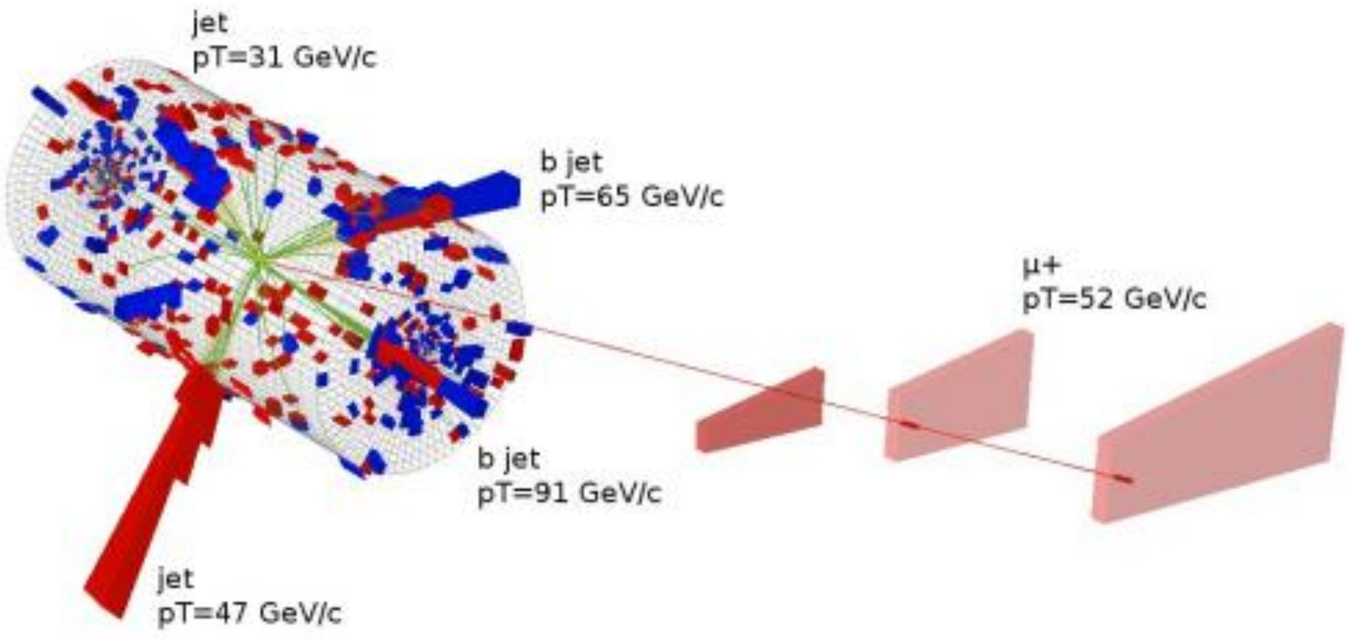

The top secrets (at the LHC)

Roberto Chierici
CNRS (IPN Lyon)

GGI – Arcetri – 7 October 2014

Contents

This talk will focus on (precision) measurements in the domain of top physics at the LHC

Total and differential cross-sections on single top, top-pair, top and bosons

Top mass and properties

Selected(*) experimental results

Twist towards the open questions to TH/phenomenology

The ubiquitous TH uncertainties

Special focus on LHC combined results

In-talk discussion welcome

(*) Disclaimer: this is not a complete review of results on top physics. The choice made is personal and, by definition, biased. This talk will mostly cover LHC results. Tevatron results are flashed when relevant. For the state of the art of experimental results please go here:

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- http://www-cdf.fnal.gov/physics/new/top/top.html
- http://www-d0.fnal.gov/Run2Physics/top/

2014

7th International Workshop on Top Quark Physics

TOP 2014
Cannes, France
from September 29th to October 3rd, 2014.

NEW@TOP2014

Top2014

The TOP 2014 workshop will be held from September 29th to October 2[...]s, France.
It will bring together about 130 experimental and theoretical physici[...] quark physics and related topics. The workshop will provide a comprehensive overvi[...]ults from the LHC and Tevatron experiments as well as the most recent theoretical de[...] outlook on top quark physics at future colliders.
The programme will consist of plenary presentations, a po[...]ved for young researchers, and plenty of time for discussions.
The goal of the workshop is to provide a comprehen[...] physics and a forum where experimentalists and theorists can discuss the int[...] quark results and future measurements.
A related topical workshop about top quark dif[...]ons will be held in the same location 3 days before the conference (26-28 September 20[...] registration: http://indico.cern.ch/e/top-differential-distributions-2014 .

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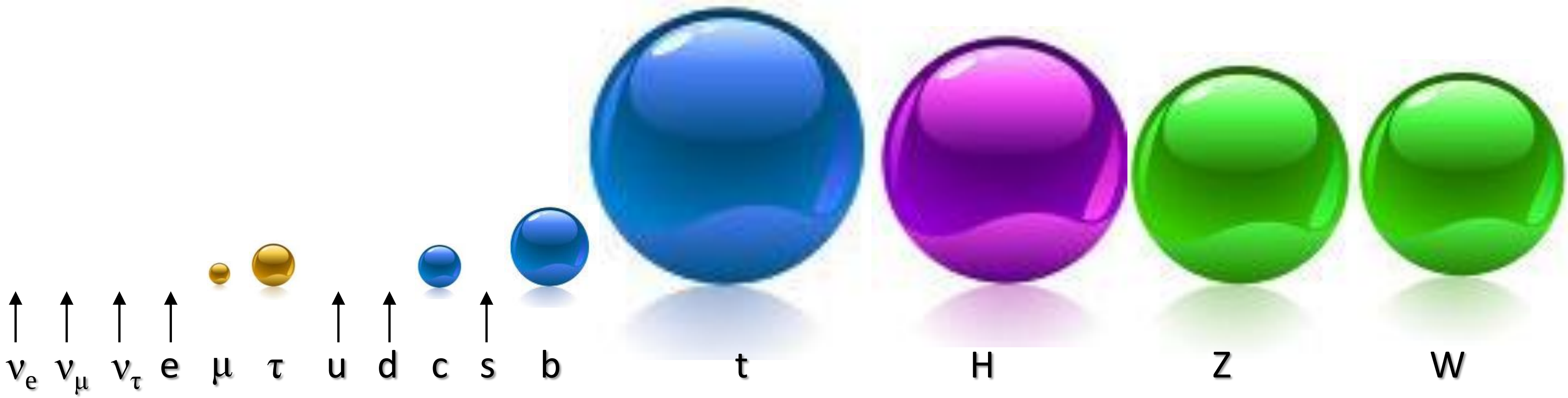
INTRODUCTION

Motivation and experimental setup



A particle with unique characteristics

- Interesting per se: a fundamental fermion weighting like a tungsten atom !
- A particle that is "strongly" coupled to the Higgs sector
  - Can use to constrain the SM, or any new model of new physics
  - Direct measure of the top Yukawa coupling is possible
- Top physics gives direct access to fundamental parameters of the SM
  - Direct access to parameters of the SM (m_t, V_{tb})
  - Other stringent tests of SM (QCD in $d\sigma/dX$, couplings, CPT invariance,…)
- It is the only quark that does not hadronise
  - No bound tq states, its spin properties are directly passed to its decay products
- Privileged gateway to signals of new physics
  - Many new models do concern the top sector exclusively, other may involve top partners like in SUSY, UED, little Higgs, 4^{th} generation models
  - Top-like signatures are a very important background for several other searches

Why is it experimentally challenging (+interesting)

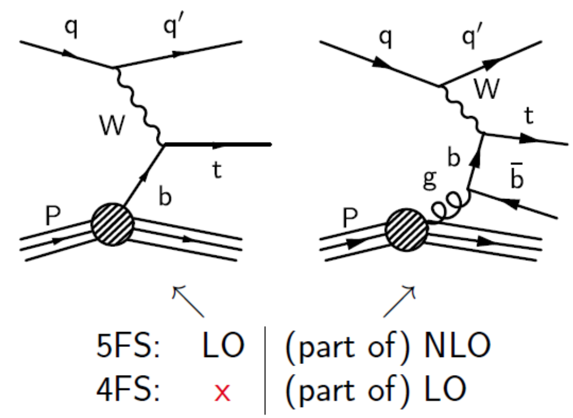
- It involves all parts of a multi-purpose detector
  - Excellent understanding of tracking, calorimetry, muon system.
  - Excellent hermeticity
  - Excellent understanding of b-tagging and energy calibrations
- Jets (in particular b-jets) are ubiquitous
  - Excellent control of the JEC for light and heavy flavours
  - Jet pairing gives rise to important combinatorial backgrounds to fight with
- Requirement to Monte Carlo predictions (ME+models) is now impressive
  - Simulating radiation in top pair still one of the most important systematic effects
  - "Soft-er" QCD effects becoming increasingly important in precision measurements (CR and fragmentation)
- Top quarks are an exceptional tool for in situ calibration (more than we expected at the beginning)
  - Control b-tagging and light JES with the W mass
  - Use top pair events to understand radiation and CR in top pair events !

Typical Monte Carlo setup

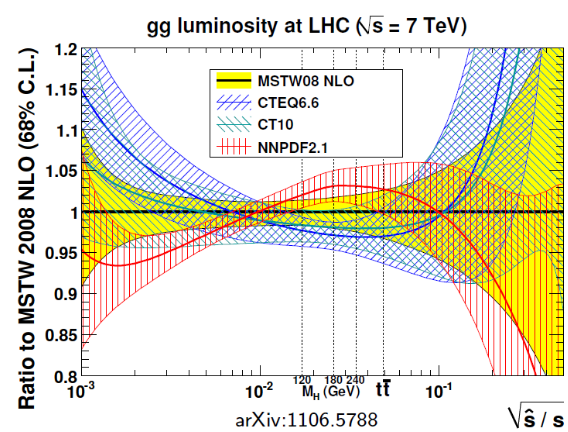
- Reference Monte Carlo setup in ATLAS and CMS include multi-leg or NLO predictions for signal regions and main background processes.

- For top pair production
  - ATLAS: Powheg+PYTHIA6 or MC@NLO+HERWIG6 (also Alpgen+HERWIG6)
  - CMS: MadGraph+PYTHIA6 (also Powheg+PYTHIA6)

- For single top production
  - ATLAS: AcerMC (4FS+5FS LO) or Powheg+PYTHIA6 (4FS NLO)
  - CMS: Powheg+PYTHIA6 (5FS NLO)
  - Plan for Run II: Powheg and aMC@NLO (4FS NLO)
  - DR and DS schemes for tW. In the future use the full WbWb calculation

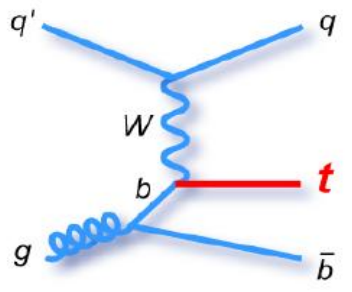


- Typical input parameter settings
  - PDF4LHC prescription where relevant: envelope of CT10, MSTW2008, NNPDF2.3 including α_S variations (±0.0012). Also CTEQ6L1 is used
  - Parton showers: PYTHIA6 vs HERWIG6 or vs HERWIG++
  - Tunings: Perugia11C, Z2*



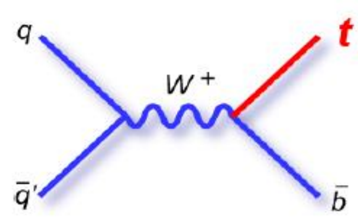
(single) top production at the LHC

- Top is produced in pairs (QCD) or singly (EWK)
- <u>Single top</u> EWK production happens via three main contributions



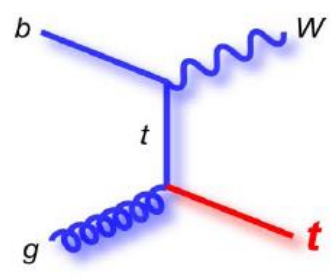
t-channel

σ(7 TeV)~64 pb



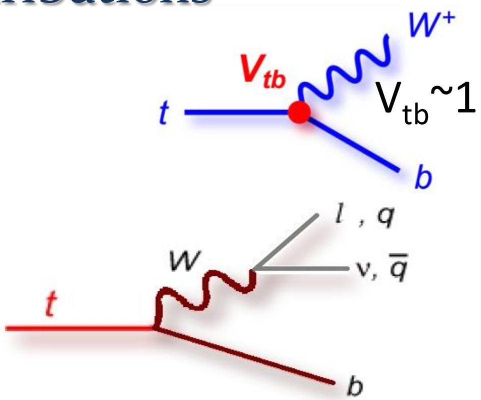
s-channel

σ(7 TeV)~4.6 pb

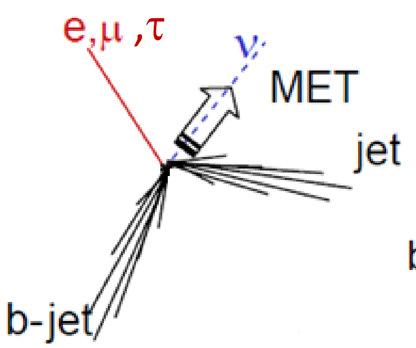


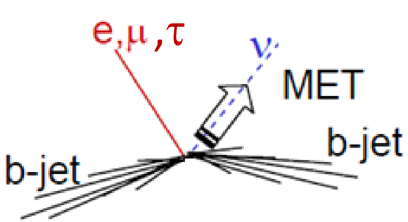
tW-channel

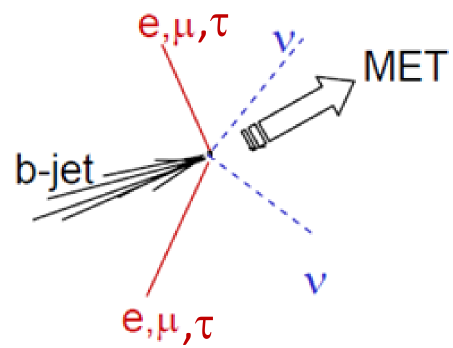
σ(7 TeV)~15.6 pb



Kidonakis, NLO+NNLL
t-channel: PRD 83 (2011) 091503
s-channel: PRD 81 (2010) 054028
tW-channel: PRD 82 (2010) 054018





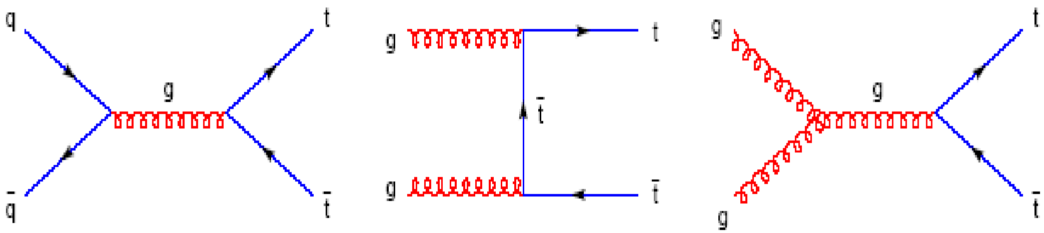


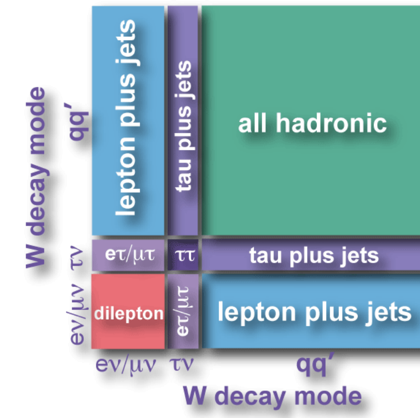
- Backgrounds coming from W/Z+jets, top pair production, QCD

Top (pair) production at the LHC

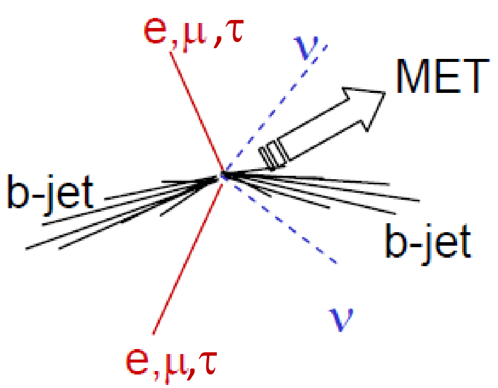
- Top pair QCD production happens mainly via gluon fusion

σ(NNLO+NNLL) ± scales ± PDFs [pb]		
	7 TeV	8 TeV
Czakon, Fiedler, Mitov (arXiv:1303.6254)	$172.0^{+4.4}_{-5.8}\,^{+4.7}_{-4.8}$	$245.8^{+6.2}_{-8.4}\,^{+6.2}_{-6.4}$



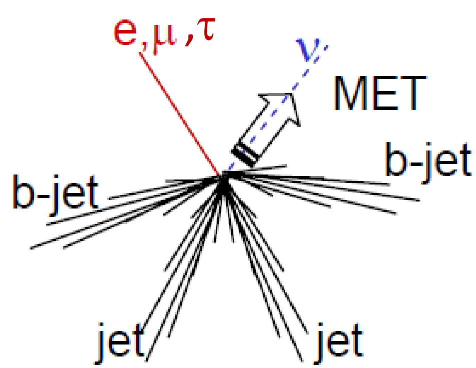


- Final states depend on the decay of the W bosons



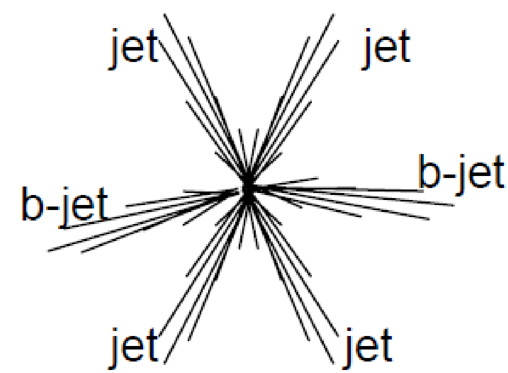
dileptons

- BR~10%



lepton + jets

- BR~44%



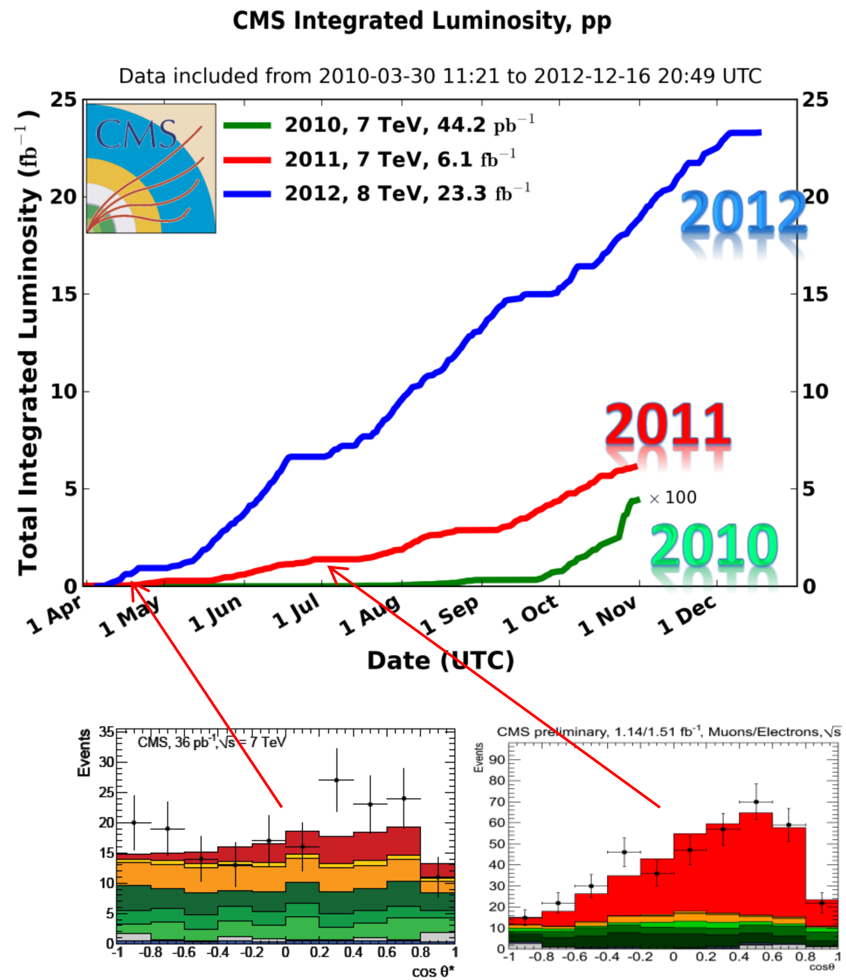
all hadronic

- BR~46%

- Backgrounds coming from W/Z+jets, single top (tW), QCD

Collected data

- Impressive performance of the LHC in 2011(@7TeV)/2012(@8 TeV)
  - ➢ About ~6/fb collected in total at 7 TeV
  - ➢ About ~23/fb collected at 8 TeV

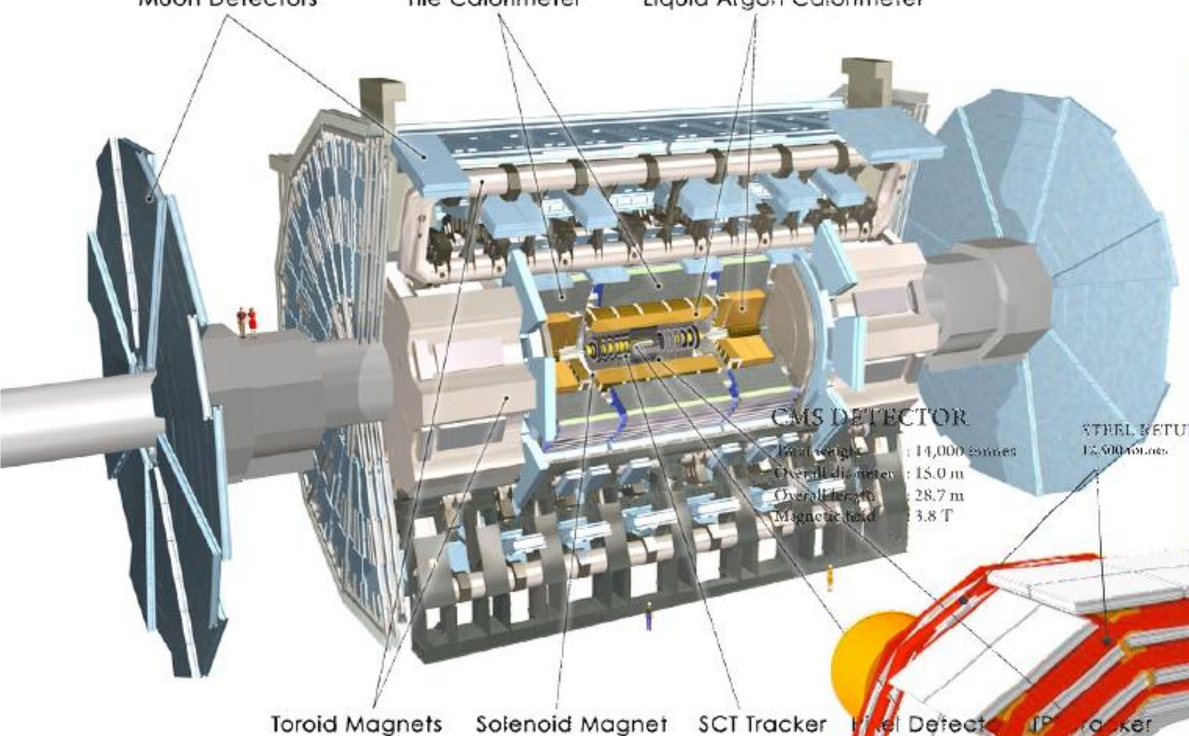


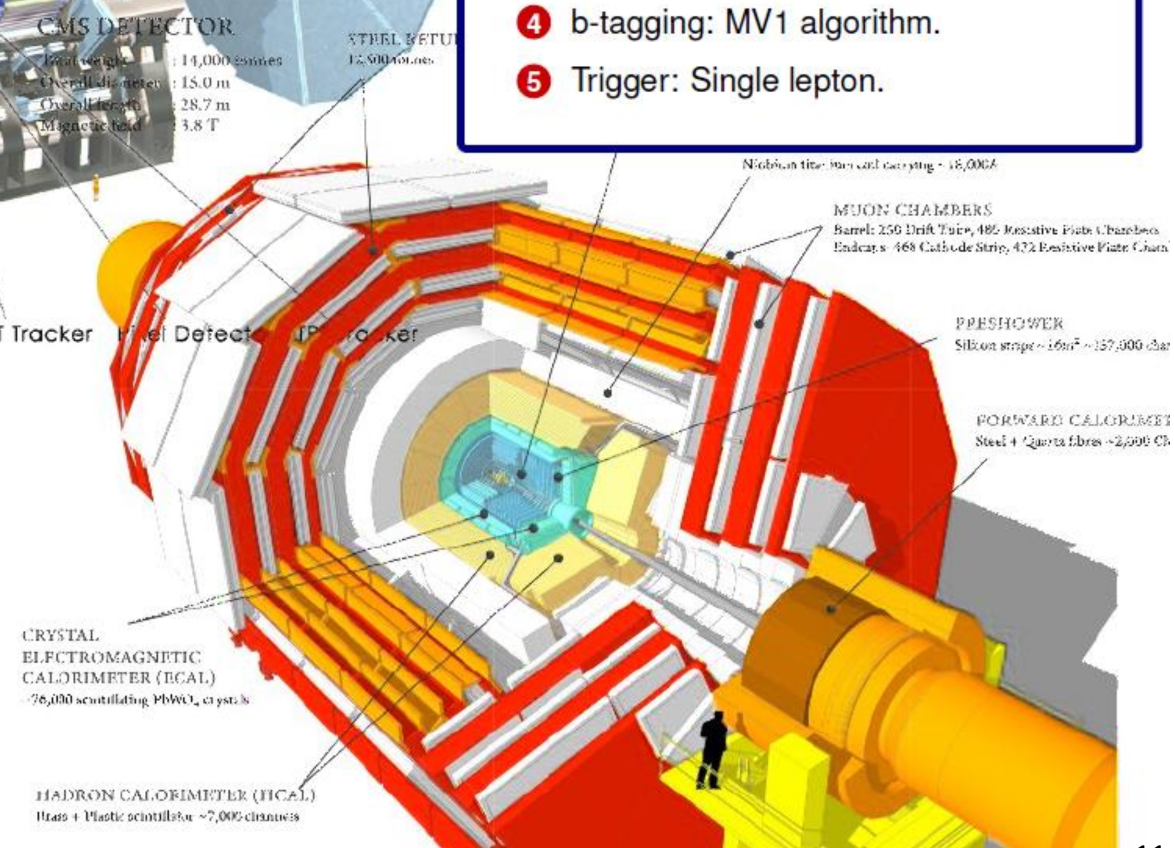
Example: how the single top signal improves

- Statistics important for top physics
  - ➢ LHC is the first top factory ever !
    - o O(1M) tt @7TeV, O(10M) @8 TeV
  - ➢ While precision measurements soon limited by systematic errors, many possibilities for other studies open up
    - o Rare processes
    - o Searches for new physics
    - o Constrain of systematic errors and backgrounds by using data

Experiments

ATLAS and CMS detectors





ATLAS Detector

1. Jets: 3D topological clusters.
2. Electron: $|\eta|<2.47$ and $p_T{}^{e}>25\,\mathrm{GeV}$
3. Muon: $|\eta|<2.5$ and $p_T{}^{\mu}>20/25\,\mathrm{GeV}$
4. b-tagging: MV1 algorithm.
5. Trigger: Single lepton.

CMS Detector

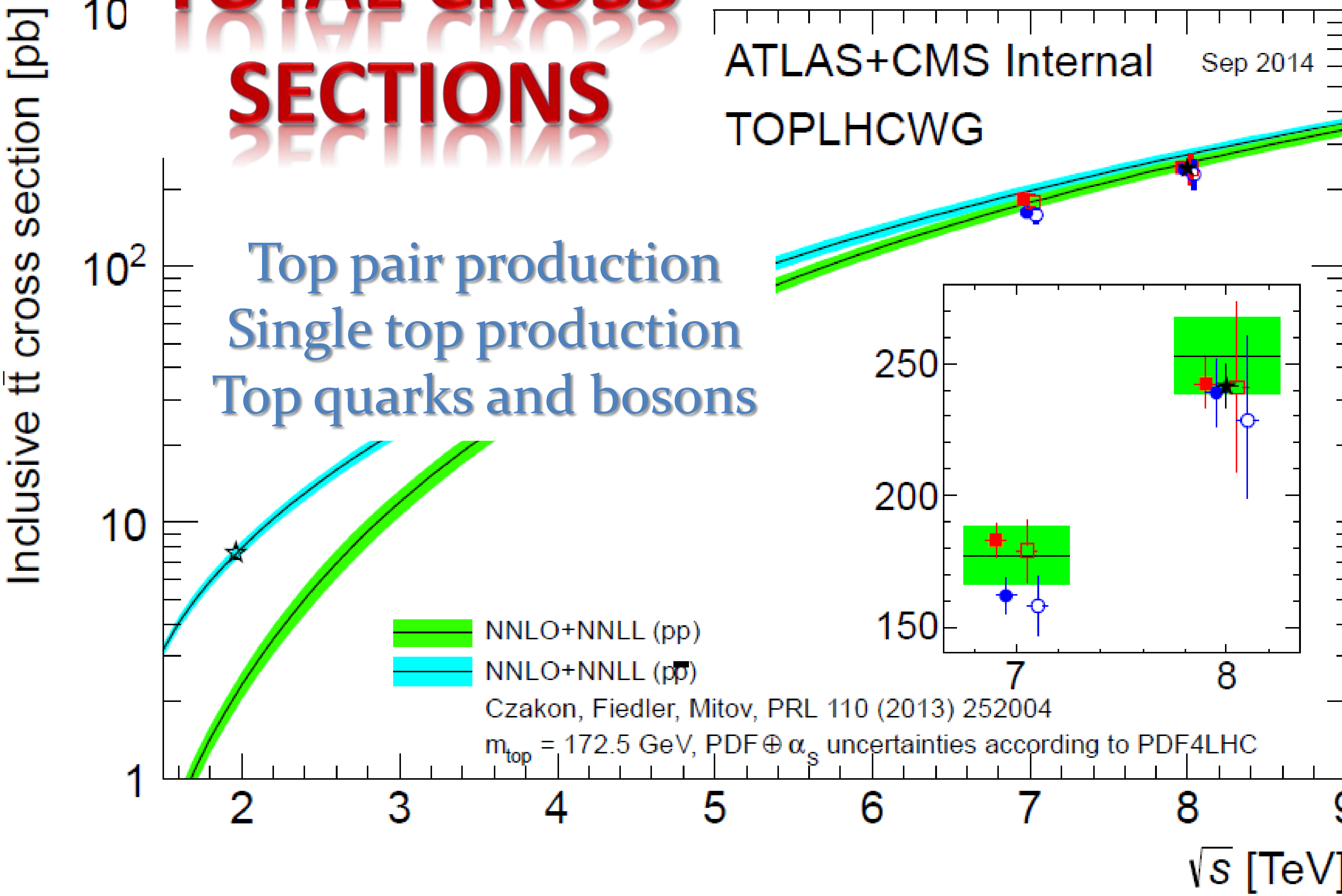
1. Particle Flow.
2. Electron: $|\eta|<2.5$ and $p_T{}^{e}>20/35\,\mathrm{GeV}$
3. Muon: $|\eta|<2.4$ and $p_T{}^{e}>20/30\,\mathrm{GeV}$
4. b-tagging: CSV algorithm.
5. Trigger: Single lepton/Dilepton.

Summary or reconstruction methods and performance and techniques for background determination

- I can (maybe) answer questions, in case…

TOTAL CROSS SECTIONS

Top pair production
Single top production
Top quarks and bosons

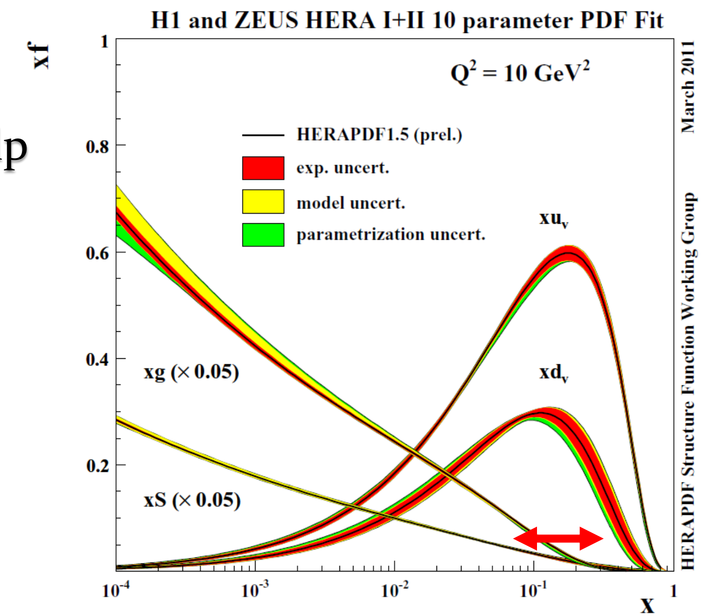


Total cross section measurements

- Monitoring the total production cross section is the first fundamental step for understanding top physics at the LHC
  - ➢ Test the presence of new production mechanisms
  - ➢ In the frame of the SM, test QCD predictions and help constraining the PDFs (especially gluons)
    - Important for Higgs production, for instance

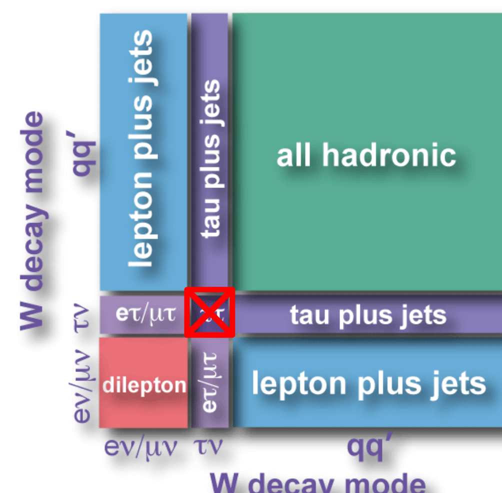
$$\sigma_{t\bar{t}}(m_t) = \sum_{i,j} \int_0^1 dx_1 dx_2\, f_i(x_1) f_j(x_2)\, \hat{\sigma}_{ij}(m_t)$$

  - ➢ Indirect determination of m_t or α_S.
  - ➢ Constrain a very important background for many searches at the LHC



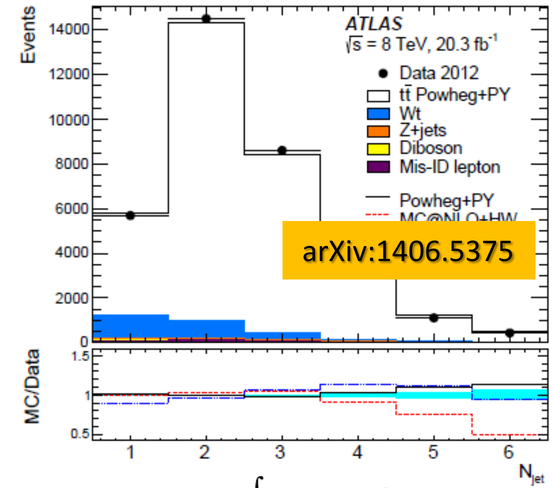
- Almost all decay modes are investigated at the LHC

- The measurements are performed at different level of complexity:
  - ➢ Counting experiment in acceptance $\sigma = \dfrac{N_{data} - N_{BG}}{\epsilon_{t\bar{t}} \int \mathcal{L} dt}$
  - ➢ Fit to data in several portions of phase space with in situ constraining of various backgrounds
  - ➢ Multivariate analyses

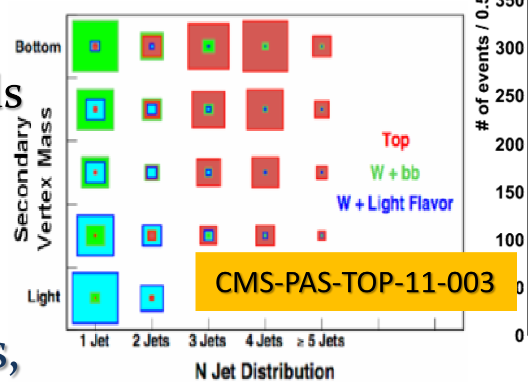


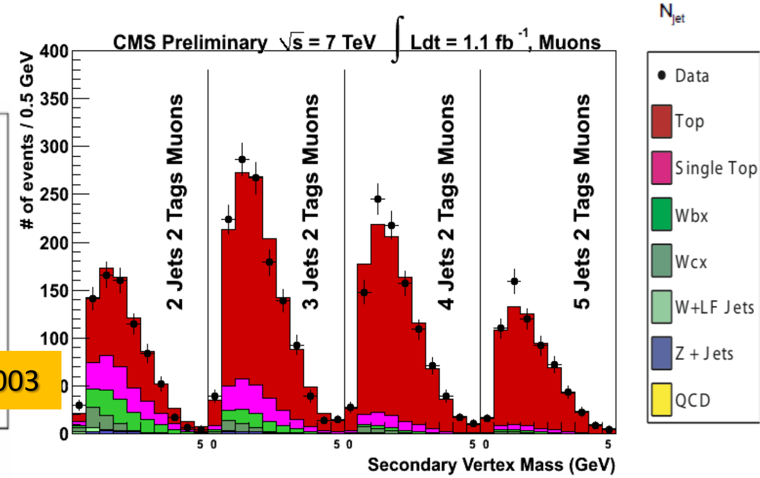
Top pair cross section

- Di-lepton final states (e, μ) background free
  - ➢ Likelihood fits to the number of reconstructed (b-tagged) jets. DY background data-driven

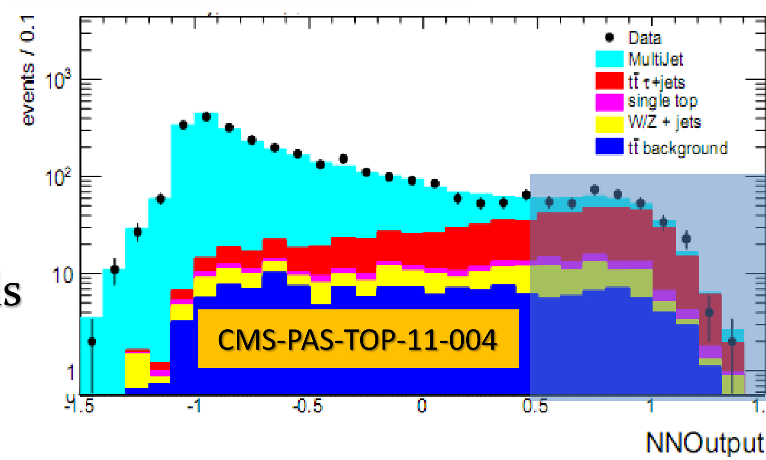


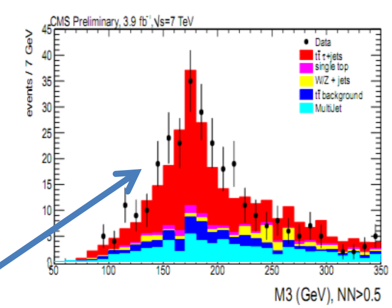
- ℓ+jets final states represent a good compromise between statistics and purity
  - ➢ Multidimensional ML fit to data
  - ➢ Use data themselves to constrain the backgrounds by including regions where they dominate





- Hadronic channels (all-jets, τ+jets) are very difficult
  - ➢ Entirely dominated by QCD, need to estimate it directly from data
  - ➢ Use NN to separate signals from backgrounds





Cross sections in fiducial regions

- Important to also provide measured cross section in the experimentally accessible phase space regions only
  - ➢ The extrapolated cross sections are 1/ε larger. May be a factor of 50-100 depending on the analysis, and is just coming from MC predictions
  - ➢ Fiducial cross sections are much less sensitive to important systematic errors, typically QCD scales and PDFs
  - ➢ If the phase space can be simply defined, easier comparison to theory
- Example: ATLAS extracts simultaneously tt, WW, Z/γ→ττ from a template fit over the eμbb final state

