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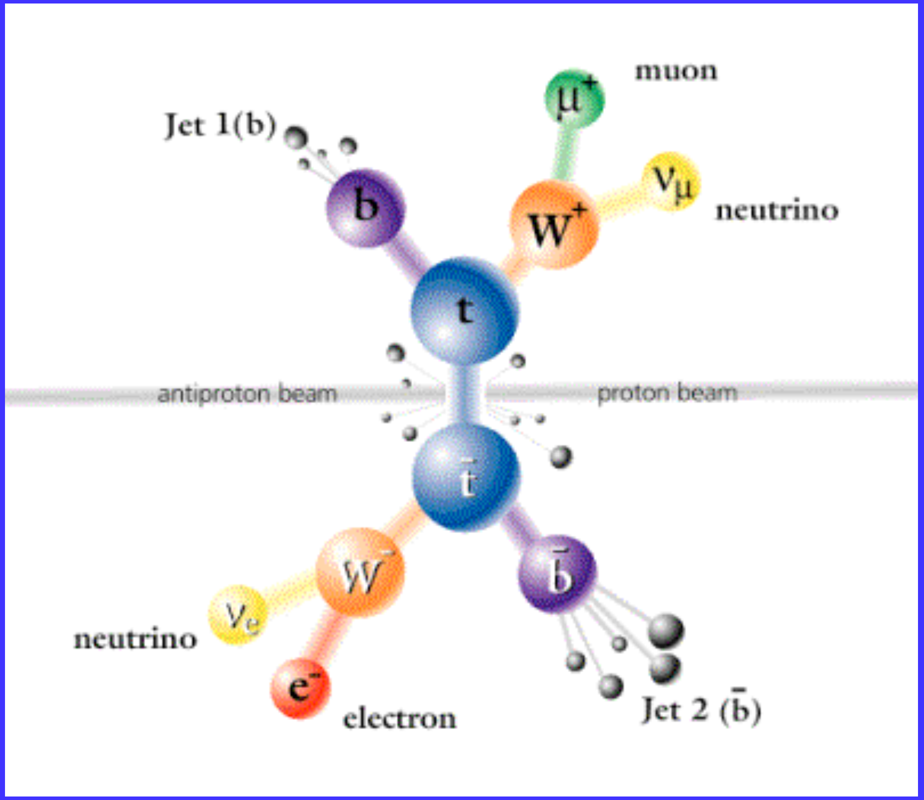
Top Quark Mass at Hadron Colliders

On behalf of ATLAS, CDF, CMS and D0 collaborations

Lepton Photon 2013 - San Francisco

The top quark

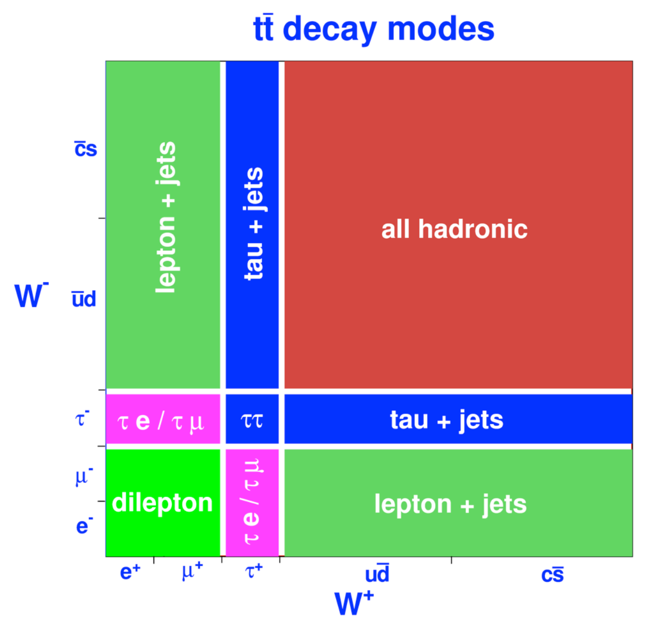
$$p\bar{p}\ (pp)\ \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$$



BR(LJ)≈30%

BR(DIL)≈5%

BR(AJ)≈45%



- Mainly produced in pairs, each top decays amost 100% to a W+b
- Different production mechanisms (mainly $q\bar{q}$ annihilation at Tevatron, mainly gg fusion at LHC)
- Characterized by the two W's decays:
  - single lepton + jets (LJ, golden channel, good yield and good S/B)
  - double lepton (DIL, low yield, better S/B)
  - all-jets (AJ, max yield, low S/B)
  - others (τ+jets or MET+jets)

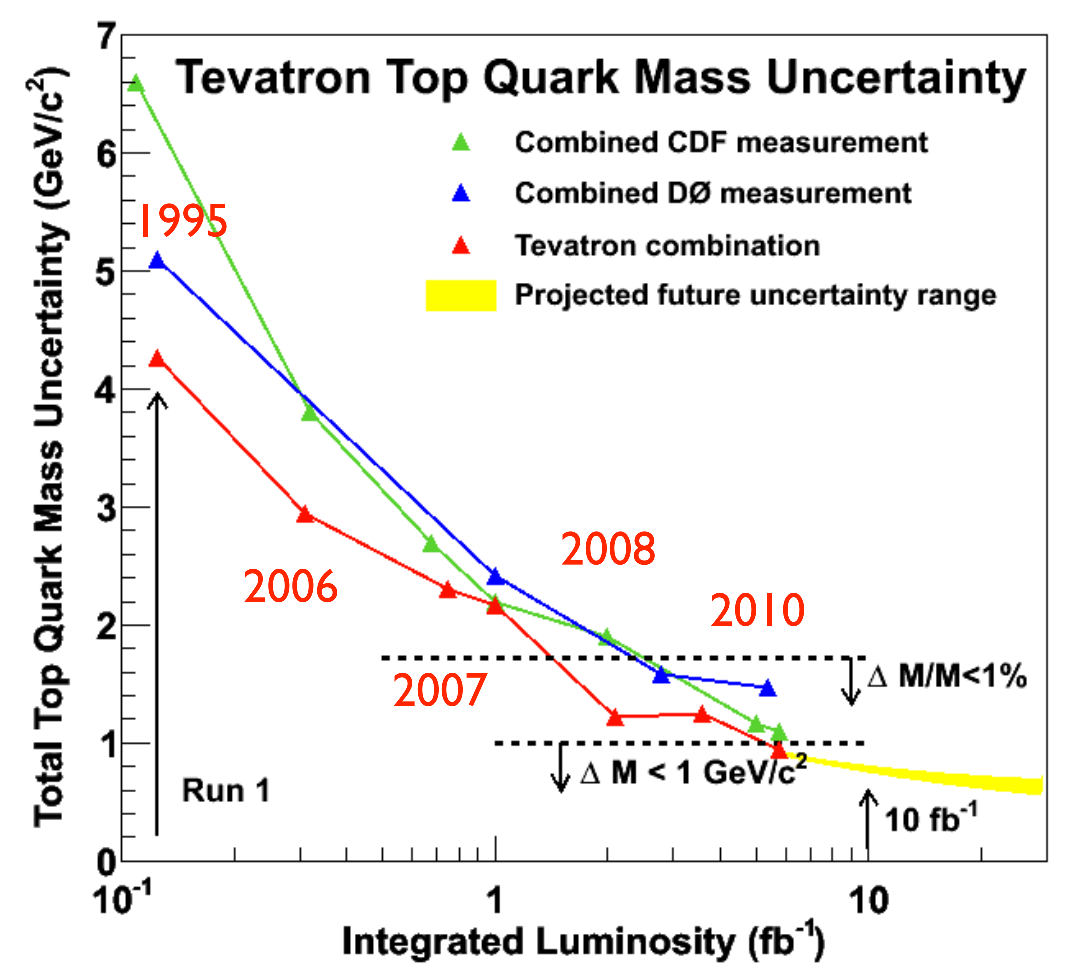
All of them useful for completeness and for uncorrelated systematics

Why measure M_t ?

M_t is a free parameter of the SM and its measurement has been strongly pursued in the past 18 years

1) The top quark decays well before hadronizing, so we can measure its mass M_t directly from the observation of its decay products (*really? see later*)

$$\Gamma_t \approx 1.5\ GeV \gg \Lambda_{QCD} \sim 200\ MeV$$

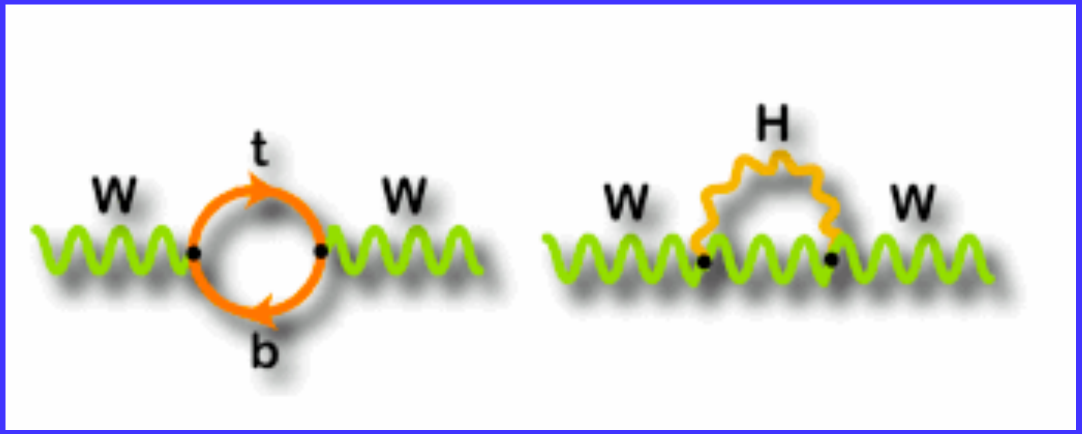


Indeed **t** is the most accurately measured quark (better than 0.5%)

Why measure M_t ?

2) Participates to quantum loop radiative corrections to the W mass constraining the Higgs boson mass
(that was important until Higgs boson discovery!)

Now assessment of self-consistency within the SM

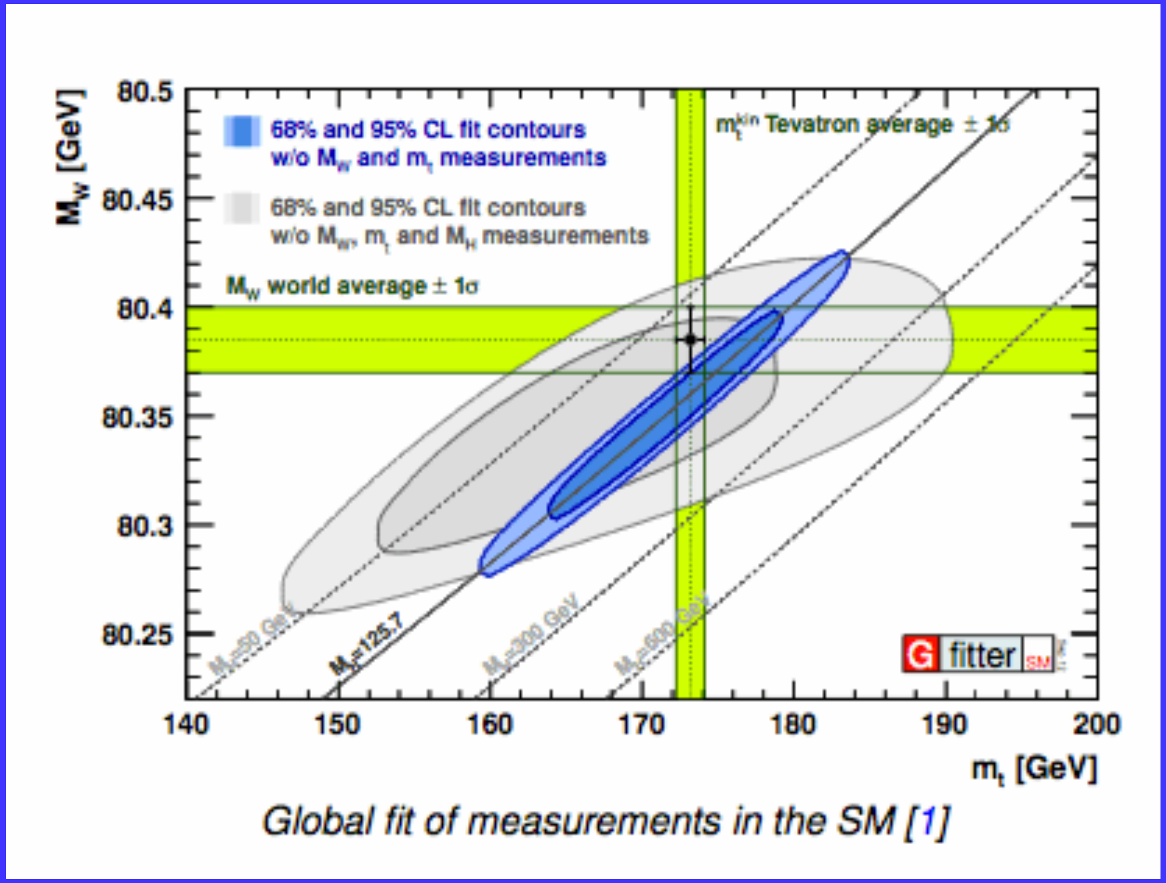


$$\Delta M_W \propto M_t^2$$

$$\Delta M_W \propto \ln M_H$$

arXiv:1209.2715

M_W vs M_t correlations not shown

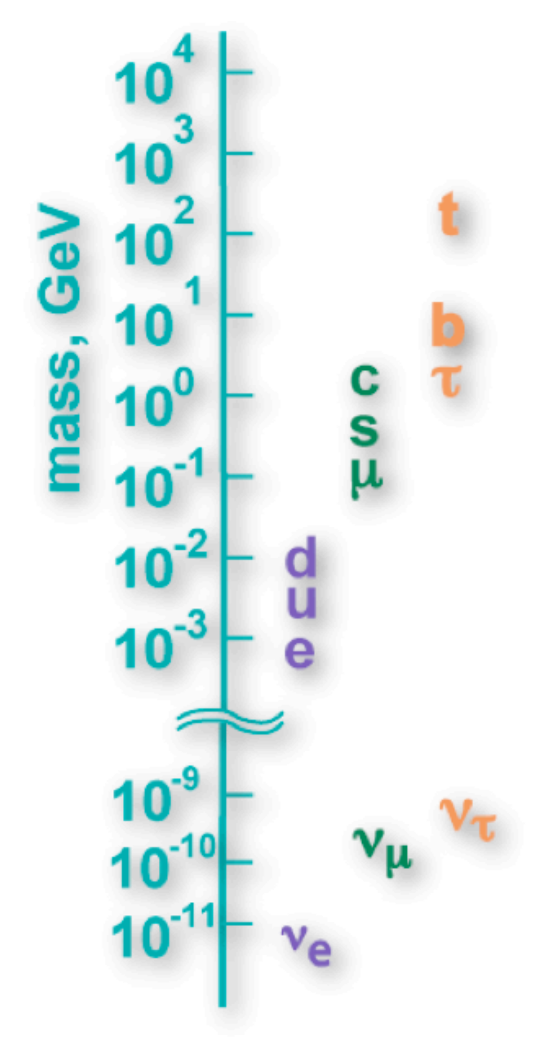


Global fit of measurements in the SM [1]

