Top quark cross section measurements with CMS

$t\bar{t}$

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For the CMS Collaboration

DIS 2014

Warsaw

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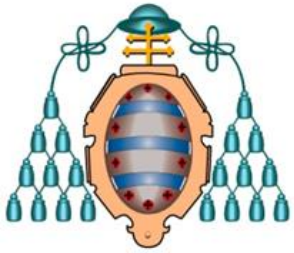

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Outline

- **Introduction**: top quark pair production
- **Inclusive measurements :**
  - lepton+jets : **Phys. Lett. B 720 (2013) 83** (2.3fb^{-1})
  - dilepton : **JHEP 11 (2012) 067** (2.3fb^{-1})
  - tau+jets : **Eur. Phys. J. C73 (2013) 2386** (3.9fb^{-1})
  - dilepton with a tau: **Phys. Rev. D 85 (2012) 112007** (2.2fb^{-1})
  - all jet: **JHEP 1305 (2013) 065** (3.5fb^{-1})
  - lepton+jets : **CMS PAS TOP-12-006** (2.3fb^{-1})
  - dilepton : **JHEP 02 (2014) 024** (5.3fb^{-1})

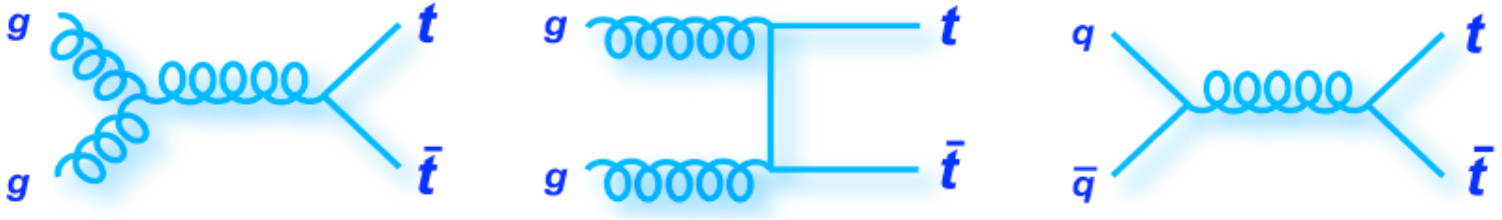
  8TeV

  7TeV

  Determination of m_t^{pole} and $\alpha_s(M_Z)$: Phys. Lett. B 728 (2013) 496
- **Differential measurements :**
  - dilepton & lepton+jets 7TeV: **Eur. Phys. J. C73 (2013) 2339** (5.0fb^{-1})
  - dilepton 8TeV: **CMS PAS TOP-12-028** (12.1fb^{-1})
  - lepton+jets 8TeV: **CMS PAS TOP-12-027** (12.1fb^{-1})
- **Jet multiplicity :**
  - lepton + jet 7TeV: **arXiv:1404.3171** (5fb^{-1})
  - dilepton 7TeV: **CMS PAS TOP-12-023** (5fb^{-1})
  - dilepton 8TeV: **CMS PAS TOP-12-041** (19fb^{-1})
- **Ratio σ(ttbb)/σ(ttjj) :**
  - **7TeV** (5fb^{-1}) **CMS PAS TOP-12-024** & **8TeV** (19.6fb^{-1}) **CMS PAS TOP-13-010**

Top quark pair production

top-pair strong production



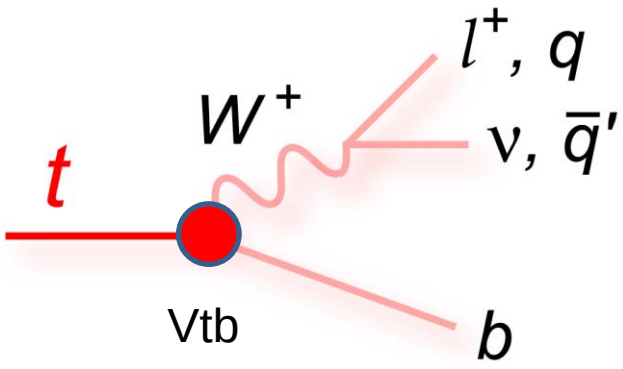
@LHC gg fusion > 84%

- Top quark is **heaviest elementary particle**
- Lifetime shorter than timescale of hadronisation
- NNLO and NNLO + NNLL calculations exist
- Sensitive to new physics & test of perturbative QCD
- Can constrain modeling (PDF, ISR/FSR)
- Important background to many Higgs and BSM searches

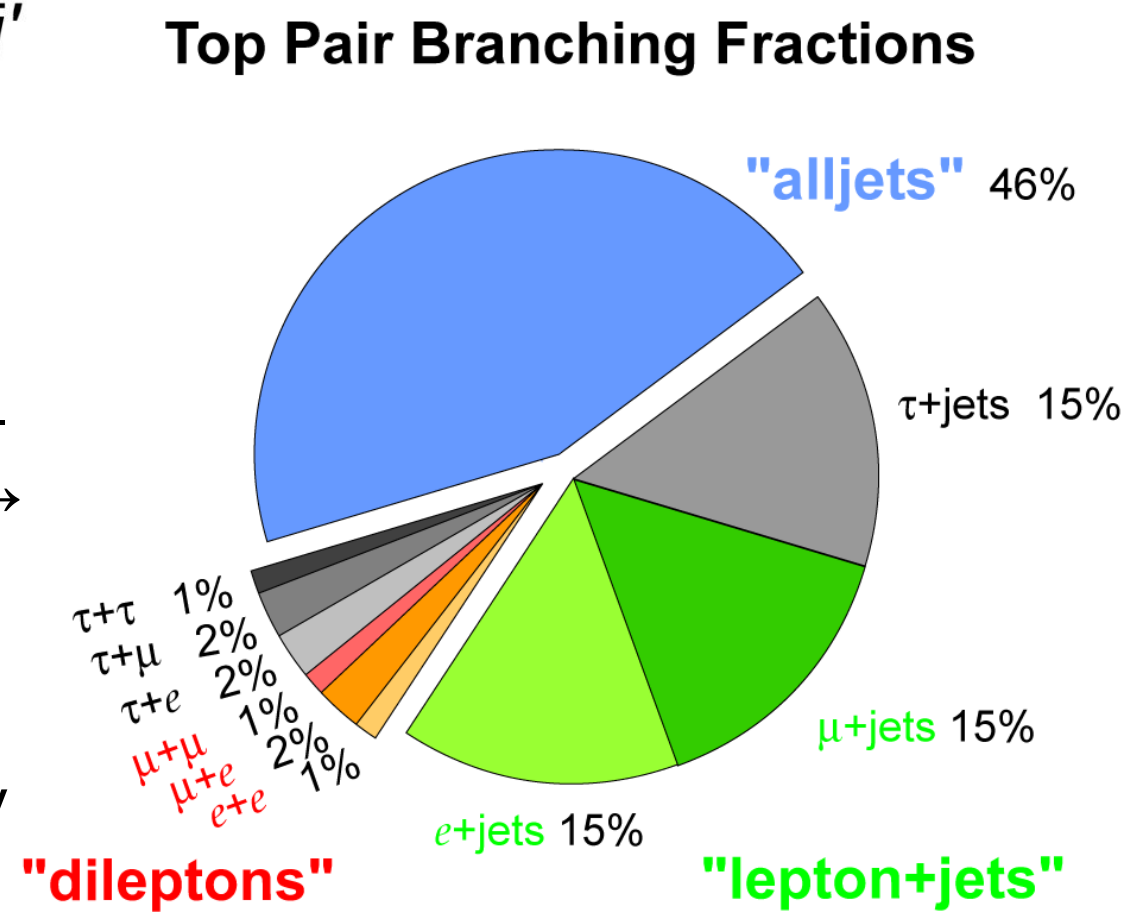
NNLO+NNLL **Czakon, et al.: PRL110(2013)252004**

	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110 (1.5%) -0.200 (2.8%)	+0.169 (2.4%) -0.122 (1.7%)
LHC 7 TeV	172.0	+4.4 (2.6%) -5.8 (3.4%)	+4.7 (2.7%) -4.8 (2.8%)
LHC 8 TeV	245.8	+6.2 (2.5%) -8.4 (3.4%)	+6.2 (2.5%) -6.4 (2.6%)
LHC 14 TeV	953.6	+22.7 (2.4%) -33.9 (3.6%)	+16.2 (1.7%) -18.8 (1.9%)

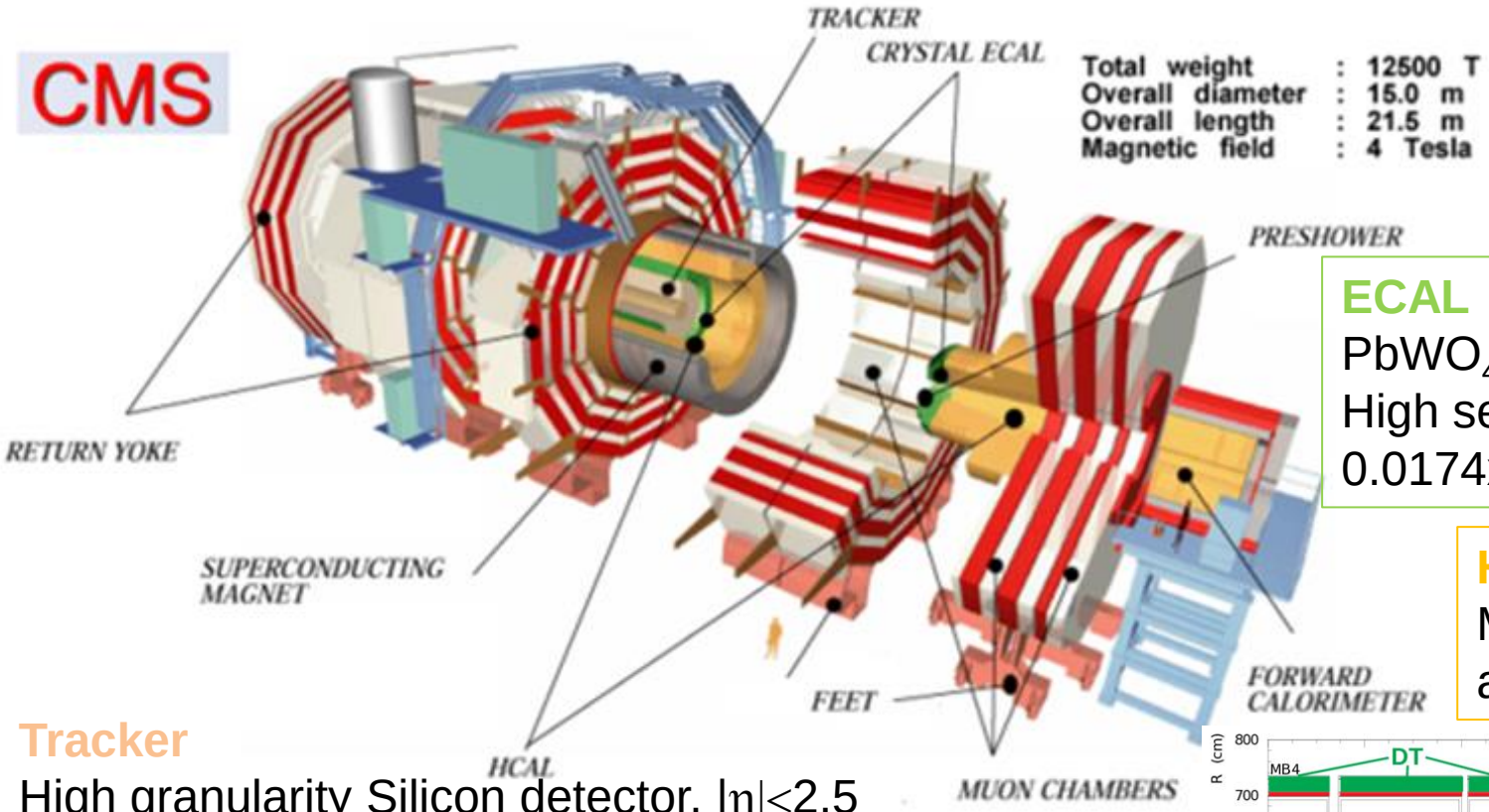
Top quark decay



- Decays ~100% to W-boson and b-quark → |Vtb| ~ unity
- Final state topology depends on W decay



Reminder: CMS detector



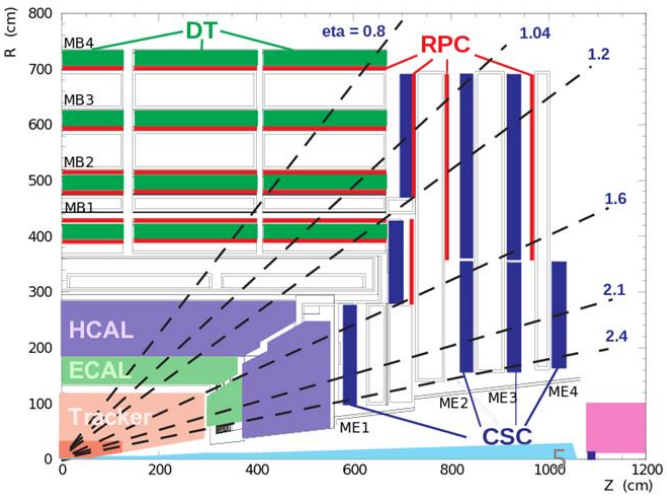
Muon System
DT, RPC, CSC.
Coverage up to $|\eta|<2.4$.

