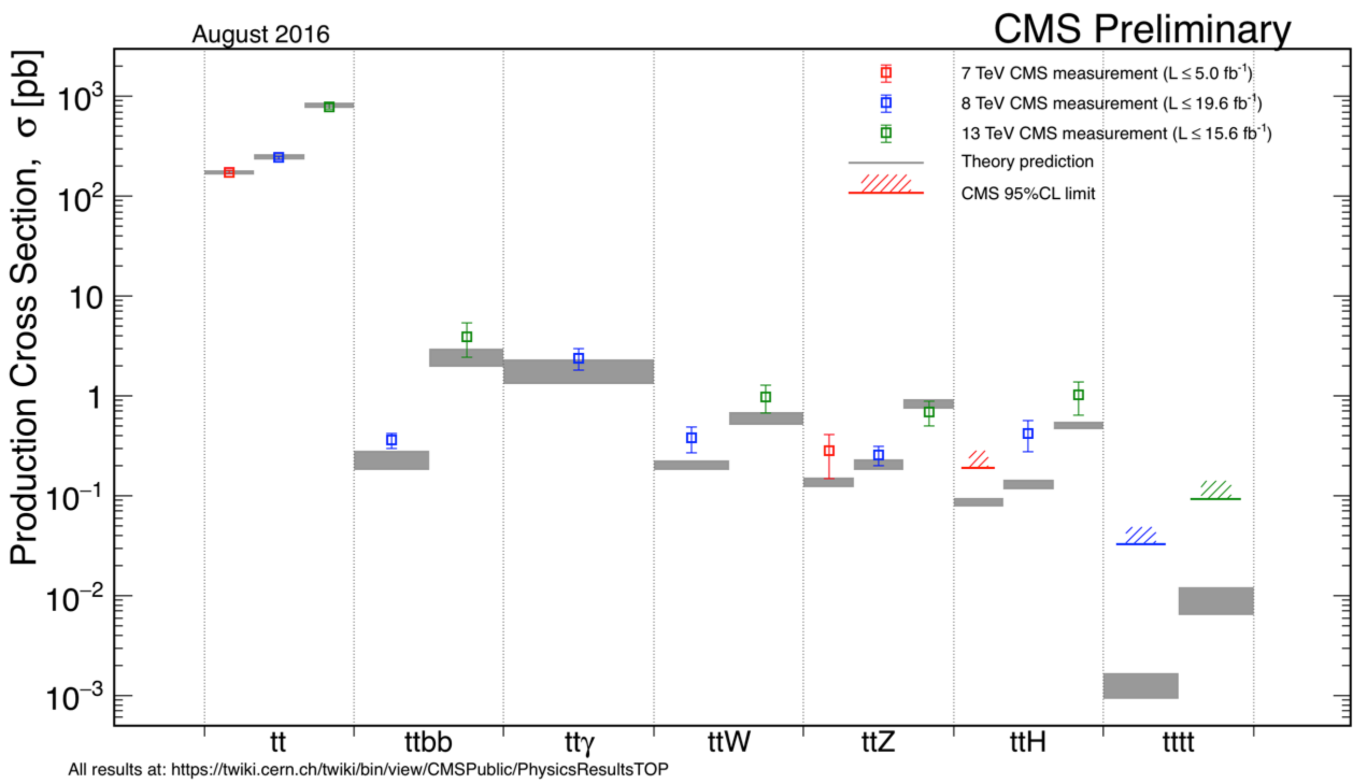
Top quark pair production with N-jets

Luke Kreczko for the CMS Collaboration

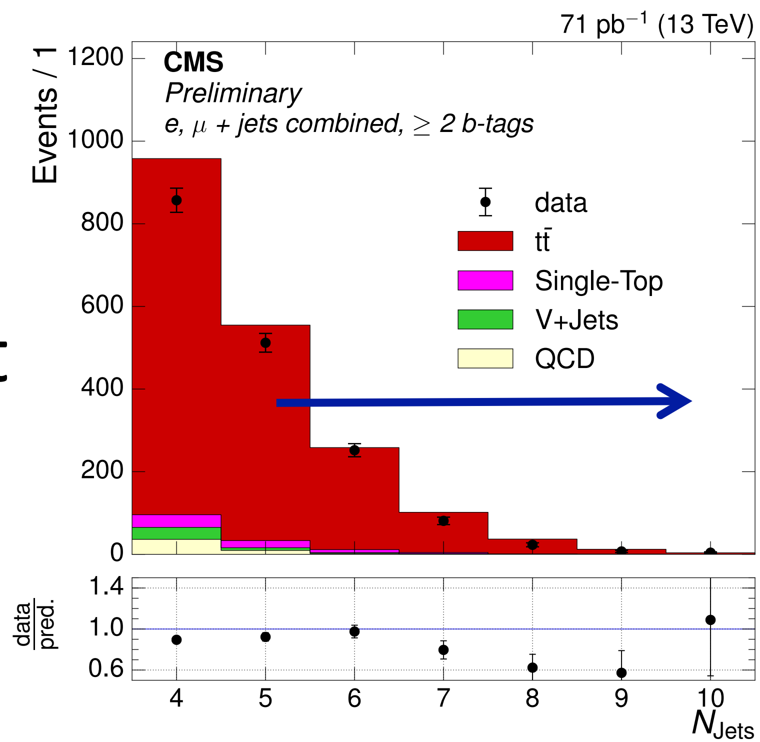
Outline

- Introduction
- Latest jet related measurements



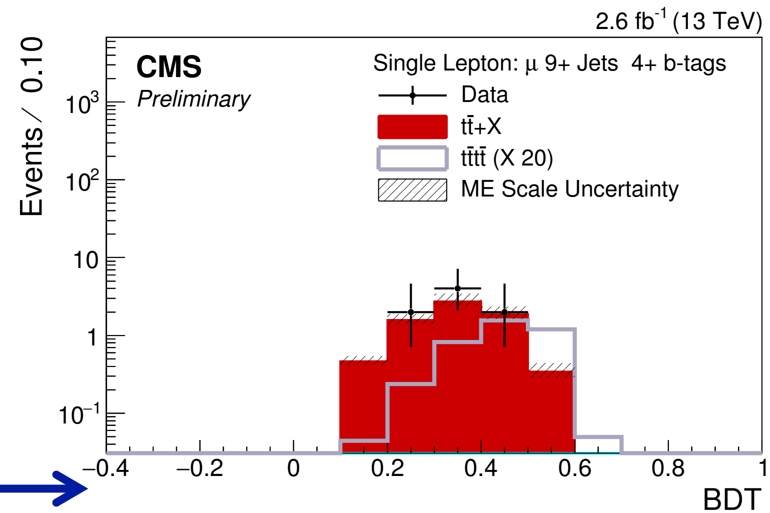
Motivation (1)

- The LHC is a top quark factory
- At the LHC energies ≥ 50% of top quark pair ($t\bar{t}$) events are produced with additional jets (not from $t\bar{t}$ decay)
- Precise understanding of these events is important



Motivation (2)

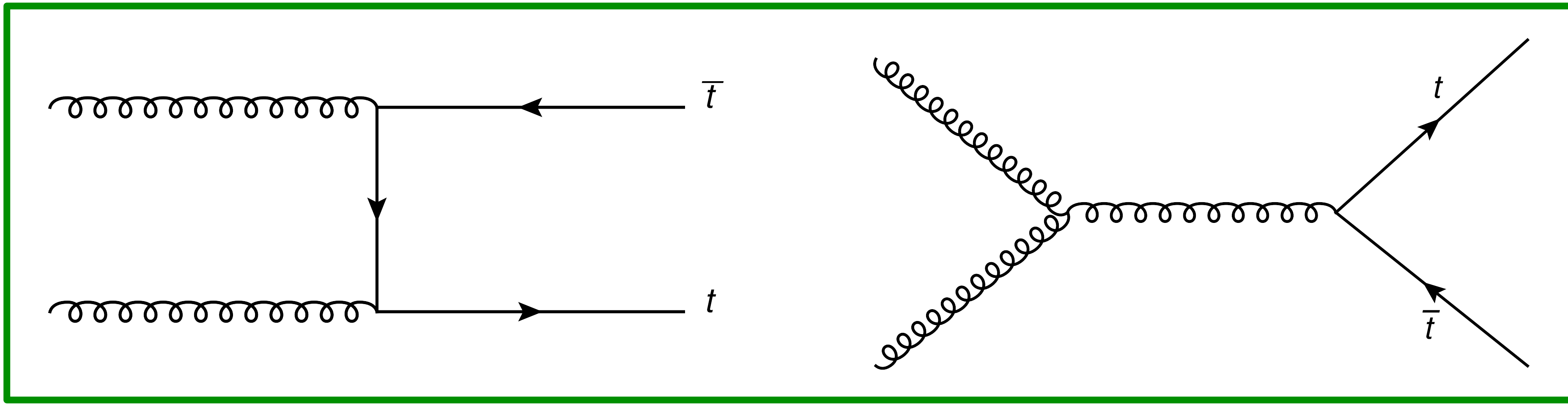
- **Benchmark generators**: test higher-order QCD predictions
- **New physics**: could be revealed by anomalous production of $t\bar{t}$(+jets)
- **$t\bar{t}$ + jets as background** for many searches and rare Standard Model processes ($t\bar{t}$H, **$t\bar{t}t\bar{t}$**)