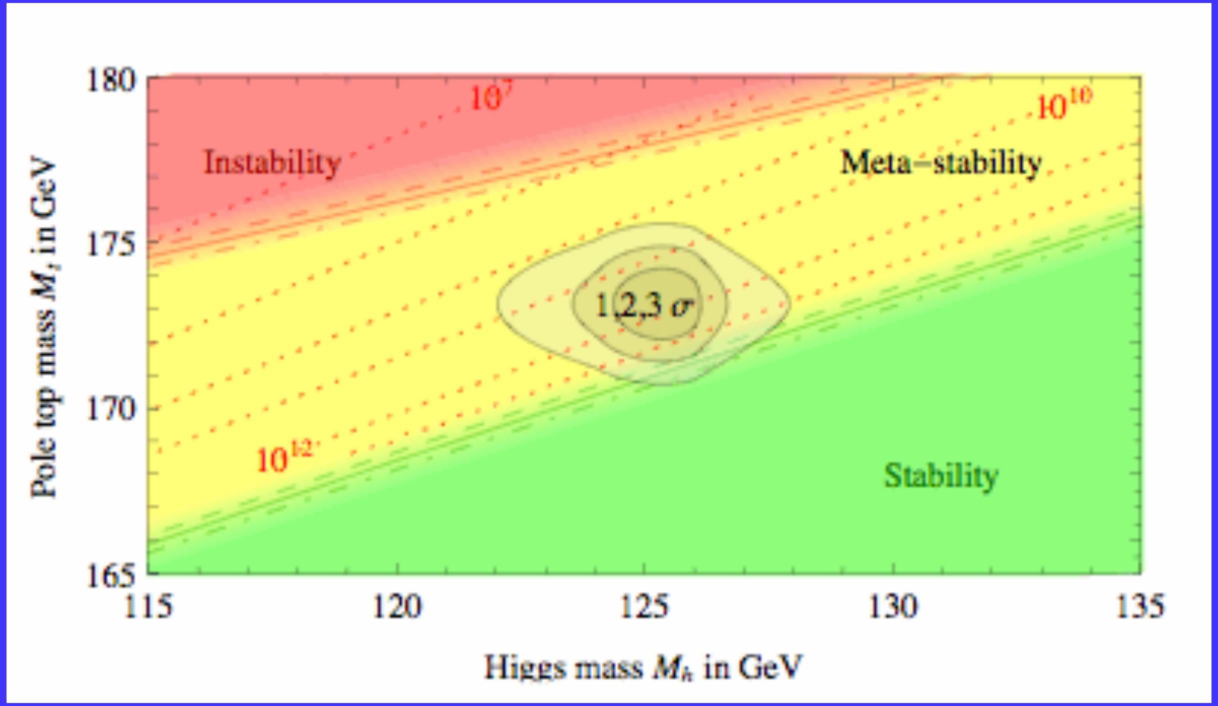
See T. Han's and K. Moenig's talks

Why measure M_t ?

3) The huge mass puts it close to the scale of EWSB, so the top quark might have a special role in it, also in the case of new physics like topcolor models for EW dynamical breaking



4) M_t is also related with M_H and the vacuum stability of the Standard Model



arXiv:1205.6497

Tevatron vs LHC

≈20 years from one to the other lead to:

	Tevatron ($p\bar{p}$)	LHC (pp)
Years	1988-2011	2010→2012→?
Radius (km)	1	4.2
$\sqrt{s}$ (TeV)	1.8→2	7→8→?
PeakLumi ($cm^{-2}s^{-1}$)	$\approx 4\times10^{32}$	$\approx 8\times10^{33}$
Int. Lumi (fb^{-1})	≈ 12	≈ 6+23
σ_{tt} (pb)	≈7	≈160→240
N_{tt} (per exp.)	$\approx 70\times10^{3}$	$\approx 5\times10^{6}$

Detectors and Physics Objects

Four multipurpose detectors designed for generic HEP: CDF / D0 (Tevatron) + ATLAS / CMS (LHC)

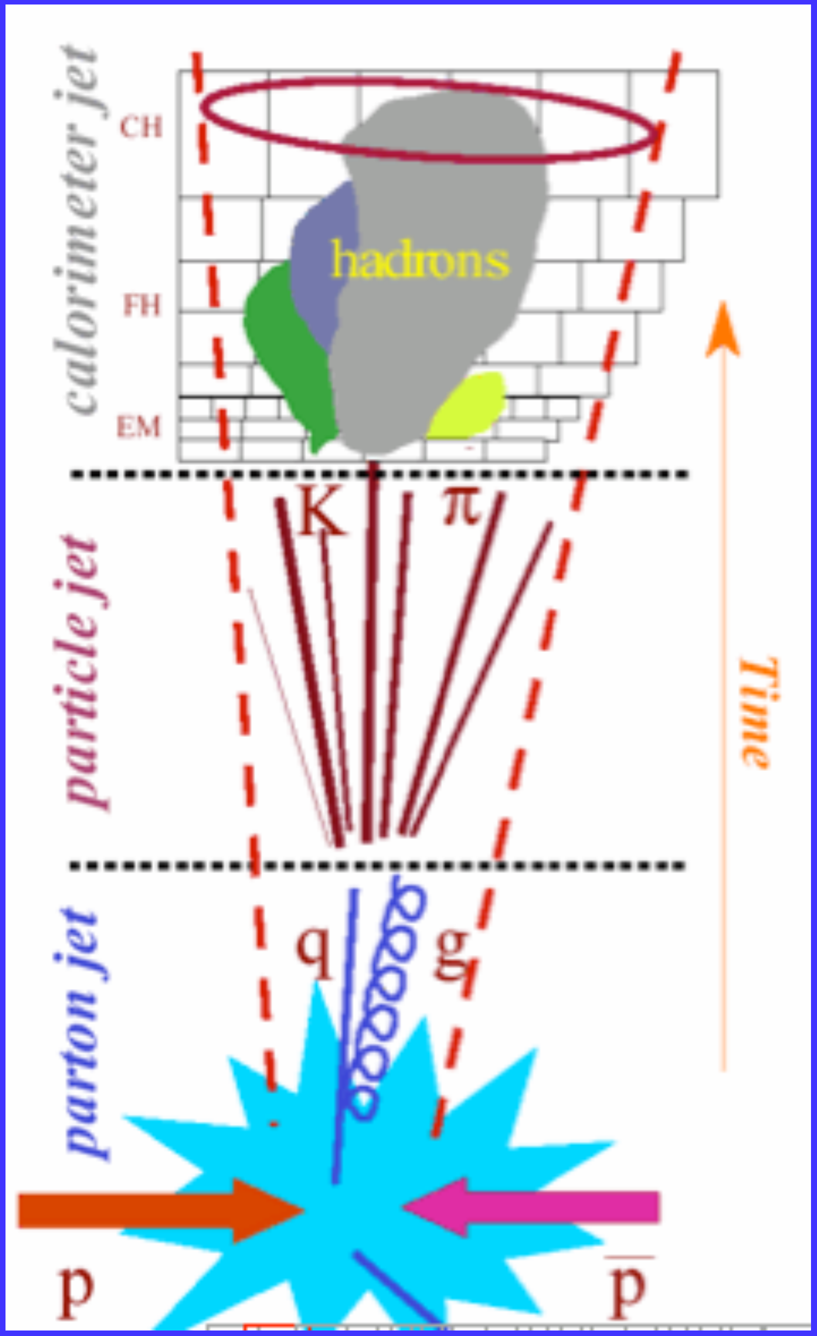
Essentially, spectrometers with:

- tracking for measuring P_T
- high-precision (microvertex) tracking
- EM calorimetry to measure e and γ
- HAD calorimetry to measure jets
- muon systems to identify/measure μ
    - High-P_T isolated leptons
    - High-P_T jets (+ b-tagged jets)
    - MET associated to neutrinos if LJ or DIL

Jets

Jets as measured from the energy flow in the calorimeters need corrections in order to derive the parton energy

Different algorithms have been introduced (cone clustering or CMS ParticleFlow which uses also the tracker) to reduce the amount of correction needed and related systematics



Measuring M_t

The measurement of M_t has been performed with different techniques having complementary and competing features, but the starting point is the reconstruction of

$$p\bar{p}\ (pp)\ \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$$

There are then issues one has to confront with:

− choice of <u>final state topology</u>

− <u>event selection</u>

− <u>mapping of the physics objects</u> used to the 4-momenta of the leptons/partons in the LO final state (this carries ambiguities and combinatorics)

− dependence on the <u>detector modeling</u> (for instance energy calibration)

− <u>unknown quantities like</u> the neutrino p_z or the sharing of MET between multiple neutrinos → the kinematics of the final state is underconstrained for DIL channel

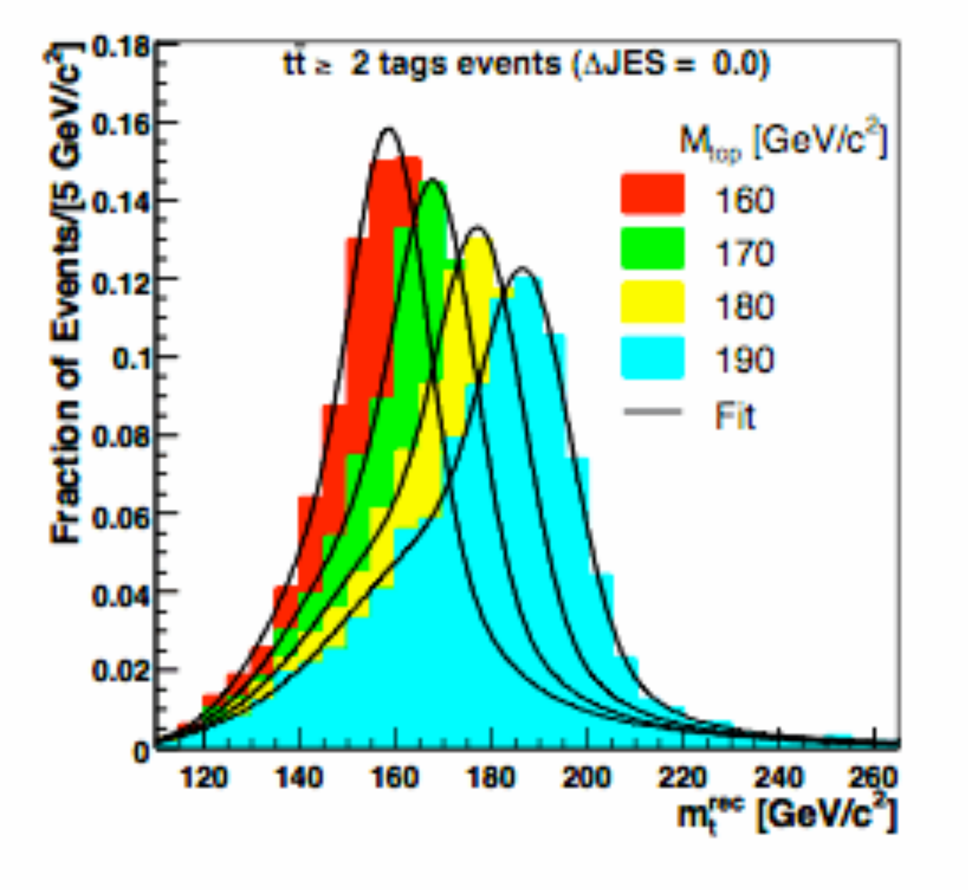
Methods for measuring M_t

1) The *template method*, based on the distributions of variables sensitive to M_t
For instance, the reconstructed top quark mass from a χ^2 fit to a given WbWb final state

