Standard Model precision measurements
Misure di precisione del modello standard
Lesson 4: top mass measurement

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Outline

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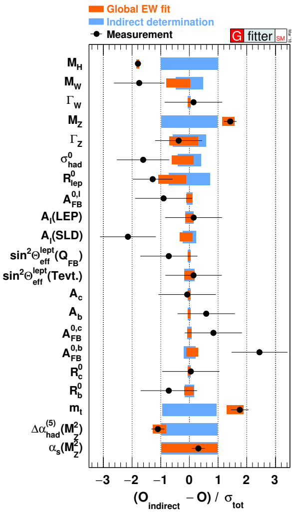
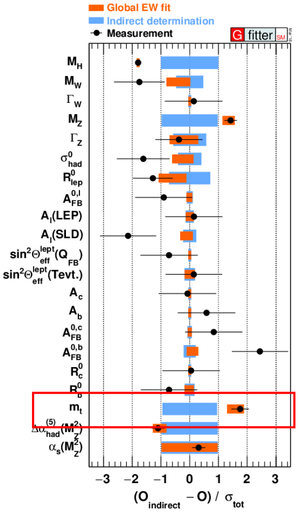
Input to global EWK fit
(in parenthesis the order followed in these lessons)



- Higgs mass (5)
  - LHC
- W mass and width (3)
  - LEP2, Tevatron
- Z-pole observables (1)
  - LEP1, SLD
  - M_Z, Γ_Z
  - σ_0^{had}
  - $\sin^2\Theta^{lept}_{eff}$
  - Asymmetries
  - BR $R^0_{lep,b,c} = \Gamma_{had}/\Gamma_{\ell\ell,b\bar{b},c\bar{c}}$
- top mass (4)
  - Tevatron, LHC
- other:
  - $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}(M_Z^2)$



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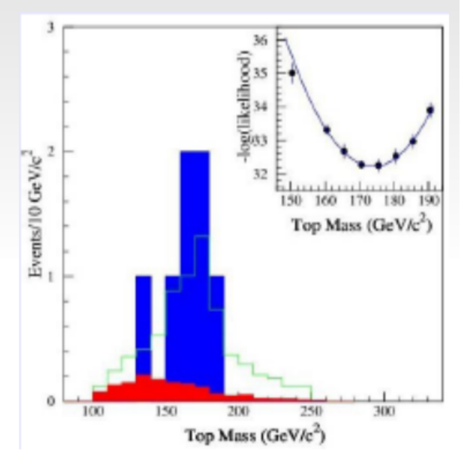
- Discovered at Tevatron in 1995 ($>$ 20 years ago);
- heaviest fundamental particle;
  - weight as an atom of ^{70}Yt, little less than Pl, or Au.
- Yukawa coupling $G_i = \frac{\sqrt{2}M_{top}}{\nu} \sim 1$;
- it decays before hadronization:
  - $\mathcal{B}(t \to bW) \approx 100\%$
    - ★ $|V_{tb}| \approx 1$
  - $\Gamma_t \simeq \frac{G_F m_t^3}{8\sqrt{2}\pi}|V_{tb}|^2 \sim 1.5\,\text{GeV} \gg \Lambda_{QCD}$
  - $\tau_{top} \sim 10^{-25}$ $s < \tau_{QCD} \sim 10^{-24}$ s;
  - unique chance to study bare quark;
- M_{top} enters (quadratically) in basically all radiative corrections



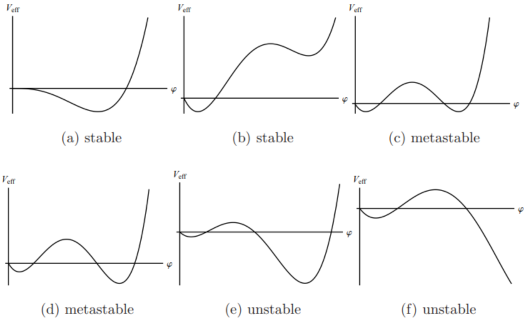
$$M_{top} = 174 \pm 10\ ^{+13}_{-12}\ \text{GeV}$$

M_{top} and vacuum stability [1]

SM $\mathcal{L}$ at tree level, in the Higgs sector, has a potential $V(\phi) = m^2|\phi|^2 + \lambda|\phi|^4 = \frac{1}{2}m^2H^2 + \frac{1}{4}\lambda H^4 + \ldots$,

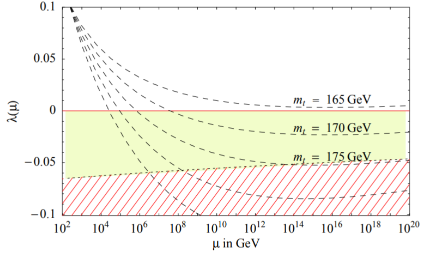
where $\langle H \rangle = v = \sqrt{\frac{1}{\sqrt{2}G_F}} = 246.2\,\text{GeV}$ and $m_H^2 = 2\lambda v^2$

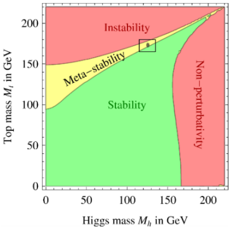
- if energy scale $\mu \gg v$ (eg plank scale), use a single running coupling $\lambda(\mu)$: $V(\mu \gg v) \approx \frac{1}{4}\lambda(\mu)H^4$
- If for some (large) value of H $\lambda(\mu) < 0$, the potential become instable (or metastable)
- Minimum closer to 0 is the EWK one. A second, deeper minimum can be there also.
- If $\mathcal{P}$-tunnel low (wrt age of universe): metastable, otherwise unstable
- Correction, and stability depends on M_H, M_{top}, and $\alpha_s(M_Z)$

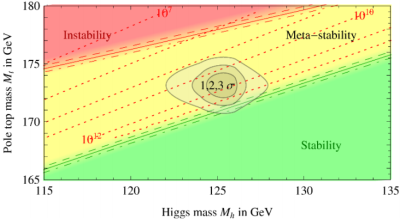


Apparently we (the universe?) are very close to the metastbility region (yellow area)

Stability for $M_H[\,\text{GeV}] > 129.5 + 1.4\left(\frac{M_{top}[\,\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right)$







Absolute stability is excluded at 98%C.L. for $M_H < 126$ GeV [1].
So, it is not just yet-an-other ingredient of the global SM fit.
Improving the precision of M_{top} (and M_H) is crucial to understand the vacuum stability.
Th. computation rely on the assumption that the pole mass is the world average

Experiment vs Theory

What are we talking about when we talk about M_{top}? [2]

- M_{exp} vs M_{theo}
- in QFT mass is a bare quantity that need to be renormalized to have physical relevance;
- What we measure experimentally, from direct measurement, is the MC mass M_{MC} (eg via template method), namely a mass of a theory prediction
  - M_{MC} is related to the pole of the propagator M_{pole} in the $\mathcal{L}$ but are not the same thing.
  - close, but different:

$$M_{pole} = M_{MC} + Q_0[c_1\alpha_S(Q_0) + \ldots]$$

    - where Q_0 is a scale used in the definition of M_{MC} ($\sim 1\ GeV$ in Pythia)
- *"The uncertainty on the translation from the MC mass definition to a theoretically well defined shortdistance mass definition at a low scale is currently estimated to be of the order of 1 GeV [3]."*
- on the other hand, theoretically M_{MC} is typically evaluated in a given renormalization schema taking into account the self-energy radiative contribution and a given cutoff;

Experiment vs Theory (II)

- Theory definition of M_{top} depends on renormalization schema
- several schema are used, each with its own problems

$\overline{MS}$: "modified minimal subtraction", introduces an arbitrary mass scale in the theory, $M_{\overline{MS}}$

OS : "on-shell (pole) mass scheme" connection to the top quark's kinematical properties physically limited for color confinement

RGI

...

- $M(\overline{MS}) = M_{pole}(1 + 4/3\alpha_S/\pi + \ldots)$ (known up to $\mathcal{O}(\alpha_S^4)$ [4])
- Note that $M_{top}(\overline{MS}) - M_{top}(pole) \sim 10\,\text{GeV}$

MSR "low-scale short distance masses" schema interpolates smoothly between pole and $\overline{MS}$

- $M_{MSR}(R) \xrightarrow{R\to 0} M_{pole}$, and $M_{MSR}(R = M_{\overline{MS}}) = M_{\overline{MS}}$ (R is infrared scale)
- with $R \sim 1\,\text{GeV}$, M_{MSR} is as close as possible to pole

- $M_{top}^{MC} = M_{top}^{MSR}(R = 3^{+6}_{-2})$ GeV which correspond to "...order of 1 GeV" [5]
- Side remark: σ_{tt} depends on M_{pole} so it can be used for direct M_{pole} measurement

$M(pole)$ vs $M(\bar{MS})$

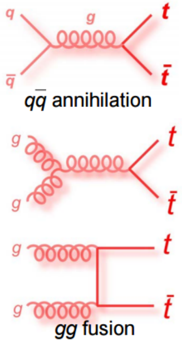
$$M_{top}^{MC} = M_{top}^{MSR}(3^{+6}_{-2})\ \text{GeV}$$

