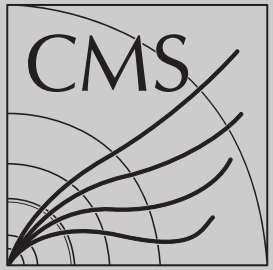
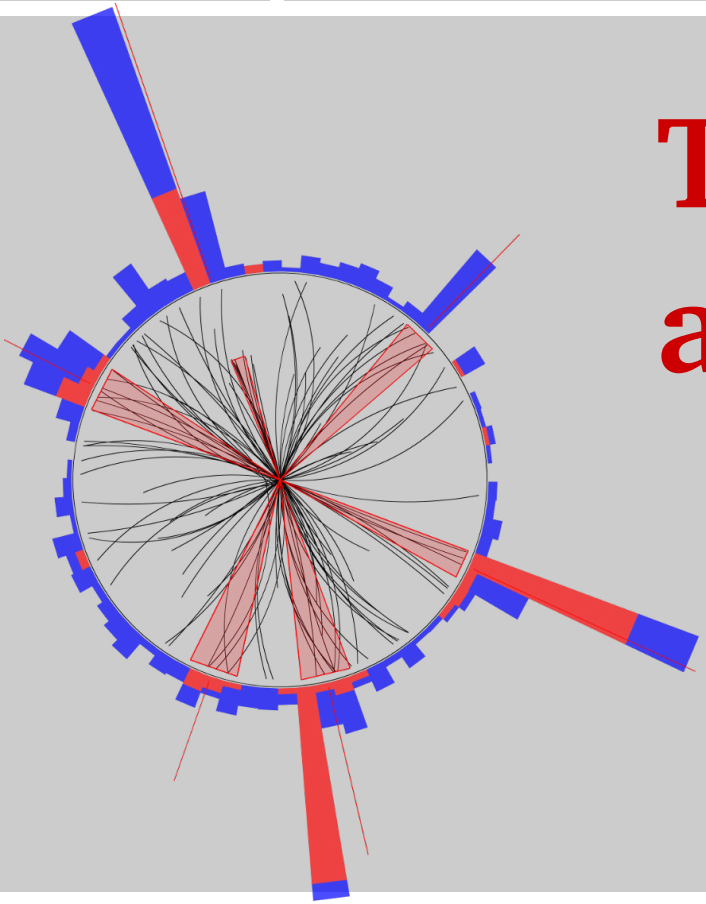


11th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"

Tuesday 28th November, 2017



Top quark mass at CMS in Run II

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Christoph Garbers

Johannes Lange
johannes.lange@cern.ch

Hartmut Stadie

Nataliia Kovalchuk

Peter Schleper

Fred Stober

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

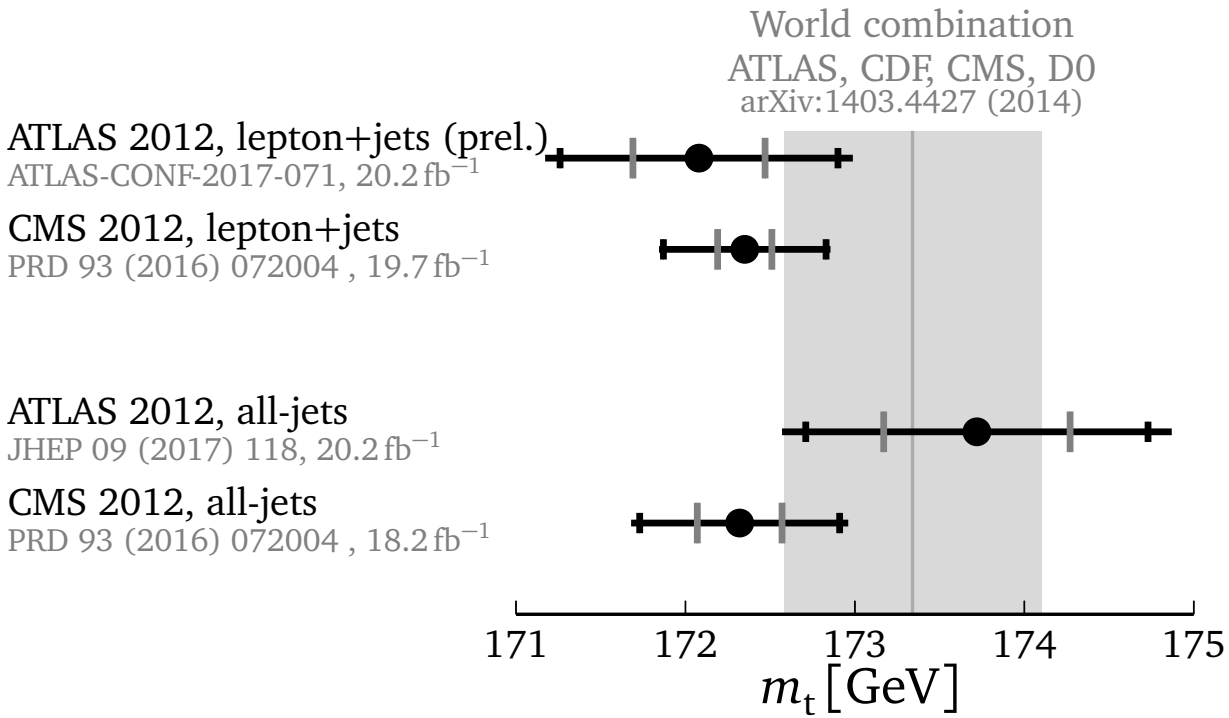
Introduction

Status of "classical" m_t measurements in Run II

- lepton+jets [CMS-PAS-TOP-17-007]
- all-jets [work in progress]
- (near) future plans

improvements w.r.t. Run I:

- $3 \times \sigma_{t\bar{t}}$
- $2 \times \mathcal{L}$
- NLO MC



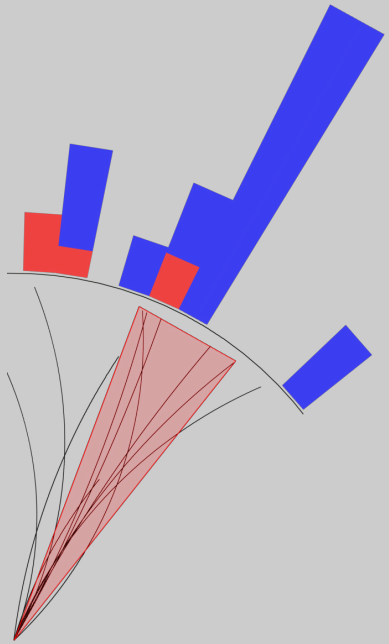
Object definitions

Jets

- clustered with anti-k_t algorithm ($D = 0.4$) from particle flow (PF) objects
- charged hadron subtraction
- $p_\mathrm{T} > 30\,\mathrm{GeV}$
- $|\eta| < 2.4$
- $H_\mathrm{T} = \sum_\mathrm{jets} p_\mathrm{T}$
- CSVv2 b tagger: medium/tight WP

