Review of ATLAS & CMS top-quark pair differential cross sections

María Aldaya (CMS, University of Hamburg)
Francesco Spanò (ATLAS, Royal Holloway University of London)

for the ATLAS & CMS top-quark pair differential cross section groups

TOPLHCWG Meeting, CERN, 28 November 2013

Universität Hamburg
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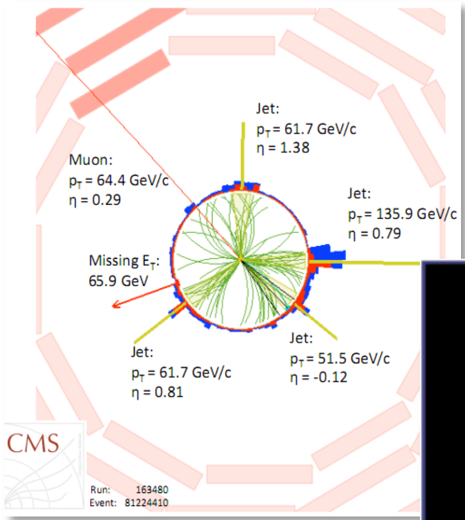
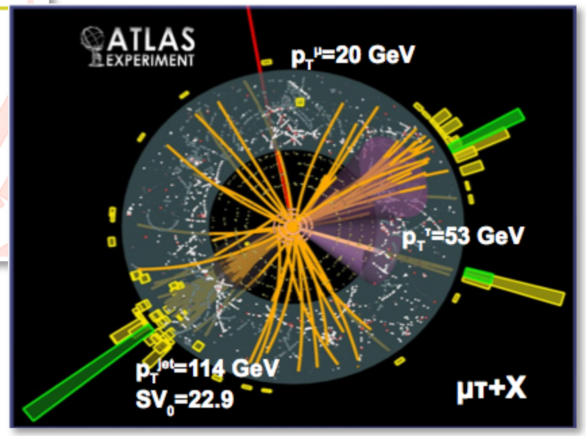
Bundesministerium für Bildung und Forschung

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Outline

- Introduction
- Description of analyses
  - Event selection
  - Kinematic reconstruction
  - Unfolding



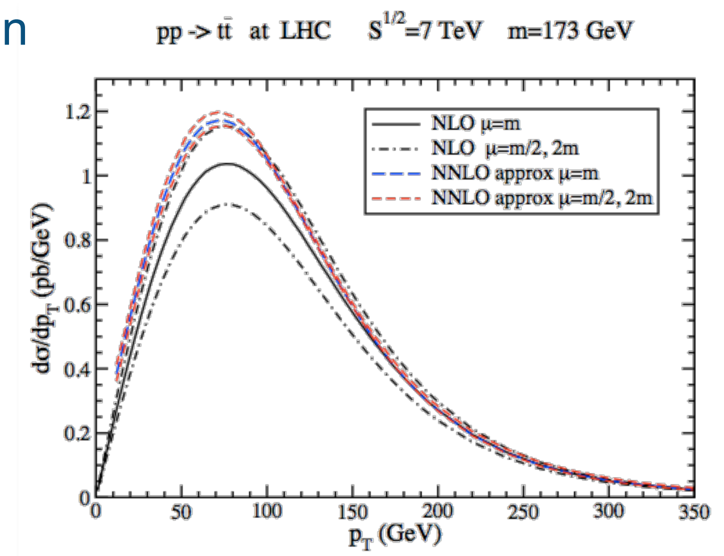


- Measurements:
  - ATLAS (l+jets) @ 7 TeV: **ATLAS-CONF-2013-099**
  - CMS (l+jets, dileptons) @ 7 TeV: **Eur. Phys. J. C73 (2013) 2339**
  - CMS (l+jets, dileptons) @ 8 TeV: **CMS-PAS TOP-12-027, CMS-PAS-TOP-12-028**

- First studies at generator level on definition of top quark

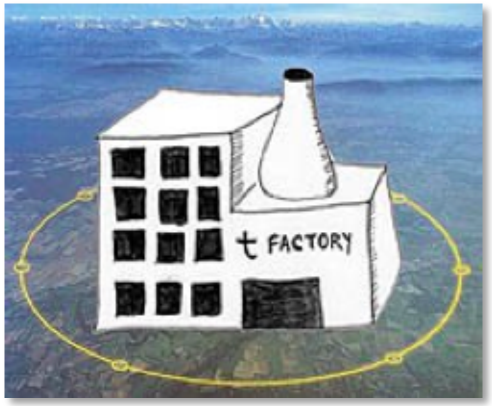
Why measure differentially?

- Precise understanding of top quark distributions is crucial:
  - Precise tests of pQCD for top quark production in different regions of the phase space
  - Theory predictions and models need to be tuned and tested with measurements
  - Extract/use for PDF fits
  - Enhance sensitivity to New Physics
  - Background for Higgs, rare processes and many BSM searches



[Kidonakis, arXiv:1009.4935]

- LHC 2010 – 2012:
  7 TeV: ~ 1 M $t\bar{t}$ pairs
  8 TeV: ~ 5.5 M $t\bar{t}$ pairs
  (each ATLAS & CMS)

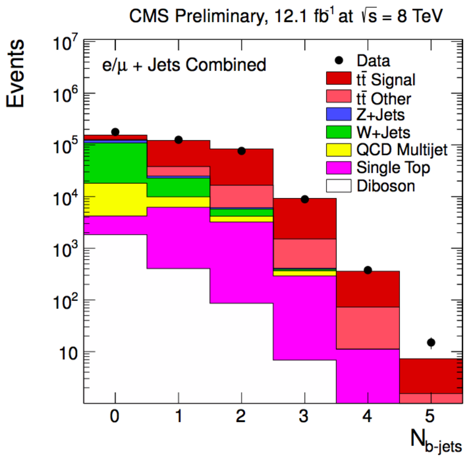


Entered the era of precision measurements in top-quark-pair production

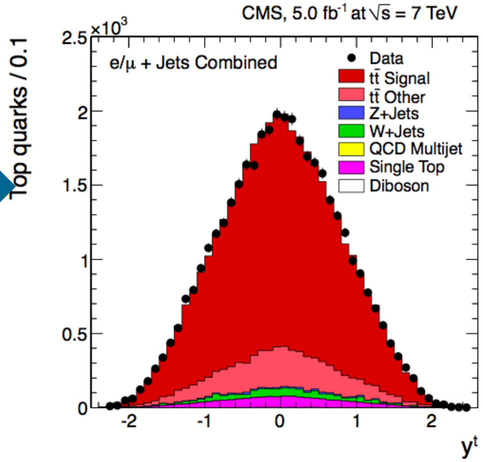
General analysis strategy

Measure σ($t\bar{t}$) as a function of kinematic distributions of **top, top pairs, b-jets, leptons, and lepton pairs**

(1) Event selection



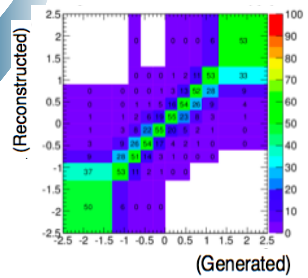
(2) $t\bar{t}$ kinematic reconstruction



(3) Bin-wise cross section measurement

- Subtract background
- Unfolding: correct for detector effects and acceptance

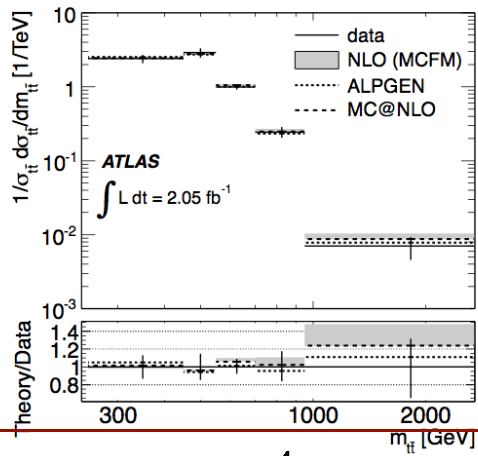
$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\mathrm{Data}} - N^i_{\mathrm{BG}}}{\Delta^i_X \epsilon^i L}$$



Response matrix

(4) Differential $t\bar{t}$ cross sections

- Normalised to in-situ measured σ($t\bar{t}$)
- 'Visible' or extrapolated to full phase space
- Compare to theory predictions

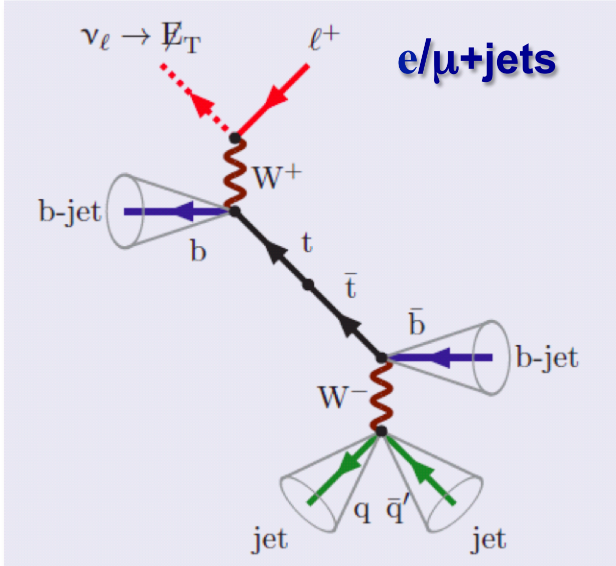


Event selection

Lepton+jets:

- Exactly 1 isolated high-p_T lepton (μ or e)
  - CMS: $p_T > 30$ GeV, $|\eta| < 2.1$
  - ATLAS: $p_T > 25$ GeV, $|\eta| < 2.5$
- Veto additional leptons
- ≥ 4 high-p_T jets, ≥ 2 b-tagged jets
  - CMS: $p_T > 30$ GeV, $|\eta| < 2.4$
  - ATLAS: $p_T > 25$ GeV, $|\eta| < 2.5$
- Additionally: ATLAS: $E_T^{miss} > 30$ GeV, $m_T^W > 35$ GeV

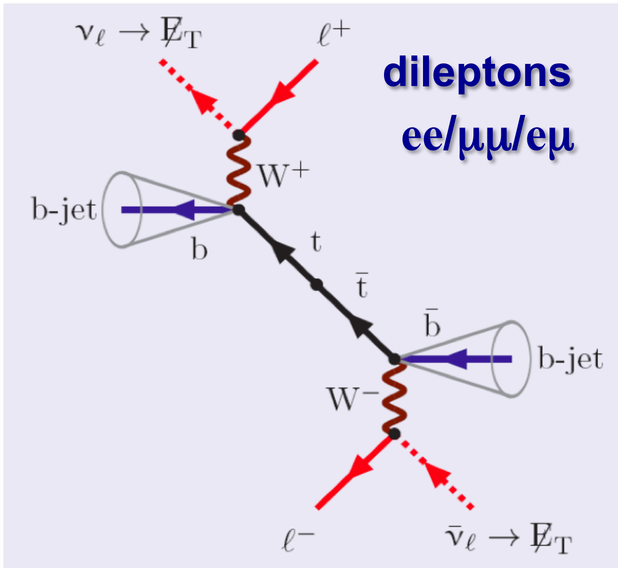
Kinematic reconstruction of the $t\bar{t}$ system



Dileptons:

- 2 opp.-sign, high-p_T isolated leptons (ee, μμ, μe)
  - $p_T > 20$ GeV, $|\eta| < 2.4$
- QCD veto: $m_{ll} < 20$ GeV (12 GeV for 7 TeV)
- ≥ 2 jets ($p_T > 30$ GeV, $|\eta| < 2.4$), ≥ 1 b-tagged jets
- ee, μμ channels: $E_T^{miss} > 40$ GeV (30 GeV for 7 TeV),
  $|m_{ll} - m_Z| > 15$ GeV

Kinematic reconstruction of the $t\bar{t}$ system



Kinematic distributions – ℓ+jets (7 TeV, 5 bf-1)

- Pure $t\bar{t}$ samples after event selection:

  ~ 80% $t\bar{t}$

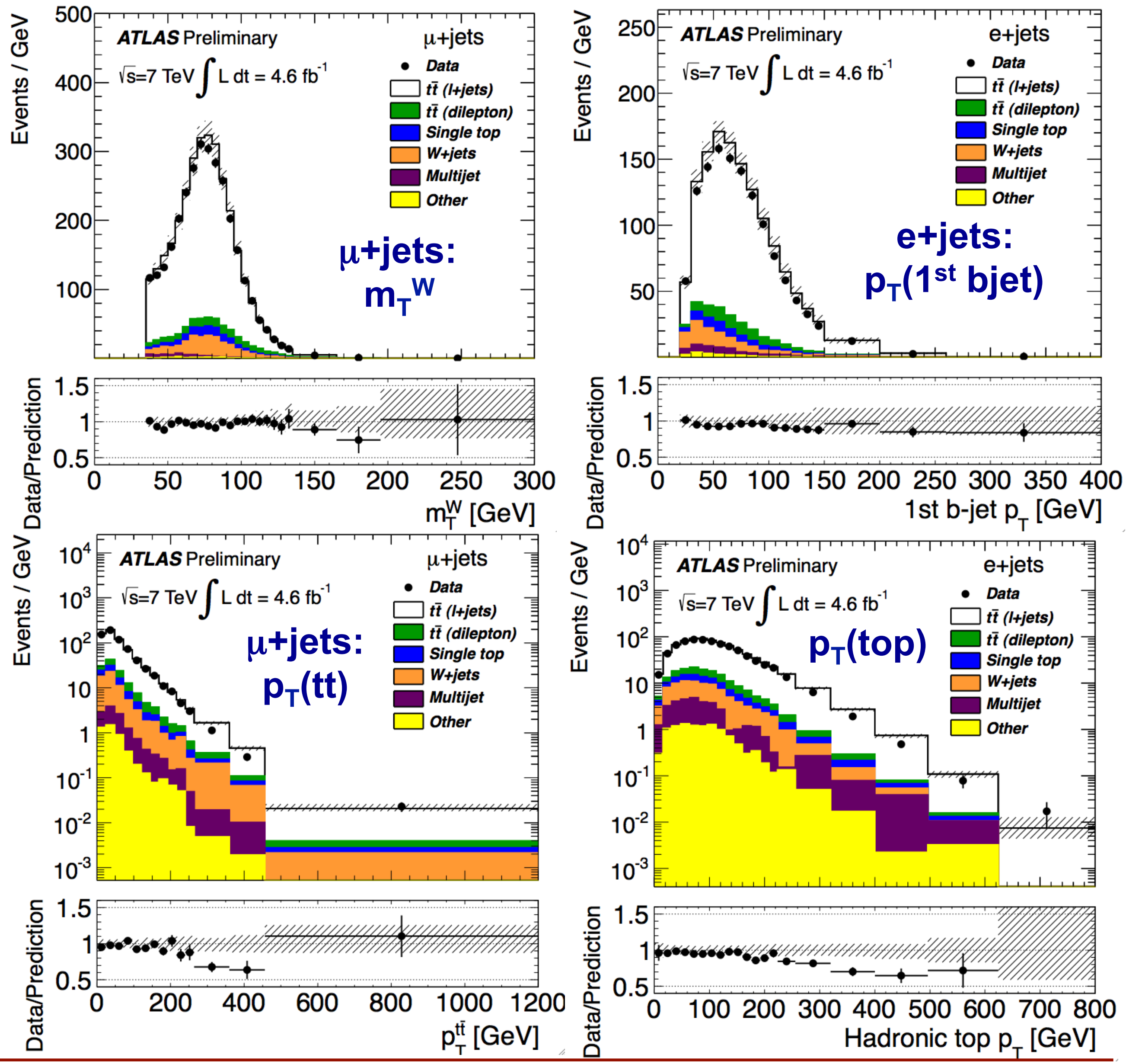
- Main backgrounds:
  W+jets(*), $t\bar{t}$(dilep), single top, multijet(*)

  (*) data-driven normalisation

- Reference $t\bar{t}$ prediction:

