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CMS
Compact Muon Solenoid

Top-Quark-Pair Cross Section Measurements at CMS

inclusive $\sigma(t\bar{t})$

additional jet activity

differential $\sigma(t\bar{t})$

$t\bar{t} + b\bar{b}$

α_s from $\sigma(t\bar{t})$

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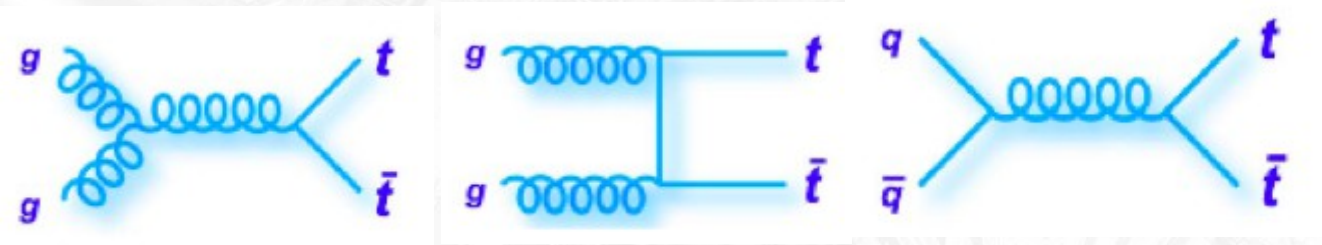
for the CMS Collaboration

LHCP 2013, Barcelona
13th - 18th May

Top Quark Pairs

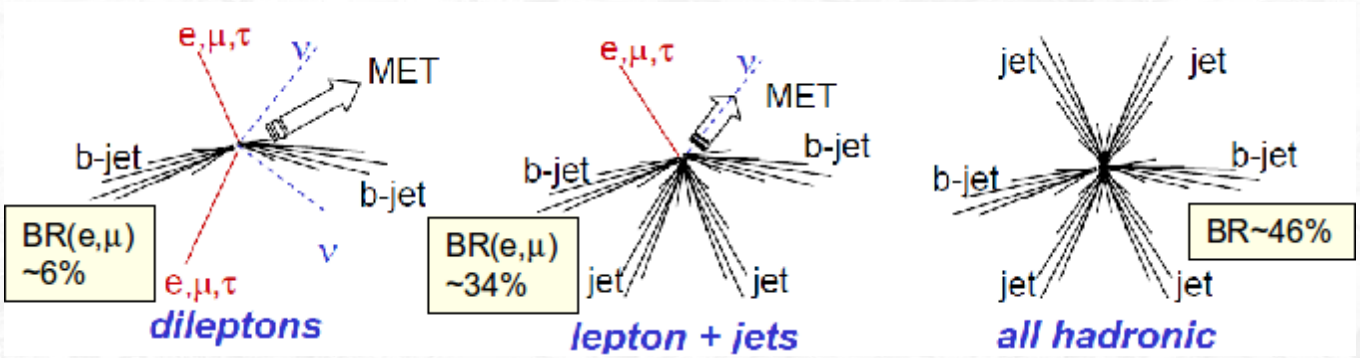
$t\bar{t}$ Production

- at the LHC mainly via gluon-gluon fusion (~80% at √s=7/8 TeV)



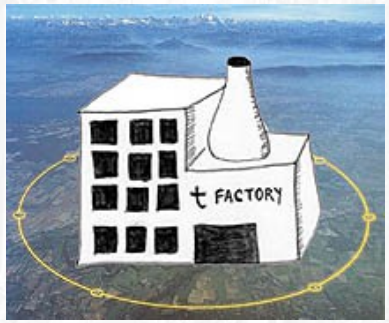
$t\bar{t}$ Decay

- in Standard Model ~100% t→bW, W decay defines final state



LHC

- √s=7 TeV: ~ 1.0 M $t\bar{t}$ pairs
- √s=8 TeV: ~ 5.5 M $t\bar{t}$ pairs



$\sigma(t\bar{t})$ from Theory

- full NNLO+NNLL predictions available

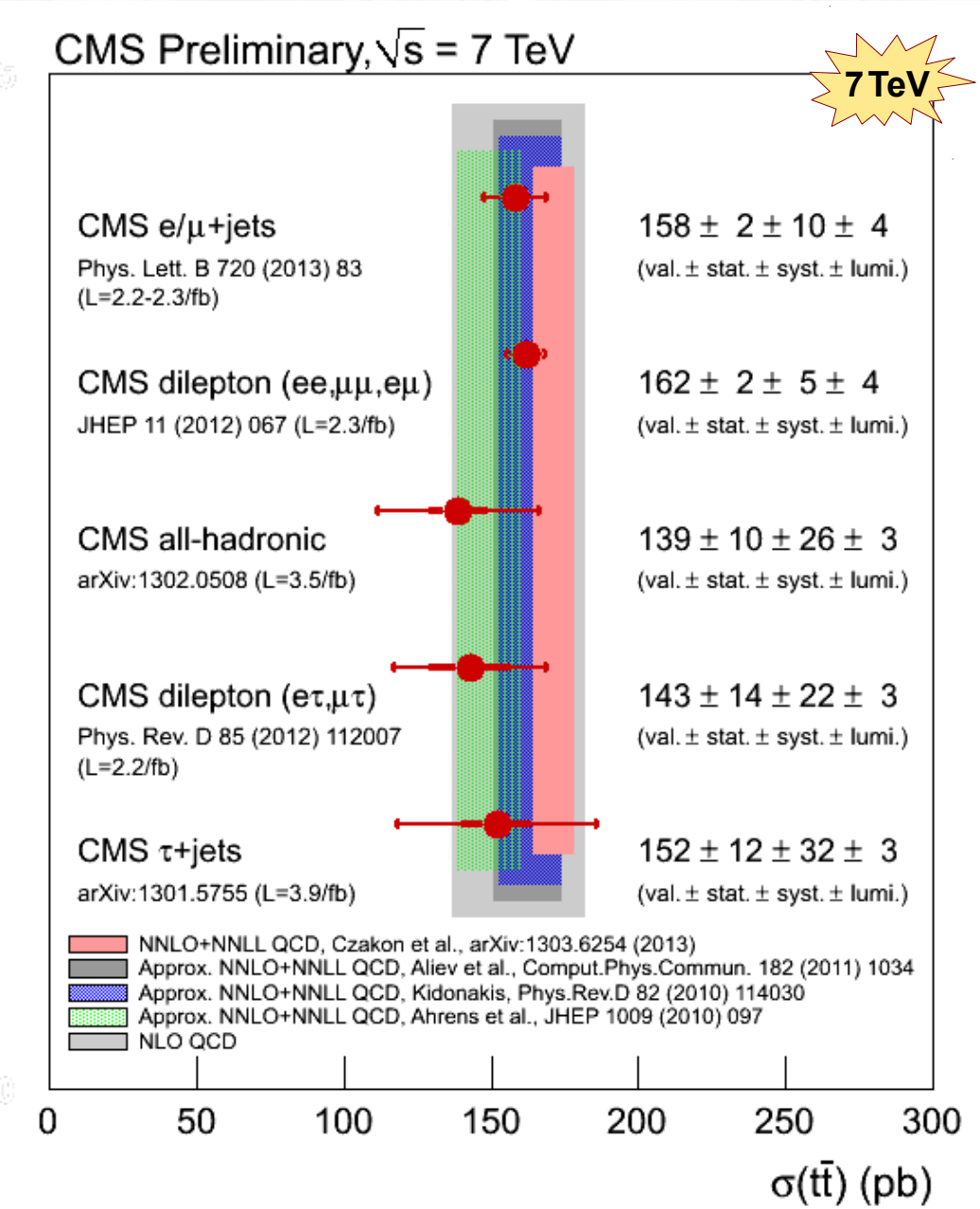
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
LHC 7 TeV	172.0	+4.4 -5.8	+4.7 -4.8
LHC 8 TeV	245.8	+6.2 -8.4	+6.2 -6.4

~ 4 % precision

→ inclusive cross section measurements

(Czakon, Fiedler, Mitov, arXiv:1303.6254)

Overview: $\sigma(t\bar{t})$ at $\sqrt{s}=7$ TeV



CMS Results

- all final states investigated (except $\tau\tau$)
- consistent results among channels
- good agreement with theory predictions
- similar precision as for theory prediction (4% in dilepton channel)

Inclusive Cross Section (e/μ+jets)

CMS-PAS-TOP-12-006

e/μ+jets

2.8 fb^{-1}

8 TeV

Selection

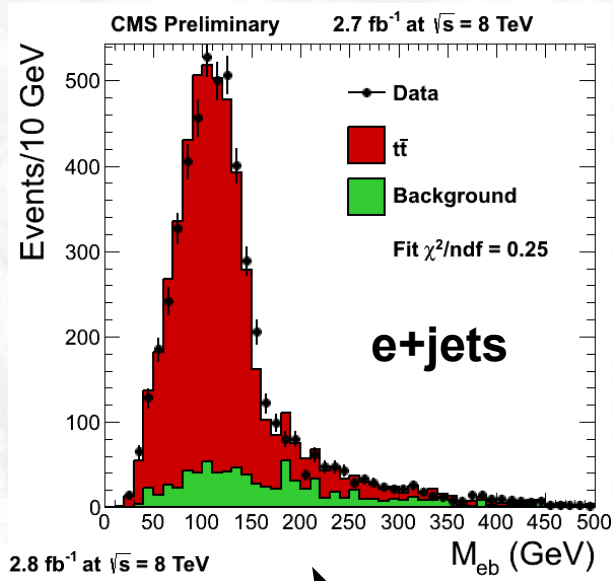
- 1 isolated high p_T lepton & ≥ 4 high p_T central jets
- jet assigned to leptonic top identified as b jet