  efficiency $\approx 69/49\,\%$

  mistag rate $\approx 1/0.1\,\%$



Muons

$p_\mathrm{T} > 26\,\mathrm{GeV}$, $|\eta| < 2.4$

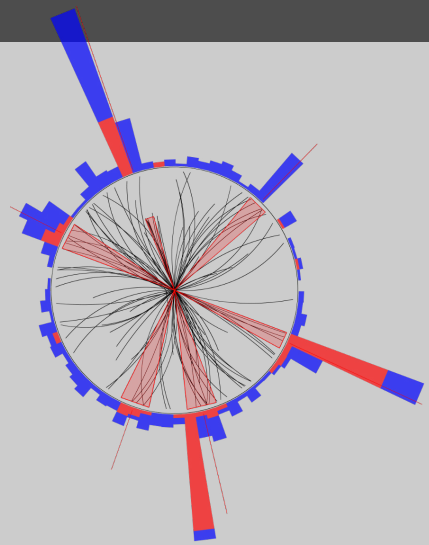
Electrons

$p_\mathrm{T} > 34\,\mathrm{GeV}$, $|\eta| < 2.1$

Event selection

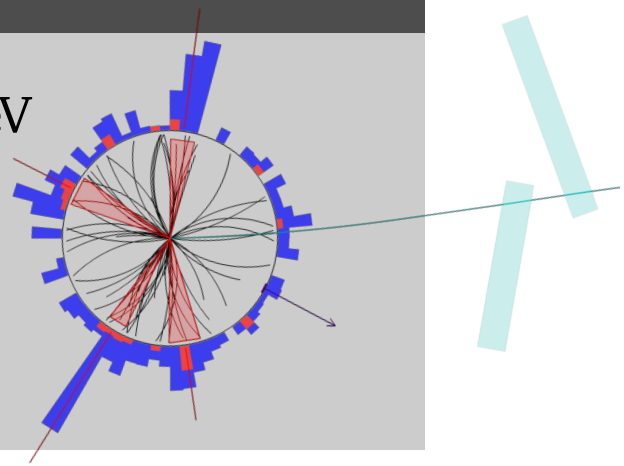
All-jets

- trigger: six jets, one b tag
- $H_T > 450\,\text{GeV}$
- six jets, $p_T > 40\,\text{GeV}$
- two tight b tags
- $\Delta R(b\bar{b}) > 2.0$

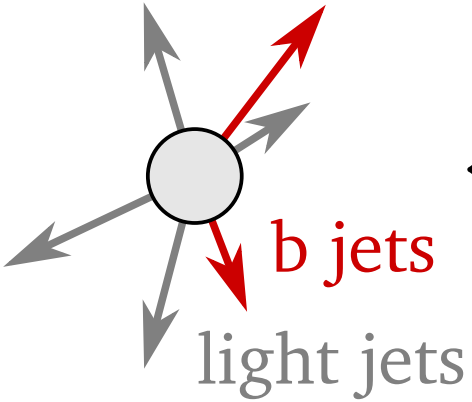


ℓ+jets

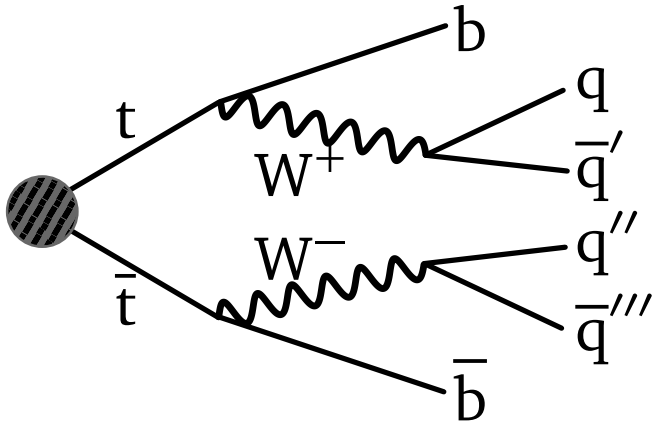
- trigger: isolated μ/e with $p_T > 24/32\,\text{GeV}$
- exactly one isolated lepton ($\ell = \text{e}, \mu$)
- four jets
- two medium b tags



Kinematic fit



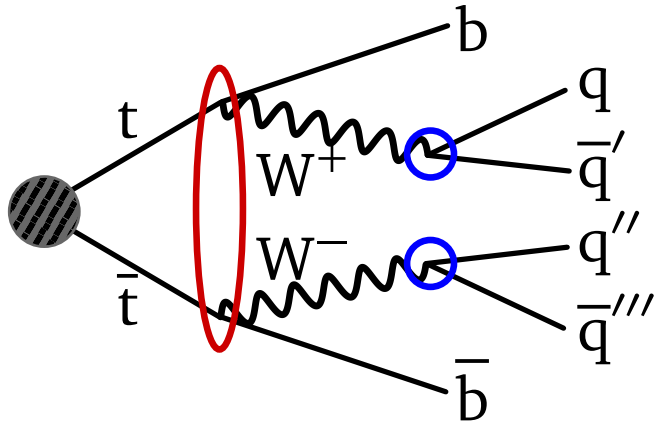
?



Kinematic fit

Known decay topology:

- pair production of heavy particle and anti-particle
- each decaying to Wb
- $W \to q\bar{q}'$ or $W \to \ell\,\nu$



Minimize χ^2 with constraints: $m_{W^+} = m_{W^-} = 80.4\,\text{GeV}, m_t = m_{\bar{t}}$

- trying all possible parton-jet assignments
- only b-tagged jets used as b candidates

all-jets

- 12 possibilities for parton-jet assignment
- only best assignment used

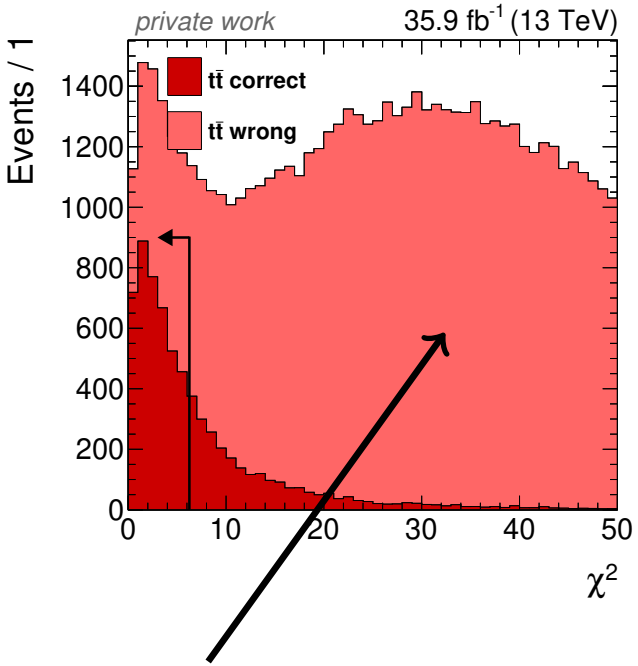
$P_{\text{gof}}(\chi^2) > 0.1$

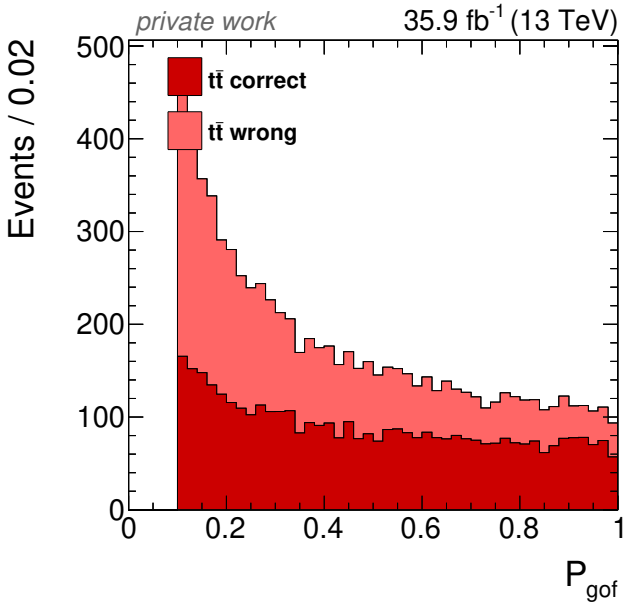
ℓ+jets

- 2 assignment possibilities
- neutrino: 2 solutions for z component
- all 4 permutations used

