Latest results on differential cross sections at the LHC and Tevatron

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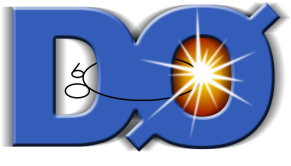
for the ATLAS, CDF, CMS, D0 collaborations

Talk prepared with the help of F. Spanò (RHUL)

7th International Workshop on Top Quark Physics,
Sept. 29-Oct. 3, 2014,
Cannes (France)

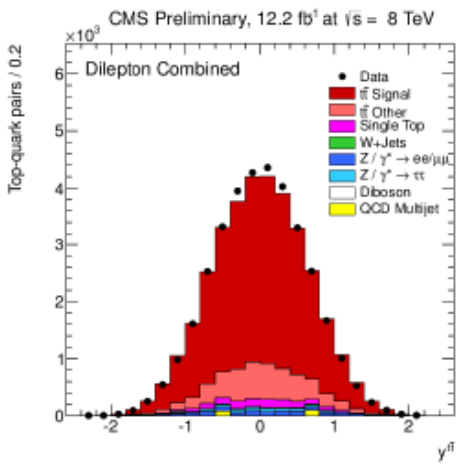


Introduction

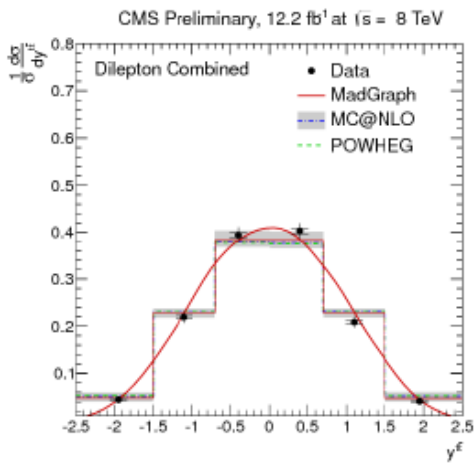
- Why differentially?
  - Scrutinise theory, predictions & models
  - Enhance sensitivity to new physics
  - Extract/use for PDF fits
  - Background for Higgs, rare processes and many BSM searches

  Cross section measurements presented:

- **Top quark pairs (l+jets, dilepton channel)** at Tevatron and LHC
  - ◇ Focus on what we learnt since last year (tension and agreements between ATLAS/CMS)
  - ◇ Exploring wider kinematic ranges (boosted tops)
- **First single top quark differential measurements (t-channel)** in ATLAS and CMS



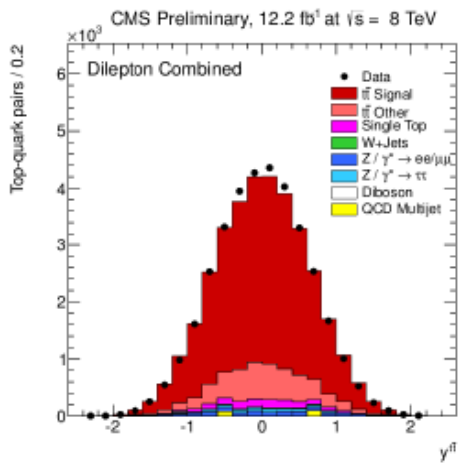
$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\mathrm{Data}} - N^i_{\mathrm{BG}}}{\Delta^i_X \epsilon^i L}$$



General analysis strategy

1. Event selection
2. Top quark kinematic reconstruction
3. Bin-wise cross section measurement:
   - ◇ Subtract background
   - ◇ Unfolding: correct for detector effects & acceptance to particle or parton level in full or visible phase space
     - Regularisation used to remove large statistical fluctuations
     - Δ_X - bin width: chosen to limit migration effects (in terms of stability and purity, resolution and statistical errors in data)
4. Compare diff. cross section to theory predictions/calculations: Absolute or normalised to in-situ measured σ extrapolated to full or in the visible phase space (minimise dependence on theory input)

   σ vs several kinematic distributions of top quark, $t\bar{t}$, (b)-jets, leptons, lepton pairs, etc.



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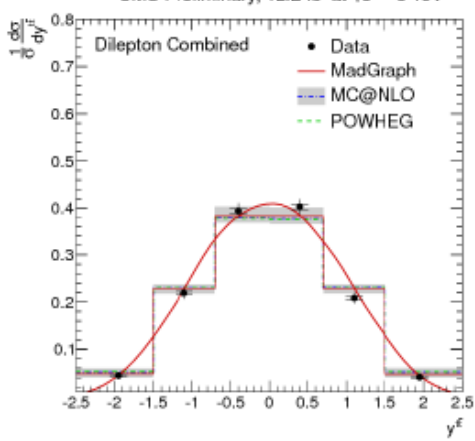
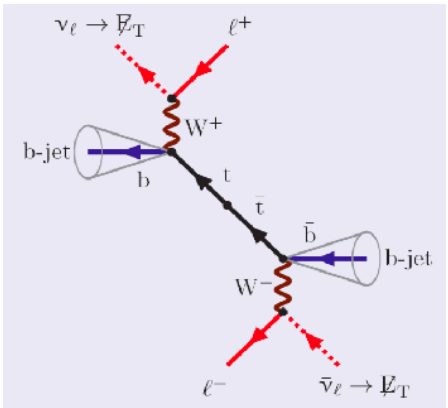


$t\bar{t}$ production cross sections

- $t\bar{t}$ lepton+jets channel
  - CDF: PRL 102 222003 (2009)
  - D0: arXiv:1401.5785 NEW!
  - ATLAS: arXiv:1407.0371 (7 TeV), accepted by PRD NEW!, ATLAS-CONF-2014-059 (7 TeV) NEW! ATLAS-CONF-2014-057 (8TeV) NEW!
  - CMS: EPJ C73 (2013) 2339 (7 TeV), CMS-PAS-TOP-12-027 (8 TeV)
- $t\bar{t}$ dilepton channel
  - CMS: EPJ C73 (2013) 2339 (7 TeV), CMS-PAS-TOP-12-028 (8 TeV)

$t\bar{t}$: Typical event selection

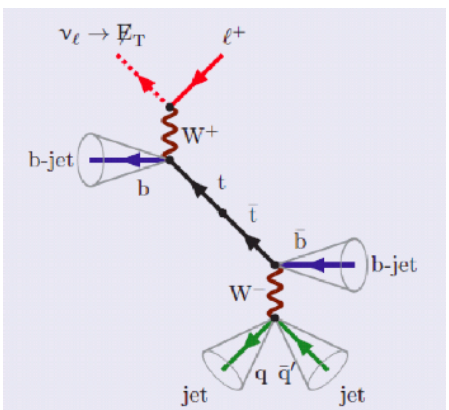
Dilepton



1. At least two isolated leptons ($p_T > 20$ GeV, $|\eta| < 2.4$), opposite sign
2. $\geq$2 jets (anti-k_T, R<0.5) with $p_T > 30$ GeV, $|\eta| < 2.4$
3. Additional QCD and Z veto (in ee, $\mu\mu$)
4. At least one b-tagged jet

Lepton+jets

1. One isolated lepton ($p_T >$ 20-30 GeV, μ: $|\eta| <$2.0-2.5)
2. $\geq$4 jets (anti-k_T, R=0.5/0.4) with $p_T >$ 25-35 GeV, $|\eta| <$2.0-2.5
3. Veto additional leptons
4. $\geq$1/2 b-tagged jets
5. E_T^{miss} >20-35 GeV, $M_{W,T}$ >35 GeV, leading jet



+ Kinematic reconstruction of top quarks (back up)

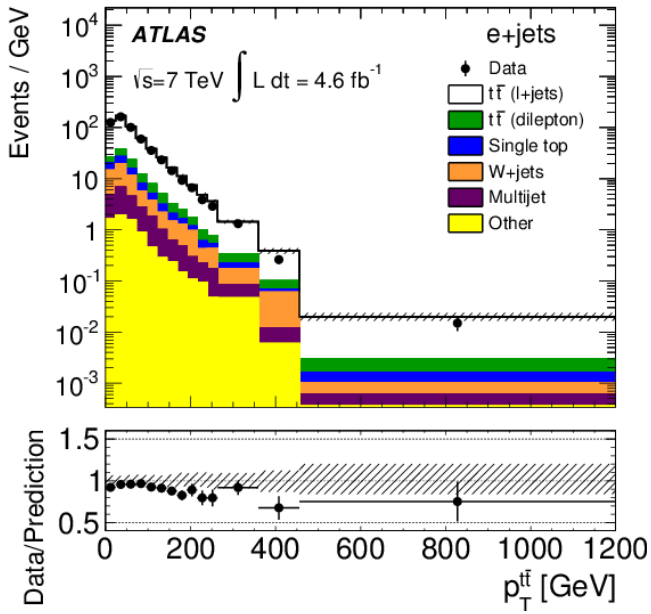
Kinematic distributions (ATLAS/CMS/D0)

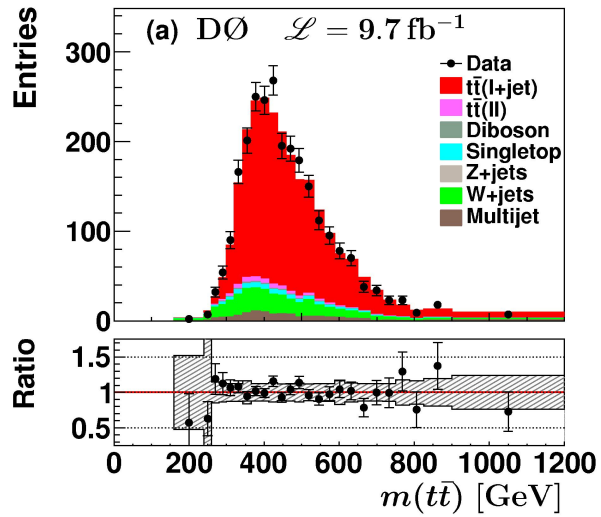
- Pure $t\bar{t}$ sample ($\sim$80%)
- Main backgrounds:
  - ◇ l+jets: W+jets, other $t\bar{t}$, single top
  - ◇ dilepton: other $t\bar{t}$, single top, Z+jets
- Reference MC

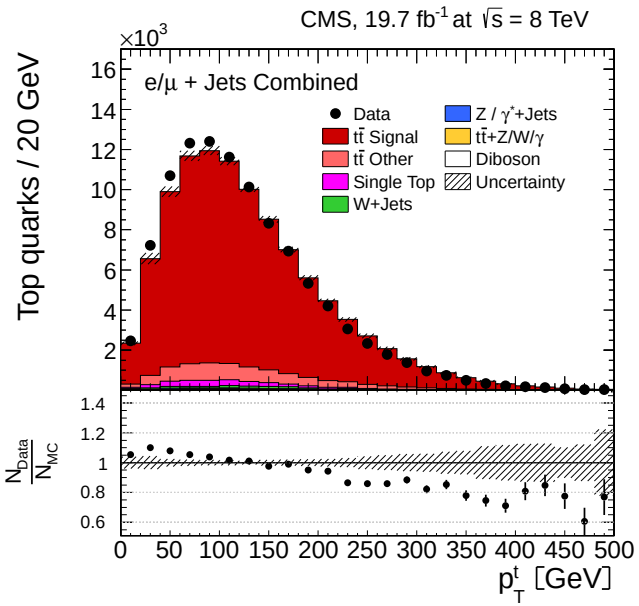
  ATLAS: Alpgen+Herwig

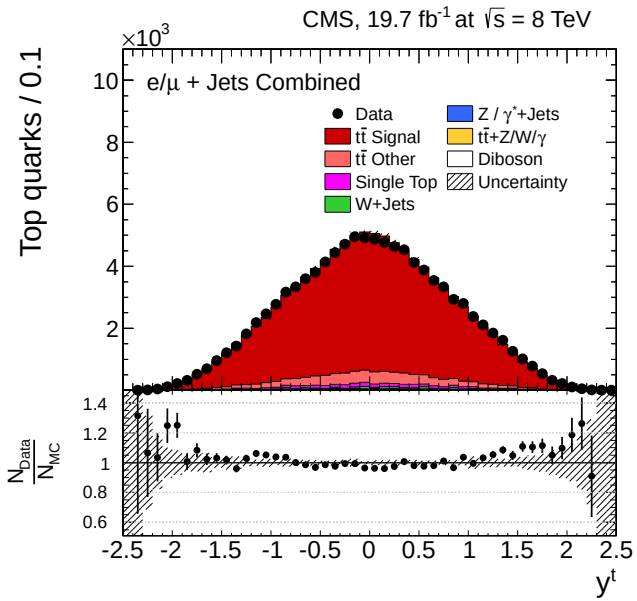
  CMS: MadGraph+Pythia

  D0: MC@NLO+Herwig







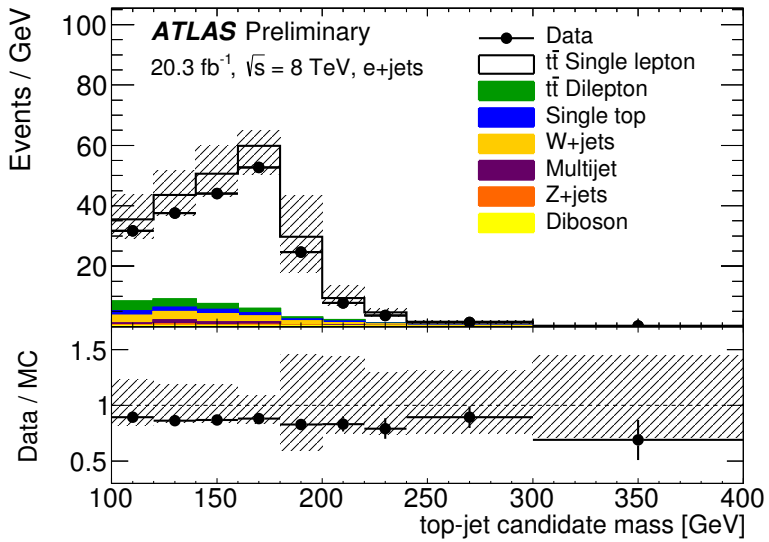


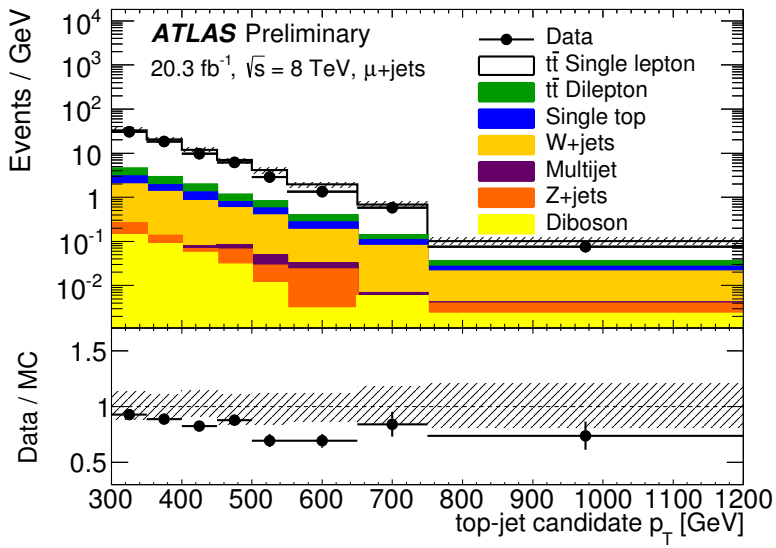
Kinematic distributions: boosted tops (ATLAS NEW!)

