

First measurements of top quark mass and other properties with Run 2 data in CMS

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on behalf of the CMS Collaboration



Universität Hamburg
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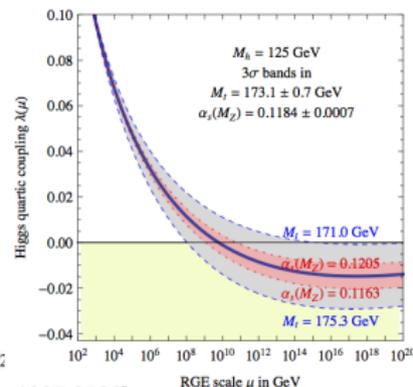
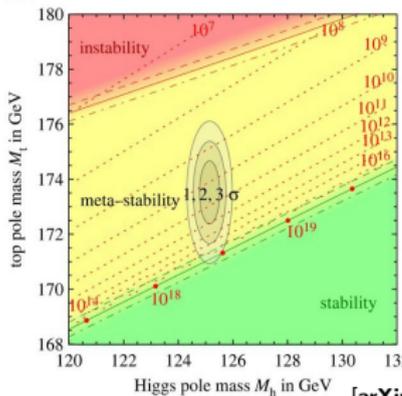
Introduction

Top quark mass (m_t)

- fundamental parameter of the Standard Model
- crucial role in the electroweak symmetry breaking
- dominant contribution to Higgs boson mass radiative corrections
- related with EW vacuum stability

$$\lambda_t = \frac{\sqrt{2}m_t}{v} \simeq 1$$

- Standard Model may stay consistent up to M_{Pl}
- quartic coupling $\lambda(\mu)$ depends heavily on m_t , may turn negative \Rightarrow vacuum instability



[arXiv:1307.3536]

Top quark width (Γ_t), inversely proportional to its life time

- expected to be of order 1 GeV
- deviation from the SM prediction \Rightarrow indicate non-SM decay channels

Achievements of m_t measurements

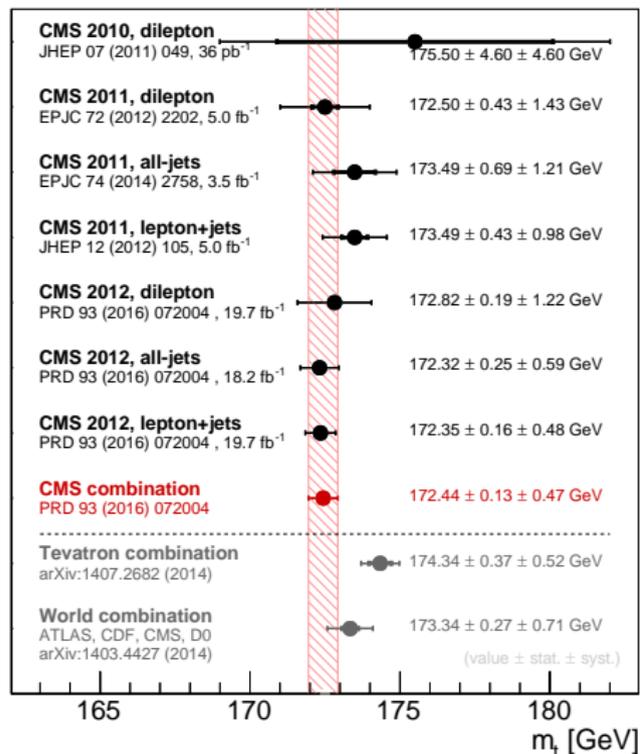
Decays before hadronizing

⇒ measure m_t directly

from decay products

This talk:

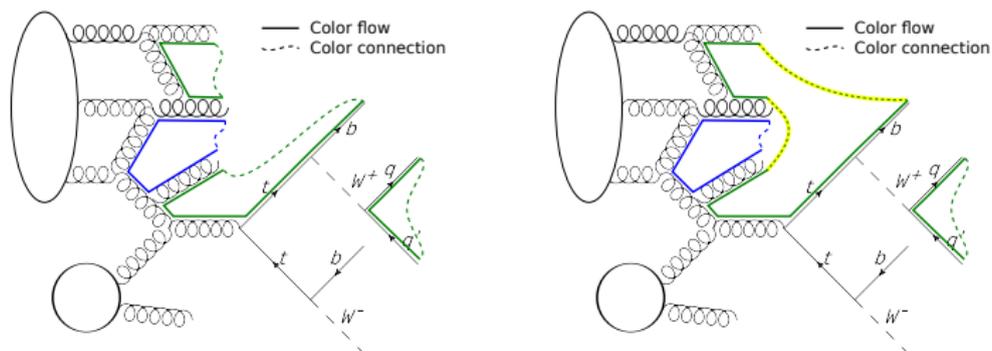
- first measurement of m_t at 13 TeV in the ℓ +jets final state [arXiv:1805.01428] in the all-jets final state [CMS-PAS-TOP-17-008]
- first direct top quark width measurement at 13 TeV [CMS-PAS-TOP-16-019]



[arXiv:1509.04044]

What is new compared to measurement of m_t at 8 TeV?