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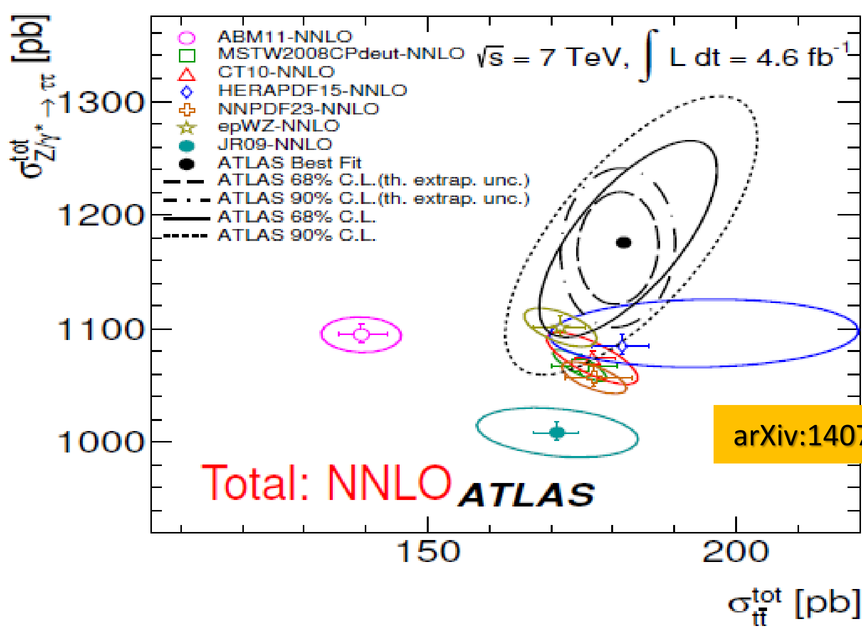
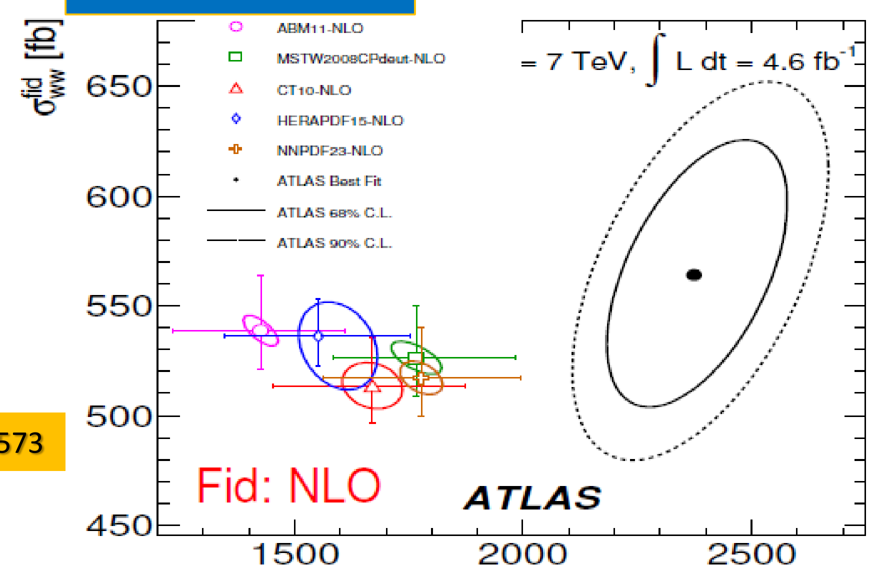


arXiv:1407.0573

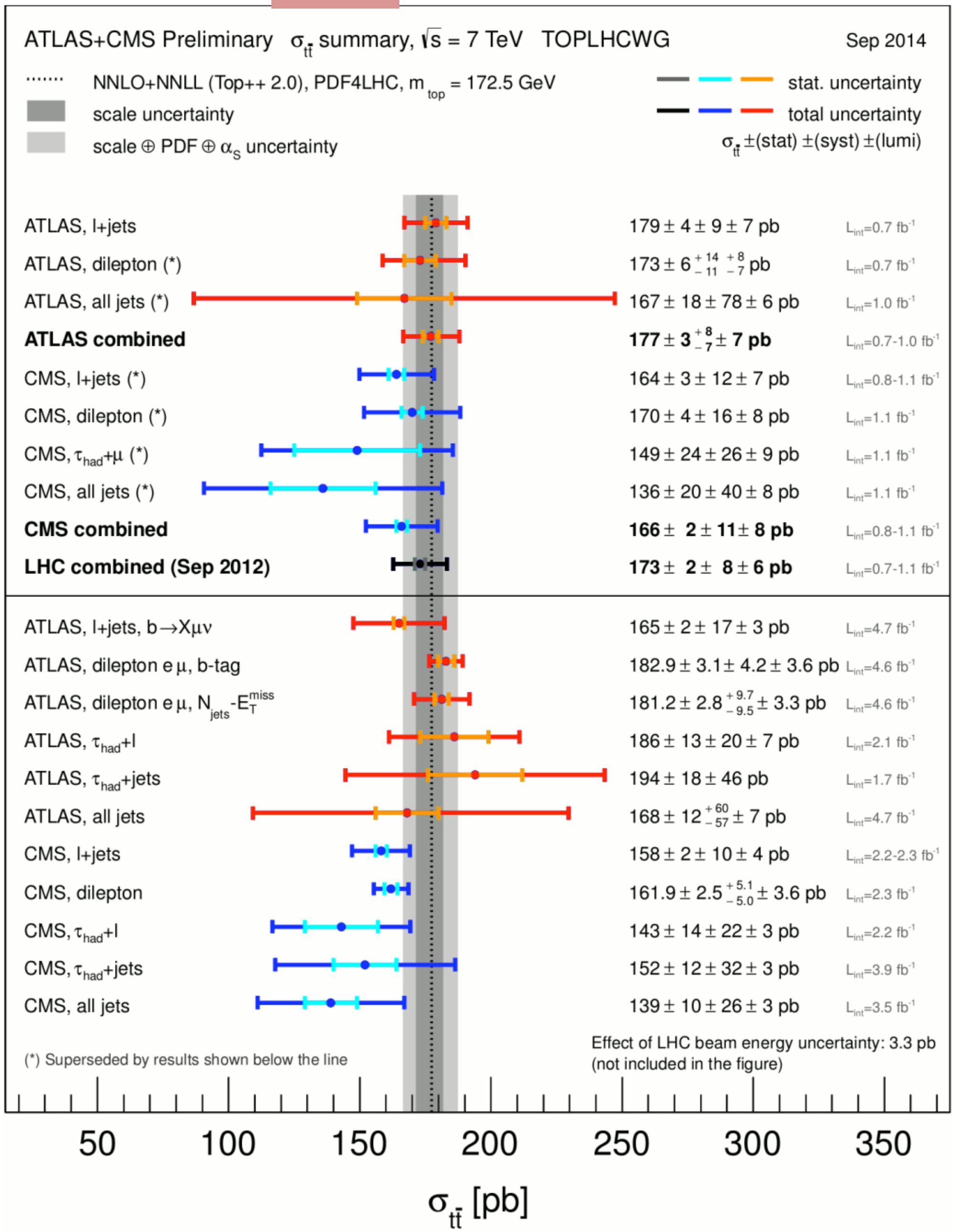


Fiducial cuts: $[p_T^{e(\mu)} > 25(20)\ \mathrm{GeV}; |\eta^{e(\mu)}| < 2.5(2.47)]$

Cross section combination

TOPLHCWG

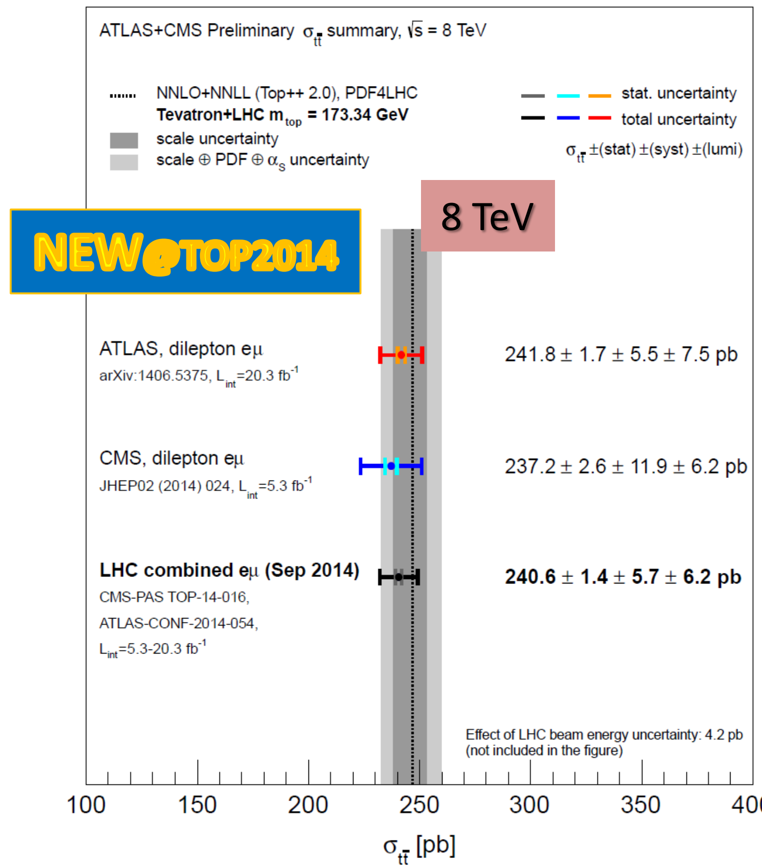
7 TeV



- Combination performed(*) accounting for correlations
  - Several categories introduced (experiments, energies, channels)

(*) With Best Linear Unbiased Estimator

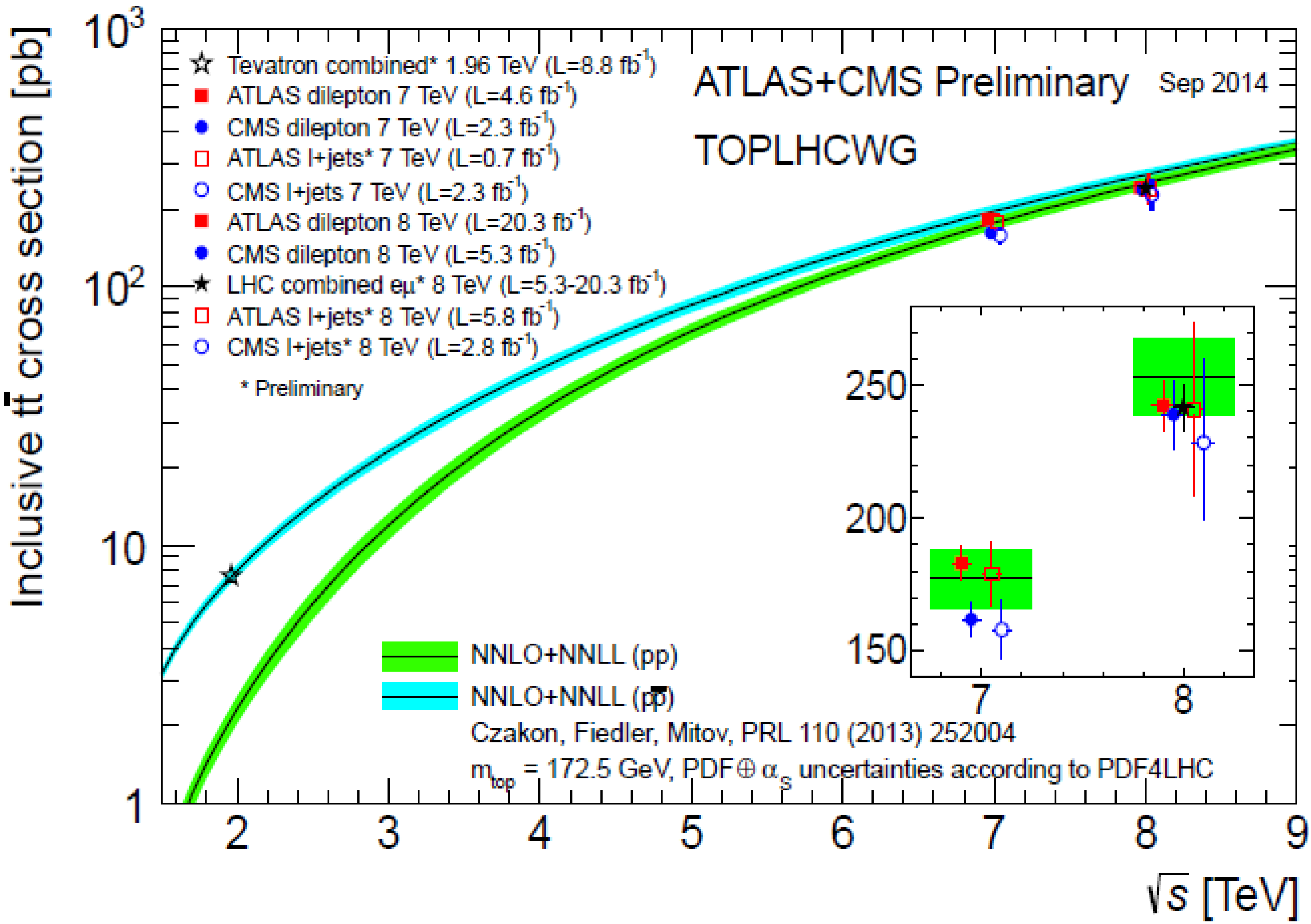
[Lyons, Gibaud, Clifford; Nucl. Instr. Meth. A270 (1988), 16.]



Cross sections results

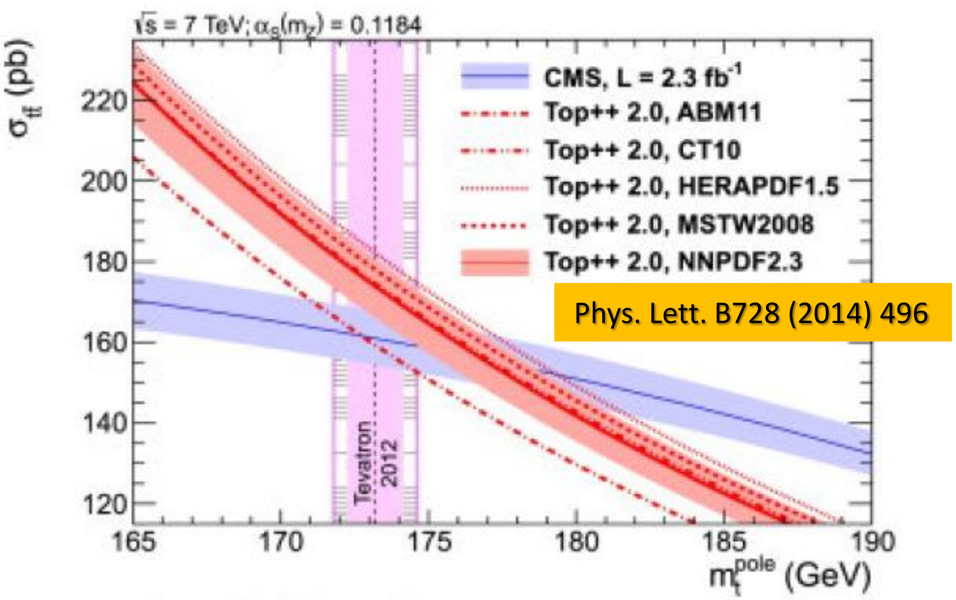
- Top pair production is measured and predicted to unprecedented precisions
  - Experiments more and more going towards presenting cross sections in fiducial regions

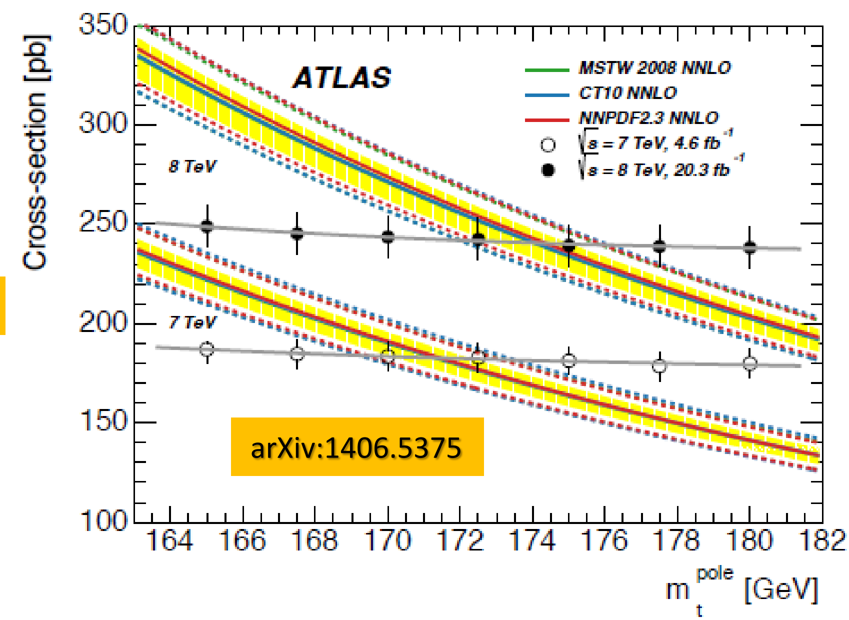
$$\sigma_{t\bar{t}}^{Theory} = 245.9\,\mathrm{pb} \pm 5.7\%$$
$$\sigma_{t\bar{t}}^{\mu e} = 241.8\,\mathrm{pb} \pm 3.5\%$$



Extraction of m_t and α_S

- Exploit the dependence of σ_{tt} on m_t and α_S
  - ➢ Parametrize measured and predicted cross section as a function of the top mass
    - ○ Need the full dependence of analyses' acceptances on m_t.
    - ○ Extract m_t by using a joint likelihood approach
  - ➢ Method to directly access the pole mass
    - ○ Not competitive with direct measurements





▷ fixed $\alpha_S(m_Z) = 0.1184 \pm 0.0007$

$m_t^{\text{pole}} = 176.7^{+3.0}_{-2.8}$ GeV →

$\sigma_{t\bar{t}}^{meas}$: $^{+2.1}_{-2.0}$

LHC beam energy: $^{+0.9}_{-0.9}$

PDF: $^{+1.5}_{-1.3}$, $\mu_{R,F}$: $^{+0.9}_{-0.9}$, α_S: $^{+0.7}_{-0.7}$

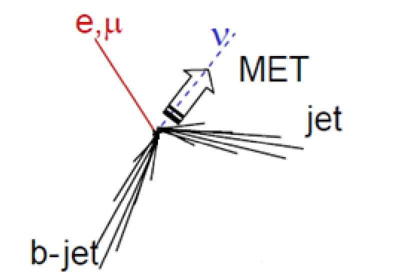
m_t^{MC}: $^{+0.5}_{-0.4}$

▷ fixed $m_t = 173.2 \pm 1.4$ GeV:

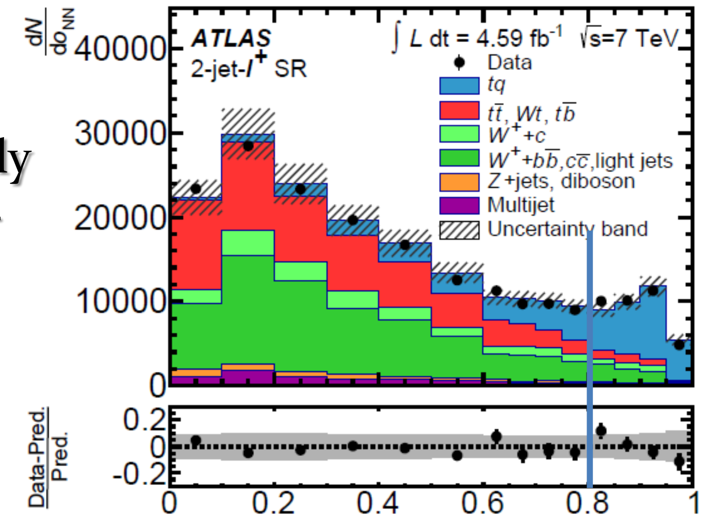
$\alpha_S(m_Z) = 0.1151^{+0.0028}_{-0.0027}$

PDF	m_t^{pole}(GeV) from $\sigma_{t\bar{t}}$ $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
CT10 NNLO	171.4 ± 2.6	174.1 ± 2.6
MSTW 68 % NNLO	171.2 ± 2.4	174.0 ± 2.5
NNPDF2.3 5f FFN	$171.3^{+2.2}_{-2.3}$	174.2 ± 2.4

Single top cross sections – t channel



- Typically use multivariate techniques (NN, BDT)
  - ➢ Optimize S/B separation using full event properties, constrain systematic effects by simultaneously analyzing S and B dominated regions
  - ➢ Results typically obtained by fitting simultaneously different regions of the phase space (eg 2J-1tag, 3J-1tag, divided into ℓ^+ and ℓ^-)



arXiv:1406:7844

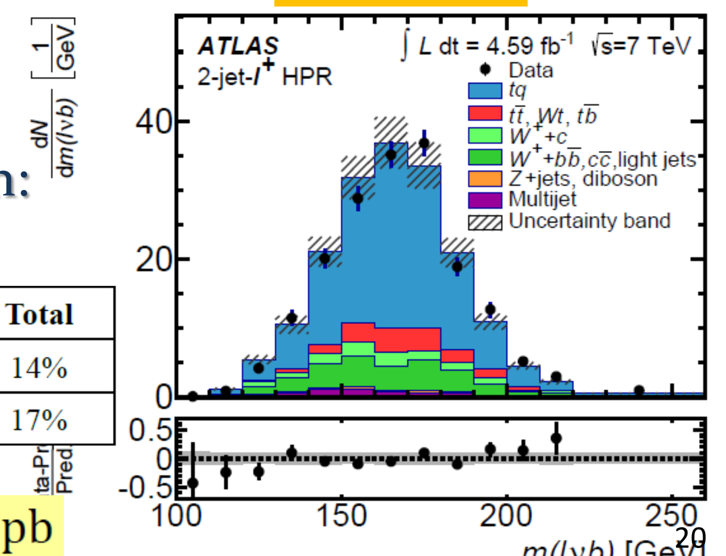
- Via independent counting on different charge samples one can determine

$$R = \frac{\sigma(tq)}{\sigma(\bar{t}q)} = \left\langle \begin{array}{l} ATLAS\,@\,7: 2.04 \pm 0.13(stat.) \pm 0.12(syst.) \\ CMS\,@\,8: 1.95 \pm 0.10(stat.) \pm 0.19(syst.) \end{array} \right.$$

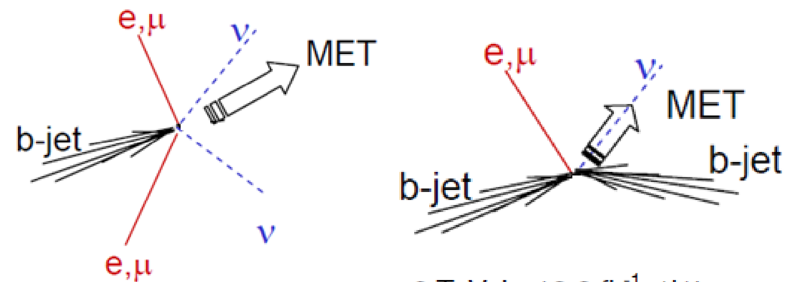
- ATLAS determines the first fiducial cross section:
  - ➢ Marginal effect due to acceptance, better comparison to theory
  - ➢ Much reduced impact of the TH uncertainties

	Generator	PDF	Total
Fiducial	8%	1%	14%
Inclusive	13%	4%	17%

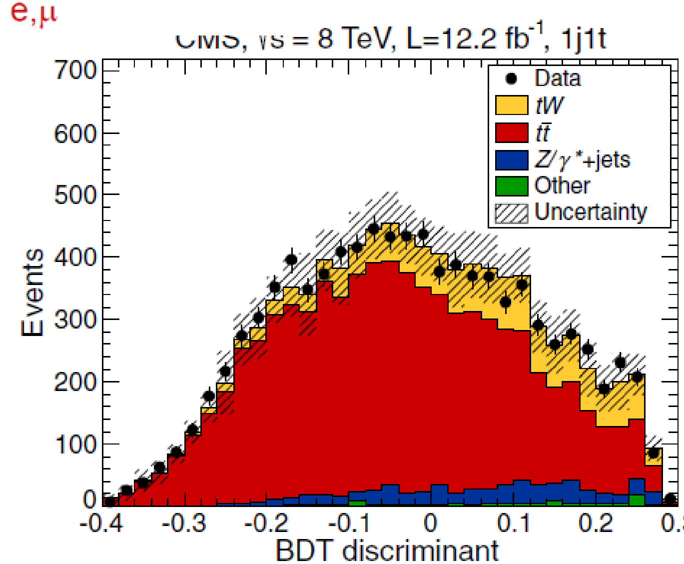
$$\sigma_{fid} = 3.37 \pm 0.05(\text{stat.}) \pm 0.47(\text{syst.}) \pm 0.09(\text{lumi.})\ \text{pb}$$



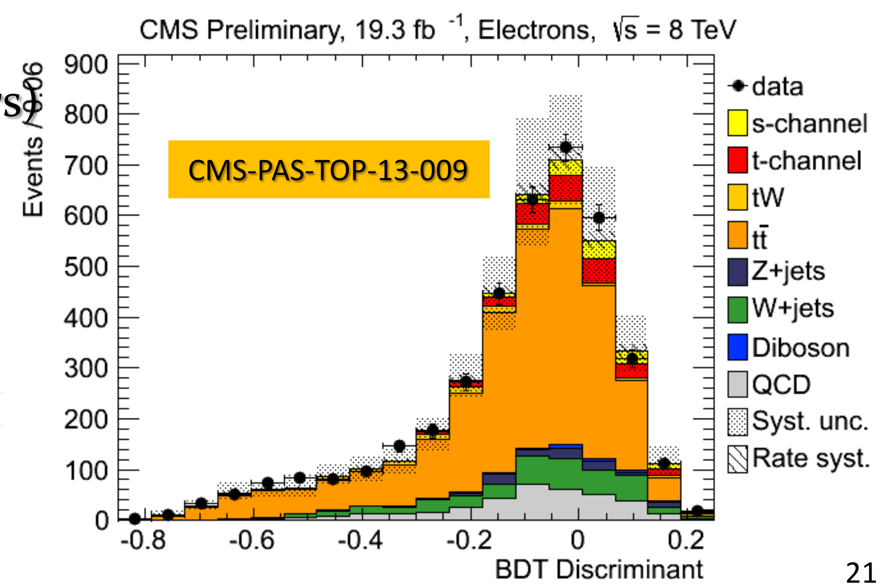
Single top cross sections – tW and s channel



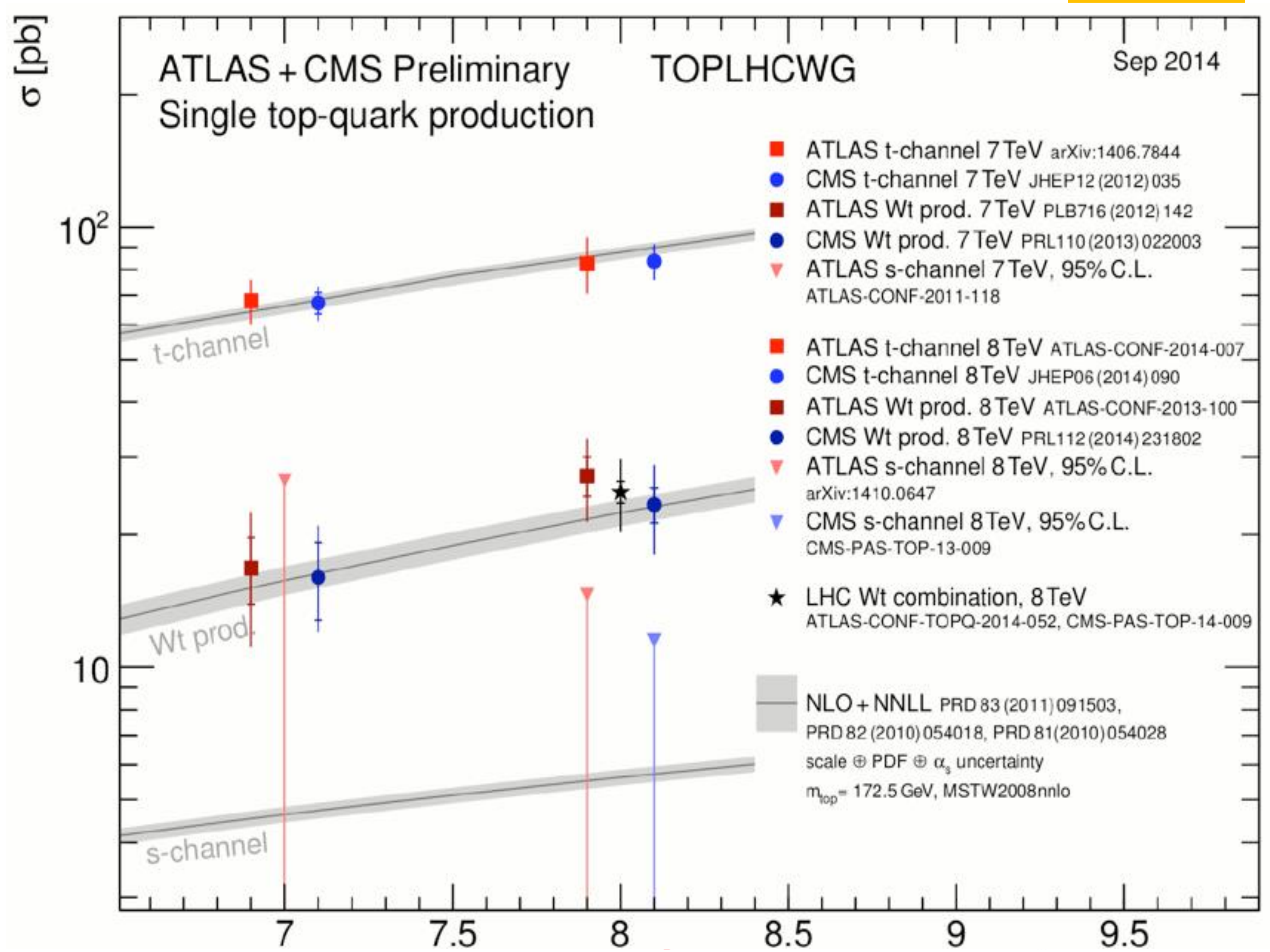
- tW channel is seen via template fit to output discriminants
  - Templates typically taken from MCs
  - CMS sees a 6.1 σ significance (expected 5.4 σ)
  - ATLAS sees a 4.2 σ (expected 4.0 σ)



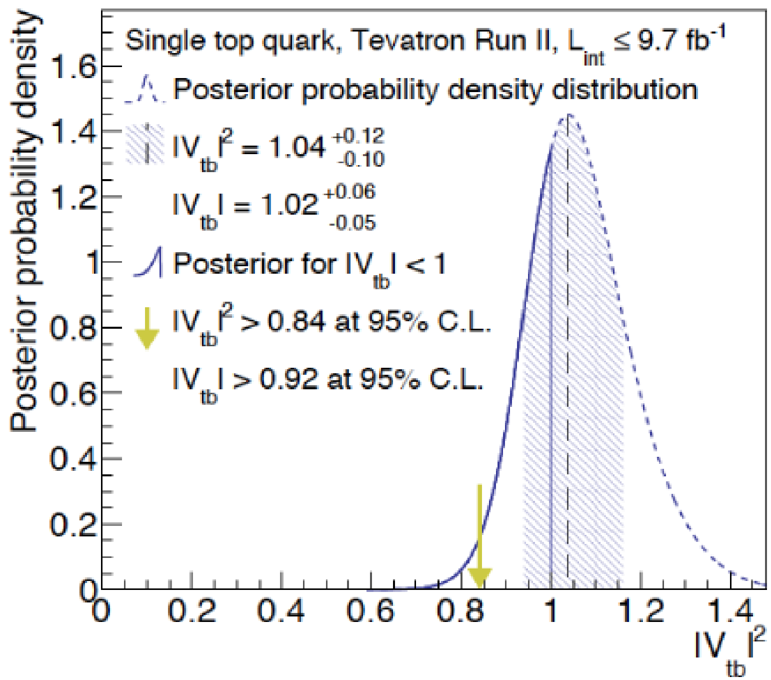
- Only limits on the s-channel can be set for the moment at the LHC
  - Multivariate methods by using single top (2jets+2b-tags) and background (top pairs) regions (3jets+2b-tags)



- **Observed @ 95% CL :** $\sigma_{s\text{-ch.}} < 11.5$ pb
- **Expected @ 95% CL :** $\sigma_{s\text{-ch.}} < 17.0$ pb


σ [pb]
ATLAS + CMS Preliminary
TOPLHCWG
Sep 2014
Single top-quark production
ATLAS t-channel 7 TeV arXiv:1406.7844
CMS t-channel 7 TeV JHEP12 (2012) 035
ATLAS Wt prod. 7 TeV PLB716 (2012) 142
CMS Wt prod. 7 TeV PRL110 (2013) 022003
ATLAS s-channel 7 TeV, 95% C.L.
ATLAS-CONF-2011-118
ATLAS t-channel 8 TeV ATLAS-CONF-2014-007
CMS t-channel 8 TeV JHEP06 (2014) 090
ATLAS Wt prod. 8 TeV ATLAS-CONF-2013-100
CMS Wt prod. 8 TeV PRL112 (2014) 231802
ATLAS s-channel 8 TeV, 95% C.L.
arXiv:1410.0647
CMS s-channel 8 TeV, 95% C.L.
CMS-PAS-TOP-13-009
LHC Wt combination, 8 TeV
ATLAS-CONF-TOPQ-2014-052, CMS-PAS-TOP-14-009
NLO + NNLL PRD 83 (2011) 091503,
PRD 82 (2010) 054018, PRD 81(2010) 054028
scale ⊕ PDF ⊕ α_s uncertainty
m_top = 172.5 GeV, MSTW2008nnlo
t-channel
Wt prod.
s-channel
10^2
10
7
7.5
8
8.5
9
9.5

Single top cross sections – Vtb



- The single top cross sections are in agreement with the SM expectations.
- The $|V_{tb}|$ element of the CKM matrix can be derived with the assumption that:

$$|V_{td}|, |V_{ts}| << |V_{tb}|$$

t-channel

tW

$$|V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma^{th}_{t-ch.}}} =$$

ATLAS: $|V_{tb}| = 1.02 \pm 0.07$ $\quad$ $1.10 \pm 0.12(exp.) \pm 0.03(th.)$

$|V_{tb}| < 1$ ➡ $0.88 < |V_{tb}| <= 1$ @ 95% C.L.

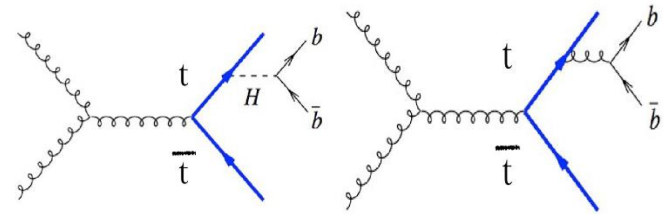
CMS: $|V_{tb}| = 1.020 \pm 0.049$ $\quad$ $1.03 \pm 0.12(exp.) \pm 0.04(th.)$

$|V_{tb}| < 1$ ➡ $0.92 < |V_{tb}| <= 1$ @ 95% C.L.

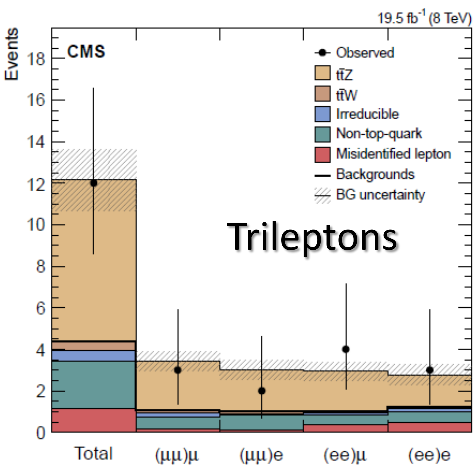
- Working towards an LHC combination of $|V_{tb}|$ (one day a world average as well)
  - The t-channel combination would be dominated by CMS
  - The extraction from the tW channel is not competitive

Associated production of top and bosons

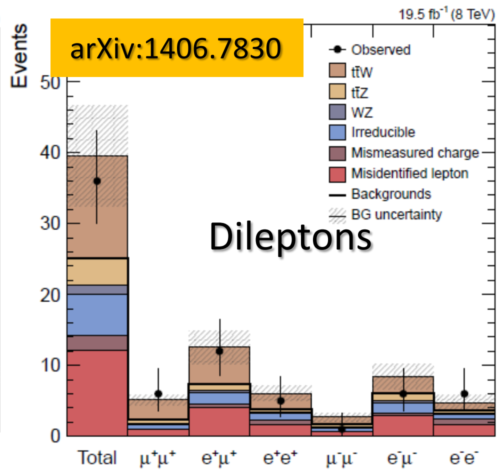
- tt+W/Z are rare processes in the SM
  - Monitor couplings between t and Z
  - Investigate top pair in association with extra leptons: studied by looking for same-sign dilepton events (ttW) and tri- or four- lepton events (ttZ)

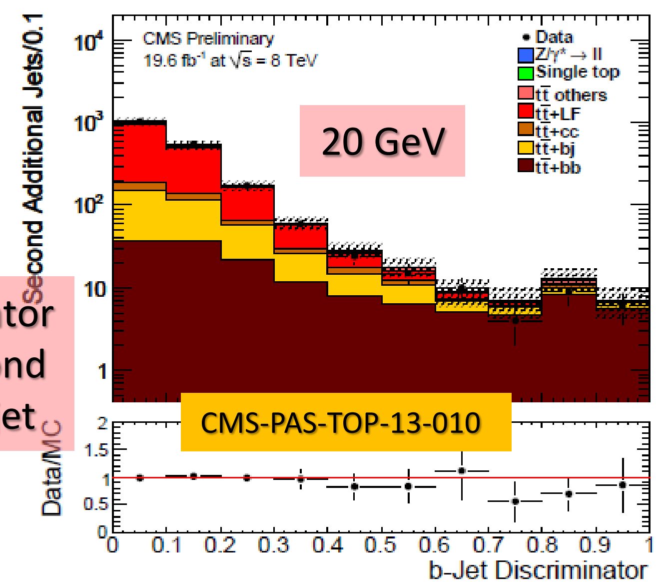


- tt+bb. Important also for SM physics
  - Higgs in association to top. Top Yukawa.
- Study N(b-jet) in di-lepton events



arXiv:1406.7830



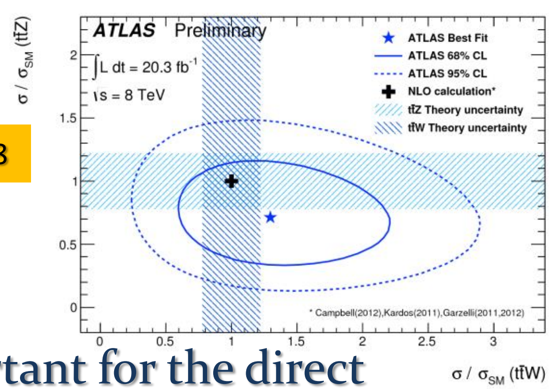


20 GeV

b-discriminator for the second additional jet

CMS-PAS-TOP-13-010

ATLAS-CONF-NOTE-2014-038



20 GeV

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(\text{stat.}) \pm 0.005(\text{syst.})$$

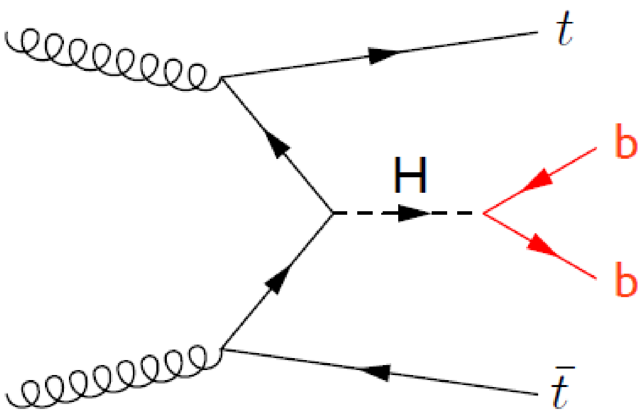
40 GeV

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.022 \pm 0.004(\text{stat.}) \pm 0.005(\text{syst.})$$

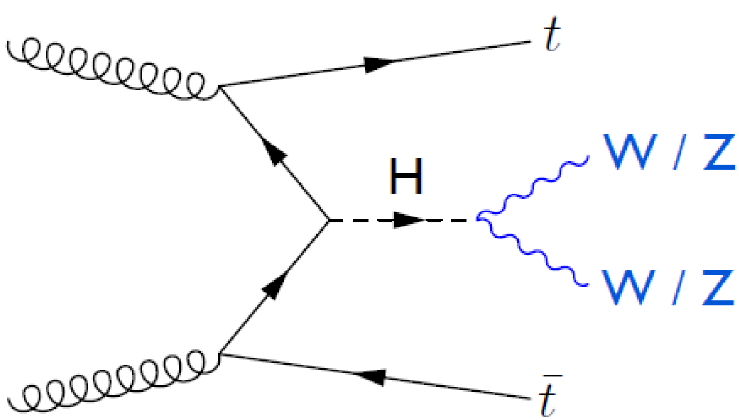
- MadGraph: 1.6%@20GeV, 1.7%@40GeV; POWHEG: 1.3%@20GeV, 1.4%@40GeV

- tt+γ also important for the direct measurement of the top charge.

