Top physics at the LHC

Marino Romano

Top quark ID card

Name: `Top quark`

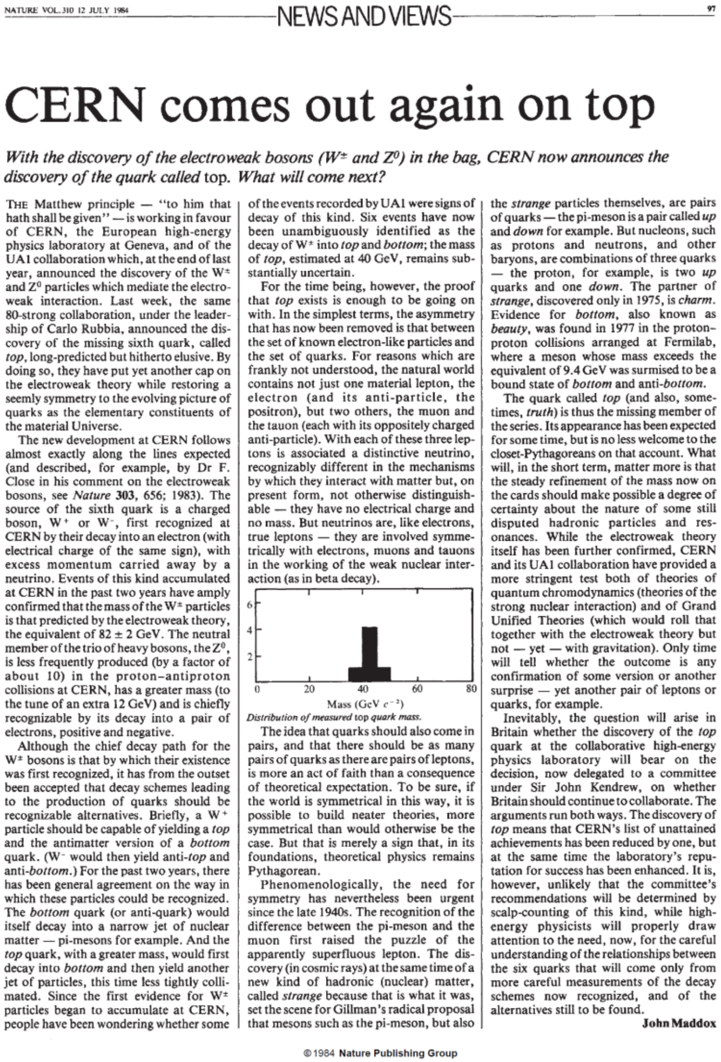
Discovery: `CERN (UA1), 1984 (Nature 310, 97)`

Mass: 40 `GeV`

Charge: `+2/3e`

Generation: `Third`

Production: $W \rightarrow tb$ (~100%)



CERN comes out again on top

With the discovery of the electroweak bosons ($W^{\pm}$ and Z^0) in the bag, CERN now announces the discovery of the quark called top. *What will come next?*

THE Matthew principle — "to him that hath shall be given" — is working in favour of CERN, the European high-energy physics laboratory at Geneva, and of the UA1 collaboration which, at the end of last year, announced the discovery of the $W^{\pm}$ and Z^0 particles which mediate the electroweak interaction. Last week, the same 80-strong collaboration, under the leadership of Carlo Rubbia, announced the discovery of the missing sixth quark, called *top*, long-predicted but hitherto elusive. By doing so, they have put yet another cap on the electroweak theory while restoring a seemly symmetry to the evolving picture of quarks as the elementary constituents of the material Universe.

The new development at CERN follows almost exactly along the lines expected (and described, for example, by Dr F. Close in his comment on the electroweak bosons, see *Nature* **303**, 656; 1983). The source of the sixth quark is a charged boson, W^+ or W^-, first recognized at CERN by their decay into an electron (with electrical charge of the same sign), with excess momentum carried away by a neutrino. Events of this kind accumulated at CERN in the past two years have amply confirmed that the mass of the $W^{\pm}$ particles is that predicted by the electroweak theory, the equivalent of 82 ± 2 GeV. The neutral member of the trio of heavy bosons, the Z^0, is less frequently produced (by a factor of about 10) in the proton–antiproton collisions at CERN, has a greater mass (to the tune of an extra 12 GeV) and is chiefly recognizable by its decay into a pair of electrons, positive and negative.

Although the chief decay path for the $W^{\pm}$ bosons is that by which their existence was first recognized, it has from the outset been accepted that decay schemes leading to the production of quarks should be recognizable alternatives. Briefly, a W^+ particle should be capable of yielding a *top* and the antimatter version of a *bottom* quark. (W^- would then yield anti-*top* and anti-*bottom*.) For the past two years, there has been general agreement on the way in which these particles could be recognized. The *bottom* quark (or anti-quark) would itself decay into a narrow jet of nuclear matter — pi-mesons for example. And the *top* quark, with a greater mass, would first decay into *bottom* and then yield another jet of particles, this time less tightly collimated. Since the first evidence for $W^{\pm}$ particles began to accumulate at CERN, people have been wondering whether some of the events recorded by UA1 were signs of decay of this kind. Six events have now been unambiguously identified as the decay of W^+ into *top* and *bottom*; the mass of *top*, estimated at 40 GeV, remains substantially uncertain.

For the time being, however, the proof that *top* exists is enough to be going on with. In the simplest terms, the asymmetry that has now been removed is that between the set of known electron-like particles and the set of quarks. For reasons which are frankly not understood, the natural world contains not just one material lepton, the electron (and its anti-particle, the positron), but two others, the muon and the tauon (each with its oppositely charged anti-particle). With each of these three leptons is associated a distinctive neutrino, recognizably different in the mechanisms by which they interact with matter but, on present form, not otherwise distinguishable — they have no electrical charge and no mass. But neutrinos are, like electrons, true leptons — they are involved symmetrically with electrons, muons and tauons in the working of the weak nuclear interaction (as in beta decay).

Distribution of measured top *quark mass.*

The idea that quarks should also come in pairs, and that there should be as many pairs of quarks as there are pairs of leptons, is more an act of faith than a consequence of theoretical expectation. To be sure, if the world is symmetrical in this way, it is possible to build neater theories, more symmetrical than would otherwise be the case. But that is merely a sign that, in its foundations, theoretical physics remains Pythagorean.

Phenomenologically, the need for symmetry has nevertheless been urgent since the late 1940s. The recognition of the difference between the pi-meson and the muon first raised the puzzle of the apparently superfluous lepton. The discovery (in cosmic rays) at the same time of a new kind of hadronic (nuclear) matter, called *strange* because that is what it was, set the scene for Gillman's radical proposal that mesons such as the pi-meson, but also the *strange* particles themselves, are pairs of quarks — the pi-meson is a pair called *up* and *down* for example. But nucleons, such as protons and neutrons, and other baryons, are combinations of three quarks — the proton, for example, is two *up* quarks and one *down*. The partner of *strange*, discovered only in 1975, is *charm*. Evidence for *bottom*, also known as *beauty*, was found in 1977 in the proton–proton collisions arranged at Fermilab, where a meson whose mass exceeds the equivalent of 9.4 GeV was surmised to be a bound state of *bottom* and anti-*bottom*.

The quark called *top* (and also, sometimes, *truth*) is thus the missing member of the series. Its appearance has been expected for some time, but is no less welcome to the closet-Pythagoreans on that account. What will, in the short term, matter more is that the steady refinement of the mass now on the cards should make possible a degree of certainty about the nature of some still disputed hadronic particles and resonances. While the electroweak theory itself has been further confirmed, CERN and its UA1 collaboration have provided a more stringent test both of theories of quantum chromodynamics (theories of the strong nuclear interaction) and of Grand Unified Theories (which would roll that together with the electroweak theory but not — yet — with gravitation). Only time will tell whether the outcome is any confirmation of some version or another surprise — yet another pair of leptons or quarks, for example.

Inevitably, the question will arise in Britain whether the discovery of the *top* quark at the collaborative high-energy physics laboratory will bear on the decision, now delegated to a committee under Sir John Kendrew, on whether Britain should continue to collaborate. The arguments run both ways. The discovery of *top* means that CERN's list of unattained achievements has been reduced by one, but at the same time the laboratory's reputation for success has been enhanced. It is, however, unlikely that the committee's recommendations will be determined by scalp-counting of this kind, while high-energy physicists will properly draw attention to the need, now, for the careful understanding of the relationships between the six quarks that will come only from more careful measurements of the decay schemes now recognized, and of the alternatives still to be found.

John Maddox

Top quark ID card

Name: Top quark

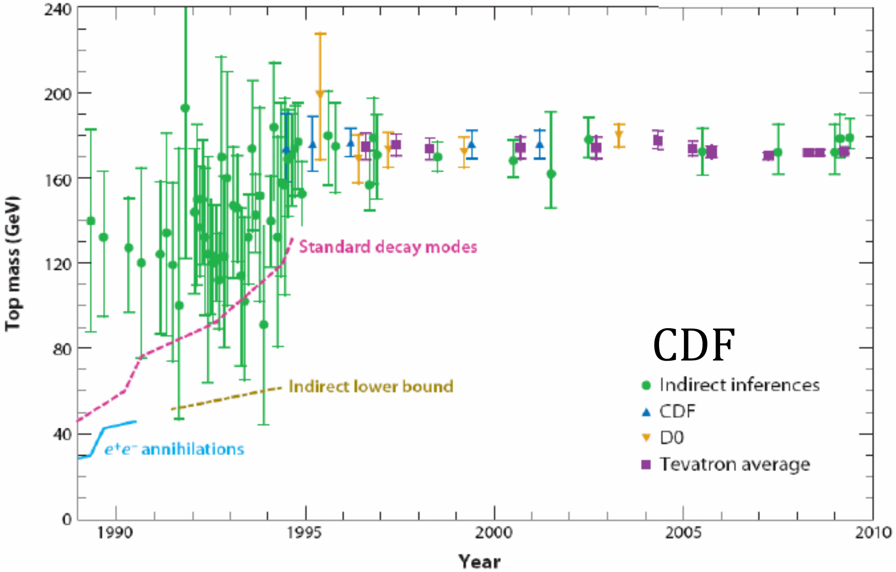
Discovery: Tevatron, 1995
(CDF, PRL 74 p. 2626 and
D0, PRL 74 p. 2422)

Mass: 173.34 ± 0.76 GeV
(Tevatron – LHC combination
arXiv:1403.4427)

Charge: +2/3e

Generation: Third

Decays: *Wb* (~100%)

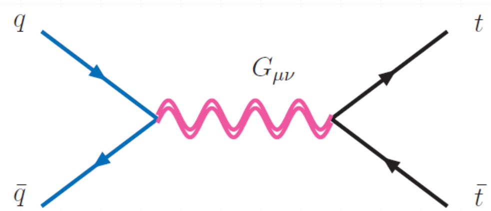


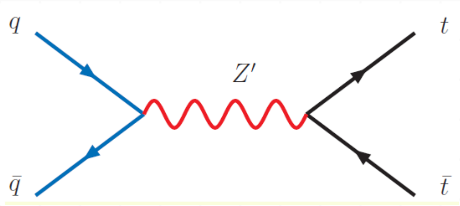
Why top quark physics?

- Most massive known fundamental particle
  - Large Yukawa coupling: $Y_t > 0.9$
  - Production time < Lifetime < Hadronization time < Spin decorrelation time:

$$\frac{1}{m_t} < \frac{1}{\Gamma_t} < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2}$$

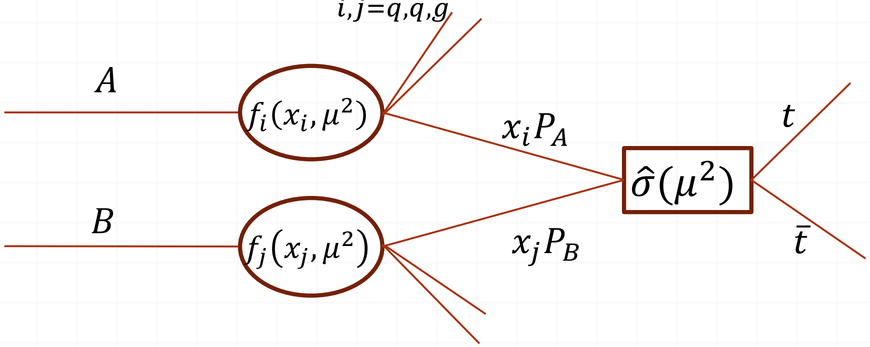
  unique opportunity to study a “bare” quark
- Production and decay rates are strong tests for SM predictions
- Background to Higgs and new physics (SUSY,…)
- (In)Direct coupling to new physics in many scenarios





Top quark production at the LHC

$$\sigma^{AB\to t\bar{t}}(\sqrt{s}, m_t) = \sum_{i,j=q,\bar{q},g} \int dx_i dx_j f_i^A(x_i,\mu_f^2) f_j^B(x_j,\mu_f^2) \hat{\sigma}^{ij\to t\bar{t}}(\rho, m_t^2, x_i, x_j, \alpha_s(\mu_r^2), \mu_f^2)$$



	LHC(14)	LHC(7)	Tev(1.96)
gg	~90%	~85%	~10%
$q\bar{q}$	~10%	~15%	~90%

To produce top pairs (assuming massless partons)

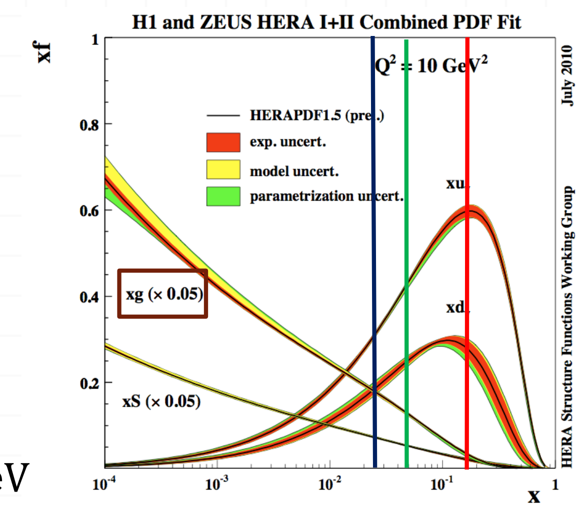
$$\hat{s} \geq 4m_t^2 \;\rightarrow\; x_i x_j = \frac{\hat{s}}{s} \geq \frac{4m_t^2}{s}$$

Typical $x_i x_j$ near threshold

On average $x \approx \frac{2m_t}{\sqrt{s}} =$

0.18 @ Tevatron $\sqrt{s} = 1.96$ TeV

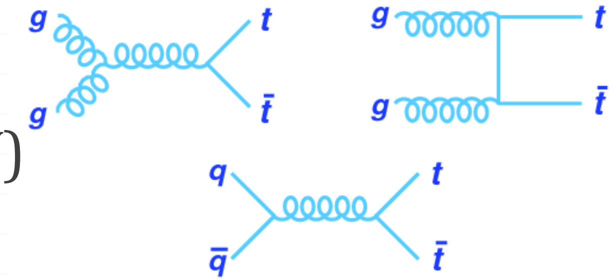
(0.048, 0.025) @ LHC $\sqrt{s} = (7,14)$TeV



Top quark pair production and decays

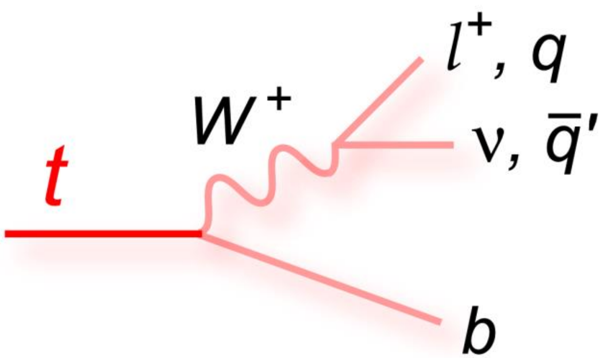
Pair production mechanisms at LHC

- Gluon-gluon fusion (~85% @ 7 TeV)
- Quark-antiquark annihilation



Decays

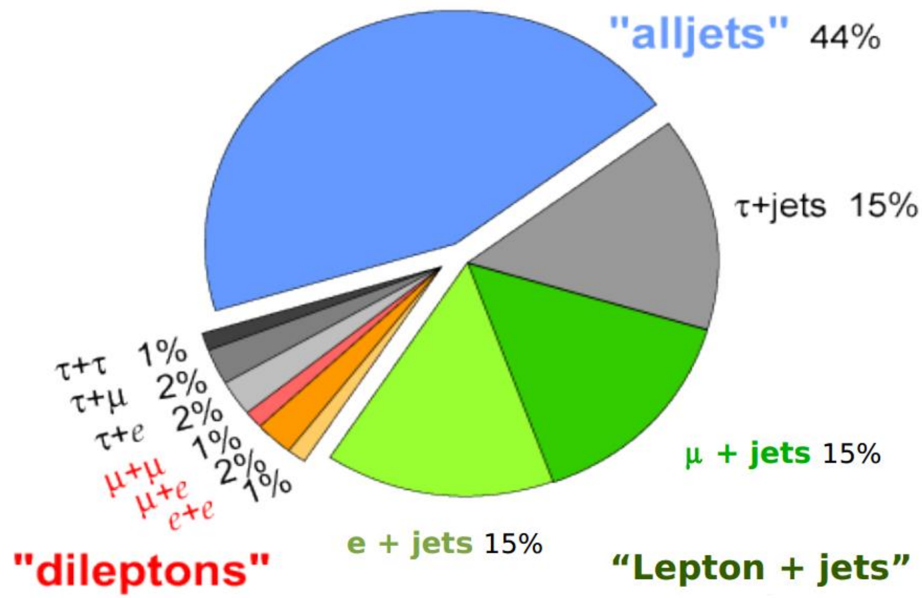
- $t \to Wb (\sim 100\%)$



$W \to l\nu_l \sim 33\%$

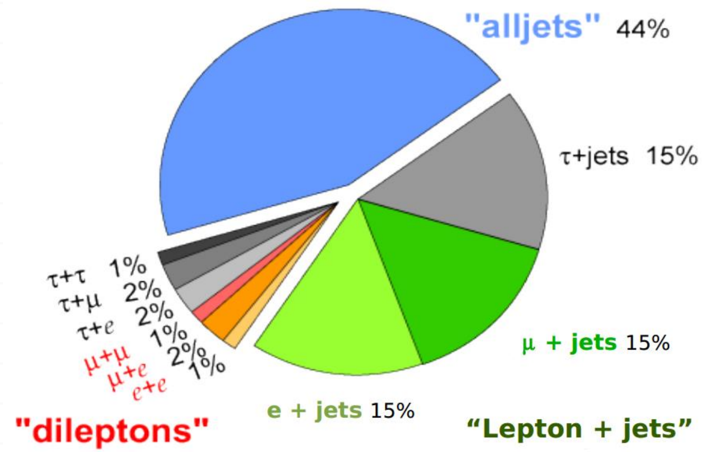
$W \to q\overline{q}' \sim 66\%$

Top pair final states



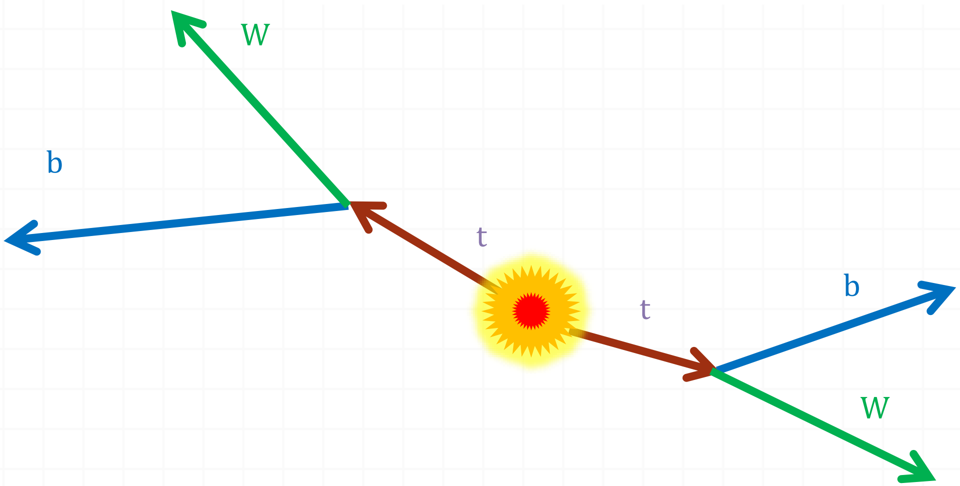
Top pair signatures

- High p_T (b)jets
- Up to 2 high p_T leptons
- Missing transverse energy

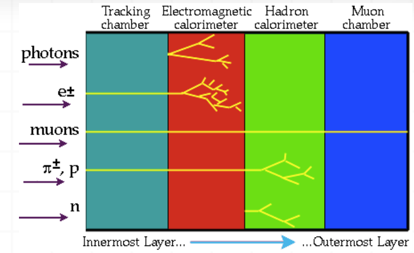


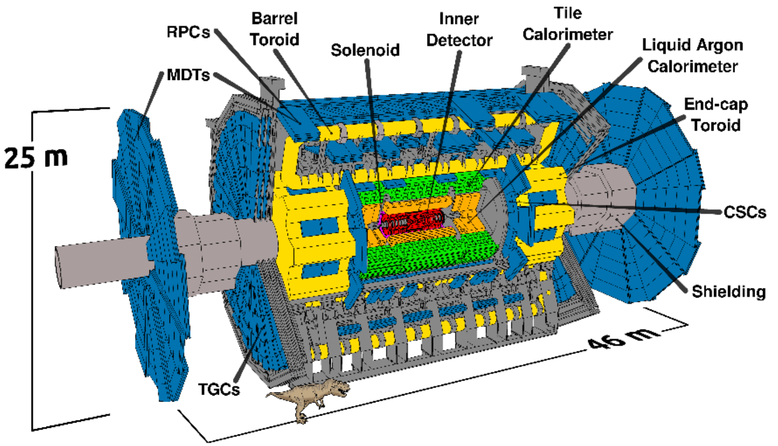
Tipical backgrounds:

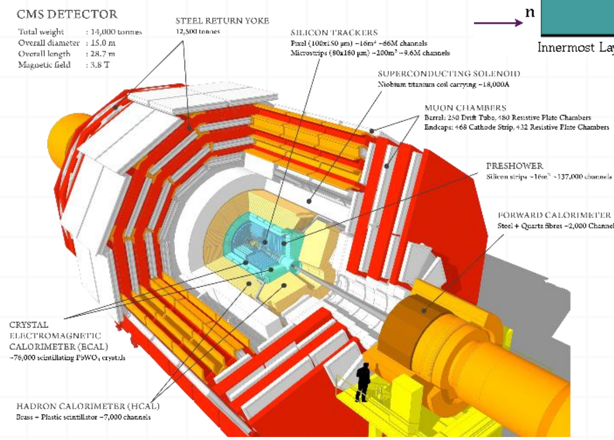
- W/Z + jets
- Single top
- QCD processes
- Dibosons



ATLAS & CMS







	ATLAS	CMS
Magnetic field	2T solenoid + toroid (0.5 T barrel, 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixel, strip + TRT $\frac{\sigma}{p_T} \approx 5 \cdot 10^{-4} p_T + 0.01$	Si pixels, strips $\frac{\sigma}{p_T} \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM Calorimeter	Pb+LAr $\frac{\sigma}{E} \approx \frac{10\%}{\sqrt{E}} + 0.007$	PbWO4 crystals $\frac{\sigma}{E} \approx \frac{2-5\%}{\sqrt{E}} + 0.005$
Hadronic Calorimeter	Fe+scint./Cu+LAr/W+Lar (10λ) $\frac{\sigma}{E} \approx \frac{50\%}{\sqrt{E}} + 0.03$	Cu+scintillator (5.8λ+catcher)/Fe+quartz fibres $\frac{\sigma}{E} \approx \frac{100\%}{\sqrt{E}} + 0.05$
Muon	$\frac{\sigma}{p_T} \approx$ 2% @ 50 GeV to 10% at 1 TeV (ID+MS)	$\frac{\sigma}{p_T} \approx$ 1% @ 50 GeV to 5% at 1 TeV (ID+MS)
Trigger	L1+RoI-based HLT (L2+EF)	L1+HLT(L2+L3)

Cross section measurements

How to measure cross section?

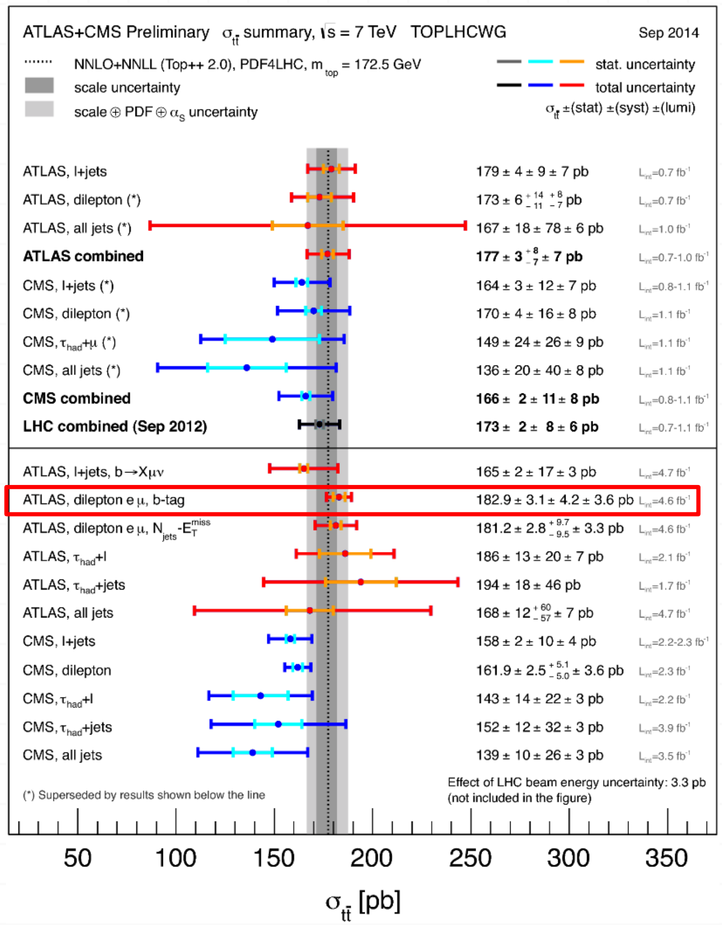
Definition: $n_{sig} = n_{bkg} + L \cdot \sigma$ ·detector/selection efficiency

With $f(n_{data}; n_{sig}) = \frac{n_{sig}^{n}}{n_{data}!} e^{-n_{sig}}$

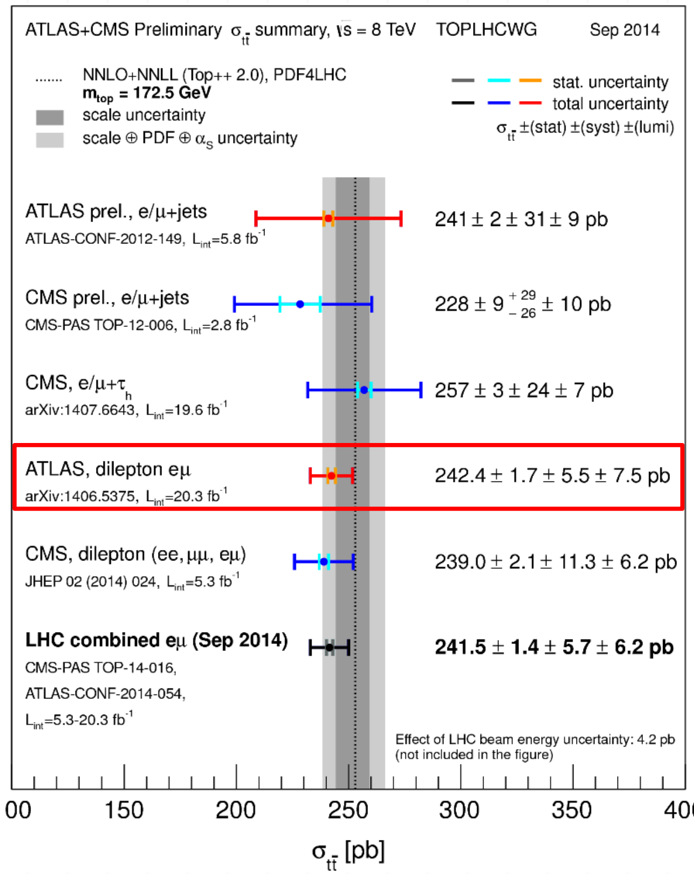
- **Cut and count** ($n_{data} = n_{sig}$): maximum likelihood solution of the poisson hypothesis
- **Using shapes**: use variable(s) sensitive to cross section to separate signal from bg
  - Fit number of signal events→$\sigma = \frac{n_{fit}}{L \cdot \epsilon}$
  - Fit cross section directly

