Top quark mass measurements at CMS

38th International Conference on High Energy Physics

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on behalf of the CMS collaboration

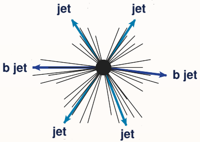
August 6, 2016

"Standard" measurements

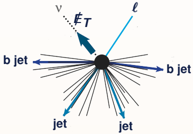
PRD 93(2016)2004

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

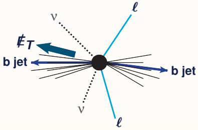
all-jets



lepton+jets



dilepton



- Using the ideogram method after a kinematic fit
- Simultaneously measuring m_{t} and JSF, assuming that JSF is normally distributed with 1 as expected value and the JEC uncertainty as standard deviation

- Using the analytical matrix weighting technique
- Reconstructing each event 500 times, varying the jet p_{T} with a Gaussian distribution whose standard deviation is the JEC uncertainty

all-jets: $m_{\mathrm{t}} = 172.32 \pm 0.25(\mathrm{stat}) \pm 0.59(\mathrm{syst})$ GeV
JSF $= 1.002 \pm 0.001$

lepton+jets: $m_{\mathrm{t}} = 172.35 \pm 0.16(\mathrm{stat}) \pm 0.48(\mathrm{syst})$ GeV
JSF $= 1.002 \pm 0.001$

dilepton: $m_{\mathrm{t}} = 172.82 \pm 0.19(\mathrm{stat}) \pm 1.22(\mathrm{syst})$ GeV

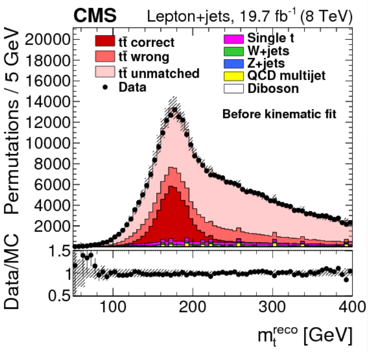
Resolution on m_t

PRD 93(2016)2004

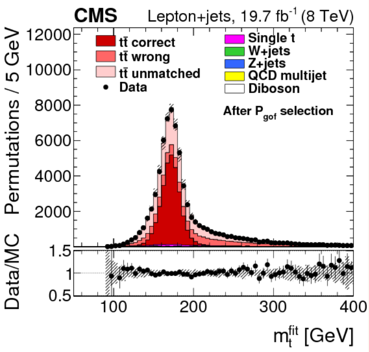
$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}

Assigning to each event a weight reflecting the probability that the parton/jets permutations are correct to improve the resolution on m_t

Before kinematic fit



After kinematic fit



Combination of the "standard" measurements

PRD 93(2016)2004

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

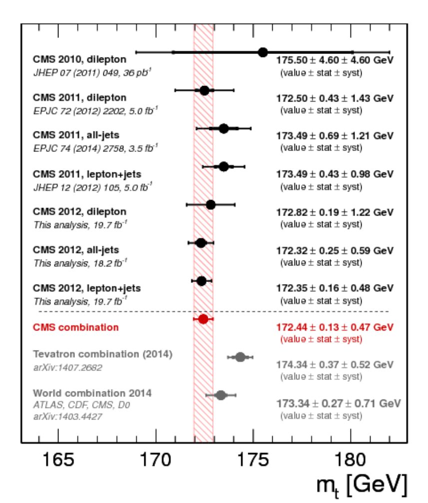
- Using the Best Linear Unbiased Estimate (BLUE) method
- Main systematic uncertainties
  - hadronization ~ 0.35 GeV
  - jet energy corrections ~ 0.15 GeV
  - hard-process scattering ~ 0.15 GeV

$\hookrightarrow$ correlated between measurements

- Combination result:

$$m_t = 172.44 \pm 0.13\,(\text{stat}) \pm 0.47\,(\text{syst})\ \text{GeV}$$

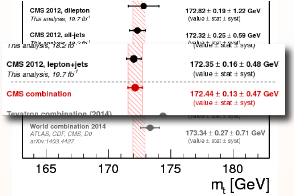
$\hookrightarrow$ total uncertainty $< 0.3\%$



How to further reduce the uncertainty ?

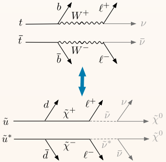
"Standard" measurements

- exploiting full kinematics of $t\bar{t}$ events
- Monte Carlo calibrated
- leading to precision better than 0.3%
- hitting a wall of systematic uncertainties



Where to search ?

- more constraints from data in $t\bar{t}$ event modeling (underlying event, color reconnection, fragmentation. . .)
  $\hookrightarrow$ some hints in backup
- "alternative" measurements
  $\hookrightarrow$ *alternative systematic sensitivity and/or better defined top quark mass*
  - alternative event topologies
  - alternative observables:
    - using theoretically-calculable observables
    - only partially exploiting $t\bar{t}$ event kinematic
    - using techniques from New Physics searches

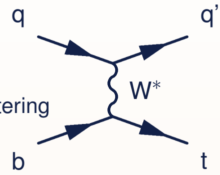


m_t from single-top events

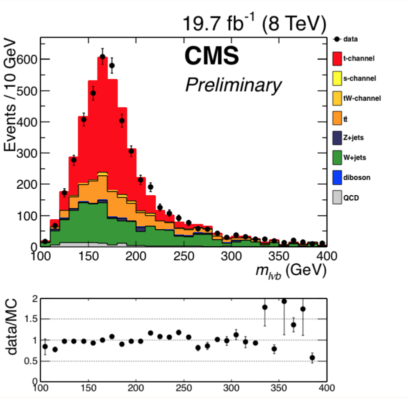
CMS PAS TOP-15-001 (2016)