  Alpgen+Herwig

  Hadronic top:
  slope observed in data for p_T > 200 GeV



Kinematic distributions – ℓ+jets (7 TeV, 5 fb^{-1})

- Pure $t\bar{t}$ samples after event selection:

  ~ 90% $t\bar{t}$

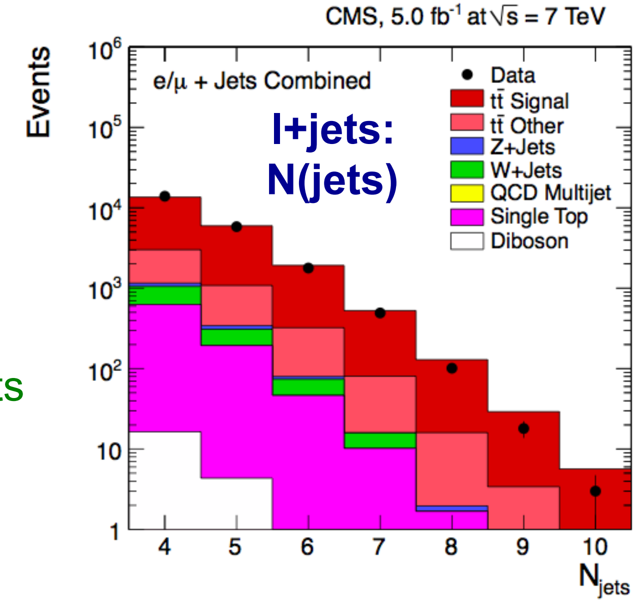
- Main backgrounds:

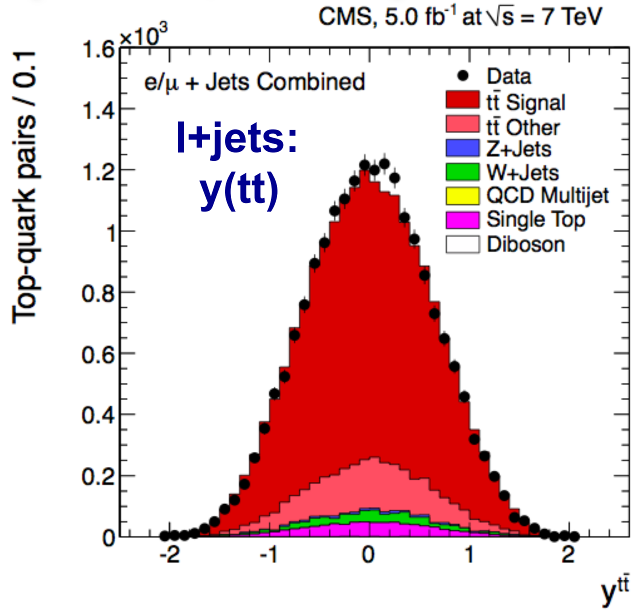
  $t\bar{t}$(other), single top, W+jets
  (all derived from MC)

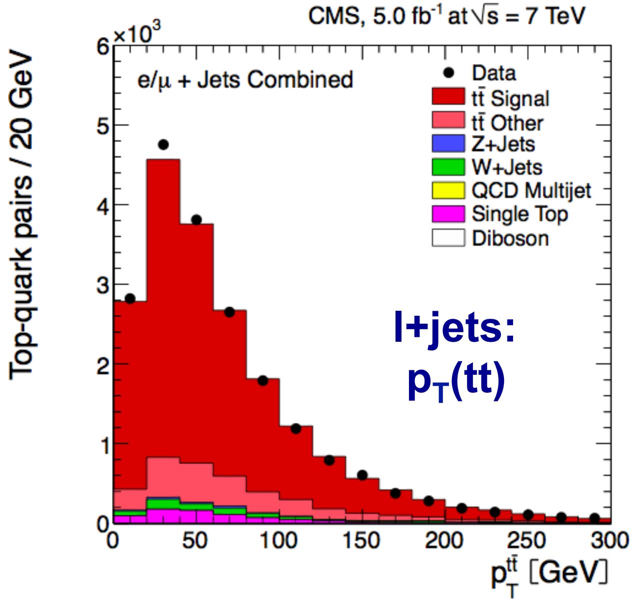
- Reference $t\bar{t}$ prediction:

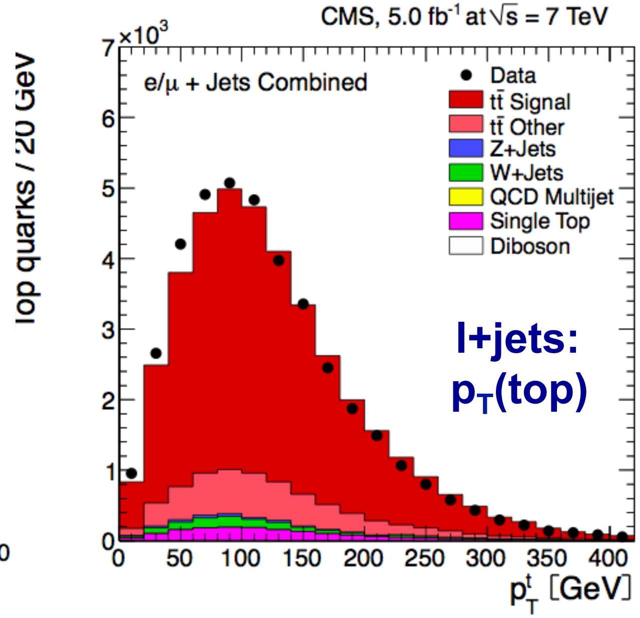
  MadGraph+Pythia

Top p_T spectrum tends to lower p_T values in data than in simulation









Kinematic distributions – dileptons (7 TeV, 5 fb^{-1})

- Pure $t\bar{t}$ samples after event selection:

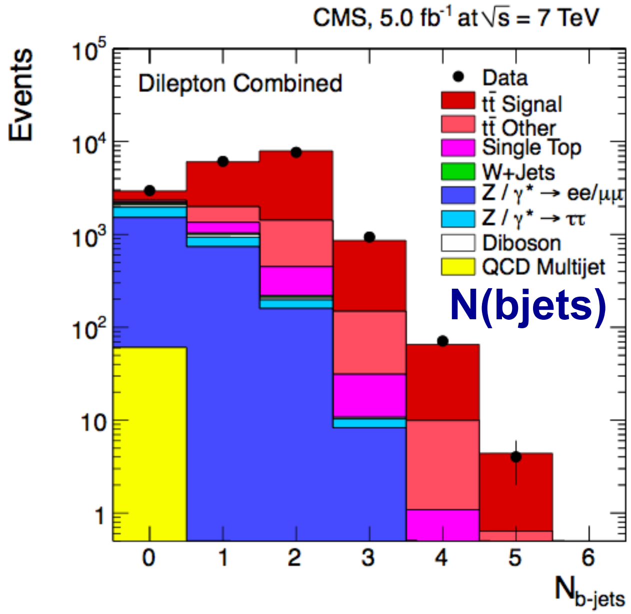
  ~ 80% $t\bar{t}$

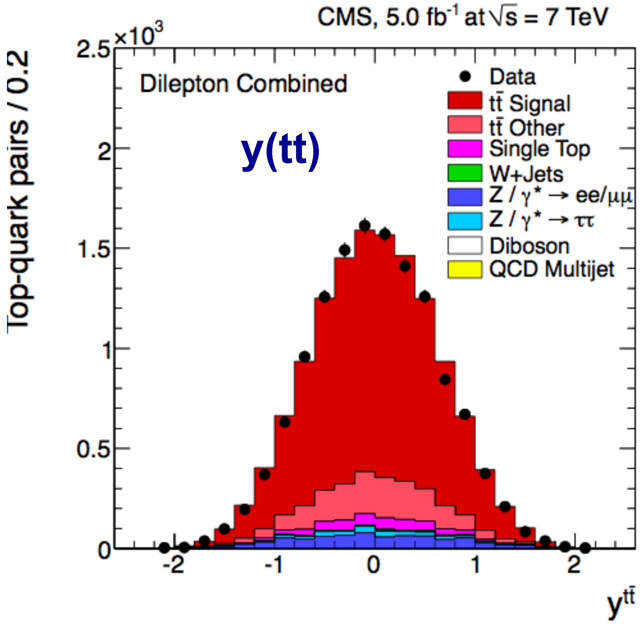
- Main backgrounds:
  $t\bar{t}$(other), single top, Z+jets (→ data-driven)

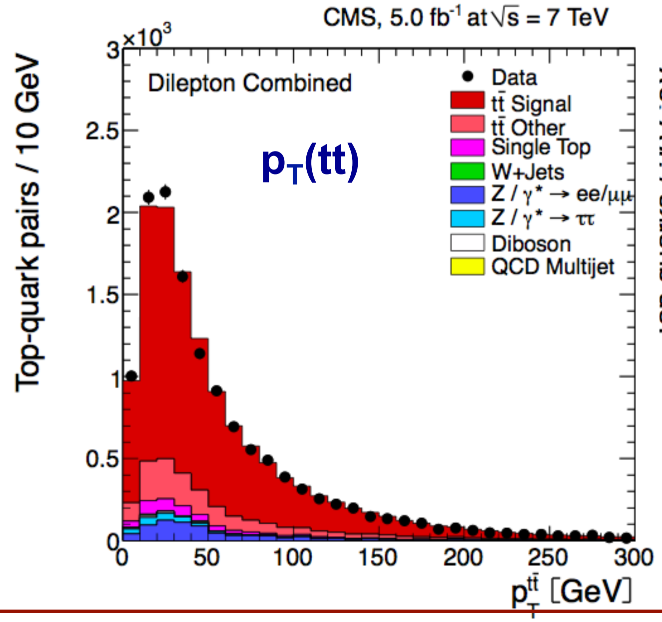
- Reference $t\bar{t}$ prediction:

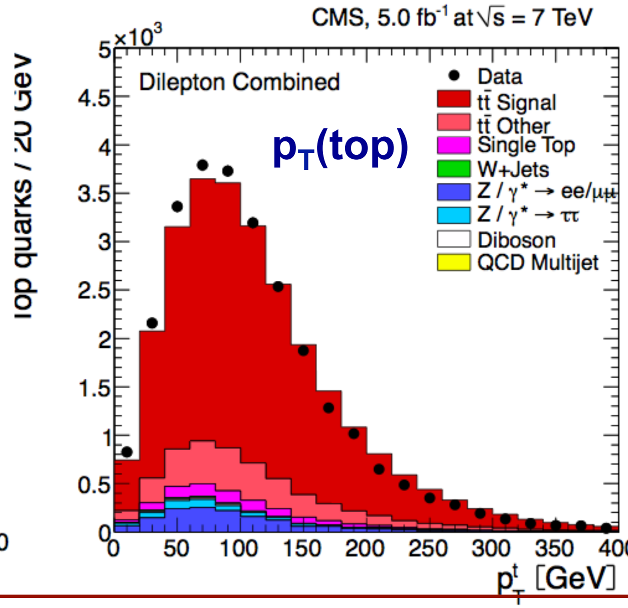
  MadGraph+Pythia

Top p_T spectrum tends to lower p_T values in data than in simulation







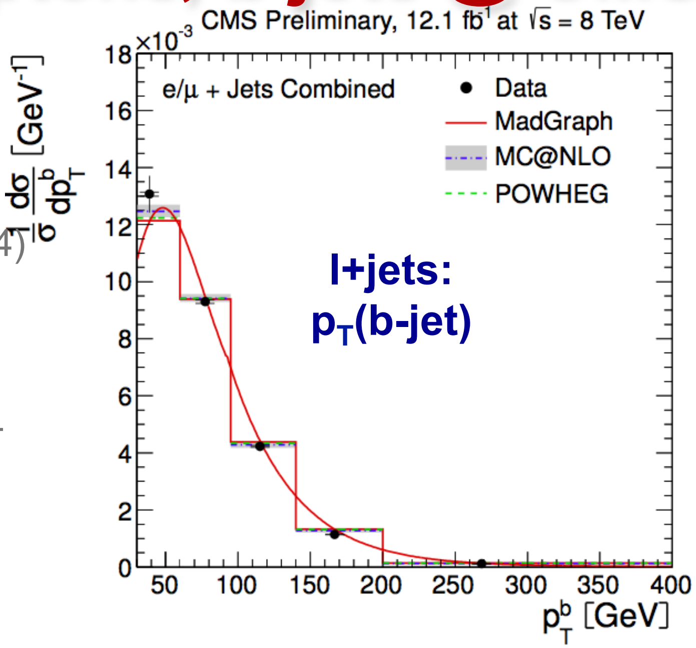


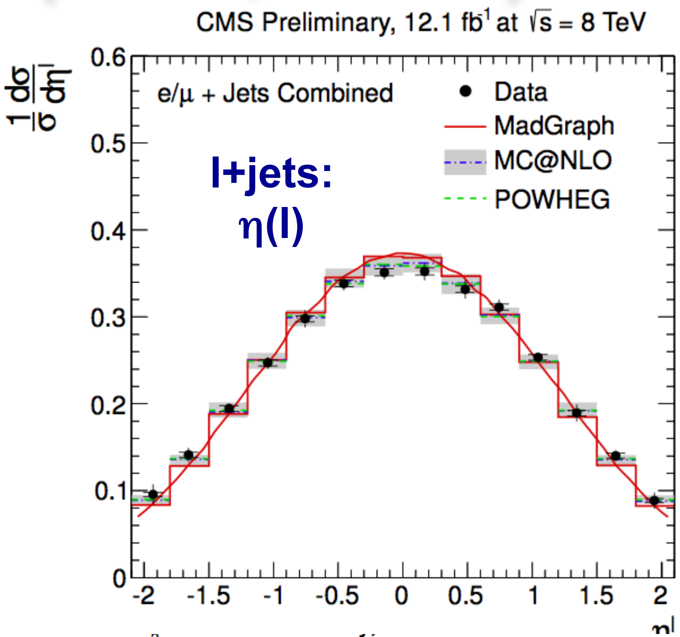
Results: leptons, b-jets @ CMS (8 TeV, 12 fb^{-1})

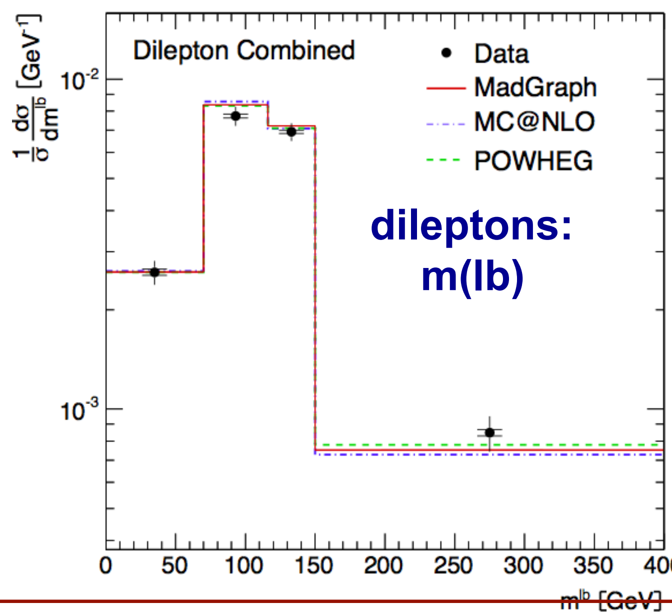
- ‘Visible’ phase space:
  - l+jets:
    lepton (jets) within
    $p_T > 30$ GeV, $|\eta| < 2.1$ (2.4)
  - dileptons:
    leptons (jets) within:
    $p_T > 20$ (30) GeV, $|\eta| < 2.4$