$t\bar{t}$ inclusive cross section: summary

$\sigma(t\bar{t})$ @ $\sqrt{s} = 7$ TeV



$\sigma(t\bar{t})$ @ $\sqrt{s} = 8$ TeV



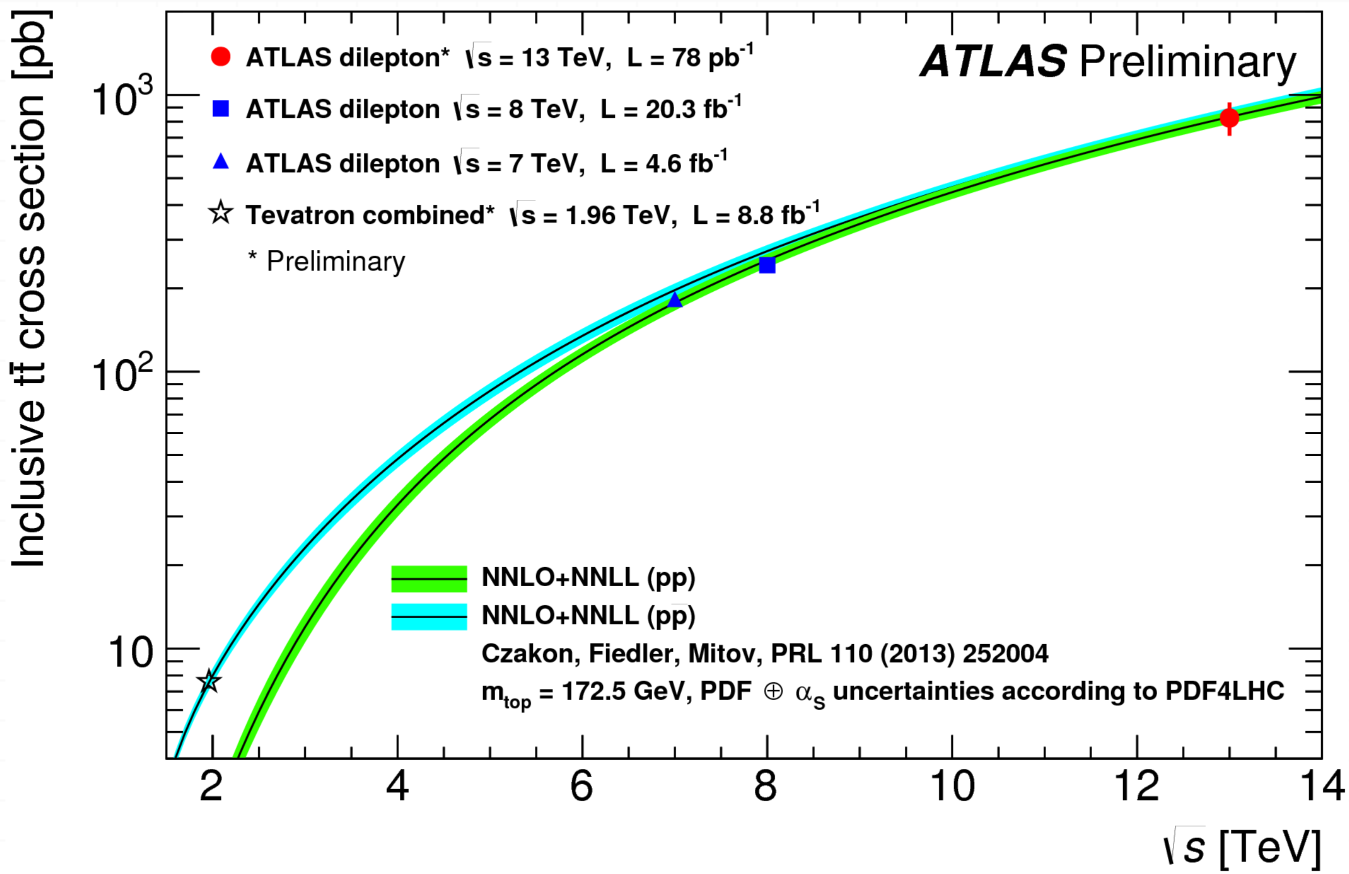
Good agreeement of all measurements with SM predictions

Experimental uncertainties already comparable with theoretical ones

Dilepton $e\mu$ measurement is the most precise measurement to date

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

$t\bar{t}$ inclusive cross section: summary



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

Top quark measurements

Phase space definitions

'Fiducial' phase space:

- Phase space region that closely mimic the actual detector coverage
- Same reco cuts applied to "truth" objects
  - Define "truth" objects, e.g. stable particles entering the detector, as close as possible to physics objects reconstructed in the detector
- ✓ Avoids model-dependent large extrapolations
- ✓ Common fiducial regions can be defined among different experiments
- ✗ Measurements cannot be compared with higher order predictions

'Full' phase space

- Measurements extrapolated to 4π and in the total energy range
- ✓ Common fiducial regions can be defined among different experiments
- ✓ *Could* allow comparisons with higher order predictions
- ✗ Model-dependet extrapolation outside the detector acceptance

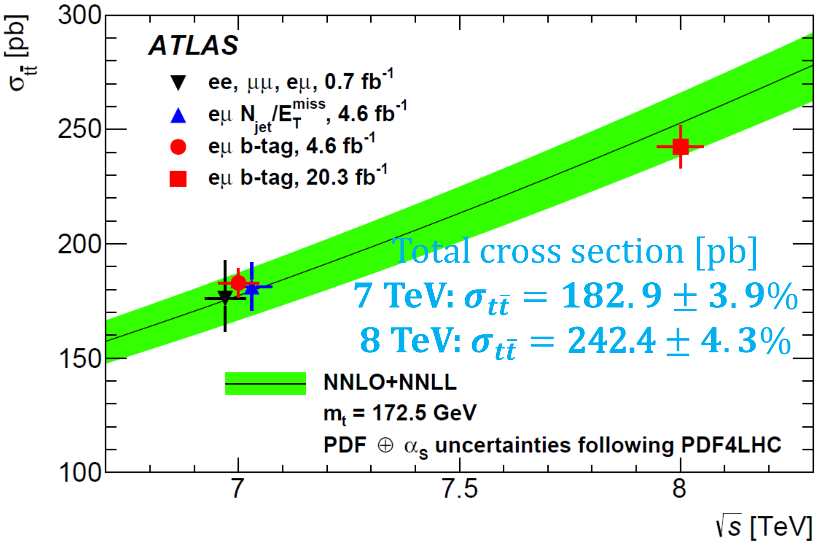
$t\bar{t}$ inclusive cross section $e\mu$ channel

EPJC 74 (2014) 3109

$\sqrt{s} = 7$ TeV, $\int Ldt = 4.6$ fb^{-1}
$\sqrt{s} = 8$ TeV, $\int Ldt = 20.3$ fb^{-1}

- Simultaneous fit of the total and fiducial $t\bar{t}$ production cross section, b-jet reconstruction and tagging efficiency in 1- and 2-btag samples
  - Significant reduction of major (btag) systematics
- Fiducial phase space: less MC generator dependent
  - No extrapolation to the full phase space

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\rm bkg}$$
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}C_b{\epsilon_b}^2 + N_2^{\rm bkg}$$



Total cross section [pb]
7 TeV: $\sigma_{t\bar{t}} = 182.9 \pm 3.9\%$
8 TeV: $\sigma_{t\bar{t}} = 242.4 \pm 4.3\%$

NNLO+NNLL predictions
7 TeV: $\sigma_{tt}^{th} = 177.3 \pm 9^{+4.6}_{-6.0}$ pb
8 TeV: $\sigma_{tt}^{th} = 252.9 \pm 11.7^{+6.4}_{-6.0}$ pb

Fiducial cross section
7 TeV: $\sigma_{t\bar{t}} = 2.615$ pb $\pm 3.8\%$
8 TeV: $\sigma_{t\bar{t}} = 3.448$ pb $\pm 4.1\%$

$t\bar{t}$ inclusive cross section $e\mu$ channel

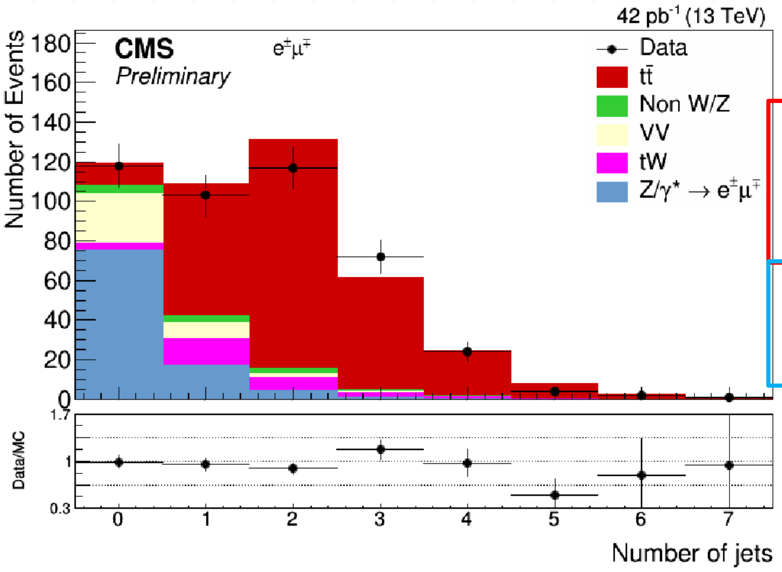
CMS-PAS-TOP-15-003

$\sqrt{s}$ = **13 TeV**, $\int Ldt = 42\text{pb}^{-1}$

Cut and count:

- Isolated OS $e\mu$ pair, $p_T > 20$ GeV
- ≥ 2 jets, $p_T > 30$ GeV, no btag
- $m_{ll} > 20$ GeV

Source	Number of events $e^{\pm}\mu^{\mp}$
Drell–Yan	6.4 ± 1.2
Non-W/Z leptons	8.5 ± 4.3
Single top quark	10.6 ± 3.4
VV (V = W or Z)	2.6 ± 0.9
Total background	28.1 ± 5.7
$t\bar{t}$ dilepton signal	207 ± 16
Data	220



Measured cross section

Total: $\sigma_{t\bar{t}} = 772 \pm 60(stat) \pm 62(syst) \pm 93\ (lumi)$ **pb**

Fiducial: $\sigma_{t\bar{t}} = 12.9 \pm 1.0(stat) \pm 1.1(syst) \pm 1.5(lumi)$ **pb**

NNLO+NNLL predictions

$\sigma_{tt} = 832^{+20}_{-29}(scale) \pm 35(PDF + \alpha_s)$

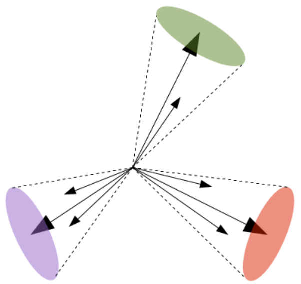
Top quark pairs differential cross section measurements

Total $\sigma_{t\bar{t}}$ measurements show very good agreement with the SM

- New physics phenomena can still affect the *shape* of $\sigma_{t\bar{t}}$

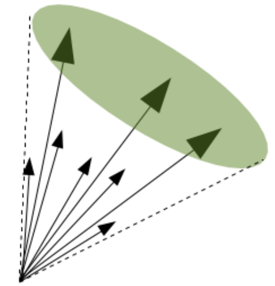
Top reconstruction strategies

'Resolved' topology



- Optimized for low-p_T (< 300 GeV) top quarks
- Top-quark decay products are well separated and can be recostructed individually
- Top-antitop kinematic evaluated from the reconstructed decay products

'Boosted' topology



- Optimized for high-p_T (> 300 GeV) top quarks
- Top quark decay products are not isolated
- Hadronically decaying top quark is reconstructed in a single large radius jet

Top quark pairs differential cross section measurement: what do we meausure?

Definition of the object "top-quark"

'Parton-level' top:

- the top quark approximately after final state radiation and before decay.

'Particle level' top (or pseudo-top):

- Observable constructed from *stable* particles directly related to the top

✓"Defined" in the full phase space
  - ✗ Parton top is a colored object → definition dependent on the MC generator

✓ Comparable with higher order Matrix Element predictions (with some caveat…)

✓Defined in detectable phase space.
✓Based on well defined quantities
✓Easier comparison to future MCs
✓Should be formulable as Rivet routine to act on MC generated final state

- ✗ Not directly comparable to ME calculations.
- ✗ "true" top kinematics are smeared→ could be less sensitive to new effects.

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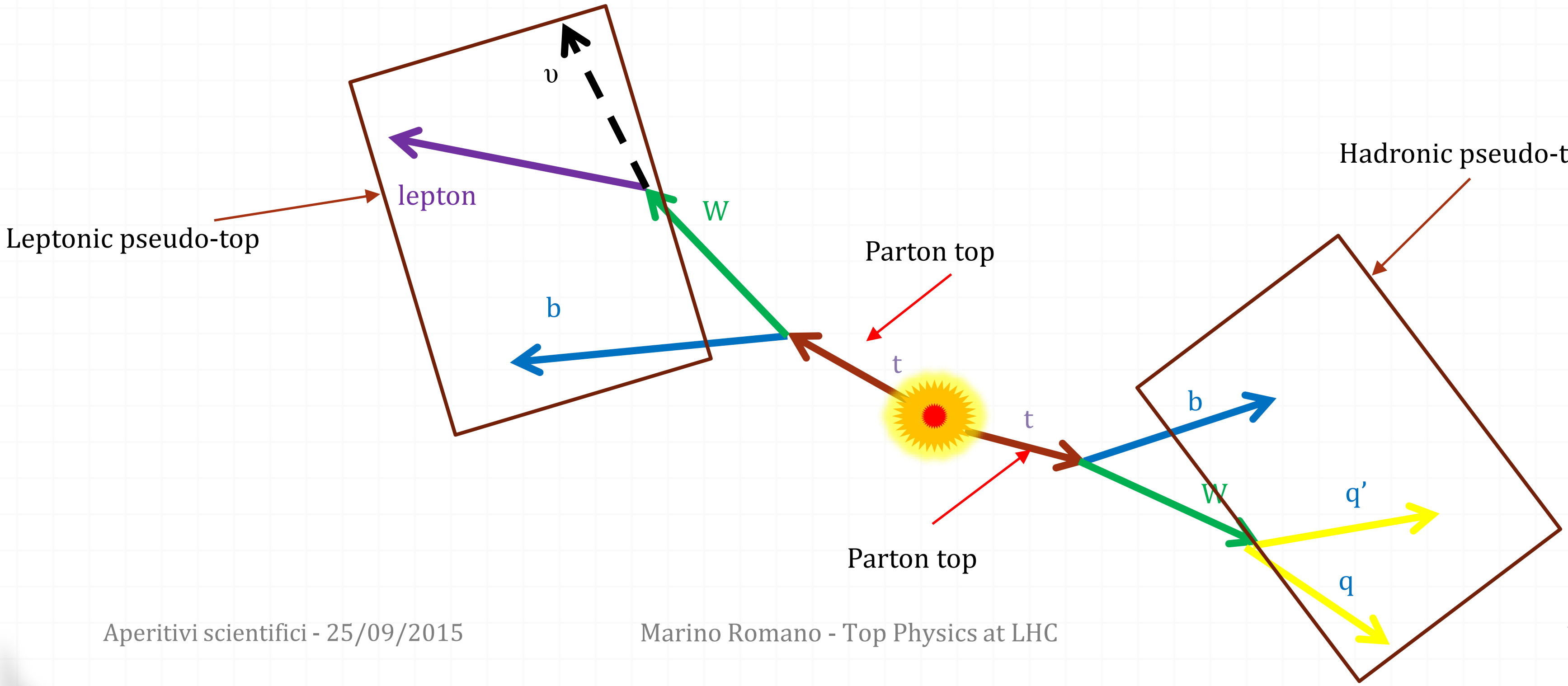

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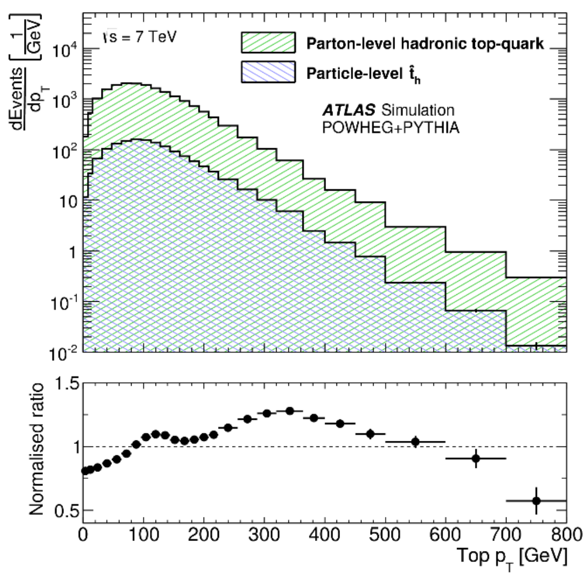
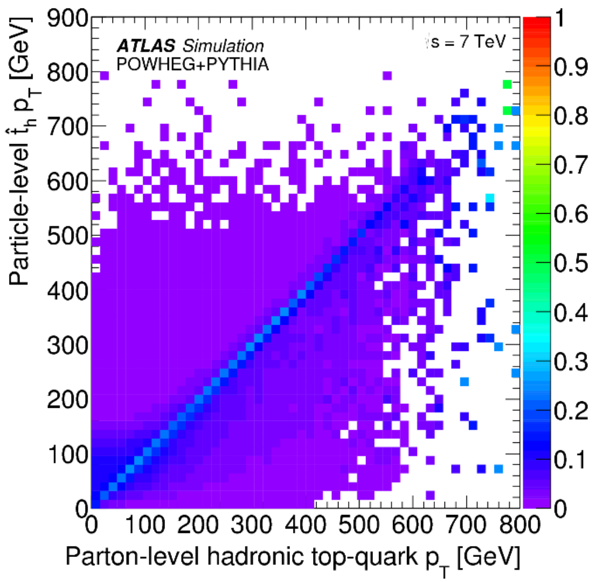
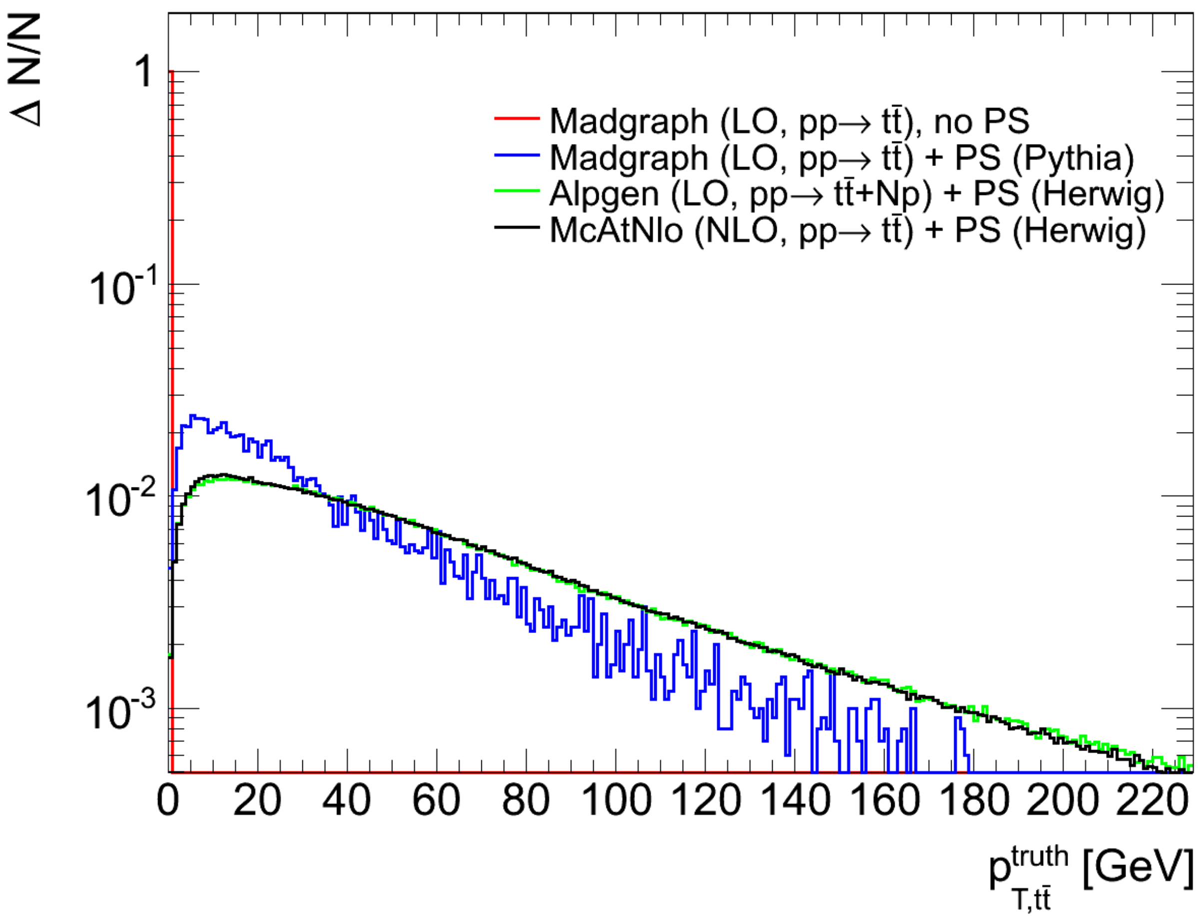
ATLAS: JHEP 06 (2015), 4.6 fb^{-1}, 7TeV

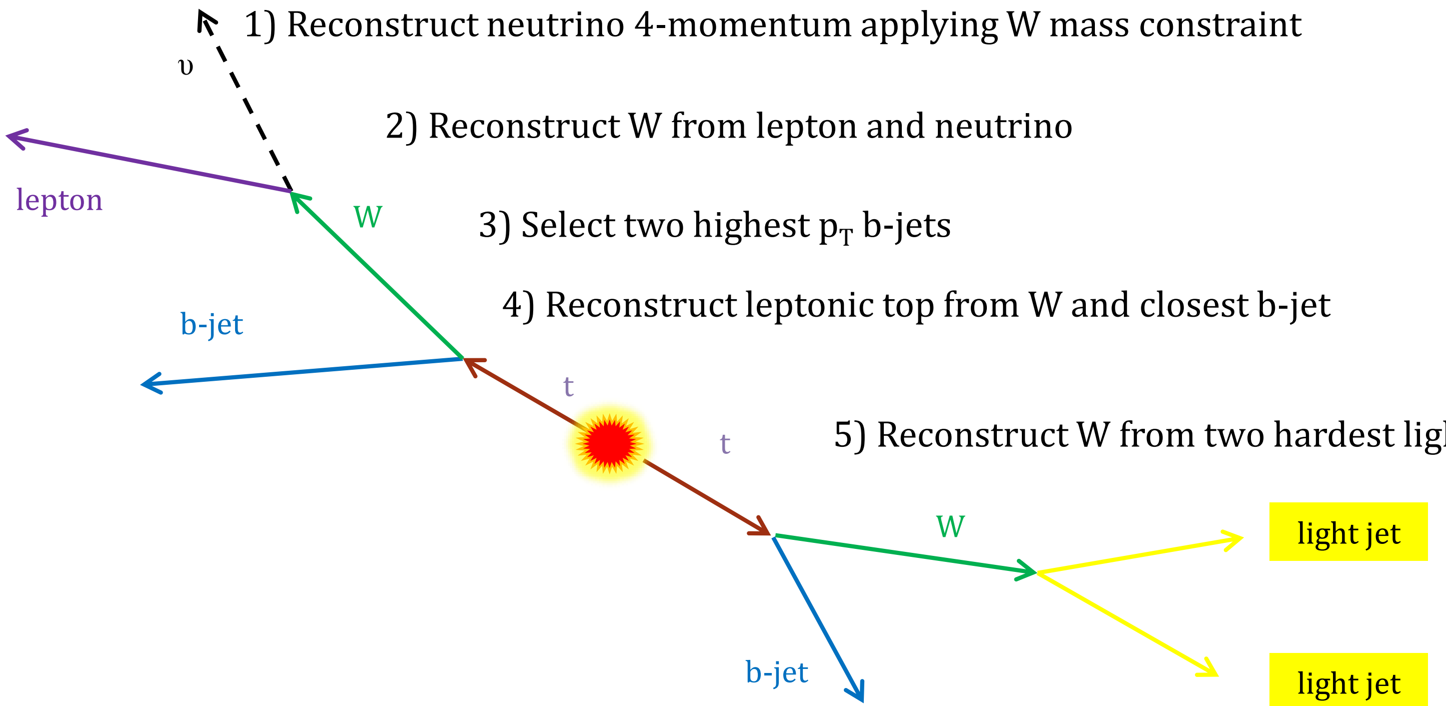




$\frac{1}{\sigma}\frac{d\sigma}{dp_{T,tt}}$, ME & PS dependence



Particle level reconstruction



1) Reconstruct neutrino 4-momentum applying W mass constraint

2) Reconstruct W from lepton and neutrino

3) Select two highest p_T b-jets

4) Reconstruct leptonic top from W and closest b-jet

5) Reconstruct W from two hardest light jets

6) Reconstruct hadronic top from W and the remaining b jet

The pseudo-tops reconstruction is identical at reco and particle level with the exclusion of the neutrino that at particle level is taken from truth

Parton level $t\bar{t}$ via a kinematic likelihood fit

- The $t\bar{t}$ system reconstruction is performed trough a kinematic fit using a maximum likelihood approach

$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{B}\left(\widetilde{E}_{p,1},\widetilde{E}_{p,2}|m_W,\Gamma_W\right)\cdot\mathcal{B}\left(\widetilde{E}_l,\widetilde{E}_\nu|m_W,\Gamma_W\right)\cdot \\
\cdot\; & \mathcal{B}\left(\widetilde{E}_{p,1},\widetilde{E}_{p,2},\widetilde{E}_{p,3}|m_t,\Gamma_t\right)\cdot\mathcal{B}\left(\widetilde{E}_l,\widetilde{E}_\nu,\widetilde{E}_{p,4}|m_t,\Gamma_t\right)\cdot \\
\cdot\; & \mathcal{W}\left(\widehat{E}_x^{miss}|\tilde{p}_{x,\nu}\right)\cdot\mathcal{W}\left(\widehat{E}_y^{miss}|\tilde{p}_{y,\nu}\right)\cdot\mathcal{W}\left(\widehat{E}_{lep}|\widetilde{E}_{lep}\right)\cdot \\
\cdot\; & \prod_{i=1}^{4}\mathcal{W}\left(\widehat{E}_{jet,i}|\widetilde{E}_{p,i}\right)\cdot P\left(b\text{ tag}\mid\text{quark}\right),
\end{aligned}
$$

Breit-Wigner functions for top and W decays ($m_{W/t}$ and $\Gamma_{W/t}$ from PDG)

Energy transfer functions

Jet flavor probability

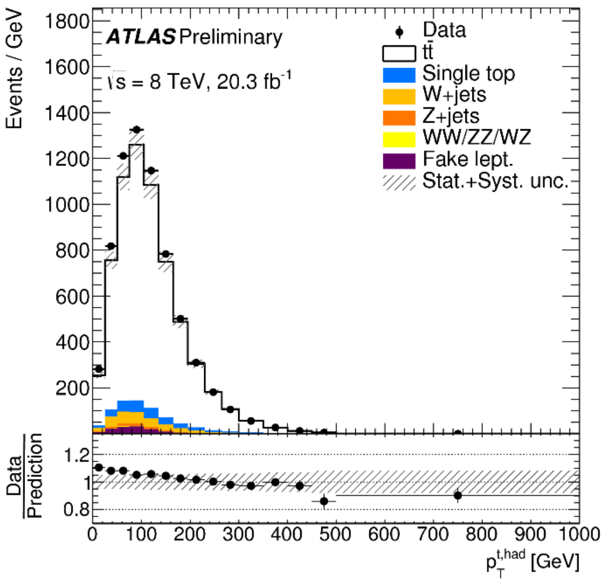
- The likelihood assesses the compatibility of the event with a top-antitop pair production
- The algorithm is fed with ≥ 4 reconstructed highest-pt jets (and their *b*-tag info), the lepton and the E_T^{miss}
- The output is the permutation of the four jets, lepton and E_T^{miss} that maximizes the likelihood

From reco to ‘truth’ spectra

Reconstructed spectra

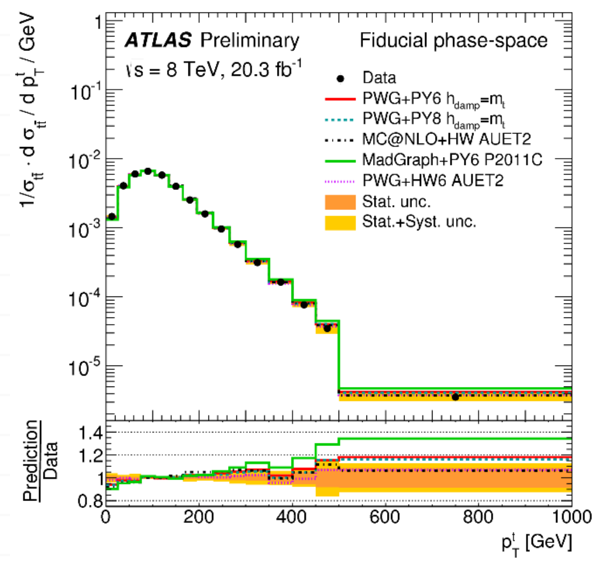
$$x^i_{part} = \varepsilon^i_{eff} \cdot \sum_j M^{-1}_{ij} \cdot \varepsilon^j_{acc}(N^j_{reco} - N^j_{bkg})$$