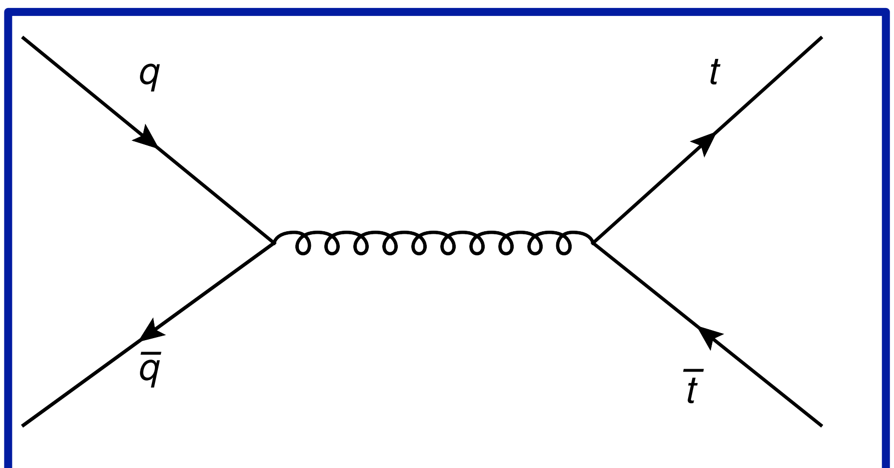
≥ 9 jets search region

Top quark production

Top quark pair production at the LHC (LO):



≈ 90%

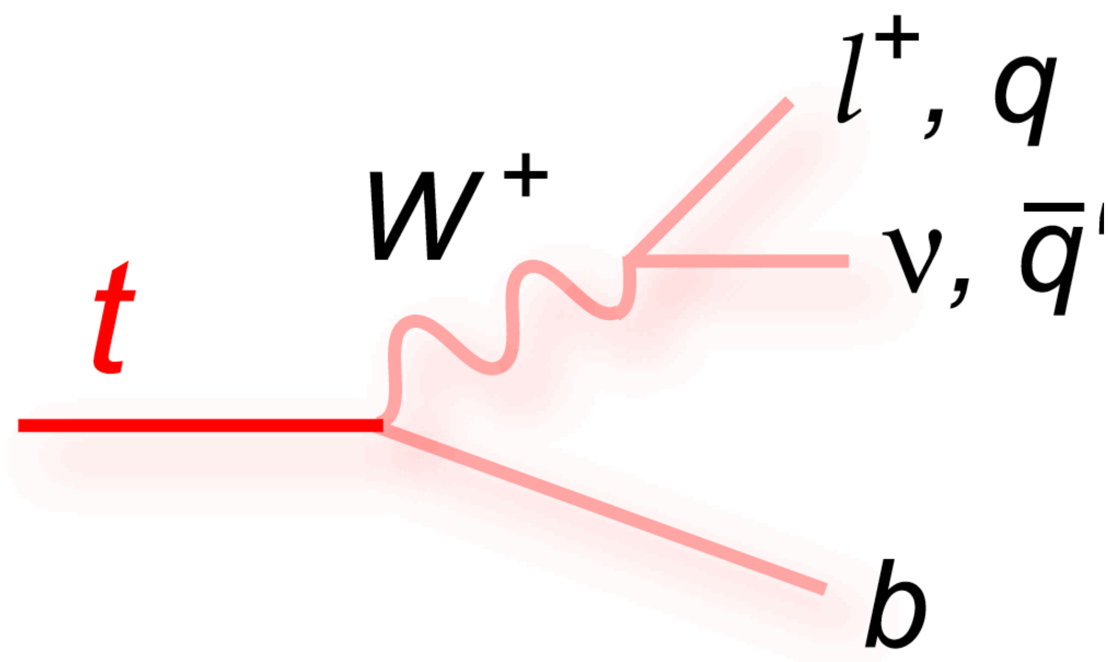


≈ 10%

at √s = 13 TeV

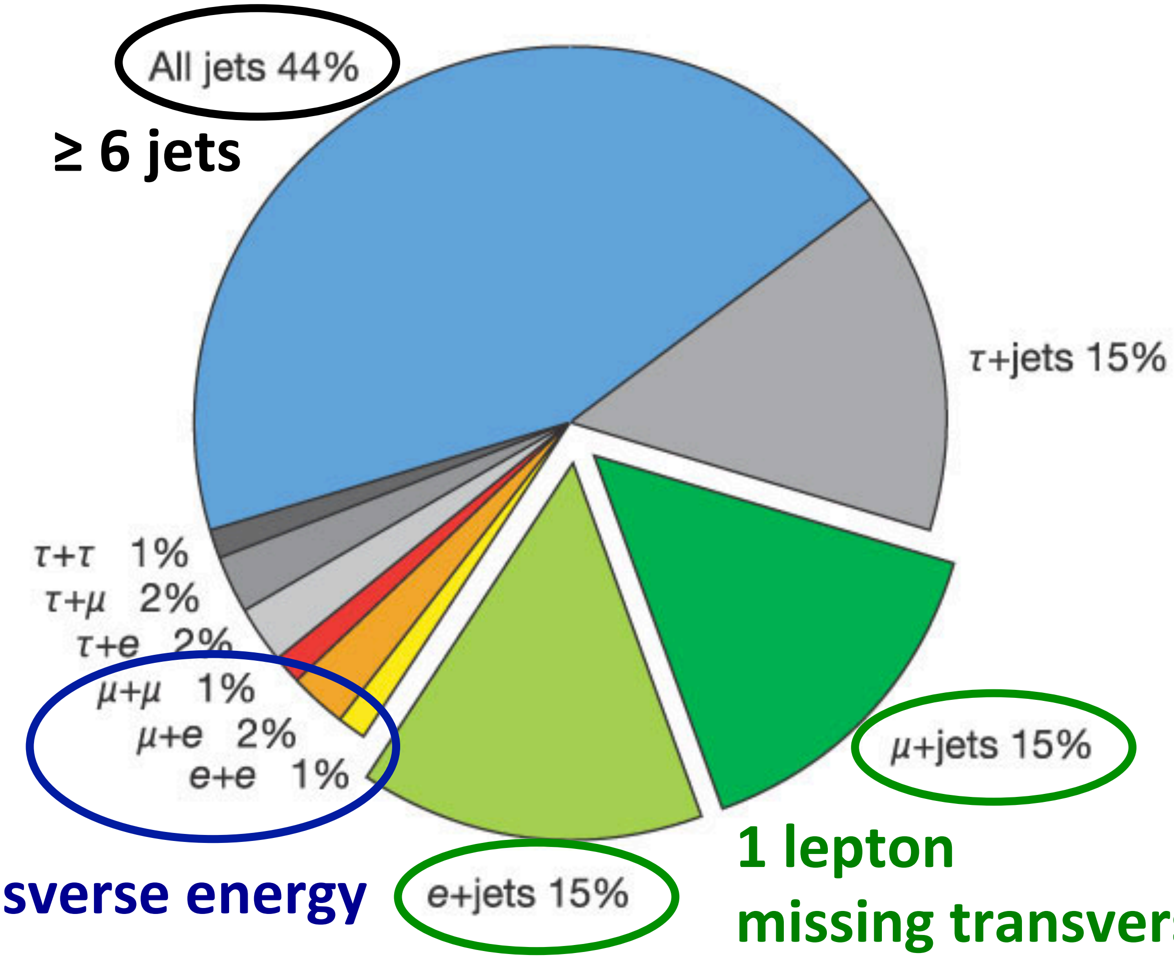
Top quark decay

Almost 100% of the time the top quark will decay into a W boson and a b-quark



The event signature is then characterised by the W boson decays

Top quark pair decay channels

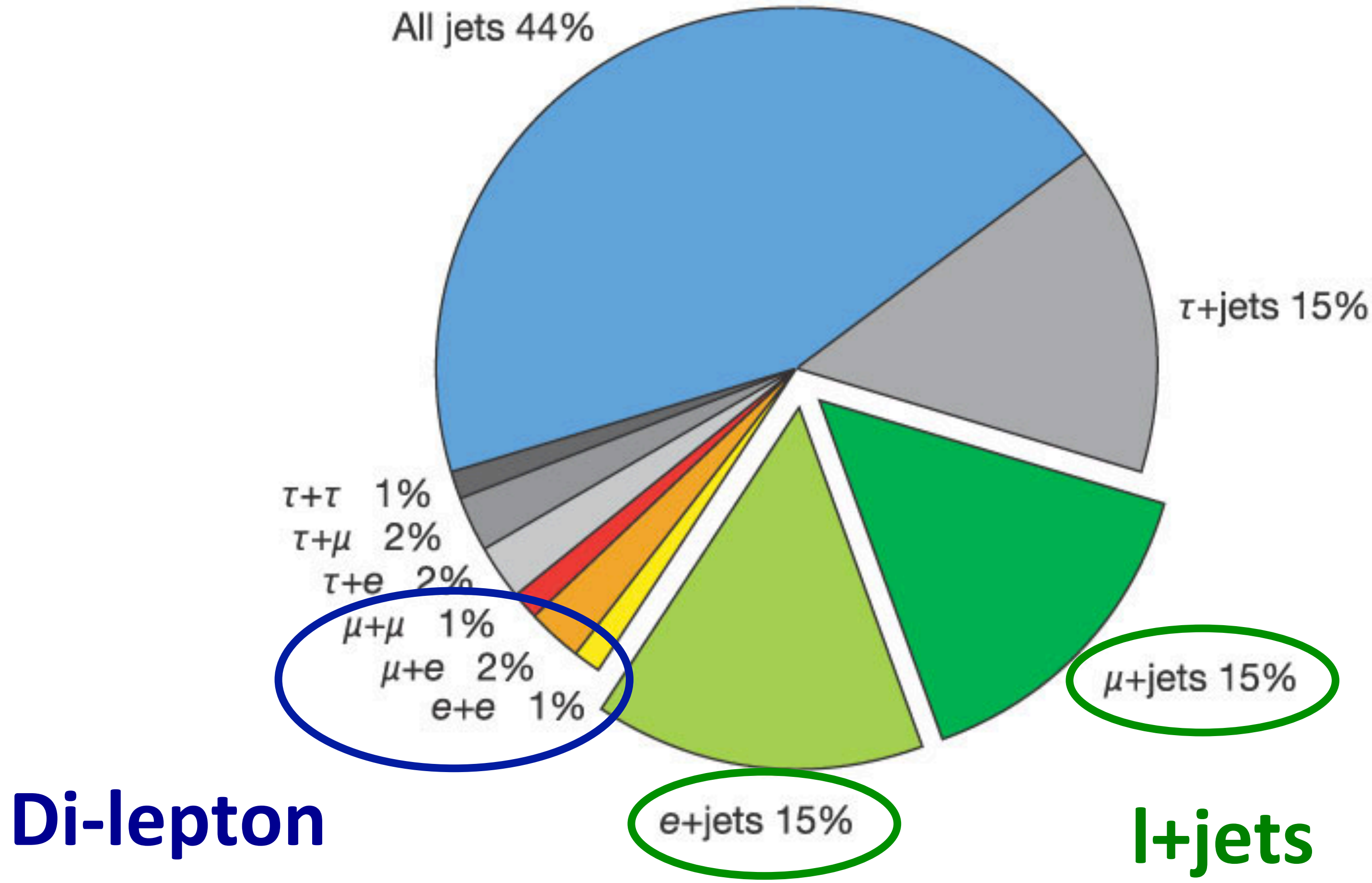


≥ 6 jets

2 leptons
missing transverse energy (MET)
≥ 2 jets

1 lepton
missing transverse energy (MET)
≥ 4 jets

In this talk


All jets 44%
τ+jets 15%
τ+τ 1%
τ+μ 2%
τ+e 2%
μ+μ 1%
μ+e 2%
e+e 1%
μ+jets 15%
e+jets 15%
Di-lepton
l+jets