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

- Electroweak process:
  - different CR
  - different hard scattering
  - different PDFs



- Enriched sample in t-channel single top events (71%)
  $\hookrightarrow$ 1 isolated μ, 1 b-tagged jet, E_T^{miss},
  1 light jet with $|\eta| > 2.5$
- Extraction of m_t from $m_{\ell\nu b}$
  $\hookrightarrow$ Monte Carlo based calibration
- Main sources of systematic uncertainties:
  JEC, background calculations, fit calibration
  ~ 0.65 GeV ~ 0.40 GeV ~ 0.40 GeV



$$m_t = 172.60 \pm 0.77\,(\text{stat})^{+0.97}_{-0.93}\,(\text{syst})\ \text{GeV}$$

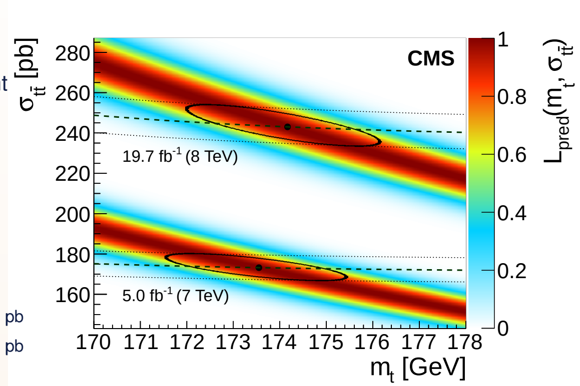
m_t from the $t\bar{t}$ cross section

arXiv:1603.02303 (2016)

$\sqrt{s} = 7$ TeV, $\mathcal{L} = 5.0$ fb^{-1}
$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}

- Dilepton $e^{\pm}\mu^{\mp}$ channel
- Constraining $\alpha_s(m_Z)$ to the current world average
- Computing the expected $\sigma_{t\bar{t}}$ at NNLO+NNLL with TOP++
- $\sigma_{t\bar{t}}$ measurement limited by luminosity uncertainty

$\sigma_{t\bar{t}}(7\text{ TeV}) = 173.6 \pm 2.1(\text{stat})^{+4.5}_{-4.0}(\text{syst}) \pm 3.8(\text{lumi})$ pb
$\sigma_{t\bar{t}}(8\text{ TeV}) = 244.9 \pm 1.4(\text{stat})^{+6.3}_{-5.5}(\text{syst}) \pm 6.4(\text{lumi})$ pb



$$m_t^{pole} = 173.8^{+1.7}_{-1.8} \text{ GeV}$$

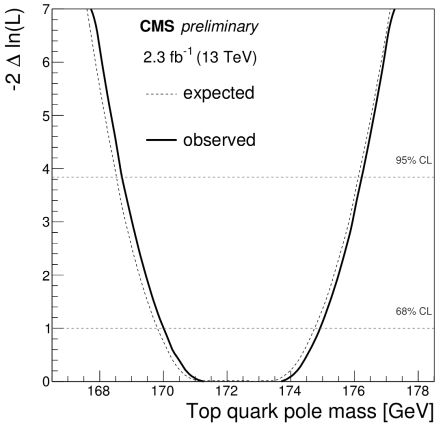
m_t from the $t\bar{t}$ cross section

CMS PAS TOP-16-006 (2016)

$\sqrt{s} = 13$ TeV, $\mathcal{L} = 2.3$ fb^{-1}

- Lepton+jets channel
- Constraining $\alpha_s(m_Z)$ to the current world average
- Computing the expected $\sigma_{t\bar{t}}$ at NNLO+NNLL with TOP++
- $\sigma_{t\bar{t}}$ measurement limited by luminosity uncertainty

$\sigma_{t\bar{t}} = 834.6 \pm 2.5(\text{stat}) \pm 22.8(\text{syst}) \pm 22.5(\text{lumi})$ pb



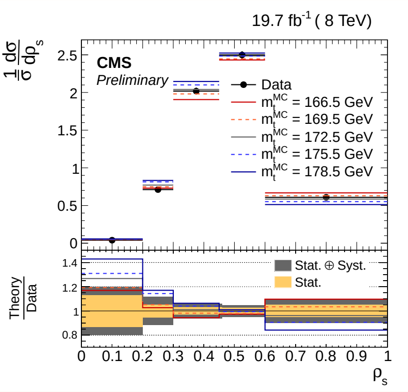
$$m_t^{\text{pole}} = 172.5^{+2.7}_{-2.3}\ \text{GeV}$$

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

CMS PAS TOP-13-006 (2016)

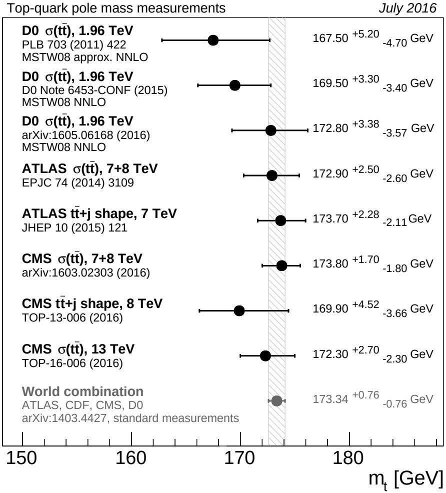
$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}

- Kinematic reconstruction of dileptonic $t\bar{t}$ events with additional hard jets ($p_T > 50$ GeV)
- Measuring the differential cross section wrt $\rho_S = 2 \times 170\ \text{GeV}/m(t\bar{t}+\text{jet})$
  ↪ unfolding at particle level in visible phase space with MadGraph+Pythia
- Comparing to the expected NLO cross section using Powheg+Pythia
- Main systematic uncertainties:
  - Powheg $t\bar{t}$+jet modeling ~ 3.5 GeV
  - Ren. and fact. scales ~ 2.5 GeV
  - ME/PS matching ~ 1.5 GeV