Lepton+jets: boosted tops

1. Lepton: p_T-dependent isolation, close to a R(=0.4) jet $\Delta R(l, \text{jet}_{R=0.4}) < 1.5$
2. Top jet candidate reconstructed using leading anti-k_T, R=1 jet, with $p_T > 300$ GeV, applying jet substructure cuts
3. Leptonic and hadronic candidates in opposite hemispheres
4. $\geq$1 b-tagged top candidate
5. E_T^{miss}, $M_{W,T}+E_T^{miss}$

- Reference MC: Powheg+Pythia
- Prediction overestimates data, shape well described
- $p_T >$ spectrum softer in data (up to approx. 50% highest bin)

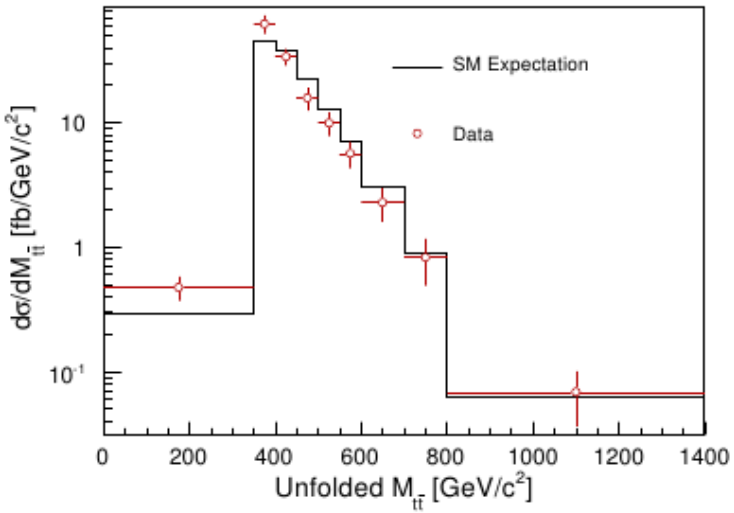


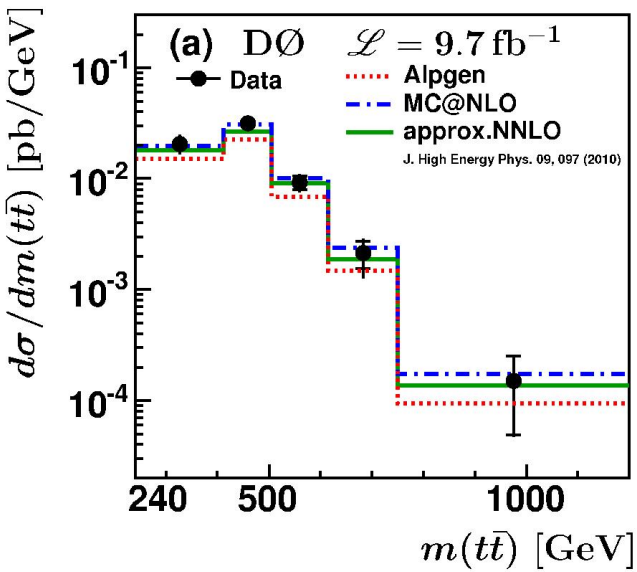


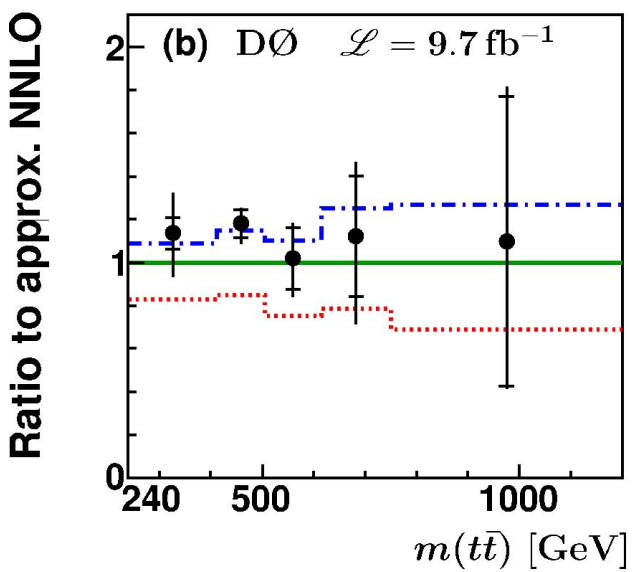
Results at Tevatron: $m_{t\bar{t}}$

CDF (2.7 fb^{-1}), D0 (9.7 fb^{-1})

- **Absolute differential cross section**
- General good agreement between data and predictions for both CDF & D0
- D0: ALPGEN+Pythia gives lower normalisation



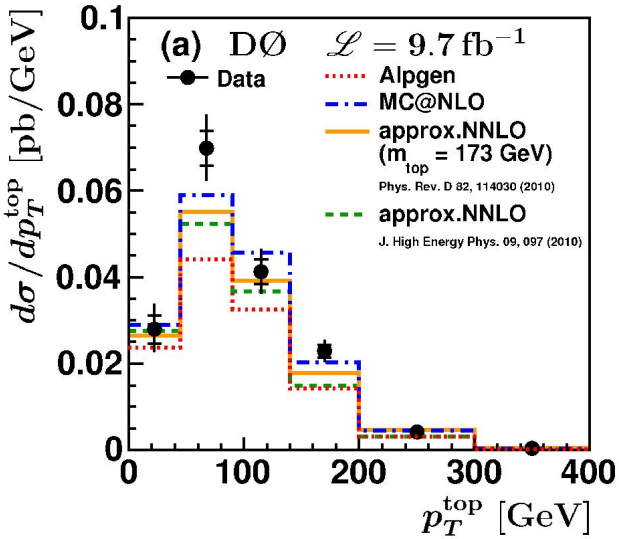


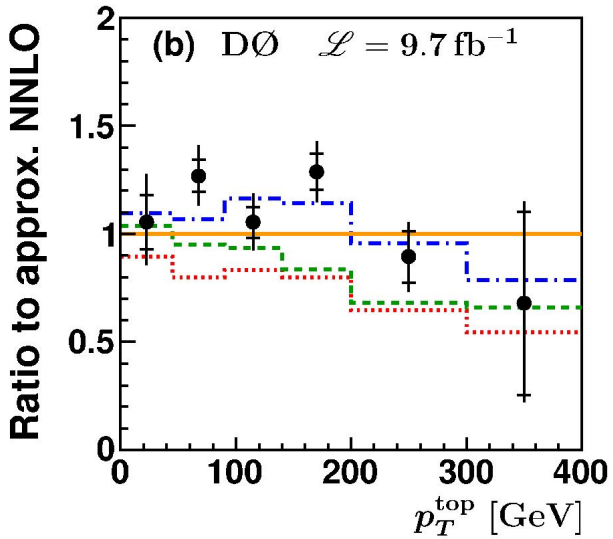


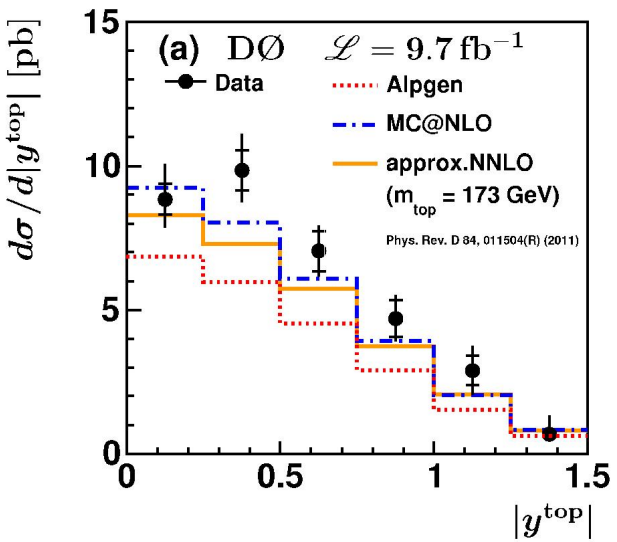
$|y_T^t|$ and p_T^t (D0)

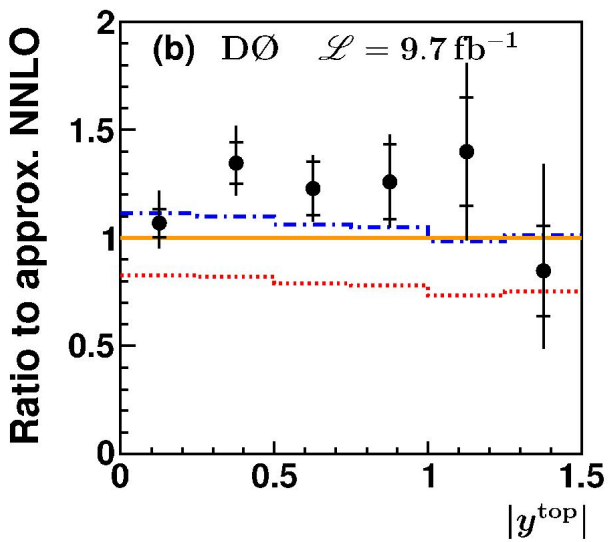
Absolute differential cross sections

- General good description
- ALPGEN+Pythia gives lower normalisation
- MC@NLO+Herwig and both approx. NNLO calculations describe data better



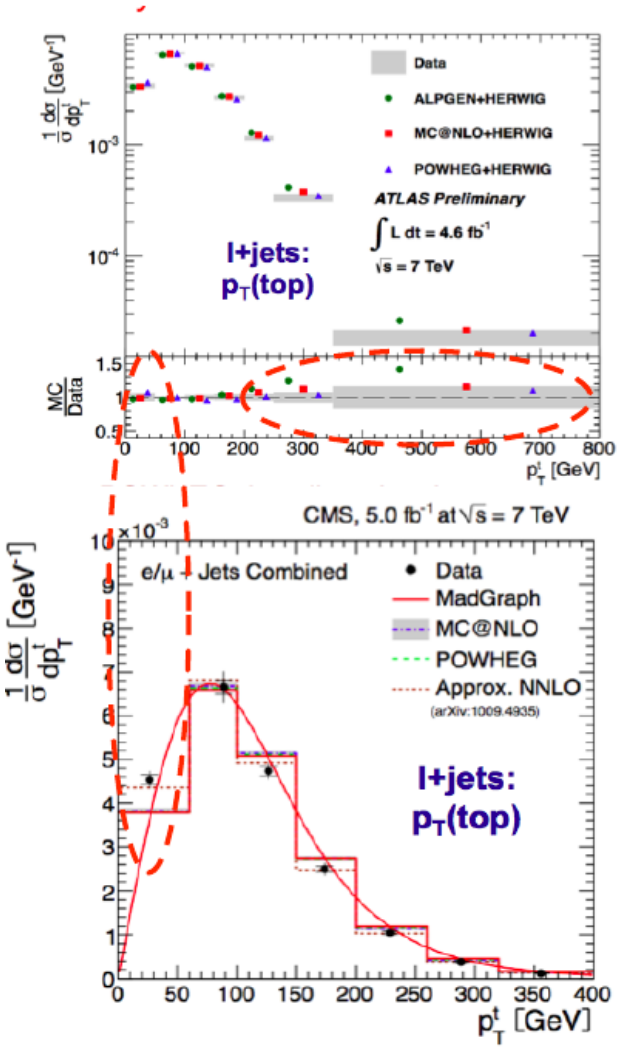




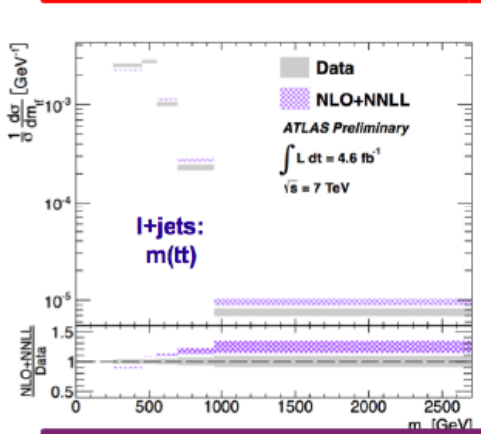


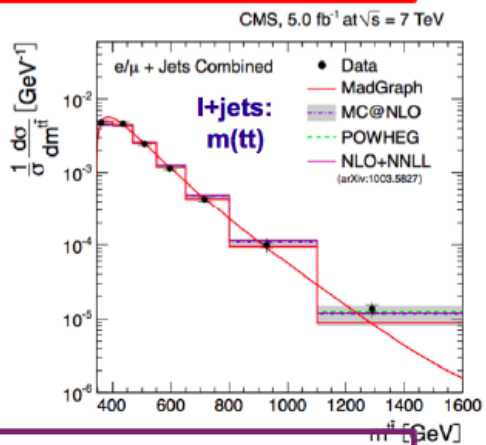
Results at the LHC: From TOP2013 to TOP2014

A. Juste (Summary talk TOP2013)



- Top p_T: in general softer spectrum in data than predicted by MCs.
- Some tension between ATLAS and CMS in the first bin affects conclusion on agreement with NLO+NNLL prediction.
- Partonic level defined in the same way? Non-perturbative corrections missing?





- m_{tt}: very sensitive to PDFs but also to NP. Beware of EW effects not accounted for!
- Somewhat contradictory conclusions by ATLAS and CMS regarding agreement with NLO+NNLL.