- data collected at $\sqrt{s} = 13 \text{ TeV}$
in 2016 with CMS detector, $\mathcal{L} = 35.9 \text{ fb}^{-1}$
- $t\bar{t}$ cross section is 3 times larger
- MC is based on new **NLO ME** (POWHEG) and
new PS implementation (PYTHIA8)
- new underlying event tune
- new **color reconnection** tunes: **“QCD-based”** and **“Gluon move”**
[arXiv:1505.01681] [arXiv:1407.6653]
(see O. Zenaiev's talk for more detail)



Golden channel for m_t measurement

- for $\mu/e + \text{jets}$ BR $\sim 30\%$
- small contamination from BG

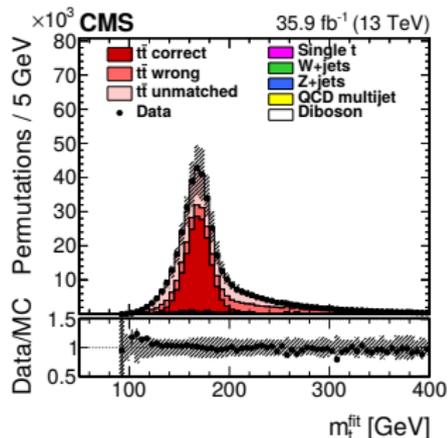
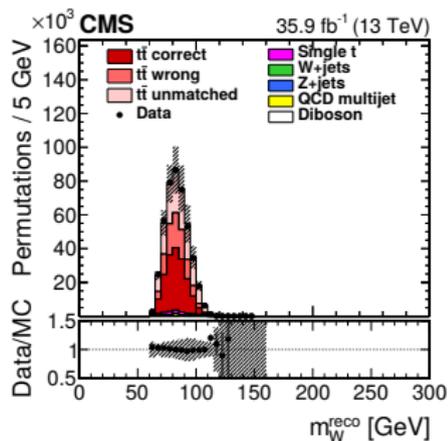
► Selection

exactly 1 isolated lepton, ≥ 4 jets,
exactly 2 b tagged jets

► Kinematic fit to a $t\bar{t}$ hypothesis

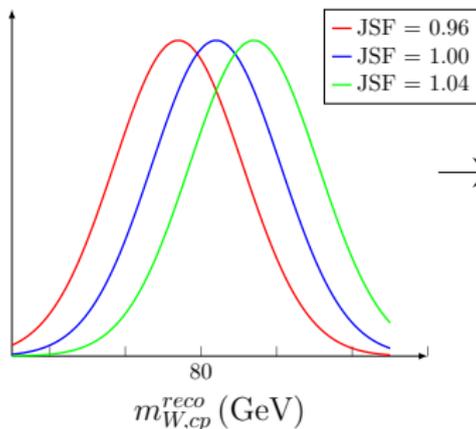
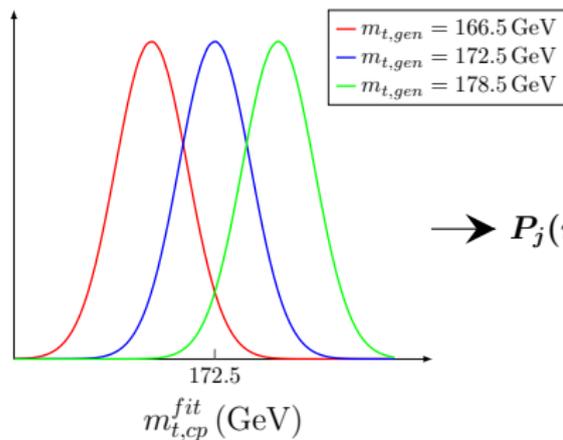
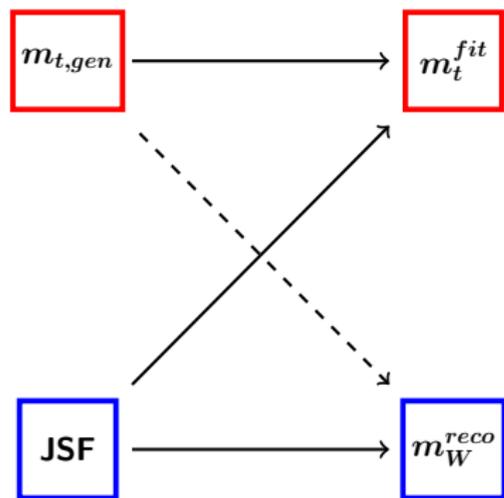
- 1 unknown
- 3 constraints
 - $m_{W_{q_h a'_h}} = m_{W_{l\nu}} = 80.4 \text{ GeV}$
 - $m_t = m_{\bar{t}}$,
 - 2 ν_l solutions