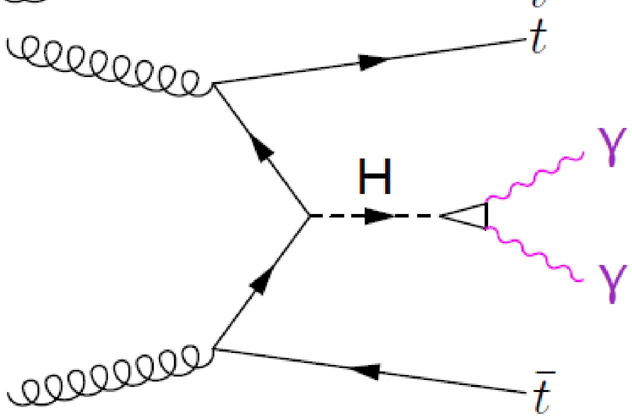
Top pair in association with a Higgs boson



- Largest branching ratio, about 58%
  - ➢ Final state with multiple b quarks, challenging to reconstruct the Higgs boson (for combinatorial and resolution issues)
  - ➢ Large background from tt+jets



- Significant branching ratio, about 22%
  - ➢ Leptonic decays of W/Z bosons can give distinctive multi-lepton signatures, but difficult to reconstruct the Higgs boson
  - ➢ Main backgrounds from tt+W/Z and non-prompt leptons



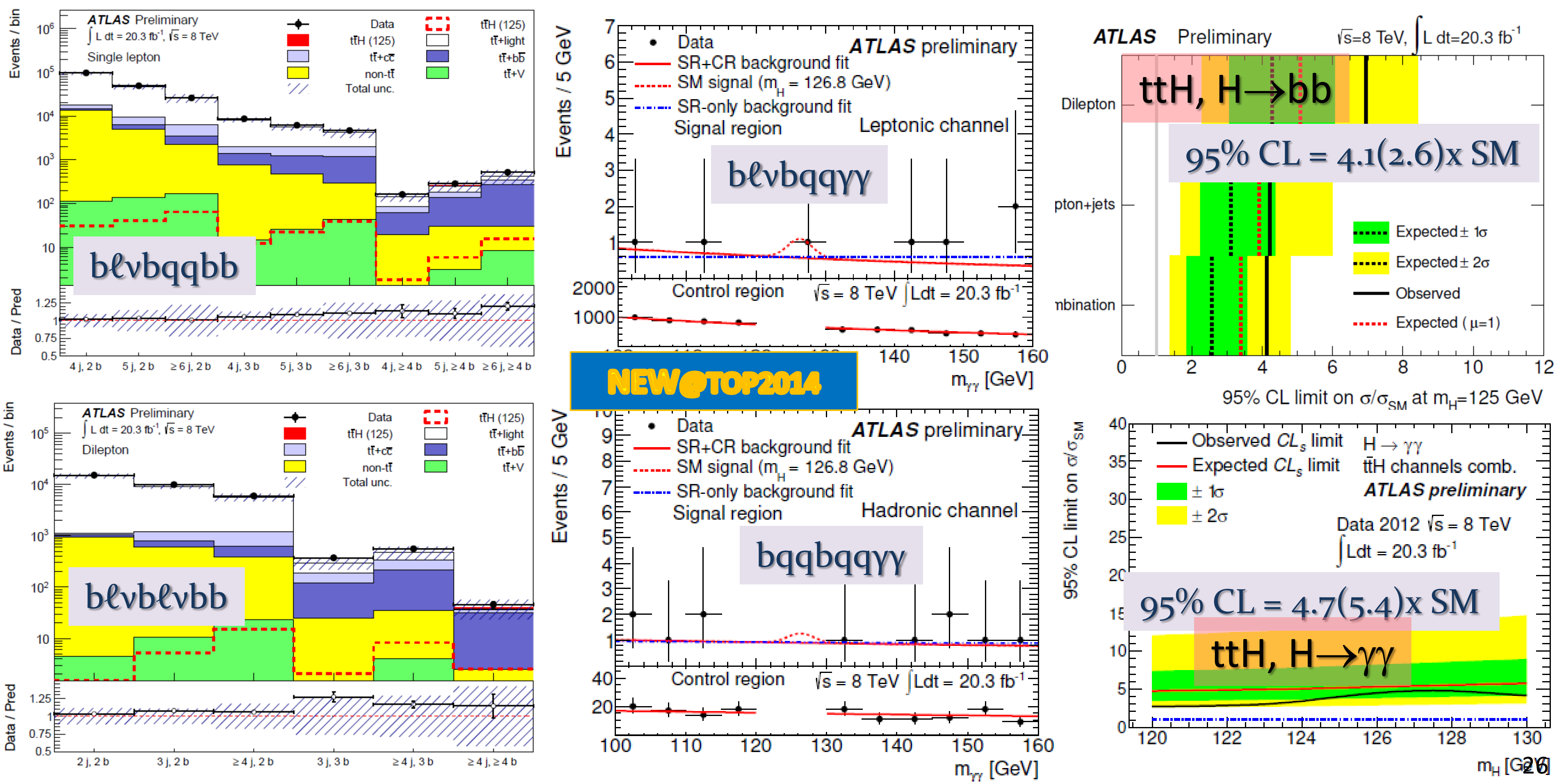
- Small branching ratio, about 0.2%
  - ➢ The Higgs boson can be directly reconstructed as a narrow γγ mass peak
  - ➢ Main backgrounds from tt+γ and QCD multi-γ/jet final states

Search for ttH in ATLAS

arXiv:1409.3122

ATLAS-CONF-NOTE-2014-011

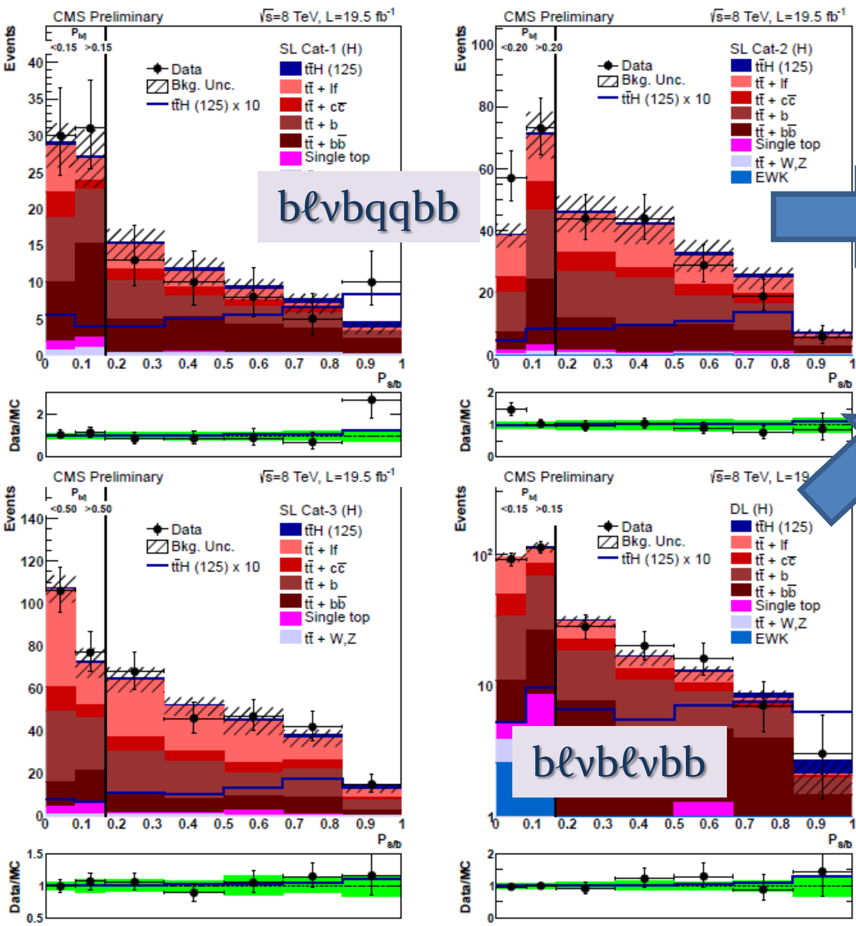
- Performed in ttbb (bℓνbqqbb and bℓνbℓνbb) and ttγγ (bℓνbqqγγ and bqqbqqγγ)
  - ➢ ttbb divided into different regions of number of jets and leptons. The distributions of NN discriminants per bin are fitted simultaneously looking for a signal at 125GeV
  - ➢ For ttγγ the invariant mass of the two γ is fitted using templates for the background determined on data from control regions

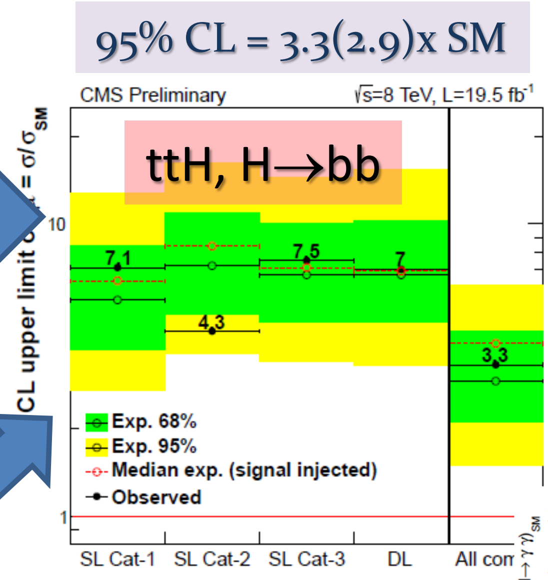


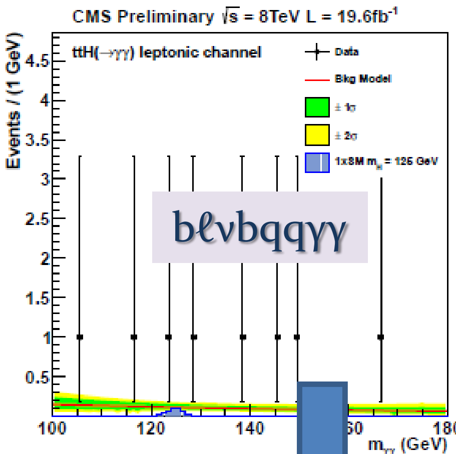
Search for ttH in CMS (1)

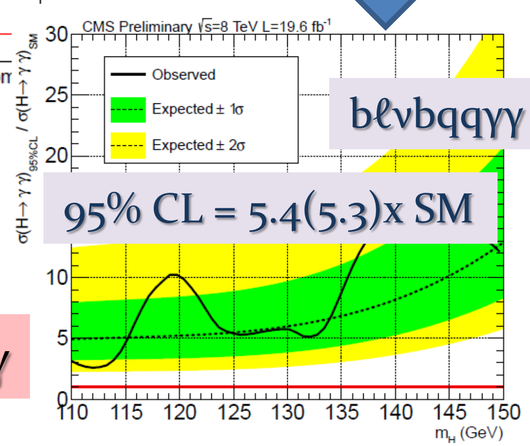
CMS-PAS-HIG-13-015
CMS-PAS-HIG-13-019
CMS-PAS-HIG-14-010

- Performed in ttbb (bℓνbqqbb and bℓνbℓνbb) and ttγγ (bℓνbqqγγ and bqqbqqγγ)
  - ➢ ttbb divided into categories. In each category a probability, based on the LO ME, quantifies the compatibility of the event to the ttbb background or the ttH signal. The ratio defines a discriminant that is then fit to find a signal
  - ➢ For ttγγ the analysis is similar than the one in ATLAS.







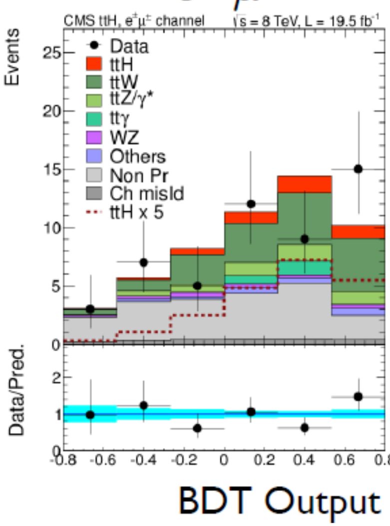


Search for ttH in CMS (2)

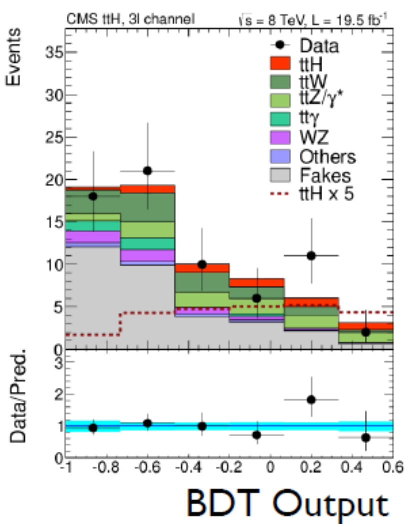
arXiv:1408.1682

- Performed in ttWW/ZZ (in same-sign charge di-leptons, tri-leptons and four-lepton events in addition to two jets) and ttττ
  - ➢ BDTs with different working points are used for all the event selections
  - ➢ Rare tt+V SM backgrounds estimated via NLO MC and checked on data. Signal is then extracted by fitting the final discriminating variable

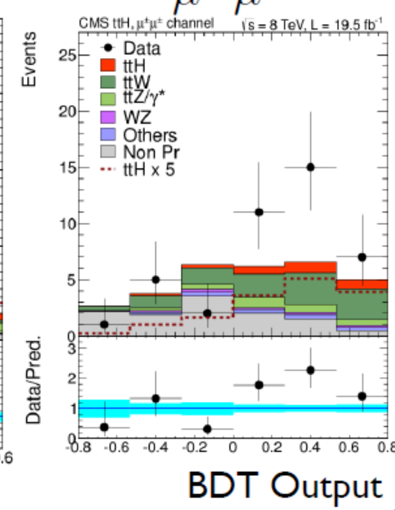
$e^{\pm}\mu^{\pm}$

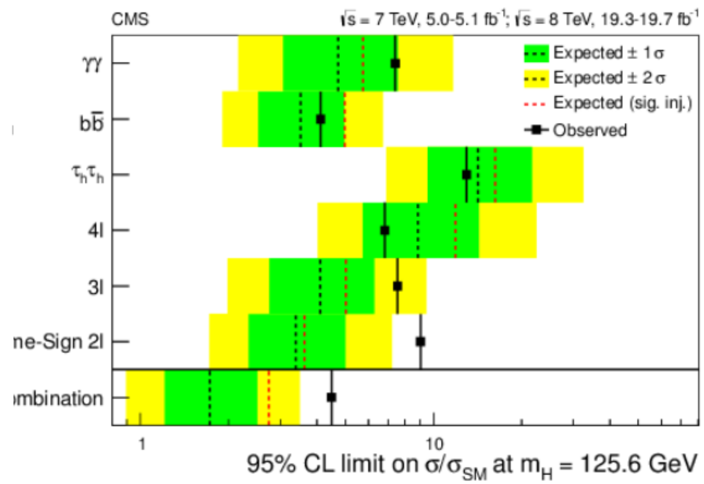


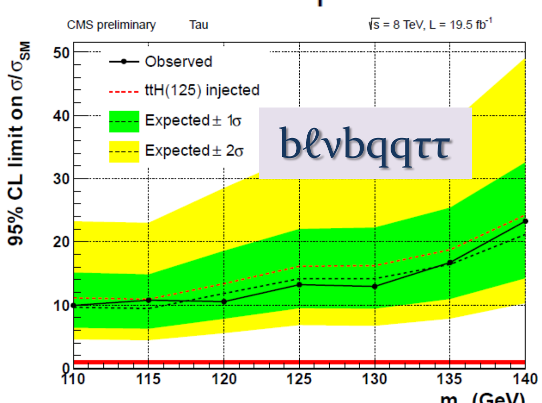
3ℓ



$\mu^{\pm}\mu^{\pm}$

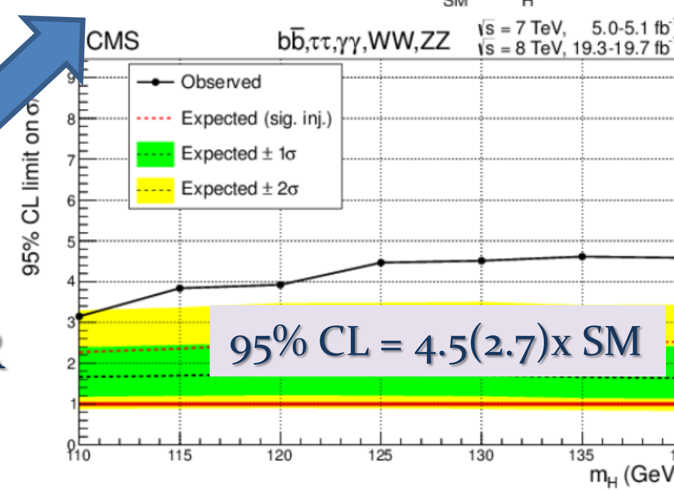






bℓνbqqττ

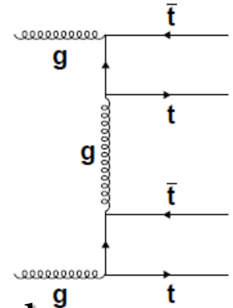
- CMS combines all channels to maximise sensitivity. The SM BR are assumed



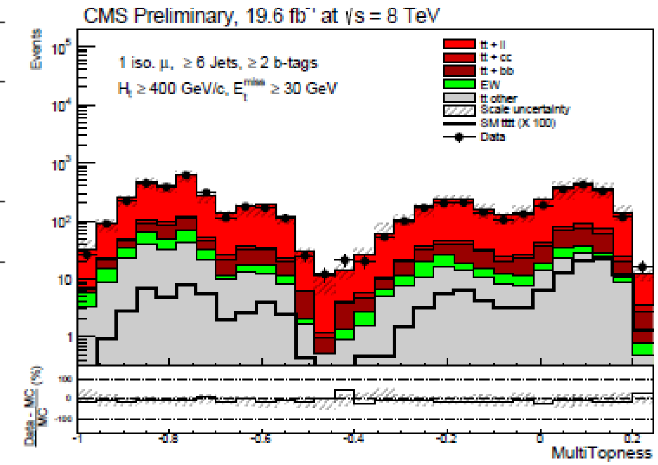
95% CL = 4.5(2.7)x SM

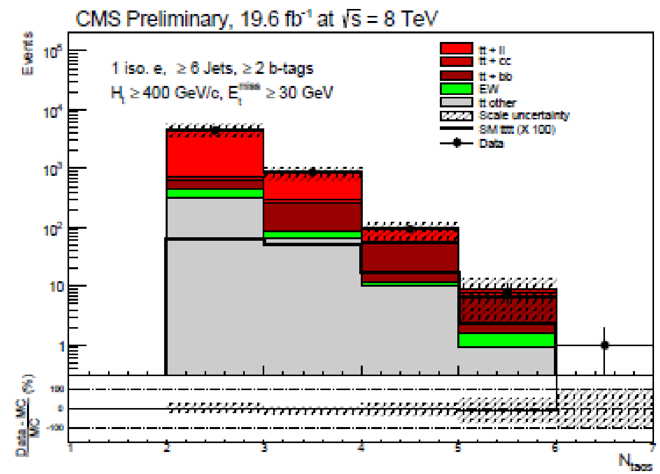
Four tops

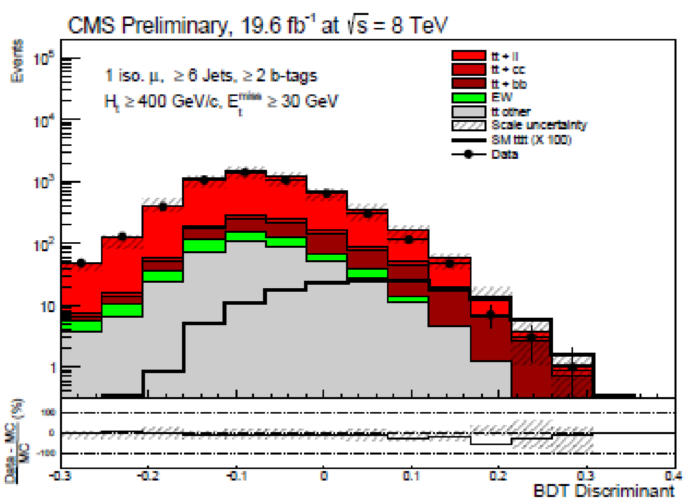
CMS-PAS-TOP-13-012



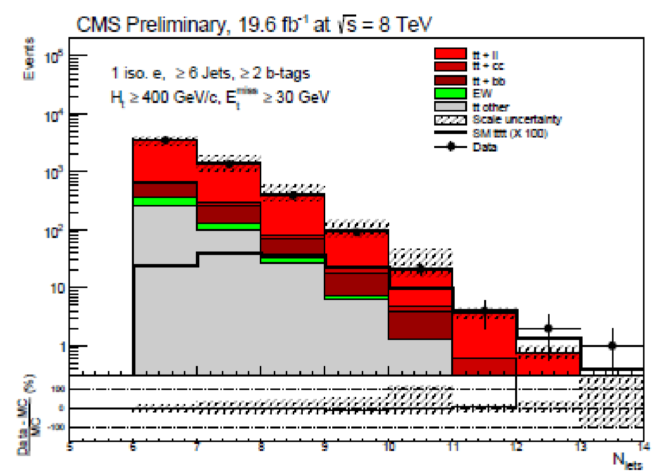
- Tiny SM process (σ_{SM}(tttt)~1fb)
  - ➢ Important to monitor since various NP models can enchance it by orders of magnitude
- Simple selection, however a BDT is used to maximize the sensitivity
  - ➢ After a pre-selection, use variables able to discriminate between the largely dominating background and four top production
    - Multi-top contents: the number of "good" tri-jet combinations
    - Event activity variables such as HT and N(jets)
    - B-jet content of the event

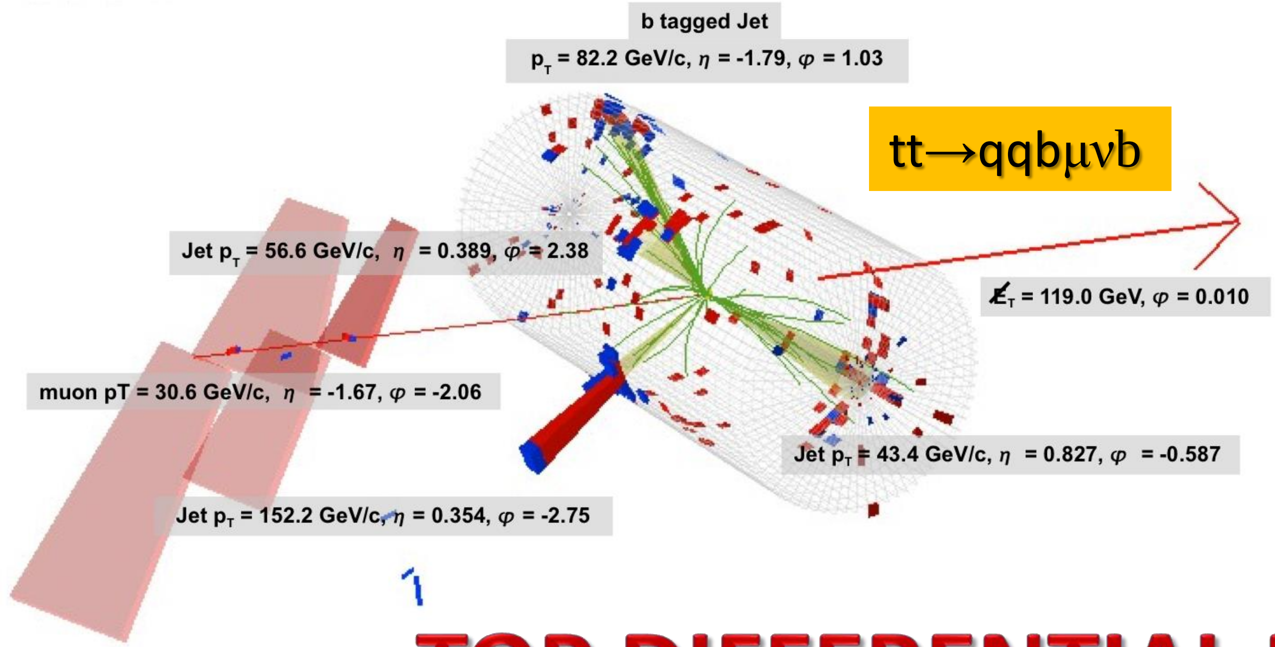


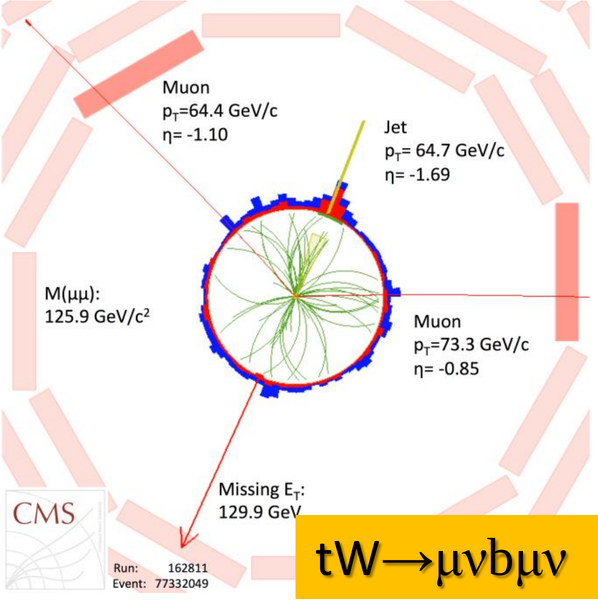




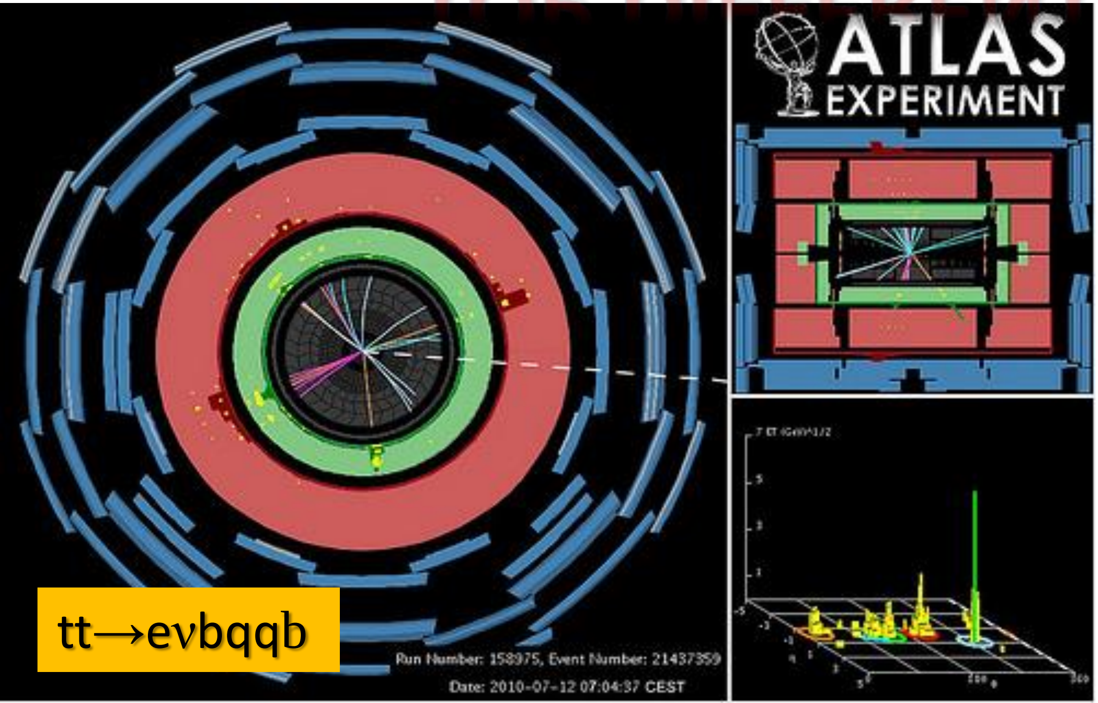
95% CL limits:
42+18-13 fb (observed)
63 fb (expected)







TOP DIFFERENTIAL PRODUCTION CROSS SECTIONS



Unfolded distributions
Constraining of radiation

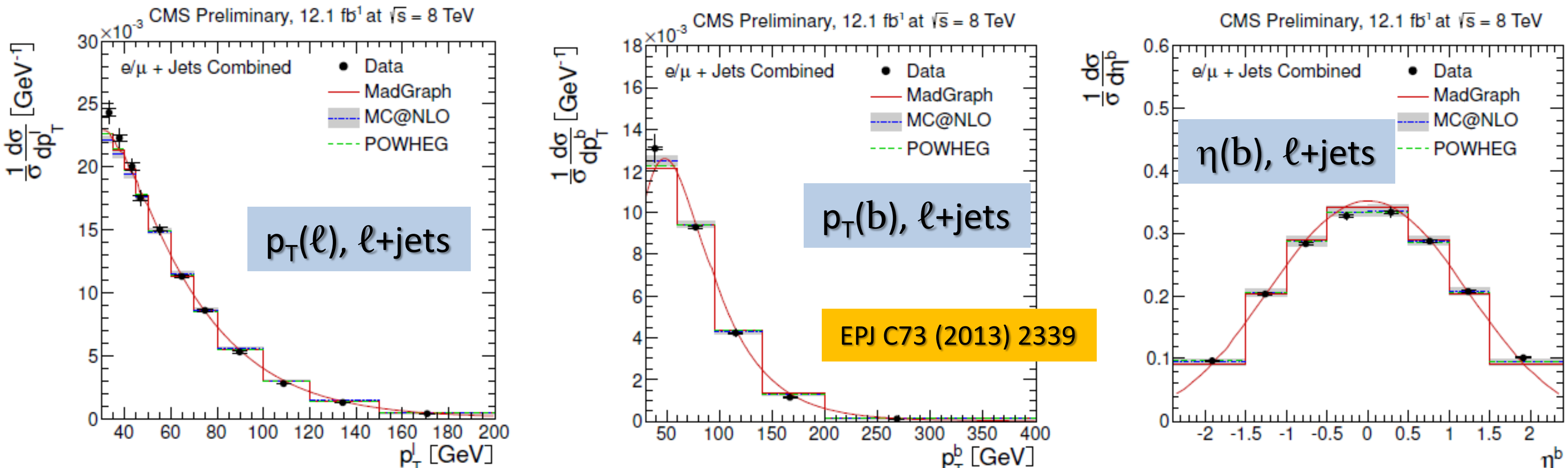
Top pair differential cross sections

- Test top physics in different portions of the phase space

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

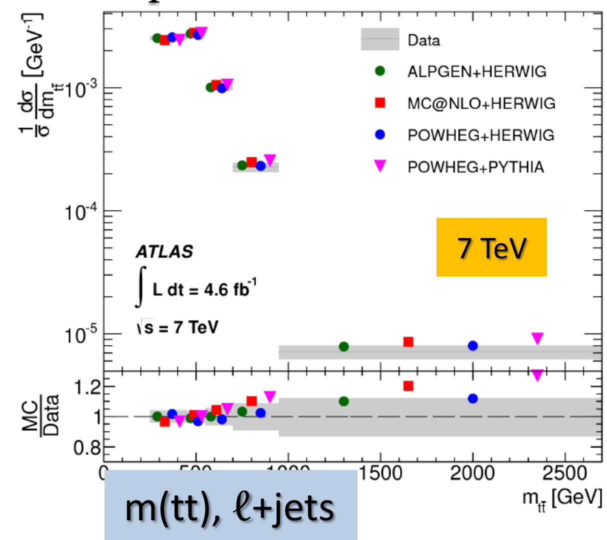
  - Important test of pQCD, constrain of MC models and systematic effects, sensitive to new physics
  - Use unfolding techniques on background-subtracted reconstructed distributions for a direct comparison to theory predictions
  - Propagation of the systematic errors (only shape errors important)
    - Most relevant coming from background knowledge, radiation and hadronization

- First step: look at basic distributions concerning leptons and jets, but also at more complex variables involving top quarks
  - Compare to reference generators and predictions on differential distribution from theory

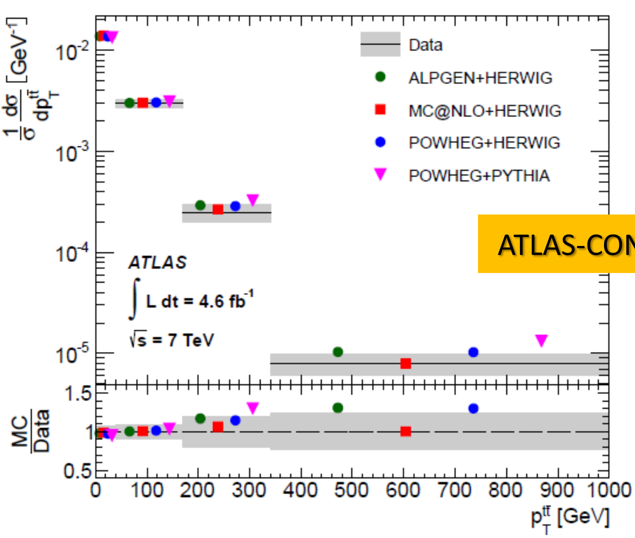


Top pair differential cross sections (cont.)