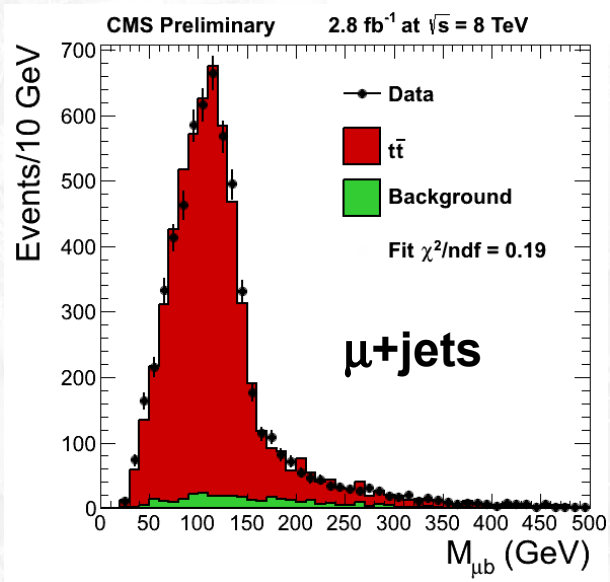
Cross Section

- lepton – b jet association via χ^2 (using m_{top} & m_W)
- N($t\bar{t}$) from 3 component template fit to m(lb)
  - $t\bar{t}$ (simulation)
  - QCD multijet (from sideband region with non-isolated leptons)
  - other backgrounds (simulation)
- combination of channels: BLUE

Main Systematic Uncertainties

- jet energy scale, b-tagging efficiency, matching & Q^2 scale





m(lb) after fit

14 % total uncertainty

$$\sigma_{t\bar{t}}(\text{combined}) = 228.4 \pm 9.0\ (\text{stat.})\ ^{+29.0}_{-26.0}\ (\text{syst.}) \pm 10.0\ (\text{lumi})\ \text{pb}$$

Inclusive Cross Section (ee/eμ/μμ)

CMS-PAS-TOP-12-007

ee/eμ/μμ

2.4 fb^{-1}

8 TeV

Selection

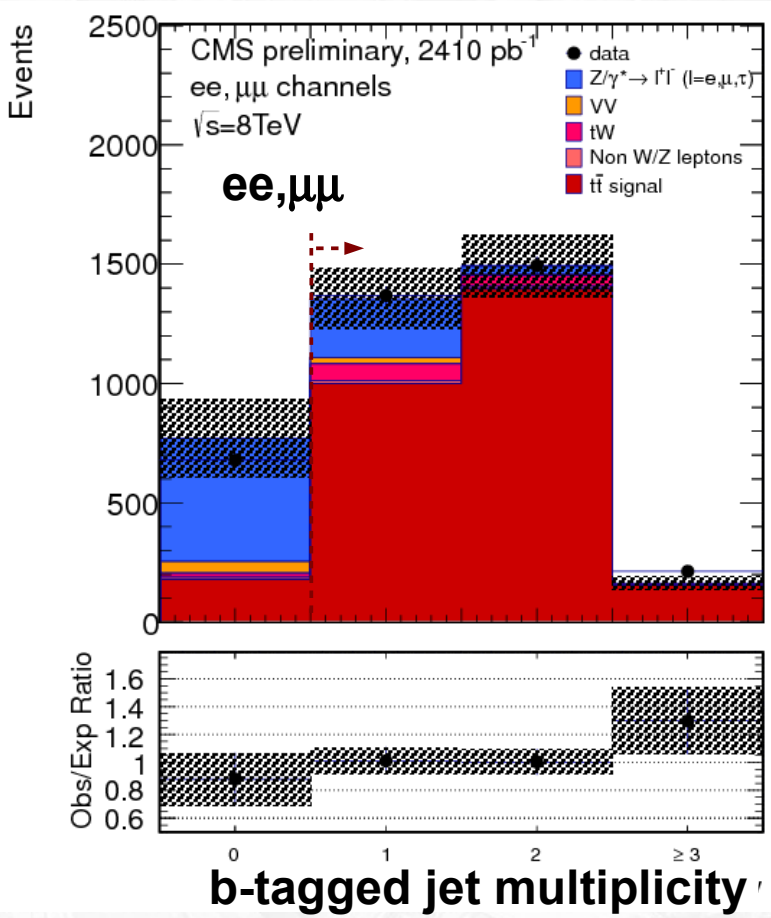
- 2 isolated opposite sign leptons
- ≥ 2 jets (≥ 1 identified b jet)
- ee/μμ: $\not{E}_T > 40$ GeV, veto m_Z-region

Cross Section

- cut and count approach
- data driven background estimation:
  - Z+jets from m(ll) in m_Z window
  - W+jets&QCD from same sign lepton events
- combination of channels: BLUE

Main Systematic Uncertainties

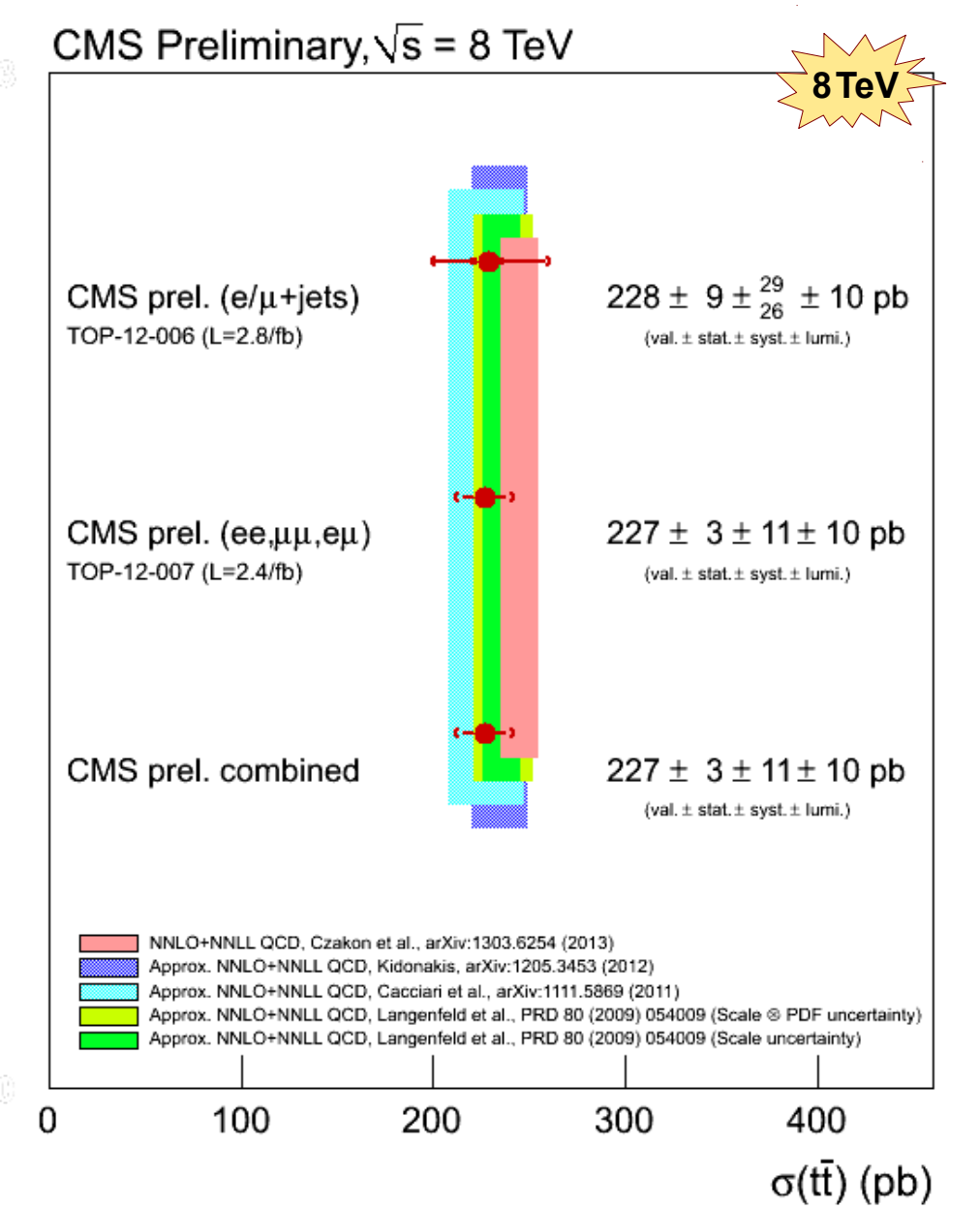
- jet energy scale & resolution, pileup, lepton efficiencies, branching ratio



$$\sigma_{t\bar{t}}(\text{combined}) = 227 \pm 3\ (\text{stat.}) \pm 11\ (\text{syst.}) \pm 10\ (\text{lumi})\ \text{pb}$$

7 % total uncertainty

Summary: $\sigma(t\bar{t})$ at $\sqrt{s}=8$ TeV



CMS Combination

- consistency among channels
- dominated by dilepton result
- good agreement with theory predictions (including full NNLO+NNLL)
- 7% precision already with first data

Cross Section ratio

- systematic uncertainties limits precision
- experimental (theoretical) uncertainties assumed as uncorrelated (correlated)
- measurements from different analysis

$$\frac{\sigma_{t\bar{t}}(\sqrt{s}=8\ \text{TeV})}{\sigma_{t\bar{t}}(\sqrt{s}=7\ \text{TeV})} = 1.41 \pm 0.10$$