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

m_t^{pole} vs MC-calibrated m_t measurements

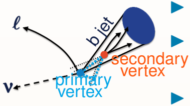


⇒ Compatibility between m_t^{pole} and MC-calibrated m_t measurements

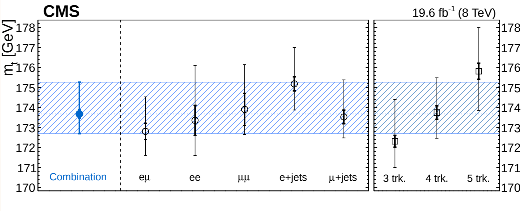
m_t from $m_{sv\ell}$

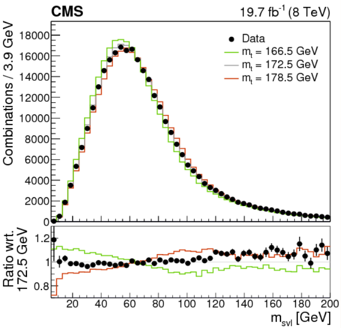
PRD 93(2016)2006

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



- Dilepton and lepton+jets channels
- Reconstruction of secondary vertices (sv) with 3, 4, and 5 tracks within jets
- Combined fit of 15 $m_{sv\ell}$ distributions





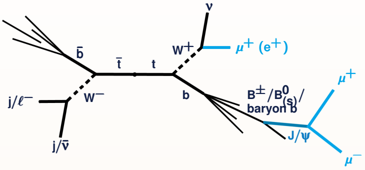
$$m_t = 173.68 \pm 0.20\ (\text{stat})^{+1.58}_{-0.97} (\text{syst})\ \text{GeV}$$

- Systematic uncertainties:
  - Main sources: b quark fragmentation, $p_T(t)$, and ME generator
    ~ 1 GeV ~ 0.8 GeV ~ 0.4 GeV
  - Experimental uncertainty < 0.5 GeV

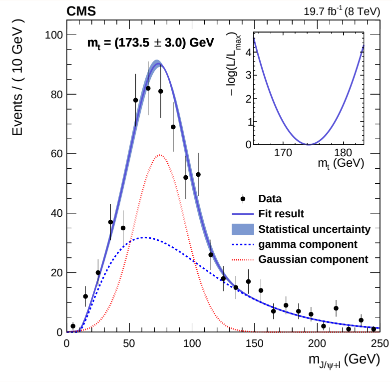
m_t from $m_{J/\psi+\ell}$

CMS PAS TOP-15-014 (2016)

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



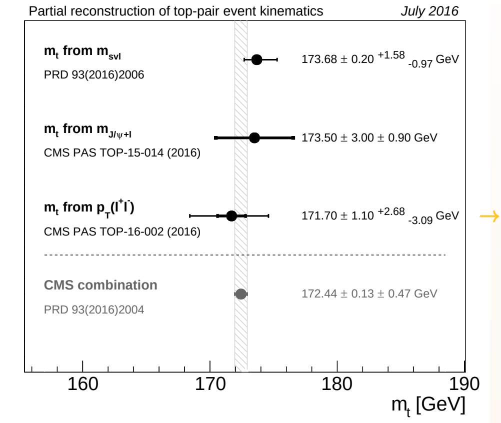
- Dilepton and lepton+jets channels
- Reconstruction of $J/\psi \to \mu^+\mu^-$
  ↪ very small branching fraction



- Extraction of m_t from $m_{J/\psi+\ell}$
  ↪ Monte Carlo based calibration

  $m_t = 173.5 \pm 3.0\,(\text{stat}) \pm 0.9\,(\text{syst})$ GeV
- Systematic uncertainties
  - Main sources:
    - $p_T(t)$ ~ 0.65 GeV
    - ME/PS matching ~ 0.55 GeV
    - Ren. and fact. scales ~ 0.45 GeV
  - b-fragmentation uncertainty of ± 0.30 GeV
  - Relevant exp. uncertainty < 0.10 GeV

Overview



→ **see Cristina's poster !**

at 8 TeV: $m_{\mathrm{sv}\ell}$ most interesting observable
↪ good sensitivity to m_{t}, different systematic uncertainties

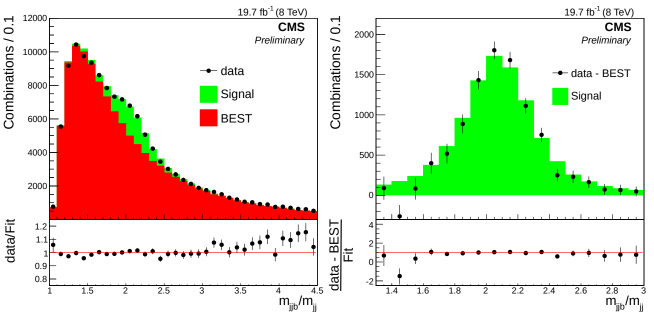
in the future: maybe superseding $m_{\mathrm{sv}\ell}$ with $m_{\mathrm{J}/\psi+\ell}$

Bi-event subtraction technique

CMS PAS TOP-14-011 (2015)

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

- μ+jets channel
- m_t extracted from $R = m_{jjb}/m_{jj}$
- no kinematic fit, all possible combinations kept
  $\hookrightarrow$ estimation of the combinatorial background from data, by combining jets from 2 events



$$m_t = 172.61 \pm 0.57\,(\text{stat}) \pm 0.90\,(\text{syst})\ \text{GeV}$$

- Main systematic uncertainties: ren. and fact. scales, $p_T(t)$, hadronization
  ~ 0.40 GeV $\quad \sim 0.35$ GeV $\quad \sim 0.35$ GeV