$P_{\text{gof}}(\chi^2) > 0.2$

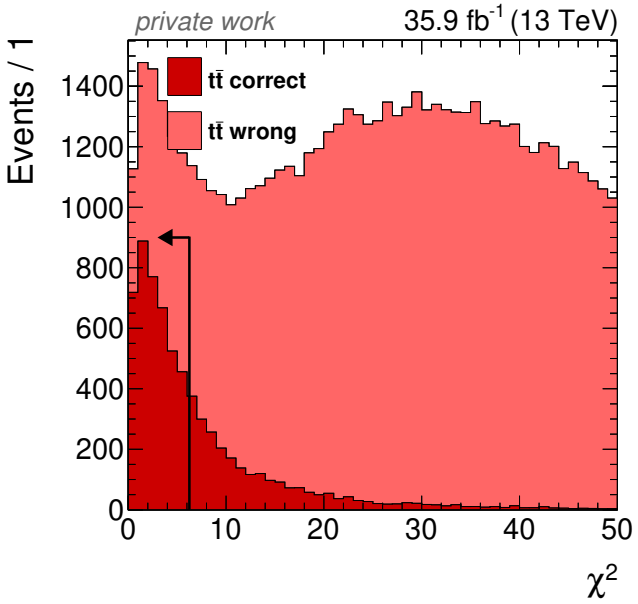
Kinematic fit
Best permutation selected by fit

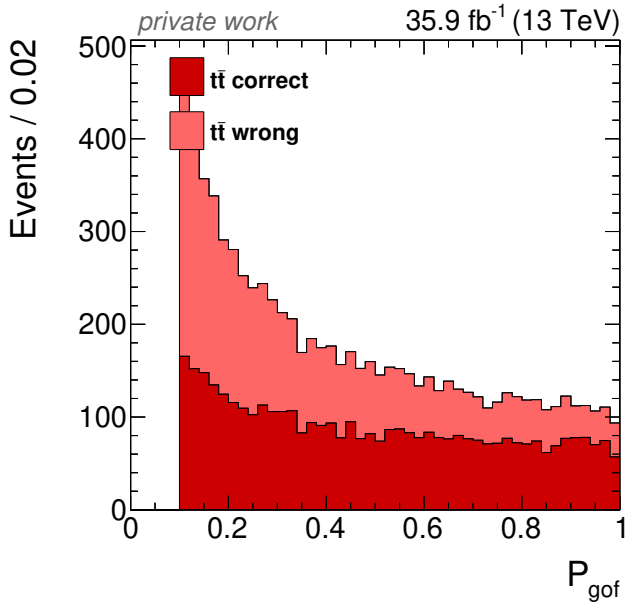




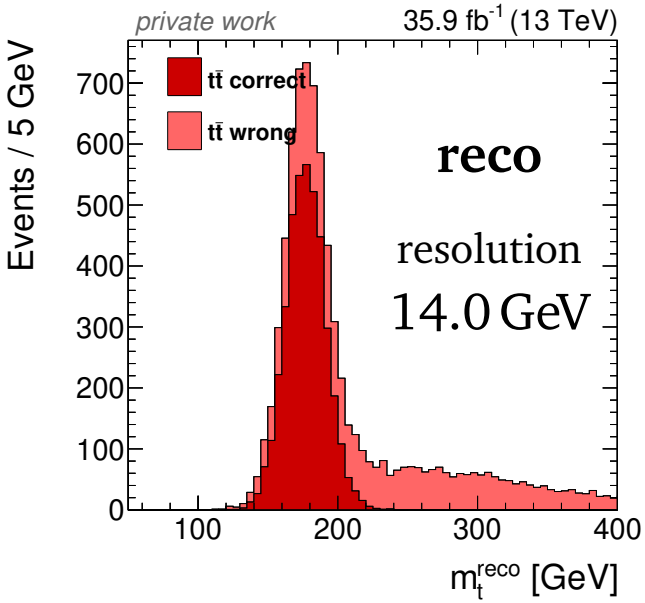
wrong parton-jet assignment

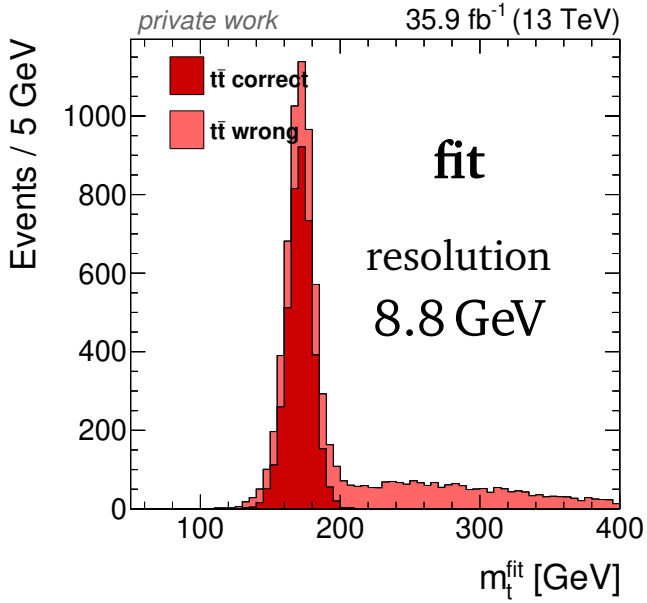
Kinematic fit
Best permutation selected by fit





$P_{\text{gof}} > 0.1$

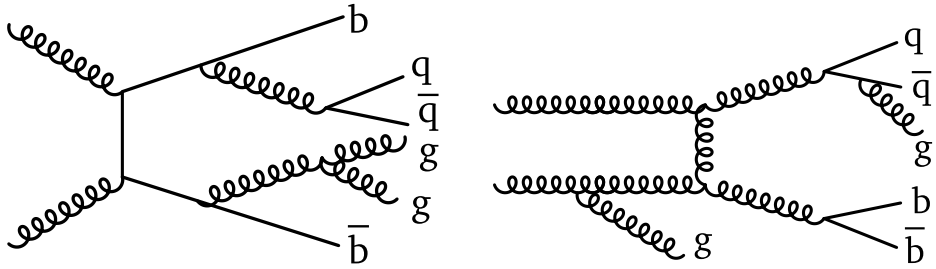




Background estimation

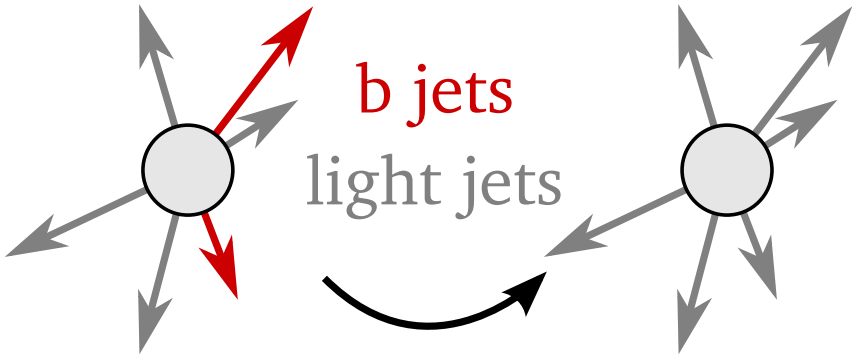
- ℓ+jets almost background-free → taken from MC

- QCD multijet production: huge cross section
- non-negligible contribution passing the P_{gof} cut
- purely combinatorial