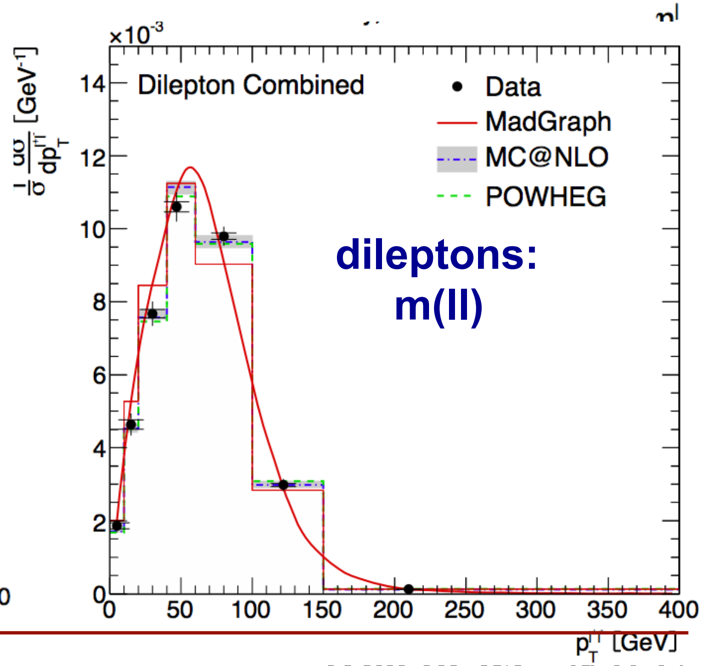
- Comparison to:
  - MadGraph+Pythia
  - MC@NLO+Herwig
  - POWHEG+Pythia

Consistent with
7 TeV results at CMS



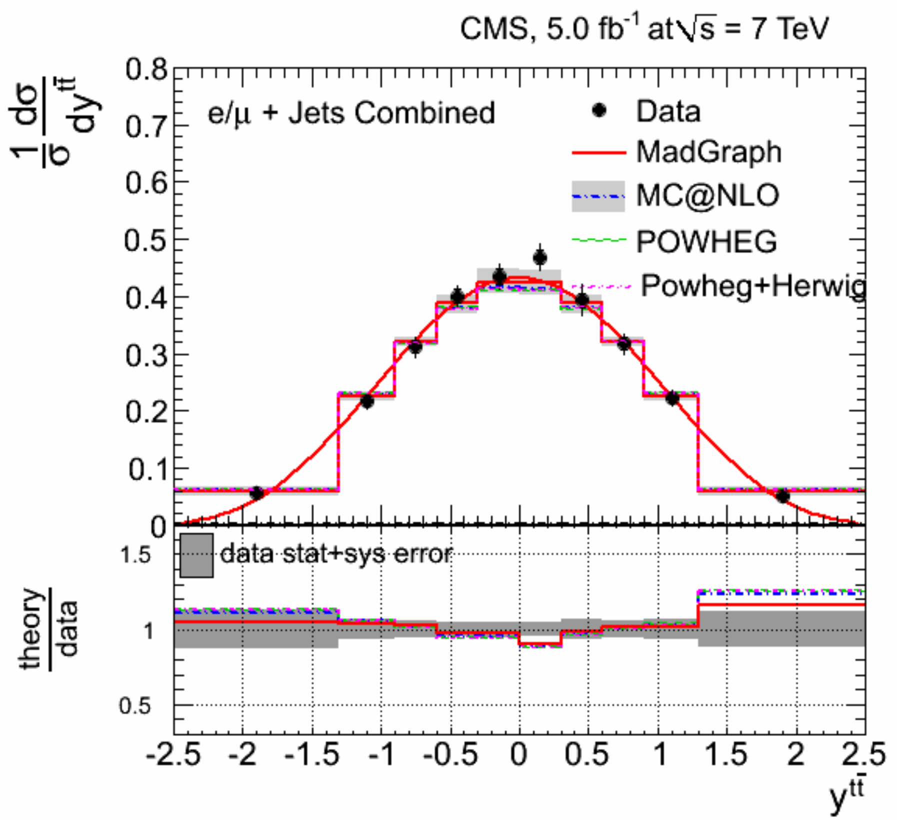


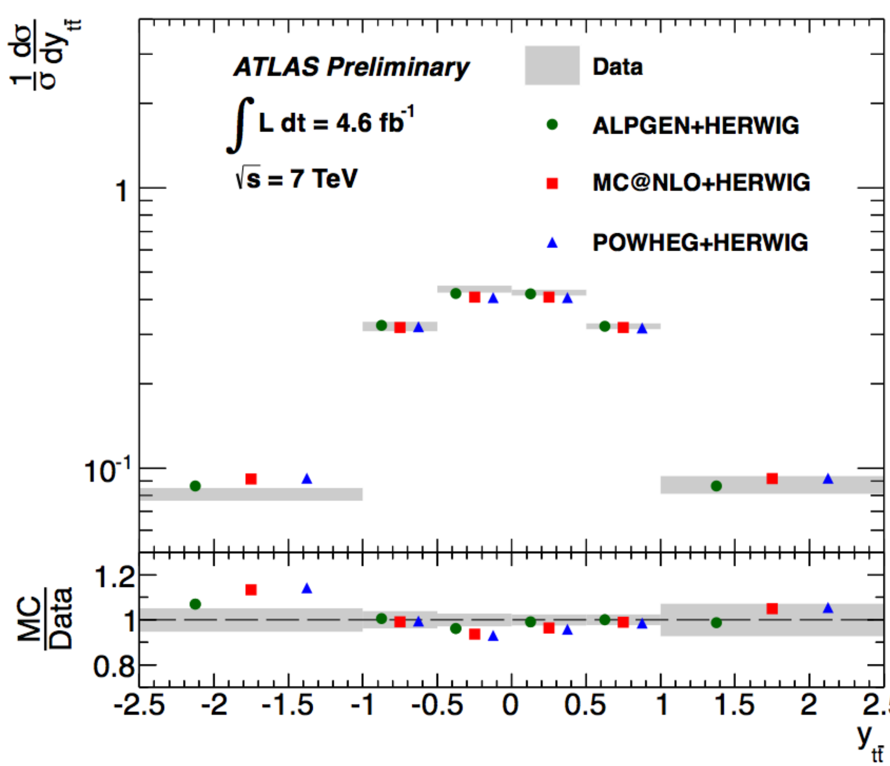




Results: ATLAS & CMS (7 TeV, ℓ+jets) – y($t\bar{t}$)

- CMS: Comparison to MadGraph+Pythia, MC@NLO+Herwig, POWHEG+Pythia, POWHEG+Herwig
- ATLAS: Comparison to ALPGEN+Herwig, MC@NLO+Herwig, POWHEG+Herwig



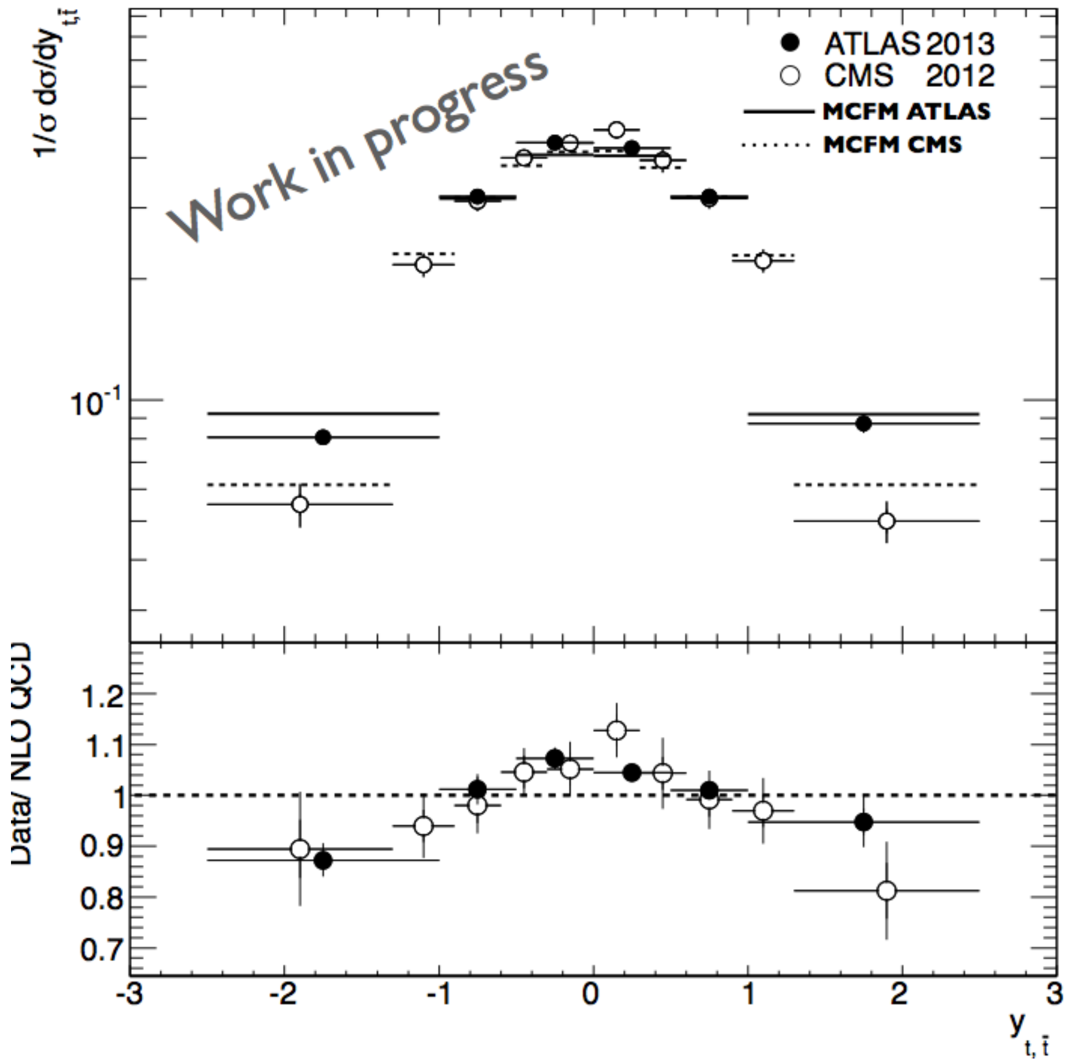


- General good agreement between data & simulation
- Similar behaviour for dileptons, both at 7 and 8 TeV

- Data better described by Alpgen+Herwig
- MC@NLO+Herwig & Powheg+Herwig show similar behaviour

Results: ATLAS & CMS (7 TeV, ℓ+jets) – y($t\bar{t}$)

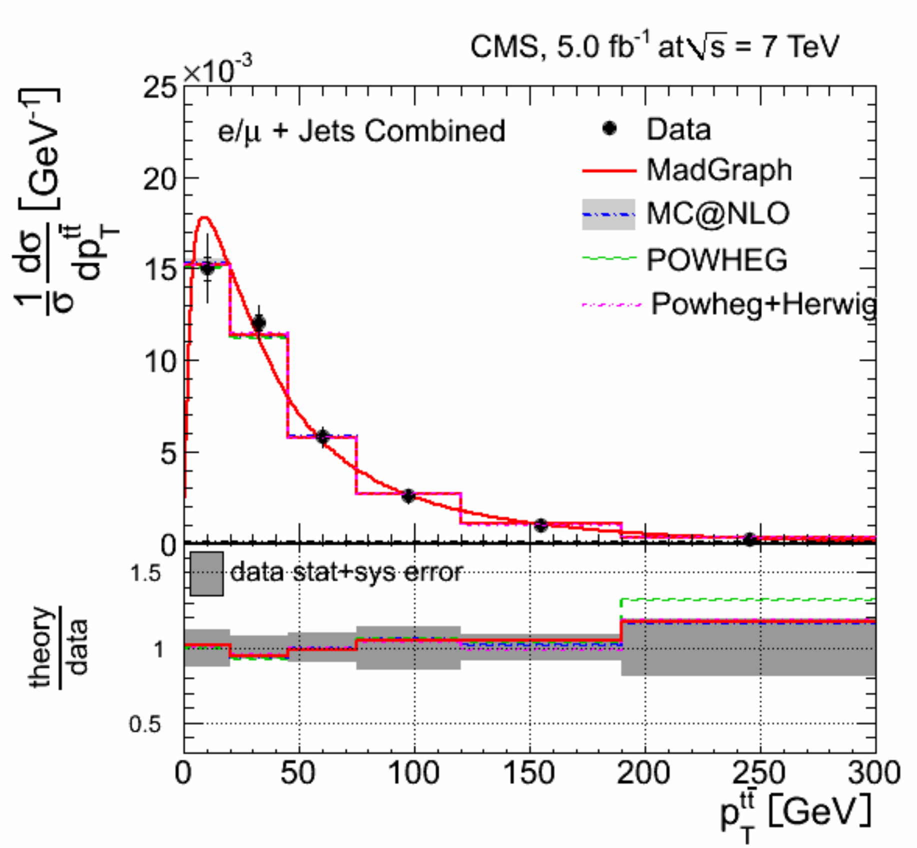
- First attempt at direct data comparison: data/NLO prediction (MCFM)

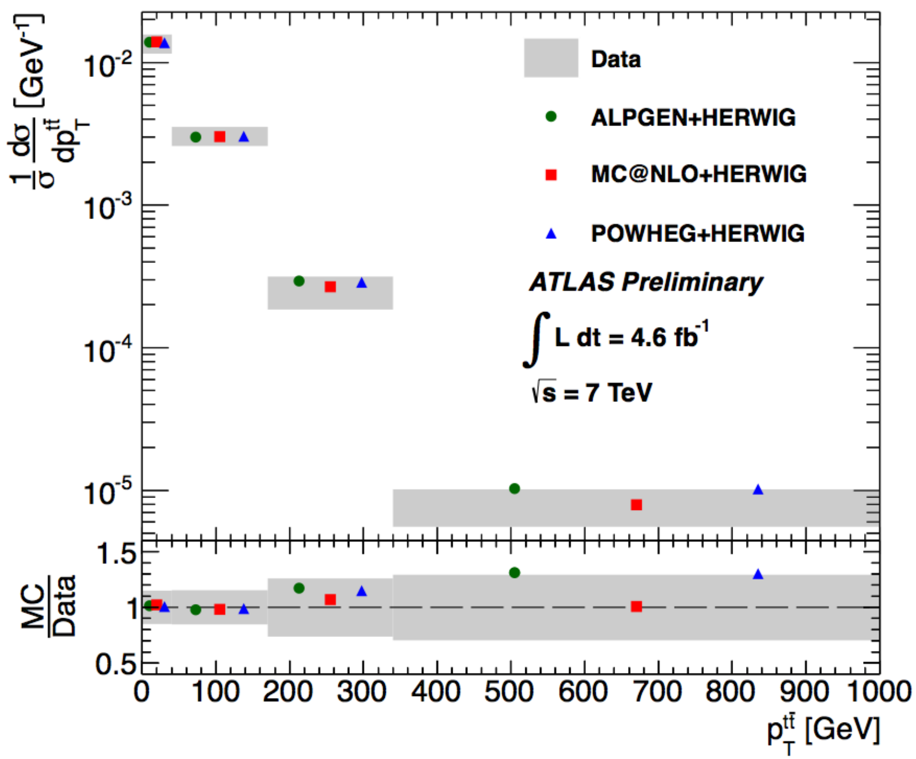


General good agreement between ATLAS & CMS results, within uncertainties

Results: ATLAS & CMS (7 TeV, ℓ+jets) – $p_T(t\bar{t})$

- CMS: Comparison to MadGraph+Pythia, MC@NLO+Herwig, POWHEG+Pythia, POWHEG+Herwig
- ATLAS: Comparison to ALPGEN+Herwig, MC@NLO+Herwig, POWHEG+Herwig