α_s (M_Z) from $\sigma(t\bar{t})$

CMS-PAS-TOP-12-022

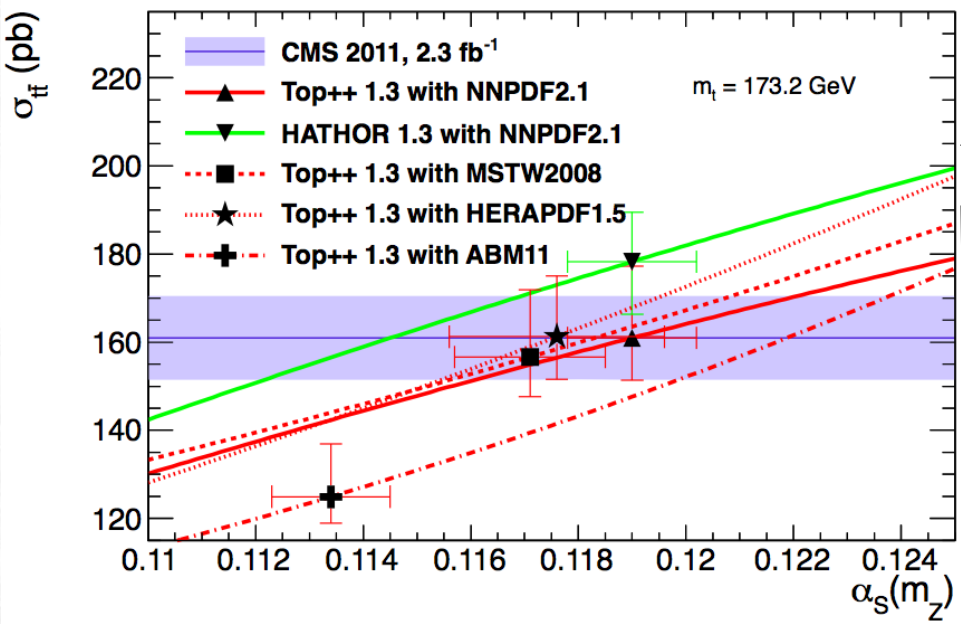
ee/eμ/μμ

2.3 fb^{-1}

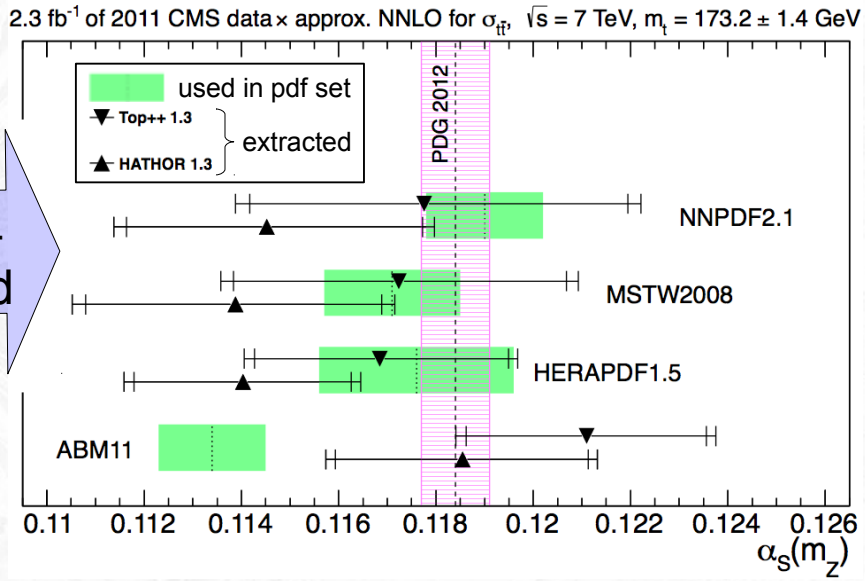
7 TeV

Idea

- $\sigma(t\bar{t}) = \sigma(m_t, \alpha_s, \text{PDF})$
- approx. NNLO calculations used to parametrise $\sigma(t\bar{t})$ as function of α_s (for fixed m_t and PDF)
- most precise CMS **7 TeV** result used to extract α_s (for fixed m_t and PDF set)



$\mathcal{L}$ike-lihood



- joint $\mathcal{L}$ikelihood approach (theory ⊗ experiment) to determine most probable result

Result

- first α_s from $\sigma(t\bar{t})$ measurement
- compatible with PDG value

results with full NNLO+NNLL in progress

Differential Cross Sections (e/μ+jets)

CMS-PAS-TOP-12-027

e/μ + jets

12.1 fb^{-1}

8 TeV

Motivation

- precision test of perturbative QCD
- sensitive to BSM effects
- can constrain (gluon) pdf
- model comparison: MadGraph+Pythia, Powheg+Pythia, MC@NLO+Herwig, Approx. NNLO

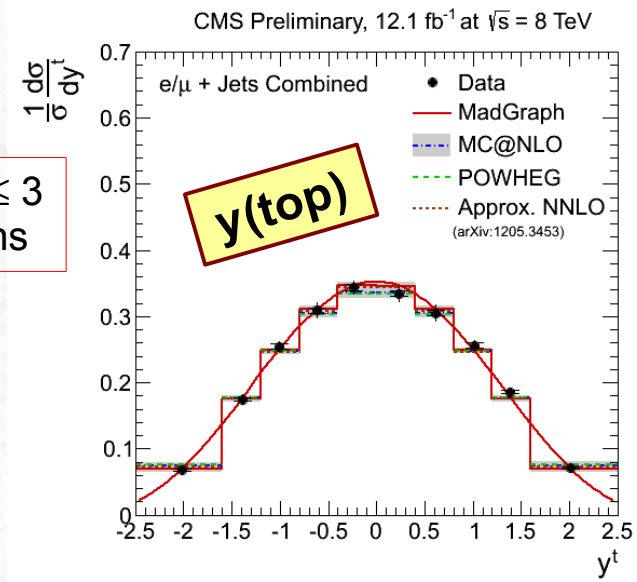
MadGraph: $t\bar{t} + \leq 3$ additional partons

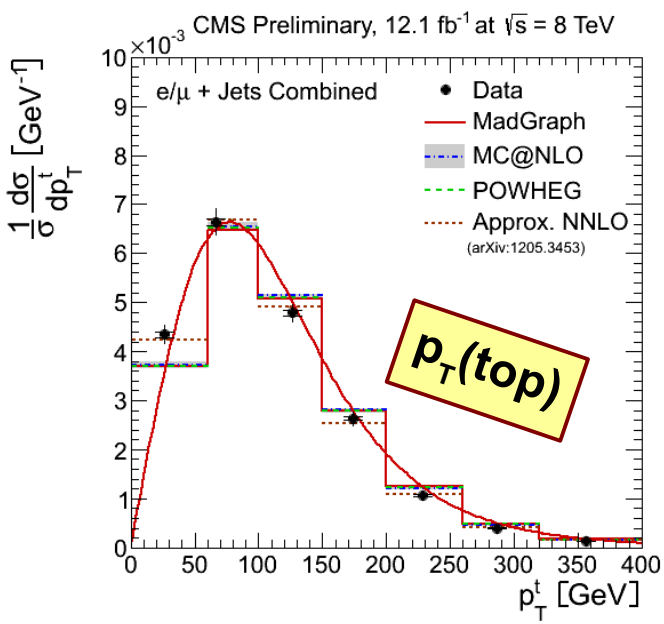
Results

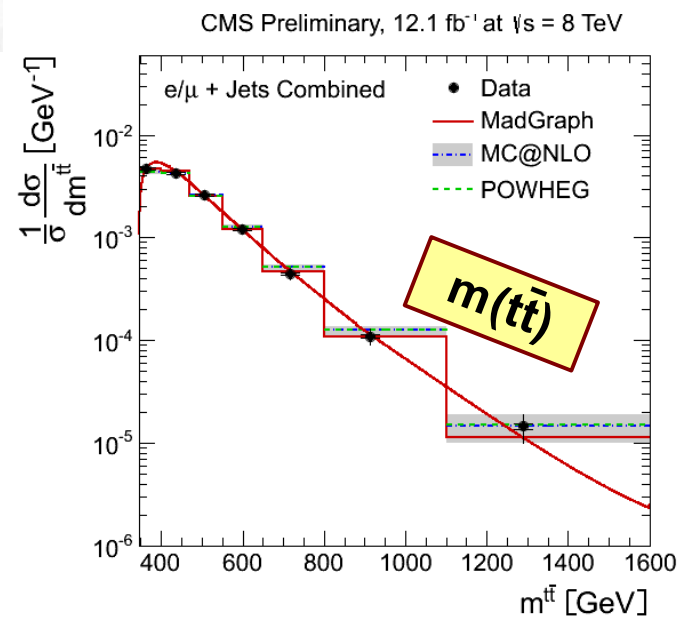
- good agreement for most quantities
  - between data and predictions
  - between different models
- for p_T(top) approx. NNLO describes data best

Uncertainty

- typical precision: 5-10% per bin
- main uncertainties from model (e.g. matching or Q^2 scale)







Differential Cross Sections (ee/eμ/μμ)