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Comparison ATLAS-CMS (7 TeV in same binning): see here (CERN-THESIS-2014-110)

Progress in comparison between ATLAS & CMS

7 TeV results, l+jets

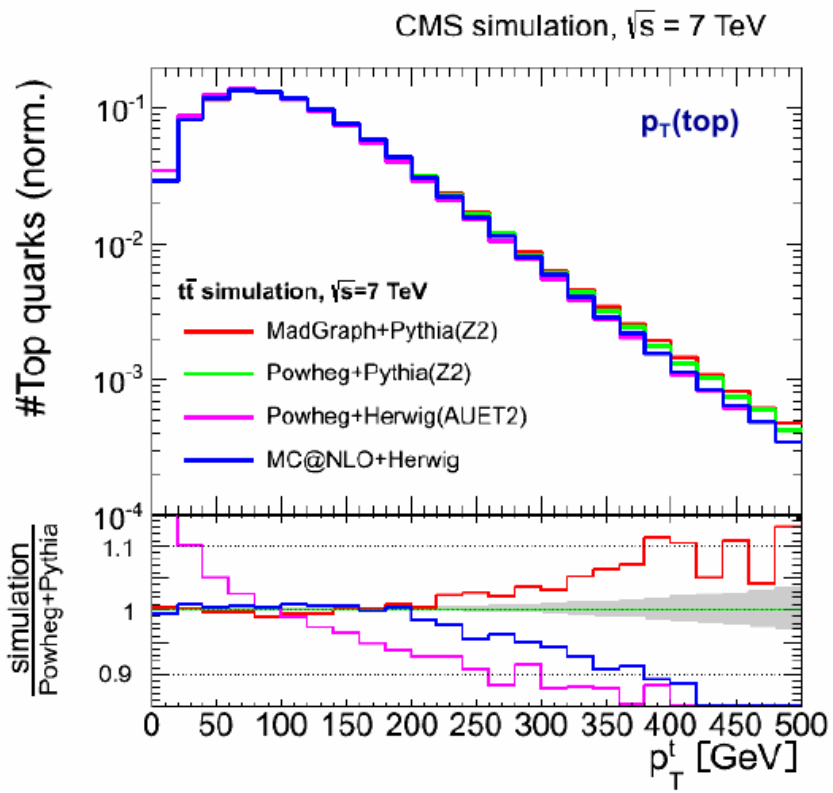
- ATLAS and CMS have consistent definition of the top quark
- Compatible behaviour in corresponding sample pairs: same differences between generator and parton shower schemes

Monte Carlo simulations

- Generators:
  - ◇ ME at tree level (Alpgen, MadGraph)
  - ◇ NLO (POWHEG, MC@NLO)
- Showering:
  - ◇ Pythia (transverse-momentum-ordered evolution scale)
  - ◇ HERWIG (angular-ordered)

- Powheg+Herwig provides reasonable description of the data for both experiments (different treatment of the hardest ISR than Pythia)

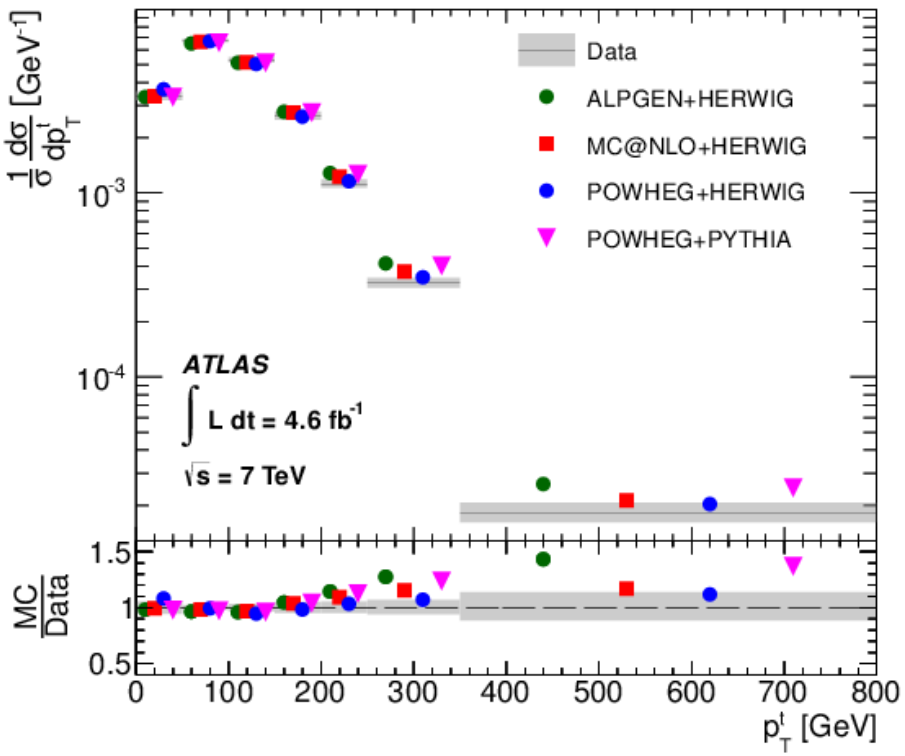
▪ Ratio wrt CMS Powheg+Pythia

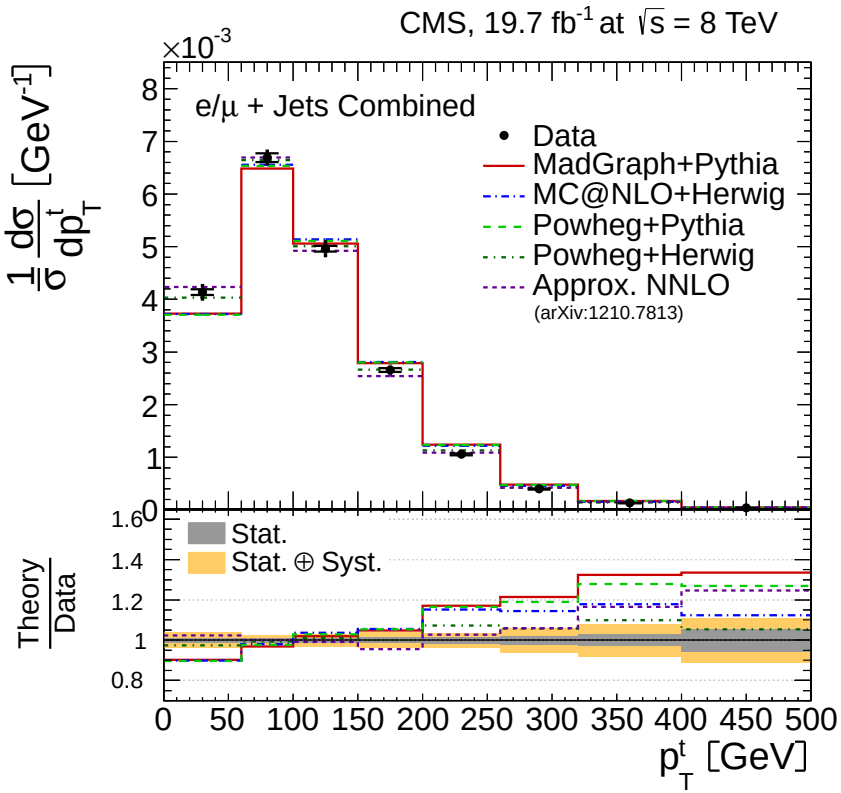


p_T^t, ATLAS (7 TeV), CMS (8 TeV)

Comparison to MC generators

- ATLAS: ALPGEN, POWHEG+Pythia are above data for $p_T > 200$ GeV
- ◇ CMS: MadGraph, MC@NLO, POWHEG+Pythia show similar behaviour. Consistent with dilepton channel and 7 TeV results
- CMS/ATLAS: POWHEG+Herwig describes data better

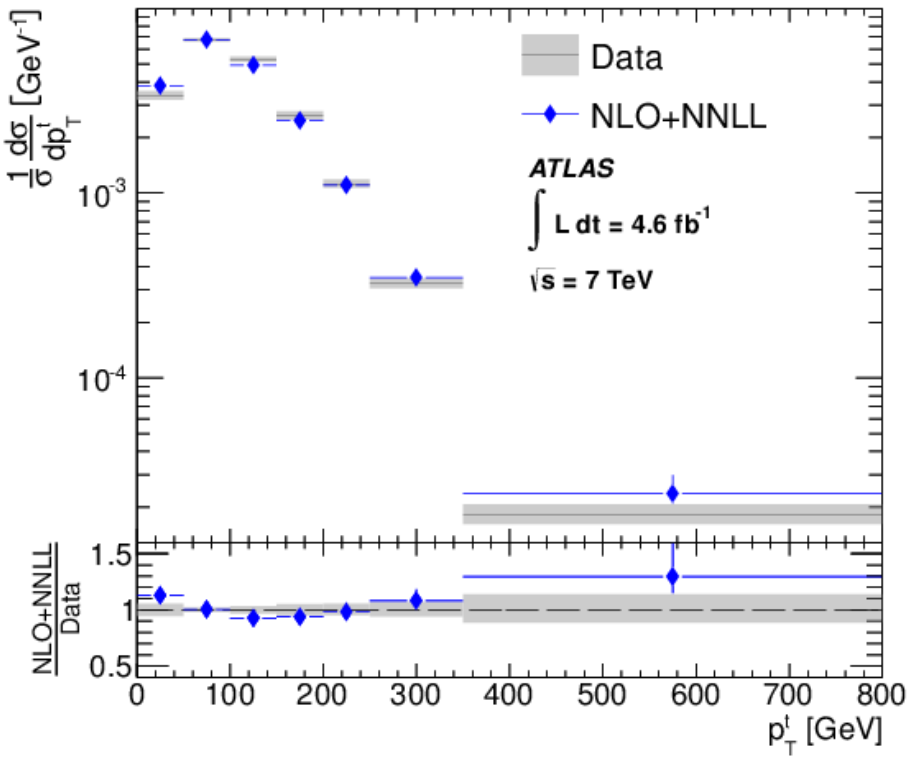


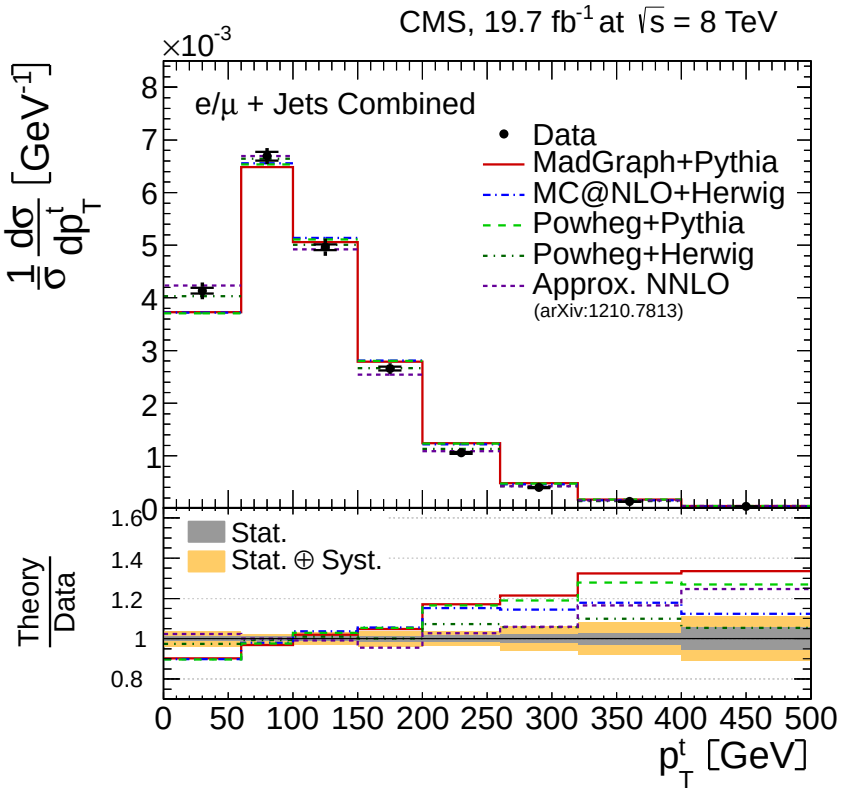


- Total uncertainties: ∼3%-∼15%

p_T^t, ATLAS (7 TeV), CMS (8 TeV)

Comparison with Approx. NNLO



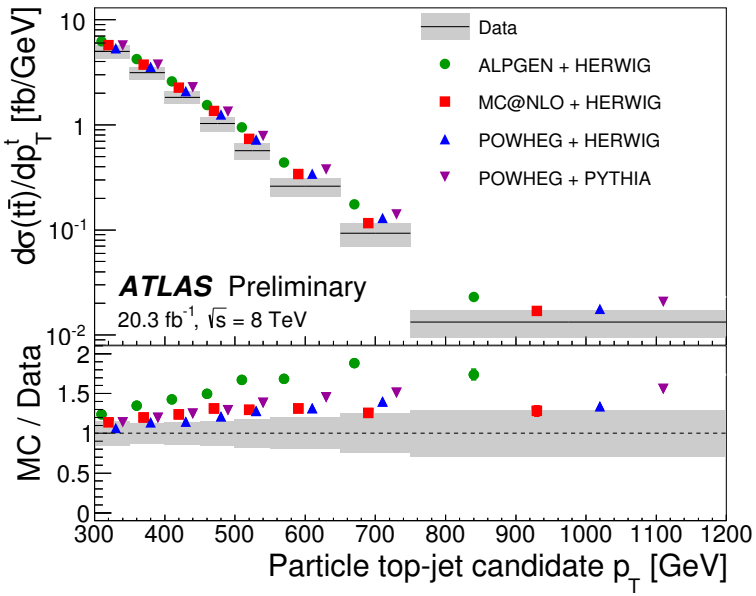


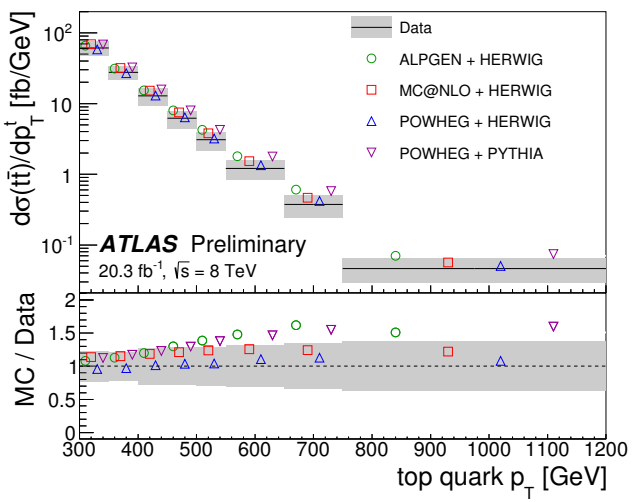
- CMS: Softer spectrum in data, better described by Approx. NNLO
- ATLAS: theory calculation is slightly above data for $p_T < 50$ GeV and $p_T > 200$ GeV

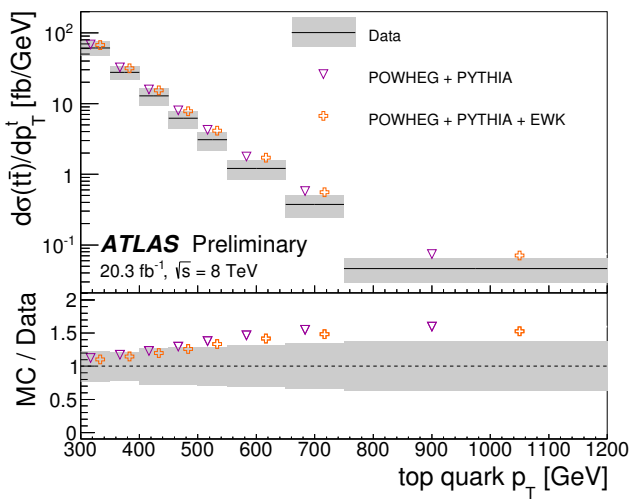
Boosted $t\bar{t}$: p_T^t (p_T^t >300 GeV)

ATLAS (8 TeV) NEW!