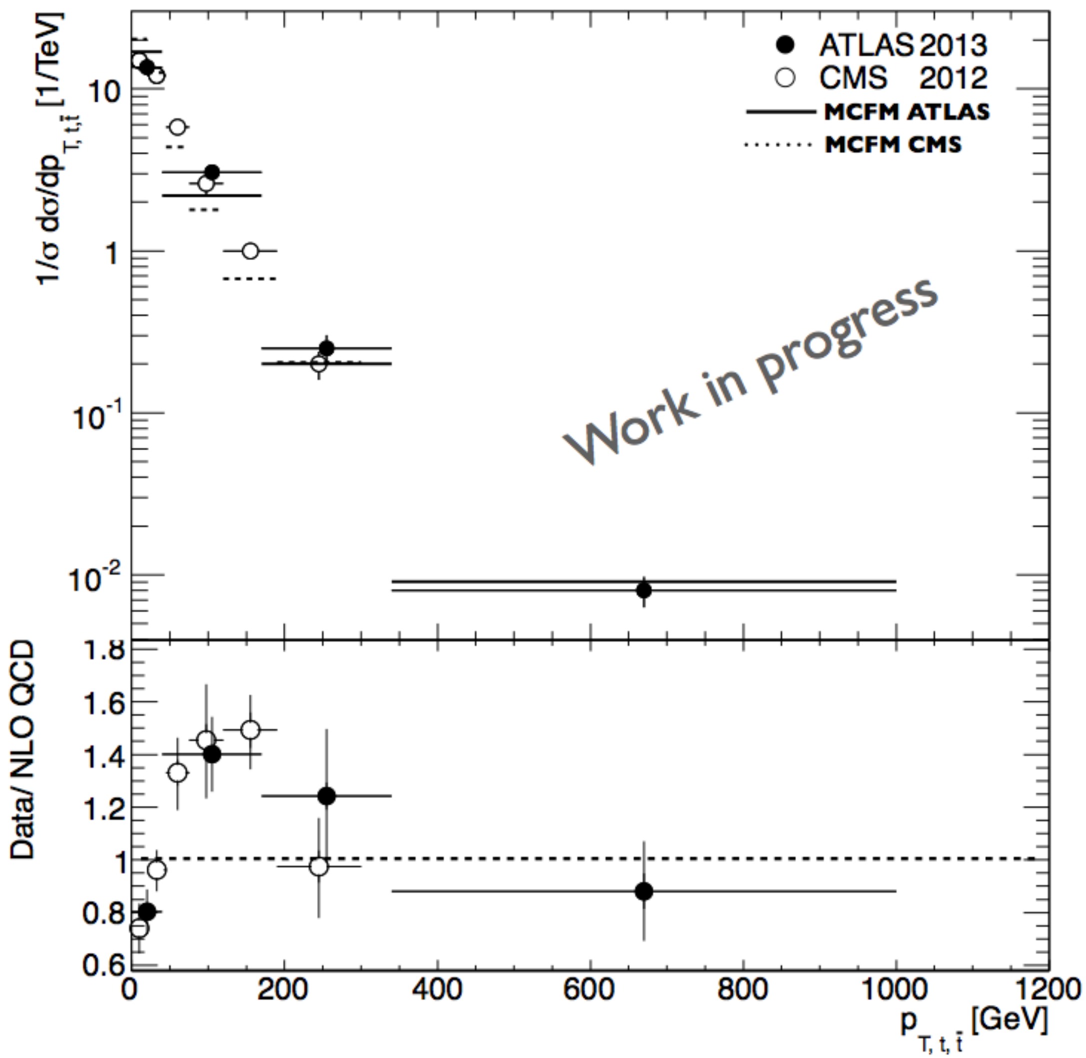




- General good agreement between data & simulation, both for ATLAS & CMS
- CMS: Similar behaviour for dileptons, both at 7 and 8 TeV

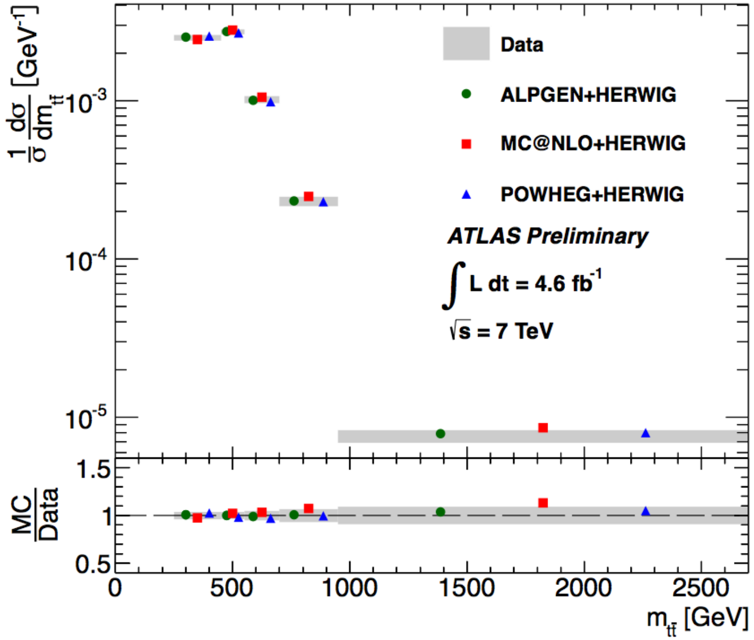
Results: ATLAS & CMS (7 TeV, ℓ+jets) – $p_T(t\bar{t})$

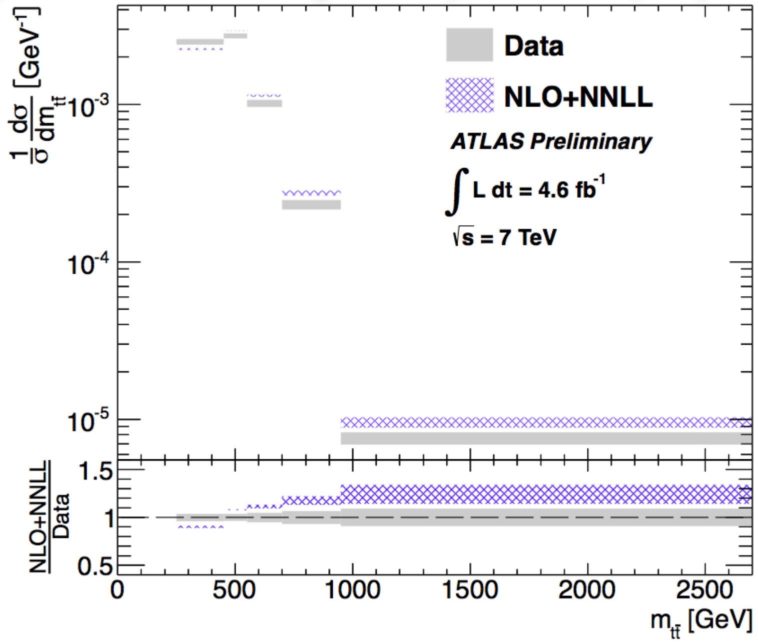
- First attempt at direct data comparison: data/NLO prediction (MCFM)

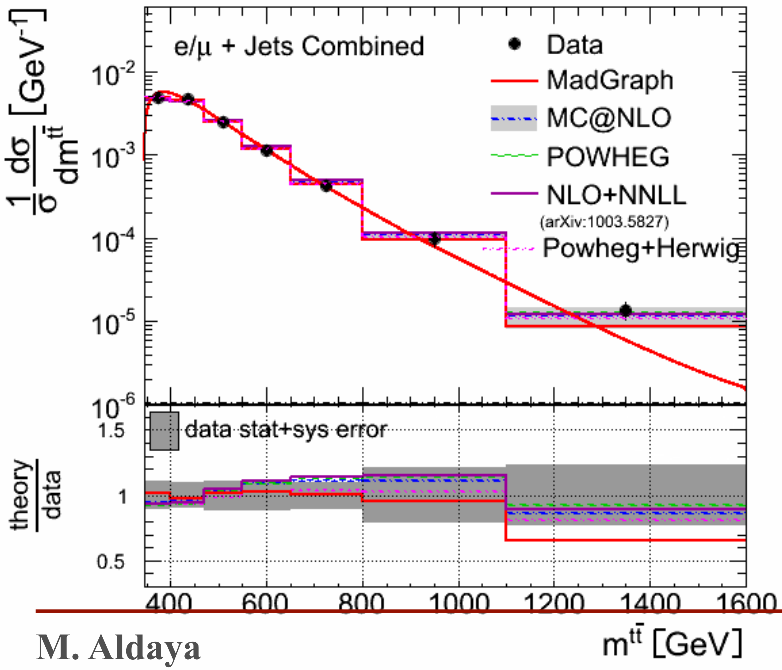


Reasonable agreement between ATLAS & CMS data

Results: ATLAS & CMS (7 TeV, ℓ+jets) – m($t\bar{t}$)



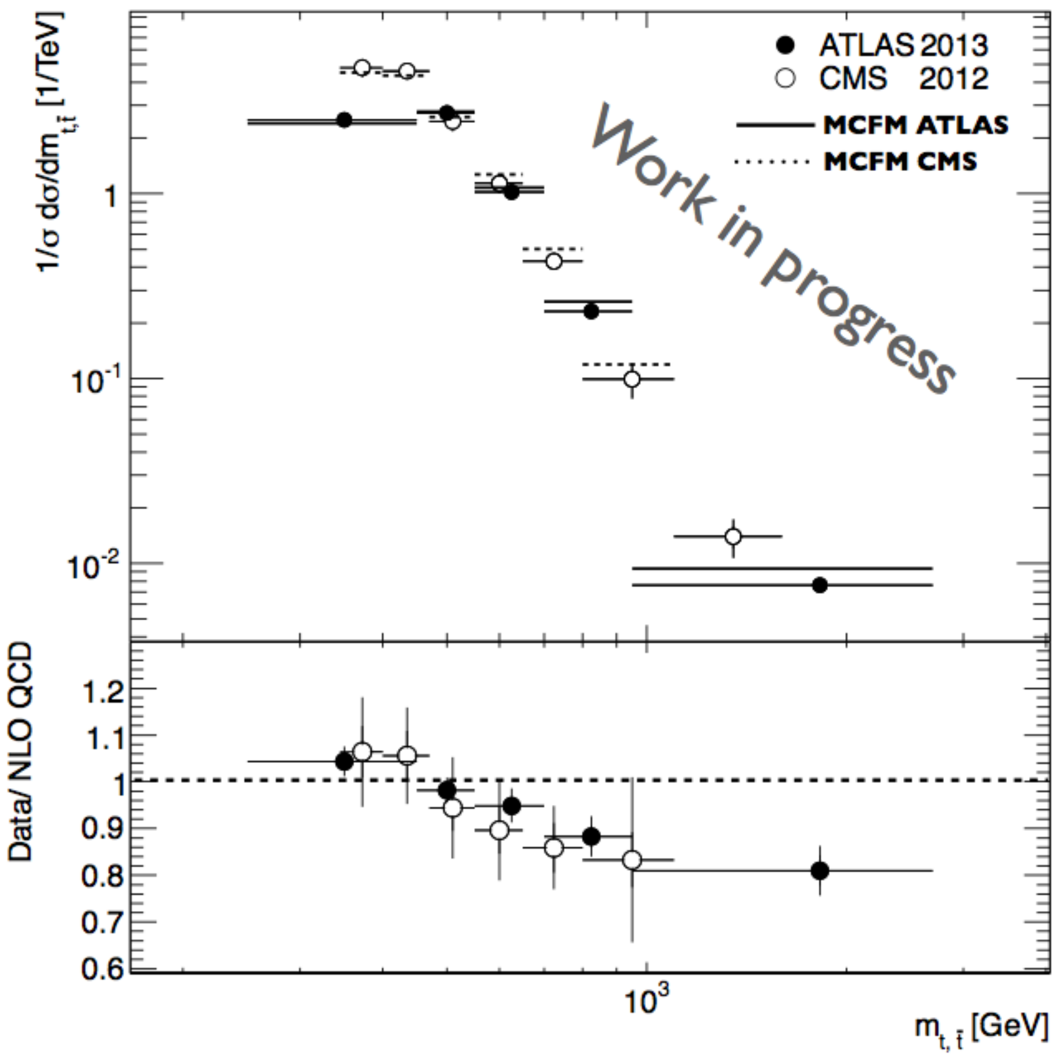




- ATLAS: Comparison to ALPGEN+Herwig, MC@NLO+Herwig, POWHEG+Herwig, NLO+NNLL
- CMS: Comparison to MadGraph+Pythia , MC@NLO+Herwig, POWHEG+Pythia, POWHEG+Herwig, NLO+NNLL
- General good agreement between data & simulation, both for ATLAS and CMS
- NLO+NNLL: good agreement, within uncertainties, for CMS; ATLAS data not well described
- CMS: Similar for dileptons, both at 7 and 8 TeV

Results: ATLAS & CMS (7 TeV, ℓ+jets) – m($t\bar{t}$)

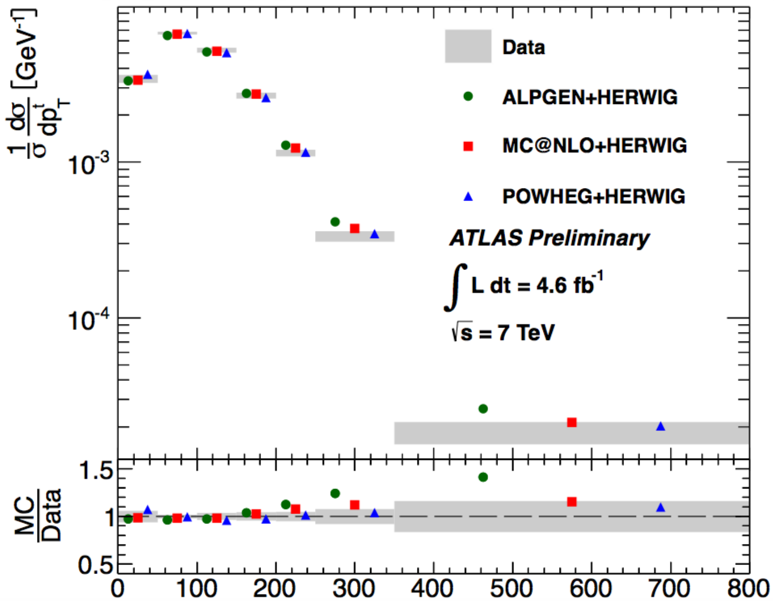
- First attempt at direct data comparison: data/NLO prediction (MCFM)

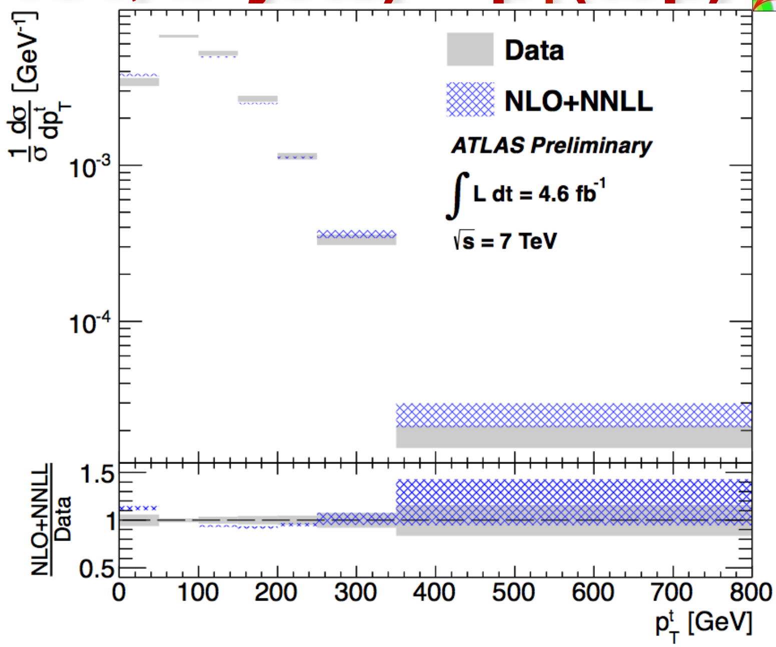


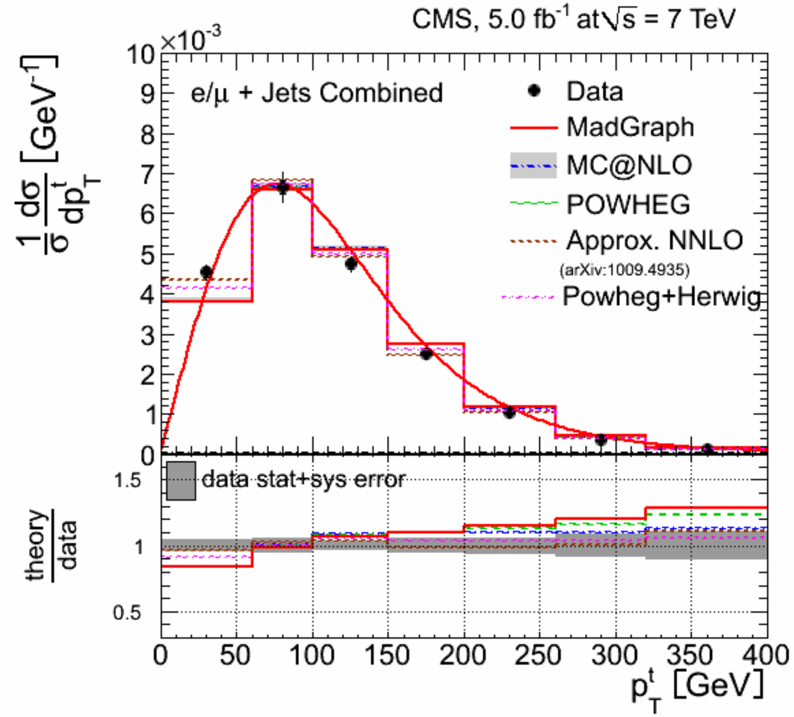
General good agreement between ATLAS & CMS data