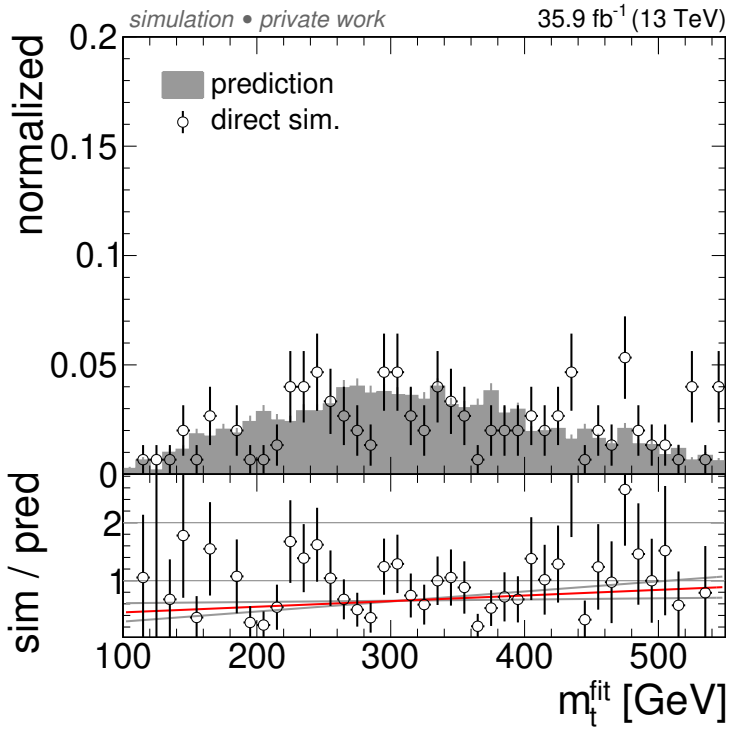
Data-driven estimation:

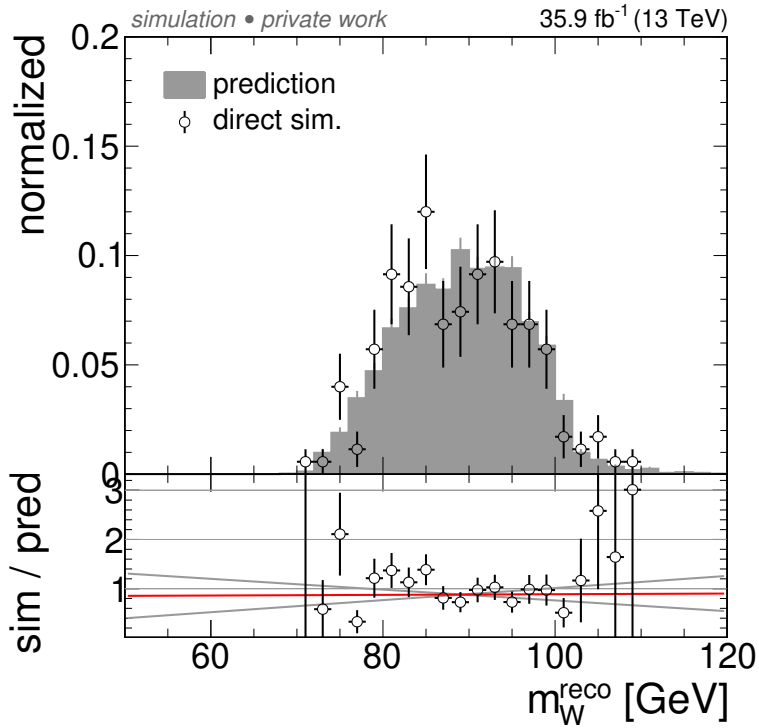
- same selection as before, but **exactly 0** b tags
- veto with very loose b tagger ⇒ no signal contamination
- kinematic fit: 90 possible permutations



Background estimation
Test on simulation

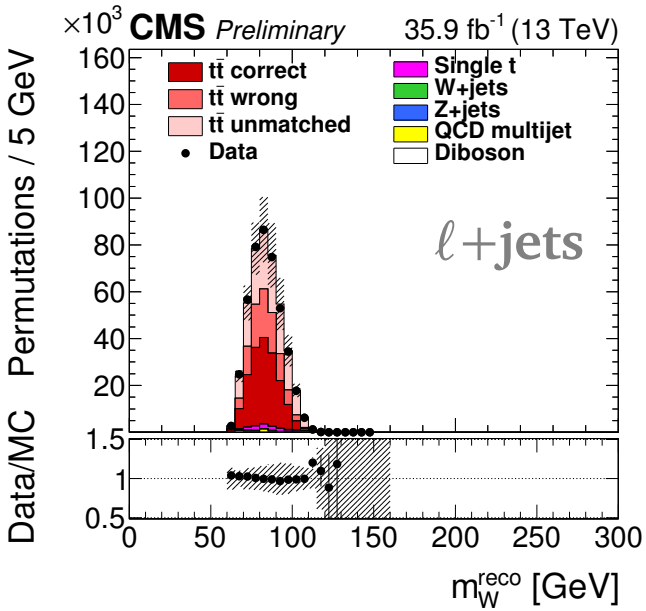
Apply method to QCD MC and compare to direct signal selection

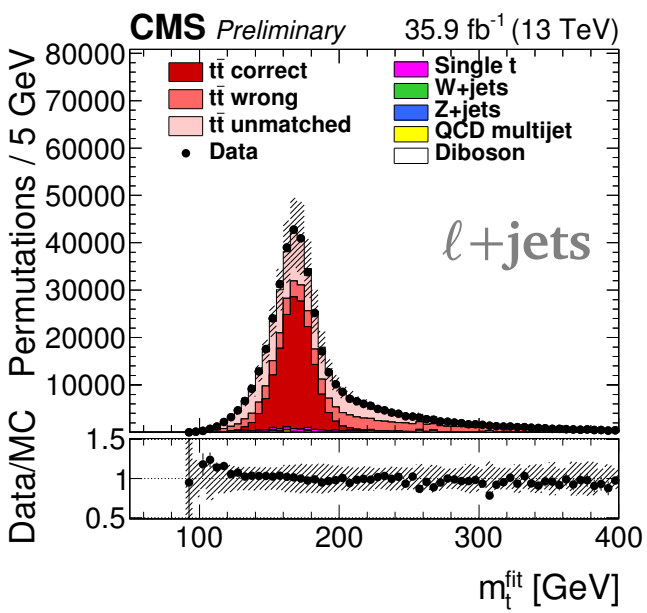


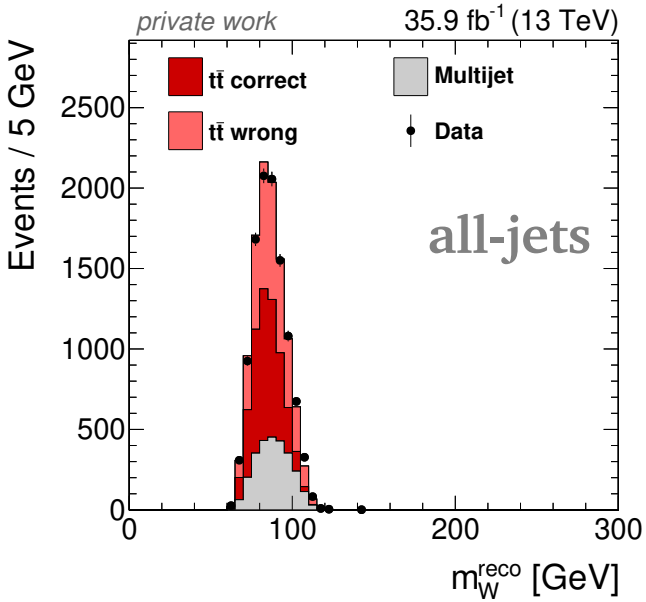


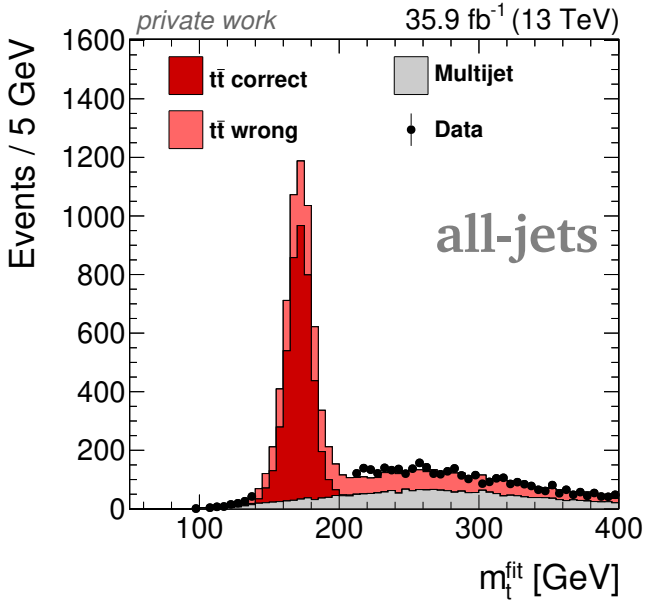
- good description within statistical uncertainties
- decorrelated straight line fit: $\pm 1\sigma$ variations of slope parameter (gray) used for systematic unc.

