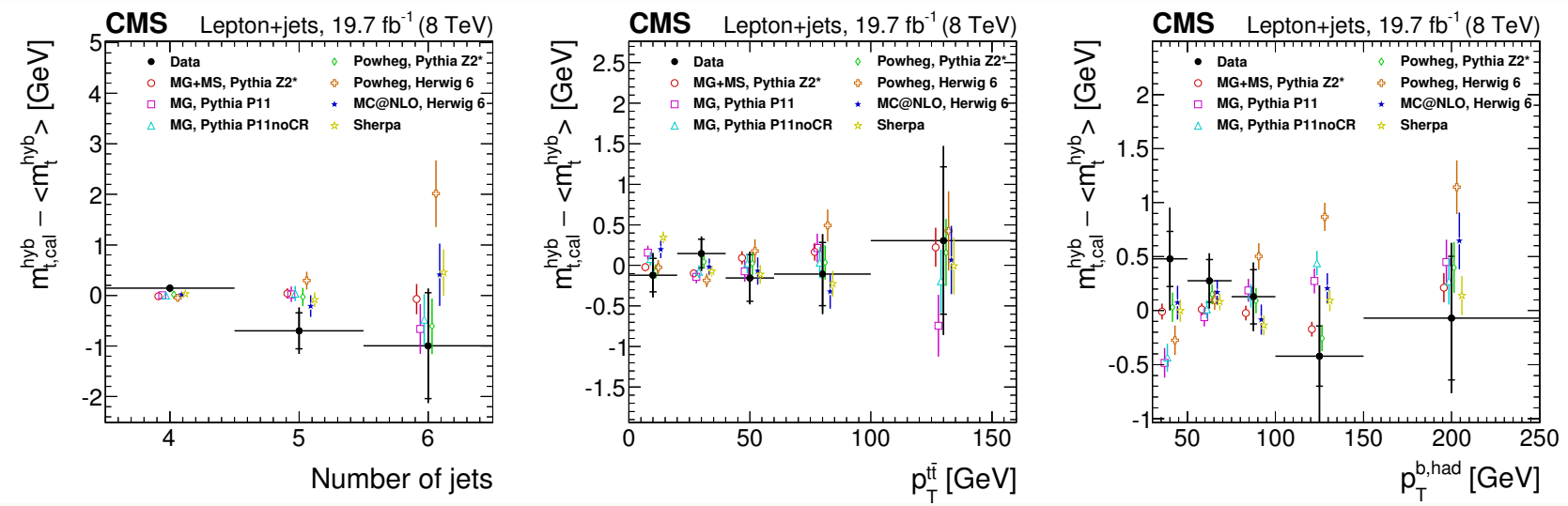
top event modeling

Testing QCD modeling (and JES)

δm_t vs event kinematics (Sep 2015)

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}

PRD 93 (2016) 2004



With higher statistics, the m_t stability could be checked in many phase-space corners.

Measuring Δm_t

PLB 728 (2013) 363 (ATLAS) $\Delta m_t = 0.67 \pm 0.61\,(stat) \pm 0.41\,(syst)$ GeV ($\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7$ fb^{-1})

PLB 770 (2017) 50 (CMS) $\Delta m_t = -0.15 \pm 0.19\,(stat) \pm 0.09\,(syst)$ GeV ($\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1})