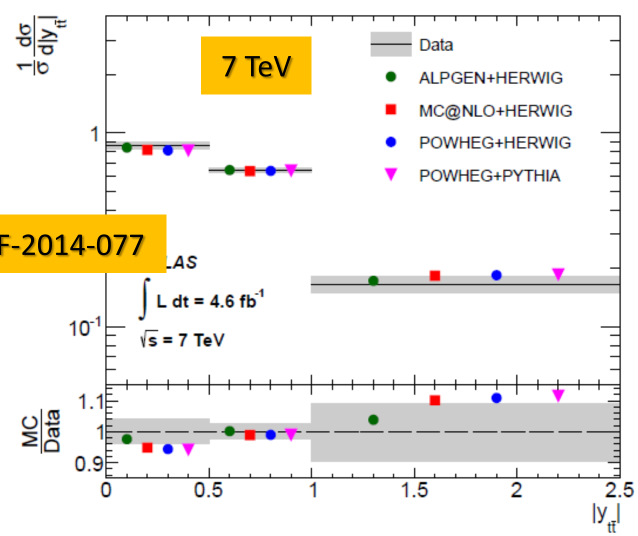
- Very interesting to look at more complex variables involving top quarks
  - ➢ Need a full reconstruction of top kinematics, and a definition of pseudo-observables
  - ➢ Compare to reference generators and predictions on differential distribution from theory
  - ➢ Generic acceptable agreement for variables connected to the top pair system

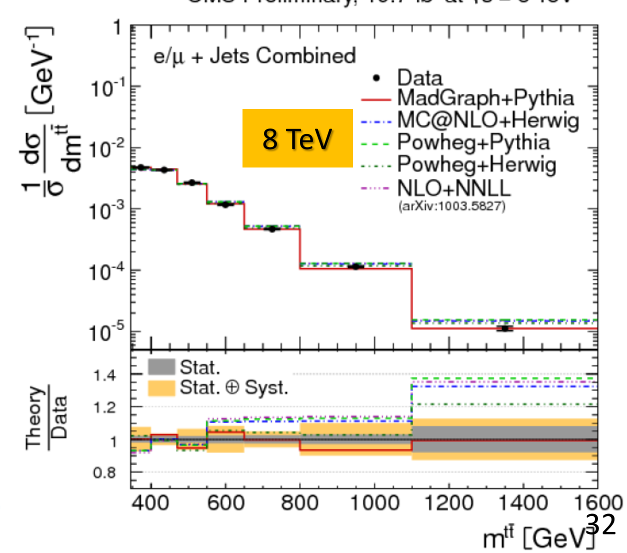


- Work towards a common definition of top quarks
  - ➢ Need to adopt a common definition at particle level for ideal comparisons and future combinations



ATLAS-CONF-2014-077

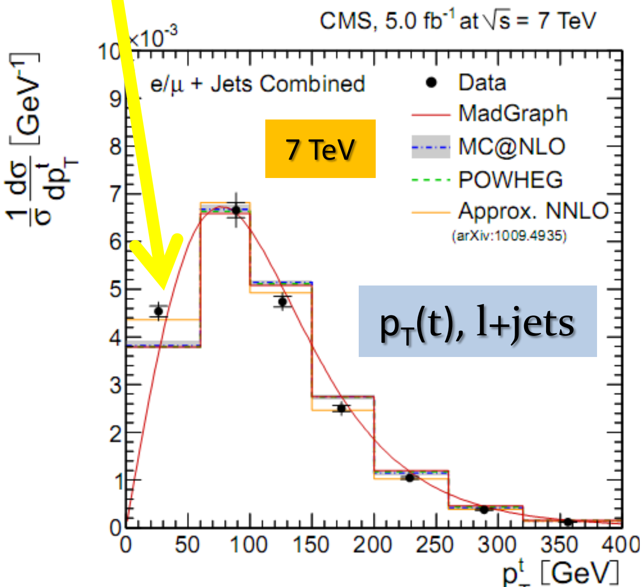


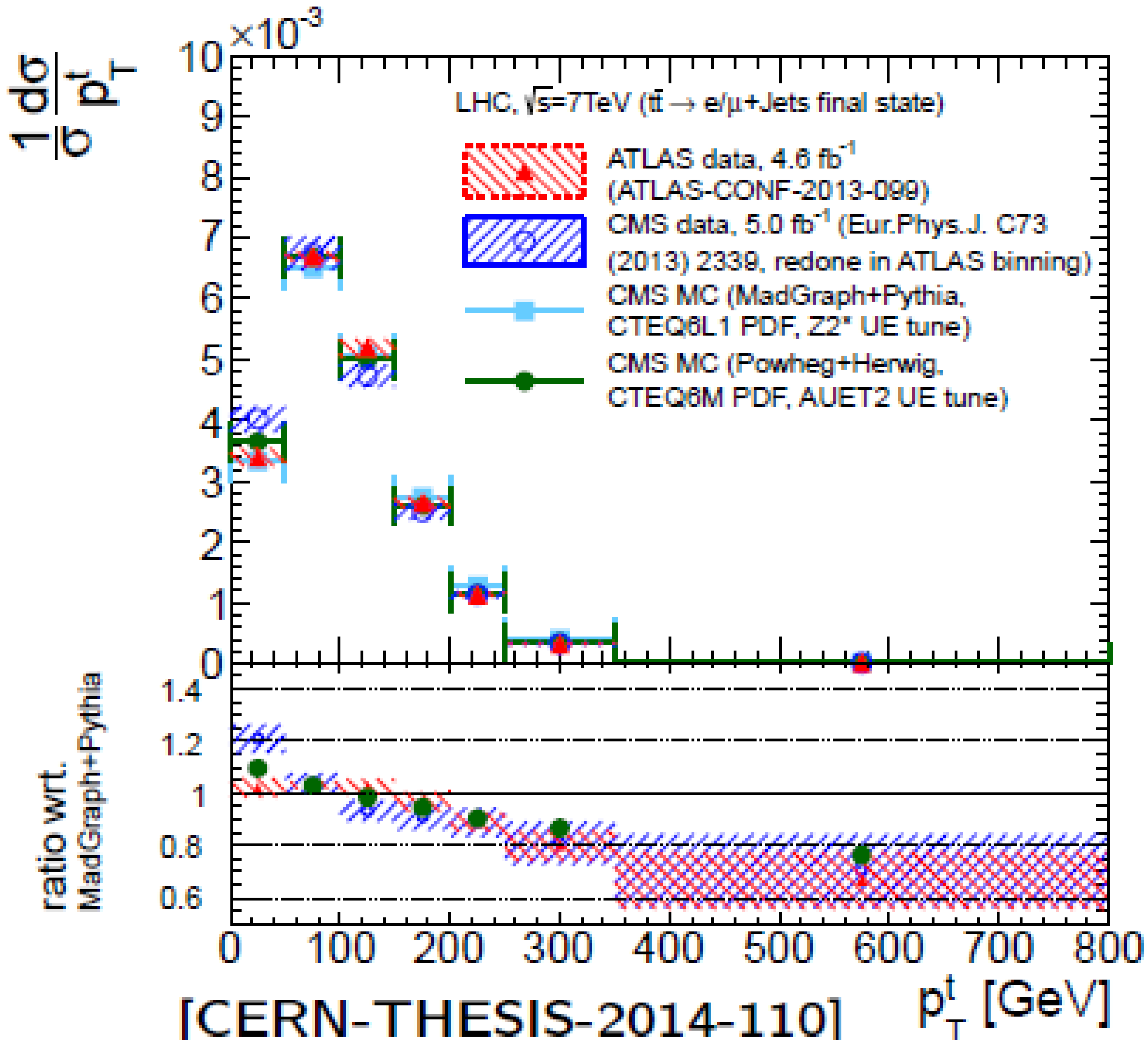


The mystery of the top transverse momentum (1)

- Significant differences between data and MC were seen by CMS in the top p_T spectrum since 2011 data
  - ➢ Consistent in all channels and in different years
  - ➢ ATLAS confirmed some of the discrepancy (at high p_T)
  - ➢ Not obvious that, after all, ATLAS and CMS do agree or n

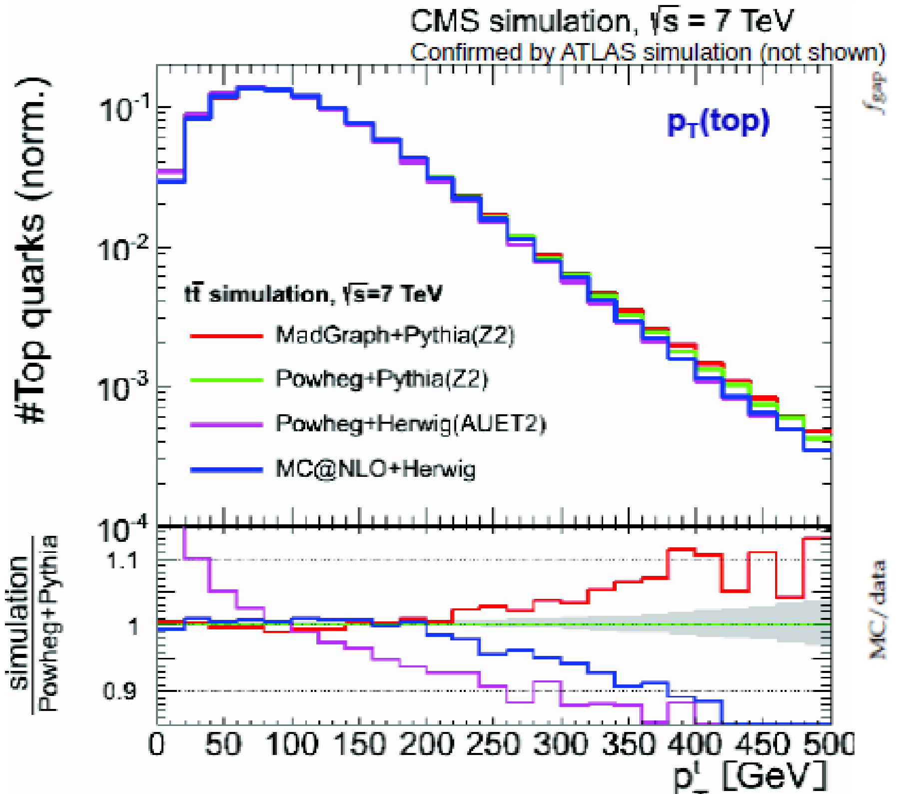
Data start to challenge NLO predictions

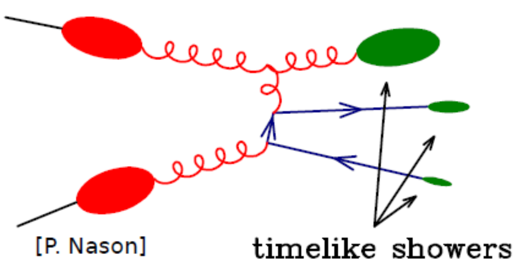




The mystery of the top transverse momentum (2)

- When switching from PYTHIA to HERWIG in POWHEG, important changes in the top pair event kinematics are observed
  - Observation confirmed in both ATLAS and CMS generation setup
  - See P.Nason's talk at the last open session of the TOPLHCWG: https://indico.cern.ch/event/301787/other-view?view=standard
  - CMS temporary solution: additional uncertainty from this top pT reweighting

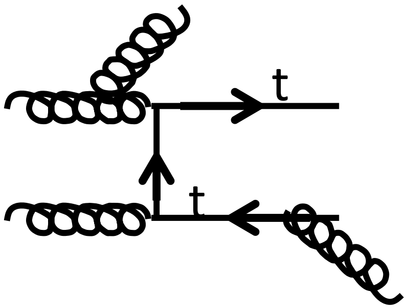


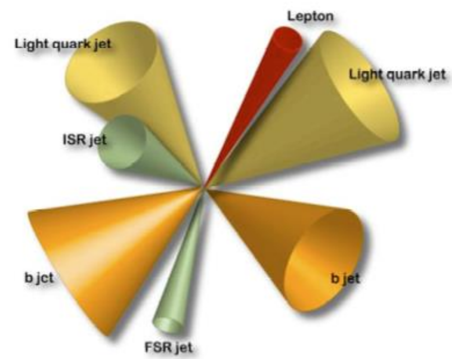


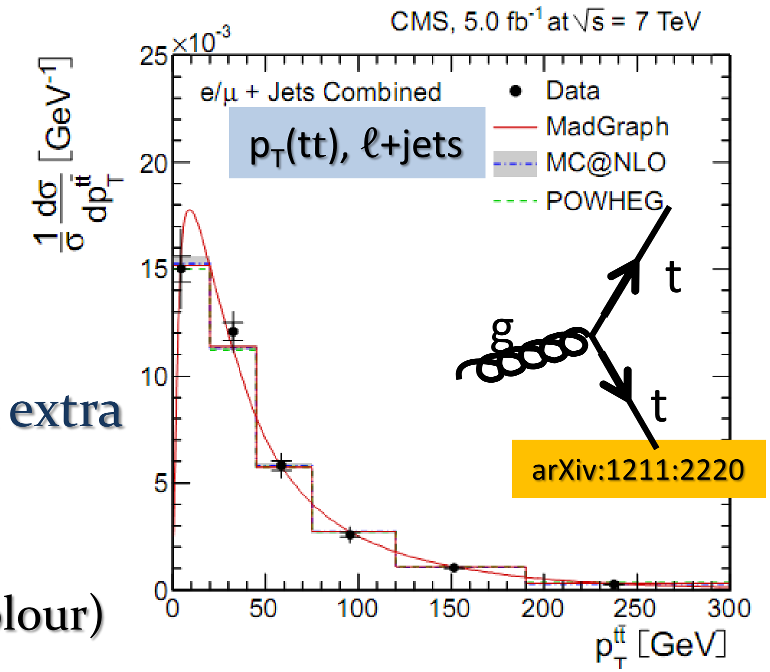
More specifically (HERWIG manual and private communication by B. Webber), one goes to the CM of the system of timelike showers and rescales all their 3-momenta by a common factor, so that the energy of the system matches the hard process energy.

It is now clear what happens: the light parton shower can build up a sizeable mass; the t and $\bar{t}$ do not radiate much in the shower. Assuming that they don't radiate at all, in order to conserve energy the momenta of the t, $\bar{t}$ and parton jet are reduced by a common factor, to compensate for the energy increase due to the mass of the parton jet. Thus, the $t\bar{t}$ mass is decreased by this momentum reshuffling.

A special case: radiation in top pair





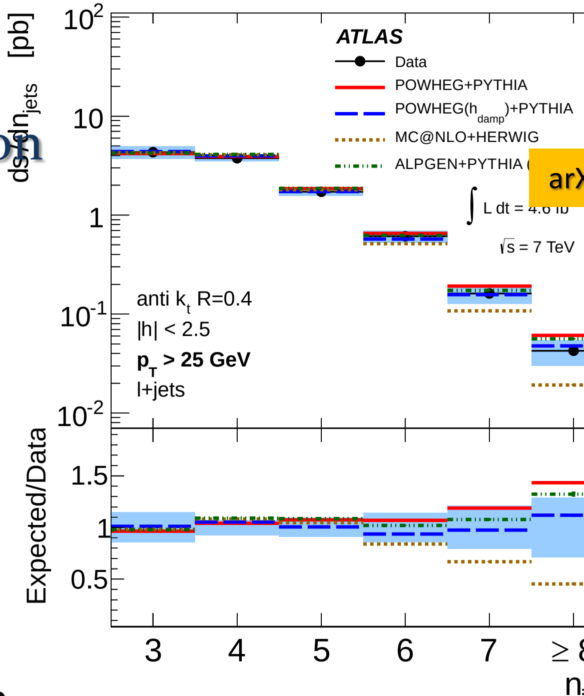


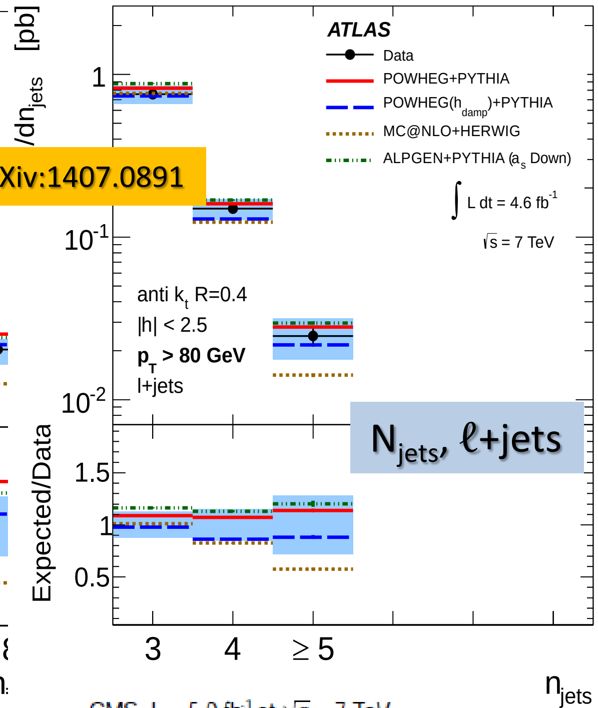
- At the LHC top quark are often produced with extra jets from initial (or final) state radiation
  - ➢ Higher energy and high scale of the process
  - ➢ Initial state preferentially from gluons (more colour)
- Impact in the ability to reconstruct top pair
  - ➢ About half of the event with an extra jet with p_T >50 GeV!
  - ➢ Jet pairing may be difficult (see following)
  - ➢ Systematic errors due to radiation description in MC can be dominant
  - ➢ Important to use data to monitor and describe jet production

Channel/Method	CMS 2012 standard	CMS 2014 standard	ATLAS 2013 standard	ATLAS 2013 3D
l+jets				
PDF	70	90	90	170
μ_r and μ_{fac}	240	120 ± 130		
ME-PS Matching	180	150 ± 130		
AcerMC ISR/FSR			960	450
ME-generator	(20)	230 ± 140	360	190

Constraining systematic effects: jet multiplicity

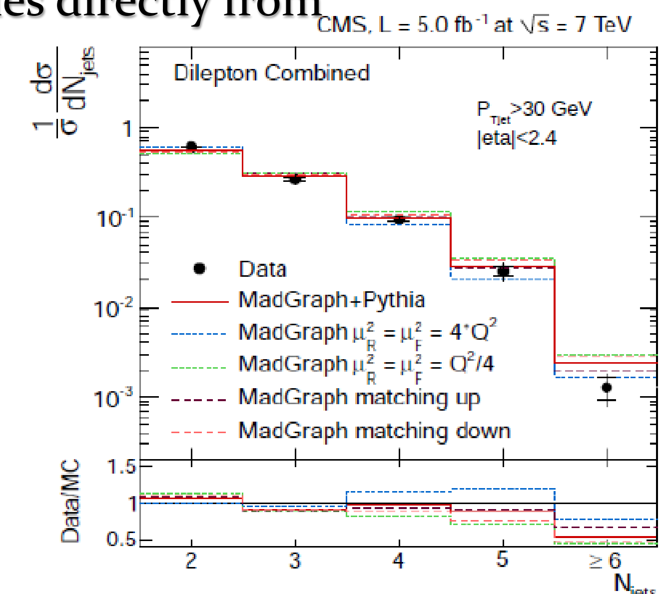
- Inclusive jet multiplicity strongly affected by radiation
  - ➢ Consistent results across channels, energies and experiments
  - ➢ TH uncertainties typically bracket the data
  - ➢ Can one go even more differentially and try to constrain radiation uncertainties directly from the data?

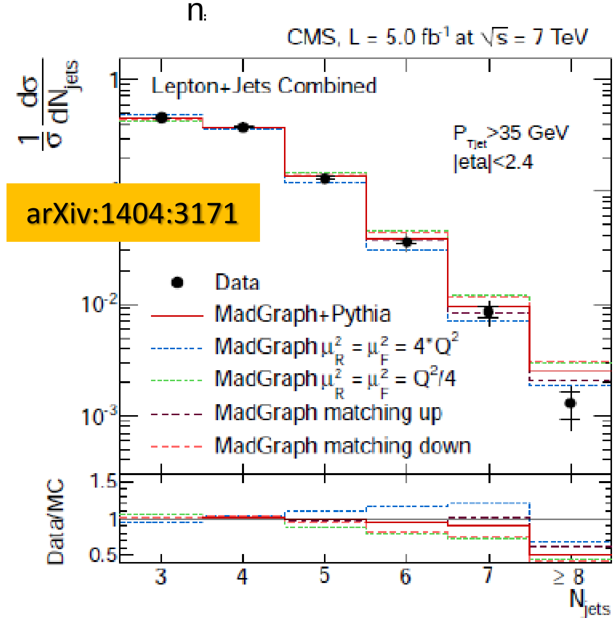




arXiv:1407.0891

N_{jets}, ℓ+jets



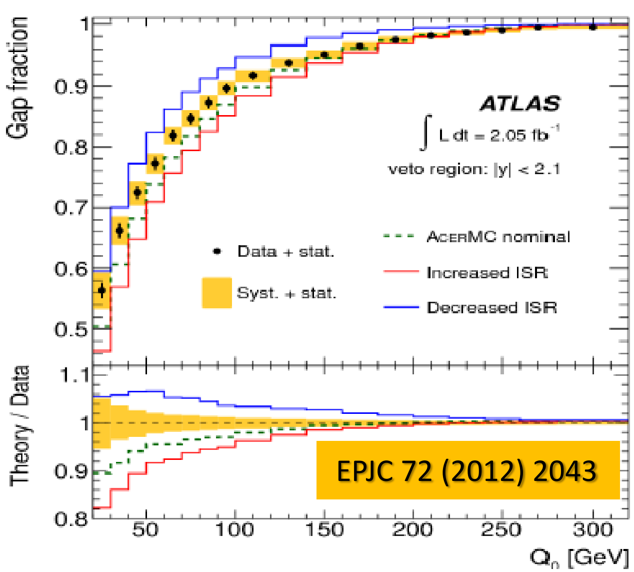


arXiv:1404:3171

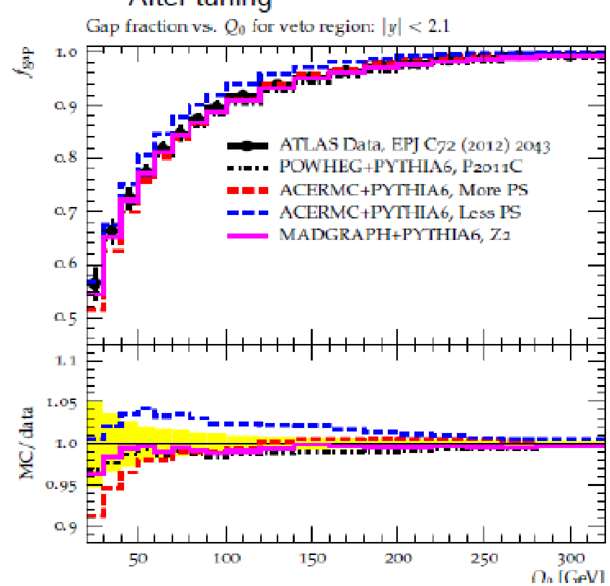
Constraining systematic effects: jet gap fraction

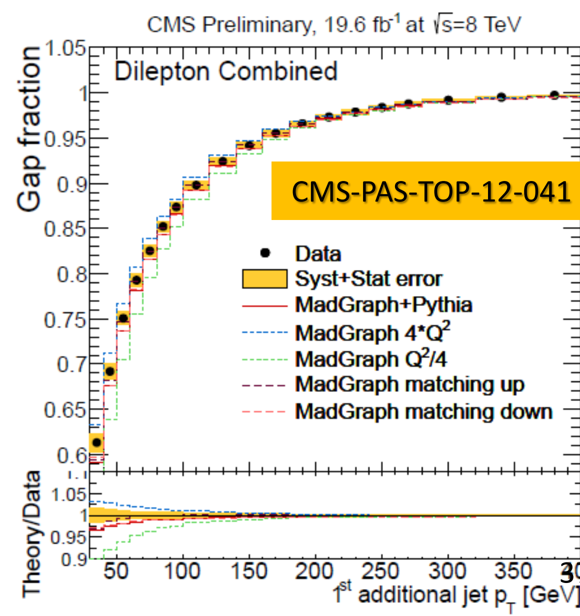
- The pragmatic approach consists in using measured observables which are maximally sensitive to radiation to constrain Monte Carlos
  - ➢ Use jet gap fraction: fractions of events that do not have a jet emission (in a defined angular range) above a certain p_T cut
  - ➢ ATLAS: check ISR/FSR parameters as in ACERMC/PYTHIA
  - ➢ CMS: change by a factor two the renormalization and factorization scales in the ME MC. Shower emission scale in the PS is changed accordingly
  - ➢ Central CMS tuning also describes well ATLAS data
  - ➢ The ATLAS comparison was used to considerably reduce the parameter variation defining the systematic error → important reduction of systematic errors

Settings estimated before measurement



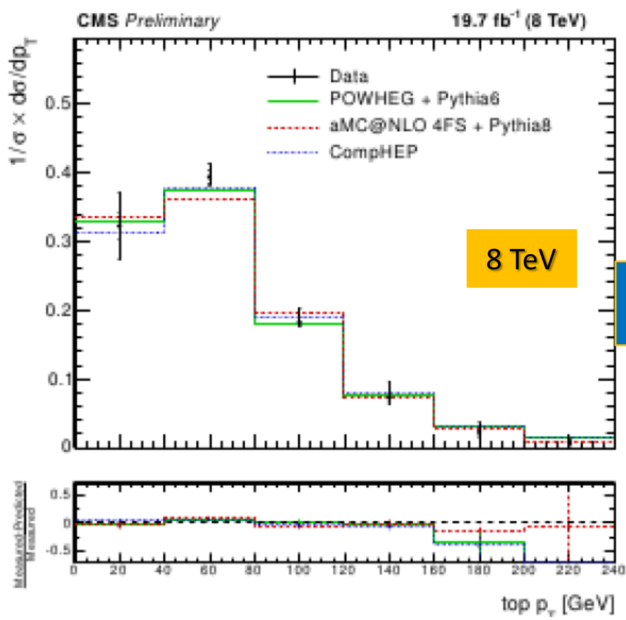
After tuning





Differential single top cross sections

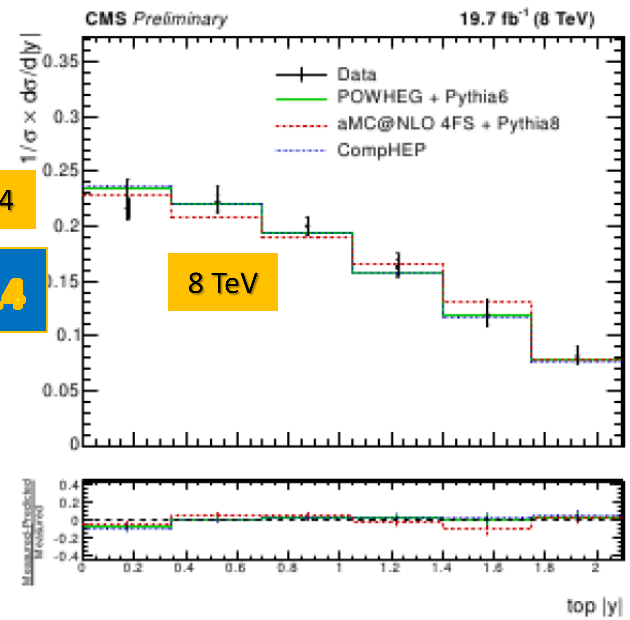
- Enough statistics to start looking in single top acceptance in a differential way
  - ➢ Neutrino reconstructed via MET conditions (2) and the requirement of the W mass
  - ➢ Differential distributions can also be separated according to the top charge



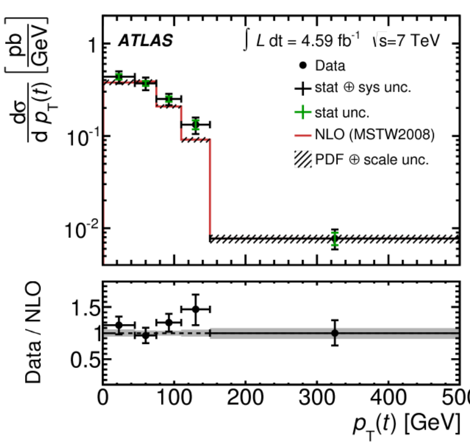
8 TeV

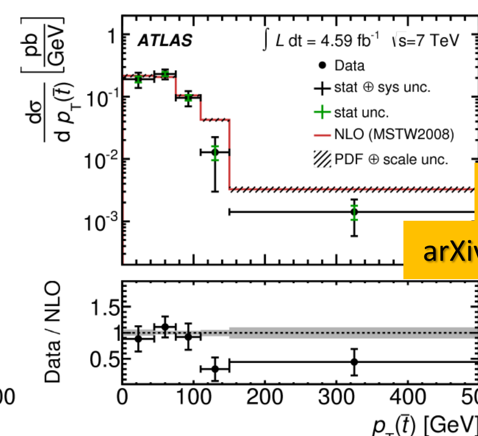
CMS-PAS-TOP-14-004

NEW@TOP2014



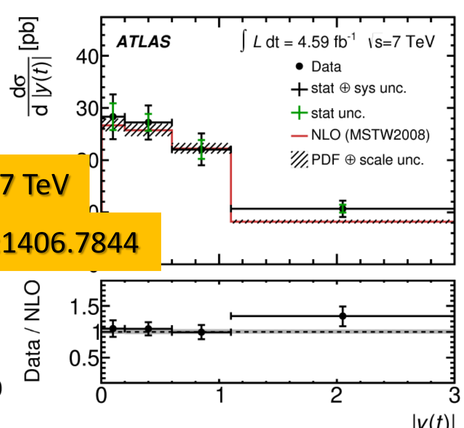
8 TeV

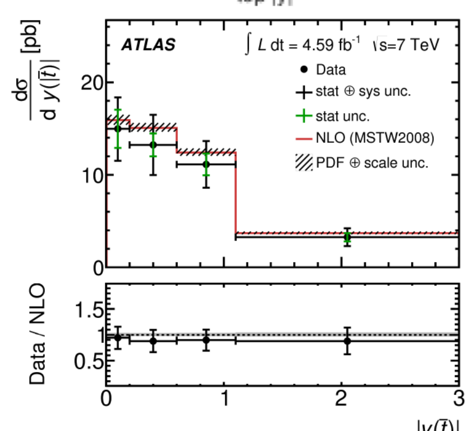


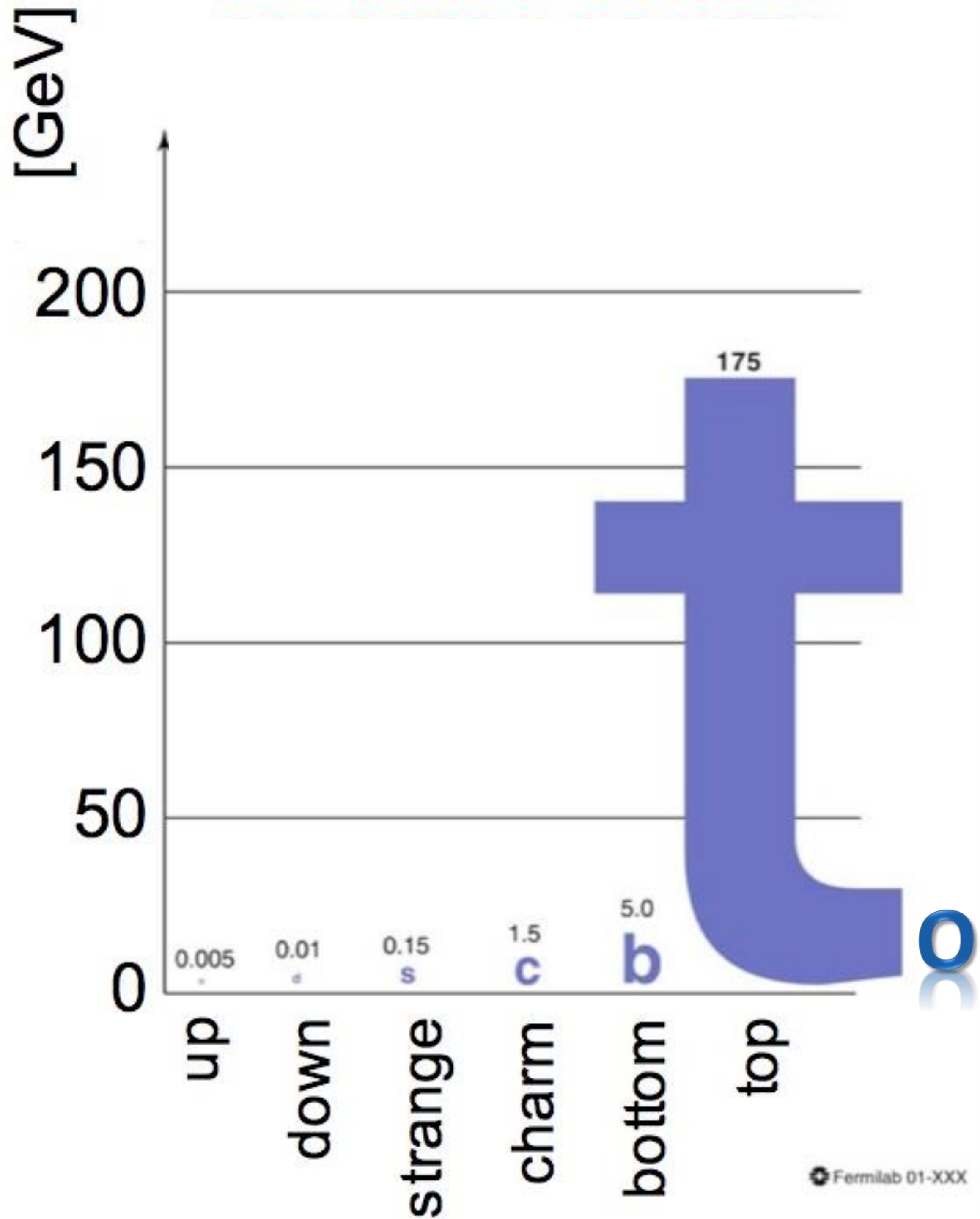


7 TeV

arXiv:1406.7844



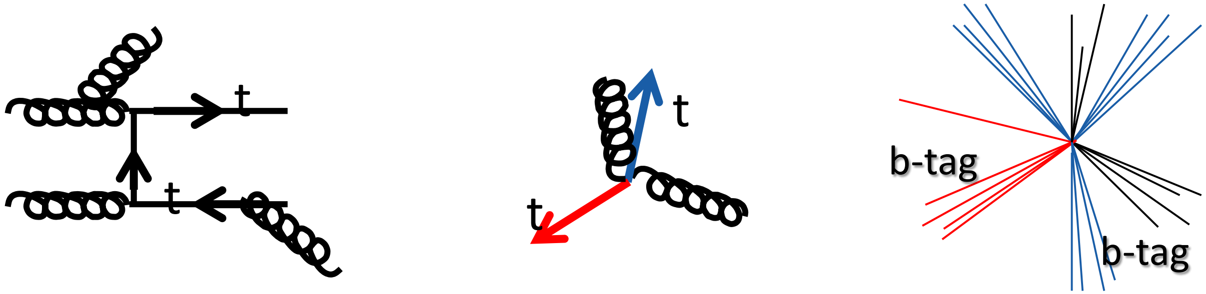




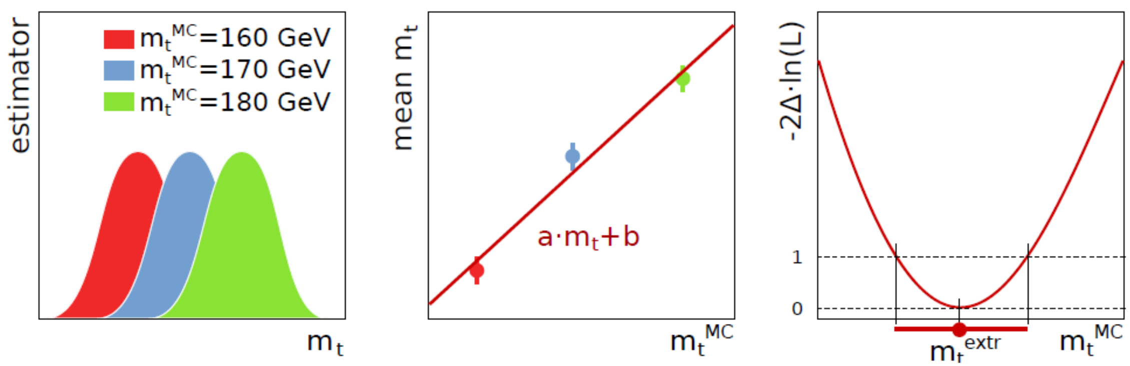
OP PROPERTIES

Mass
Charge

Direct determination of the top mass



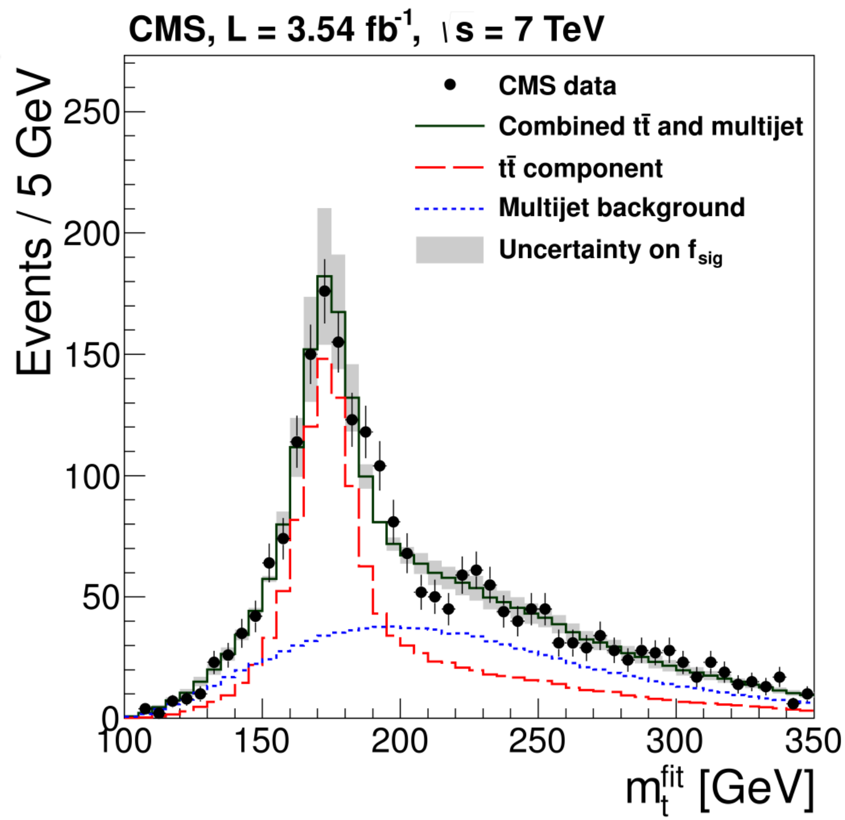
- Direct reconstruction methods
  - ➢ Full reconstruction by resolving the pairing ambiguities (all channels studied)
  - ➢ Use kinematic constrained fitting to improve the mass resolution
    - o Constrain the light jet energy scale in situ by using the W mass constraint
  - ➢ Fit the mass with MC template fits or event by event likelihood fits
    - o Calibration are determined by using Monte Carlos



- ➢ Multi-dimensional fits, determining the top mass with the largest systematic source (eg. JES) may improve the error (learning from their correlation)

The fully hadronic channel

- Kinematic fit for reconstruction and also for resolving the jet-pairing ambiguities
- QCD background determined from data
  - Event mixing and/or control regions



Source	Unc. [GeV]	Unc. [GeV]	Unc. [GeV]
JES+PU	0.52	0.97	0.48
bJES+Had	0.80	0.49	0.39
Detector modelling	0.17	0.29	0.21
Signal modelling	0.51	0.46	0.52
Background	0.35	0.13	0.22
Method	0.42	0.13	0.06
Syst.	1.22	1.23	0.86
Stat.	1.40	0.69	0.27
Total	1.86	1.41	0.90

ATLAS@8TeV

m_t = 175.1 ± 1.9 GeV (1.06%)

arXiv:1409.0832

NEW@TOP2014

CMS@7TeV

m_t = 173.49 ± 1.41 GeV (0.81%)

Eur. Phys. C74 (2014) 2758

Tighter selection

Better resolution

CMS@8TeV

m_t = 172.08 ± 0.90 GeV (0.53%)

CMS-PAS-TOP-14-002

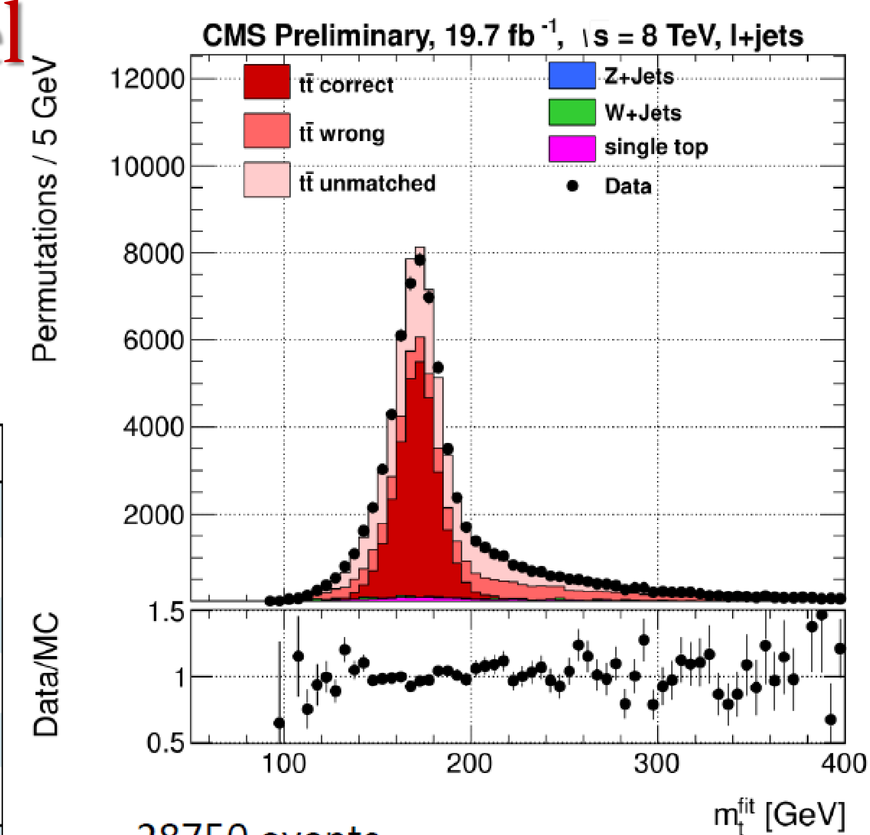
2D fit with JES

JSF = 1.007 ± 0.011

Larger statistics

The semi-leptonic channel

- Kinematic fit, moderate background controlled on data (W+jets, single top)
- Constrained JES and bJES in situ



28750 events

Source	Unc. [GeV]	Unc. [GeV]	Unc. [GeV]
JES+PU+JSF	0.83	0.43	0.36
bJES+Had+bJSF	0.73	0.61	0.44
Detector modelling	0.84	0.27	0.28
Signal modelling	0.62	0.64	0.39
Background	0.10	0.13	0.11
Method	0.13	0.06	0.10
Syst.	1.53	1.03	0.76
Stat. (m_t only)	0.23	0.27	0.11
Total	1.55	1.06	0.77

ATLAS@8TeV

m_t = 172.31 ± 1.55 GeV (0.90%)

JSF = 1.014 ± 0.021; bJSF = 1.006 ± 0.022

ATLAS-CONF-2013-046

Increased b-tagging uncertainty

CMS@7TeV

m_t = 173.49 ± 1.06 GeV (0.61%)

JSF = 0.994 ± 0.009

JHEP 12 (2012) 105

Use all jet permutations

CMS@8TeV

m_t = 172.04 ± 0.77 GeV (0.45%)