$$P_{\text{gof}} = \exp\left(-\frac{1}{2}\chi^2\right) > 0.2 \text{ increase } f_{cp} \\ \text{from } \mathbf{15\%} \Rightarrow \mathbf{46\%}$$



Ideogram method

Simultaneous measurement of m_t and jet scale factor (JSF)



Ideogram method

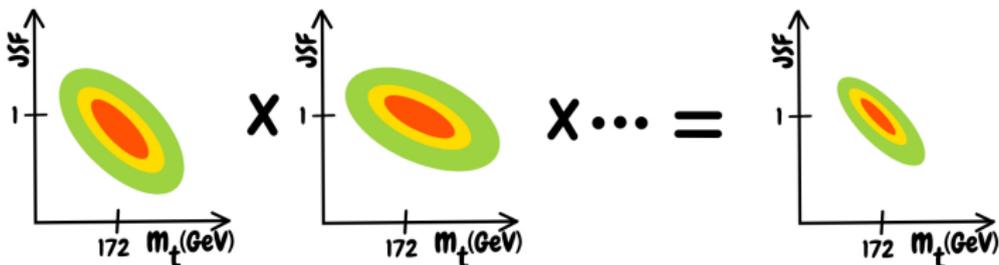
- 2D permutation probability density for all allowed permutation

$$P(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}} | m_t, \text{JSF}) = \sum_j f_j P_j(m_{t,i}^{\text{fit}} | m_t, \text{JSF}) \times P_j(m_{W,i}^{\text{reco}} | m_t, \text{JSF}),$$

- $\mathcal{L}(\text{event} | m_t, \text{JSF}) = \left(\sum_{i=1}^n P_{\text{gof}}(i) P(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}} | m_t, \text{JSF}) \right)^{w_{\text{evt}}}$

- $\mathcal{L}(\text{sample} | m_t, \text{JSF}) \sim P(\text{JSF}) \cdot \prod_{\text{events}} \mathcal{L}(\text{event} | m_t, \text{JSF})$

- **most likely m_t and JSF:** $-2\ln\mathcal{L}(\text{sample} | m_t, \text{JSF})$



1D approach $P(\text{JSF}) = \delta(1)$

2D approach unconstrained JSF

Hybrid approach JSF constraints from jet-energy uncertainties

Results on m_t from ℓ +jets at 13 TeV [arXiv:1805.01428]

- dominant uncertainties

	2D approach		1D approach	Hybrid
	δm_t^{2D} (GeV)	δJSF^{2D} (%)	δm_t^{1D} (GeV)	δm_t^{hyb} (GeV)
JEC	0.13	0.2	0.83	0.18
JEC: Flavor	0.42	0.1	0.31	0.39
ME generator	0.19	0.1	0.29	0.22
ERD	0.22	0.8	0.42	0.03
CR modeling	0.34	0.1	0.23	0.31

- alternative CR models developed and tuned to data \Rightarrow

$\delta m_t = m_t(\text{CR default}) - m_t(\text{CR alt}) \Rightarrow$
more reliable estimation of CR uncertainty

NEW!

- for the first time* different CR models are used to measure m_t

$$m_t^{\text{hyb}} = 172.25 \pm 0.08 \text{ (stat+JSF)} \pm 0.62 \text{ (syst) GeV,}$$
$$\text{JSF}^{\text{hyb}} = 0.996 \pm 0.001 \text{ (stat)} \pm 0.008 \text{ (syst)}$$

m_t from all-jets at 13 TeV [CMS-PAS-TOP-17-008]

NEW!