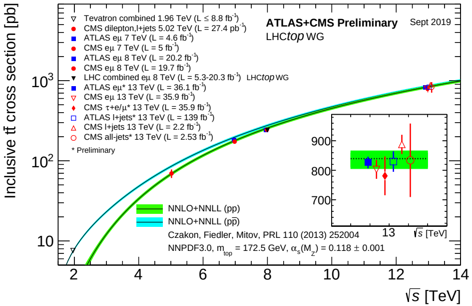
$m^{\text{MSR}}(1)$	$m^{\text{MSR}}(3)$	$m^{\text{MSR}}(9)$	$\overline{m}(\overline{m})$	$m^{\text{pl}}_{\text{1lp}}$	$m^{\text{pl}}_{\text{2lp}}$	$m^{\text{pl}}_{\text{3lp}}$	$m^{\text{pl}}_{\text{1lp}}$	$m^{\text{pl}}_{\text{2lp}}$	$m^{\text{pl}}_{\text{3lp}}$
172.52	172.20	171.58	162.62	170.14	171.75	172.25	172.52	172.67	172.78
172.72	172.40	171.78	162.81	170.34	171.95	172.45	172.72	172.87	172.98
172.92	172.60	171.98	163.00	170.54	172.15	172.65	172.92	173.07	173.18
173.12	172.80	172.18	163.19	170.73	172.35	172.85	173.12	173.27	173.38
173.32	173.00	172.38	163.38	170.93	172.55	173.05	173.32	173.47	173.58
173.52	173.20	172.58	163.57	171.13	172.75	173.25	173.52	173.67	173.78
173.72	173.40	172.78	163.76	171.33	172.95	173.45	173.72	173.87	173.98
173.92	173.60	172.98	163.95	171.53	173.15	173.65	173.92	174.07	174.18
174.12	173.80	173.18	164.14	171.72	173.35	173.85	174.12	174.27	174.38
174.32	174.00	173.38	164.33	171.92	173.55	174.05	174.32	174.47	174.58
174.52	174.20	173.58	164.52	172.12	173.74	174.25	174.52	174.67	174.78

Table 2.1: Top quark MSR and $\overline{\text{MS}}$ masses at different scales converted at $\mathcal{O}(\alpha_s^3)$ for $\alpha_s(M_Z) = 0.1185$. Columns 5-7 show the 1, 2 and 3 loop pole masses converted from the $\overline{\text{MS}}$ mass $\overline{m}(\overline{m})$. Columns 8-10 show the 1, 2 and 3 loop pole masses converted from the MSR mass $m^{\text{MRS}}(3\ \text{GeV})$. All numbers are given in GeV units.

Production mechanism:

- $q\bar{q} \to t\bar{t}$
  - Dominant at Tevatron (85%-15%)
- $gg \to t\bar{t}$
  - Dominant at LHC (90%-10%)





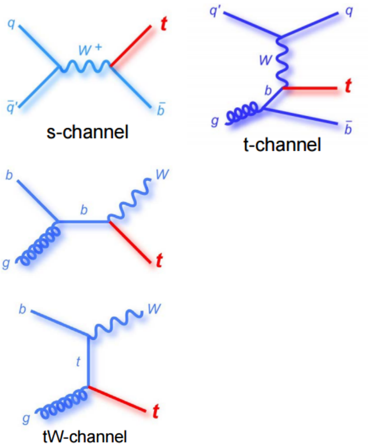
(stat)±(syst)±(lumi)

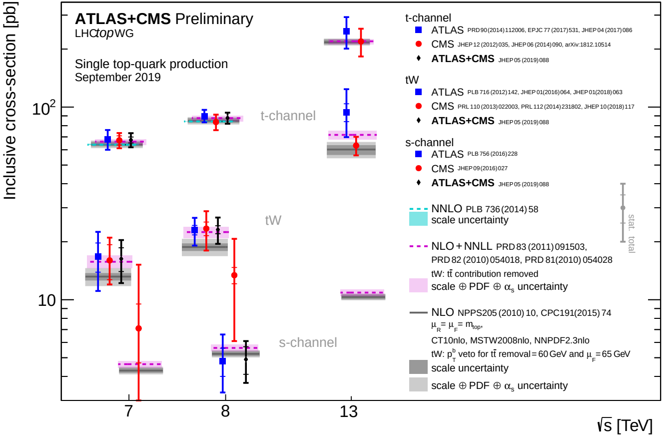
$$\sigma_{t\bar{t}}(\sqrt{s} = 1.96\ \text{TeV}) = 7.16 \pm 0.2\ pb$$
$$\sigma_{t\bar{t}}(\sqrt{s} = 7\ \text{TeV}) = 173.0 \pm 2 \pm 8 \pm 6\ pb$$
$$\sigma_{t\bar{t}}(\sqrt{s} = 8\ \text{TeV}) = 241.5 \pm 1.4^{+6.3}_{-5.5} \pm 6.4\ pb$$
$$\sigma_{t\bar{t}}(\sqrt{s} = 13\ \text{TeV}) = 818 \pm 8 \pm 27 \pm 19\ pb\ (\text{ATLAS}\ e\mu)$$
$$\sigma_{t\bar{t}}(\sqrt{s} = 13\ \text{TeV}) = 815 \pm 2 \pm 25 \pm 20\ pb\ (\text{CMS}\ e\mu)$$

NB: $\sigma(\sqrt{s})$ depends on M_{top}^{pole}

$$\mathcal{L}_{LHC}^{max} = 2 \cdot 10^{34}\ cm^{-2} s^{-1} = 20\ \text{nb}^{-1}/s.\ \text{Rate}\ t\bar{t} \approx 16\ Hz$$

Single top production also present

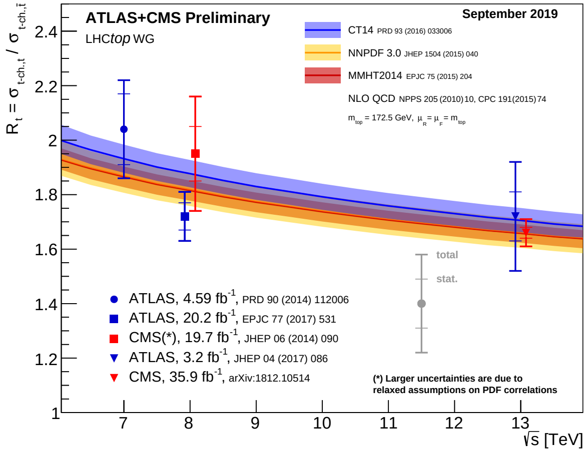




s and t-channels seen at TeVatron
all channels measured at LHC

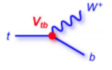
Single top vs anti-top

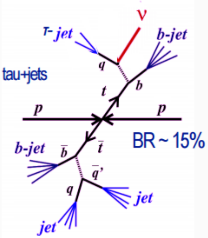
- In general $\sigma_t \neq \sigma_{\bar{t}}$
- measured for $t-$channel at different $\sqrt{s}$
- $\sigma_{t-channel} > \sigma_{tW} > \sigma_{s-channel}$

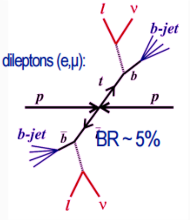


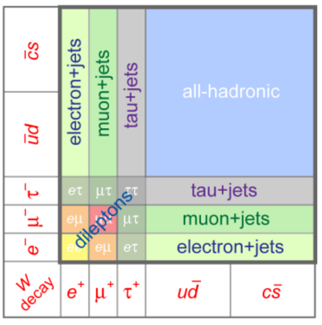
$t\bar{t}$ event signatures

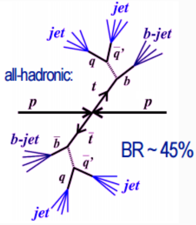
- In SM, B(t→ Wb)~100%
  - presence of b-quark
  - final states with different S/B ratio

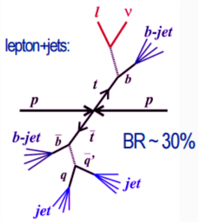












Different decay channels are complementary and have different sensitivity to systematics

General technique

- Issues:
  - complex final state: jets, b-tagging, leptons, MET;
    - combinatorics
  - The name of the game is: jet energy scale
- Techniques:
  - kinematical fit to $M(jj) = M_W$ and $M_t = M_{\bar{t}}$;
  - kin fit also to reduce combinatorics;
  - use unconstrained $W \to jj$ decay to simultaneously fit JES ;
  - residual JES for b-jets can also be exctacted from a fit from data;
- M_{top} extractions:
  - Template Method (standard);
  - Matrix Element Method;
  - Ideogram Method;
  - Analytical Matrix Weighting Technique;
  - many alternative others ...
- At Tevatron statistics is relevant, not much at LHC.

