Top-quark mass measurements with CMS

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects

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The top-quark mass in the Standard Model:

How fundamental is this parameter ?

- key role in the prediction of many observables either directly or via electroweak radiative corrections $\hookrightarrow m_W = f(m_{top}^2, \ln m_H)$
- key input to electroweak fit, which enables comparisons between experimental results and predictions within and beyond the SM
- highest Yukawa coupling to the Higgs boson: probe for the stability of the electoweak vacuum and Higgs boson properties

http://cern.ch/Gfitter

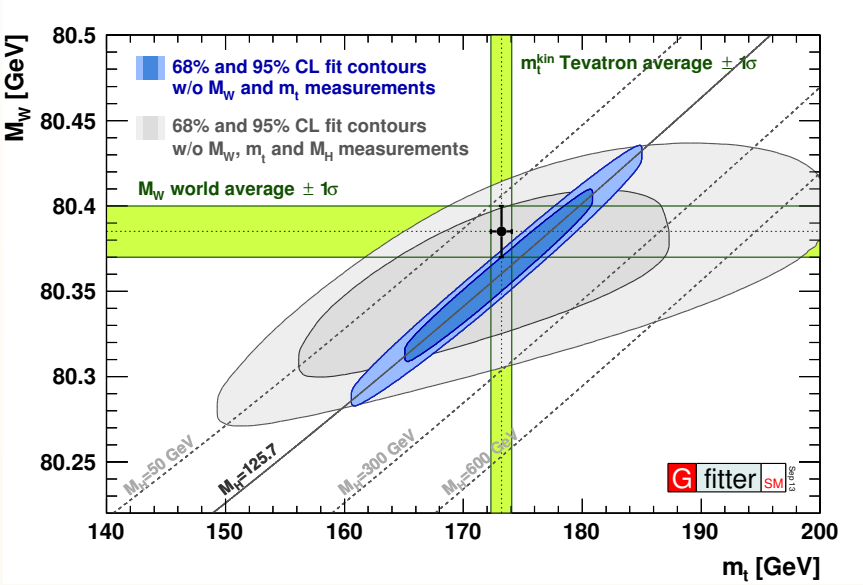


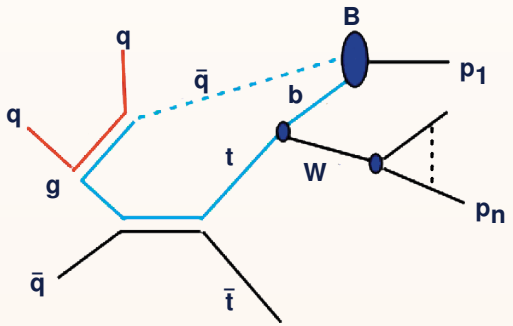
Figure 1: Contours of 68% and 95% confidence level obtained from scans of fits with fixed variable pairs M_W vs m_{top}. The narrower blue and larger grey allowed regions are the results of the fit including and excluding the M_H measurements respectively.

The top-quark mass in the Standard Model:

What can we tap into ?

- a reconstructed invariant mass, a parameter of MC event generator
  $\hookrightarrow$ believed to be close to the pole mass at the level of < 500 MeV/c^2
  cf. M. Mangano's talk, given at the TOP2013 conference

- the pole mass from the $t\bar{t}$ cross section measurement
  - uncertainty of $\delta m_{\text{top}} \sim \Lambda_{\text{QCD}}$ since the top-quark is a coloured object
  - relation between the pole mass and the $\overline{\text{MS}}$ mass known to the 3-loop level in QCD but might receive large electroweak corrections



Outline

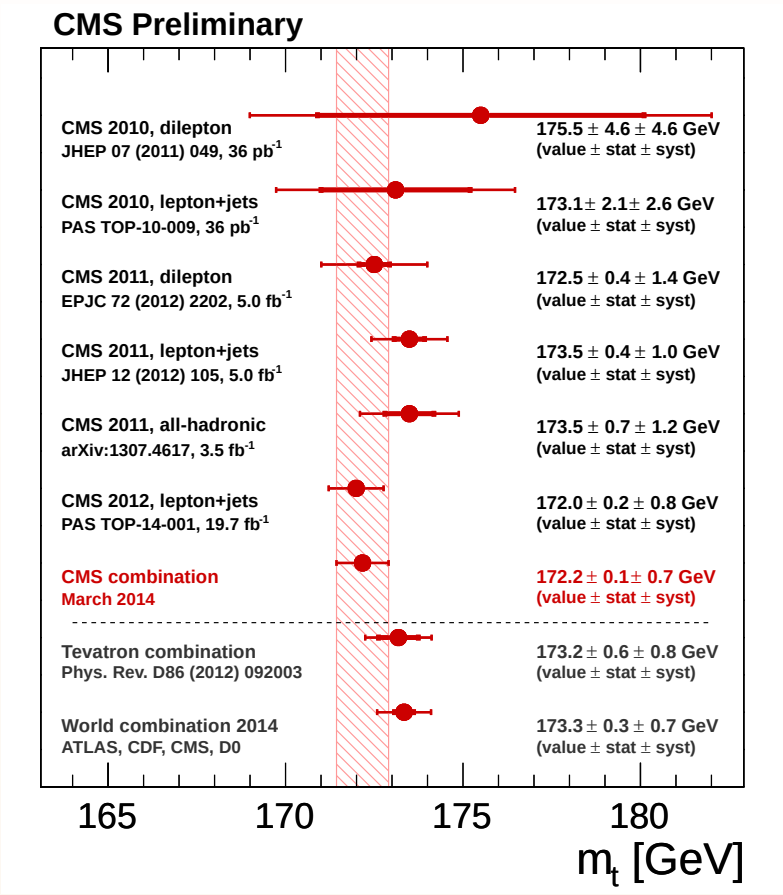
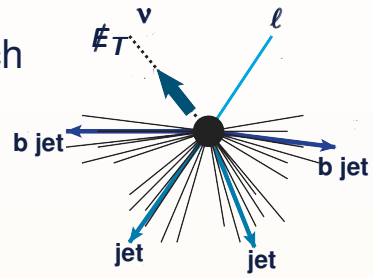


Figure 2: Overview of the CMS standard top-quark mass measurements, their combination, and the Tevatron and World Average.