- full kinematics available, large BR $\sim 44\%$
- large QCD BG contamination

► Selection

≥ 6 jets, exactly 2 b tagged, $\Delta R_{b\bar{b}} > 2.0$

► Background estimation

Data-driven method:

★ same selection, but **exactly 0** b tags

★ veto with very loose b tagger

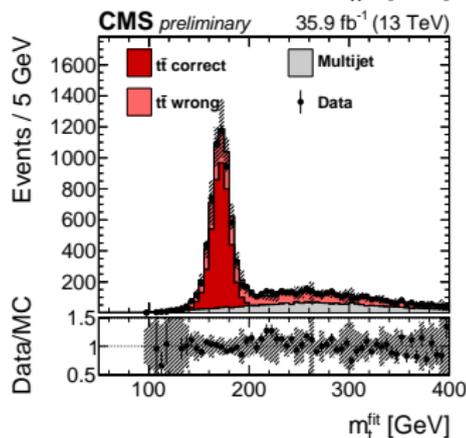
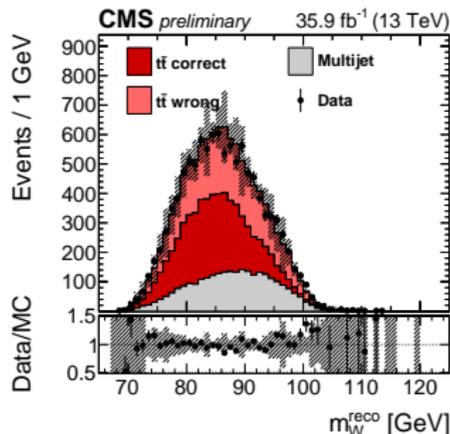
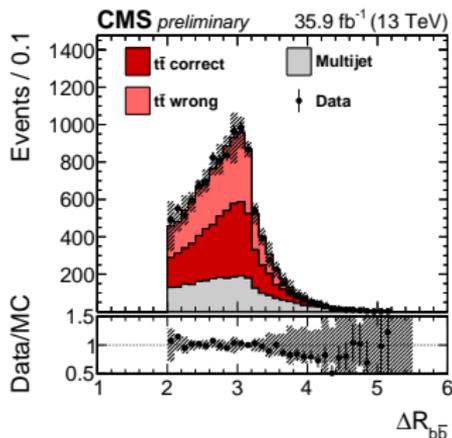
⇒ no signal contamination

► Kinematic fit

$$m_t = m_{\bar{t}},$$

$$m_W = 80.4 \text{ GeV},$$

$$P_{gof} > 0.1$$



NEW!

- *ideogram method* to extract m_t and JSF
- dominant uncertainties

	2D approach		1D approach	Hybrid
	δm_t^{2D} (GeV)	δJSF^{2D} (%)	δm_t^{1D} (GeV)	δm_t^{hyb} (GeV)
JEC	0.18	0.3	0.73	0.15
JEC: Flavor	0.35	0.1	0.31	0.34
ME generator	0.34	0.1	0.36	0.31
ERD	0.28	0.4	0.38	0.24
CR modeling	0.41	0.4	0.43	0.36

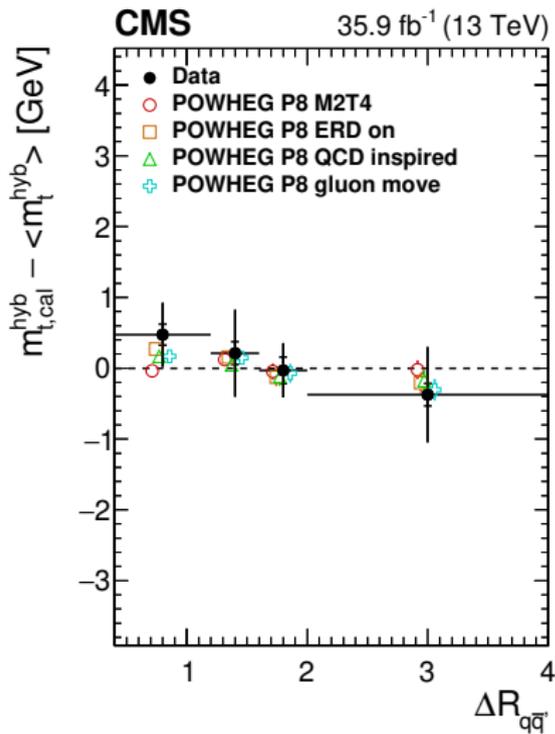
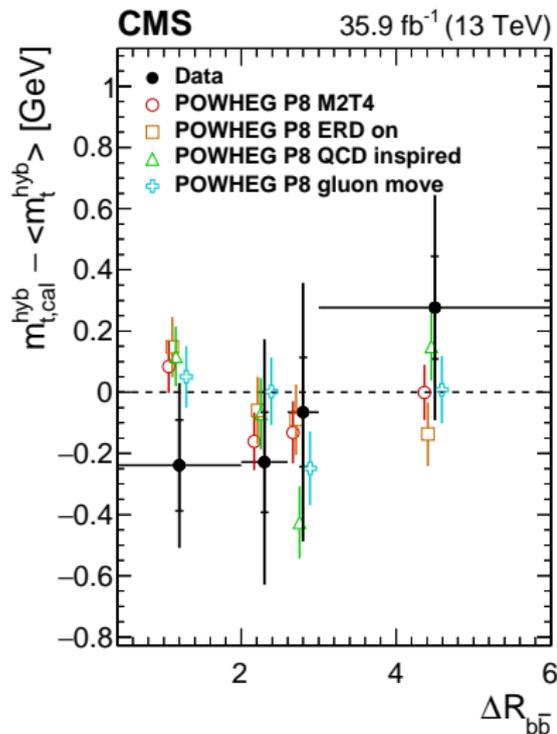
- more sophisticated CR estimation
(same procedure as for ℓ +jets)