CMS-PAS-TOP-12-028

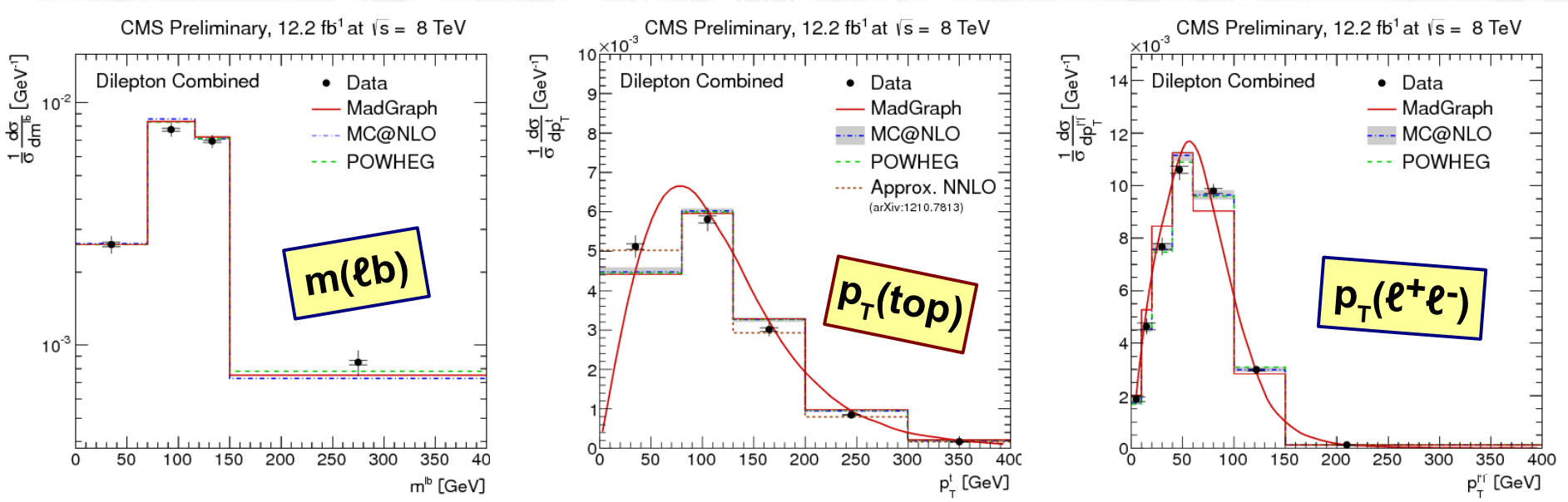
ee/eμ/μμ

12.1 fb^{-1}

8 TeV

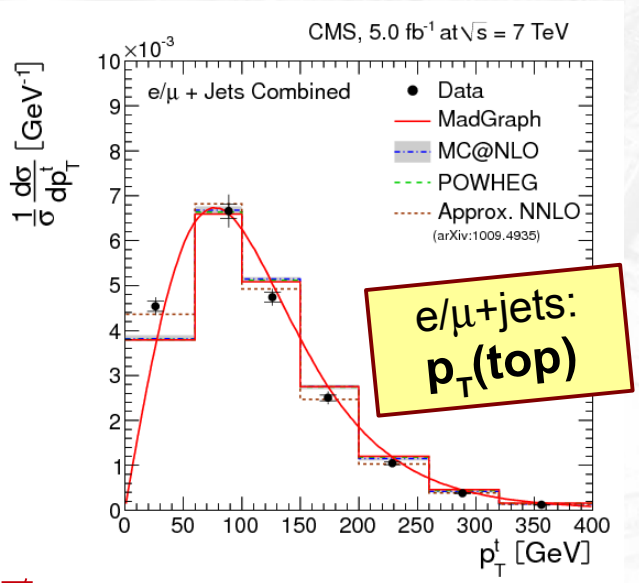
Results (Dilepton)

- consistent with lepton+jets results (similar precision)
- good agreement
- same behaviour for p_T(top) observed
- dilepton system quantities
  → models including spin correlations (SC) preferred
  (here: MadGraph+Pythia without SC)

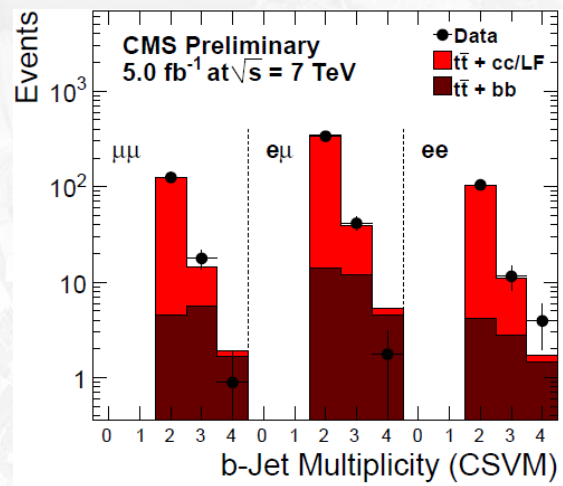


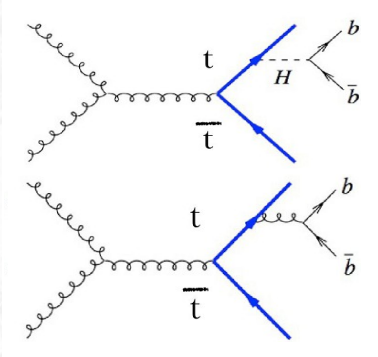
More Results ($\sqrt{s}$=7 TeV)

Differential Cross Sections
(Eur. Phys. J. C73 (2013) 2339)



$\bar{t}\bar{t}$+$b\bar{b}$ (CMS-PAS TOP-12-024)



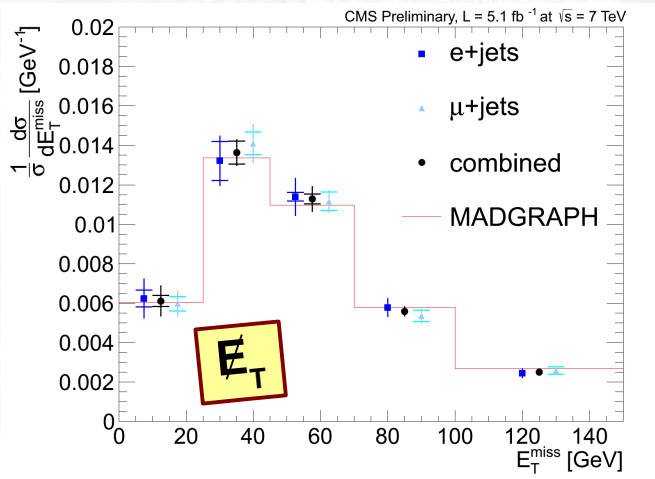


MadGraph+Pythia: 1.2 %

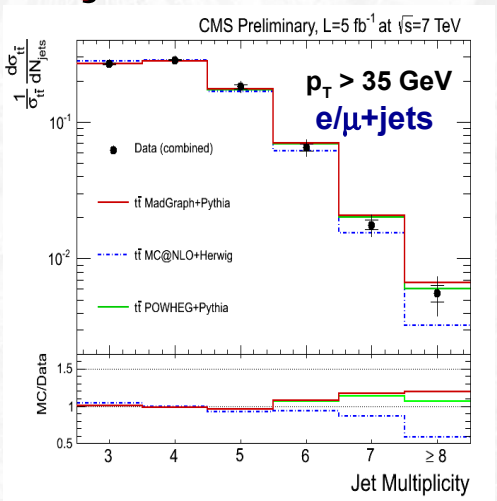
Powheg+Pyhia: 1.3 %

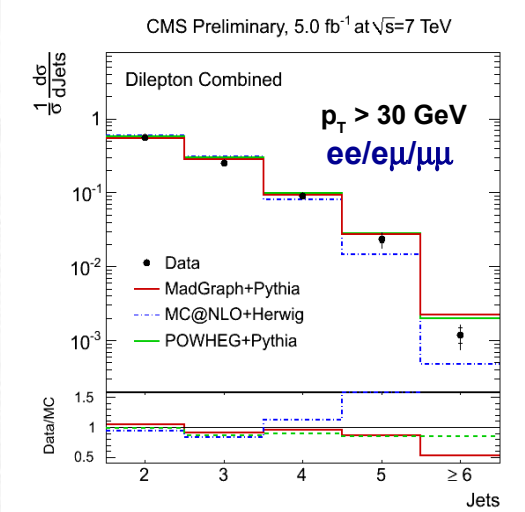
$$\sigma(t\bar{t}b\bar{b}) / \sigma(t\bar{t}jj) = 3.6 \pm 1.1\ (\text{stat.})\ \pm 0.9\ (\text{syst.})\ \%$$

$\not{E}_T$ (CMS-PAS TOP-12-019)



$t\bar{t}$+jets (CMS-PAS TOP-12-018, CMS-PAS TOP-12-023)





Additional Jet Activity (N_{Jets})