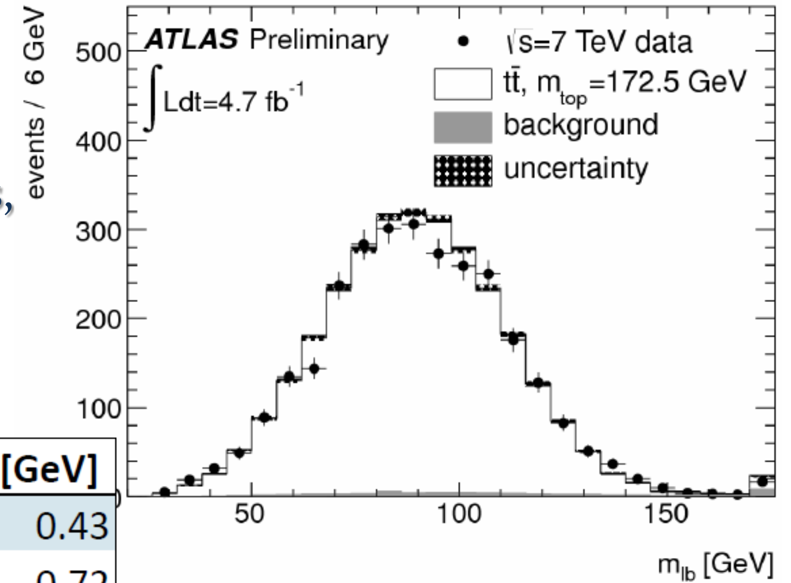
CMS-PAS-TOP-14-001 JSF = 1.007 ± 0.012

Larger dataset and MC

Refined treatment of hadronisation and bJES

The fully leptonic channel

- Weighting techniques to resolve the two neutrinos, or look for visible masses (as $m_{\ell b}$) as proxies.
- Small background under control with data



Source	Unc. [GeV]	Unc. [GeV]	Unc. [GeV]	Unc. [GeV]
JES+PU	0.88	0.98	0.69	0.43
bJES+Had	0.84	0.76	0.69	0.72
Detector modelling	0.52	0.25	0.17	0.31
Signal modelling	0.67	0.61	0.99	0.99
Background	0.14	0.05	0.02	0.12
Method	0.07	0.40	0.03	0.07
Syst.	1.49	1.46	1.40	1.29
Stat.	0.64	0.43	0.17	0.32
Total	1.62	1.52	1.41	1.33

NEW@TOP2014

ATLAS@7TeV

m_t = 173.09 ± 1.62 GeV (0.94%)

ATLAS-CONF-2013-077

Fit to m(ℓb)

CMS@7TeV

m_t = 172.50 ± 1.52 GeV (0.88%)

EPJC72 (2012) 2202

Weighting technique

CMS@8TeV

m_t = 172.47 ± 1.41 GeV (0.81%)

CMS-PAS-TOP-14-010

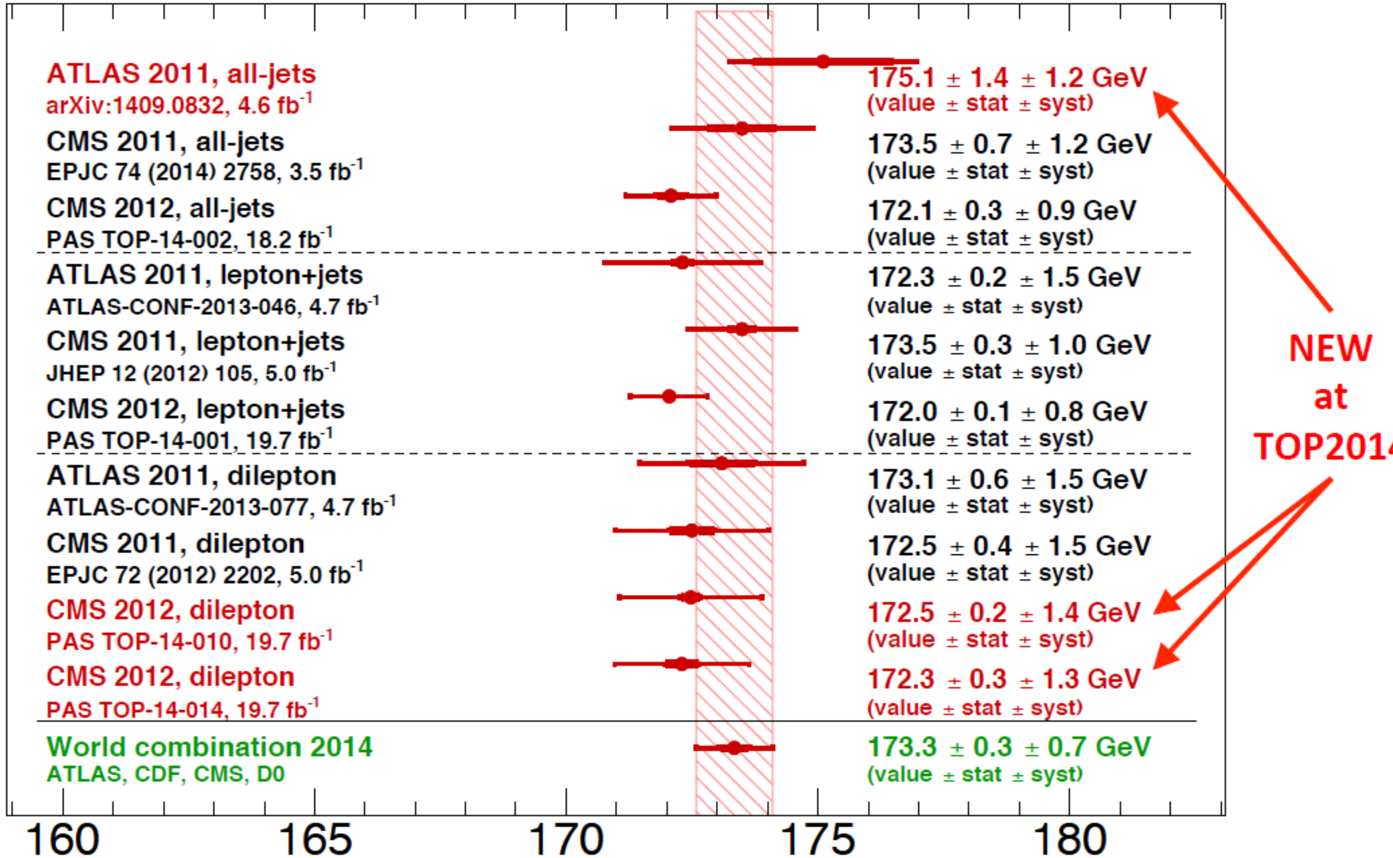
Weighting technique

m_t = 172.3 ± 1.33 GeV (0.77%)

CMS-PAS-TOP-14-014

Fit to m(ℓb)

Top mass summary



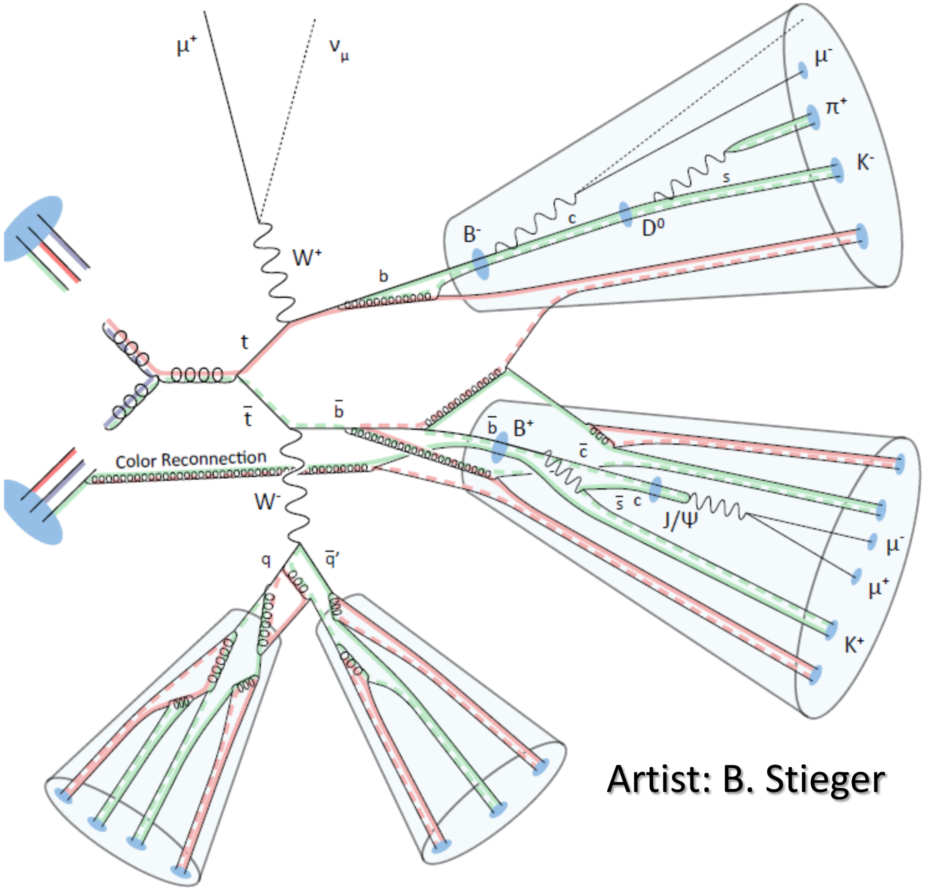
- JES uncertainty aside, errors are dominated by modelling uncertainties
  - ➢ Hard radiation and PS (determined as seen in previous slides)
  - ➢ Softer QCD effects (implemented by models in the Monte Carlos)
    - Underlying Event
    - Colour connection
    - Fragmentation
  - ➢ How are these effects studied with data?

	δm_t^{2D} (GeV)
Modeling of the hard scattering process	
PDF	0.09
Renormalization and factorization scales	0.12±0.13
ME-PS matching threshold	0.15±0.13
ME generator	0.23±0.14
Modeling of non-perturbative QCD	
Underlying event	0.14±0.17
Color reconnection modeling	0.08±0.15

CMS-PAS-TOP-14-001

Jet fragmentation and top physics

- In the experiments the uncertainty on the modelling of jet fragmentation is largely included in the jet energy scale errors
  - ATLAS: compare PYTHIA and HERWIG and study the jet energy response. Add the resulting difference as error to the JES in quadrature
  - CMS: same procedure, using HERWIG++. The difference in jet energy response is treated separately for light jets, gluon jets and b jets

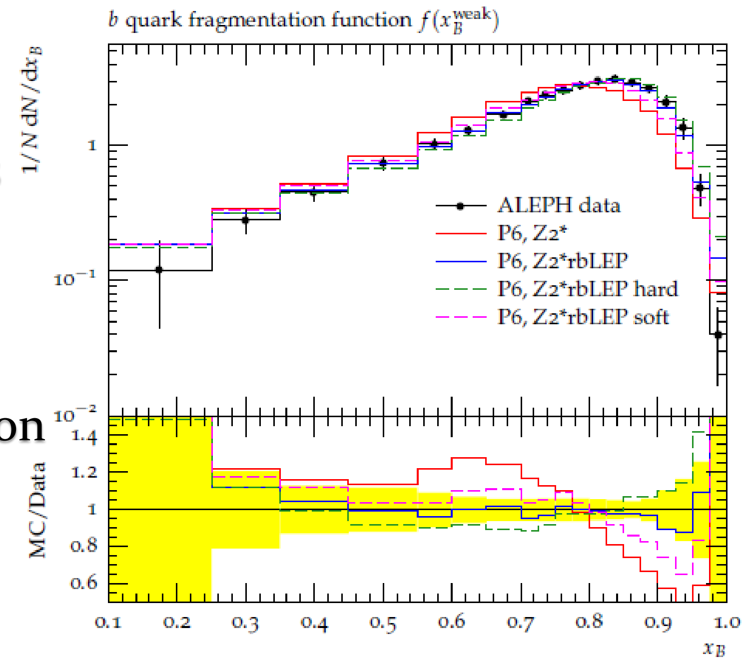


Artist: B. Stieger

- NB: both CMS and ATLAS compare again PYTHIA and HERWIG at analysis level. CMS uses it as a consistency crosscheck, ATLAS quote any further difference on the final measurement as additional systematic uncertainty

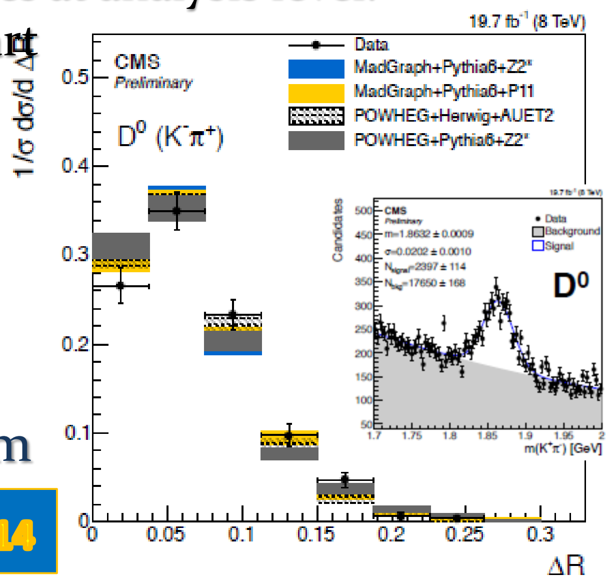
b jet fragmentation specific studies

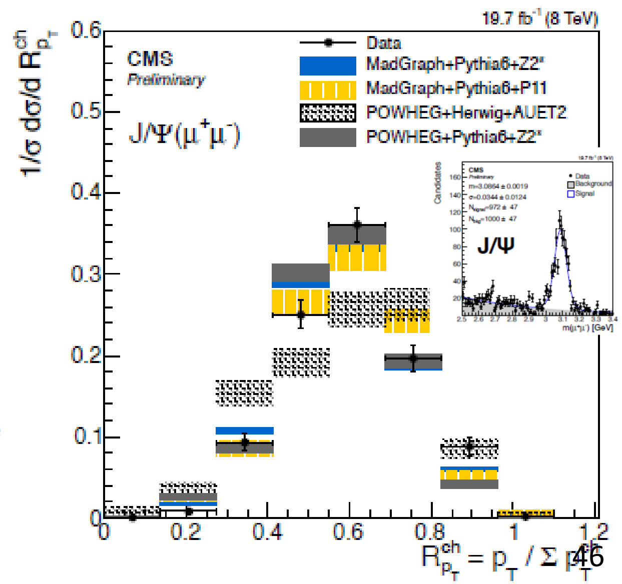
- More specific uncertainties (less important for the bulk of the analyses). Several components are taken into account for b-jet fragmentations
  - For the FF the strategy is to compare nominal Bowler FF with tuned versions to the LEP data
  - This, with the standard Z2 tune in PYTHIA, is used to define the uncertainty on b fragmentation
  - The branching ratios of semi leptonic B hadron decays are also varied in the MC (according to PDG uncertainties)
  - CMS applies these changes at analysis level. ATLAS has this also as part of the JES uncertainties



ALEPH data: arXiv:hep-ex/0106051

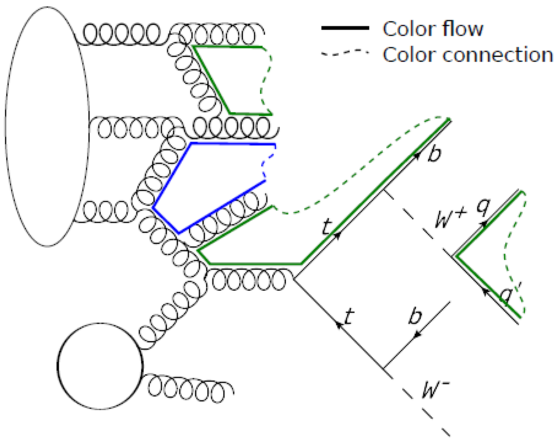
- CMS has also started studying b fragmentation directly in top pair events, with tuning as ultimate aim

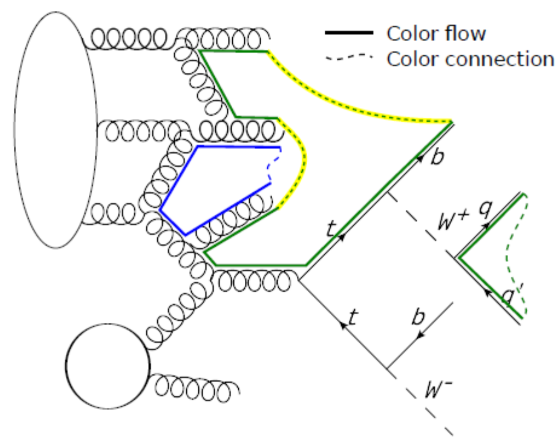




NEW@TOP2014

Colour (re)-connection (and underlying event)



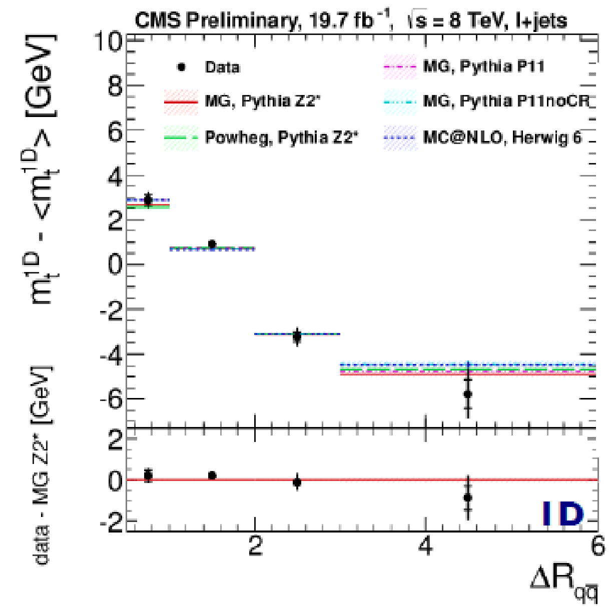


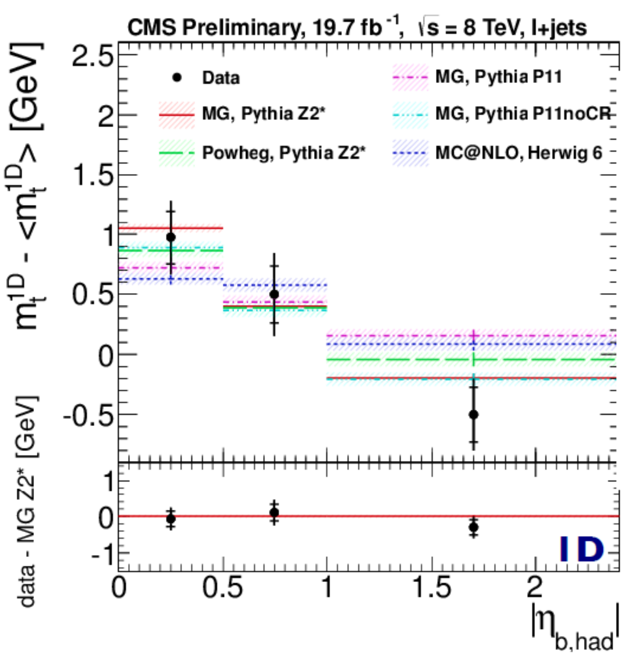
- The issue of the decay of an unstable coloured particle before hadronization
  - One of the decay products is colour connected to the rest of the event (beam remnant). This effect was studied already in the past ("beam drag" and "cluster collapse" effects, in EPJ C17 (2000) 137)
  - In Monte Carlos the effect is driven by shower evolution and the specific colour connection model. Connection probability in MCs steered by parameters.
- Possible phenomenology
  - Different soft particle/jet emission between the b jet and the remnants
  - UE also affects emission of soft (with respect to the process scale) jets and may influence the event kinematics
  - Affects in turn observables and measurements. Can we study e.g. the top mass as a function of observables which are particularly sensitive to this effect?

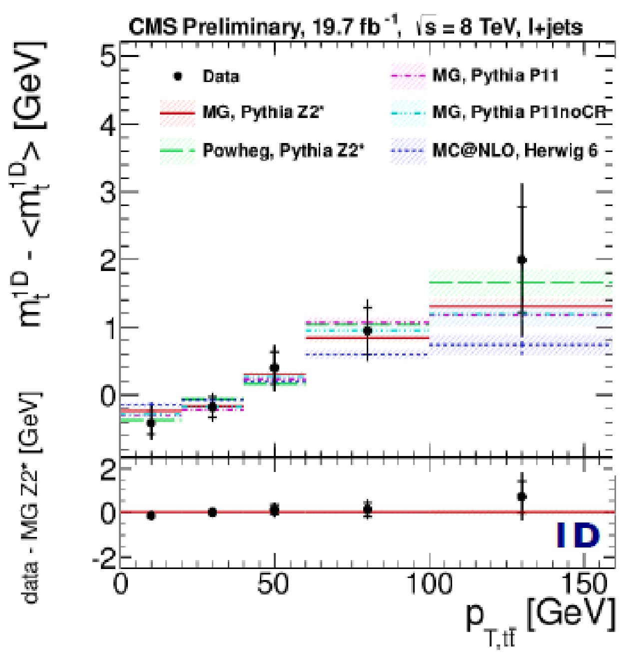
Top mass as a function of kinematics

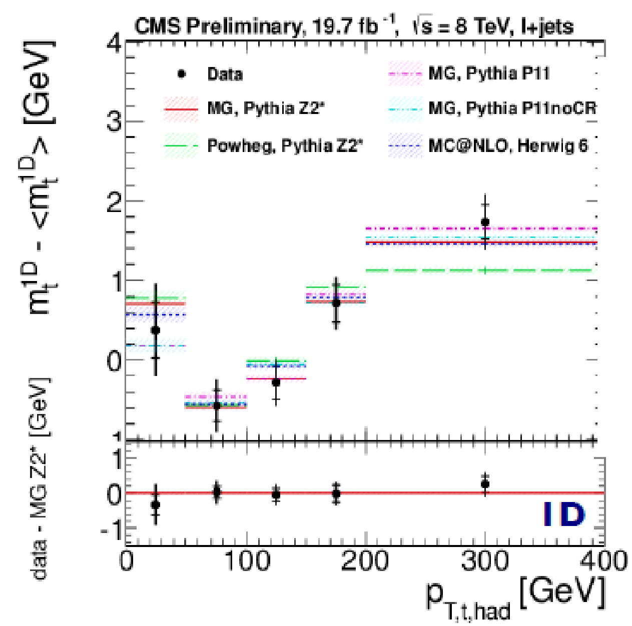
CMS-PAS-TOP-14-001

- CMS expands the top mass reference measurement as a function of ΔR_{qq}, η_b, $p_T(t)$, $p_T(tt)$.
  - ➢ Use semileptonic events and choose the two best jet permutations after a kinematic fit. Both permutations are used.
  - ➢ The 1D mass determination are shown. Agreement also for the 2D analyses
  - ➢ Data not sufficient yet for a discrimination among the models







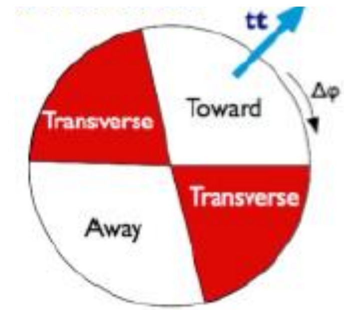


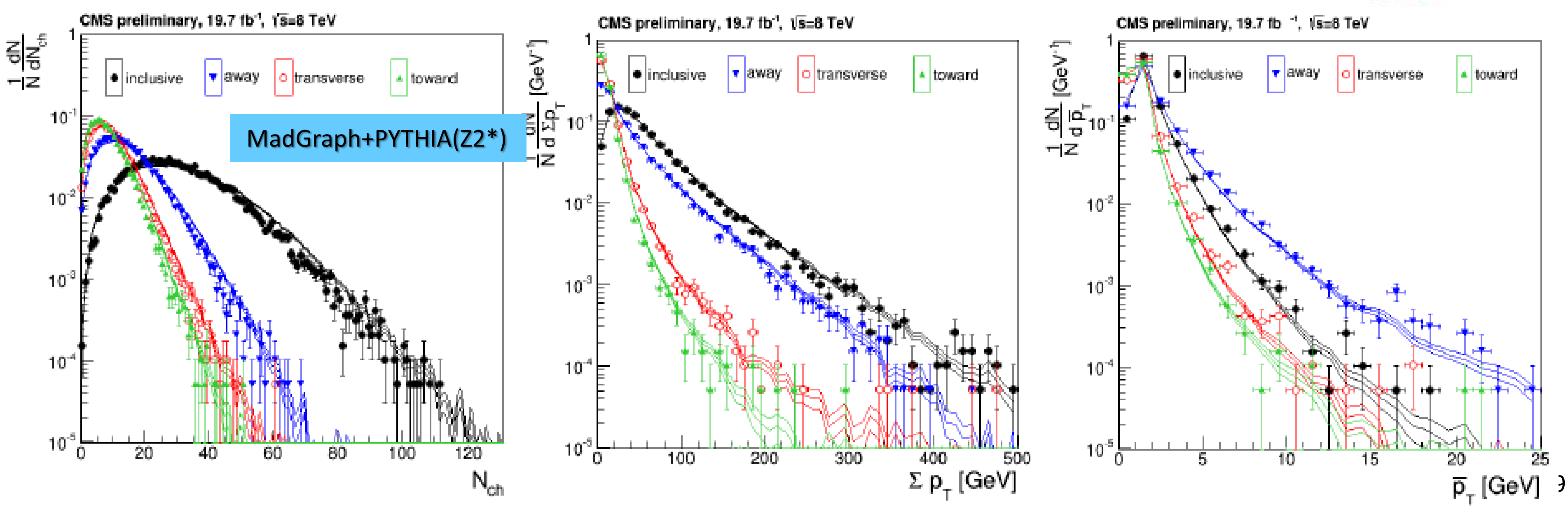
Underlying event: a more detailed look

JHEP 12 (2012) 105

- Directly check UE activity by using track information
  1. Remove all particles associated to the candidate lepton and jets from top pairs
  2. Define an estimator of the $\vec{p}_T^{\,t\bar{t}} \approx \vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{p}_T^{\,b_1} + \vec{p}_T^{\,b_2} + \vec{\not{p}}_T$
  - ➢ Define a $\Delta\Phi$ with respect to this direction, and check charged particle multiplicity, momentum flux and average p_T per charged particle as a function of $\Delta\Phi$.

- Impressive agreement with MadGraph+PYTHIA6 Z2*
  - ➢ Toward region with softer multiplicity and spectrum
  - ➢ Away region increase of particle multiplicity correlated with ISR

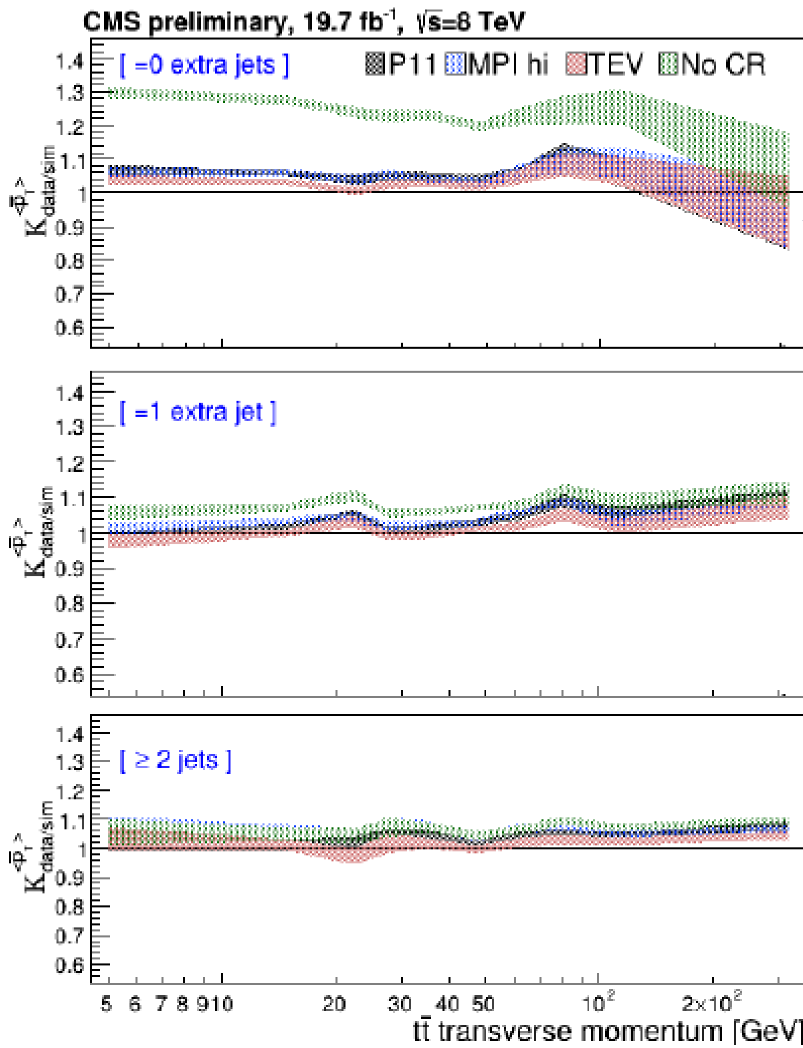


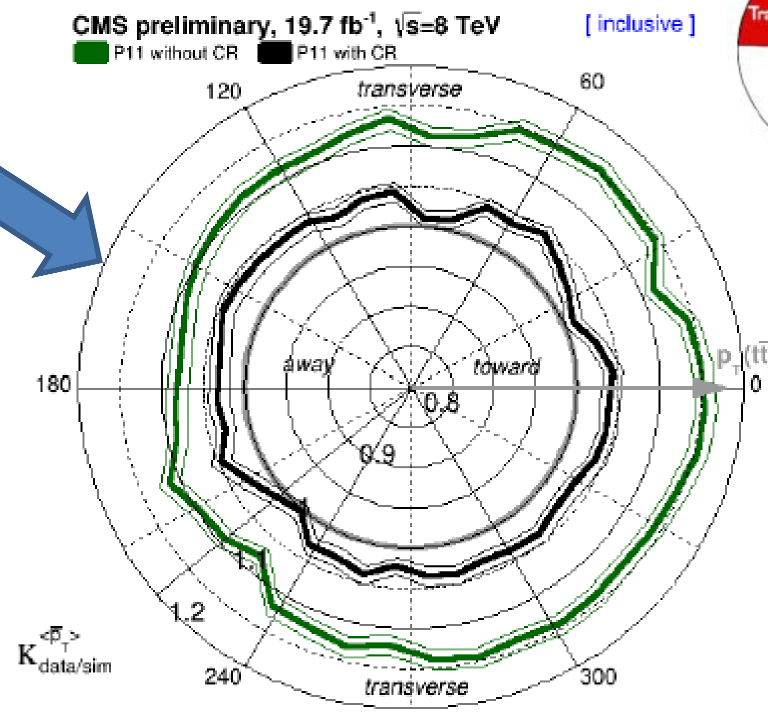


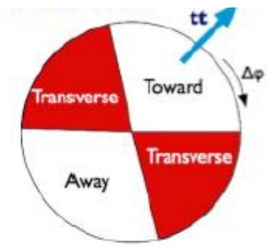
Underlying event: a more detailed look

- One can test data/MC ratios and expand them as a function of p_T(tt) or ΔΦ.
  - ➢ CR models give appreciable differences when the top pair system is at rest, and along the direction of the tt system

Mean pT per particle (DT/MC)



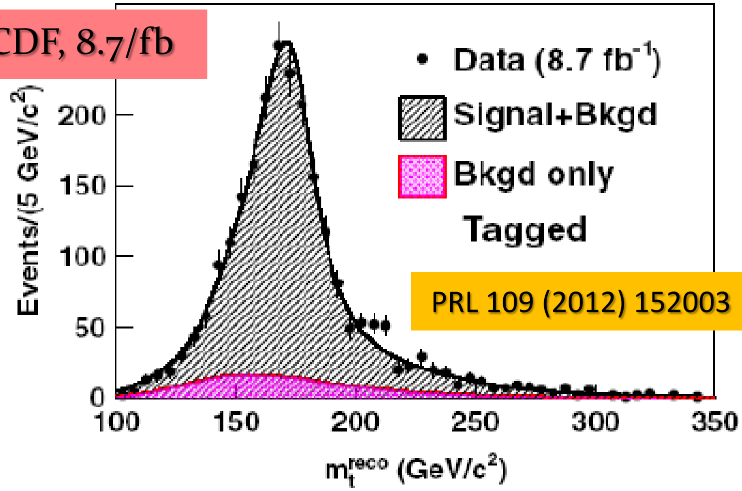




- Data exclude no CR models in PYTHIA
  - ➢ More constraints and studies need to be performed in a similar way

In the meanwhile at the Tevatron

CDF, 8.7/fb



PRL 109 (2012) 152003

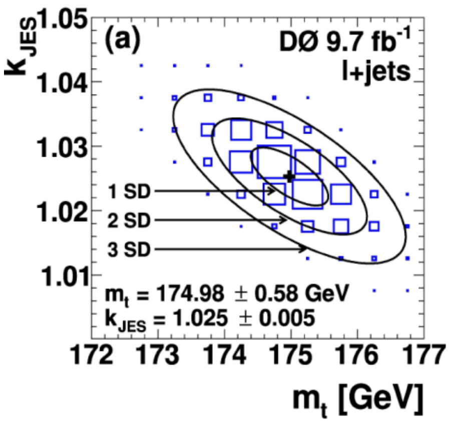
Residual jet energy scale	0.52
Signal modeling	0.56
Higher-order corrections	0.09
b jet energy scale	0.18
b-tagging efficiency	0.03
Initial and final state radiation	0.06
Parton distribution functions	0.08
Gluon fusion fraction	0.03
Lepton energy scale	0.03
Background shape	0.20
Multiple hadron interaction	0.07
Color reconnection	0.21
MC statistics	0.05

Do, 9.7/fb

PRL 113 (2014) 032002

$$P(x,H) \sim \int d^6\sigma(y,H)W(x,y)f_{PDF}(q_1)f_{PDF}(q_2)dq_1dq_2$$

Diff. xsection with LO ME — Detector response (Transfer Function) — PDFs



Signal and background modeling:	
Higher order corrections	+0.15
Initial/final state radiation	±0.09
Hadronization and underlying event	+0.26
Color reconnection	+0.10
Multiple $p\bar{p}$ interactions	−0.06
Heavy flavor scale factor	±0.06
b quark jet modeling	+0.09
Parton distribution functions	±0.11
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	±0.16
b tagging	±0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet identification efficiency	−0.01
Method:	
Modeling of multijet events	+0.04
Signal fraction	±0.08
MC calibration	±0.07
Total systematic uncertainty	±0.49
Total statistical uncertainty	±0.58
Total uncertainty	±0.76

CDF **m_{top} = 172.85 ± 0.71 (stat+JES) ± 0.84 (syst) GeV**

Do m_{top} = 174.98 ± 0.41(stat) ±0.41(JES) ±0.49(syst) GeV

March 2013: first ever top mass World Average

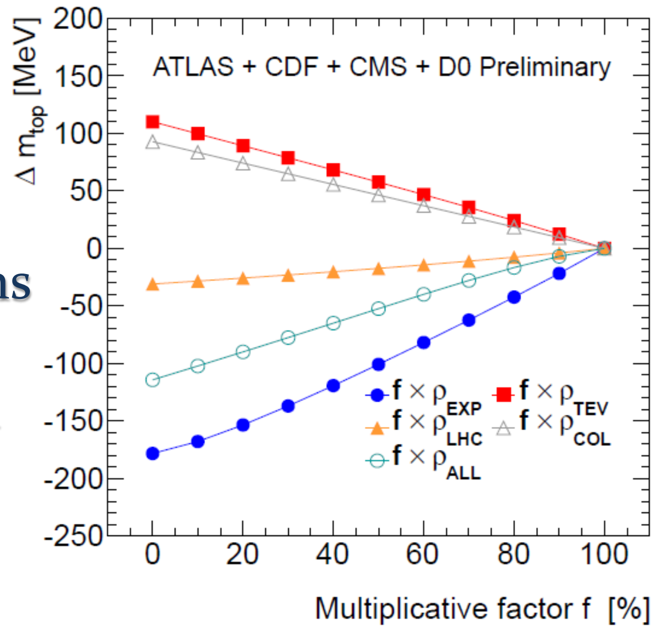
- Big effort for reaching common conventions in the splitting of systematic unc.s
  - ➢ Across the LHC experiments, but also talking with the Tevatron.
  - ➢ The correlation of these systematics is sometime difficult to asses
- Most notably (but not only) reached conclusions on the JES uncertainties
  - ➢ iJES: in situ calibration, statistical origin
  - ➢ stdJES: light jet calibration with data, only correlated within the same exp
  - ➢ flavourJES : from different jet energy responses (gluon vs quarks)
  - ➢ bJES : modelling of the response for b jets. TH uncertainties correlate it among experiments

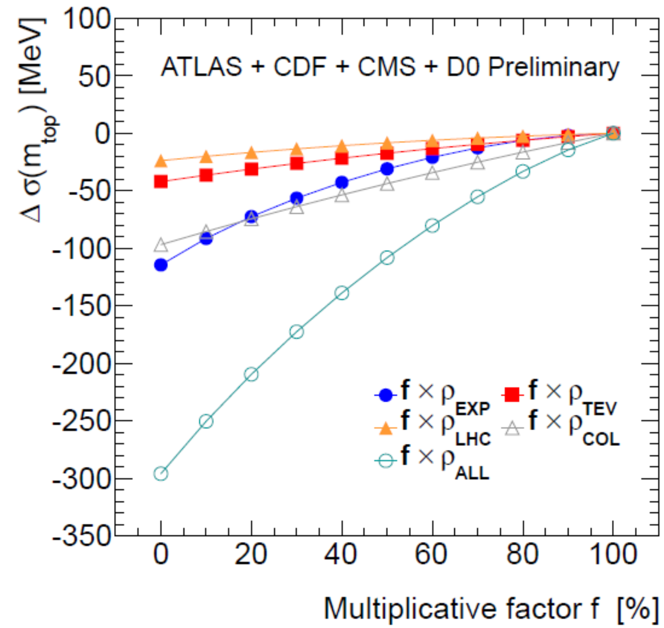
	Input measurements and uncertainties in GeV											
	CDF				D0		ATLAS		CMS			World
Uncertainty	l+jets	di-l	all jets	E_T^{miss}	l+jets	di-l	l+jets	di-l	l+jets	di-l	all jets	Combination
m_{top}	172.85	170.28	172.47	173.93	174.94	174.00	172.31	173.09	173.49	172.50	173.49	173.34
Stat	0.52	1.95	1.43	1.26	0.83	2.36	0.23	0.64	0.27	0.43	0.69	0.27
iJES	0.49	n.a.	0.95	1.05	0.47	0.55	0.72	n.a.	0.33	n.a.	n.a.	0.24
stdJES	0.53	2.99	0.45	0.44	0.63	0.56	0.70	0.89	0.24	0.78	0.78	0.20
flavourJES	0.09	0.14	0.03	0.10	0.26	0.40	0.36	0.02	0.11	0.58	0.58	0.12
bJES	0.16	0.33	0.15	0.17	0.07	0.20	0.08	0.71	0.61	0.76	0.49	0.25
MC	0.56	0.36	0.49	0.48	0.63	0.50	0.35	0.64	0.15	0.06	0.28	0.38
Rad	0.06	0.22	0.10	0.28	0.26	0.30	0.45	0.37	0.30	0.58	0.33	0.21
CR	0.21	0.51	0.32	0.28	0.28	0.55	0.32	0.29	0.54	0.13	0.15	0.31
PDF	0.08	0.31	0.19	0.16	0.21	0.30	0.17	0.12	0.07	0.09	0.06	0.09
DetMod	<0.01	<0.01	<0.01	<0.01	0.36	0.50	0.23	0.22	0.24	0.18	0.28	0.10
b-tag	0.03	n.e.	0.10	n.e.	0.10	<0.01	0.81	0.46	0.12	0.09	0.06	0.11
LepPt	0.03	0.27	n.a.	n.a.	0.18	0.35	0.04	0.12	0.02	0.14	n.a.	0.02
BGMC	0.12	0.24	n.a.	n.a.	0.18	n.a.	n.a.	0.14	0.13	0.05	n.a.	0.10
BGData	0.16	0.14	0.56	0.15	0.21	0.20	0.10	n.a.	n.a.	n.a.	0.13	0.07
Meth	0.05	0.12	0.38	0.21	0.16	0.51	0.13	0.07	0.06	0.40	0.13	0.05
MHI	0.07	0.23	0.08	0.18	0.05	<0.01	0.03	0.01	0.07	0.11	0.06	0.04
Total Syst	0.99	3.13	1.41	1.36	1.25	1.49	1.53	1.50	1.03	1.46	1.23	0.71
Total	1.12	3.69	2.01	1.85	1.50	2.79	1.55	1.63	1.06	1.52	1.41	0.76