Generator setups

Mainly using NLO matrix Element generators with Pythia8 for Parton Shower (m_t=172.5 GeV):

Matrix element	Shower & Hadronisation	PDF	Tune
Powheg (v2)	**Pythia8**	NNPDF3.0	CUETP8M1
Powheg (v2)	Herwig++	NNPDF3.0	EE5C
MadGraph5_amc@NLO	Pythia8	NNPDF3.0	CUETP8M1
MadGraph5	Pythia8	NNPDF2.3	CUETP8M1

Additional samples with different top masses (175.5 & 169.5 GeV) exist for comparison

Radiative Corrections

- The Q^2 scale variations address two aspects
  - renormalisation and factorisation scale (ME)
  - amount of ISR/FSR
- For each event Q^2 is defined as
  - Powheg/MC@NLO: $Q^2 = m_t^2$
  - MadGraph: $Q^2 = m_t^2 + \sum p_T^2$
- Samples with 0.25 x Q^2 and 4 x Q^2 exist for comparison

New Measurements (w.r.t. JetVM 2014)

Differential cross section measurements

- **N_{jets} (l+jets)**: CMS-PAS-TOP-15-006 (8 TeV)
- **N_{jets} (l+jets)**: CMS-PAS-TOP-15-013 (13 TeV, EA)
- **N_{jets} (di-lepton)**: CMS-PAS-TOP-16-011 (13 TeV)
- **N_{jets} and 2D distributions (l+jets)**: CMS-TOP-16-008 (13 TeV)
- **Ratio of σ_{ttbb} / σ_{ttjj} (di-lepton)**: CMS-PAS-TOP-16-010 (13 TeV)
- Quick update on jet vetoes

Normalised diff. cross section

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma^i}{dN_j} = \frac{1}{\sigma_{t\bar{t}}}\frac{x^i}{\Delta^i_X\, L}$$

- x^i number of events after background subtraction, corrected for detector efficiencies, acceptances and migration to particle level with regularised unfolding
- σ_{tt} inclusive tt cross section in the same, visible phase space
- Δ^i_x: bin width, L: integrated luminosity

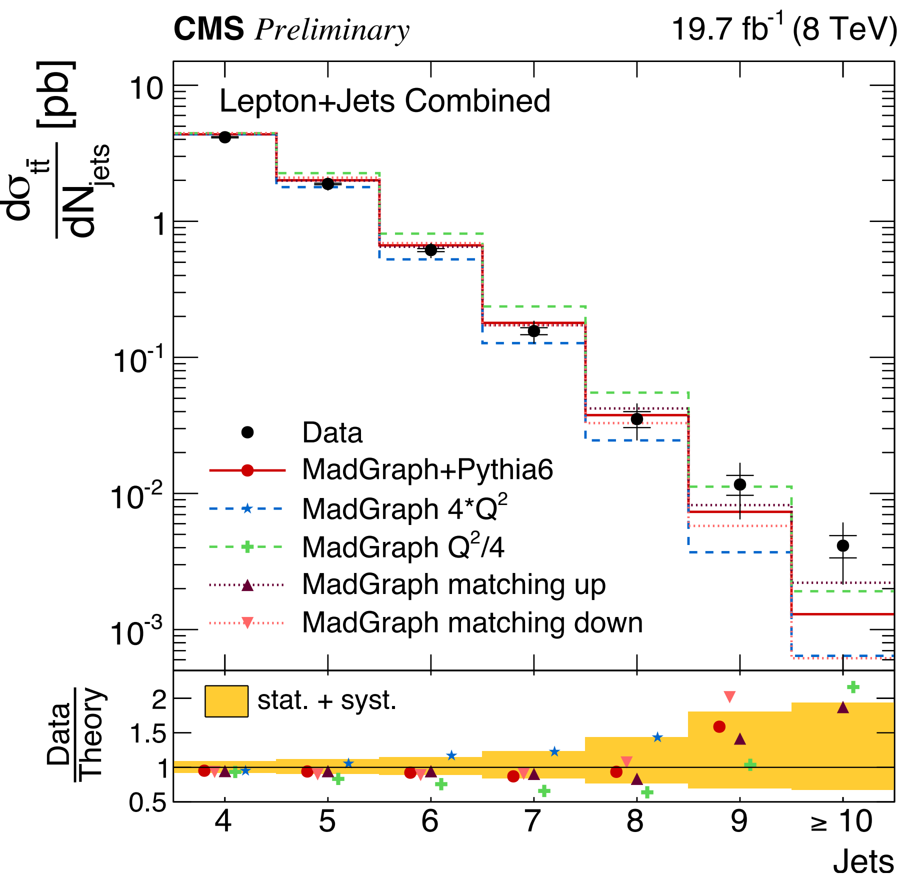
Measurements in visible phase space and corrected to particle level

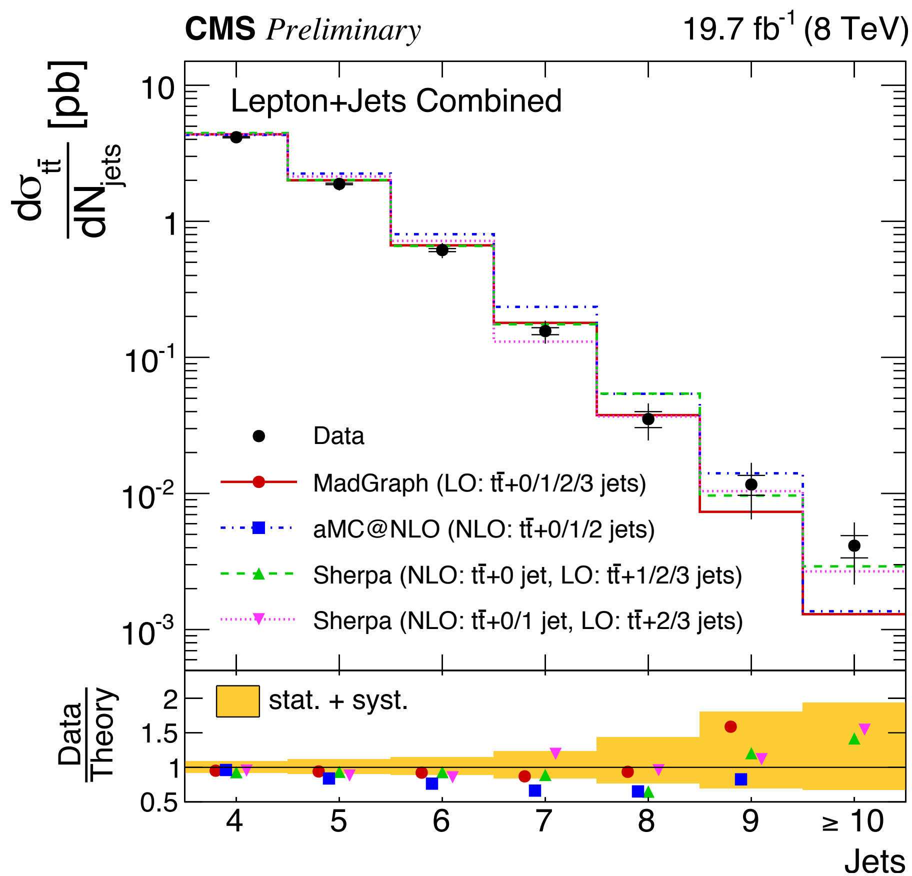
- Phase space recommendations provided by the LHC Top WG)

CMS-PAS-TOP-15-006

- Update to N_{jets} from CMS-TOP-12-041
  - Added more theory comparisons: MadGraph Q^2 & matching threshold variations & Sherpa
- Using 19.7 pb^{-1} of 8 TeV data
- Event selection
  - Exactly 1 isolated lepton (electron or muon)
  - ≥ 4 jets of which ≥ 2 are b-tagged