$$m_t^{\text{hyb}} = 172.34 \pm 0.20 \text{ (stat+JSF)} \pm 0.76 \text{ (syst)} \text{ GeV},$$

$$\text{JSF}^{\text{hyb}} = 0.997 \pm 0.002 \text{ (stat)} \pm 0.007 \text{ (syst)}$$

Differential m_t study [arXiv:1805.01428]

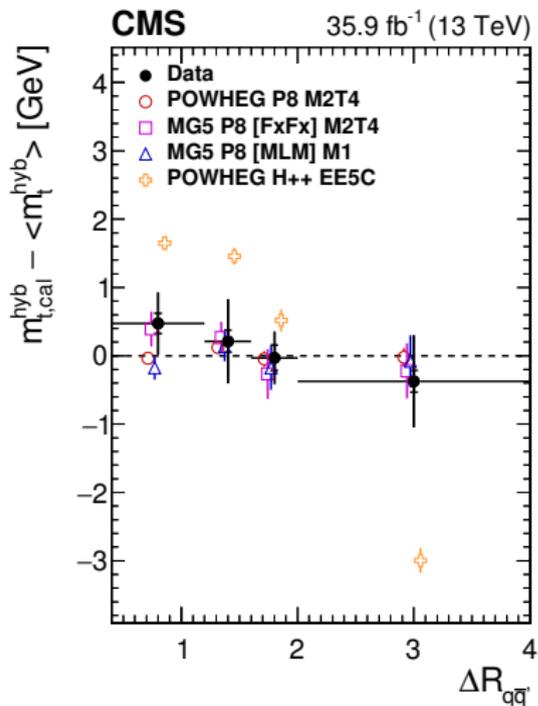
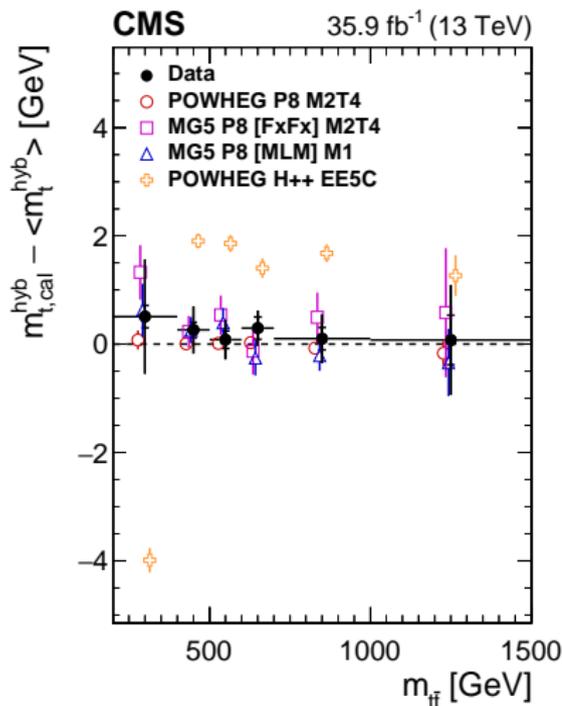
- compare different CR models



Better statistical uncertainty for full dataset at 13 TeV

Differential m_t study [arXiv:1805.01428]

- check for different MC generators



Including ME corrections to the top quark decay in Herwig++ reduces the deviation but it is still present (see arXiv:1509.04044)

Top quark width at 13 TeV [CMS-PAS-TOP-16-019]

CMS first direct measurement at 13 TeV

- larger dataset \Rightarrow fine-grained analysis
- dilepton channel used
- very small BG contamination
- small BR

