Physics prospects for Top (experiments)

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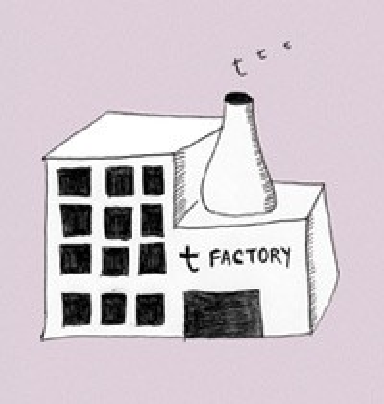
Why top physics at LHC

LHC is a top factory

Tevatron: $\sigma_{t\bar{t}}$~7 pb (~10^4 events)
LHC@8TeV: $\sigma_{t\bar{t}}$~240 pb (~5×10^6 events)



Top physics at LHC moved to precision measurements

- Precision tests of QCD with NNLO predictions available
- Exploring low-populated regions of the phase space
- Precision measurements can be used for PDF fits
- Modeling of SM $t\bar{t}$ background for BSM physics searches

Italian top groups activities

Present contributions:

- $t\bar{t}$ differential cross section measurements (**BO, CS**)
- $t\bar{t}$ charge asymmetry (**UD**)
- Fake leptons and W+jets background estimates (**UD**)
- Boosted top reconstruction (**BO**)

Plans for the future:

- $t\bar{t}$ differential cross section measurements (incl. boosted) (**BO, CS**)
- Fake leptons and W+jets background estimate (**UD**)
- $t\bar{t}H$ (**BO, Roma1, UD**)
- Study of multi-top final states (**UD**)

LHC schedule

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 ...

LS1 LS2 LS3

HL-LHC

$0.7\times10^{34}\ cm^{-2}s^{-1}$	$1.5\times10^{34}\ cm^{-2}s^{-1}$	$2\times10^{34}\ cm^{-2}s^{-1}$	$5\times10^{34}\ cm^{-2}s^{-1}$
pile-up ~30	pile-up ~40	pile-up ~60	pile-up ~140
25 fb^{-1}	~100 fb^{-1}	~300 fb^{-1}	~3000 fb^{-1}

Many measurements in top physics already limited by systematics

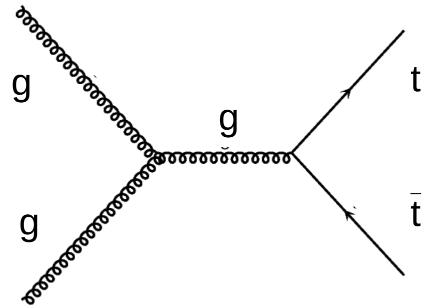
Studies that will profit from the increased energy and luminosity:

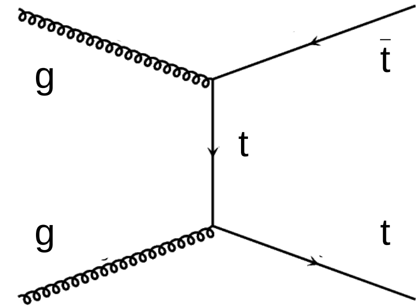
- All searches (FCNC decays, $t\bar{t}$ resonances, top partners, ...)
- Top quark mass
- Differential cross section
- Charge asymmetry
- $t\bar{t}V$, $t\bar{t}H$
- Measurements using boosted tops

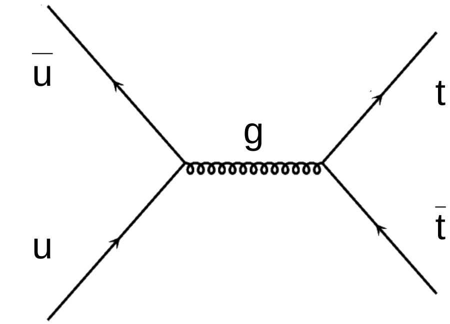
Top quark production

Top pair

σ_{tt} = 240 pb (8 TeV)

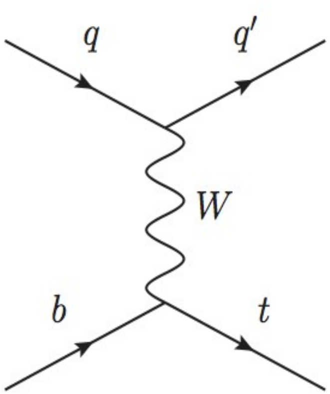




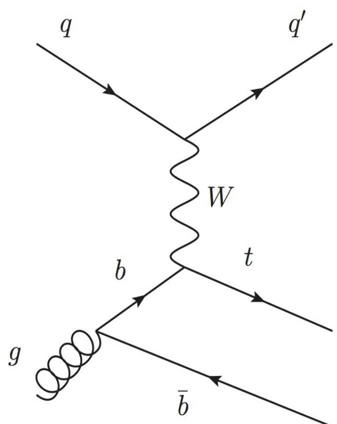


	Tevatron 2 TeV	LHC 8 TeV	LHC 14 TeV
gg	10%	85%	90%
qq	90%	15%	10%

Single top

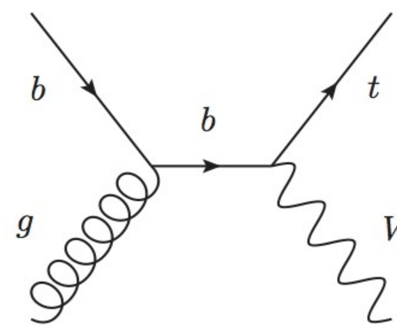


t-channel



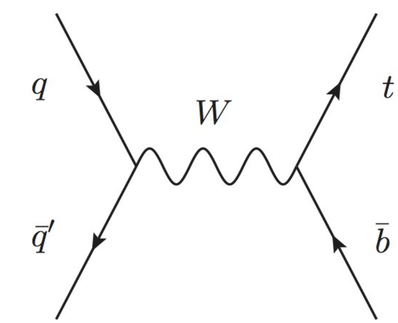
t-channel

σ_t = 88 pb (8 TeV)



Wt production

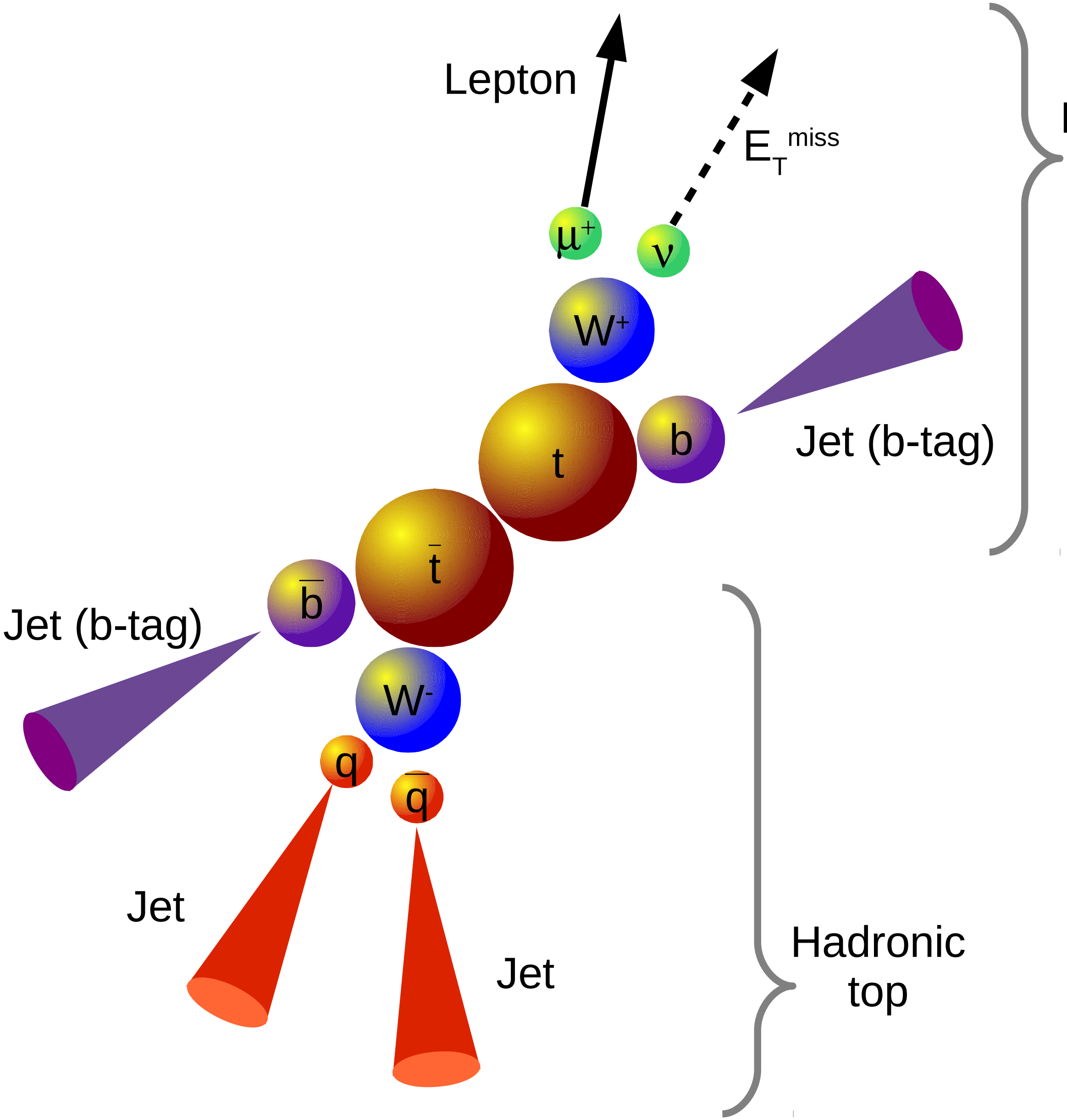
σ_t = 22 pb (8 TeV)

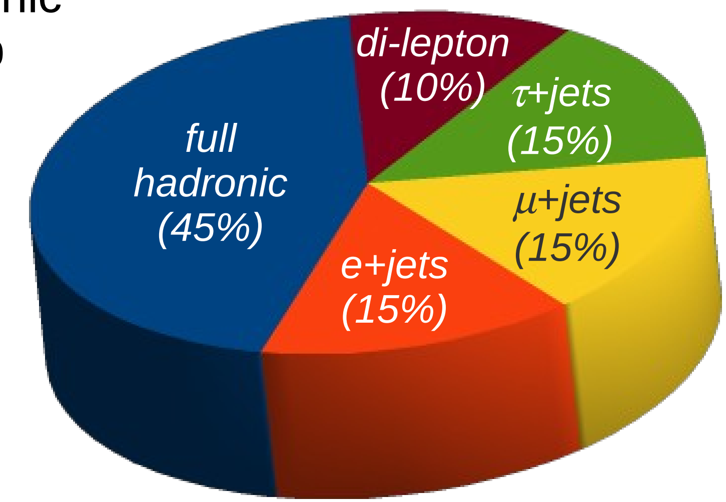


s-channel

σ_t = 5.6 pb (8 TeV)

Top quark signatures





Branching fractions for $t\bar{t}$ events

Main background sources:

Full hadronic: QCD
Single lepton: W+jets, fake leptons, single top
Dilepton: Z,γ^*+jets, fake leptons

Top quark mass

Top quark pair production cross section

Top quark pair production charge asymmetry

$t\bar{t}$ resonances search

Boosted tops

$t\bar{t}H$

Top FCNC

Top quark mass: ATLAS

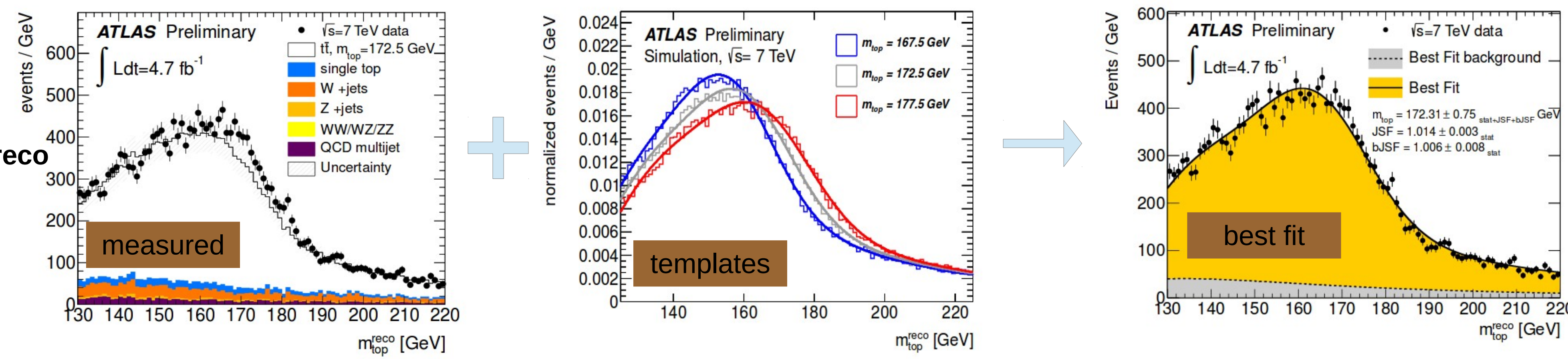
Strategy: fit a distribution using theoretical predictions where m_t enters as a free parameter.
Ingredients: NLO predictions needed to push the accuracy below the GeV level
Kinematical distributions with a strong dependence on m_t

Template method: build a series of templates using different m_t values and setting different values for the JES to extract a likelihood function that is used to fit data