Assuming CPT, test of QCD modeling t vs $\bar{t}$

top event modeling

Data-driven MC tuning

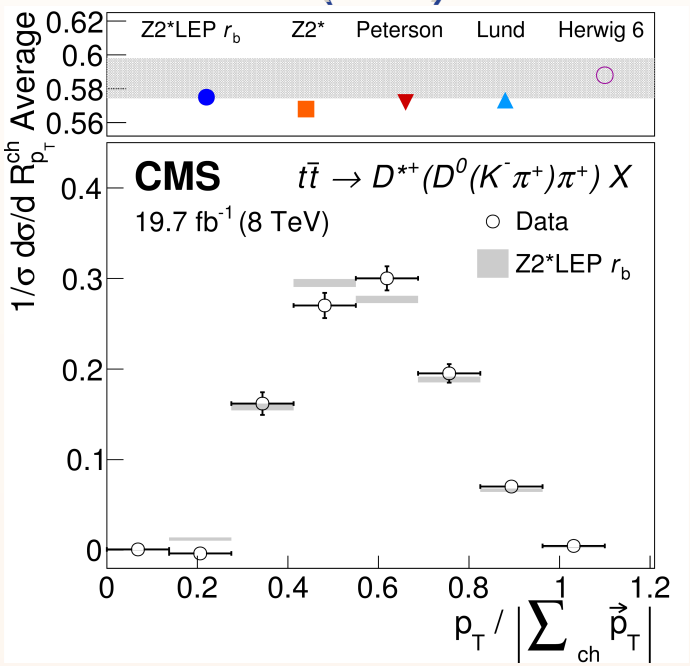
Soft QCD

With the increasing statistics, tuning CR, UE, MPI, and PS (e.g. α_S and h_{damp}) parameters in $t\bar{t}$ events are more and more precise.

See James' and Javier's presentations from yesterday.

b fragmentation

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1} PRD 93 (2016) 2006



- Need of more accuracy in the fragmentation modeling and decay branching fractions
- Check of universality by comparing $t\bar{t}$ and $b\bar{b}$ events

Pioneering studies have all been statistically limited for now.

(see also ATLAS-PHYS-PUB-2014-008)

top event modeling

Higher-order calculations for $p_T(t)$ and $\sigma_{t\bar{t}+jet}$

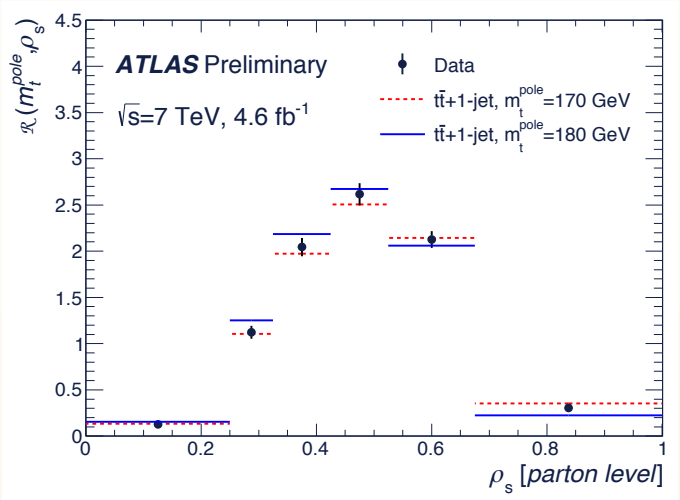
$p_T(t)$ modeling

In addition to an improvement in its treatment as a source of systematic uncertainty, a better modeling is crucial for many analyses (J/ψ, isolated leptons...).

m_t from $\sigma_{t\bar{t}+jet}$

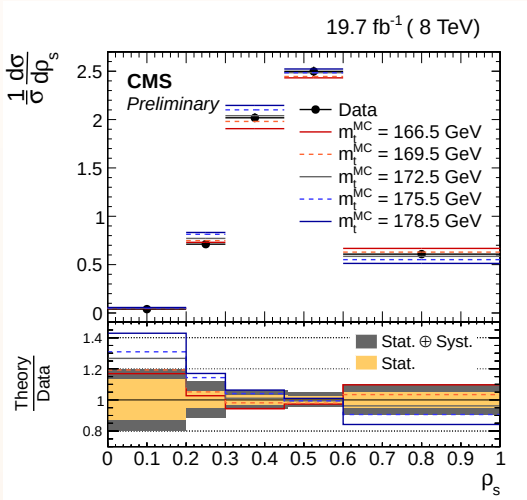
Based on the large dependence of gluon radiation on m_t:
comparing the differential $\sigma_{t\bar{t}+jet}$ distribution to NLO+PS predictions

$\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.6$ fb^{-1} — ATLAS-CONF-2014-053 — (8 TeV analysis targeting TOP2017)



$m_t^{pole} = 173.7 \pm 1.5$ (stat.) ± 1.4(syst.)$^{+1.0}_{-0.5}$(theo.) GeV

CMS PAS TOP-13-006 — $\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}



$m_t^{pole} = 169.9 \pm 1.1$ (stat.) $^{+2.5}_{-3.1}$(syst.)$^{+3.6}_{-1.6}$(theo.) GeV

top event modeling

Higher-order calculations for $\sigma_{t\bar{t}}$

Inclusive $\sigma_{t\bar{t}}$

Available predictions using m_t^{pole} are available at NNLO.