► **Selection:** $ee, \mu\mu, e\mu$

two opposite-charge leptons
two jets, ≥ 1 b tag

► **Background estimation**

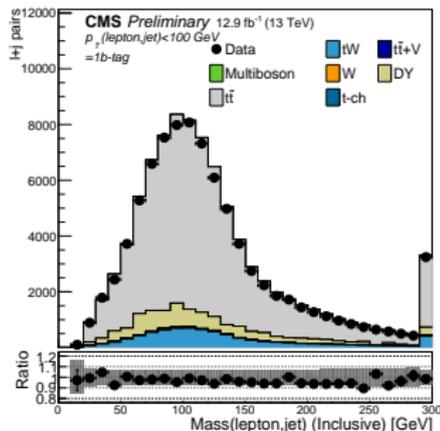
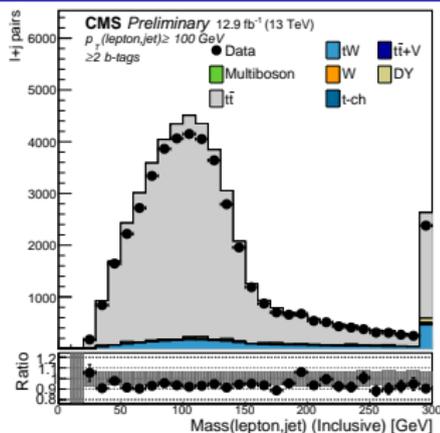
data from Z pole mass is used
for Drell-Yan BG estimation

► **Sensitive distribution:**

inclusive mass of the (lepton, b)

► **Categories:**

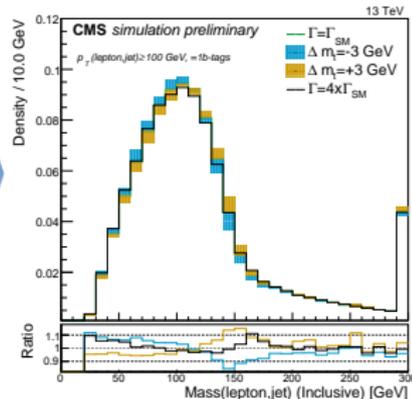
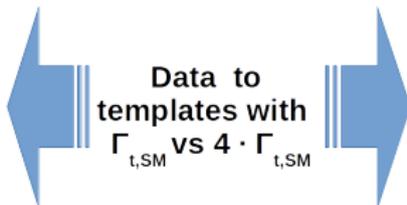
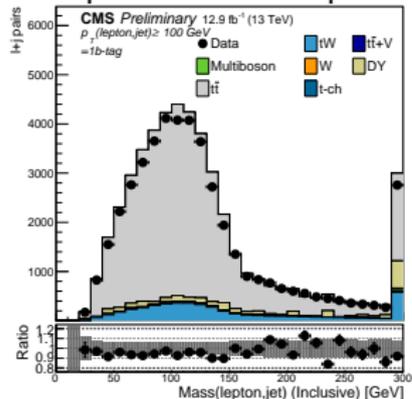
=1 or ≥ 2 b tagged;
boosted or non-boosted



Top quark width at 13 TeV [CMS-PAS-TOP-16-019]

► Hypotheses tested:

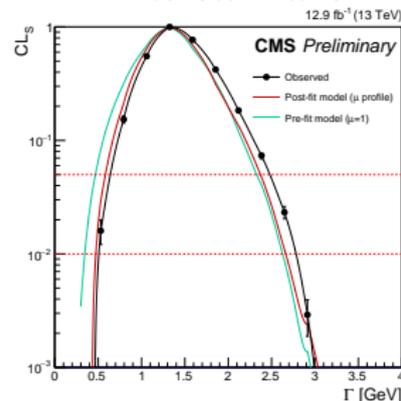
compare the SM expectation for different width scenarios to data



hypotheses separation measured via CL_s criterion

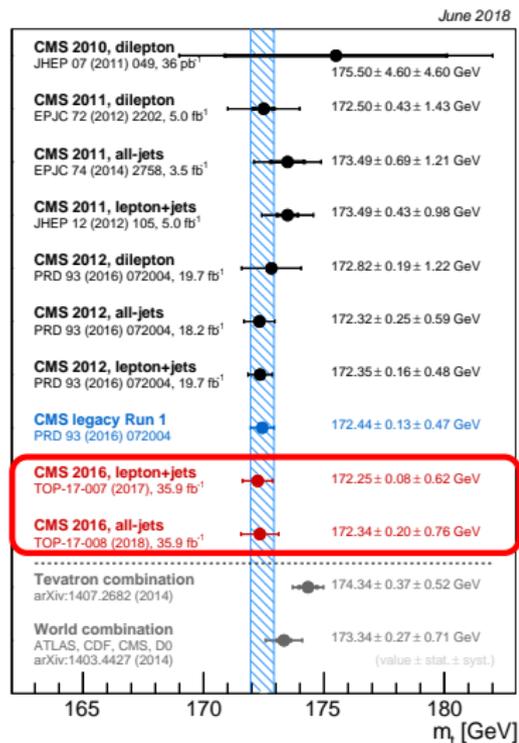
$0.6 < \Gamma_t < 2.5$ GeV at 95% CL,
 expected bounds at 95% CL:
 $0.6 < \Gamma_t < 2.4$ GeV