ATLAS single-lepton: three dimensional template fit

- m_t^{reco} : top quark mass, extracted from likelihood fit
- m_W^{reco} : invariant mass of the chosen jet permutation
- R_{lb}^{reco} : ratio of the scalar sum of p_T of b-tagged jets and the scalar sum of the p_T of the two light jets from W decay

m_t^{reco}



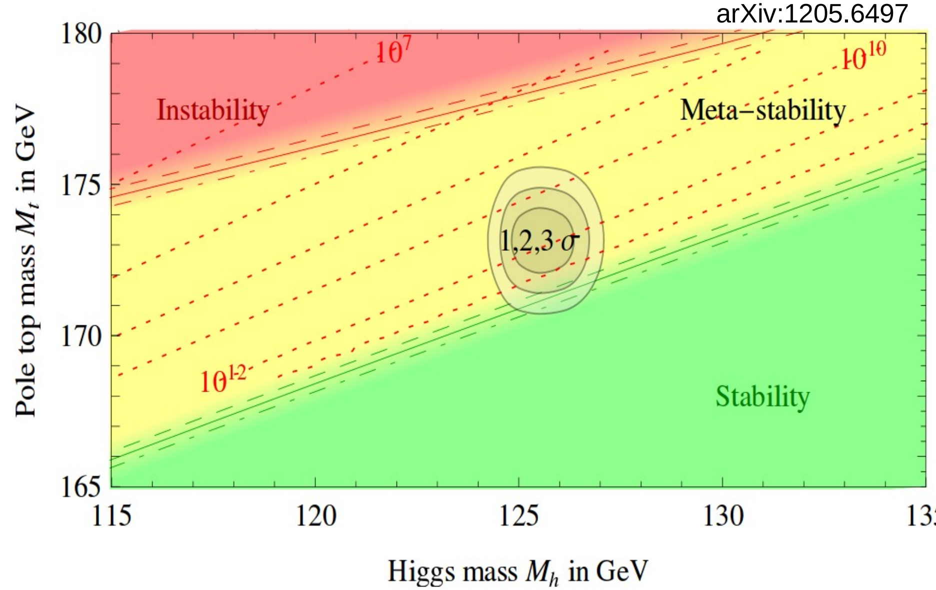
ATLAS-CONF-2013-046

m_t = 172.31 ± 0.75 (stat+JES) ± 1.35 (syst) GeV
Systematics dominated (mainly JES and b-tagging efficiency/mistag rate)

Top quark mass: LHC

Precision measurement of the top mass needed for precision EW fits and to address the question of vacuum stability in the SM

arXiv:1205.6497

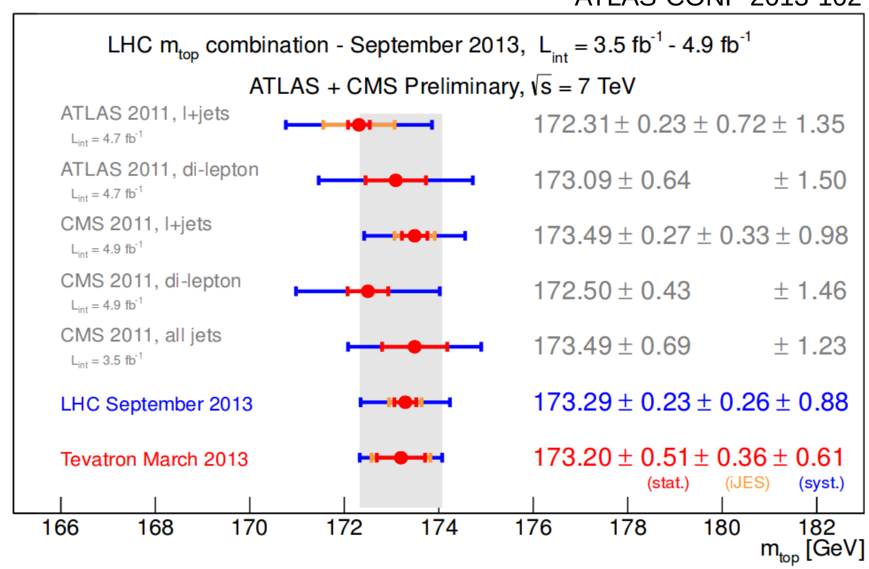


LHC combination of top quark mass measurements:
173.29 ± 0.23 (stat) ± 0.92 (syst) GeV

Current measurements are already systematics dominated

Improvements in m_t measurement may be achieved applying alternative techniques with large statistics

ATLAS-CONF-2013-102



	7 TeV	14 TeV (projections)		
Luminosity (fb^{-1})	5	100	300	3000
Template method Tot. uncertainty (GeV)	1.0	0.7	0.6	0.6
CMS end-point method Tot. uncertainty (GeV)	2.0	1.0	0.7	0.5

Example: extrapolation on m_t uncertainty using the template or the CMS end-point methods (Snowmass 2013 top quark WG, arXiv:1311.2028)

Top quark mass

Top quark pair production cross section

Top quark pair production charge asymmetry

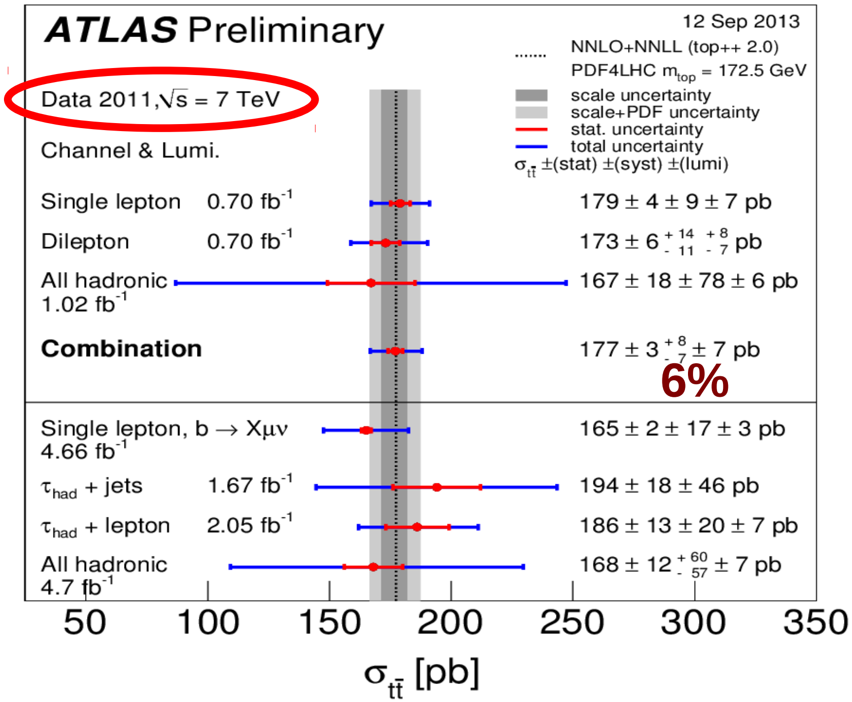
$t\bar{t}$ resonances search

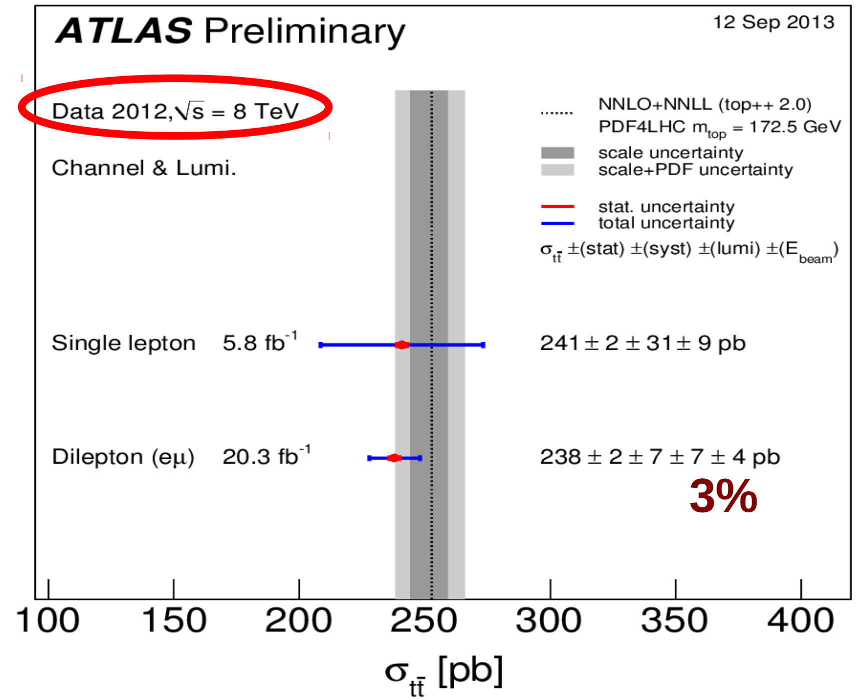
Boosted tops

$t\bar{t}H$

Top FCNC

Cross section: tt

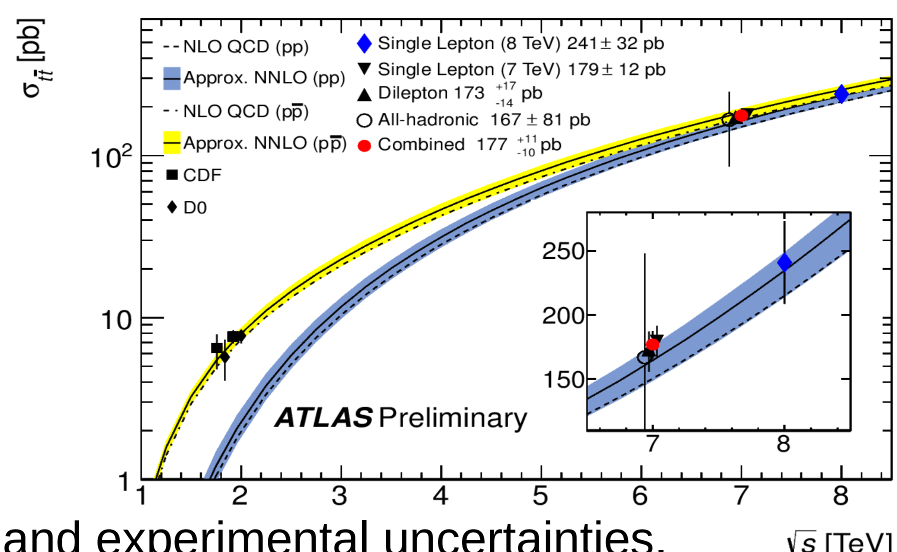




Latest NNLO+NNLL theoretical predictions
(Czakon, Fiedler, Mitov 2013)

arXiv:1303.6254

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$



Excellent agreement. Comparable theoretical and experimental uncertainties.

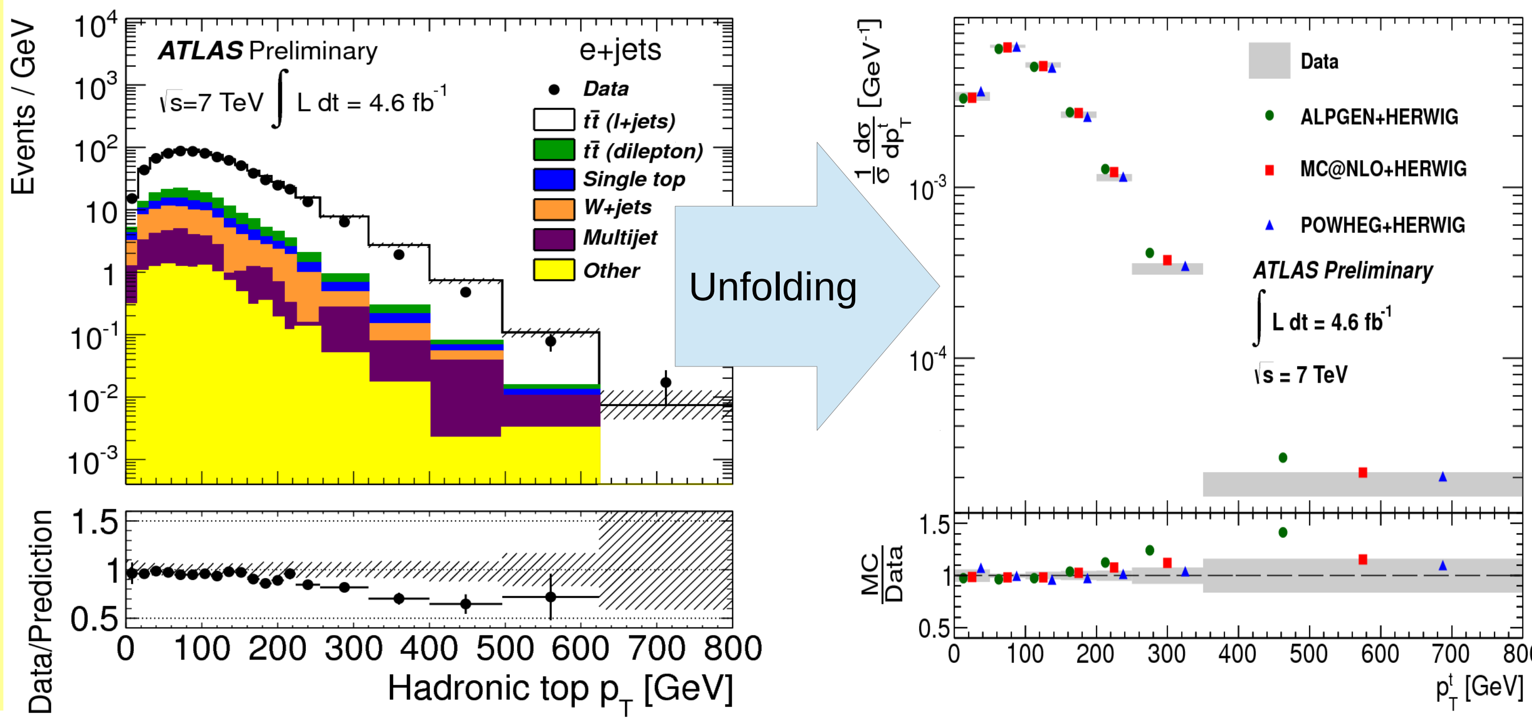
Differential cross section

Large $t\bar{t}$ samples available at the LHC allow the measurement of differential cross sections:
- test/tune $t\bar{t}$ production models in different phase space regions
- look for discrepancies wrt SM predictions
- measurements to include in PDF fits
- background for BSM searches