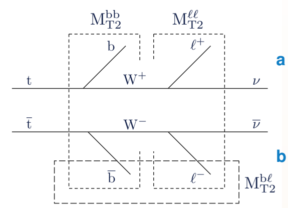
m_t from $m_{\ell b}$ and m_{T2}^{bb}

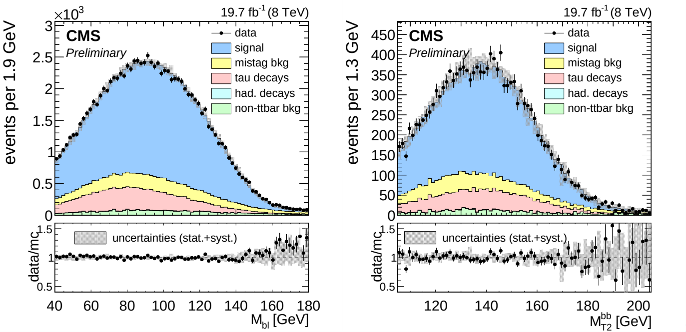
CMS PAS TOP-15-008 (2016)

New for this conference!

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

- Dilepton channel
  $\hookrightarrow$ 2 identical decay branches a and b
- m_t extracted from $m_{\ell b}$ and m_{T2}^{bb} ("stransverse mass")
  - $m_{T2} = \min_{\vec{p}_T^a + \vec{p}_T^b = \vec{p}_T^{miss}} [\max(M_T^a, M_T^b)]$
  - "child" particles: W bosons
  - "upstream" momentum source: ISR



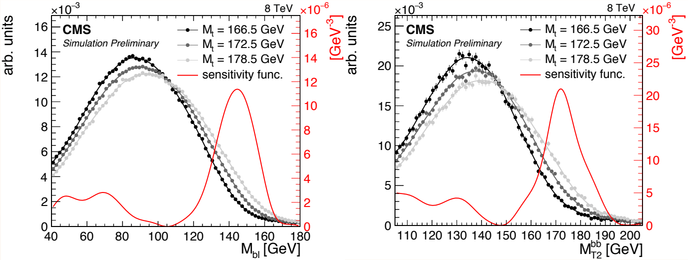


m_t from $m_{\ell b}$ and m_{T2}^{bb}

CMS PAS TOP-15-008 (2016)

New for this conference!
$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}

- m_t extracted from $m_{\ell b}$ and m_{T2}^{bb} ("stransverse mass")
  $\hookrightarrow$ better sensitivity around the kinematic endpoints (Fisher information density)

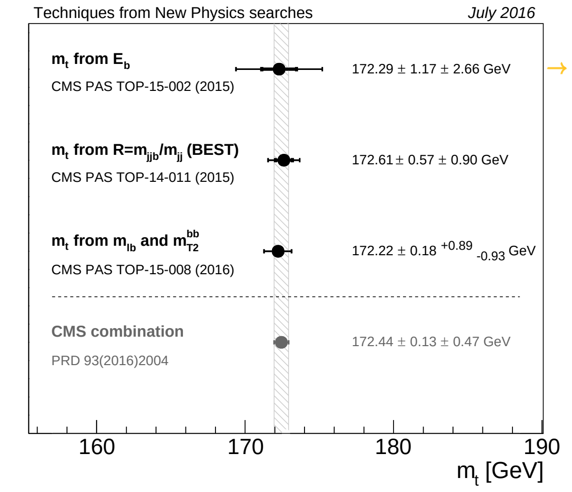


- Combination of 1D (m_t) and 2D (m_t and JSF) fits: $m_t = 0.8\, m_t^{1D} + 0.2\, m_t^{2D}$
  $\hookrightarrow$ shape estimation from MC templates with the Gaussian Processes regression technique

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

- Main systematic uncertainties: $p_T(t)$, ren. and fact. scales, JEC
  ~ 0.5 GeV $\quad \sim 0.45$ GeV $\quad \sim 0.45$ GeV

Overview



→ see Daniel's poster !

Conclusion and outlook

- Precision from standard measurements < 0.5 GeV
  - total uncertainty dominated by systematic uncertainties
  - correlation between channels for the main sources
    $\hookrightarrow$ b hadronization, jet energy response, hard-scattering process
- Promising alternative measurements
  - good precision already at 8 TeV for most of them
    $\hookrightarrow$ m_{t} from $m_{\ell\mathrm{b}}$ and $m_{\mathrm{T2}}^{\mathrm{bb}}$ more precise than the "standard" measurement in the dilepton channel
  - various systematic uncertainties
    $\hookrightarrow$ m_{t} from single-top events for QCD modeling,
    m_{t} from $m_{\mathrm{sv}\ell}$ or $m_{\mathrm{J}/\psi+\ell}$ for detector resolution
- Consistency between all measurements
  $\hookrightarrow$ including $m_{\mathrm{t}}^{\mathrm{pole}}$ from $\sigma(\mathrm{t\bar{t}})$ and $\mathrm{t\bar{t}}$+jet shape

For more top-quark related results from the CMS collaboration:
preliminary results and publications

Backup

m_t from $m_{\ell b}$

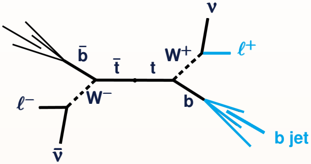
CMS PAS TOP-14-014 (2014)