ECAL
$PbWO_4$ crystals $|\eta|<3$.
High segmentation: 0.0174x0.0174 in $\eta x \Phi$.

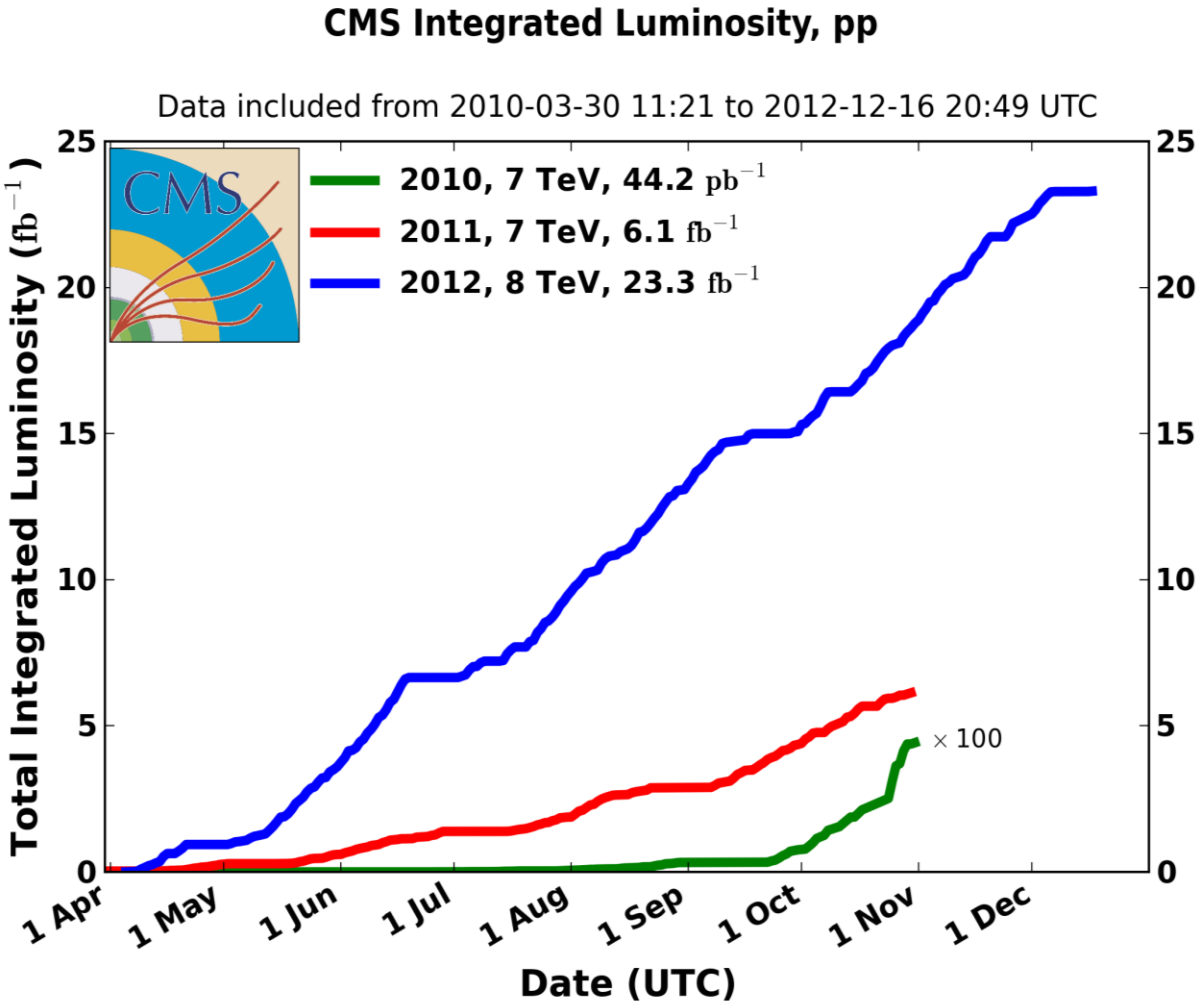
HCAL
Made of brass alloy and iron.

Tracker
High granularity Silicon detector. $|\eta|<2.5$
Pixels: sensors 100x150 μm^2. 66M channels.
Strips: pitch 80-183 μm. 9.6M channels

Solenoid
Superconduting solenoid in NbTi. High magnetic field (3.8 T) surrounds the tracker and calorimeters. Inside the muon chambers the magnetic field value is 1.8 T



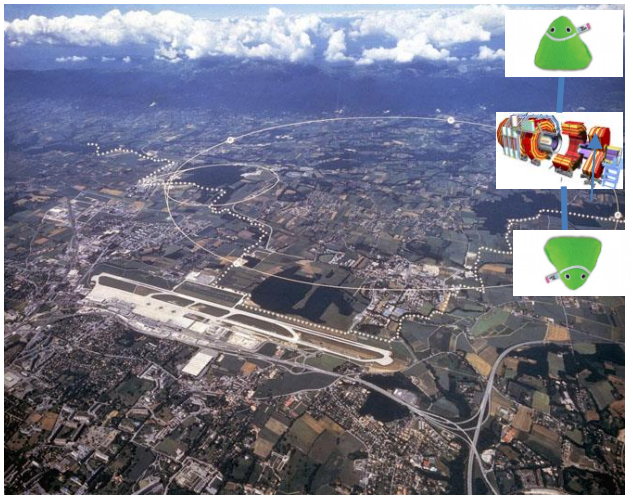
CMS data at LHC 7 & 8 TeV



5fb^{-1} @7TeV + 20fb^{-1}@8TeV:

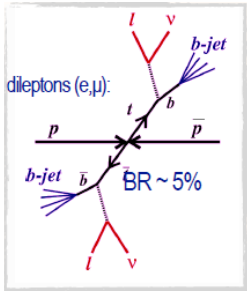
5.5 million top pairs

~1 top pair / second in 2012!!



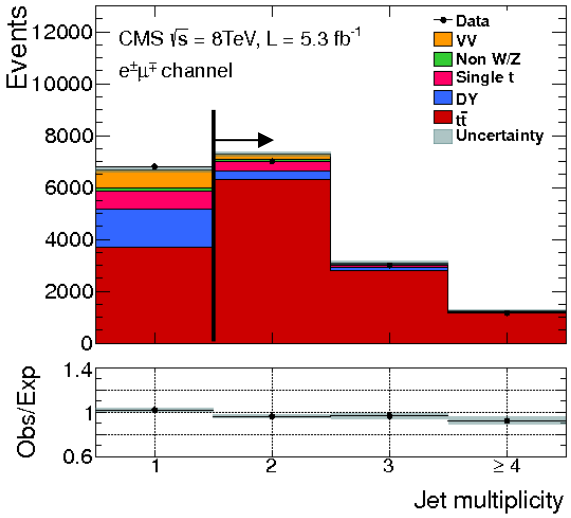
Inclusive measurements

Dilepton 8TeV



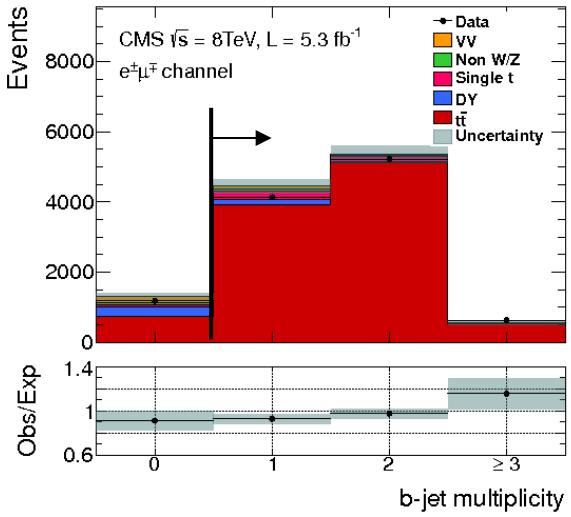
JHEP 02 (2014) 024
CMS PAS TOP-12-007

- **2 opposite sign isolated** high-pT leptons
  - mll > 20 GeV
- 2 high-pT jets (pT>30GeV), at least one b-tagged jet
- Cut and count approach, dominated by eμ, significantly less affected by DY background
- DY and non-W/Z background estimated from data
- **Dominant systematics**: fact./ren. scale, lepton efficiencies and jet energy scale



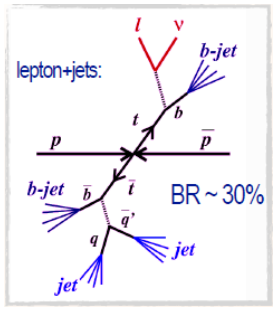
5.3fb^{-1} @8TeV

Uncertaintity 5.3%



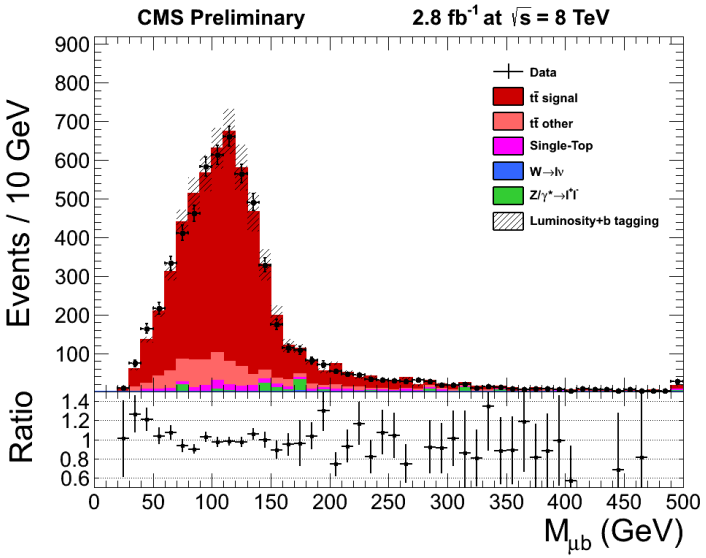
σ_{tt}=239 +/- 2 (stat.) +/- 11 (syst.) +/- 6 (lum.) pb, for an assumed top-quark mass of 172.5 GeV