Top-quark mass in the ℓ+jets channel

The golden channel

- selecting events with 1 isolated lepton (e or μ) and ≥ 4 jets (of which 2 b-tagged jets) among $\sqrt{s} = 8$ TeV data (19.7 fb^{-1})
- using a kinematic fit to check compatibility of an event with the $t\bar{t}$ hypothesis and improve resolution



The ideogram method

- Performing a joint likelihood fit of:
  - the fitted top-quark mass
  - the unconstrained W-boson reconstructed mass
- Using the convolution of a Breit-Wigner function with:
  - a Gaussian one for correct permutations
  - a Crystal Ball one for wrong or unmatched permutations

$$m_{top} = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\ \text{GeV/c}^2$$

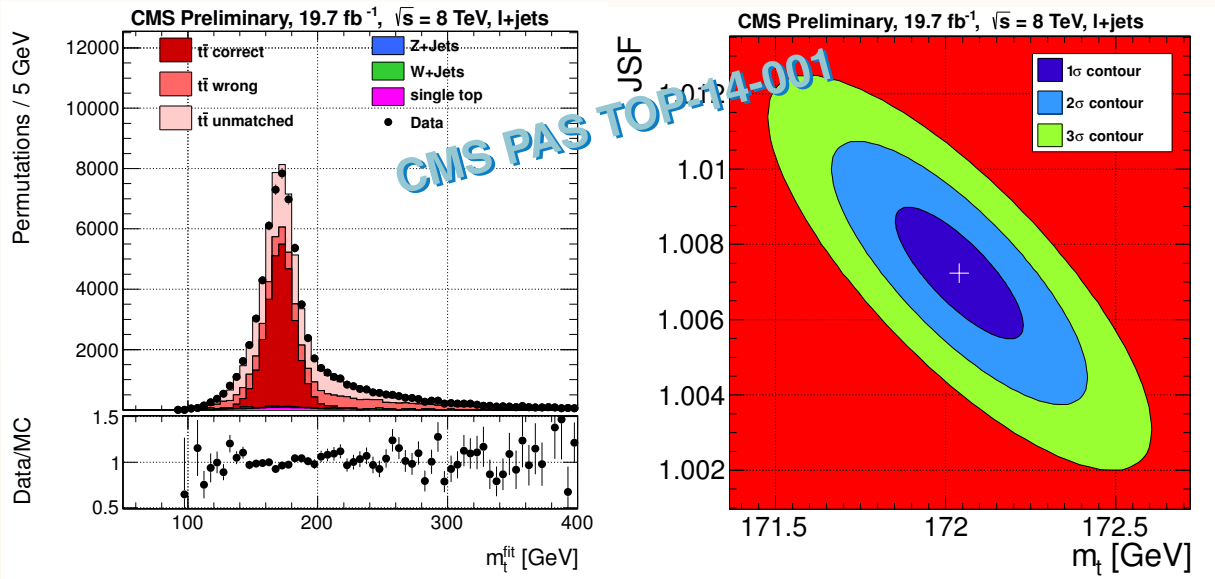


Figure 3: Fitted top-quark mass distribution after the goodness-of-fit selection and weighting (left) and the 2D likelihood (right).

Kinematic phase space in MC models

CMS PAS TOP-14-001

- 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 golden channel strategy (selection criteria, kinematic fit, 2D likelihood procedure) → but instead of correcting kinematic biases, studying them

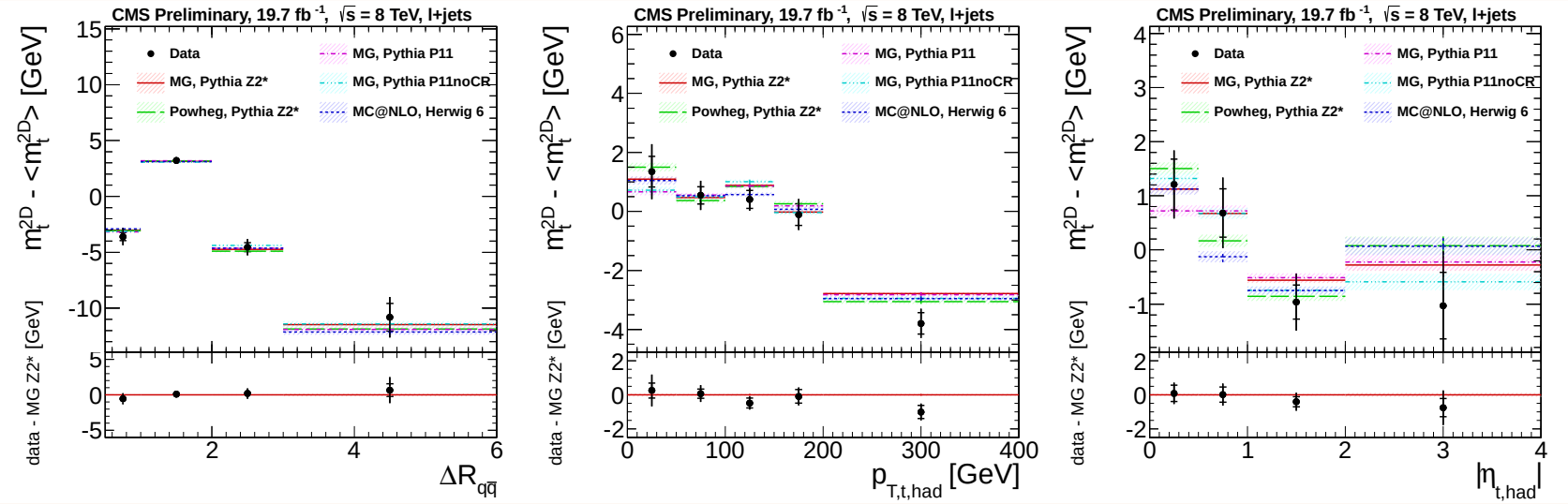


Figure 4: Measurements in dependency of the opening angle between the jets in terms of the separation in $\eta - \phi$ space (left), of the transverse momentum of the hadronically decaying top-quark (center), and of its pseudo-rapidity (right).

Fair agreement between data and MC within statistical uncertainties

↪ more data needed to further constrain model uncertainties

Combination of the standard measurements

The Best Linear Unbiased Estimate method

- from several unbiassed estimates y_i of the top-quark mass with their error matrix E
- to the linear combination of the individual estimates $\hat{y} = \alpha_i \cdot y_i$ that has the minimum possible variance $\sigma^2 = E_{ij} \cdot \alpha_i \cdot \alpha_j$

Sources of systematic uncertainties

- Experimental uncertainties

fit calibration, lepton energy scale, jet energy resolution, pile-up, $\not{E}_T$, JES dependency on p_T and η...

- Modeling of hadronization

b fragmentation, flavor-dependent JSF...

- Modeling of the hard scattering process

PDF, renormalization and factorization scales, ME-PS matching treshold, ME generator...