Final selection







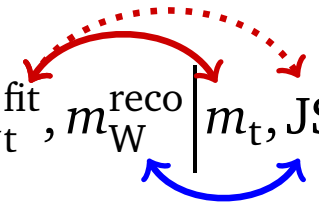


Mass extraction: ideogram method

Estimate m_t and additional jet scale factor (JSF)

$$P(m_t, \mathrm{JSF}|\mathrm{sample}) \propto P(\mathrm{JSF}) \cdot \mathcal{L}(\mathrm{sample}|m_t, \mathrm{JSF})$$

$$\mathcal{L}(\mathrm{sample}|m_t, \mathrm{JSF}) = \prod_{\mathrm{events}} \mathcal{L}(\mathrm{event}|m_t, \mathrm{JSF}) = \prod_{\mathrm{events}} P\left(m_t^{\mathrm{fit}}, m_W^{\mathrm{reco}} \middle| m_t, \mathrm{JSF}\right)$$



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For ℓ+jets:

$$\mathcal{L}(\mathrm{sample}|m_t, \mathrm{JSF}) = \prod_{\mathrm{events}} \left(\sum_{i=1}^{N_{\mathrm{perm}}} P_{\mathrm{gof}}(i) \cdot P\left(m_t^{\mathrm{fit}}, m_W^{\mathrm{reco}} \middle| m_t, \mathrm{JSF}\right) \right)^{w_{\mathrm{evt}}}$$

$$\propto \sum_i P_{\mathrm{gof}}(i)$$

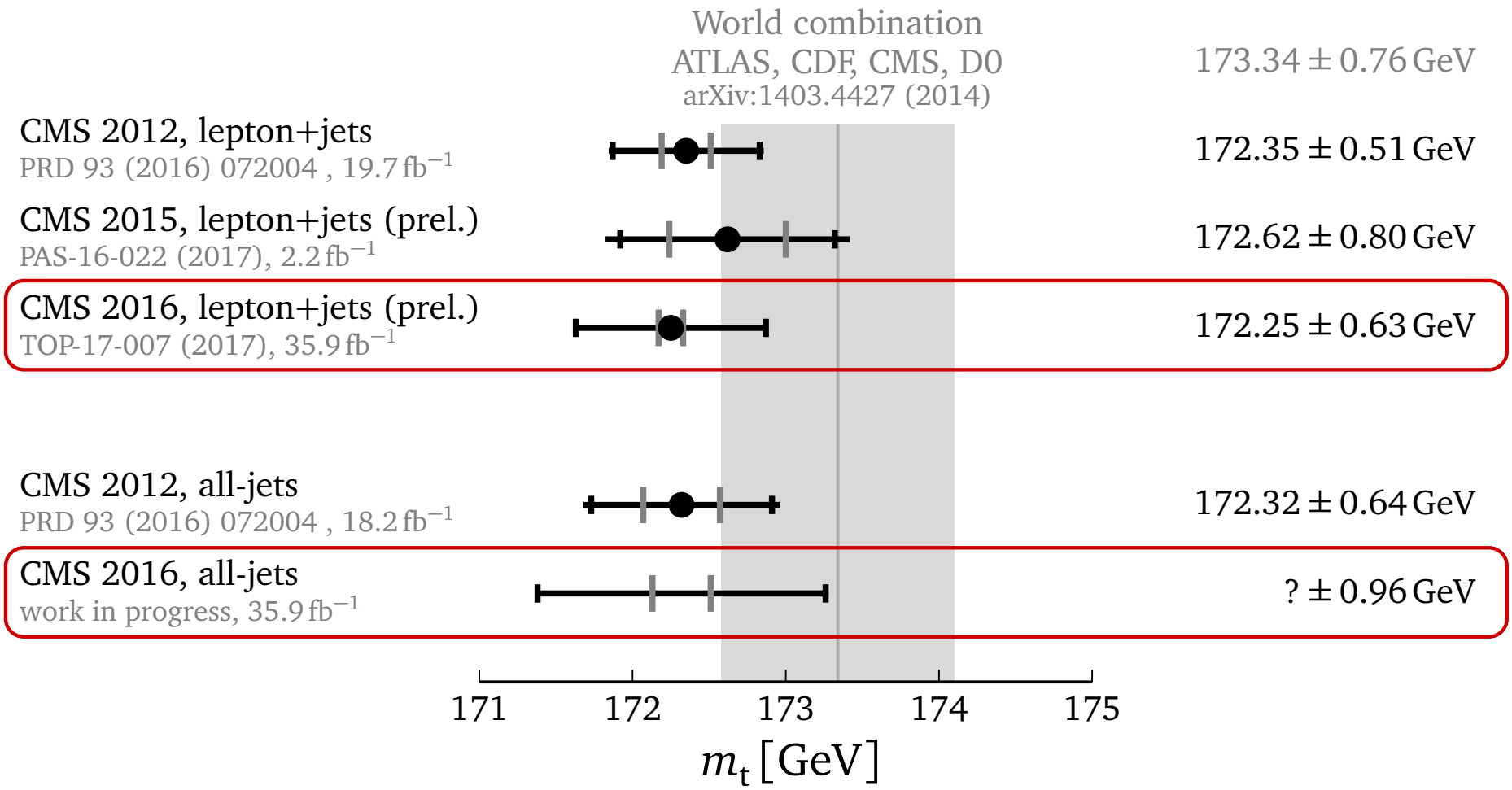
Three versions of ideogram fit:

- m_t and JSF free (2D)
- fixed JSF = 1 (1D)
- Gaussian JSF constraint (hybrid)

Systematic uncertainties

	ℓ+jets					all-jets				
	2D		1D	hybrid		2D		1D	hybrid	
	δm_t^{2D}	$\delta \mathrm{JSF}^{2D}$	δm_t^{1D}	δm_t^{hyb}	$\delta \mathrm{JSF}^{hyb}$	δm_t^{2D}	$\delta \mathrm{JSF}^{2D}$	δm_t^{1D}	δm_t^{hyb}	$\delta \mathrm{JSF}^{hyb}$
Experimental uncertainties										
JEC	0.13	0.002	0.85	0.19	0.003	0.19	0.011	0.73	0.30	0.006
Jet energy resolution	0.08	0.001	0.04	0.04	0.001	−0.05	0.001	0.05	0.01	0.000
b tagging	0.03	< 0.001	0.01	0.03	< 0.001	0.01	0.000	0.01	0.01	0.000
Pileup	0.08	0.001	0.02	0.05	0.001	0.06	0.001	0.00	0.03	0.000
Background	0.04	0.001	0.02	0.02	0.001	0.10	0.001	0.04	0.05	0.001
Modeling of hadronization										
JEC: Flavor	0.42	0.001	0.31	0.39	< 0.001	−0.34	0.000	−0.30	−0.32	0.000
b jet modeling	0.13	0.001	0.09	0.12	< 0.001	0.09	0.000	0.09	0.09	0.000
Modeling of perturbative QCD										
PDF	0.02	< 0.001	0.02	0.02	< 0.001	0.09	0.001	0.06	0.07	0.000
Ren. and fact. scale	0.02	0.001	0.02	0.01	< 0.001	0.11	0.001	0.07	0.09	0.000
ME/PS matching threshold	0.08	0.001	0.03	0.05	0.001	0.32	0.003	0.15	0.18	0.002
ME generator	0.19	0.001	0.29	0.22	0.001	0.36	0.003	0.37	0.32	0.002
ISR PS scale	0.07	0.001	0.10	0.06	< 0.001	0.19	−0.002	0.11	0.12	−0.001
FSR PS scale	0.24	0.004	0.22	0.13	0.003	0.26	−0.008	−0.37	0.15	−0.004
Top-quark p_T	< 0.01	< 0.001	< 0.01	< 0.01	< 0.001	0.06	−0.000	0.03	0.04	−0.000
Modeling of soft QCD										
Underlying event	0.07	0.001	0.10	0.06	< 0.001	0.19	0.003	0.14	0.15	0.001
Early resonance decays	0.22	0.008	0.42	0.03	0.005	0.31	0.002	0.47	0.39	0.001
Color reconnection modeling	0.34	0.001	0.23	0.31	0.001	0.62	0.002	0.52	0.57	0.001
Total systematic	0.71	0.010	1.09	**0.62**	0.008	1.02	0.016	1.21	**0.94**	0.008
Run I				0.48					0.59	