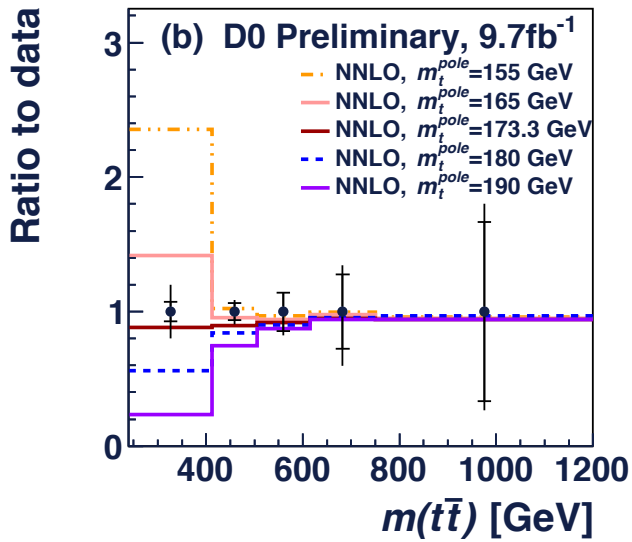
EPJC 74 (2014) 3109 (ATLAS) $m_t^{pole} = 172.9^{+2.5}_{-2.6}$ GeV ($\sqrt{s} = 7$ and 8 TeV)

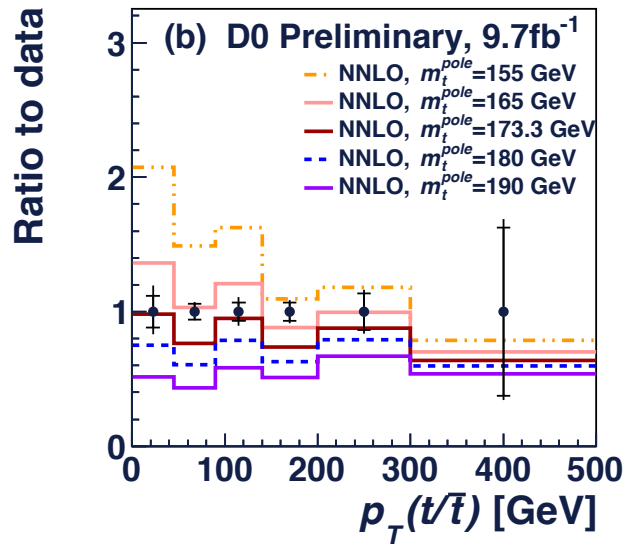
JHEP 08 (2016) 029 (CMS) $m_t^{pole} = 173.8^{+1.7}_{-1.8}$ GeV ($\sqrt{s} = 7$ and 8 TeV)