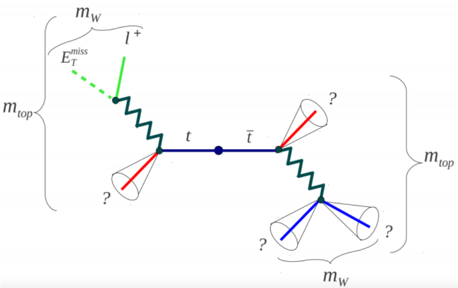
Lepton+jets channel

- Semi-Leptonic decay.
- Golden channel
  - low background and high BR.
  - one top fully reconstructed $t \to bW \to bjj$, one with missing nutrino $t \to bW \to b\ell\nu$.
- A critical element is the knowledge of Jet (and b-jet) Energy Scale
- use a kinematical likelihood fit for full reconstruction.
- fit can be done in three ways:
  - **1D fit** reconstruct $t \to bjj$: depends strongly on M_{top}, JES, bJES.
  - **2D fit** reconstruct $W \to jj$: strong dep. on JES, neglibible to M_{top}, jJES
  - **3D fit** use an other variable strong dep. on bJES and weak on M_{top} and JES
  - eg:

$$R_{lb} = p_T^b / p_T^W$$

$$R_{lb}^{1b} = \frac{p_t^b}{\left(p_t^{jet_{W,1}} + p_t^{jet_{W,2}}\right)/2}$$

$$R_{lb}^{2b} = R_{qb}^{reco} = \frac{p_t^{b_{had}} + p_t^{b_{lep}}}{p_t^{jet_{W,1}} + p_t^{jet_{W,2}}}$$

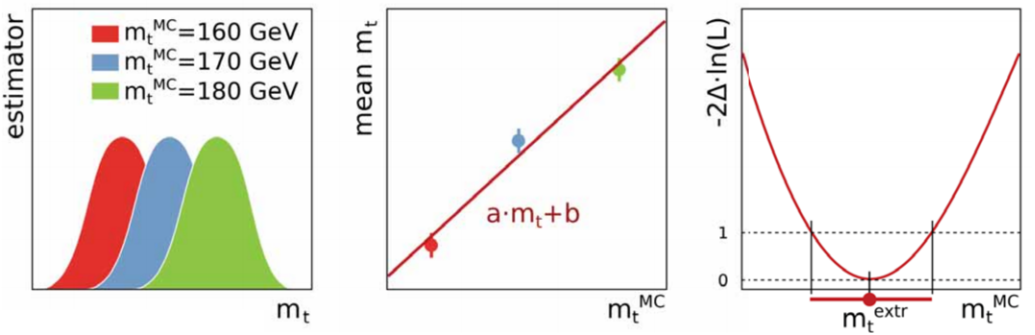


- 3D simultaneous fit to extract M_{top}, JES, bJES
- Use Template method

Template method

Extensively used by Tevaton and LHC: similar to that used for M_W

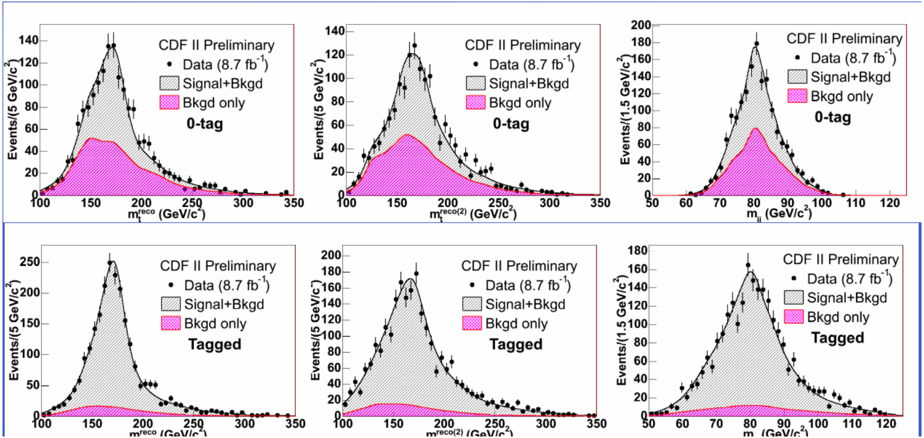
- build an estimator sensitive to M_{top}
  - eg invariant mass of daughters $t \to bjj$, or P_t^{ℓ} or whatever;
- build various template distribution for different values of M_{top};
  - parametrize the estimator vs M_{top} (mean M_{top} in the example below);
- Perform a maximum likelihood fit to the data;
- extract M_{top} (and uncertainty);



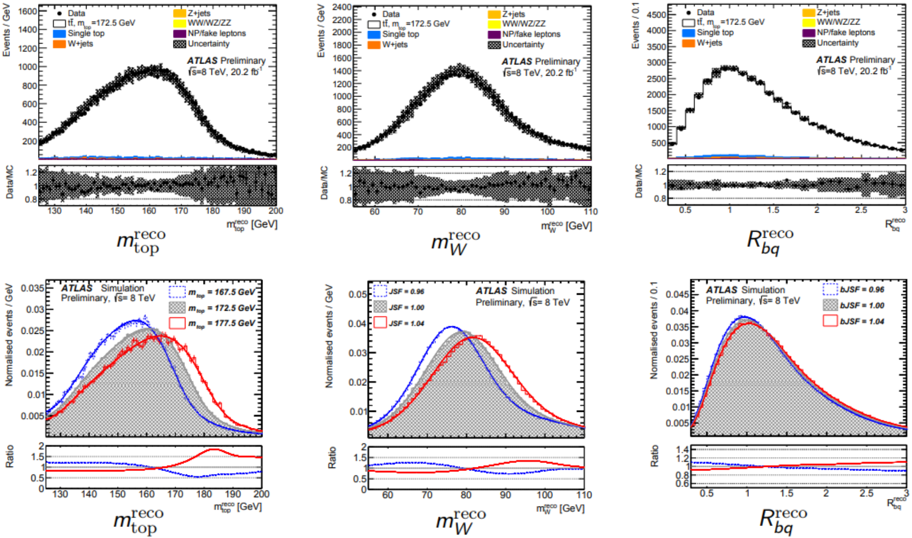
Consider separately 0,1,2 b-tags events, 2D fit (M_{top}, JES) template fit on 3 distribution

M_{bjj}^{reco}, $M_{bjj}^{reco,2^{nd}\text{choice}}$ (takes into account combinatorics), M_{jj}

M_{bjj}^{reco} $M_{bjj}^{reco,2^{nd}\text{choice}}$ M_{jj}

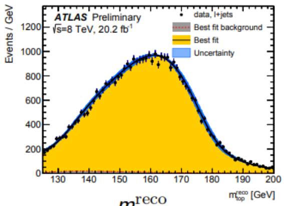


ATLAS lepton+jet: Template 3D [6]

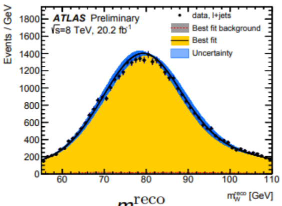


ATLAS lepton+jet: results (8 TeV) [6]

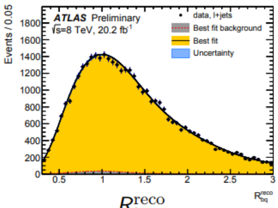
$m_{\rm top} = 172.08 \pm 0.39(\text{stat})$ GeV JSF $= 1.005 \pm 0.001(\text{stat})$ bJSF $= 1.008 \pm 0.005(\text{stat})$



$m_{\rm top}^{\rm reco}$



$m_W^{\rm reco}$

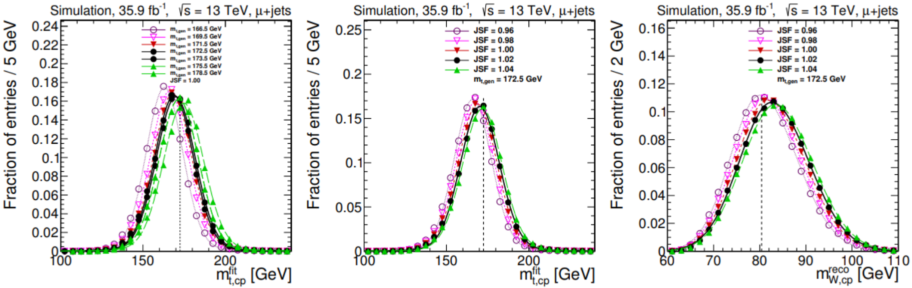


$R_{bq}^{\rm reco}$

$$M_{top} = 172.08 \pm 0.39 \pm 0.82\ \text{GeV} = 172.08 \pm 0.91\ \text{GeV}$$

main systematics: JES (0.54 GeV), b-tagging (0.38 GeV)

- Build a event likelihood based on templates derived from MC (Ideograms)
  - build templates for M_{top}, M_W, and background for different M_{top} (7), JES(5)
  - consider separately templates for correct permutation and wrong permutation, based on MC jet-parton match;
- loop over all permutations;
- kinematic fit to tt-hypothesis
  - use goodness-of-fit to cut and as a weight
- Simultaneous fit of M_{top} and JES

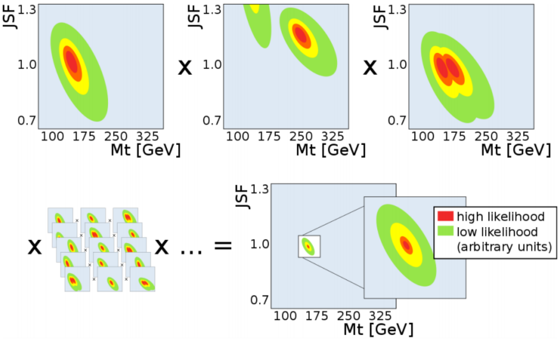


Ideogram Method Likelihood

$\mathcal{L}$ fit for every event $(M_{top}^{k.fit}, M_W^{reco})$ to 2D (M_{top}, JES) templates from simulation.

$$\mathcal{L}(M_{top}, JES|ev) \sim \mathcal{L}(ev|M_{top}, JES) = \prod_{ev} \mathcal{L}(M_{top}^{k.fit}, M_W^{reco}|M_{top}, JES)$$

$$\mathcal{L}(M_{top}^{k.fit}, M_W^{reco}|M_{top}, JES) = \sum_{j \in permutation} f_j P_j(M_{top}^{k.fit}|M_{top}, JES) \times P_j(M_W^{reco}|M_{top}, JES)$$



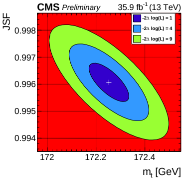
Complication for correct and wrong permutations, background.