Lepton + Jets 8TeV



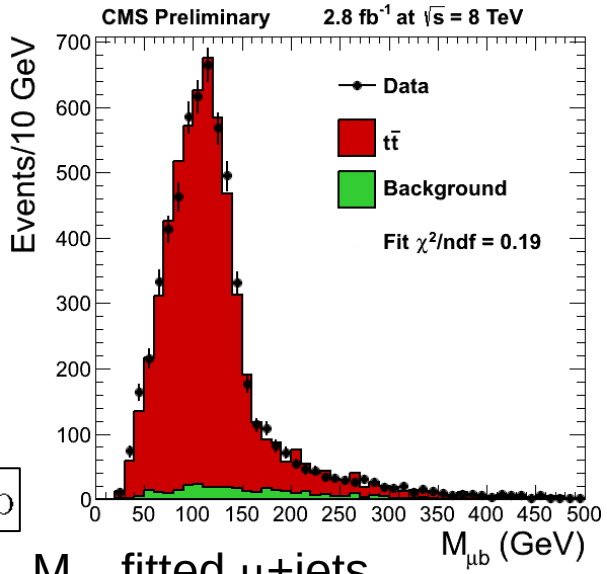
- **Exactly 1 isolated high-pT leptón**
- At least 4 high-pT jets (pT>30GeV)
- At least one b-tagged jet
- QCD background shape from data:
  - Require non-isolated leptons
  - Remove all non-QCD contributions using simulation
- Binned likelihood fit of Mlb:
  - Top pair signal & QCD shape
  - Other backgrounds from MC
- **Dominant systematics**: b-tagging and jet energy scale

CMS PAS TOP-12-006



e/μ +jets, 2.8fb^{-1} @8TeV

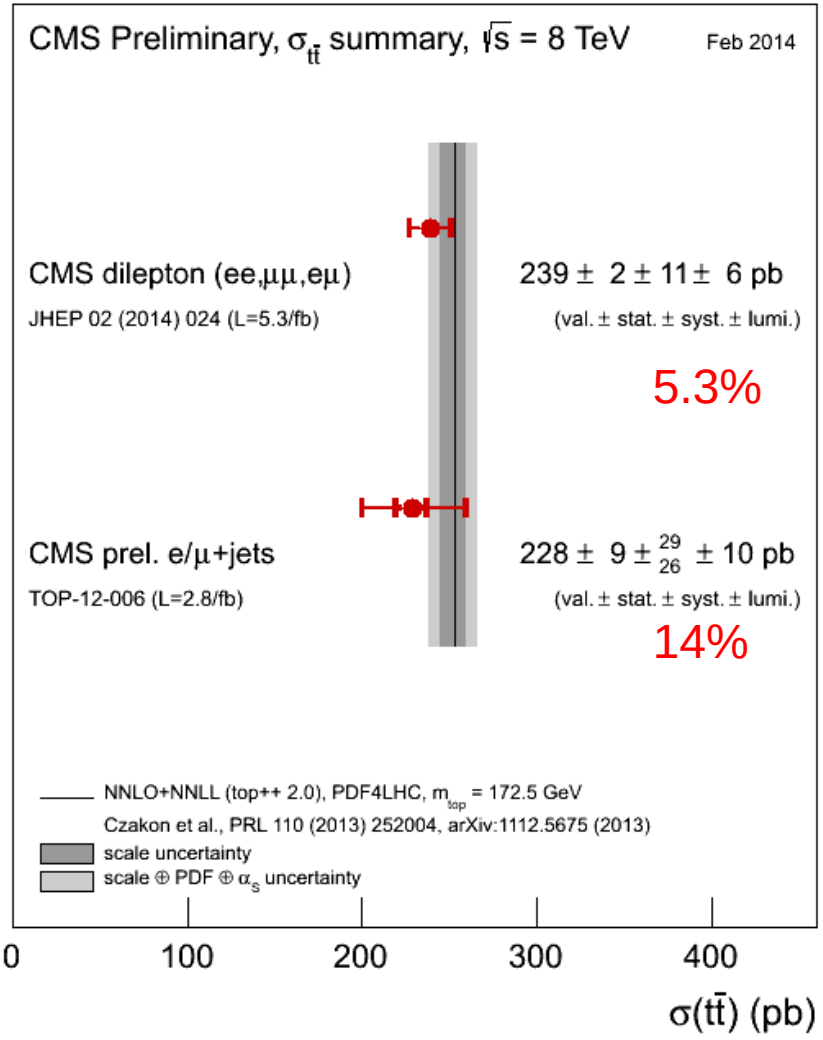
Uncertaintity 14%



$M_{\mu b}$ fitted μ+jets

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

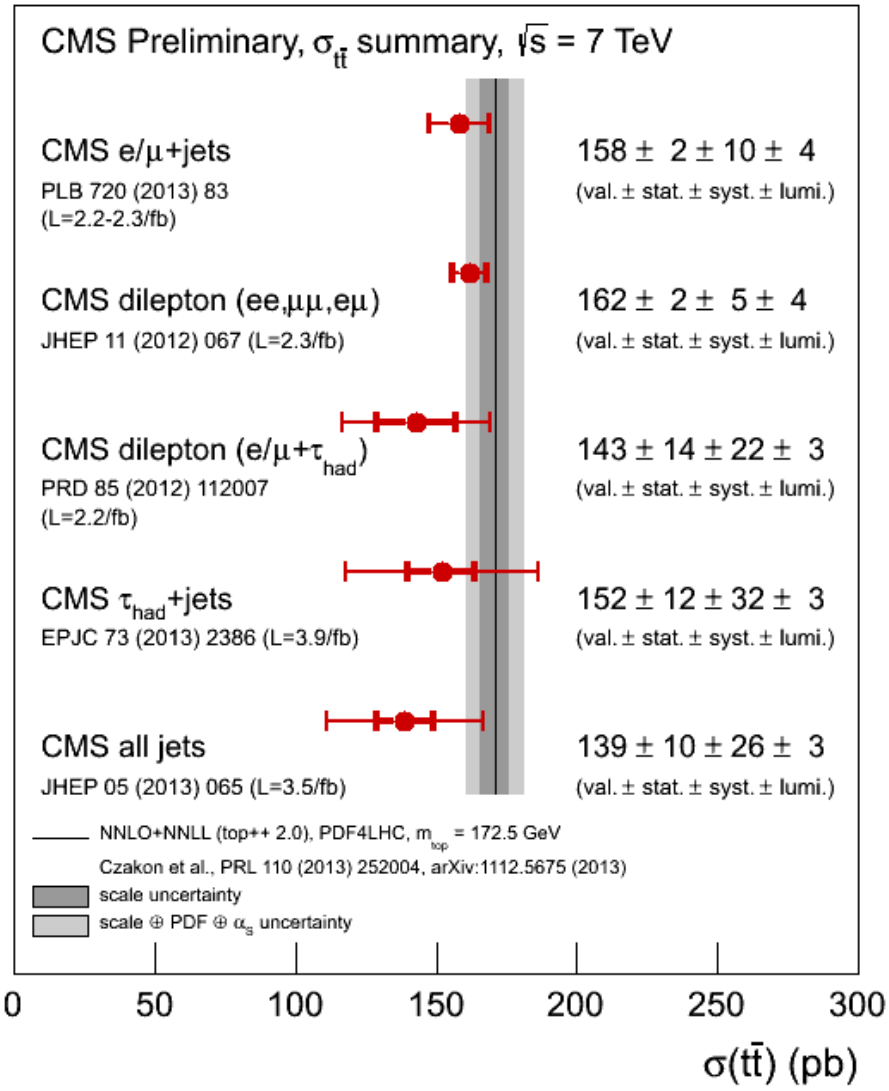
Summary Inclusive 8TeV



In preparation:
result with full lumi and Top LHC WG common systematics

Inclusive Cross Sections 7TeV

- **All final states investigated** (except tautau)
- Similar event selection in dilepton and lepton+jets modes
  - All hadronic: at least 6 high-pT jets, at least 2 b-tagged
  - Tau+jets: at least 3 high-pT jets (>1 b-tagged) + tau jet; fed into ANN
- Measurements from likelihood fits
- Data-driven estimates for main backgrounds
- Good agreement between data and predictions
- **CMS dilepton (4.2%) more precise than LHC (Sep 2012) combination!**



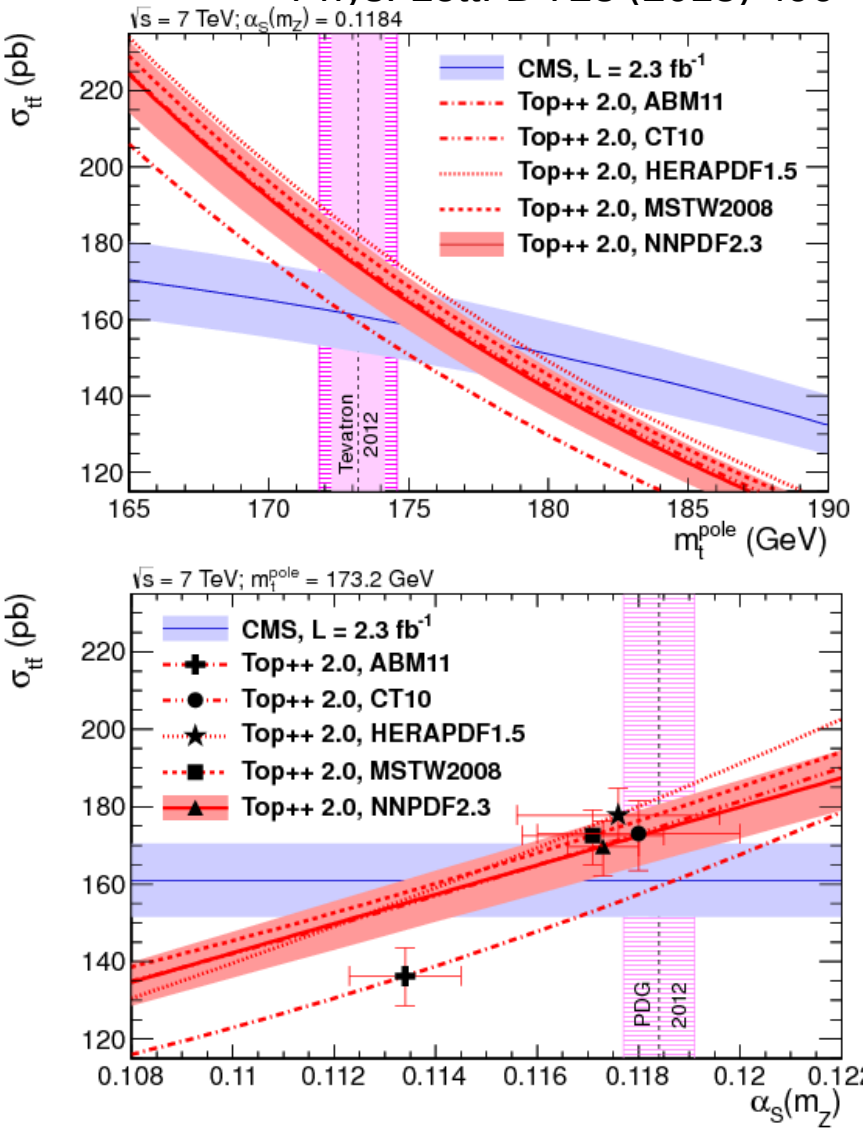
m_t^{pole} and $\alpha_s(M_Z)$ from cross section

Phys. Lett. B 728 (2013) 496

- **Turning cross-section dependence on α_s and m_t into measurements**

- Based on the most precise CMS measurement at 7 TeV in the dilepton channel (JHEP 211(2012)067):
  - At hadron colliders α_s has large theory uncertainty (missing NNLO contributions)
  - Use approx. NNLO calculations for σ(tt̄) to determine α_s at fixed m_t
  - Most probable result from joint likelihood theory ⊗ experiment