CMS: Better agreement with MCFM than ATLAS, within uncertainties

Results: ATLAS & CMS (7 TeV, ℓ+jets) – p_T(top)







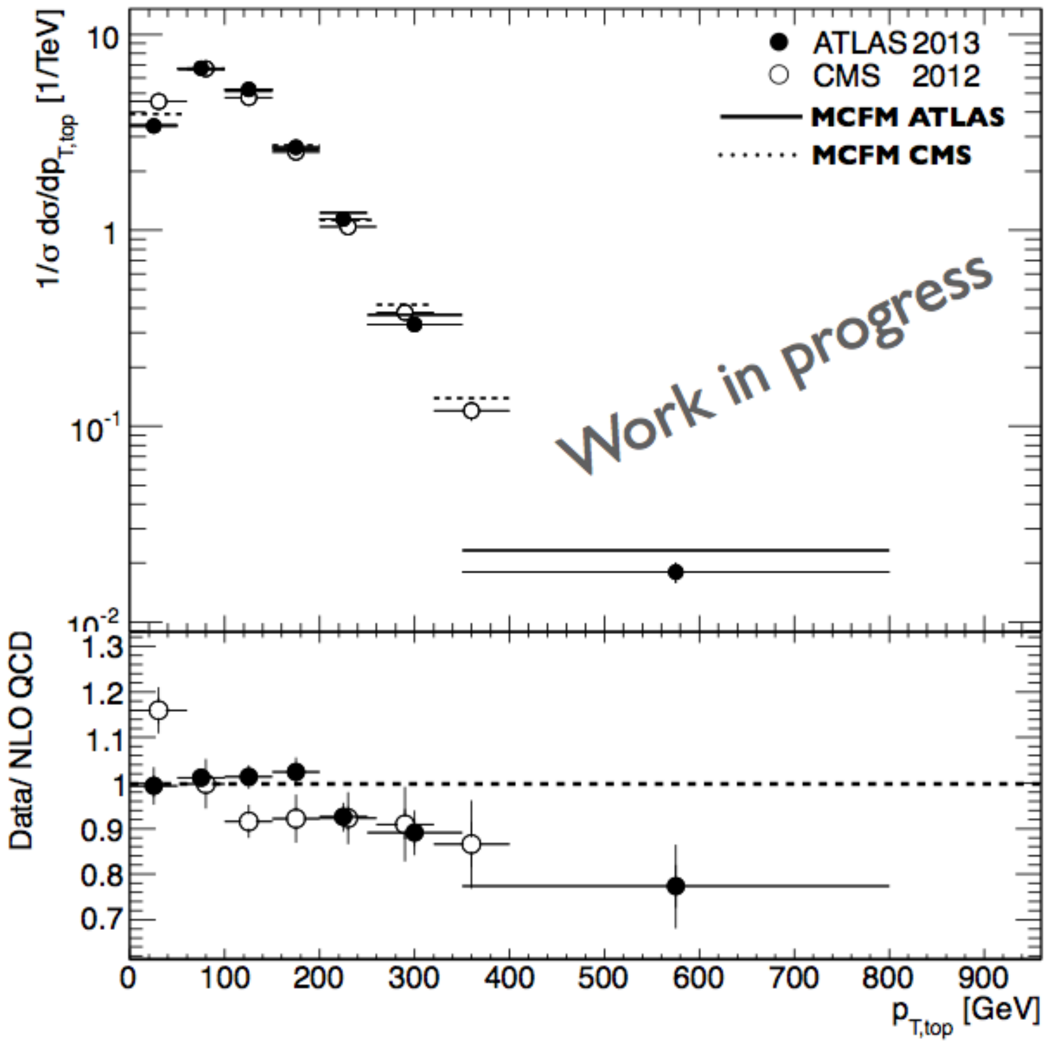
- Powheg+Herwig describes ATLAS & CMS data reasonably well over the full p_T range

- **p_T(top) < 200 GeV: disagreement btw ATLAS & CMS**
  - CMS: softer spectrum in data, best described by Approx. NNLO
  - ATLAS: disagreement with Approx. NNLO

- CMS: Similar behaviour for dileptons, both at 7 & 8 TeV

Results: ATLAS & CMS (7 TeV, ℓ+jets) – p_T(top)

- First attempt at direct data comparison: data/NLO prediction (MCFM)



p_T(top) < 200 GeV:

- Disagreement between ATLAS & CMS data
- ATLAS result in agreement with MCFM

p_T(top) > 200 GeV:

- Good agreement between ATLAS & CMS data
- ATLAS & CMS in disagreement with MCFM

TOPLHCWG meeting

Ttbar differential cross-section

M. Aldaya Martin, L. Bellagamba, M. Goerner, F. Spano'
for the differential cross-section analysis group from ATLAS and CMS

17/10/2013

- The idea is to define an efficient process in order to compare the respective measurements and understand possible differences in procedures and/or results

- First discussions among analyzers and conveners involved in the analysis started at TOP2013.

- The first step was the exchange of a list of questions/clarifications between the two experiments. Starting from such lists, a summary set of relevant items has been produced which could represent a draft agenda for a next close meeting between the respective analyzer teams.

- Comparison based on 7 TeV results in l+jets for p_T(top), m($t\bar{t}$), p_T($t\bar{t}$), y($t\bar{t}$)

ATLAS & CMS to-do list (I)

Definition of the top quark: "top quark at parton level after QCD radiation"

- Which is exactly the top parton used for the unfolding ?
- Check for possible differences between Pythia and Herwig

MC samples and theory predictions (NLO+PS, multi-leg tree-level+PS, MCFM, NLO +NNLL, approx. NNLO):

- Exchange parameters and tunes used for the signal MC samples
- For each signal MC sample used provide a tree with generator-level information to exchange with the other experiment
- For the multi-leg tree-level signal MC check possible differences in the treatment of topologies with large numbers of extra partons.
- Check if the NLO+NNLL and approx. NNLO predictions are treated consistently in both experiments

Selection & Analysis + background uncertainties:

- Check consistency in purity and efficiency definition: in particular is tau+jets considered as signal or background ?
- Provide detailed efficiency tables separated for electron and muon channels.
- Exchange details on the treatment of uncertainties, in particular the background shape uncertainties

ATLAS & CMS to-do list (II)

Unfolding: exchange details of the procedure

- Are corrections (migrations at reco level and correction from reco to parton level) performed in one step?
- Exchange response matrices
- How is the regularisation performed?
- How large is the extrapolation to the full phase space?

Results:

- Provide detailed systematic tables for the different spectra and channels in order to compare the impact of the different sources of systematic uncertainties.
- Provide ratio plots for a direct data/prediction comparison both for reco and unfolded level results.

Suggestions for further checks are welcome !

First study:

- Check definition of ***top parton after QCD radiation and before decay***
- Consistency of the MC samples at generator level used in the ATLAS & CMS differential cross section analyses

MC $t\bar{t}$ samples: parameters & tunes (7 TeV)

Default samples

ATLAS

Matrix element	Shower & Hadronization	PDF	Tune
MC@NLO v4	Herwig 6.5 + Jimmy 4.31	cteq66 or CT10	AUET1/2
Powheg	Pythia 6	cteq66 (7 TeV)	Perugia 2011 C
Alpgen	Herwig 6.5 + Jimmy 4.31	cteq6ll	AUET2

- Additional Powheg+Herwig sample: NLO PDF CT10, AUET2 Herwig 6.5 tune

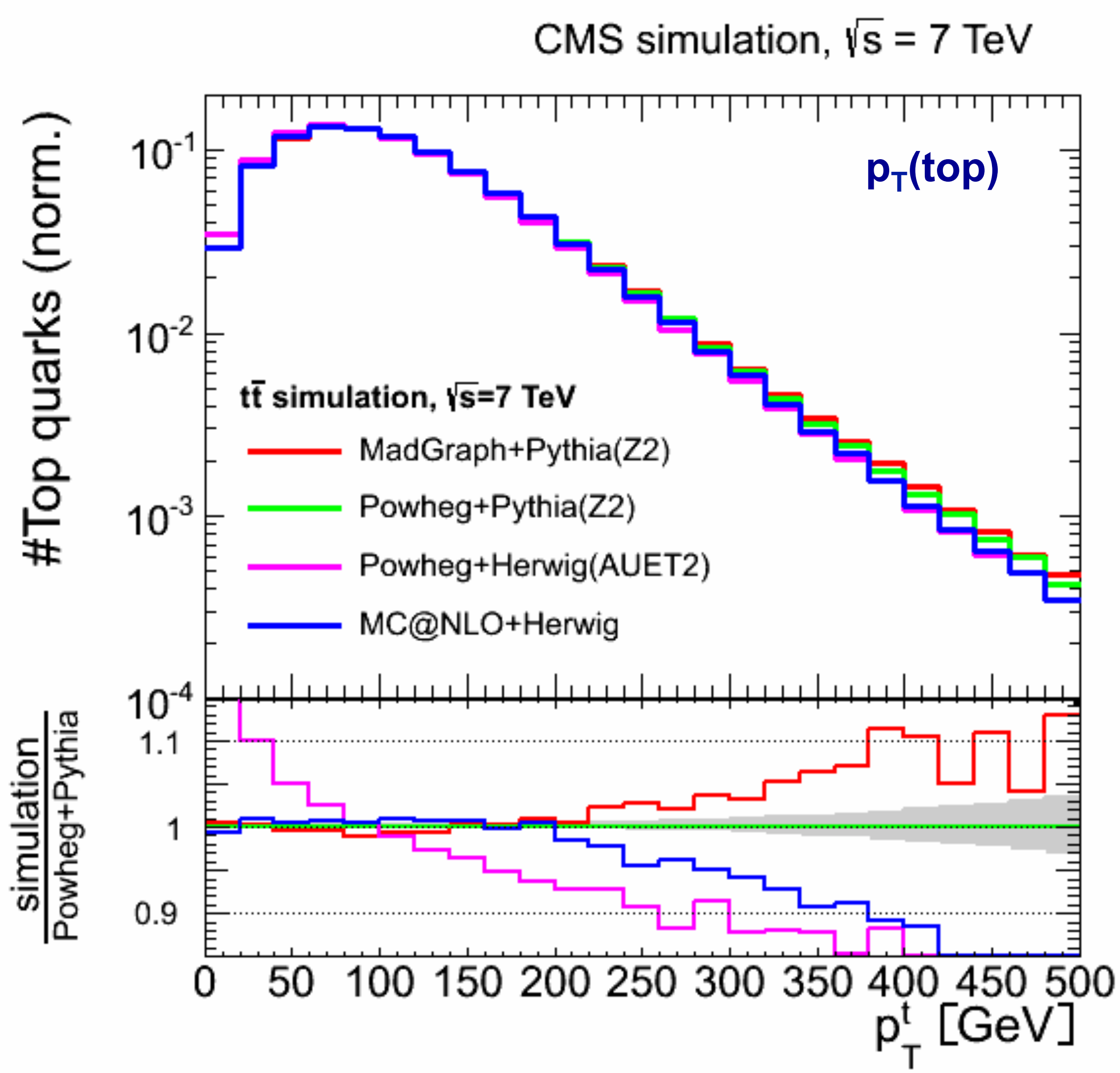
CMS

Matrix element	Shower & Hadronization	PDF	Tune
MadGraph v5	Pythia 6	cteq6l	Z2 (7 TeV)
Powheg	Pythia 6	cteq6m (7 TeV)	Z2 (7 TeV)
MC@NLO v3.4	Herwig 6 + Jimmy	cteq6m	default tune

- Additional Powheg+Herwig sample: NLO PDF CTEQ6M, AUET2 Herwig 6 tune

All CMS samples overview: p_T(top)