Parton/particle level cross section



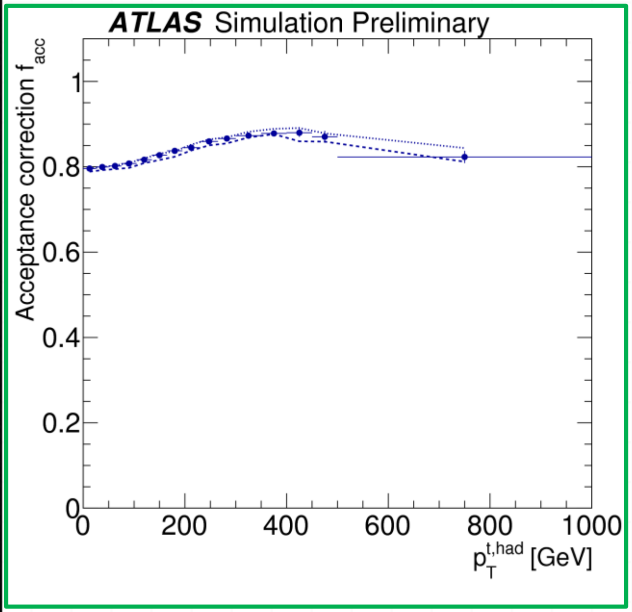
Unfolding

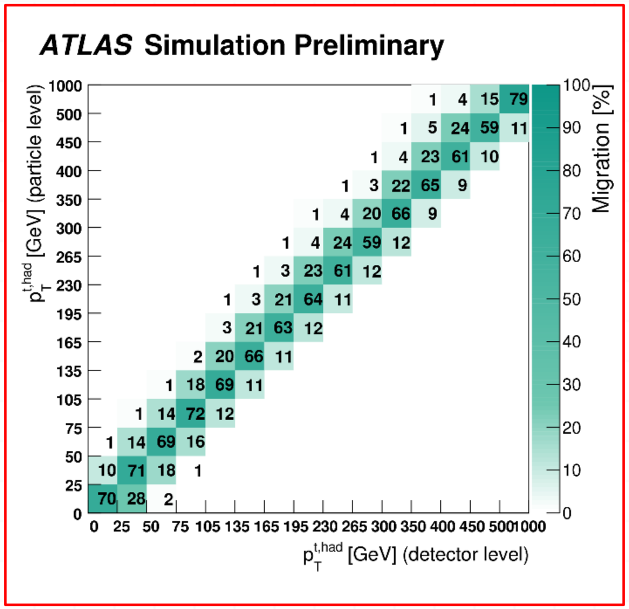
Procedure applied everytime we want to correct distributions from reconstruction and selection effects

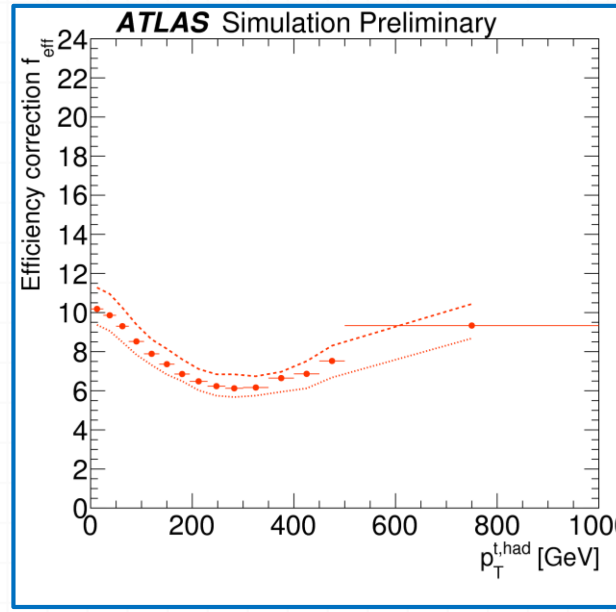


From reco to ‘truth’ spectra

$$x_{part}^{i} = \varepsilon_{eff}^{i} \cdot \sum_{j} M_{ij}^{-1} \cdot \varepsilon_{acc}^{j} (N_{reco}^{j} - N_{bkg}^{j})$$





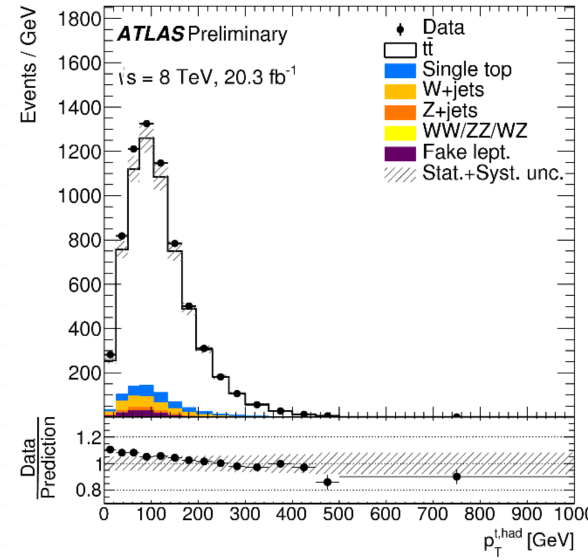


$\varepsilon_{acc}^{j} = 1$ @ parton level if there are no over/underflow

Differential cross section @ 8 TeV

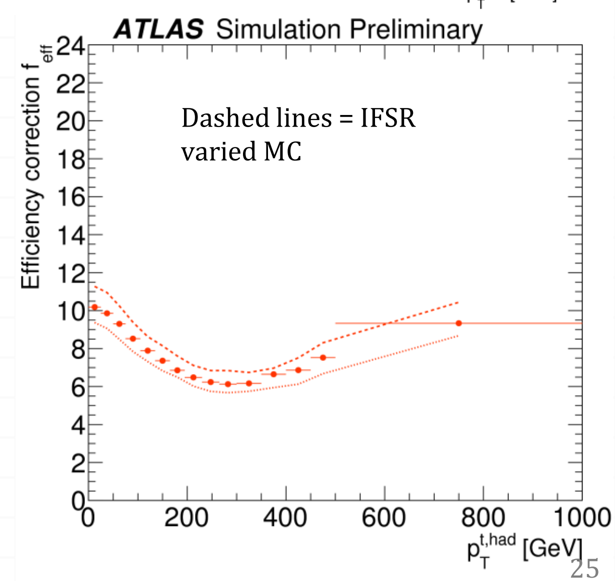
NEW ATLAS: TOPQ-15-06

- Top-antitop normalized differential cross section $\left(\frac{1}{\sigma}\frac{d\sigma}{dX}\right)$ where $X = m_{t\bar{t}}, p_{\mathrm{T},t\bar{t}}, |y_{t\bar{t}}|, p_{T,t}$ and $|y_t|$ + 6 more kinematic variables built from t and $\bar{t}$ 4-momenta (particle and parton level)
  - *Normalized* measurement more precise than the *absolute* →cancellation of correlated systematics
- Cut-based analysis in the $l(e/\mu)$+4jets(2 b-tag) channel
- Main uncertainties: b-tag, JES and IFSR



Selection cuts

- Electrons, muons, and jets: $p_t > 25\ GeV, |\eta| < 2.5$
- Exactly one lepton
- At least four jets, at least 2 b jets.
- No E_T^{miss} cut (the 2 b-jet cut is strong enough to suppress the QCD background)



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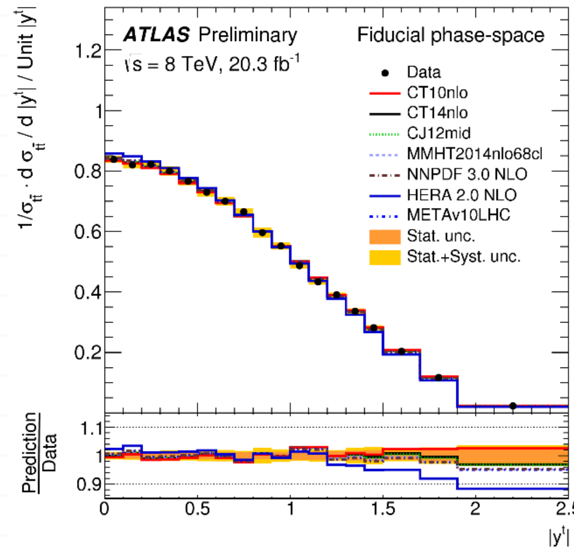
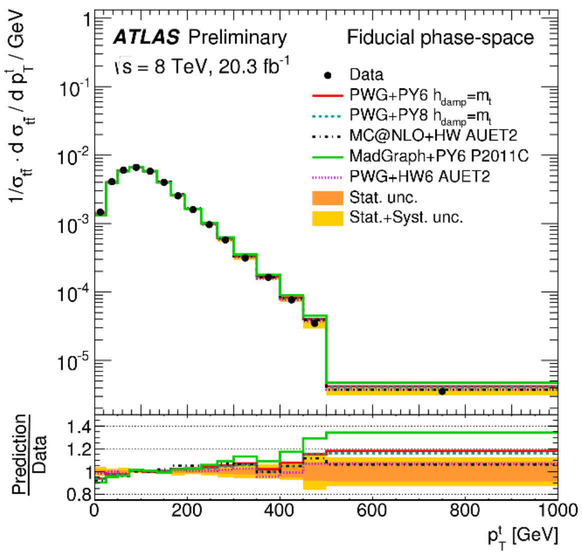
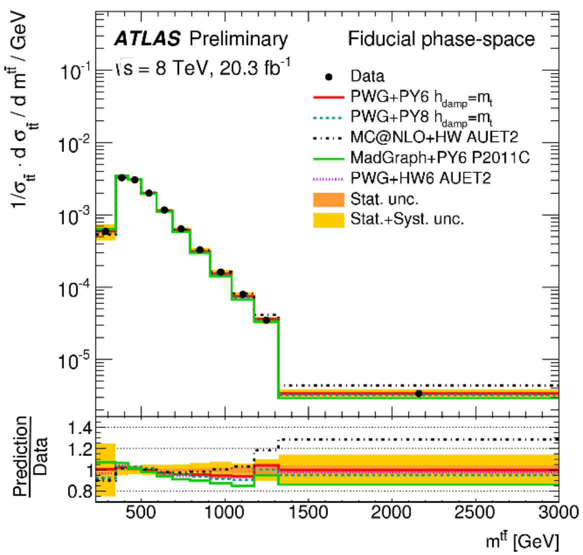
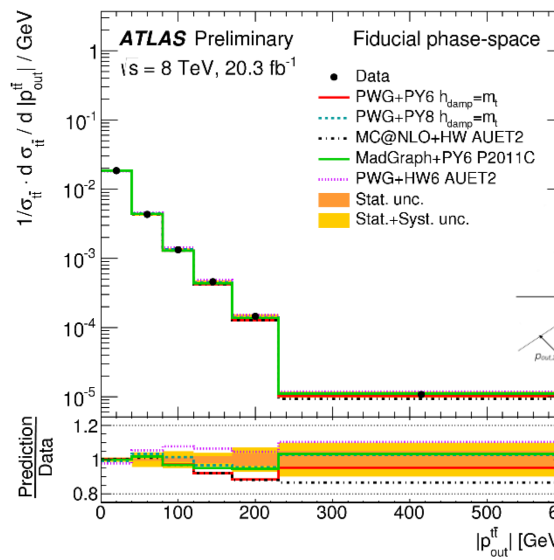
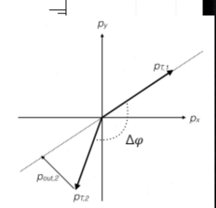










Differential cross section @ 8 TeV

CMS: CERN-PH-EP-2015-117 (arXiv:1505.04480)

Analysis performed in the single lepton and dilepton channels

Normalized differential cross section $\frac{1}{\sigma}\frac{d\sigma}{dX}$ at parton and particle level

- $X = p_T^l, \eta^l, p_T^b, \eta^b, p_T^{b\bar{b}}$ and m^{bb} at particle level
- $X = p_T^t, y^t, p_T^{t\bar{t}}, y^{t\bar{t}}, m^{t\bar{t}}$ + 4 more kinematic variables built from t and $\bar{t}$ 4-momenta at parton level

Single lepton (e/μ) selection:

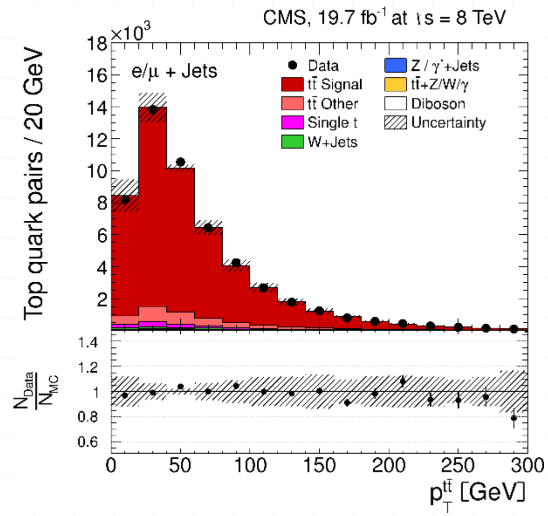
- Lepton $p_T > 33$ GeV, $|\eta| < 2.1$
- >= 4 jets (2 b-tag), $p_T > 30$ GeV, $|\eta| < 2.1$

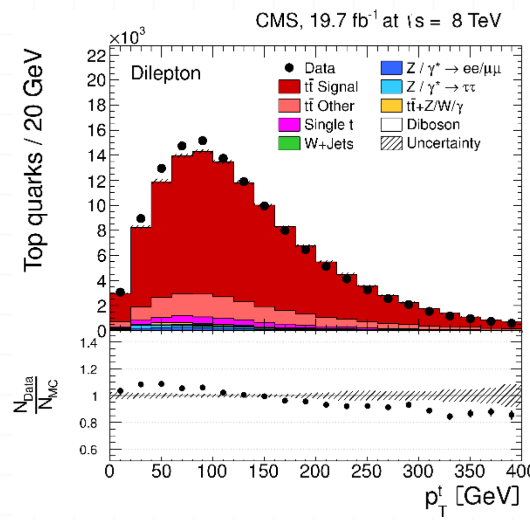
Dilepton ($ee/e\mu/\mu\mu$) selection:

- 2 leptons $p_T > 20$ GeV, $|\eta| < 2.1$
- Exclude Z boson mass window
- >= 2 jets (at least one b-tag), $p_T > 30$ GeV, $|\eta| < 2.1$
- $E_T^{miss} > 40$ GeV

Dilepton recontruction:

- Algebraic reconstruction of neutrino momenta: event p_T balance, $M_t = M_{\bar{t}}, M_W = 80.4$ GeV constraints
- M_t smearing according to detector resolution to increase the number of solvable events

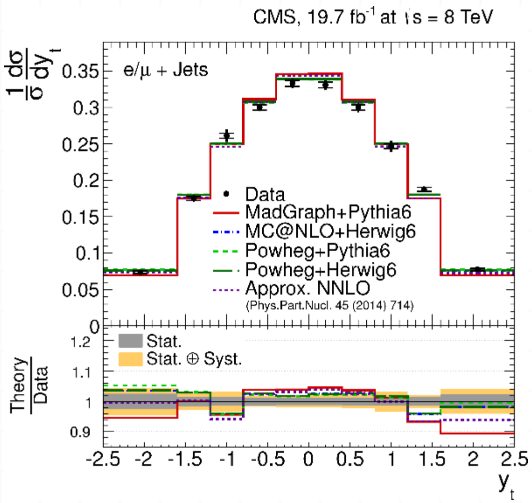


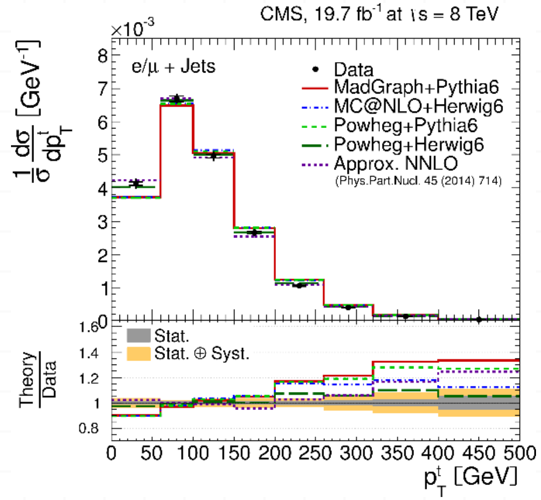


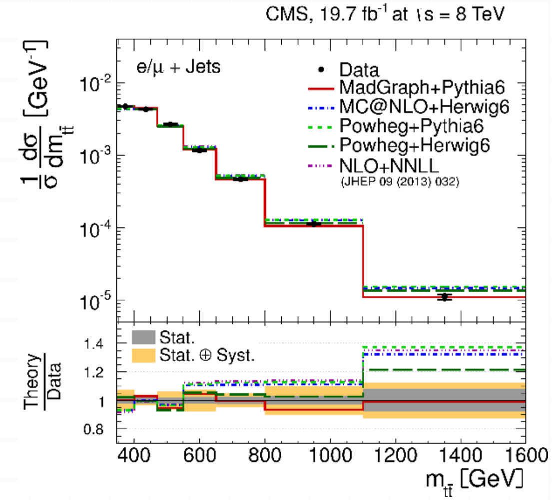
Differential cross section @ 8 TeV

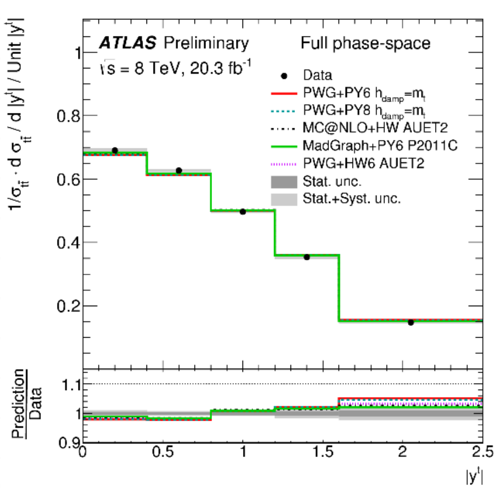
CMS: CERN-PH-EP-2015-117 (arXiv:1505.04480)

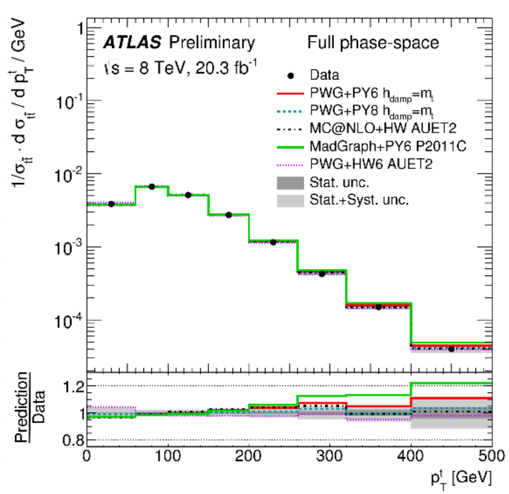
Parton level results (+ comparison with ATLAS)

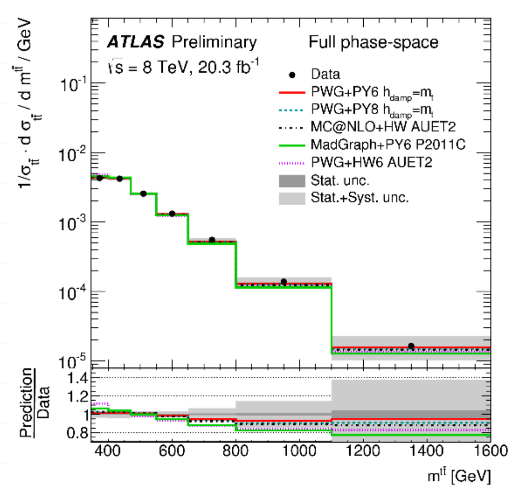








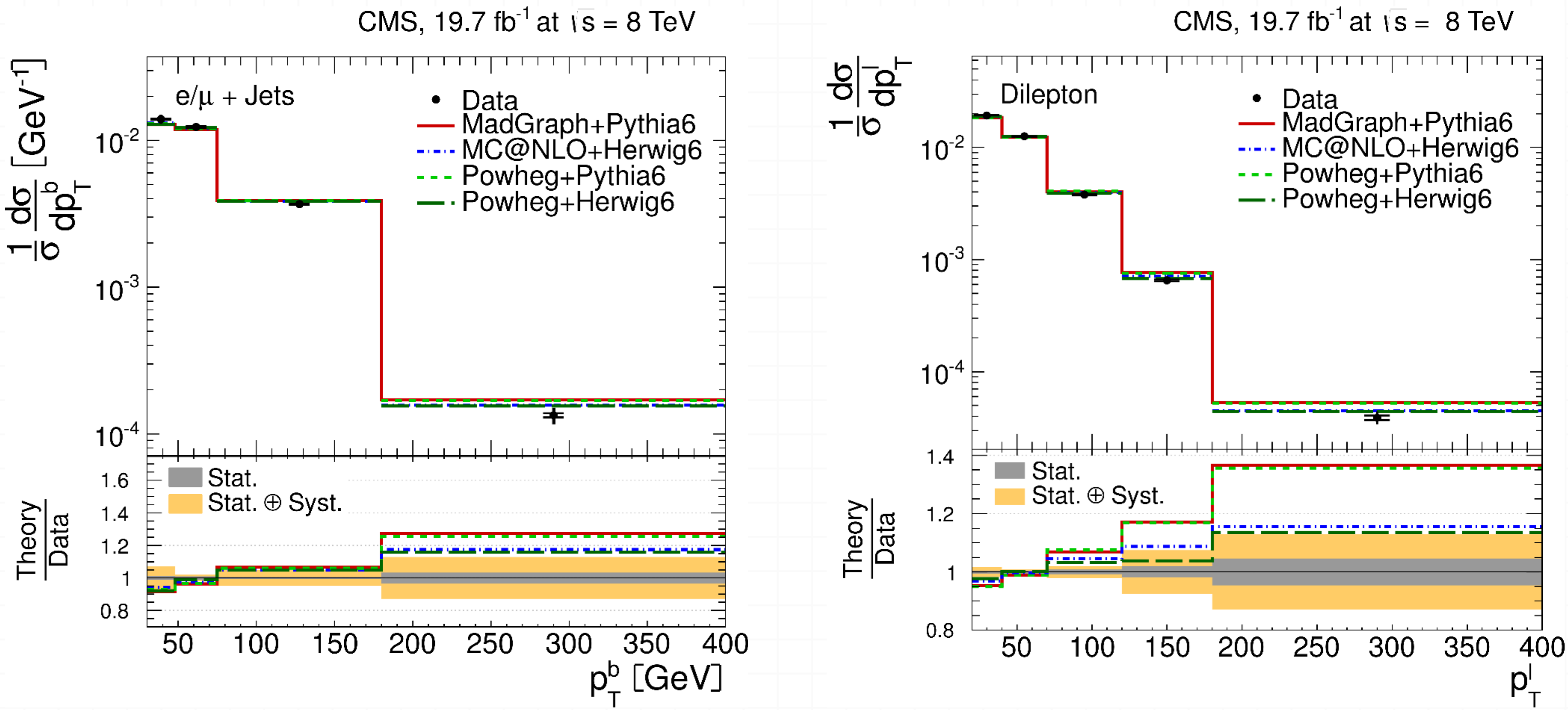




Differential cross section @ 8 TeV

CMS: CERN-PH-EP-2015-117 (arXiv:1505.04480)

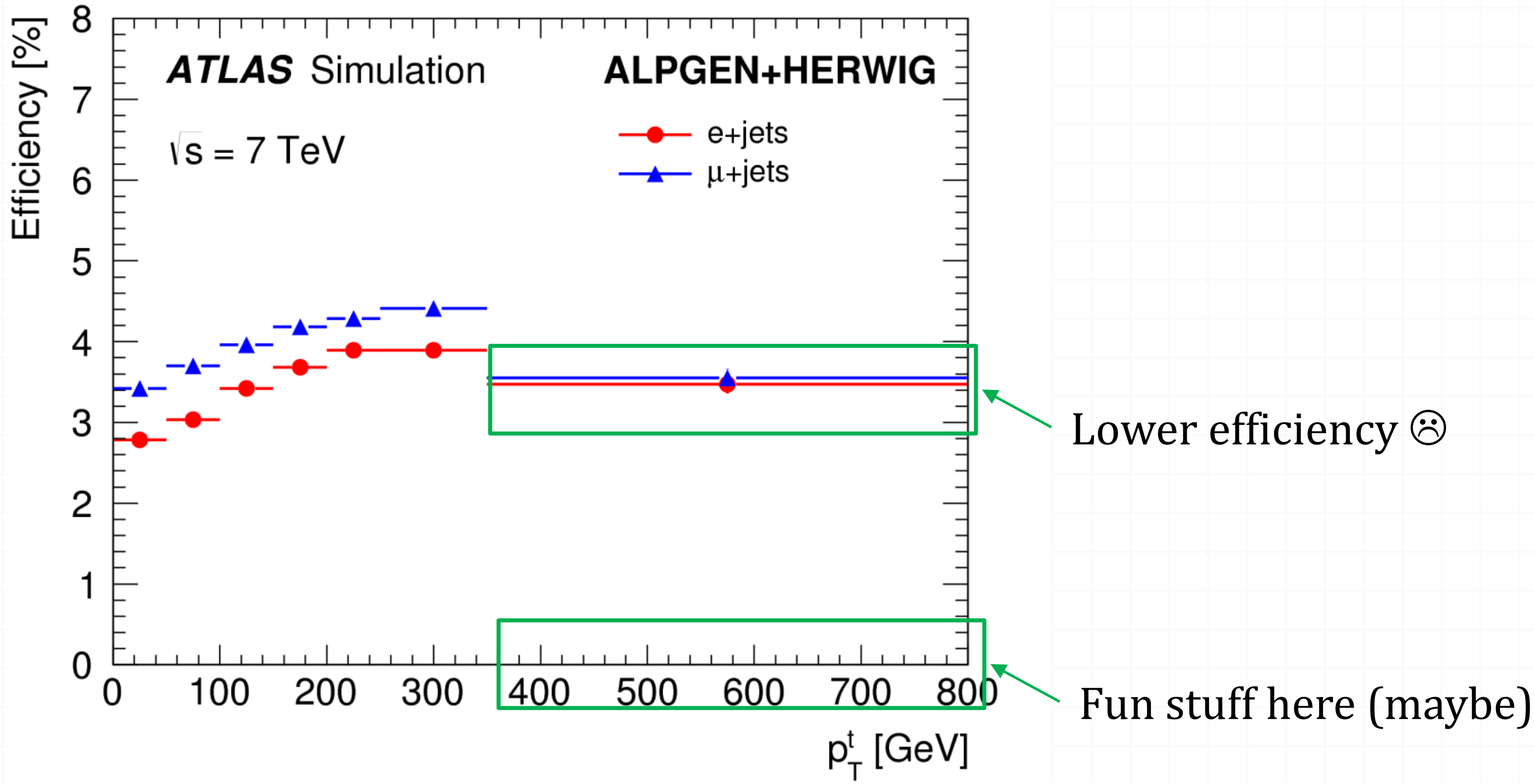
Particle level results



Main sys. uncertainty: parton shower/hadronization (comparison between Pythia6 and Herwig).

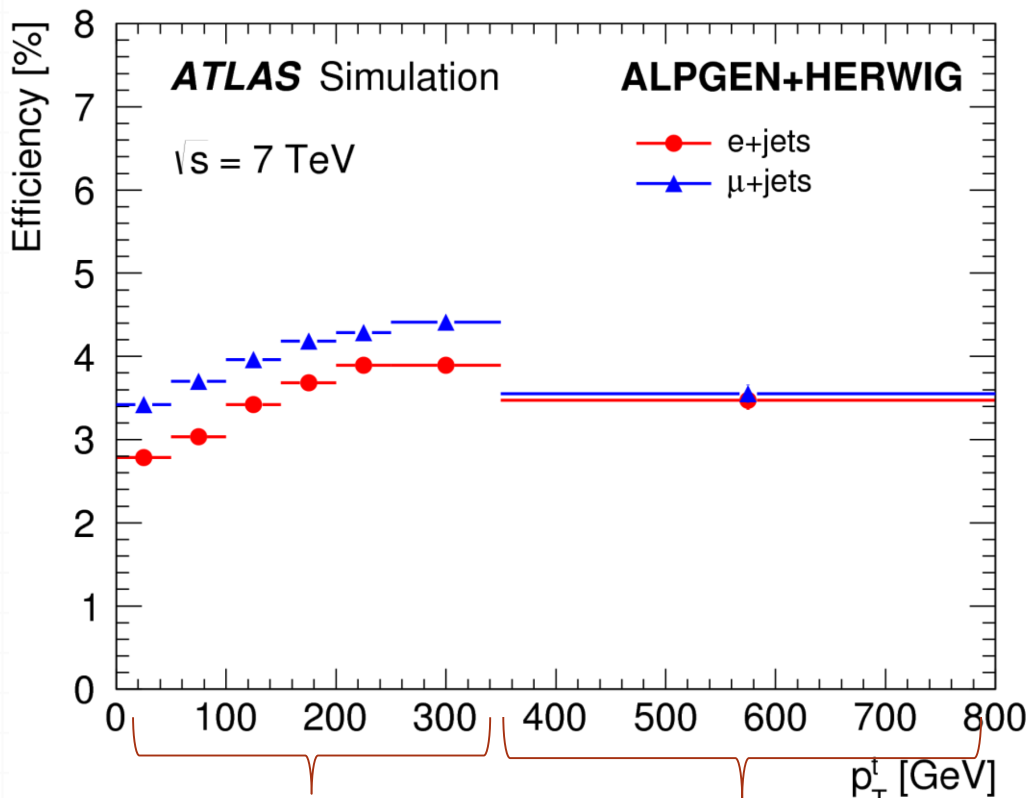
Can we do better?