Ideogram Results: semi-leptonic [7]

Type of Fit (Prior on JES)

- **1D** $\mathcal{L}(sample|M_{top}, JES = 1)$
- **2D** $\mathcal{L}(sample|M_{top}, JES)$ JES free
- **Hybrid** $\mathcal{L}(sample|M_{top}, JES = 1)$ JES constrained from jet-energy uncertainties

Results:



$M_{top}^{1D} = 171.93 \pm 0.07(stat) \pm 1.09(syst)$ GeV

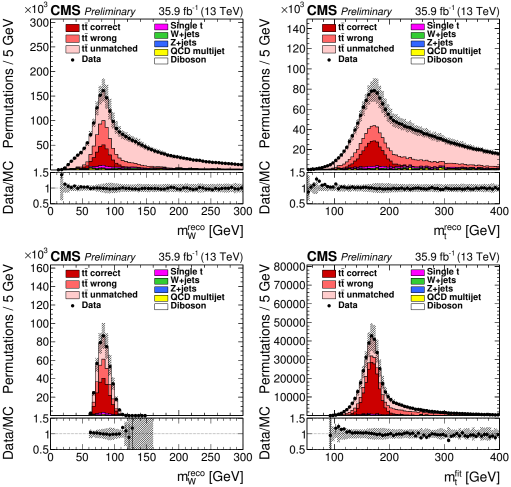
$M_{top}^{2D} = 172.40 \pm 0.09(stat + JES) \pm 0.68(syst)$ GeV

$\mathbf{M_{top}^{hyb} = 172.25 \pm 0.08(stat + JES) \pm 0.62(syst)}$ **GeV**

syst from ME generator, FSR, **color reconnection modelling**

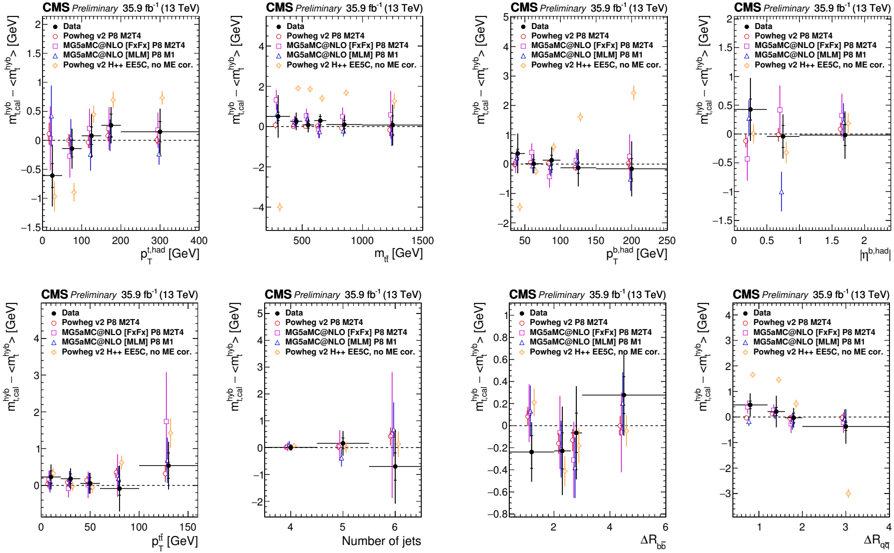
Most precise LHC results so far

M_{top} M_W before and after goodness-of-fit cut



M_{top} dependency on kinematic observables

test different modeling of color reconnections and generator (ME)



Matrix Element Method

Use all information from the event integrating over the least known variables

- Observables: measured momentum of jets and leptons **x**.
- Question: what is the most probable M_{top} given the set of observables **x**?
- Method: at parton level, we can compute the probability of having a set of pseudo-observables **y** (partons 4-momenta) given M_{top} (matrix element). But we observe **x** (jets and leptons), need to relate **x** to **y** (partons).

We have signal and background:

$$P_{ev}(x|M_{top}) = f_{top} P_{sgn}(x|M_{top}) + (1 - f_{top}) P_{bkg}(x)$$

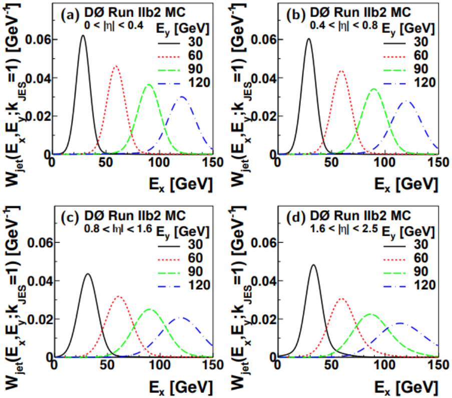
$P_{bkg}(x)$ depends on decay channel, $P_{sgn}(x|M_{top})$ is the key

$P_{sgn}(x|M_{top})$ is the probability to have a set of kinematical variable x for a given M_{top}.
Can be calculated event by event.

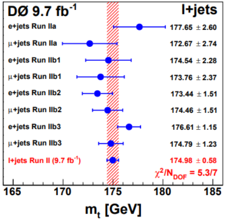
$$P_{sgn}(x|M_{top}) = \frac{1}{\sigma(M_{top})} \int d^n\sigma(y|M_{top}) dp_1 dp_2 f(p_1) f(p_2) W(x,y)$$

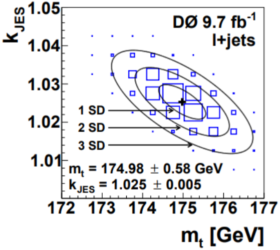
- $\frac{1}{\sigma(M_{top})}$ normalization: depends on M_{top}.
- $\int$ integrate over all unknown variables of initial state partons p_1, p_2 and final state partons y.
- $d^n\sigma(y|M_{top})$ contains the LO matrix element of the process at parton-level ($q\bar{q} \to t\bar{t}$ or $gg \to t\bar{t}$);
- $f(p)$ is PDF (parton density function)
- $W(x,y)$ is probability that parton-level y will be measured as a set of variables x
- To include also JES: $P_{sgn}(x|M_{top}, JES)$
  - use Bayes' theorem to get $P_{sgn}(M_{top}, JES|x)$ for each events
  - and then sum over all events $\Pi_i(P_{sgn}(M_{top}, JES|x_i))$

Transfer functions $W(x, y)$



Separate for b-jets and b-jets with μ inside

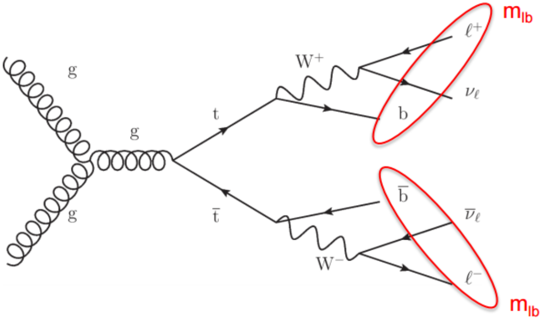


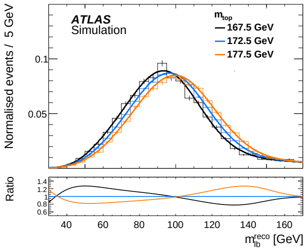


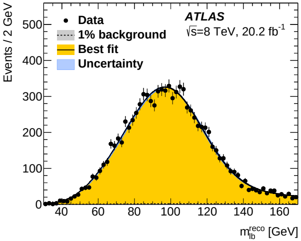
$$M_{top} = 174.98 \pm 0.58(stat + JES) \pm 0.49(syst) \text{ GeV}$$
$$= 174.98 \pm 0.76 \text{ GeV}$$

main systematics:
residual JES (0.21 GeV), hadronization (0.26 GeV)

- very clean signal, almost no background
- but not possible full event reconstruction
- Template method on $M_{\ell b}$
- correct match (ℓb from same *top*) as well as wrong match (25%)





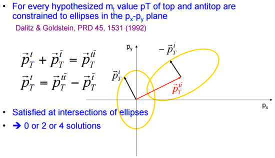


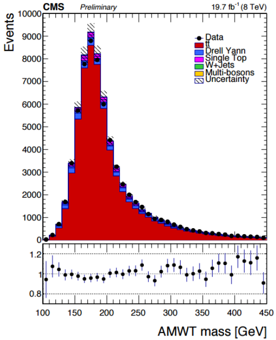
$M_{top} = 172.99 \pm 0.41 \pm 0.74$ GeV $= 172.99 \pm 0.84$ GeV syst uncert from b-JES

Analytical Matrix Weighting Technique (CMS) [10] [CDF did something similar]

- Assume pure $t\bar{t}$ signal;
- kin-fit underconstrained
  - $2\nu \times 3 = 6$ variables
  - $p_x = 0 = p_y$, $M(\ell\bar{\nu}) = M(\bar{\ell}\nu) = M_W$, $M_t = M_{\bar{t}}$: 5 constraints
- scan over possible M_{top};
- for each M_{top} we have 0,2, or 4 solutions (intersection of two ellipses), plus permutation $(2b, 2\ell)$;
- for each solution build a weight taking into account the LO matrix element
- take M_{top} corresponding to highest $\sum w$: M_{AMWT}
- likelihood fit to extract mass;

$M_{top} = 172.8 \pm 0.2 \pm 1.2\ GeV$ (syst dominated by JES)