NEW

CMS-PAS-TOP-12-041

ee/eμ/μμ

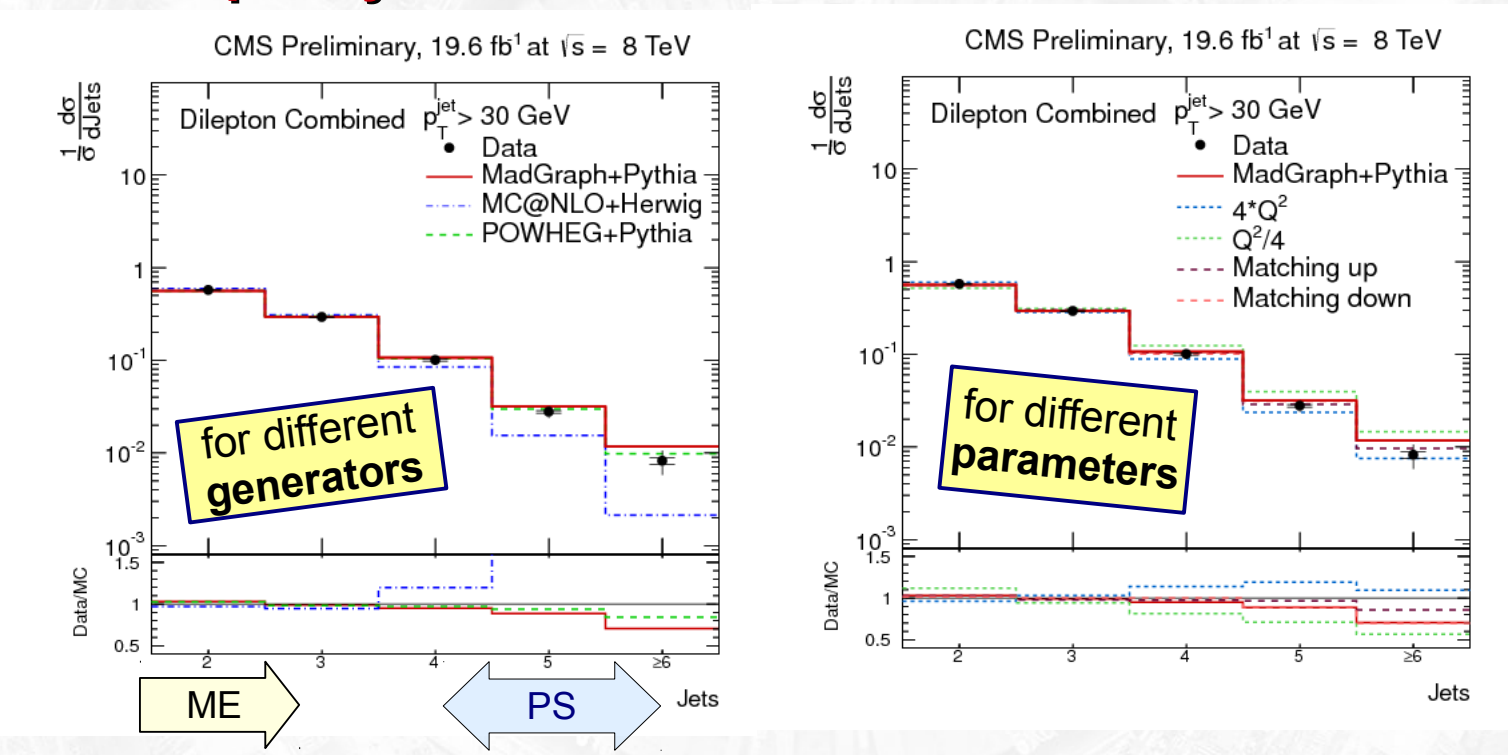
19.6 fb^{-1}

8 TeV

Motivation

- can help to constrain simulation parameters and models

Jet Multiplicity Measurement



- MC@NLO+Herwig underestimates higher jet multiplicities

- MadGraph: decreased Q^2 scale slightly worsens agreement

Main Systematic Uncertainties

- jet energy scale, model (Q^2 and matching scale, hadronisation)

Additional Jet Activity (f_{Gap})

NEW

CMS-PAS-TOP-12-041

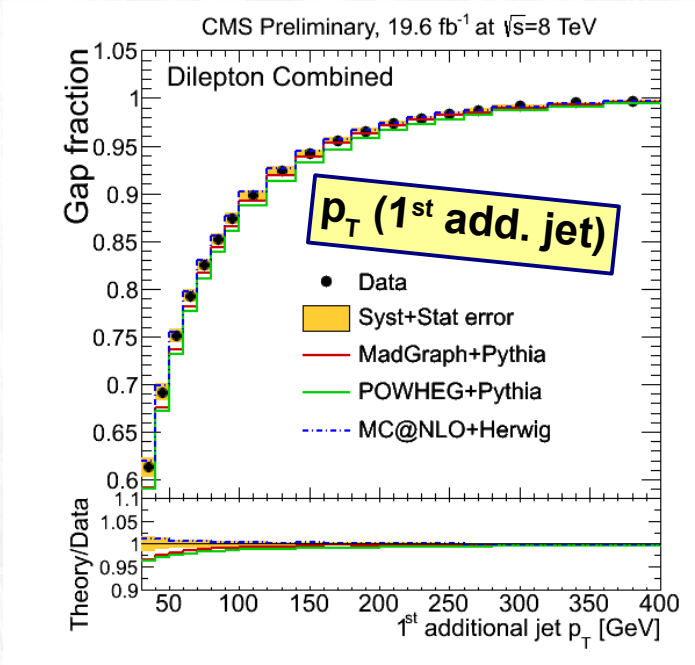
ee/eμ/μμ

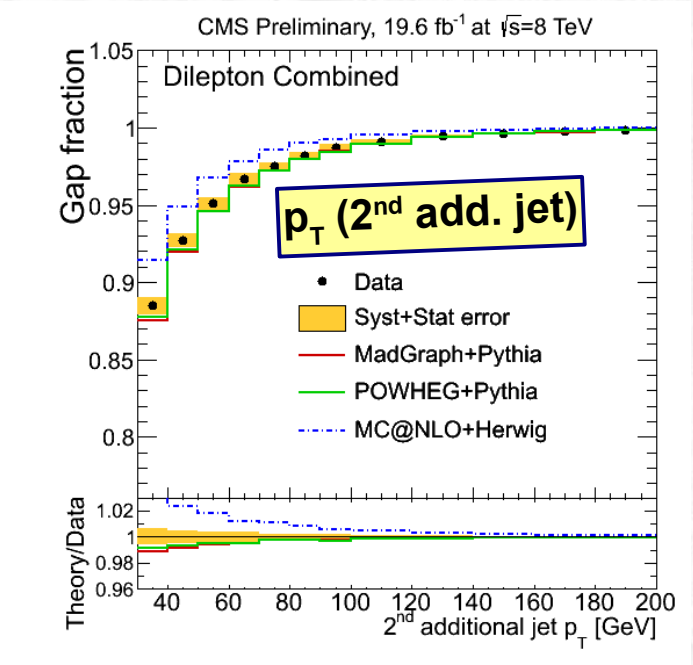
19.6 fb^{-1}

8 TeV

Jet Veto Measurement

- probe additional radiation
- Gap fraction $f_{Gap}(x) = \frac{N(\textbf{not } x > \text{threshold})}{N_{total}}$, e.g. $x = p_T$ (1st, 2nd additional jet)
- already sensitive to differences between predictions
  - same behaviour of MadGraph+Pythia and Powheg+Pythia





- good description within uncertainties
- too few (soft) radiation by MC@NLO+Herwig

Main Systematic Uncertainties: jet energy scale, background

Conclusion

Many Precise $t\bar{t}$ Cross Section Results from CMS

- **inclusive** $\sigma(t\bar{t})$
  - 7 TeV: all channels (except $\tau\tau$), precision comparable to NNLO+NNLL prediction
  - 8 TeV: five channels, up to 7% precision from first data
- **$t\bar{t}$ differential** cross section measurements
  - $t\bar{t}$, top quark, b-jets, leptons, lepton pairs, $\not{E}_T$, ...
- **$t\bar{t}$+X** measurements, where X = (b) jets,...

Good agreement between theory/simulation and data
→ gaining sensitivity to model differences

Entered new era of precision measurements for $t\bar{t}$!

Backup

Radiative Corrections

Purpose of Q^2 Scale Variation

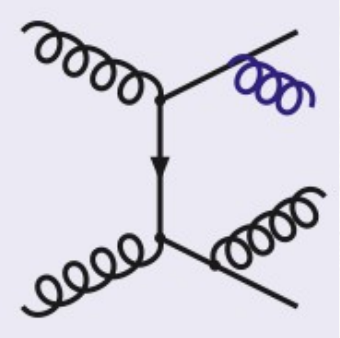
- adresses renormalisation and factorisation scale (ME)
- adresses amount of initial and final state radiation (ISR/FSR)

Q^2 Definition and Variation

$$Q^2 = m_t^2 + \sum p_T^2 \text{ (MadGraph)}$$

$$Q^2 = m_t^2 \text{ (POWHEG/MC@NLO)}$$

→ Q^2 varied up (down) by a factor 4.0 (0.25)



Parton showering

- p_T-ordered evolution scale of ISR/FSR
- shares Q^2 factor α_S scale with ME
- implicitly: starting scale changes with ΔQ^2

MadGraph

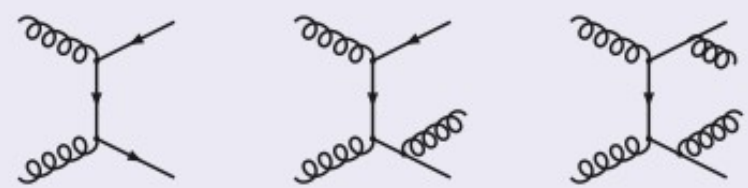
- tree-level diagrams for hard radiation and interferences (up to 3 final-state partons for $t\bar{t}$)
- parton showering for soft and collinear region (with Pythia 6.42X)
- matching via ktMLM, thresholds varied by factor 0.5 to 2.0 (nominal = 20 GeV)

CMS MC Generator Setups

process	ME	PS	method	PDF	Tune
$t\bar{t}$ + jets	MadGraph v5.x	Pythia v6.42x	ME+PS	CTEQ6L1	Z2(*)
$t\bar{t}$	POWHEG-box 1.0	Pythia v6.42x	NLO	CTEQ6M	Z2(*)
$t\bar{t}$	MC@NLO v3.41	Herwig v6.520	NLO	CTEQ6M	