- **First determination of α_s from σ(tt̄)**
- m_t^{pole} = 176.6+3.8-3.4 GeV
- $\alpha_s(M_Z)$ = 0.1151+0.0033-0.0032

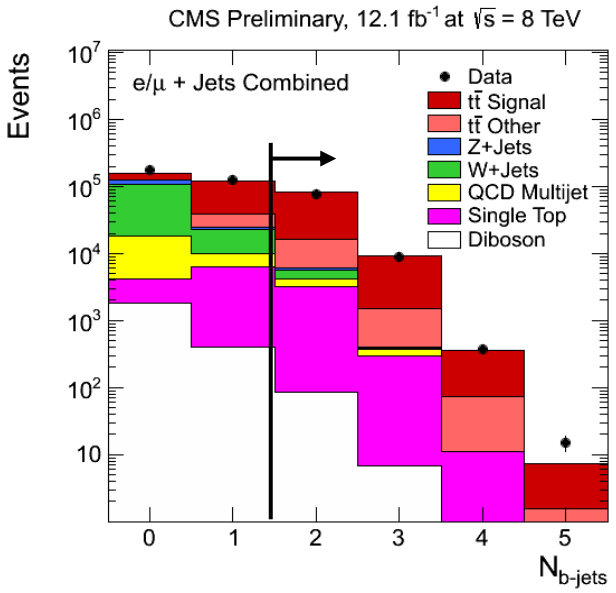


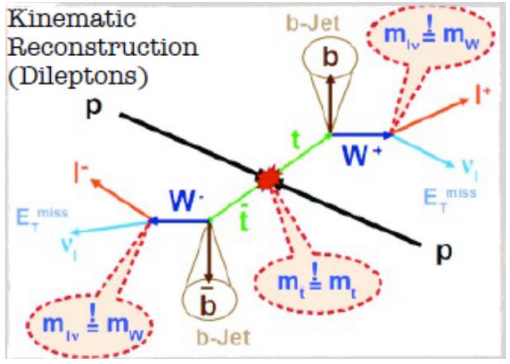
Differential measurements

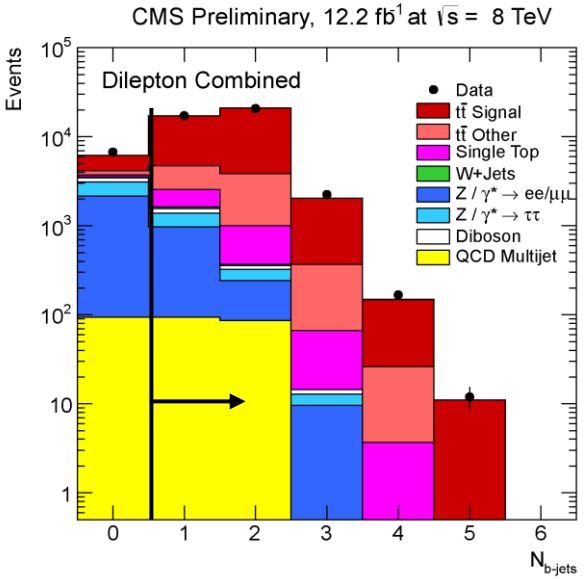
Differential Top Pair Cross Sections at 8 TeV

CMS PAS TOP-12-027/028 : Lepton+jets and dilepton,12.2fb^{-1} @8TeV

- Unfold experimental distribution by instrumental effects **correcting bin-by-bin migrations**
- Similar selections to inclusive meas.
- **Measurement of kinematic distributions**
  - Test theory predictions
  - Enhance sensitivity to new physics
  - Use for PDF constraints
- **Strategy**
  - Reconstruction of the top-pair system
  - Correct for detector effects (unfolding)
  - Differential cross sections normalised to cross section measured in-situ



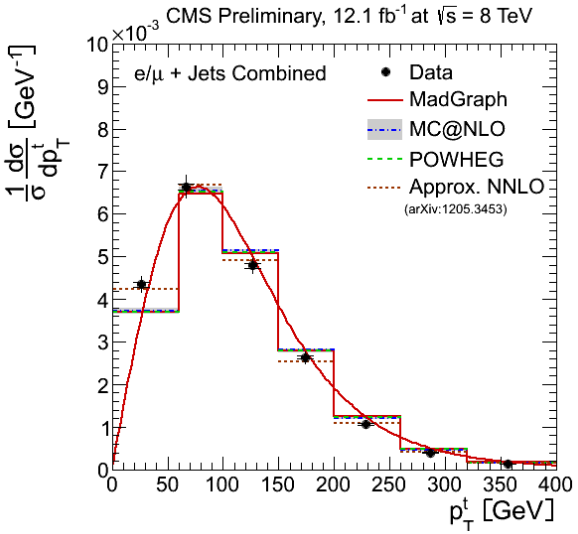


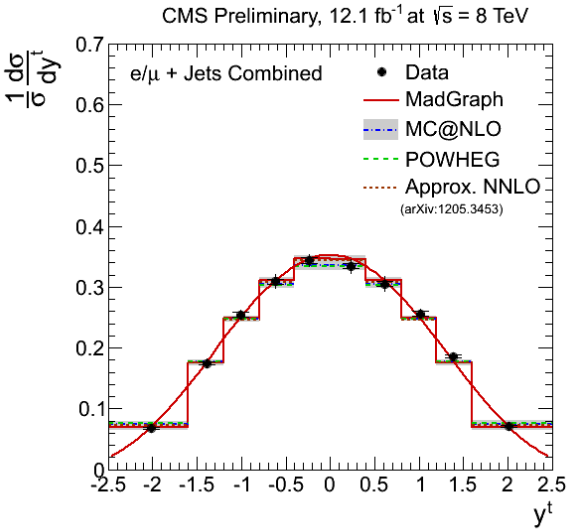


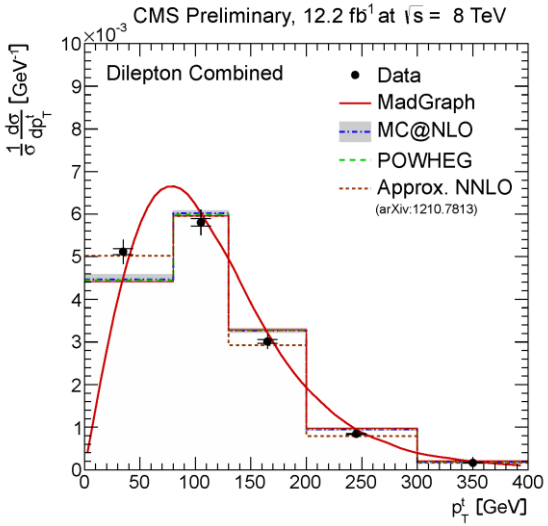
Top quark kinematics: p_T^t, y^t

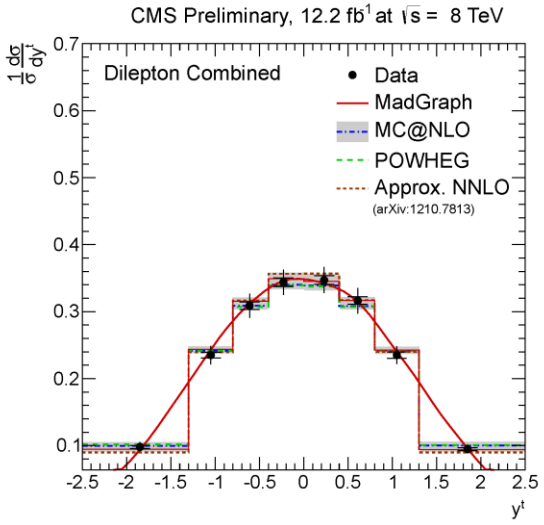
CMS PAS TOP-12-027/028 : Lepton+jets and dilepton,12.2fb^{-1} @8TeV

- Compared to
  - **MadGraph+Pythia**
  - MC@NLO+Herwig
  - POWHEG+Pythia
  - **Approx NNLO**
- Good agreement between prediction and data in rapidity distributions
- **Top p_T spectrum best described by approx. NNLO** in particular for low p_T





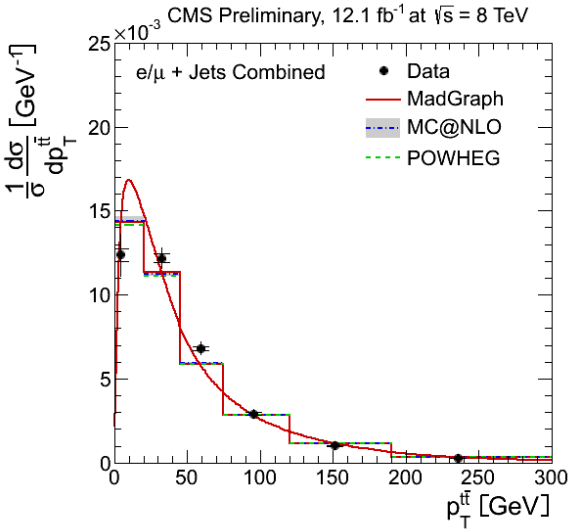


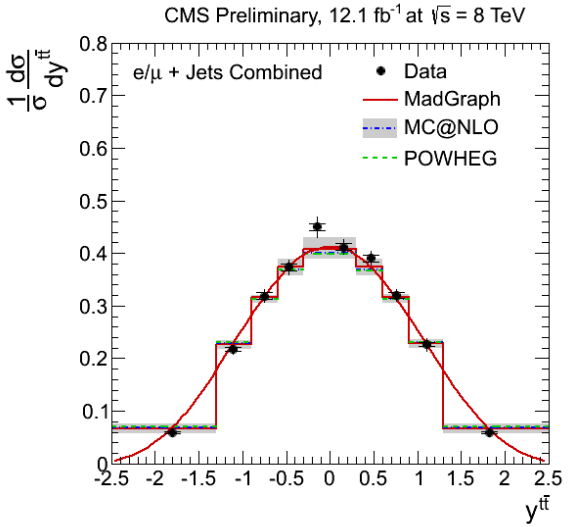


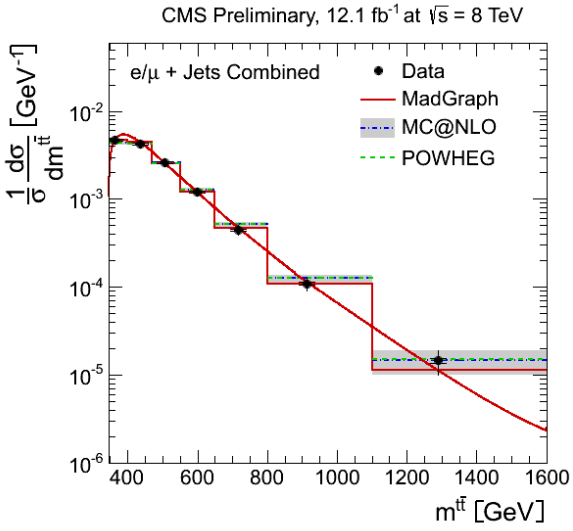
Extrapolated to full phase space

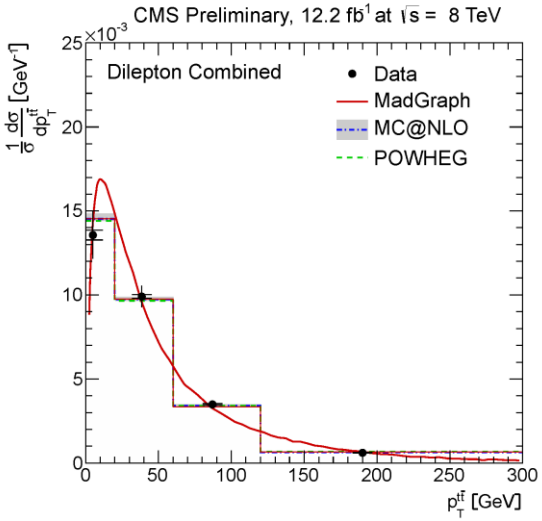
Top Pair System Kinematics: p_T^{tt}, y^{tt}, m^{tt}