- ⇒ the most precise direct bound of the top quark width performed to date!
- ⇒ systematically limited by MC modeling



Conclusions

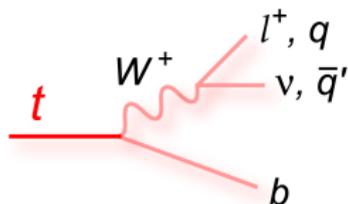
- for the first time m_t is measured at $\sqrt{s} = 13$ TeV at CMS
- both ℓ +jets and all-jets decay channels are investigated
- measured m_t is stable when using higher order ME calculations (NLO MC) and with soft QCD effects (new UE tune)
- the possible biases arising from color reconnection are probed in a differential m_t study
- CMS first direct measurement of the top quark width are performed at $\sqrt{s} = 13$ TeV
- the most precise direct bound of the top quark width performed to date



- Top quark mass definition
- Color reconnection in $t\bar{t}$
- Indirect Measurement

Top quark mass definition

- ▶ decays before hadronizing
⇒ measure m_t directly
from decay products



- ▶ in theory m_t needs to be renormalized
⇒ to account for the loop contributions to the fermion propagator, subtract the UV divergences in the self energy $\Sigma(p, m_0)$

$$\text{---}\text{---}\text{---} + \text{---}\text{---}\text{---} = \frac{i}{\not{p} + m_0 - \Sigma(p, m_0)}$$

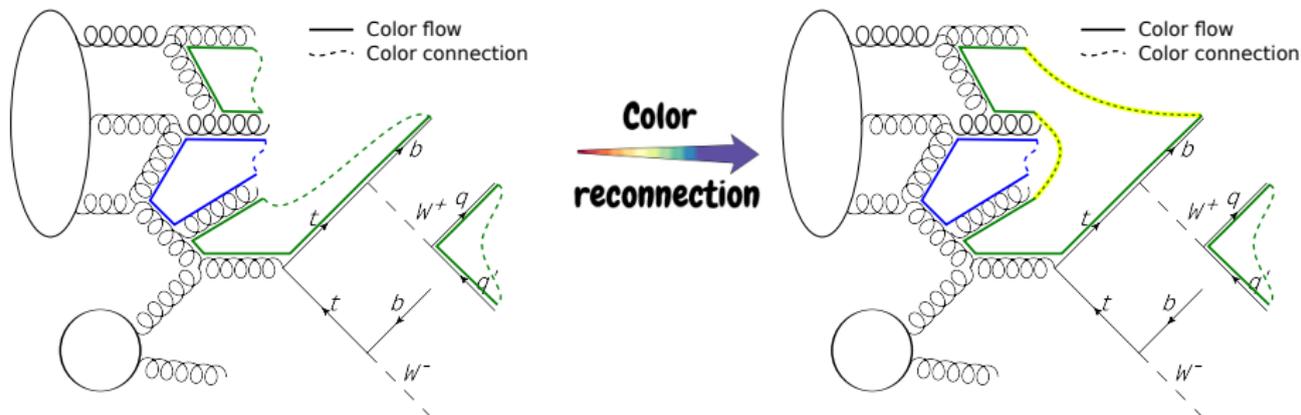
- **Pole mass** the pole is fixed order by order
- **$\overline{\text{MS}}$ mass** the pole is shifted at each order

$$m_{\text{pole}} = m_{\overline{\text{MS}}} \left(1 + 0.4244\alpha_S + 0.8345\alpha_S^2 + 2.375\alpha_S^3 + \dots \right) + \mathcal{O}(\Lambda_{QCD})$$

m_{pole} and $m_{\overline{\text{MS}}}$ differ already at the NLO

Color reconnection in $t\bar{t}$

CR affects the reconstruction of the top quark system



Early Resonance Decay (ERD) option for top quark:

- ERD “on” decay products of the top quark can color reconnect to other partons
- ERD “off” top quark can colour reconnect to other partons

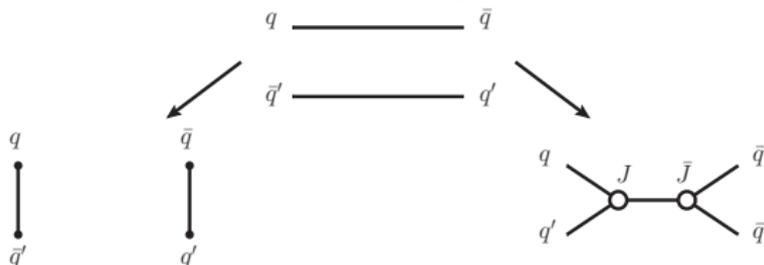
Color reconnection models in Pythia 8

MPI-based

- reconnections are chosen randomly
- softer systems \Rightarrow higher reconnection probability