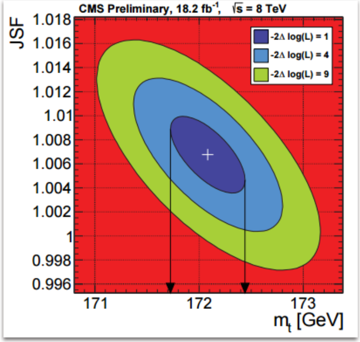


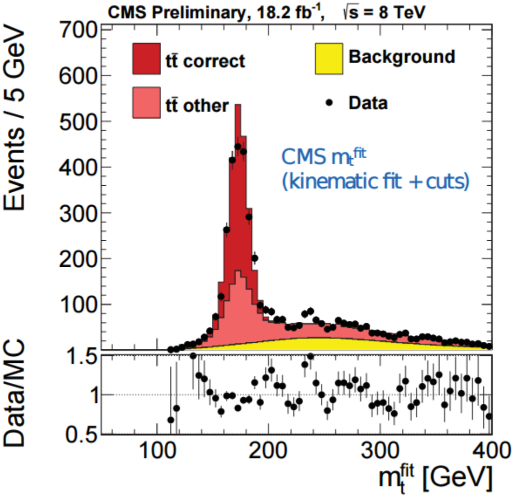
Full hadronic

- Large background;
- not trivial to trigger (no lepton, purely jet-like, high threshold);
- independent data sample;
- no MET, no dependence on MET modelling;
- full reconstruction but large combinatorics;
- color reconnections;
- JES, bJES,...
  - Ideogram 1D (M_{top}) and 2D (M_{top} + JSF) or Hybrid (JSF gaussian constraint)
    - different weight for correct/uncorrect combinations
  - Template fit from $R_{3/2} = M(bjj)/M(jj)$

CMS Ideogram method 2D at 8 TeV

- Selected objects:
  - ≥ 4 light jets, 2 b-tagged jets
- Same methods as l+jet (2D fit)
  - bJES (0.36), signal modelling (0.29 GeV)
  - $JSF - 1 = +0.7 \pm 1.1\%$ (syst.+stat.)
- Purity 78% with narrow signal peak
  - cut on goodness-of-fit + $\Delta R(b,b) > 2.0$





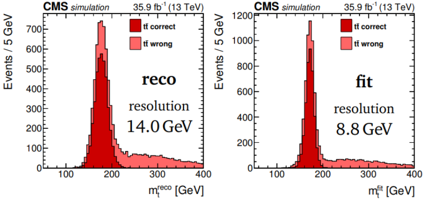
$m_t = 172.1 \pm 0.4(\text{stat}) \pm 0.8(\text{syst})$ GeV

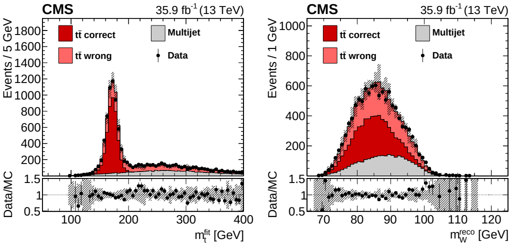
CMS-PAS-TOP-14-002 (Jul '14)

CMS Ideogram method 2D at 13 TeV [11]

- trigger:
  - $HT > 450$ GeV (scalar sum of hadronic energy in event)
  - $N \geq 6$ jets ($p_T > 40$ GeV)
  - $N \geq 1$ jets b-tagged
- selection:
  - 6 Jets
  - 2 b-tagged
  - $p_T(jets) > 40$ GeV
  - $\Delta R(b\bar{b}) > 2.0$

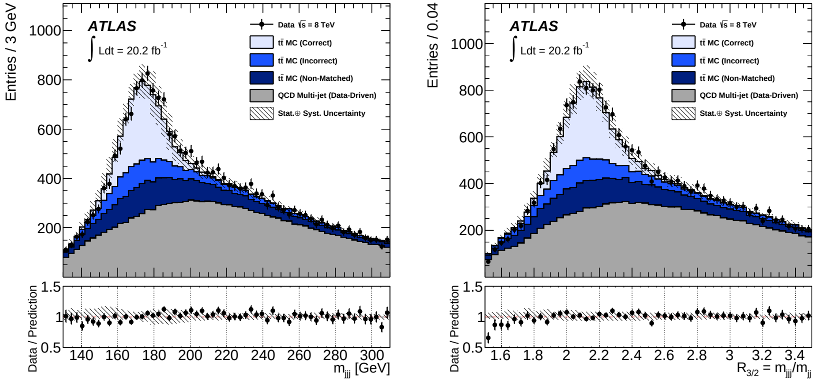
- kin-fit: $M_{W^+} = M_{W^-} = M_W(PDG)$ and $M_t = M_{\bar{t}}$
- large combinatorics! Select best χ^2 of kin-fit





- Ideogram fit (1D, 2D, hybrid)
- $M_{top} = 172.34 \pm 0.20(stat + JSF) \pm 0.76(syst)$ GeV
- syst from Color Reconnection, bJet correction

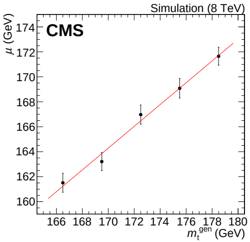
- All hadronic final states.
- Use the $R_{3/2}$ distribution as the estimator for M_{top} instead of m_{jjj}
  - More protected from JES variation: $R_{3/2} = \frac{m_{bjj}}{m_{jj}} \propto \frac{JES \cdot bJES}{JES}$

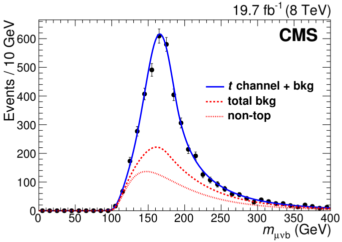


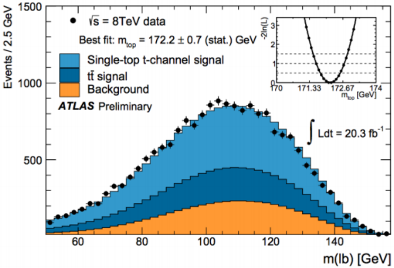
$$M_{top} = 173.72 \pm 0.55 \pm 1.01 \ GeV$$

Method:

- decay channel: $t \to bW \to \mu\nu$.
- production: mostly t-channel
- Requires: $1\mu^+$ $(\sigma_t > \sigma_{\bar{t}})$, MET, 1 b-jet (plus other forward jet $|\eta_j| > 2.5$ - associated prod-).
- Template method on $M_{\mu\nu b}$ or $M_{\ell b}$







Results:

CMS [13]

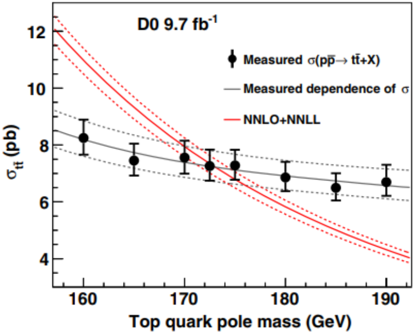
$$M_{top} = 172.95 \pm 0.77^{+0.97}_{-0.93}\ \text{GeV} = 172.95 \pm 1.24\ \text{GeV}$$

syst: JES (0.68 GeV), bkgn (0.39 GeV), fit (0.39 GeV)

ATLAS [14] $M_{top} = 172.2 \pm 0.7 \pm 2.0$ GeV

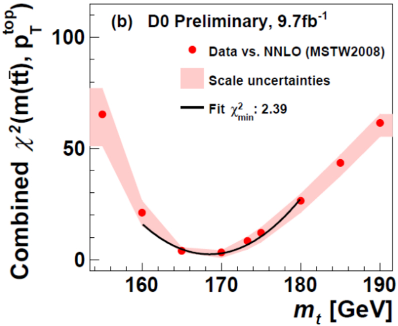
D0: Pole mass M_{top} measurements

- Indirect pole mass measurement can be extracted from a x-section measurement, total or differential.
- Compare $\sigma_{t\bar{t}}$ with NNLO+NNLL prediction [15] a function of MC M_{top}.
  - in semi-leptonic and di-leptonic channels
- the fit to extract the σ is based on a signal which depends on M_{top}^{MC}
  - so we measure σ for different M_{top}^{MC}.



$M_{top}^{pole} = 172.8 \pm 1.1(th)^{+3.3}_{-3.1}$ GeV

Or from differential $\sigma_{t\bar{t}}(p_T)$

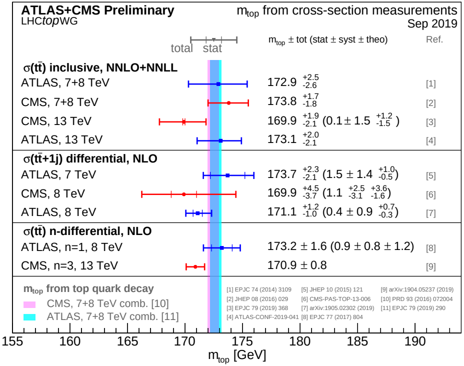


$M_{top}^{pole} = 169.1 \pm 2.5(total)$ GeV

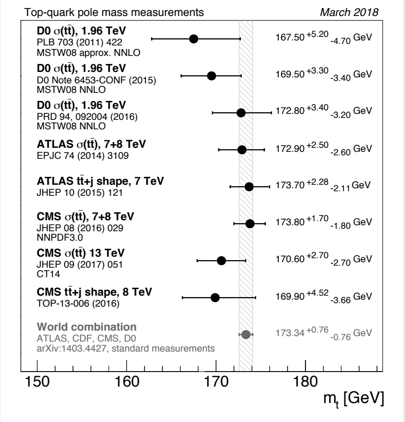
Pole mass M_{top} measurements at LHC

ATLAS [16, 17, 18], CMS [19, 20, 21]

- Inclusive $\sigma_{t\bar{t}}$ 7+8+13 TeV
- $\sigma_{t\bar{t}+jet}$ 7+8 TeV
- Differential vs $p_T^{\ell}, p_T^{\ell\ell}, m_{e\mu}, \ldots$ for $t\bar{t} \to e\mu + X$ events 8+13 TeV



Summary (march 2018, last meas. from CMS [21] not included)