Differential $\sigma_{t\bar{t}}$

available at NNLO

D0 Note 6473-CONF





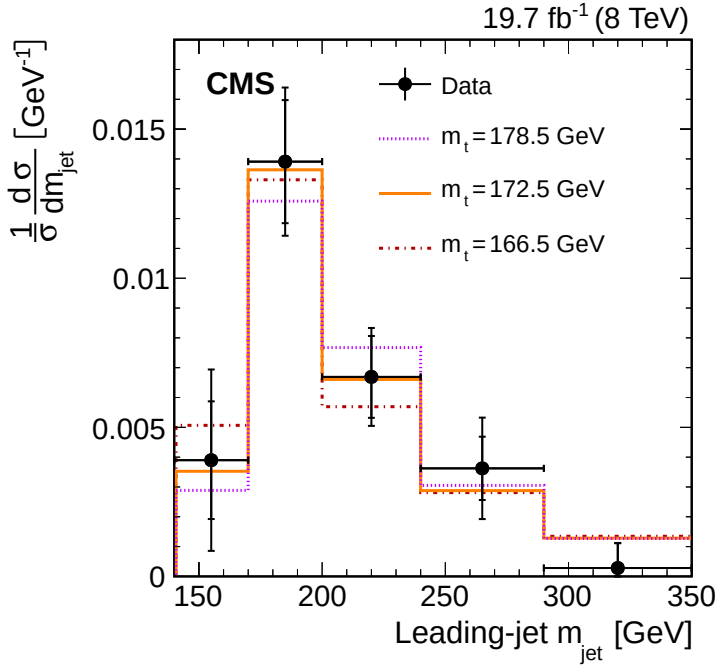
top event modeling

Soft collinear theory for the dijet mass distribution in pp collisions

- Reconstructing highly boosted hadronic top quark decays in ℓ+jets $t\bar{t}$ events
- Measuring the particle-level $\sigma_{t\bar{t}}$ for the fiducial phase space differentially as a function of the invariant mass of a single Cambridge-Aachen jet with $R = 1.2$ and $p_T(\text{jet}) > 400\,\text{GeV}$

Calculations of m_{jet} for $t\bar{t}$ production in pp collisions from 1st principles (not relying on PS and hadronization models) would enable to infer m_t^{pole}.

arXiv:1837158 $\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7\,\text{fb}^{-1}$



From a MC calibration:

$m_t = 170.8 \pm 9.0$ GeV

Projections (1)

CMS PAS FTR-16-006

- Assuming that PU subtraction will be such that JER is not worsened
- Focusing on some of the most promising methods for now
- Focusing on systematic uncertainties
  $\hookrightarrow$ scaling stat. unc. with $\sqrt{\mathcal{L}}$
- Assuming
  - larger MC samples
  - improvements in soft QCD, fragmentation modeling from data-driven MC tuning
  - more precise determination of PDFs and b-tagging efficiencies
  - a better $p_T(t)$ modeling and higher-order predictions
  - steady lepton energy scale, E_T^{miss} scale, ME-PS matching, and PU uncertainties

ℓ+jets channel

- assuming a 3D fit of m_t, JES, and b-JES

single top channel

- interesting in view of a combination
- could benefit from the in-situ constraint of JES an b-JES in the ℓ + jets analysis
- extended detector coverage not considered

m_t from $m_{sv\ell}$

- assuming an improved b had. modeling
- assuming an improved m_{sv} modeling thanks to more accurate tracking efficiencies

m_t from $m_{J/\psi+\ell}$

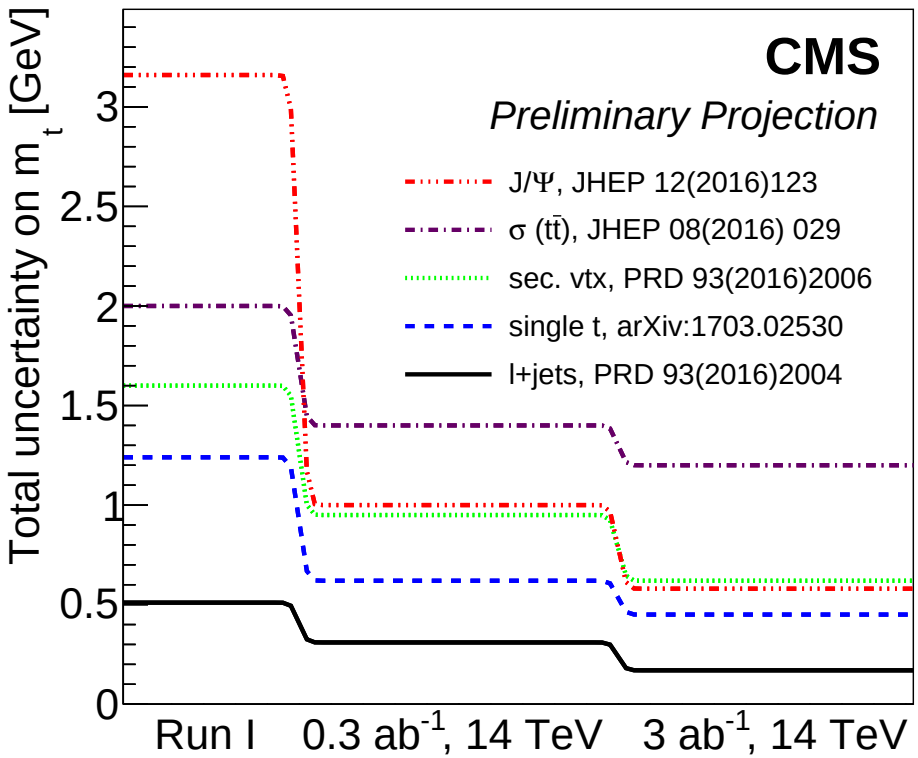
- assuming a better $m_{J/\psi}$ modeling thanks to a constrained J/ψ vertex fit
- still statistically limited with $0.3\,ab^{-1}$