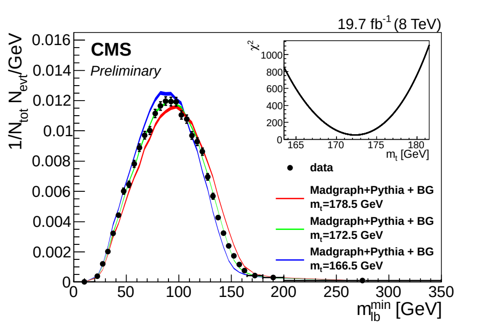
$\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.7$ fb^{-1}

- Dilepton $e^{\pm}\mu^{\mp}$ channel
- *Theoretically:*

$$m_{\ell b}^2 = \frac{m_t^2 - m_W^2}{2}(1 - \cos\theta_{\ell b})$$

Experimentally:
combination of lepton and highest-p_T b jet with smallest $m_{\ell b}$





- Extraction of m_t from $m_{\ell b}$
  $\hookrightarrow$ Monte Carlo based measurement

$m_t = 172.3 \pm 0.3\,(\text{stat}) \pm 1.3\,(\text{syst})$ GeV

- Main sources of systematic uncertainties:
  - $p_T(t)$ ~ 0.65 GeV
  - Ren. and fact. scales ~ 0.60 GeV
  - b-fragmentation ~ 0.60 GeV
  - JEC ~ 0.45 GeV
- Possibility to determine m_t^{pole} using MCFM
  $\hookrightarrow$ smaller sensitivity to $p_T(t)$

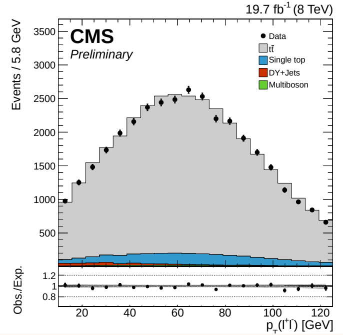
m_t from $p_T(\ell^+\ell^-)$

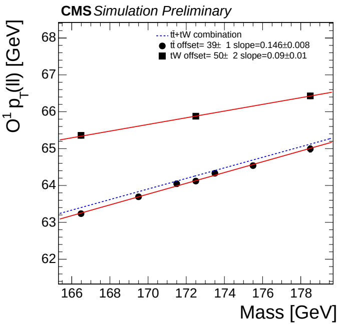
CMS PAS TOP-16-002 (2016)

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

see Cristina's poster !

- Dilepton $e^\pm\mu^\mp$ channel
- Extracting m_t from $p_T(\ell^+\ell^-)$ through $O^1 = \int x f(x)\,dx$
  $\hookrightarrow$ Monte Carlo based measurement





$$m_t = 171.7 \pm 1.1\,(\text{stat}) \pm 0.5\,(\text{exp})^{+2.5}_{-3.1}(\text{th})^{+0.8}_{-0.0}(p_T(t))\ \text{GeV}$$

- Main systematic uncertainties: ren. and fact. scales, ME-PS matching, $p_T(t)$
  ~ 2.5 GeV ~ 1.0 GeV ~ 0.85 GeV

m_t from E_b

CMS PAS TOP-15-002 (2015)

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

see Daniel's poster !

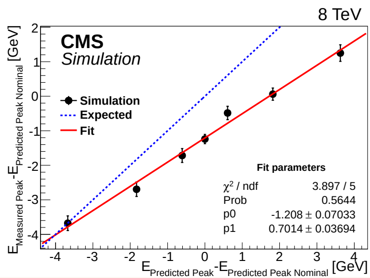
- Dilepton channel
- *Theoretically* — *Experimentally*

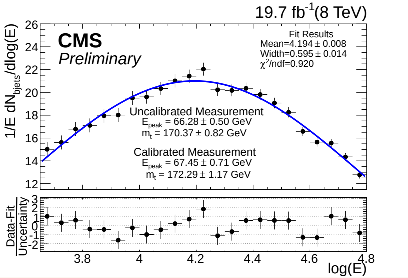
Theoretically:

- $E_b^{peak} = \dfrac{m_W^2 - m_b^2 - m_t^2}{2\, m_t}$
- Robustness wrt $\sqrt{s}$, β_t, and ISR

Experimentally:

- MC-based calibration needed
- Very sensitive to $p_T(t)$





$$m_t = 172.29 \pm 1.17\ \text{(stat)} \pm 2.66\ \text{(syst) GeV}$$

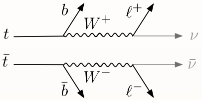
- Main systematic uncertainties: $p_T(t)$, ME generator, JEC

~ 1.5 GeV $\quad \sim 1.5$ GeV $\quad \sim 1.2$ GeV

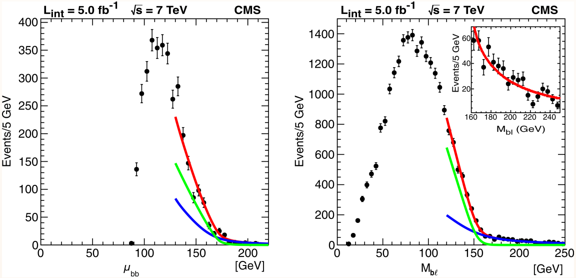
Kinematic endpoint method

EPJC 73 (2012) 2494

$\sqrt{s} = 7$ TeV, $\mathcal{L} = 5.0$ fb^{-1}



- Dilepton channel
- Underconstrained system
  ↪ μ_{bb}: variable designed on purpose, weakly-correlated to the invariant mass $M_{b\ell}$
- m_t extracted from μ_{bb}^{max} and $M_{b\ell}^{max}$, assuming $m_\nu = 0$ and $M_W = 80.4$ GeV
  ↪ **no** Monte Carlo calibration needed