CMS-PAS-TOP-15-006: results



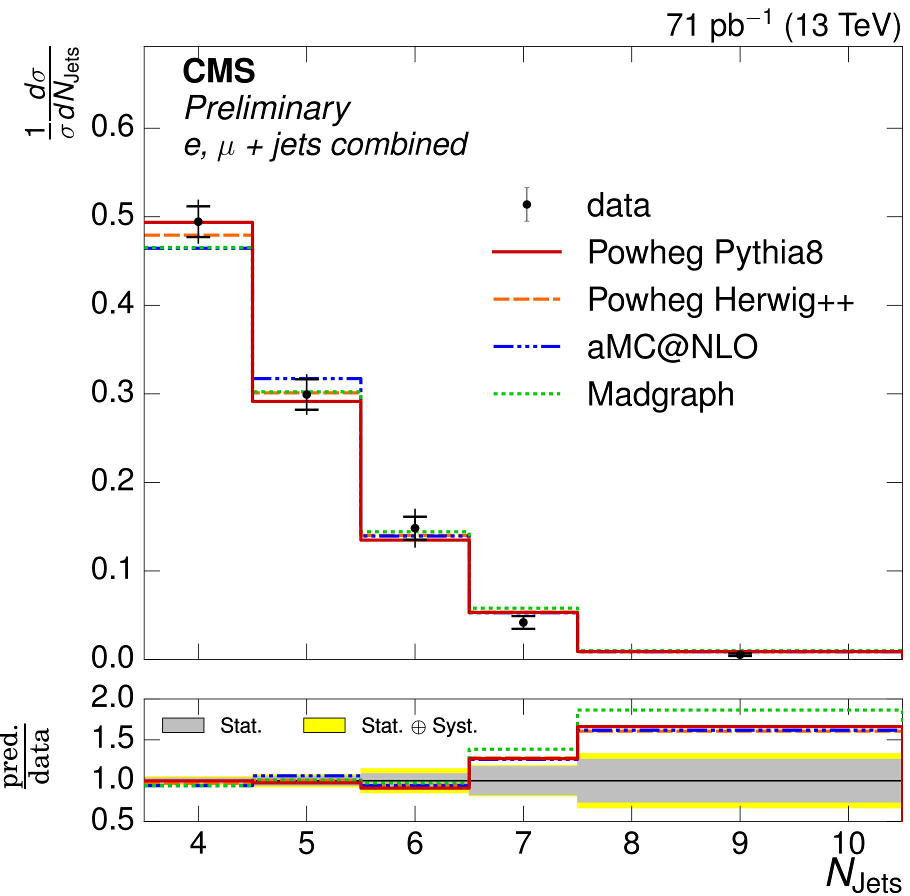


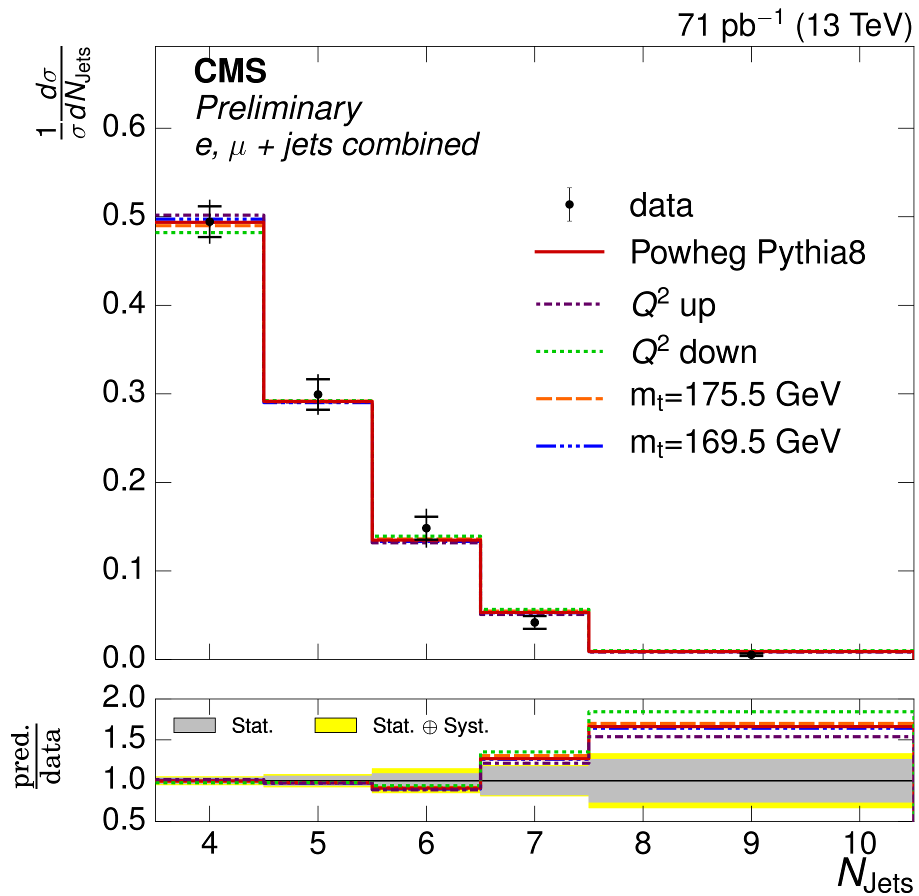
With the exception of MadGraph $Q^2/4$ and MadGraph matching threshold of 10 GeV (down) most variations and generators agree with the data within the uncertainty

CMS-PAS-TOP-15-013

- Measures several observables without top quark reconstruction in the l+jets channel:
- Using 71 pb^{-1} of 13 TeV data (early analysis)
- Event selection
  - Exactly 1 isolated lepton (electron or muon)
  - $\geq$ 4 jets of which $\geq$ 2 are b-tagged

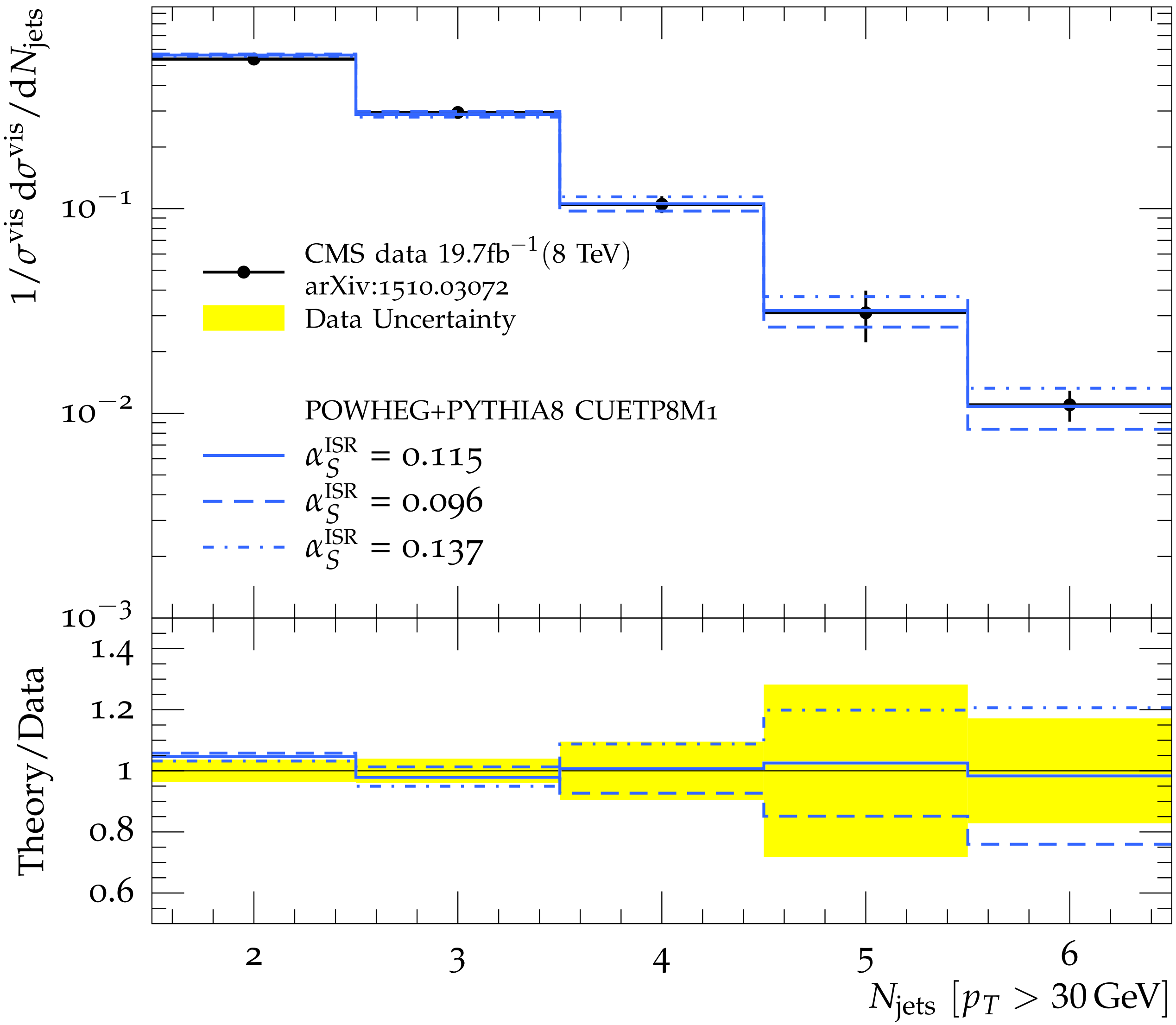
CMS-PAS-TOP-15-013: results





Too many jets in simulation explained by switch from Pythia6 to Pythia8: Sensitivity to the α_S(ISR) choice in Pythia; data seems to prefer lower values.