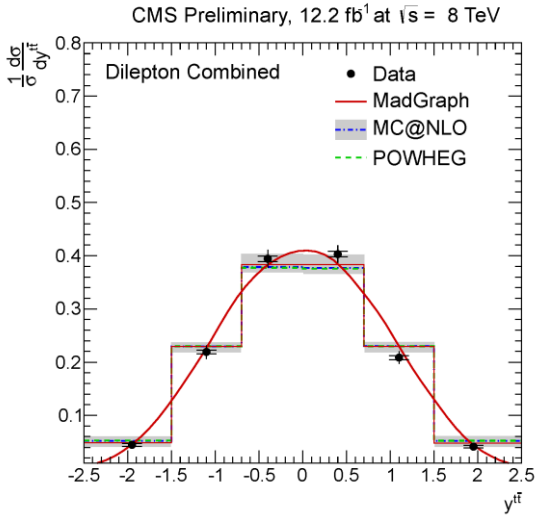
CMS PAS TOP-12-027/028 : Lepton+jets and dilepton, 12.2 fb^{-1} @8TeV

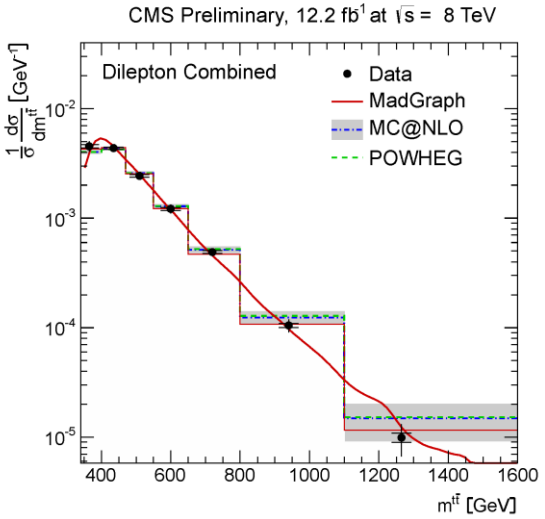












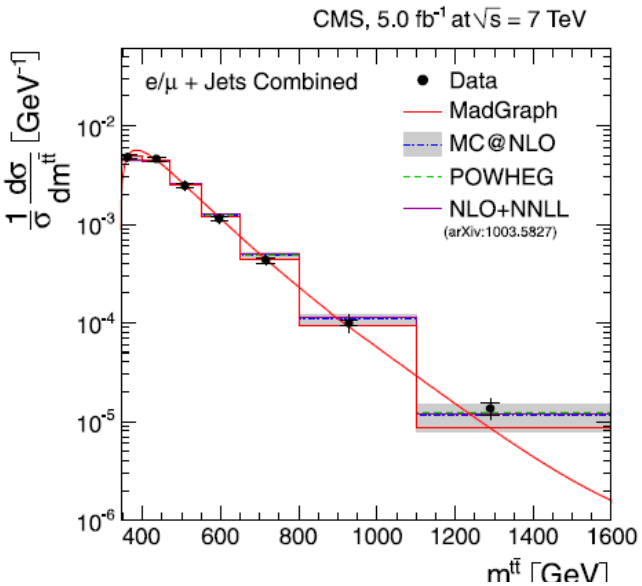
Sensitive to high orders

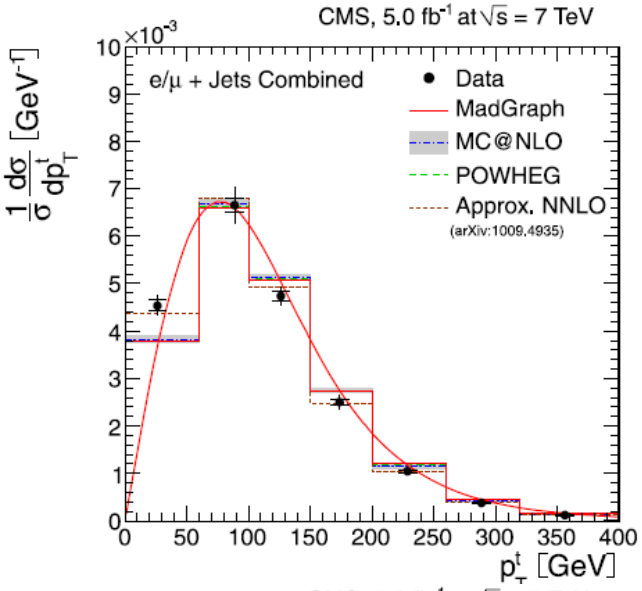
Sensitive to resonances

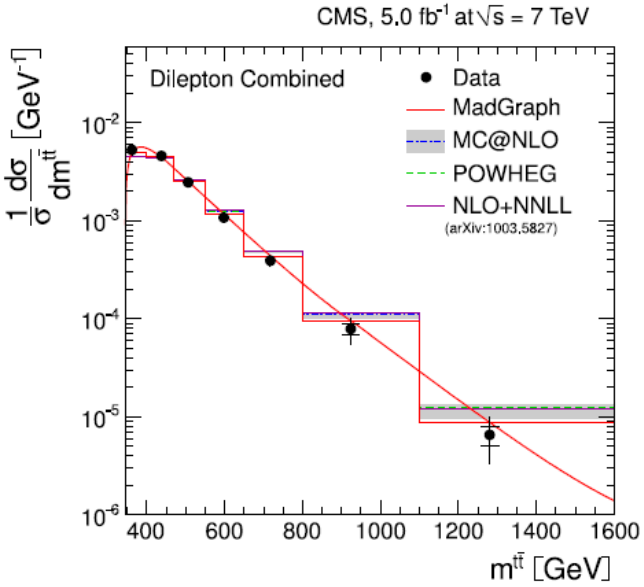
Differential Top Pair Cross Sections at 7 TeV

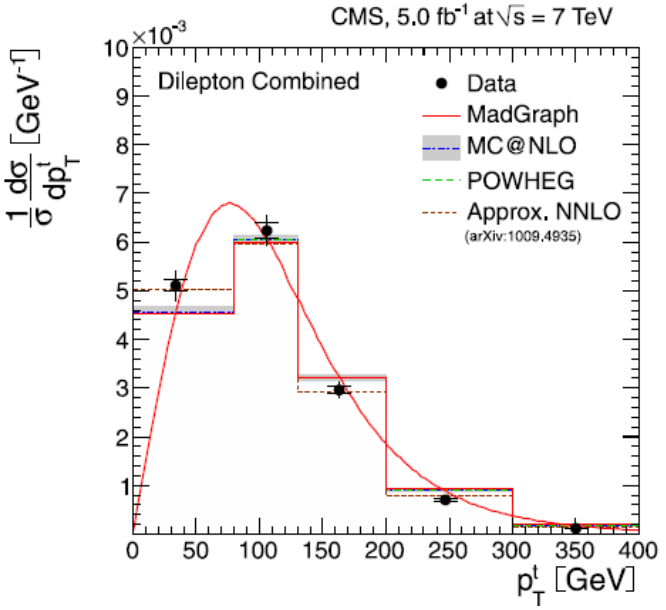
Eur. Phys. J. C73 (2013) 2339 : Lepton+jets and dilepton,5.0fb^{-1} @7TeV

- **Using same analysis strategy as at 8 TeV**
- Compared to:
  - MadGraph+Pythia
  - MC@NLO+Herwig
  - POWHEG+Pythia
  - Approx NNLO
- Also for 7 TeV: **top p_T spectrum best described by approx. NNLO**







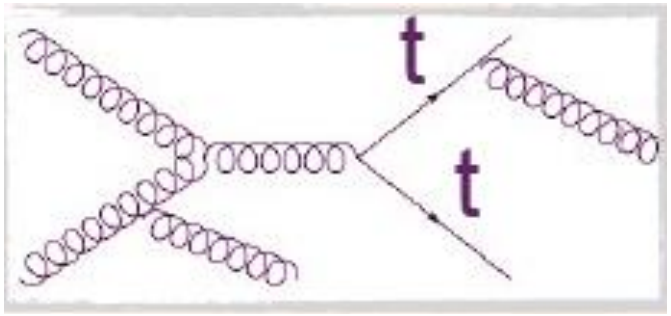


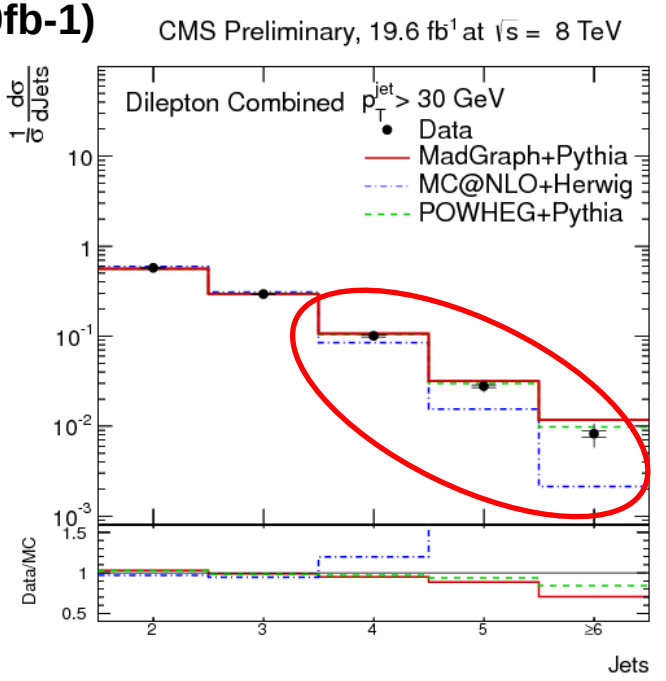
Jet multiplicity

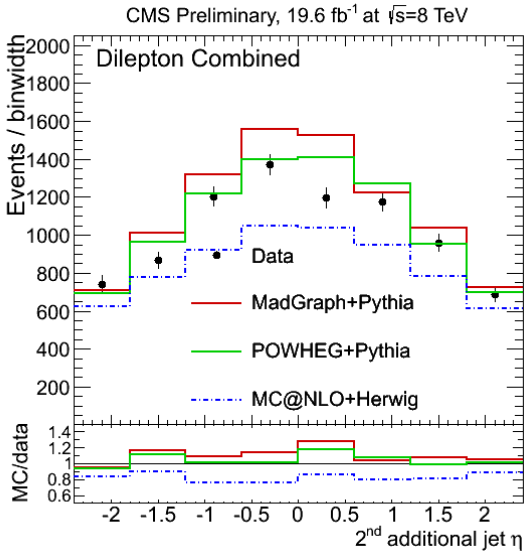
Differential Top Pair Cross Sections at 8 TeV

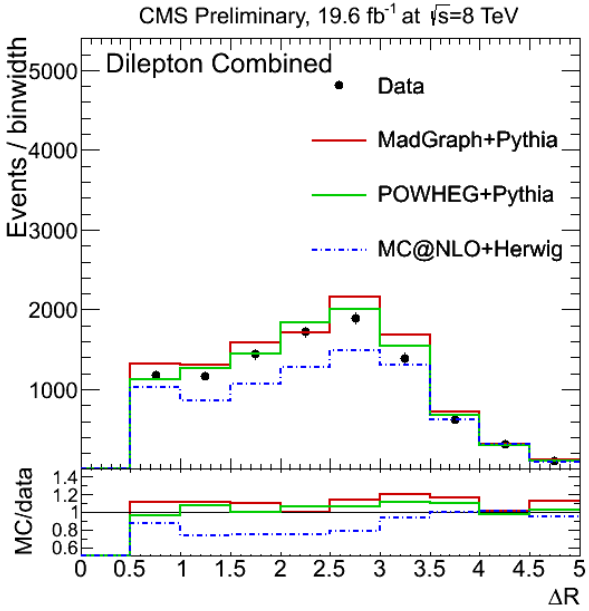
dilepton 8TeV: CMS PAS TOP-12-041 (19fb-1)