m_t from $\sigma_{t\bar{t}}$

- luminosity uncertainty as limiting factor to infer m_t^{pole} from the inclusive $\sigma_{t\bar{t}}$
- possible reduction of many unc. in the extrap. to full phase space with NNLO diff. and fid.

Projections (2)

CMS PAS FTR-16-006

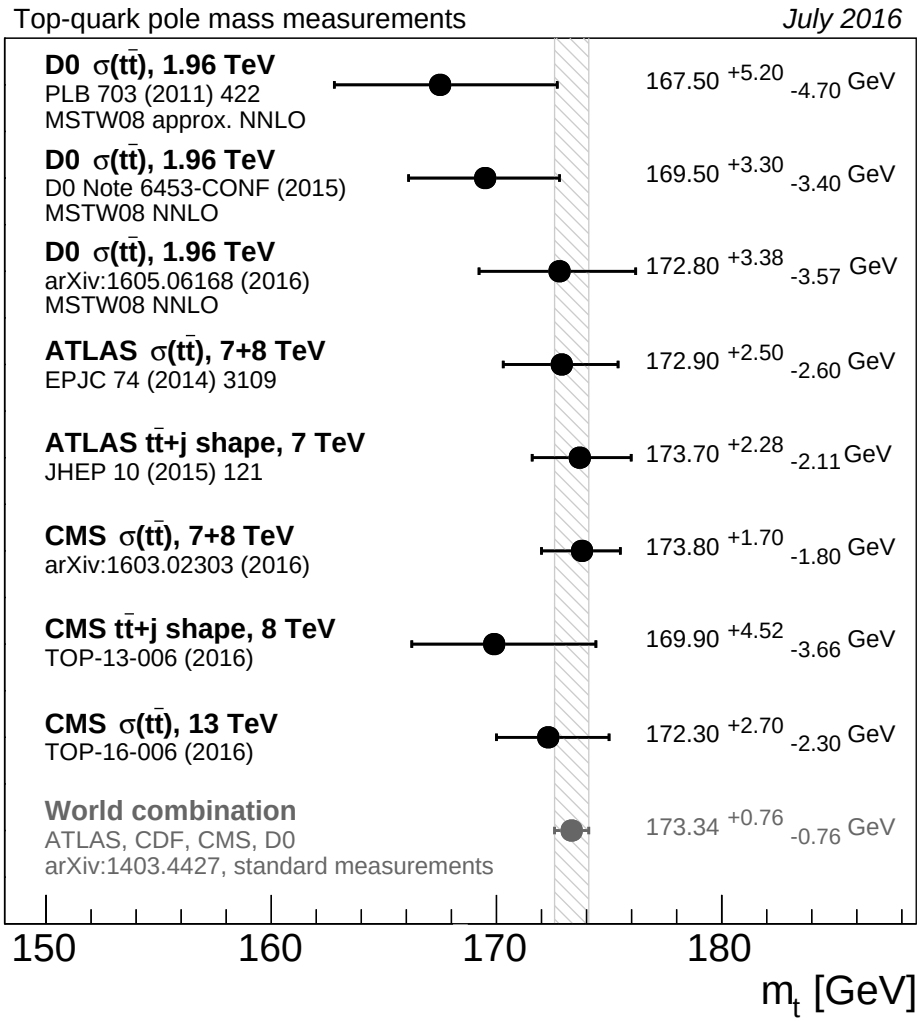


Ultimate experimental precision $< 0.1\%$?

What about the interpretation of MC-calibrated measurements ?