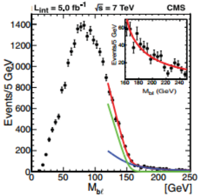
$$M_{top}^{pole} = 173.34 \pm 0.76\ \text{GeV}$$

Incomplete list of M_{top} measurements technique

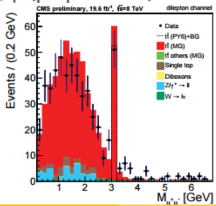
- Extract M_{top} in well defined renormalization schema, eg via template method
- Observables/final states sensitive to different systematic uncertainties:
- in particular, less sensitive to JES and bJES.
  - **dilepton channel**
    - End Point [22];
    - $M_{T2}/MAOS$ [23];
    - M_{lb} [24];
    - bJet Energy (E_b) [25];
    - dilepton p_T [26]
  - **lepton+jets channel**
    - boosted top: e/μ+jets [27];
    - Bi-Event Subtraction Technique (BEST) [28]
  - **dilepton and lepton+jets channels**
    - B-hadron lifetime [29];
    - lepton + Secondary Vertex Mass [30];
    - lepton+$b \to J/\psi$ exclusive decay[31];

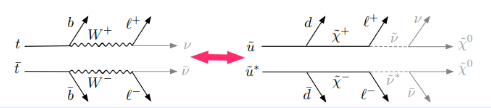
B-hadron lifetime

Kinematic endpoints



b→J/ψ (propaedeutic)





- Using di-lepton decays, usual selections;
- possibly sensitive to DM candidates (WIMPS) (not really)
- basic idea similar to $M_T =$ in $W \to \ell\nu$ decay:
  - $M_T^2 = m_\nu^2 + m_\ell^2 + 2(E_T^\nu E_T^\ell - \vec{p}_T^\nu \vec{p}_T^\ell)$
  - where $\vec{p}_T^\ell = \vec{p}_T^{miss}$
  - $M_T \leq M_W$ always. For each event not so important, but for an ensamble of events the endpoint is sensitive to M_W
- based on $M_{T2}(p_T^\ell, p_T^b, p_T^{miss})$ using "min-max" strategy for two identical decay chain
  - It is always true $\max(M_T^a, M_T^b) \leq M_{top}$.
  - but $\vec{p_\nu}_T^{a,b}$ cannot be know separately, only the sum $\vec{p_\nu}_T^a + \vec{p_\nu}_T^b$
  - consider all possible partition such that $\vec{p_\nu}_T^a + \vec{p_\nu}_T^b = \vec{p}_T^{miss}$ and take the minimum.
  - sensitive to minimum parent mass M consistent with observed event kinematics

$$M_{T2} = \min_{\vec{p_\nu}_T^a + \vec{p_\nu}_T^b = \vec{p}_T^{miss}} \left(\max\{M_T^a, M_T^b\} \right)$$

  - M_{T2} endpoint is related to the unseen parent mass (ν or WIMPS)

Observables and results

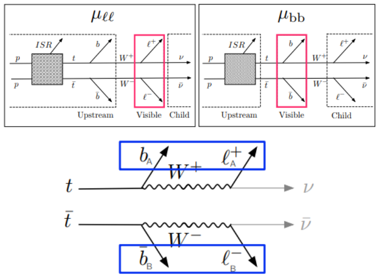
Three observables can be used to extract three masses M_{top}, M_W, and $M_{\nu,WIMP}$

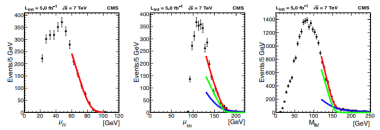
- $\mu_{\ell\ell}$
  - considering the $W^{\pm}$ decays only, and the ν as lost child particles;
  - $\mu_{\ell\ell}^{max} \propto M_W$
- μ_{bb}
  - considering the $t\bar{t}$ decays only, and considering $W^{\pm}$ as lost child particles;
  - $\mu_{bb}^{max} \propto M_{top}$
  - sensitive to JES
- M_{bl}
  - third variables
  - $M_{bl} = \sqrt{(p_b + p_\ell)^2}$
  - combinatorial problem: which b goes with wich ℓ?
  - $M_{bl}^{max} \sim \sqrt{M_{top}^2 - M_W^2} \sim 153\,\text{GeV}$

$$\text{Results: } m_\nu^2 = -556 \pm 473 \pm 622\,\text{GeV},$$

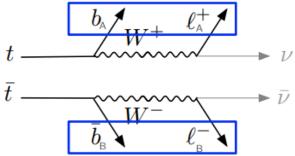
$$M_{top} = 173.9 \pm 0.9(stat)^{+1.7}_{-2.1}(syst)\,\text{GeV [22]}$$

syst from JES



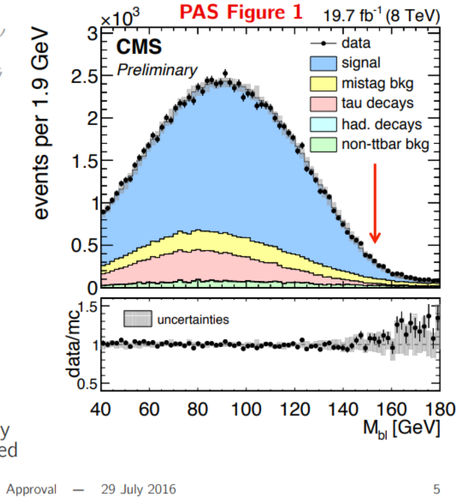


Observables: M_{bl}

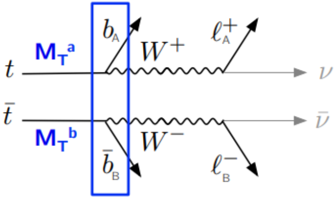


$$M^2_{b\ell} = (p_b + p_\ell)^2$$

- Invariant mass of **b jet, lepton pairs**.
- **Kinematic endpoint** at $[M_t^2 - M_W^2]^{1/2} \sim 153$ GeV.
- We use an algorithm for selecting bl pairs.
  - 2 or 3 pairs are chosen for each event.
  - Pairs are not necessarily "correct", but guaranteed to fall below the kinematic endpoint.



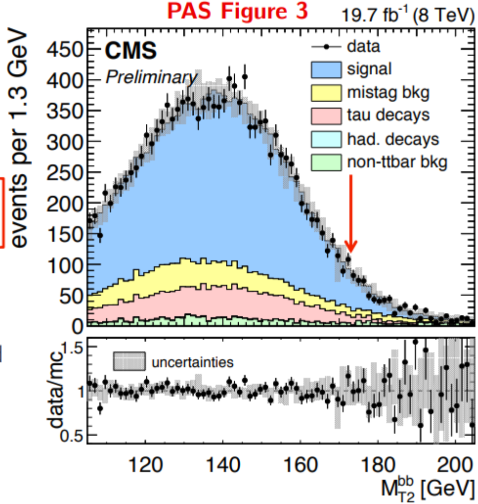
Observables: M_{T2}^{bb}



$$M_{T2} = \min_{\vec{p}_T^{\,a}+\vec{p}_T^{\,b}=\vec{p}_T^{\,miss}} \left[\max\{M_T^a, M_T^b\}\right]$$

- M_{T2} is the **minimum parent mass consistent with the observed kinematics**.
  - Minimization conducted over neutrino p_T values.
- M_{T2}^{bb} uses **two b jets** as the visible system.
  - W bosons are treated as invisible particles.
- **Kinematic endpoint** at M_t.

PAS Figure 3

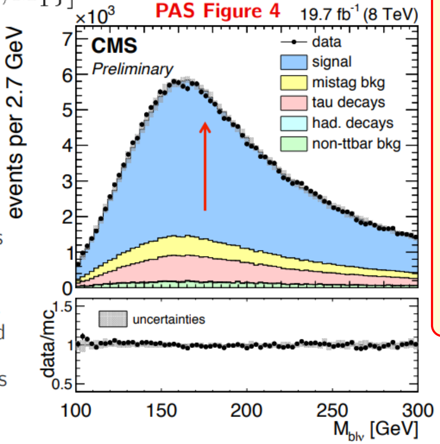


Observables: MAOS $M_{bl\nu}$

M$_{T2}$-**A**ssisted **O**n-**S**hell reconstruction technique

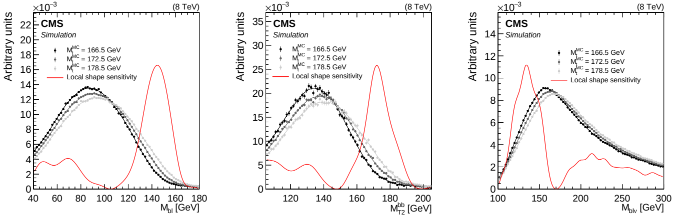
$$M_{T2} = \min_{\vec{p}_T^{\,a}+\vec{p}_T^{\,b}=\vec{p}_T^{\,miss}} \left[\max\{M_T^a, M_T^b\}\right]$$

- Utilizes **neutrino p_T estimates** output by the **M_{T2}^{ll} algorithm**.
  - Takes leptons as the visible system.
- Applies **W mass on-shell constraint** to get neutrino p_z values.
  - Quadratic equation yields 2 solutions for each neutrino p_z.
  - 2 leptons x 2 bl matches.
  - **8 values of $M_{bl\nu}$** are used for each event.
- MAOS $M_{bl\nu}$ distribution contains a **peak near M_t**.