Analysis strategy (2011 data)

- Event selection (l+jets)
- $t\bar{t}$ kinematic fit
- Background subtraction
- Unfolding (correct for resolution and acceptance)
- Comparison with theoretical predictions

ATLAS-CONF-2013-099



Normalized diff. cross sections

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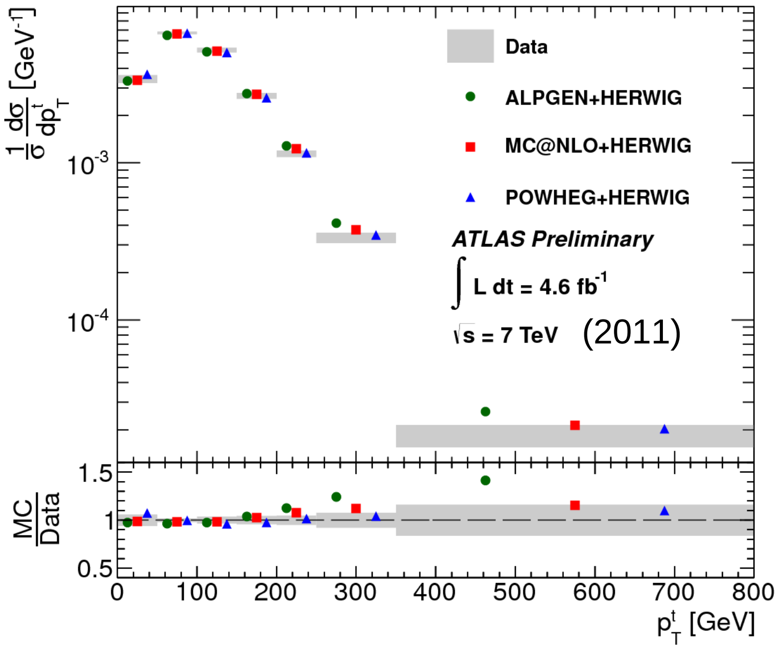
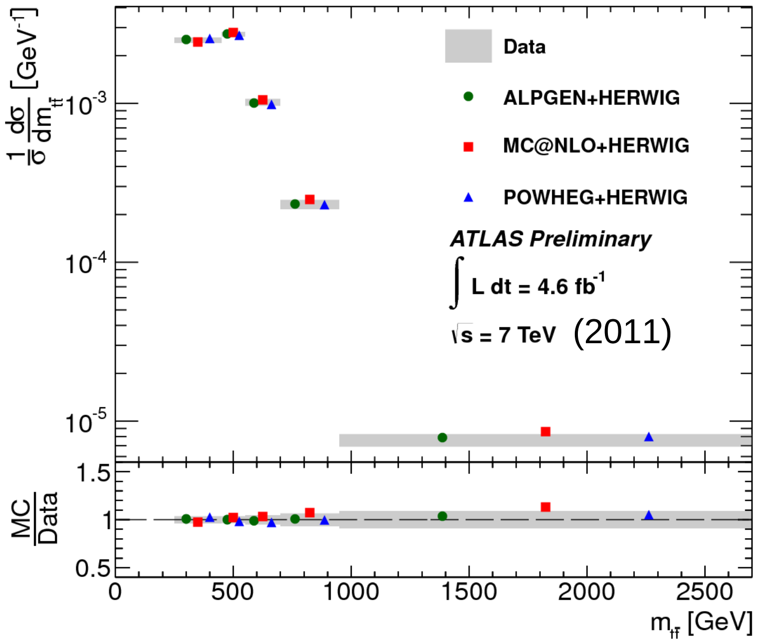
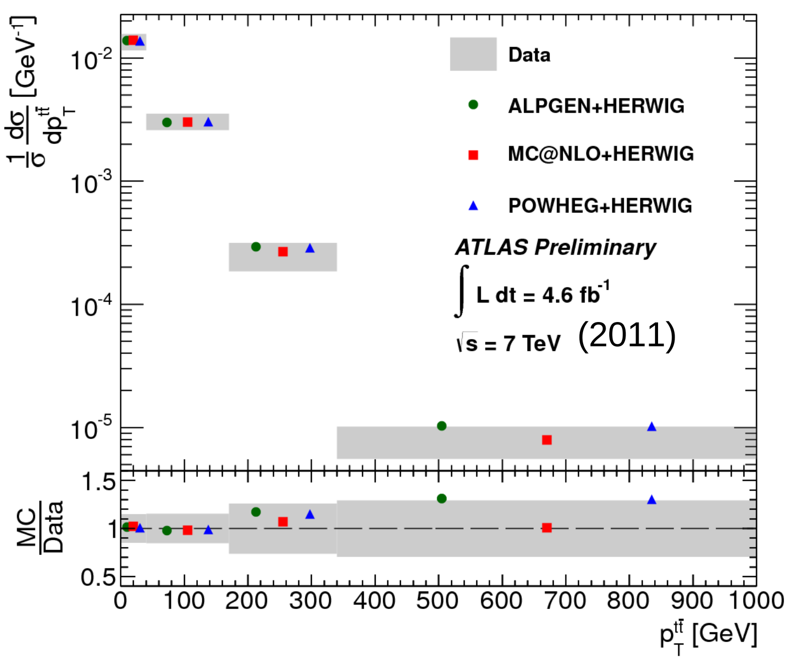
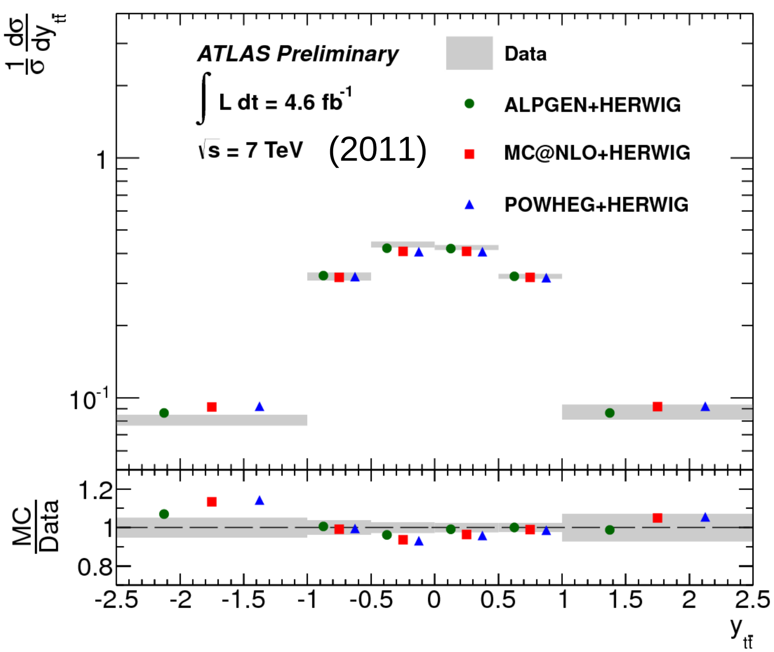
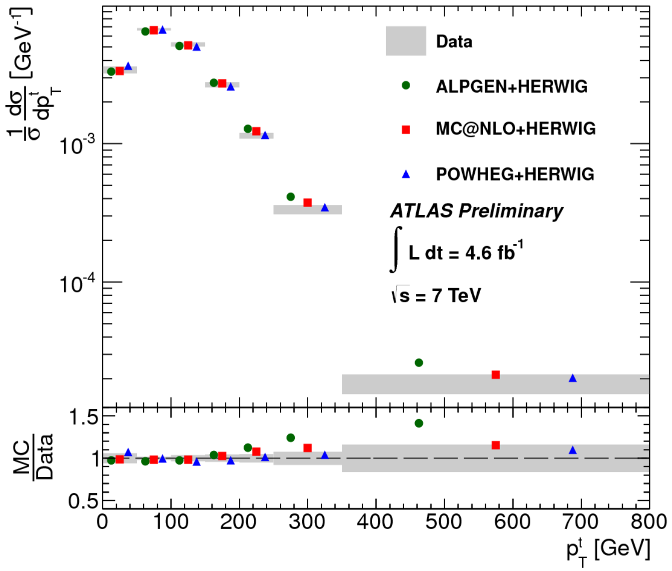


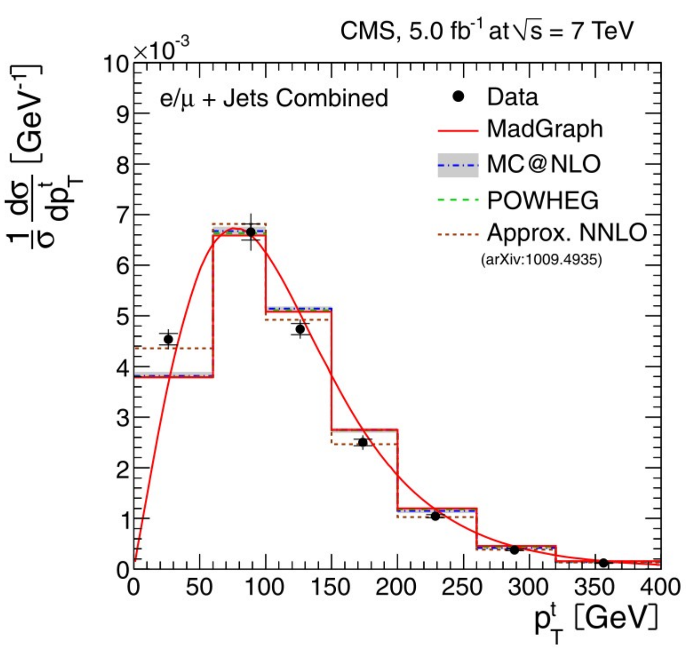






Comparison with CMS





ATLAS and CMS results generally consistent with SM predictions, but...

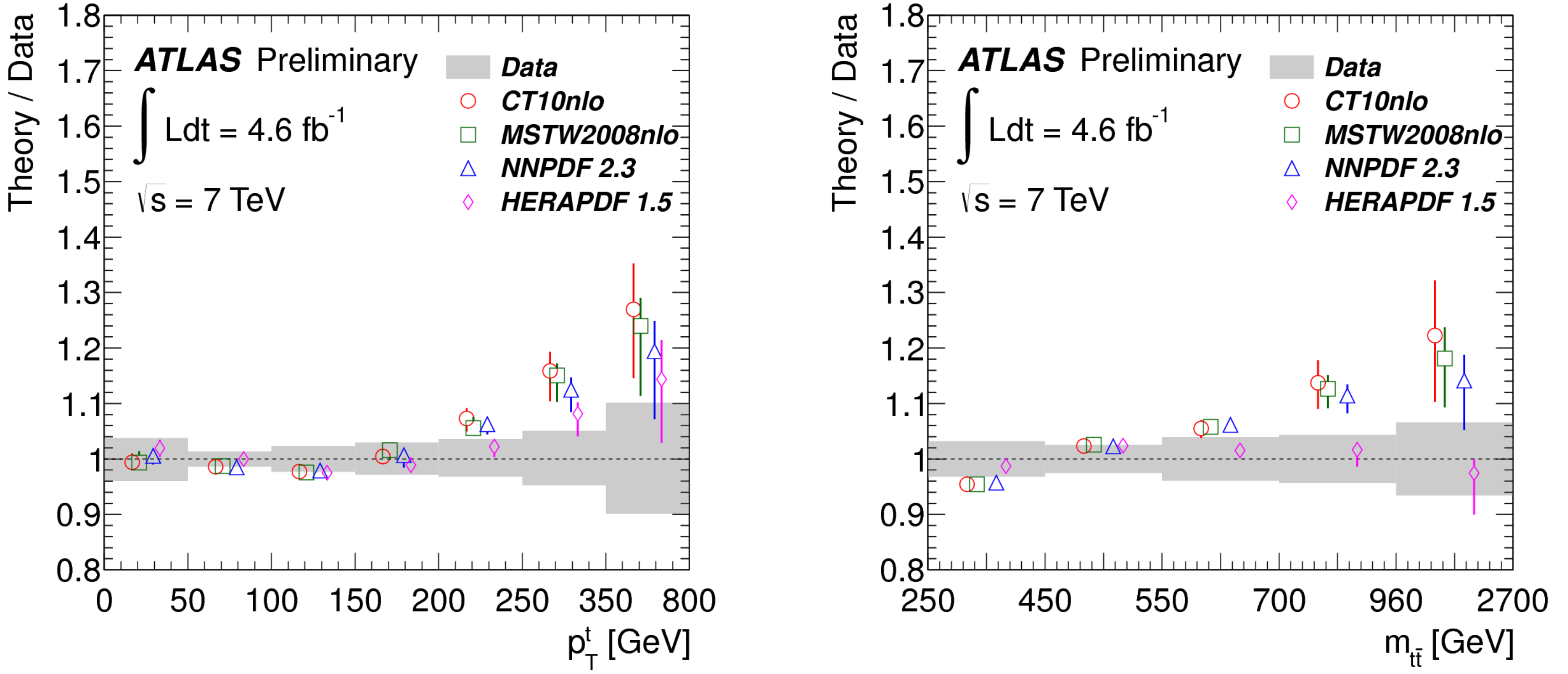
- Some tension between ATLAS and CMS in the lowest p_T^t bin
- MC tend to overestimate the measured cross section at large p_T^t for both ATLAS and CMS