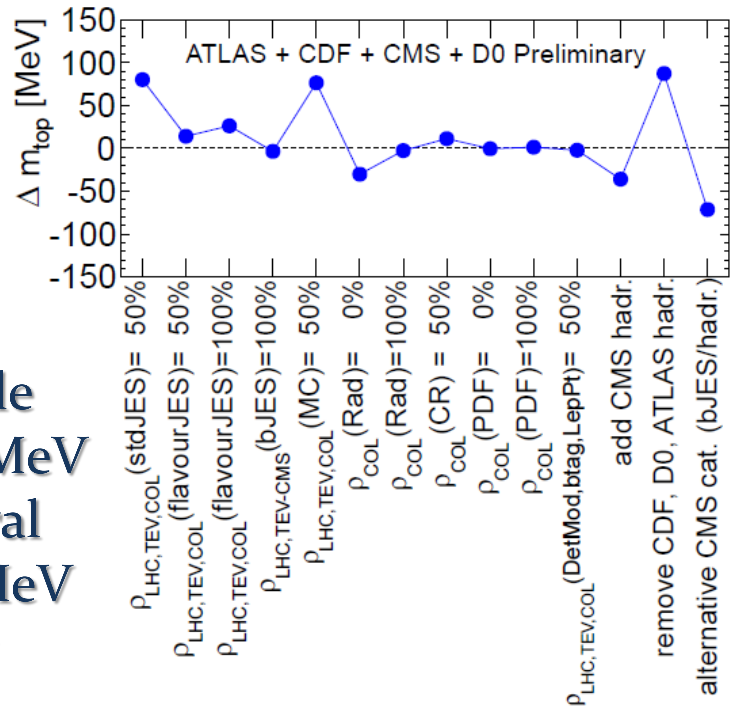
ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
		$\rho_{ATL-TEV}$	$\rho_{CMS-TEV}$
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.5	1.0	1.0	0.5
1.0	1.0	1.0	1.0
1.0	1.0	0.5	0.5
1.0	1.0	1.0	1.0
1.0	1.0	0.5	0.5
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
1.0	1.0	1.0	1.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
1.0	0.0	0.0	0.0

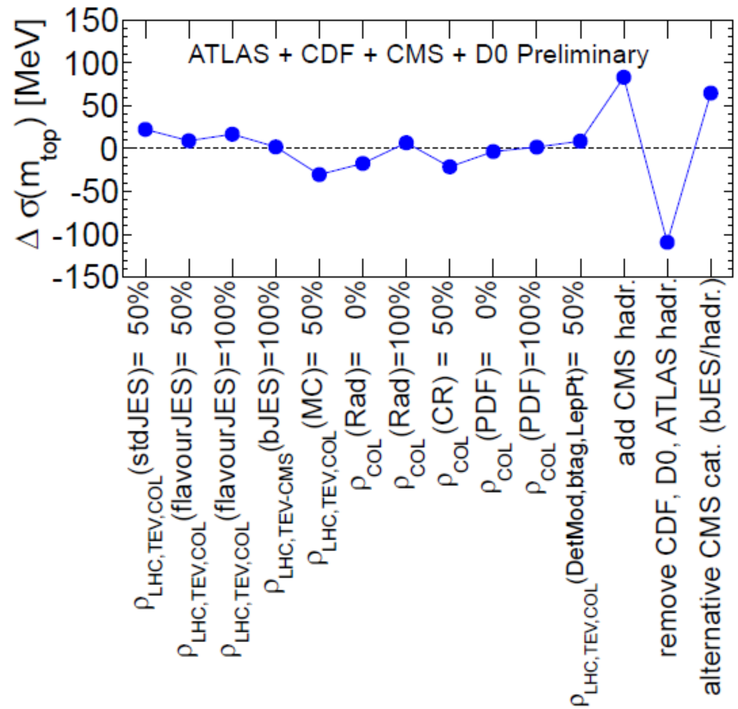
Testing the stability

- Different correlations are tested, varying them separately and even in a correlated way



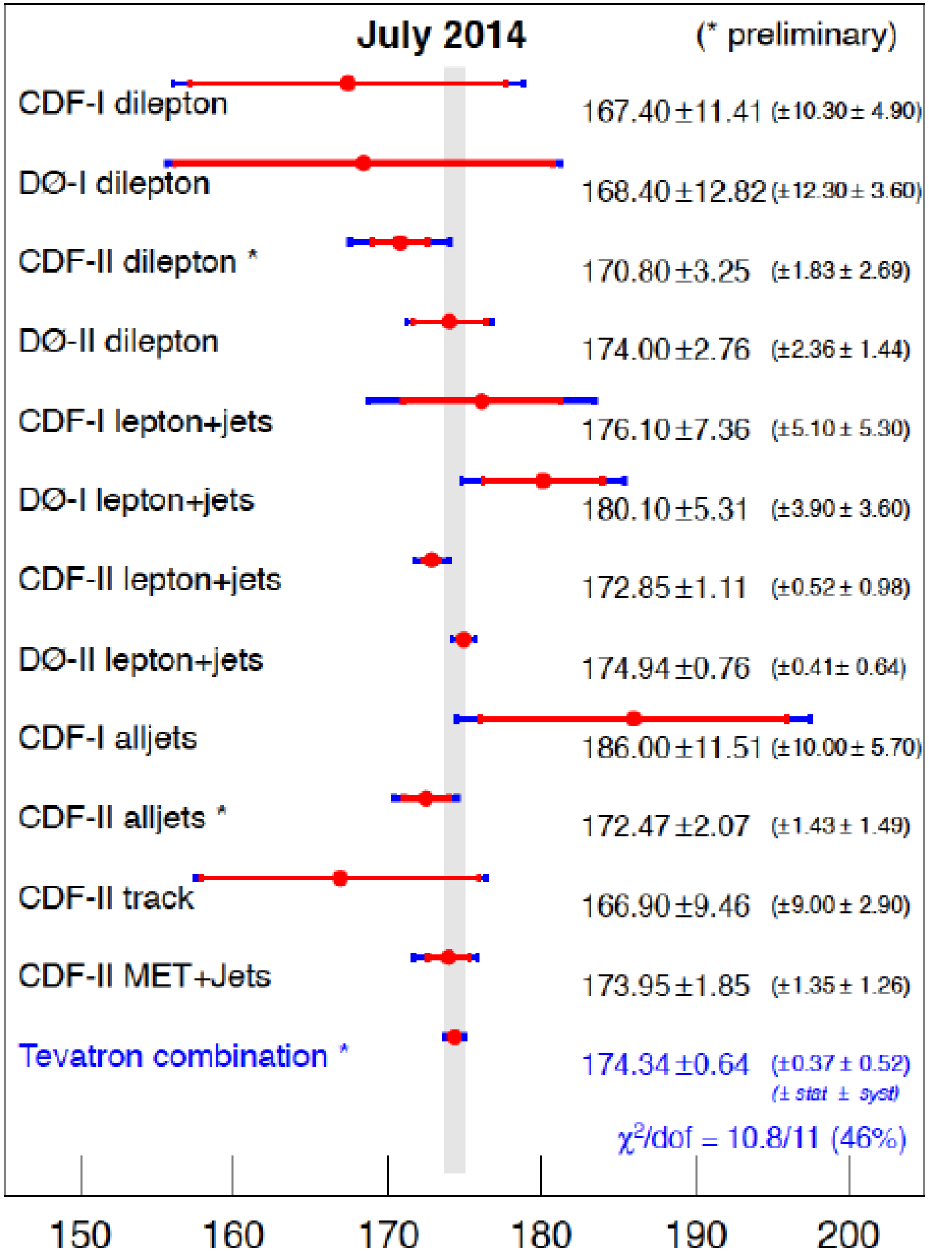


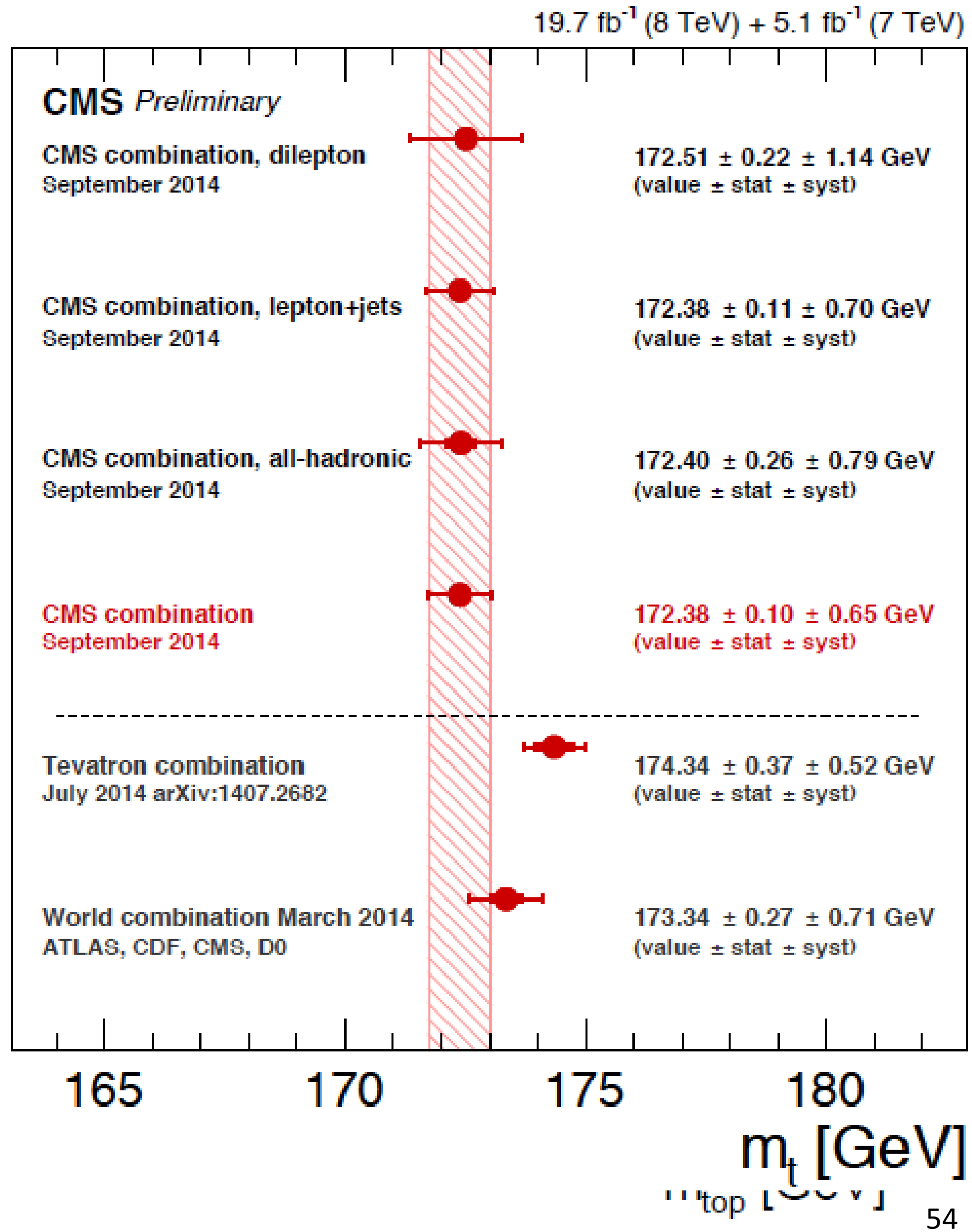




- Results stable within 200 MeV for the central value, 300 MeV for the error

Top mass combinations

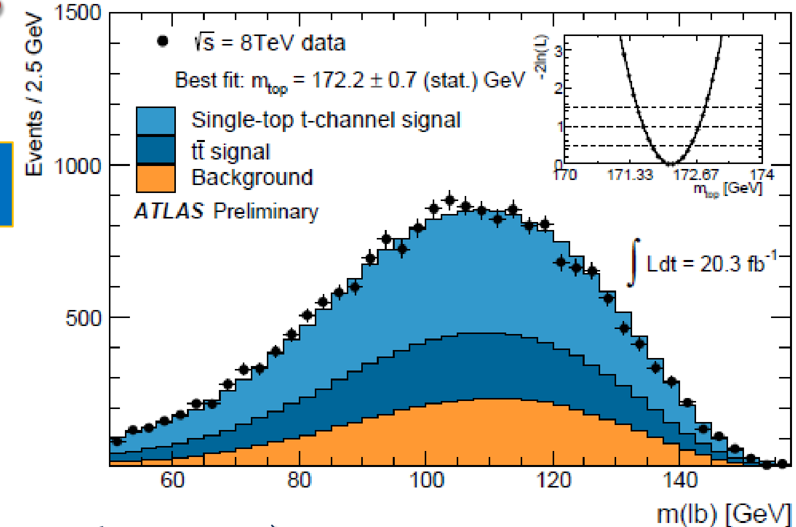




Alternative m_t measurements

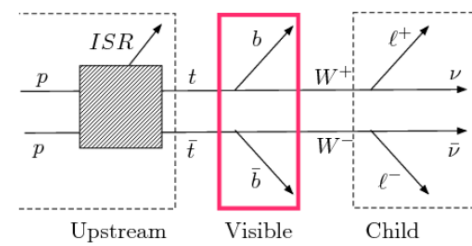
- More direct methods. Examples: top mass from pure single top events **NEW@TOP2014**
  - Template fit to the m(ℓb) mass – also includes the tt background **ATLAS-CONF-2014-055**

$$m_t = 172.2 \pm 0.7\,(\text{stat.}) \pm 2.0\,(\text{syst.})\ \text{GeV}$$



- Indirect methods (most of them in the works at the LHC)
  - Use the dependence on the top mass on other variables
    - Decay length of the B-hadron **CMS-PAS-TOP-12-030**

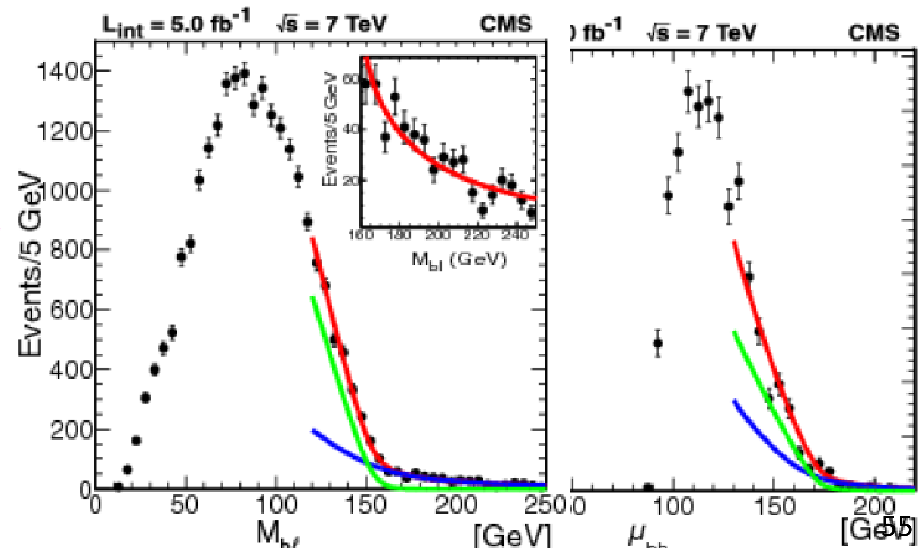
$$m_t = 173.5 \pm 1.5\,(\text{stat.}) \pm 1.3\,(\text{syst.}) \pm 2.6\,(p_T^{\text{top}})\ \text{GeV}$$



    - Lepton end-point methods

Eur. Phys. J. C73 (2013) 2494

$$m_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.7}_{-2.2}\,(\text{syst.})\ \text{GeV}$$

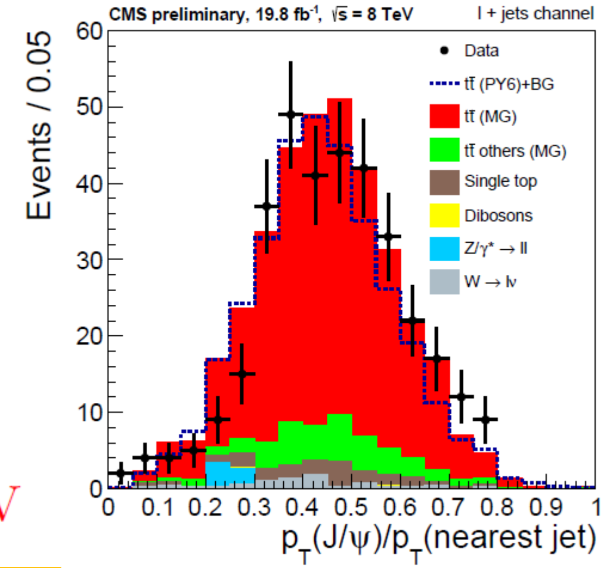


$$M_{T2} \equiv \min_{\mathbf{p}_T^{\nu a} + \mathbf{p}_T^{\nu b} = \mathbf{p}_T^{\text{miss}}} \{\max(m_T^a, m_T^b)\}$$

$$M_{T2} \to M_{T2\perp} \equiv \mu_{bb}$$

Alternative m_t measurements (continued)

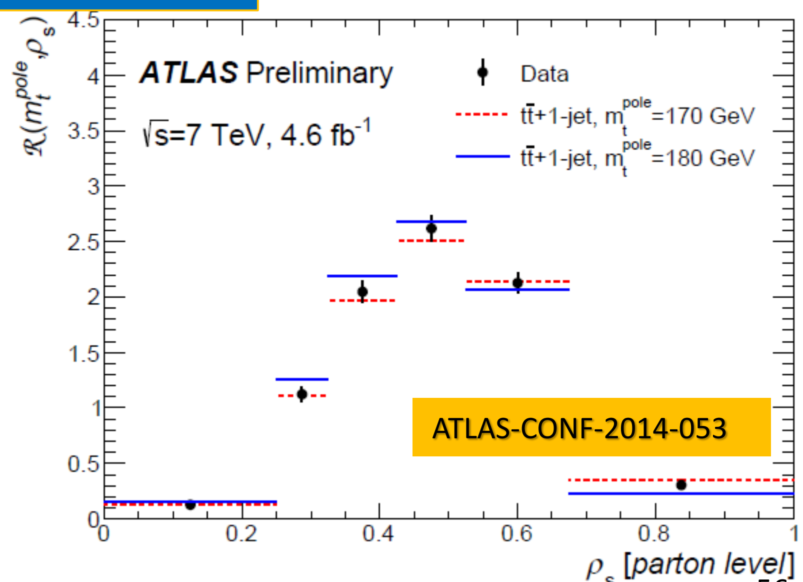
- Other indirect methods
  - Use the dependence on the top mass on other variables
    - Invariant mass of the system J/Ψ+lepton from W (ongoing)
  - Indirectly access the pole mass
    - Top pair cross section (see previous slides)
    - Top mass from normalized tt+1jet cross section



$$m_t^{\mathrm{pole}} = 173.7 \pm 1.5\,(\mathrm{stat.}) \pm 1.4\,(\mathrm{syst.})\,^{+1.0}_{-0.5}(\mathrm{theo.})\ \mathrm{GeV}$$

Eur.Phys.J C73 (2013) 2438

NEW@TOP2014

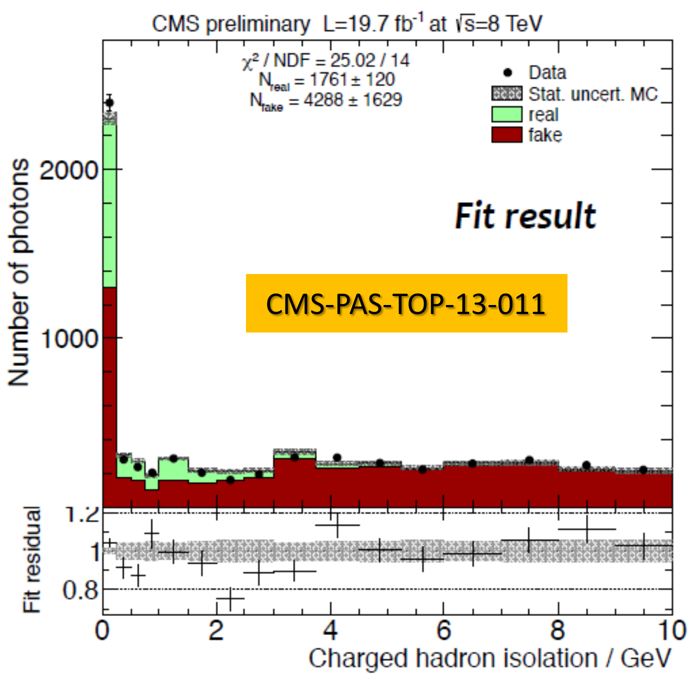


ATLAS-CONF-2014-053

- All useful crosschecks. Many analyses still needing more statistics
  - Need to scrutinize the meaning of the measurement before including them in top mass combinations

The charge of the top quark

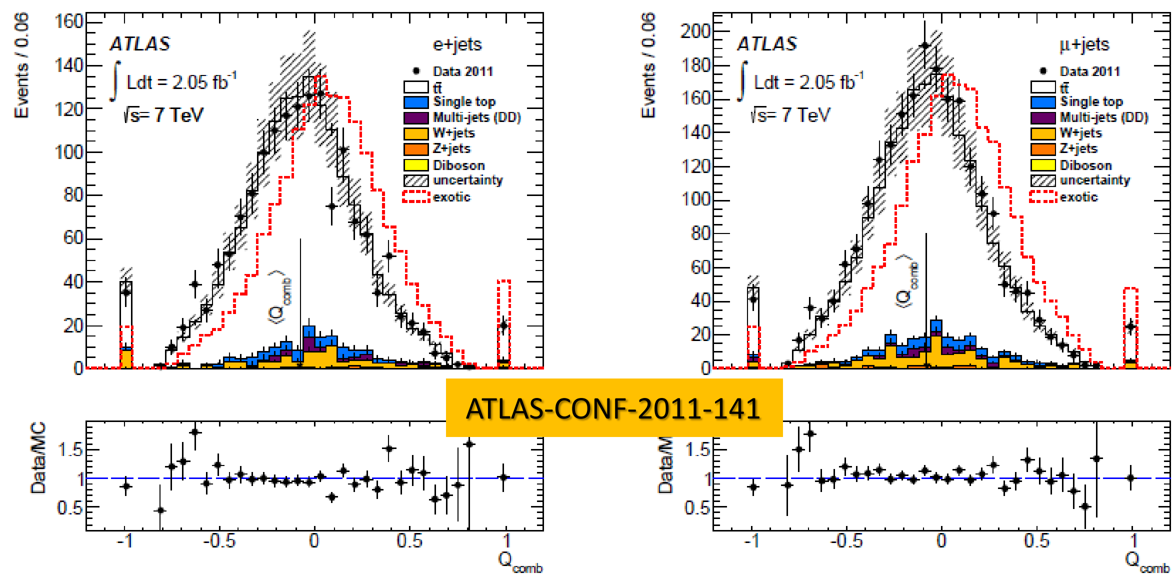
- Measured from the ttγ coupling
  - Look for isolated photons
  - Extract the ttγ component via a fit to the isolation variable
  - More statistics is needed for a refined measurement



$$\sigma^{CMS}_{\bar{t}t+\gamma} = 2.4 \pm 0.2\,(\text{stat.}) \pm 0.6\,(\text{syst.})\ \text{pb}$$

$$R = \sigma_{\bar{t}t+\gamma}/\sigma_{\bar{t}t} = (1.07 \pm 0.07\,(\text{stat.}) \pm 0.27\,(\text{syst.})) \times 10^{-2}$$

- The top charge can be determined directly
  - Build a b-jet charge via a p_T weighted sum of the charges of its components (ε~60%)
  - Consider only those pairing giving only one (ℓb) mass solution in the kinematically allowed region (p~90%)
  - Q_t from the sum of the mean value of the calibrated and background subtracted b-jet charge, and the associated lepton charge

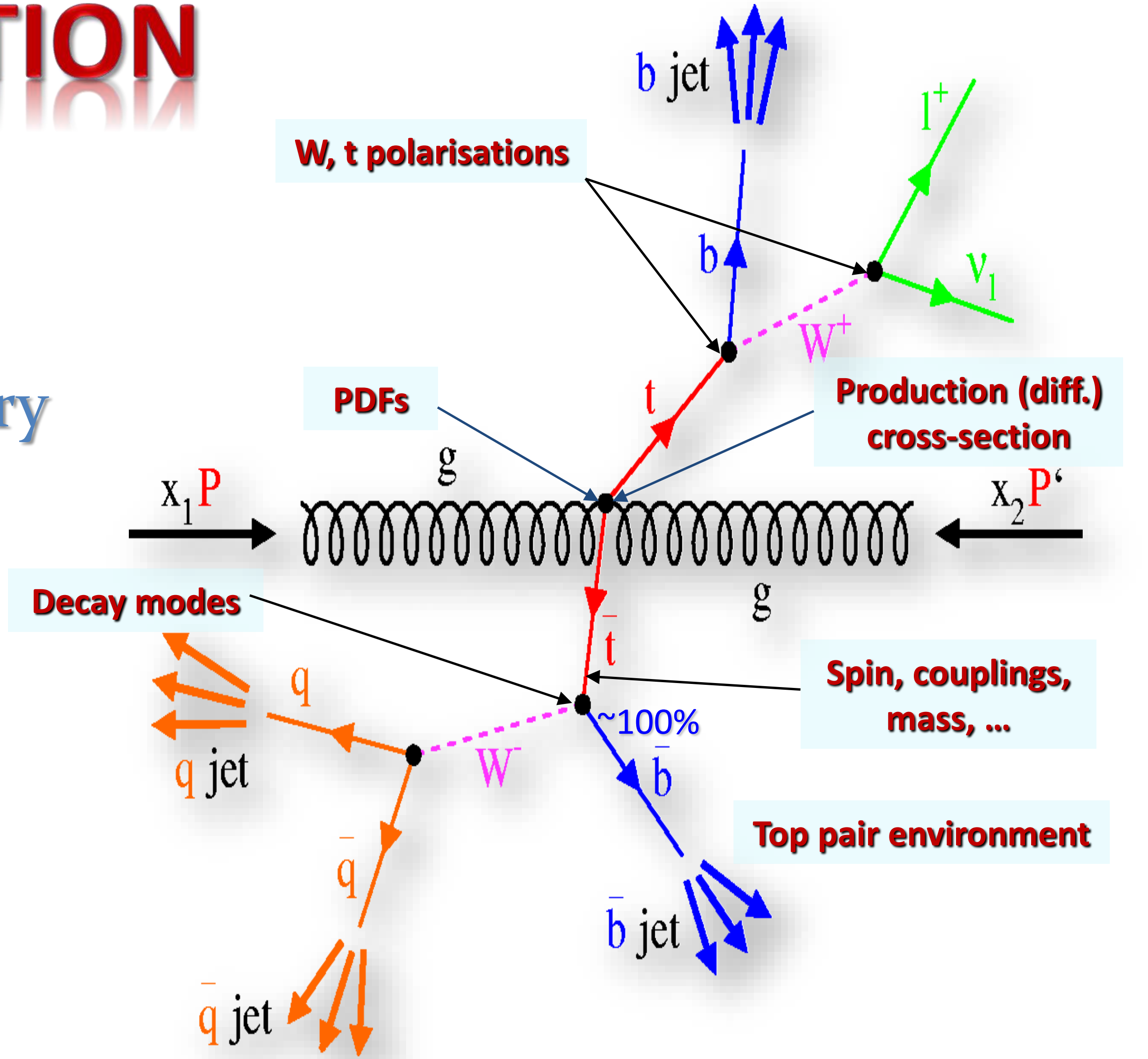


$$Q_t = 0.64 \pm 0.02(stat.) \pm 0.08(syst.)$$

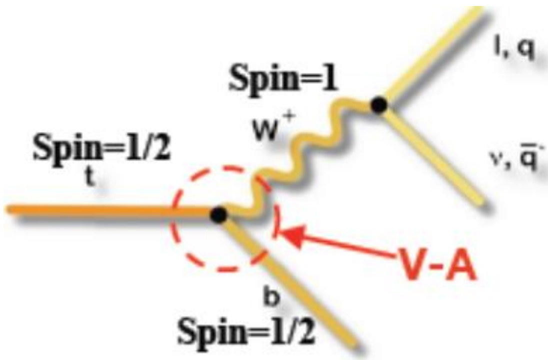
- Exotic quarks with Q_t=4/3 excluded at more than 8 standard deviations

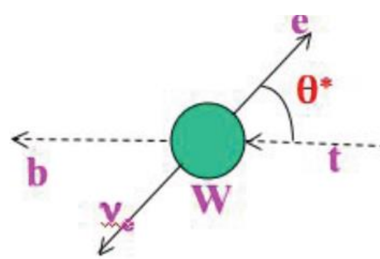
OTHER PROPERTIES OF TOP PRODUCTION

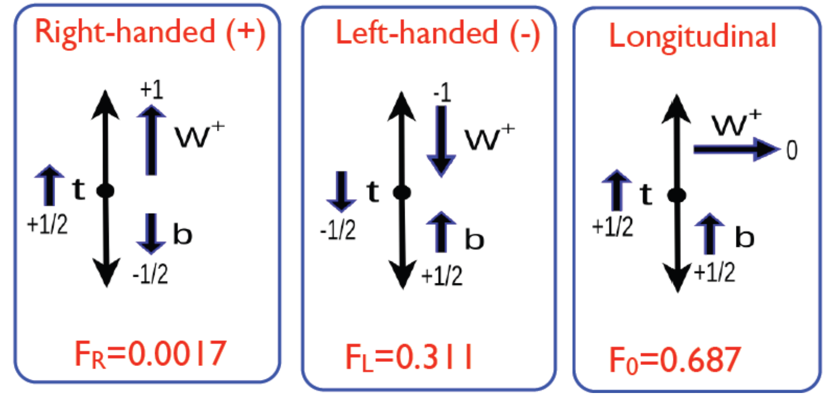
Polarizations
Spin correlations
Charge asymmetry



Spin structure of top decays

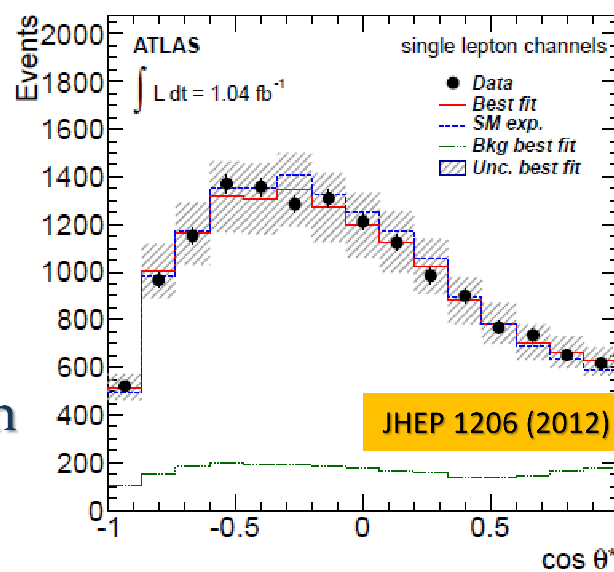


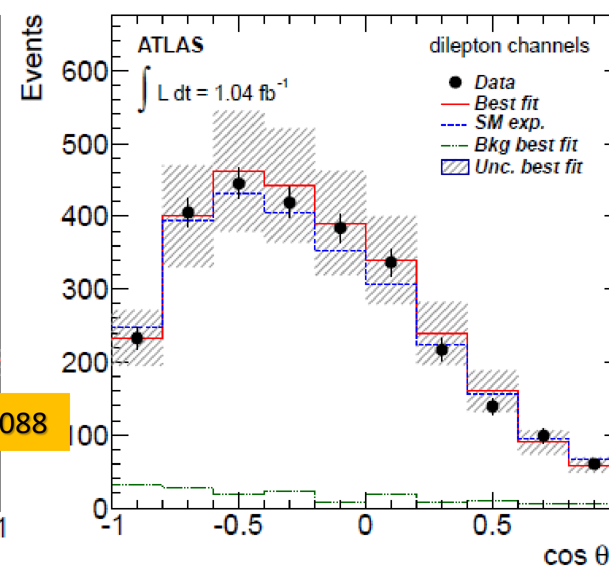




$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_\ell} = \frac{3}{8}(1+\cos\theta^*_\ell)^2 F_R + \frac{3}{8}(1-\cos\theta^*_\ell)^2 F_L + \frac{3}{4}\sin^2\theta^*_\ell F_0$$

- The spin structure of the top decay is transmitted to its daughters
  - By investigating the helicity of Ws from top we can test the V-A structure of the coupling
    - The experimental "analyzers" are the decay product of the Ws
- Measure $d\sigma/d\cos\theta^*_\ell$, the angle between the lepton and the b direction (in the W rest frame)



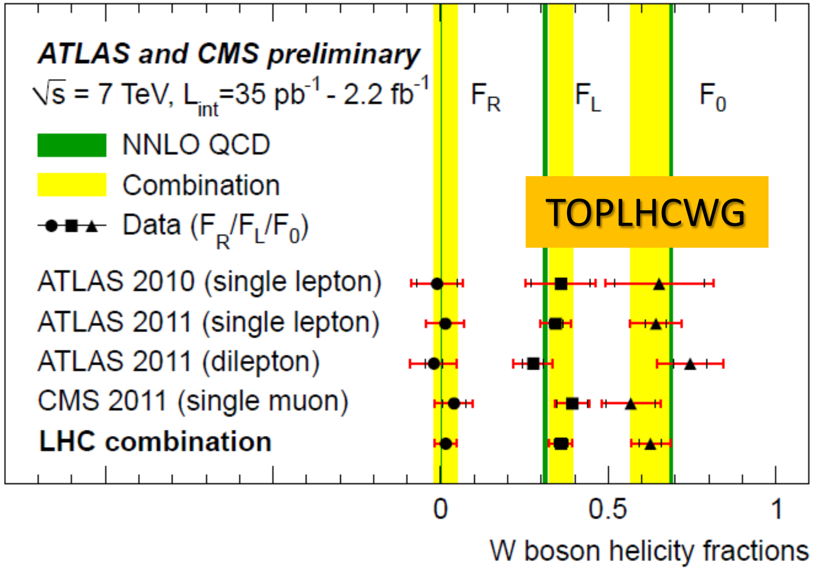


JHEP 1206 (2012) 088

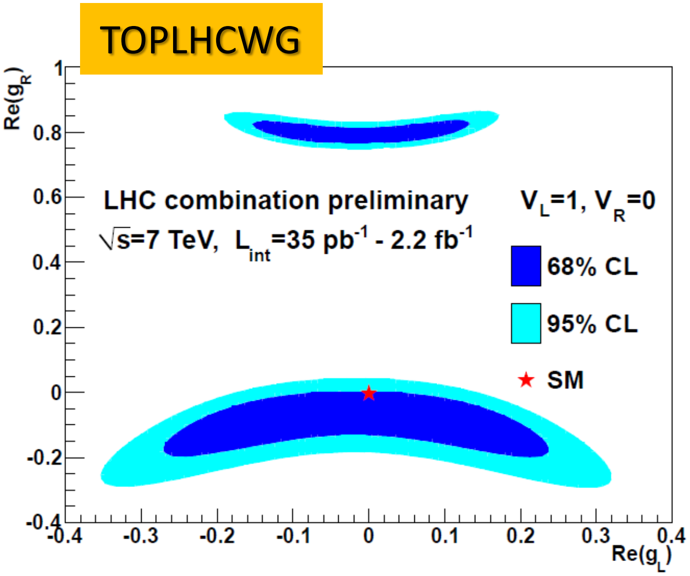
Constraining anomalous couplings

- The polarization fractions can be extracted by a fit to data
  - Fit performed with and without the assumption of F_R=o
  - Main systematic errors represented by JES and theory uncertainties/W+jets normalization
  - Agreement with the expectations in both ATLAS, CMS and combined results

	F_0	F_L
ATLAS	0.66 ±0.06 ±0.07	0.33 ±0.03 ±0.03
CMS	0.567 ±0.074 ±0.047	0.393 ±0.045 ±0.029



- The helicity fractions can be translated into constraints of anomalous couplings and NP operators
  - The LHC combination is consistent with the expectation of the SM

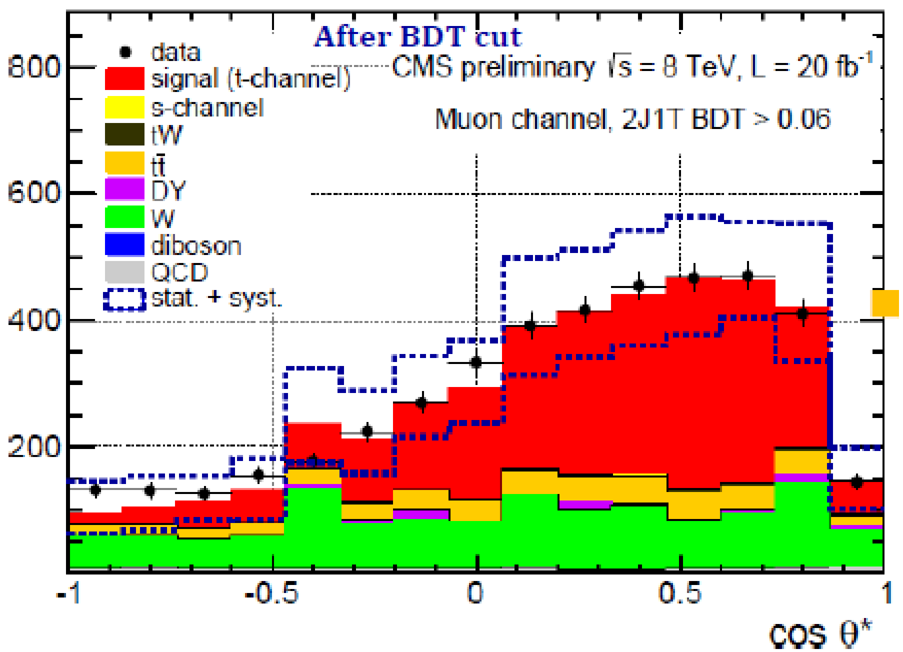


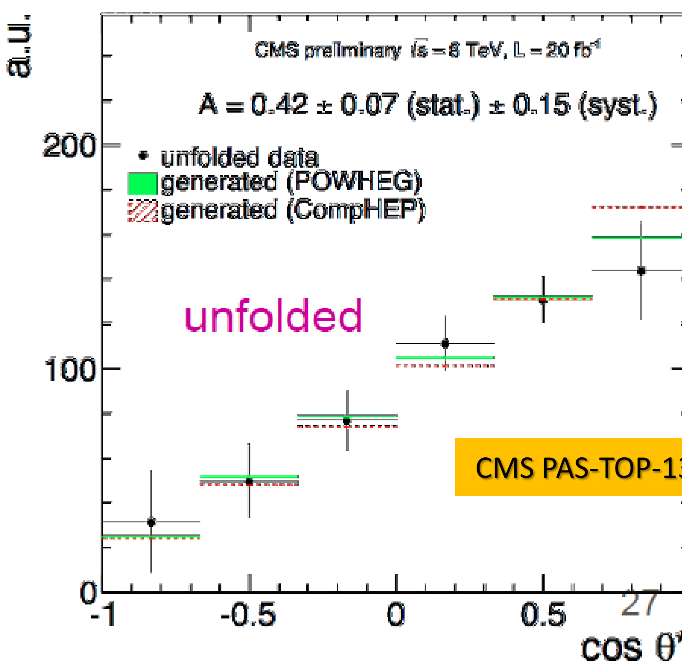
0 in the SM

$$\mathcal{L}_{tWb} = \mathcal{L}_{tWb}^{\rm SM} - \frac{g}{\sqrt{2}}\bar{b}\Big[(V_L P_L + V_R P_R)\gamma^\mu + \frac{i\sigma^{\mu\nu}q_\nu}{m_W}(G_L P_L + G_R P_R)\Big]tW_\mu$$

Polarization in single top events

- Single top events provide a source of polarized top quarks
  - Also sensitive to the V-A structure of the Wtb vertex.
  - Probed by studying the cosθ* between the lepton and (untagged) forward jet in the top rest frame. The distribution is unfolded to correct for detector, acceptance and background effects
  - By combining the electron and muon channel the resulting polarization is $P_t = 0.82 \pm 0.12(\text{stat.}) \pm 0.32(\text{syst.})$, compatible with the SM expectation of about 0.9.