[Phys. Rev. D 90, 072004]



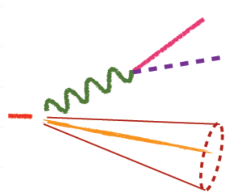
Can we do better?

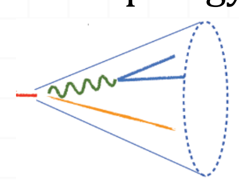
[Phys. Rev. D 90, 072004]

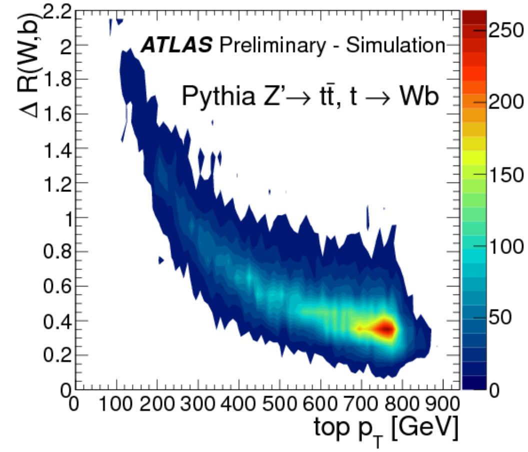


'Resolved' topology

'Boosted' topology







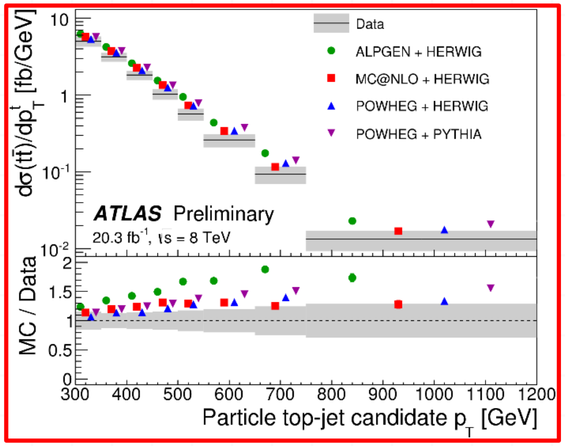
Rule of thumb:

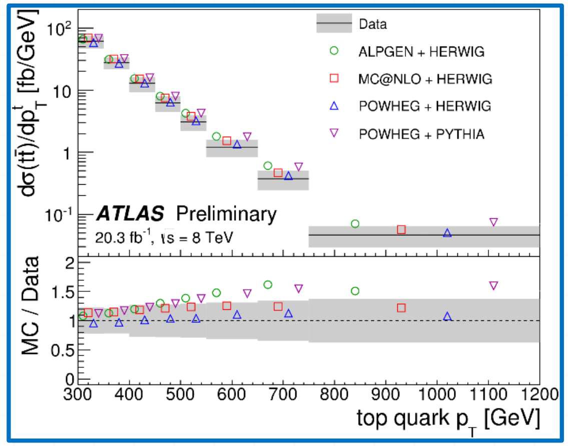
$$\Delta R(W,b) \approx \frac{2m_t}{p_T}$$

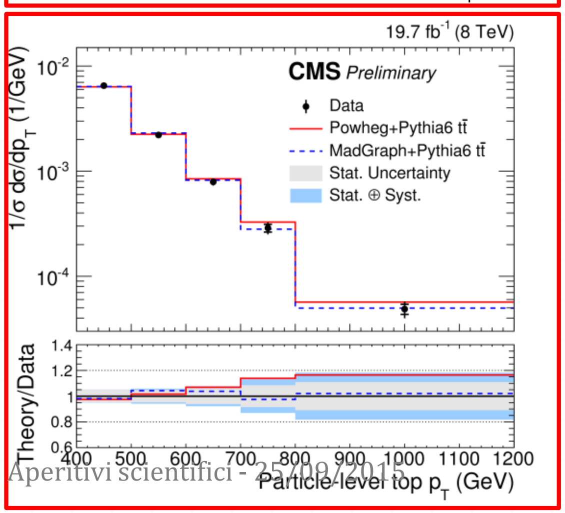
$t\bar{t}$ differential cross section: boosted tops

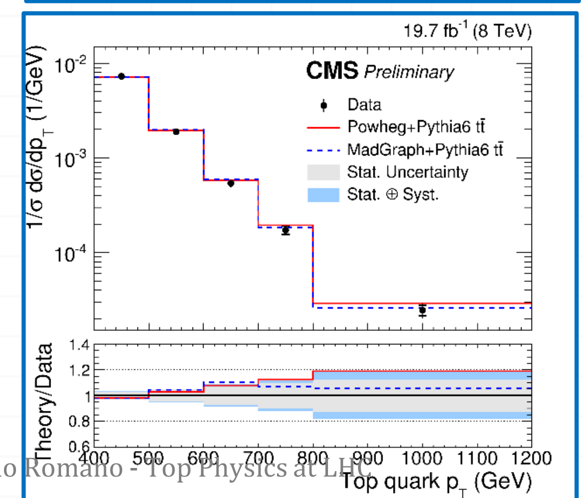
CMS-PAS-TOP-14-012 ATLAS-CONF-2014-057

- First measurement of $\frac{d\sigma}{dp_{T,t}}$ (ATLAS) and $\frac{1}{\sigma}\frac{d\sigma}{dp_{T,t}}$ (CMS) for high-p_T top quarks
- Semi-leptonic (e/μ) channel: boosted hadronic top defined as a single large-R jet
- Fiducial (particle pseudo tops) and total (parton tops) phase space measurements









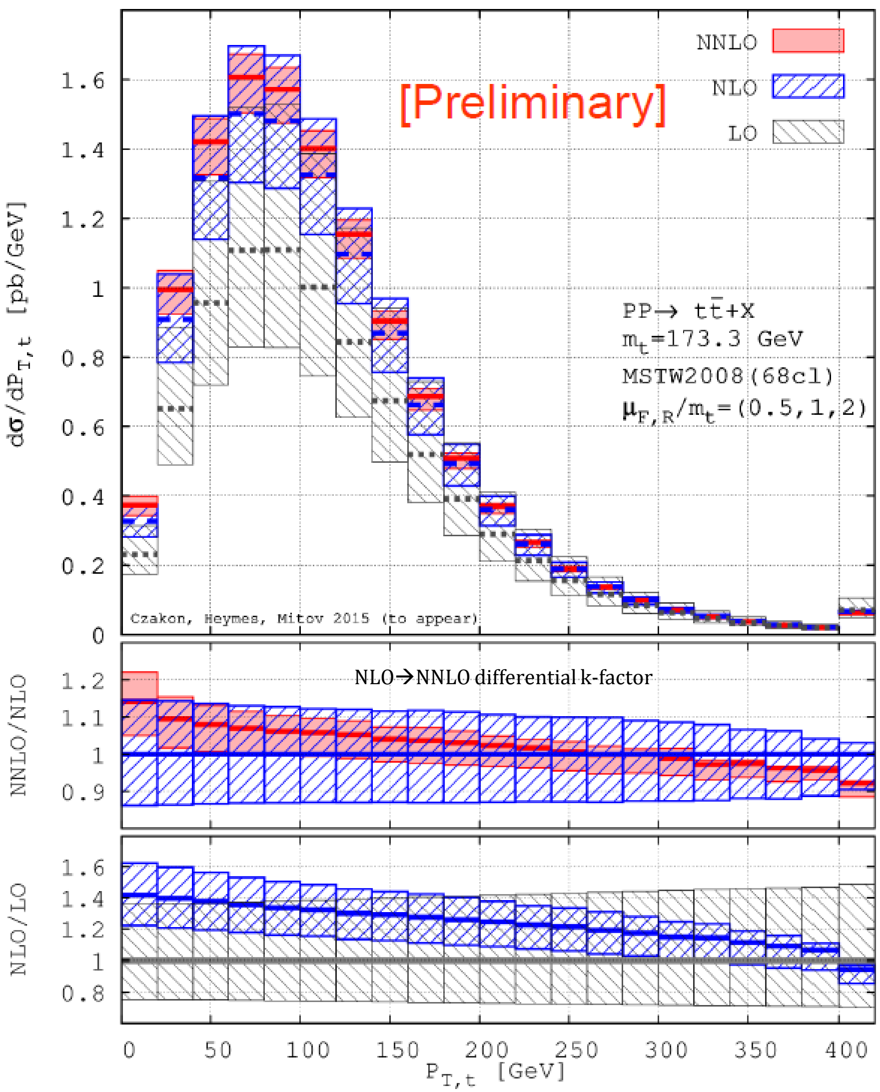
Measured σ in general lower than predictions

- Discrepancy tends to increase at high p_T
- In agreement with the behavior observed in resolved analyses

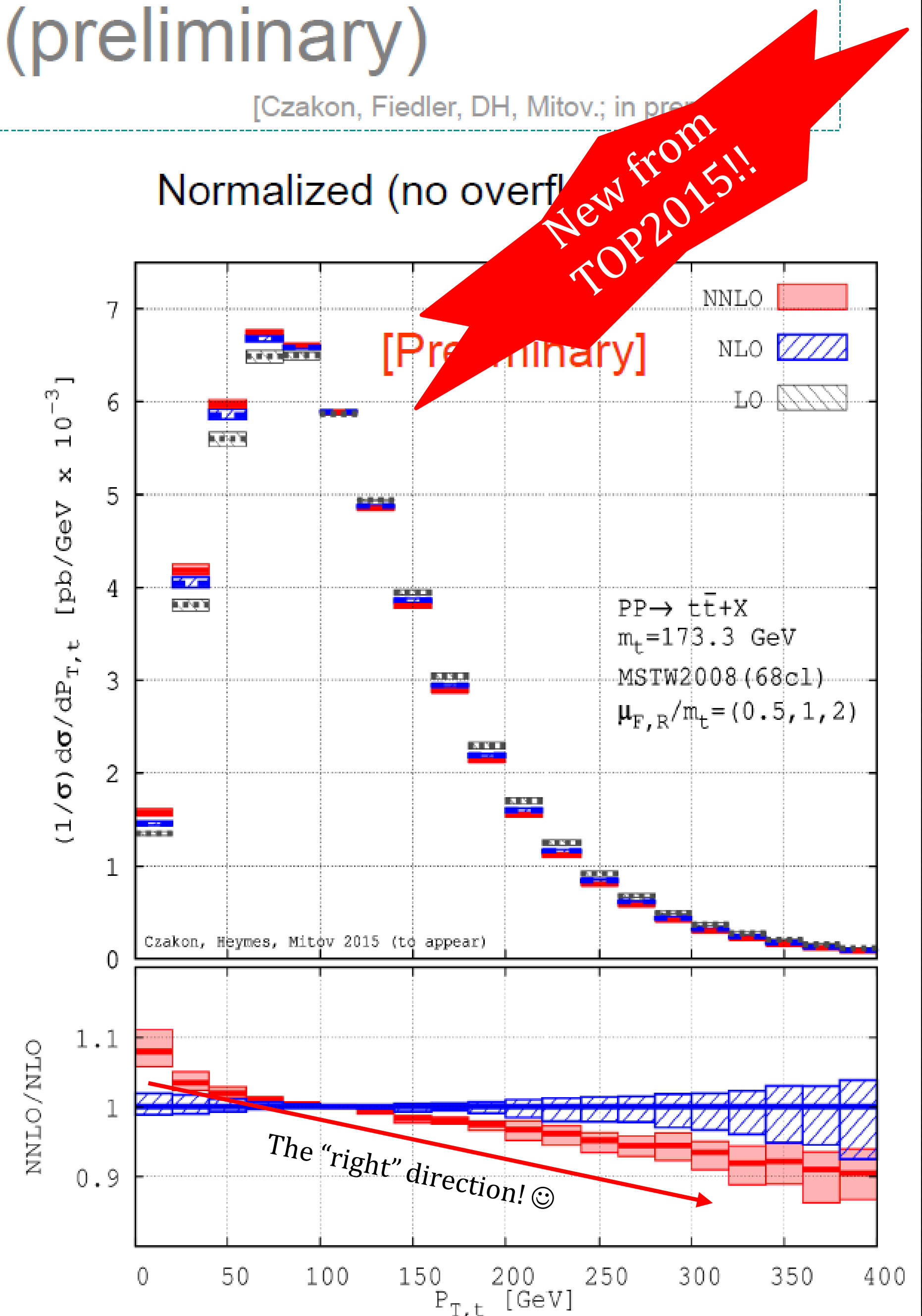
P_T-distribution LHC 8TeV (preliminary)

[Czakon, Fiedler, DH, Mitov.; in pre

Absolute normalization



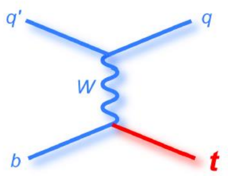
Normalized (no overfl



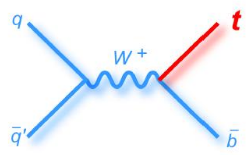
Let’s not forget about single top!

Single top-quark can be produced via electroweak interaction, involving a *Wtb* vertex

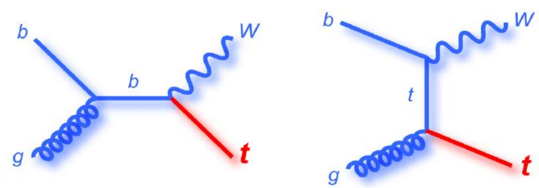
t-channel



s-channel



Wt-channel



$\sqrt{s}$	σ (*t-channel*)[pb]	σ (*s-channel*) [pb]	σ (*Wt-channel*) [pb]
8 TeV	87.8 ± 3.4 Phys. Rev. D 83, 091503(R) (2011)	5.6 ± 0.2 Phys. Rev. D 81, 054028 (2010)	22.4 ± 1.5 Phys. Rev. D 82, 054018 (2010)

NLO+NNLL with mt = 172.5 GeV

Measurement of the single top production provide a test of SM predictions:

- Production cross section and determination of $|V_{tb}|$
  → test of unitarity of the CKM matrix
- Probe *b*-quark structure function

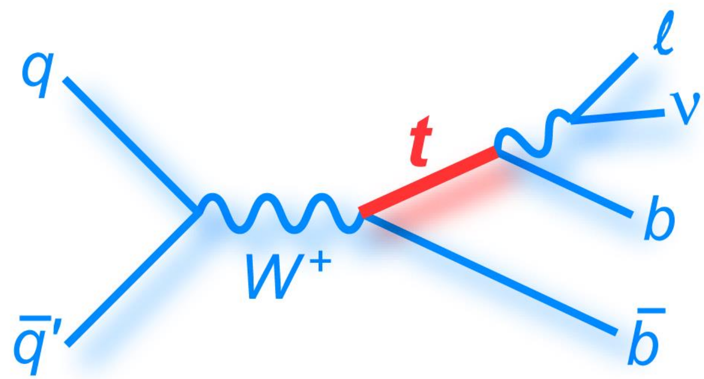
Probe for BSM physics

- Resonances (*W',H+,…*), vector like quarks, anomalous couplings
- Background for Higgs and several BSM processes

s-channel cross section

Semileptonic signature:

- One isolated high-p_T lepton
- Two central b-jet
- Missing transverse energy



- The most channeling single top process at the LHC
  - Low cross section
  - Difficult to separate from the backgrounds
- Main backgrounds: top pair and W+jets
- Multiavariate analyses based on Boosted Decision Tree (ATLAS/CMS) and Matrix Element method (ATLAS)

s-channel at 8 TeV (ME method)

ATLAS-CONF-2015-047

New from TOP2015!!

Event selection:

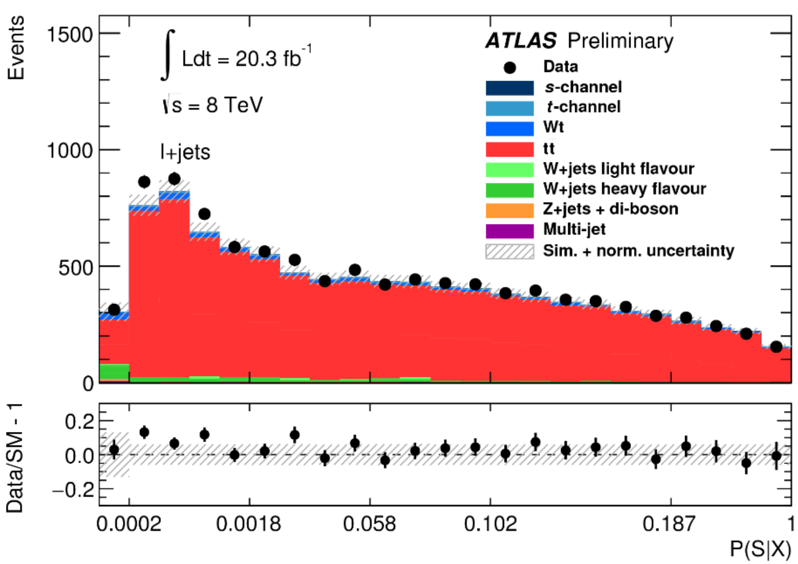
- Single isolated lepton ($p_T > 30\text{GeV}, |\eta| < 2.5$)
- 2 central, b-tagged jets ($p_T > 40(30)\text{GeV}$ for 1°(2°) jet

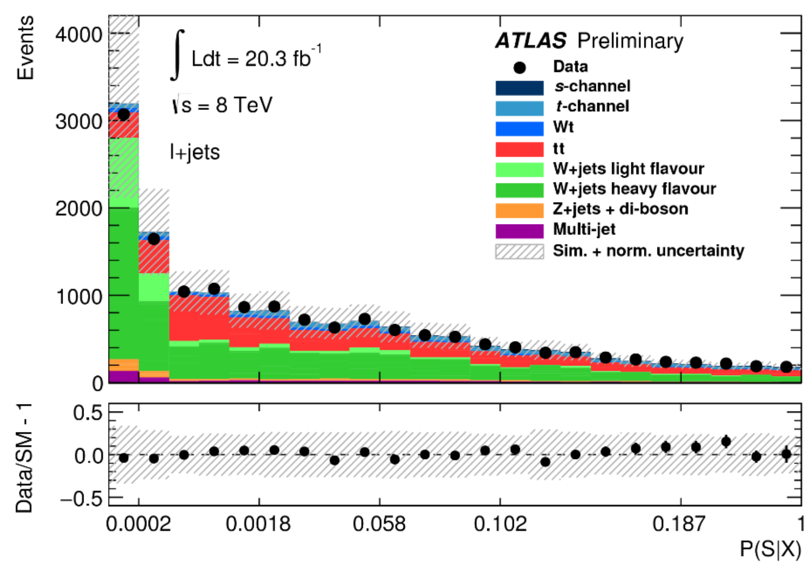
Analysis strategy:

- Define a discriminant

$$P(S|X) = \frac{\sum_i \alpha_{S_i} P(X|S_i)}{\sum_i \alpha_{S_i} P(X|S_i) + \sum_i \alpha_{B_i} P(X|B_i)}$$ → probability for a measured event (X) to be a signal event (S)

  - Per event probabilities computed using theoretical calculations
  - Discriminant evaluated in the signal region, $t\bar{t}$ and W+jets control regions



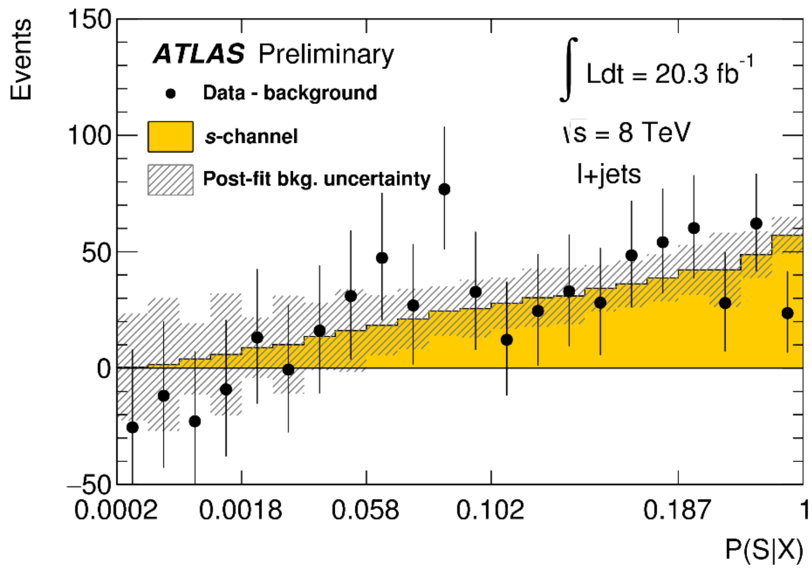


s-channel at 8 TeV (ME method)

ATLAS-CONF-2015-047

New from TOP2015!!

- *s*-channel cross section extracted via a binned maximum likelihood fit of the ME discriminant in the signal region



$\sigma_s = 4.8 \pm 1.1(stat.)^{+2.2}_{-2.0}(syst.)$ pb
Significance 3.2σ (exp. 3.9σ)
$\sigma_s^{th} = 5.61 \pm 0.22$ pb

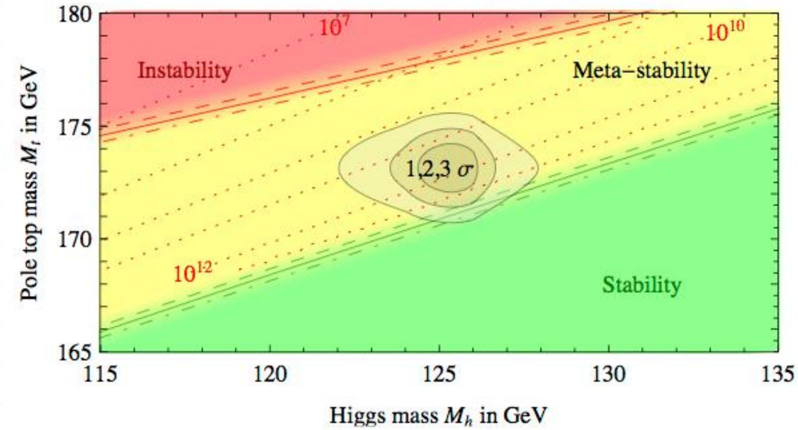
→ First EVIDENCE of the s-channel production at LHC

Top Mass measurements

Higgs potential stability

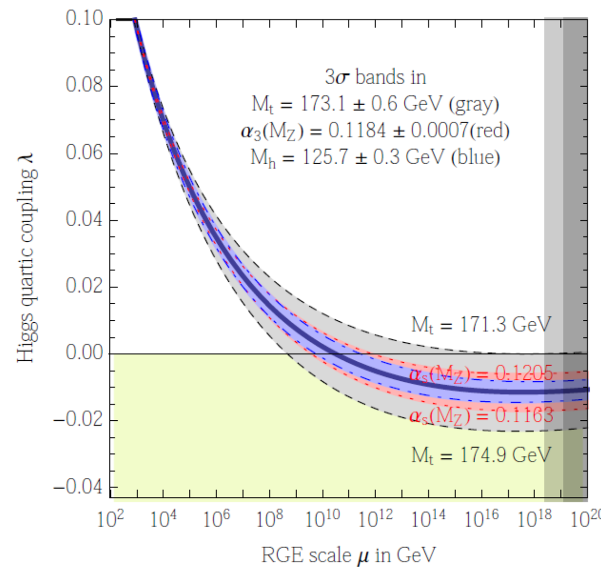
The current experimental values for m_H and m_t are very intriguing

- They put us in a region where the Higgs quartic coupling could be rather small, null or even negative near the Plank scale
- If $\lambda(\mu)$> 0, the EW vacuum is a global minimum
- If $\lambda(\mu)$<0 the EW vacumm is meta-stable (lifetime longer than the age of the universe



Renewed interest for precision m_t measurements:

- Even in the absence of direct evidences for new physics at the LHC, the experimental information top and Higgs masses gives us useful hints on the structure of the theory at very short distances



Top quark mass measurements

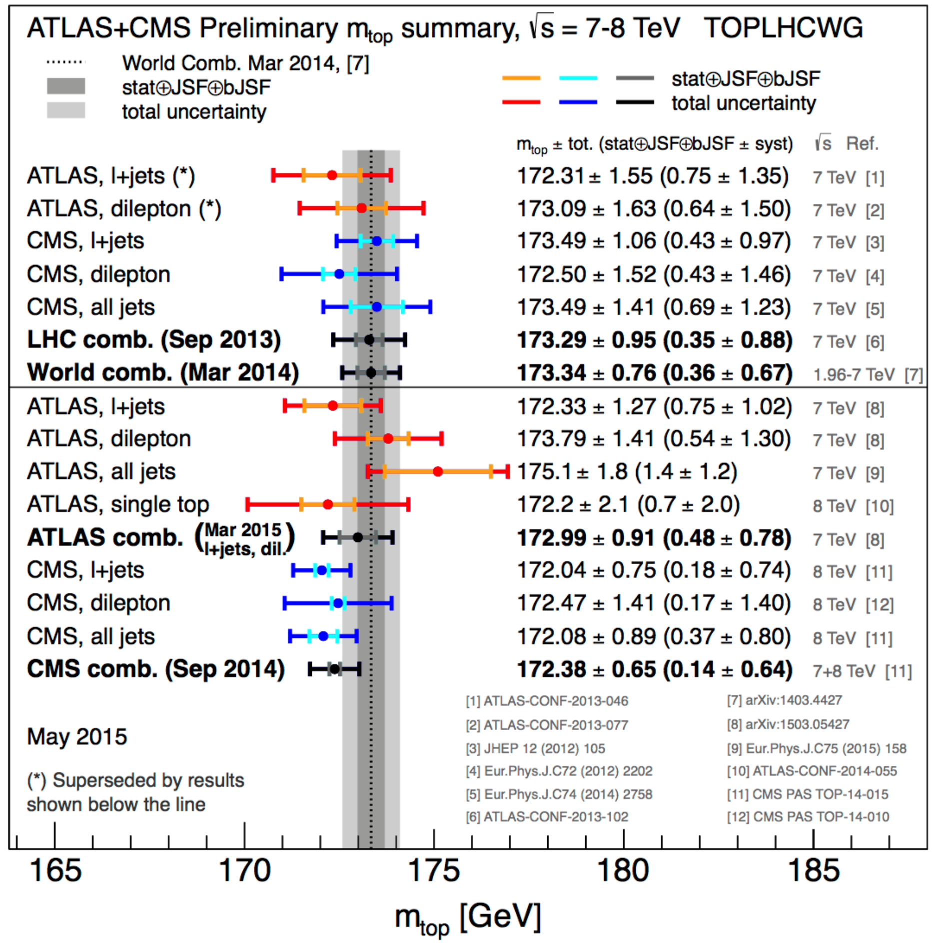
- What do we measure?
  - M_t generally extracted directly from decay products
  - We compare to Monte Carlo expectations, so basically we really measure "MC parameter" m_t
- How?
  - Variety of techniques: compare a predicted shape with measurement, calculate likelihood of a sample as a function of top mass…
- Uncertainties:
  - Dominated by systematics: mostly jet & theory related
  - The top is actually the most precised measured quark

Top quark mass in Run I

Top mass summary

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TopLHCWGSummaryPlots

Precision on m_t measurement at LHC is constantly improving and getting closer to the precision achieved at Tevatron



Top quark mass at ATLAS

Most precise measurement in ATLAS

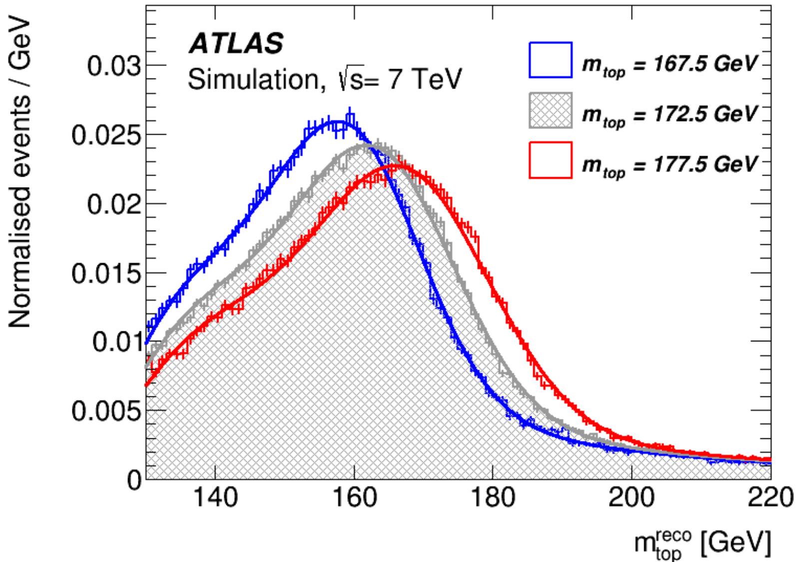
EPJC 75 (2015) 330

$\sqrt{s} = 7$ TeV, $\int Ldt = 4.6$ fb^{-1}

- *3D template fit* in the lepton+jets channel
  - m_t, global jet energy scale factor (JSF) and bJet energy scale factor (bJSF)
- 1D template fit in dilepton channel
- Templates: $m_{t,reco}$, $m_{lb,reco}$, $m_{W,reco}$ and R_{lb}^{reco} (ratio of the sum of the p_T of the bjets from the top and light jets from the W)
  - Templates built by varying the fit parameters in Monte Carlo