Templates/pdf's are derived for MC events assuming different values of M_t and parametrized as a function of M_t
A likelihood is computed based on these functions/distributions

Including M_W templates allows for in-situ calibration of the JES; possible also to add constraints on b-jet JES

There is also a non-parametric N-dimensional version (*Kernel Density Estimate*)



Relatively simple, fast, but non optimal statistical uncertainty

Methods for measuring M_t

2) The *Matrix Element* method computes the probability to obtain the observed set **x** of variables given an assumed top quark mass and a generated set **y** of variables

The full event information is used and compared to what derived from the matrix elements, the PDF's and the transfer functions W(x,y)

$$P(t\bar{t}; M_t) \propto \int \sum_{flavors} dq_1 dq_2 \frac{d\sigma(p\bar{p} \to t\bar{t} \to y; M_t)}{dy} f(q_1) f(q_2) W(x,y) dy$$

An event probability is defined in terms of $P(t\bar{t})$ and P(bkg), then a total likelihood is computed

Methods for measuring M_t

3) The *Ideogram method* is a modification of the template method to account for the M_t resolution on an event-by-event basis

Starts from the kinematical reconstruction and then computes an event likelihood as a function of M_t

4) In the *Matrix Weighting (Neutrino Weighting, Kinematic Analysis) techniques* a given M_t is used to constrain the $t\bar{t}$ system, inferring the neutrino momenta from the MET and assuming values for unobserved quantities

Weights are assigned to the possible solutions and templates are built from these weights

Systematic uncertainties

There are different sources of systematic uncertainty. Among them, effects due to imperfect knowledge of:

- the jet energy scale (JES)
- signal modeling (generator, color reconnection, hadronization, underlying event)
- b energy (bJES) and b-tagging efficiency
- background modeling
- amount of radiation (ISR/FSR)
- PDFs
- lepton energy/momentum determination

... and those depending on the MC statistics and specific features of the method

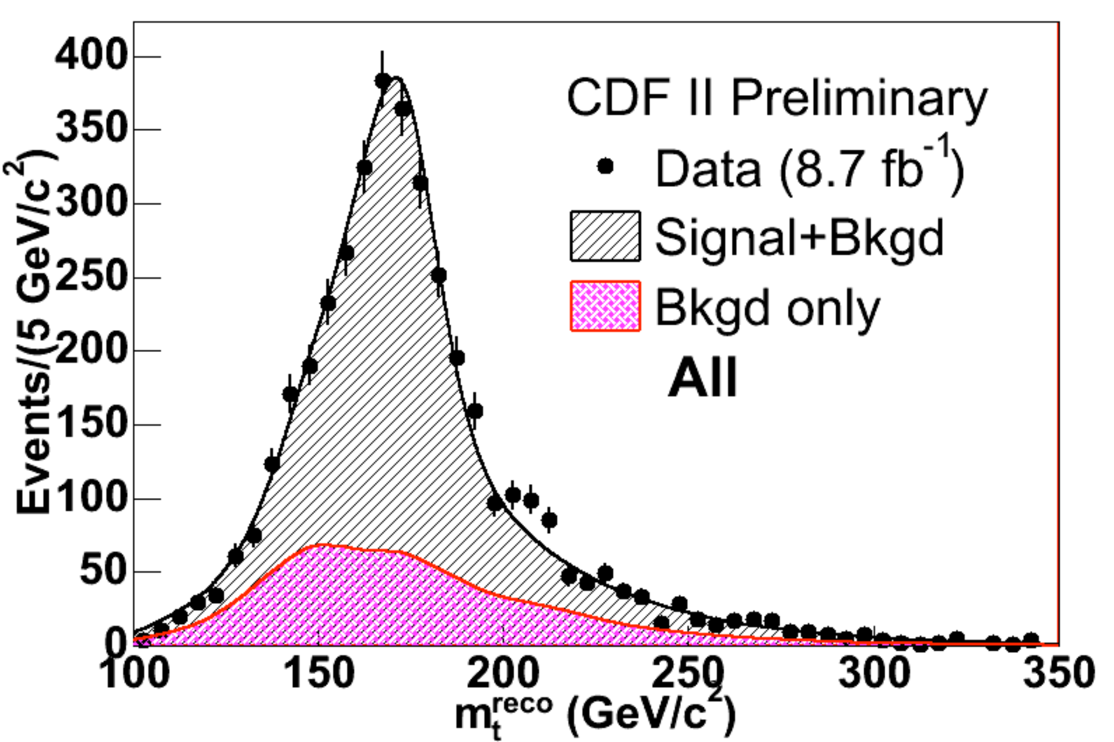
M_t at Tevatron: lepton + jets

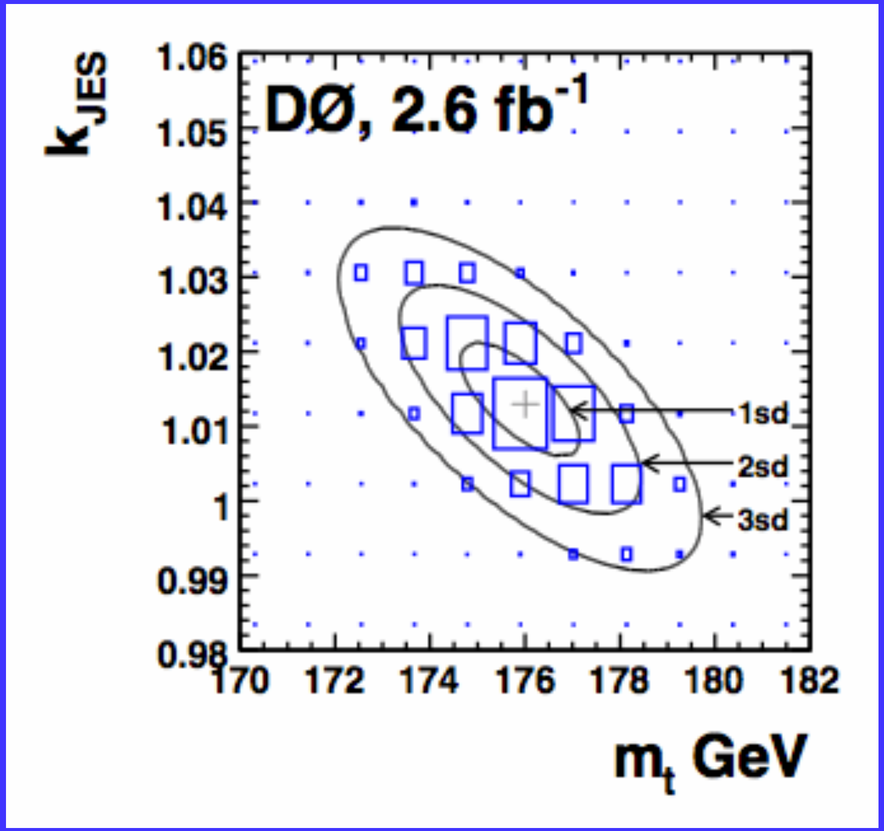
Kernel Density Estimation
(m_t^{reco}, m_t^{reco2}, m_W^{reco})
+ *in situ JES* (8.7 fb^{-1})

Matrix Element + in situ JES
(1.0+2.6 fb^{-1})

Phys. Rev. Lett. 109, 152003 (2012)

Phys. Rev. D 84, 032004 (2011)





$M_t = 172.85 \pm 0.52(stat) \pm 0.49(JES) \pm 0.84(syst)\ GeV$

$\delta M_t = 1.1\ GeV\ \ (0.64\%)$

$\delta M_t^{res-JES} = 0.52\ GeV$

$\delta M_t^{generator} = 0.56\ GeV$

$M_t = 174.94 \pm 0.83(stat) \pm 0.78(JES) \pm 0.96(syst)\ GeV$

$\delta M_t = 1.5\ GeV\ \ (0.85\%)$

$\delta M_t^{generator} = 0.58\ GeV$

$\delta M_t^{JER} = 0.32\ GeV$

M_t at Tevatron: MET+jets/dilepton

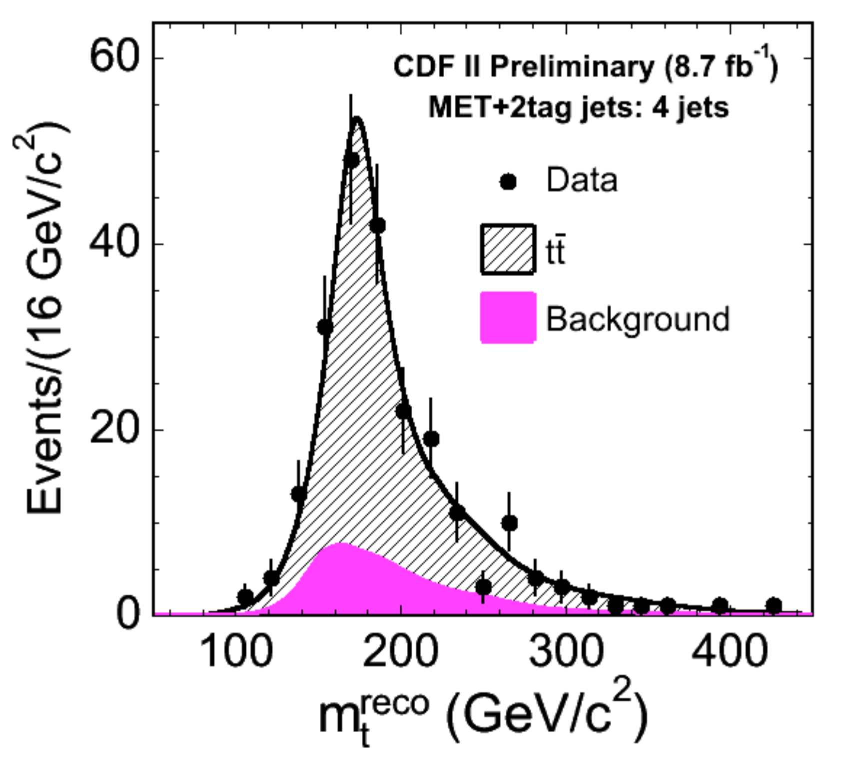
MET+jets (NN+b-tag)

Kernel Density Estimation

(m_t^{reco}, m_t^{reco2}, m_W^{reco})

+ *in situ JES* (8.7 fb^{-1})

CDF Conf. Note 10810



$$M_t = 173.9 \pm 1.3(stat) \pm 1.1(JES) \pm 0.9(syst)\ GeV$$

$$\delta M_t = 1.9\ GeV\ \ (1.1\%)$$

$$\delta M_t^{generator} = 0.4\ GeV$$

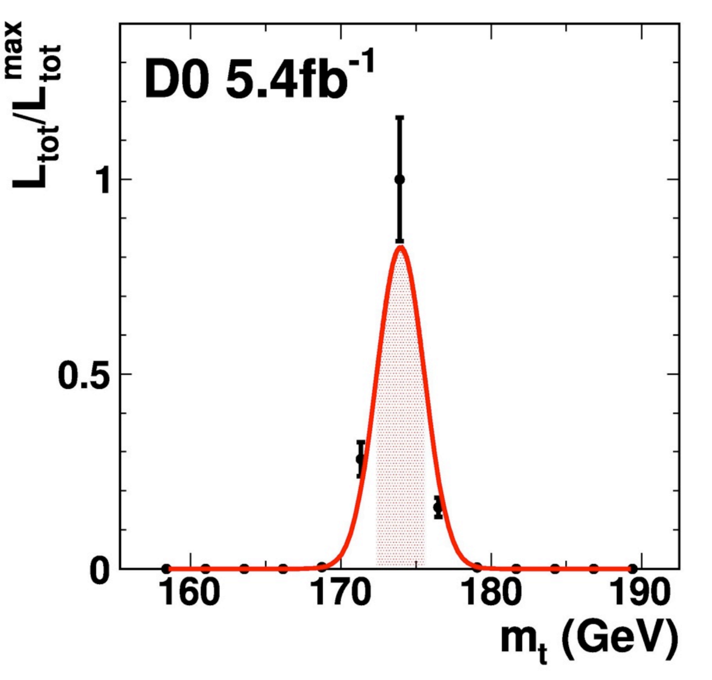
$$\delta M_t^{res-JES} = 0.4\ GeV$$

Dilepton

Matrix Element + neutrino-weighting combined (4.3+1.0 fb^{-1})

Phys. Rev. Lett. 107, 082004 (2011)