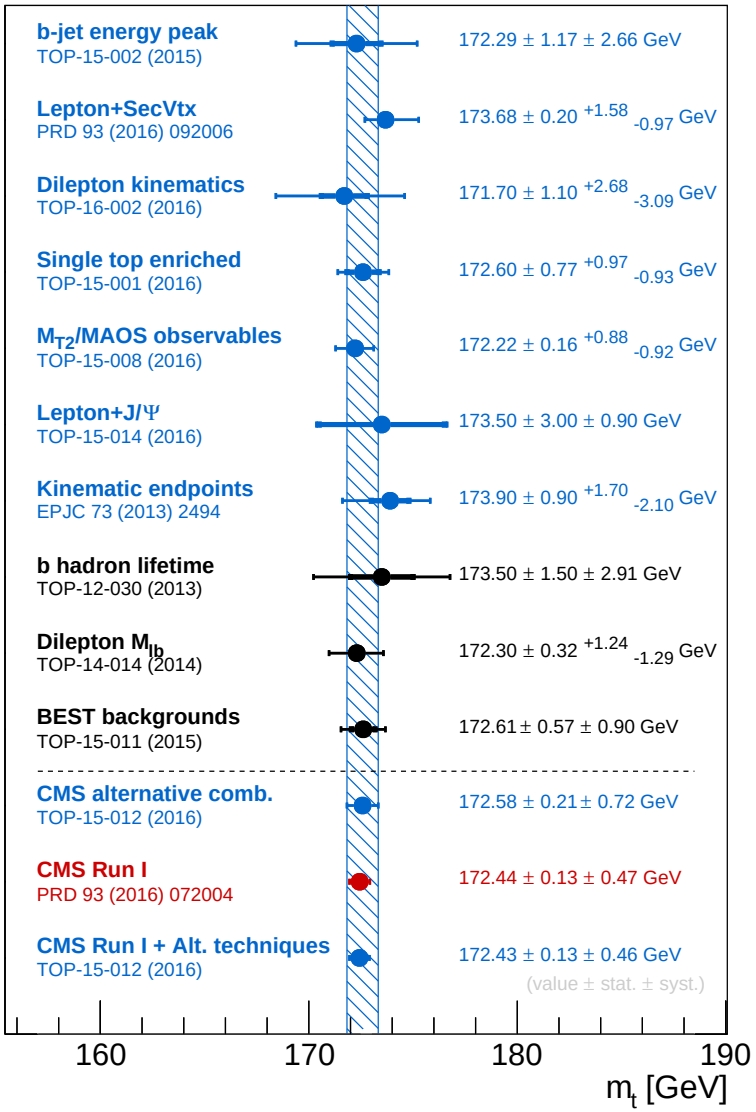
Backup

m_t^{pole} vs MC-calibrated m_t measurements



$\Rightarrow$ Compatibility between m_t^{pole} and MC-calibrated m_t measurements