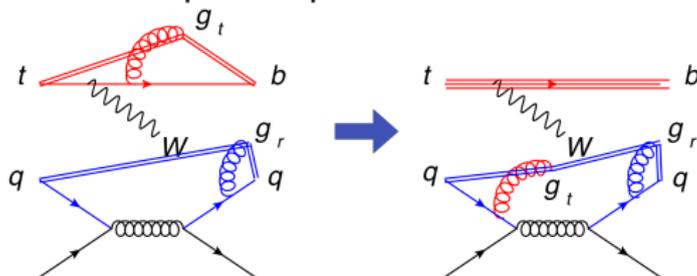
QCD-based

- uses QCD color rules to construct the pairs of dipoles
- allows the creation of junction structures



Gluon move

- gluons are moved to a string piece belonging to a different pair of partons



	2D approach		1D approach	Hybrid
	δm_t^{2D} (GeV)	δJSF^{2D} (%)	δm_t^{1D} (GeV)	δm_t^{hyb} (GeV)
POWHEG P8				
ERD on	-0.22	+0.8	+0.42	-0.03
QCD inspired	-0.11	-0.1	-0.19	-0.13
gluon move	+0.34	-0.1	+0.23	+0.31

- m_W^{reco} observable is affected more when including ERD
- “gluon move” leads to larger shifts
- simultaneously determined JSF reduces the modeling uncertainty

The validation of new CR models should be performed

m_t^{pole} from $\sigma_{t\bar{t}}$ at 13 TeV [arXiv:1701.06228]

- extract m_t^{pole} value using the expected dependence of $\sigma_{t\bar{t}}$ on the pole mass of the top quark

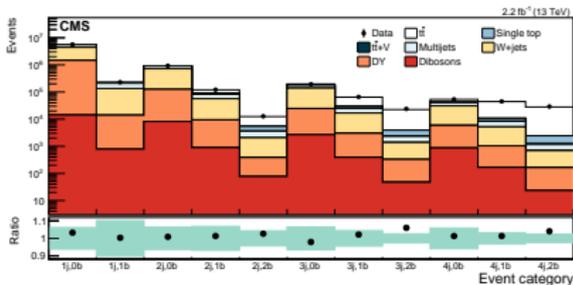
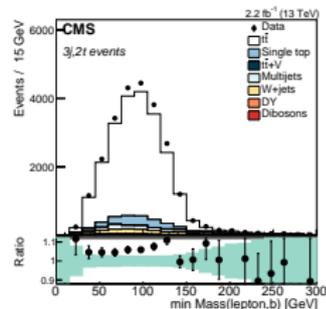
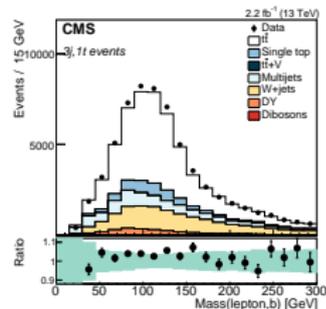
- **Selection: l+jets**

1 isolated μ/e , ≥ 1 jet

- **Multiple categories:**

e.g. Njets, b-tagged jet, lepton flavour, charge (total 44 categories)

- simultaneous binned likelihood fit to $M_{l\bar{b}}$ or $\min(M_{l\bar{b}})$



- $M_{l\bar{b}}$ is used for events with one b-tag
- $\min(M_{l\bar{b}})$ is used for events with more than one b-tag

m_t^{pole} from $\sigma_{t\bar{t}}$ at 13 TeV [arXiv:1701.06228]

- $\sigma_{t\bar{t}}$ measured by performing a maximum-likelihood fit to event numbers in each category
- signal expectation is modulated by a multiplicative factor $\mu = \sigma/\sigma_{\text{th}}$
- parameterize dependence of measured $\sigma_{t\bar{t}}$ on m_t^{pole} by transforming μ into a functional form that depends on m_t^{pole}

$$\mu(m_t^{\text{pole}}) = \frac{\sigma(m_t^{\text{pole}})}{\sigma_{\text{th}}} \frac{A}{A(m_t^{\text{pole}})} \quad (\text{corrected to the acceptance})$$

Dominant Uncertainties

from fit in the fiducial region ~ 2.2 GeV

Extrapol. to the full phase space ~ 1.1 GeV

μ_R/μ_F and PDF+ $\alpha_S \sim 0.9$ GeV

$$m_t^{\text{pole}} = 170.6 \pm 2.7 \text{ GeV}$$