Phys. Rev. D 86, 051103 (2012)



$$M_t = 173.9 \pm 1.9(stat) \pm 1.6(syst)\ GeV$$

$$\delta M_t = 2.5\ GeV\ \ (1.4\%)$$

$$\delta M_t^{JES} = 0.9\ GeV$$

$$\delta M_t^{generator} = 0.6\ GeV$$

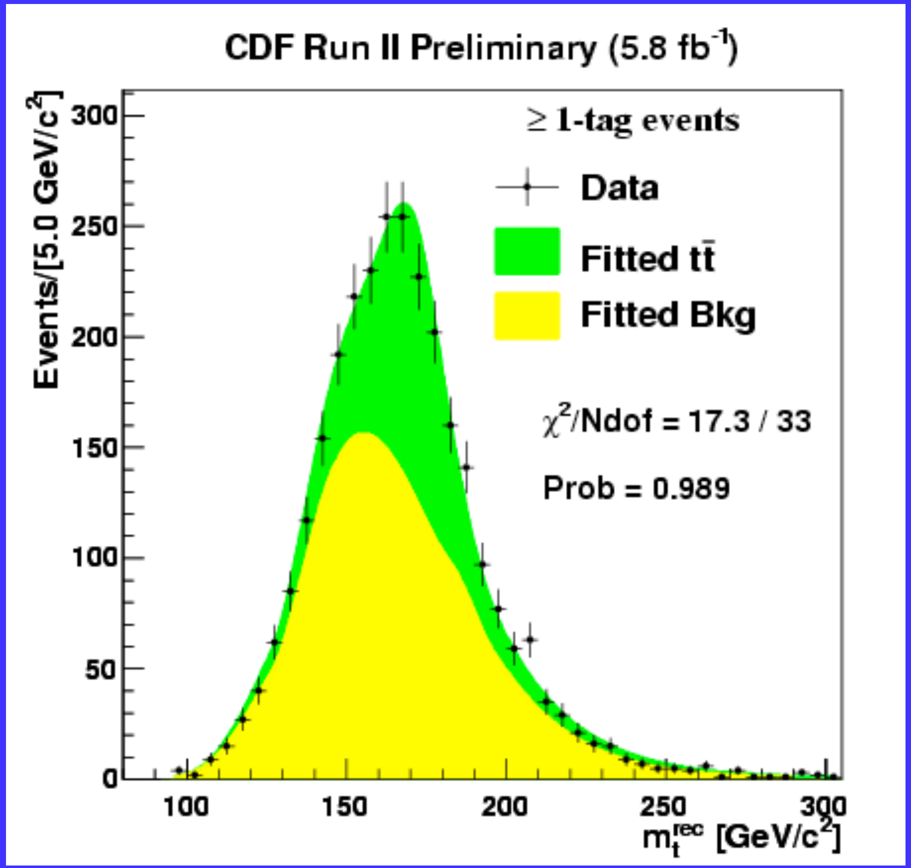
M_t at Tevatron: all-jets

The selection of this difficult channel requires:

- ≥6 high-E_T jets
- Neural-network- based kinematical selection
- ≥1 sec-vertex b-tag
- data-driven bkgd modeling

Template method (m_t^{reco}, m_W^{reco}) + *in situ JES* (5.8 fb^{-1})

Phys. Lett. B 714, 24 (2012)



$$M_t = 172.5 \pm 1.4(stat) \pm 1.0(JES) \pm 1.1(syst)\ GeV$$

$$\delta M_t = 2.0\ GeV(1.2\%)$$

$$\delta M_t^{bckgd} = 0.6\ GeV$$

$$\delta M_t^{generator} = 0.5\ GeV$$

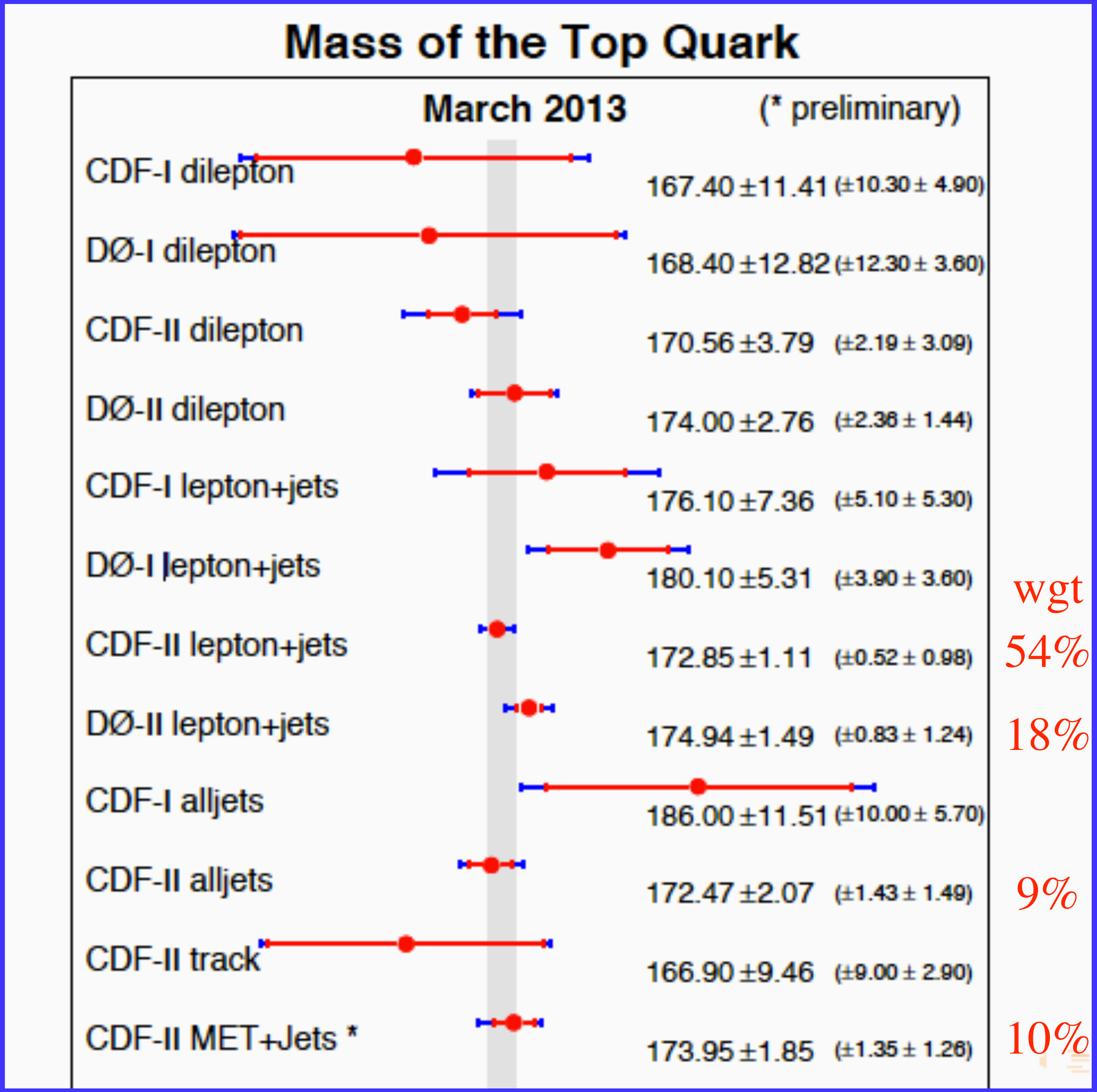
$$\delta M_t^{res-JES} = 0.4\ GeV$$

Tevatron average

A big effort goes into computing the average because one needs to evaluate all possible correlations among the various systematic uncertainties

Crucial a precise/common definition of subsets to allow for 0 or 100% correlation between channels and experiments

The average is computed with the Best Linear Unbiased Estimator assuming symmetric gaussians



arXiv:1305.3929

$$M_t^{TEV} = 173.20 \pm 0.51(stat) \pm 0.71(syst)\ GeV$$

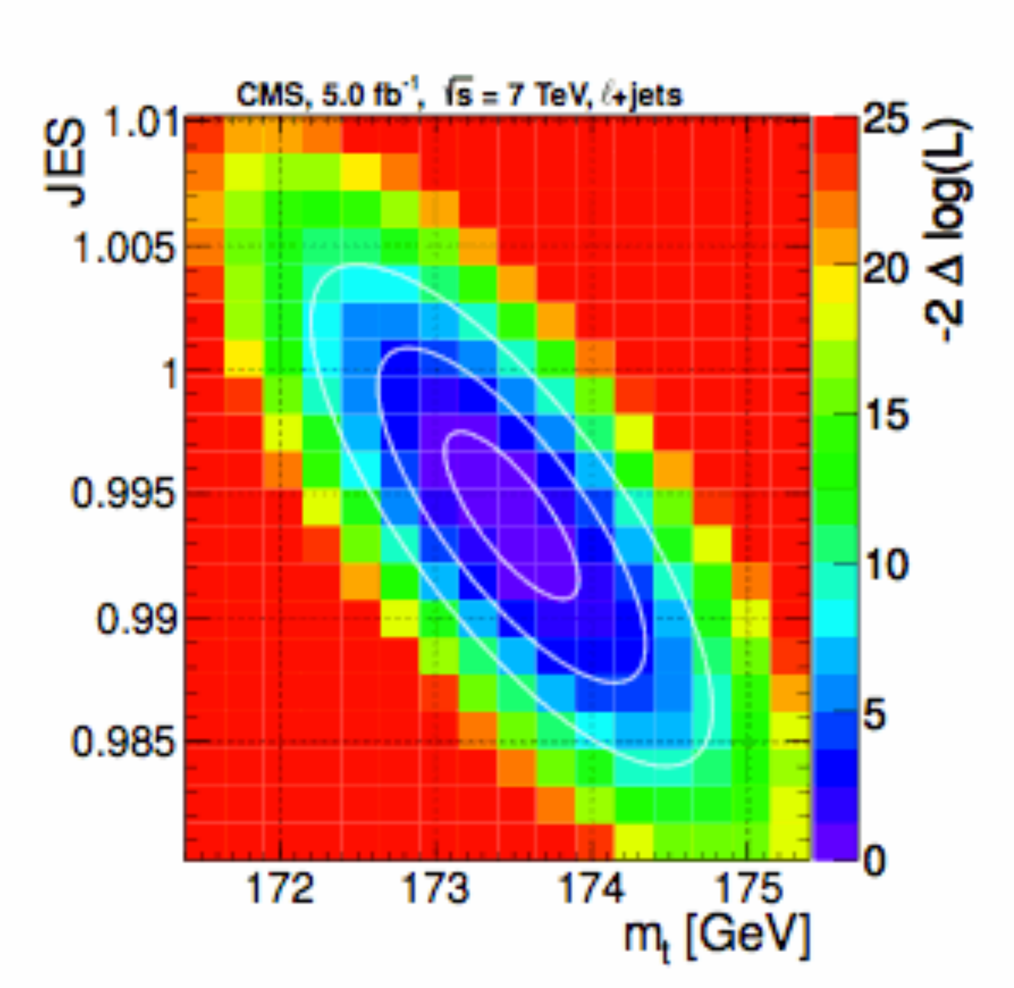
$$\delta M_t = 0.87\ GeV\,(0.50\%)$$

$$\chi^2/N_{dof} = 8.5/11 \ \rightarrow\ P = 67\%$$

M_t at LHC: lepton + jets

Ideogram method (m_t^{reco}, m_W^{reco})
+ *in situ JES* (5.0 fb^{-1})

JHEP 12, 105 (2012)

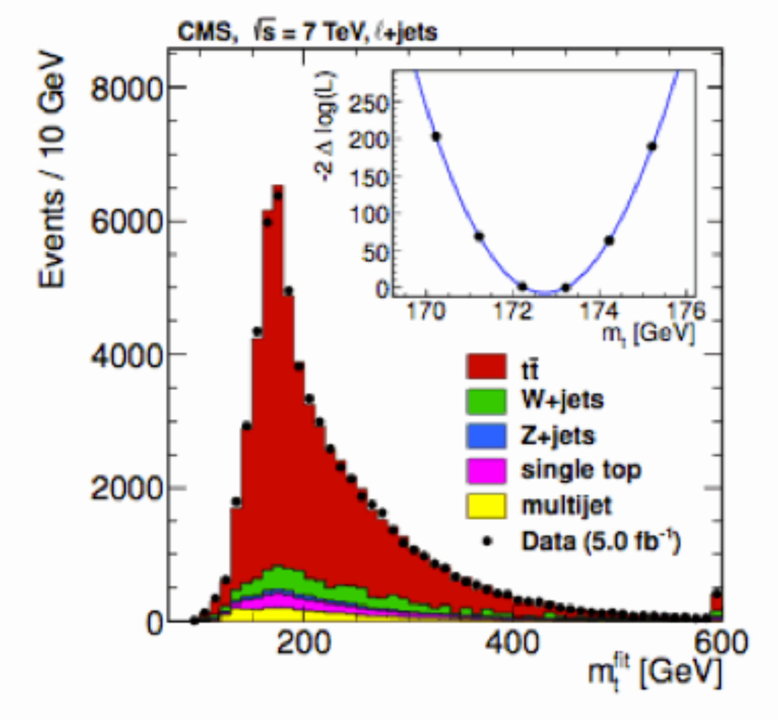


$$M_t = 173.49 \pm 0.43(stat + JES) \pm 0.98(syst)\ GeV$$

$$\delta M_t = 1.1\ GeV (0.63\%)$$ $$\delta M_t^{b-JES} = 0.6\ GeV$$ $$\delta M_t^{col-rec} = 0.54\ GeV$$