POWHEG+HERWIG provides the best description of the p_T^t distribution over the full range

PDFs

All the ingredients are available to use top quark pair cross section measurements to test the PDFs

- Large statistics
- Differential measurements
- NLO predictions (MCFM)



Theoretical predictions tend to show an excess on data at large p_T

Theory/data in better agreement using HERAPDF 1.5

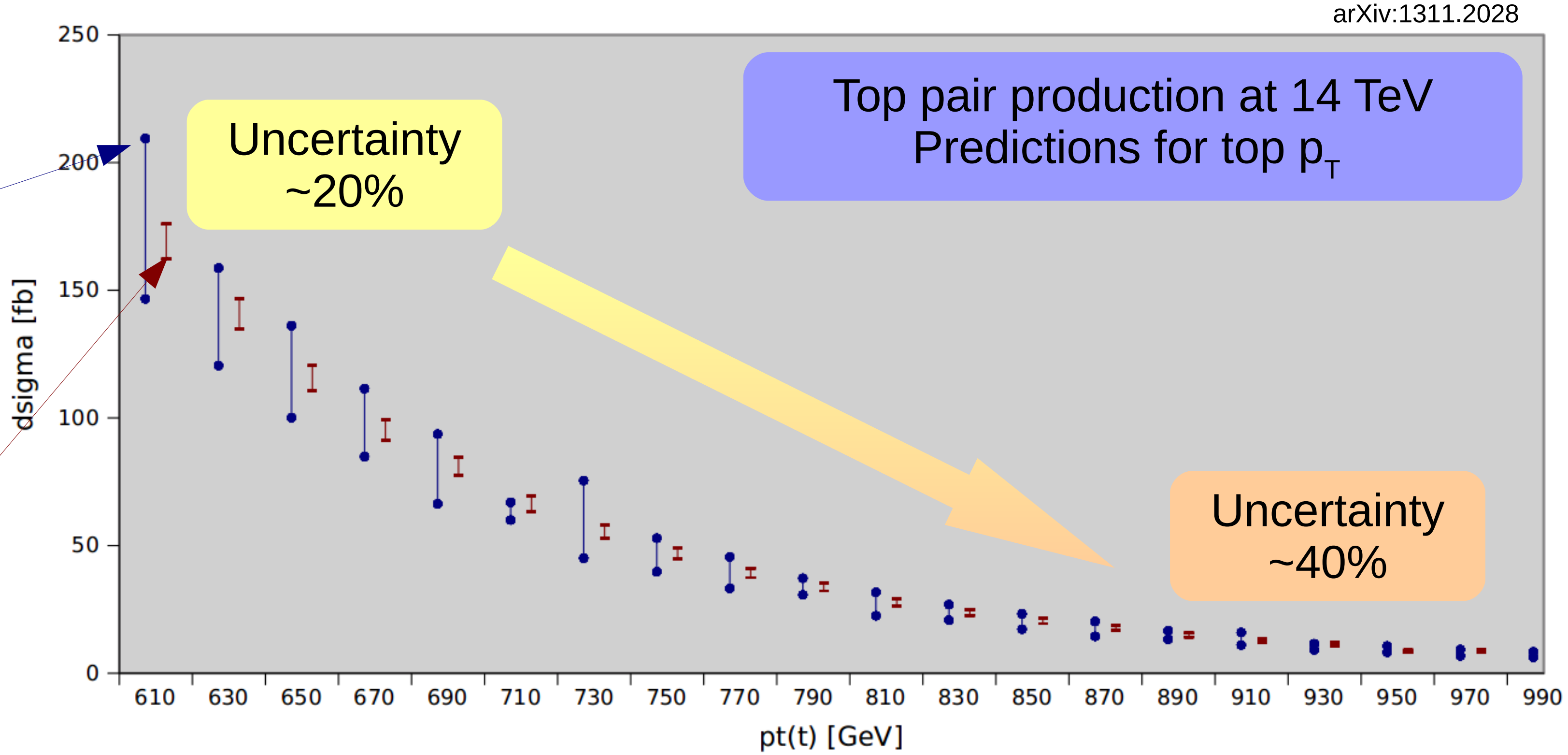
Cross section: prospects

- Experimental and theoretical uncertainties with similar accuracy needed to test theoretical predictions
- More statistics will help in the tails of the distributions

NLO prediction based on MCFM

Variation of renormalization and factorization scales by a factor 2 around $\mu=m_t$

Uncertainty on PDFs (MSTW)



- Uncertainty increasing at large p_T
- Scale uncertainty dominating the predictions

NNLO differential predictions needed

Top quark mass

Top quark pair production cross section

Top quark pair production charge asymmetry

$t\bar{t}$ resonances search

Boosted tops

$t\bar{t}H$

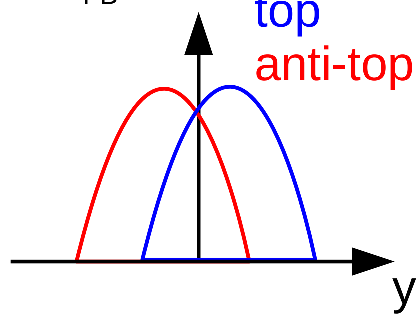
Top FCNC

$t\bar{t}$ production charge asymmetry

Forward-backward asymmetry (A_{FB}) observed at the Tevatron

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

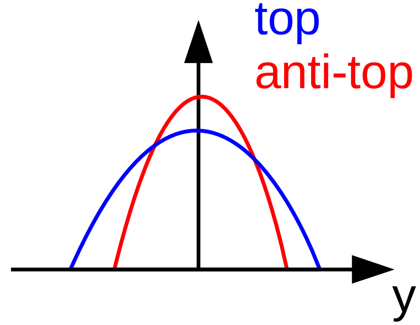
$$\Delta y = y_t - y_{\bar{t}}$$



Measurement of a charge asymmetry (A_C) at the LHC

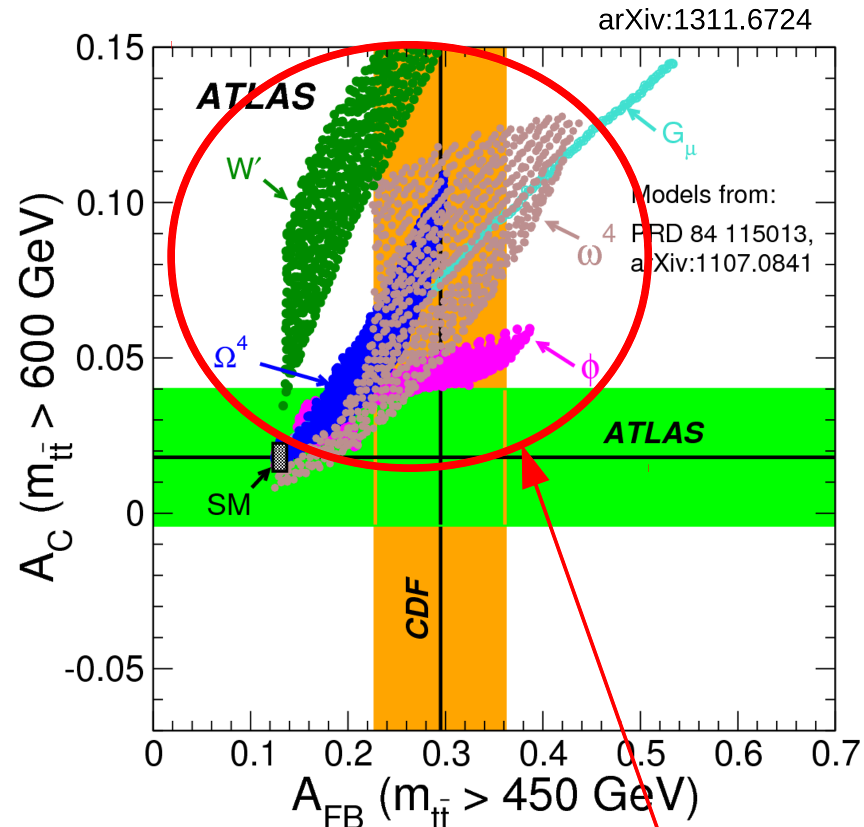
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



Measured: $A_C = 0.006 \pm 0.010$
Uncertainty (stat+syst) obtained after unfolding

Observations consistent with the SM predictions:
$A_C = 0.0123 \pm 0.0005$



Plot restricted to high $m_{t\bar{t}}$

Predictions incorporating contributions from different models of new physics

Top quark mass

Top quark pair production cross section

Top quark pair production charge asymmetry

$t\bar{t}$ resonances search

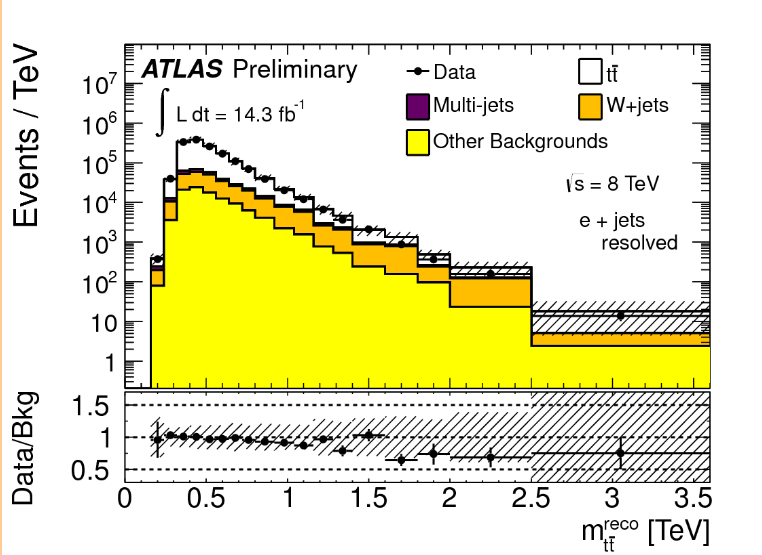
Boosted tops

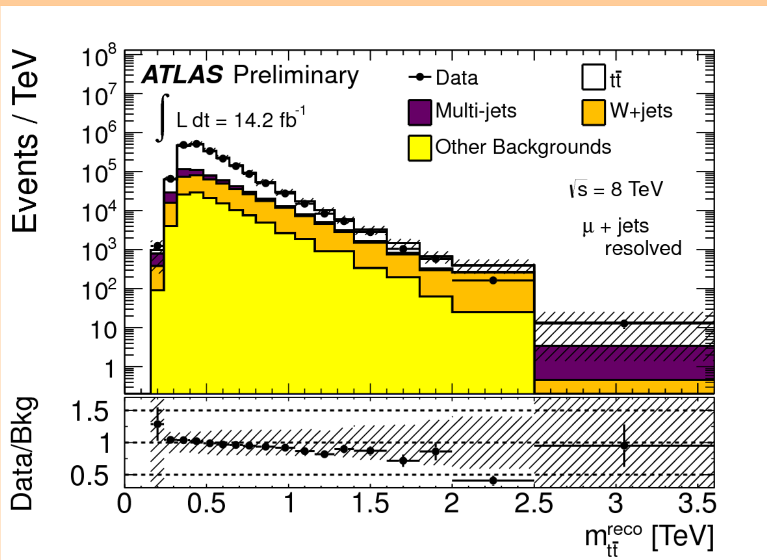
$t\bar{t}H$

Top FCNC

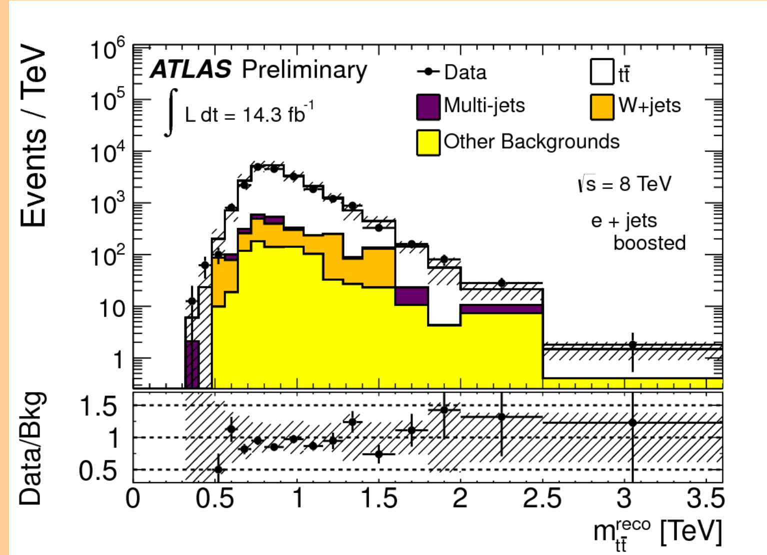
$t\bar{t}$ resonance search

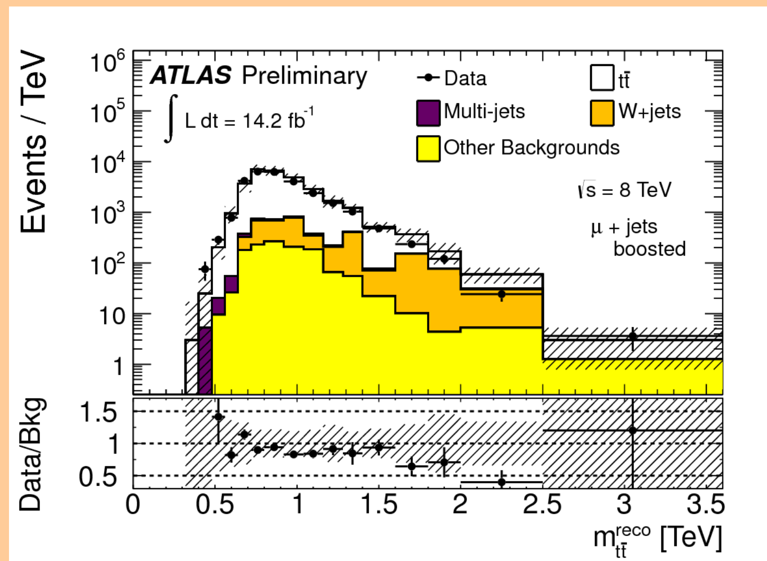
Resolved selection (~10^5 events)