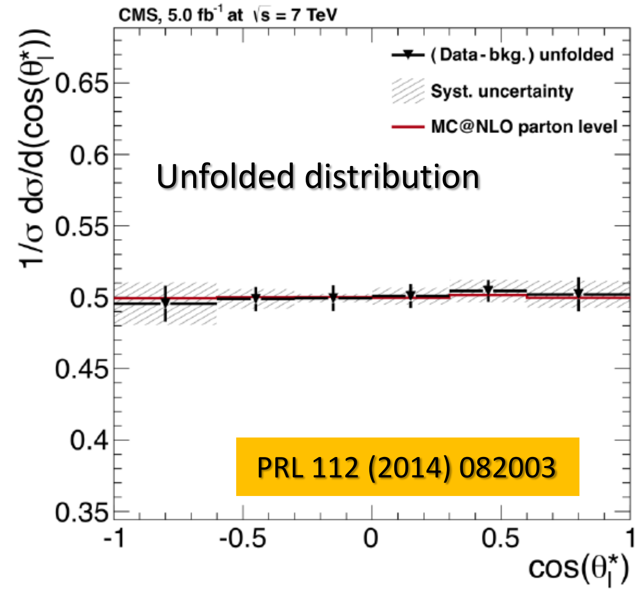


CMS PAS-TOP-13-001

Top polarization and spin correlations

- While top quarks are produced individually unpolarized in top pair production…
  - ➢ Can be studied via the angular distributions of the leptons from W decay
  - ➢ Fully leptonic final states particularly well suited

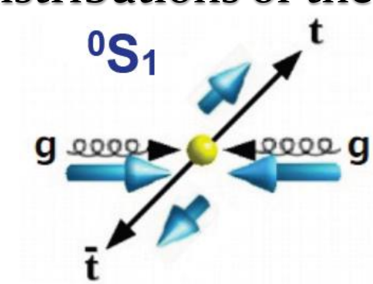
$$\frac{1}{\Gamma}\frac{d\Gamma}{\cos\ \theta_{l,n}} = \frac{1}{2}(1 + 2\alpha_l P_n \cos\ \theta_{l,n})$$



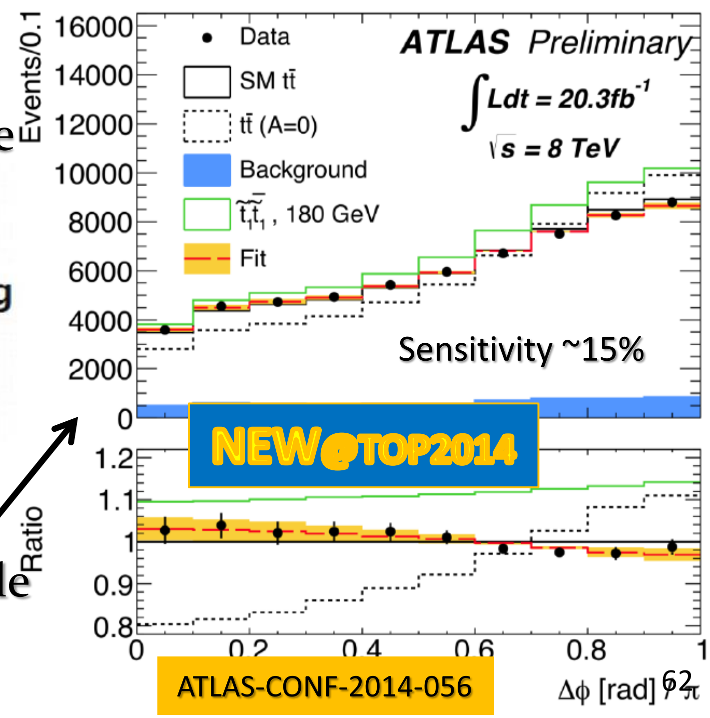
- …the spin of the two tops are correlated
  - ➢ Strength depending on the spin quantization axis
  - ➢ Can be measured from angular distributions of the top decay products

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

where $C = A\alpha_1\alpha_2$

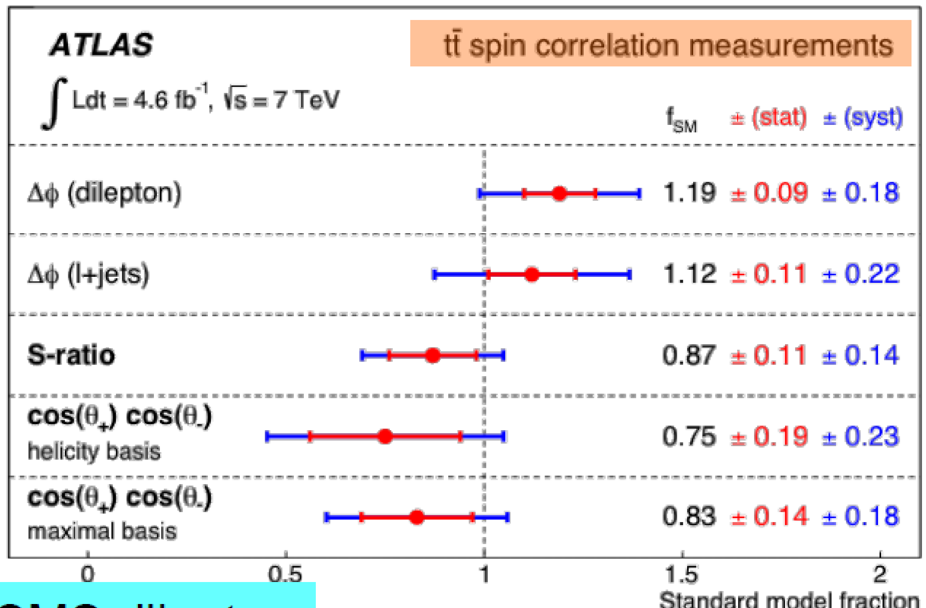


  - ○ A: correlation strength at production
  - ○ α_i: amount of spin information from each probe
  - ➢ Δφ between leptons particularly well suited variable
  - ➢ Sensitive to NP in both production and decay !



Summary on top polarization and spin correlation

- No evidence, as expected, of polarized top production in top-pair eventss
  - Experimental sensitivity at the level of 2%
- Observation, as expected, of correlation between the spins of the top quarks
  - More than 5σ significance at 7 TeV



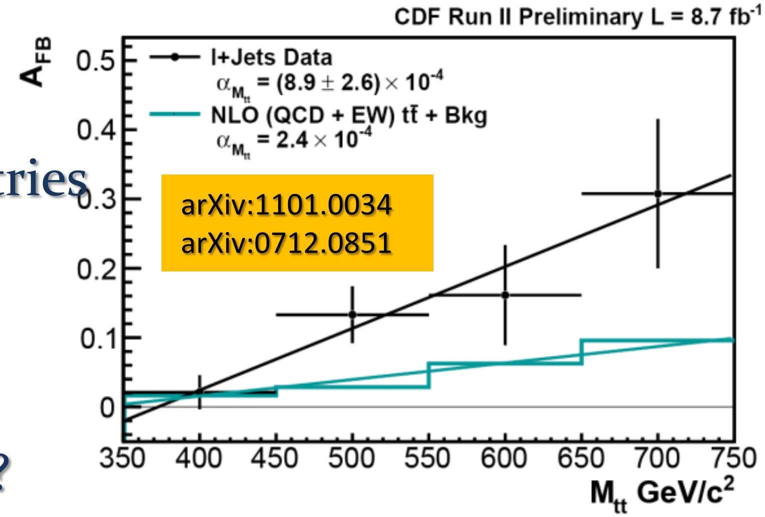
ATLAS dilepton/l+jets

Channel	$\alpha_\ell P_{\mathrm{CPC}}$	$\alpha_\ell P_{\mathrm{CPV}}$
ee	$0.12 \pm 0.10^{+0.09}_{-0.12}$	$-0.04 \pm 0.12^{+0.18}_{-0.12}$
$e\mu$	$-0.07 \pm 0.04^{+0.05}_{-0.06}$	$0.00 \pm 0.04^{+0.05}_{-0.04}$
$\mu\mu$	$-0.04 \pm 0.06^{+0.07}_{-0.07}$	$0.04 \pm 0.07^{+0.06}_{-0.06}$
Dilepton	$-0.04 \pm 0.03^{+0.05}_{-0.05}$	$0.01 \pm 0.03^{+0.04}_{-0.04}$
e + jets	$-0.031 \pm 0.028^{+0.043}_{-0.040}$	$0.001 \pm 0.031^{+0.019}_{-0.019}$
μ + jets	$-0.033 \pm 0.021^{+0.039}_{-0.039}$	$0.036 \pm 0.023^{+0.018}_{-0.017}$
ℓ + jets	$-0.034 \pm 0.017^{+0.038}_{-0.037}$	$0.023 \pm 0.019^{+0.012}_{-0.011}$
Combined	$-0.035 \pm 0.014^{+0.037}_{-0.037}$	$0.020 \pm 0.016^{+0.013}_{-0.017}$

CMS dilepton

Asymmetry	Data (unfolded)	MC@TNLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.006 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.025 \pm 0.010$	-0.078 ± 0.001	-0.078 ± 0.006	0
A_P	$0.005 \pm 0.013 \pm 0.014 \pm 0.008$	0.000 ± 0.001	...	...

Charge asymmetries



- Tevatron observes anomalous charge asymmetries

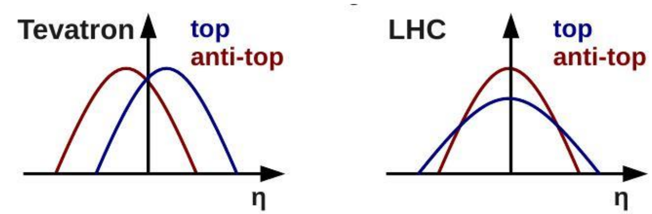
$$\frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- Indication of new physics mechanisms in the production of top pair, both in s- or t-channel?

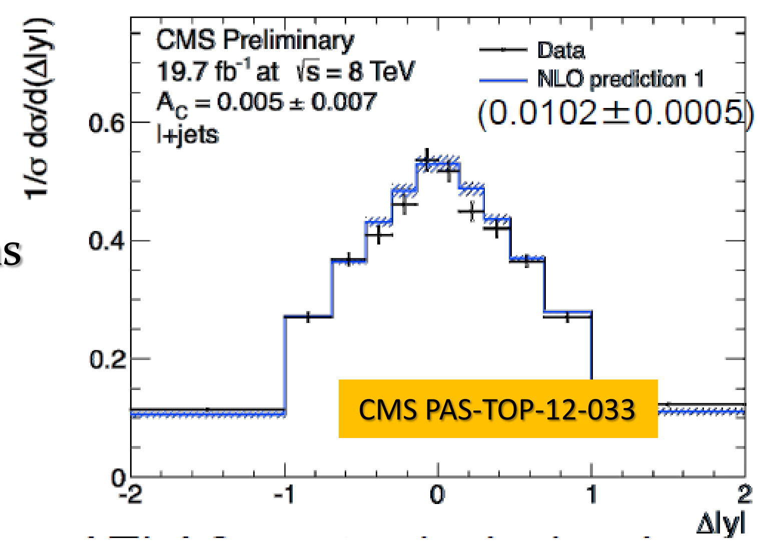
- LHC asymmetry needs to be defined differently (initial state charge symmetric)
- In the SM the asymmetry is not exactly zero
  - ➢ Introduced by interferences between ISR and FSR

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

$$A_C = +0.0115 \pm 0.0006$$



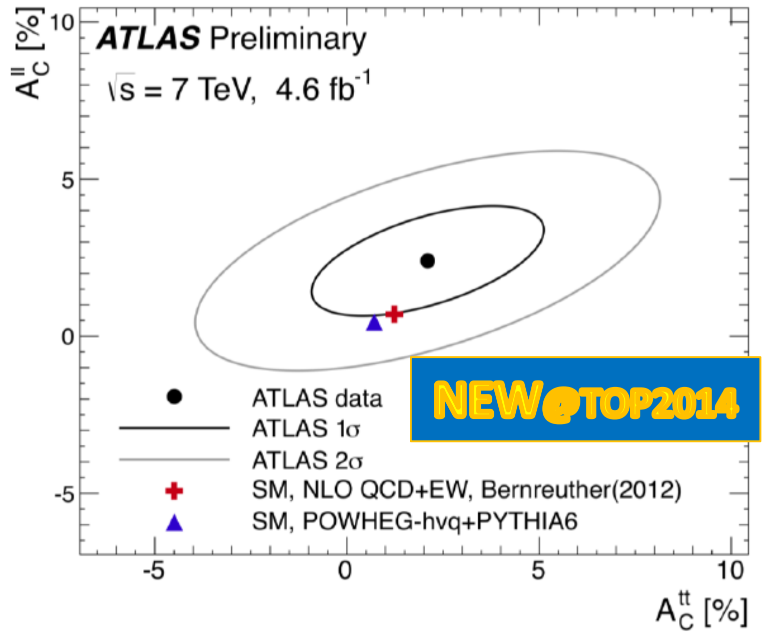
- Experimental approach at the LHC:
  - ➢ Determine background-subtracted distributions $|y_t|-|y_{tbar}|$ at reconstruction level (full event reconstruction in both l+jets and di-leptons)
  - ➢ Unfold to parton level
  - ➢ Determine total and differential asymmeries

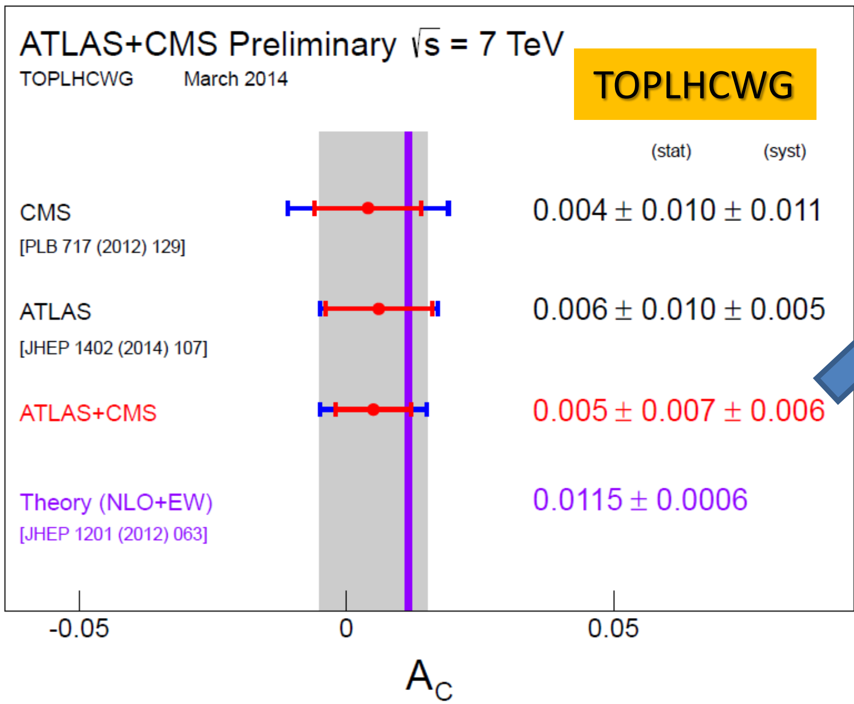


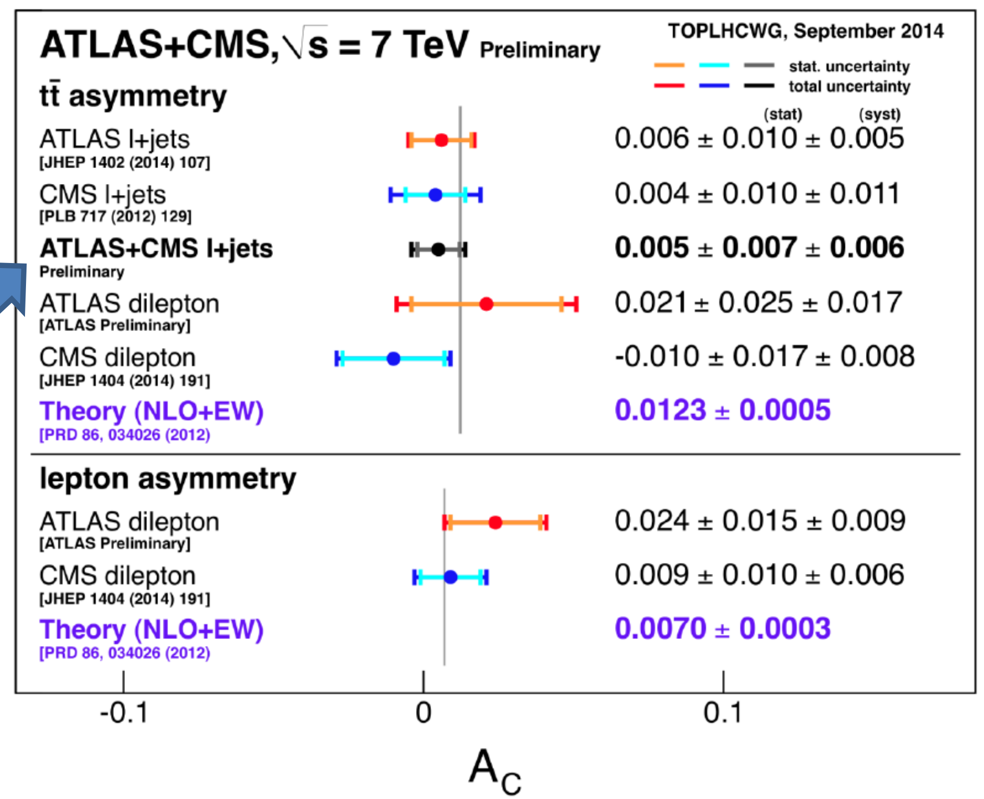
Summary of results

- Statistical errors are still important
  - Most important systematic contributions are given by detector response
  - Also use the leptonic asymmetry

$$A_C^{\mathrm{lep}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}.$$

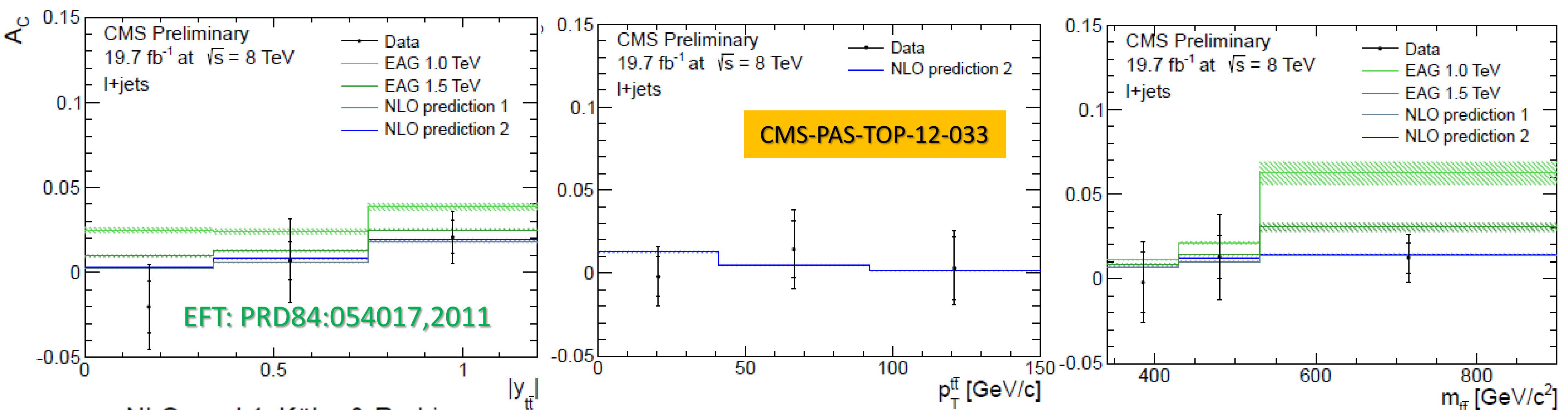






Differential asymmetries at the LHC

- In many new physics scenarios the charge asymmetry depends on phase space
  - ➢ High mass/p_T regimes enhance the quark annihilation part of the initial state
  - ➢ Measure A_c differentially as a function of p_T, y or mass of the top pair system
- Good agreement between data and SM expectations within uncertainties
  - ➢ Results compared to NLO+EW predictions and with EFT predictions
    - ○ Anomalous axial coupling of gluons to quarks: capable to explain the Tevatron anomaly



NLO pred.1: Kühn & Rodrigo
NLO pred.2: Bernreuther & Si

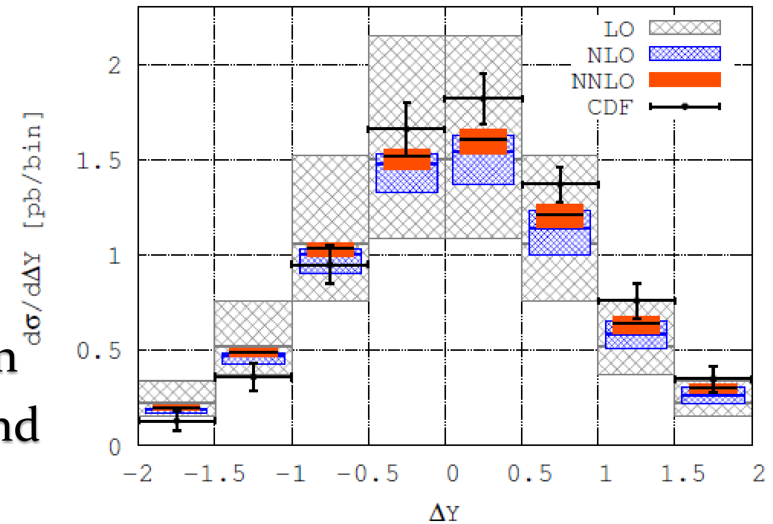
- Results still not able to discriminate between SM and BSM models

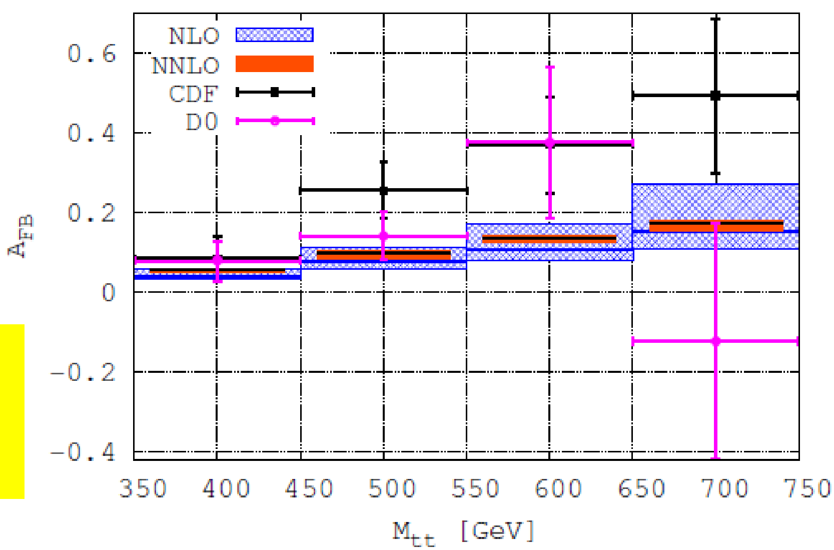
Update on Tevatron anomaly

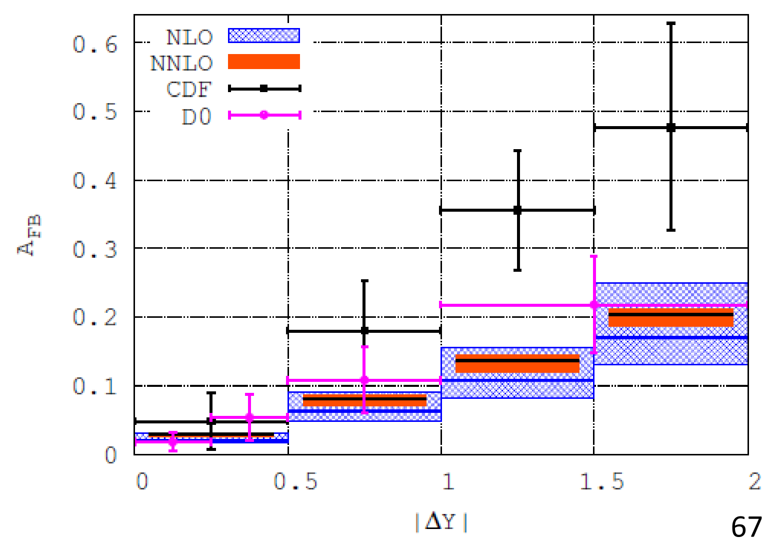
NEW@TOP2014

- LHC data cannot confirm nor exclude an anomaly in charge asymmetry yet
  - ➢ Though no indications of apparent tensions

- News from TOP2014: first (preliminary !) differential distributions at full NNLO were presented (Czakon, Fiedler, Mitov)
  - ➢ AFB@Tevatron about 10% now
  - ➢ Agree with D0 and CDF+D0 naïve combination
  - ➢ “We consider this as agreement between SM and experiments”







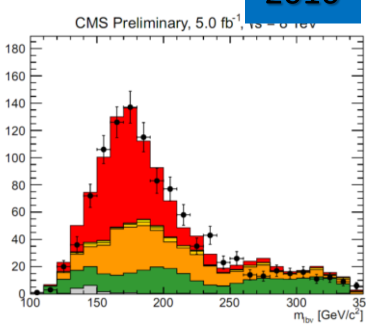
Only scale uncertainties are shown

OUTLOOK

Discussion and outlook (1)

Evidence

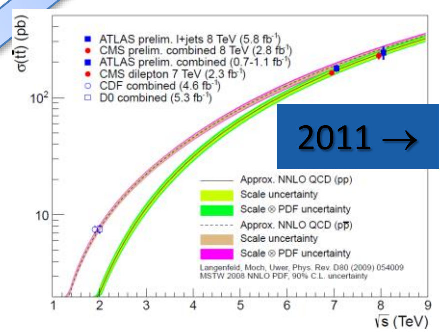
2010

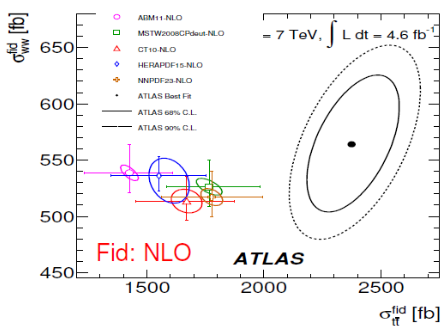


↳ +direct searches

Inclusive quantities

2011 →

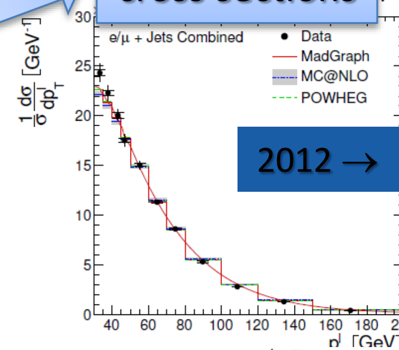


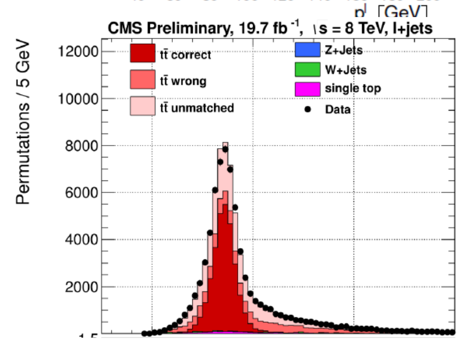


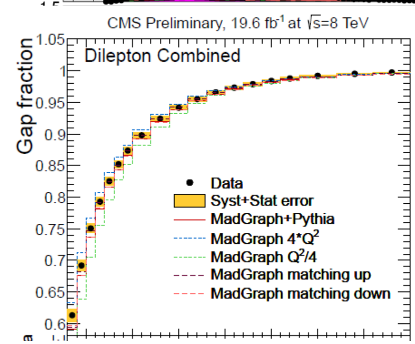
↳ total cross sections
+direct searches

Differential cross sections

2012 →



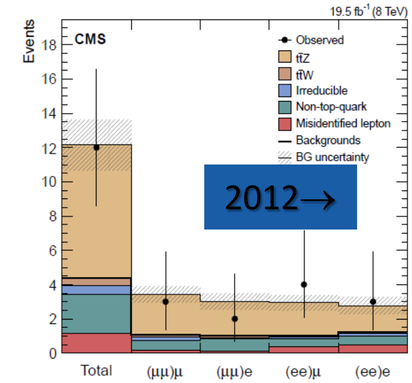


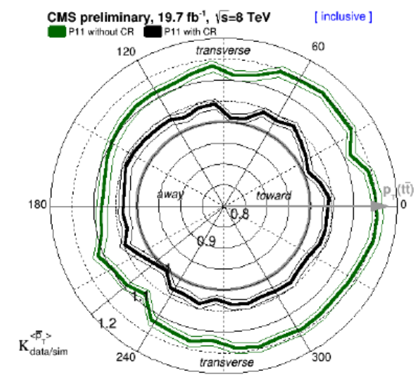


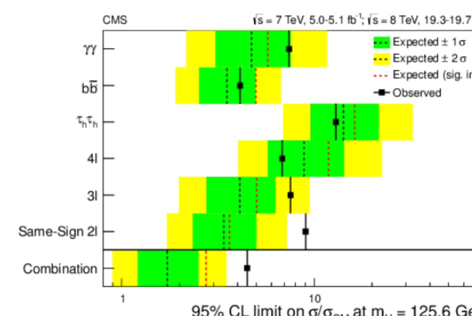
↳ Wtb vertex structure
top properties
constrain systematics, PDFs
+direct/indirect searches

Top-pair "environment"

2012→







↳ top properties
top couplings
constrain systematics
+direct/indirect searches

Discussion and outlook (2)

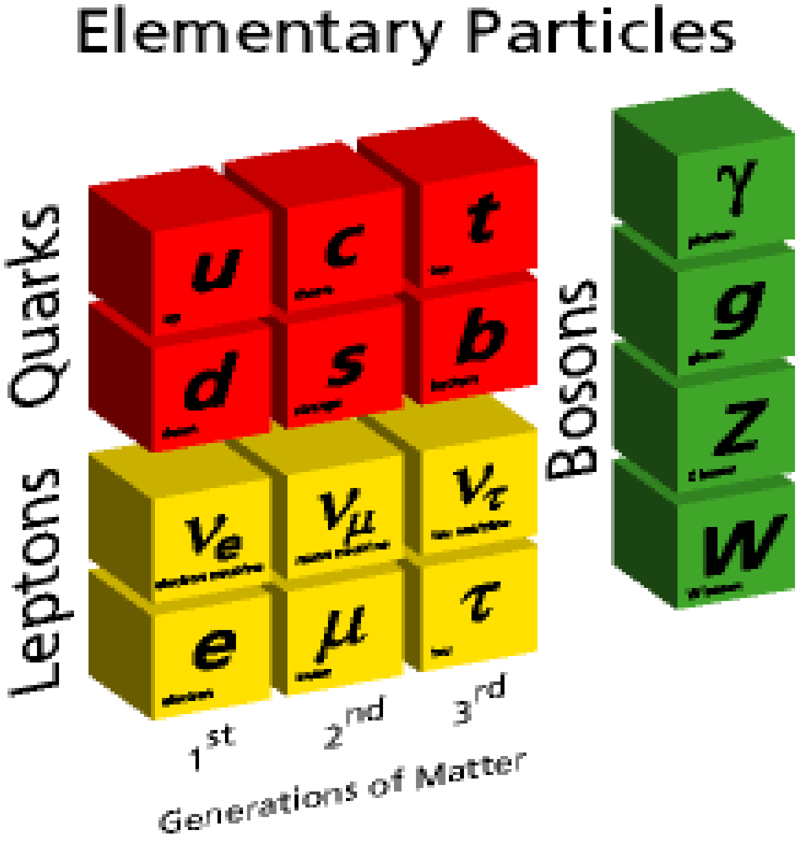
- Top physics is a pillar of the current research program in HEP
  - ➢ Ideal probe for constraining (directly+indirectly) the symmetry breaking of the SM
    - ttH will be one of the mainstream analyses in Run II
  - ➢ Ideal probe for looking for new physics beyond the model itself
    - Via precision measurements or direct searches for new signals
  - ➢ The Tevatron has now handed the baton over to the LHC
    - The top is the “swiss knife” at the LHC: calibration purposes, constraining of systematics

- In the absence of direct evidence of new physics, precision measurements will be more vibrant than ever
  - ➢ Most QCD/EWK measurements in top physics are dominated by systematic errors
    - Still able to challenge theory predictions in many measurements
  - ➢ We will have more and more the possibility to constrain them with data
    - With particular emphasis on systematic sources of theory/modelling origin

- Diversify analyses !
  - ➢ Exploit different (smaller) region of acceptance, much less sensitive to traditional systematic error sources
  - ➢ Use different techniques with independent systematic sources and combine measurements (across the LHC when possible). Always room for new ideas….

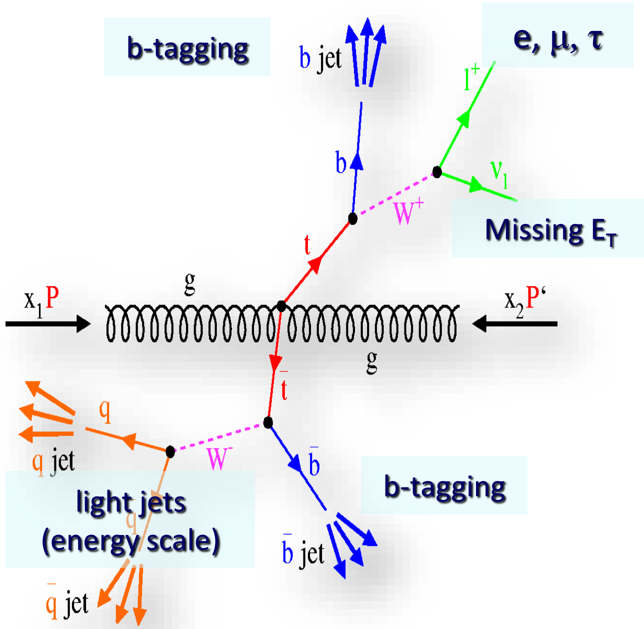
thank you !

BACKUP

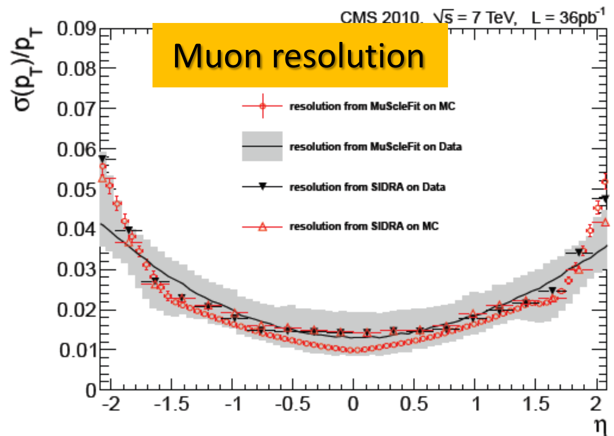


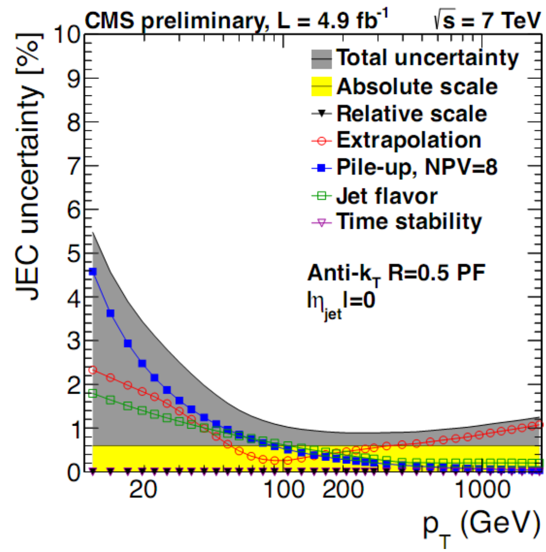
Elementary Particles
Quarks
u
c
t
d
s
b
Leptons
ν_e
ν_μ
ν_τ
e
μ
τ
Bosons
γ
g
Z
W
1st
2nd
3rd
Generations of Matter

Experimentally challenging

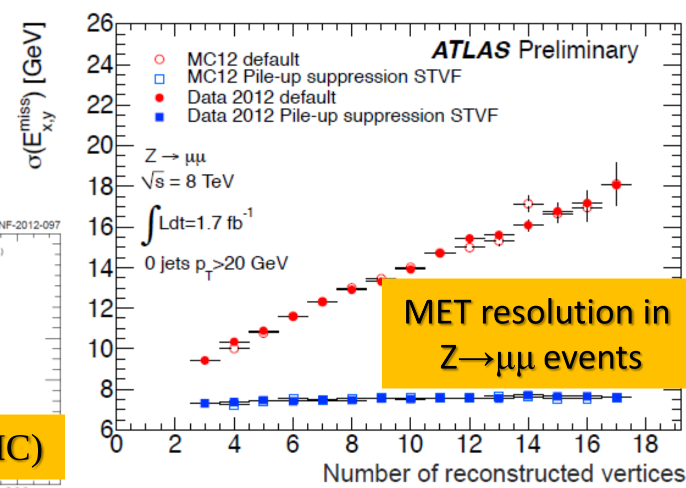


- Top pair studies use all parts of HEP detectors…
  - ➢ Charged lepton reconstruction
  - ➢ Jet reconstruction
  - ➢ Missing transverse energy

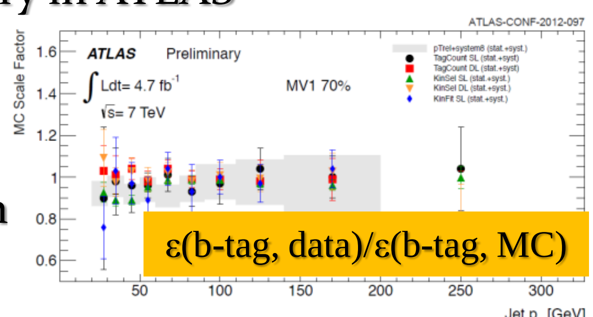




- Optimal use of the detectors…
  - ➢ Particle Flow reconstruction in CMS
    - Combine all sub-detector information to reconstruct and identify particles
  - ➢ Exploit excellent calorimetry in ATLAS



- … and sophisticated analysis tools:
  - ➢ B-tagging, τ reconstruction kinematic fitting

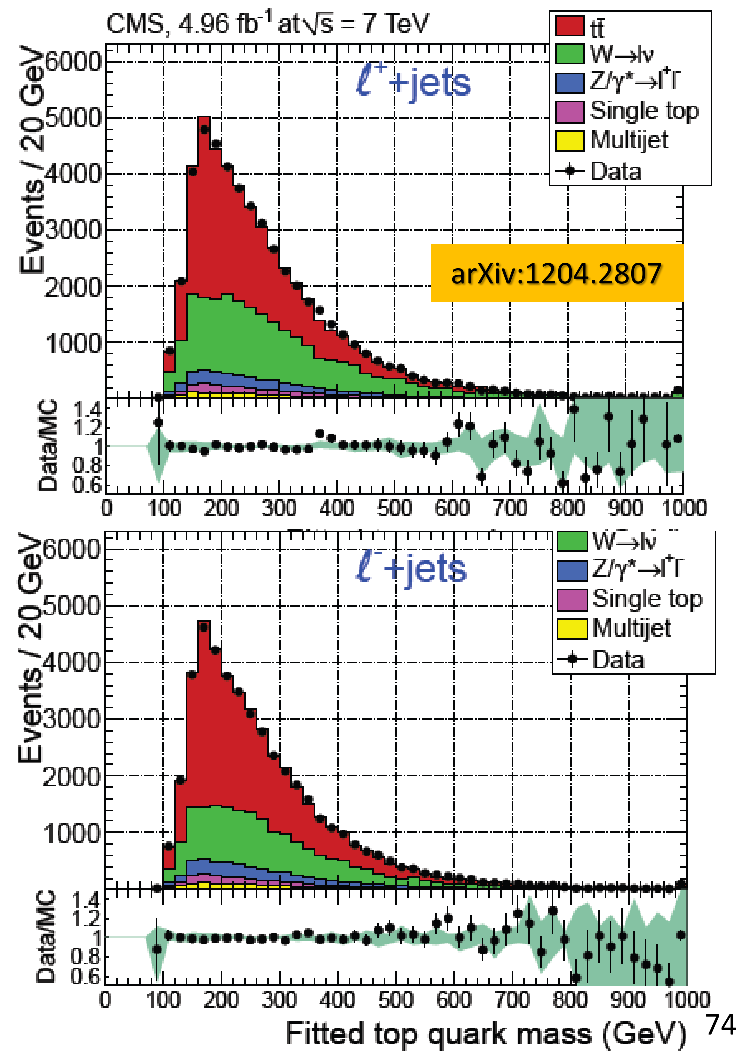


Top-antitop mass difference

- Test CPT invariance in the top sector
  - Reconstruction of the hadronic side: compare ℓ^++jets and ℓ^-+jets events
  - Use kinematic fit, and an event-per-event likelihood for ℓ^- and ℓ^+ separately
    - Same method of the top mass extraction
- Most systematic effects cancel out
  - Measurement is still statistically limited
  - Consistent with the SM, and consistency also between e and μ channel

$$\Delta m_t = -0.44 \pm 0.46 \text{ (stat.)} \pm 0.27 \text{ (syst.) GeV}$$

Source	Estimated effect (GeV)
Jet energy scale	$0.04 \pm \mathbf{0.08}$
Jet energy resolution	$0.04 \pm \mathbf{0.06}$
b vs. $\overline{\mathrm{b}}$ jet response	$\mathbf{0.10} \pm 0.10$
Signal fraction	$\mathbf{0.02} \pm 0.01$
Difference in W^+/W^- production	$\mathbf{0.014} \pm 0.002$
Background composition	$\mathbf{0.09} \pm 0.07$
Pileup	$\mathbf{0.10} \pm 0.05$
b-tagging efficiency	$\mathbf{0.03} \pm 0.02$
b vs. $\overline{\mathrm{b}}$ tagging efficiency	$\mathbf{0.08} \pm 0.03$
Method calibration	$0.11 \pm \mathbf{0.14}$
Parton distribution functions	**0.088**
Total	0.27



MC top mass vs TH top mass (A. Hoang)

→ The MC top mass parameter has the status of a hadronic parameter and is therefore not a field theoretic mass definition

→ The issue is becomes relevant when uncertainties in the MC top mass are becoming smaller than 1 GeV.