- **Fiducial particle level and full phase space parton level, up to the TeV scale**
- Data/MC agreement: better at parton-level than at particle-level for Powheg, MC@NLO, Alpgen+Herwig
- All generators: harder spectrum, increasing with p_T (discrepancy: 30% to 70%)
- Total uncertainties ∼15-30% (particle level), ∼20-40% (parton level)
- Result qualitatively consistent with 7 TeV
- EW corrections: softer spectrum, not significant improvement
- Also investigated modelling radiation in Powheg (back up)



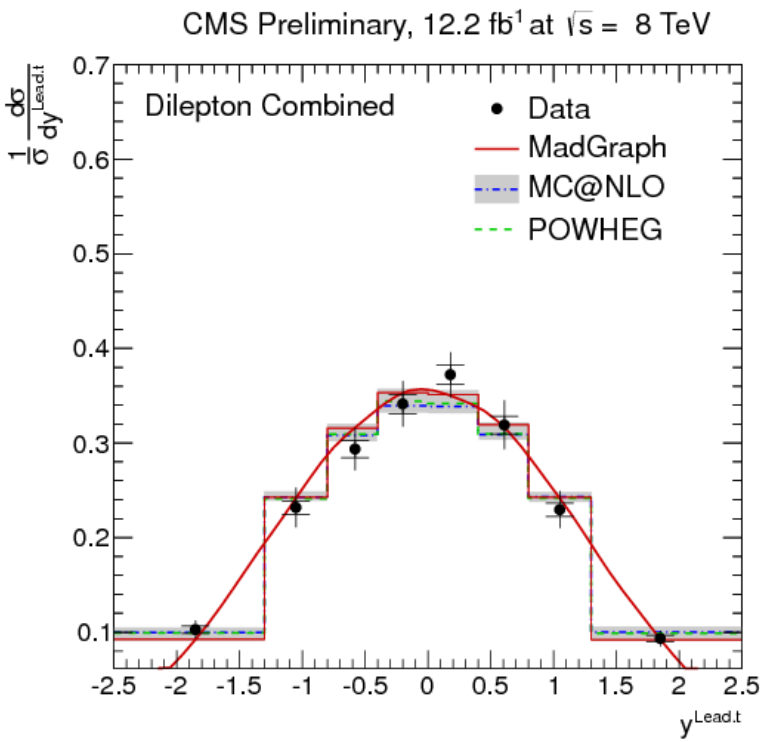


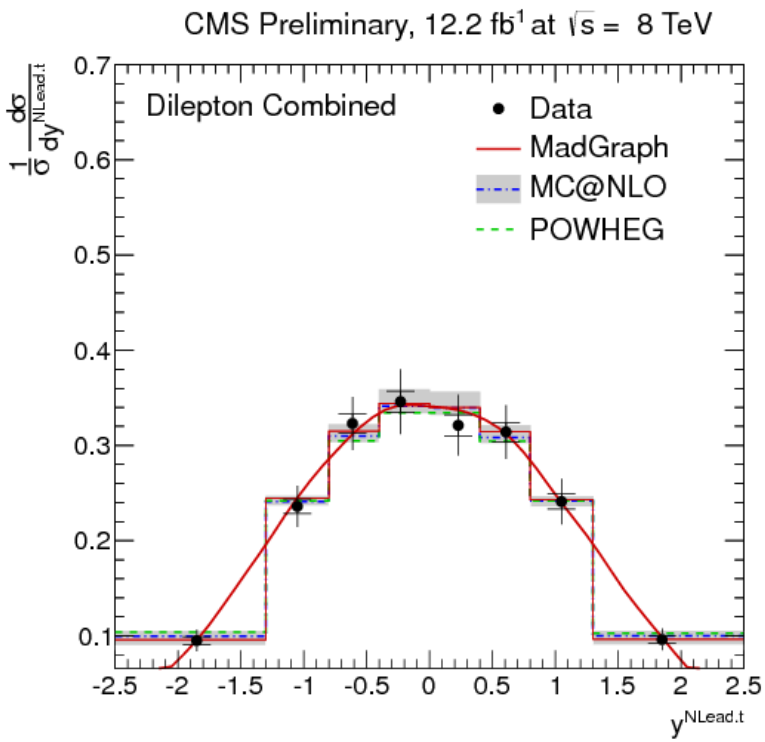


Top rapidity, y^t

CMS (8TeV)

- General good agreement between data and predictions, also with Approx. NNLO
- MadGraph+Pythia is slightly more central than data
- Compatible results in both channels and with 7 TeV results





- Typical precision: 2–6% depending on the bin

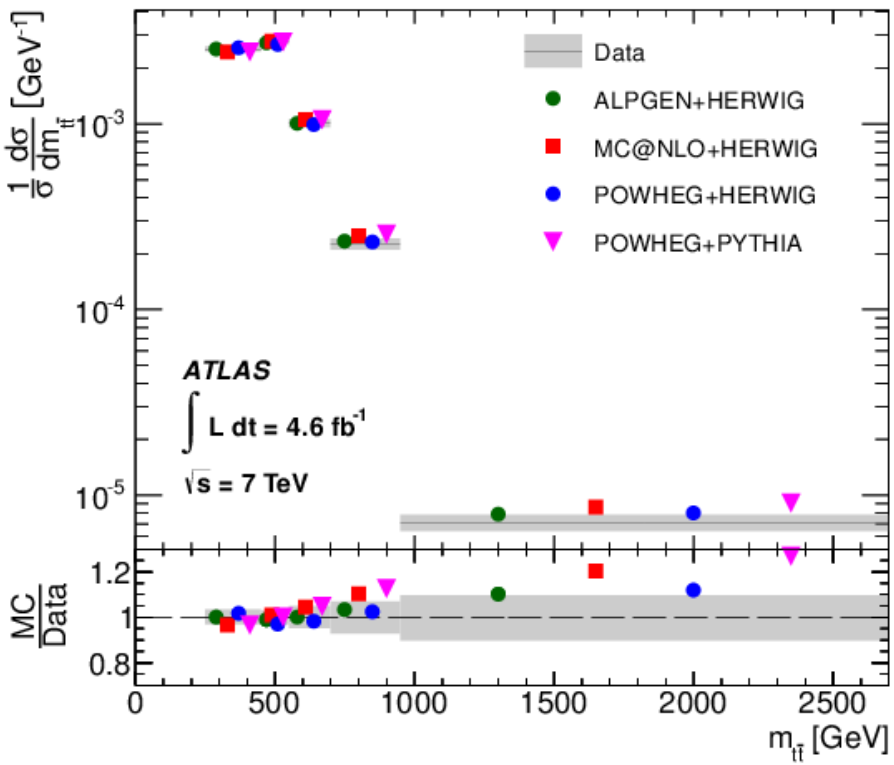
$m_{t\bar{t}}$

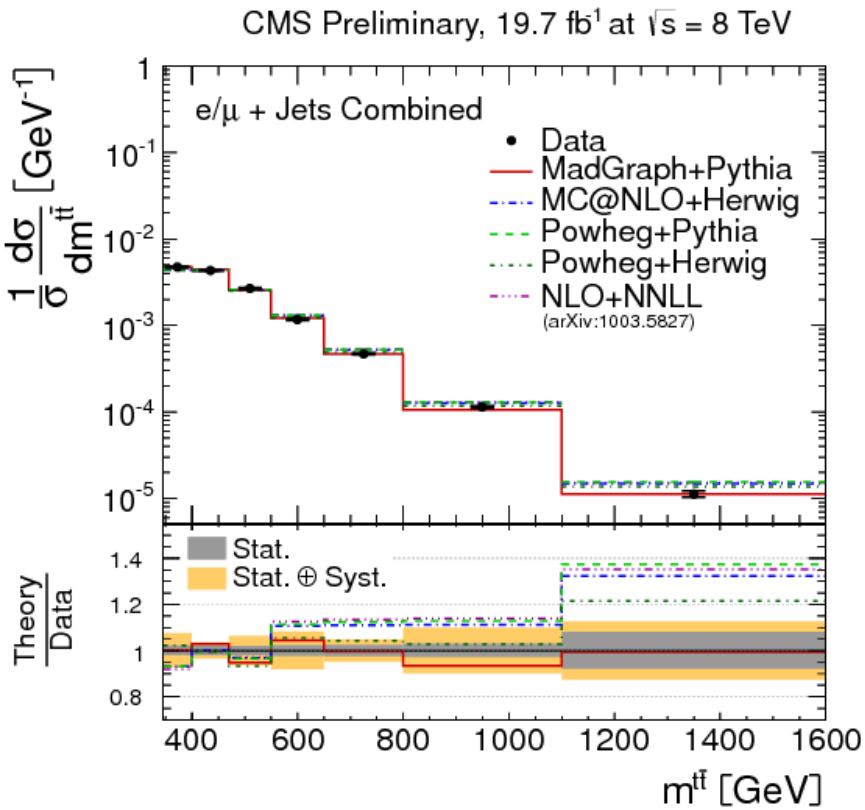
ATLAS (7 TeV), CMS (8 TeV)

- In general the predictions are softer than data for ATLAS and CMS

→ Best description: POWHEG+Herwig, MadGraph+Pythia (CMS)

- NLO+NNLL softer than data (ATLAS/CMS)



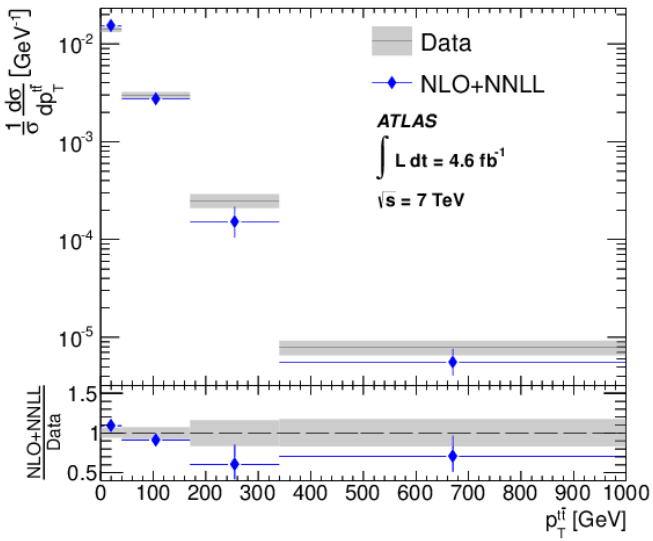


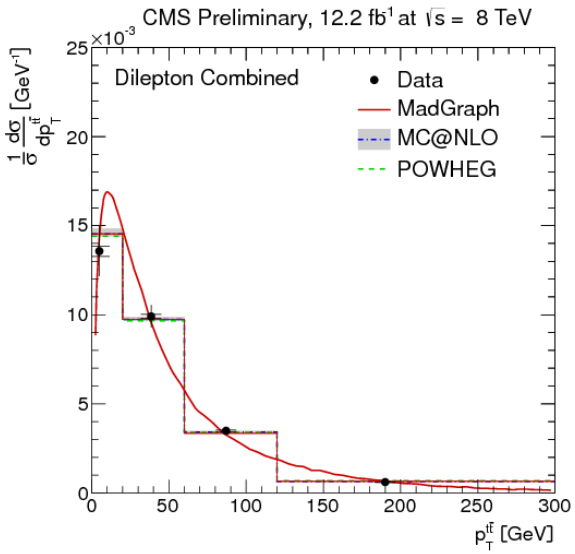
- Typical precision: 5–10% per bin
- ATLAS: comparison with MCFM + NLO PDF sets in back up

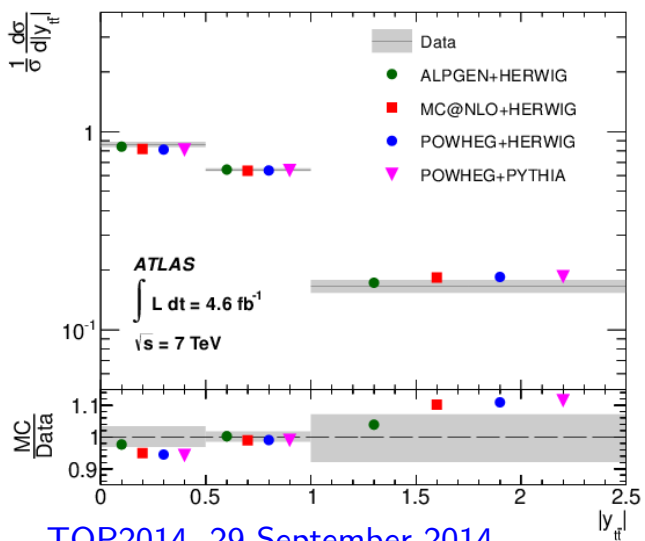
$p_T^{t\bar{t}}$ & $y^{t\bar{t}}$

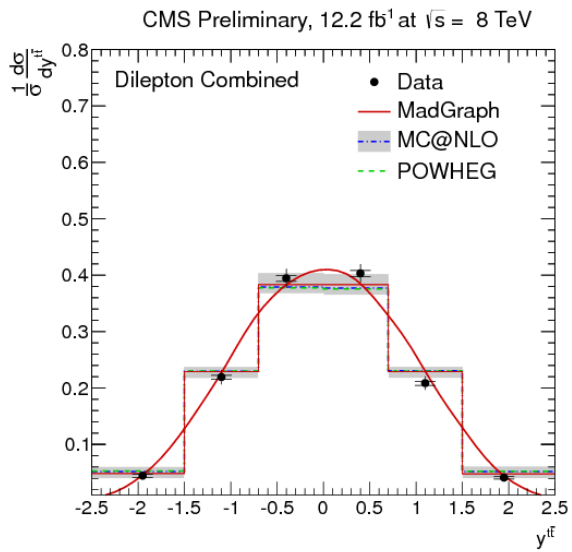
ATLAS (7 TeV), CMS (8 TeV)

- ATLAS: Alpgen/MC@NLO+Herwig best description
- CMS: MadGraph+Pythia, MC@NLO+Herwig better description of data
- NLO+NNLO calculation does not describe data well (ATLAS/CMS)
- Typical precision: 2-10% (y), 5-20% (p_T)