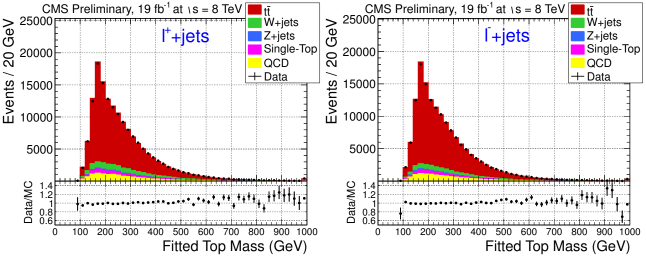
$$m_t = 173.9 \pm 0.9\ (\text{stat})^{+1.7}_{-2.1}(\text{syst})\ \text{GeV}$$

Top quark-antiquark mass difference

CMS PAS TOP-12-031

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 18.9\ \text{fb}^{-1}$

- $\Delta m_t = m_t - m_{\bar{t}}$ as a test of CPT symmetry
- Lepton+jets channel
- Reconstruction of hadronically decaying top quarks after a kinematic fit
- Ideogram likelihood method for $\ell^+ +$jets events and $\ell^- +$jets events separately



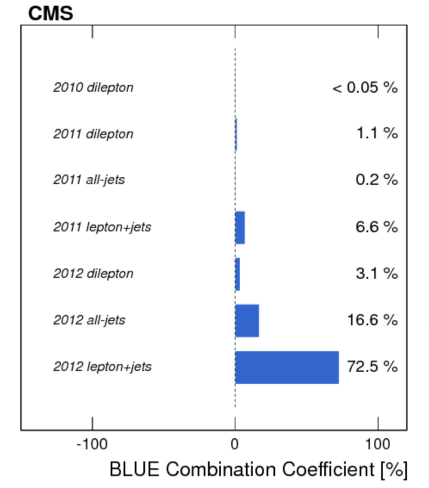
$$\Delta m_t = -272 \pm 196\ \text{(stat)} \pm 122\ \text{(syst) GeV}$$

Combination of the “standard” measurements

PRD 93(2016)2004

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

Using the Best Linear Unbiased Estimate (BLUE) method



Combination of the "standard" measurements

PRD 93(2016)2004

$\sqrt{s} = 8$ TeV

Main systematic uncertainties:

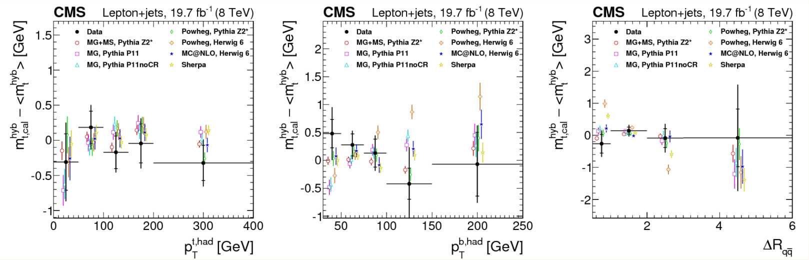
	δm_t (GeV) all-jets	δm_t (GeV) lepton+jets	δm_t (GeV) dilepton	
Experimental uncertainties				
Jet energy corrections				
• JEC: intercalibration	+0.02	+0.01	+0.03	~ 0.15 GeV
• JEC: *in situ* calibration	+0.19	+0.12	+0.24	
• JEC: uncorrelated non-pileup	−0.16	−0.10	−0.28	
• JEC: uncorrelated pileup	−0.06	−0.04	−0.12	
⋮				
Modeling of hadronization				
b jet modeling				
• b fragmentation	+0.04	< 0.01	−0.69	~ 0.35 GeV
• semileptonic b hadron decays	−0.13	−0.16	−0.17	
JEC: flavor-dependent				
• bottom	−0.29	−0.32	−0.34	
⋮				
Modeling of perturbative QCD				
Ren. and fact. scales	-0.12 ± 0.12	-0.09 ± 0.07	-0.75 ± 0.20	~ 0.15 GeV
ME-PS matching threshold	$+0.13 \pm 0.12$	$+0.03 \pm 0.07$	-0.12 ± 0.20	
ME generator	-0.16 ± 0.14	-0.12 ± 0.08	-0.24 ± 0.20	
⋮				
Modeling of soft QCD				
Underlying event	$+0.14 \pm 0.18$	$+0.08 \pm 0.11$	$+0.04 \pm 0.20$	
Color reconnection	$+0.16 \pm 0.16$	$+0.01 \pm 0.09$	-0.11 ± 0.20	
Total systematic	0.59	0.48	1.22	

Kinematic phase space in MC models

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

PRD 93(2016)2004

- Different ME generators, hadronization models, UE tunes compared to CMS standard MC (MADGRAPH+PYTHIA6 with Z2* tune)
- Probing variables sensitive to color-(re)connection effects
- Following the standard lepton+jets strategy
  (selection criteria, kinematic fit, 2D likelihood procedure)
  ↪ instead of correcting kinematic biases, studying them

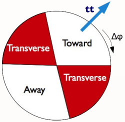


Fair agreement between data and MC within statistical uncertainties
↪ more data needed to further constrain model uncertainties

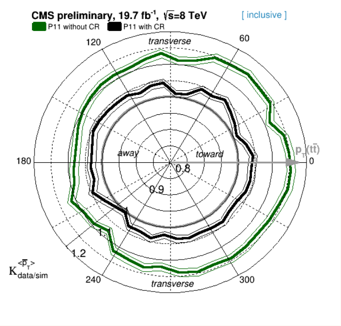
Color (re)connection effects

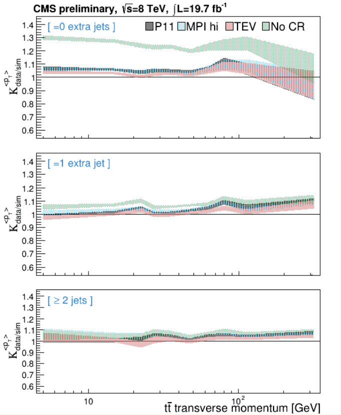
CMS PAS TOP-13-007

- High purity dilepton sample
- Characterization of the soft charge activity
- Factorization the recoil contribution
- MC-to-date comparison for several Perugia 11 variations