- Modeling of non-perturbative QCD

underlying event modeling, color (re)connection modeling...

$$m_{top} = 172.2 \pm 0.1\,(stat.) \pm 0.7\,(syst.)\ GeV/c^2$$

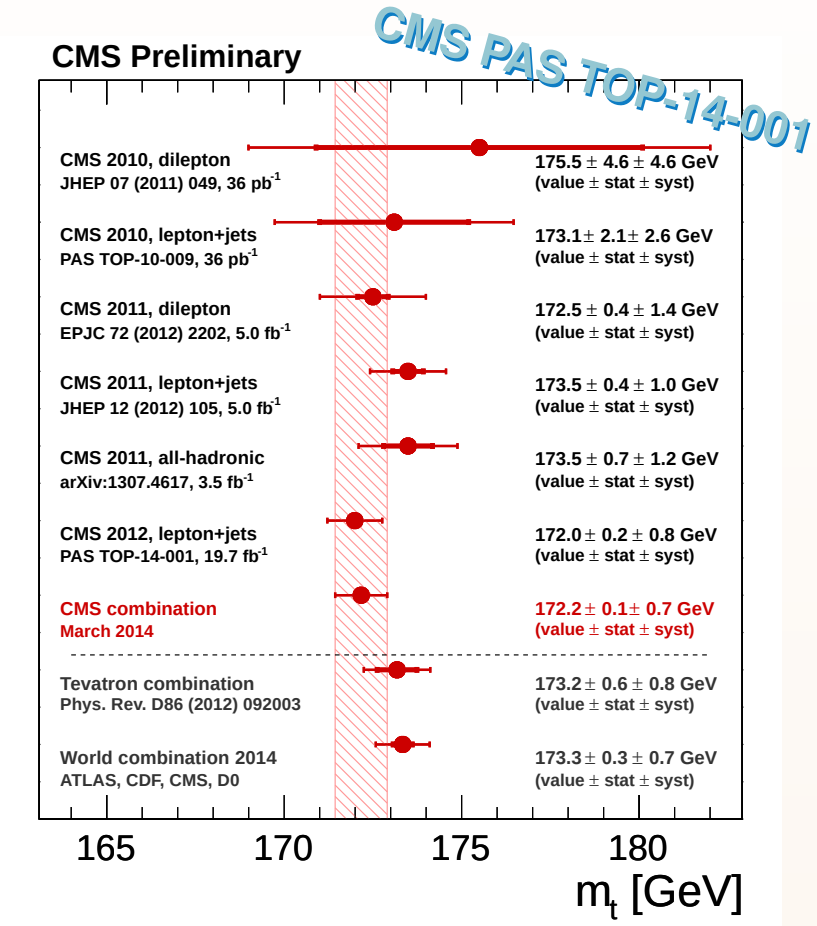


Figure 5: Overview of the CMS standard top-quark mass measurements, their combination, and the Tevatron and World Average.

Top-quark pole mass from $\sigma_{t\bar{t}}$

- Using the measurement of $\sigma_{t\bar{t}}$ derived at $\sqrt{s} = 7$ TeV from data collected in the dileptonic decay channel (2.3 fb^{-1})
  $\rightarrow$ arXiv:1208.2671
- Constraining α_S at the scale of the Z-boson mass to the current world average and assuming that the measured $\sigma_{t\bar{t}}$ is not affected by non-SM physics
- Constructing a Bayesian prior from the expected $\sigma_{t\bar{t}}$:
  - expected $\sigma_{t\bar{t}}$ calculated to NNLO by the program TOP++ 2.0
  - soft-gluon resummation performed at NNLL accuracy
  - dependence on $m_{\text{top}}^{\text{pole}}$ described by a 3rd-order polynomial divided by $(m_{\text{top}}^{\text{pole}})^4$

$$m_{\text{top}}^{\text{pole}} = 176.7\,^{+3.8}_{-3.4}\ \text{GeV/c}^2$$

PLB 728 (2013) 496

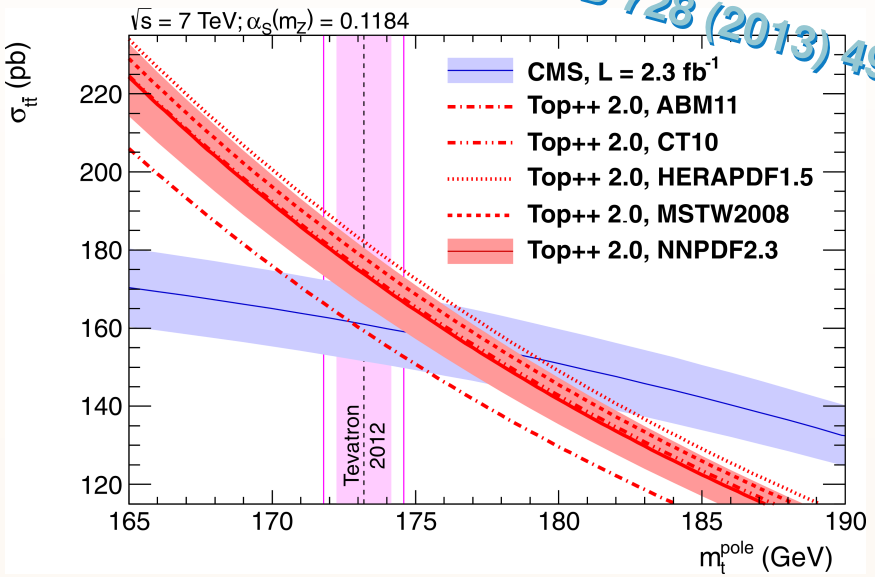
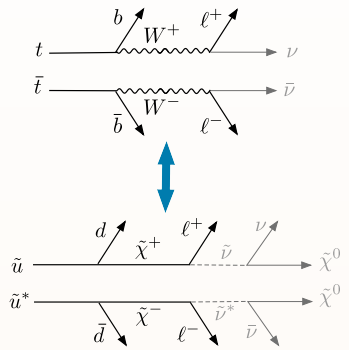


Figure 6: Predicted $t\bar{t}$ cross section at NNLO+NNLL as a function of the top-quark pole mass, using 5 different NNLO PDF sets, compared to the cross section measured by CMS assuming $m_{\text{top}} = m_{\text{top}}^{\text{pole}}$.