$$\delta M_t^{res-JES} = 0.28\ GeV$$

Looser selection and 1D fit



Consistent M_t but with larger systematics

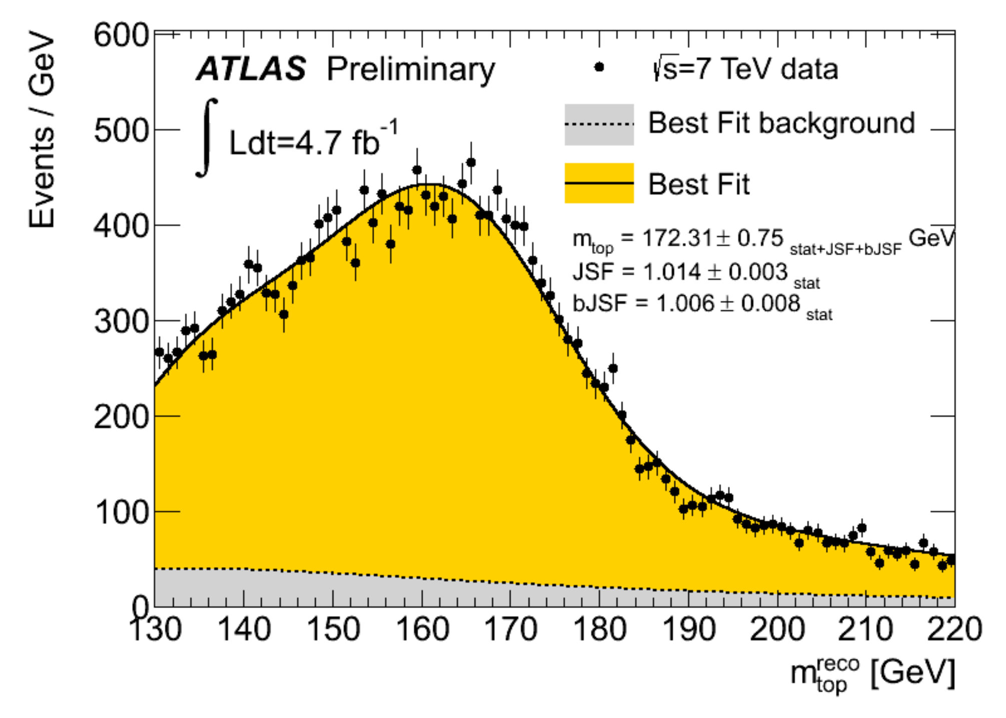
Lepton Photon 2013 - San Francisco

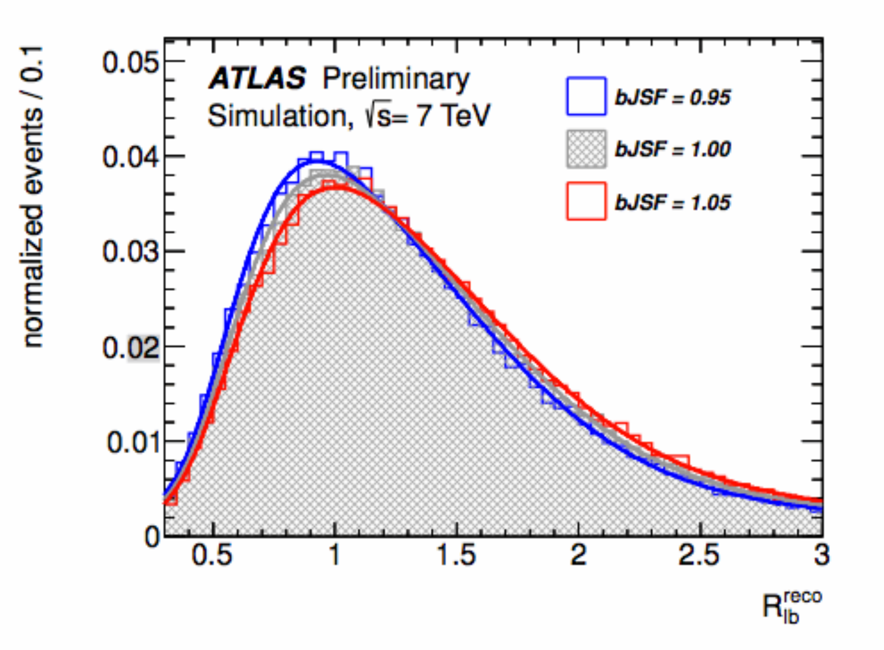
M_t at LHC: lepton + jets

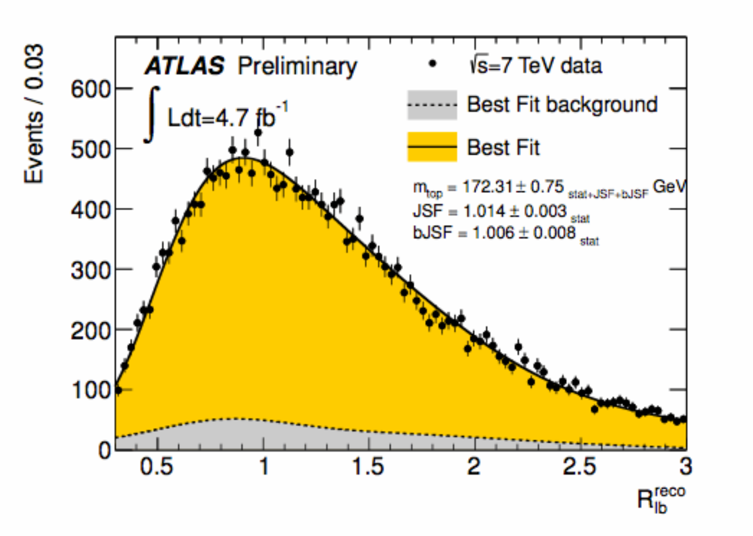
3D *Template* (m_t^{reco}, m_W^{reco}, R_{lb})

also *in situ bJES* ! (4.7 fb^{-1})

ATLAS-CONF-2013-046







$$R_{lb}^{reco,1b} = \frac{p_T^{b_{tag}}}{(p_T^{W_{jet_1}} + p_T^{W_{jet_2}})/2}$$

$$R_{lb}^{reco,2b} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet_1}} + p_T^{W_{jet_2}}},$$

2D → 3D

$$\delta M_t^{total-syst} = 2.02 \rightarrow 1.35$$

$$\delta M_t^{hadronization} = 1.30 \rightarrow 0.27$$

$$\delta M_t^{b-JSF} = 0.92$$
$$\rightarrow 0.08(syst) + 0.67(stat)$$

$$\delta M_t^{ISR/FSR} = 0.96 \rightarrow 0.45$$

$$M_t = 172.31 \pm 0.75(stat + JSF + bJSF) \pm 1.35(syst)\ GeV$$

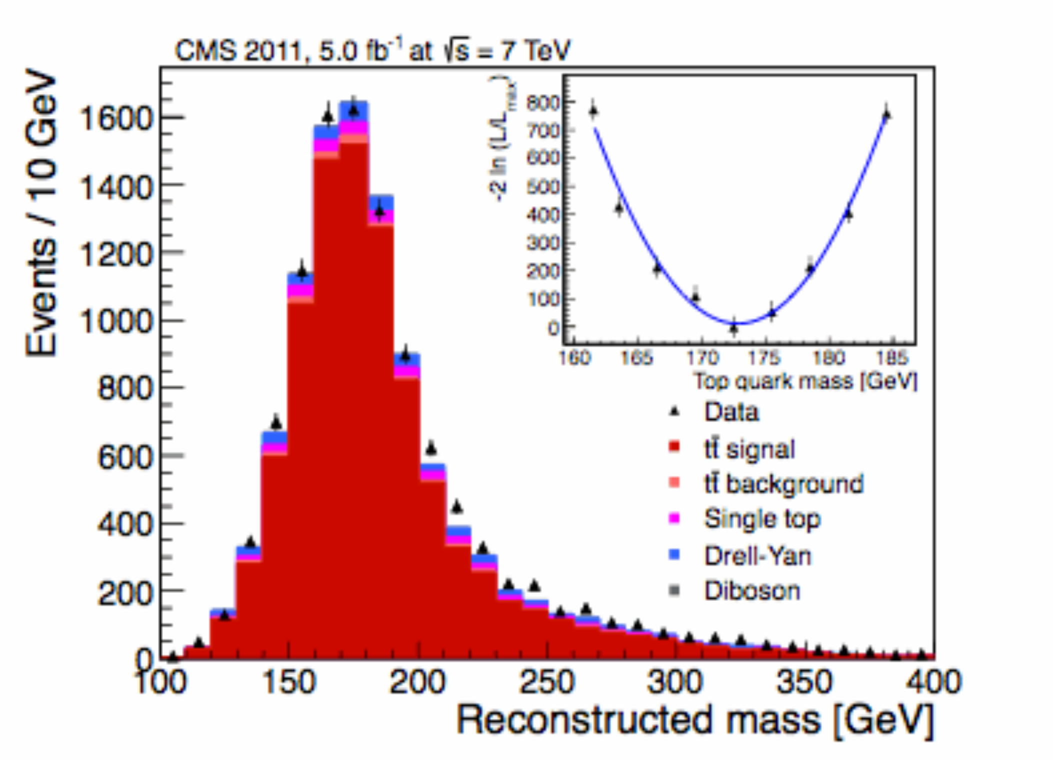
$$\delta M_t = 1.5\ GeV(0.90\%)$$

$$\delta M_t^{btag-eff} = 0.81\ GeV \quad \delta M_t^{JSF} = 0.79\ GeV \quad \delta M_t^{ISR/FSR} = 0.45\ GeV$$

M_t at LHC: dilepton

Analytical Matrix Weighting Technique
(5.0 fb^{-1})

EPJC 72, 2202 (2012)



$$M_t = 172.5 \pm 0.4(stat) \pm 1.5(syst)\ GeV$$

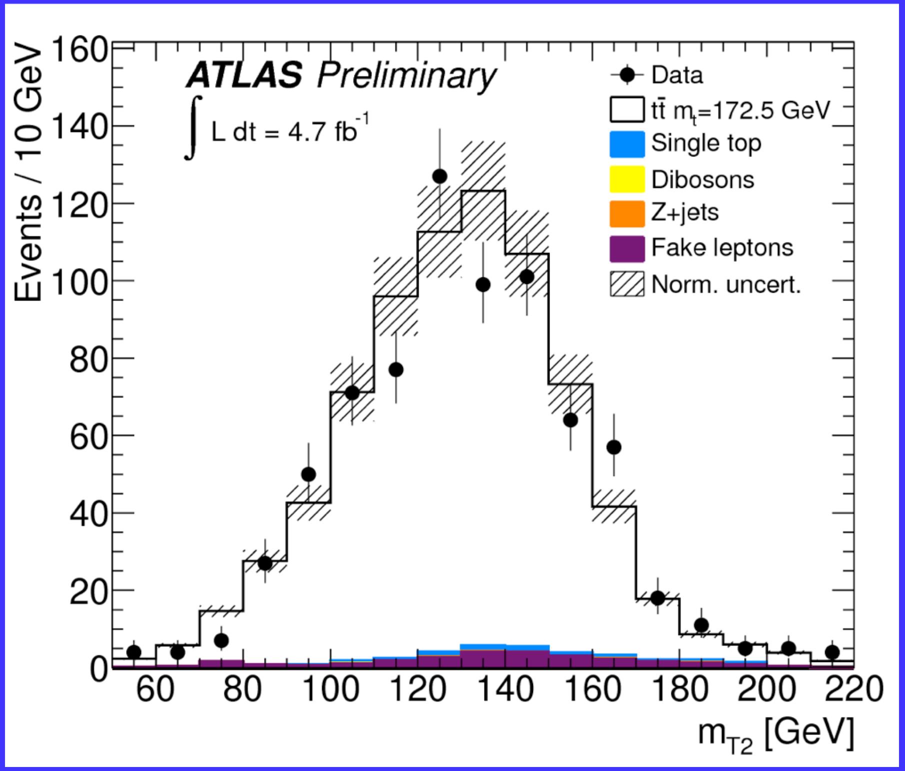
$$\delta M_t = 1.6\ GeV\,(0.93\%)$$

$$\delta M_t^{JES} = 1.0\ GeV$$

$$\delta M_t^{b-JES} = 0.6\ GeV$$

m_{T2} variable, i.e.
lower bound on the parent particle mass
(4.7 fb^{-1})

ATLAS-CONF-2012-082 (2012)



$$M_t = 175.2 \pm 1.6(stat)^{+3.1}_{-2.8}(syst)\ GeV$$

$$\delta M_t = 3.5\ GeV\,(2.0\%)$$

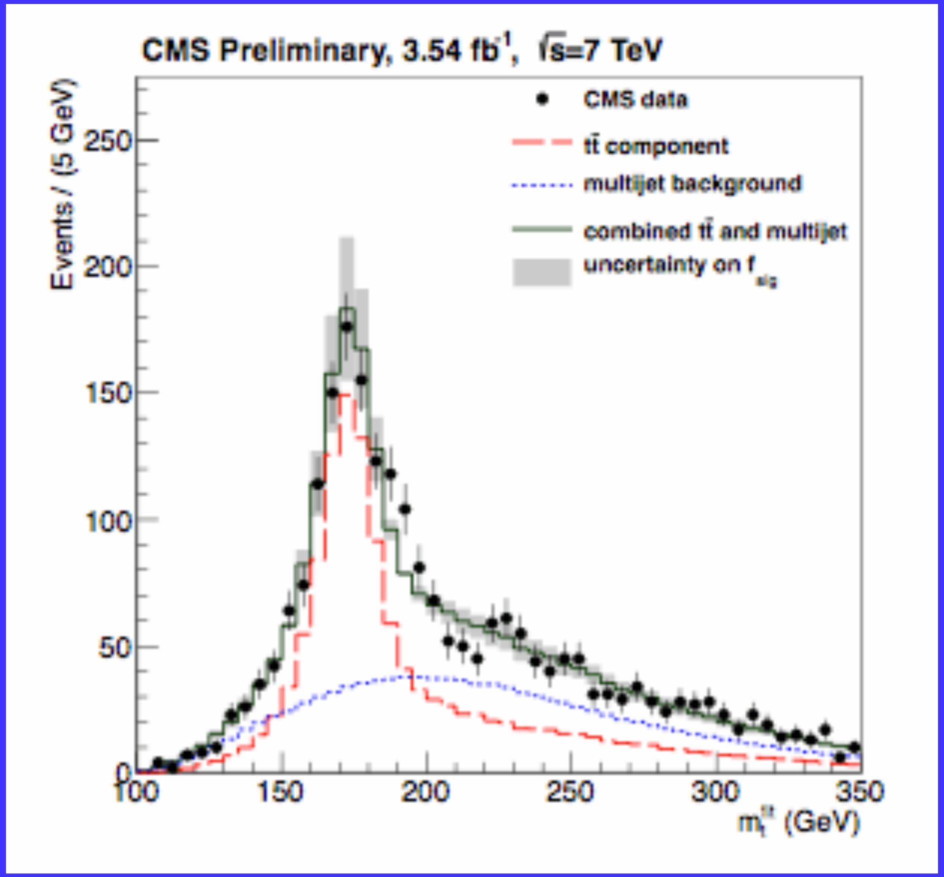
$$\delta M_t^{JES} = 1.5\ GeV \qquad \delta M_t^{b-JES} = 1.4\ GeV$$

$$\delta M_t^{generator} = 1.3\ GeV$$

M_t at LHC: all-jets

Ideogram method
(3.5 fb^{-1})