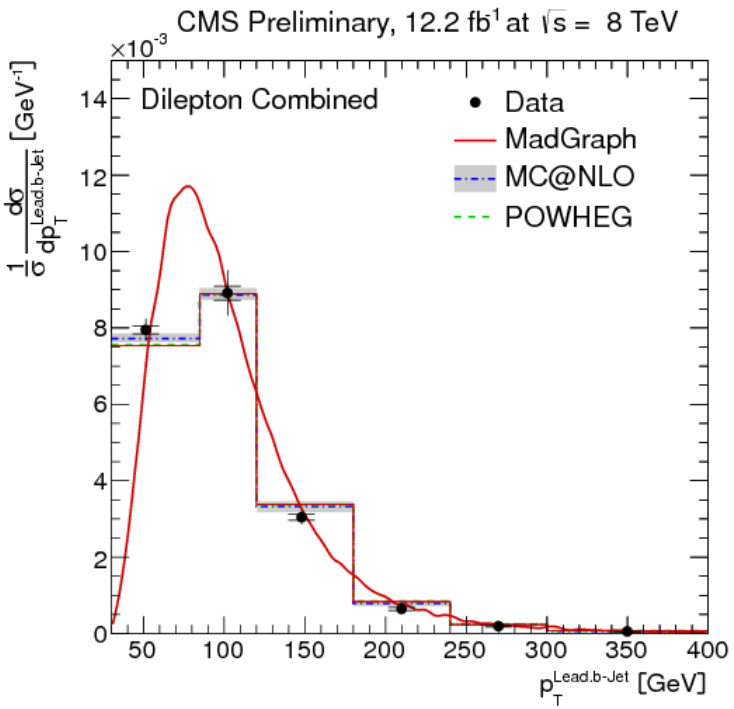


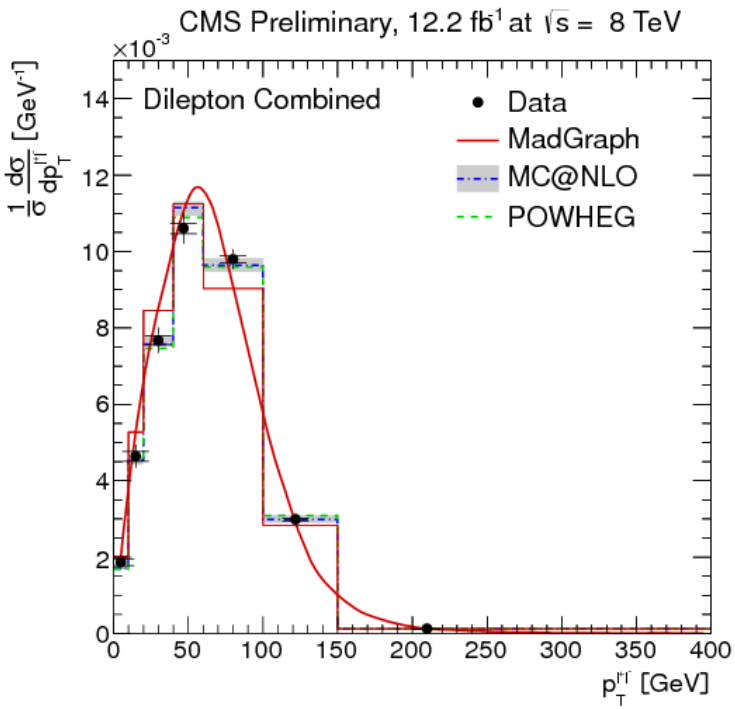


Visible cross section: leptons, b jets

CMS, 8 TeV

- **Normalised cross section in visible phase space** (leptons, b jets p_T, η cuts)
- p_T(l, b jets) softer than the predictions
- Typical precision: 5–10% per bin
- Consistent results dilepton - l+jets channels
- CMS: Results consistent with 7 TeV measurement



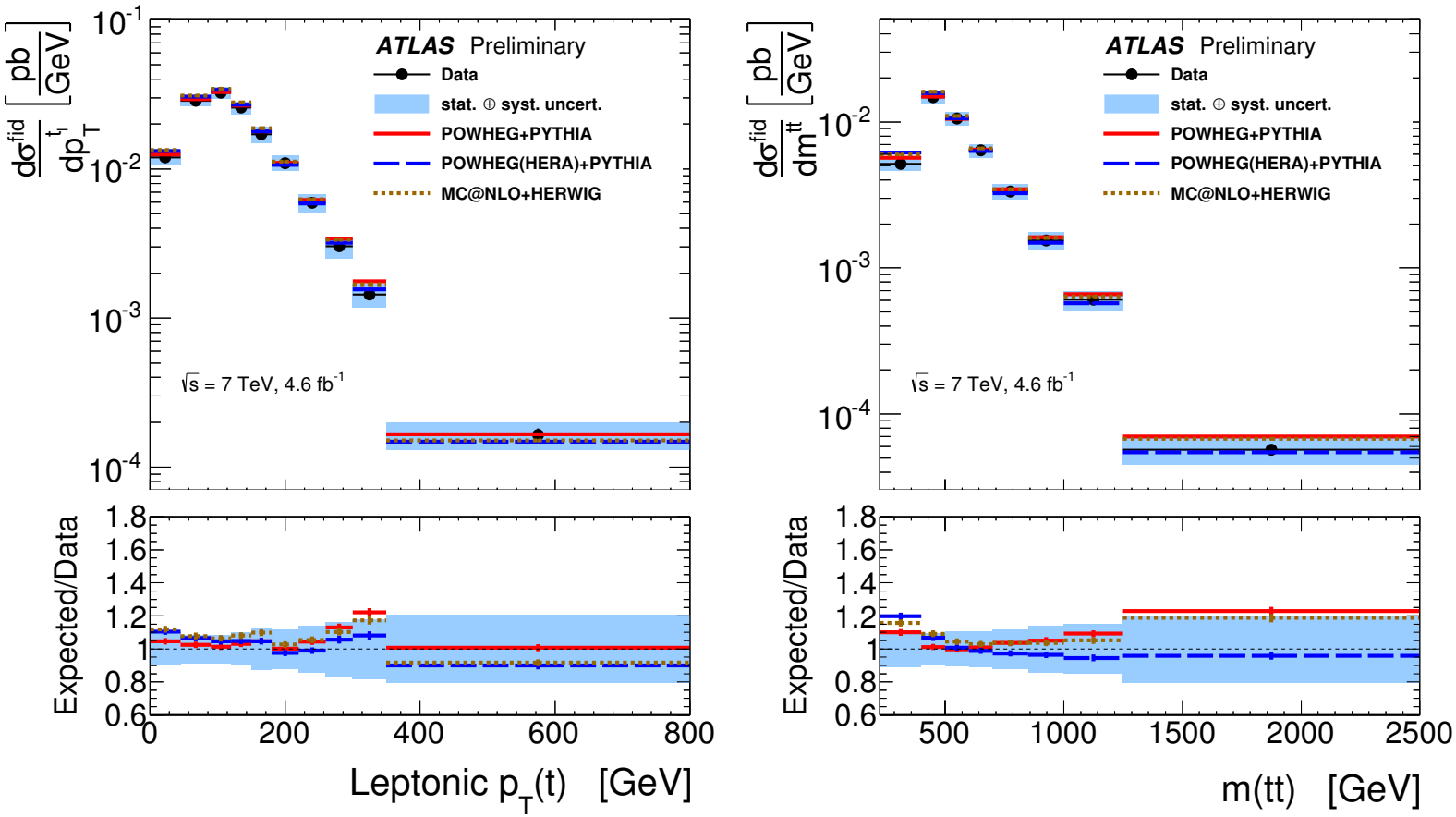


$t\bar{t}$: "Pseudo-top-quark" ATLAS (7 TeV) NEW!

- Variables constructed from objects directly related to detector-level observables (jets, leptons and missing transverse momentum)

→ Details in J. Katzy's talk

- **Absolute cross section** in the visible phase space, compared to LO and NLO models.



Single top: t-channel

ATLAS (7 TeV): arXiv:1406.7844, submitted to PRD

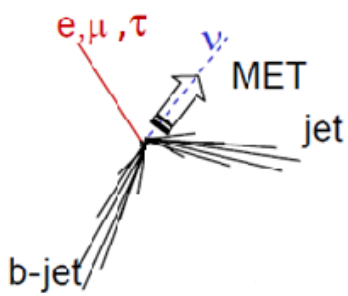
CMS (8 TeV): CMS-PAS-TOP-14-004 NEW!

Selection and top reconstruction

Kinematics of the top quark might depend on the PDFs and/or can improve QCD modeling of top production

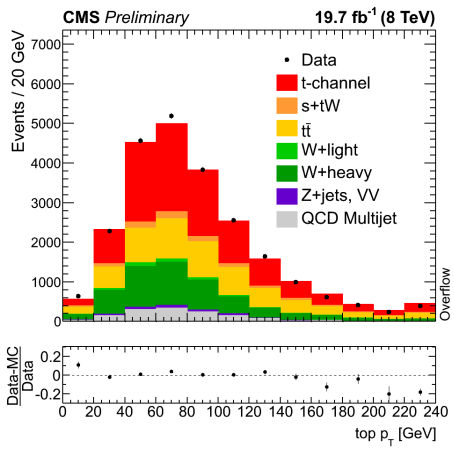
Typical selection:

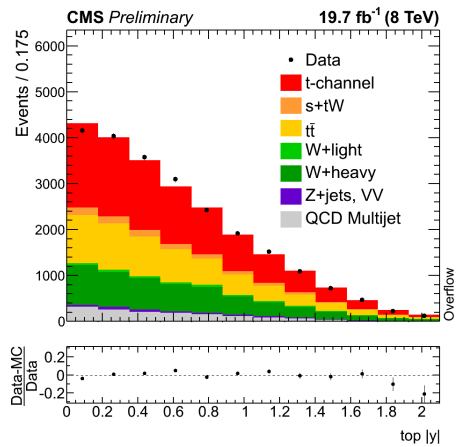
- Exactly one isolated lepton (e/μ), p_T > 25-30 GeV, $|\eta| < 2.1$-2.5
- Only 2 jets p_T >30-40 GeV and $|\eta| < 4.5$
- $\geq$1 b-tagged jet ($|\eta|$ <2.5)
- MET, M_T > 30-50 GeV
- ATLAS: QCD multijet veto
- **+ Kinematic reco. top quark (back up)**

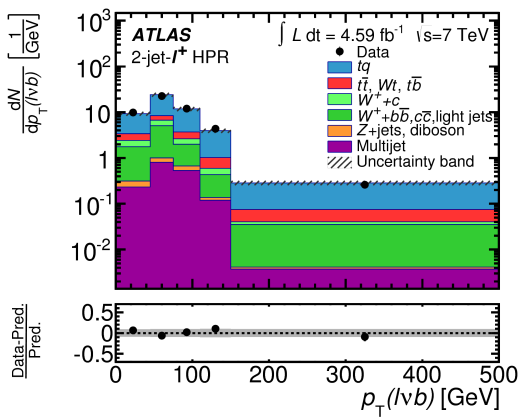


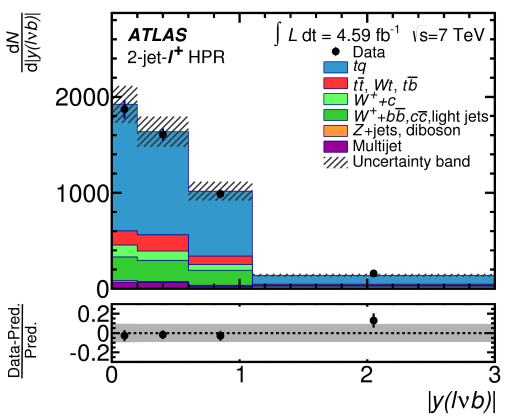
- Main backgrounds: $t\bar{t}$, W+jets
- Reference MC: PowHeg+Pythia (4FS Atlas, 5FS CMS)

- Use MVA to separate signal and background
  - ATLAS: S/B $\sim$ 1-2
  - CMS: S/B $\sim$ 0.5







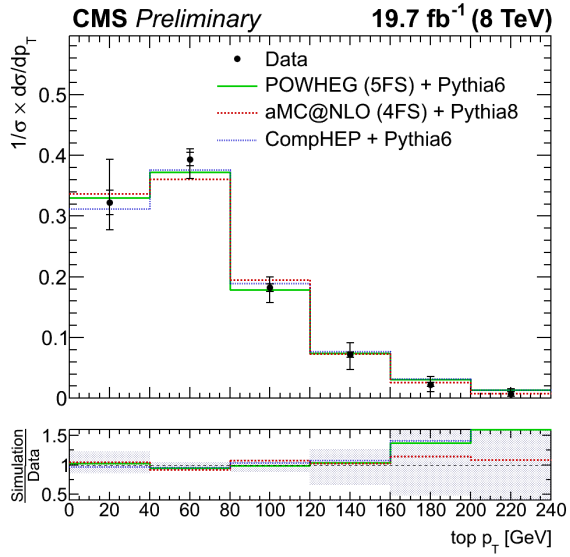


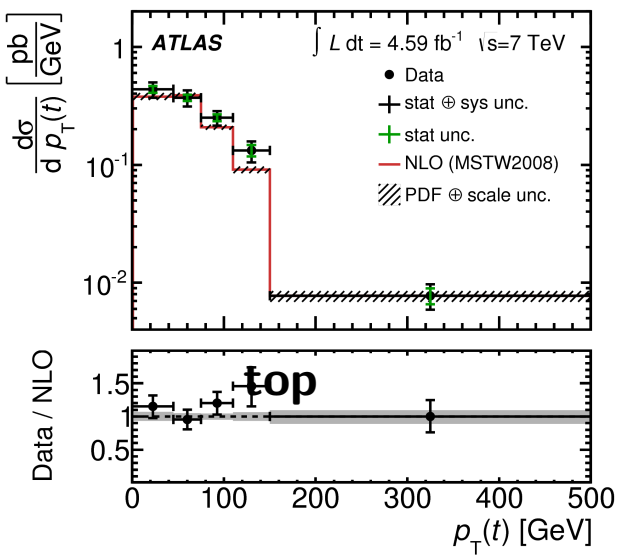
Single top: (Anti-)Top p_T

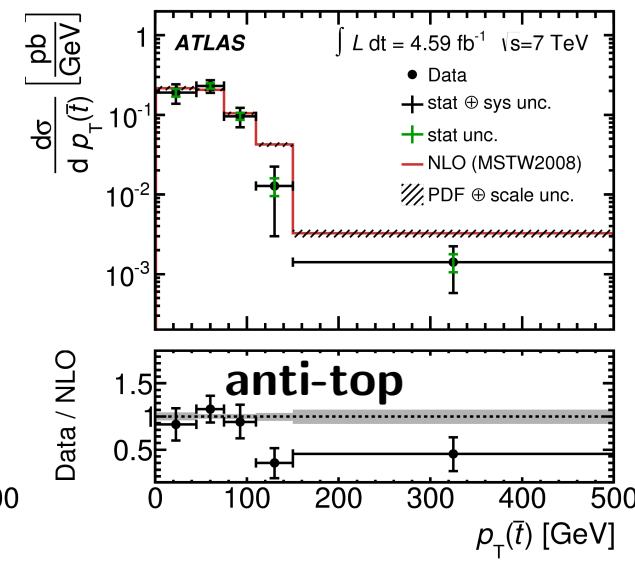
ATLAS (7 TeV) & CMS (8 TeV) NEW!