RIVET tuning



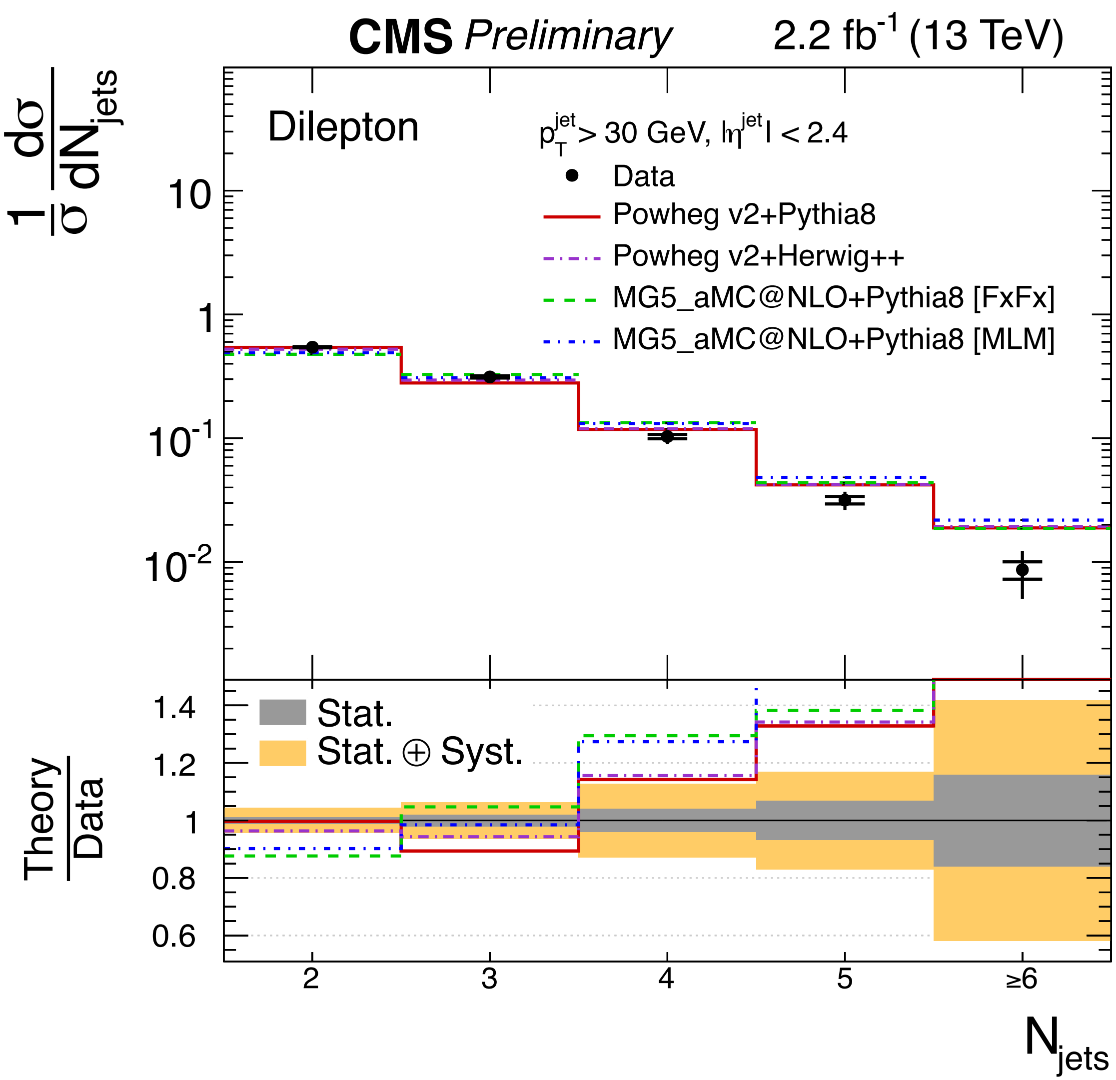
Using previous measurements at 8 TeV the value of α_S(ISR) was tuned in RIVET

Best agreement is found with α_S(ISR) = 0.115

CMS-PAS-TOP-16-011

- Measures several observables in the di-lepton channel using top reconstruction:
  - Jet multiplicity, $\mathbf{N_{jets}}$, without top reconstruction
- Using **2.2 fb**$^{-1}$ of 13 TeV data
- Event selection
  - Require 2 isolated leptons with opposite charge
  - ≥ 2 b-tagged jets
  - Veto Z boson events and require MET

CMS-PAS-TOP-16-011: results



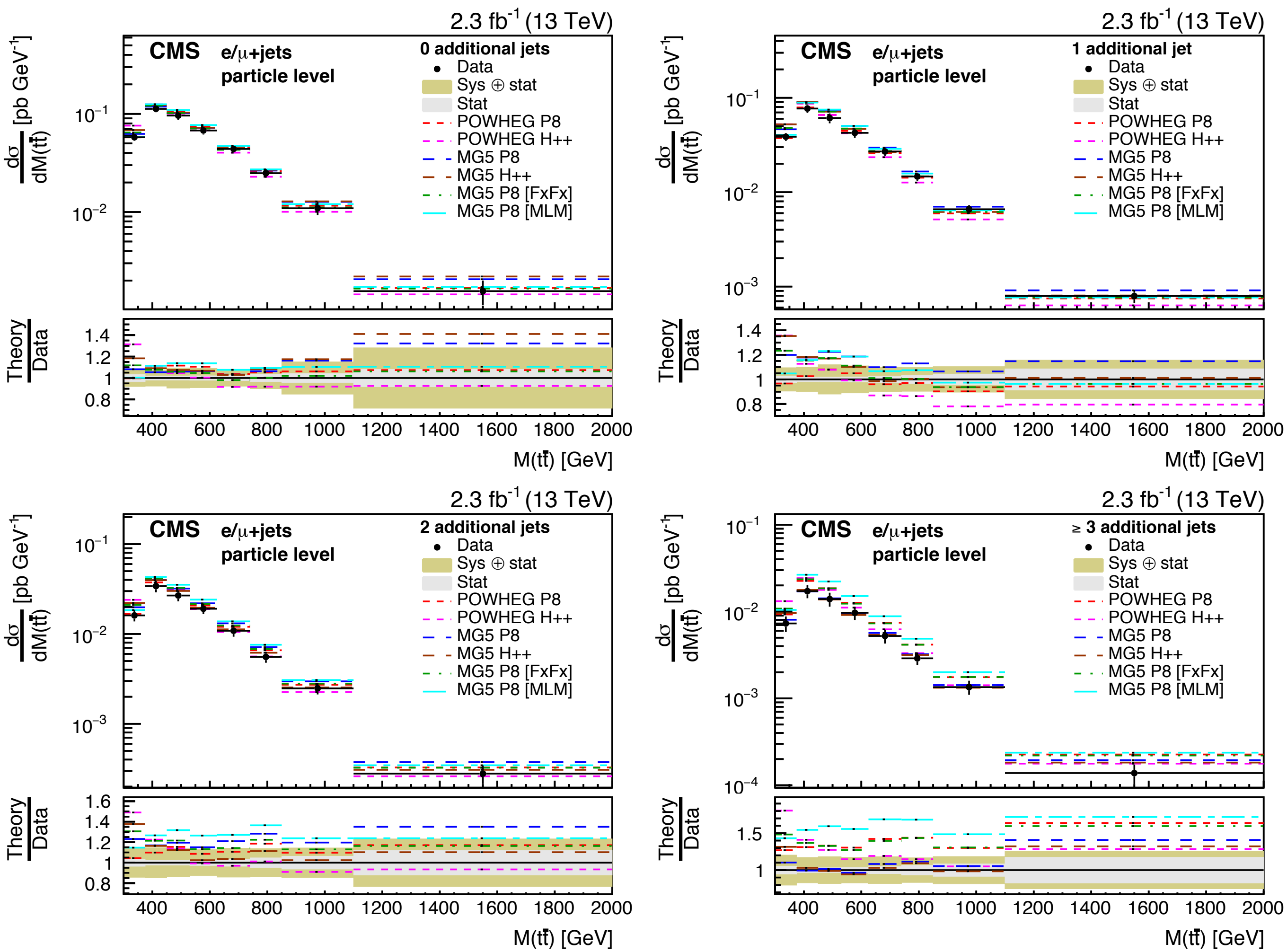
In the di-lepton channel N_{jets} + 2 corresponds to N_{jets} in l+jets channel

More data increases sensitivity also in lower multiplicity bins (2 additional jets)

CMS-TOP-16-008

- Measures several observables in the l+jets channel using top reconstruction:
  - **N additional jets** (jets not from top quark decays)
- Using 2.3 fb^{-1} of 13 TeV data
- Event selection
  - Exactly 1 isolated lepton (electron or muon)
  - ≥ 4 jets of which ≥ 2 are b-tagged