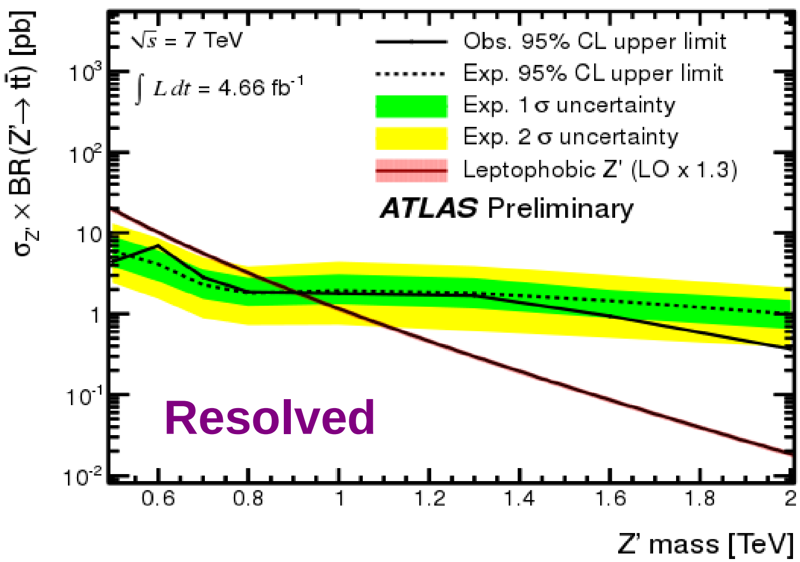
Boosted selection (~10^3 events)

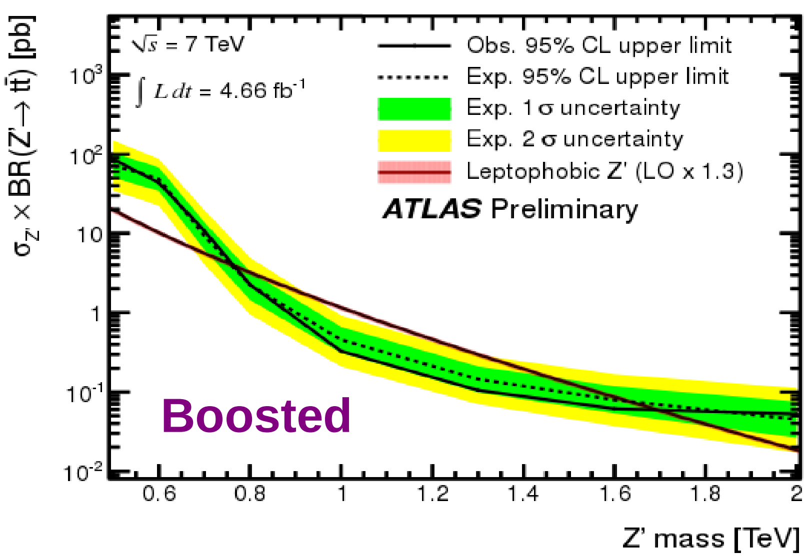




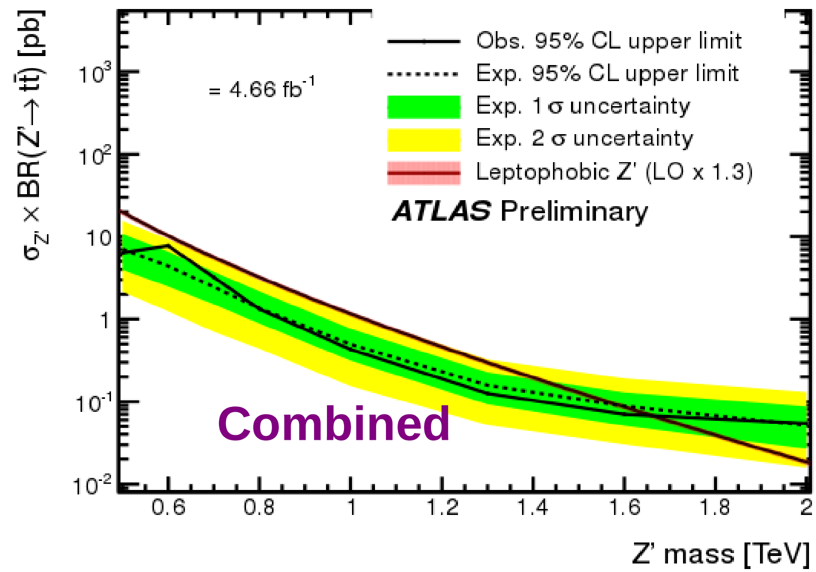
ATLAS-CONF-2013-052

Setting limits on $t\bar{t}$ resonances





Boosted selection plays a fundamental role!



arXiv:1307.7292

l+jets channel	14 TeV (ATLAS projections)	
Luminosity (fb^{-1})	300	3000
pile-up	50	140
Z' - 95% CL exclusion (TeV)	3.3	5.5
KK gluon -95% CL exclusion (TeV)	4.3	6.7

Top quark mass

Top quark pair production cross section

Top quark pair production charge asymmetry

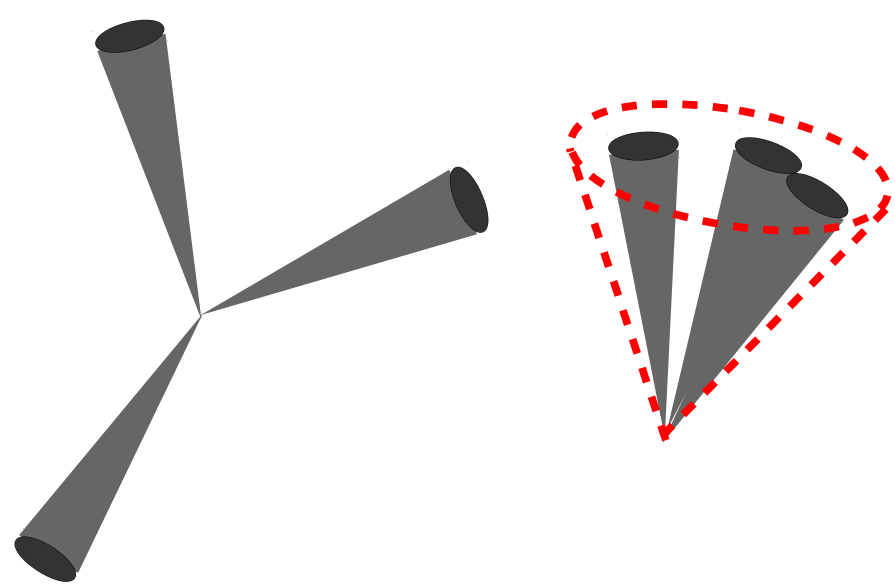
$t\bar{t}$ resonances search

Boosted tops

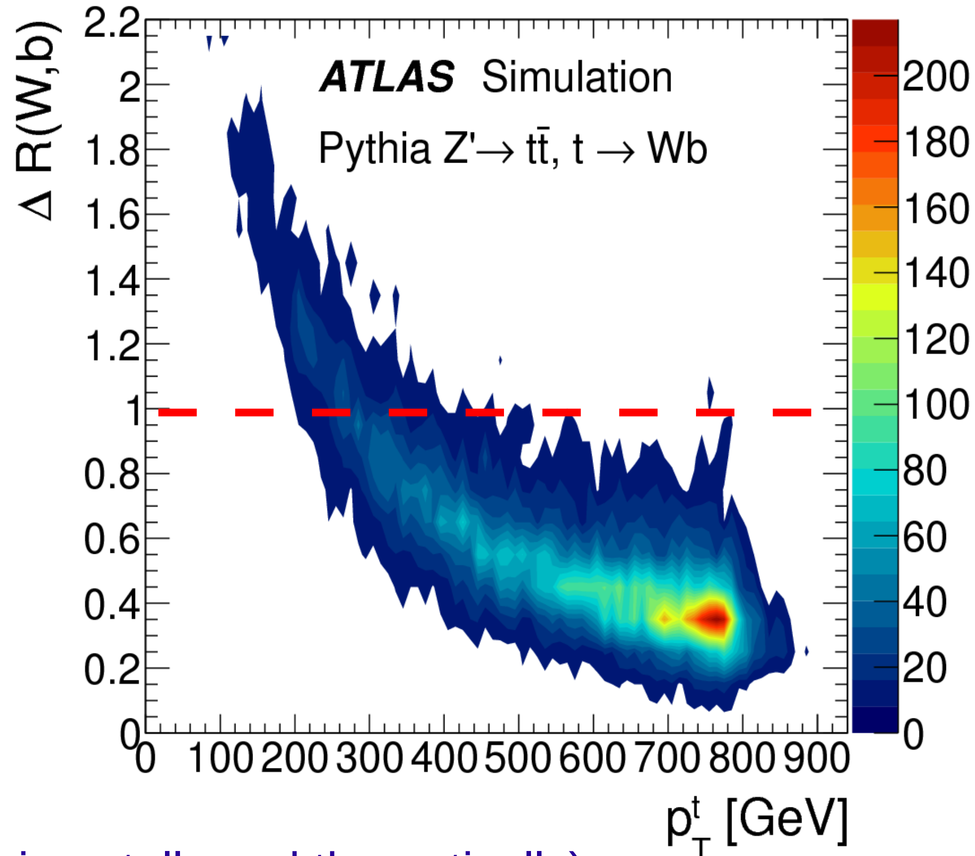
$t\bar{t}H$

Top FCNC

Boosted objects



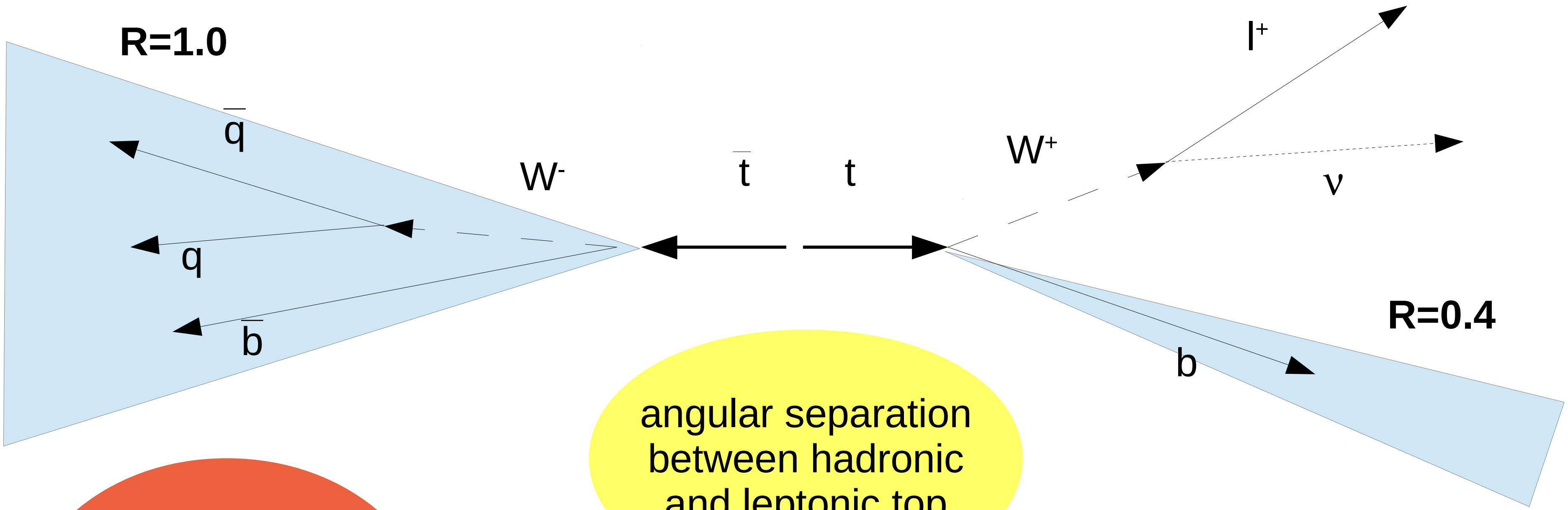
The large-R jet radius sets the p_T threshold



Boosted objects: rapidly evolving field (experimentally and theoretically)

2010	2011	2012	2013
Preparatory studies	Calibrations Validations	First physics results	Start precision studies