Kinematic endpoint method

Testing a new technique of mass extraction

- selecting dileptonic $t\bar{t}$ events among $\sqrt{s} = 7$ TeV data (5.0 fb^{-1})
- testing mass determination method that may be used in beyond SM physics scenarios
  $\hookrightarrow$ topological resemblance: 2 cascade decays ending in invisible particles



Strategy

- Underconstrained system
  $\hookrightarrow$ μ_{bb}: variable designed on purpose, weakly-correlated to the invariant mass $M_{b\ell}$
- μ_{bb}^{max} and $M_{b\ell}^{max}$ correlated to the top-quark mass
- Assuming $m_\nu = 0$ and $M_W = 80.4$ GeV/c^2 in the joint unbinned likelihood fit procedure
- No MC calibration needed

$$m_{top} = 173.9 \pm 0.9\,(stat.)^{+1.7}_{-2.1}\,(syst.)\ GeV/c^2$$

EPJC 73 (2012) 2494

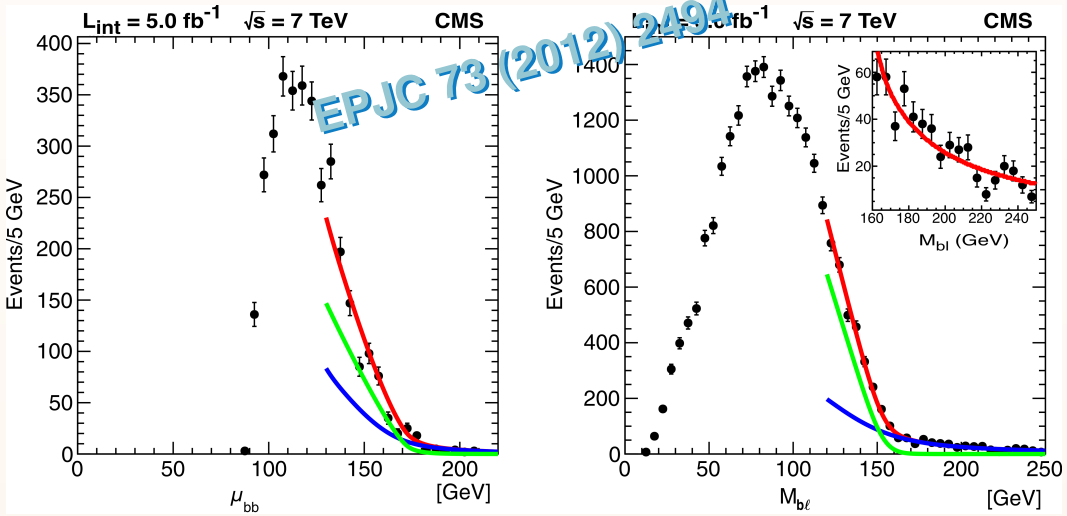


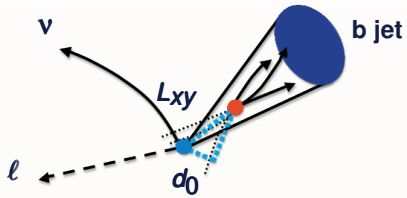
Figure 7: Simultaneous fit of the μ_{bb} (left) and $M_{b\ell}$ (right) distributions. The red line is the full fit, while the blue and green curves are for the background and signal shapes.

B hadron lifetime technique (L_{xy})

CMS PAS TOP-12-030

Use of the kinematics of the top-quark decay products

- selecting among $\sqrt{s} = 8$ TeV data
  - events with 1 charge isolated lepton (e or μ), ≥ 4 jets
  - events with 1 electron, 1 muon, and ≥ 2 jets
- starting from the fact that, in the rest frame of the top-quark, the top-quark decay producs momenta are correlated to m_{top}
- considering the B-hadron decay length L_{xy} to be analogously correlated to m_{top} as most of the energy is transfered from the b-quark to the B-hadron



The B-hadron lifetime technique

- selecting the secondary vertex with the largest L_{xy} and the median $\widehat{L_{xy}}$ of the distribution of secondary vertices with maximal L_{xy}
- exploiting the linear dependency of $\widehat{L_{xy}}$ on the top-quark mass of $\mathcal{O}(0.0025 - 0.0030\ \text{cm})$ per GeV/c^2
  $\hookrightarrow$ calibration based on pseudo-experiments

$$m_{\text{top}} = 173.5 \pm 1.5\ (\text{stat.}) \pm 1.3(\text{syst.}) \pm 2.6\,(p_T\,(\text{t}))\ \text{GeV/c}^2$$

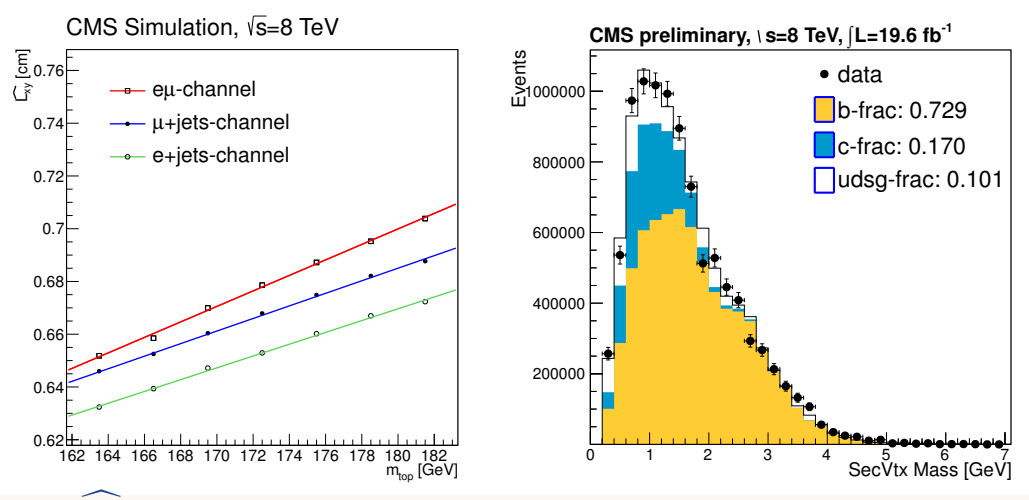


Figure 8: $\widehat{L_{xy}}$ as a function of m_{top} from simulation (left) and inclusive fit to the flavour content of a dijet sample based on the secondary vertex mass distribution (right).

Comparison to the standard measurements and outlook

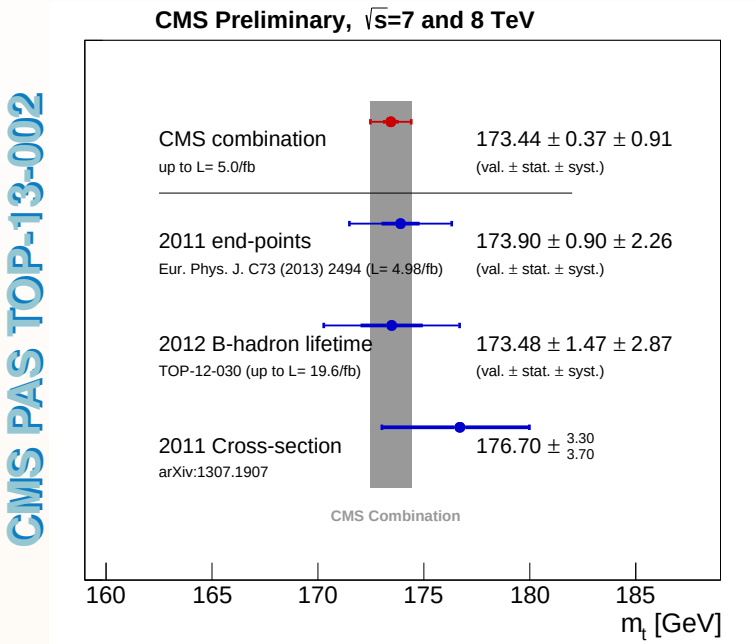


Figure 9: Comparison of the previous CMS top-quark-mass combination and measurements obtained using alternative analysis techniques.