- CMS: normalised cross section well described by POWHEG+Pythia, aMC@NLO, CompHEP
- ATLAS: absolute cross section. Good agreement with NLO prediction (MCFM) and between $t/\bar{t}$ rates

  (Normalised cross sections in backup)
- Dominated by the total syst. uncertainty (1-3 times larger than the statistical one)





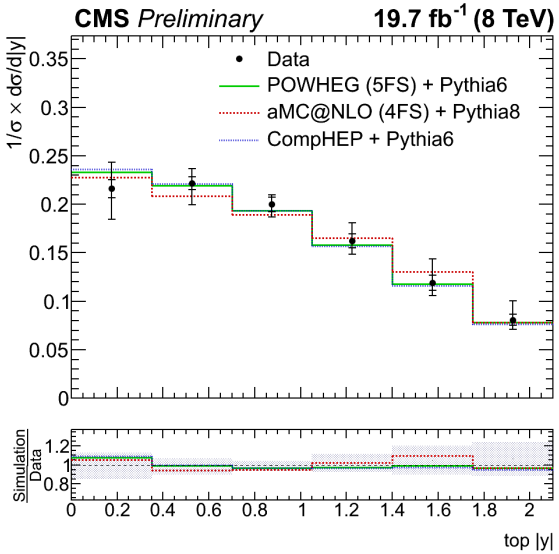


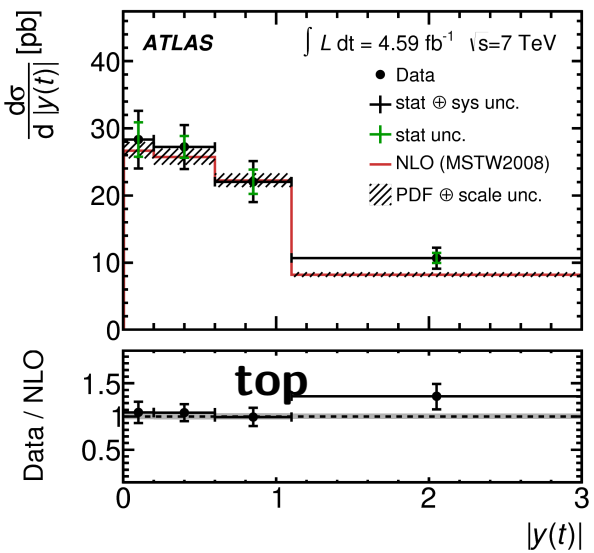
Single top: (Anti-)Top $|y|$

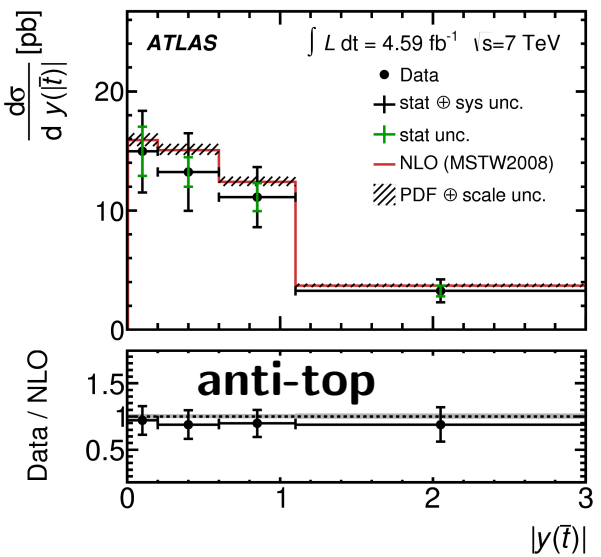
ATLAS (7 TeV) & CMS (8 TeV) NEW!

- CMS: normalised cross section well described by POWHEG+Pythia, aMC@NLO, CompHEP
- ATLAS: absolute cross section. Good agreement with NLO prediction (MCFM) and between $t/\bar{t}$ rates

  (Normalised cross sections in backup)
- Dominated by the total syst. uncertainty (1-3 times larger than the statistical one)







Summary and Outlook

- Presented $t\bar{t}$ cross section as a function of different kinematic variables (syst. dominated)
  - ◇ Normalised and absolute cross sections
  - ◇ Full phase space and visible phase space, particle and parton level
  - ◇ $d\sigma/dp_T$ extended to 1 TeV regime
- In general, reasonable description of data, some discrepancies observed between data and certain predictions for $t\bar{t}$ cross sections
  - → Measured spectrum is generally softer than predictions (ie. p_T^t, $m_{t\bar{t}}$)
  - → Comparison between ATLAS & CMS: consistent definition of the top quark (top parton after radiation), default generators (CMS MadGraph+Pythia, ATLAS Alpgen+Herwig) are similar
- Differential measurements performed for the first time in single top: Good agreement between data-predictions observed
- Single top: total systematic uncertainties larger than statistical one
- Consistent result among channels, measurements and experiments.
- Looking forward to having the full NNLO calculations

BACK UP

Monte Carlo $t\bar{t}$: CMS & ATLAS

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) or CT10 (8 TeV)	Perugia 2011 C
Alpgen	Herwig 6.5 + Jimmy 4.31	cteq6ll	AUET2

CMS

Matrix element	Shower & Hadronization	PDF	Tune
MadGraph v5	Pythia 6	cteq6l	Z2 (7 TeV) Z2* (8 TeV)
Powheg	Pythia 6	cteq6m (7 TeV) CT10 (8 TeV)	Z2 (7 TeV) Z2* (8 TeV)
MC@NLO v3.4	Herwig 6 + Jimmy	cteq6m	default tune

T. Pfeiffer, TOP2013

Monte Carlo $t\bar{t}$: CDF & D0

CDF

Matrix element	Shower & Hadronization	PDF	Tune
Pythia 6	Pythia 6	cteq5l	Tune A or Tune A-pro
Powheg	Pythia 6	cteq66	Tune A-pro

D0

Matrix element	Shower & Hadronization	PDF	Tune
Alpgen	Pythia 6	cteq6l	Modified Tune A
MC@NLO	Herwig 6	cteq66	Modified Tune A

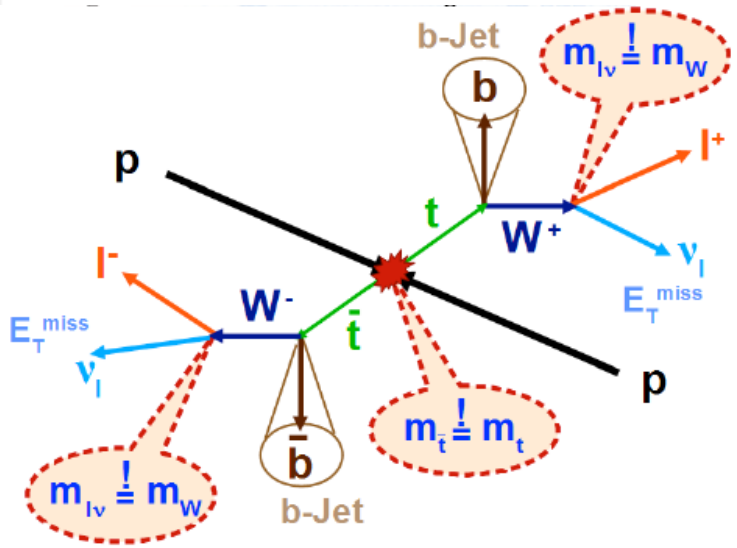
T. Pfeiffer, TOP2013

Kinematic reconstruction

Dilepton

Due to the 2ν the system is underconstrained

- $m_W \equiv$80.4 GeV, $m_t \equiv m_{\bar{t}}$ fixed
- $p_T^{\nu 1} + p_T^{\nu 2} = E_T^{miss}$
- vary m_T between 100-300 GeV (1 GeV steps) to account for resolution effects
- prefer solutions with b-tagged jets
- choose solution with best reco. neutrino energy w.r.t MC spectrum



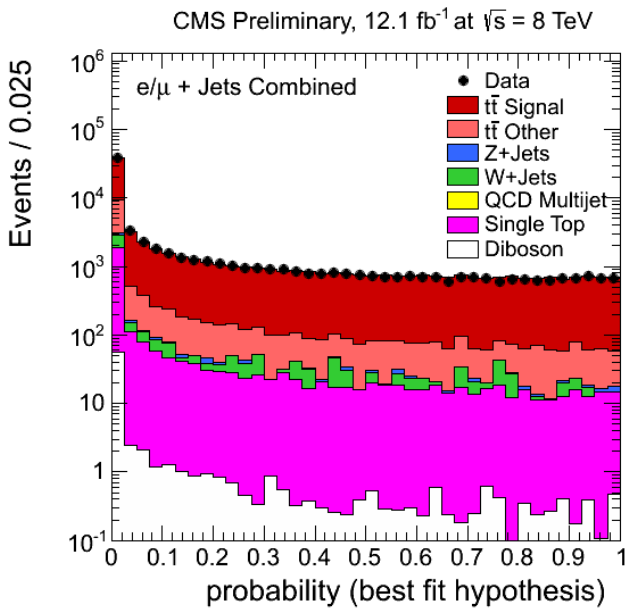
Kinematic reconstruction

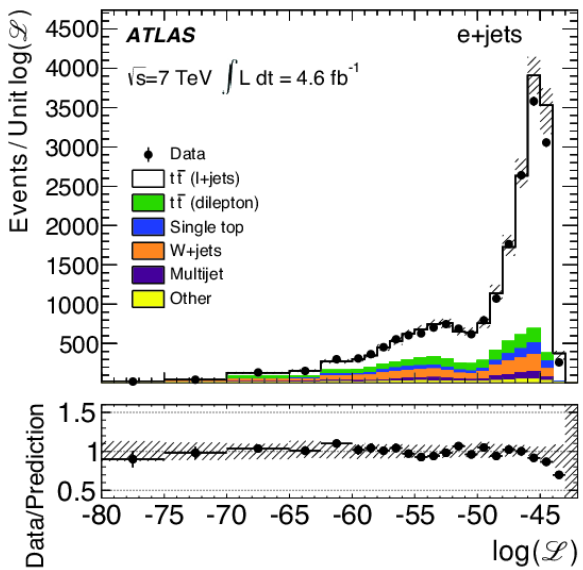
Lepton+jets - CMS/D0

- Vary 4-momenta of leptons, jets, neutrino within resolutions
- Constraints: $m_t = m_{\bar{t}}$, $m_{qq} = m_{l\nu} = m_W$=80.4 GeV
- D0: $m_t = 172.5$ GeV
- Limit permutations: consider 4-5 leading jets, use b-tag information
- Take 4-jet permutation with min. χ^2

Lepton+jets - ATLAS

- max. likelihood fit to the measured objects to a LO representation of the $t\bar{t}$ decay
- Leptonic top: fitted lepton, ν, b-parton
- Hadronic: remaining 3 partons





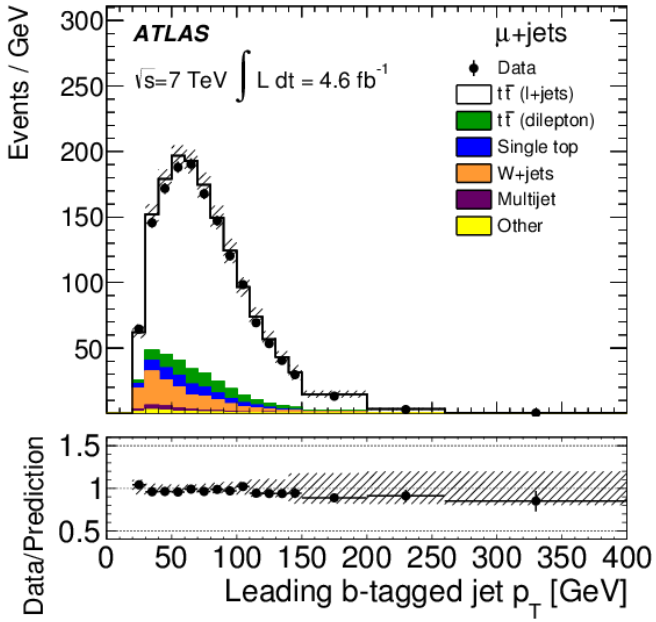
Kinematic distributions: Top decay products

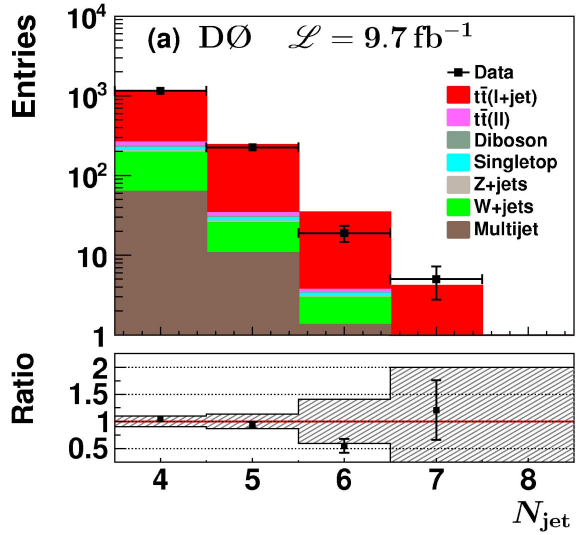
- Pure $t\bar{t}$ sample (∼80%)
- Reference MC