CMS-TOP-16-008: results

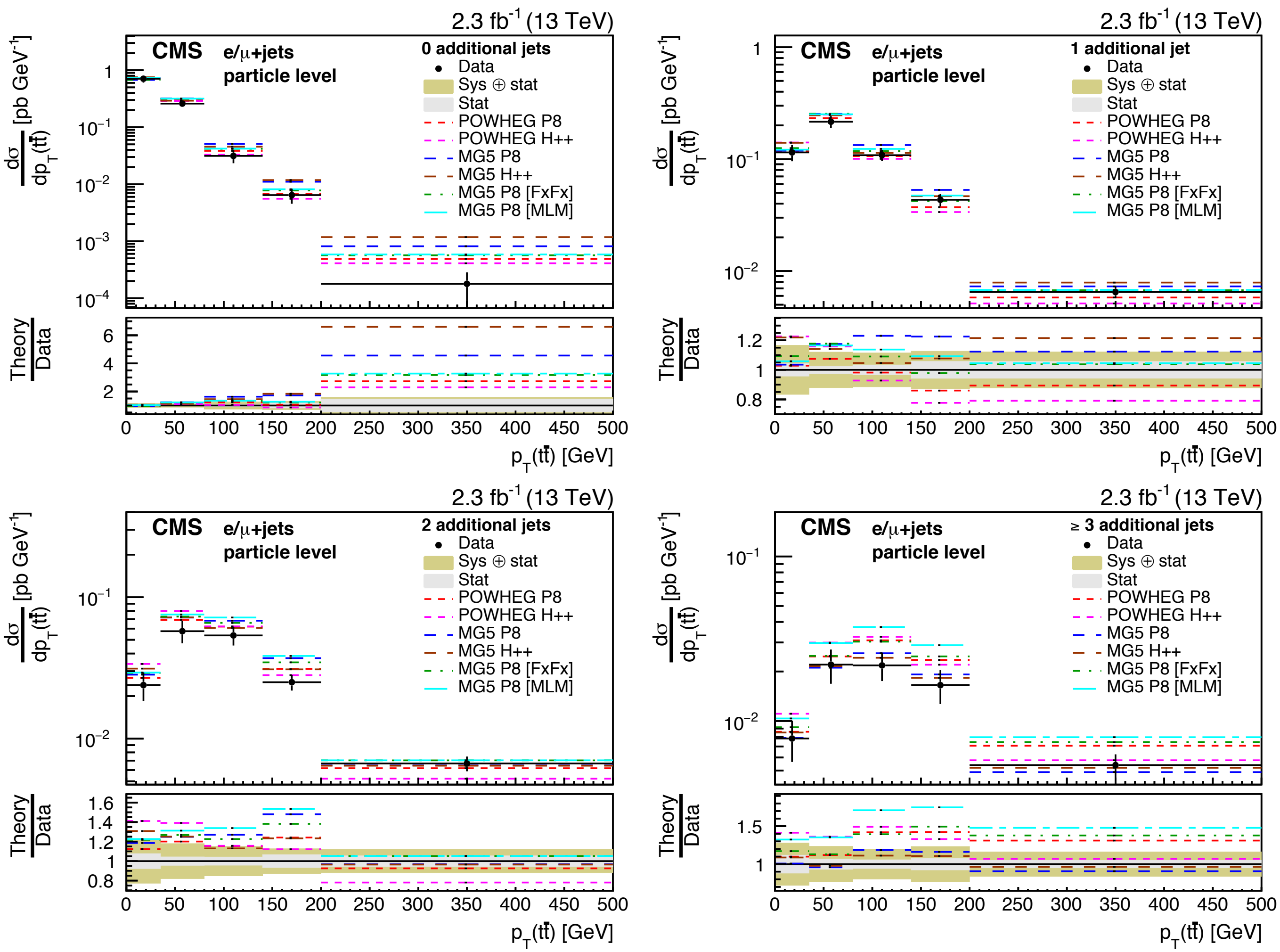


M($t\bar{t}$) in different N_{jets} bins:

The results agree with Powheg + Pythia within uncertainties

In the ≥ 3 jets the cross section is higher for most samples

CMS-TOP-16-008: results



$p_T(t\bar{t})$ in different N_{jets} bins:

Similar picture as for $M(t\bar{t})$.

Spectrum **softer** than in simulation and is predicted by the **NNLO** and the **NLO+NNLL`** QCD calculations

CMS-TOP-16-008: results

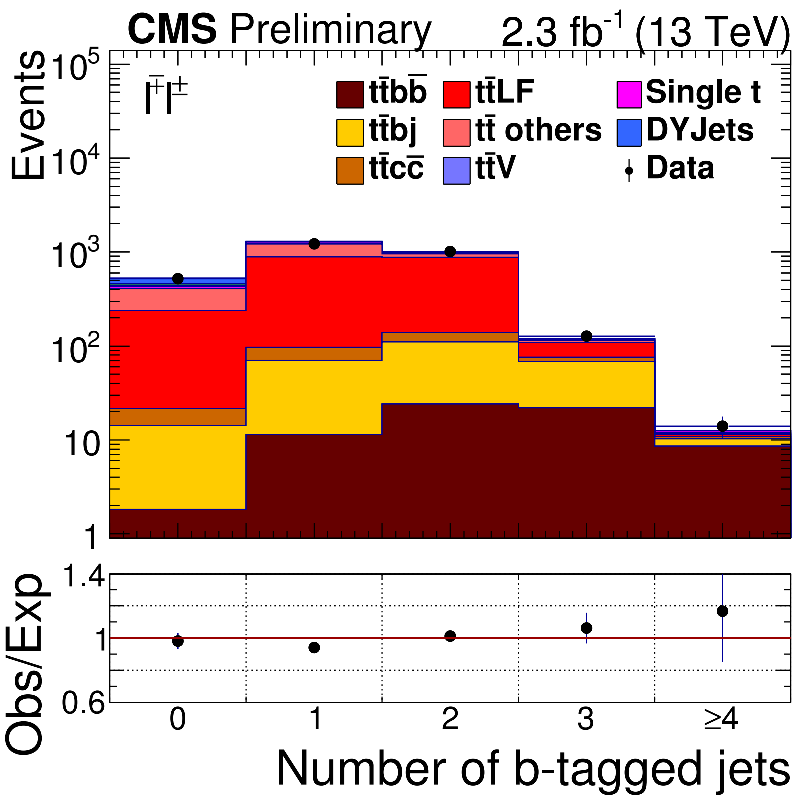
Also contains a big table of χ^2 evaluations w.r.t the different MCs, please do check the paper for details. Here a snippet:

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8		POWHEG+H++		MG5_AMC@NLO+P8 MLM	
Additional jets	27.6/5	< 0.01	16.2/5	< 0.01	36.3/5	< 0.01
Additional jets vs. $p_T(t\bar{t})$	70.3/20	< 0.01	95.4/20	< 0.01	168/20	< 0.01
Additional jets vs. $p_T(t_h)$	96.2/36	< 0.01	218/36	< 0.01	180/36	< 0.01
	MG5_AMC@NLO+P8		MG5_AMC@NLO+H++		MG5_AMC@NLO+P8 FXFX	
Additional jets	36.2/5	< 0.01	15.7/5	< 0.01	10.8/5	0.056
Additional jets vs. $p_T(t\bar{t})$	237/20	< 0.01	192/20	< 0.01	87.2/20	< 0.01
Additional jets vs. $p_T(t_h)$	251/36	< 0.01	76.0/36	< 0.01	45.6/36	0.132

CMS-PAS-TOP-16-010

- Measurements in di-lepton channel:
  - cross section of $t\bar{t}$ + light jets (σ_{ttjj})
  - the cross section of $t\bar{t}$ + bb (σ_{ttbb})
  - their ratio in the di-lepton channel
- Using 2.3 fb^{-1} of 13 TeV data
- Event selection:
  - Require 2 isolated leptons with opposite charge
  - $\geq$ 2 b-tagged jets
  - Veto Z boson events and require MET

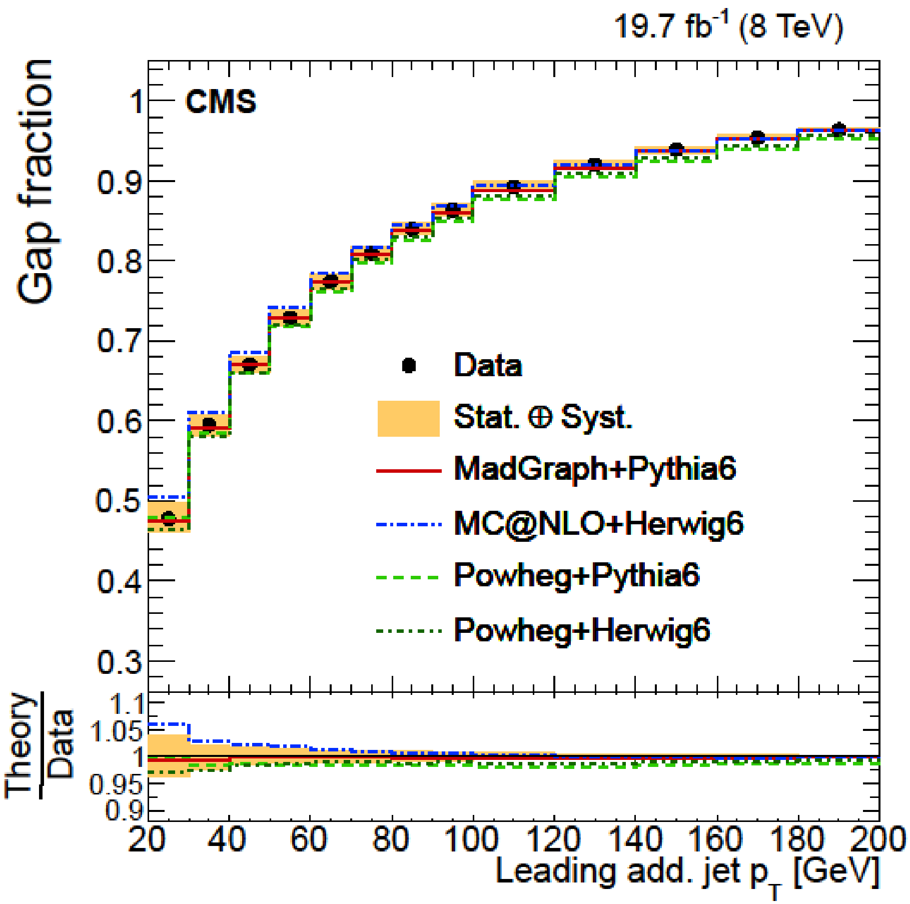
CMS-PAS-TOP-16-010



Measurement compatible with Powheg + Pythia8 simulation

Phase Space	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}} / \sigma_{t\bar{t}jj}$
Measurement			
Visible	$0.085 \pm 0.012 \pm 0.029$	$3.5 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
Full	$3.9 \pm 0.6 \pm 1.3$	$176 \pm 5 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
Simulation (POWHEG)			
Visible	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

CMS-TOP-12-41



- Presented at [JetVM2014]
- Now RIVET plugin is available
  - used for tuning α_s(ISR)
- Latest measurement of the gap fraction

Summary and Outlook (1)

- Presented $t\bar{t}$ measurements with additional jets in the l +jets and in the dilepton channels
- **Compared** them to different MC **generators** and **parameter variations**
- **Starting to explore the different measurements to improve the ttbar description**
  - E.g. **tuning α_s(ISR)** parton shower **using Run 1 data**
- **Softer p_T(tt) spectrum is expected** from NNLO calculations
- **Ratio of σ_{ttbb} / σ_{ttjj}** is well described by Powheg (+Pythia)

Summary and Outlook (2)

- **RIVET plugins** for the presented analysis are either available or in preparation
- **All measurements available in HepData**
- Often experimental precision smaller than spread due to parameter variation -> **variations can be reduced**
- With more data the reach can be expanded (NNLO comparisons?)
- **Updates** with all of 2016 data expected **end of this year/ early next year**.