☑ (green) = linear dependency for signal and bg
☑ = linear dependency but not fitted
✓ = linear dependency for signal only

	m_t	JSF	bJSF
$m_{t,reco}$	✓	☑ (green)	☑ (green)
$m_{W,reco}$		☑ (green)	
R_{lb}^{reco}	✓		☑ (green)
$m_{lb,reco}$	✓	☑	☑



- Probability density functions for each parameter evaluated by fitting each template distribution for signal and background

Top quark mass

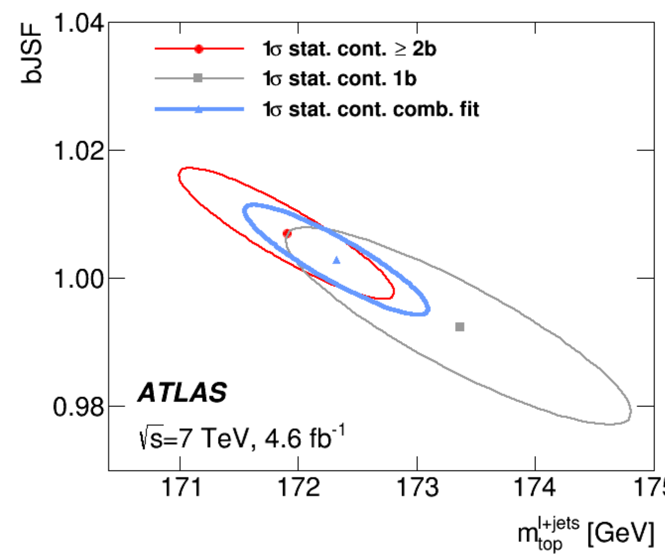
arXiv:1503.05427, Submitted to EPJC

$\sqrt{s} = 7$ TeV, $\int Ldt = 4.6$ fb^{-1}

- $t\bar{t}$ kinematics reconstructed by a fit maximizing an event likelihood→ $m_{t,reco}$, $m_{W,reco}$ and R_{lb}^{reco}
  - m_t is not fixed in the fit
- Signal and background PDFs are used in an unbinned likelihood fit to the data for all events separately for 1 and 2+ btag samples:

$$L(m_{t,reco}, m_{W,reco}, R_{lb}^{reco} | m_t, JSF, bJSF, n_{bkg}), \text{ l+jets}$$

$$L(m_{lb,reco} | m_t, n_{bkg}), \text{ dilepton}$$



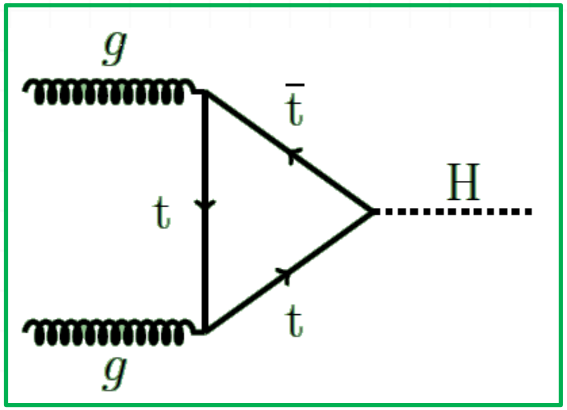
- Results in the 1 btag and 2 btag samples are in good agreement
- First time implementation of an m_t measurement with simultaneous constraint on m_t, JES and bJSF
- Single and di-lepton results are combined using BLUE

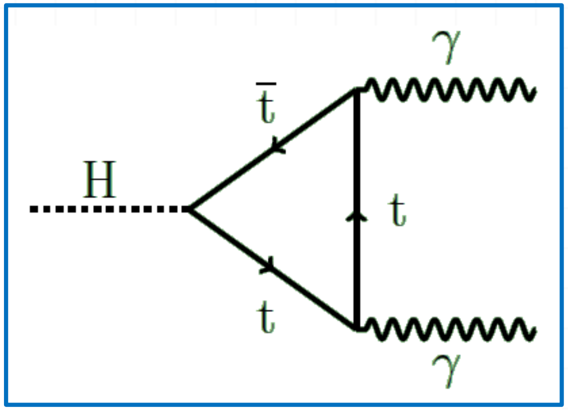
$$\boldsymbol{m_t^{comb} = 172.99 \pm 0.48(stat) \pm 0.78(syst)}$$

Top and Higgs

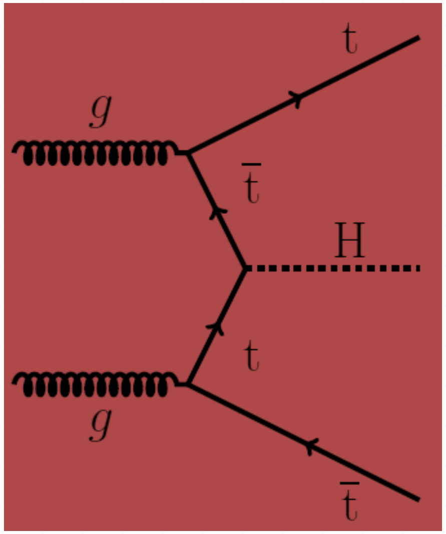
Top & Higgs associate production

- Since the Higgs discoveries the focus of experiment has been to measure its properties including its coupling to SM particles.
  - Higgs observed decaying to $H\to\gamma\gamma$, $H\to ZZ^*\to 4\ell$, $H\to WW^*\to \ell\upsilon\ell\upsilon$, evidence for $H\to\tau\tau$.
- The large mass of the top quark implies a top Yukawa coupling ~1.
  - There is already sensitivity in to the top-Higgs coupling from *gg* fusion Higgs production and from the decay to photons via loop interactions



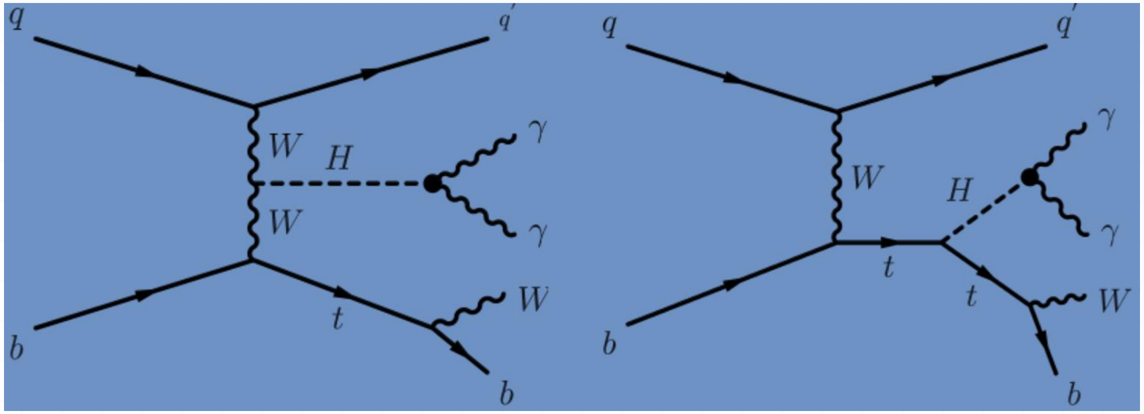


Top & Higgs associate production



Production mechanisms:

- **Higgs + top pair**: direct measurement of the top-Higgs coupling
- **Higgs + single top**: sensitive to *Wt* interference→relative sign of the top-Higgs coupling

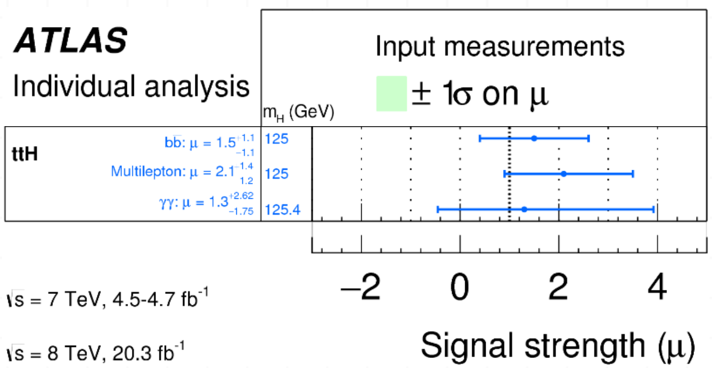


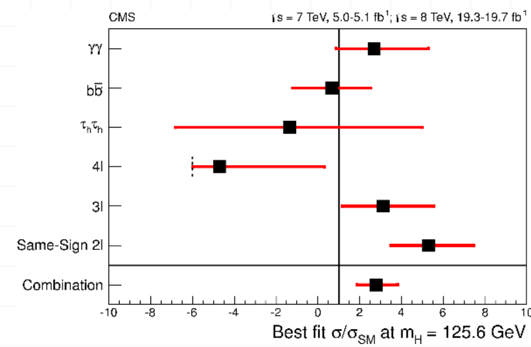
$t\bar{t}H$ results from ATLAS and CMS

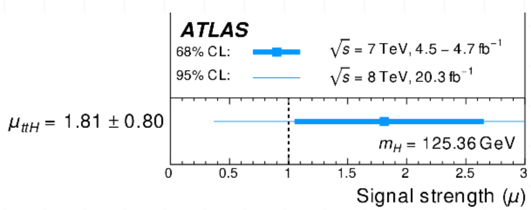
- Measurements performed in the $\gamma\gamma$, bb and leptons ($H \rightarrow \tau\tau$ and $H \rightarrow WW \rightarrow leptons$) decay channels
- The **combined** observed **best-fit signal strengths** $\left(\mu = \frac{\sigma}{\sigma_{SM}}\right)$:

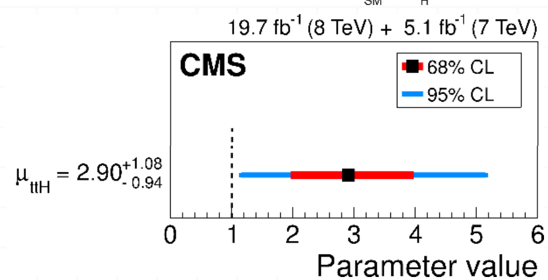
ATLAS: $\mu = 1.81 \pm 0.8$,

CMS: $\mu = 2.90^{+1.08}_{-0.94}$









hep-ph 1507.04548

HIG-14-009

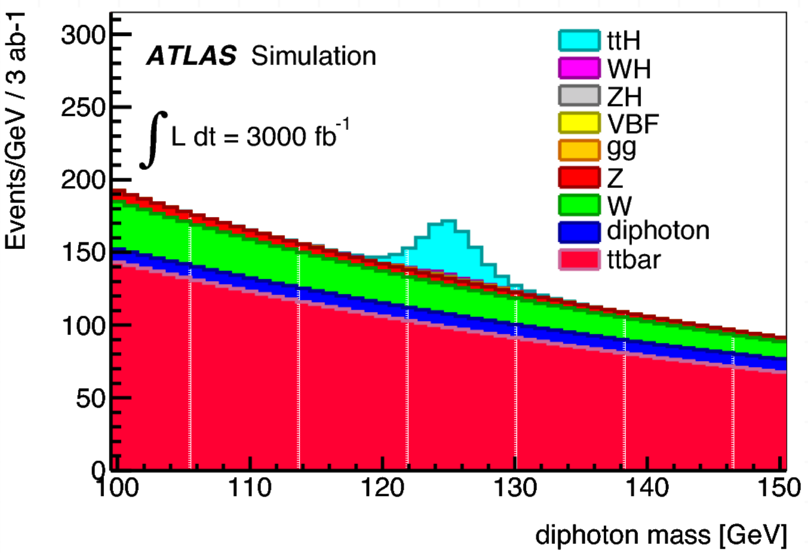
$t\bar{t}H$ prospects at 13 TeV

- $t\bar{t}H$ is a top target for observation at 13 TeV
- First stage of run2: factor ~5 improvement in stat sensitivity:
  - 5-6 more integrated lumi and 4.6 increase in signal cross section
  - Bkg rises more slowly (factor 3.6 increase)

Full simulation ($H \rightarrow \gamma\gamma$) @ 14 TeV

$$\frac{S}{B} \sim 20\%$$

ATLAS-PHYS-PUB-2013-007



Self-referential parenthesis: **boosted $t\bar{t}H$**

Top and Higgs can be produced with p_T considerably larger than their masses → potential for boosted topologies

- ✘ Lower rates: can be explored only in Run 2 and beyond
- ✓ Much less combinatorial bkg (top and Higgs can be reconstructed as single fat jets)
- ✓ Improvement for $\frac{S}{\sqrt{B}}$

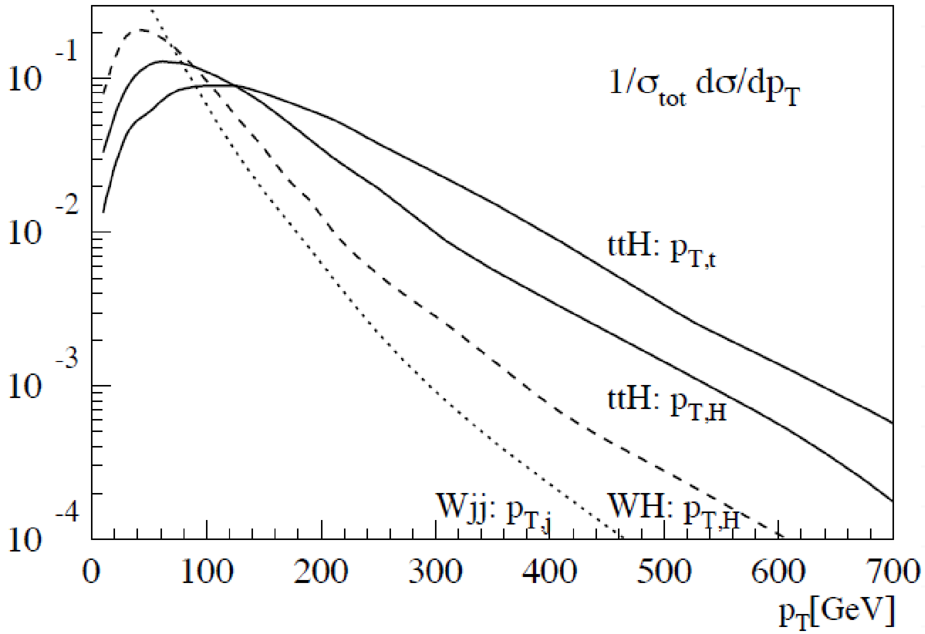


FIG. 1: Normalized top and Higgs transverse momentum spectra in $t\bar{t}H$ production (solid). We also show $p_{T,H}$ in W^-H production (dashed) and the p_T of the harder jet in W^-jj production with $p_{T,j} > 20$ GeV (dotted).

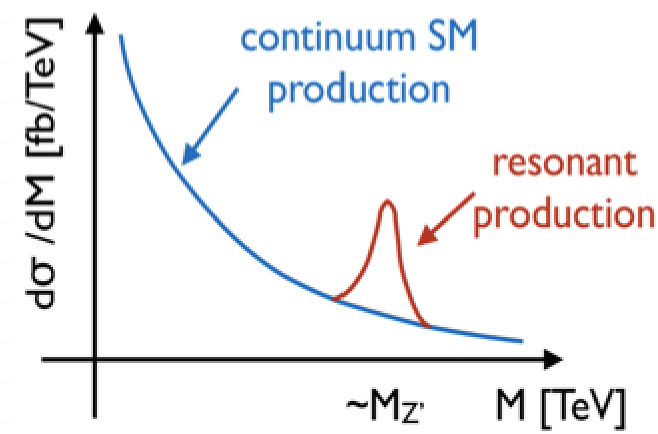
Plehn, Spannowsky, Salam
Phys.Rev.Lett. 104 , 111801 (2010)

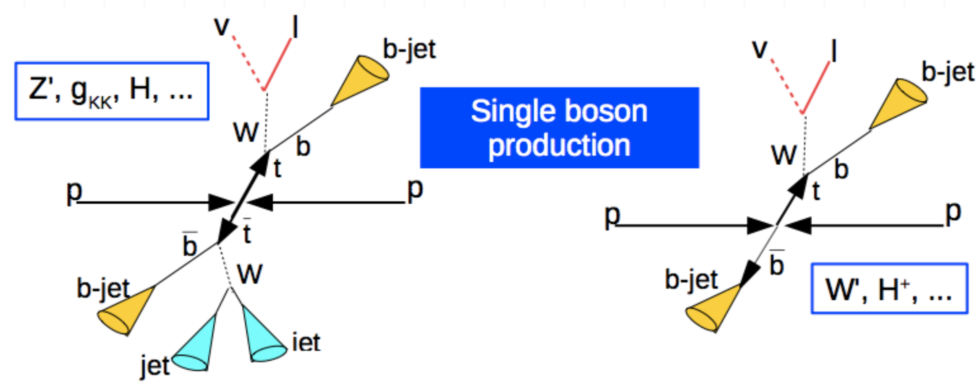
$t\bar{t}$ resonances

Searches for BSM

BSM searches using top quarks

- Many theories of new physics BSM predict final states with top quarks
- One of the most direct ways to find new physics at TeV scale is searching for resonances
  - Extra gauge bosons
- Typical signatures:
  - (boosted) tops
  - (boosted) W
  - *b*-jets



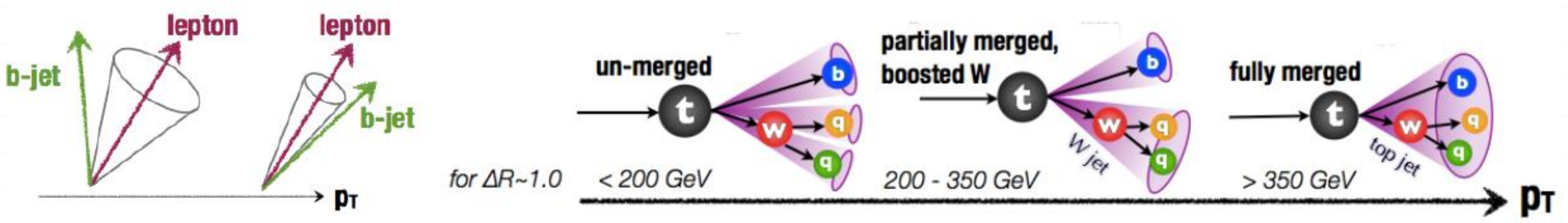


'$t\bar{t}$' resonance   'Single top' resonance

$t\bar{t}$ resonances

$$Z' \rightarrow t\bar{t} \rightarrow W^+ b W^- \bar{b}$$

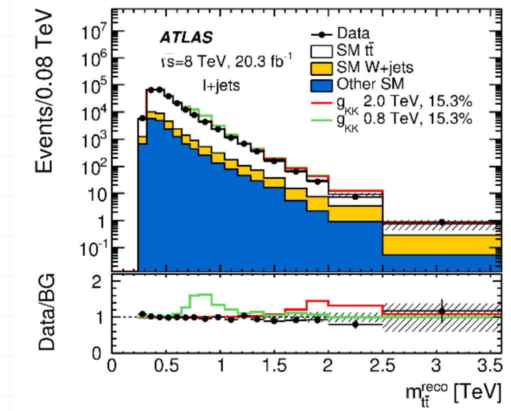
- Generally referred to as *Z'*
  - Sensitive to topcolor Z', RS KK gluons, etc.
  - Z' with widths (1-10%) of mass, g_{kk} with 10-40%
- Massive enough to produce highly boosted top quarks



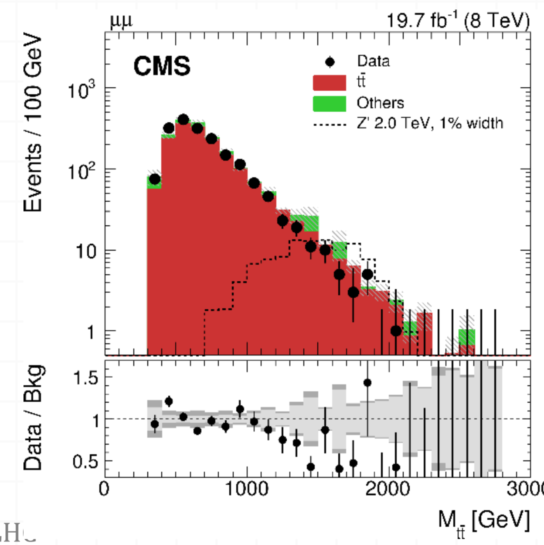
$t\bar{t}$ resonances

$$Z' \to t\bar{t} \to W^+ b W^- \bar{b}$$

- ATLAS: semileptonic channel only
  - Both boosted and resolved topologies



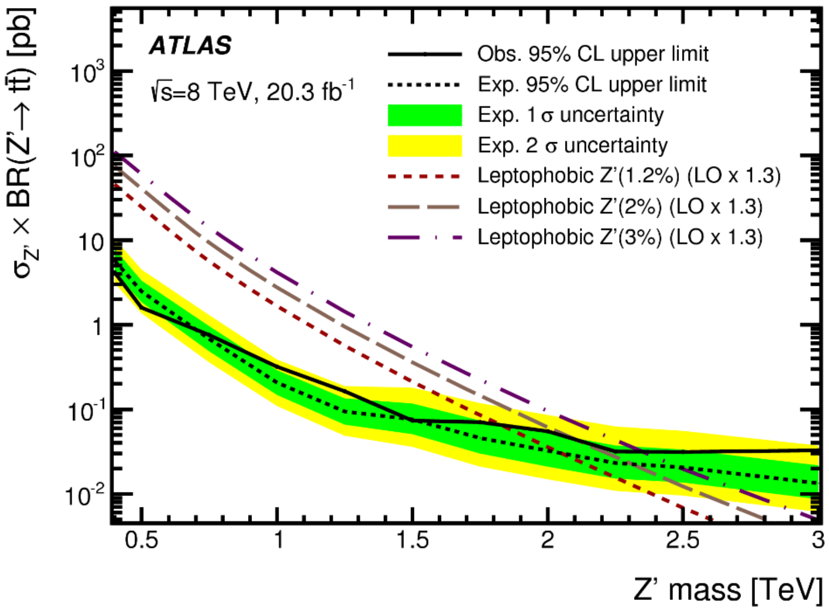
- CMS: semileptonic/dileptonic/full hadronic channels
  - Both boosted and resolved topologies

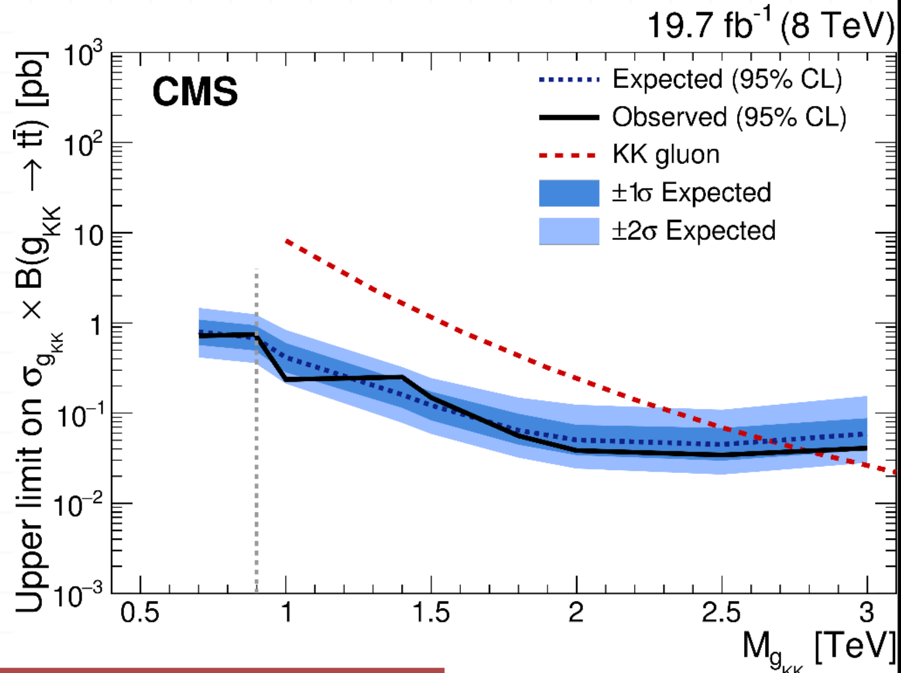


$t\bar{t}$ resonances limits

ATLAS: JHEP 08 (2015) 148

CMS: arXiv:1506.03062, submitted to PRD





Model ($m_{Z'}$ = 2 TeV)	Observed (expected) limit [TeV]		
	ATLAS		CMS
Z' narrow (1.2%)	1.8 (2.0)		2.4 (2.4)
Z' wide	2%: 2.0 (2.3)	3%: 2.3 (2.5)	10%: 2.9 (2.8)
g_{kk} wide	15.3%: 2.2 (2.3)		20%: 2.8 (2.7)

Conclusions (1)

- **Top analyses is in full swing** thanks to the combined performance of LHC & detectors: **a very rich program is under way.**
- Thanks LHC top quark factory (~6M $t\bar{t}$, ~3M single top events produced in ATLAS only during 2011+2012) **top strong and electroweak inclusive production has been measured with exceptional precision**
  - $\frac{\delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \sim$ 4.7% compared to ~4% prediction uncertainty (NNLO+NNLL)
  - $\frac{\delta\sigma_{t\bar{t}}}{\sigma_{t}}$ ~12% to 15%: still space for improvement
    - More statistics @ 13 TeV, more refined analysis techniques…
- **Differential cross sections measurements test SM tt production and complement new physics searches in completely new phase space** with 10% to 50% relative unc. Expect higher reach in Multi TeV region with reduced syst uncertainties

Conclusions (2)

- The **top mass** is measured at 0.83% (ATLAS)/0.4%(World) level.
- **Direct determination of top** quark **coupling to** the newly found **Higgs** boson is still limited by number of events. Run2 expects observation with high luminosity.
- **New physics** connected to top quark by resonances/asymmetries and top rare decays **is being searched in previously unexplored regions** of mass and cross sections
- Measurement @ 13 TeV already on going:
  - Inclusive cross section (shown in this talk)
  - Differential cross section
  - Resonances

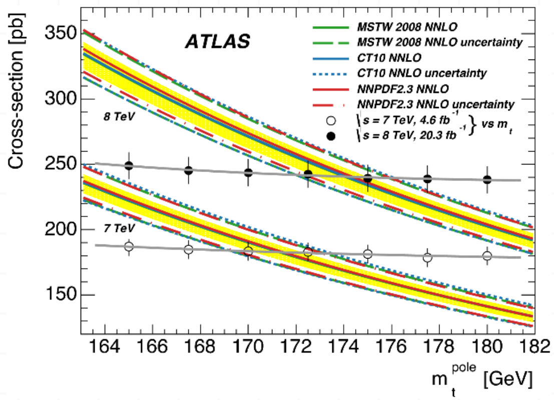
Backup

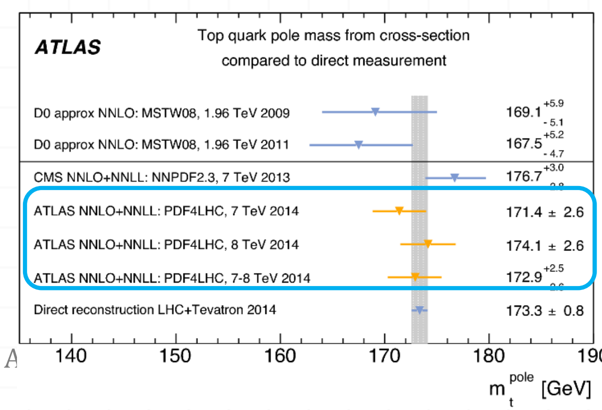
$t\bar{t}$ inclusive cross section $e\mu$ channel