Results


World combination
ATLAS, CDF, CMS, D0
arXiv:1403.4427 (2014)
173.34 ± 0.76 GeV
CMS 2012, lepton+jets
PRD 93 (2016) 072004 , 19.7 fb−1
172.35 ± 0.51 GeV
CMS 2015, lepton+jets (prel.)
PAS-16-022 (2017), 2.2 fb−1
172.62 ± 0.80 GeV
CMS 2016, lepton+jets (prel.)
TOP-17-007 (2017), 35.9 fb−1
172.25 ± 0.63 GeV
CMS 2012, all-jets
PRD 93 (2016) 072004 , 18.2 fb−1
172.32 ± 0.64 GeV
CMS 2016, all-jets
work in progress, 35.9 fb−1
? ± 0.96 GeV
171
172
173
174
175
mt [GeV]

Differential measurements

Measure m_t in bins of

- $p_T(t_{had})$, $m_{t\bar{t}}$, $p_T(t\bar{t})$, N_{jets}
- $p_T(b_{had})$, $\eta(b_{had})$, $\Delta R(b\bar{b})$, $\Delta R(q\bar{q})$

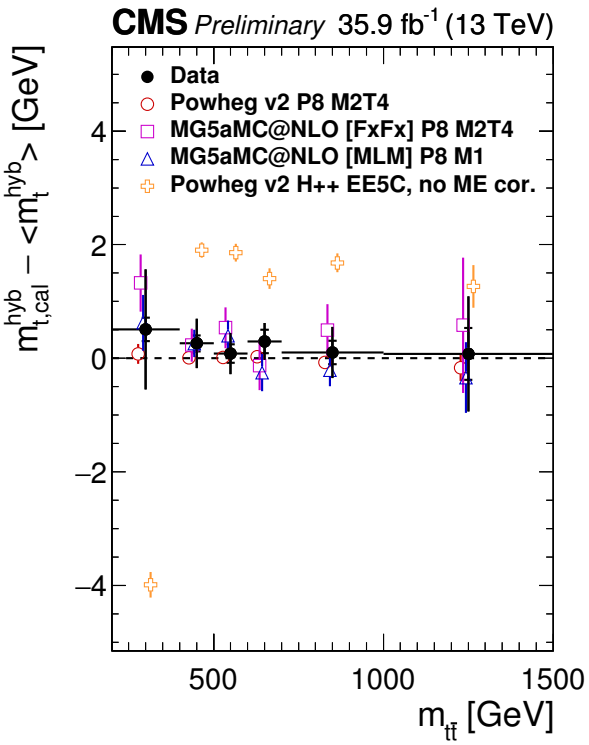
For different generator setups

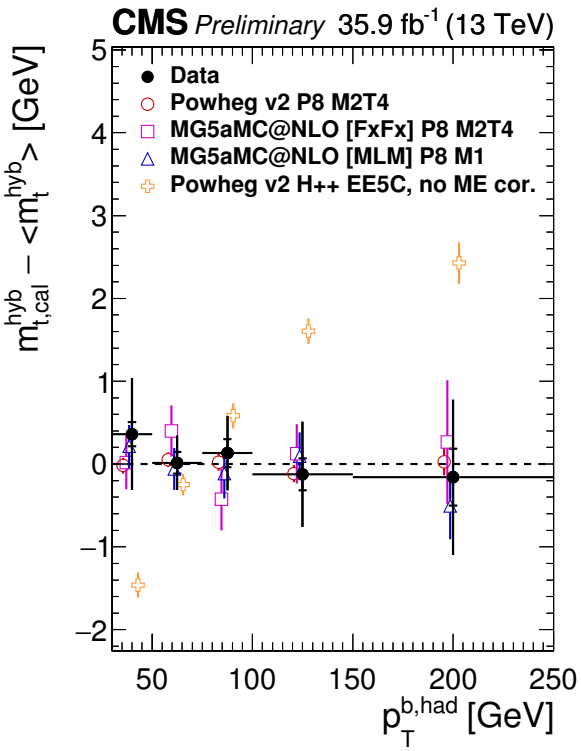
- MadGraph5_aMC@NLO at LO, MLM matching, Pythia8
- MadGraph5_aMC@NLO at NLO, FxFx matching, Pythia8
- Powheg v2, Herwig++

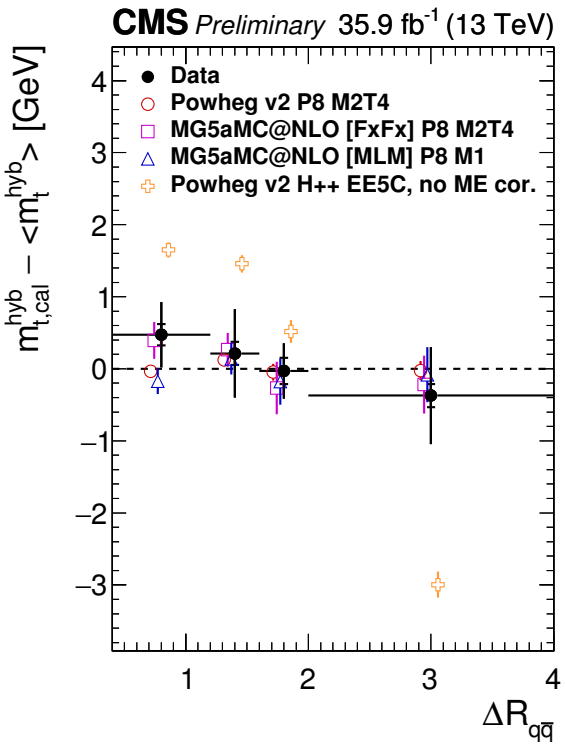
Color reconnection models with "early resonance decays" in Pythia8

- default setup
- string formation beyond leading color ("QCD inspired") [JHEP **1508** (2015) 003]
- gluons can be moved to another string ("gluon move") [JHEP **1411** (2014) 043]