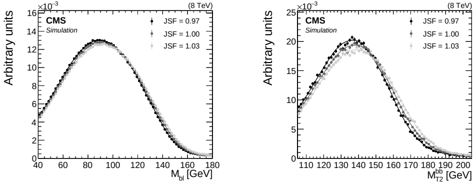


- MAOS $M^{b\ell\nu}$
- $b\ell\nu$ inv mass
- the neutrino p_T is obtained, event per event, as the results of minimization of $M_{T2}^{\ell\ell}$
  - $M_{T2}^{\ell\ell}$ sensitive to M_W
  - equivalent to assume null neutrino masses
- applies M_W constraint to get p_ν^z
- 8-fold ambiguities
- peaked around M_{top}
- not very sensitive to JES ($M_{T2}^{\ell\ell}$)

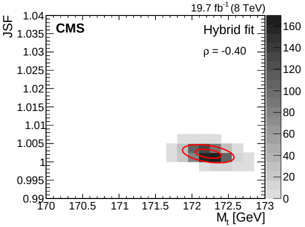
$M_{b\ell}$, M_{T2}^{bb}, and MAOS $M^{b\ell\nu}$ dependence on M_{top} and sensitivity

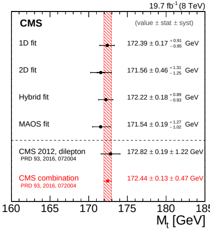


Sensitivity to Jet Scale Factor



fit: 1D (only M_{top}), 2D (M_{top} and JES) hybrid 1/2D linearly combined

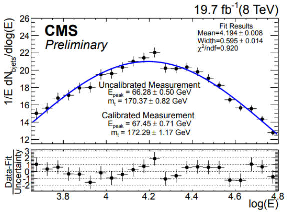


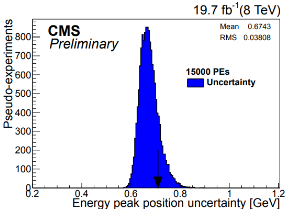


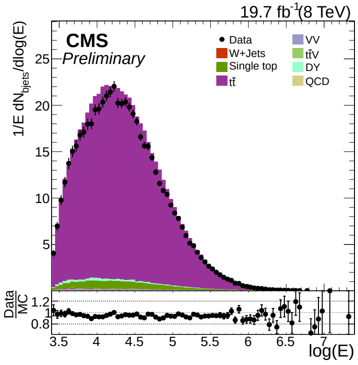
$$M_{top} = 172.22 \pm 0.18^{+0.89}_{-0.93}\ \text{GeV}$$

- Di lepton channels: $e + \mu$
- top produces W on-shell, so
  $m_t = E_b^{rest} + \sqrt{m_W^2 - m_b^2 + {E_b^{rest}}^2}$
- measure of b-quark energy in the top rest frame E_b^{rest} and get M_{top}
- possible if assume top to be unpolarized

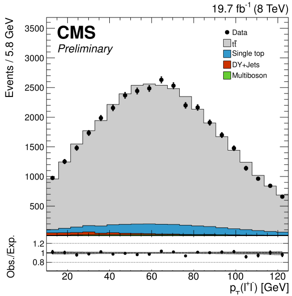
$M_{top} = 172.29 \pm 1.17(stat) \pm 2.66(syst)$ GeV

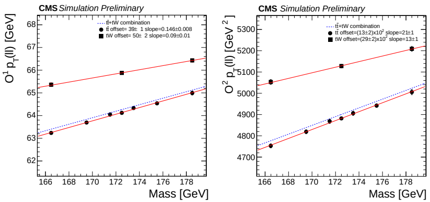






- Di lepton channels: $e + \mu$
- using only leptonic observables not sensitive to JES/bJES systematics
- Using $p_T(\ell^+\ell^-)$ as observable
- compute first and second moment of $p_T(\ell^+\ell^-)$ distribution $O^{(1,2)}$, also from shape analysis
- $O^{(1,2)}$ sensitive to M_{top} (and production mechanism: $t\bar{t}$, tW)



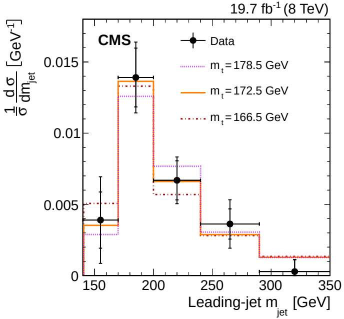


$$M_{top} = 171.7 \pm 1.1(stat) \pm 0.5(exp) \pm 3.0(th)^{+0.8}_{-0.0}(p_T(top))\ \text{GeV}$$

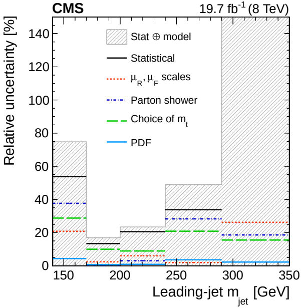
syst dominated by theo uncertainties on modeling

- Selection is: 1 e/μ, ≥ 2 narrow jets, ≥ 2 fat jets, MET
- top boost is such that the $W \to jj$ decay is not resolved into two different jet, but in a "fat" one.
- Sensitive quantity is the fat jet mass

differential σ



uncertaities

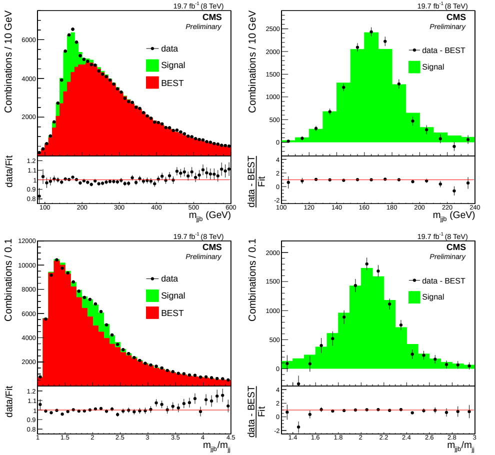


$M_{top} = 170.8 \pm 6.0(stat) \pm 2.8(syst) \pm 4.6(model) \pm 4.0(th)$ GeV $= 170.8 \pm 9.0$ GeV

Not yet competitive: need more data, better modelling, and higher order calculations

M_{top} Bi-Event Subtraction Technique (BEST) assisted [28]

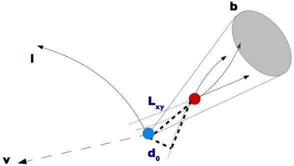
- Measurement is based on semileptonic events, using M_{jjb} and $R_{3/2} = M_{jjb}/M_{jj}$ observables
- BEST is a data-driven background-estimation technique, originally developed for squark searchs in SUSY
- Basic idea is to mix jets from different events to estimate combinatorial background.
- Template fit on M_{jjb} and $R_{3/2}$ to extract M_{top}

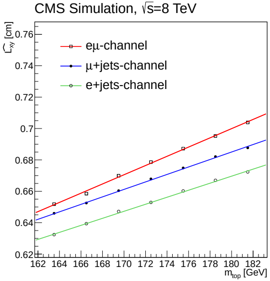


$M_{top} = 171.61 \pm 0.57(stat) \pm 0.90(syst)$ GeV

syst dominated by JES for m_{bjj} and background (BEST)/model/p_T(top) for $R_{3/2}$

- $t \to Wb$: in the top rest frame, the b momentum is linearly dependent on top mass $p \approx 0.4 M_{top}$
- the (transverse) decay lenght of the b depends on b boost $\gamma_b \sim 0.4(M_{top}/M_b)$
- $L_{xy} = \gamma_b \beta_b c\tau_b \sim 0.4 M_{top}/M_b \beta_b c\tau_b$
- given $c\tau_b \sim 500\mu m$, $M_{top}/M_b \sim 34.5$:
- $\Delta L_{xy}/M_{top} \sim 50\mu m/GeV$
- Template method based on L_{xy} (median)
  - Statitstics is high
  - no jet-related measurement
  - main syst: top $p_T$modelling, b-fragmentation and hadronization
- still a long way to go...





$M_{top} = 173.5 \pm 1.5(stat) \pm 1.3(syst) \pm 2.6(top\ p_T)$ GeV

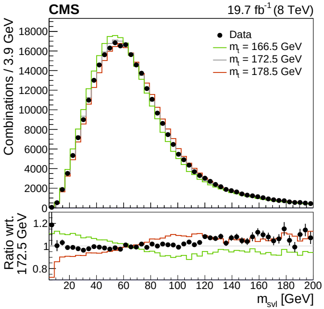
Channel	Median L_{xy} [cm] Data	MC	MC (signal only)
muon+jets	0.6690 ± 0.0013	0.6679 ± 0.0004	0.7173 ± 0.0004
electron+jets	0.6536 ± 0.0013	0.6529 ± 0.0004	0.7177 ± 0.0004
electron-muon	0.682 ± 0.004	0.6789 ± 0.0003	0.6840 ± 0.0002

Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$

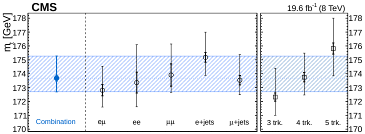
- Semi or full-leptonic $t \to W(\to \ell\nu)b$ decay;
  - different categories SL $e + jets$, $\mu + jets$ and FL ee, $e\mu$, $\mu\mu$
- b decay produces a secondary vertex displaced wrt primary and reconstructed;
- M_{top} sensitive variable is the invariant mass $M_{sv\ell}$:
  - ℓ from W
  - the secondary vertex tracks
- it is similar to the $\ell + J/\psi$ method (next slide)
- much larger statistics (inclusive vs esclusive b decay)
- does not relies on jet reconstruction so no JES scale issue

$$M_{top} = 173.68 \pm 0.20^{+1.58}_{-0.97}\ \mathrm{GeV}$$

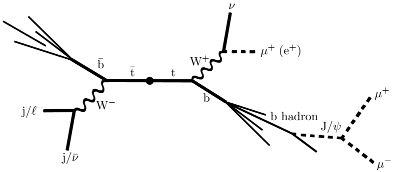
syst dominated: b-quark fragmentation, top $p_T$modelling, $\sigma(t\bar{t} + HF)$, ME, ℓ energy scale, SV modelling ...