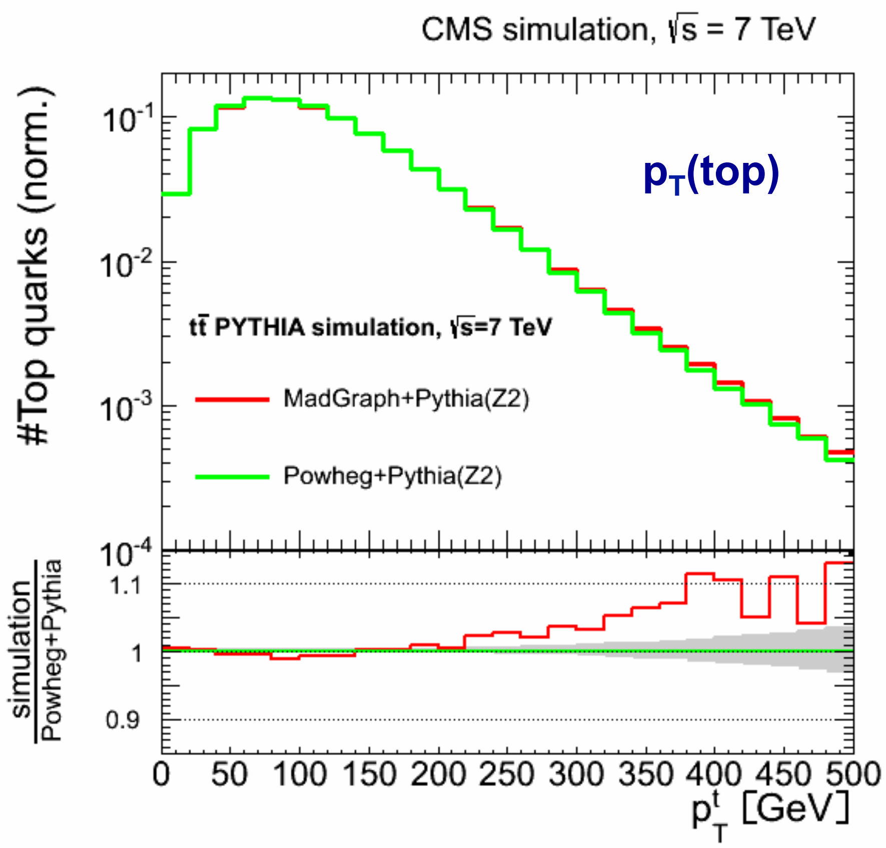
- Ratio wrt CMS Powheg+Pythia



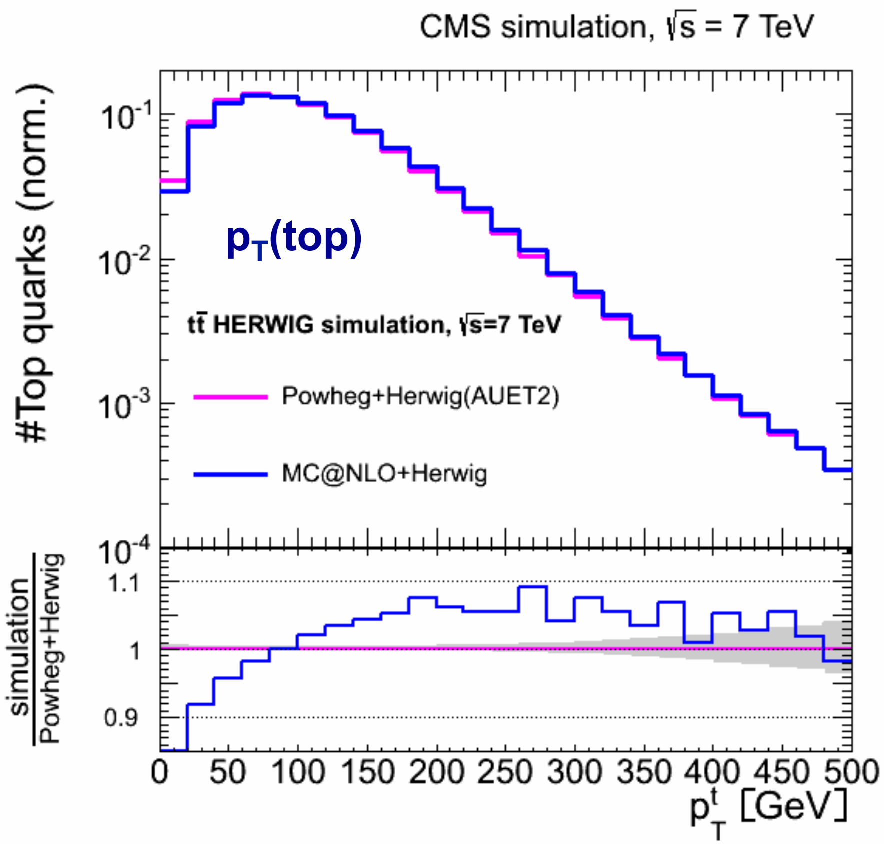
- Low p_T region mostly similar
- Some differences for p_T > 300 GeV between **Pythia** (green, red) and **Herwig** (pink, blue)
- Different behaviour of Powheg+Herwig, especially for p_T < 100 GeV
- Powheg+Herwig provides reasonable description of the data both for ATLAS and CMS
- **Similar** behaviour in **ATLAS & CMS**

PYTHIA-SHOWERED samples vs. HERWIG-SHOWERED samples

Pythia-showered:
ratio wrt CMS Powheg+Pythia



Herwig-showered:
ratio wrt CMS Powheg+Herwig

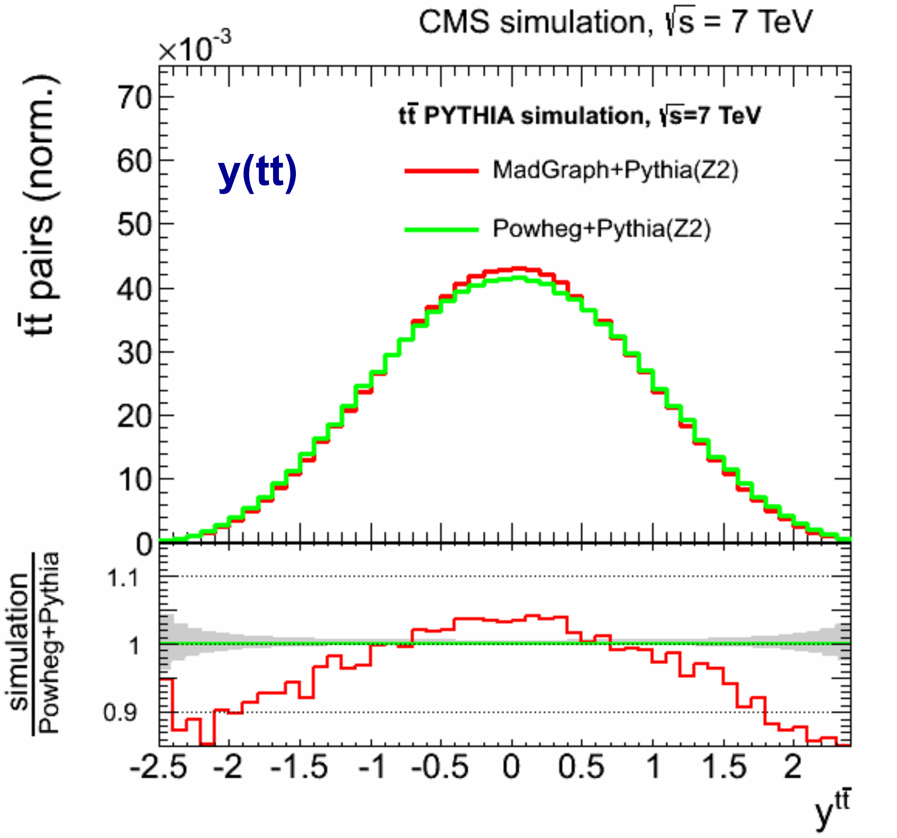


Consistent top quark definition in HERWIG- & PYTHIA-showered samples btw ATLAS & CMS:

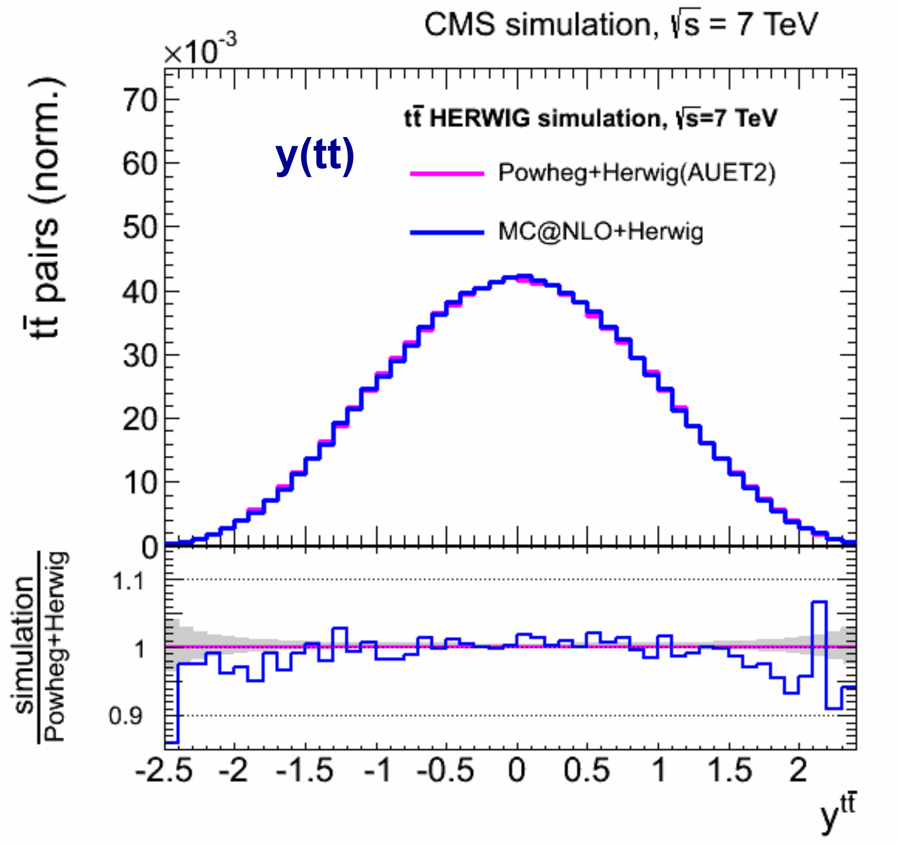
- events produced with the same generator and parton shower/hadronization scheme are compatible within the statistical uncertainty of the samples
- **Powheg+Herwig**: different shape over the whole p_T spectrum, both for ATLAS & CMS

PYTHIA-SHOWERED samples vs. HERWIG-SHOWERED samples

Pythia-showered:
ratio wrt CMS Powheg+Pythia



Herwig-showered:
ratio wrt CMS Powheg+Herwig

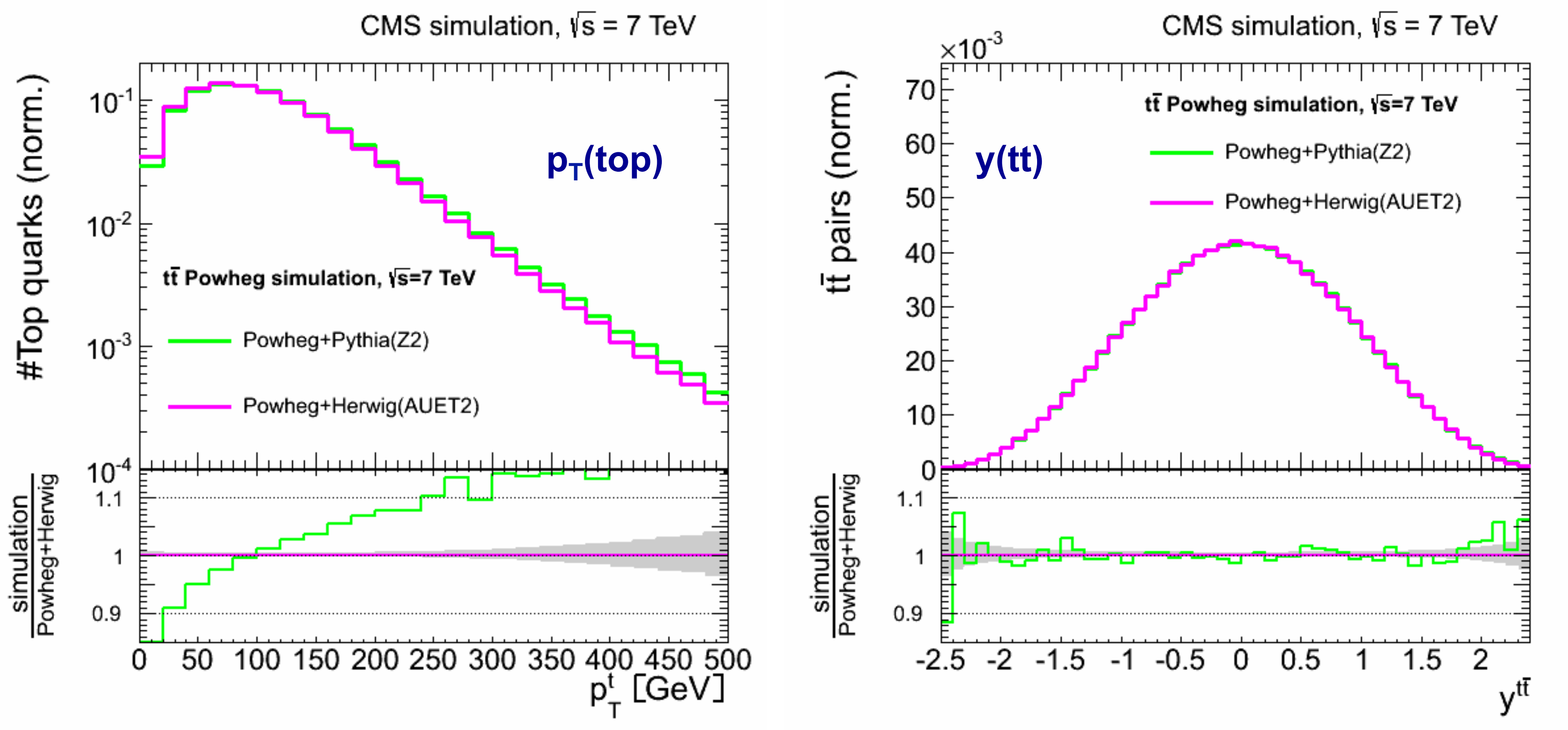


Consistent top quark definition in HERWIG- & PYTHIA-showered samples btw ATLAS & CMS:

- events produced with the same generator and parton shower/hadronization scheme are compatible within the statistical uncertainty of the samples
- MadGraph+Pythia (Alpgen+Herwig) more central than other Pythia- (Herwig-) showered samples

POWHEG SAMPLES: Pythia vs. Herwig

- Ratio wrt CMS Powheg+Herwig



Given a generator, **the relative differences between PYTHIA & HERWIG** are observed by both experiments with sizes that **are consistent** within the statistical uncertainties of the samples

- **Powheg+Herwig**: different shape over the whole p_T spectrum, both for ATLAS & CMS

Summary & outlook

- **ATLAS & CMS $t\bar{t}$ differential cross sections**
  - Largely consistent with SM predictions
  - Some tension between ATLAS & CMS at low p_T(top) values

  → Collaboration between both experiments started to understand differences

- **First comparison between ATLAS & CMS**
  - ATLAS and CMS have consistent definition of the top quark (*top parton after radiation*)
  - Compatible behaviour in corresponding sample pairs: same differences between generators and hadronisation schemes
  - Default generators (CMS MadGraph+Pythia, ATLAS Alpgen+Herwig) are similar, consistent within statistical uncertainties

- **Powheg+Herwig describes p_T(top) in data better, both for ATLAS & CMS**

→ <u>Question for theorists/MC experts</u>:

What is the main difference to other generators where the p_T(top) distribution is different ?

- **Next steps in ATLAS & CMS comparison:**
  - consistency of theory precictions, data/MC comparison, further cross-checks on unfolding, etc

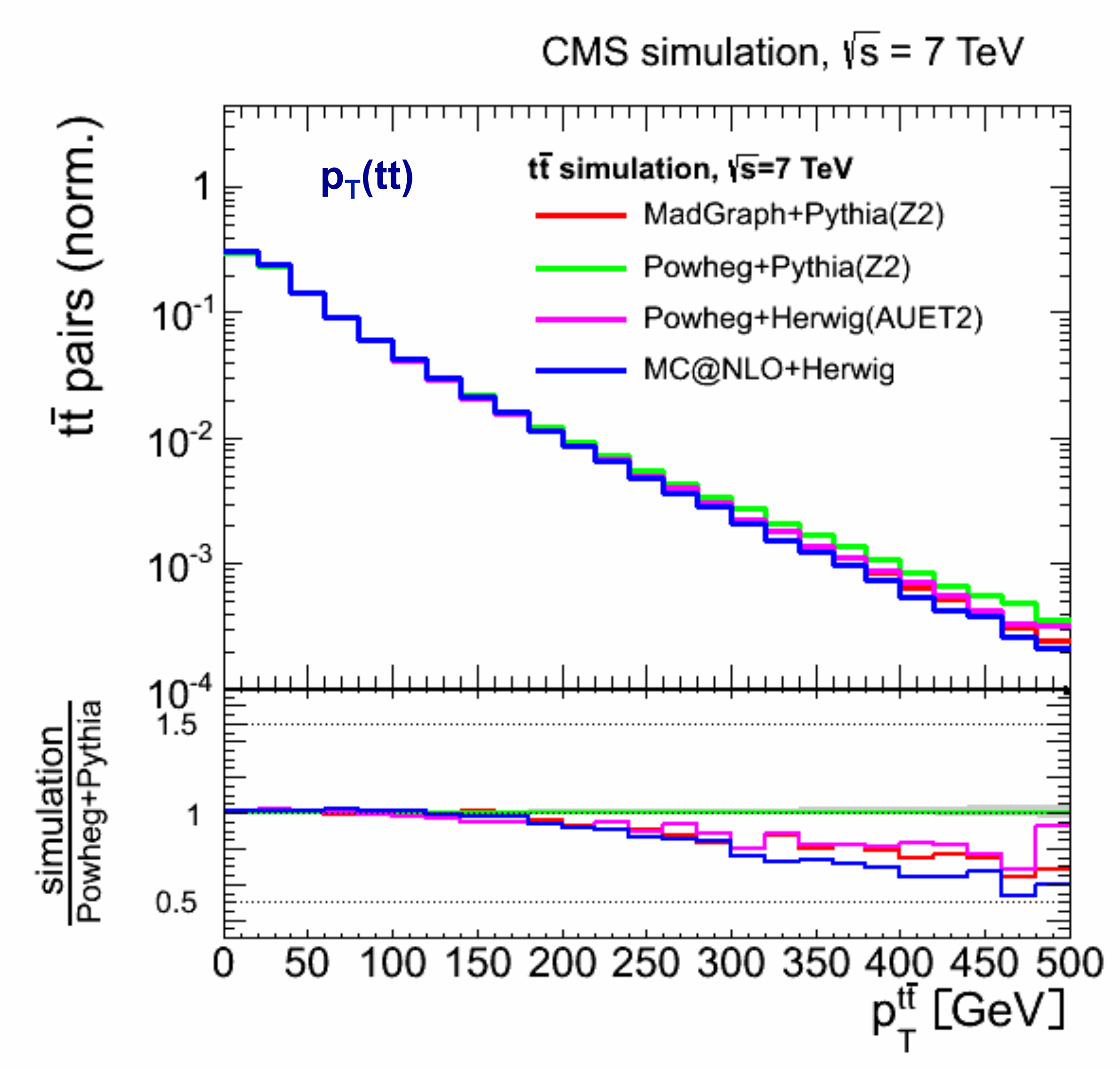
Additional information

Summary of differential $\sigma(t\bar{t})$ measurements

	CMS	ATLAS
channels	e/μ+jets ee/μμ/eμ 7 and 8 TeV	e/μ+jets 7 TeV
simulation default	MadGraph+Pythia	Alpgen+Herwig
simulation cross check	Powheg+Pythia, MC@NLO+Herwig, (Powheg+Herwig)	Powheg+Herwig, MC@NLO+Herwig
event reconstruction	l+jets: kinematic fit dilepton: ~MWT, ν spectrum (MC)	log likelihood fitter
unfolding	regularized unfolding (continuous regularisation parameter)	SVD unfolding (integer regularisation parameter)
phase space	top/tt: fully extrapolated (status 3) lepton/b-jet: visible particle level	top/tt: fully extrapolated (status 155)
background	Z->ll data driven, others: MC	data driven N(QCD&W+jets) shape: MC, others: MC