→ Ignoring the issue means that there is a conceptual uncertainty of about 1 GeV one needs to account for when relating the MC mass to a field theory mass.

→ Suitable field theory mass definition in this context: e.g. MSR mass (R=1-3 GeV)

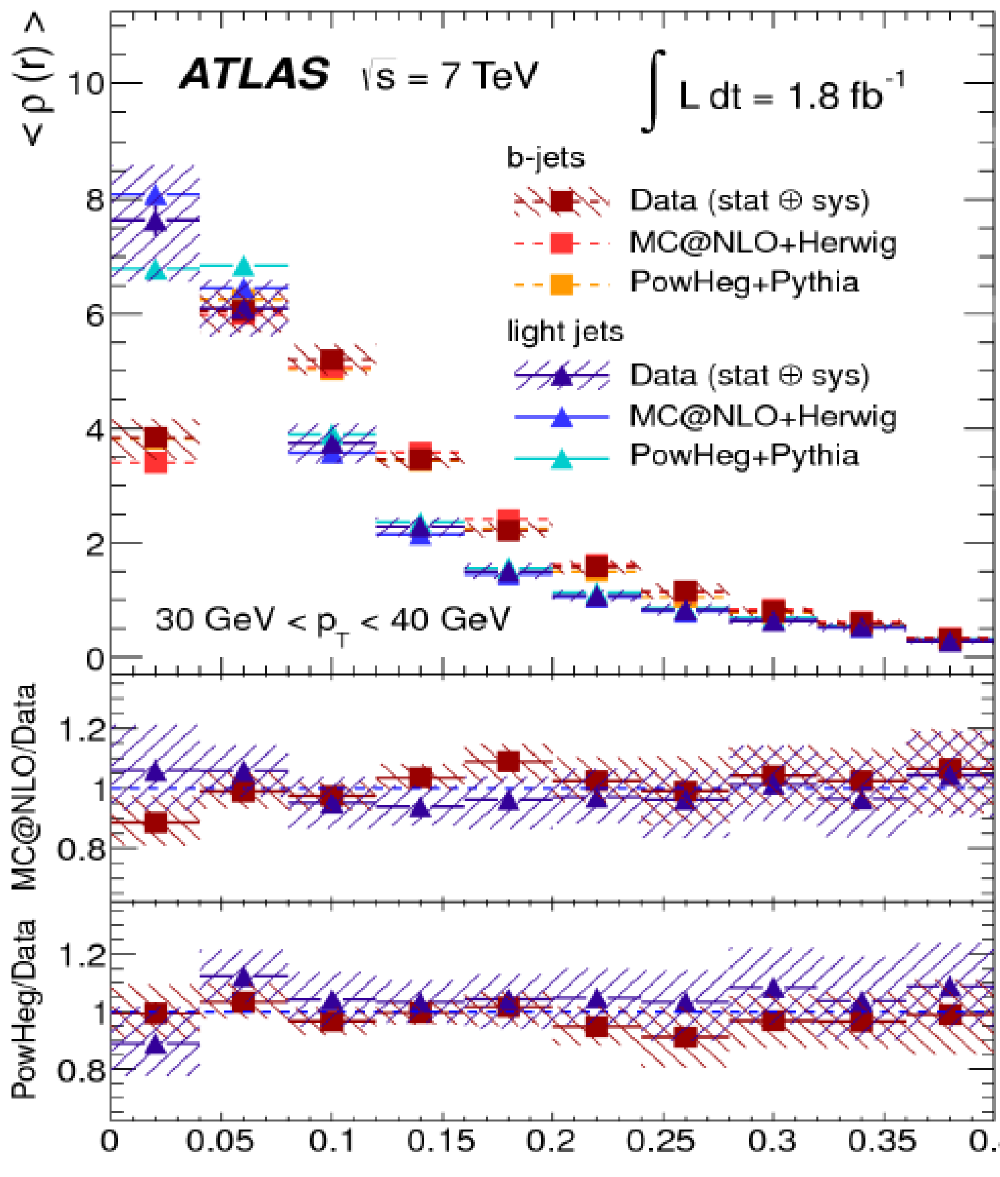
→ It is possible to relate the MS top mass to a field theoretic mass by fits of QCD calculations at the hadron level to MC output for very mass sensitive quantities.

→ When one does that there are still theoretical uncertainties (in the QCD predictions used for the fit) one has to account for.

Jet shape in top pair events

- Use light jets from W and b jets from top in selected top pair events
- Check energy distribution in an annulus around the jet direction
  - ➢ Excellent agreement of both fragmentation models (attached to NLO predictions) and data

Eur. Phys. J. C73 (2013) 2676

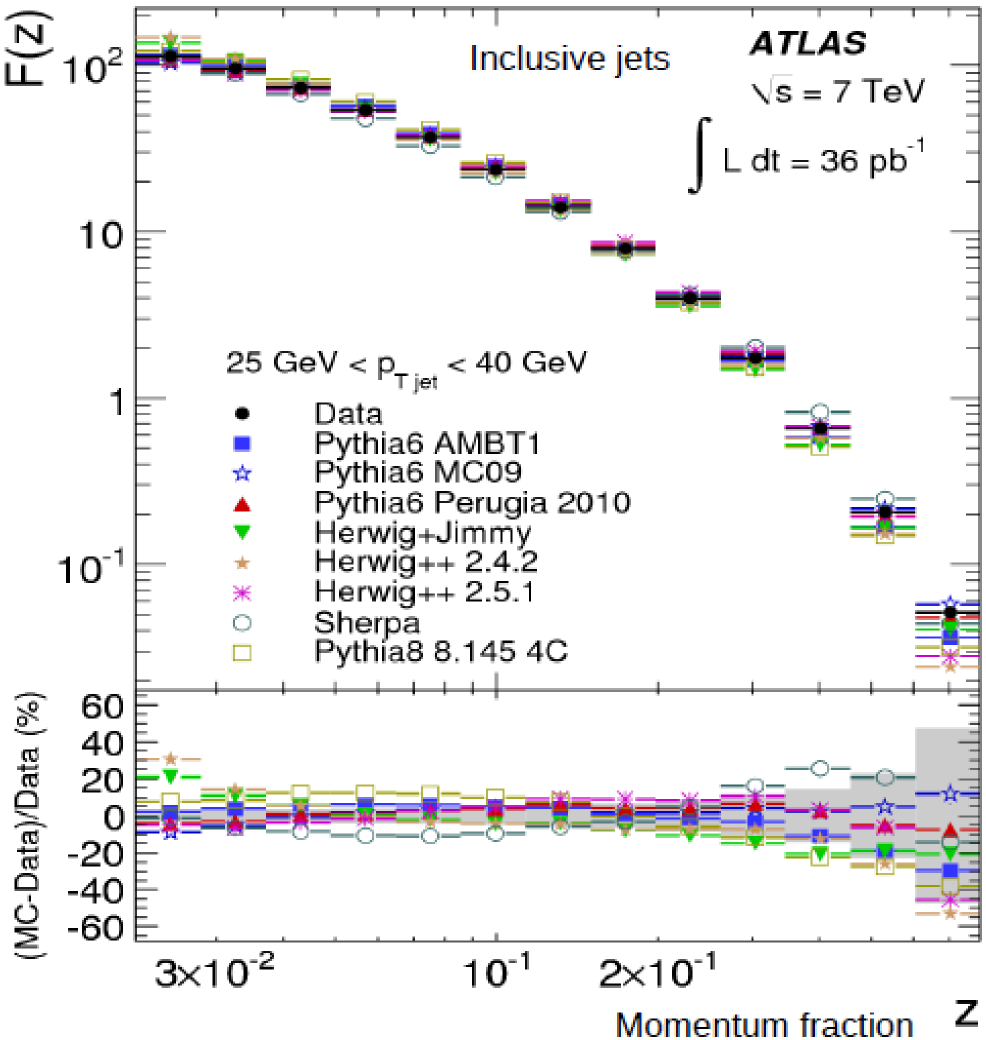


Jet fragmentation

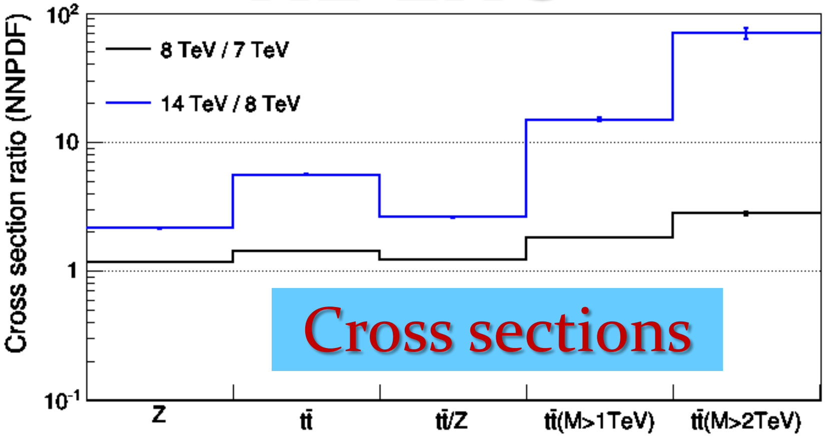
$$z = \frac{p_{jet} \cdot p_{ch}}{|p_{jet}|^2}$$

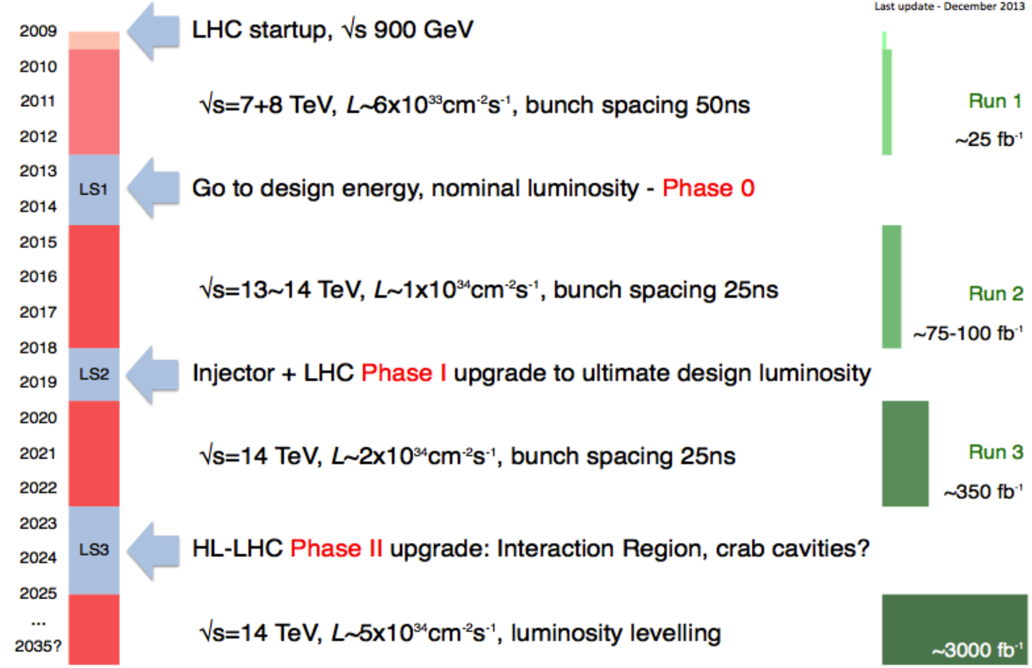
- Use light jets from W and b jets from top in selected top pair events

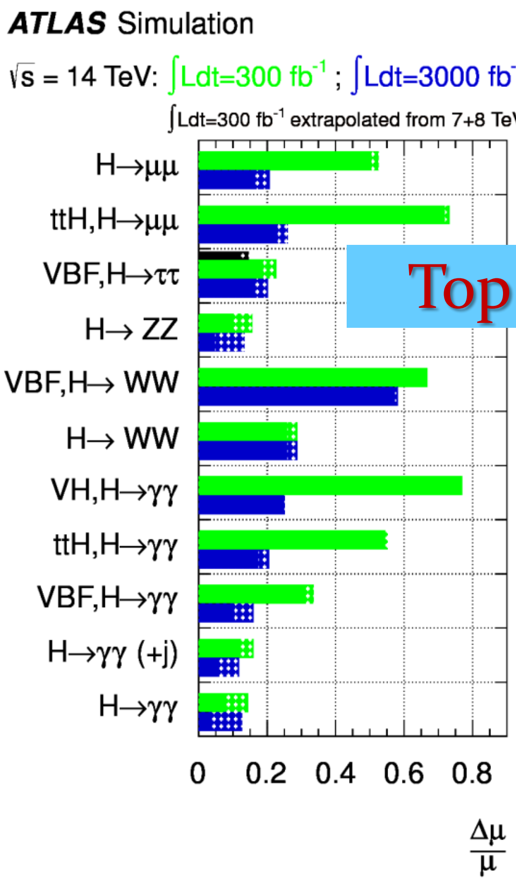
- Check energy distribution in an annulus around the jet direction
  - ➢ Excellent agreement of both fragmentation models (attached to NLO predictions) and data

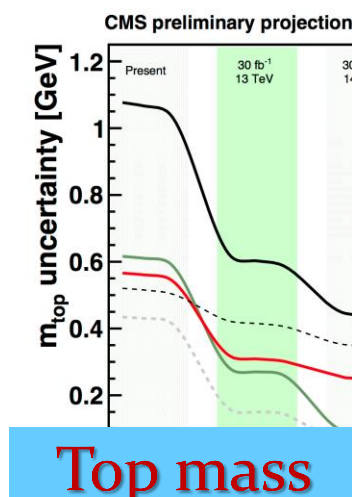


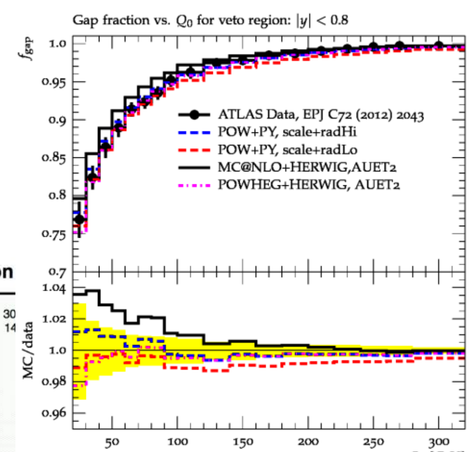
HL-LHC

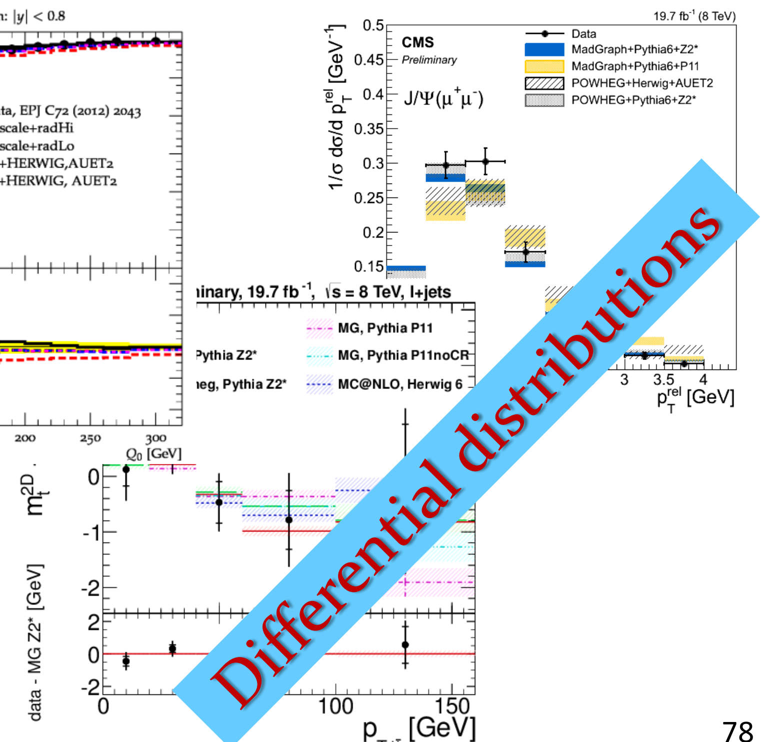

Cross section ratio (NNPDF)
8 TeV / 7 TeV
14 TeV / 8 TeV
Z
tt̄
tt̄/Z
tt̄(M>1TeV)
tt̄(M>2TeV)
Cross sections


Last update - December 2013
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
...
2035?
LHC startup, √s 900 GeV
√s=7+8 TeV, L~6x10³³cm⁻²s⁻¹, bunch spacing 50ns
Run 1
~25 fb⁻¹
LS1
Go to design energy, nominal luminosity - Phase 0
√s=13~14 TeV, L~1x10³⁴cm⁻²s⁻¹, bunch spacing 25ns
Run 2
~75-100 fb⁻¹
LS2
Injector + LHC Phase I upgrade to ultimate design luminosity
√s=14 TeV, L~2x10³⁴cm⁻²s⁻¹, bunch spacing 25ns
Run 3
~350 fb⁻¹
LS3
HL-LHC Phase II upgrade: Interaction Region, crab cavities?
√s=14 TeV, L~5x10³⁴cm⁻²s⁻¹, luminosity levelling
~3000 fb⁻¹


ATLAS Simulation
√s = 14 TeV: ∫Ldt=300 fb⁻¹ ; ∫Ldt=3000 fb⁻¹
∫Ldt=300 fb⁻¹ extrapolated from 7+8 TeV
H→μμ
ttH,H→μμ
VBF,H→ττ
H→ ZZ
VBF,H→ WW
H→ WW
VH,H→γγ
ttH,H→γγ
VBF,H→γγ
H→γγ (+j)
H→γγ
Δμ/μ
Top Yukawa


CMS preliminary projection
Present
30 fb⁻¹
13 TeV
m_top uncertainty [GeV]
Top mass


Gap fraction vs. Q₀ for veto region: |y| < 0.8
f_gap
ATLAS Data, EPJ C72 (2012) 2043
POW+PY, scale+radHi
POW+PY, scale+radLo
MC@NLO+HERWIG,AUET2
POWHEG+HERWIG, AUET2
MC/data
Q₀ [GeV]


19.7 fb⁻¹ (8 TeV)
CMS
Preliminary
J/Ψ(μ⁺μ⁻)
Data
MadGraph+Pythia6+Z2*
MadGraph+Pythia6+P11
POWHEG+Herwig+AUET2
POWHEG+Pythia6+Z2*
p_T^rel [GeV]
MG, Pythia P11
MG, Pythia P11noCR
MC@NLO, Herwig 6
data - MG Z2* [GeV]
p_T,tt̄ [GeV]
Differential distributions

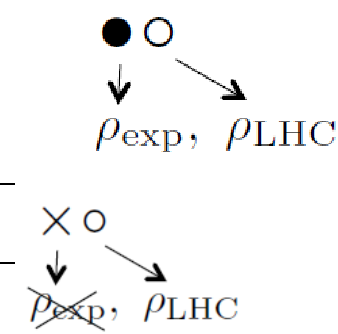
Tt modelling uncertainties for ttH

	ATLAS	CMS
Baseline Model	Powheg+Pythia, normalized to NNLO	Madgraph+Pythia, normalized to NNLO
Reweighting to differential cross section	top p_T and ttbar p_T	top p_T
Model uncertainty	Vary reweighting (9 comps.) Pythia vs Herwig	Vary reweighting Vary scales in MC
Additional heavy flavour modelling uncertainty	On/off reweighting, uncorrelated with ttbar + light jets Vary scales in Madgraph+Pythia Compare Madgraph+Pythia to Powheg+Pythia	Scale variations are uncorrelated between ttbar + light / c / b / bb
Additional heavy flavour normalization uncertainty	$t\bar{t} + b(\bar{b})$: 50% $t\bar{t} + c(\bar{c})$: 50%	$t\bar{t} + b\bar{b}$: 50% $t\bar{t} + b$: 50% $t\bar{t} + c(\bar{c})$: 50%

Grand summary of LHC combinations

Overview (Sept. 2014)	$\sigma(t\bar{t})$ [pb] 7 TeV		8 TeV		$\sigma(t)$ 8 TeV [pb] t − ch		tW	
value	173.3		241.4		85.3		25.0	
statistics ($\star$)	2.8	(0.08)$^{\circ\circ}$	1.4	(0.03)$^{\times\circ}$	4.1	(0.11)$^{\times\circ}$	1.5	(0.10)$^{\times\circ}$
MC model/ theory	4.9	(0.23)$^{\bullet\bullet}$	4.1	(0.23)$^{\times *}$	7.7	(0.40)$^{\times *}$	4.0	(0.72)$^{\times *}$
Detector model (†)	4.6	(0.21)$^{\bullet\circ}$	2.7	(0.10)$^{\times\circ}$	5.5	(0.20)$^{\times *}$	1.2	(0.06)$^{\times *}$
JES/Jets ($\odot$)	2.1	(0.04)$^{\bullet\circ}$	1.7	(0.04)$^{\times *}$	4.5	(0.14)$^{\times\circ}$	1.3	(0.08)$^{\times\circ}$
Background	2.3	(0.05)**	2.3	(0.07)$^{\times *}$	3.2	(0.07)$^{\times *}$	0.6	(0.02)$^{\times\circ}$
Luminosity	6.3	(0.39)$^{\bullet *}$	6.2	(0.53)$^{\times *}$	3.4	(0.08)$^{\times *}$	0.7	(0.02)$^{\times *}$
Total uncertainty	10.1		8.5		12.2		4.7	
Relative unc. [%]	5.8		3.5		14.3		18.8	
Best single meas.	182.9 ± 6.3		242.4 ± 9.5		83.6 ± 7.8		27.2 ± 5.8	
Ref. (ATLAS, CMS)	arXiv 1406.5375		arXiv 1406.5375		JHEP 06 (2014) 090		ATL-CONF 2013-100	

Overview (Sept. 2014)	m_{top} [GeV]		W polarization F_0		F_L		A_C	
value	173.29		0.626		0.359		0.005	
statistics ($\star$)	0.24	(0.06)$^{\circ\circ}$	0.035	(0.35)$^{\circ\circ}$	0.022	(0.38)$^{\circ\circ}$	0.007	(0.61)$^{\times\circ}$
MC model/ theory	0.59	(0.38)$^{\bullet\bullet}$	0.034	(0.33)$^{\bullet *}$	0.019	(0.30)$^{\bullet *}$	0.002	(0.07)$^{\times *}$
Detector model (†)	0.32	(0.12)$^{\bullet\circ}$	0.020	(0.11)$^{\bullet\circ}$	0.011	(0.11)$^{\bullet\circ}$	0.004	(0.21)$^{\times\circ}$
JES/Jets ($\odot$)	0.61	(0.42)$^{\bullet *}$	0.020	(0.11)$^{\bullet\circ}$	0.012	(0.12)$^{\bullet\circ}$		
Background	0.09	(0.01)**	0.019	(0.10)$^{\bullet\circ}$	0.010	(0.09)$^{\bullet\circ}$	0.003	(0.11)$^{\times *}$
Luminosity								
Total uncertainty	0.95		0.059		0.035		0.009	
Relative unc. [%]	0.5		9.5		9.7		181	
Best single meas.	172.22 ± 0.73		0.659 ± 0.027		0.350 ± 0.026		0.006 ± 0.011	
Ref. (ATLAS, CMS)	CMS-PAS-TOP 14-001		CMS-PAS-TOP 13-008		CMS-PAS-TOP 13-008		JHEP 1402 (2014) 107	



i.e.: one input / experiment

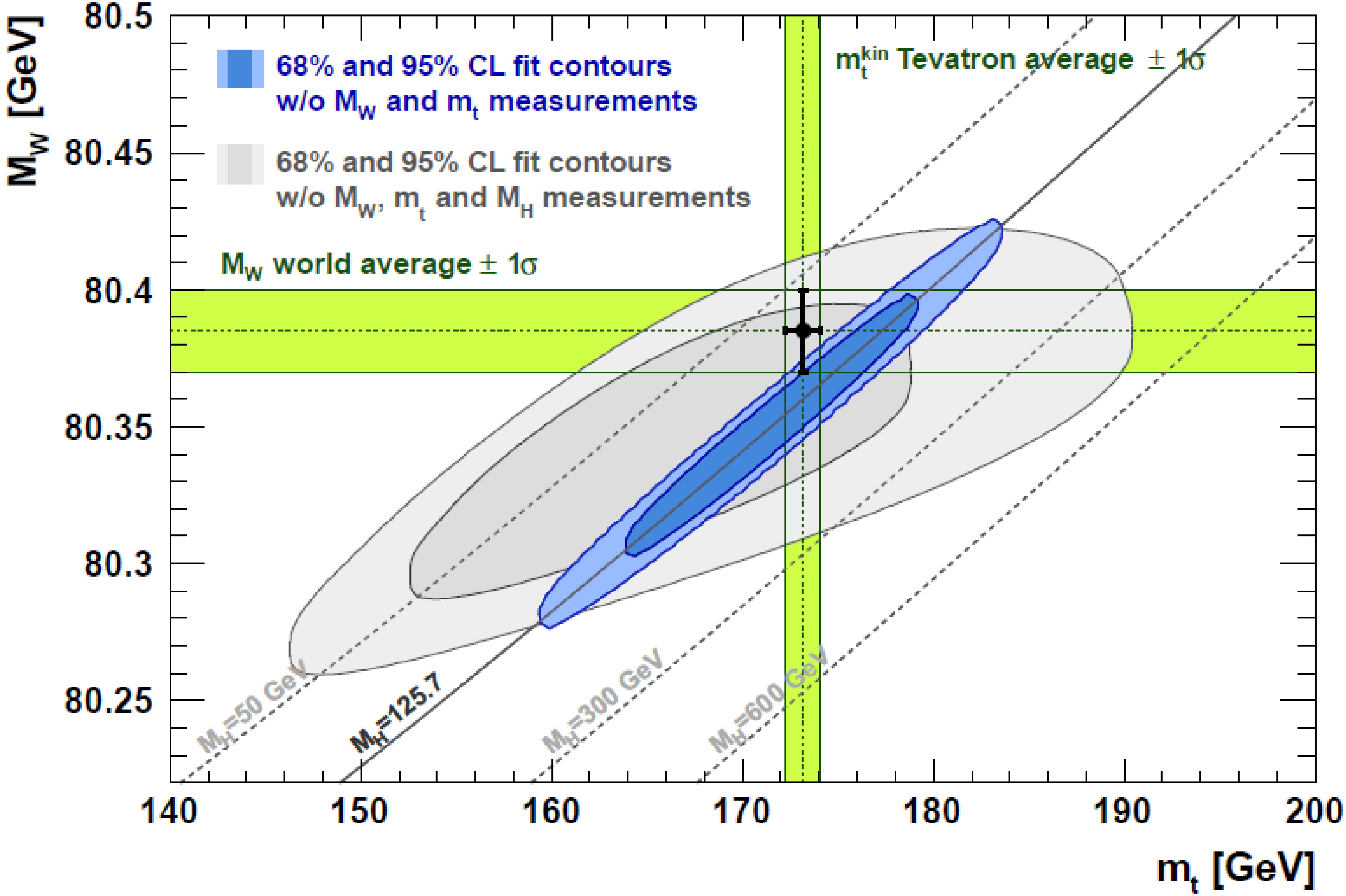
Single best meas. better than combined result. Combination needs to be updated!

$\circ$, $*$, $\bullet$

stand for uncorrelated, partially correlated and fully correlated uncertainty.

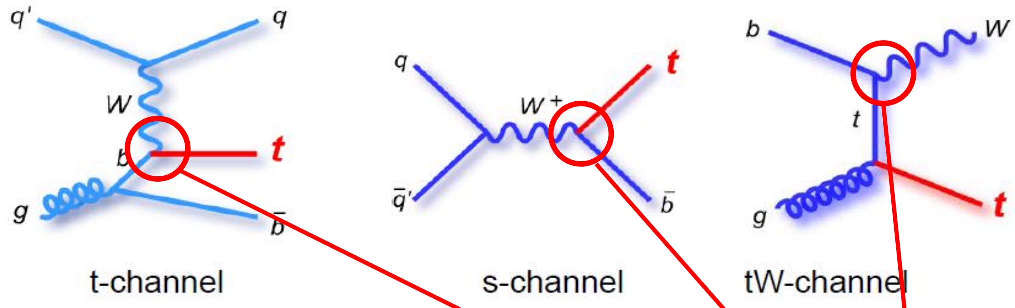
Constraining the SM with the top mass

- Remember: the top mass, the W mass and the Higgs mass depend on each other



Single top: why is that important?

- The production cross section gives direct access to the CKM matrix element $|V|_{tb}$
  - ➢ May also test the presence of a possible 4th generation quark
  - ➢ Check for presence of FCNC
  - ➢ Important background for Higgs searches in associated production $W/ZH \rightarrow qqbb$



	LHC [pb] √s=7 TeV	LHC [pb] √s=8 TeV
s-channel	5	6
t-channel	65	87
tW	16	22

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Investigate t-channel and tW production
  - ➢ s-channel still out of range for an observation
  - ➢ t-channel: 1 isolated e or μ, one b-tagged jet, one forward jet, missing E_T
  - ➢ tW channel: 2 isolated charged leptons (e, μ), one b-tagged jet, missing E_T

- Main backgrounds from top-pair production, W+jets, QCD
  - ➢ Use data whenever possible to constrain the backgrounds

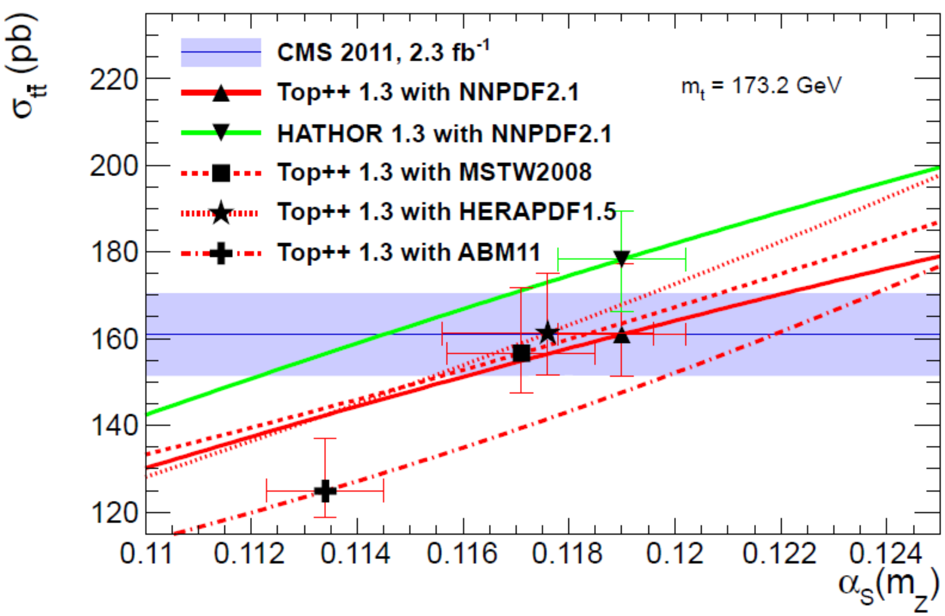
Correlations in cross section combinations

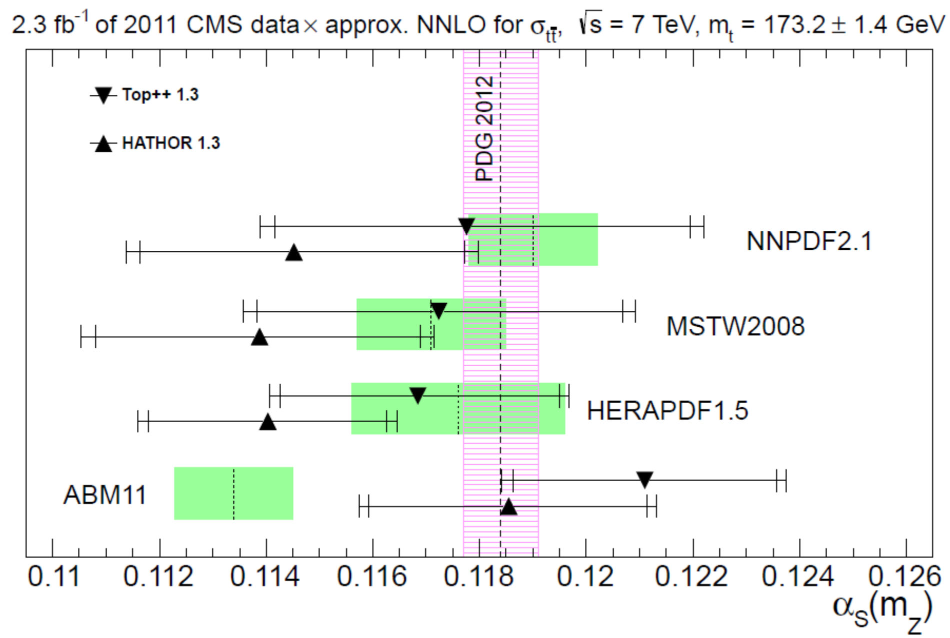
Category	ATLAS		CMS		ρ
Statistics	Stat. data	2.4%	Stat. data	7.1%	0
	Stat. sim.	2.9%	Stat. sim.	2.2%	0
Total		**3.8%**		**7.5%**	**0**
Luminosity	Calibration	3.0%	Calibration	4.1%	1
	Long-term stability	2.0%	Long-term stability	1.6%	0
Total		**3.6%**		**4.4%**	**0.78**
Simulation and modelling	ISR/FSR	9.1%	Q^2 scale	3.1%	1
	PDF	2.8%	PDF	4.6%	1
	t-ch. generator	7.1%	t-ch. generator	5.5%	1
	$t\bar{t}$ generator	3.3%			0
	Parton shower/had.	0.8%			0
Total		**12.3%**		**7.8%**	**0.83**
Jets	JES	7.7%	JES	6.8%	0
	Jet res. & reco.	3.0%	Jet res.	0.7%	0
Total		**8.3%**		**6.8%**	**0**
Backgrounds	Norm. to theory	1.6%	Norm. to theory	2.1%	1
	Multijet (data-driven)	3.1%	Multijet (data-driven)	0.9%	0
			W+jets, $t\bar{t}$ (data-driven)	4.5%	0
Total		**3.5%**		**5.0%**	**0.19**
Detector modelling	b-tagging	8.5%	b-tagging	4.6%	0.5
	E_T^{miss}	2.3%	Unclustered E_T^{miss}	1.0%	0
	Jet Vertex fraction	1.6%			0
			pile up	0.5%	0
	lepton eff.	4.1%			0
			μ trigger + reco.	5.1%	0
	lepton res.	2.2%			0
	lepton scale	2.1%			0
Total		**10.3%**		**6.9%**	**0.27**
Total uncert.		**19.2%**		**16.0%**	**0.38**

	ATLAS	CMS	Correlation	LHC combina
Cross section [pb]	242.4	239.0		241.5
Uncertainty [pb]				
Statistical	1.7	2.6	0	1.4
Detector model				
Trigger	0.4	3.6	0	1.0
Lepton scale and resolution	1.2	0.2	0	0.9
Lepton identification	1.7	4.0	0	1.6
Jet resolution	1.2	3.0	0	1.2
Jet identification	0.1	–	–	0.1
b-tagging	1.0	1.7	0	0.8
Pileup	–	2.0	–	0.5
Non-JES subtotal	2.6	6.7	0	2.6
UncorrJES	0.6	4.3	0	1.2
InsituJES	0.6	0.6	0	0.5
IntercalibJES	0.3	0.1	0.5	0.2
FlavourJES	0.9	2.9	1	1.4
bJES	0.1	–	–	0.1
JES subtotal	1.3	5.2	0.4	1.9
Class subtotal	2.9	8.5		3.2
Signal model				
Scale	0.7	5.6	0.5	1.9
Radiation	–	3.8	–	1.0
Generator and parton shower	3.0	3.3	0.5	2.7
PDF	2.7	0.5	1	2.1
Class subtotal	4.1	7.5	0.3	4.0
Background from data				
Z+jets	<0.1	1.5	0	0.4
Lepton misidentification	0.8	1.9	0	0.8
Class subtotal	0.8	2.4	0	0.9
Background from simulation				
Dibosons	0.3	0.5	1	0.4
Single top quark	2.0	2.3	1	2.1
Class subtotal	2.0	2.4	1	2.1
Luminosity				
Beam modelling	2.9	5.0	1	3.5
Luminosity determination	6.9	3.6	0	5.1
Class subtotal	7.5	6.2	0.3	6.2
Total systematic	9.3	13.4		8.4
Total	9.4	13.6		8.5

α_S from the top-pair cross-section

- Measurement based on a joint likelihood approach
  - Fix the top mass to the world average
  - Vary α_S in parton distribution functions
    - Exploit $\sigma_{tt}(m_t, \alpha_S)$ as in approximate NNLO (HATHOR)





- First determination by using top pair events
  - Precision is comparable with the one obtained at hadron colliders