- **LHC**: high fraction of events with extra hard jets from ISR/FSR
- **Tune and test radiation modelling**







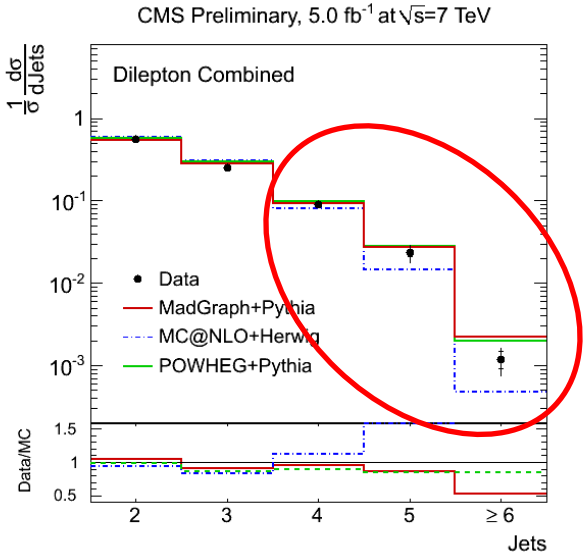


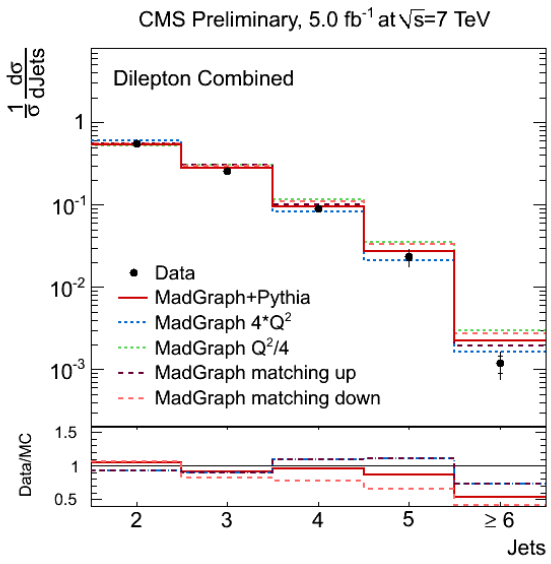
MC@NLO+Herwig underestimates data for high nJets

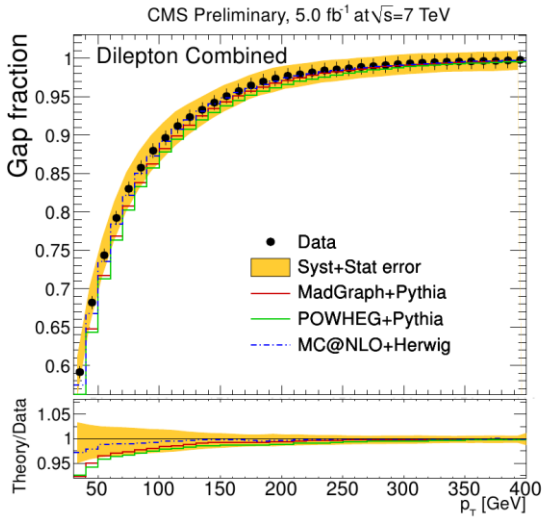
Differential Top Pair Cross Sections at 7 TeV

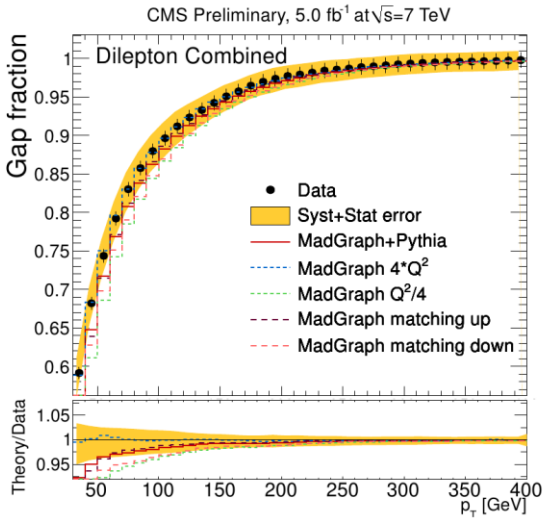
lepton + jet (arXiv:1404.3171), dilepton (CMS PAS TOP-12-023): 5fb^{-1}

- Similar analysis to 8TeV
  - **Same issue with MC@NLO+Herwig**
- Gap fraction:
  - Veto events with extra jets
  - **General good data/MC agreement**
  - Data best described by:
    - MC@NLO+Herwig
    - MadGraph+Pythia with higher scale







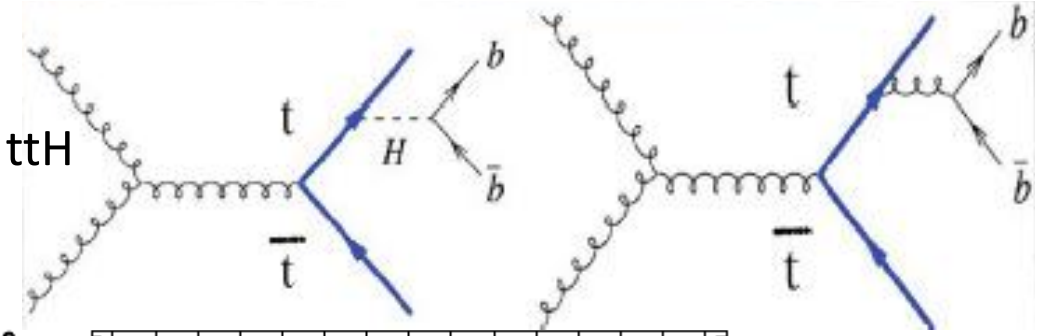


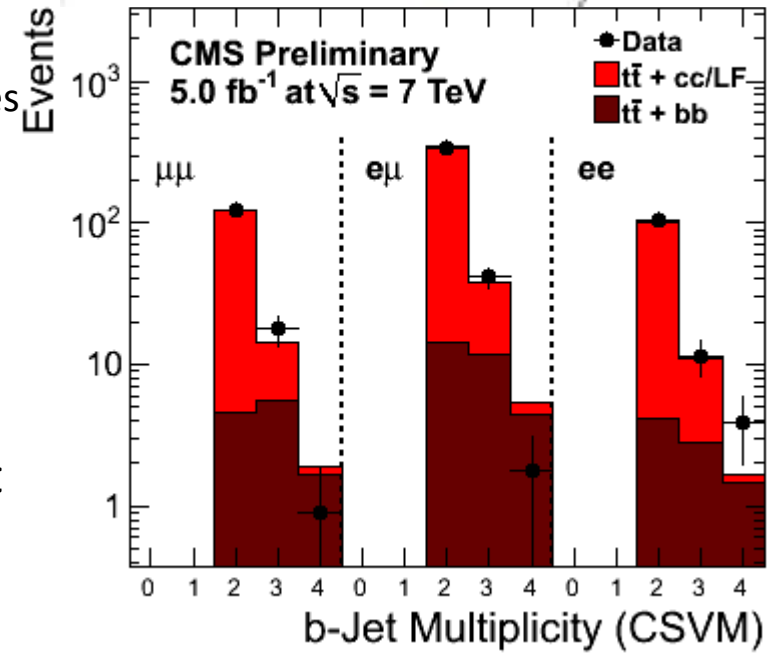
Ratio σ(ttbb)/σ(ttjj)

Associated ttbb Production at 7TeV

Dilepton ($5fb^{-1}$) **CMS PAS TOP-12-024**

- Test pQCD calculations
- Irreducible, non resonant BG to ttH
  - large uncertainties on predictions (scales)
- **Measure ratio**
  - large cancellation of uncertainties
- Dilepton events with at least 4 jets, 2b-tags
- Signal extraction by fit to b-jet multiplicity
- **Dominant systematic**: mistag efficiency





Slightly higher than MadGraph (1.2%) and POWHEG (1.3%) predictions

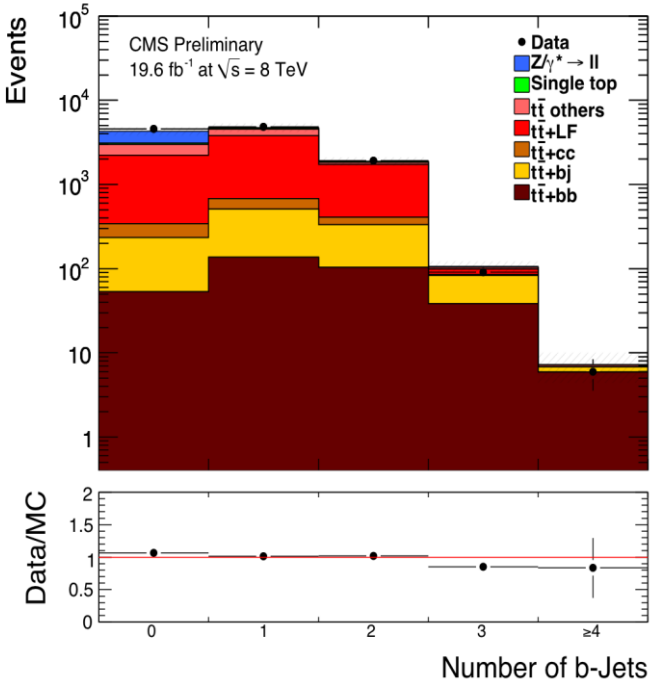
First measurement!!

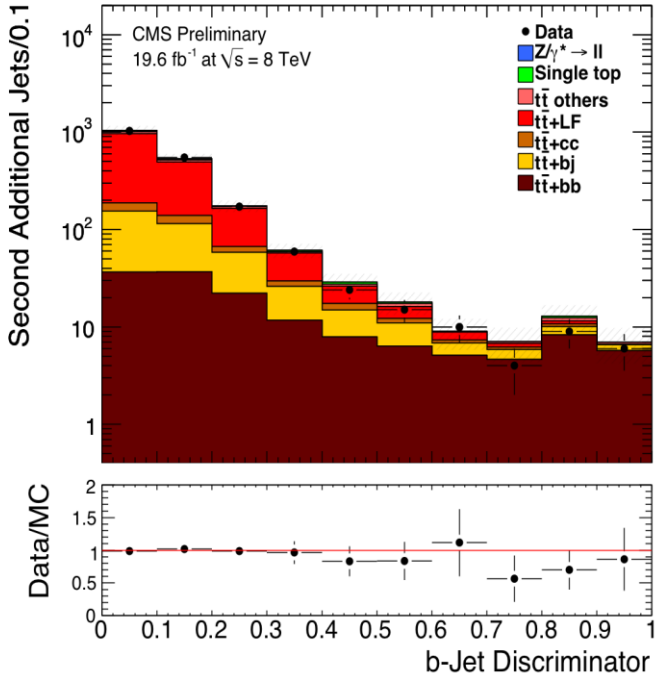
$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(stat.) \pm 0.9(sys.)\%$$

Associated ttbb Production at 8TeV

Dilepton (19fb^{-1}) **CMS PAS TOP-13-010**

- Dilepton events with at least 4 jets, 2b-tags
- Fit to b-tag discriminator performed on signal plus background categories
- Measurements of the absolute cross sections are also presented.
- **Dominant systematic**: mistag efficiency





$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) =$$

$0.023 \pm 0.003\,(\text{stat.}) \pm 0.005\,(\text{syst.})$ at Jet $p_T > 20$ GeV