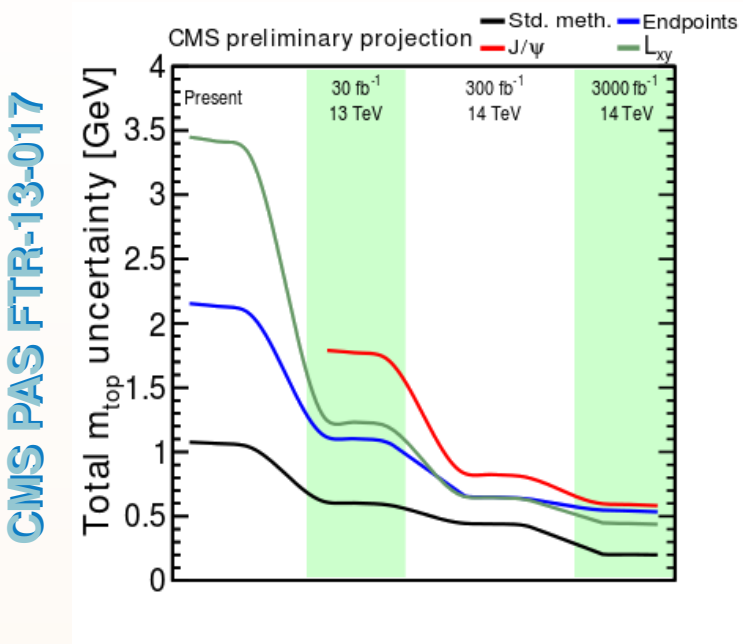
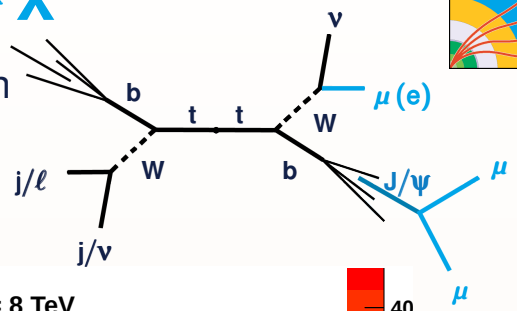


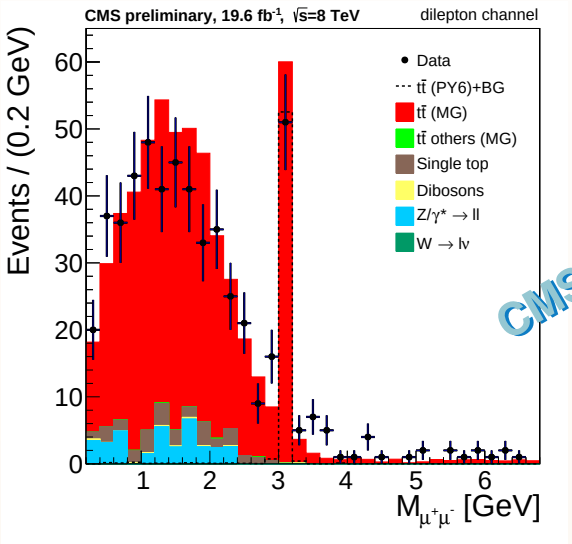
Figure 10: Projection of the top-quark-mass precision obtained with different measurement methods, for various integrated luminosity.

- Using 5 fb^{-1} of data at $\sqrt{s} = 7$ TeV as a baseline for the projection
- Assuming jet reconstruction is not affected by the increase of PU
- Systematics uncertainties differing from standard measurements:
  - Pole mass from $\sigma_{t\bar{t}}$: theoretically defined
  - Endpoint method: analytical calculation but b-JES sensitive
  - L_{xy} technique: no JES dependency but good understanding of B-hadron fragmentation and top-quark p_T needed

Leptonic final states with $b \to J/\psi + X \to \mu^+\mu^- + X$



- Selecting events with 1(2) isolated lepton(s) (e or μ), 1 opposite-sign di-muon pair whose invariant mass is around the J/ψ one, and satisfying a jet criterion, among $\sqrt{s} = 8$ TeV data (19.8 fb^{-1})



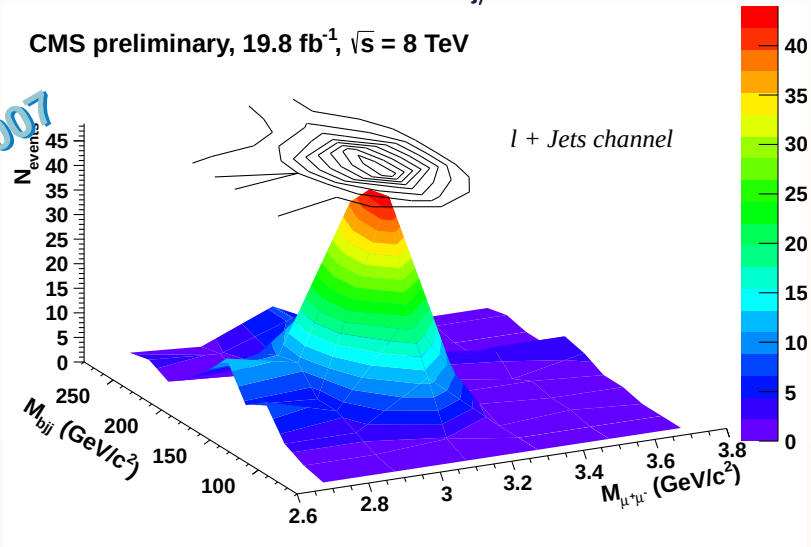


Figure 11: Di-muon invariant mass after requiring 1 isolated lepton (e or μ), a di-muon pair, and a jet criterion.

Figure 12: Di-muon invariant mass and top-quark mass estimate after the final selection.