Boosted tops



angular separation between hadronic and leptonic top

large-R jet (akt10) with high p_T

jet substructure analysis

akt4 jet close to the lepton

b-tag

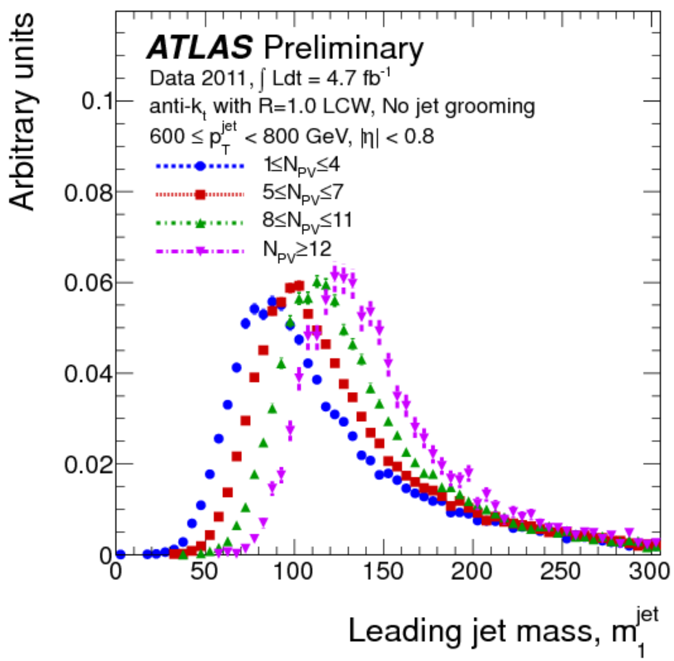
E_T^{miss}

Large-R jet grooming

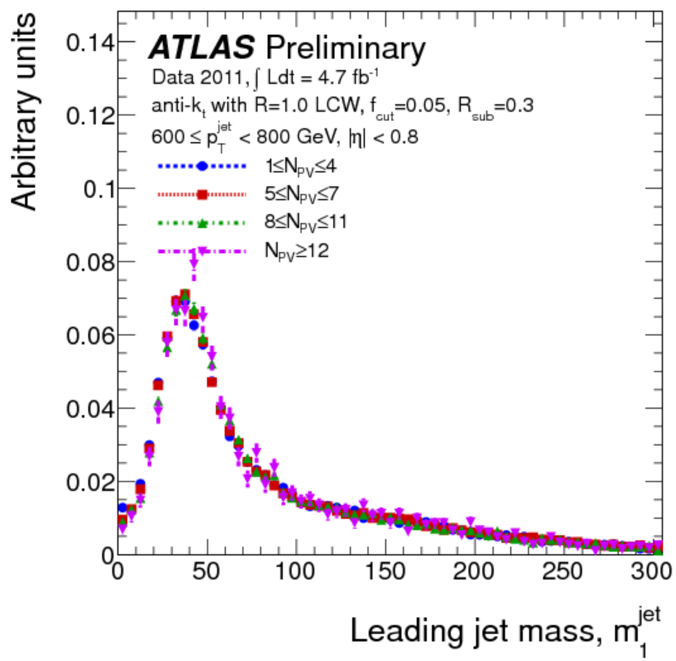
Jet grooming techniques (Mass-drop filering, Trimming, Pruning): mitigate the effect of the pile-up by removing soft radiation spatially uncorrelated with the main energy deposits

Trimming in ATLAS (default: f_{cut} = 5%, R_{sub} = 0.3)

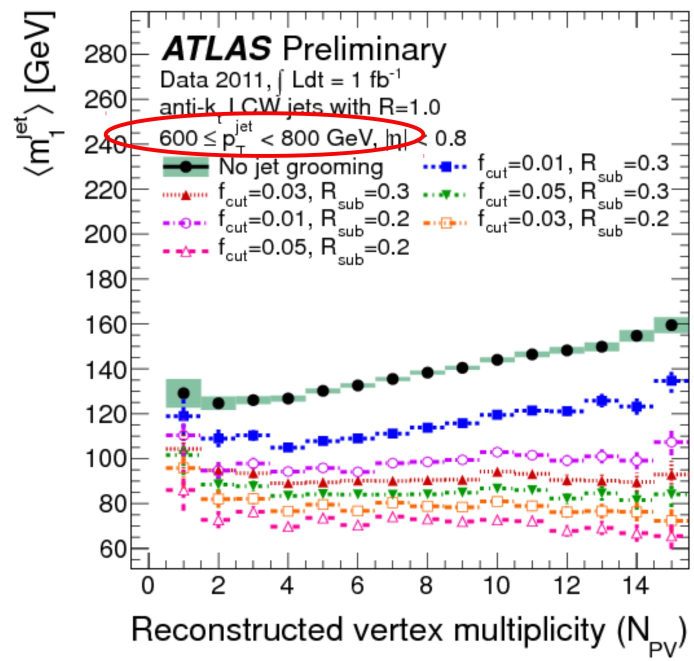
JHEP09 (2013) 076



Untrimmed



Trimmed



Effect of different trimming settings

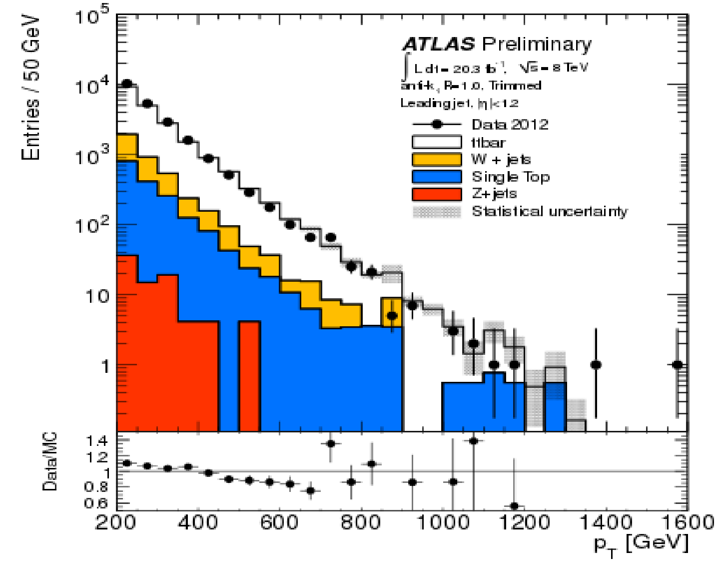
Mass and p_T of large-R jets

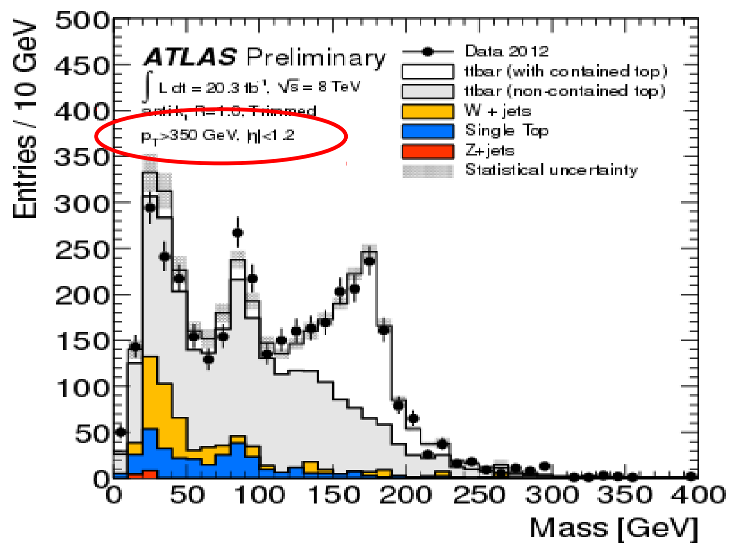
ATLAS-CONF-2013-084

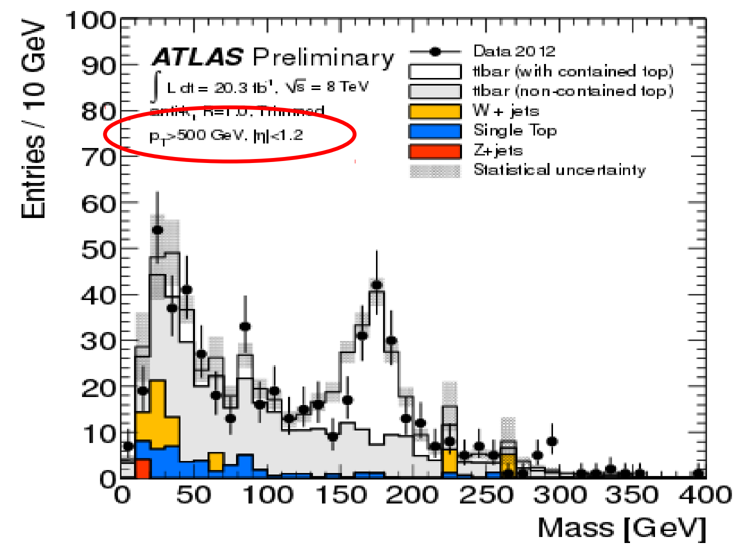
Boosted $t\bar{t}$ event selection

Hadronic top identified as large-R jet

Overall good agreement with theoretical expectations



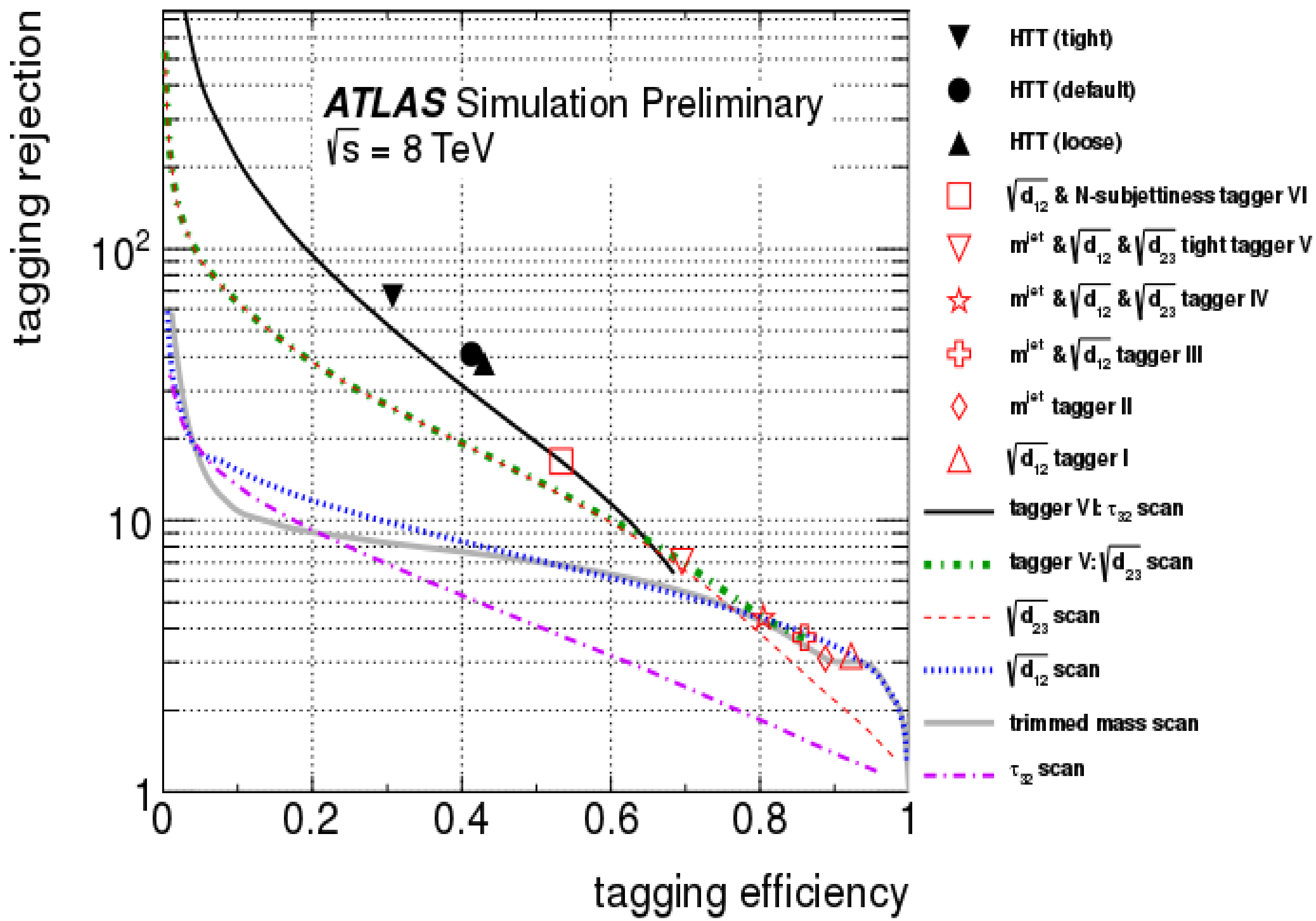




Top tagging techniques

Several techniques based on the analysis of the substructure of the large-R jet are used for tagging

- Mass
- Splitting scales
- n-subjettiness
- HEPTopTagger
- Template Overlap
- Shower deconstruction



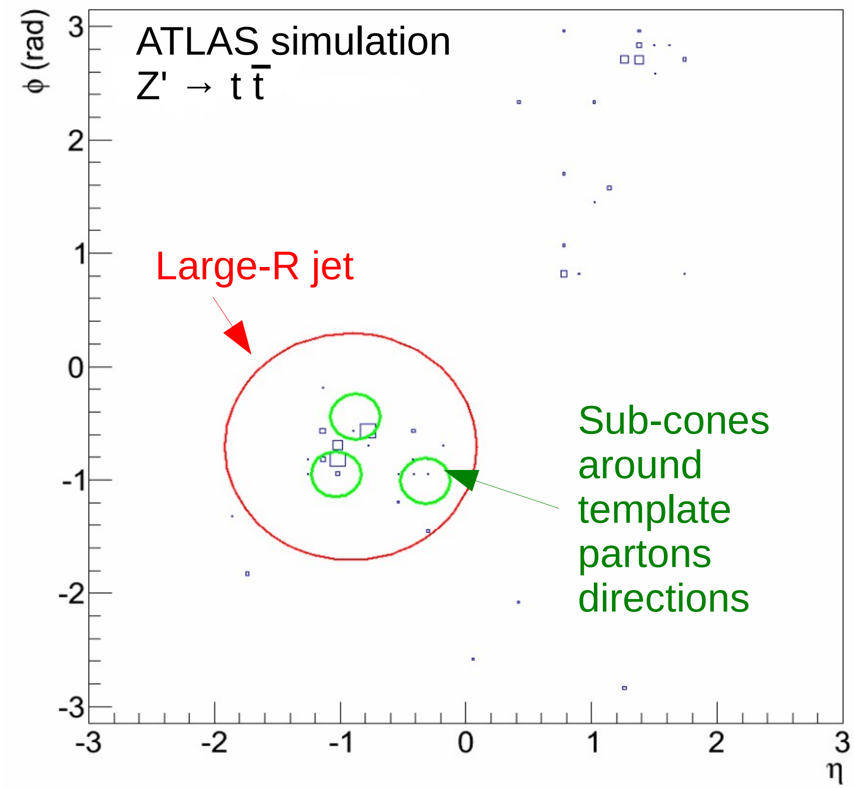
Template Overlap method

Generation of a large sample of top hadronic decays at the parton level (templates)