CMS PAS-TOP-11-017 (2012)



$$M_t = 173.49 \pm 0.69(stat) \pm 1.25(syst)\ GeV$$

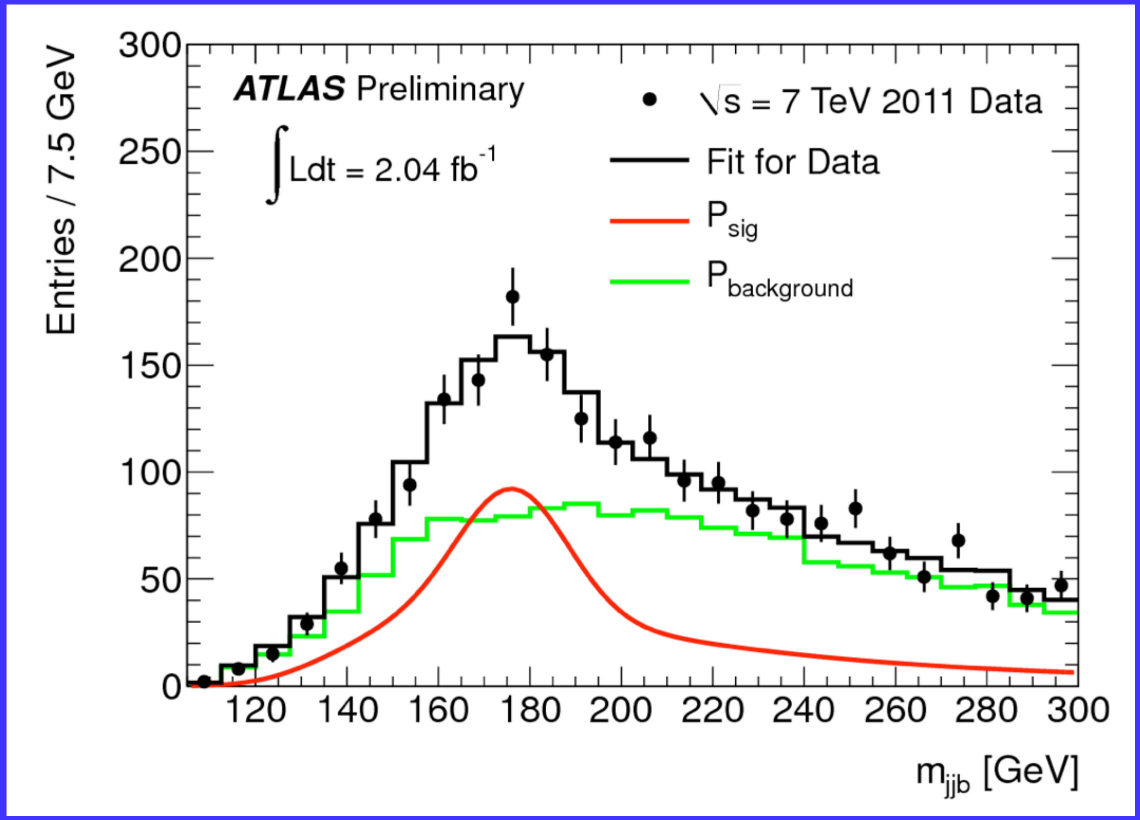
$$\delta M_t = 1.5\ GeV (0.85\%)$$

$\delta M_t^{JES} = 0.97\ GeV$ $\delta M_t^{b-JES} = 0.49\ GeV$

$\delta M_t^{UE} = 0.32\ GeV$

Template method
(2.0 fb^{-1})

ATLAS-CONF-2012-030 (2012)



$$M_t = 174.9 \pm 2.1(stat) \pm 3.8(syst)\ GeV$$

$$\delta M_t = 4.3\ GeV (2.5\%)$$

$\delta M_t^{JES} = 2.1\ GeV$ $\delta M_t^{b-JES} = 1.4\ GeV$

$\delta M_t^{bkg-model} = 1.9\ GeV$

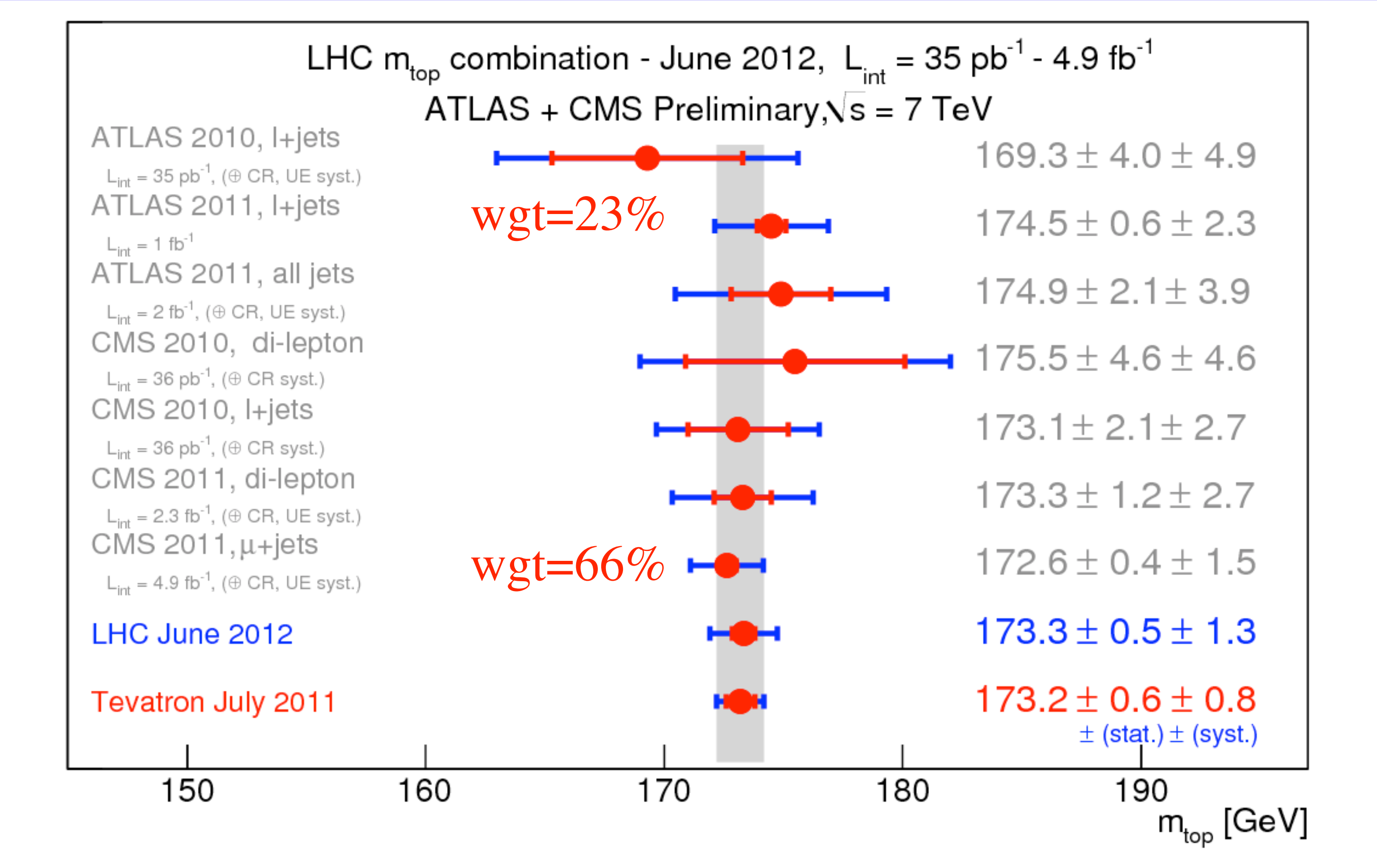
LHC average

Average computed with the Best Linear Unbiased Estimator

ATLAS-CONF-2012-095 **CMS PAS-12-001**

Common definition of syst. unc. in progress, for instance ATLAS has an additional hadronization systematics

This is last year avg. but new individual results are much better now



A combination Tevatron +LHC is in progress and will hopefully be ready this Fall

$$M_t = 173.3 \pm 0.5(stat) \pm 1.3(syst)\ GeV$$

$$\delta M_t^{LHC} = 1.4\ GeV (0.80\%)$$

$$\chi^2/N_{dof} = 2.5/6 \ \rightarrow \ P = 86\%$$

Mtop – Mantitop (Tevatron):

A way to test CPT invariance which predicts same mass for particles and antiparticles

Again, this can be done directly only on **t**, using techniques similar to the M_t measurement

Matrix Element

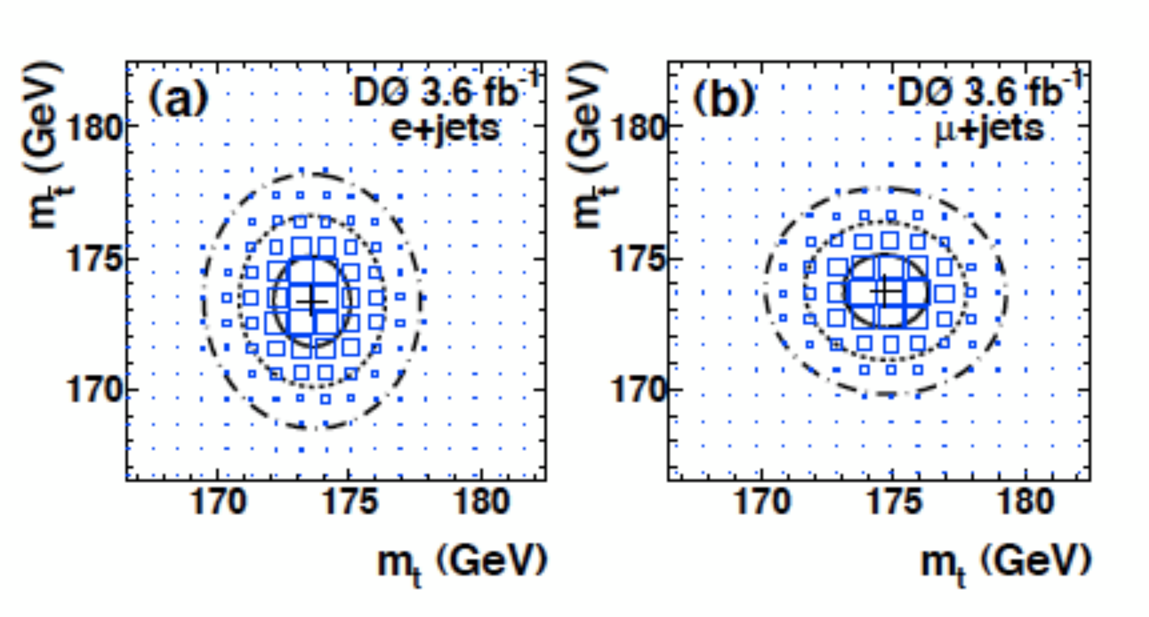
LJ ($3.6\ fb^{-1}$)

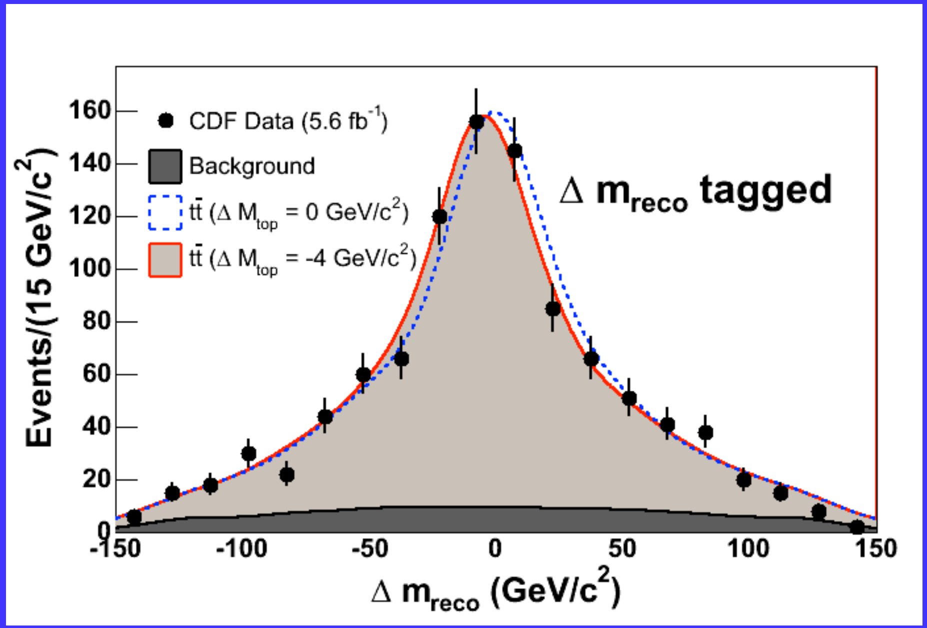
Phys. Rev. D 84, 052005 (2011)