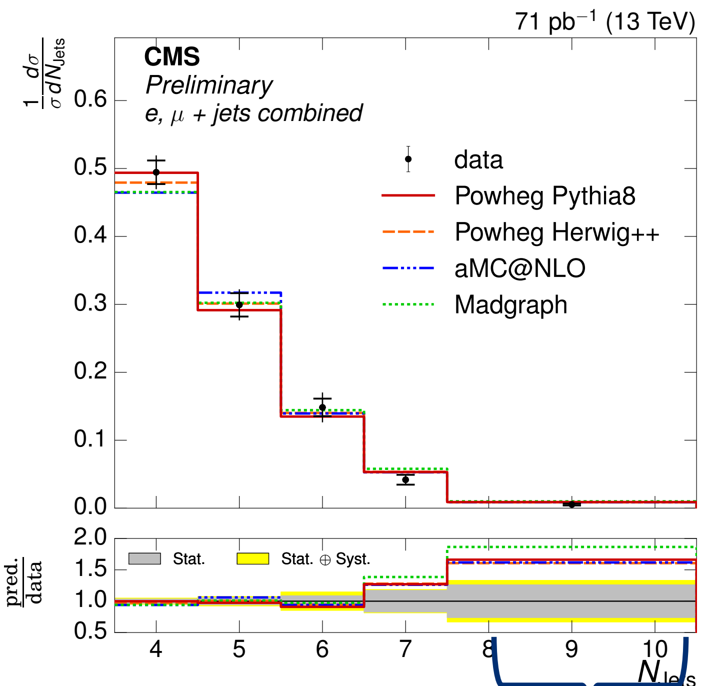
Thank you for listening.

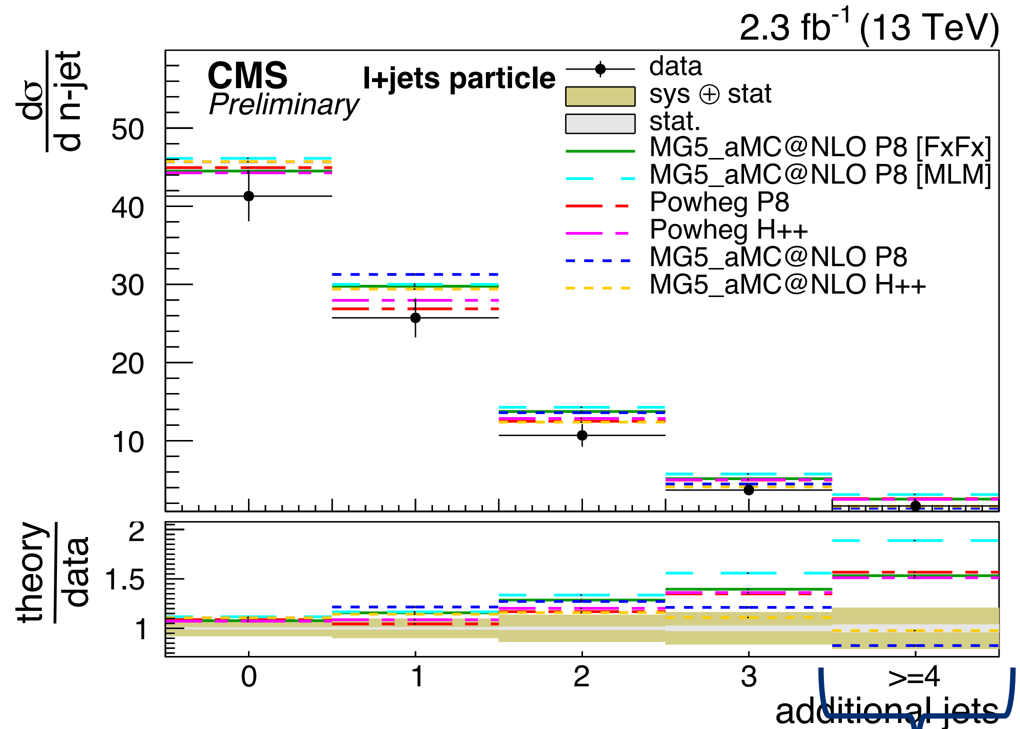
QUESTIONS?

BACKUP SLIDES

LHC Top WG visible phase space

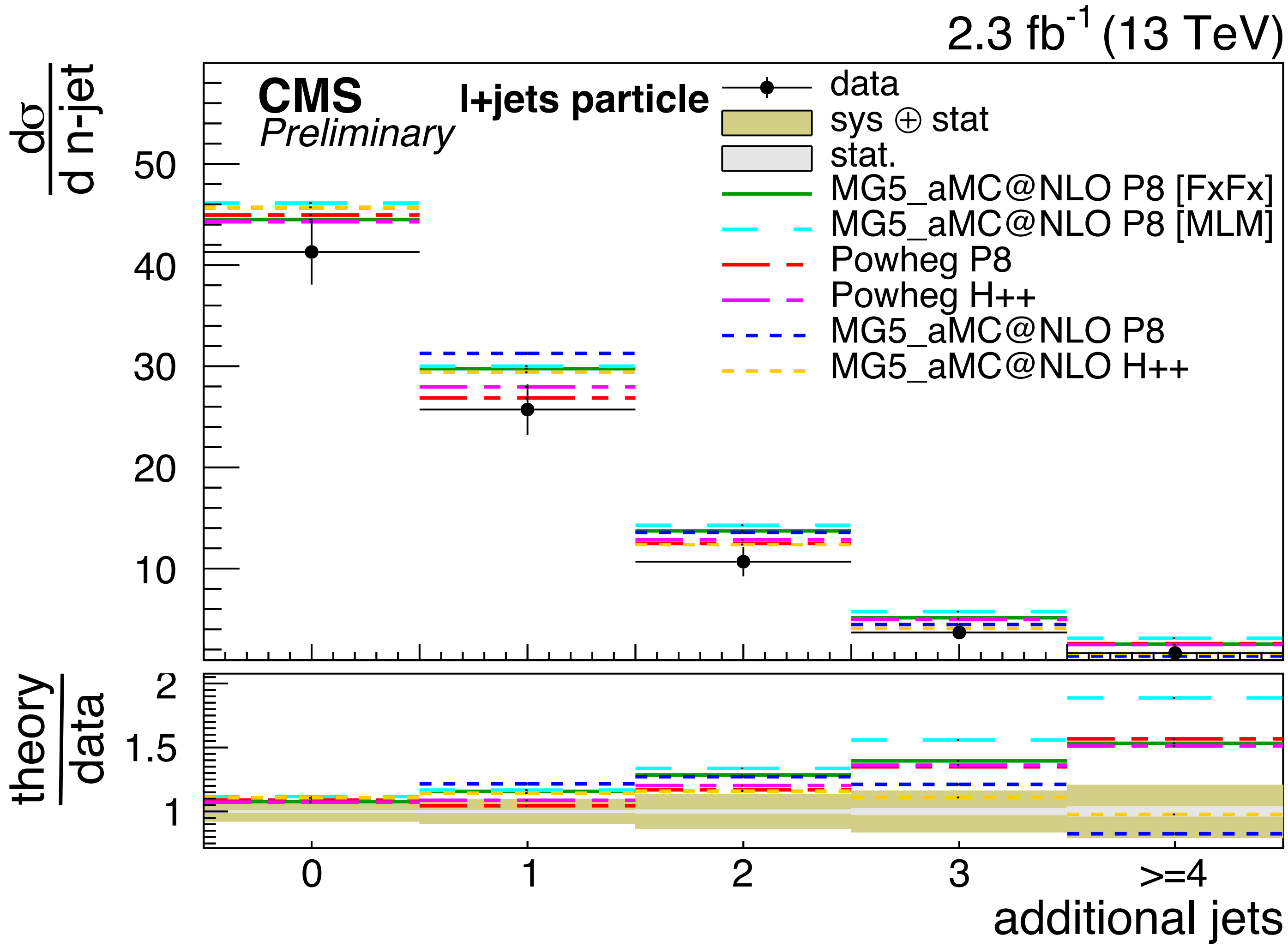
- Single lepton channels (l+jets):
  - exactly one electron or muon with $p_T > 30$ GeV, $|\eta| < 2.4$
  - not any other lepton (electron or muon) with $p_T > 15$ GeV, $|\eta| < 2.5$
  - $M^W{}_T > 30$ GeV
  - At least two b-tagged jets in the region $|\eta| < 2.4$ and $p_T > 30$ GeV
  - At least four jets in the region $|\eta| < 2.4$ and $p_T > 30$ GeV
- Di-lepton channels
  - At least two selected leptons (ee, eμ, μμ) with $|\eta| < 2.4$ and $p_T > 30$ GeV
  - For same-flavour channels neutrino sum $p_T > 60$ GeV
  - At least two b-tagged jets in the region $|\eta| < 2.4$ and $p_T > 30$ GeV