- Using the correlation between the the top-quark mass and the invariant mass of the combination $J/\psi + \ell$

  $\hookrightarrow$ systematic uncertainties mainly imputable to b-fragmentation, not impacted by jet-related sources

Conclusion

- Dileptonic and all-jets channels becoming competitive to the semi-leptonic one
- Efforts ongoing for harmonization of systematic uncertainties

- NLO-multileg generators expected to provide a finer description
- b-JES, soft QCD, and more generally models expected to be better constrained by data

- Multiple techniques to measure the top-quark mass
- Studying kinematic dependencies and colour (re)connection effects

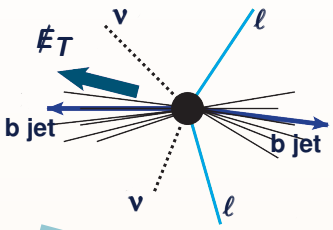
For more top-quark related results from the CMS collaboration:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Backup

Top-quark mass measurement using the dilepton channel

The smallest branching ratio but the channel least contaminated by background processes

- selecting events with 2 oppositely charged leptons, ≥ 2 jets, and $\not{E}_T > 40$ GeV among $\sqrt{s} = 7$ TeV data (5.0 fb^{-1})
- b-tagging algorithm to classify jets, Z and low-mass Drell-Yan vetos



The analytical matrix weighting technique (AMWT)

EPJC 72 (2012) 2202

- For each $t\bar{t}$ event, kinematic properties fully specified by the 4-momenta of the 6 particles in the final state
  $\hookrightarrow$ system closed only if m_{top} is used as a constraint
- Kinematic equations solved many times per event using a serie of top-quark mass hypotheses
  $\hookrightarrow$ weight assigned to each solution
- Sources of improvement of the method:
  - Fraction of correctly assigned jets increased using leading b-tagged jets
  - Analytical method to determine the momenta of ν

$$m_{\text{top}} = 173.3 \pm 1.2\,(\text{stat.})^{+2.5}_{-2.6}(\text{syst.})\ \text{GeV/c}^2$$

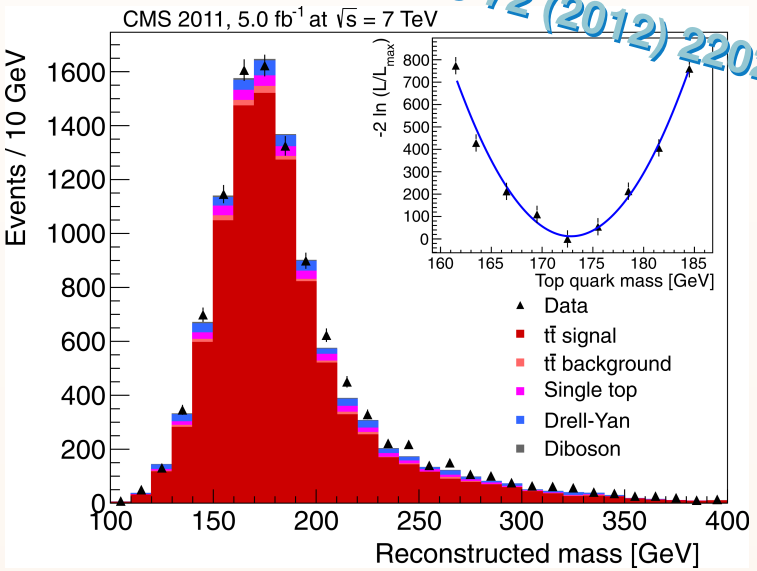


Figure 13: Distribution of the reconstructed mass in data and simulation for a top-quark mass hypothesis of 172.5 GeV/c^2 with the AMWT.

The analytical matrix weighting technique (AMWT)

- The top-quark mass is used as a constraint to close the kinematic system
- To determine a preferred value of m_{top}, a weight is determined as:

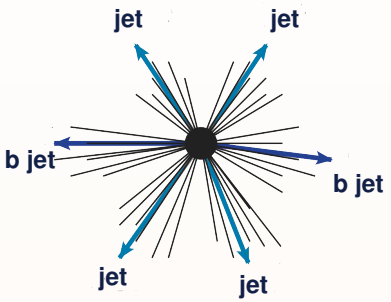
$$w = \left(\sum F(x_1)F(\bar{x}_2)\right) \cdot p(E^*_{\ell+}|m_{\text{top}}) \cdot p(E^*_{\ell-}|m_{\text{top}})$$

  where x_i are the Björken values of the initial state partons, $F(x)$ is the parton distribution function, and $p(E^*|m_{\text{top}})$ 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_{top}
- 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_{top} hypothesis with maximum average weight is taken as the reconstructed top-quark mass m_{AMWT}
- Using simulated $\text{t}\bar{\text{t}}$ samples generated with m_{top} values between 151 and 199 GeV/c^2 in steps of 3 GeV/c^2, a binned likelihood fit is performed for $100 < m_{AMWT} < 300$ GeV/c^2

Top-quark mass from all-hadronic channel

The all-jets channel

- selecting events with ≥ 6 jets (of which ≥ 2 b-tagged jets) among $\sqrt{s} = 7$ TeV data (3.54 fb^{-1})
- using a kinematic least-squares fit
  $\hookrightarrow$ repeating the fit procedure for each jet permutation
- additional criterion on the separation of the 2 b-quark candidates
- multijet background estimated through an event mixing technique



The ideogram method

- Performing a joint likelihood fit of:
  - the fitted top-quark mass distribution
  - the mean of the unconstrained 2 W-boson masses
- Using analytic expressions for the probability densities:
  - convolution of a Breit-Wigner function and a Gaussian one for correct permutations
  - sum of a Landau function and a Gaussian one for wrong and unmatched permutations
- 1D analysis: m_{top} only free parameter,
  2D analysis: cross-check

$$m_{\text{top}} = 173.49 \pm 0.69\ (\text{stat.}) \pm 1.21\ (\text{syst.})\ \text{GeV/c}^2$$

EPJC 74(2014) 2758

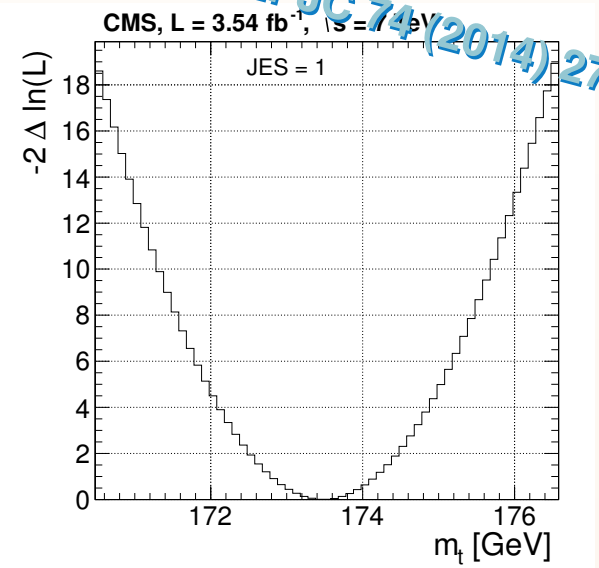


Figure 14: The 1D likelihood profile with the JES fixed to unity.