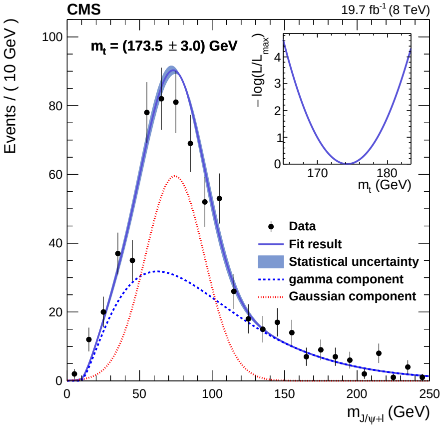
Different final states and num tracks categories considered:



- Decay channel is:
  $t \to W(\to \ell\nu)b \to (J/\psi(\to \mu\mu) + X)$
  - $\mathcal{B}(W \to \ell\nu) \sim N_\ell \cdot 10\%$
  - $\mathcal{B}(B \to J/\psi X) \sim 0.1\%$
  - $\mathcal{B}(J/\psi \to \mu\mu) \sim 6\%$



- double and single top production
- Limited statistics (666 ev in 19.7 fb^{-1})
- Template method based on $M(J/\psi + \ell)$
  - Purely leptonic quantities
  - no jet related ones! (JES, bJES, etc)

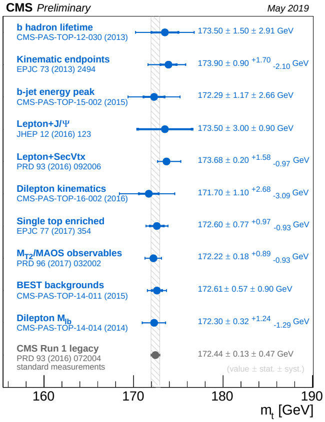


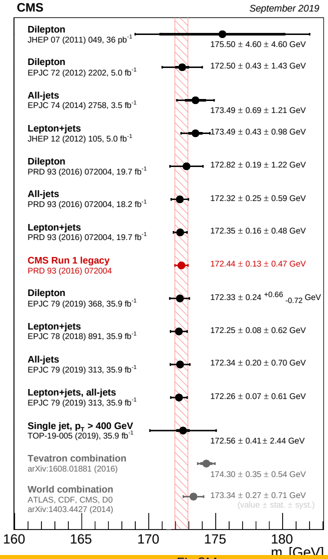
$M_{top} = 173.5 \pm 3.0 \pm 0.9$ GeV
Limited statitics, top $p_T$modelling and QCD scales

CMS: alternative M_{top} measurement summary

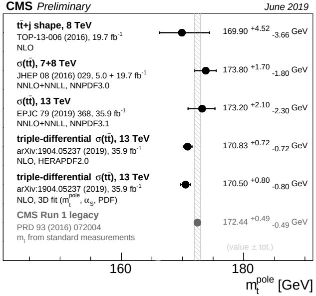
Standard

Alternative





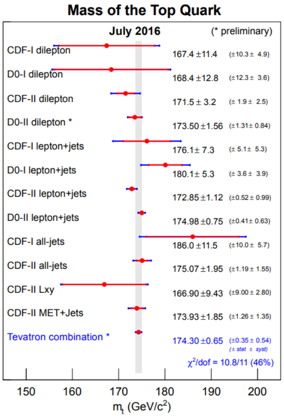
M_{pole}



Alternative techniques are competitive with standard ones
multi-differntial pole measurement also
Different systematics, important cross check

Summary of M_{top} measurement

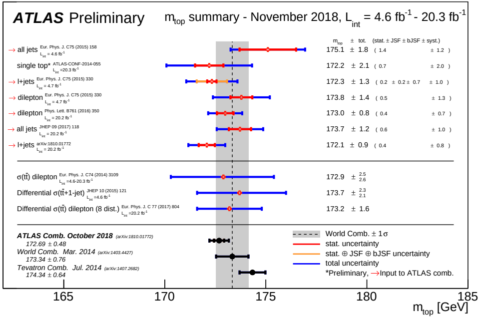
Tevatron



$174.30 \pm 0.35 \pm 0.54$ *GeV*

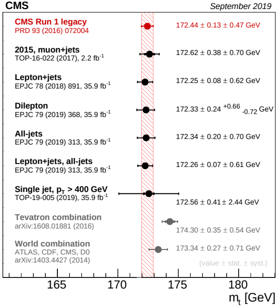
ATLAS

Run I+II combination (2018)



172.69 ± 0.48 GeV

CMS

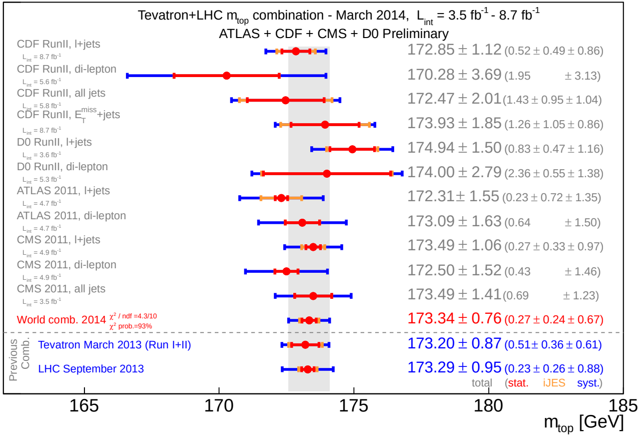


Run I combination (2016)

$172.44 \pm 0.13 \pm 0.47$ *GeV*

Weighted avg (uncorrelated):
172.38 ± 0.23 GeV

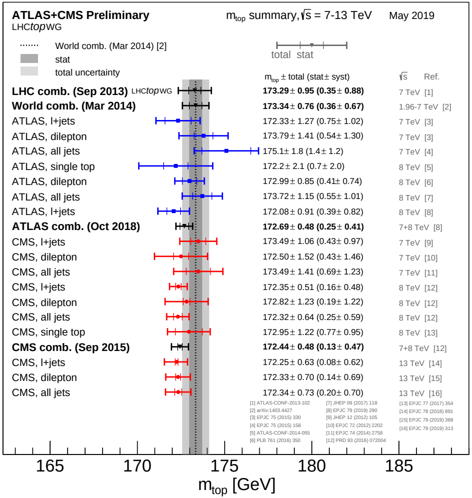
Summary of M_{top} measurement



World combination (2014): $M_{top} = 173.34 \pm 0.27 \pm 0.71$ GeV

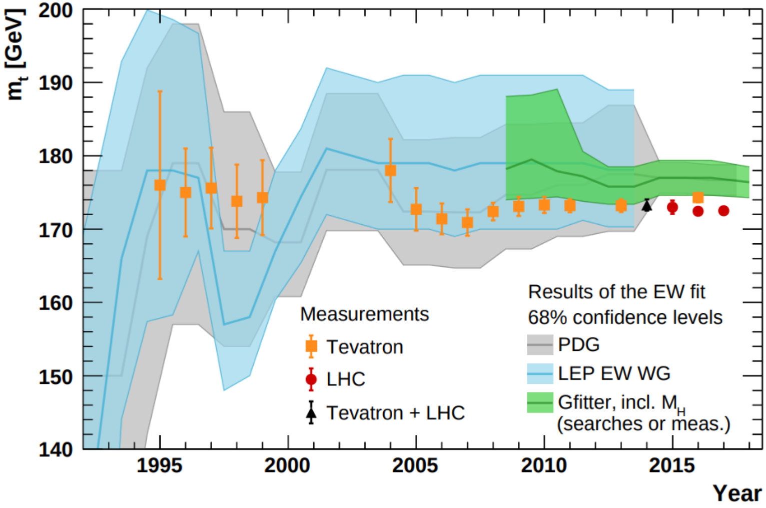
PDG (2020): $M_{top} = 172.9 \pm 0.4$ GeV (PDG combination)

Summary of M_{top} measurement

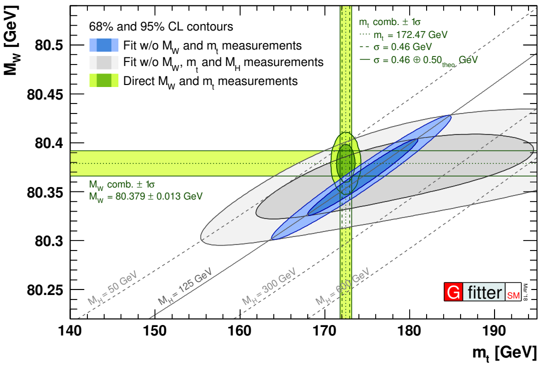


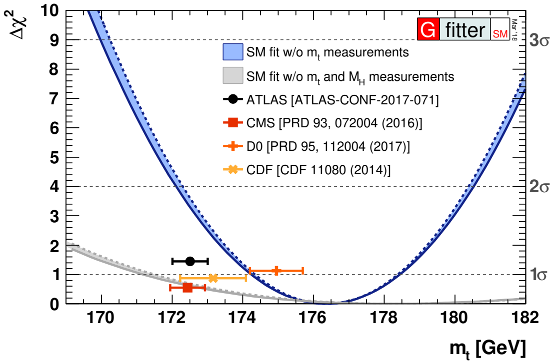
Many new measurement available, no world combination update yet. ATLAS in 2018, CMS in 2015

History of M_{top}: measuremnt, prediction, and SM global fit



Global EWK fit for M_W and M_{top}





Outline

Outline

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