EPJC 74 (2014) 3109

Strong dependence of NNLO σ_{tt} on m_t

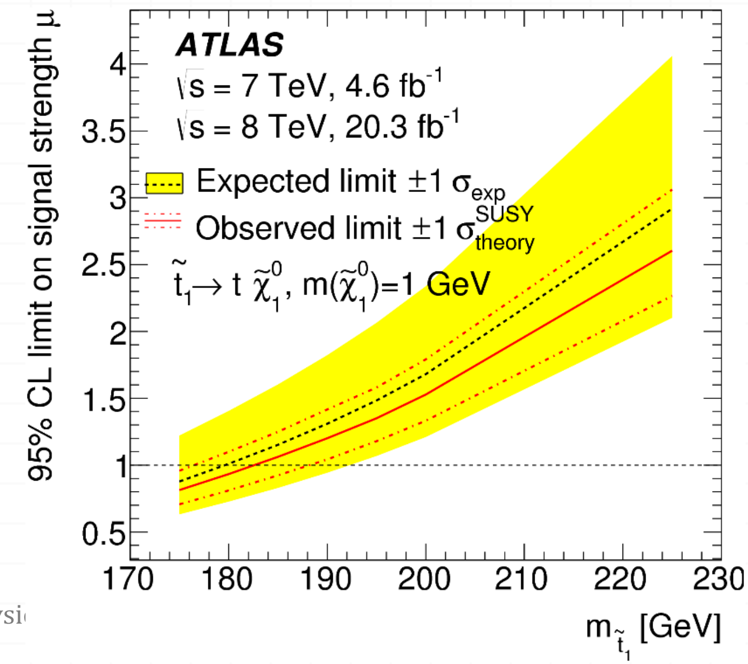
- Also σ_{tt}^{meas} shows (weak) dependence on m_t
- Extraction of top *pole* mass via the maximization of a Baysian likelihood function





Constraints on stop pair production

- R-parity conserving SUSY extension of SM with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (BR = 100%)
- Fit $\sigma_{\tilde{t}_1\tilde{t}_2}$ to the $\sigma_{tt}^{meas} - \sigma_{tt}^{th}$ difference
- 95% CL exclusion of stop with $m_t < m_{\tilde{t}_1} < 177$ GeV

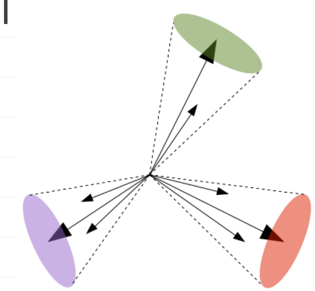


$t\bar{t}$ differential cross section

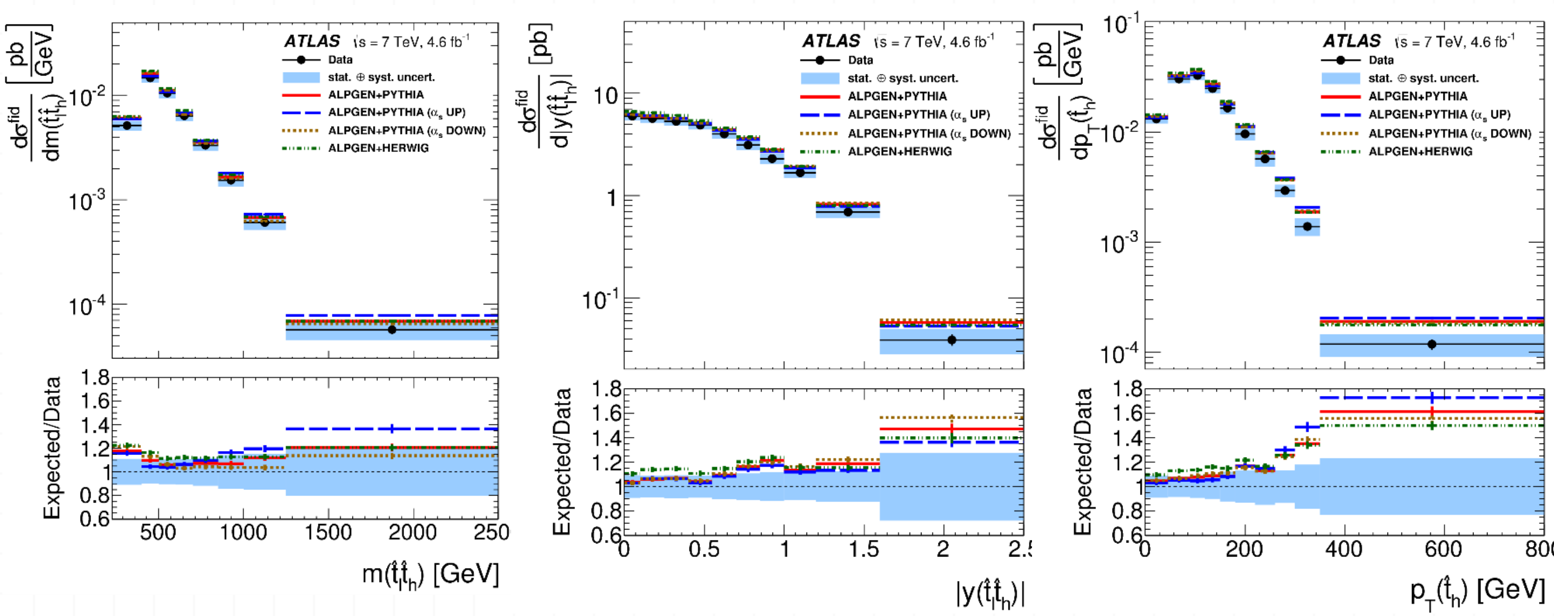
JHEP 06 (2015) 100

$\sqrt{s} = 7$ TeV, $L = 4.6$ fb^{-1}

- Top-antitop differential cross section $\left(\frac{d\sigma}{dX}\right)$ where $X = m_{t\bar{t}}, p_{\mathrm{T},t\bar{t}}, |y_{t\bar{t}}|, p_{T,t}$ and $|y_t|$
  - *Fiducial* measurement: limited to the actual «visible» phase space
  - Pseudo top ($\hat{t}$) observables built from stable final state objects
- Cut-based analysis in the $l(e/\mu)$+jets channel
- Main uncertainties: b-tag, JES and IFSR



- General trend of data being softer in $p_{T,t}$ above 200 GeV
- Same behavior is observed by the parton level analysis



$t\bar{t}$ + jets differential cross section

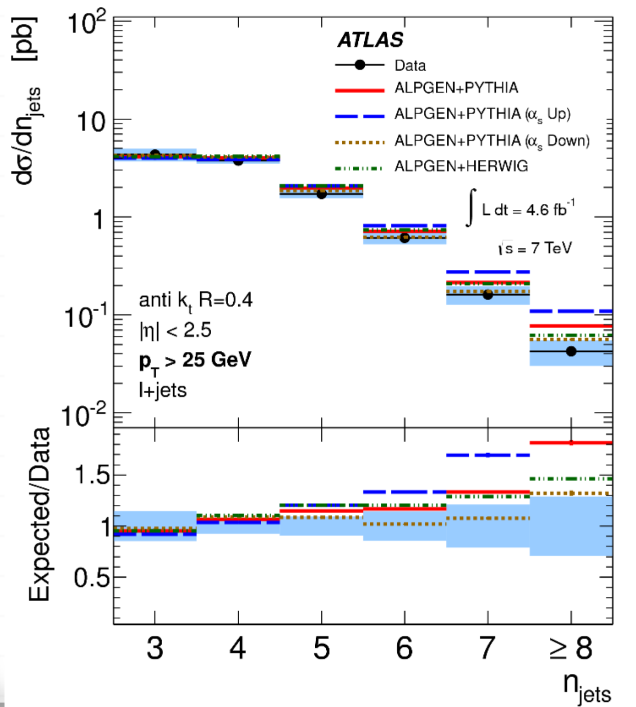
JHEP 01(2015)020

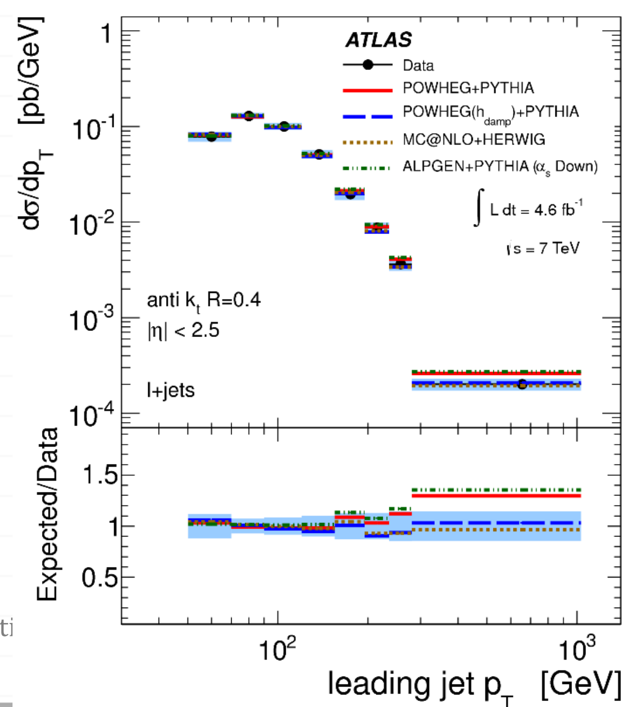
$\sqrt{s} = 7$ TeV, $\int Ldt = 4.6\text{fb}^{-1}$

- *Particle level* measurement of $\frac{d\sigma_{t\bar{t}}}{dN_{jets}}$ (with different cuts on $p_{T,jet}$) and $\frac{d\sigma_{t\bar{t}}}{dp_{T,jet}}$
- Limited by systematic uncertainties: background modelling (for $n_{jets} < 4$) and jet energy scale ($n_{jets} \geq 4$)

$\frac{d\sigma_{tt}}{dN_{jets}}$: sensitive to hard emissions in QCD bremsstrahlung processes.

$\frac{d\sigma_{tt}}{dp_{T,jet}}$: sensitive to the modelling of higher-order QCD effects in MC





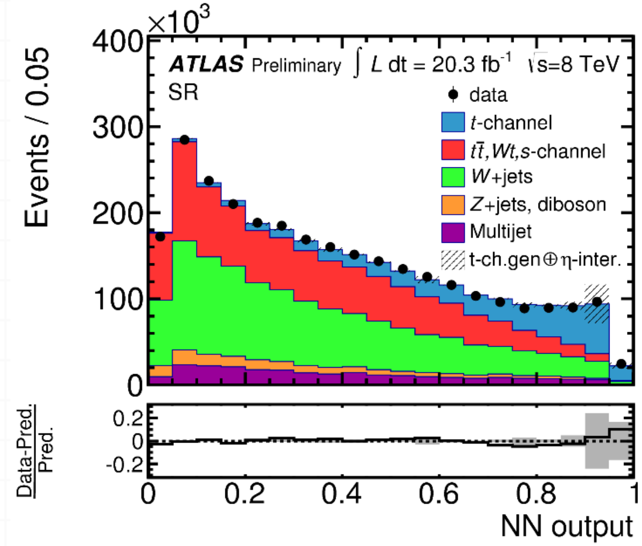
Jet multiplicity in top–anti-top final states

- Useful to constrain models of initial and final state radiation (ISR/FSR)
- Provides a test of perturbative QCD
- Single-lepton channel
  - Four jet p_T thresholds: (25, 40, 60, and 80 GeV)
- Results are corrected for all detector effects through unfolding
  - Reconstructed level → particle level
- Measurement is limited by systematic uncertainties,
  - background modelling (at lower jet multiplicities)
  - jet energy scale (at higher jet multiplicities)

Single top *t*-channel cross section

ATLAS-CONF-2014-007

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1}



- A multivariate Neural Network (NN) discriminant trained with the 14 most-sensitive variables
  - Contributions from signal and background evaluated via MC (data driven for Multijet bkg in the μ channel)
- Lepton + 2 jets channel, 1 *b*-tag
- $\boldsymbol{\sigma_{t-chan}}$ extracted via a maximum-likelihood fit of the NN output in the data
- Fiducial and total phase space measurements

$$\boldsymbol{\sigma^{fiducial}_{t-chan}(\sqrt{s} = 8\ \text{TeV}) = 3.4\ \pm 0.48\ \text{pb}\ (\pm 14\%)}$$

Main uncertainties: JES and signal modelling

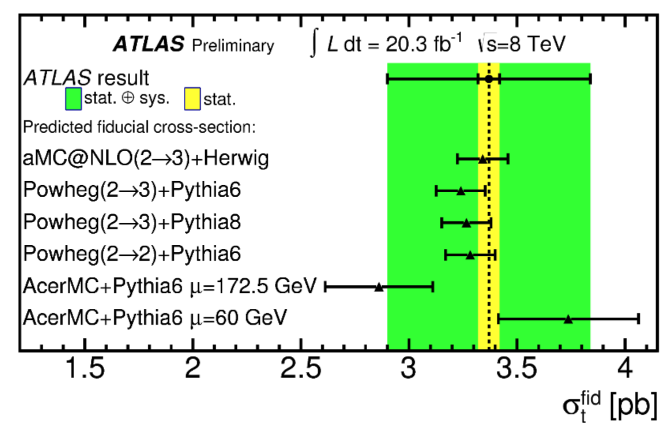
$$\boldsymbol{\sigma^{total}_{t-chan}(\sqrt{s} = 8\ \text{TeV}) = 82.6 \pm 12.1\ \text{pb}\ (\pm 15\%)}$$

(extrapolated via MG5_aMC@NLO)

Additional uncertainty: PDF

$$\sigma^{th}_{t-chan}(\sqrt{s} = 8\ \text{TeV}) = 87.8^{+3.4}_{-1.9}\ \text{pb}\ (^{+3.9\%}_{-2.2\%})$$

N. Kidonakis, Phys. Rev. D 83 (2011) 091503



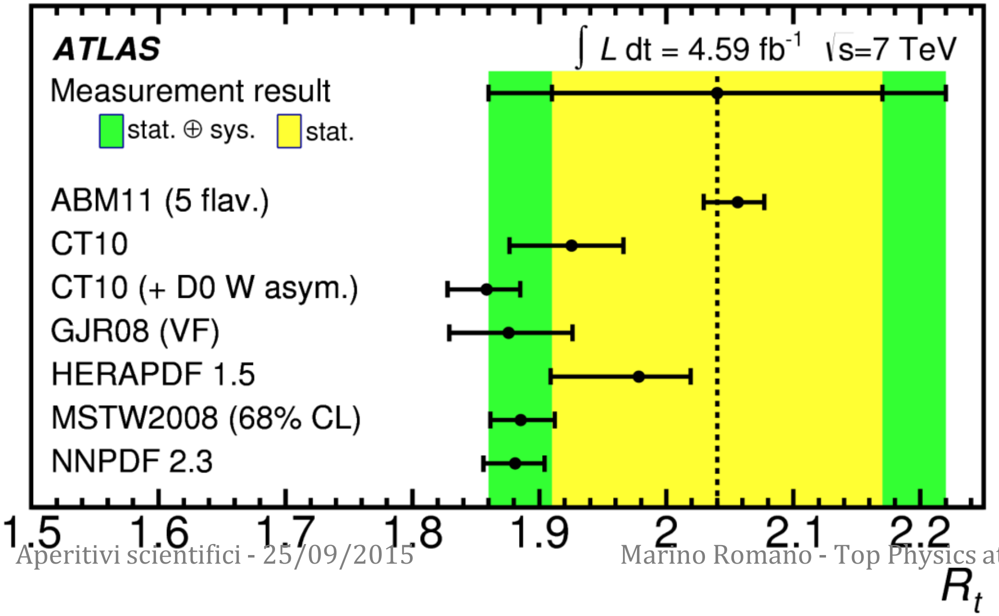
Single top/antitop t-chan ratio

$R_t = \frac{\sigma_t}{\sigma_{\bar{t}}}$

Phys. Rev. D. 90, 112006 (2014)

$\sqrt{s} = 7$ TeV, $L = 4.6$ fb^{-1}

- Very sensitive to the ratio of the PDF of the valence quark in the high *x* regime
  - Smaller uncertainties because of error cancelations
- Sensitive to new physics effects
- Same analysis technique used in the σ_{tchan} measurement at 8 TeV



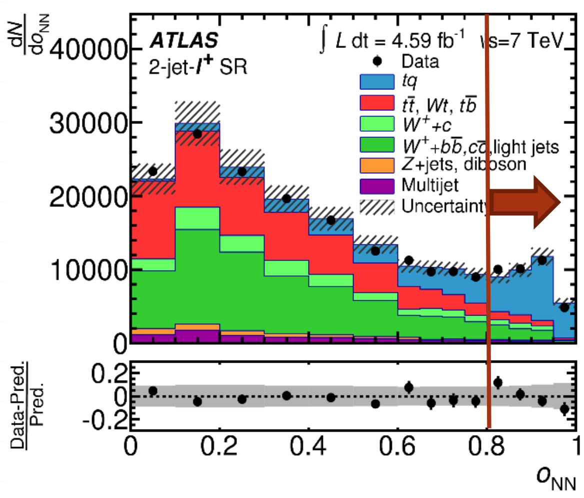
The measurement is in agreement with the predictions from different PDF sets and is dominated by statistical and systematic (MC statistics and PDF) uncertainties

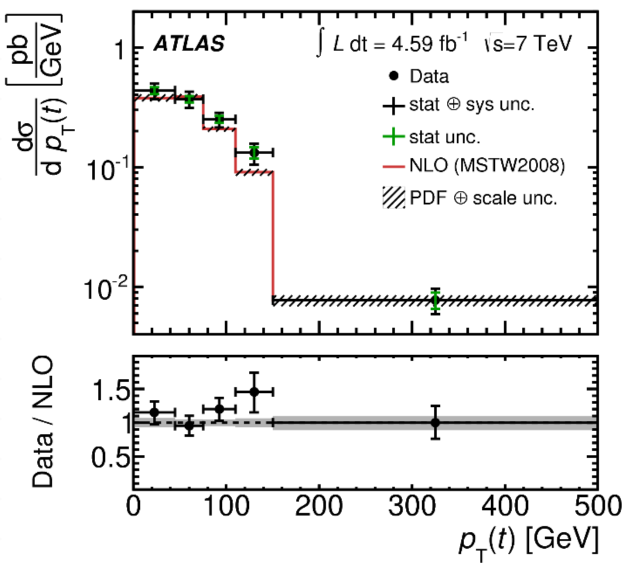
Single top t-channel differential cross section

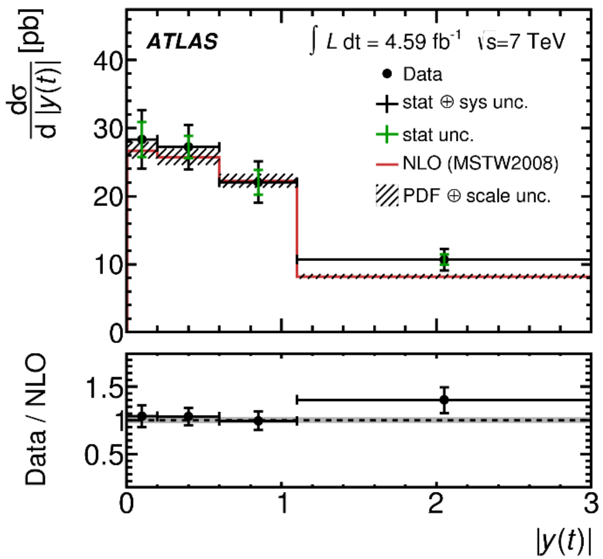
Phys. Rev. D. 90, 112006 (2014)

$\sqrt{s} = 7$ TeV, $\int Ldt = 4.6$ fb^{-1}

- Events selected in a high purity ($O_{NN} > 0.8$) region
  - Allows the measurement of differential distributions
- Differential cross section as a function of $p_T(t/\bar{t})$ and $|y(t/\bar{t})|$
  - Reconstructed spectra corrected to parton level via unfolding procedures
- General good agreement with NLO predictions







V_{tb} extraction

A direct determination of V_{tb} can be extracted from the cross-sections measurements (t- and Wt-channel)

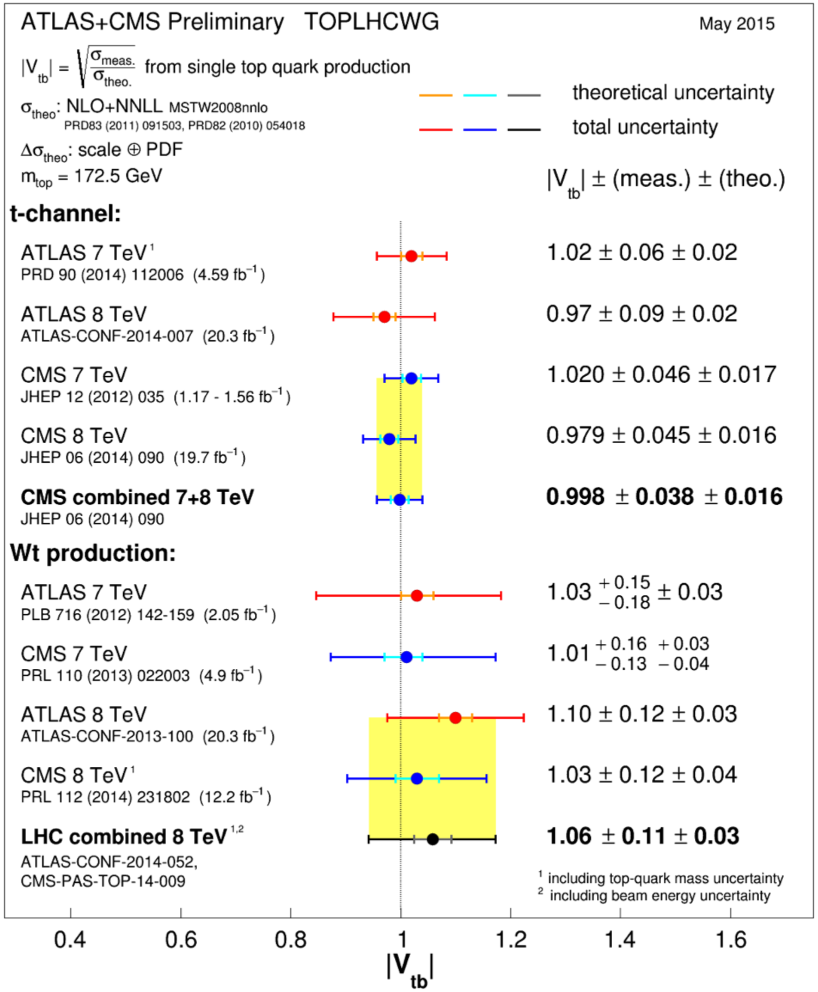
Two general assumptions

1. W – t – b interaction is left-handed
2. top quark production and decay through |Vts| and |Vtd| are negligible

|Vtb| is extracted by the ratio

$$|V_{tb}f|^2 = \frac{\sigma_{st}^{exp}}{\sigma_{st}^{th}}$$

Where, for the SM, $f = 1$

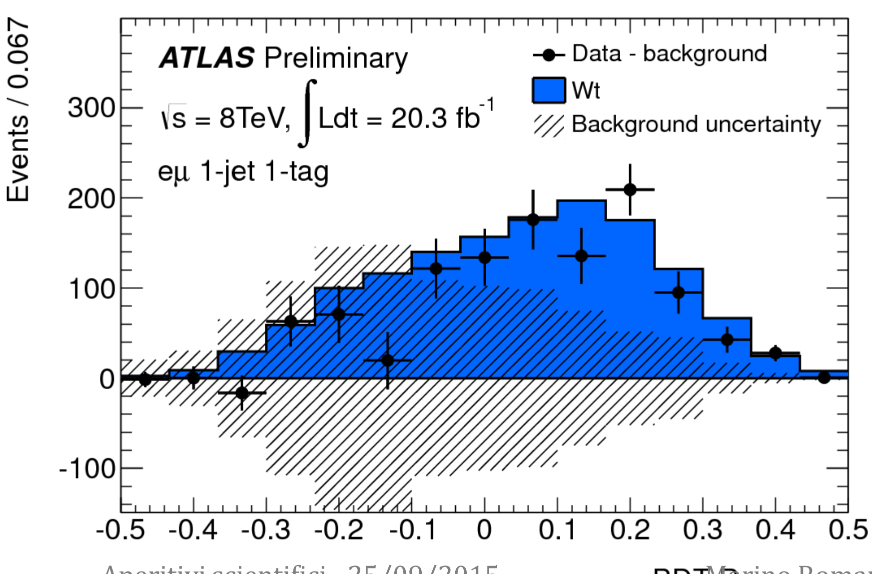


Single top Wt-channel cross section

ATLAS-CONF-2013-100

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1}

- Hard to separate from $t\bar{t}$, interference at NLO
  - Event selected requiring $1e$, 1μ, 1/2jet, 1b-tag, E_T^{miss}
  - Multivariate analysis based on Boosted Decision Tree (BDT) employed to increase the discrimitation power
    - BDT trained using Wt as signal and $t\bar{t}$ as background
    - BDT discriminants built separately for 1 and 2 jet samples
  - Most discriminating variable: $p_T^{sys}(lep1, lep2, E_T^{miss}, jet1)$
  - Maximum likelihood fit to the BDT output to extract the signal cross section



$\boldsymbol{\sigma_{Wt}(\sqrt{s} = 8\ \text{TeV}) = 27.2 \pm 5.8\ \text{pb}\ (\pm 21\%)}$

(observed $\mathbf{4.2\sigma}$, expected 4.0σ)

Main systematics: b-tagging, JES, generator uncertainties

$$\sigma_{Wt}^{th}(\sqrt{s} = 8\ \text{TeV}) = 22.4 \pm 1.5\ \text{pb}(\pm 6.7\%)$$

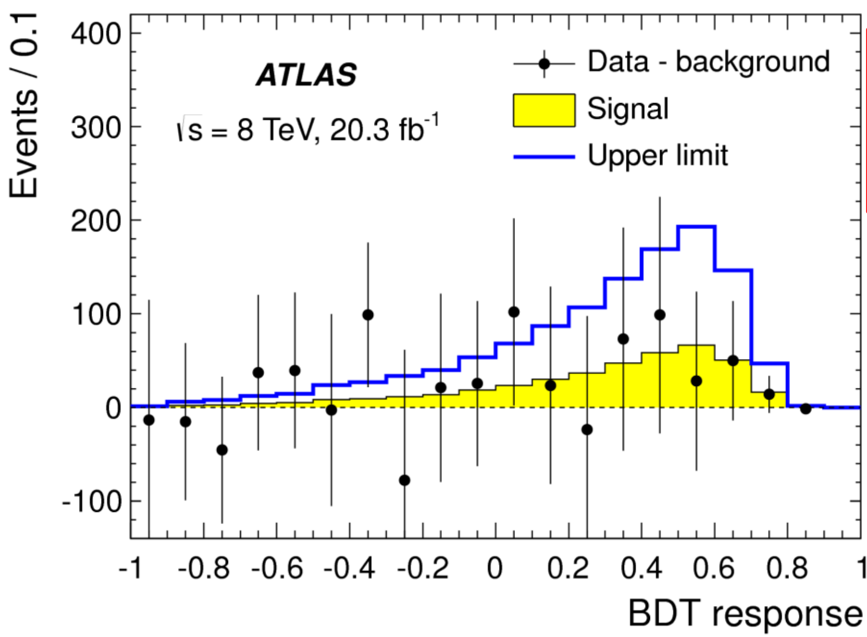
N. Kidonakis, Phys. Rev. D 82 (2010) 054018

Single top *s*-channel search

Phys. Lett. B740 (2015) 118

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1}

- Low rate in *pp* collissions (was dominant at Tevatron)
  - Event selected requiring 1l, 2b-tag, E_T^{miss}
  - Multivariate analysis based on Boosted Decision Tree (BDT) employed to increase the discrimitation power
  - Most discriminating variable: $|\Delta\phi(t, b)|$
  - Maximum likelihood fit to the BDT output to extract the signal cross section



$\boldsymbol{\sigma_{s-chan}(\sqrt{s} = 8\ \text{TeV}) = 5.0 \pm 4.3}$ **pb** $(\pm 86\%)$

(**1.3σ**, expected 1.4σ)

Upper limit: **14.6 pb** @ 95%CL

Main uncertainties: E_T^{miss} and jet energy scale, data & MC statistics

$\sigma_{s-chan}^{th}(\sqrt{s} = 8\ \text{TeV}) = 5.61 \pm 0.22$ pb $(\pm 3.9\%)$

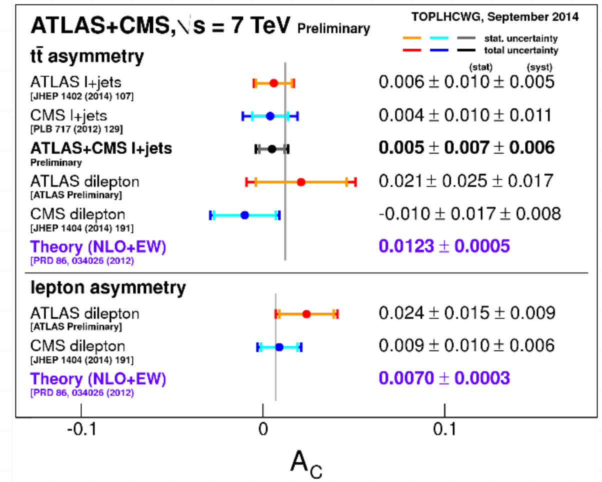
N. Kidonakis, Phys. Rev. D 81 (2010) 054028