MADGRAPH/POWHEG: 0.016/0.017 ± 0.002

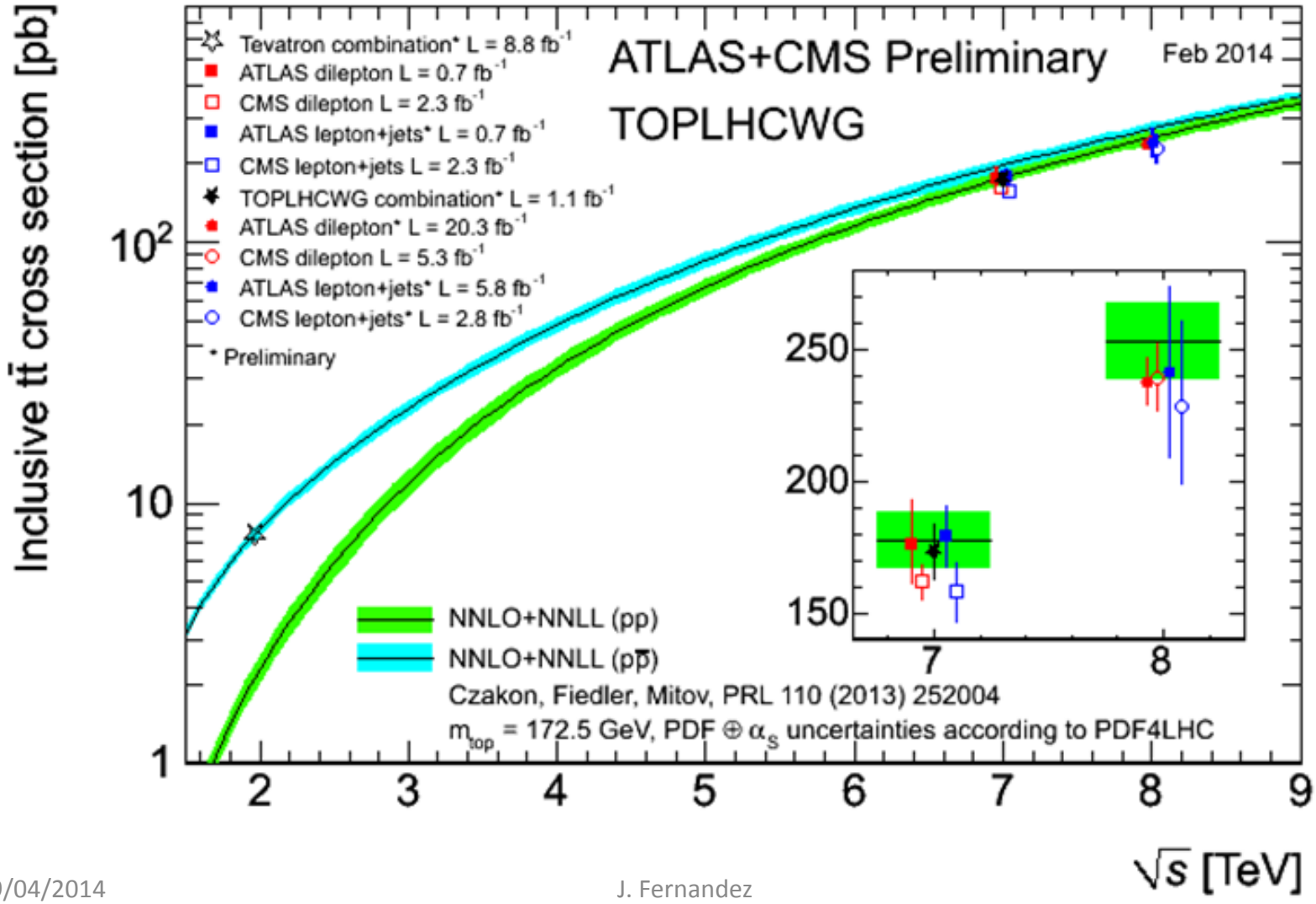
$0.022 \pm 0.004\,(\text{stat.}) \pm 0.005\,(\text{syst.})$ at Jet $p_T > 40$ GeV

MADGRAPH/POWHEG: 0.013/0.014 ± 0.002

Summary

- **Inclusive top-pair cross section measurements**
  - Measured at 7 TeV in 9 different channels (all except tautau). Published with precision up to 4.2% (dilepton), used to extract $\alpha_s(M_Z)$ for the first time
  - Measured at 8 TeV in 5 different dilepton and lepton+jets channels. Preliminary results with precision 5.3% (dilepton) 14% (lepton+jets)
- **Normalised differential top-pair cross section measurements**
  - 5 channels in total and suite of kinematic variables for different observables
  - Higher order predictions describe data better and Jet multiplicities and gap fraction can be used to constrain radiation modelling parameters and scales
- **First measurement of associated bottom-pair production**
- Precision of top production measurements is steadily improving:
  - Focus now on precise understanding of top production mechanism
  - Detailed comparisons with state-of-the-art QCD predictions (NNLO, approx. NNLO and NLO +PS multi-leg MC)
  - Cross section in fiducial regions, avoiding model-dependent extrapolations
- **Next targets**:
  - Targeting ultimate precision for upcoming 7 and 8 TeV run-I legacy measurements
  - Get ready to look at run-II data at higher energy

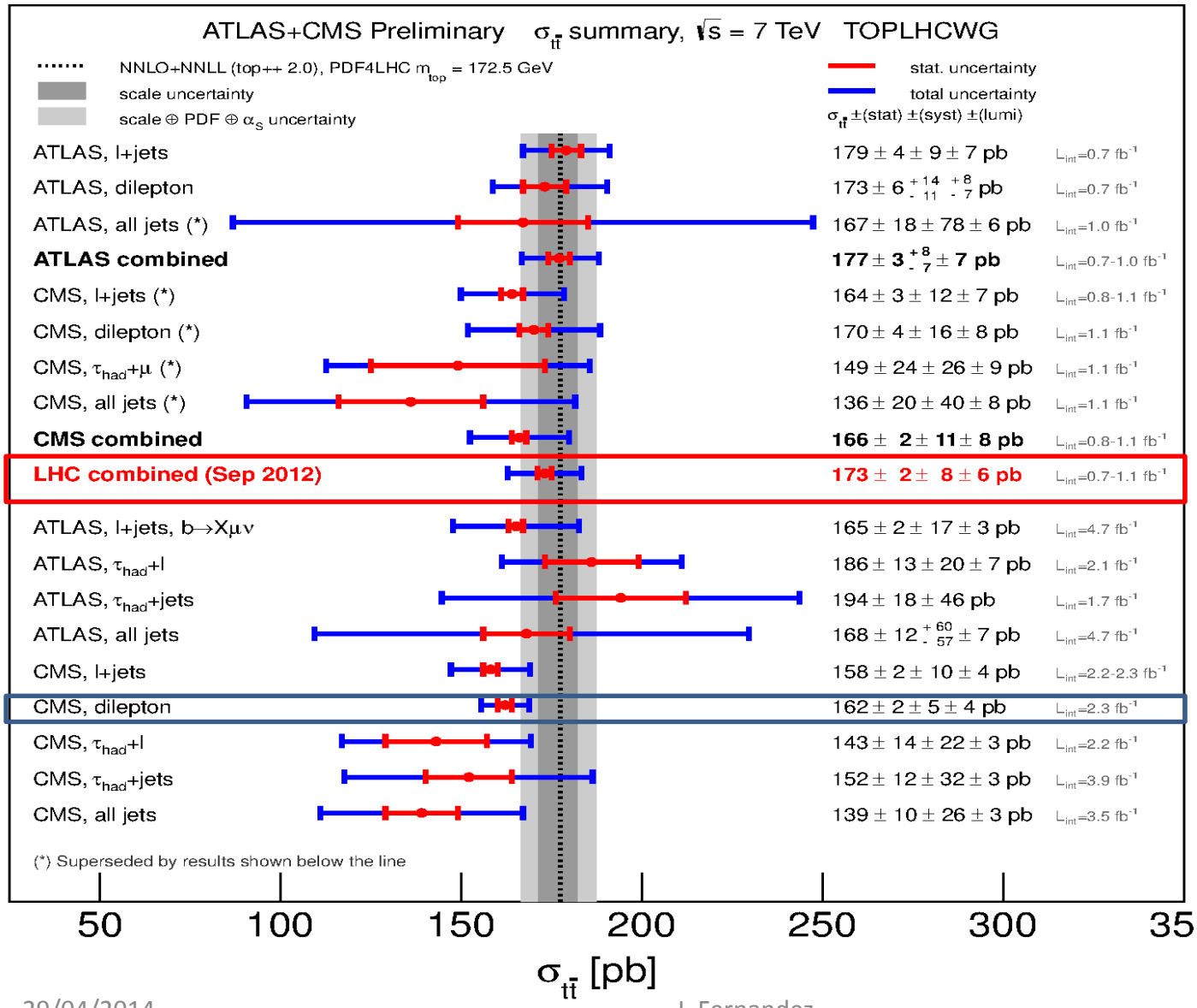
Looking forward to new LHC combinations



THANK YOU!

BACKUP

LHC 7TeV Combination



5.8%

4.2%

LHC σ_{tt} combination 7TeV

- **ATLAS-CONF-2012-134**
- **CMS PAS TOP-12-003**

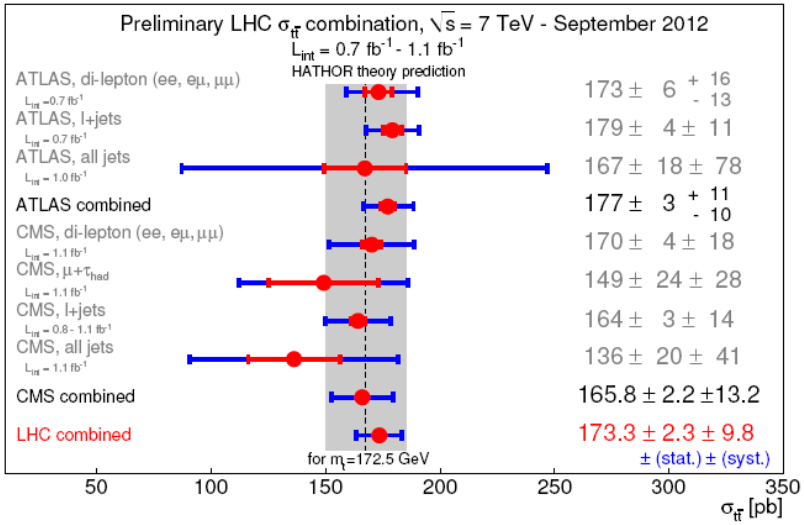
- **Detector model**: This class of uncertainty includes contributions due to uncertainties in the modelling of detector effects in the simulation.

- For **ATLAS** these include uncertainties in the **electron,muon** and jet identification efficiencies, **electron energy scale and resolution, muon momentum scale and resolution**, jet resolution, the calculation of the missing transverse momentum, trigger and in the b jet identification in the all-jets channel.

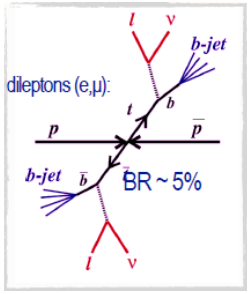
- For **CMS**, this class includes uncertainties in **the modelling of efficiencies for lepton triggering, reconstruction and identification**, in b tagging calibration and in the data-driven W+jets heavy flavour fractions determination which depends on it, in the trigger in the all-jets channel, in the hadronic decay modelling and in the effects of pileup.

- These uncertainties are taken as **uncorrelated between the two collaborations**.