The ideogram method

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

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

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

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

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

  where the b-tag probability p^j can be either ε_l, $(1 - \varepsilon_l)$, ε_{b}, or $(1 - \varepsilon_{\text{b}})$ 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:

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

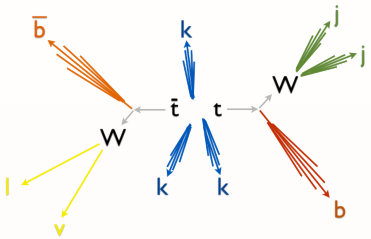
- The $\bar{\text{t}}\text{t}$ signal probability can be expressed as:

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

- The overall sample likelihood is calculated by combination:

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

Bi-Event Subtraction Technique (BEST)



- testing mass determination method that may be used in beyond SM physics scenarios
- subtracting combinatorial background due to inclusion of particles which do not come from the cascade decay of interest
  $\hookrightarrow$ combining jet information from a different event several times for the same decay chain reconstruction
  - m_{jj}^{same} dijet invariant mass distribution from one sample
  - m_{jj}^{bi} dijet invariant mass distribution from a bi-event sample not coming from a W
  - $m_{jj}^{BEST} = m_{jj}^{same} - C_{jj}^{BEST} \cdot m_{jj}^{bi}$ showing a W-boson mass peak almost without combinatorial background

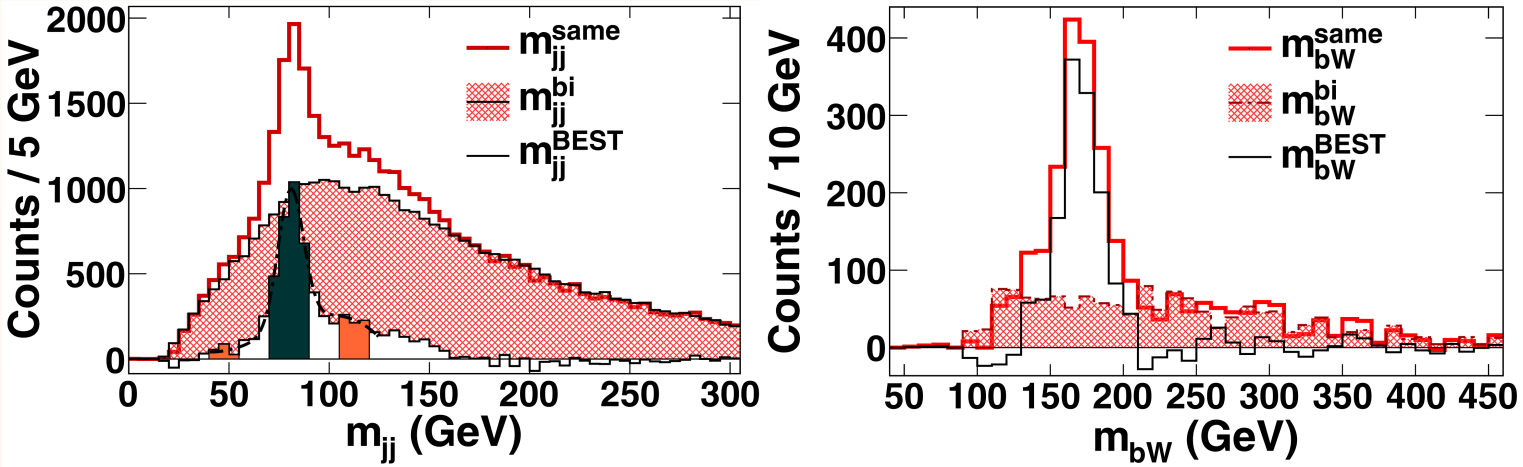


Figure 15: Dijet invariant mass distribution (left) and W+b invariant mass distribution (right) using BEST.

Phys. Lett. B 703:475 (2011)

Top quark-antiquark mass difference

CMS PAS TOP-12-031

A test of CPT symmetry

- selecting semi-leptonic $t\bar{t}$ events among $\sqrt{s} = 8$ TeV data (18.9 fb^{-1})
- measuring $\Delta m_t = m_t - m_{\bar{t}}$

The ideogram likelihood method

- Using a kinematic fit to reconstruct the mass of the hadronically decaying top-quark assuming $m_{W^-} = m_{W^+} = 80.4$ GeV/c^2
- Applying the analysis separately to $\ell^+ +$jets events and to $\ell^- +$jets events

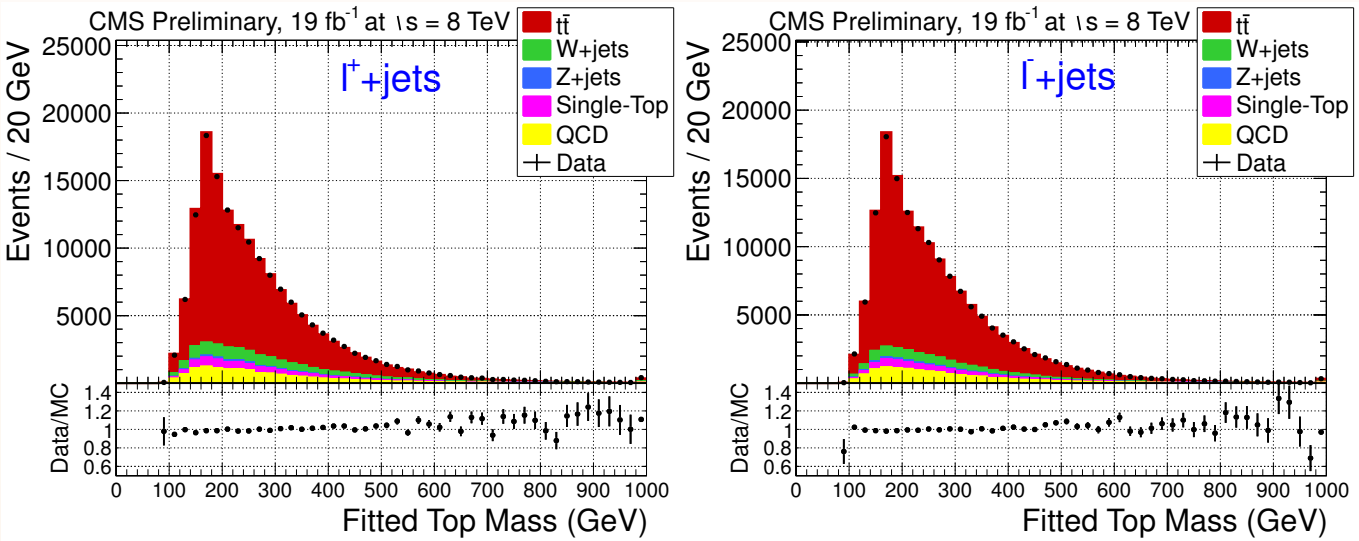


Figure 16: Distributions of the fitted top-quark mass for $\ell^+ +$jets events (left) and $\ell^- +$jets events (right).