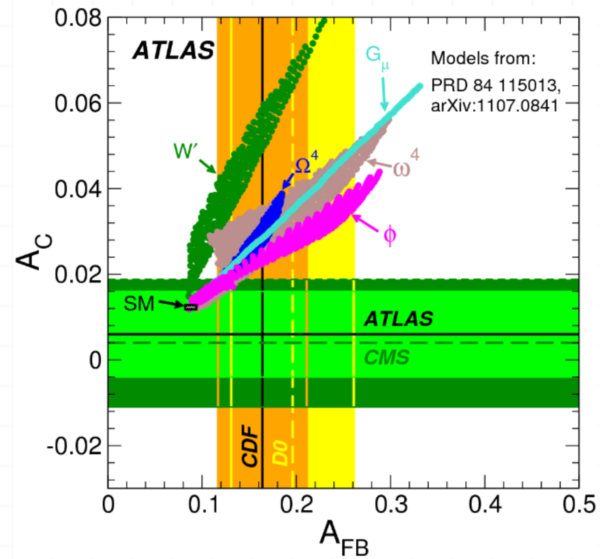
$t\bar{t}$ charge asymmetry in Run I

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}| \qquad \Delta|y| = |y_{l^+}| - |y_{l^-}|$$

$$A_{FB} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} \qquad \Delta y = y_t - y_{\bar{t}}$$

- A_{FB} measured at Tevatron
  - Not a "good" observable at LHC
- A_C Extensively measured @ 7 TeV
- All results obtained after unfolding to parton level
  - Dilepton channel (submitted to JHEP)
    - Simultaneous measurement of $A_C(tt)$ and $A_C(ll)$
  - Single lepton channel (JHEP02(2014)107)
  - Combination with CMS (ATLAS-CONF-2014-012)
- Results in agreement with SM predictions



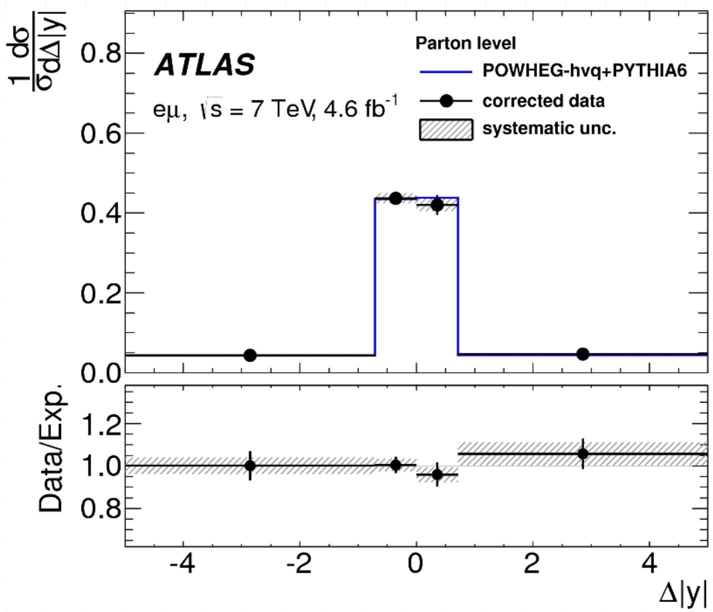


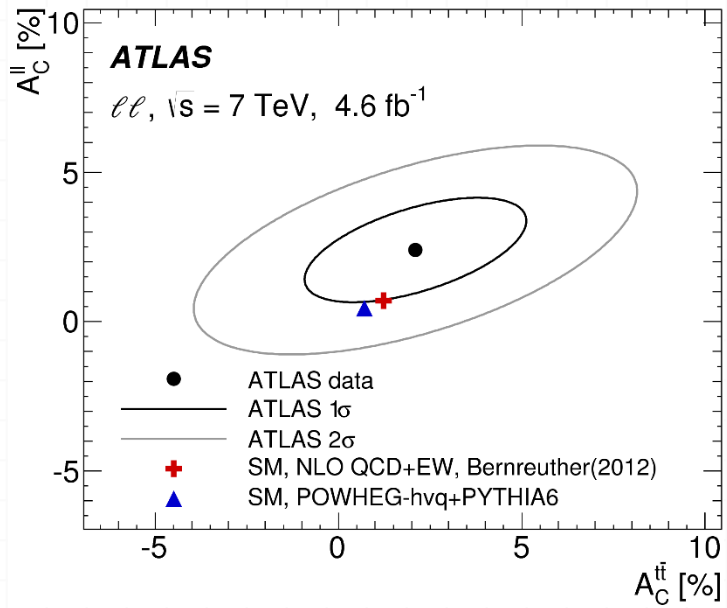
$t\bar{t}$ charge asymmetry in l^+l^- channel

arXiv:1501.07383, Submitted to JHEP

$\sqrt{s} = 7$ TeV, $\int L dt = 4.6$ fb^{-1}

- Dilepton channel allows lepton-based asymmetry
  - No dependence on top reco algorithms
- Unfolding procedures to correct reco $\Delta|y|$ spectra for detector response and acceptance



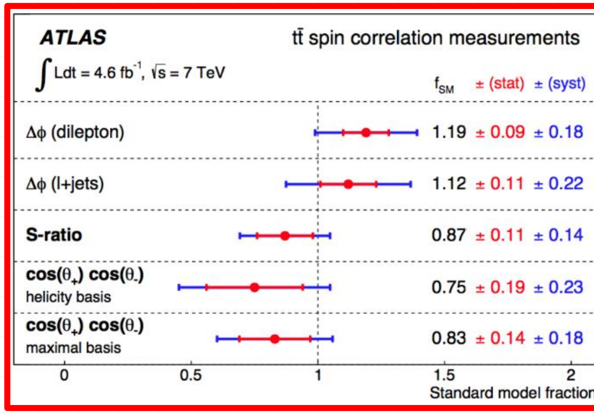


$$A_C^{ll} = 0.024 \pm 0.015 \pm 0.009$$
$$A_C^{tt} = 0.021 \pm 0.025 \pm 0.017$$

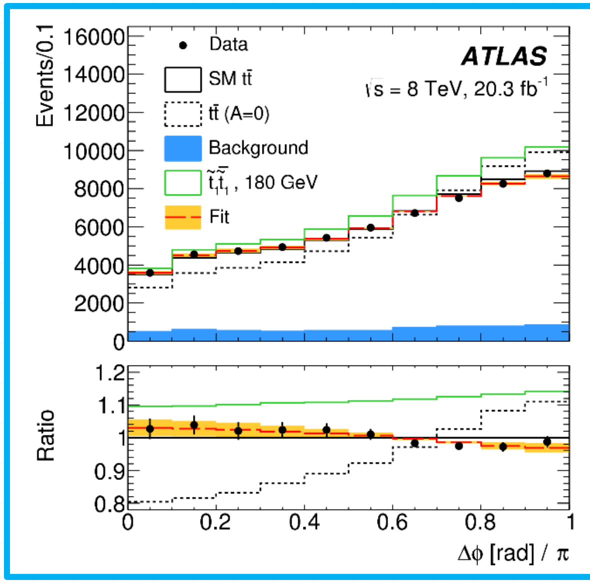
Spin correlation measurements

$$A = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)} \quad A^{SM}_{helicity} = 0.38 \pm 0.04$$

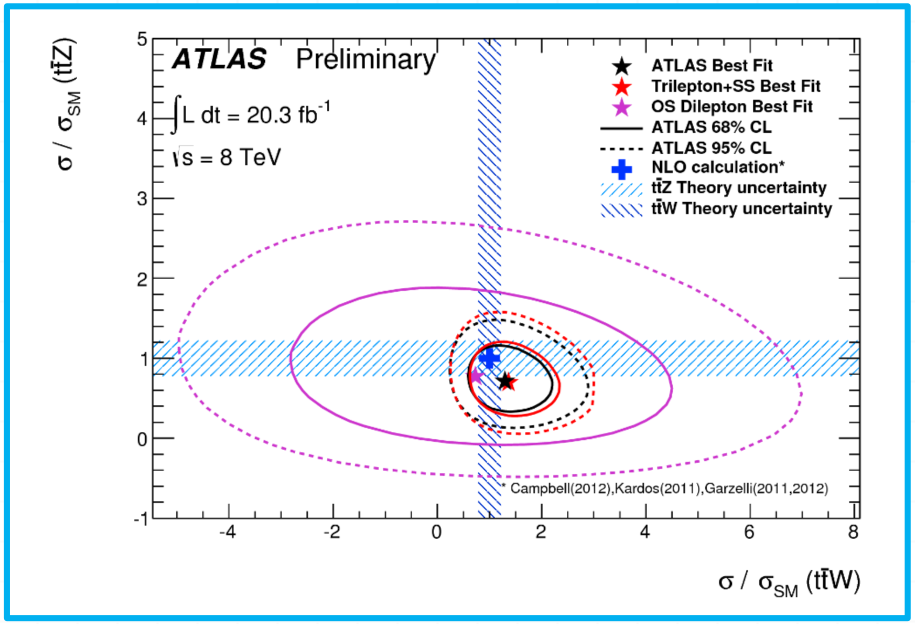
- 7 TeV analysis: Phys. Rev. D. 90, 112016 (2014)
  - Four observables used to extract the spin correlation from a binned likelihood fit of f_{SM} where
  $$A_{measured} = f_{SM} A^{th}_{SM}$$
  - $\Delta\phi(ll)$ shows highest sensitivity



- 8 TeV analysis: arXiv:1412.4742, submitted to PRL
  - Spin correlation extracted via a template fit on $\Delta\phi(ll)$ distribution
  $$f_{SM} = 1.20 \pm 0.05(stat) \pm 0.13(syst)$$
  - Most precise measurement to date
  - See Paolo Dondero's poster for stop exclusion from $t\bar{t}$ spin correlation

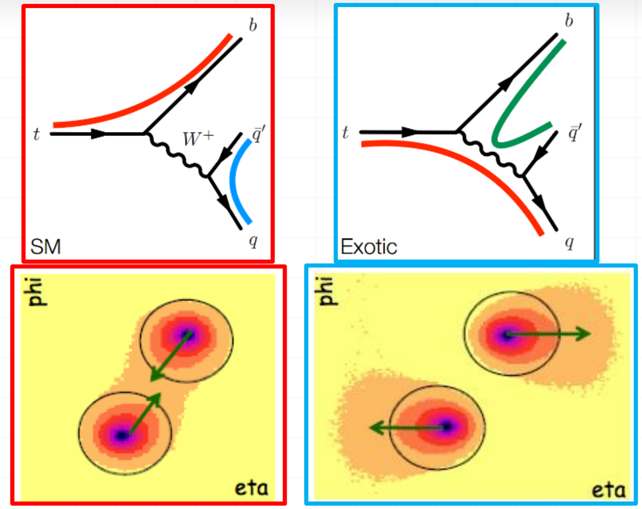


$t\bar{t}V$ in Run I



- Precision test of SM predictions
- Final states
  - $t\bar{t} \rightarrow ll,\ l$+jets, all hadronic
  - $Z \rightarrow ll,\ \nu\nu, q\bar{q}$
  - W $\rightarrow l\nu, q\bar{q}$
- Dilepton and trilepton analysis (ATLAS-CONF-2014-38)
  - Same sign di-muon: $t\bar{t}(\rightarrow \mu$+jets$)W(\rightarrow \mu\nu)$
  - Opposite sign dilepton: $t\bar{t}(\rightarrow l^{\pm}$+jets$)W(\rightarrow l^{\mp}\nu)$ and $t\bar{t}(\rightarrow$

Color flow



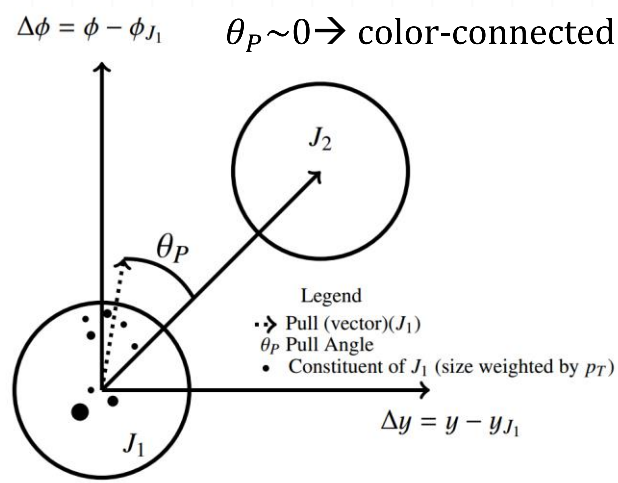
Analysis ongoing on 8 TeV

Single lepton channel

- Goal: unfold pull angle between the two jets coming from a W and compare it to different color flow models
- Pull vector of a jet J is defined as:

$$\vec{v}(J) = \sum_{i \in J} \frac{p_T^i |r_i|}{p_T^J} \vec{r}_i$$

$\theta_P \sim 0 \rightarrow$ color-connected



Where i runs over the subcomponents of J and r_i is the i-J vector in the $y - \phi$ plane

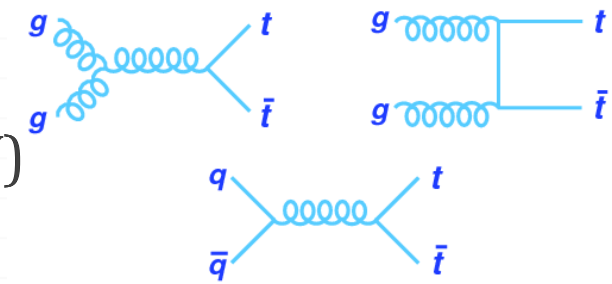
- Pull angle $\theta_P(J_1, J_2)$:

angle between $\vec{v}(J_1)$ and $\overrightarrow{J_1 J_2}$

Top quark pair production and decays

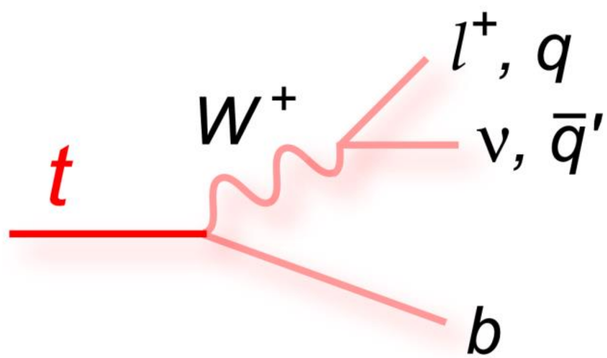
Pair production mechanisms at LHC

- Gluon-gluon fusion (~85% @ 7 TeV)
- Quark-antiquark annihilation



Decays

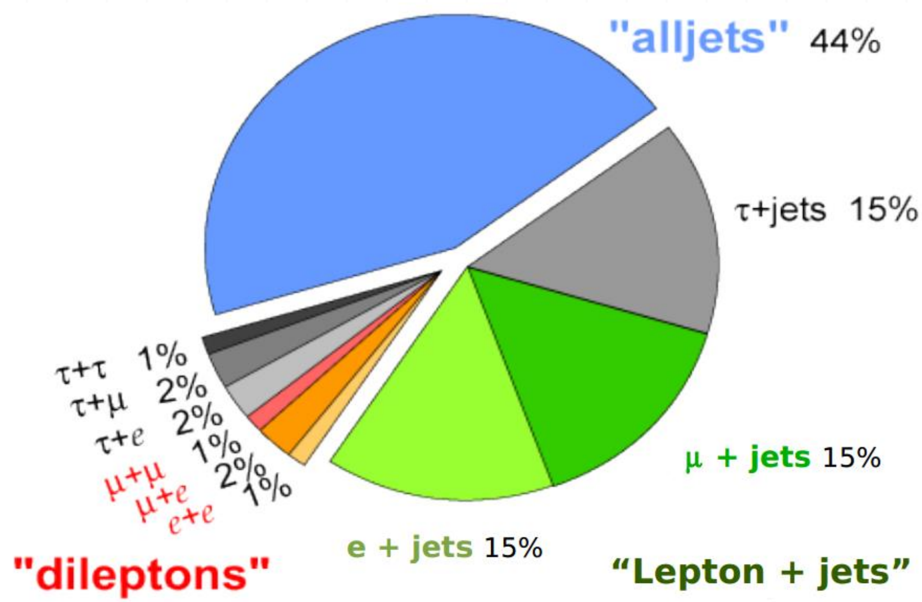
- $t \rightarrow Wb (\sim 100\%)$



$W \rightarrow l\nu_l \sim 33\%$

$W \rightarrow q\bar{q}' \sim 66\%$

Top pair final states



Common object definitions

- Details can vary among the different analyses
- Jets:
  - Reconstructed from topological clusters using the anti-kt algorithm ($R = 0.4$)
  - p_T> 25 GeV, $|\eta|$ <2.5
- B-tagging via a Neural network based algorithm (MV1) with average efficiency of 70% and light jet rejection factor ~140
- Electrons:
  - EM cluster with track matched
  - Isolation in tracker and calorimeter
  - E_T > 25 GeV, $|\eta|$<1.37 or 1.52 < $|\eta|$ <2.47
- Muons:
  - Tracks in inner detector and muon spectrometer
  - Isolation in tracker and calorimeter
  - $p_T > 20$ GeV, $|\eta|$ <2.5
- Missing transverse energy
  - Vector sum of energy deposits in calorimeters, with corrections based on the associated reconstructed object

Top quark pairs differential cross section measurements in ATLAS

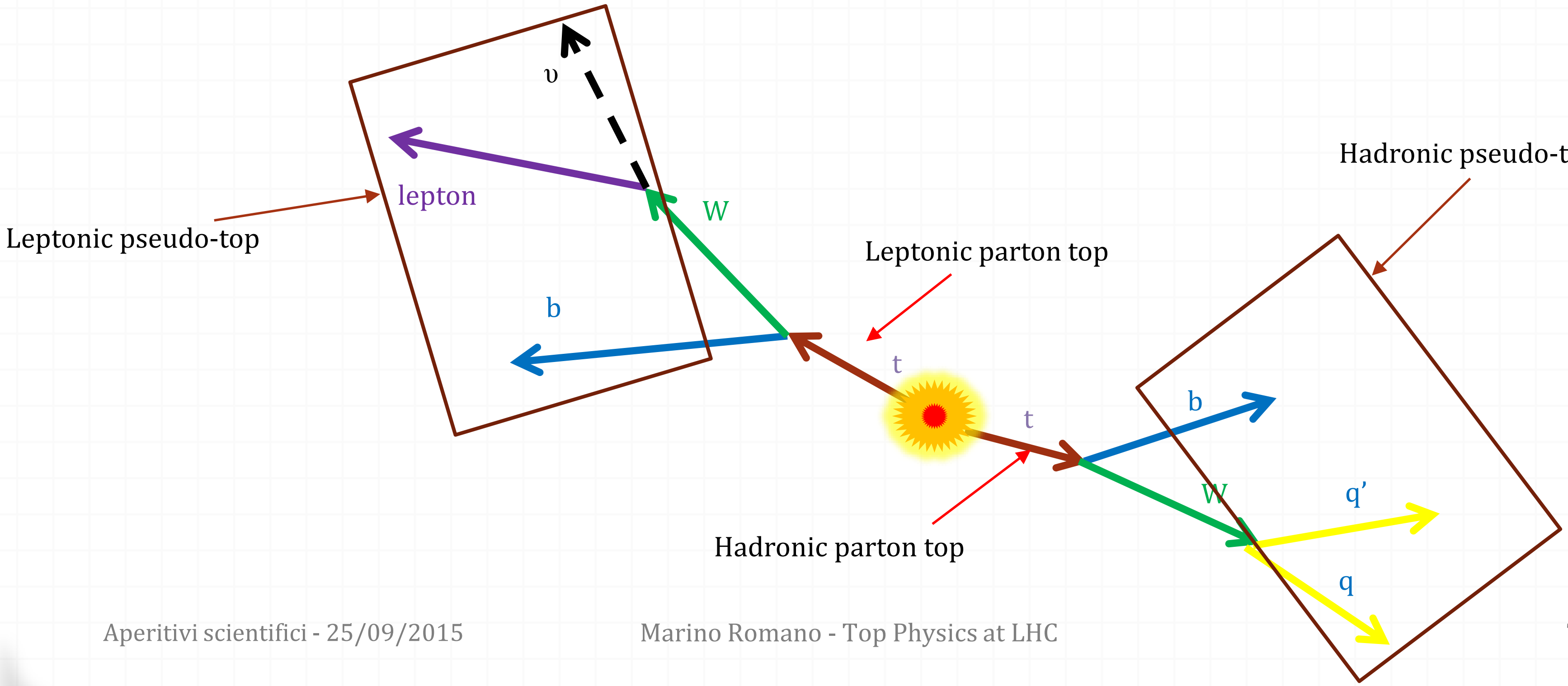
Definition of the object "top-quark"

'Parton-level' top:

- the top quark approximately after final state radiation and before decay.

'Particle level' top (or pseudo-top):

- Observable constructed from *stable* particles directly related to the top



From the detector-level spectra to the cross section measurement

The 'detector-level' spectra are linked to the 'parton level'cross section σ_j via

$$N_i = \sum_j M_{ij} \epsilon_j \sigma_j \beta L + B_i$$

Where

- N_i is the number of observed data events in the bin j.
- L is the luminosity
- B_i is the number of background events in the bin i.
- β is the branching ratio
- M_{ij} is the 'migration matrix'
- ϵ_j is the efficiency of the selection

$t\bar{t}$ normalized differential cross section

Phys. Rev. D 90, 072004

$\sqrt{s} = 7$ TeV, $L = 4.6$ fb^{-1}

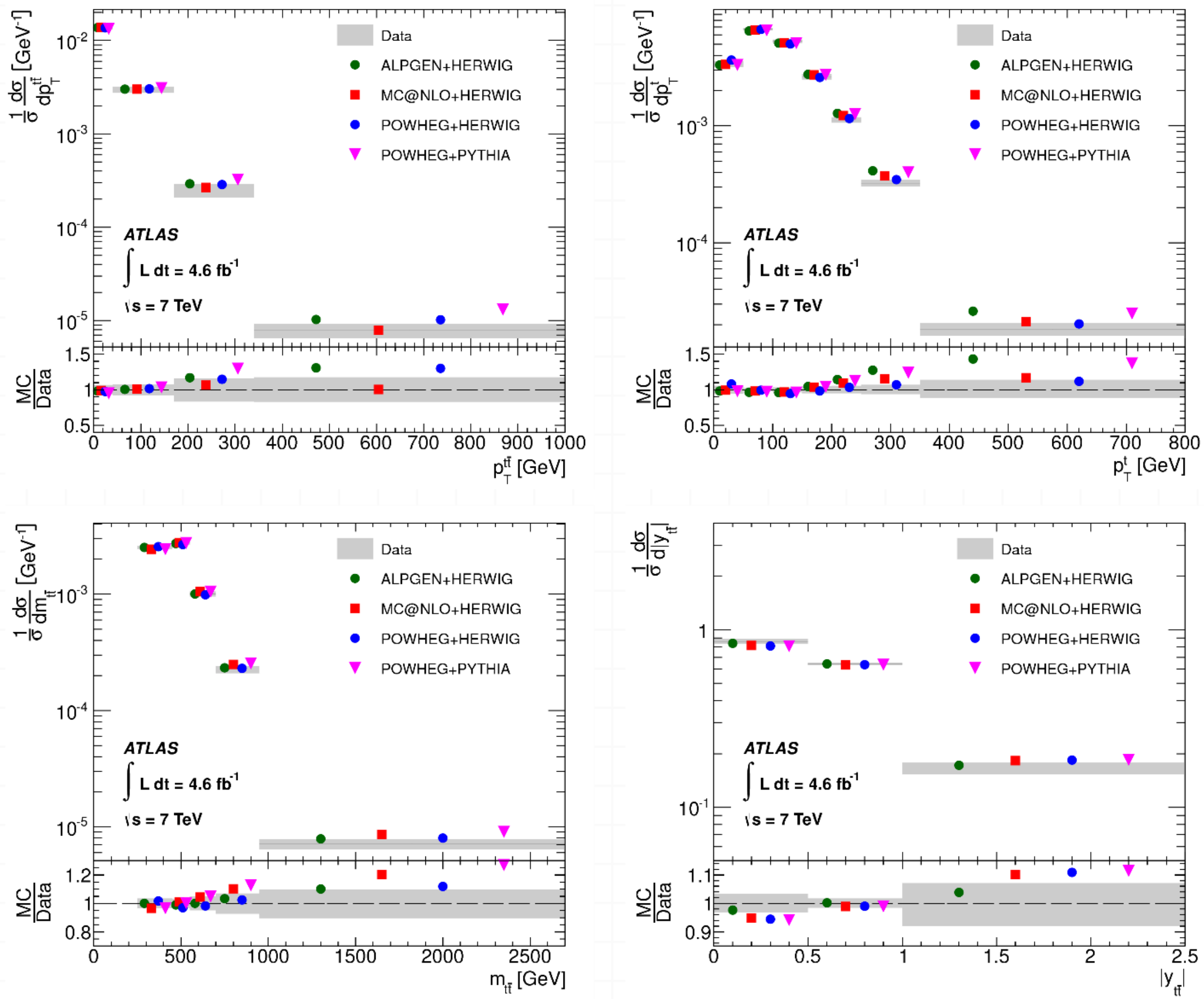
Electron and muon channel combination via the Asymmetric Iterative BLUE (AIB)

Main uncertainties:

- $p_{T,t}$, $m_{t\bar{t}}$: JES, generator b-tag;
- $p_{T,t\bar{t}}$: IFSR, generator, PS, JER
- $|y_{t\bar{t}}|$: generator and PS

Comparison to MC generators: Alpgen, Powheg and MC@NLO interfaced with Herwig+Jimmy and Powheg+Pythia

- General trend of data being softer in $p_{T,t}$ above 200 GeV
- All four MC generators describe well the shape of $m_{t\bar{t}}$ and $p_{T,t\bar{t}}$
- Alpgen gives the best prediction of the $|y_{t\bar{t}}|$

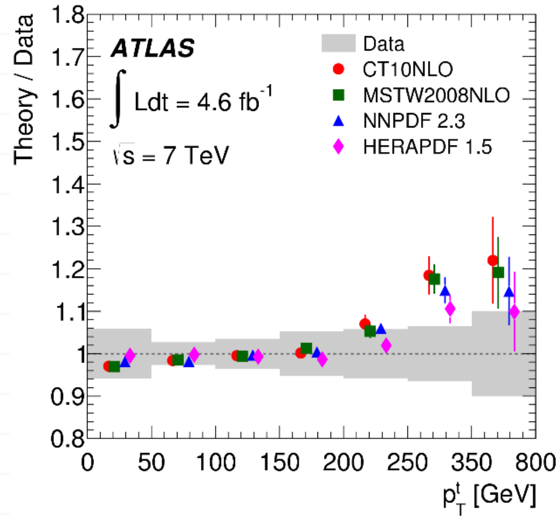


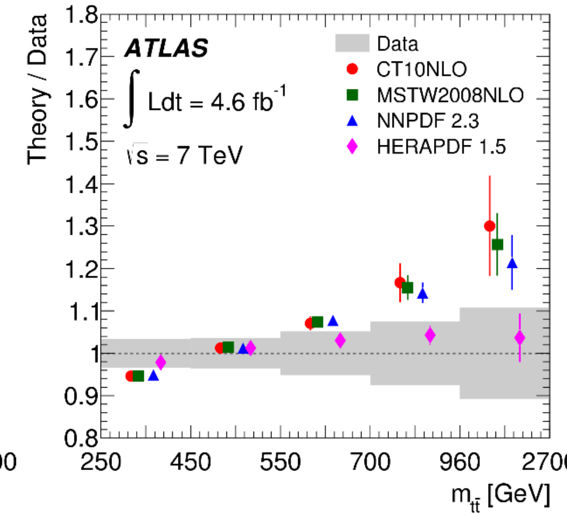
Results: comparison with NLO calculations

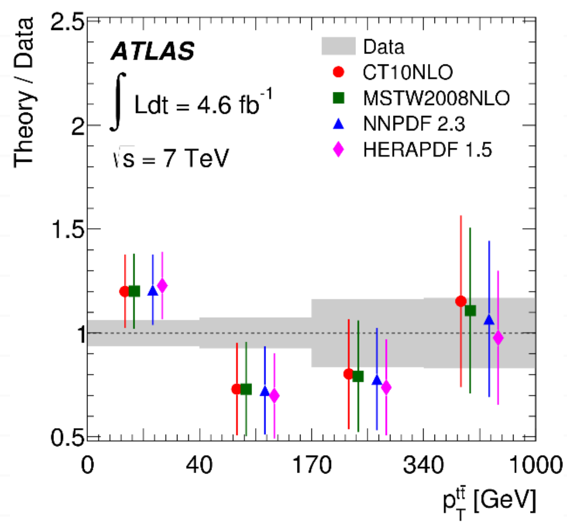
NLO prediction based on MCFM with different PDF sets

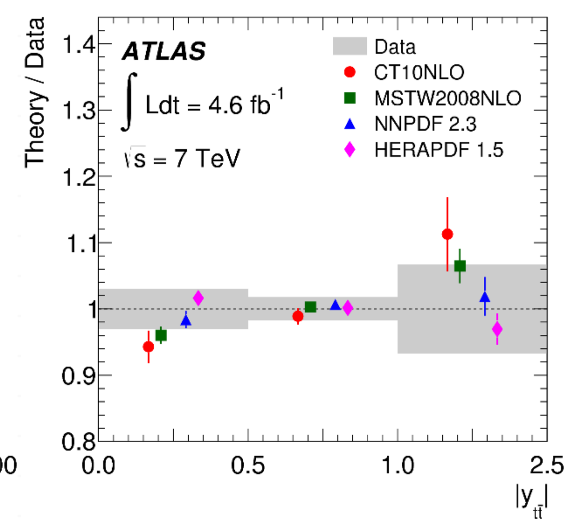
Uncertainty: scale (fixed) and PDF

- A small discrepancy between data and all predictions is observed in $p_{T,t}$ at higher p_T
- Overall better agreement with HERAPDF1.5
- Poor constraining power for $p_{T,t\bar{t}}$ (LO observable)