Combination of “alternative” measurements

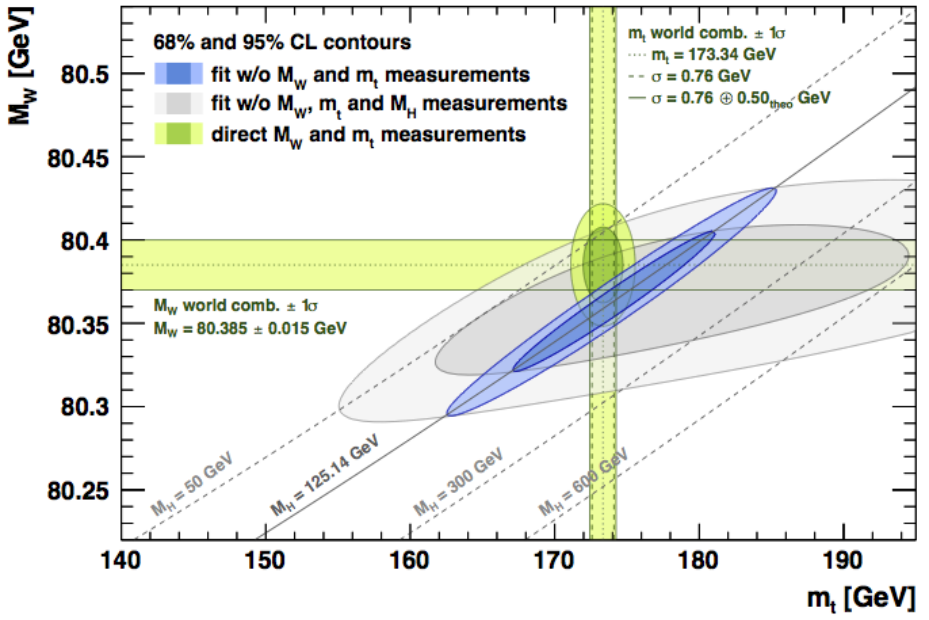


- Compatible with “standard” measurements
- Slightly less precise
- Combination with “standard” measurements not yet interesting
  ↪ “alternative” measurements strongly correlated to “standard” measurements and/or not yet precise enough

Importance of a precise m_t determination

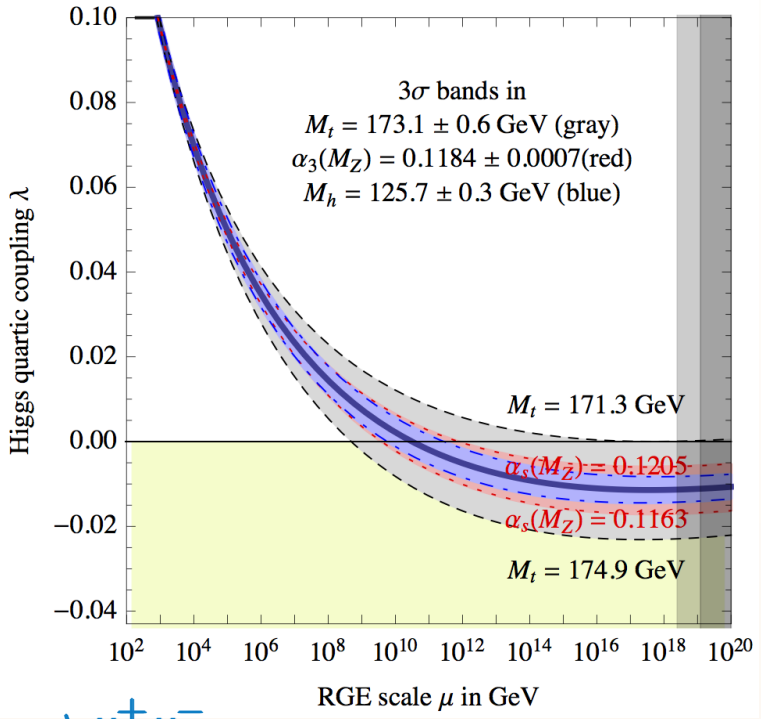
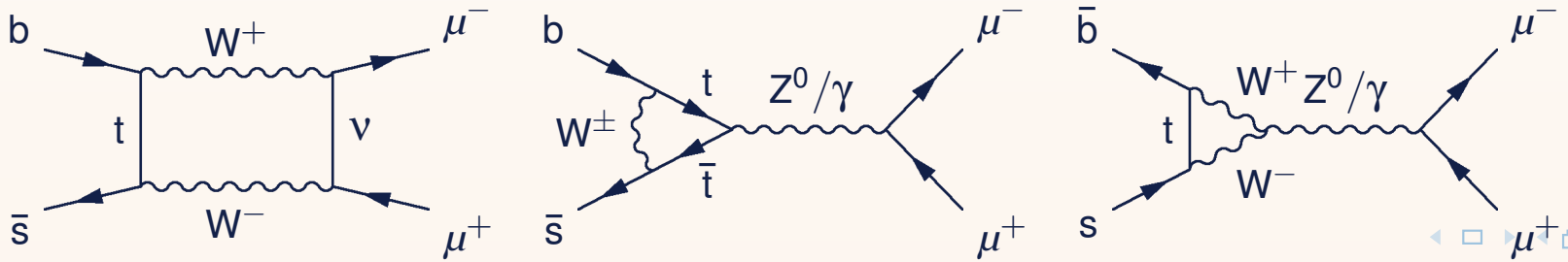
The electroweak fit and indirect measurement of m_W

EPJC 74(2014)3046



The electroweak vacuum stability

JHEP 1208(2012)098



Rare decays such as $B_s \to \mu^+\mu^-$