Color (re)connection effects

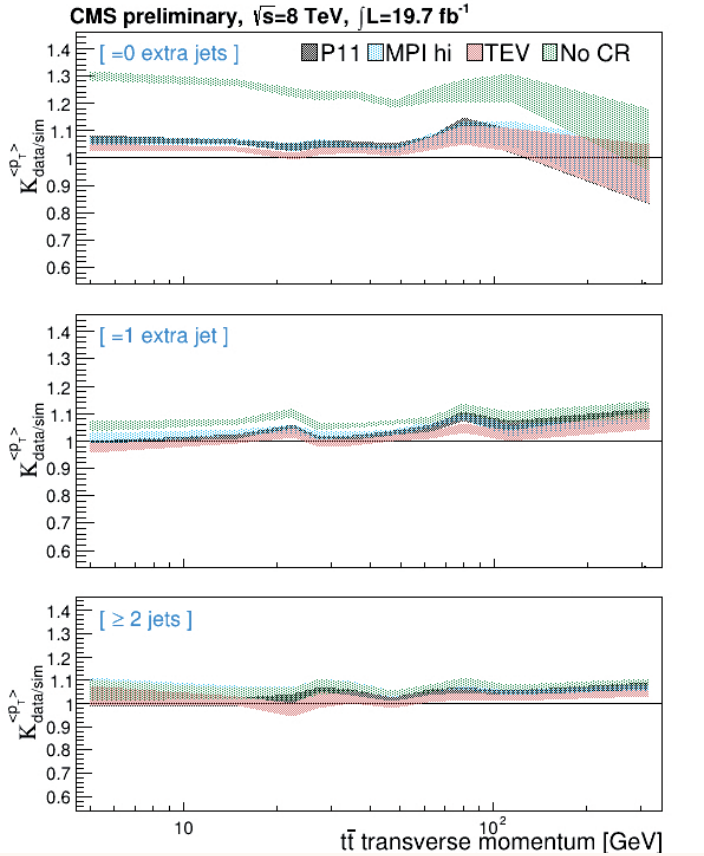
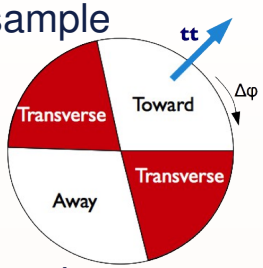


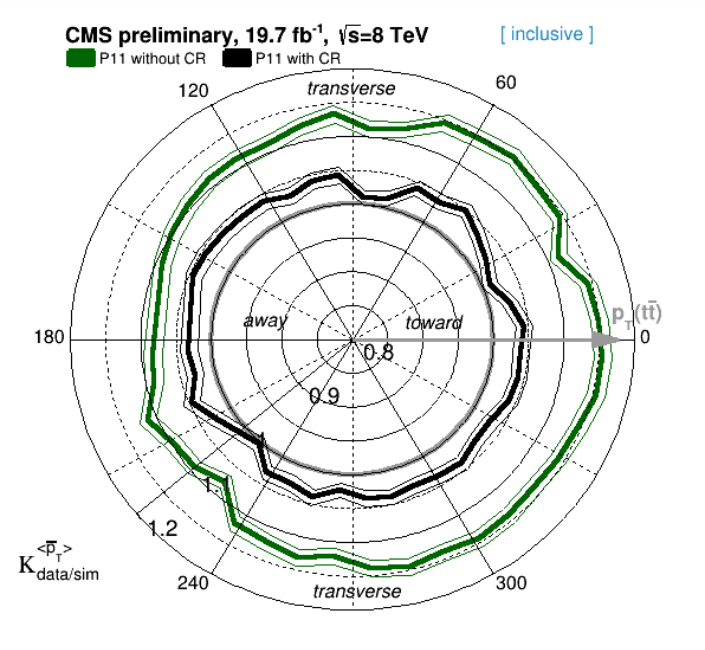
Figure 17: Data-to-simulation scale factors for the average p_T of charged particles as function of $p_T(t\bar{t})$.

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

- selecting a high purity dilepton sample
- characterizing the soft charge activity after the subtraction of the estimated contribution from the hard process



- using the $t\bar{t}$ system direction for each event to factorize the recoil contribution
- comparing data to MC for several Perugia 11 variations

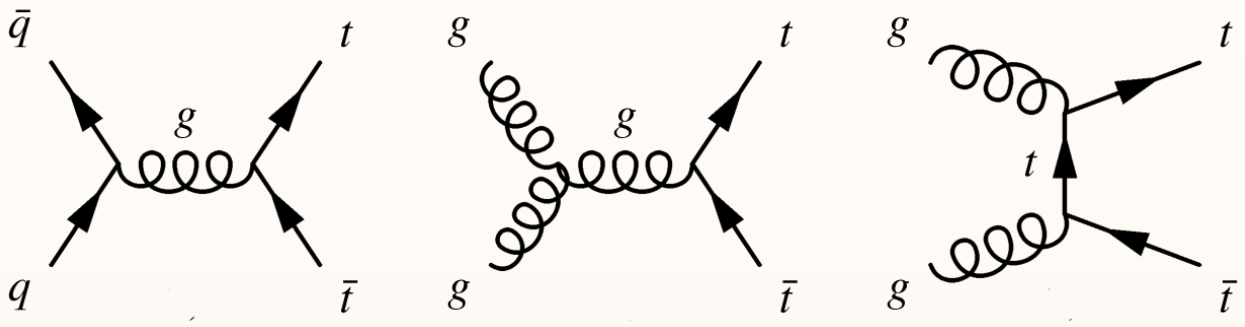


CMS PAS TOP-13-007

Figure 18: Data-to-simulation scale factors for the average p_T of charged particles as function of the angle to the $t\bar{t}$ direction.

Top-quark production

- Pair production at the LHC:
  - @ 7 TeV : $\sigma_{t\bar{t}} = 139 \pm 10(\text{stat.}) \pm 26(\text{syst.}) \pm 3(\text{lum.})$ pb — JHEP 1305 (2013) 065
  - @ 8 TeV : $\sigma_{t\bar{t}} = 239 \pm 2(\text{stat.}) \pm 11(\text{syst.}) \pm 6(\text{lum.})$ pb — JHEP 02 (2014) 024
  - 85% gluon fusion



- Decay width ~ 1.4 GeV/c^2 ; lifetime $\sim 5 \cdot 10^{-25}$ s
- Decaying into b-quarks through W-boson emission instead of hadronizing