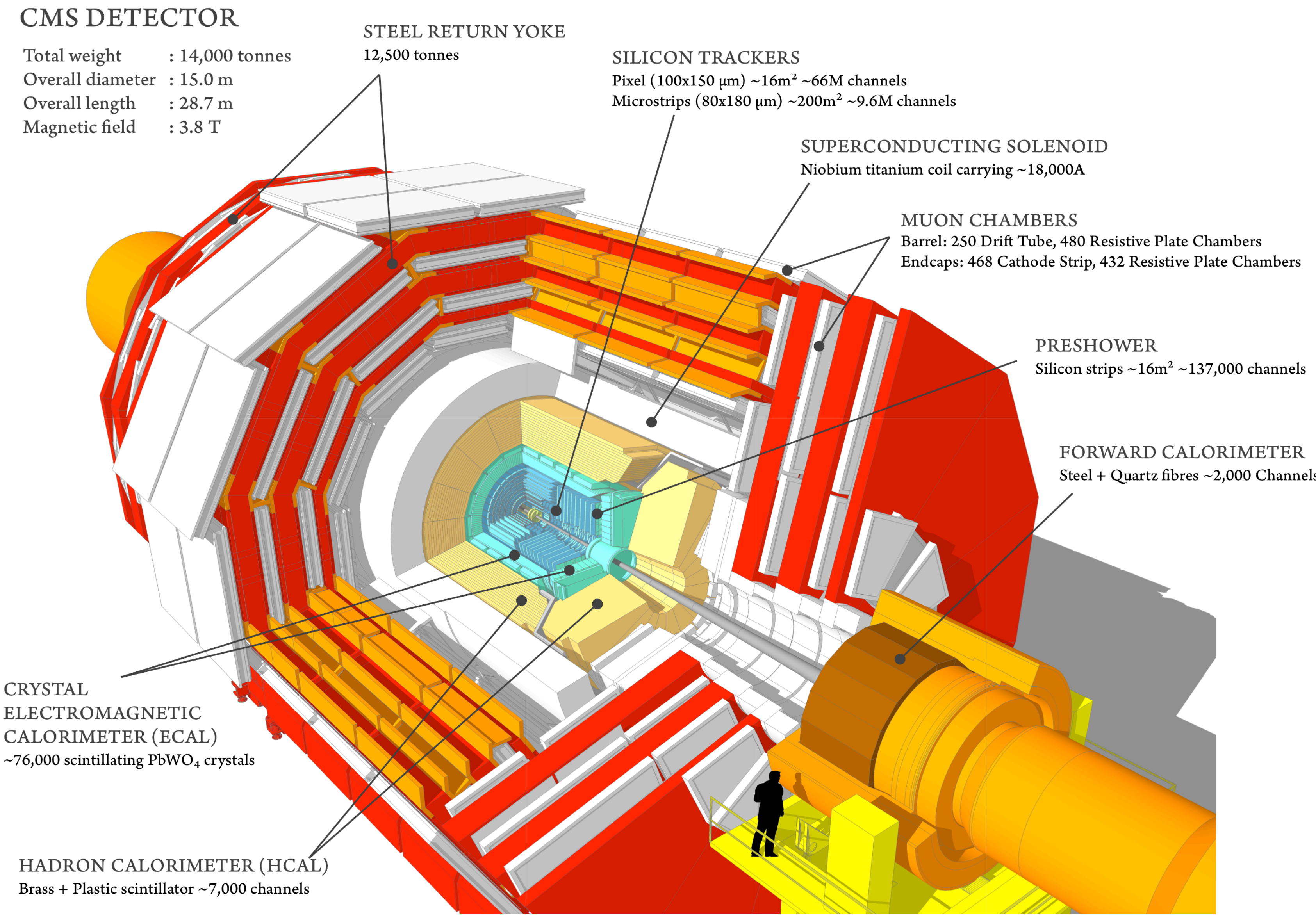


approx. corresponds to

CMS-PAS-TOP-16-008: results



The CMS detector



SELECTION DETAILS

CMS-PAS-TOP-15-006: event selection

- Require ==1 isolated lepton
  - $p_T > 27$ (24) GeV & $|\eta| < 2.5$ (2.1) for electrons (muons)
  - ID & isolation
  - conversion veto (electrons)
  - Veto additional leptons
  - >= 4 ak5 jets with $p_T > 30$ GeV and $|\eta| < 2.5$
  - Remove jets within $\Delta R(\text{jet, lepton}) < 0.5$
  - >= 2 b-tagged jets
- Visible phase space modifications:
  - Jets: $|\eta| < 2.5$ (from $|\eta| < 2.4$)
  - Remove jets within $\Delta R(\text{jet, lepton}) <$ **0.5**

CMS-PAS-TOP-15-013: event selection

- Require ==1 isolated lepton
  - p_T > 30 (23) GeV for electrons (muons), |η| < 2.1
  - ID & isolation
  - conversion veto (electrons)
  - Veto additional leptons
  - >= 4 ak4 jets with p_T > 25 GeV and |η| < 2.4
  - Remove jets within ΔR(jet, lepton) < 0.4
  - >= 2 b-tagged jets
- Visible phase space modifications:
  - Jets: p_T > 25 GeV (down from 30 GeV)
  - Leptons: p_T > 23 GeV (down from 30 GeV)

CMS-PAS-TOP-16-008: event selection

- Require ==1 isolated lepton
  - p_T > 30 GeV, $|\eta|$ < 2.1
  - ID & isolation
  - conversion veto (electrons)
  - Veto other leptons
  - >= 4 ak4 jets with pT > 30 GeV and $|\eta|$ < 2.4
  - Remove jets within ΔR(jet, lepton) < 0.4
  - >= 2 b-tagged jets
  - >=1 b-tagged and one other jet with p_T > 35 GeV
- Visible phase space modifications:
  - Jets: p_T > 25 GeV, $|\eta|$ < 2.5 (from p_T > 30 GeV, $|\eta|$ < 2.4)
  - Leptons: $|\eta|$ < 2.5 ($|\eta|$ < 2.4)

CMS-PAS-TOP-16-010: Event selection

- Require 2 isolated leptons with opposite charge
  - $p_T > 20$ GeV, $|\eta| < 2.4$
  - ID & isolation
  - conversion veto
  - Veto Z events: $m_Z - 15$ GeV $< m_{ll} < m_Z + 15$ GeV
  - MET > 40 GeV
  - >= 2 ak4 jets with $p_T > 30$ GeV and $|\eta| < 2.4$
  - Remove jets within ΔR(jet, lepton) < **0.5**
  - >= 2 b-tagged jets
- Visible phase space modifications:
  - Leptons: $p_T > 20$ GeV (down from 30 GeV)
  - Remove jets within ΔR(jet, lepton) < **0.5**

CMS-PAS-TOP-16-011: Event selection

- Require 2 isolated leptons with opposite charge
  - $p_T > 20$ GeV, $|\eta| < 2.4$
  - ID & isolation
  - conversion veto
  - Veto Z events: $m_Z - 15$ GeV $< m_{ll} < m_Z + 15$ GeV
  - MET > 40 GeV
  - >= 2 ak4 jets with $p_T > 30$ GeV and $|\eta| < 2.4$
  - Remove jets within ΔR(jet, lepton) < 0.4
  - >= 2 b-tagged jets
- Visible phase space modifications:
  - Leptons: $p_T > 20$ GeV (down from 30 GeV)

Distribution	χ^2/dof	p-value	χ^2/dof	p-value	χ^2/dof	p-value
	POWHEG+P8		POWHEG+H++		MG5_aMC@NLO+P8 MLM	
$p_T(t_h)$	14.3/9	0.111	26.3/9	< 0.01	34.9/9	< 0.01
$\|y(t_h)\|$	4.76/7	0.690	7.61/7	0.368	9.08/7	0.247
$p_T(t_\ell)$	22.9/9	< 0.01	40.8/9	< 0.01	54.6/9	< 0.01
$\|y(t_\ell)\|$	7.14/7	0.415	10.6/7	0.156	18.2/7	0.011
$M(t\bar{t})$	9.25/8	0.322	173/8	< 0.01	13.4/8	0.100
$p_T(t\bar{t})$	2.31/5	0.805	39.6/5	< 0.01	48.9/5	< 0.01
$\|y(t\bar{t})\|$	1.37/6	0.967	2.44/6	0.876	14.5/6	0.025
Additional jets	27.6/5	< 0.01	16.2/5	< 0.01	36.3/5	< 0.01
Additional jets vs. $p_T(t\bar{t})$	70.3/20	< 0.01	95.4/20	< 0.01	168/20	< 0.01
Additional jets vs. $p_T(t_h)$	96.2/36	< 0.01	218/36	< 0.01	180/36	< 0.01
$\|y(t_h)\|$ vs. $p_T(t_h)$	60.1/36	< 0.01	212/36	< 0.01	128/36	< 0.01
$M(t\bar{t})$ vs. $\|y(t\bar{t})\|$	28.2/24	0.251	280/24	< 0.01	41.2/24	0.016
$p_T(t\bar{t})$ vs. $M(t\bar{t})$	16.7/32	0.988	465/32	< 0.01	97.6/32	< 0.01
	MG5_aMC@NLO+P8		MG5_aMC@NLO+H++		MG5_aMC@NLO+P8 FXFX	
$p_T(t_h)$	13.1/9	0.159	6.85/9	0.653	5.05/9	0.830
$\|y(t_h)\|$	9.91/7	0.194	13.5/7	0.060	8.12/7	0.322
$p_T(t_\ell)$	13.4/9	0.147	8.02/9	0.533	7.97/9	0.538
$\|y(t_\ell)\|$	14.3/7	0.045	7.24/7	0.404	15.9/7	0.026
$M(t\bar{t})$	10.9/8	0.206	34.2/8	< 0.01	33.0/8	< 0.01
$p_T(t\bar{t})$	40.0/5	< 0.01	7.65/5	0.177	27.8/5	< 0.01
$\|y(t\bar{t})\|$	2.72/6	0.843	2.77/6	0.837	3.58/6	0.733
Additional jets	36.2/5	< 0.01	15.7/5	< 0.01	10.8/5	0.056
Additional jets vs. $p_T(t\bar{t})$	237/20	< 0.01	192/20	< 0.01	87.2/20	< 0.01
Additional jets vs. $p_T(t_h)$	251/36	< 0.01	76.0/36	< 0.01	45.6/36	0.132
$\|y(t_h)\|$ vs. $p_T(t_h)$	48.9/36	0.074	100/36	< 0.01	49.1/36	0.071
$M(t\bar{t})$ vs. $\|y(t\bar{t})\|$	25.1/24	0.403	53.4/24	< 0.01	56.7/24	< 0.01
$p_T(t\bar{t})$ vs. $M(t\bar{t})$	133/32	< 0.01	157/32	< 0.01	109/32	< 0.01