Energy deposits in the large-R jet are compared with the expectations from each template by summing energy deposition in sub-cones around the partons directions

Definition of an overlap function and loop over all templates to look the for maximum overlap

Technique with low sensitivity to pile-up



$$Ov = max_{(TS)} \left\{ exp \left[- \sum_i \frac{1}{2\sigma_i^2} \left[\sum_j E_j - E_i \right]^2 \right] \right\}$$

Maximum over all templates

Energy resolution (~E_i/3)

Sum over all reconstructed large-R jet constituents in a cone around the i[th] parton direction

Template parton energy

Top quark mass

Top quark pair production cross section

Top quark pair production charge asymmetry

$t\bar{t}$ resonances search

Boosted tops

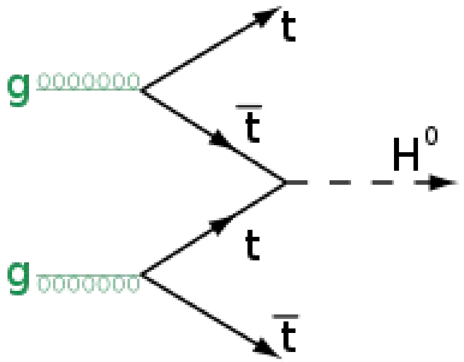
$t\bar{t}H$

Top FCNC

$t\bar{t}H$

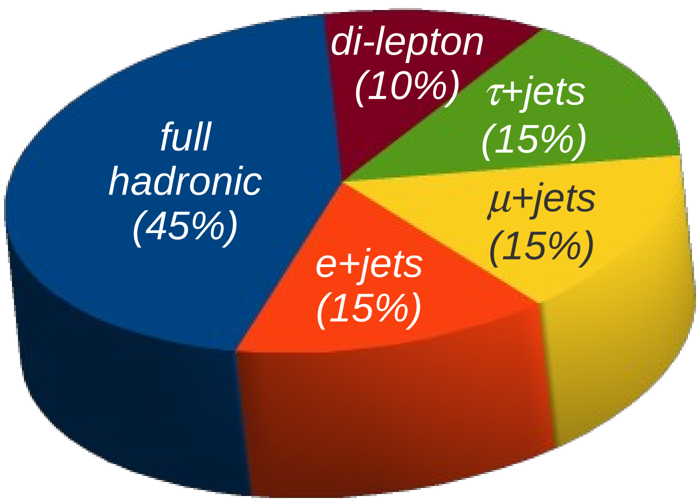
Measurement of the top-Higgs coupling

Cross section for $t\bar{t}H$ at the LHC:
 0.13 pb (8 TeV)
 0.61 pb (14 TeV)

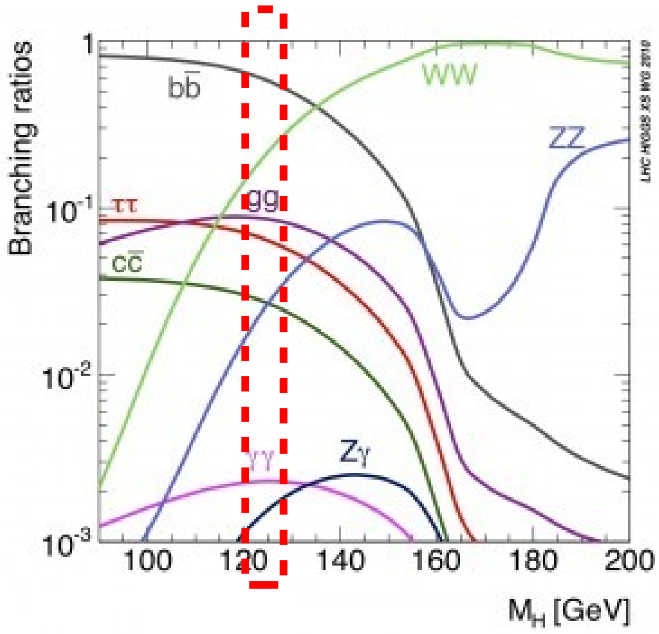


Complex final state with at least 8 objects
Several final states depending on $t\bar{t}$ and H decay modes

Natural "extension" of $t\bar{t}$ event selection
Main backgrounds from $t\bar{t}$ production associated with jets or EW bosons

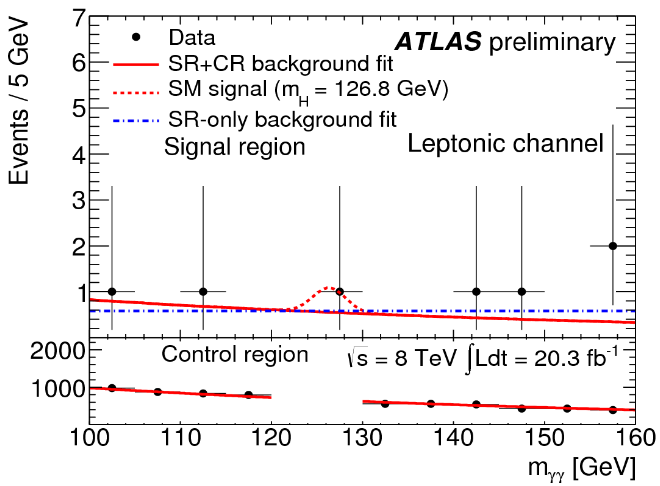


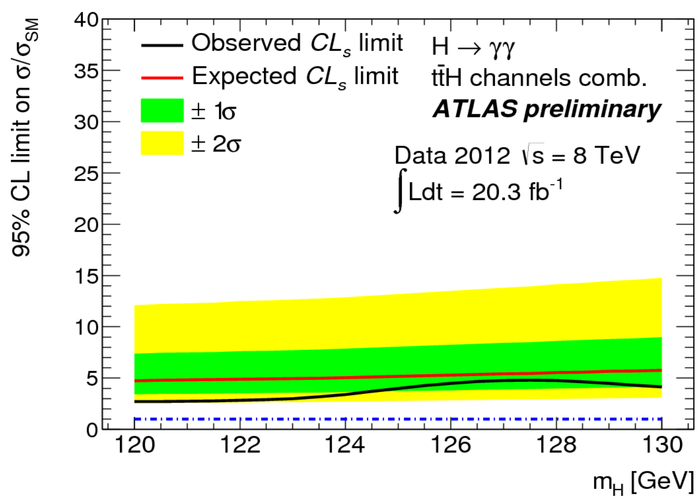
X



$t\bar{t}H$: examples

$t\bar{t}H$, $H \to \gamma\gamma$





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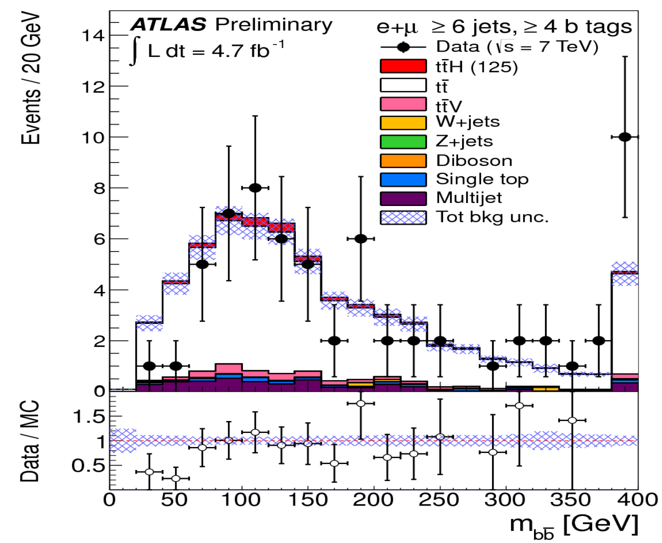
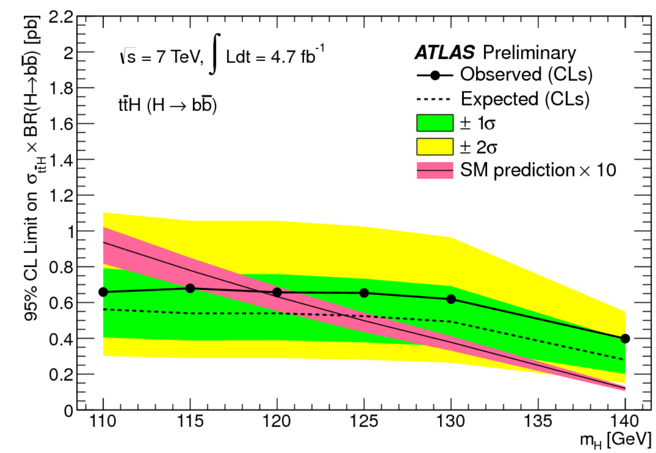
$t\bar{t}H$, $H \to b\bar{b}$





Expected precision on top Yukawa coupling at 14 TeV LHC: ~15% (300 fb^{-1}) - ~10% (3000 fb^{-1})

More details on $t\bar{t}H(\gamma\gamma)$ in the talk by Leandro

Top quark mass

Top quark pair production cross section

Top quark pair production charge asymmetry

$t\bar{t}$ resonances search

Boosted tops

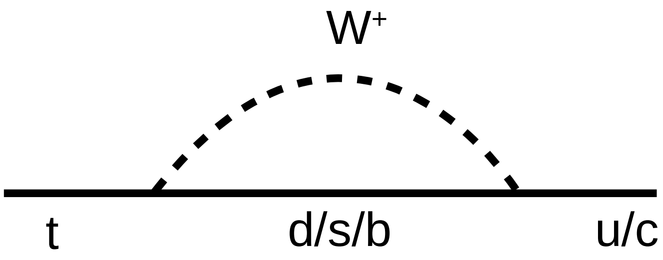
$t\bar{t}H$

Top FCNC

Top FCNC: BR limits

BR for FCNC processes <10^{-14} in the SM

Can be largely enhanced by new physics



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Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

QS: Quark-singlet model
2HDM-III: Two-Higgs doublet model without explicit flavor conservation
FC-2HDM: Two-Higgs doublet model with explicit flavor conservation
MSSM: Minimal supersymmetric model

Projected limits on top FCNC at the LHC

arXiv:1311.2028

	$t \to Zq$	$t \to \gamma q$	$t \to gu$	$t \to gc$	$t \to Hq$ ($\gamma\gamma$)	$t \to Hq$ (ll)
300 fb^{-1}	2.2×10^{-4}	8×10^{-5}	4×10^{-6}	1×10^{-5}	5×10^{-4}	2×10^{-3}
3000 fb^{-1}	7×10^{-5}	2.5×10^{-5}	1×10^{-6}	4×10^{-6}	2×10^{-4}	5×10^{-4}

Study of $t \to cH(\gamma\gamma)$ in ATLAS

ATL-PHYS-PUB-2013-012

Analysis strategy:

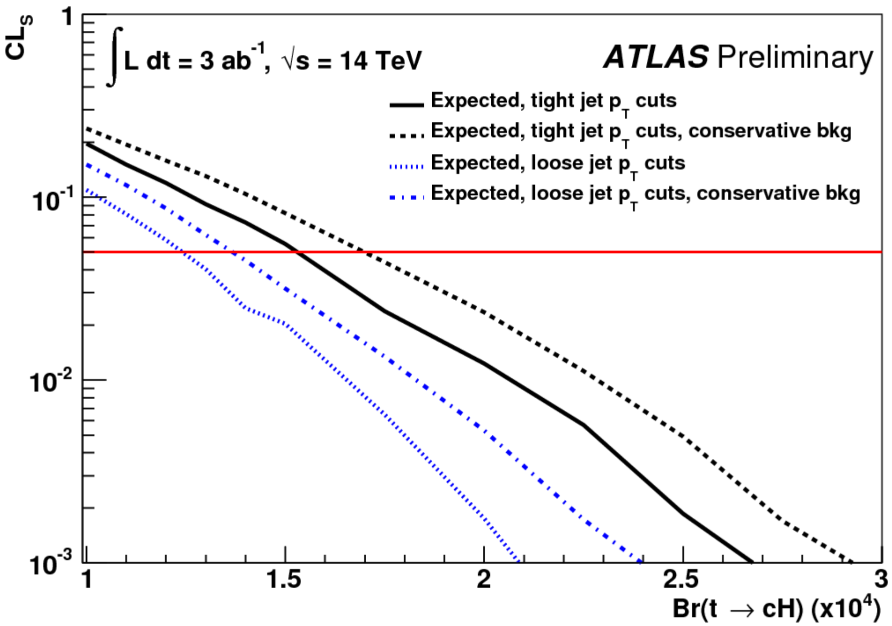
- Reconstruct the first top candidate in the $c\gamma\gamma$ channel
- Reconstruct the second top (either hadronic or leptonic decay)
- Extract number of signal events using $m_{\gamma\gamma}$ distribution

Extrapolation of the limits based on the analysis at 8 TeV (arXiv:1206.1257)

Considering different scenarios:

Nominal or conservative background
Number of background events extrapolated from the number observed at 8 TeV (or adding 1σ for a conservative estimate)

Loose or tight jet p_T cuts
30/25 GeV (or 50/35 GeV) on leading/subleading jet



LHC limit with 3 ab^{-1}: $BR(t \to cH) < 1.5 \times 10^{-4}$ at 95% C.L.