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





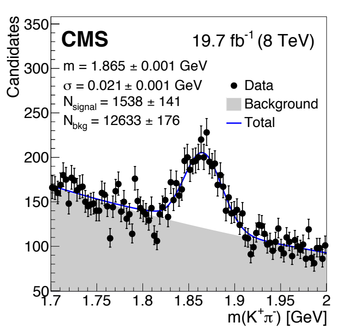
Color (re)connection model effects enhanced at low p_T, when there is no extra jet, and in the $t\bar{t}$ direction

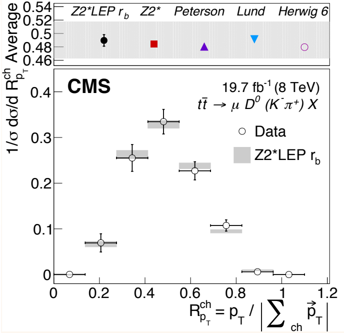
Fragmentation modeling

PRD 93(2016)2006

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

- Current tuning obtained from LEP data and ported to LHC
  ↪ tuning of Z2* mostly for UE, not for fragmentation
- Study of fragmentation in $t\bar{t}$ events with a charmed meson (J/ψ, D^0,...)
  ↪ modifying b fragmentation description of Z2* to better fit LEP data



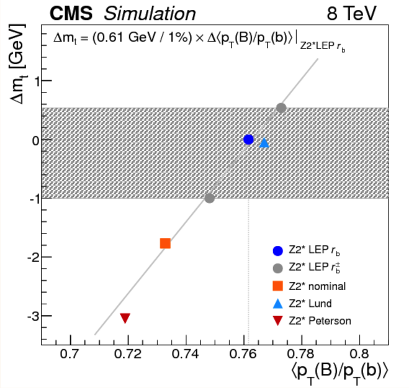


⇒ Better MC-to-data agreement for Z2*LEP r_b

Fragmentation modeling

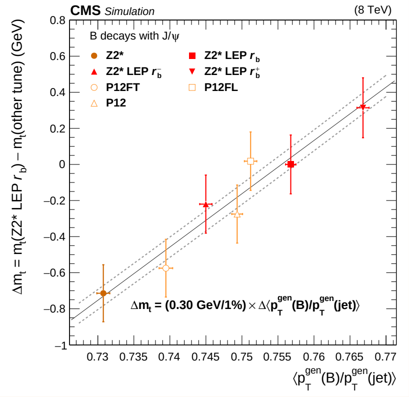
m_t from $m_{sv\ell}$

PRD 93(2016)2006



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

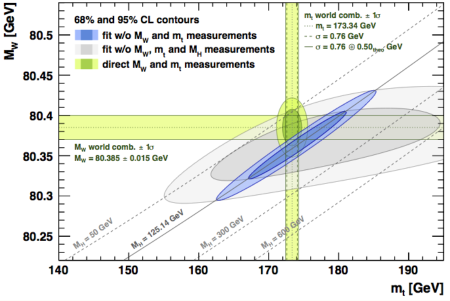
CMS PAS TOP-15-014 (2016)



Importance of a precise m_t determination

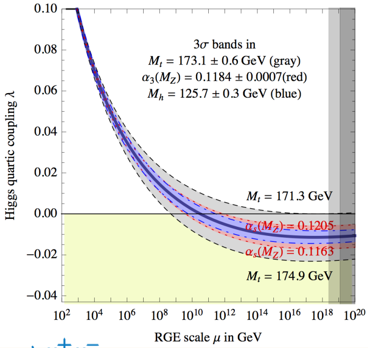
The electroweak fit and indirect measurement of m_W

EPJC 74(2014)3046

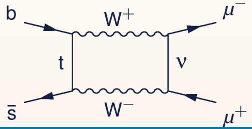


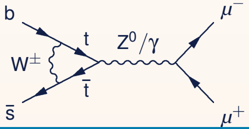
The electroweak vacuum stability

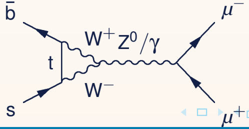
JHEP 1208(2012)098



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







From the Lagrangien parameters to the observables

m_q mass:

Lagrangien parameter

1. Field quantification
2. Gauge fixing
   $\rightarrow$ Feynman rules

$$= \frac{i}{\not{p} - m_q}$$

3. Regularization
   $\rightarrow$ loop integrals

4. Renormalization
   $\rightarrow$ series of perturbative corrections

$\Rightarrow$ As many mass definitions as renormalization schemes

Pole mass:

real part of the propagator singularity for each order of the perturbative theory

- invariant mass of a free particle
- $\Delta \sim 200$ MeV

$\overline{\text{MS}}$, PS, MSR... masses:

- short-distance masses
- convenient to parameterize the Yukawa coupling to the Higgs boson

Monte Carlo generator definition:

- interpretation depends on how much MC simulations are based on QCD
- $m_t^{MC} = m_t(R = 3^{+6}_{-2}\ \text{GeV})$
  $\hookrightarrow$ can be perturbatively related to m_t^{pole}
  NPPS 185(2008)220