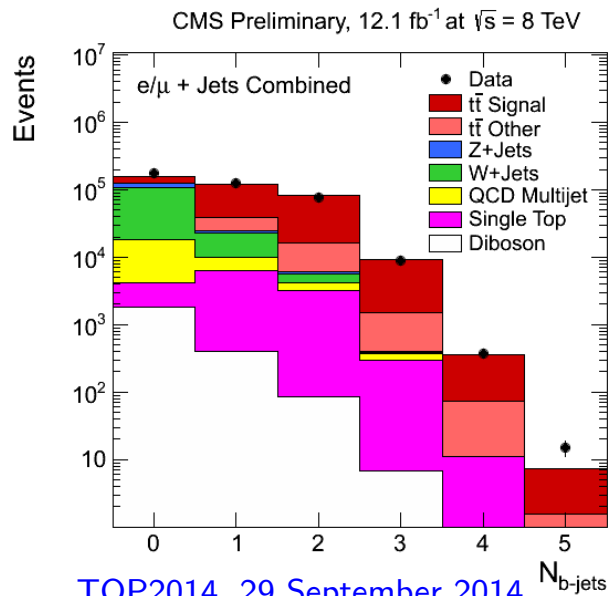
  ATLAS: Alpgen+Herwig

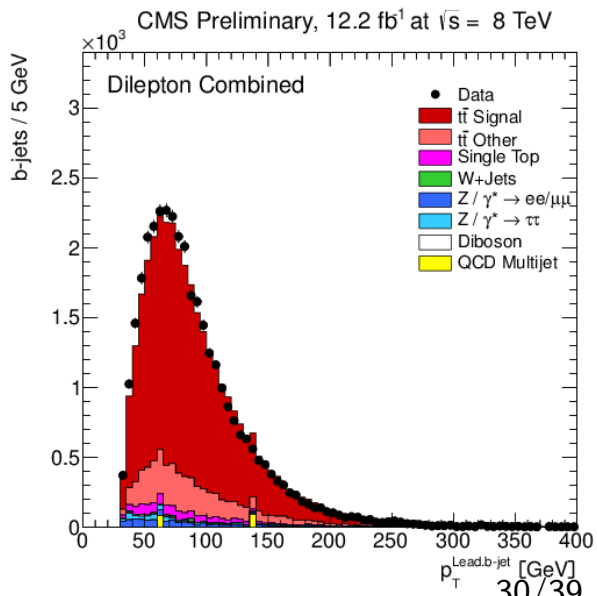
  CMS: MadGraph+Pythia

  D0: MC@NLO+Herwig
- Main backgrounds:
  - ◇ l+jets: W+jets, other $t\bar{t}$, single top
  - ◇ dilepton: other $t\bar{t}$, single top, Z+jets

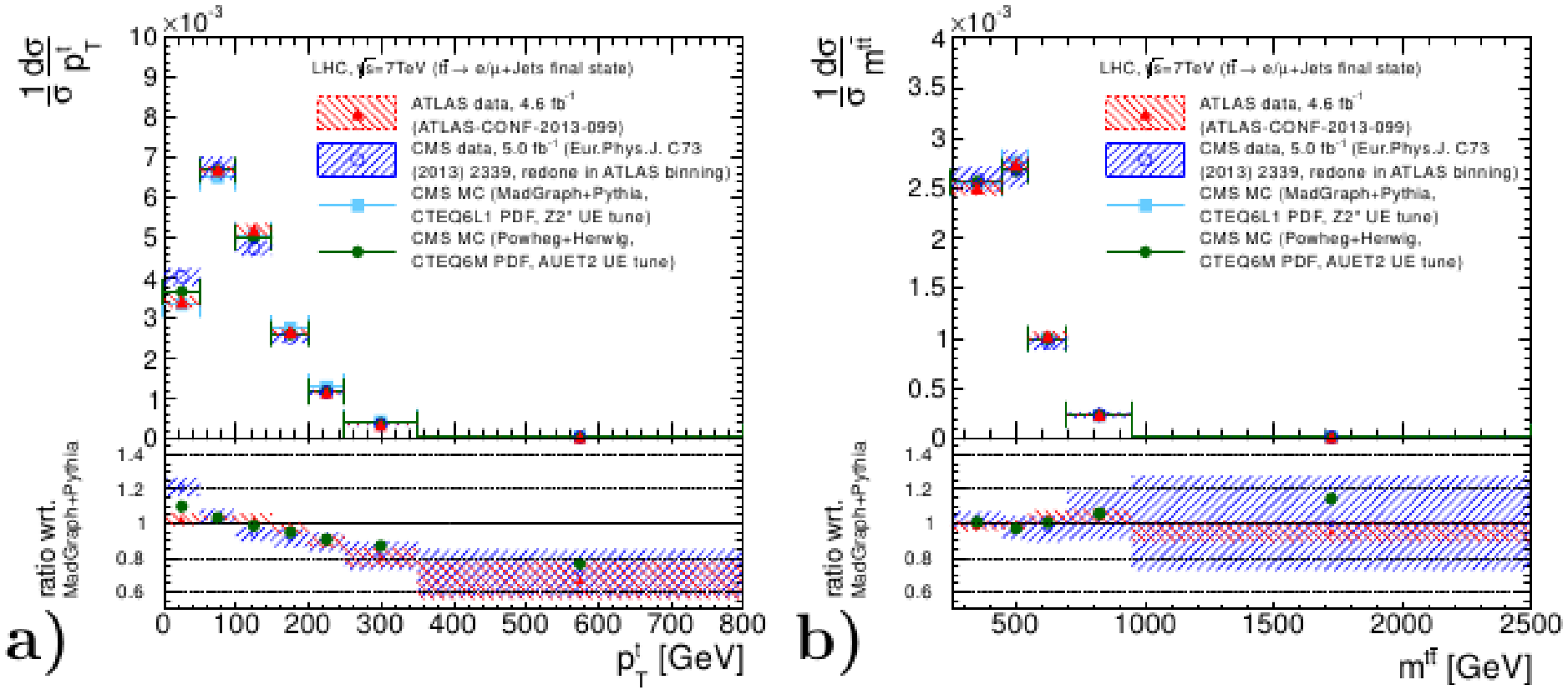






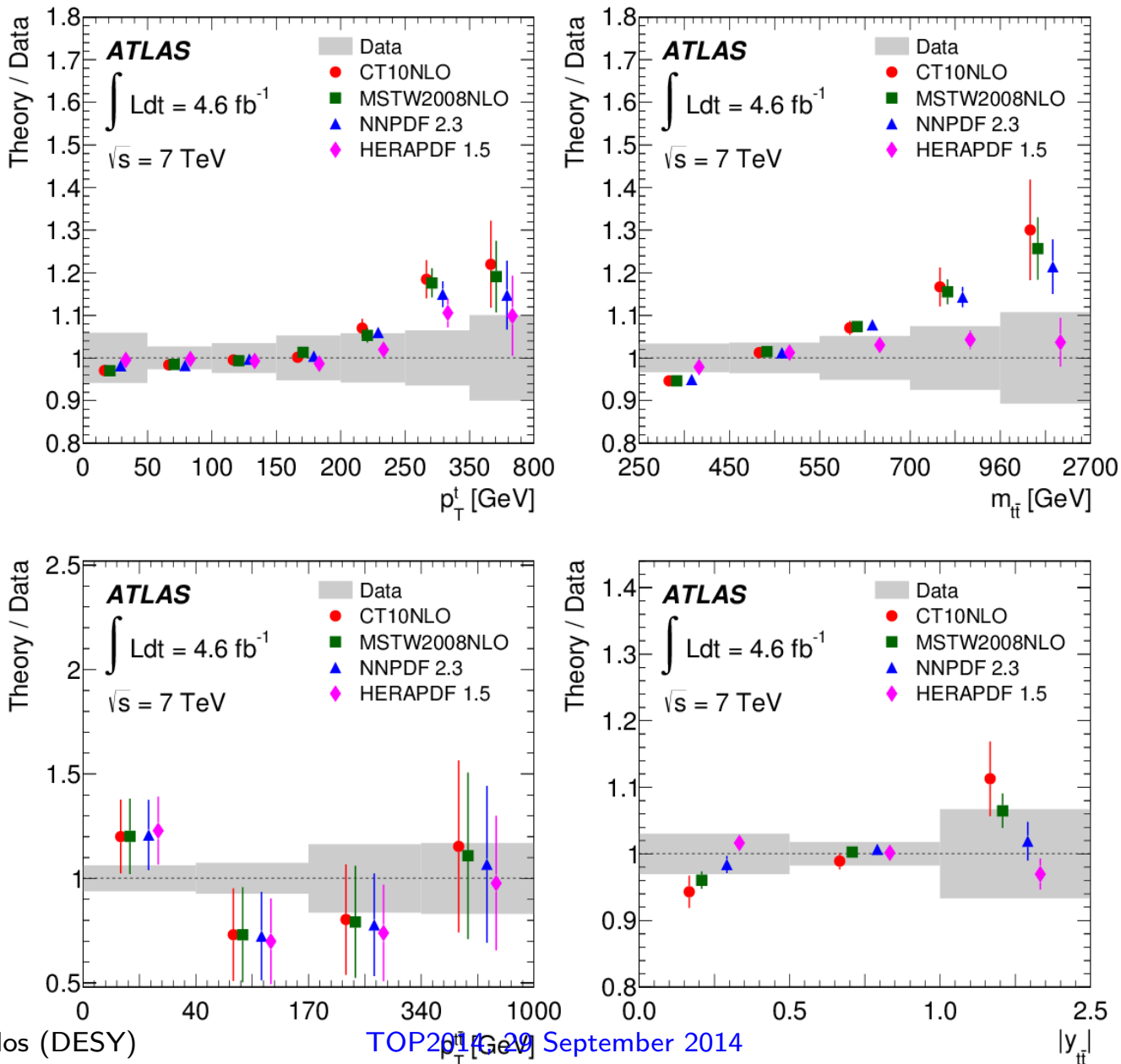


$t\bar{t}$: Comparison CMS & ATLAS l+jets, 7 TeV

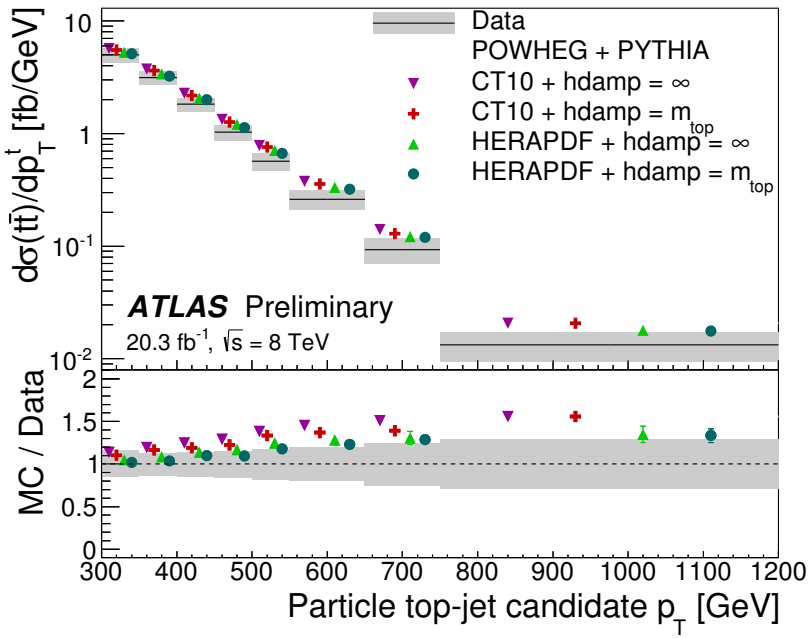


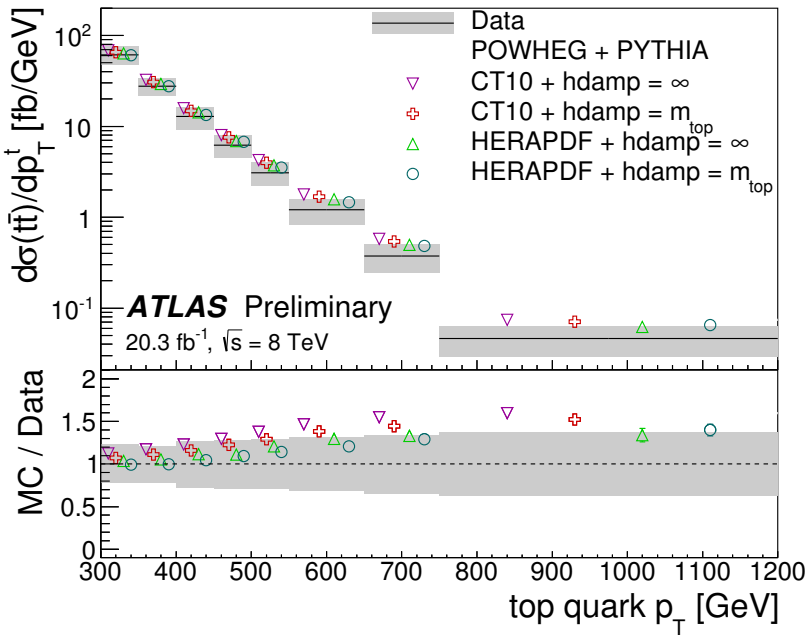
Ref: CERN-THESIS-2014-110

$t\bar{t}$: Comparison between NLO PDF ATLAS (7 TeV)



Boosted $t\bar{t}$: Particle/partonic top ATLAS (8 TeV)





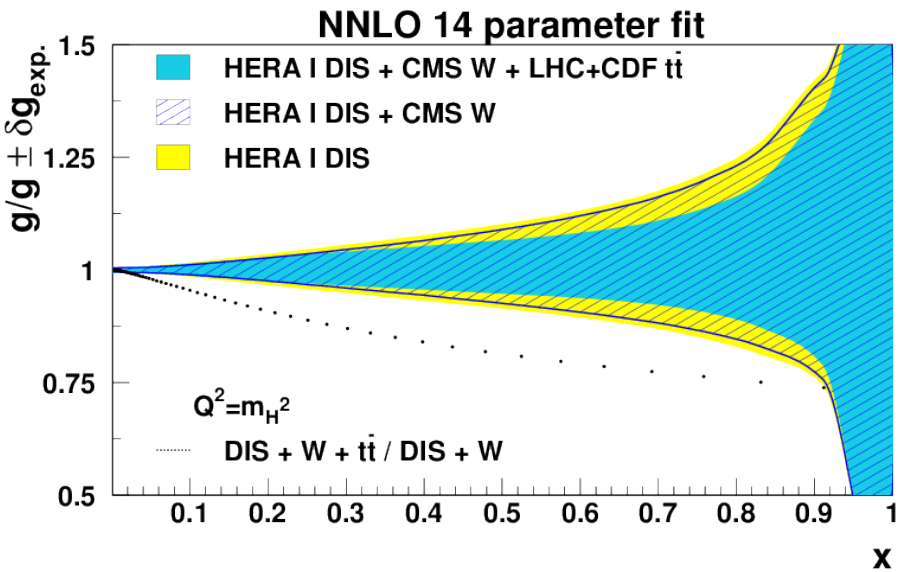
PDF constraints measurements of $t\bar{t}$ production