Matrix Element + Parton Shower generators

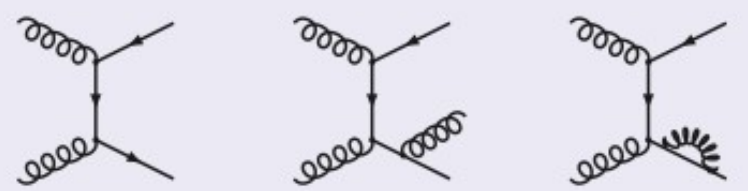
- Better description of high multiplicities
- ISR/FSR modelling via ME from assumed Q^2 variation
- Matching procedure to remove double counting between partons produced by ME and PS



tree level diagrams with up to 3 partons

Next to Leading Order generators

- More accurate in normalization
- Smaller uncertainty on Q^2



real + virtual corrections

CMS Analysis

- MadGraph(+Pythia) is the default for most of the analyses
- Uncertainty on radiation covered by variations of Q^2 and ME-PS matching

m(lb) in TOP-12-006

CMS-PAS-TOP-12-006

e/μ + jets

2.8 fb^{-1}

8 TeV

m(lb) template fit

- needs association of lepton and leptonic b-jet
- use simple χ^2 sorting for leading four jets

$$\chi^2 = \left(\frac{m_{bqq} - m_{top}}{\sigma_{top}}\right)^2 + \left(\frac{m_{qq} - m_W}{\sigma_W}\right)^2$$

- m_{top}, m_W: reconstructed top quark and W-boson mass
- σ_{top}, σ_W: widths of reconstructed masses
- permutation with lowest χ^2 is chosen
- b-jet identification is applied to leptonic b jet candidate

Differential Measurements

Available Data

- plenty of statistics: 22 fb^{-1} at 8 TeV (~5.4 M $t\bar{t}$ pairs)

→ precise, detailed and differential measurements

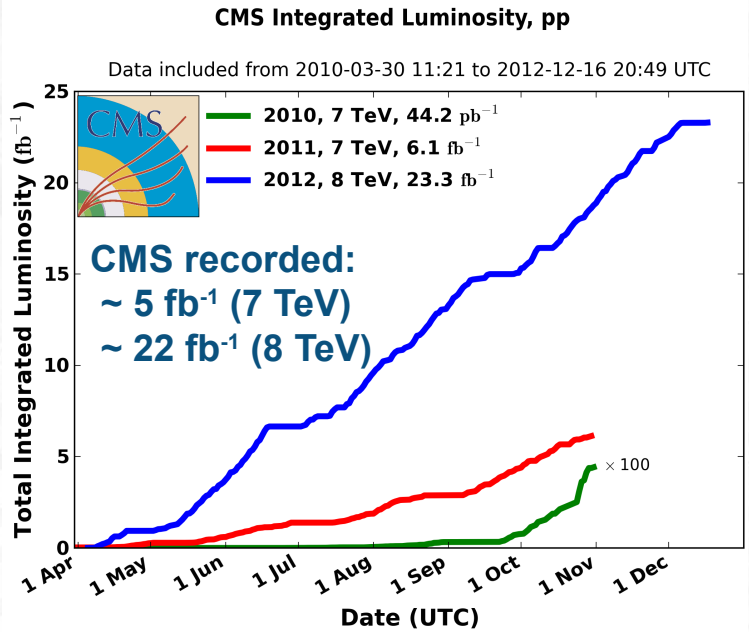
Differential Measurements at CMS

- differential cross sections (top quarks, $t\bar{t}$ system, lepton, b jet, dilepton system)

7 → 8 TeV

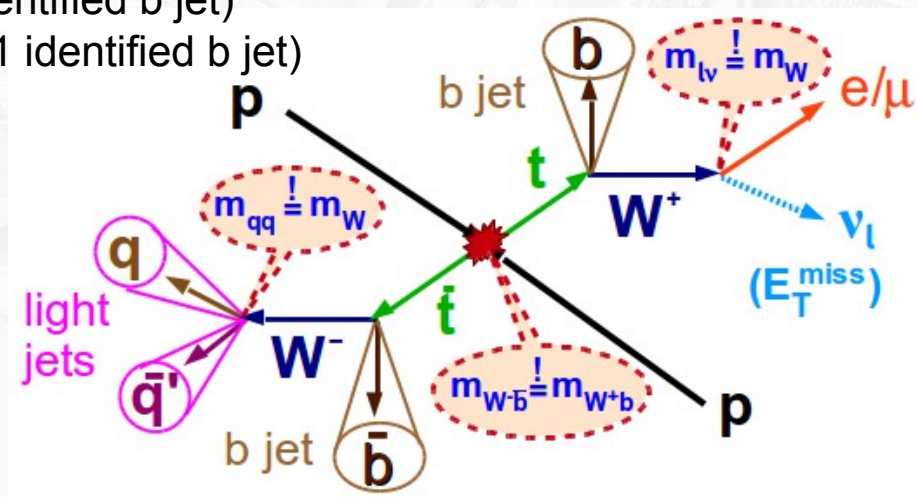
- additional jet activity
- also: global event activity (e.g. $\not{E}_T$), $t\bar{t}$+jets

7 TeV



Analysis Strategy

- selection (optimised for pure $t\bar{t}$ sample)
  - lepton+jets: 1 isolated lepton, ≥ 4 jets (≥ 2 identified b jet)
  - dilepton: 2 opposite sign leptons, ≥ 2 jets (≥ 1 identified b jet)
- event reconstruction (topological constrains)
- (regularised) unfolding method
- normalisation wrt. in situ measured $\sigma(t\bar{t})$
- measurement in phase space:
  - fully extrapolated parton level
  - visible hadron level



Details TOP-12-027

CMS-PAS-TOP-12-027

e/μ + jets

12.1 fb^{-1}

8 TeV

Selection

- 1 isolated lepton & ≥ 4 jets (≥ 2 identified b-jets)

→ pure sample of $t\bar{t}$ events

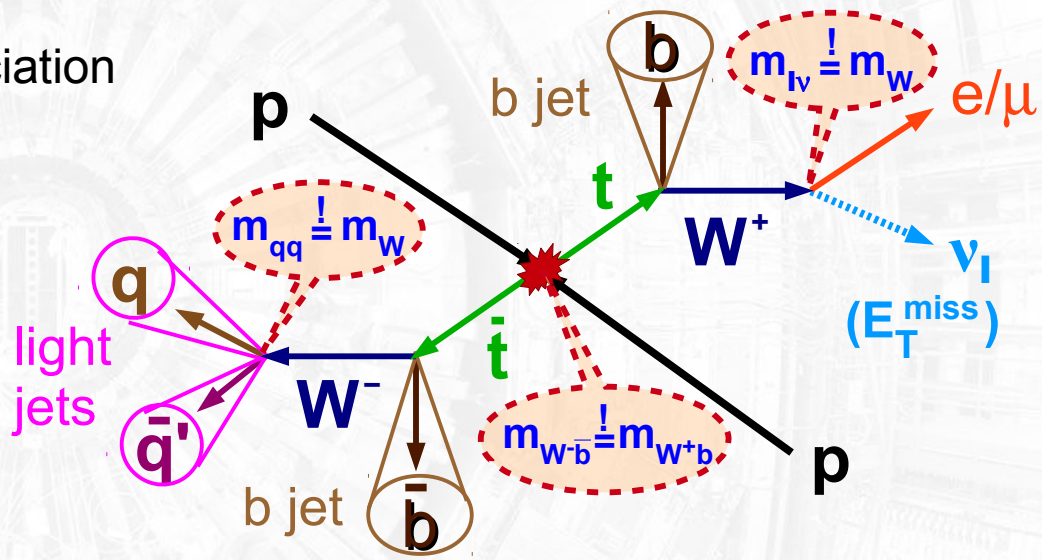
Event Reconstruction

- Kinematic fit: 5 leading jets, b jet association from b-tag information
- constrains: $2 \times m_W$, $m_t = m_{\bar{t}}$

→ choose lowest χ^2 jet permutation

Unfolding

- regularised unfolding method
- continuous regularisarion parameter (minimising global correlation)
- binning optimised to limit migration effects



Cross Section

- differentially in a variety of quantities
  - top quarks, $t\bar{t}$ system: fully extrapolated phase space
  - lepton, b jet: visible hadron level phase space
- normalised wrt. in situ measured $\sigma(t\bar{t})$

Details TOP-12-028

CMS-PAS-TOP-12-028

ee/eμ/μμ

12.1 fb^{-1}

8 TeV

Selection

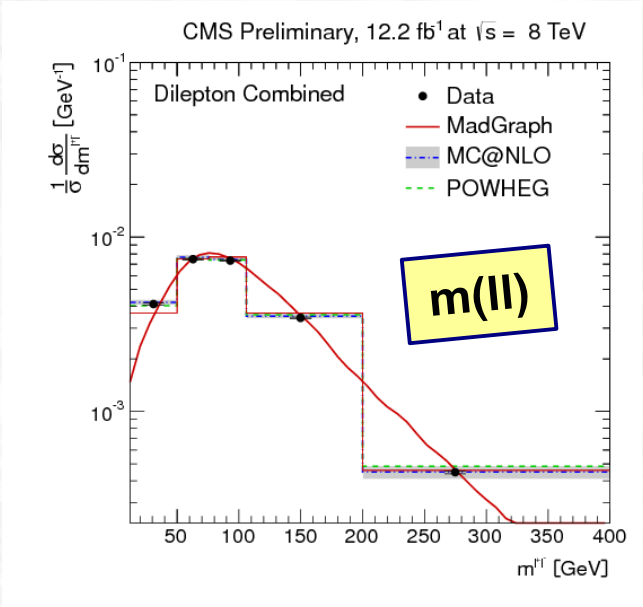
- 2 opposite sign leptons
- ≥ 2 jets (≥ 1 identified b-jet)
- data driven estimation for Z+jets background from m_Z window