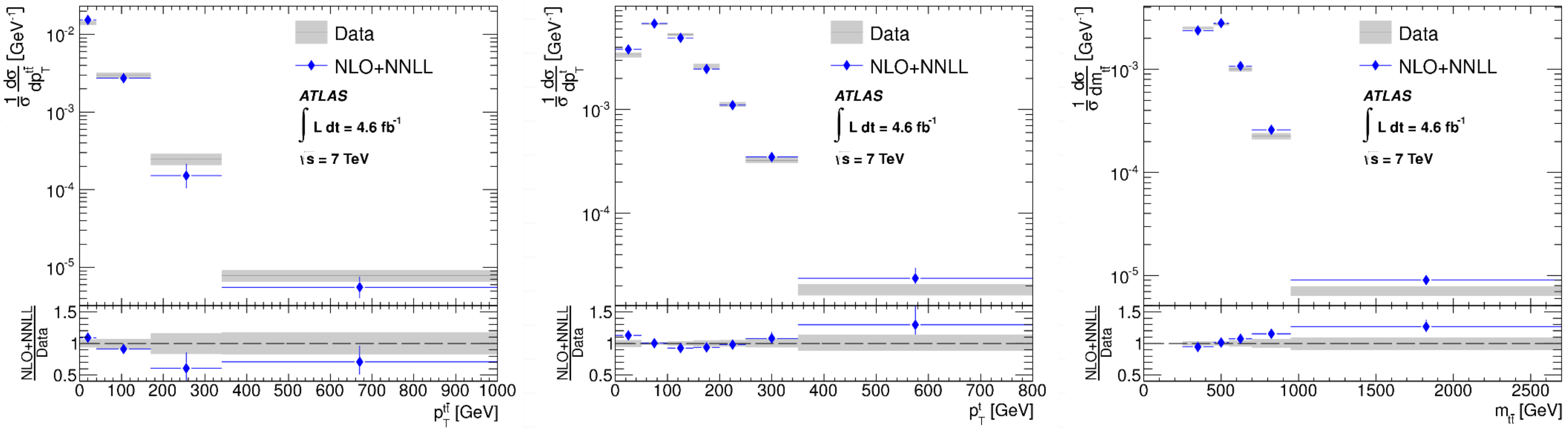








Results: comparison with approximate NNLO calculations



NLO+NNLL prediction for $p_{T,t}$ (N. Kidonakis, Phys. Rev. D82 (2010) 114030), for $m_{t\bar{t}}$ (V. Ahrens et al., JHEP 1016 (2010) 097) and for $p_{T,t\bar{t}}$ (Hua Xing Zhu et al., Phys. Rev. Lett. 110 (2013) 082001) with the MSTW2008NNLO PDF

Theory uncertainty from the fixed scale variations and, only for $p_{T,t}$, from the alternate dynamic scale $\mu = \sqrt{m_t^2 + p_{T,t}^2}$

- As in the NLO calculation, the $p_{T,t}$ spectrum in data seems softer
- Opposite trend appears for $p_{T,t\bar{t}}$ spectrum
- The $m_{t\bar{t}}$ spectrum is not well described by the NLO+NNLL prediction

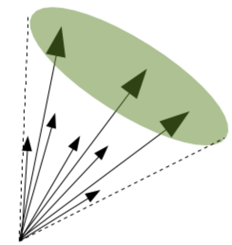
"Particle level" object definitions and selection

- Details can vary among the different analyses
- Leptons and jets are defined using particles with a mean lifetime $\tau > 3 \times 10^{-11}$s
- Prompt leptons (e/mu/nu) *not* generated by the decay of a hadron as well as leptons coming from the decay of a tau
- The electron and muon four-momenta are calculated after the addition of any photon four-momenta, not originating from hadron decay that are found $\Delta R < 0.1$ with respect to the lepton direction ("dressed" leptons)
- Jets:
  - Reconstructed from all stable particles except for the selected electrons, muons and neutrinos, using the anti-kt algorithm ($R = 0.4$)
- 'b-tagging':
  - The presence of one or more b-hadrons with pT > 5 GeV associated to a jet defines it as a b-jet.
- Missing transverse energy
  - Vector sum the neutrinos four-momenta
- Events are "selected" at particle level by applying, to the particle level objects, the same requirements applied to the "reco level" objects

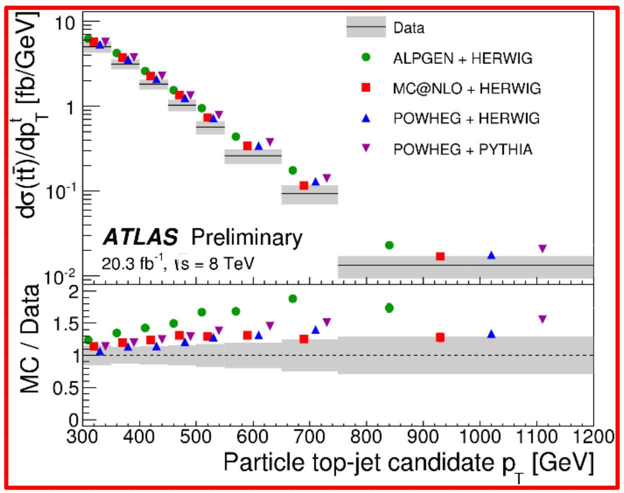
$t\bar{t}$ differential cross section: boosted tops

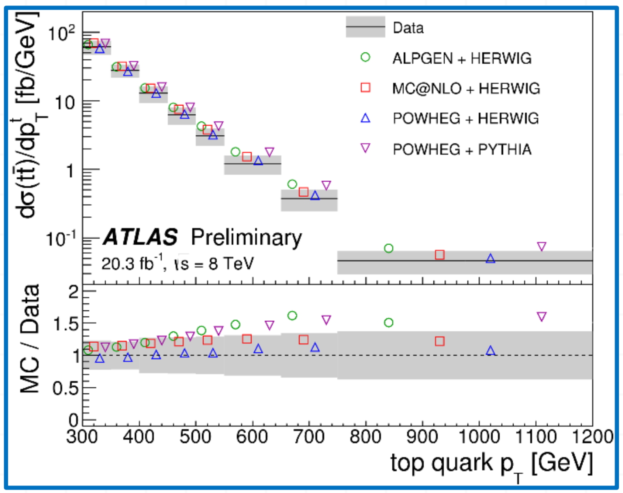
ATLAS-CONF-2014-057

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1}



- First measurement $\frac{d\sigma}{dp_{T,t}}$ for high-p_T (boosted) top quarks
- Semi-leptonic (e/μ) channel with $p_T(t_{had}) > 300$ GeV
  - Boosted hadronic top defined as a single large-R jet
- Fiducial (particle pseudo tops) and total (parton tops) phase space measurements



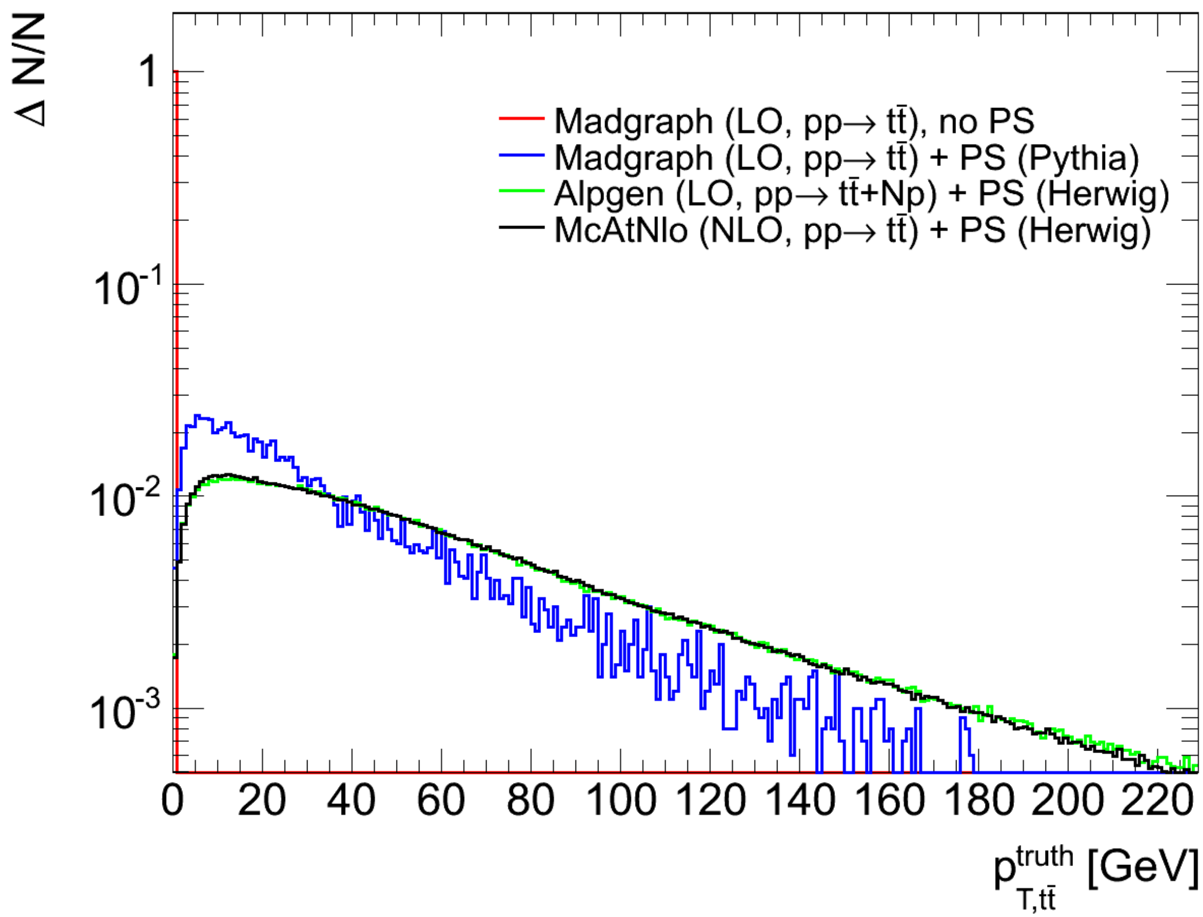


Main uncertainties: large-R jet energy scale

- Extrapolation to parton level affected by an increased signal modelling systematics

- Measured σ in general lower than predictions
  - Discrepancy tends to increase at high p_T
  - In agreement with the behavior observed in resolved analyses

$\frac{1}{\sigma}\frac{d\sigma}{dp_{T,tt}}$, PS dependence

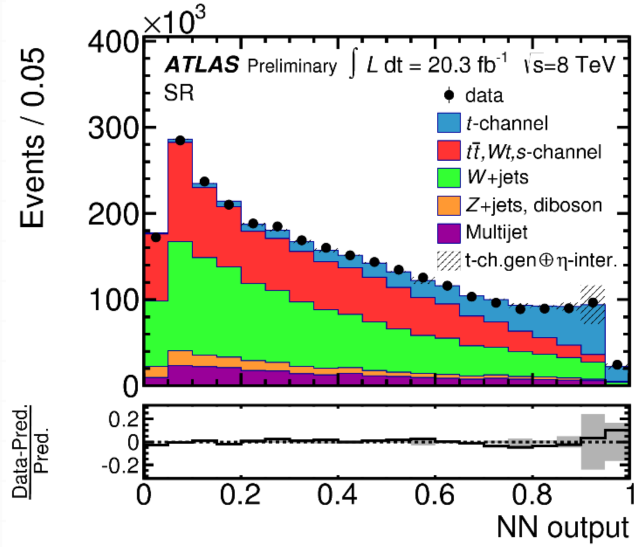


Single top t-channel cross section

ATLAS-CONF-2014-007

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1}

- A multivariate Neural Network (NN) discriminant trained with the 14 most-sensitive variables
  - Contributions from signal and background evaluated via MC (data driven for Multijet bkg in the μ channel)
- Lepton + 2 jets channel, 1 b-tag
- σ_{t-chan} extracted via a maximum-likelihood fit of the NN output in the data
- Fiducial and total phase space measurements



$$\sigma^{fiducial}_{t-chan}(\sqrt{s} = 8\text{ TeV}) = 3.4 \pm 0.48\text{ pb } (\pm 14\%)$$

Main uncertainties: JES and signal modelling

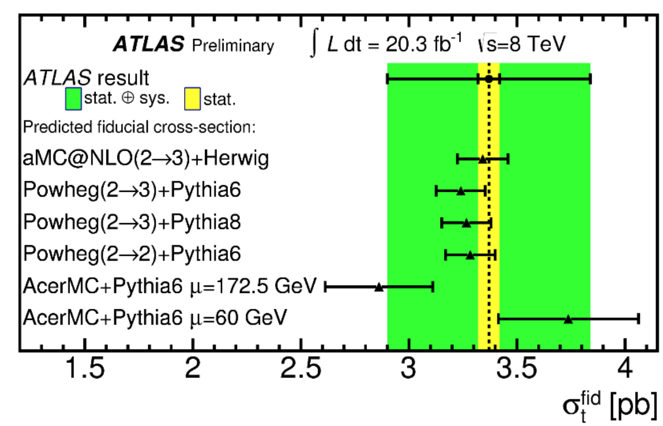
$$\sigma^{total}_{t-chan}(\sqrt{s} = 8\text{ TeV}) = 82.6 \pm 12.1\text{ pb } (\pm 15\%)$$

(extrapolated via MG5_aMC@NLO)

Additional uncertainty: PDF

$$\sigma^{th}_{t-chan}(\sqrt{s} = 8\text{ TeV}) = 87.8^{+3.4}_{-1.9}\text{ pb } (^{+3.9\%}_{-2.2\%})$$

N. Kidonakis, Phys. Rev. D 83 (2011) 091503



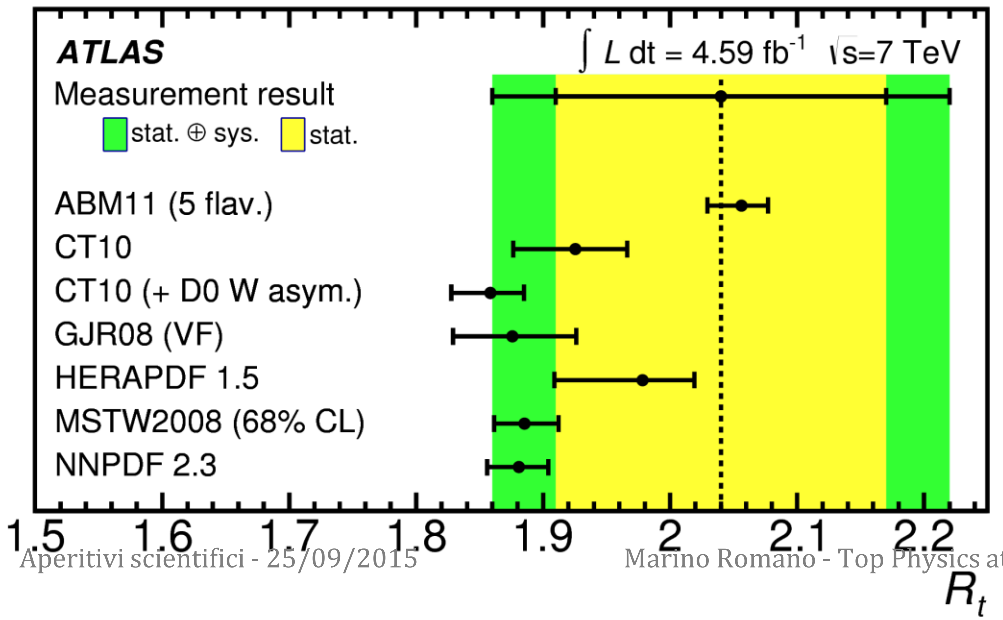
Single top/antitop t-chan ratio

$$R_t = \frac{\sigma_t}{\sigma_{\bar{t}}}$$

Phys. Rev. D. 90, 112006 (2014)

$\sqrt{s} = 7$ TeV, $L = 4.6$ fb^{-1}

- Very sensitive to the ratio of the PDF of the valence quark in the high x regime
  - Smaller uncertainties because of error cancelations
- Sensitive to new physics effects
- Same analysis technique used in the σ_{tchan} measurement at 8 TeV



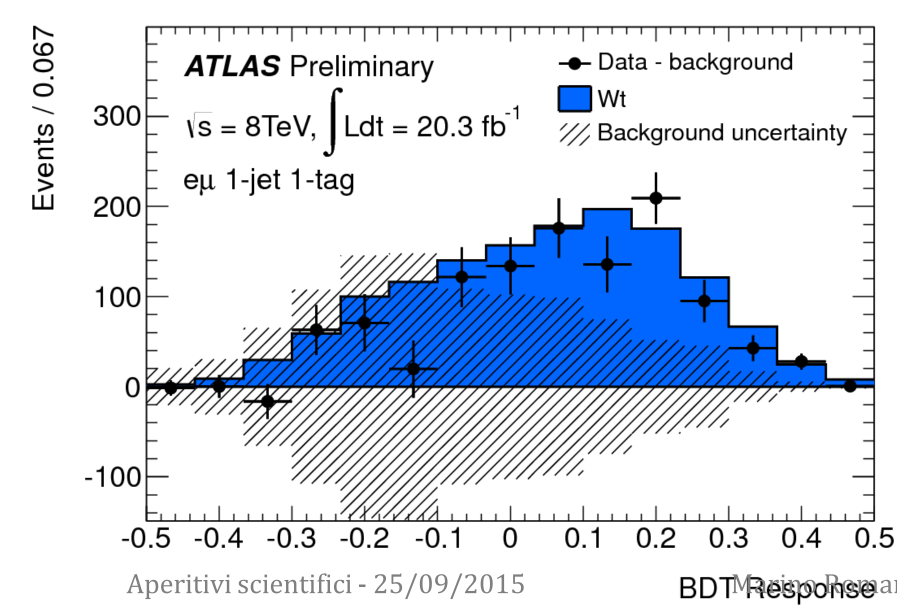
The measurement is in agreement with the predictions from different PDF sets and is dominated by statistical and systematic (MC statistics and PDF) uncertainties

Single top Wt-channel cross section

ATLAS-CONF-2013-100

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1}

- Hard to separate from $t\bar{t}$, interference at NLO
  - Event selected requiring $1e$, 1μ, 1/2jet, 1b-tag, E_T^{miss}
  - Multivariate analysis based on Boosted Decision Tree (BDT) employed to increase the discrimitation power
    - BDT trained using Wt as signal and $t\bar{t}$ as background
    - BDT discriminants built separately for 1 and 2 jet samples
  - Most discriminating variable: $p_T^{sys}(lep1, lep2, E_T^{miss}, jet1)$
  - Maximum likelihood fit to the BDT output to extract the signal cross section



$$\boldsymbol{\sigma_{Wt}(\sqrt{s} = 8\ \text{TeV}) = 27.2 \pm 5.8\ \text{pb}\ (\pm 21\%)}$$

(observed $\mathbf{4.2\sigma}$, expected 4.0σ)

Main systematics: b-tagging, JES, generator uncertainties

$$\sigma_{Wt}^{th}(\sqrt{s} = 8\ \text{TeV}) = 22.4 \pm 1.5\ \text{pb}(\pm 6.7\%)$$

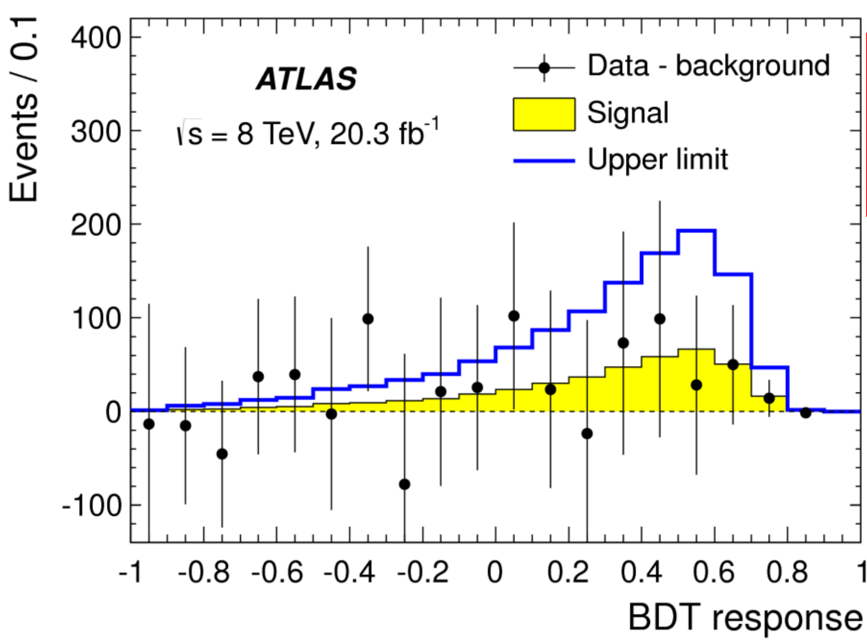
N. Kidonakis, Phys. Rev. D 82 (2010) 054018

Single top *s*-channel search

Phys. Lett. B740 (2015) 118

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb^{-1}

- Low rate in *pp* collissions (was dominant at Tevatron)
  - Event selected requiring 1l, 2b-tag, E_T^{miss}
  - Multivariate analysis based on Boosted Decision Tree (BDT) employed to increase the discrimitation power
  - Most discriminating variable: $|\Delta\phi(t, b)|$
  - Maximum likelihood fit to the BDT output to extract the signal cross section



$\boldsymbol{\sigma_{s-chan}(\sqrt{s} = 8\ \mathrm{TeV}) = 5.0 \pm 4.3\ \mathrm{pb}}$ ($\pm$**86%**)
(**1.3σ**, expected 1.4σ)
Upper limit: **14.6 pb** @ 95%CL

Main uncertainties: E_T^{miss} and jet energy scale, data & MC statistics

$\sigma_{s-chan}^{th}(\sqrt{s} = 8\ \mathrm{TeV}) = 5.61 \pm 0.22\ \mathrm{pb}\ (\pm 3.9\%)$

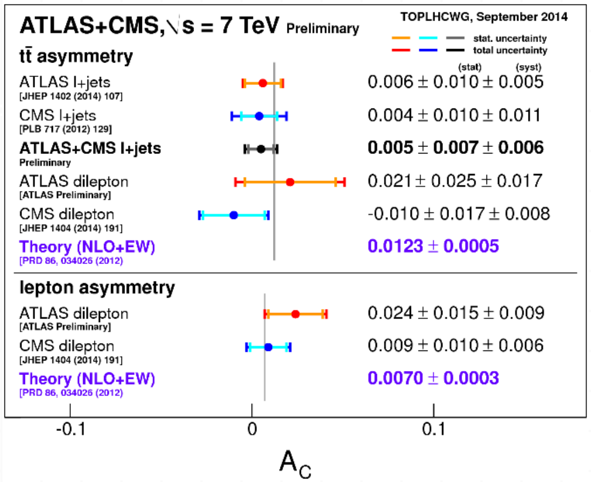
N. Kidonakis, Phys. Rev. D 81 (2010) 054028

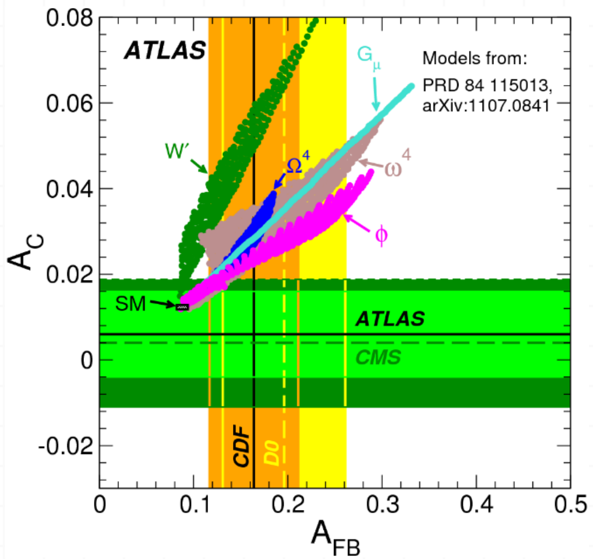
$t\bar{t}$ charge asymmetry in Run I

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}| \qquad \Delta|y| = |y_{l^+}| - |y_{l^-}|$$

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad \Delta y = y_t - y_{\bar{t}}$$

- A_{FB} measured at Tevatron
  - Not a "good" observable at LHC
- A_C Extensively measured @ 7 TeV
- All results obtained after unfolding to parton level
  - Dilepton channel (submitted to JHEP)
    - Simultaneous measurement of $A_C(tt)$ and $A_C(ll)$
  - Single lepton channel (JHEP02(2014)107)
  - Combination with CMS (ATLAS-CONF-2014-012)
- Results in agreement with SM predictions



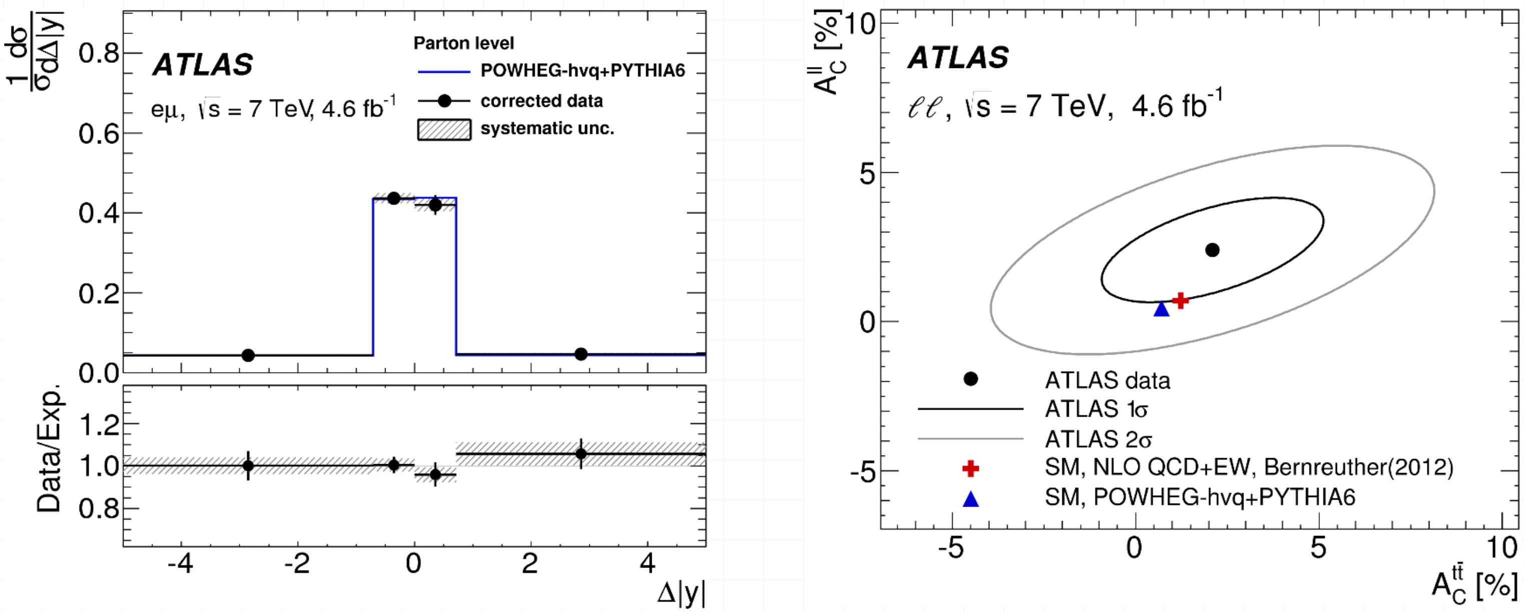


$t\bar{t}$ charge asymmetry in l^+l^- channel

arXiv:1501.07383, Submitted to JHEP

$\sqrt{s} = 7$ TeV, $\int Ldt = 4.6$ fb^{-1}

- Dilepton channel allows lepton-based asymmetry
  - No dependence on top reco algorithms
- Unfolding procedures to correct reco $\Delta|y|$ spectra for detector response and acceptance



$$A_C^{ll} = 0.024 \pm 0.015 \pm 0.009$$
$$A_C^{tt} = 0.021 \pm 0.025 \pm 0.017$$

Spin correlation measurements

$$A = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)} \quad A^{SM}_{helicity} = 0.38 \pm 0.04$$

- 7 TeV analysis: Phys. Rev. D. 90, 112016 (2014)
  - Four observables used to extract the spin correlation from a binned likelihood fit of f_{SM} where
    $$A_{measured} = f_{SM} A^{th}_{SM}$$
  - $\Delta\phi(ll)$ shows highest sensitivity
- 8 TeV analysis: arXiv:1412.4742, submitted to PRL
  - Spin correlation extracted via a template fit on $\Delta\phi(ll)$ distribution
    $$f_{SM} = 1.20 \pm 0.05(stat) \pm 0.13(syst)$$
  - Most precise measurement to date
  - See Paolo Dondero's poster for stop exclusion from $t\bar{t}$ spin correlation