Differential measurements

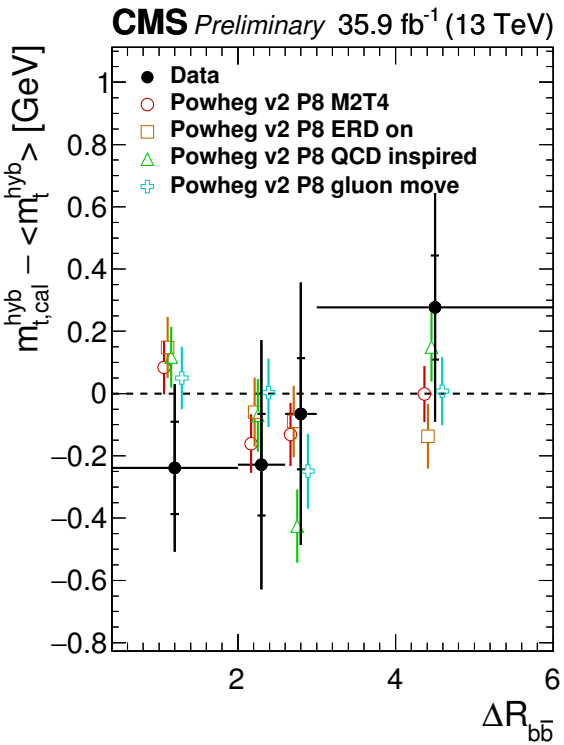


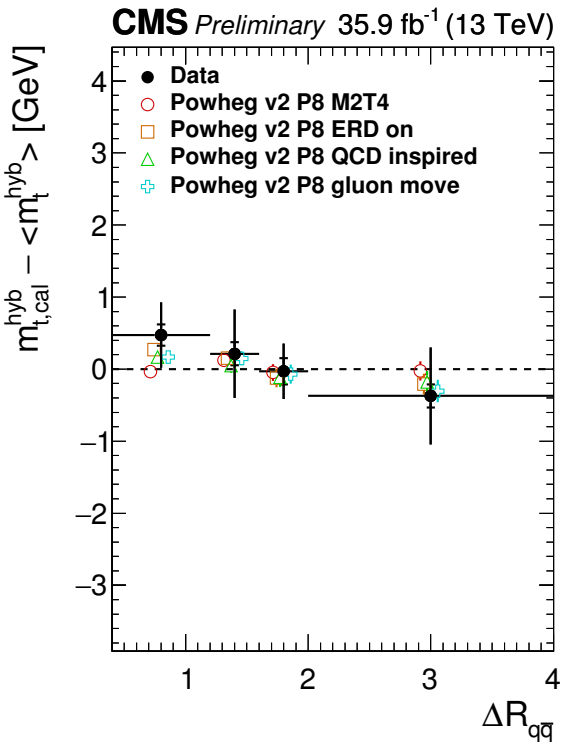


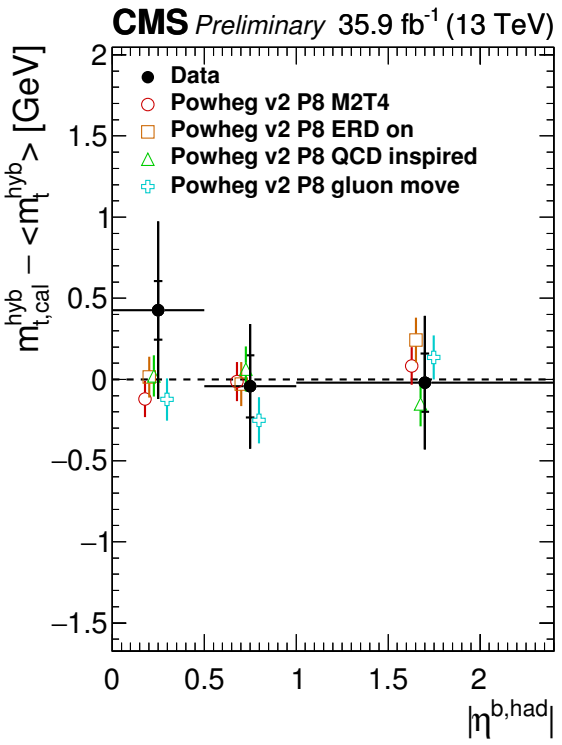


HERWIG++: without matrix element corrections

Differential measurements







Summary

- measurements of the top quark mass in the lepton+jets and all-jets channels
- improved modeling of some systematics + NLO MC compared to Run I
- ℓ+jets result in agreement with previous measurements
- high statistical precision allows for differential measurements, no kinematic dependence observed
- all-jets channel still blind

Future plans & ideas

- combination of both channels
- full likelihood fit with all nuisances

- maybe differential measurement in all-jets channel with more 13 TeV data

BACKUP

Systematic uncertainties: all-jets

	2D		1D	hybrid	
	δm_t^{2D}	$\delta \mathrm{JSF}^{2D}$	δm_t^{1D}	δm_t^{hyb}	$\delta \mathrm{JSF}^{hyb}$
Experimental uncertainties					
JEC (quad. sum)	0.19	0.011	0.73	0.30	0.006
- JEC: Intercalibration	−0.04	0.002	0.11	0.06	0.001
- JEC: MPFInSitu	−0.03	0.003	0.22	0.12	0.001
- JEC: Uncorrelated	−0.18	0.011	0.68	0.27	0.005
Jet energy resolution	−0.05	0.001	0.05	0.01	0.000
b tagging	0.01	0.000	0.01	0.01	0.000
Pileup	0.06	0.001	0.00	0.03	0.000
Background	0.10	0.001	0.04	0.05	0.001
Modeling of hadronization					
JEC: Flavor (linear sum)	−0.34	0.000	−0.30	−0.32	0.000
- light	0.10	0.001	0.01	0.05	0.001
- charm	0.03	−0.000	−0.01	0.01	−0.000
- bottom	−0.29	0.000	−0.29	−0.29	0.000
- gluon	−0.19	0.002	0.03	−0.09	0.001
b jet modeling (quad. sum)	0.09	0.000	0.09	0.09	0.000
- Bowler-Lund	−0.08	0.000	−0.07	−0.07	0.000
- Peterson	−0.04	0.000	−0.03	−0.04	0.000
- semi-leptonic B hadron decays	0.04	−0.000	0.04	0.04	−0.000
Modeling of perturbative QCD					
PDF	0.09	0.001	0.06	0.07	0.000
Ren. and fact. scale	0.11	0.001	0.07	0.09	0.000
ME/PS matching threshold	0.32	0.003	0.15	0.18	0.002
ME generator	0.36	0.003	0.37	0.32	0.002
ISR PS scale	0.19	−0.002	0.11	0.12	−0.001
FSR PS scale	0.26	−0.008	−0.37	0.15	−0.004
Top-quark transverse momentum	0.06	−0.000	0.03	0.04	−0.000
Modeling of soft QCD					
Underlying event	0.19	0.003	0.14	0.15	0.001
Early resonance decays	0.31	0.002	0.47	0.39	0.001
Color reconnection modeling	0.62	0.002	0.52	0.57	0.001
Total systematic	1.02	0.016	1.21	0.94	0.008