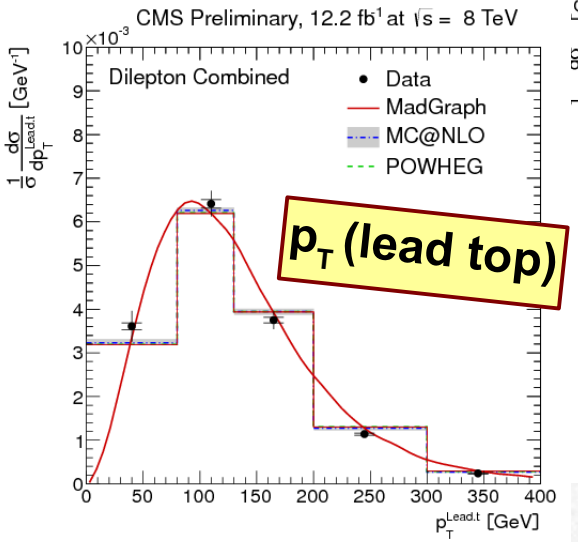
Event Reconstruction

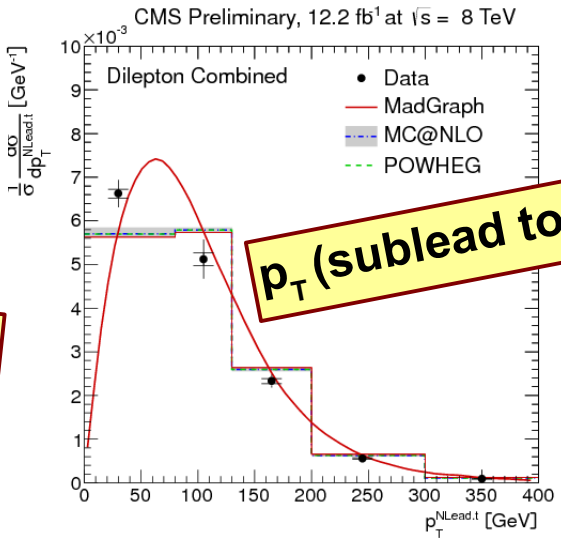
- similar to l+jets channel but 2 ν
- scan m(top) in range [100..300] GeV
- prefer solution wrt. reference $\not{E}_T$ spectrum and with identified b-jets

Unfolding+Cross section

- same method as for lepton+jets
- additional quantities:
  - ll system (MC including spin correlation prefered)
  - separate top quarks by p_T
- similar precision as as for lepton+jets channel







Pseudo Top Measurement

NEW

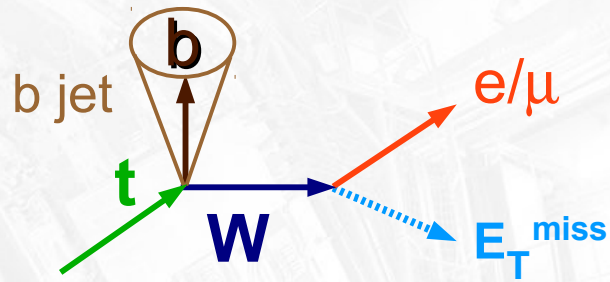
ee/eμ/μμ

12.1 fb^{-1}

8 TeV

Concept

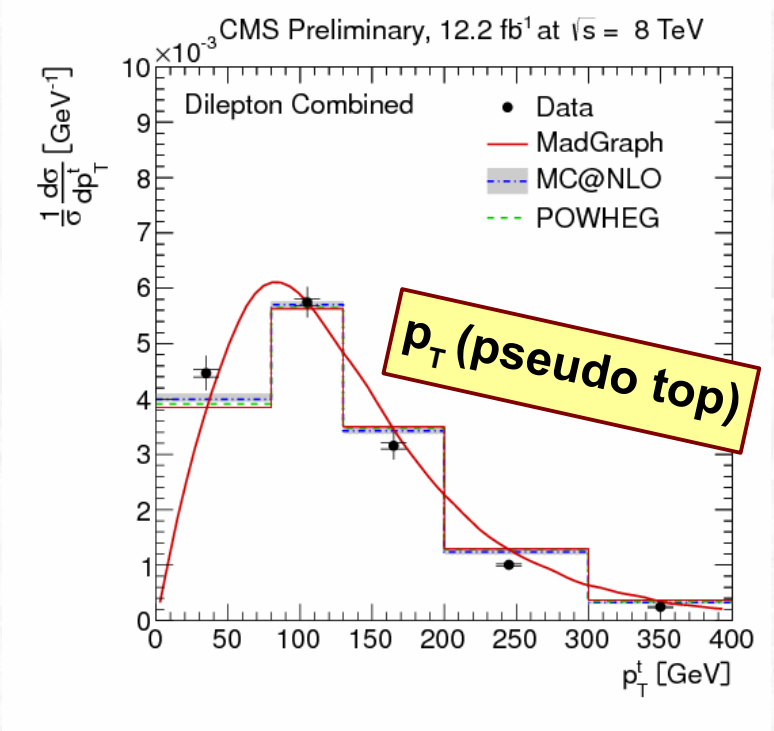
- measurement corrected only for detector effects
→ as model independent as possible
- "visible top quark" definition
→ top defined by its decay products
- joint effort of CMS, ATLAS & theory

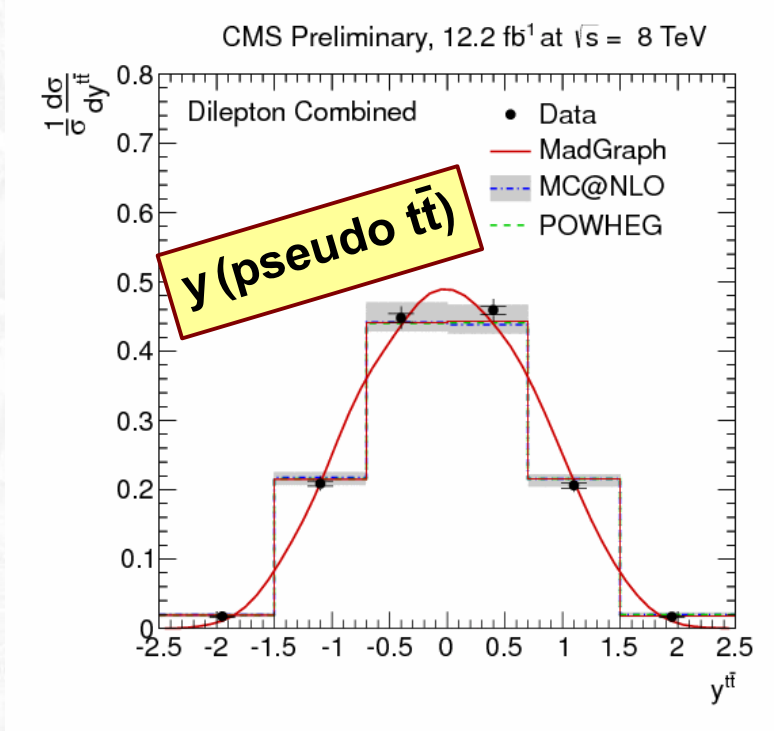


pseudo top quark = b jet + lepton + E_T^{miss}

Results

- extension of differential cross section analysis (CMS-PAS-TOP-12-028)