Conclusions

Several measurement in top physics will profit from the increased top production cross-section at 14 TeV and a larger integrated luminosity

14 TeV LHC with 300 fb^{-1} will allow precision SM physics for top:
- → m_t with sub-GeV uncertainty
- → Comparison of diff. cross section with theoretical models

Boosted top reconstruction studies needed for searches and precision physics measurements

BSM physics searches involving top quarks:
- → Push the limit on $t\bar{t}$ resonance production at ~3-4 TeV with 300fb^{-1}
- → Any top-FCNC observation implies new physics
- → Precision SM measurements needed for background modeling

Backup

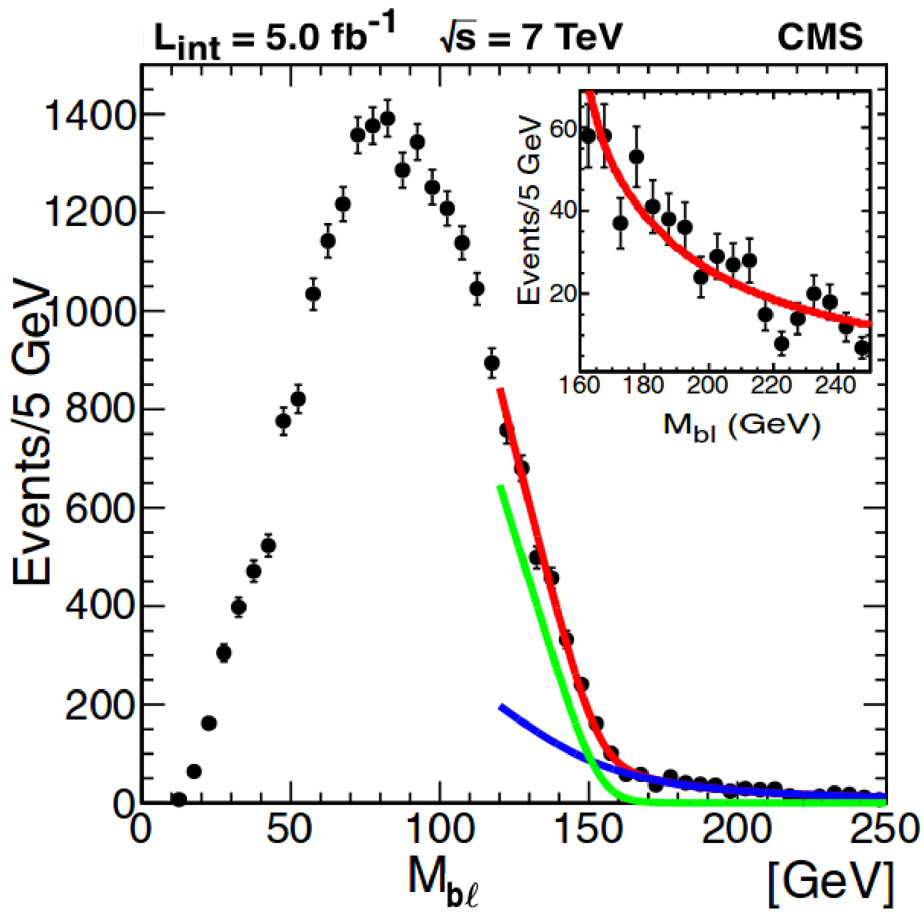
m_t with CMS endpoint method

Exploit kinematical variables correlated with m_t

Fit to the endpoint of three distributions (μ_{ll}, μ_{bb}, M_{bl}) in dilepton $t\bar{t}$ events

Precision comparable with other techniques using dilepton $t\bar{t}$ events

$m_t = 173.9 \pm 0.9\ (\mathrm{stat})\ ^{+1.7}_{-2.1}\ (\mathrm{syst})$ GeV
Main systematic contribution: JES



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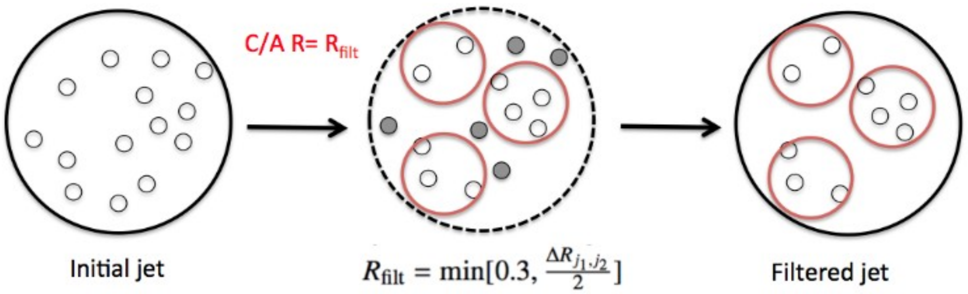
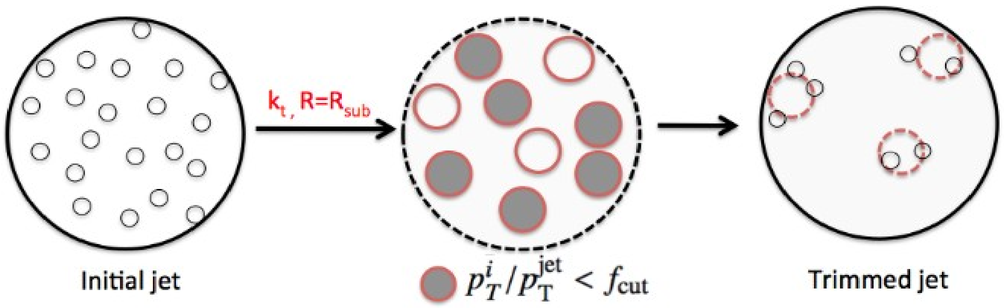
Jet grooming

Techniques used to mitigate the effect of pile-up (typically soft radiation spatially separated from the main energy deposits)

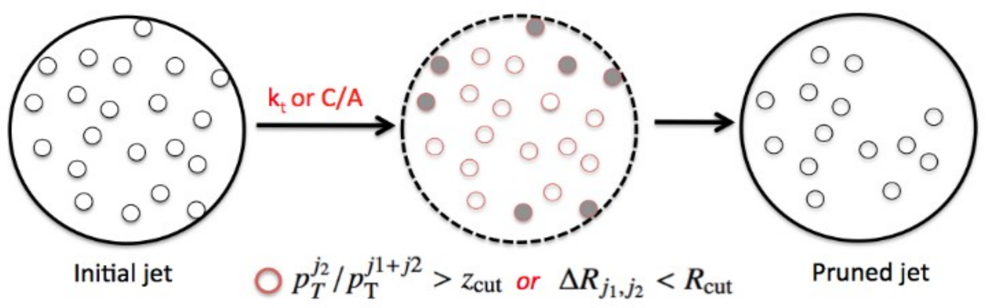
Mass-drop filtering: sub-jets with reduced R and significantly smaller mass are constructed. Residual energy deposits are rejected.



Trimming: sub-jets of smaller R are constructed. Sub-jets with p_T smaller than a fixed fraction of the p_T of the original jet are removed.



Pruning: jet reconstruction re-applied to all jet constituents. At each step of the reconstruction the constituents of small p_T and spatially separated are removed.



$t\bar{t}Z$

One event observed in ATLAS analysis ($4.7\ fb^{-1}$ at 7 TeV), in agreement with SM expectations

ATLAS: $\sigma(t\bar{t}Z)<0.71$ pb (95% CL)
SM: $\sigma(t\bar{t}Z)=0.14$ pb (NLO)

Will largely benefit from the increased energy (σ x 4) and integrated luminosity

Hundreds of events expected with $300\ fb^{-1}$ at 14 TeV

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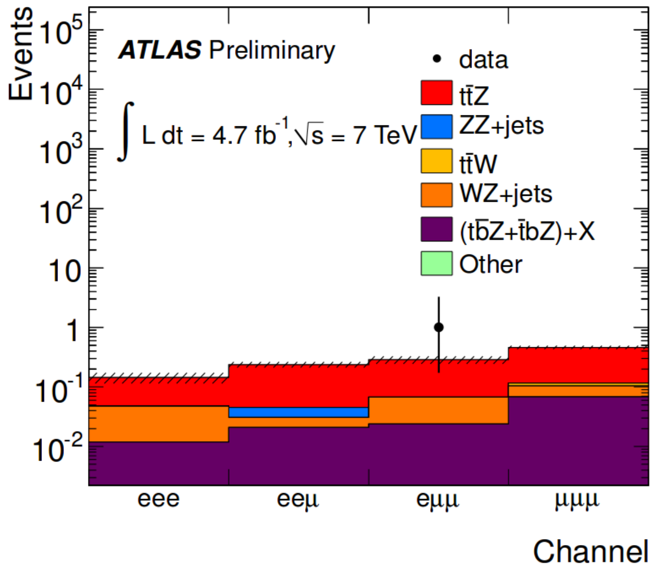
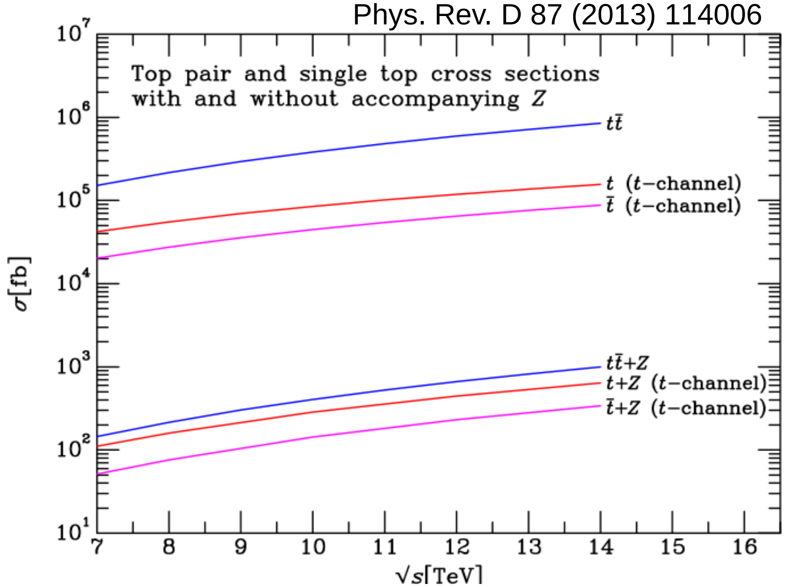


Phys. Rev. D 87 (2013) 114006



stop

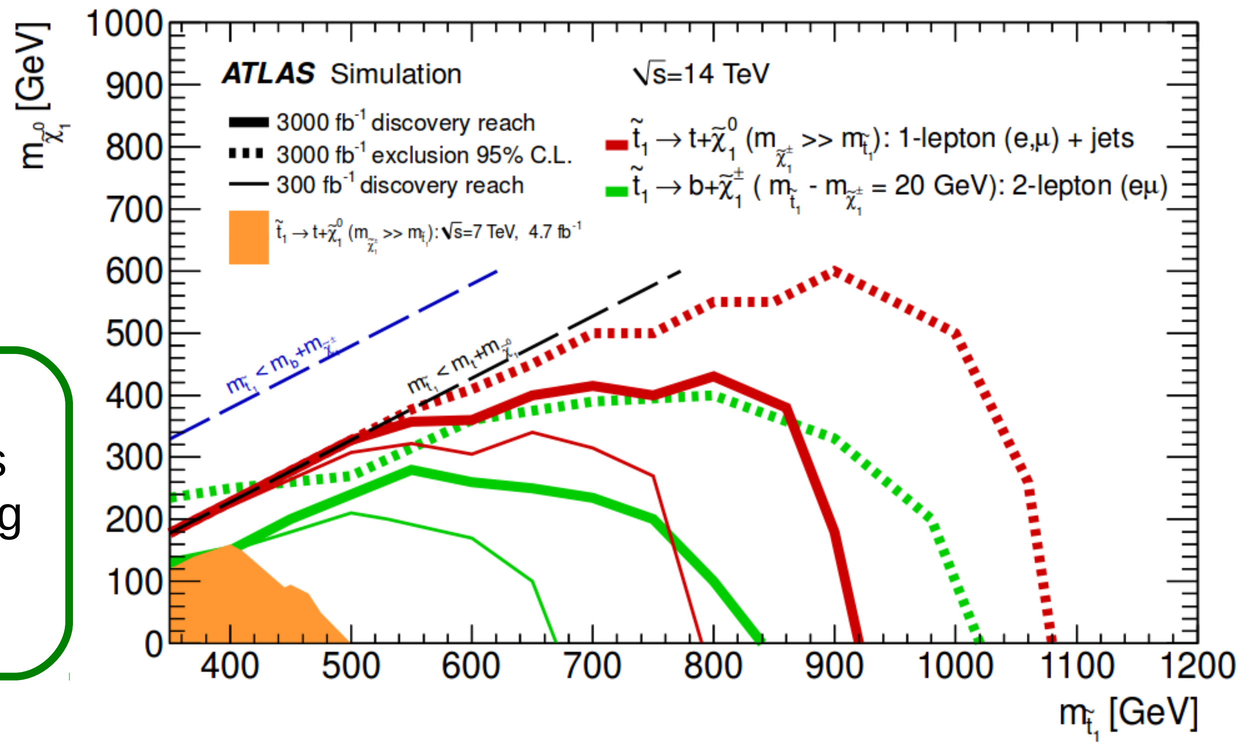
Discovery reach for a light top squark based on the decay to:

top + lightest supersymmetric particle
bottom + lightest chargino

- ✓ Top quark
- ✓ Large missing transverse momentum

- ✓ 2 b quarks
- ✓ 2 W bosons
- ✓ Large missing transverse momentum

arXiv:1307.7292



Increasing the total integrated luminosity from 300 fb^{-1} to 3000 fb^{-1} increases the stop mass discovery reach from ~800 GeV to ~920 GeV.