Systematic uncertainties: ℓ+jets

	2D approach		1D approach	Hybrid	
	δm_t^{2D} [GeV]	$\delta \mathrm{JSF}^{\mathrm{2D}}$	δm_t^{1D} [GeV]	$\delta m_t^{\mathrm{hyb}}$ [GeV]	$\delta \mathrm{JSF}^{\mathrm{hyb}}$
Experimental uncertainties					
Method calibration	0.05	<0.001	0.05	0.05	<0.001
Jet energy corrections (quad. sum)	(0.13)	(0.002)	(0.85)	(0.19)	(0.003)
– JEC: InterCalibration	0.02	<0.001	0.16	0.04	<0.001
– JEC: MPFInSitu	0.01	<0.001	0.23	0.07	<0.001
– JEC: Uncorrelated	0.13	0.002	0.78	0.16	0.003
Jet energy resolution	0.08	0.001	0.04	0.04	0.001
b tagging	0.03	<0.001	0.01	0.03	<0.001
Pileup	0.08	0.001	0.02	0.05	0.001
Non-$\mathrm{t\bar{t}}$ background	0.04	0.001	0.02	0.02	0.001
Modeling of hadronization					
JEC: Flavor (linear sum)	(0.42)	(0.001)	(0.31)	(0.39)	(<0.001)
– light quarks (uds)	0.12	−0.001	−0.01	+0.07	0.001
– charm	0.03	<0.001	−0.01	0.02	<0.001
– bottom	−0.31	<0.001	−0.31	−0.31	<0.001
– gluon	−0.23	0.003	0.02	−0.15	0.002
b-jet modeling (quad. sum)	(0.13)	(0.001)	(0.09)	(0.12)	(<0.001)
– b fragmentation Bowler-Lund	0.07	<0.001	0.01	0.05	<0.001
– b fragmentation Peterson	0.04	<0.001	0.05	0.04	<0.001
– semileptonic B hadron decays	0.11	<0.001	0.08	0.10	<0.001
Modeling of perturbative QCD					
PDF	0.02	<0.001	0.02	0.02	<0.001
Ren. and fact. scale	0.02	0.001	0.02	0.01	<0.001
ME/PS matching threshold	0.08	0.001	0.03	0.05	0.001
ME generator	0.19	0.001	0.29	0.22	0.001
ISR PS scale	0.07	0.001	0.10	0.06	<0.001
FSR PS scale	0.24	0.004	0.22	0.13	0.003
Top-quark transverse momentum	<0.01	<0.001	<0.01	<0.01	<0.001
Modeling of soft QCD					
Underlying event	0.07	0.001	0.10	0.06	<0.001
Early resonance decays	0.22	0.008	0.42	0.03	0.005
Color reconnection modeling	0.34	0.001	0.23	0.31	0.001
Total systematic	**0.71**	**0.010**	**1.09**	**0.62**	**0.008**
Statistical (expected)	0.09	0.001	0.05	0.07	0.001
Total (expected)	**0.72**	**0.010**	**1.09**	**0.62**	**0.008**

Systematic uncertainties: ℓ+jets

	2D approach		1D approach	Hybrid	
	δm_t^{2D} [GeV]	$\delta \mathrm{JSF}^{\mathrm{2D}}$	δm_t^{1D} [GeV]	$\delta m_t^{\mathrm{hyb}}$ [GeV]	$\delta \mathrm{JSF}^{\mathrm{hyb}}$
"QCD inspired" (both ERD on)	−0.11	−0.001	−0.19	−0.13	−0.001
"gluon move" (both ERD on)	+0.34	−0.001	+0.23	+0.31	−0.001
def. ERD off to def. ERD on	−0.22	+0.008	+0.42	−0.03	+0.005

	2D approach		1D approach	Hybrid	
	δm_t^{2D} [GeV]	$\delta \mathrm{JSF}^{\mathrm{2D}}$	δm_t^{1D} [GeV]	$\delta m_t^{\mathrm{hyb}}$ [GeV]	$\delta \mathrm{JSF}^{\mathrm{hyb}}$
MadGraph5_aMC@NLO MLM + P8	+0.82	+0.000	+0.80	+0.82	+0.000
powheg v2 + herwig++	−4.39	+0.014	−3.26	−4.06	+0.010
MadGraph5_aMC@NLO FxFx + P8	+0.19	+0.001	+0.29	+0.22	+0.001

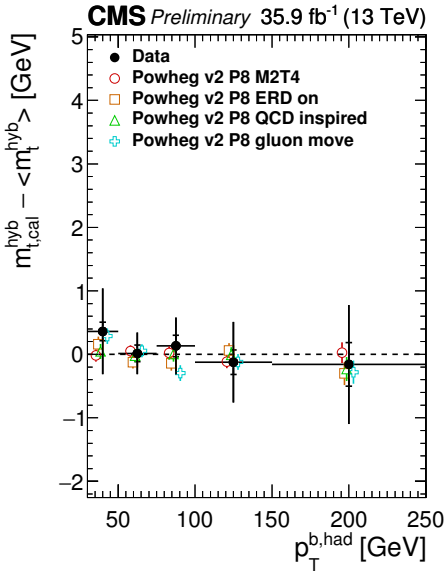
Separate e/μ+jets results

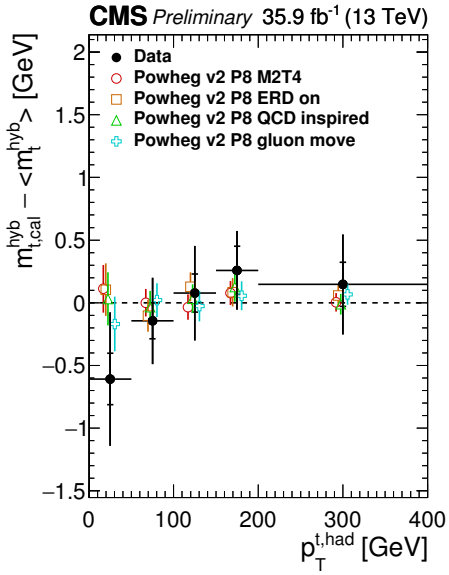
Separate fits to 101 992 muon+jets events and 59 504 electron+jets events:

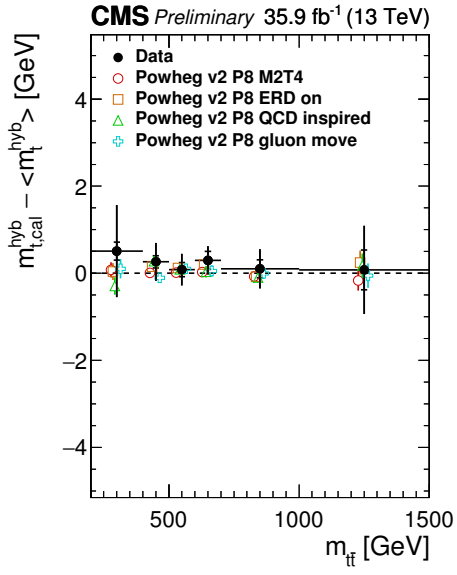
$$\mu\text{+jets: } m_{\mathrm{t}}^{\mathrm{2D}} = 172.44 \pm 0.11 \text{ (stat+JSF)}, \mathrm{JSF}^{\mathrm{2D}} = 0.995 \pm 0.001 \text{ stat}$$

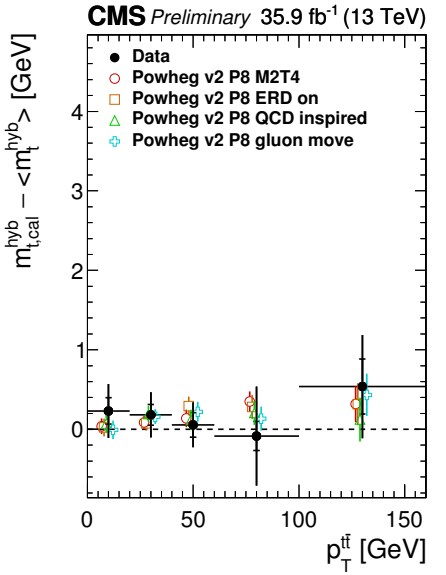
$$\text{e+jets: } m_{\mathrm{t}}^{\mathrm{2D}} = 172.32 \pm 0.16 \text{ (stat+JSF)}, \mathrm{JSF}^{\mathrm{2D}} = 0.993 \pm 0.001 \text{ stat}$$

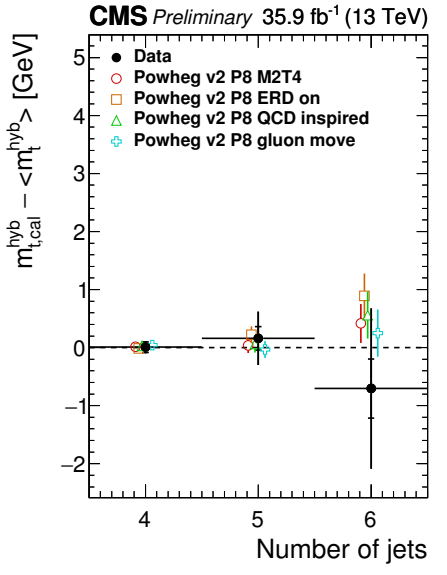
Differential measurements











Differential measurements