	ATLAS	CMS	Correlation	LHC combination
Cross-section	177.0	165.8		173.3
Uncertainty				
Statistical	3.2	2.2	0	2.3
Jet Energy Scale	2.7	3.5	0	2.1
Detector model	5.3	8.8	0	4.6
Signal model				
Monte Carlo	4.2	1.1	1	3.1
Parton shower	1.3	2.2	1	1.6
Radiation	0.8	4.1	1	1.9
PDF	1.9	4.1	1	2.6
Background from data	1.5	3.4	0	1.6
Background from MC	1.6	1.6	1	1.6
Method	2.4	n/e	0	1.6
W leptonic branching ratio	1.0	1.0	1	1.0
Luminosity				
Bunch current	5.3	5.1	1	5.3
Luminosity measurement	4.3	5.9	0	3.4
Total systematic	10.8	14.2		9.8
Total	11.3	14.4		10.1

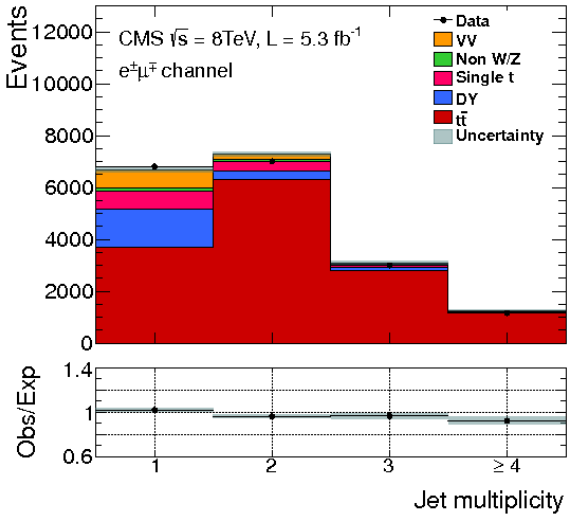


Dilepton 8TeV



JHEP 02 (2014) 024
CMS PAS TOP-12-007

- 2 opposite sign isolated high-pT leptons
  - mll > 20 GeV
- Two high-pT jets (pT>30GeV) at least one b-tagged jet
- Cut and count approach, dominated, by eμ, significantly less affected by DY background
- DY and non-W/Z background estimated from data
- Dominant systematics: fact./ren. scale, lepton efficiencies and jet energy scale
- **In preparation**: result with full lumi and Top LHC WG common systematics



5.3fb^{-1} @8TeV

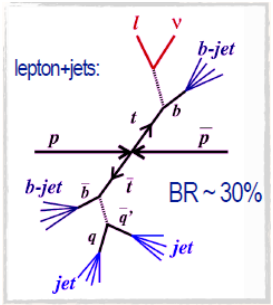
Uncertaintity 5.3%

Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
	$\sigma(t\bar{t})$ (pb)		
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to showers	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell–Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4
Integrated luminosity	6.4	6.1	6.2
Statistical	5.2	4.5	2.6

MET cut for SF leptons reflects in larger JES systematics

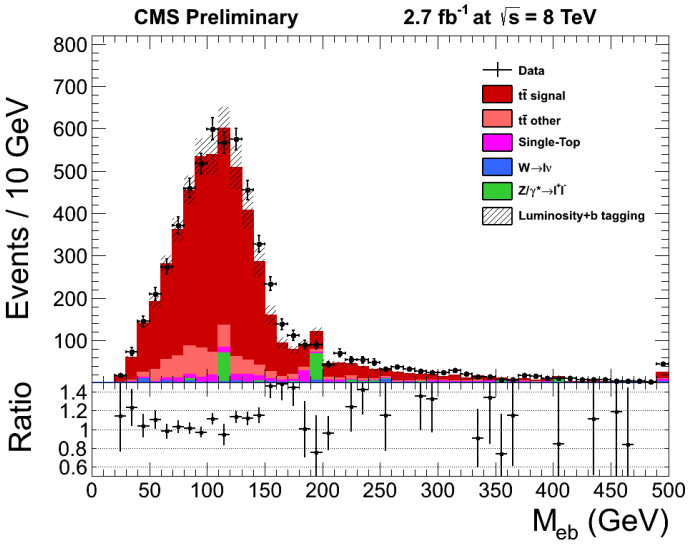
σ_{tt}=239 +/- 2 (stat.) +/- 11 (syst.) +/- 6 (lum.) pb, for an assumed top-quark mass of 172.5 GeV

Lepton + Jets 8TeV



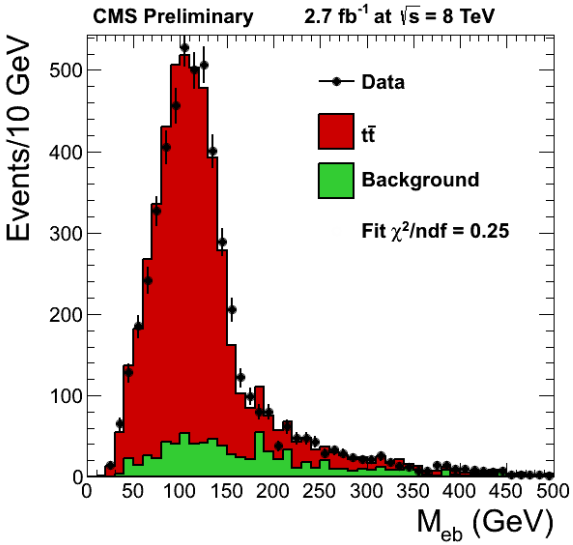
CMS PAS TOP-12-006

- Exactly 1 isolated high-pT leptón
- At least 4 high-pT jets (pT>30GeV)
- At least one b-tagged jet
- QCD background shape from data:
  - Require non-isolated leptons
  - Remove all non-QCD contributions using simulation
- Binned likelihood fit of Mlb:
  - Top pair signal & QCD shape
  - Other backgrounds from MC
- **Dominant systematics**: b-tagging and jet energy scale
- **In preparation**: result with full lumi and Top LHC WG common systematics



e/μ +jets, 2.8fb^{-1} @8TeV

Uncertaintity 14%



M_{eb} fitted e+jets

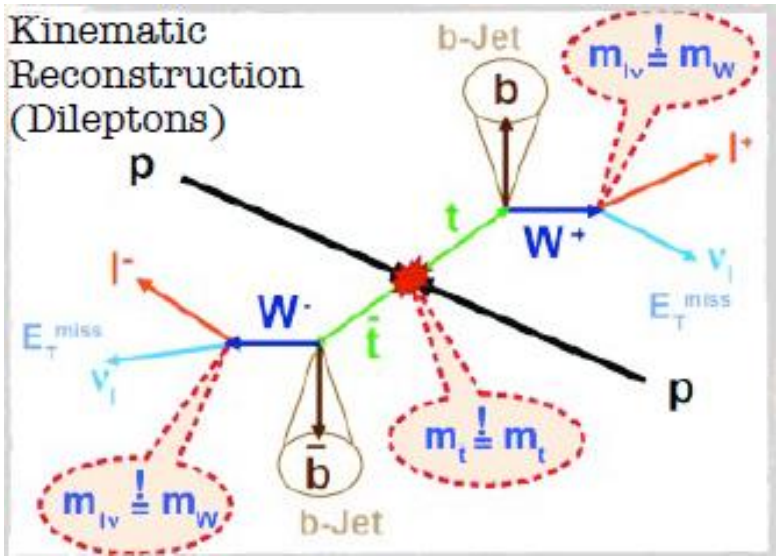
$$\sigma_{t\bar{t}}\,(\text{combined}) = 228.4 \pm 9.0\,(\text{stat.})\,^{+29.0}_{-26.0}\,(\text{syst.}) \pm 10.0\,(\text{lumi.})\ \text{pb}$$

Top Reconstruction

CMS PAS TOP-12-027/028 : Lepton+jets and dilepton,12.2fb^{-1}

Dileptons

- Kinematic reconstruction
- Underconstrained
- Input
  - 2 leading jets
  - 2 leptons
  - MET
- Constraints
  - mW
  - MET = Σ(neutrino pT)
  - mt = mt̄ [100 GeV, 300 GeV]
- Choose solution by comparing neutrino energy spectrum to prediction
- For m_{tt} only: 4-vector sum of 2 leading jets, MET, 2 leptons

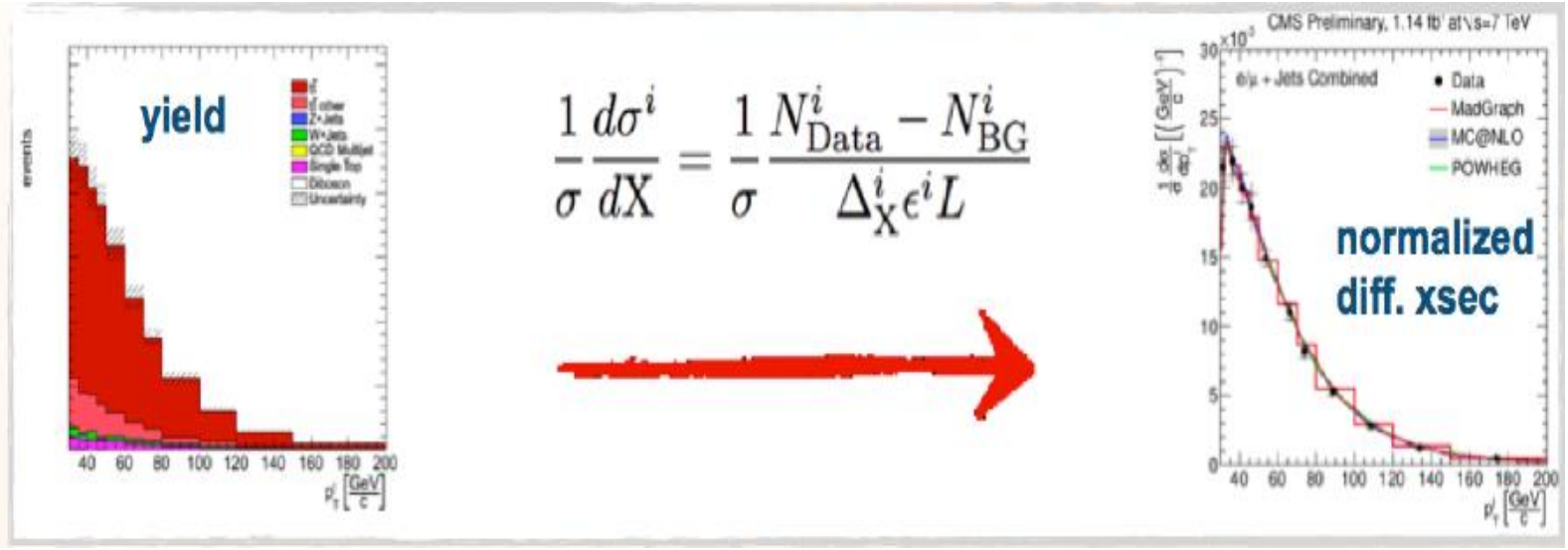


Lepton + jets

- Kinematic fit
- Input
  - Lepton & up to 5 leading jets
  - Neutrino momentum = MET
- Vary 4-Vectors within Resolution
  - mt = mt̄
  - m_W
- Choose solution with minimum χ2

Differential Cross Section Determination

CMS PAS TOP-12-027/028 : Lepton+jets and dilepton,12.2fb^{-1}



- Cut and count approach
- Data driven corrections
  - Drell-Yan background (dileptons)
  - Trigger efficiencies
  - Lepton identification and isolation
- Corrected to parton or particle level and for detector effects
  - Purity & stability typically > 50%
  - Regularised (SVD) unfolding (MadGraph+Pythia MC)
- Normalised to in-situ cross section

Diferential cross section Systematic Uncertainties

- Global uncertainties cancel due to normalisation
- Remaining shape uncertainties evaluated individually for each bin:
  - Jet energy scale and resolution
  - Lepton identification and isolation efficiencies
  - Trigger efficiencies
  - B-tagging efficiencies
  - Pile up modelling
  - Top mass uncertainties
  - Scale and matching scale variations (dominant)
  - Hadronisation (POWHEG+Pythia, MC@NLO+Herwig)
  - PDF variations