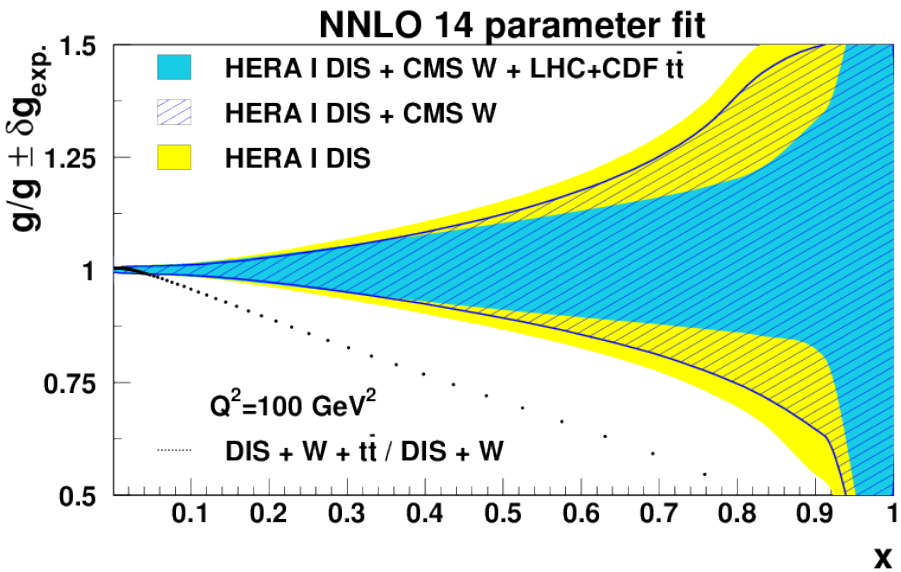
arXiv:1406.0386

Full PDF fit at NNLO using HERAFitter, DGLAP parton evolution. Data:

- in ep collisions (combined HERA I [JHEP 1001:109 (2010)])
- asymmetry in W production at 7 TeV [CMS: Phys. Rew. D 90 (2014) 032004]
- Inclusive $t\bar{t}$: CMS JHEP11 (2012) 067, CMS-PAS-TOP-12-007, ATLAS ATLAS-CONF-2012-024, ATLAS-CONF-2012-149
- Differential cross sections 7 TeV: CMS Eur. Phys. J. C73 (2013) 2339; ATLAS [arXiv:1407.0371]

Moderate improvement of the uncertainty on the gluon distribution for $x > 0.1$, significant change of the shape





aNNLO prediction for ptT implemented via DiffTop in HERAFitter, http://difftop.hepforge.org/

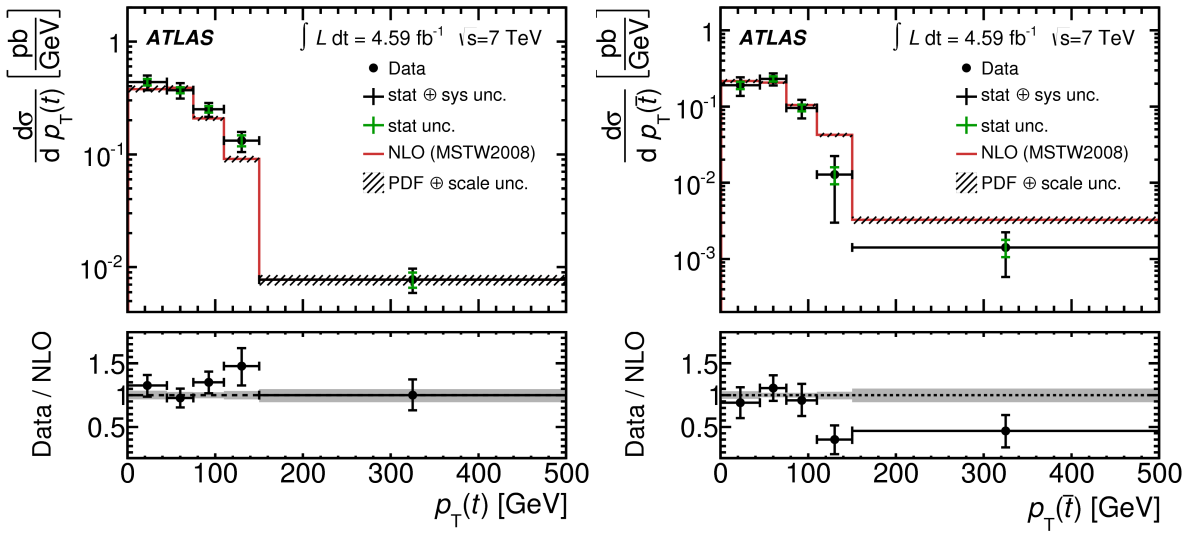
$t\bar{t}$: Comparison between data/predictions ATLAS (7 TeV)

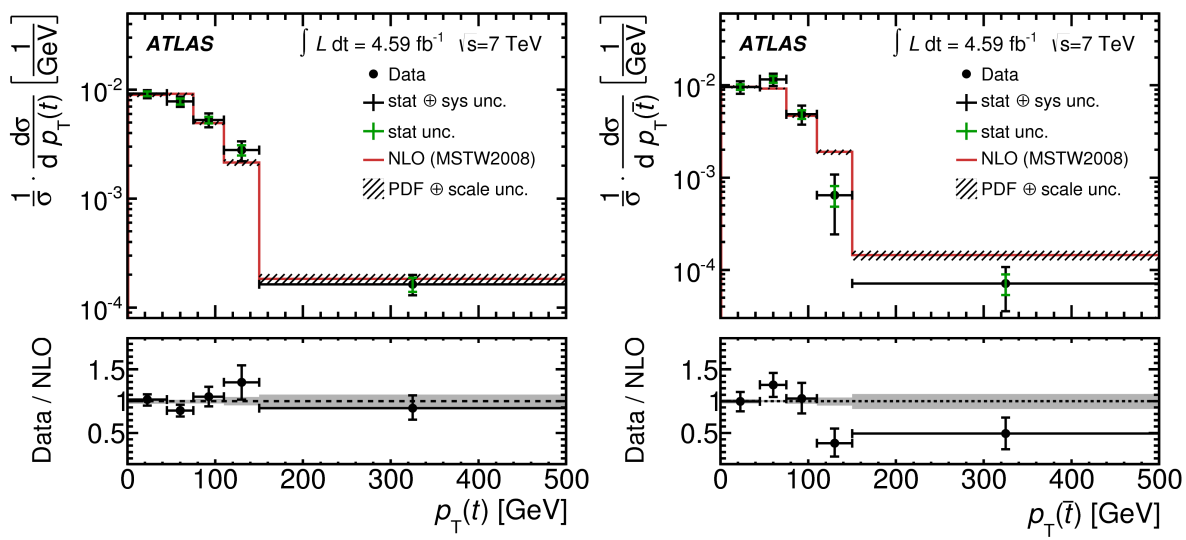
Variable	ALPGEN+HERWIG		MC@NLO+HERWIG		POWHEG+HERWIG		POWHEG+PYTHIA		NLO QCD		NLO+NNLL	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
p_{T}^{t}	24./6	0.00	8.0/6	0.24	4.8/6	0.57	19./6	0.00	9.5/6	0.15	7.6/6	0.27
$m_{t\bar{t}}$	2.6/4	0.63	6.9/4	0.14	5.5/4	0.24	13./4	0.01	5.5/4	0.24	5.9/4	0.20
$p_{\mathrm{T}}^{t\bar{t}}$	4.2/3	0.25	0.5/3	0.93	4.1/3	0.26	21./3	0.00	14./3	0.00	9.9/3	0.02
$\lvert y_{t\bar{t}}\rvert$	1.6/2	0.45	3.4/2	0.18	4.3/2	0.11	4.8/2	0.09	3.7/2	0.16		

Single top: (Anti-)Top p_T, η

ATLAS (7 TeV)

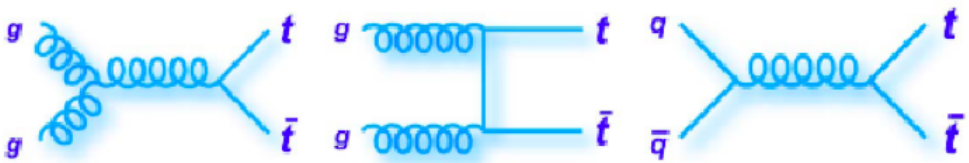
- Normalised cross section
- Dominant uncertainty: Statistical uncertainty
- Good agreement with NLO prediction and between $t/\bar{t}$





Top quark production

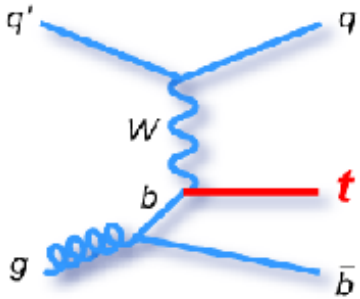
$t\bar{t}$ production mainly by gluon fusion at LHC (∼80% at 7-8 TeV)



- Full NNLO+NNLL calculation available [Czakon, Fiedler, Mitov, arXiv:1303.6254]

Collider	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	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

t production via EWK interaction

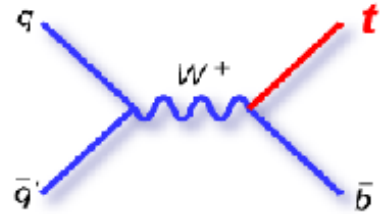


t-channel

$\sigma = 64.57^{+2.63}_{-1.74}$ pb @ 7 TeV

$\sigma = 87.76^{+3.44}_{-1.91}$ pb @ 8 TeV

Phys. Rev. D 83, 091503(R) (2011)

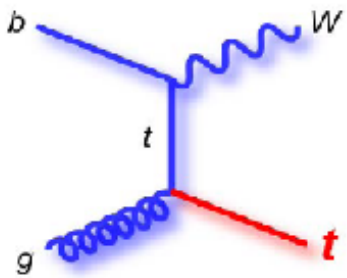


s-channel

$\sigma = 4.63^{+0.20}_{-0.18}$ pb @ 7 TeV

$\sigma = 5.61 \pm 0.22$ pb @ 8 TeV

Phys. Rev. D 81, 054028 (2010)

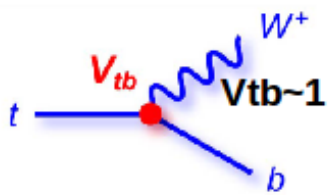


tW-channel

$\sigma = 15.74^{+1.17}_{-1.21}$ pb @ 7 TeV

$\sigma = 22.37 \pm 1.52$ pb @ 8 TeV

Phys. Rev. D 82, 054018 (2010)



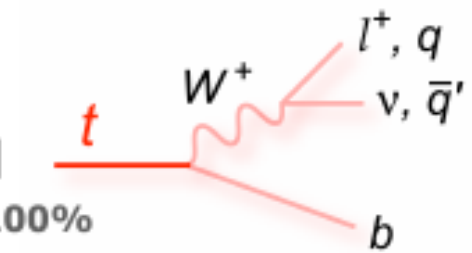
Cross section calculated at NLO+NNLL

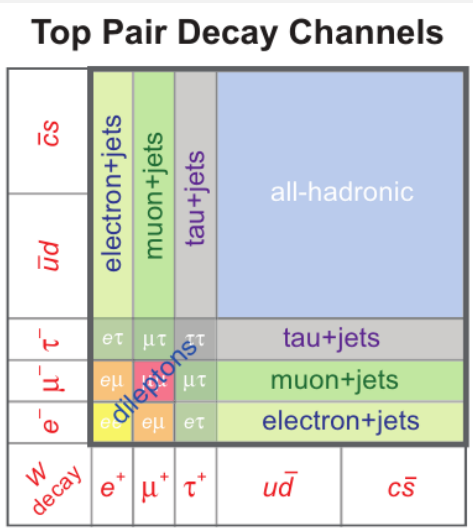
Top quark decay signatures

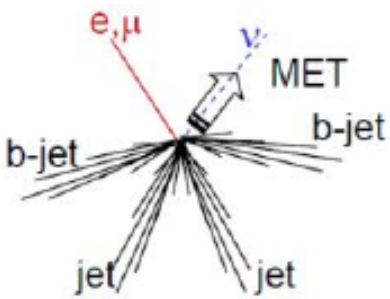
W decay defines final state

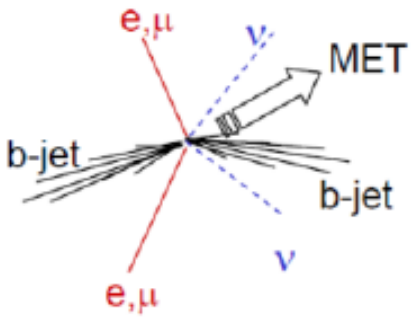
$|Vtb| \gg |Vtd|, |Vts|$

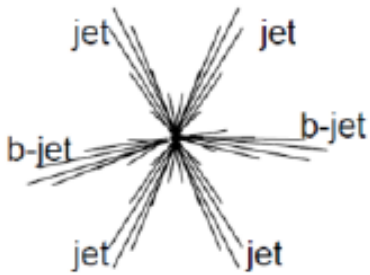
- $t \to Wb$ almost 100%

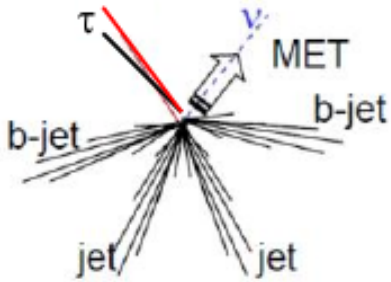












Semileptonic [e/μ]: BR$\sim$30% and manageable BG (ie. W+jets)

Dileptonic [e/μ]: BR$\sim$5% and small BG (ie. DY+jets)

All-jets: BR$\sim$46% but largest BG (ie. QCD multijet)

τ+jets: BR$\sim$15%

single-top is BG for $t\bar{t}$ (and vice-versa)

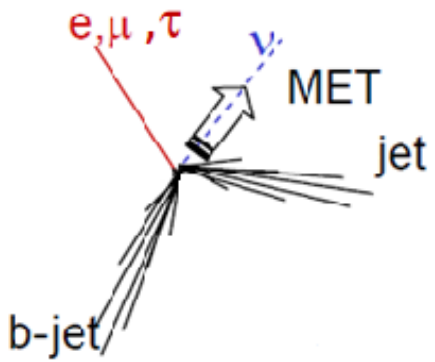
Selection and top reconstruction

Kinematics of the top quark might depend on the PDFs and/or can improve QCD modeling of top production

Typical selection:

- Exactly one isolated lepton (e/μ), $p_T > 25$-30 GeV, $|\eta| < 2.1$-2.5
- Only 2 jets $p_T > 30$-40 GeV and $|\eta| < 4.5$
- 1 b-tagged jet ($|\eta| < 2.5$)
- MET and $M_T > 30$-50 GeV
- ATLAS: QCD multijet veto

Top reconstruction



- Top quark candidate reconstructed from W boson and b-tagged jet
- W boson from lepton and MET: $|p_z^\nu|$ inferred by constraint on M_W

$\rightarrow$ Two real solutions: Choose the one with smallest $|p_z^\nu|$

$\rightarrow$ Imaginary solution: Minimal variation of MET so that $M_T = M_W$