Template method

LJ ($8.7\ fb^{-1}$)

Phys. Rev. D 87, 052013 (2013)





$$\Delta M_t = +0.8 \pm 1.8(stat) \pm 0.5(syst)\ GeV$$
$$= +0.8 \pm 1.9\ GeV$$

$$\Delta M_t = -1.95 \pm 1.11(stat) \pm 0.59(syst) = -1.95 \pm 1.26\ GeV$$

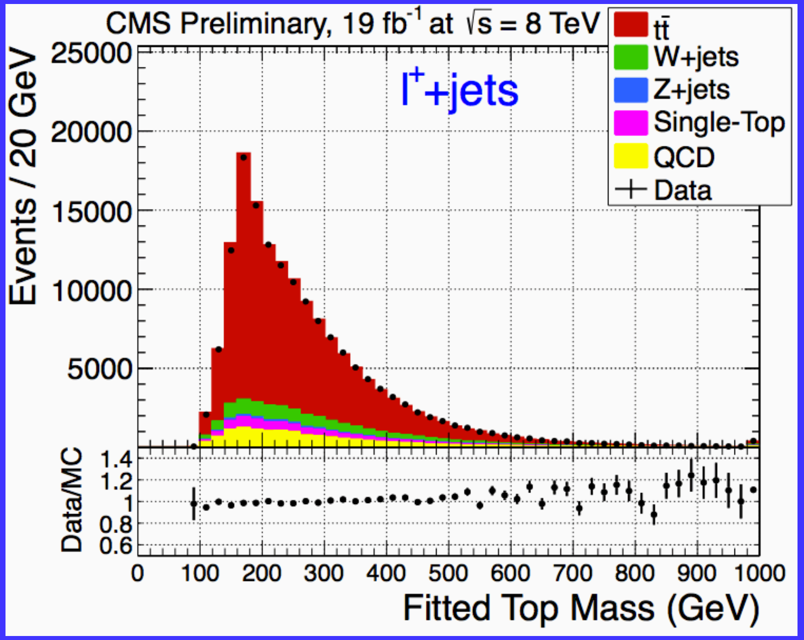
Mtop – Mantitop (LHC):

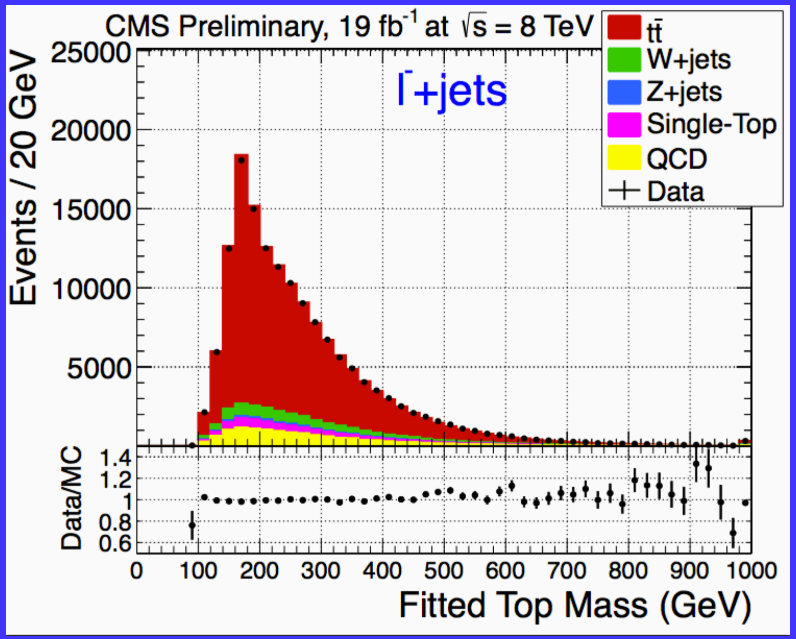
Takes advantage of the huge reduction in statistical uncertainty

Ideogram method

LJ (19 fb^{-1})

CMS PAS-TOP-12-031 (2013)





$$\Delta M_t = -272 \pm 196(stat) \pm 122(syst)\ MeV$$

$$\delta\Delta M_t^{b-\bar{b}\ response} = 64\ MeV \qquad \delta\Delta M_t^{bckgd\ composition} = 50\ MeV$$

Again, consistent with $\Delta M_t = 0$!

What mass are we measuring ?

The mass measured so far is the mass used as input in the MC generation (typically LO or NLO) and is affected by several perturbative/non-perturbative sub-1% uncertainties

The increasing level of accuracy requires to relate this to theory-based quantities like:

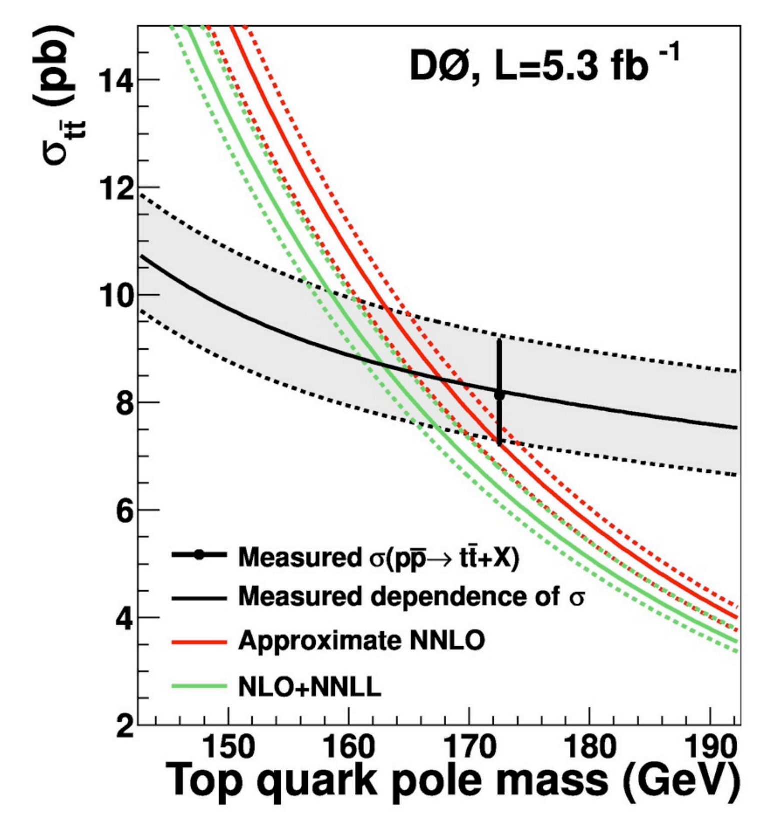
− the *pole mass*, universal but theoretically ambiguous by amounts $\mathcal{O}(\Lambda_{QCD})$ due to soft gluon radiation (*infrared renormalon problem*)

− lagrangian masses, theoretically unambiguos but not universal, like the *MS mass* which is defined only in perturbation theory

These masses can be derived from a comparison of the measured cross section to theoretical predictions of σ_{tt} on M_t

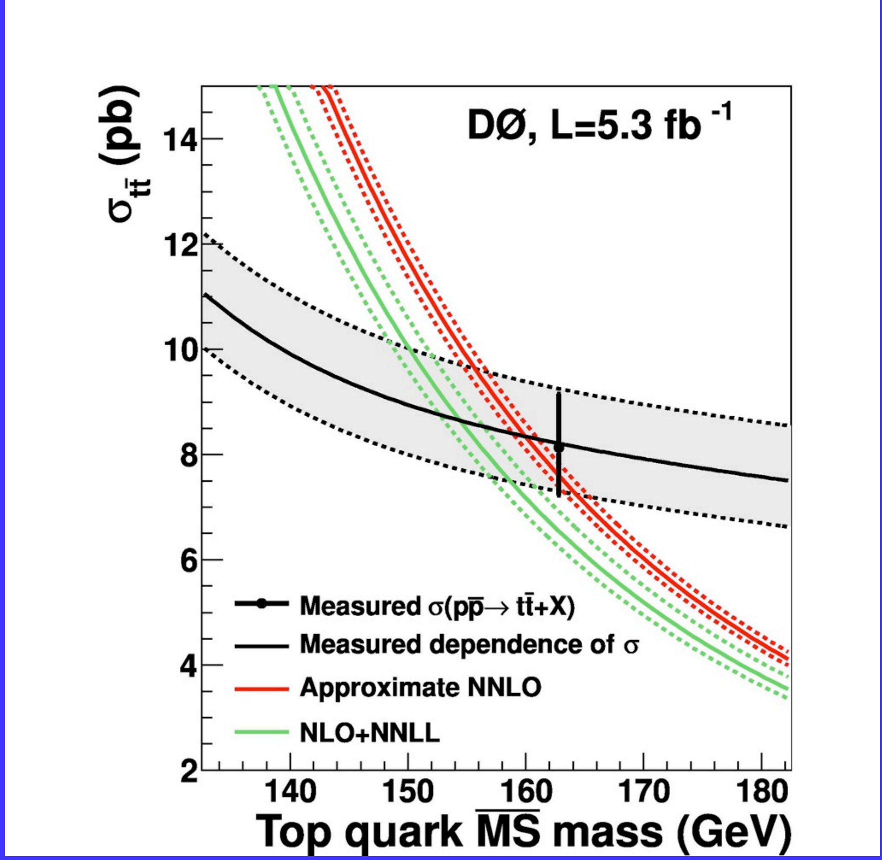
Of course one has to make assumptions on what Mt^{MC} is equal to

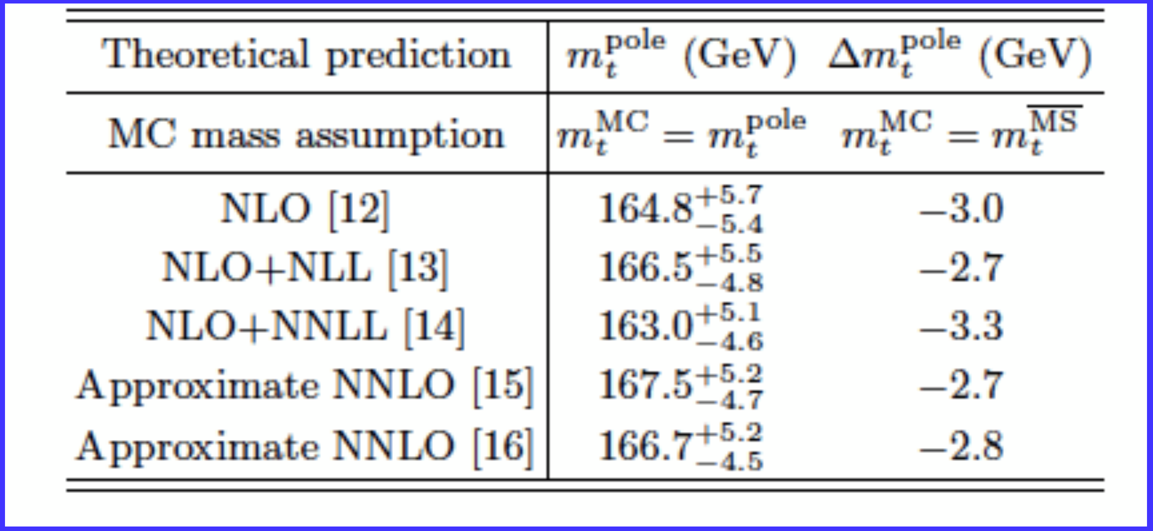
Pole mass / $\overline{\text{MS}}$ mass at Tevatron



From σ_{tt} measurement in lepton+jets ($5.3\ \text{fb}^{-1}$)

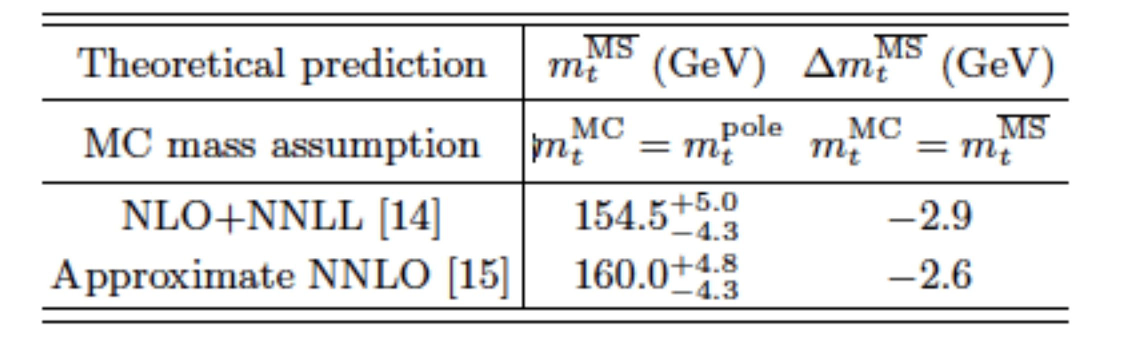
Phys. Lett. B 703, 422 (2011)