$f_{Gap}(x)$ for different parameters

NEW

CMS-PAS-TOP-12-041

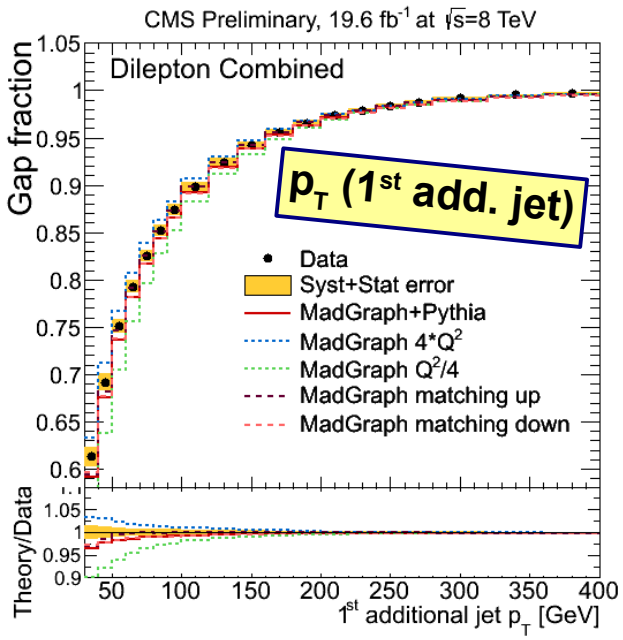
ee/eμ/μμ

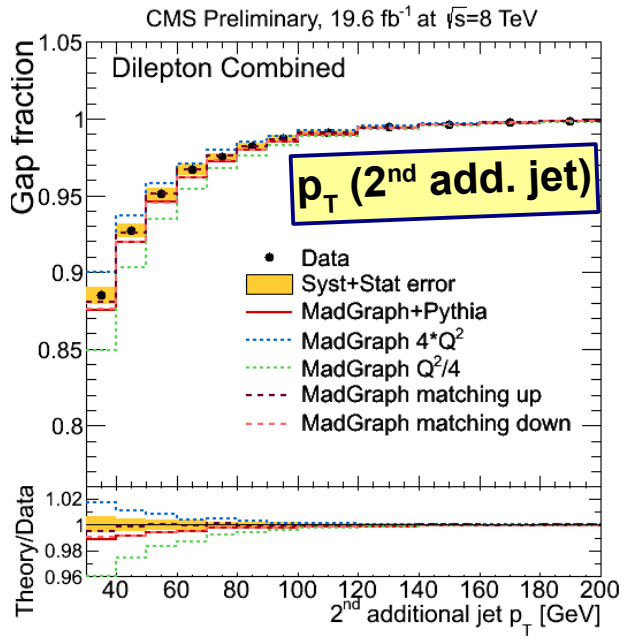
19.6 fb^{-1}

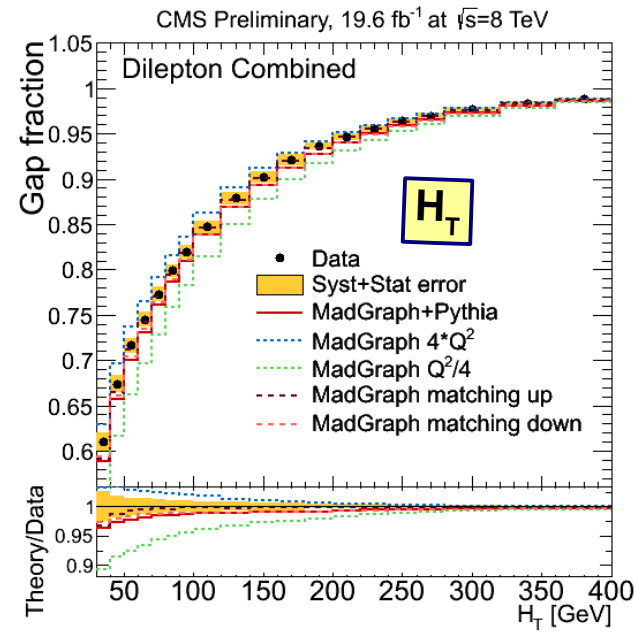
8 TeV

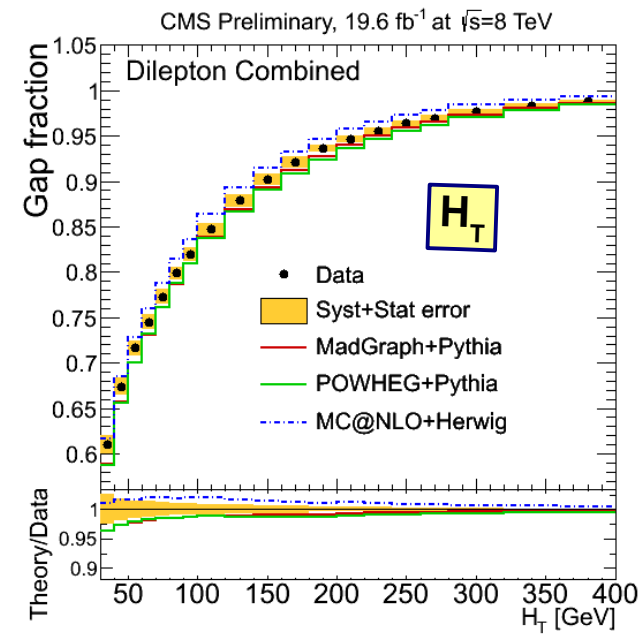
Gap Fraction Results

- compared to different MadGraph+Pythia parameters









- sensitive to choice of Q^2 scale
- Q^2 down variation performs worst
- less sensitive to choice of ME-PS matching scale

N(jets) for different p_T values

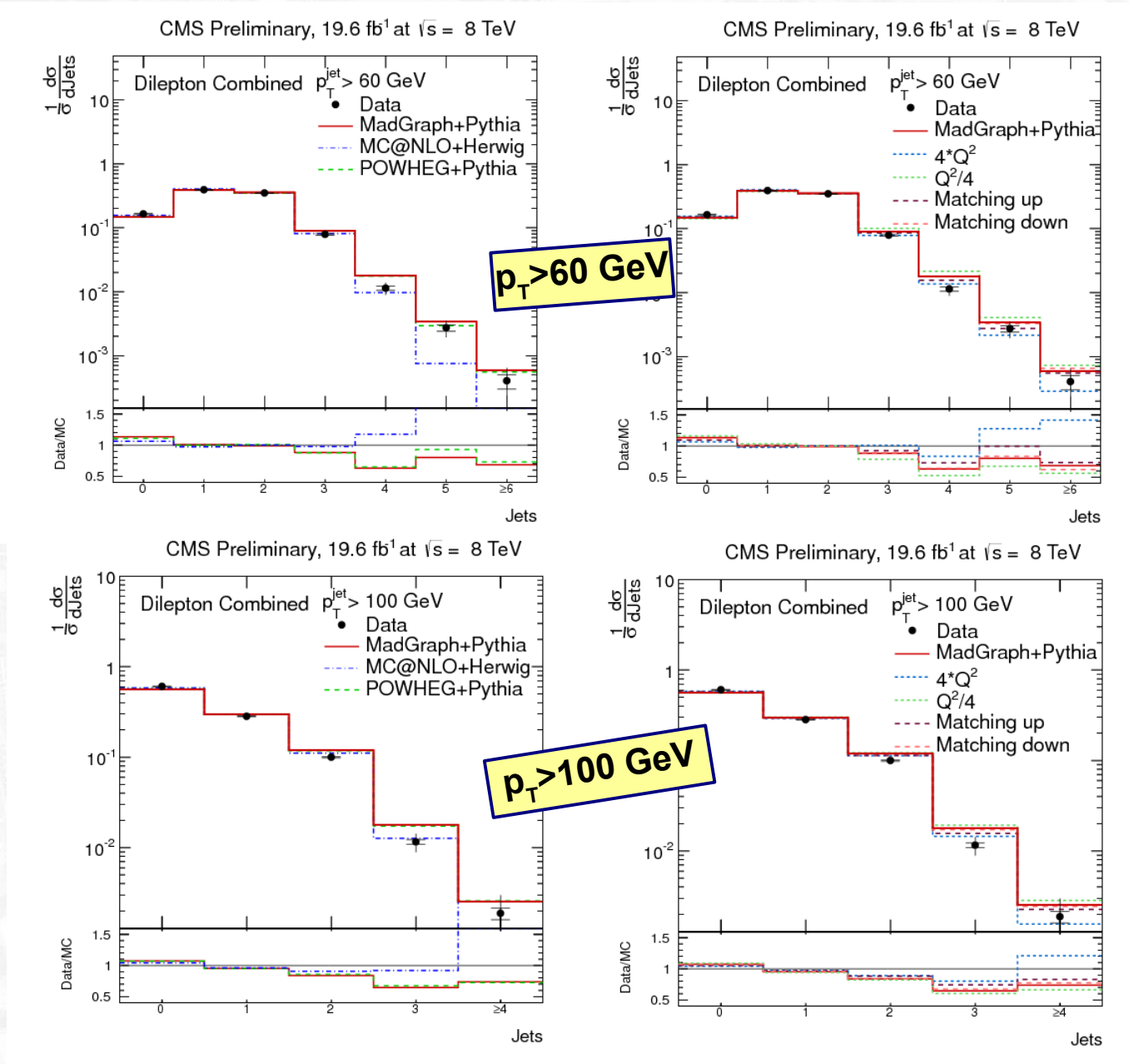
NEW

CMS-PAS-TOP-12-041

ee/eμ/μμ

19.6 fb^{-1}

8 TeV



Selection Details

TOP-12-006 (inclusive $\sigma(t\bar{t})$ in l+jets)

- lepton + jets trigger; 1 isolated lepton (p_T>26/30 GeV, $|\eta|$<2.1/2.5 for μ/e)
- $\geq$ 4 jets (p_T>45/45/35/35 GeV, $|\eta|$<2.5) b-tag for jet assigned to leptonic top (JPM algorithm)

TOP-12-007 (inclusive $\sigma(t\bar{t})$ in dilepton)

- dilepton lepton trigger; 2 isolated opposite sign leptons (p_T>20 GeV, $|\eta|$<2.4/2.5 for μ/e)
- $\geq$ 2 jets (p_T>30 GeV, $|\eta|$<2.5), $\geq$ 1 identified as b-jet (CSVL), m(ll)>20 GeV
- ee/$\mu\mu$: $\not{E}_T$ > 40 GeV, |m(ll)-mZ| >15 GeV

TOP-12-027 (differential $\sigma(t\bar{t})$in l+jets)

- 1 isolated lepton (p_T>30 GeV, $|\eta|$<2.1); $\geq$ 4 jets (p_T>20 GeV, $|\eta|$<2.4); $\geq$ 2 b-jets (CSVM)

TOP-12-028 (differential $\sigma(t\bar{t})$ in dilepton + pseudo top)

- dilepton lepton trigger; 2 isolated opposite sign leptons (p_T>20 GeV, $|\eta|$<2.4 for μ/e)
- $\geq$ 2 jets (p_T>30 GeV, $|\eta|$<2.4), $\geq$ 1 identified as b-jet (CSVL), m(ll)>20 GeV
- ee/$\mu\mu$: $\not{E}_T$ > 40 GeV, |m(ll)-m_Z| >15 GeV

TOP-12-041 (addional jet activity in dilepton)

- same as TOP-12-028