The ideogram method

- For each event, a likelihood to observe the event is calculated:

$$\mathcal{L}_{\mathrm{event}}(x|m_{\mathrm{t}}, f_{\mathrm{t\bar{t}}}) = f_{\mathrm{t\bar{t}}} \cdot P_{\mathrm{t\bar{t}}}(x|m_{\mathrm{t}}) + (1 - f_{\mathrm{t\bar{t}}}) \cdot P_{\mathrm{bkg}}(x)$$

  where x is the set of variables which characterizes the event, $f_{\mathrm{t\bar{t}}}$ is the fraction of $\mathrm{t\bar{t}}$ events in the data sample, and $P_{\mathrm{t\bar{t}}}$ and P_{bkg} the probability densities for $\mathrm{t\bar{t}}$ and background events respectively

- The probabilities are calculated as a weighted sum over all possible combinations from the kinematic fit:

$$w_i = \exp\left(-\frac{1}{2}\chi^2\right) \cdot w_{\mathrm{btag}} \quad \text{with} \quad w_{\mathrm{btag}} = \prod_{j \in \mathrm{jets}} p^j$$

  where the b-tag probability p^j can be either ε_l, $(1-\varepsilon_l)$, ε_{b}, or $(1-\varepsilon_{\mathrm{b}})$ depending on the hypothesized flavor of the jet (light or b-jet)

- Considering the number of b-tagged jets n_{btag}, signal and background probabilities to observe a set of mass variables x_{mass} can be written as:

$$P_{\mathrm{t\bar{t}}}(x|m_{\mathrm{t}}) = P_{\mathrm{t\bar{t}}}(n_{\mathrm{btag}}) \cdot P_{\mathrm{t\bar{t}}}(x_{\mathrm{mass}}|m_{\mathrm{t}}) \quad \text{and} \quad P_{\mathrm{bkg}}(x) = P_{\mathrm{bkg}}(n_{\mathrm{btag}}) \cdot P_{\mathrm{bkg}}(x_{\mathrm{mass}})$$

- The $\mathrm{t\bar{t}}$ signal probability can be expressed as:

$$P_{\mathrm{t\bar{t}}}(x_{\mathrm{mass}}|m_{\mathrm{t}}) = \sum_{1}^{24} w_i \left(f_{cp} \cdot \int_{m_{\mathrm{min}}}^{m_{\mathrm{mass}}} dm' \cdot G(m'|m_i, \sigma_i) \cdot BW(m'|m_{\mathrm{t}}, \Gamma_{\mathrm{t}}) + (1 - f_{cp}) \cdot WP(m_i|m_{\mathrm{t}}) \right)$$

- The overall sample likelihood is calculated by combination:

$$\mathcal{L}_{\mathrm{sample}}(m_{\mathrm{t}}, f_{\mathrm{t\bar{t}}}) = \prod_j \mathcal{L}_{\mathrm{event},j}(m_{\mathrm{t}}, f_{\mathrm{t\bar{t}}})$$

The analytical matrix weighting technique (AMWT)

- The top-quark mass is used as a constrain to close the kinematic system
- To determine a preferred value of m_t, a weight is determined as:

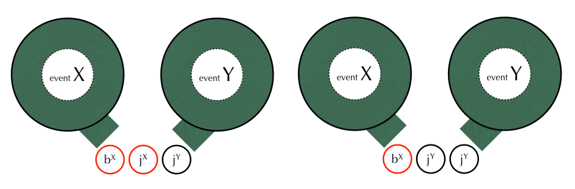
$$w = \left(\sum F(x_1)F(\bar{x}_2)\right) \cdot p(E^*_{\ell+}|m_\mathrm{t}) \cdot p(E^*_{\ell-}|m_\mathrm{t})$$

  where x_i are the Björken values of the initial state partons, $F(x)$ is the parton distribution function, and $p(E^*|m_\mathrm{t})$ the probability of observing a charged lepton of energy E^* in the rest frame of the top-quark given a top-quark mass of m_t
- Each event is reconstructed 1 000 times drawing a random number for the jet momenta. The weight is averaged over all resolution samples.
- For each event, the m_t hypothesis with maximum average weight is taken as the reconstructed top-quark mass m_{AMWT}
- Using simulated $\mathrm{t\bar{t}}$ samples generated with m_t values between 151 and 199 GeV in steps of 3 GeV, a binned likelihood fit is performed for $100 < m_{AMWT} < 300$ GeV

The bi-event subtraction technique

Combinatorial background estimation from data

- Pairing all jets in a given event X with all jets from a neighboring event Y
  - same jet multiplicity for both events
  - $\Delta R > 0.5$ for all considered jet pairs
- All combinations jjb of 2 non-b-tagged jets and 1 b-tagged jets
  - non resonant background to W: $j^X j^Y b^X$
  - wrong combination of b-tagged jets with W candidates: $j^X j^X b^Y$



The Gaussian Processes regression technique

Shape estimation

Advantages

- non parametric method
- trained as a function of several variables simultaneously

Training

- point $\boldsymbol{u}_i = (x_i, m_{\mathrm{t}i}, \mathrm{JSF}_i)$, value of the shape $f(\boldsymbol{u}_i) = f(x_i | m_{\mathrm{t}i}, \mathrm{JSF}_i)$
  $\hookrightarrow$ training each GP shape with binned x distributions for several m_{t} and JSF values
- $f(\boldsymbol{u}_i)$ distributed according to a 1D Gaussian rather than being treated as an exact quantity
  $\hookrightarrow$ most probable value at the point $\boldsymbol{u}_i$ as mean,
  variance related to the inherent modeling uncertainty
- degree to which the GP shape is allowed to vary between $\boldsymbol{u}_i$ and $\boldsymbol{u}_j$ determined by the correlation between $f(\boldsymbol{u}_i)$ and $f(\boldsymbol{u}_j)$
  $\hookrightarrow$ $\mathrm{cov}\,(f(\boldsymbol{u}_i), f(\boldsymbol{u}_j))$ determined by a kernel function set by the user