Theoretical prediction	m_t^{pole} (GeV)	Δm_t^{pole} (GeV)
MC mass assumption	$m_t^{\text{MC}} = m_t^{\text{pole}}$	$m_t^{\text{MC}} = m_t^{\overline{\text{MS}}}$
NLO [12]	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL [13]	$166.5^{+5.5}_{-4.8}$	-2.7
NLO+NNLL [14]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [15]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO [16]	$166.7^{+5.2}_{-4.5}$	-2.8

consistent within 2 σ



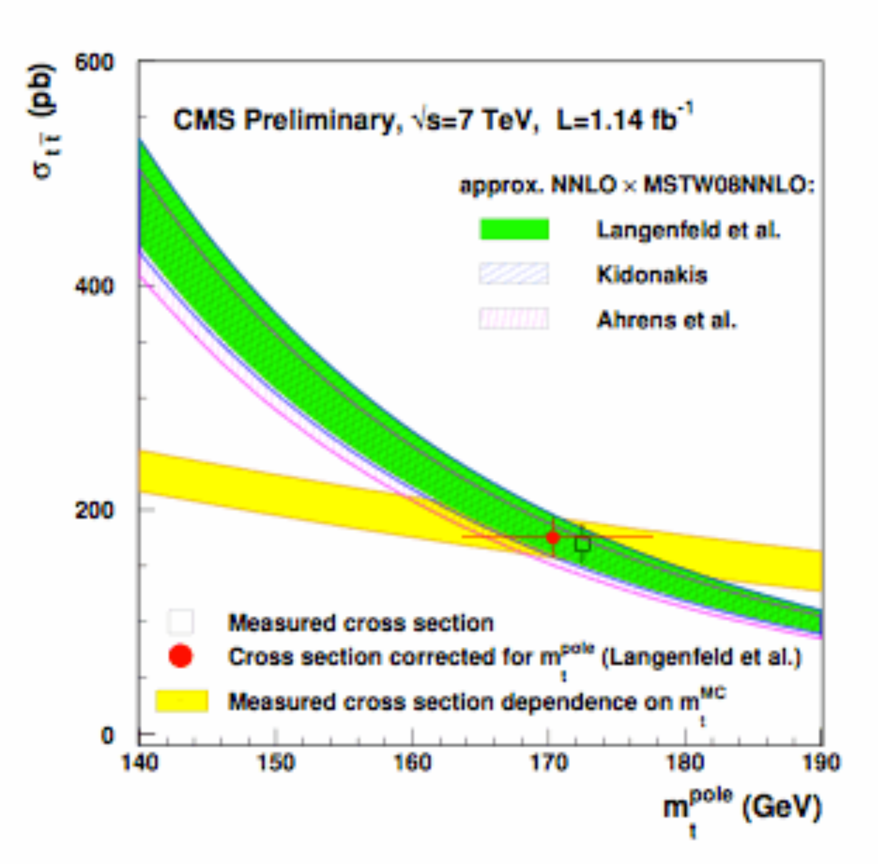
Theoretical prediction	$m_t^{\overline{\text{MS}}}$ (GeV)	$\Delta m_t^{\overline{\text{MS}}}$ (GeV)
MC mass assumption	$m_t^{\text{MC}} = m_t^{\text{pole}}$	$m_t^{\text{MC}} = m_t^{\overline{\text{MS}}}$
NLO+NNLL [14]	$154.5^{+5.0}_{-4.3}$	-2.9
Approximate NNLO [15]	$160.0^{+4.8}_{-4.3}$	-2.6

differ more than 2 σ

Pole mass / $\overline{\mathrm{MS}}$ mass at LHC

From σ_{tt} measurement
in lepton+jets
(1.1 fb^{-1})

CMS PAS-TOP-11-008 (2011)
+ other theory/PDF sets

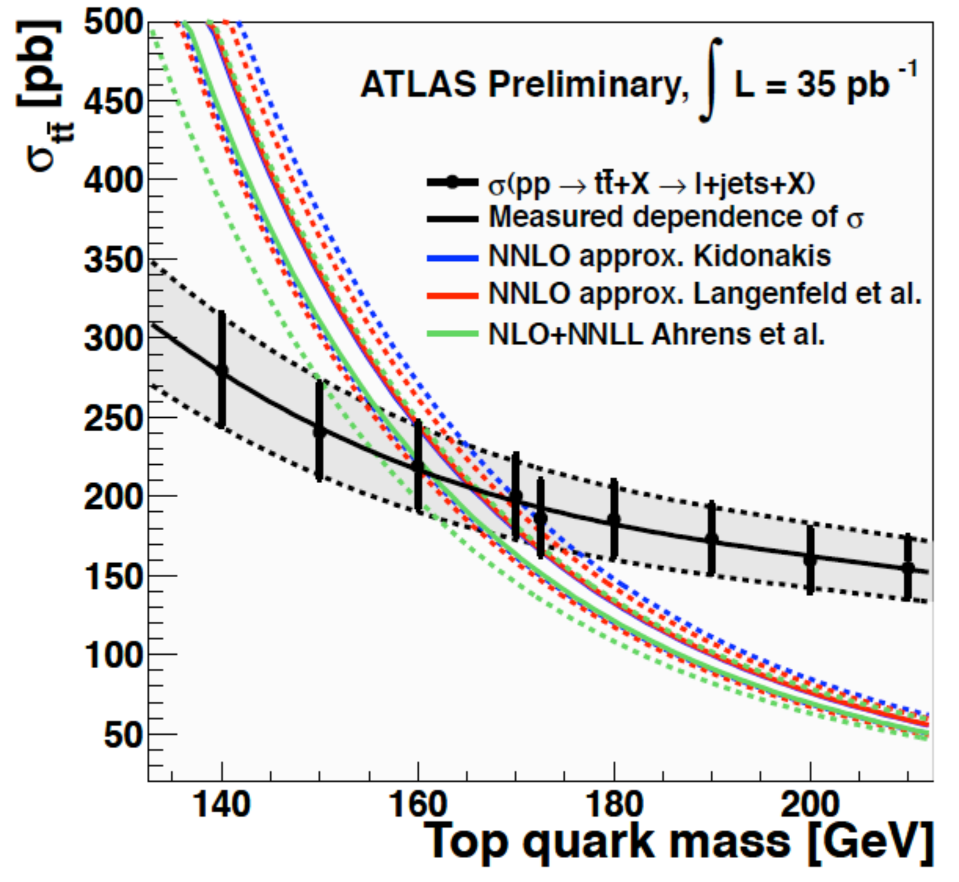


$M_t^{\mathrm{pole}} \approx 170$ GeV $\delta M_t \approx 6\ GeV$

$M_t^{\overline{\mathrm{MS}}} \approx 160$ GeV

From σ_{tt} measurement
in lepton+jets
(35 pb^{-1})

ATLAS-CONF-2011-054 (2011)



$M_t^{\mathrm{pole}} \approx 166$ GeV

$\delta M_t \approx 8\ GeV$

Conclusions

The level of precision reached (<0.5%) in the measurement of M_t is impressive but it has come from 18 years of continuous improvements

An even better precision expected from future measurements at the LHC will help to explore fundamental issues like:

– <u>cosmological models</u> for inflation
– <u>vacuum stability</u> of the Standard Model
– <u>physics beyond</u> the Standard Model

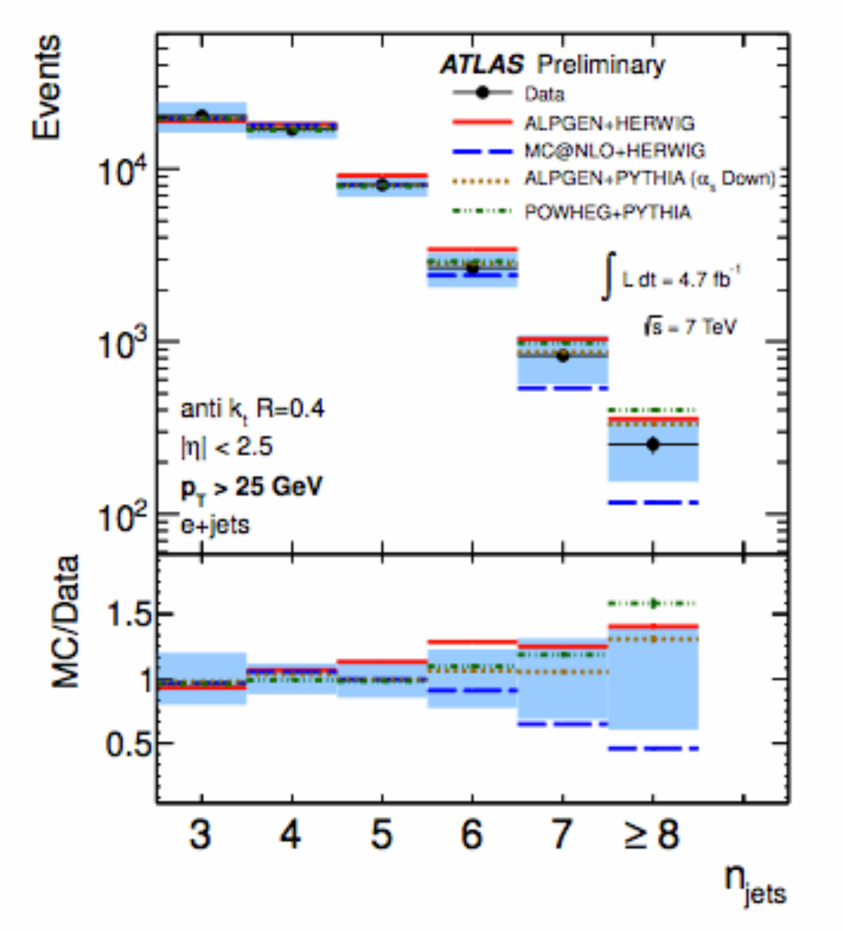
Outlook

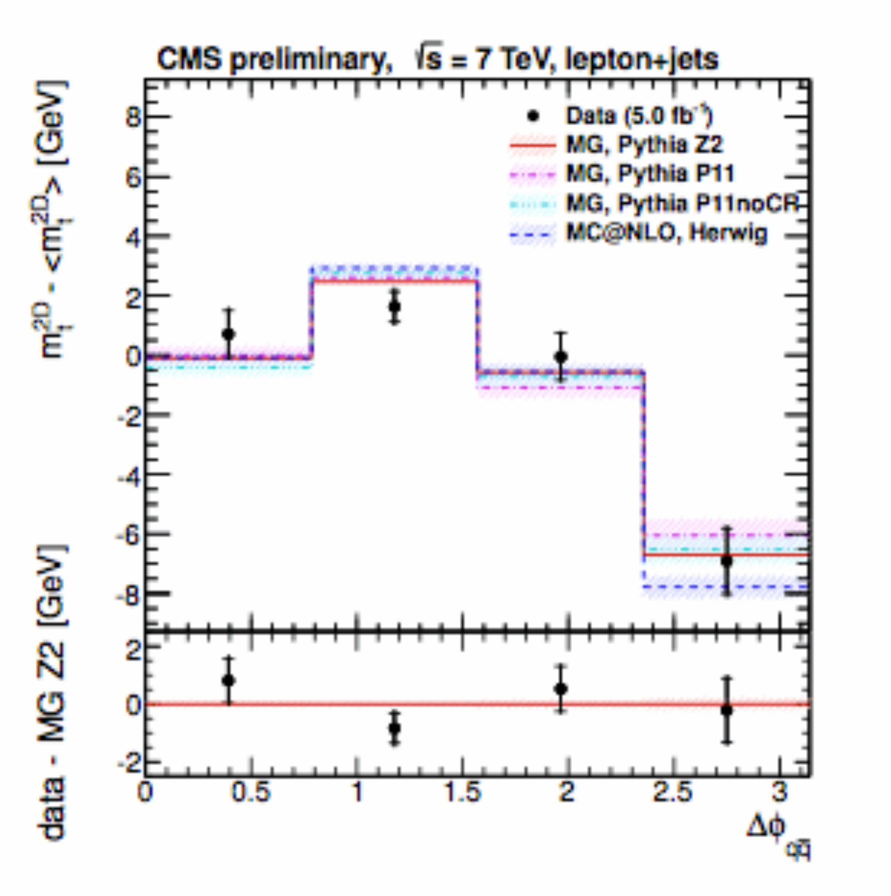
To achieve these goals is important to reduce the systematic uncertainties, for instance those related to signal modeling, see:

- ATLAS-PHYS-PUB-2013-005 on parton radiation constraining
- CMS-PAS-TOP-12-029 on color-recon. tunes (+ISR/FSR, b kin.)

LJ

N_{jet}





LJ with *Ideogram 2D*

$m_t^{2D} - \langle m_t^{2D} \rangle$

With exceptions, these and other distributions from different generators are consistent with what observed, within current accuracy

Final Message

Expect near-future improvements on the current data and then wait for next LHC runs to begin in 2015

Acknowledgements

The measurements described here are the results of the work of various physicists in 4 collaborations and is described in journal articles, arXiv documents or public collaboration documents

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