All CMS samples overview: p_T(tt)

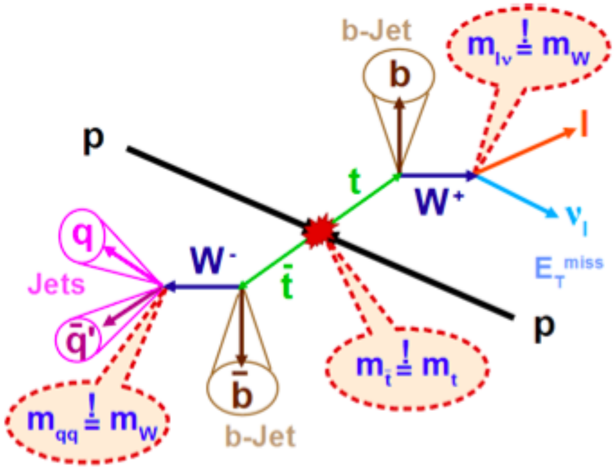
- Ratio wrt CMS Powheg+Pythia



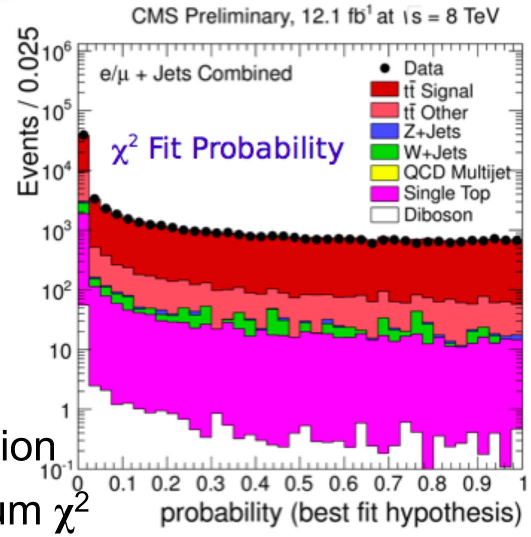
- Compatible ATLAS & CMS behaviour in corresponding sample pairs

- Different behaviour of Powheg+Pythia for p_T > 200 GeV

Kinematic reconstruction – ℓ+jets



- Vary 4-momenta of leptons, jets & neutrino within resolutions
- Constraints:
  - $m_{top} = m_{antitop}$
  - $m_{qq} = m_{l\nu} = m_W = 80.4$ GeV
- Limit permutations: consider 4/5 leading jets, use b-tag information
- Take 4-jet permutation with minimum χ^2



CMS-PAS TOP-12-027

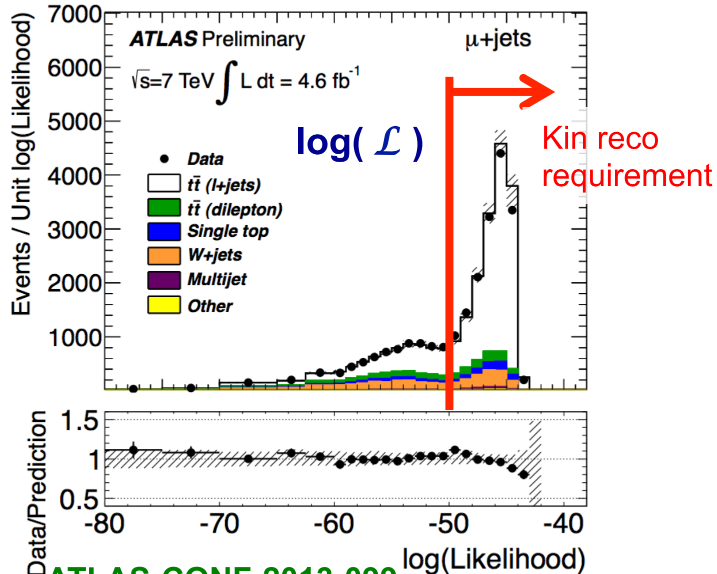
- ATLAS: maximum likelihood fit of the measured objects to a LO representation of the $t\bar{t}$ decay

$\mathcal{L}$ = transfer functions • Breit-Wigner distributions • W_{btag}

- transfer functions → Experimental resolutions of each $t\bar{t}$ decay product
- Breit-Wigner distributions → Associate E_T^{miss}, leptons, jets with W and (anti)top ($m_{(anti)top}$ = 172.5 GeV)
- W_{btag} → b-tag information

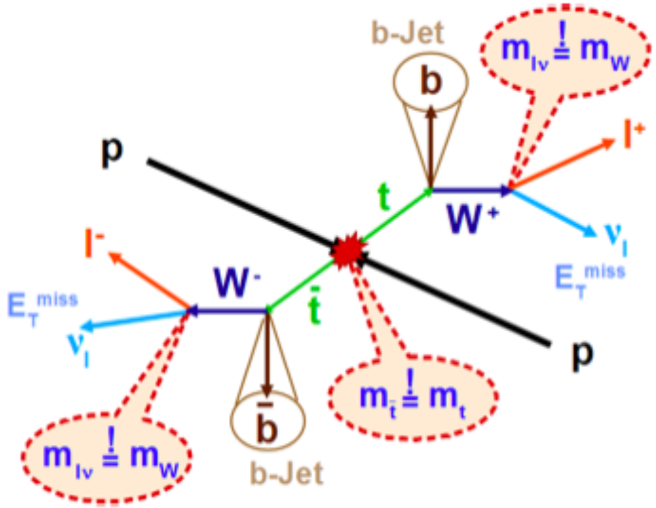
Leptonic top: reconstructed from fitted lepton, neutrino, b-parton

Hadronic top: reconstructed from remaining 3 partons



ATLAS-CONF-2013-099

Kinematic reconstruction – dileptons



- Underconstrained system (2 neutrinos)
- Constraints:
  - $m_{l\nu} = m_W = 80.4$ GeV
  - $p_{x,y}(\nu_1) + p_{x,y}(\nu_2) = E_T^{miss}{}_{x,y}$
  - $m_{top} = m_{antitop}$ = fixed
- Vary m_{top} in 1 GeV steps: 100 – 300 GeV
- Take solutions with most b-tagged jets
- Choose solution with best reconstructed neutrino energy with respect to simulated spectrum

Kinematic distributions – ℓ+jets (8 TeV, 12 fb^{-1})

- Pure $t\bar{t}$ samples after event selection:

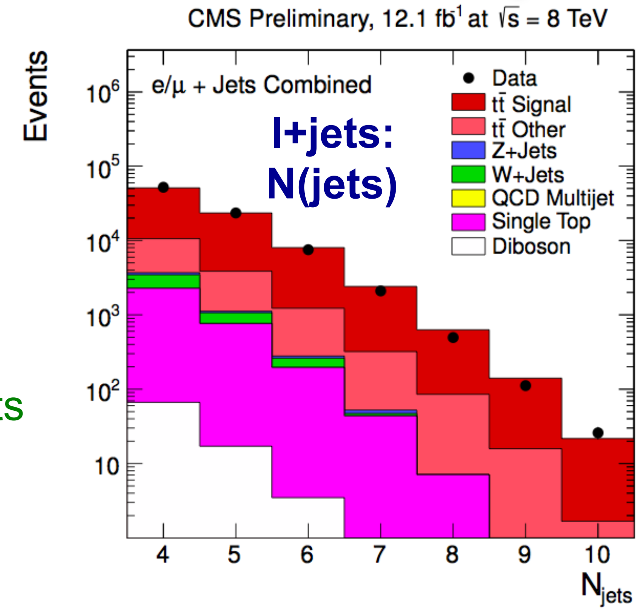
  ~ 80% $t\bar{t}$

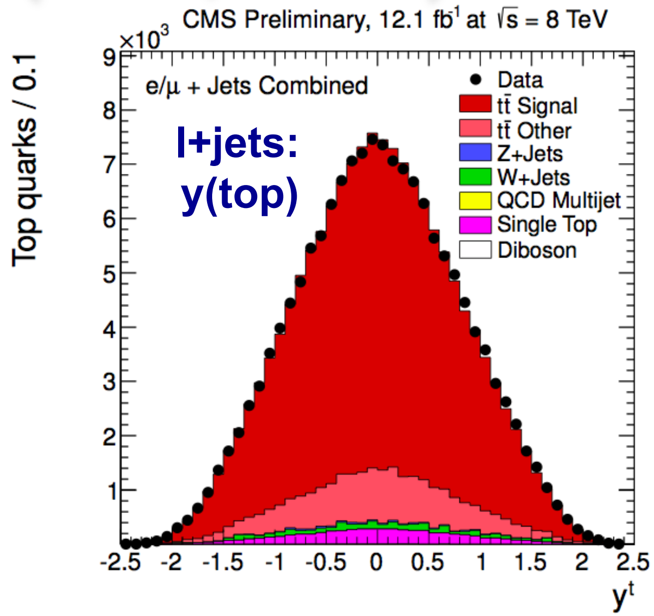
- Main backgrounds:

  $t\bar{t}$(other), single top, W+jets

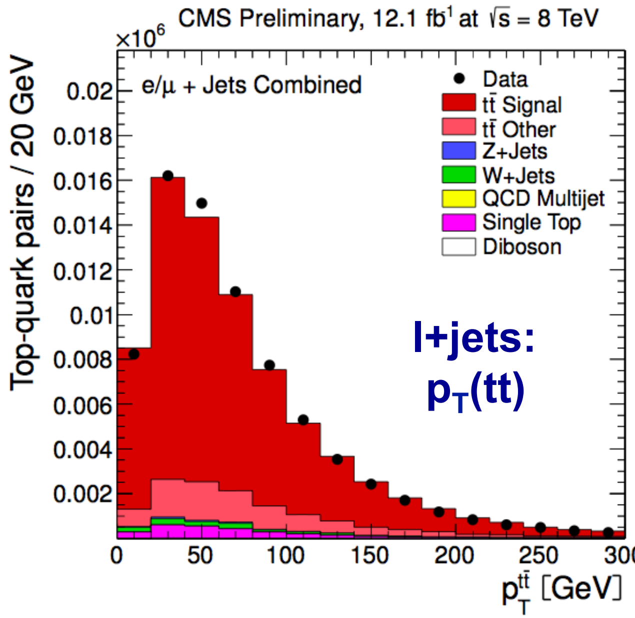
- Reference $t\bar{t}$ prediction:

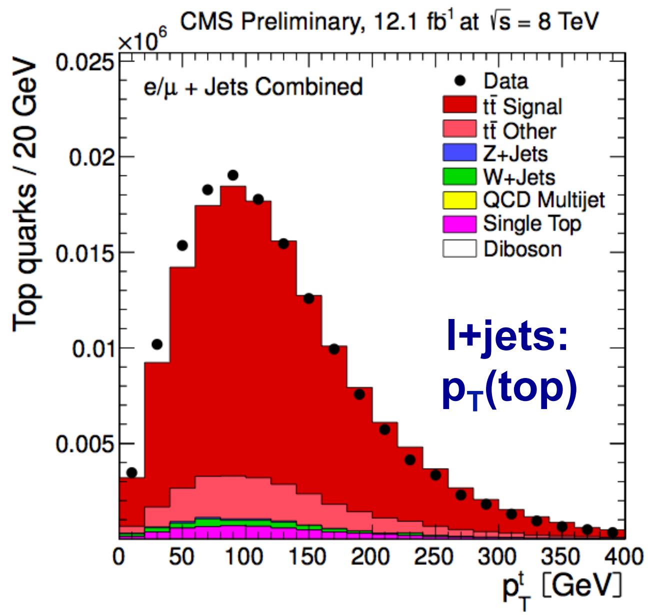
  MadGraph+Pythia





Top p_T spectrum tends to lower p_T values in data than in simulation





CMS-PAS TOP-12-027

Kinematic distributions – dileptons (8 TeV, 12 fb^{-1})

- Pure $t\bar{t}$ samples after event selection:

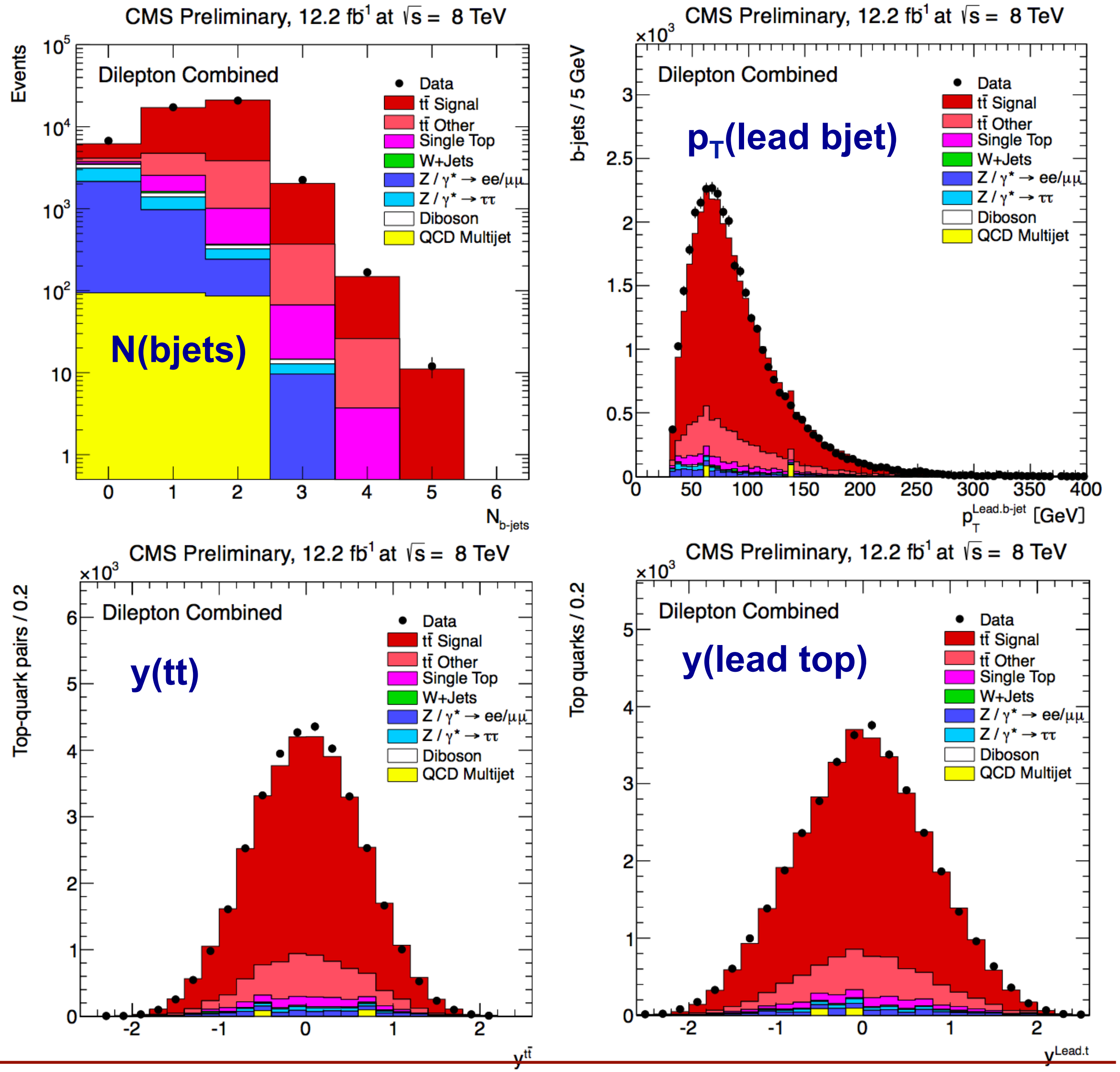
  ~ 80% $t\bar{t}$

- Main backgrounds:

  $t\bar{t}$(other), single top, Z+jets

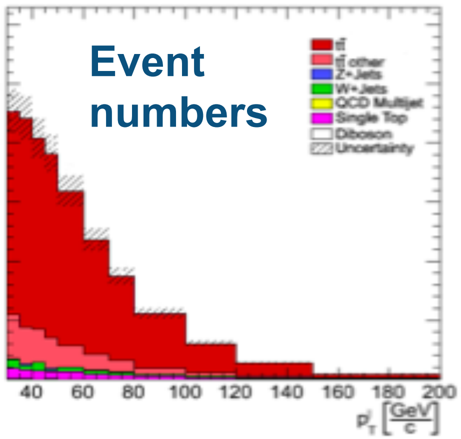
- Reference $t\bar{t}$ prediction:

  MadGraph+Pythia

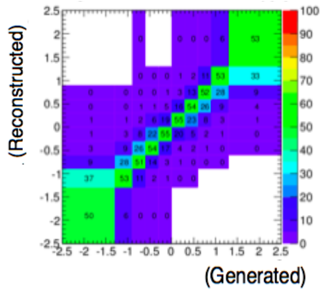


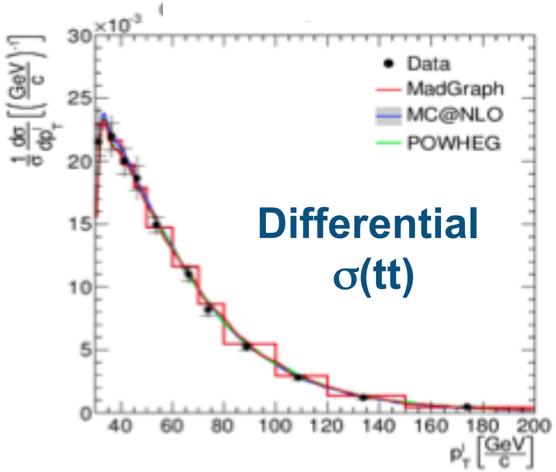
CMS-PAS TOP-12-028

Unfolding: correcting for detector effects & acceptances



Response matrix A_{ij}





$$\frac{d\sigma}{dX_i} = \frac{\sum_j \mathrm{A}_{\mathrm{ij}}^{-1} \left[(N_{\mathrm{data,j}} - N_{\mathrm{BG,j}}) \right]}{\Delta_{X_i} \cdot L}$$

Binning

Chosen to limit migration effects, quantify with:

- CMS: purity (p^i) & stability (s^i): ≥ 0.4

$$p^i = \frac{N^i_{rec\&gen}}{N^i_{rec}} \qquad s^i = \frac{N^i_{rec\&gen}}{N^i_{gen}}$$

- ATLAS: experimental resolution, optimised to minimise uncertainty on final result

Regularisation

- Basic unfolding: simple inversion of response matrix A_{ij}:

$$\mathrm{N}_{i,\mathrm{unf}} = A^{-1}_{ij} \mathrm{N}_{j,\mathrm{meas}}$$

- Regularisation used to remove large statistical fluctuations (SVD)

Phase space (PS)

Correct back to **parton** or **particle** level in **full** or **visible** phase space (variable dependent)

CMS: also visible PS

All top and tt̄ quantities are corrected to parton level after QCD radiation, in full PS

ATLAS & CMS use different criteria to choose the regularisation parameter

More info: 1/σ dσ/dX @ ATLAS – values (7 TeV)

- Systematics determined individually for each bin of the measurement
- Normalized cross sections: only shape uncertainties contribute, correlated uncertainties cancel
- Main systematics: JES , signal generator, btagging, ISR/FSR for p_T(tt)

p_T^t [GeV]	$\frac{1}{\sigma}\frac{d\sigma}{dp_T^t}$ $[10^{-3}]$	stat. [%]	syst. [%]
0 to 50	3.4±0.1	± 2	± 4
50 to 100	6.7±0.1	± 1	± 1
100 to 150	5.2±0.1	± 2	± 2
150 to 200	2.66±0.08	± 2	± 3
200 to 250	1.14±0.04	± 2	± 3
250 to 350	0.33±0.02	± 3	± 5
350 to 800	0.018±0.002	± 6	± 10

$m_{t\bar{t}}$ [GeV]	$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$ $[10^{-3}]$	stat. [%]	syst. [%]
250 to 450	2.50±0.08	± 1	± 3
450 to 550	2.73±0.07	± 1	± 2
550 to 700	1.02±0.04	± 2	± 4
700 to 950	0.23±0.01	± 3	± 4
950 to 2700	0.0076±0.0005	± 4	± 5

$p_T^{t\bar{t}}$ [GeV]	$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{t\bar{t}}}$ $[10^{-3}]$	stat. [%]	syst. [%]
0 to 40	14±2	± 3	± 10
40 to 170	3.1±0.4	± 2	± 10
170 to 340	0.25±0.06	± 4	± 20
340 to 1000	0.010±0.003	± 8	± 30

$y_{t\bar{t}}$	$\frac{1}{\sigma}\frac{d\sigma}{dy_{t\bar{t}}}$ $[10^{-3}]$	stat. [%]	syst. [%]
-2.5 to -1.0	81±3	± 2	± 3
-1.0 to -0.5	321±9	± 1	± 3
-0.5 to 0.0	436±9	± 1	± 2
0.0 to 0.5	423±7	± 1	± 1
0.5 to 1.0	321±5	± 1	± 1
1.0 to 2.5	87±5	± 3	± 4

More info: 1/σ dσ/dX @ CMS – values (7 TeV)

p_T^t bin [GeV]	$1/\sigma\, d\sigma/dp_T^t$	stat. [%]	sys. [%]	total [%]
0 to 60	$4.54 \cdot 10^{-3}$	2.5	3.6	4.4
60 to 100	$6.66 \cdot 10^{-3}$	2.4	4.9	5.5
100 to 150	$4.74 \cdot 10^{-3}$	2.4	3.2	4.0
150 to 200	$2.50 \cdot 10^{-3}$	2.6	5.1	5.8
200 to 260	$1.04 \cdot 10^{-3}$	2.9	5.5	6.2
260 to 320	$0.38 \cdot 10^{-3}$	3.7	8.2	9.0
320 to 400	$0.12 \cdot 10^{-3}$	5.8	9.5	11.1

$p_T^{t\bar{t}}$ bin [GeV]	$1/\sigma\, d\sigma/dp_T^{t\bar{t}}$	stat. [%]	sys. [%]	total [%]
0 to 20	$1.50 \cdot 10^{-2}$	4.1	11.8	12.5
20 to 45	$1.21 \cdot 10^{-2}$	3.5	7.0	7.8
45 to 75	$0.58 \cdot 10^{-2}$	3.8	9.2	10.0
75 to 120	$0.26 \cdot 10^{-2}$	4.3	14.0	14.6
120 to 190	$0.10 \cdot 10^{-2}$	4.5	7.8	8.9
190 to 300	$0.02 \cdot 10^{-2}$	6.3	18.0	19.1

$m^{t\bar{t}}$ bin [GeV]	$1/\sigma\, d\sigma/dm^{t\bar{t}}$	stat. [%]	sys. [%]	total [%]
0 to 345	-	-	-	-
345 to 400	$4.81 \cdot 10^{-3}$	5.2	9.7	11.1
400 to 470	$4.60 \cdot 10^{-3}$	5.0	8.4	9.8
470 to 550	$2.46 \cdot 10^{-3}$	5.2	10.2	11.4
550 to 650	$1.14 \cdot 10^{-3}$	5.6	10.6	12.0
650 to 800	$0.43 \cdot 10^{-3}$	6.2	8.3	10.3
800 to 1100	$0.99 \cdot 10^{-4}$	7.1	20.0	21.2
1100 to 1600	$0.14 \cdot 10^{-4}$	13.5	19.4	23.7

$y^{t\bar{t}}$ bin	$1/\sigma\, d\sigma/dy^{t\bar{t}}$	stat. [%]	sys. [%]	total [%]
−2.5 to −1.3	$0.55 \cdot 10^{-1}$	6.4	10.8	12.5
−1.3 to −0.9	$2.17 \cdot 10^{-1}$	3.4	5.8	6.7
−0.9 to −0.6	$3.12 \cdot 10^{-1}$	3.6	4.4	5.7
−0.6 to −0.3	$4.00 \cdot 10^{-1}$	3.1	3.3	4.5
−0.3 to 0.0	$4.35 \cdot 10^{-1}$	3.1	4.1	5.1
0.0 to 0.3	$4.69 \cdot 10^{-1}$	2.8	3.8	4.8
0.3 to 0.6	$3.94 \cdot 10^{-1}$	3.1	5.9	6.7
0.6 to 0.9	$3.17 \cdot 10^{-1}$	3.4	4.7	5.8
0.9 to 1.3	$2.22 \cdot 10^{-1}$	3.3	5.8	6.6
1.3 to 2.5	$0.50 \cdot 10^{-1}$	6.8	9.7	11.9

More info: $1/\sigma\ d\sigma/dX$ @ CMS – syst (7 TeV)

- Determined individually for each bin of the measurement
- Normalized cross sections: only shape uncertainties contribute, correlated uncertainties cancel

Typical values per bin at 7 TeV

	Source	Method	Systematic uncertainty (%)	
			ℓ+jets	dileptons
Experimental	Background	vary with 30%-50%	3.5	0.5
	Trigger eff.	p_T-η dependent	0.5	1.5
	Lepton sel.	p_T-η dependent	0.5	2.0
	Jet energy scale	p_T-η dependent	1.0	0.5
	Jet energy resolution	p_T-η dependent	0.5	0.5
	Pileup	vary $\sigma_{\text{inel.}}(\text{pp}) \pm 8\%$	0.5	0.5
	b tagging	p_T-η dependent	1.0	0.5
	Kinematic reco	p_T-η dependent	–	0.5
Model	Q^2	vary factor 0.25–4	2.0	1.0
	ME/PS threshold	vary factor 0.5–2	2.0	1.0
	Hadronisation	PYTHIA vs. HERWIG	2.0	2.0
	Top-quark mass	172.5 ± 0.9	0.5	0.5
	PDF choice	PDF4LHC	1.5	1.0

More info: 1/σ dσ/dX @ CMS – phase space

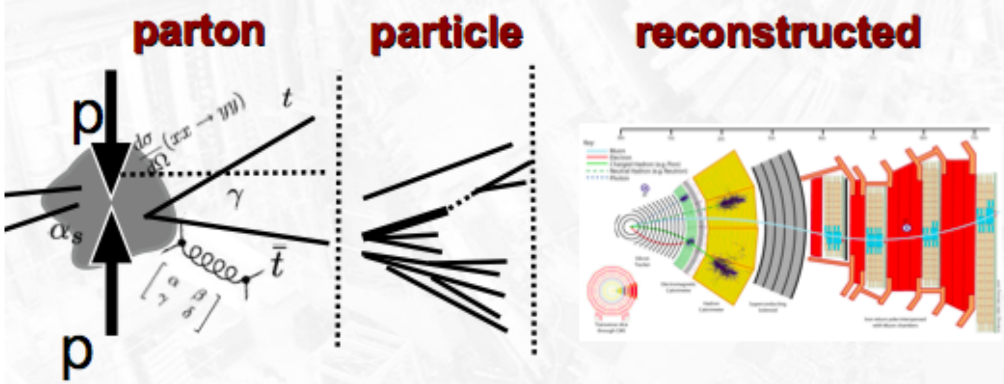
reconstructed quantities:
top quarks, $t\bar{t}$ system

→ extrapolated parton level PS

correct for

detector effects
hadronization effects
extrapolate to full PS

→ as close to theory as possible



directly measurable quantities:
lepton(s), b-jets

→ visible particle level PS

correct for

detector effects
no hadronization correction
visible PS, no extrapolation:

$p_T^{jets} > 30$ GeV, $\eta^{jets} < 2.4$,
$p_T^{lep} > 20$ (30) GeV, $\eta^{lep} < 2.4$ (2.1)
for dilepton (lepton+Jets) PS

→ object definition on generator level:

- particles after radiation & hadronization
- jets: same jet algorithm
- b-Jets: identified by B-hadron
- leptons: from W, ΔR(lep,genJet)>0.4

→ as model independent as possible

More info: 1/σ dσ/dX @ CMS – unfolding

response Matrix (from MC): $A_{ij} := \frac{N_{rec}^{j \to i}}{N_{gen}^{j}}$ ~ transition probability from generator bin j to reconstructed bin i, includes efficiency and acceptance

the corrected and **unfolded event yield** x^j is obtained **from** BG corrected event yield in **data** N^i_{Sig}

$$\sum_j A_{ij} x^j = N^i_{Sig}$$

this is equivalent to solve the following **χ^2 problem**:

$$\chi^2_A(\vec{x}) := \left(A\vec{x} - \vec{N}_{Sig}\right)^T COV_{\vec{N}_{Sig}} \left(A\vec{x} - \vec{N}_{Sig}\right)$$ (COV: covariance matrix)

regularization is needed to give (non-oszillating) stable results
→ add penalty term

$$\chi^2(\vec{x}) := \chi^2_A(\vec{x}) + \tau^2 \cdot \chi^2_L(\vec{x}) \qquad \chi^2_L(\vec{x}) := \sum_{ij} \frac{x^i}{N^i_{gen}} L^2_{ij} \frac{x^j}{N^j_{gen}}$$

$$L^2 \equiv (L^2_{ij}) := \begin{pmatrix} 1 & -1 & & & \\ -1 & 2 & -1 & & \\ & \ddots & \ddots & \ddots & \\ & & -1 & 2 & -1 \\ & & & -1 & 1 \end{pmatrix}$$

(curvature matrix)

too few regularization: large negative correlations (oszillating results)
too much regularization: large positive correlations (bias)

→ choose **unfolding parameter τ** such that average squared global correlation $\bar{\rho}$ is minimal:

$$\bar{\rho}(\tau) := \frac{1}{n}\sqrt{\sum_i \rho_i(\tau)^2} \qquad \rho_i := \max_{(\alpha_1,\ldots,\alpha_n)} \rho\left(x^i, \sum_{j \neq i} \alpha_j x^j\right)$$